Vendo o universo através dos neutrinos

FAPESP
FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

Gustavo F. S. Alves

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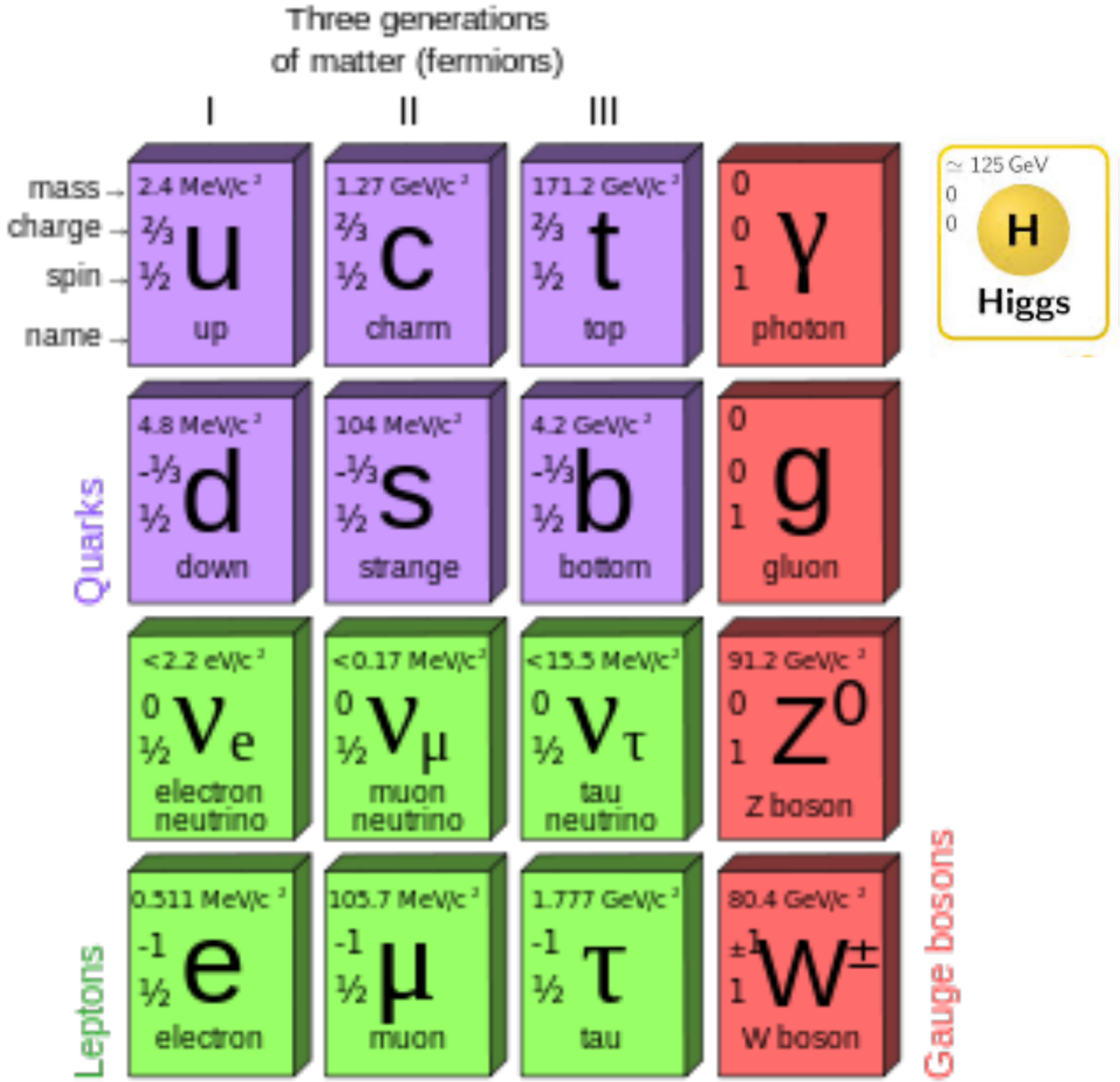
O caminho para descobrir os neutrinos

O caminho para descobrir os neutrinos

O caminho para chegar ao Modelo Padrão

O modelo padrão

A melhor descrição da natureza que temos até o presente momento.



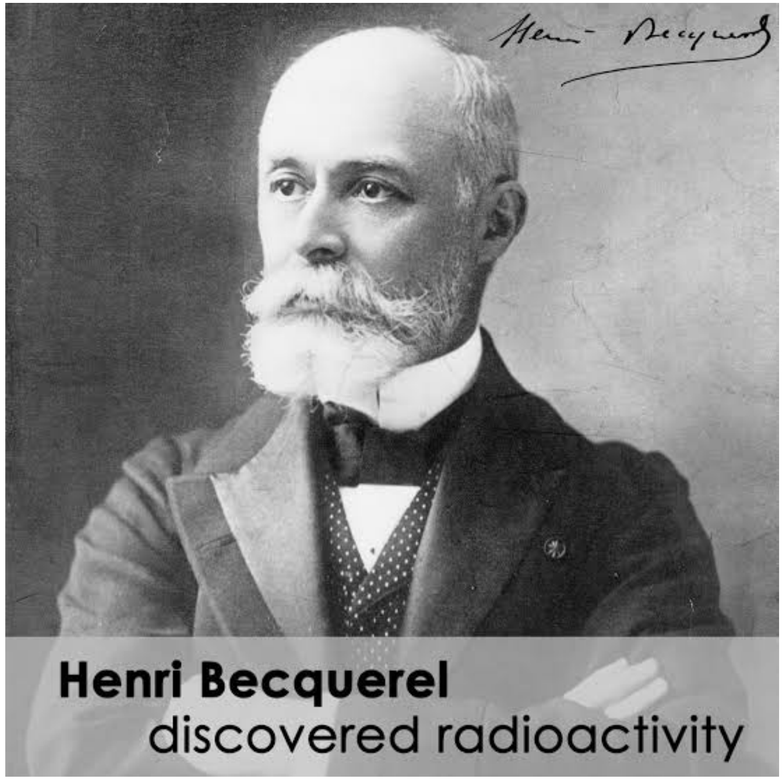
Um pouquinho de história:
O caminho para descobrir os neutrinos

Um pouquinho de história:
O caminho para descobrir os neutrinos

Descoberta da radioatividade

To test this idea (which turned out to be wrong), Becquerel wrapped photographic plates in black paper so that sunlight could not reach them. He then placed the crystals of uranium salt on top of the wrapped plates, and put the whole setup outside in the sun. When he developed the plates, he saw an outline of the crystals. He also placed objects such as coins or cut out metal shapes between the crystals and the photographic plate, and found that he could produce outlines of those shapes on the photographic plates.

Fonte: APS news: Becquerel discovers radioactivity



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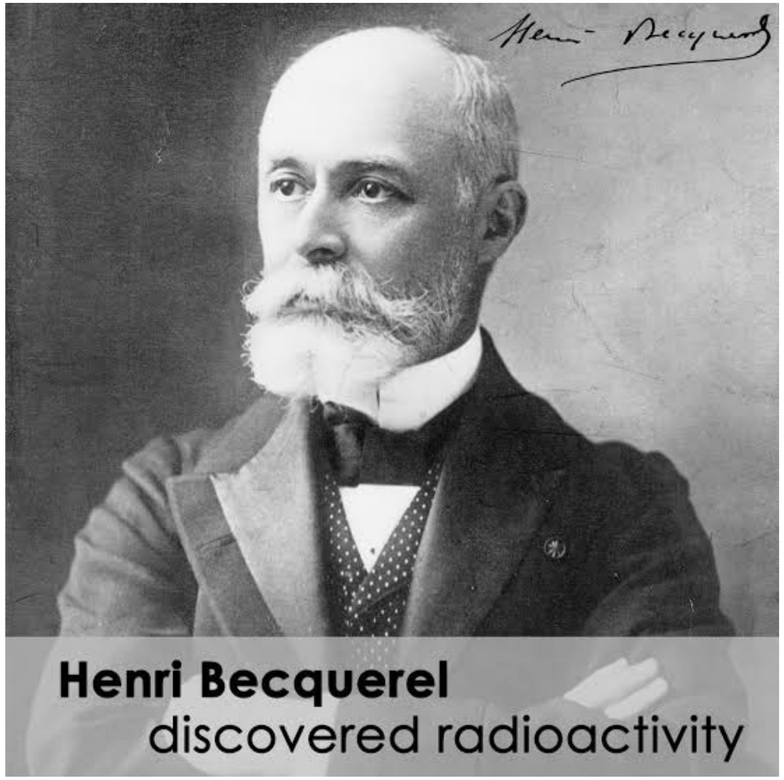
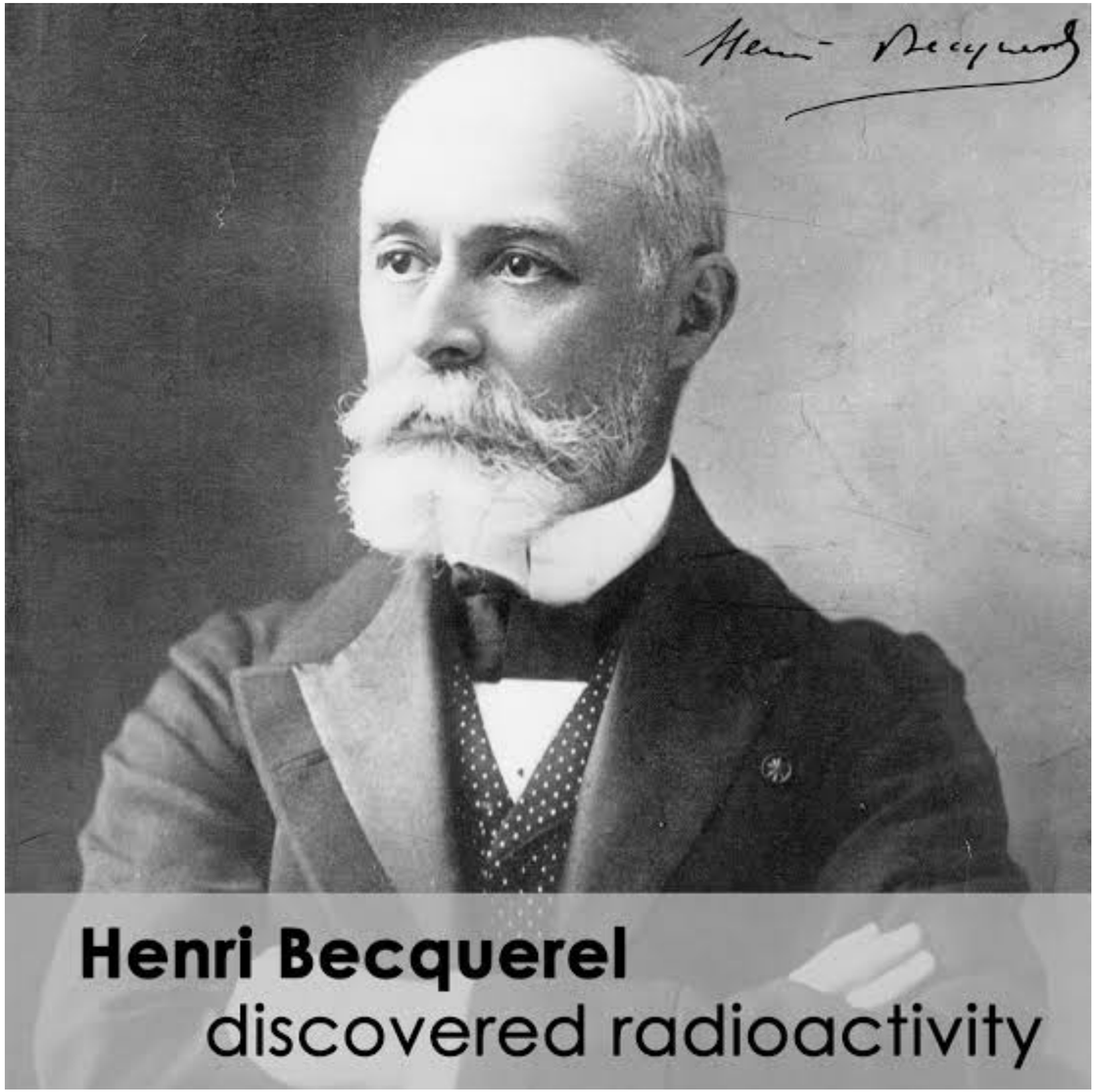


Descoberta da radioatividade

Como vocês verão todo caminho para uma descoberta é altamente não linear



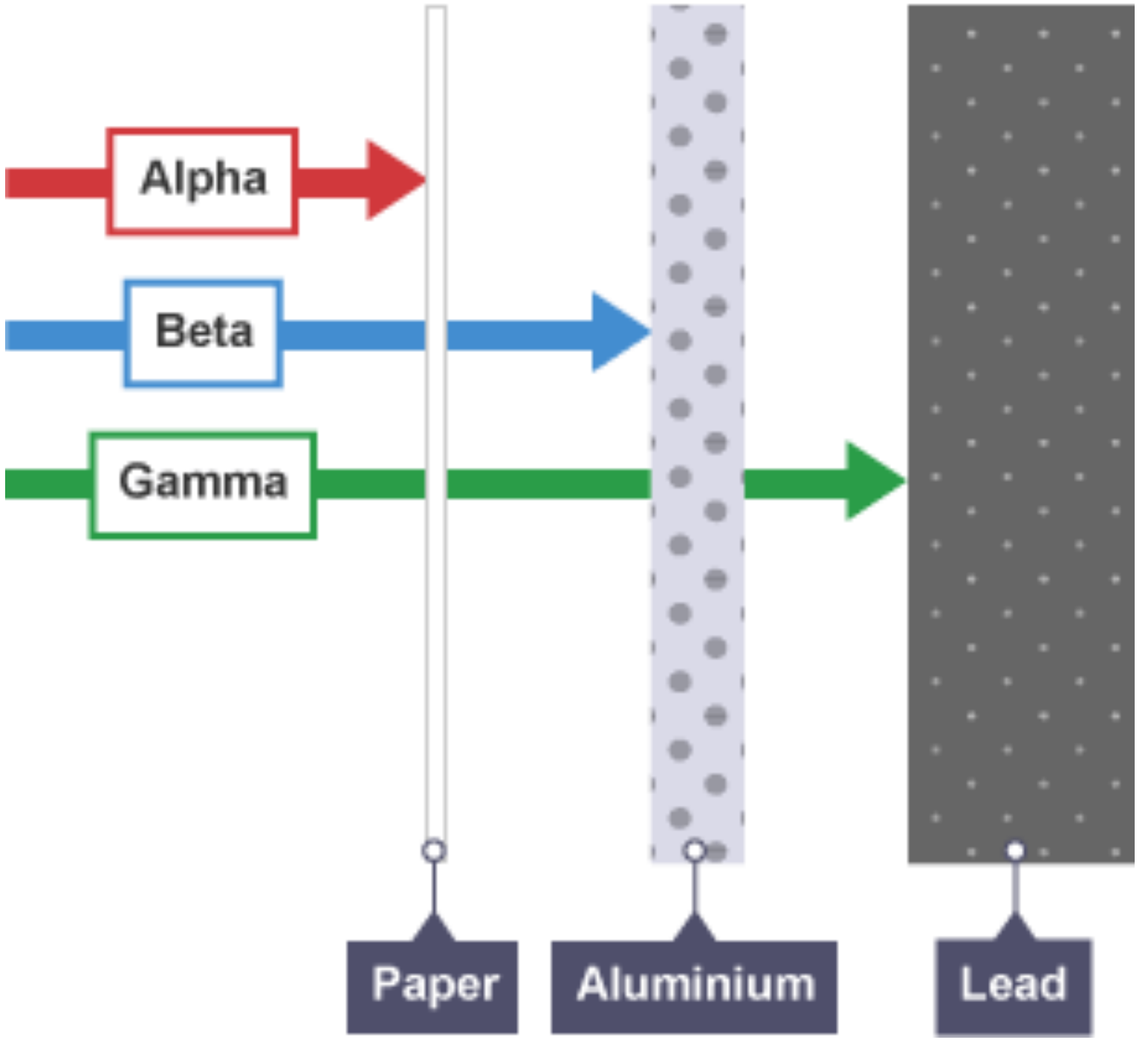
Entendendo a radioatividade

Marie and Pierre Curie

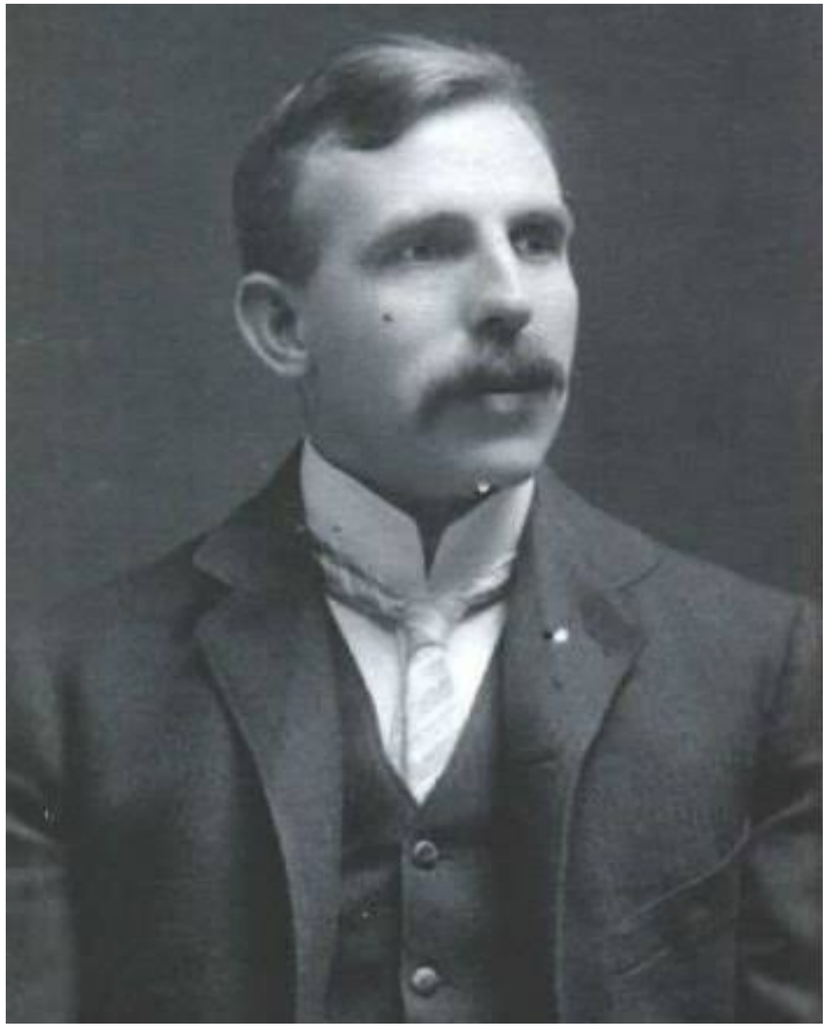
Descoberta de novos elementos radioativos

incluindo o rádio

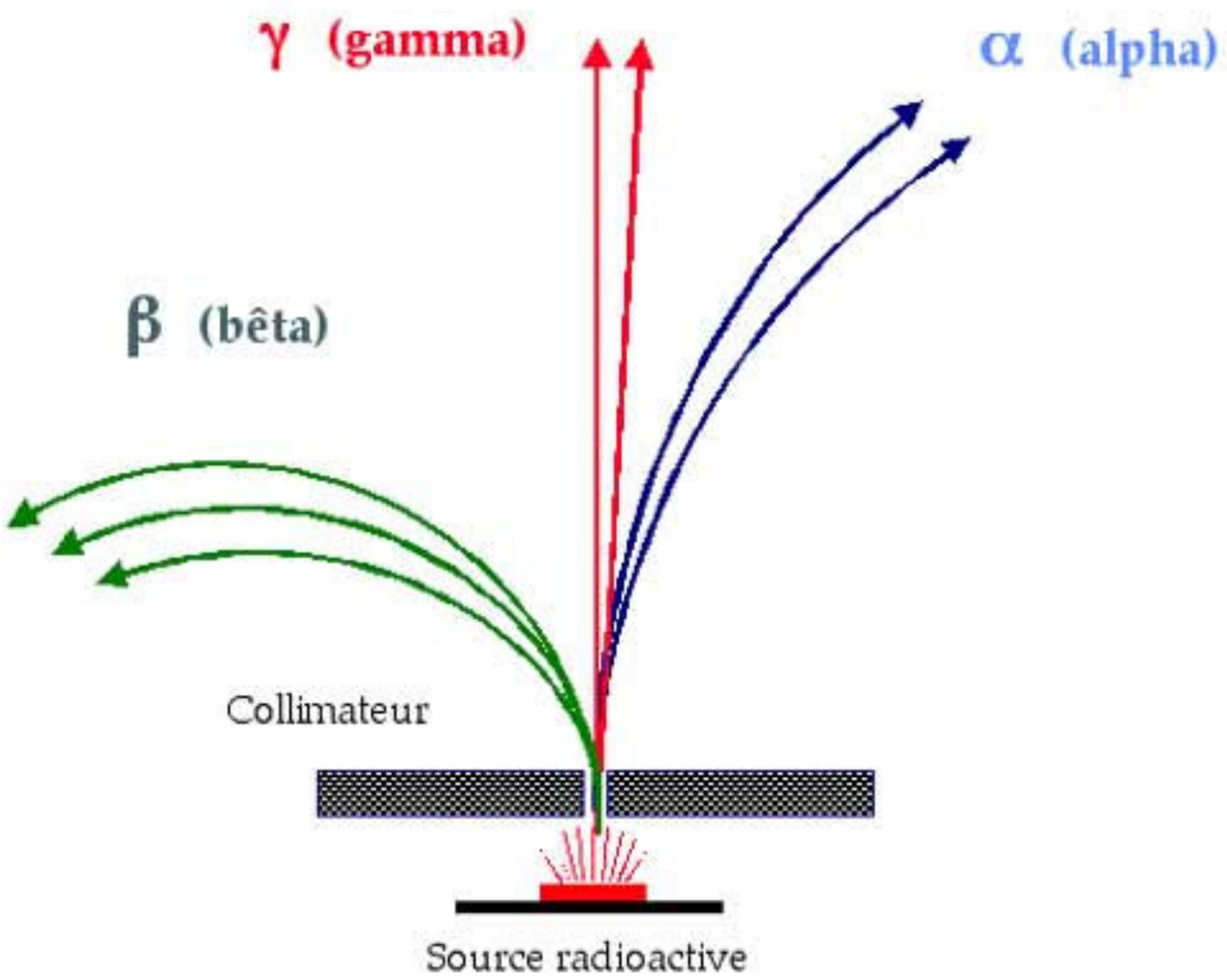
Tipos de radiação



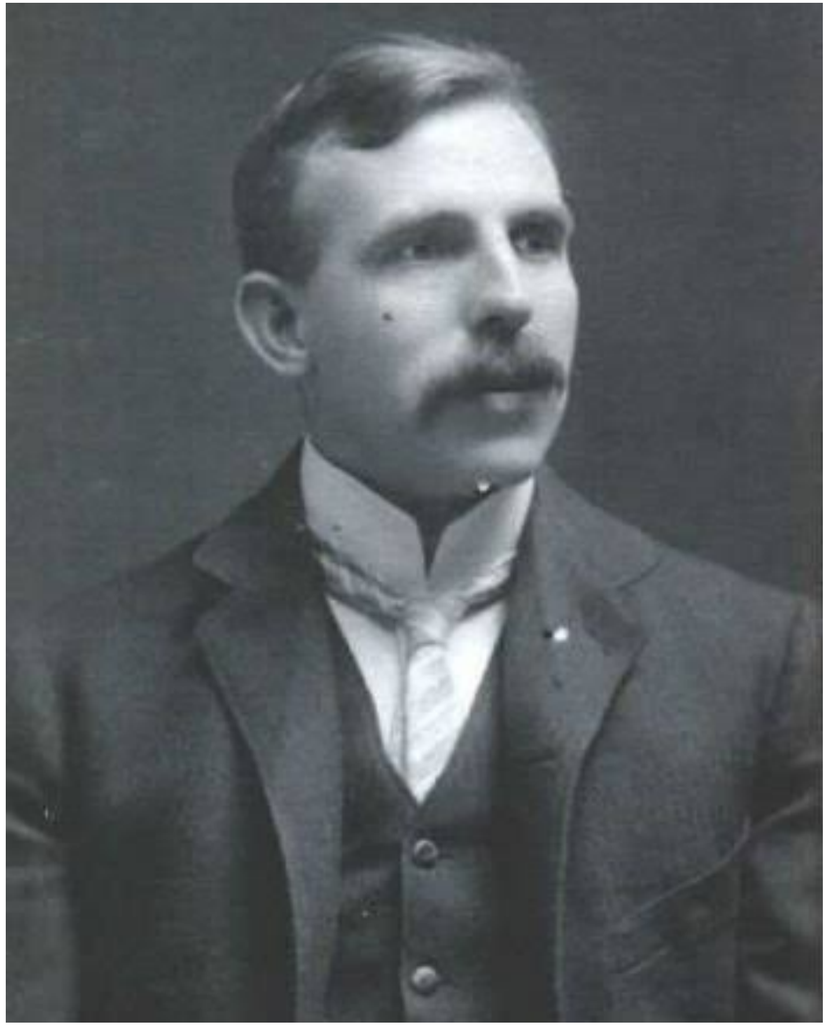
Rutherford



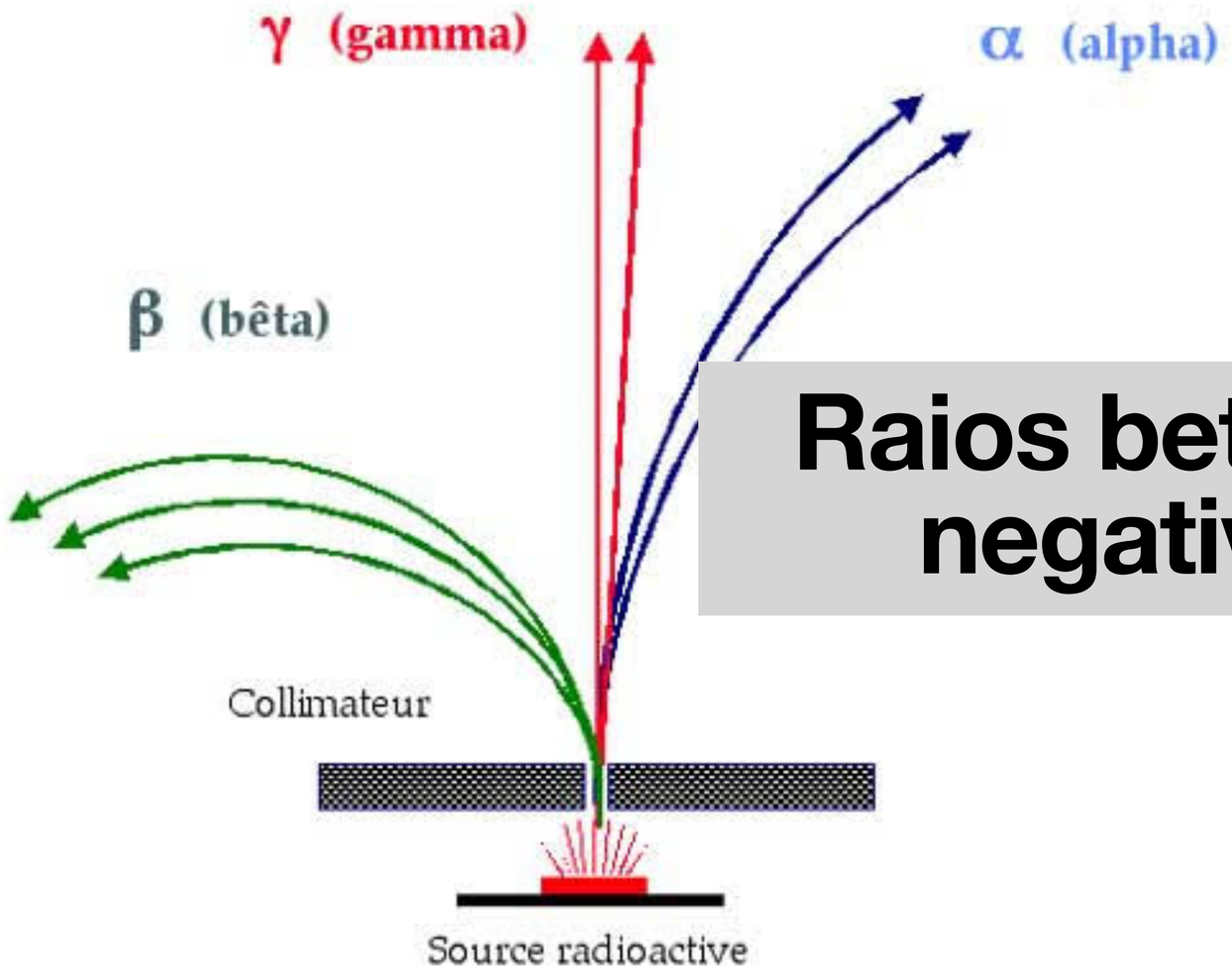
Tipos de radiação



Rutherford

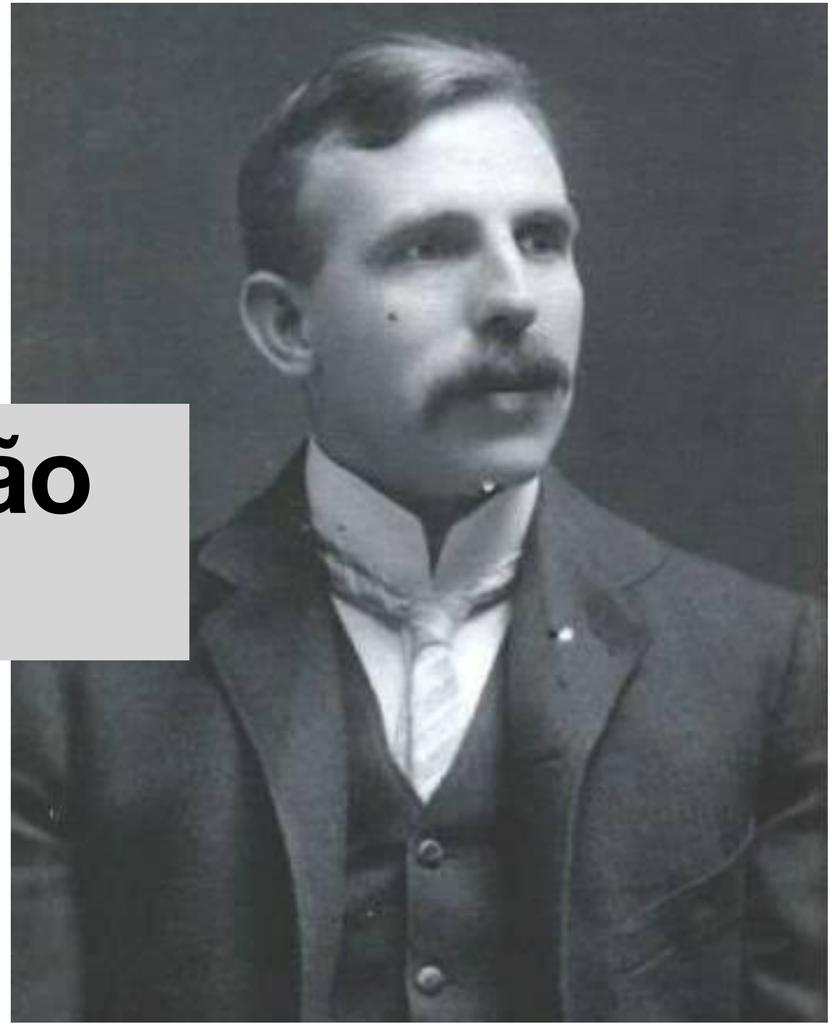


Tipos de radiação



Raios beta são negativos

Rutherford



“Unificando partículas”

“Unificando partículas”

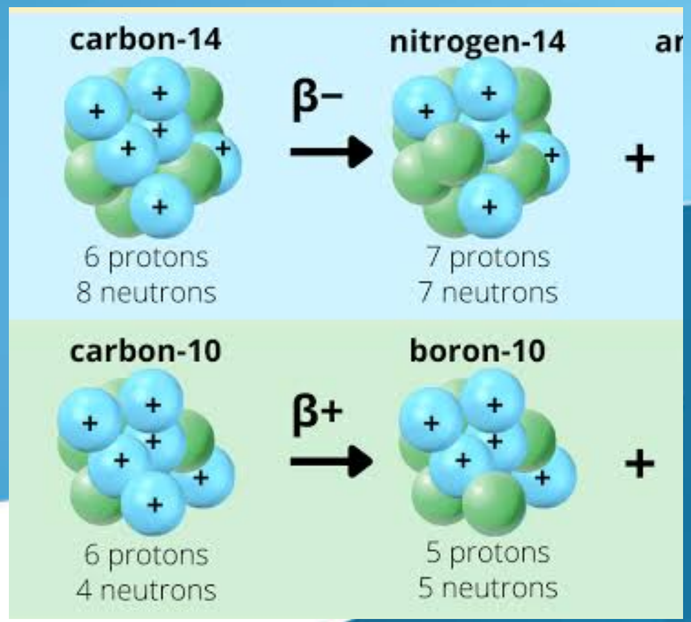
J. J. Thomson

Raios beta

🤝

Raios catódicos (elétrons)

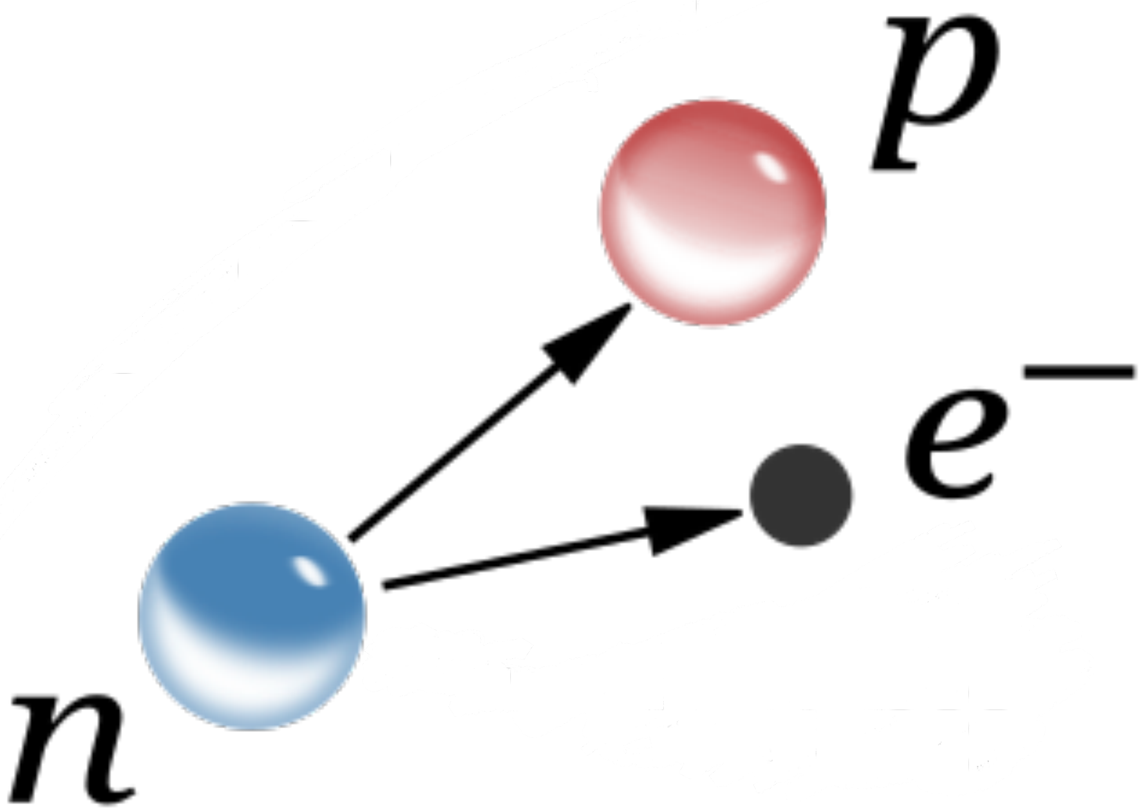
Parada número dois



O decaimento beta

O decaimento beta

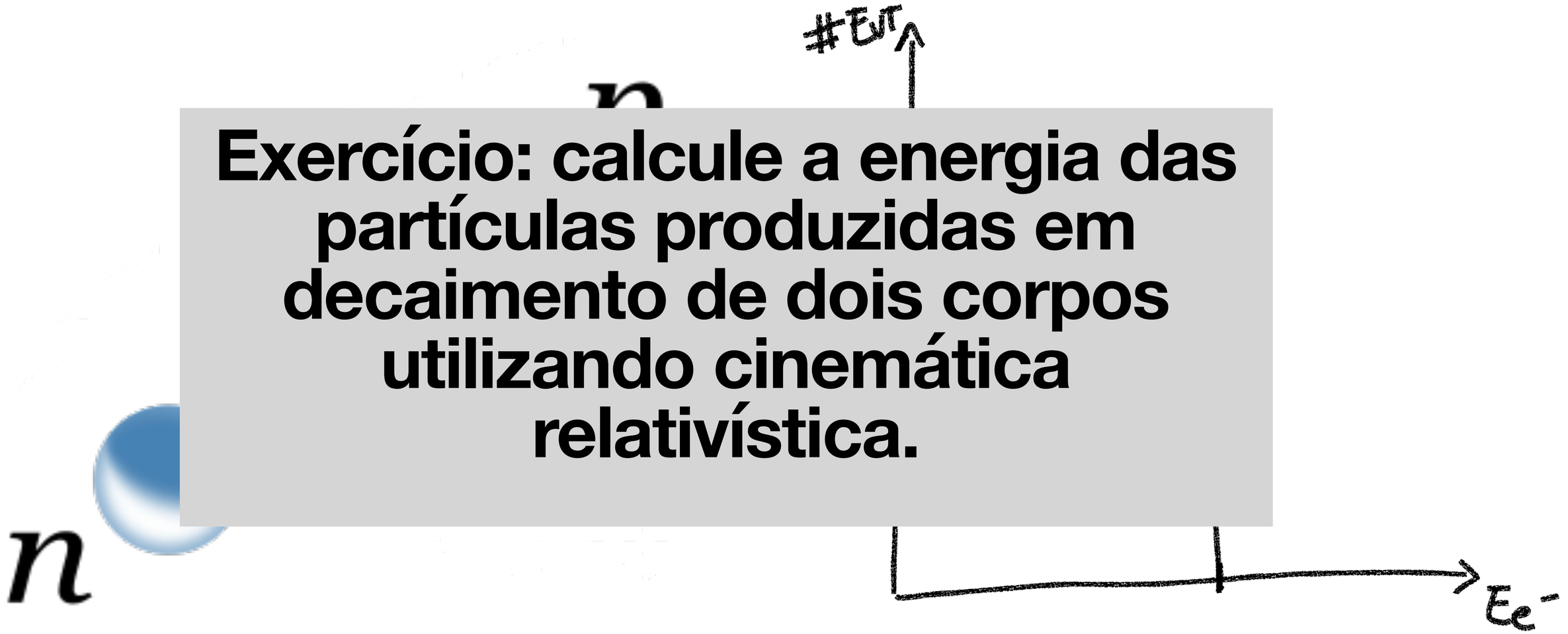
Conservação de energia



O decaimento beta

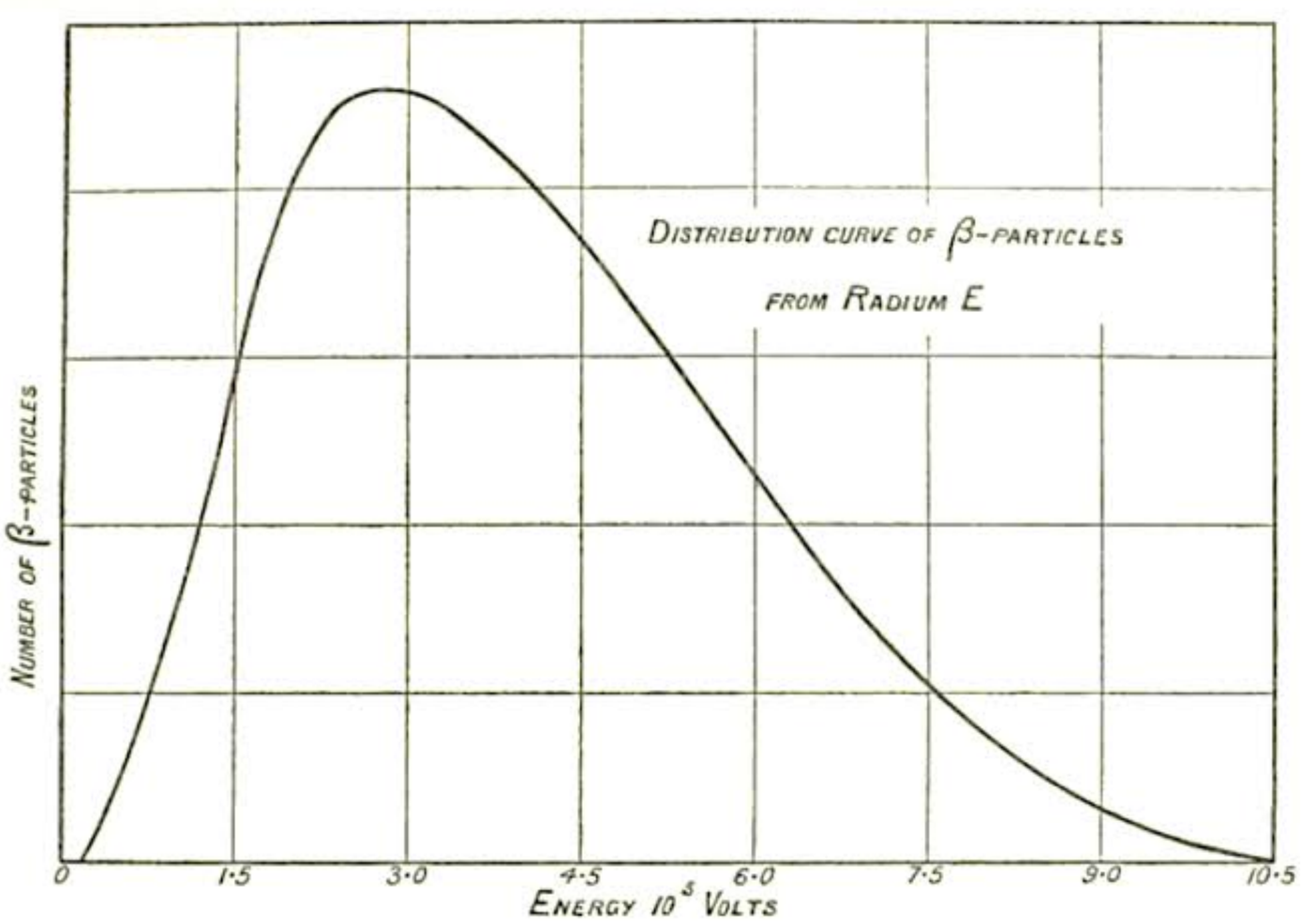
Conservação de energia

Exercício: calcule a energia das partículas produzidas em decaimento de dois corpos utilizando cinemática relativística.



O decaimento beta

Observação



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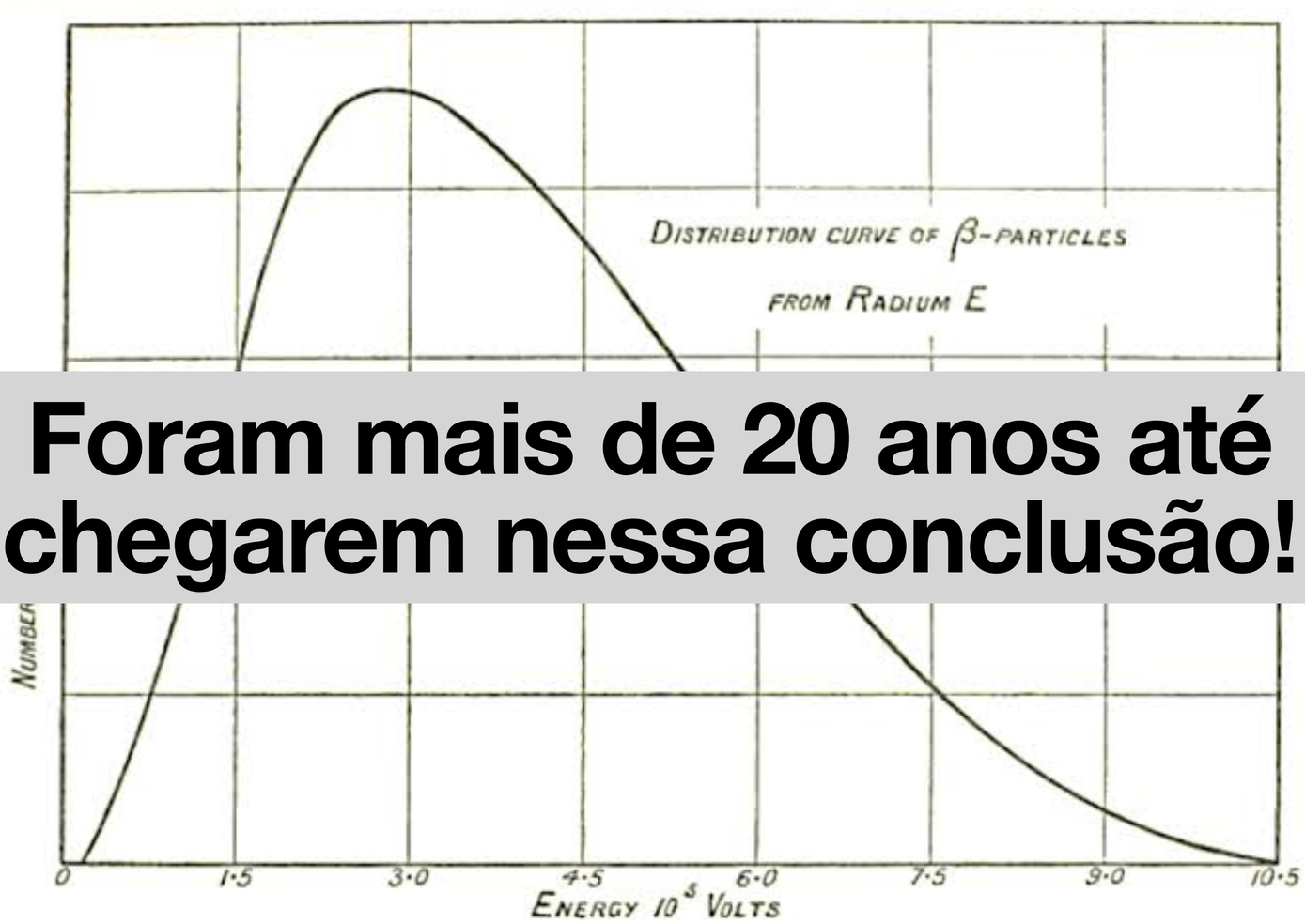

Foram mais de 20 anos até chegarem nessa conclusão!

Do lado da teoria: Conservação de energia sob ataque!

“As regards the occurrence of transitions, which is the essential feature of the quantum theory, we abandon on the other hand any attempt at a causal connection between the transitions in distant atoms, and especially a direct application of the principles of energy and momentum so characteristic for the classical theories.”

(Bohr, Kramers and Slater).

Do lado da teoria: Conservação de energia sob ataque!

“It is impossible to believe that if science of the present time had not been saturated with the idea of conservation of energy, these complications would be avoided by saying that there is no exact conservation in such cases.”

(Darwin, Sommerfeld)

“At present I have high hopes for solving the radiation problem, and that without light-quanta… One must renounce the energy principle in its present form.”

(A. Einstein)

Do lado da teoria: Conservação de energia sob ataque!

“It is impossible to believe that if science of the present time had not been saturated with the idea of conservation of energy, these complications would be avoided by saying that there is no exact conservation in such cases.”

(Darwin, Sommerfeld)

Três dias depois ele escreveu outra carta falando que não funcionou

Os defensores da conservação de energia

“I should prefer to keep rigorous conservation of energy at all costs.”

(Dirac)

“I have hearded that you [Bohr] are on the warpath and wanting to upset the Conservation of Energy both microscopically and macroscopically. I will wait and see before expressing an opinion but I always feel there are more things in Heaven and Earth than are dreamt of in our philosophy.”

(Rutherford)

Os defensores da conservação de energia

“I must say that your paper has given me little satisfaction… I do not exactly mean that this is unpermissible but it is a risky business.. Let the stars radiate in piece”

(Pauli)

Um remédio desesperado: O neutrino

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 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 den 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

Um remédio desesperado: O neutrino

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, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that 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. 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 mass. - 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.

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

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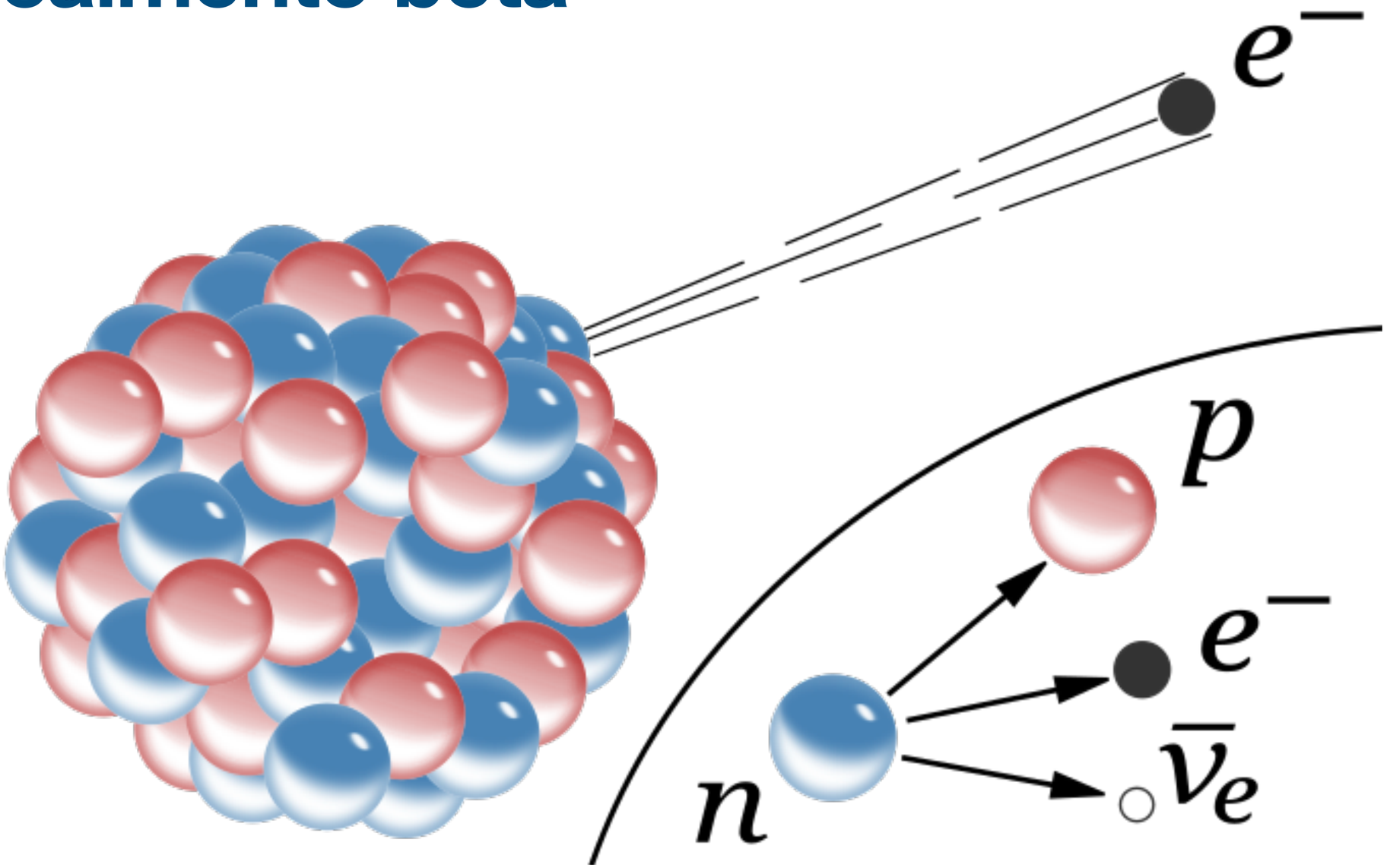
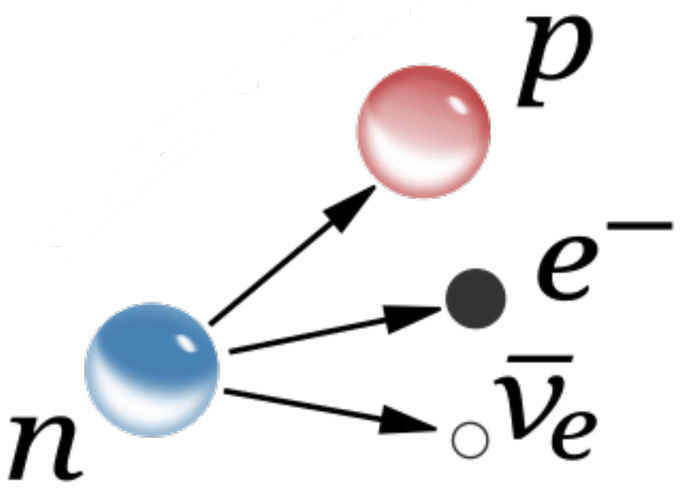
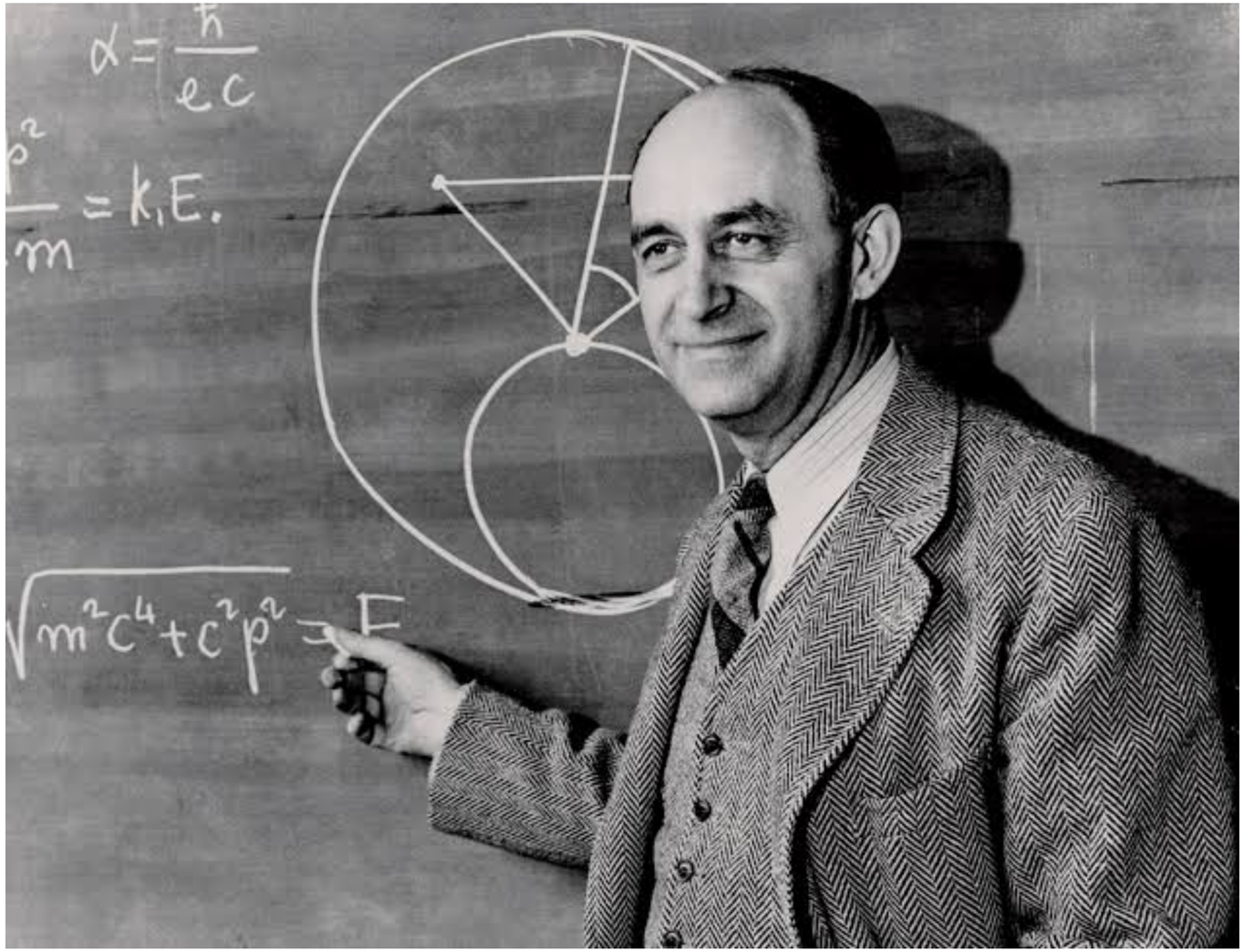
O decaimento beta



Enrico Fermi leva Pauli a sério

Teoria do decaimento beta





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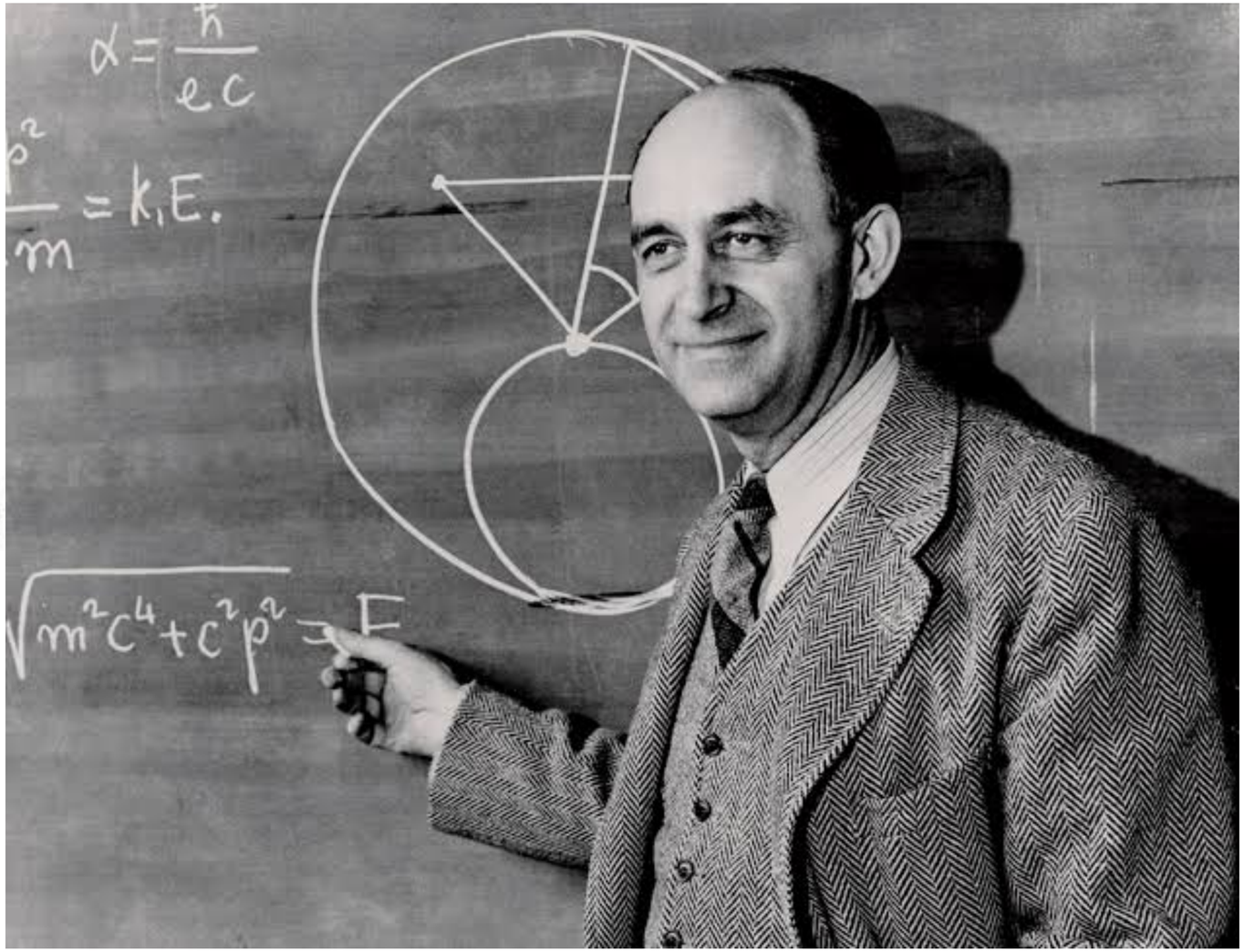
Teoria do decaimento beta

SCALAR	$\overline{\psi}\phi$
PSEUDOSCALAR	$\overline{\psi}\gamma^5\phi$
VECTOR	$\overline{\psi}\gamma^\mu\phi$
AXIAL VECTOR	$\overline{\psi}\gamma^\mu\gamma^5\phi$
TENSOR	$\overline{\psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\phi$



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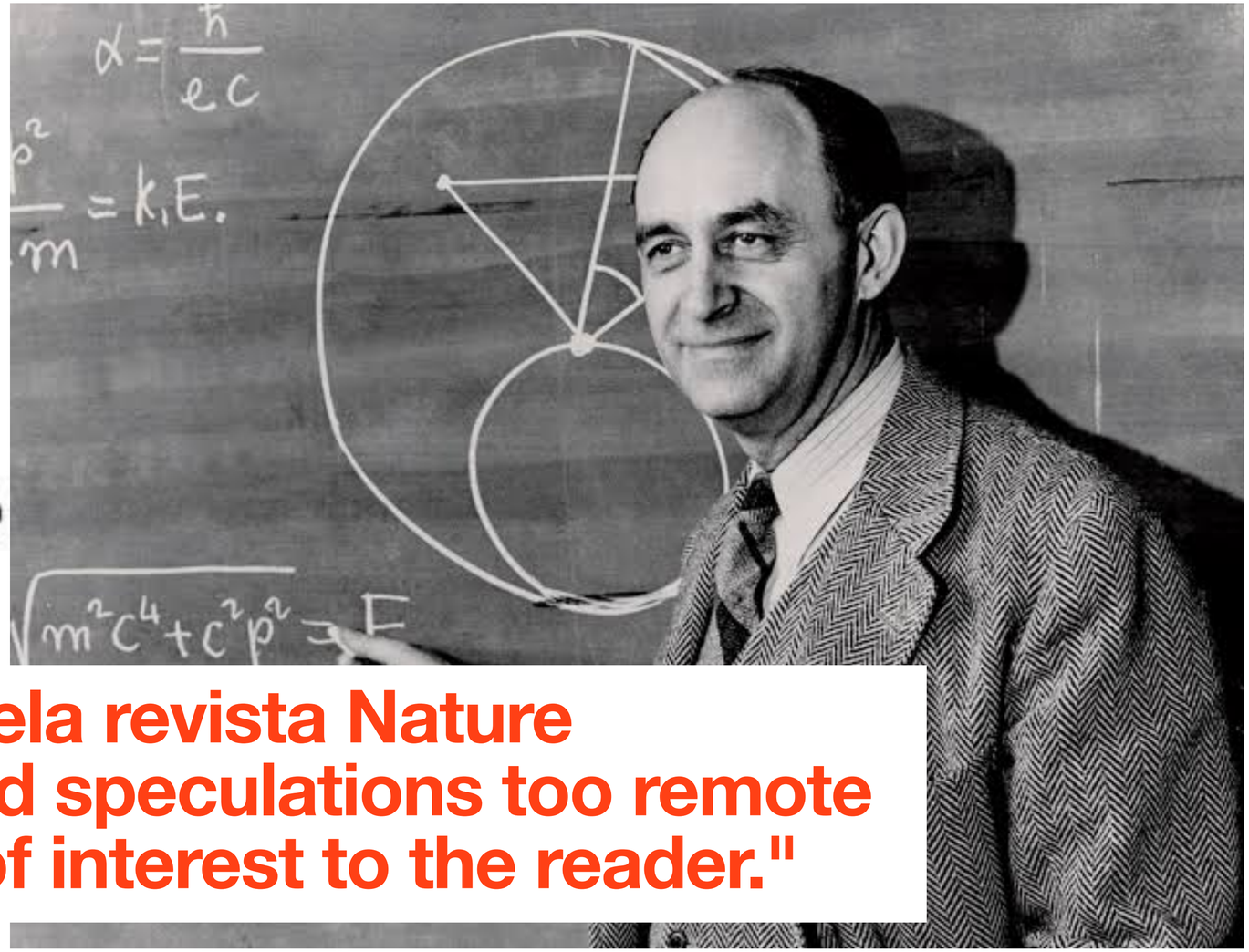
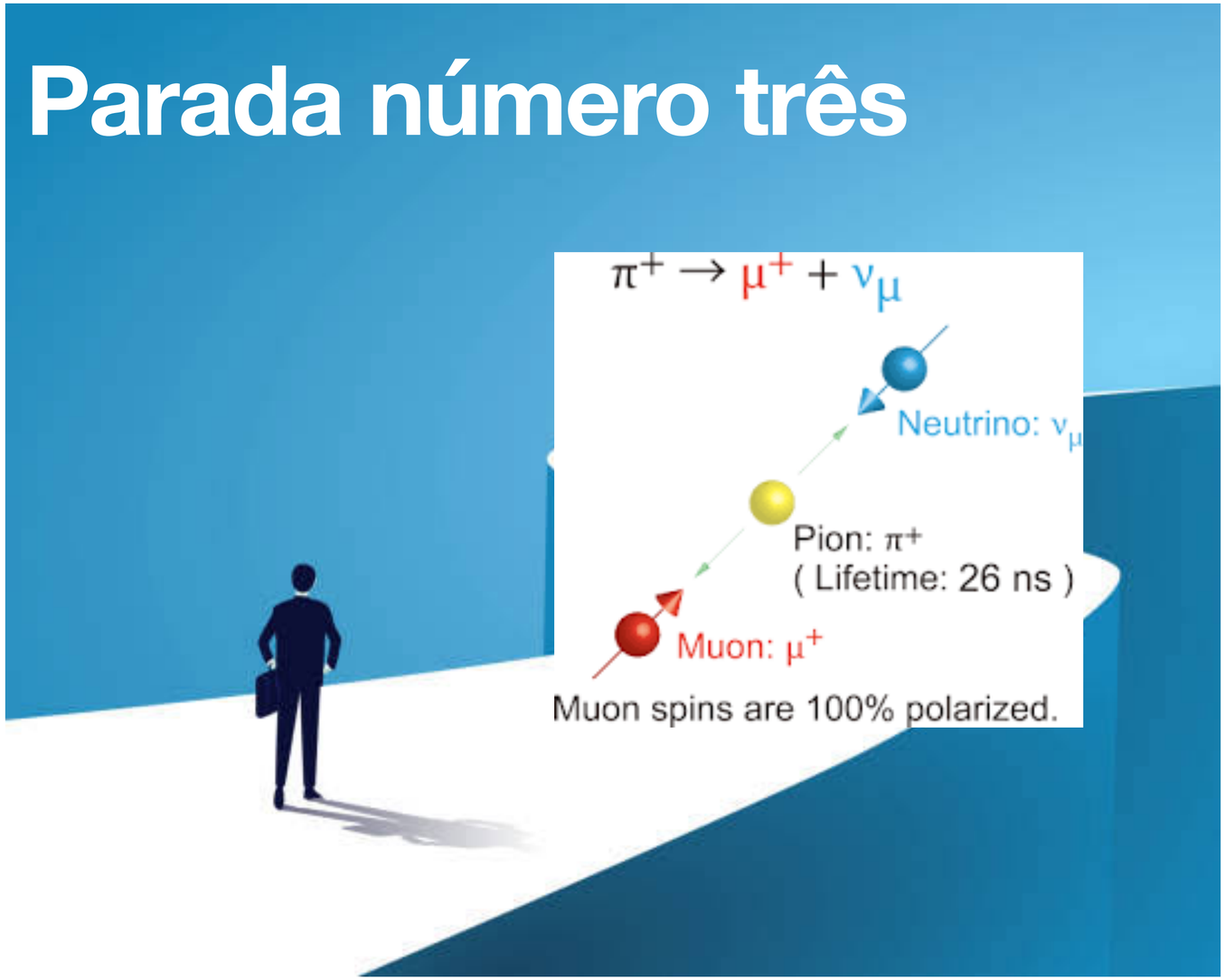
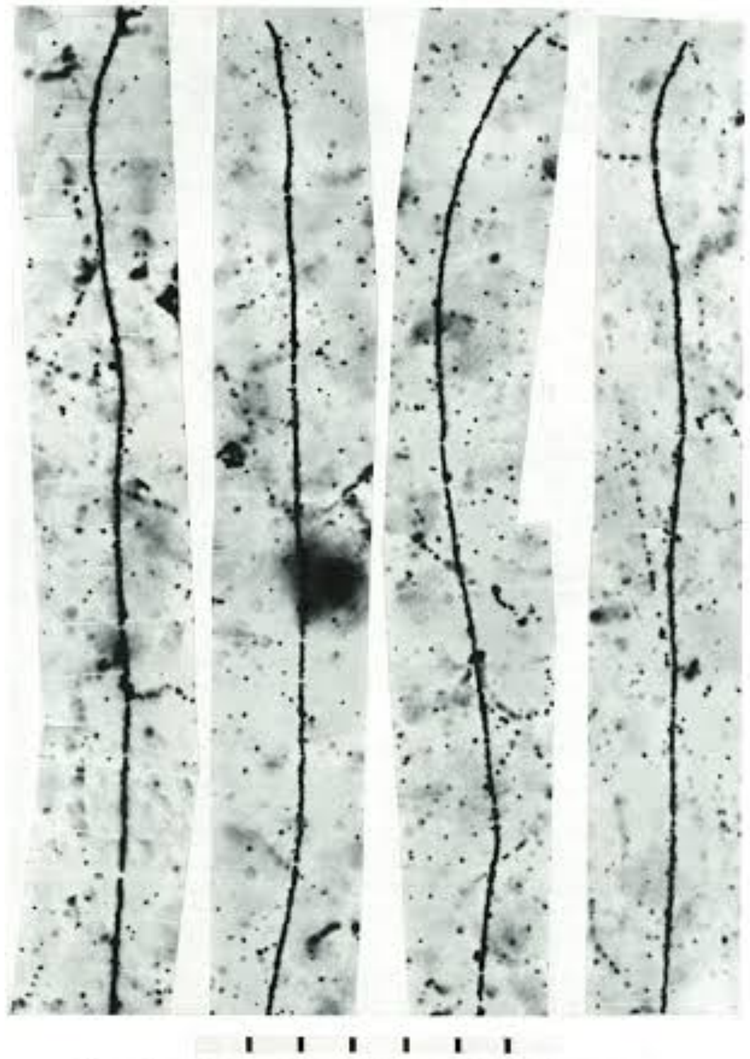


Rejeitado pela revista Nature
"because it contained speculations too remote from reality to be of interest to the reader."

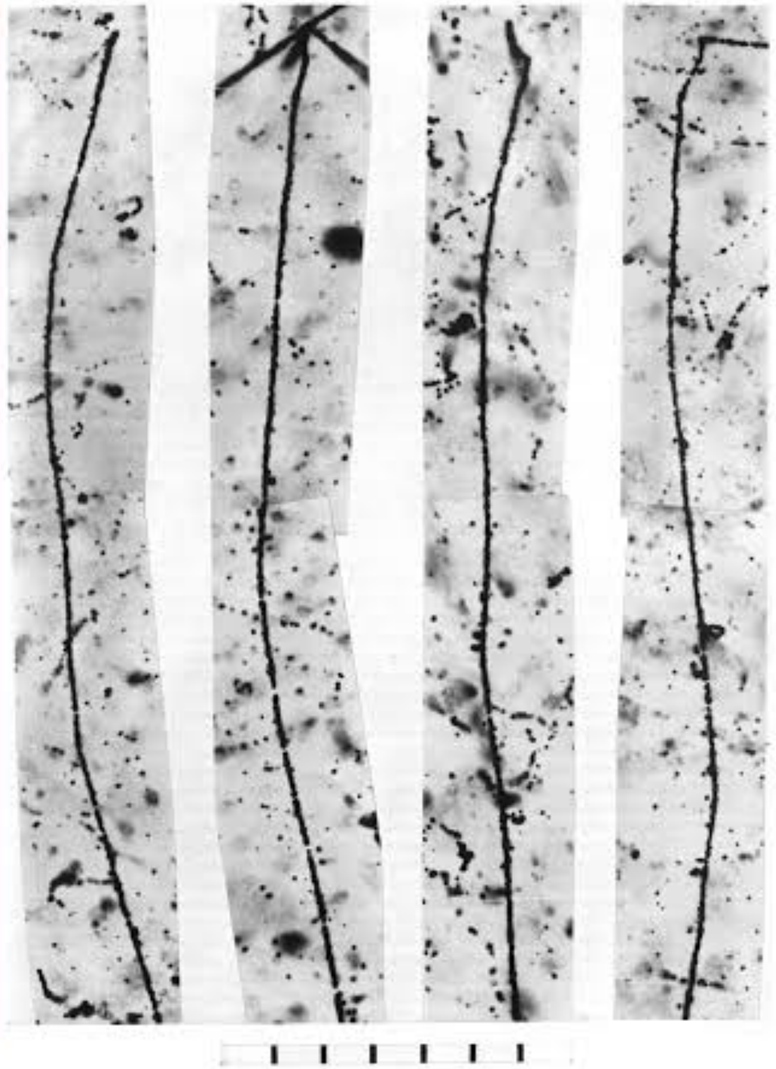
Parada número três



Decaimento beta está em todo lugar



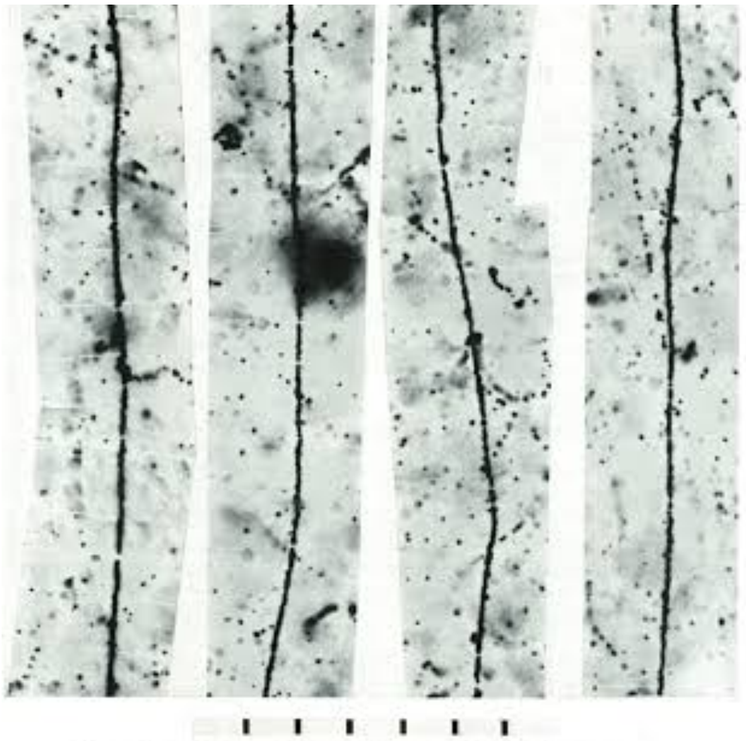
Tracks of muons at the end of their range



Tracks of pions at the end of their range

Decaimento beta está em todo lugar

Decaimento do muon e do pion tem similaridades com o decaimento beta.



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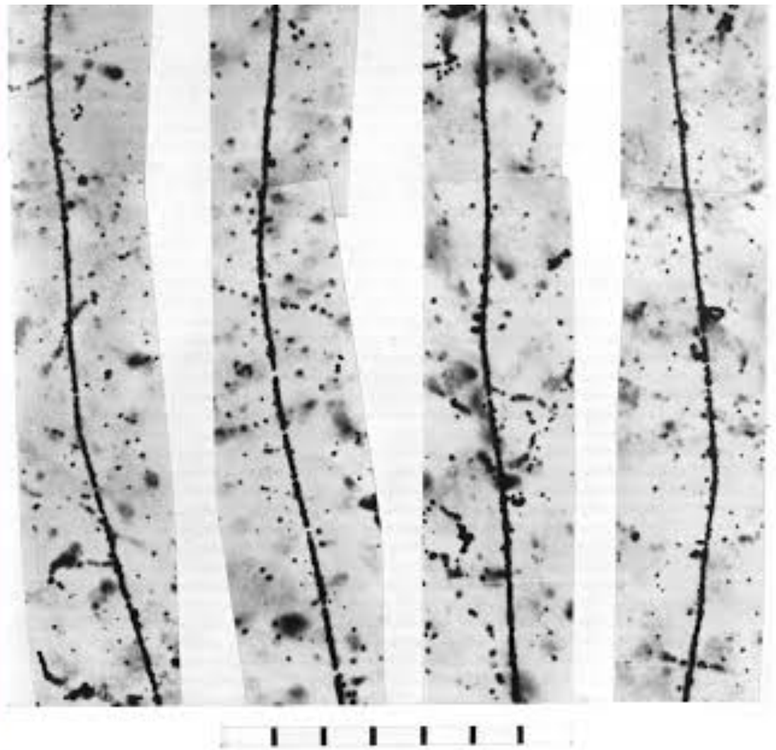

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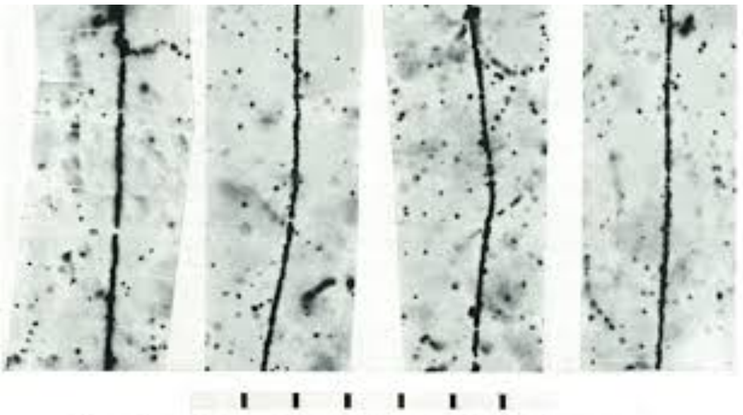
Seria a interação de Fermi universal?



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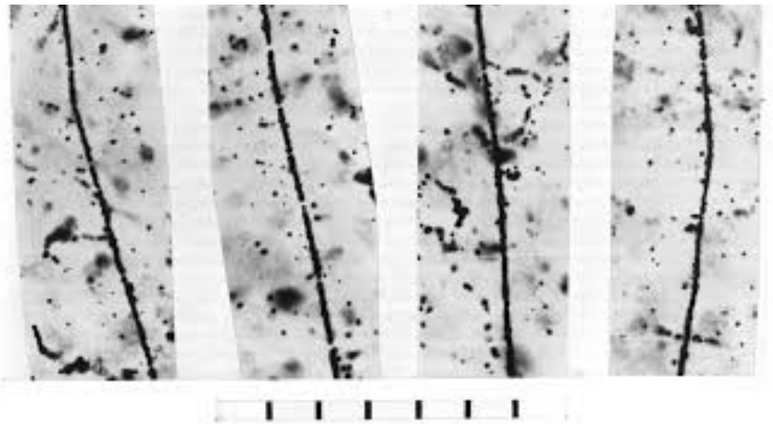

Tracks of pions at the end of their range

Decaimento beta está em todo lugar

Decaimento do muon e do pion tem similaridades com o decaimento beta.

Seria a interação de Fermi universal?

Novas portas para estudar as interações fracas

Tracks of muons at the end of their range

Tracks of pions at the end of their range

Visão geral da parte teórica

Decaimento de pions em elétrons foram observado mais tarde.

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Isso levou a comunidade preferir uma interação pseudo escalar.

Visão geral da parte teórica

Decaimento de pions em elétrons foram observado mais tarde.

Isso levou a comunidade preferir uma interação pseudo escalar.

Exercício: mostre que se o acoplamento do pion fosse pseudo escalar ele decairia preferencialmente para eletrons e não muons.

Visão geral da parte teórica

Decaimento de pions em elétrons foram observado mais tarde.

Isso levou a comunidade preferir uma interação pseudo escalar.

Ingrediente chave estava faltando:

Visão geral da parte teórica

Decaimento de pions em elétrons foram observado mais tarde.

Isso levou a comunidade preferir uma interação pseudo escalar.

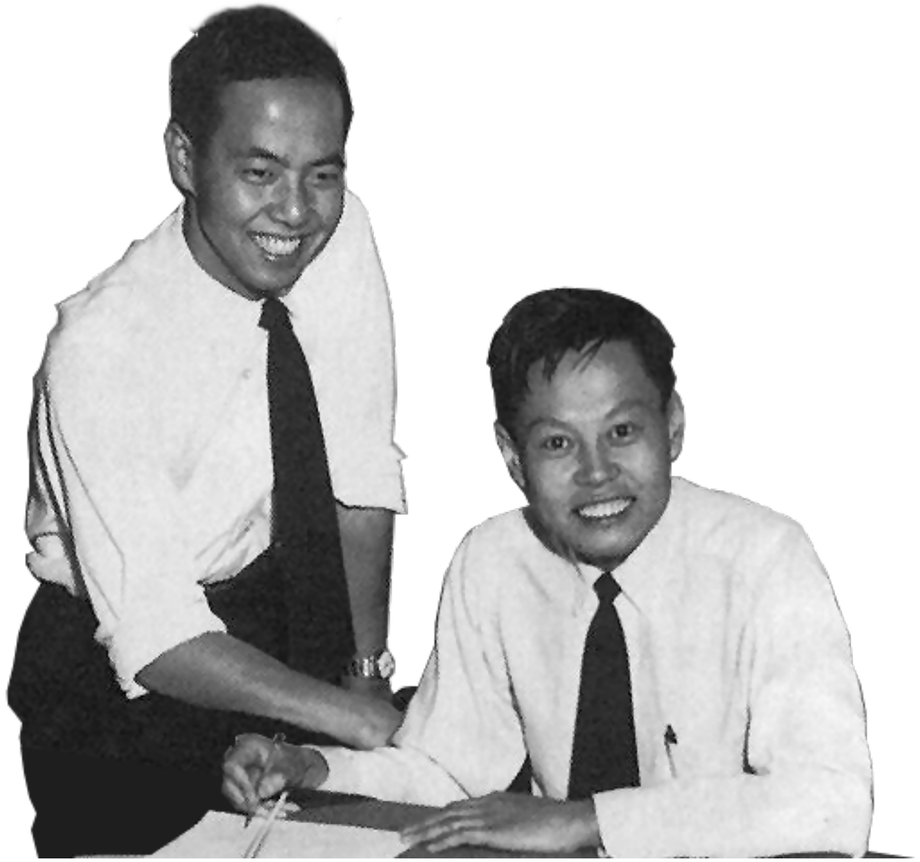
Ingrediente chave estava faltando:

“I do not believe that the Lord is a weak left-hander and I am willing to bet a very large sum that the experiments will give symmetric results.”

(Pauli)

Paridade não é conservado em interações fracas!

Lee, Yang



Madame Wu

Evidência experimental

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}^{*} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

$$\rightarrow e^{-} + \bar{\nu}_{e} + 2\gamma + {}^{60}\mathrm{Ni}$$

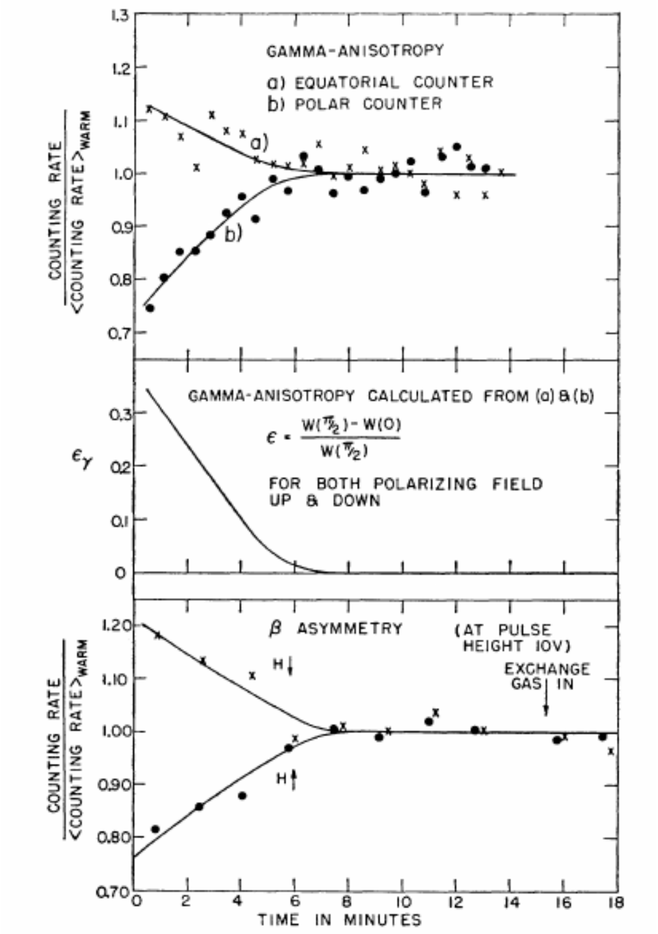
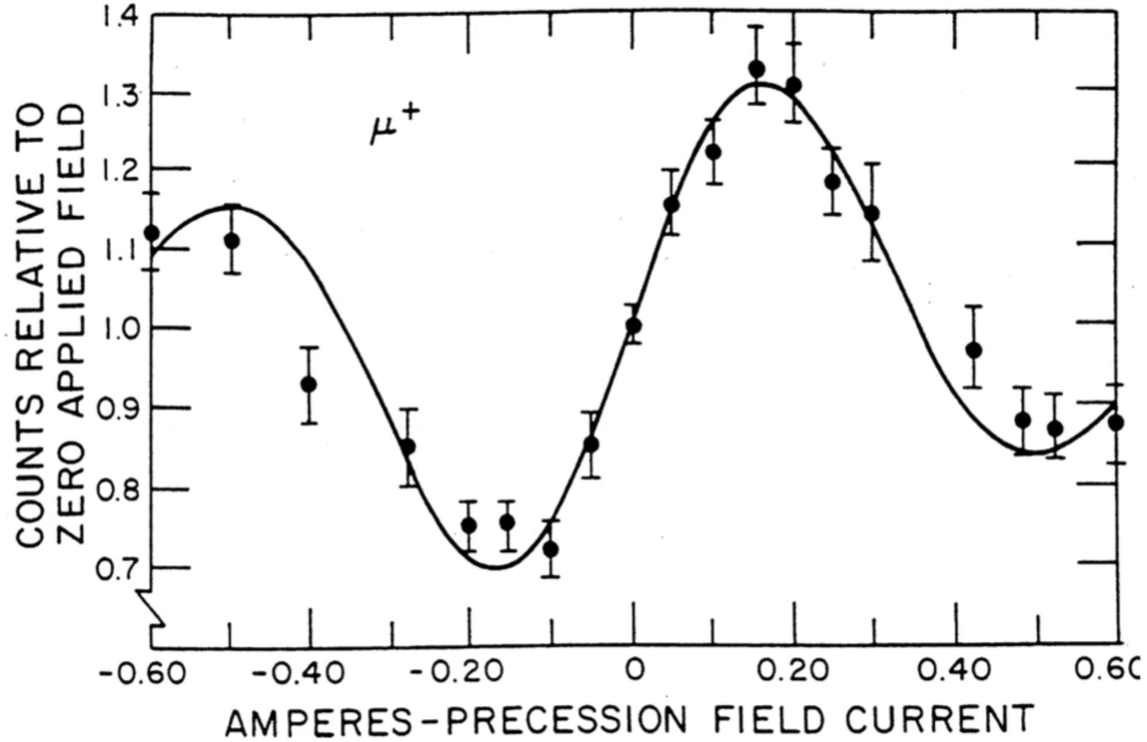


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



Revisitando experimentos anteriores

A forma “V-A” emerge

Revisitando experimentos anteriores

A forma “V-A” emerge

$$\overline{\psi}\gamma_\mu(1-\gamma_5)\psi$$

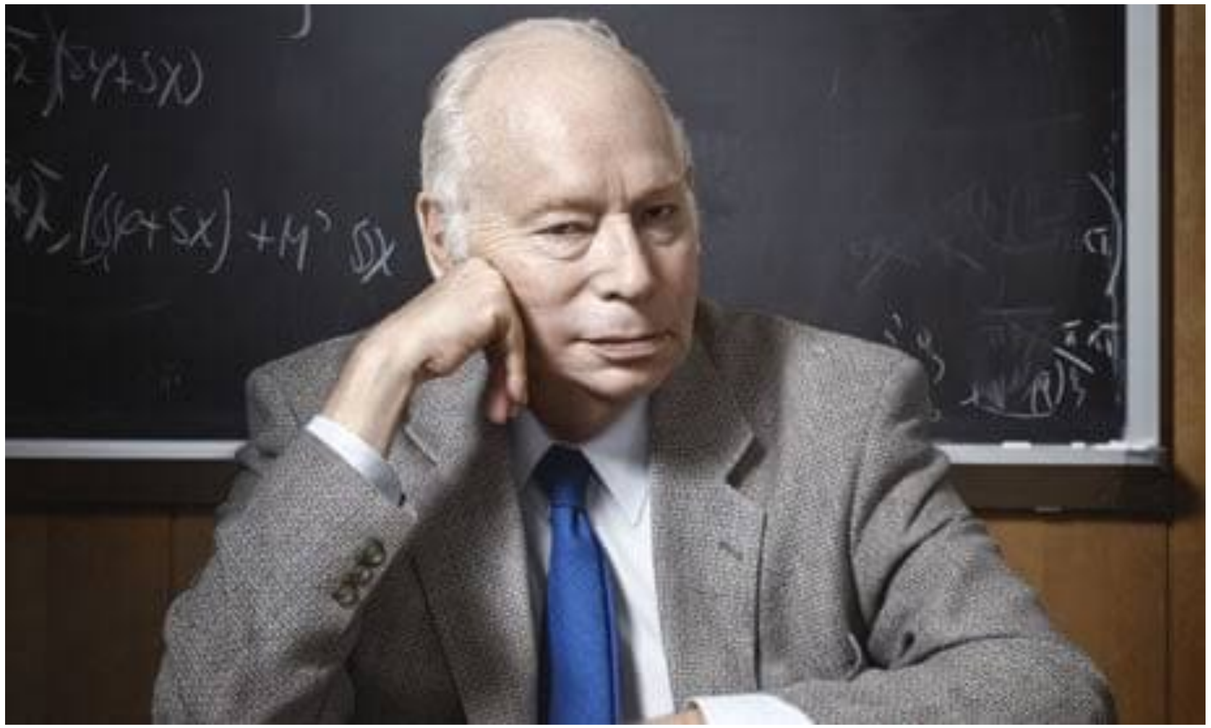
Revisitando experimentos anteriores

A forma “V-A” emerge

$$\overline{\psi}\gamma_\mu(1-\gamma_5)\psi$$

Demorou em torno de 30 anos para chegarmos na forma completa e correta da interação que descreve o decaimento beta!!

“V-A was the key”



OPEN ACCESS

V-A was the key

Steven Weinberg

Journal of Physics: Conference Series, Volume 196, SUDARSHAN: SEVEN SCIENCE QUESTS 6–7 November 2006, Austin, Texas, USA

Citation Steven Weinberg 2009 *J. Phys.: Conf. Ser.* **196** 012002

DOI 10.1088/1742-6596/196/1/012002

Article PDF

Photo from the Nobel Foundation archive.
Sheldon Lee Glashow
Prize share: 1/3

Photo from the Nobel Foundation archive.
Abdus Salam
Prize share: 1/3

Photo: Harvard University News Office. Nobel Foundation archive
Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

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Ideia intuitiva:

“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Ideia intuitiva:

Antes

“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Ideia intuitiva:

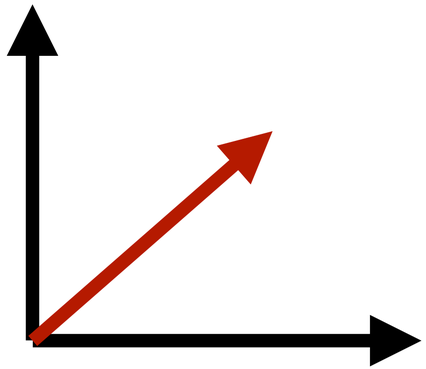
Depois

“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Ideia intuitiva:

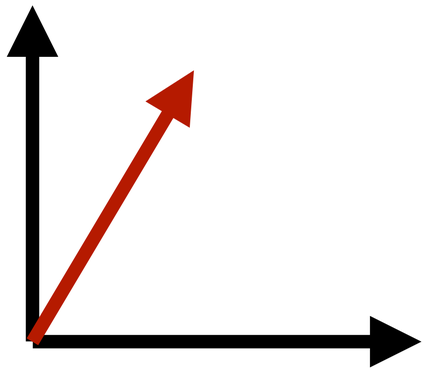


“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Ideia intuitiva:

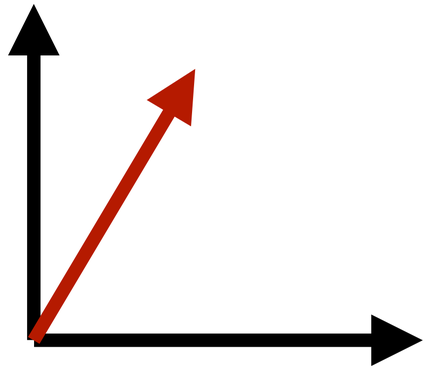


“V-A was the key”

O modelo padrão é baseado em um grupo de simetria de gauge

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Matematicamente:



$$\mathbf{v} = R\mathbf{v} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

A lagrangiana do modelo padrão

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Construímos objetos invariante sob a ação das operações acima

Ilustrando a ideia: $\psi \rightarrow U\psi$

$$\overline{\psi}\psi \rightarrow \overline{\psi}U^{\dagger}U\psi = \overline{\psi}\psi$$

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Isso representa um termo válido!

Termos de massa

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$m\overline{\psi_L}\psi_R$$

Termos de massa

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

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Termos de massa

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$m\bar{\psi}_L\psi_R$$

Seria como tentar combinar:

$$\begin{pmatrix} v_1 v_2 \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

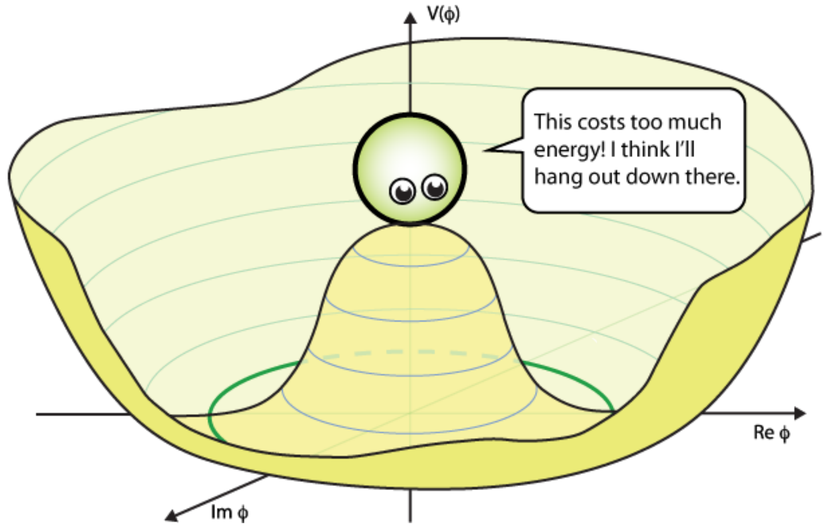
O bóson de Higgs e o mecanismo de massa

$$(v_1 v_2) \begin{pmatrix} x & x & x \\ x & x & x \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

O bóson de Higgs e o mecanismo de massa

$$-\mathscr{L}_{\text{Yuk}} \supset \bar{L} Y_e e_R H$$

$$m \bar{e}_L e_R$$

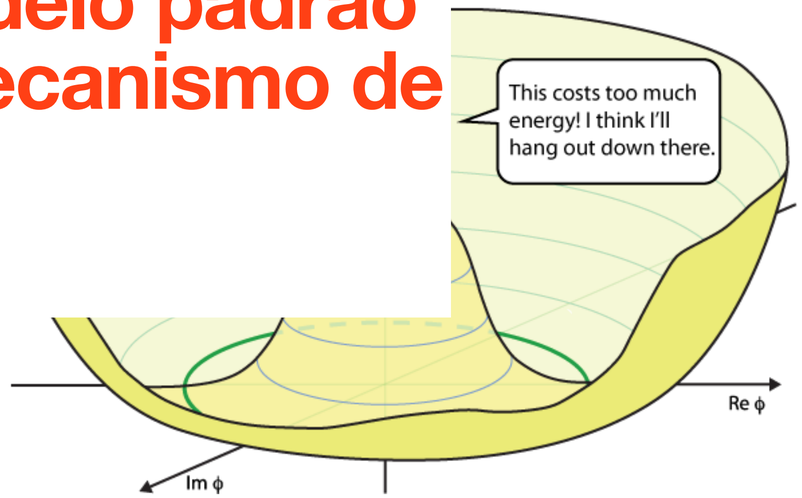


O bóson de Higgs e o mecanismo de massa

$$-\mathscr{L}_{\text{Yuk}} \supset \bar{L} Y_e e_R H$$

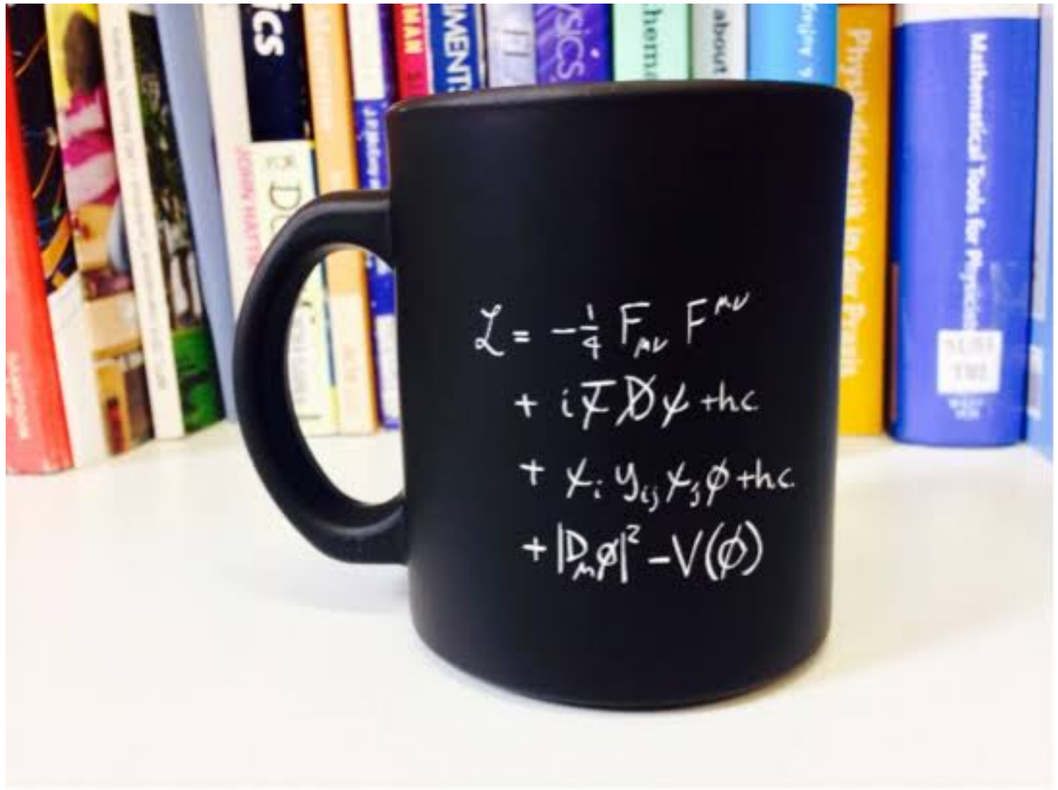
O poder de predição do modelo padrão depende crucialmente do mecanismo de massa!

$$m \bar{e}_L e_R$$



A lagrangiana do modelo padrão

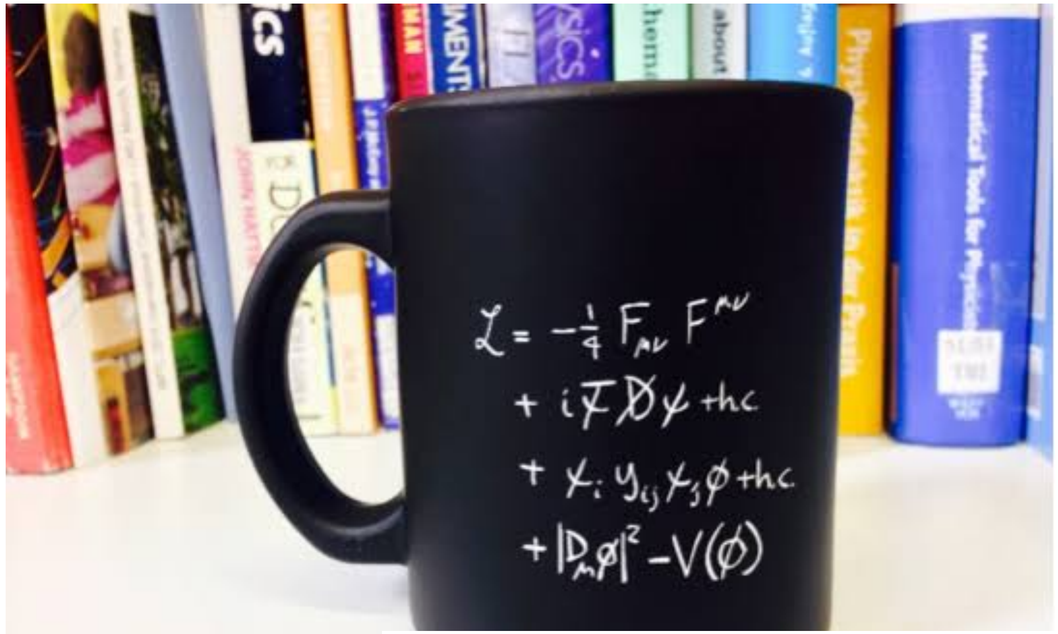
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$



$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \tfrac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2) - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-) - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{8}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).$$

A lagrangiana do modelo padrão

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$



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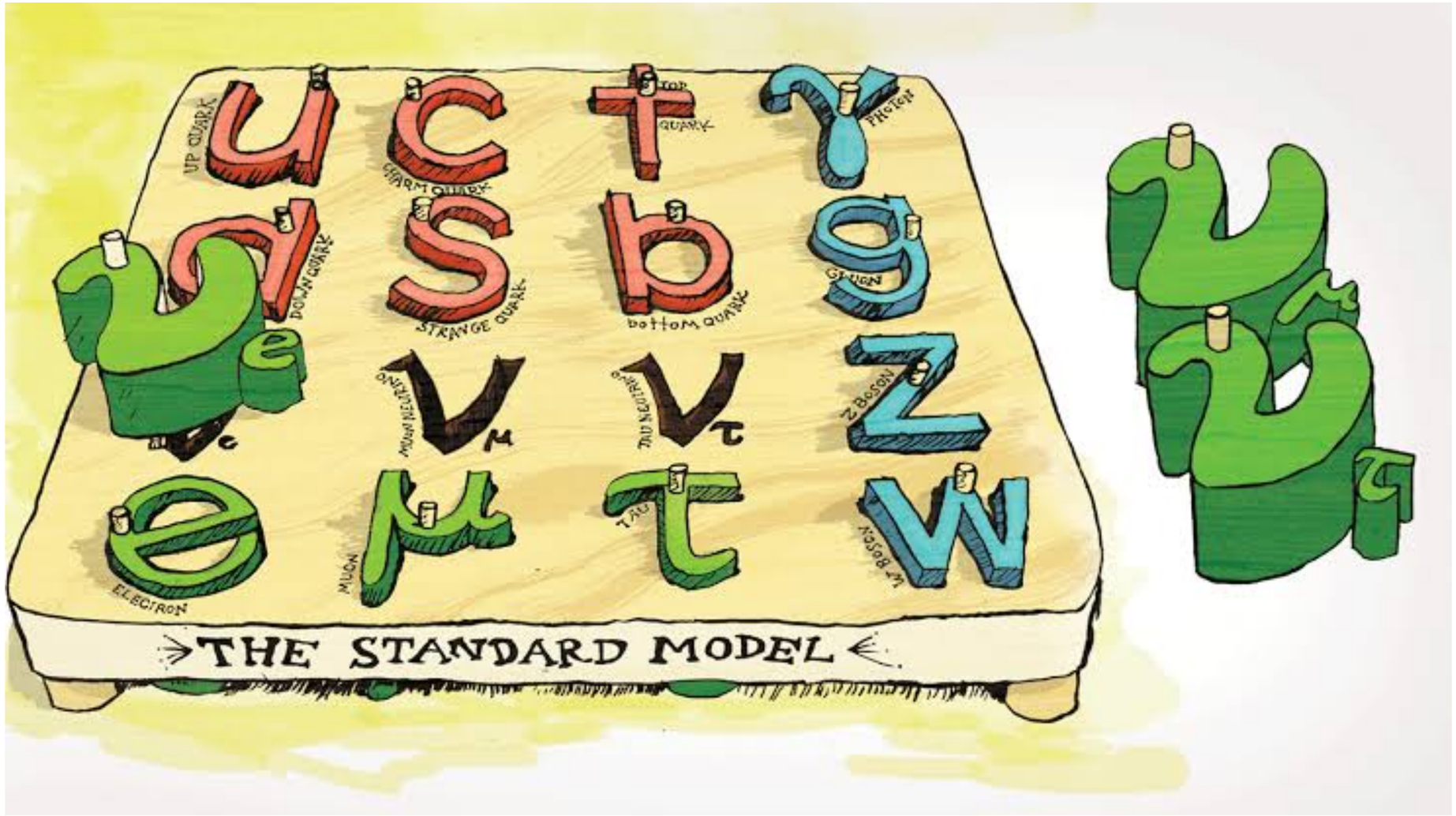
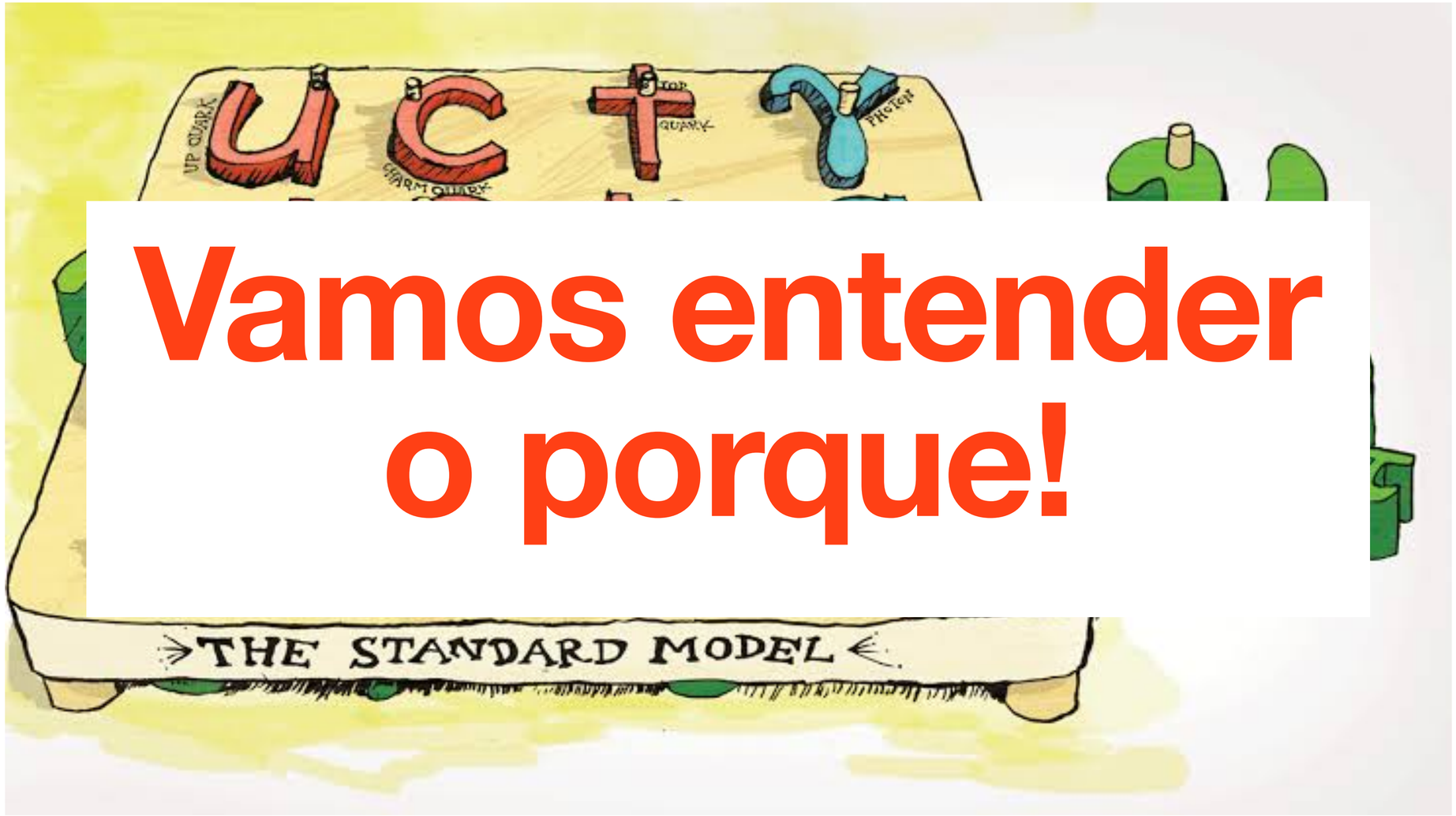
A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \tfrac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2) - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-) - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^+ X^+ - M\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).$$

A “universalidade” das interações de Fermi foi crucial no estudo de simetrias da teoria

Porém....


UP QUARK
CHARM QUARK
TOP QUARK
PHOTON
DOWN QUARK
STRANGE QUARK
BOTTOM QUARK
GLUON
ELECTRON
MUON
TAU
W BOSON
Z BOSON
THE STANDARD MODEL

Porém....



Vamos entender o porque!

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Tempo tomando dados

Como detectar partículas?

$$N_{\text{evts}} \sim T\,\rho\,V\,\sigma\,\phi$$

Números de alvos por volume

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Tamanho do detector

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Tamanho do detector

Os três até agora dependem do experimento e material

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Probabilidade de interação

“Seção de choque”

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Probabilidade de interação

“Seção de choque”

Depende da Física

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Número de partículas por unidade de área e tempo

“Fluxo”

Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Número de partículas por unidade de área e tempo

“Fluxo”

Depende da fonte!

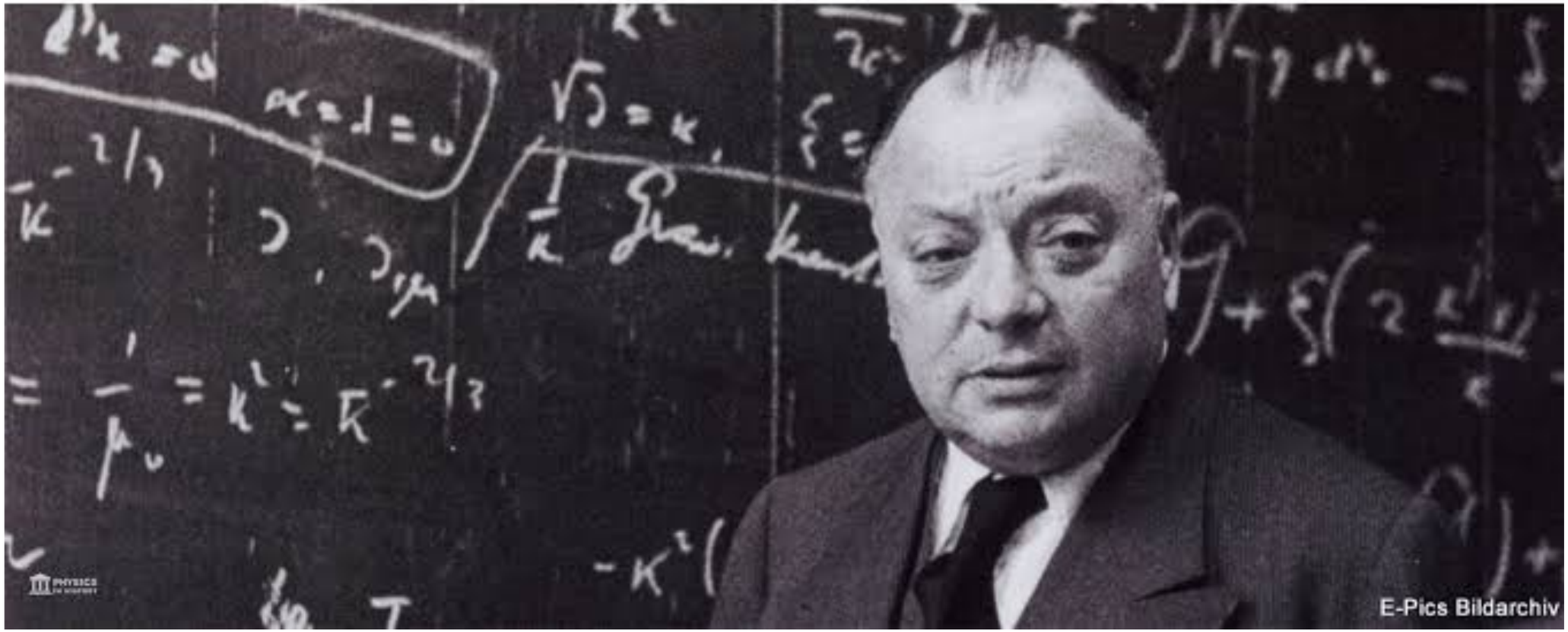
Como detectar partículas?

$$N_{\text{evts}} \sim T\ \rho\ V\ \sigma\ \phi$$

Neutrinos podem viajar até um ano luz em um bloco de chumbo sem interagir (dependendo da energia)!

"I have done a terrible thing: I have postulated a particle that cannot be detected. *[the neutrino]*"

WOLFGANG PAULI



Detecção do neutrino

Ingredientes: Fluxo alto & detectores enormes

Estimativa: suponha 3 neutrinos por hora em 400 litros de água

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$$\frac{10^{13}}{\mathrm{cm}^2\ \mathrm{s}} \times 10^{28} \times \sigma \approx \frac{3}{3600\ \mathrm{s}}$$

Detecção do neutrino

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$$\frac{10^{13}}{\text{cm}^2\ \text{s}} \times 10^{28} \times \sigma \approx \frac{3}{3600\ \text{s}}$$

$$\sigma \approx 10^{-44}\ \text{cm}^2$$

Detecção do neutrino

Ingredientes: Fluxo alto & detectores enormes

Estimativa: suponha 3 neutrinos por hor
400 litros de ág

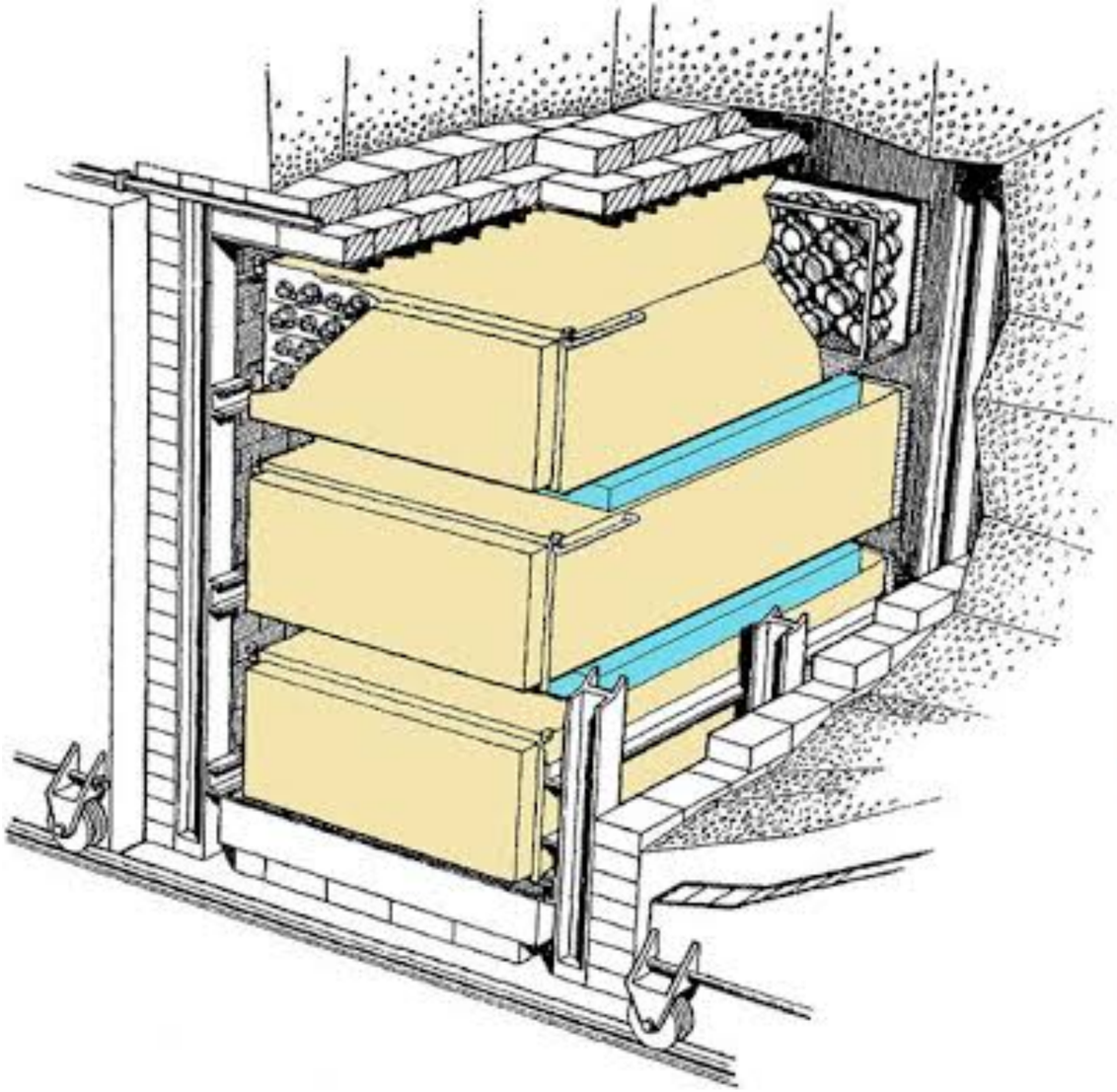
Se você jogar 10 trilhoes de neutrinos em uma área de 1 centímetro quadrado você, com sorte, terá uma interação por dia em detectores de centenas de toneladas

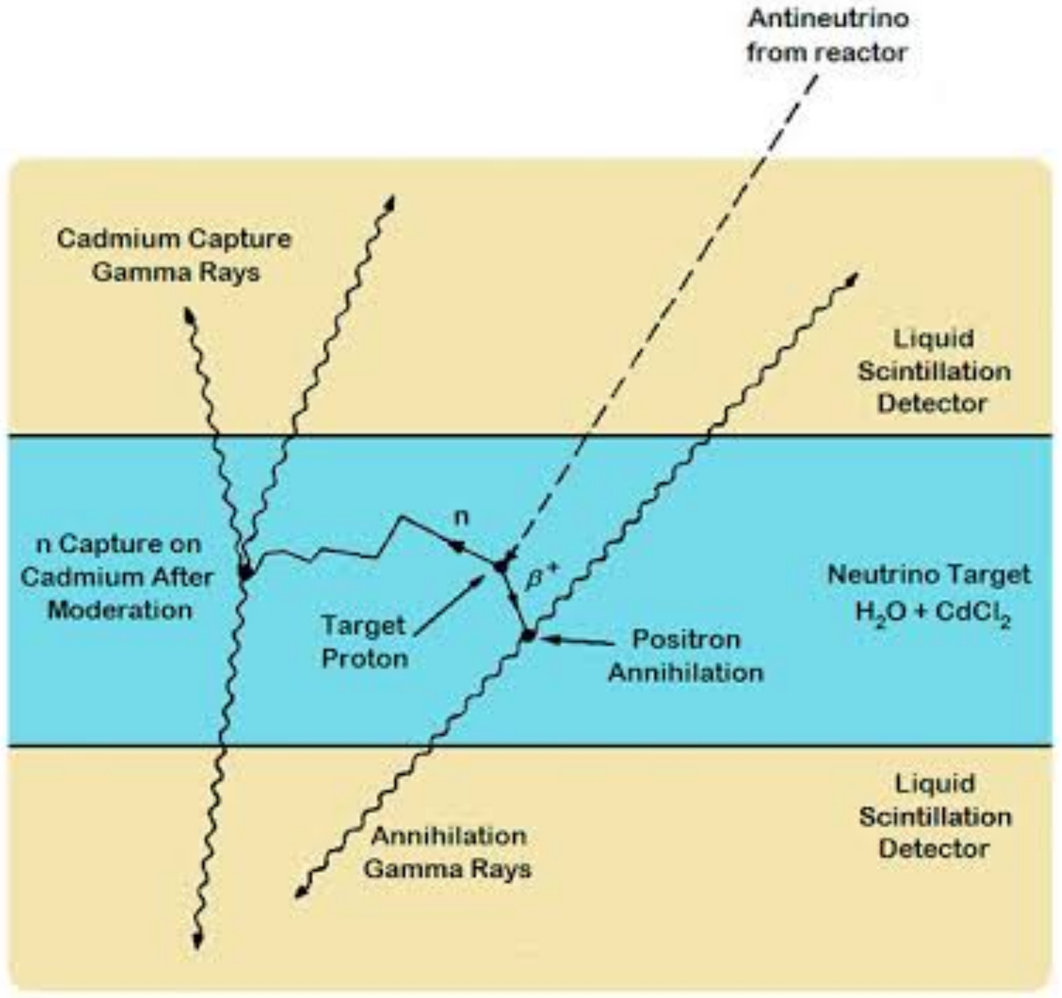
$$\sigma \approx 10^{-44}\ \mathrm{cm}^2$$

Detecção do neutrino

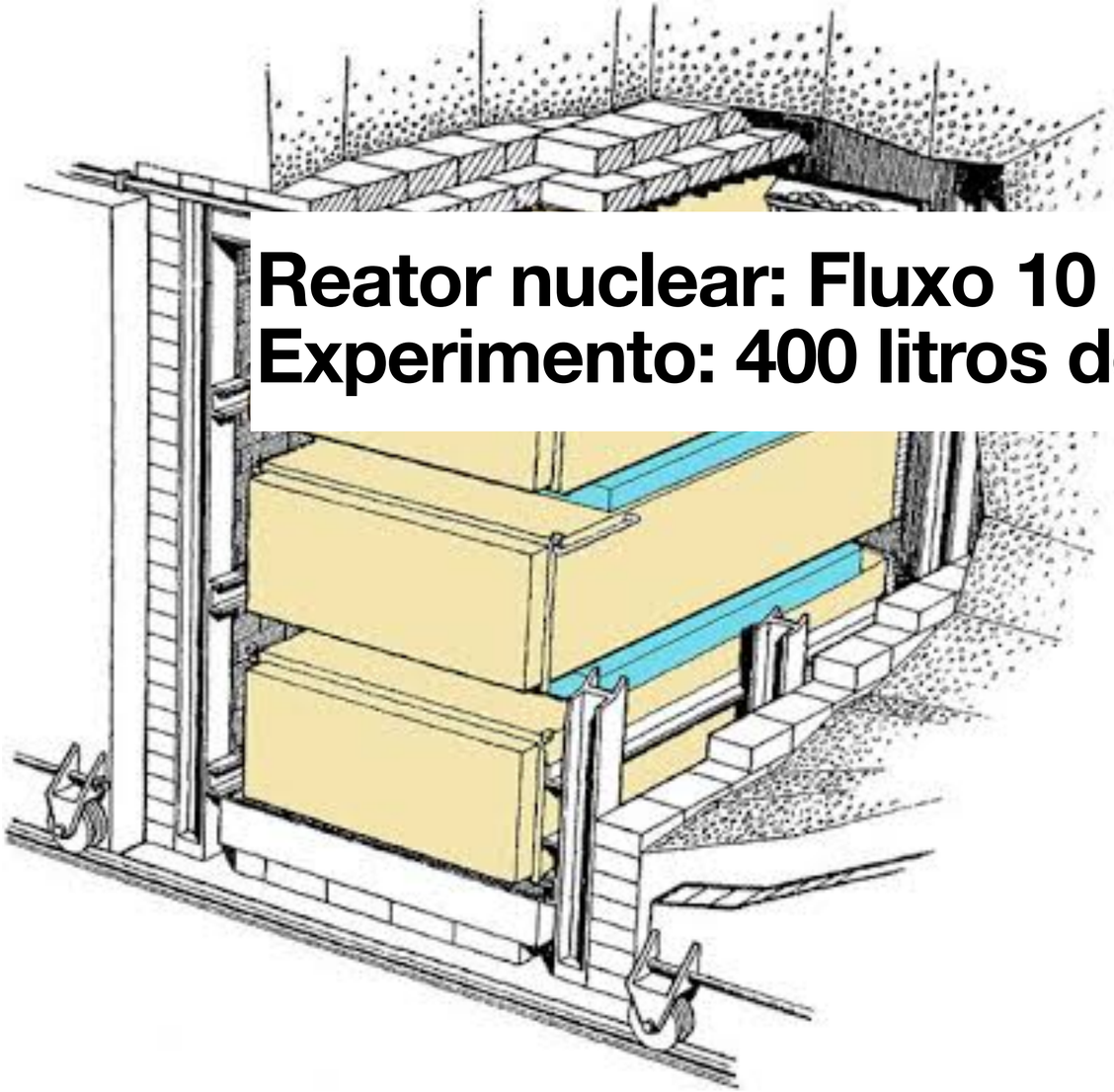
Reines & Cowan

Detecção do neutrino

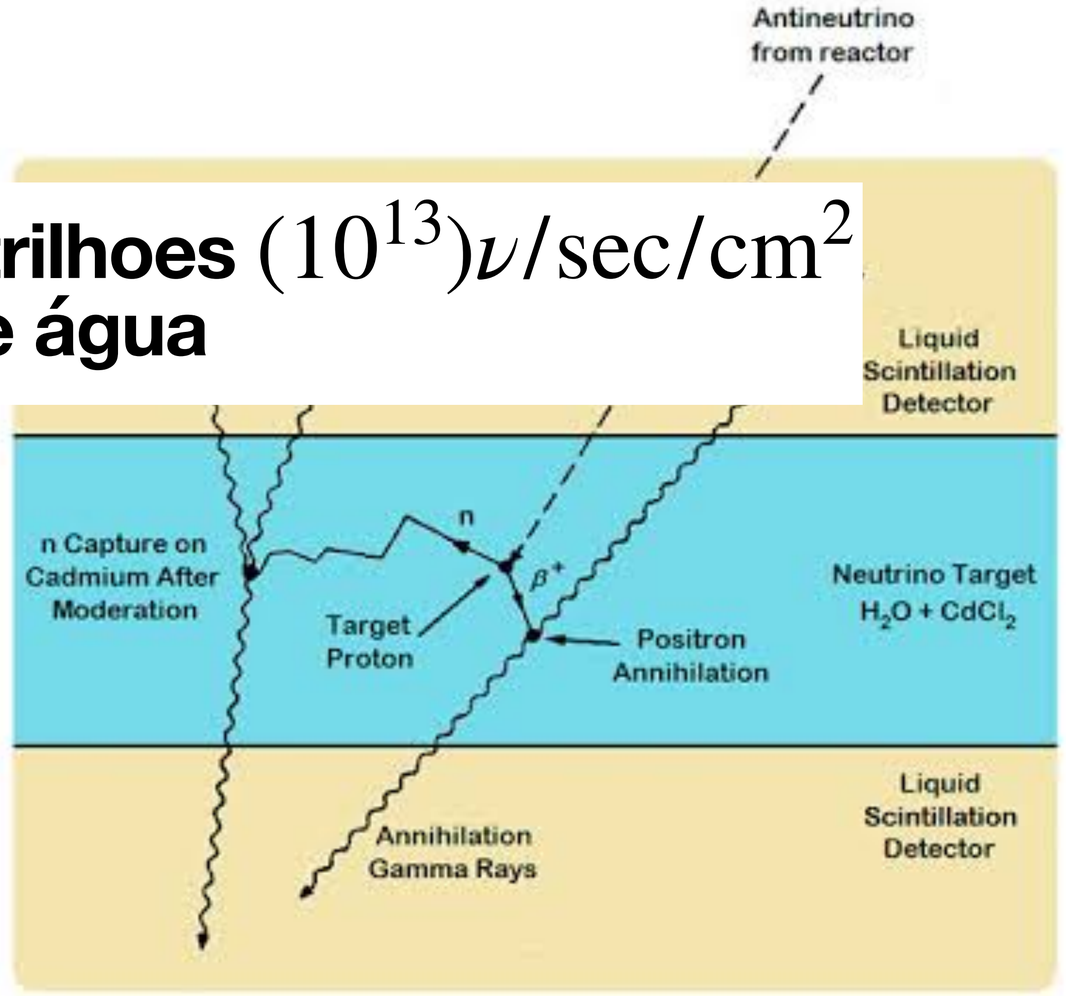




Detecção do neutrino



Reator nuclear: Fluxo 10 trilhoes $(10^{13})\nu/\mathrm{sec}/\mathrm{cm}^2$
Experimento: 400 litros de água



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NACHLASS
PROF. W. PAULI

LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

Per Post

(1)

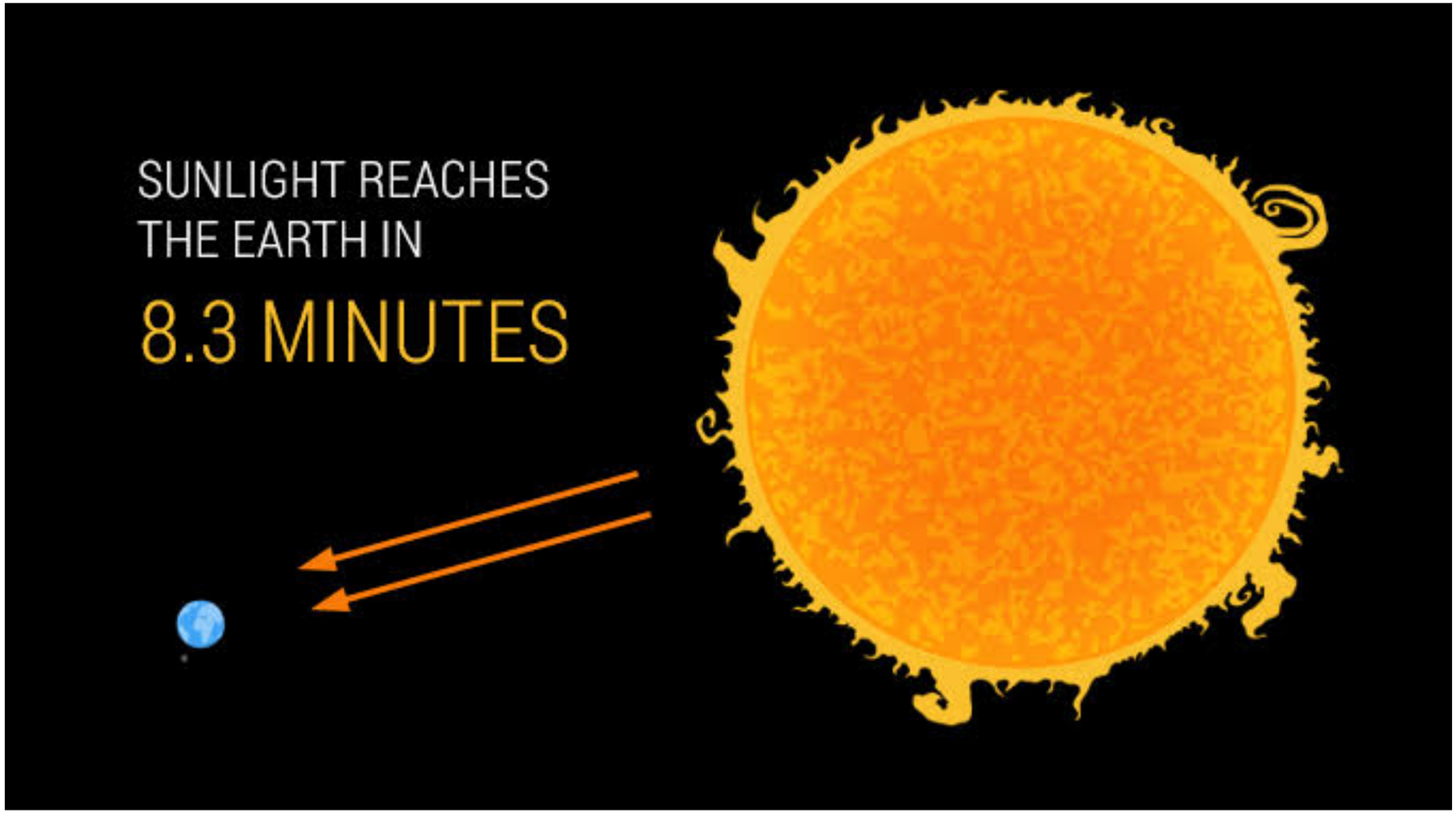
NACHLASS
PROF. W. PAULI

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

Nr. 20 6500 × 100 3/54

Neutrinos solares



Neutrinos solares

Neutrinos solares

Neutrinos solares

100000000000000000000000000000000000

10^{38}**neutrinos por segundo são produzidos no sol**

Fluxo de 100 bilhoes$(10^{11})/\mathrm{cm}^2/\mathrm{sec}$ **na terra**

65 bilhoes neutrinos solares passam pela área do tamanho do seu dedão por segundo

Neutrinos solares

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

100000 galões de fluido de limpeza

1250 banheiras cheias

Homestake Mine

Neutrinos solares

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

100000 galões de fluido de limpeza

Porém uma surpresa:

$$\frac{\text{Numero esperado}}{\text{Numero previsto}} \approx 1/3$$

Homestake Mine

Mais tipos de neutrino

Até o momento estamos falando de apenas neutrinos produzidos com elétrons e positrons

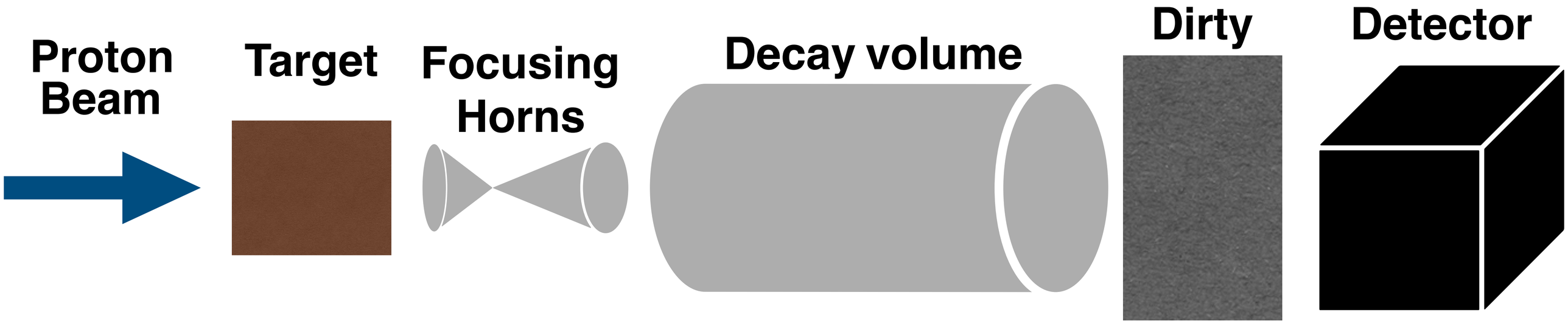
Mais tipos de neutrino

Até o momento estamos falando de apenas neutrinos produzidos com elétrons e positrons

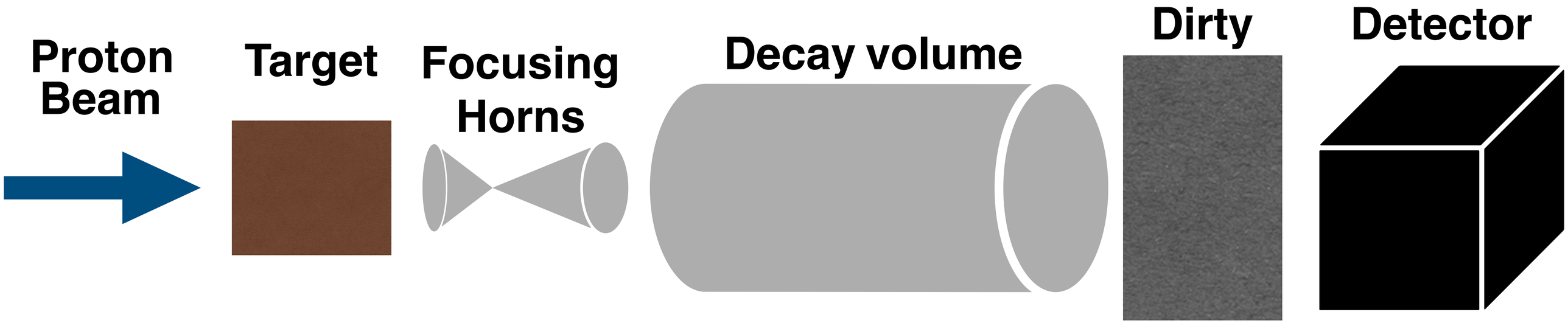
Mas será que neutrinos produzidos com outras partículas são os mesmos?

Como fazer um feixe de neutrinos?

Como fazer um feixe de neutrinos?



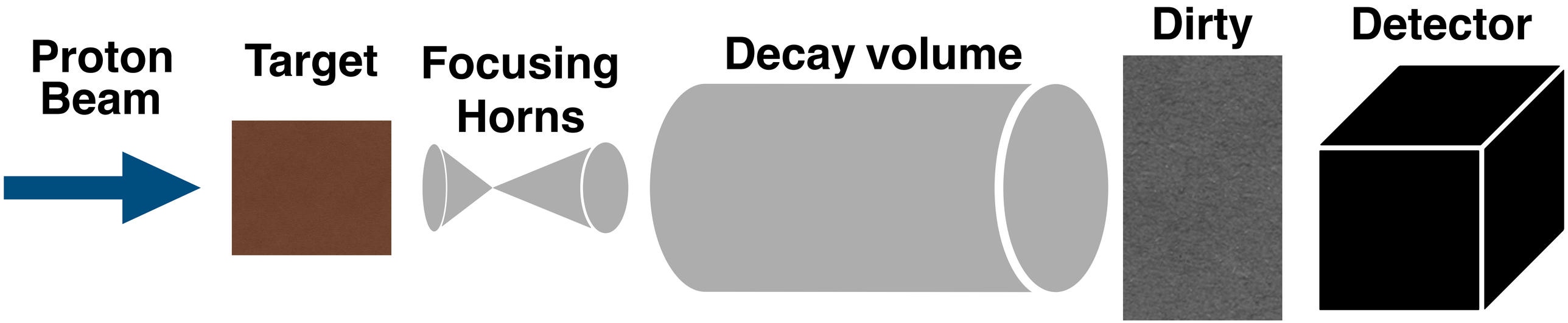
Como fazer um feixe de neutrinos?



Medem neutrinos vindo de decaimentos de, por exemplo:

$$\pi \rightarrow \mu \nu_{\mu}$$

Como fazer um feixe de neutrinos?

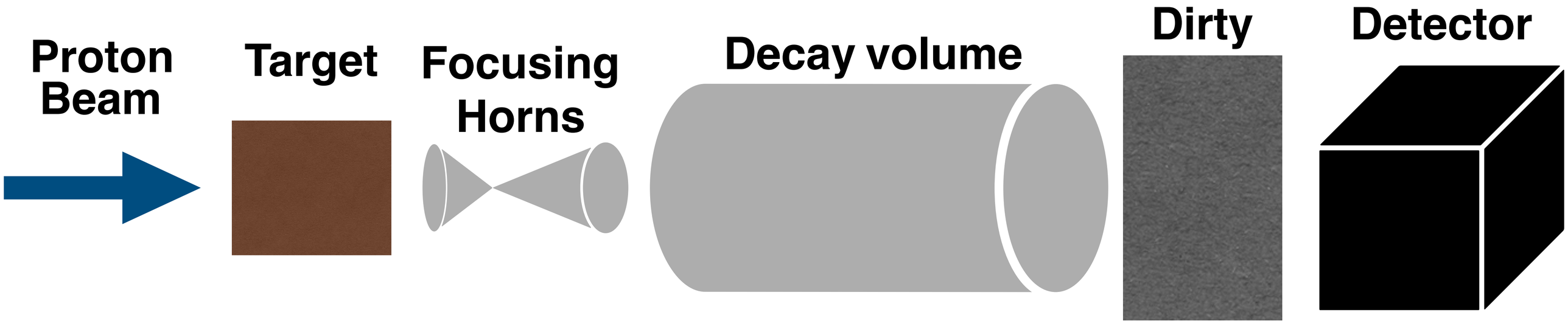


Medem neutrinos vindo de decaimentos de, por exemplo:

$$\pi \rightarrow \mu \nu_{\mu}$$

The first artificial source of pions was created in 1948 by César Lattes, Eugene Gardner, and their team at the University of California's cyclotron

Como fazer um feixe de neutrinos?



Medem neutrinos vindo de decaimentos de, por exemplo:

$$\pi \rightarrow \mu \nu_{\mu}$$

Quando os neutrinos interagem no detector, eles produzem muons ou eletrons?

Dois tipos de neutrinos

Photo from the Nobel Foundation archive.

Leon M. Lederman

Prize share: 1/3

Photo from the Nobel Foundation archive.

Melvin Schwartz

Prize share: 1/3

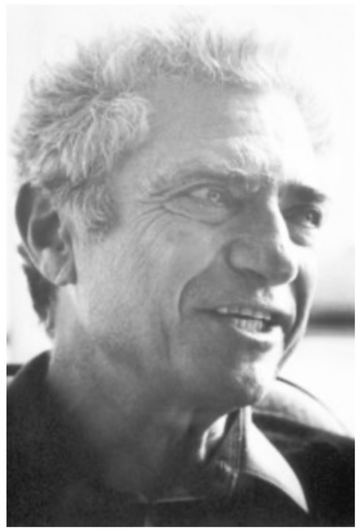


Photo from the Nobel Foundation archive.

Jack Steinberger

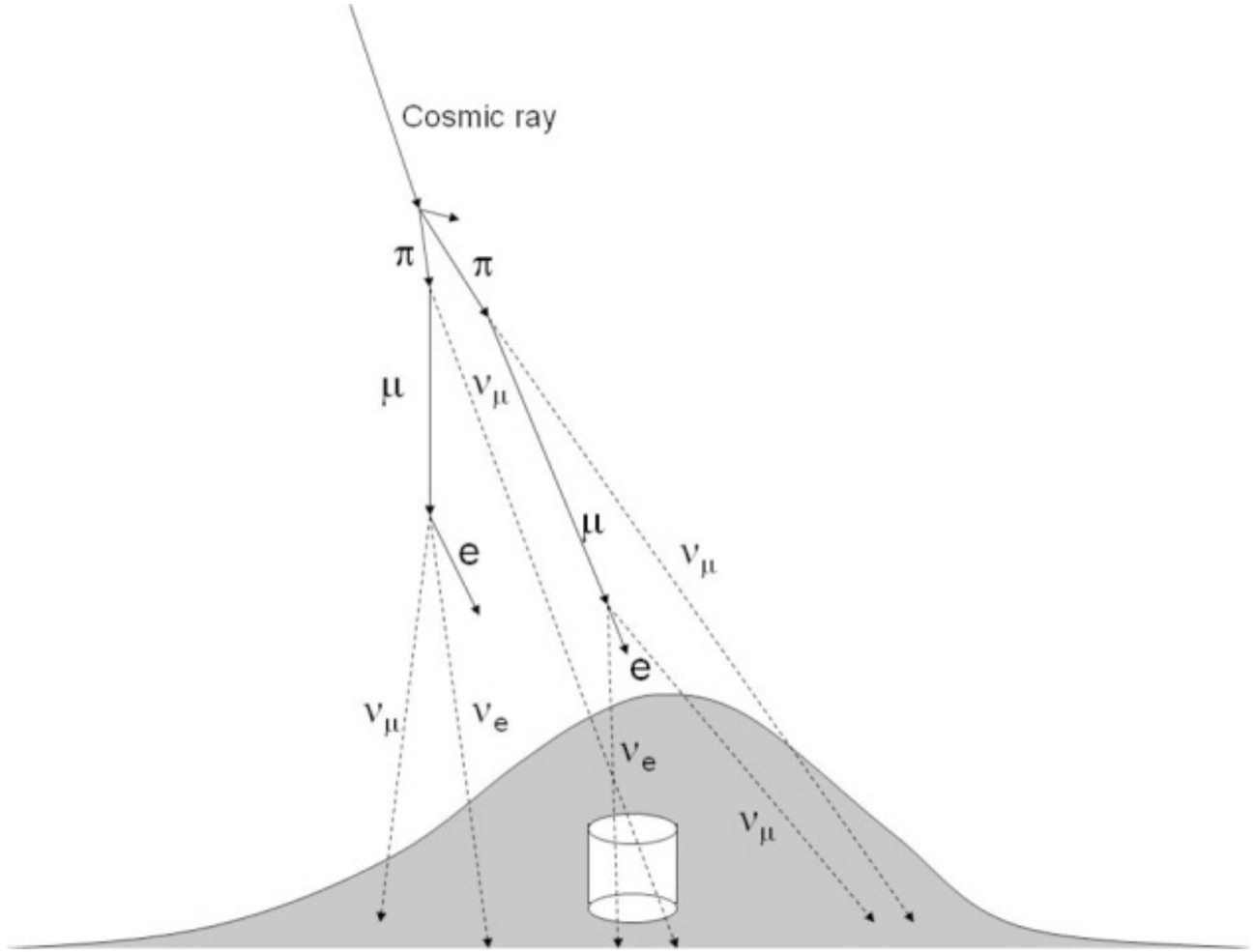
Prize share: 1/3

The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

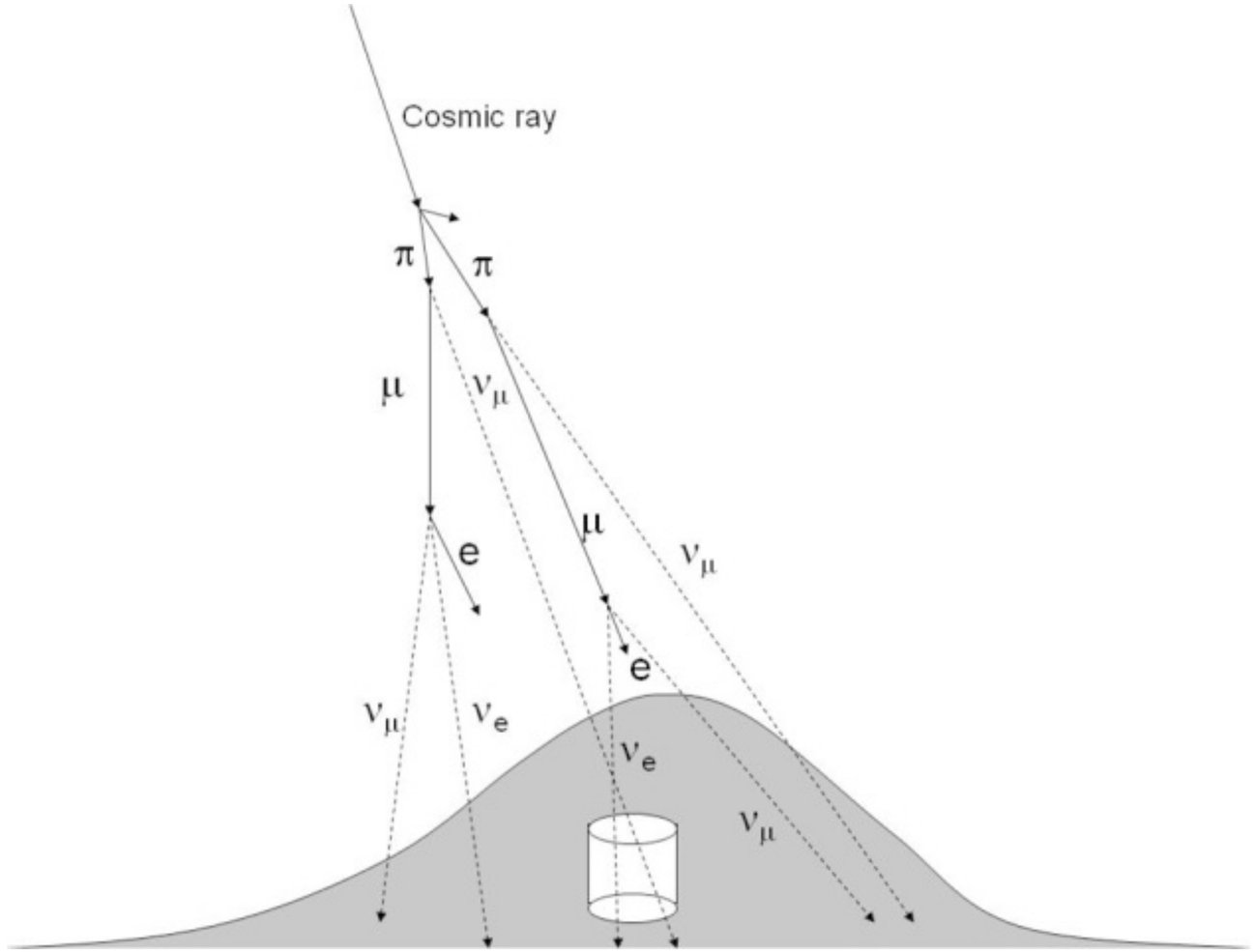
Três tipos de neutrinos

O terceiro neutrino, o neutrino do tau, foi descoberto em 2000 no experimento DONUT

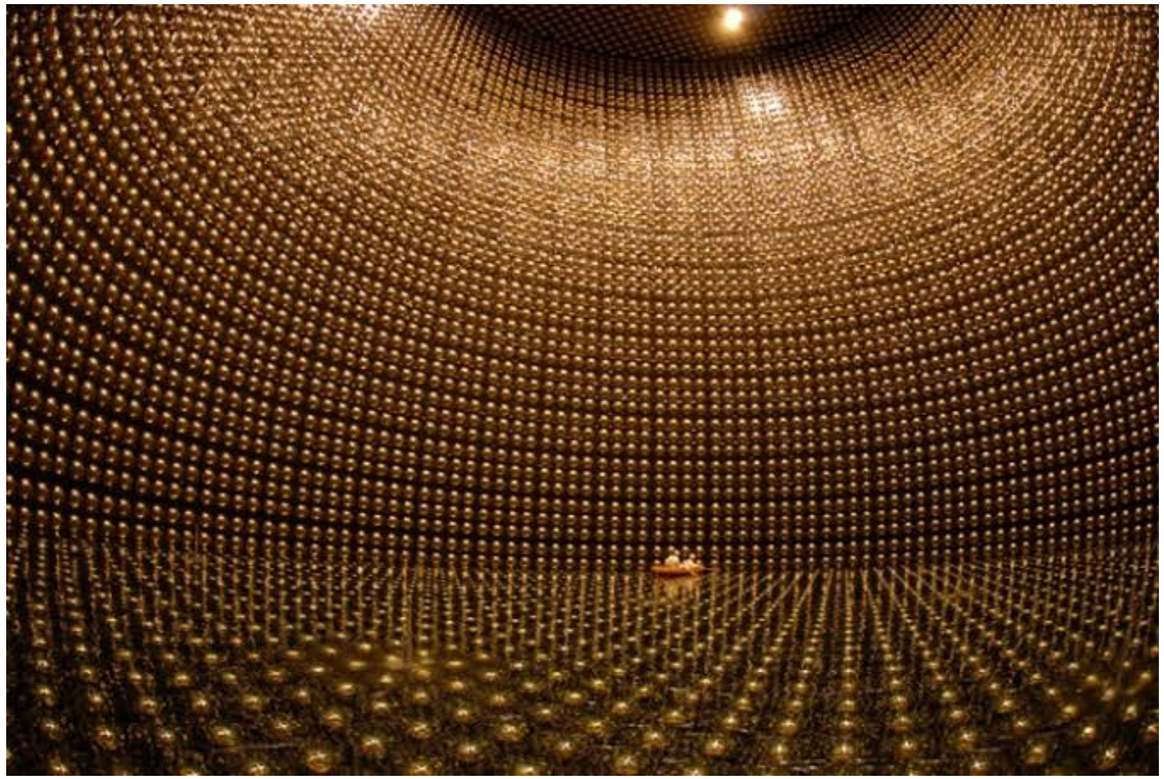
Neutrinos na atmosfera



Neutrinos na atmosfera



Super Kamiokande 50kt water detector



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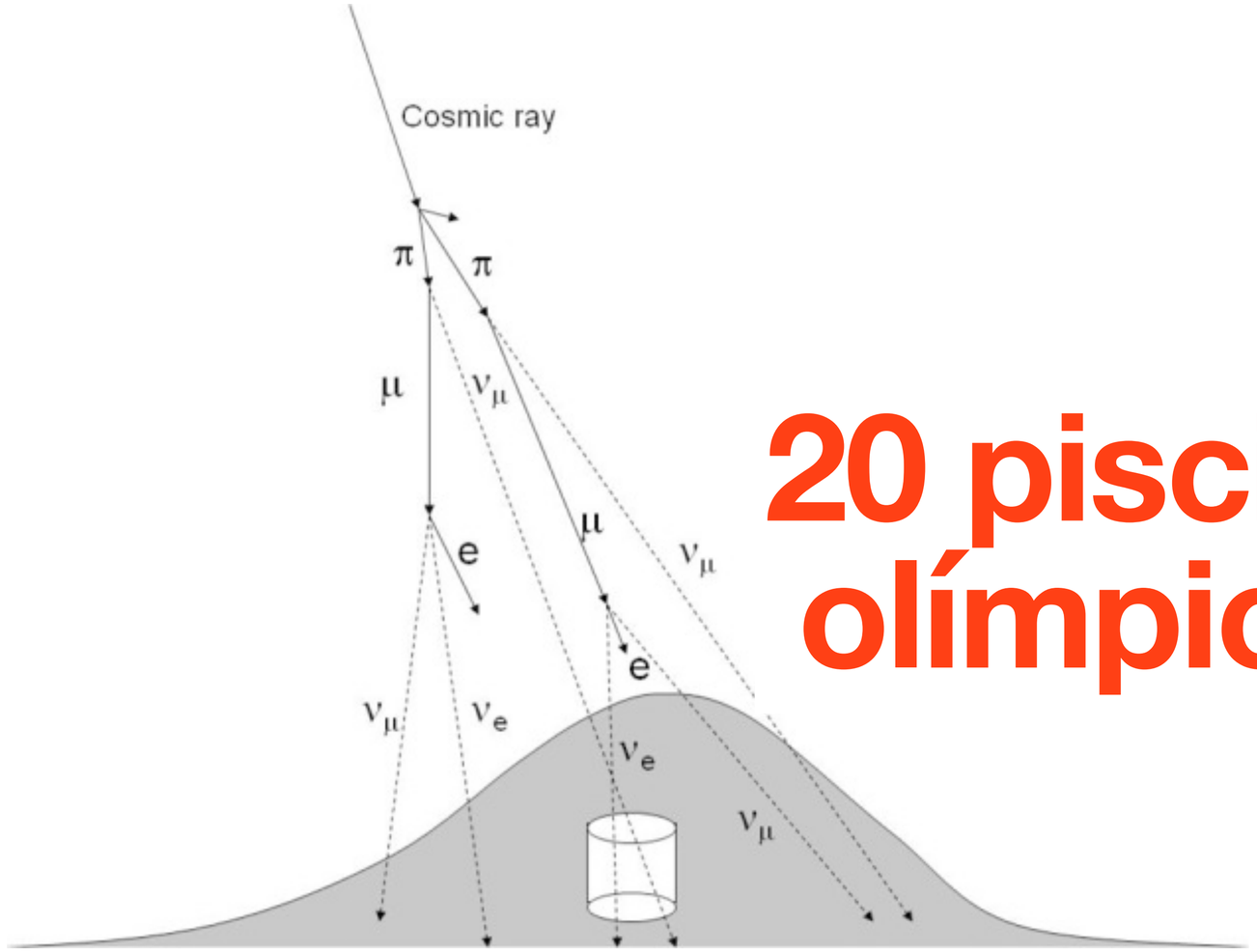
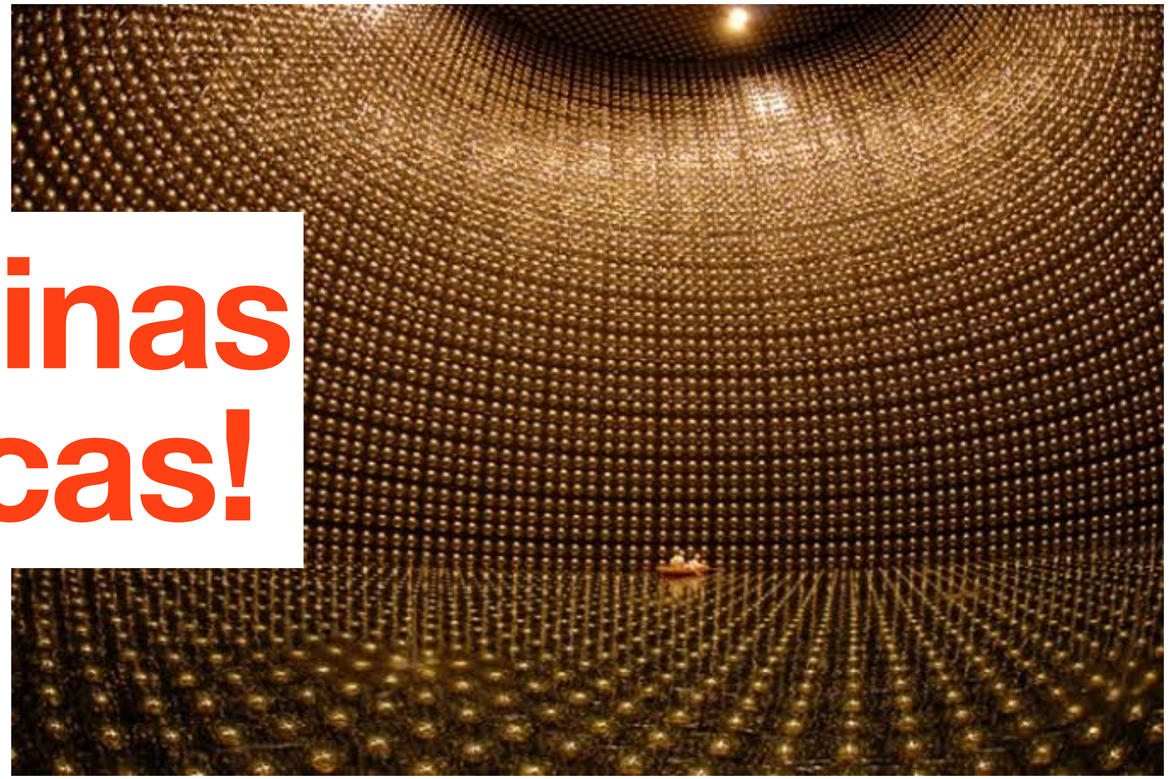
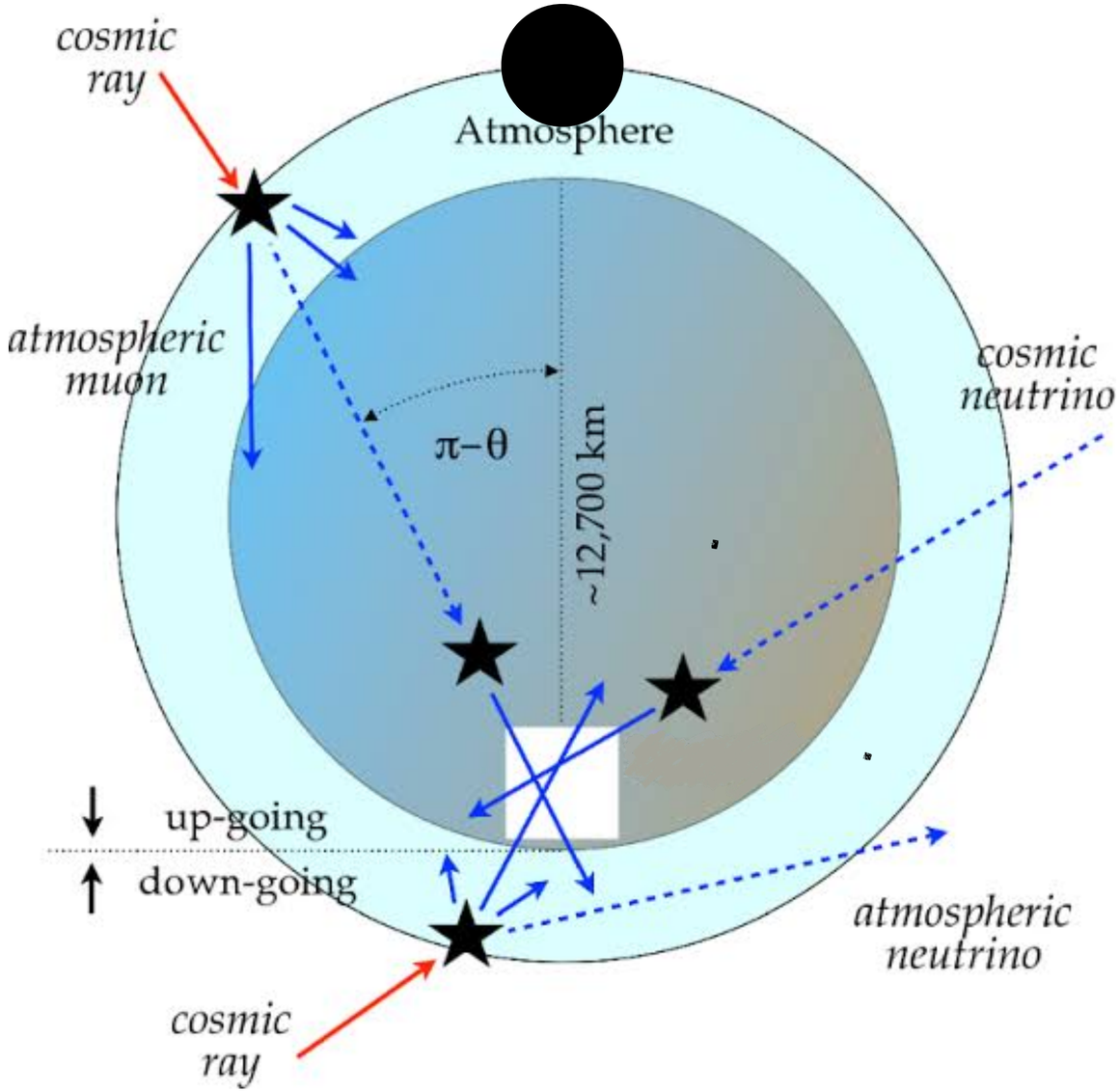


Super Kamiokande 50kt water detector



20 piscinas olímpicas!

Neutrinos na atmosfera



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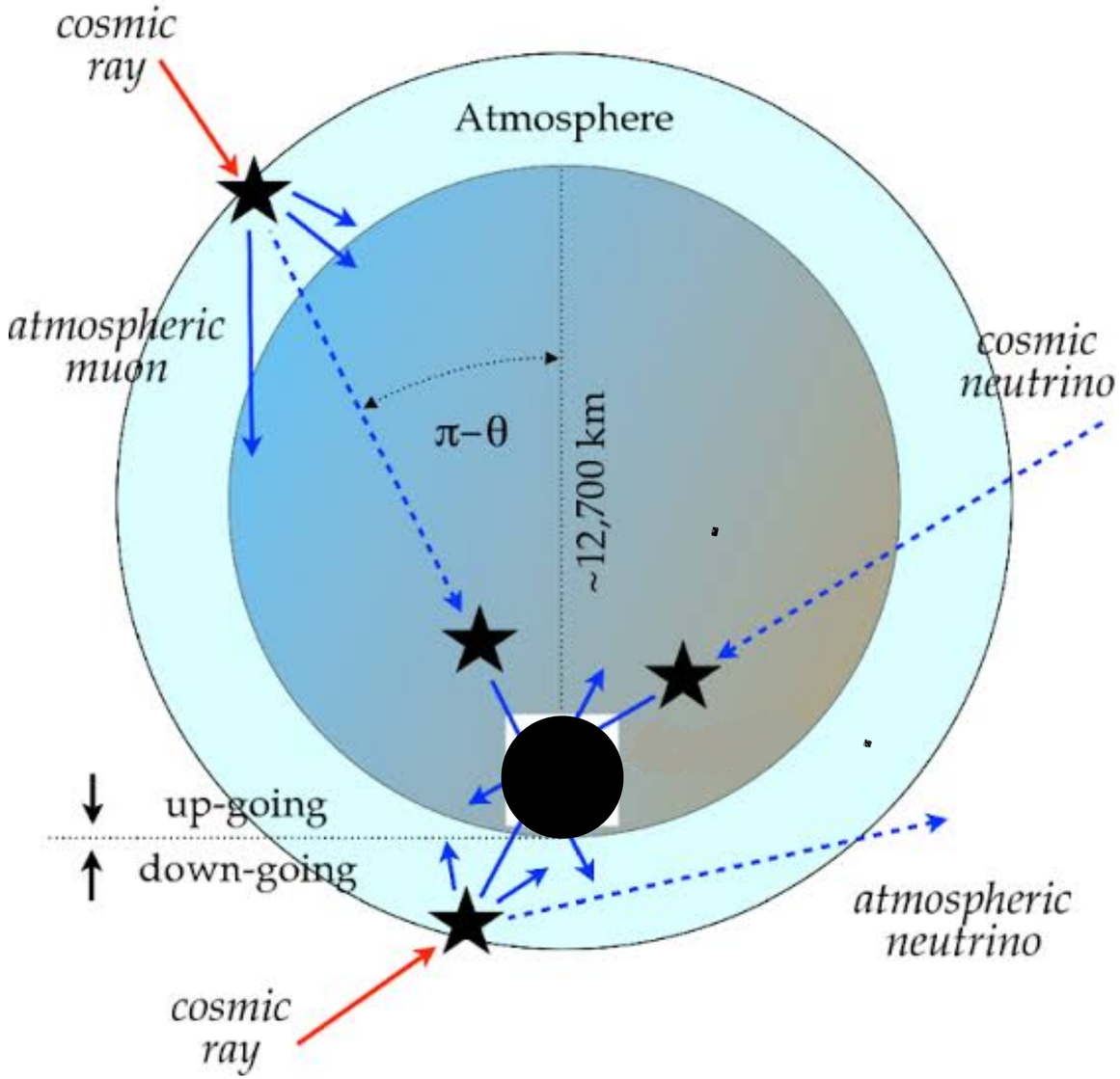
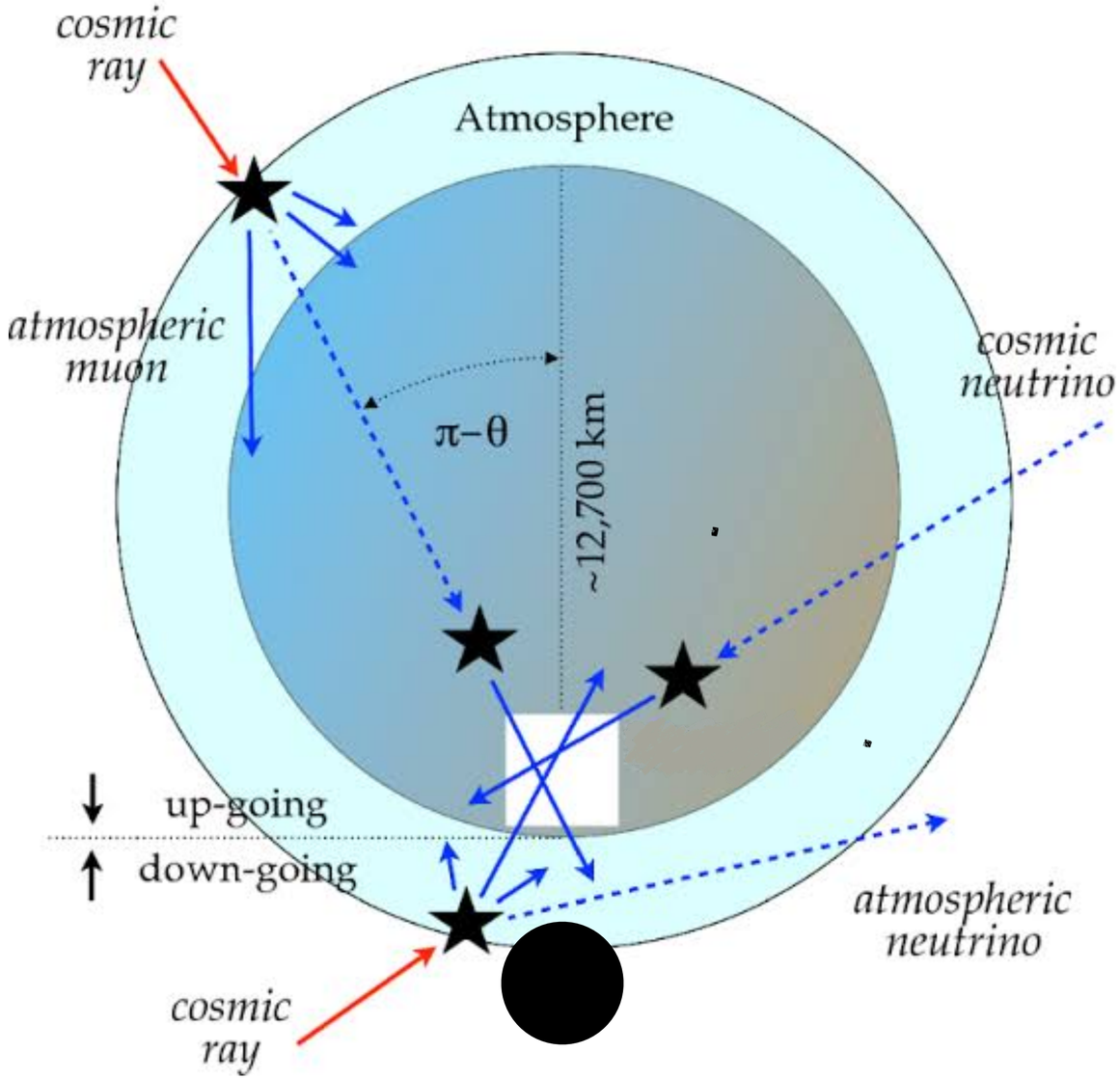


Neutrinos na atmosfera



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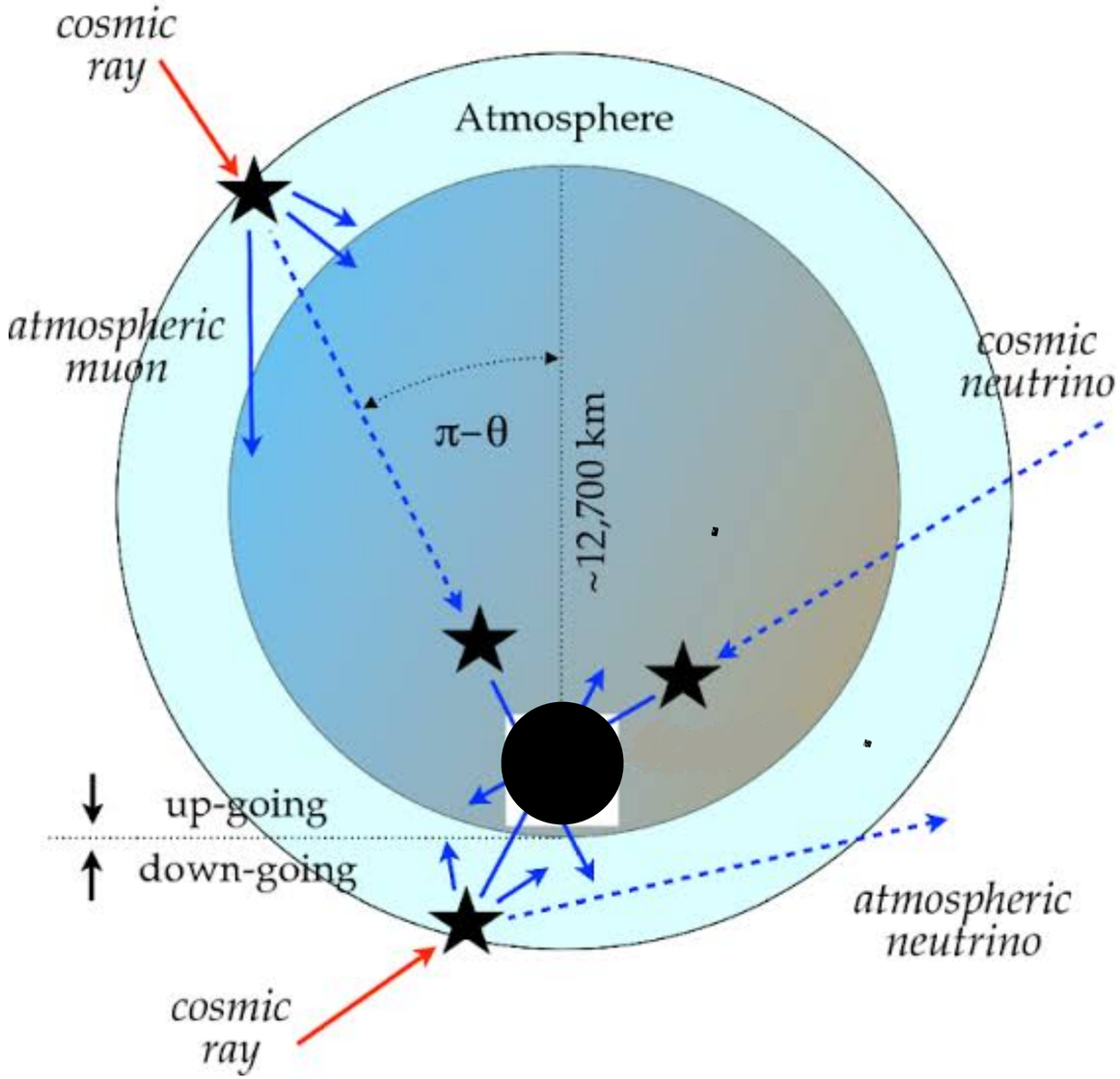
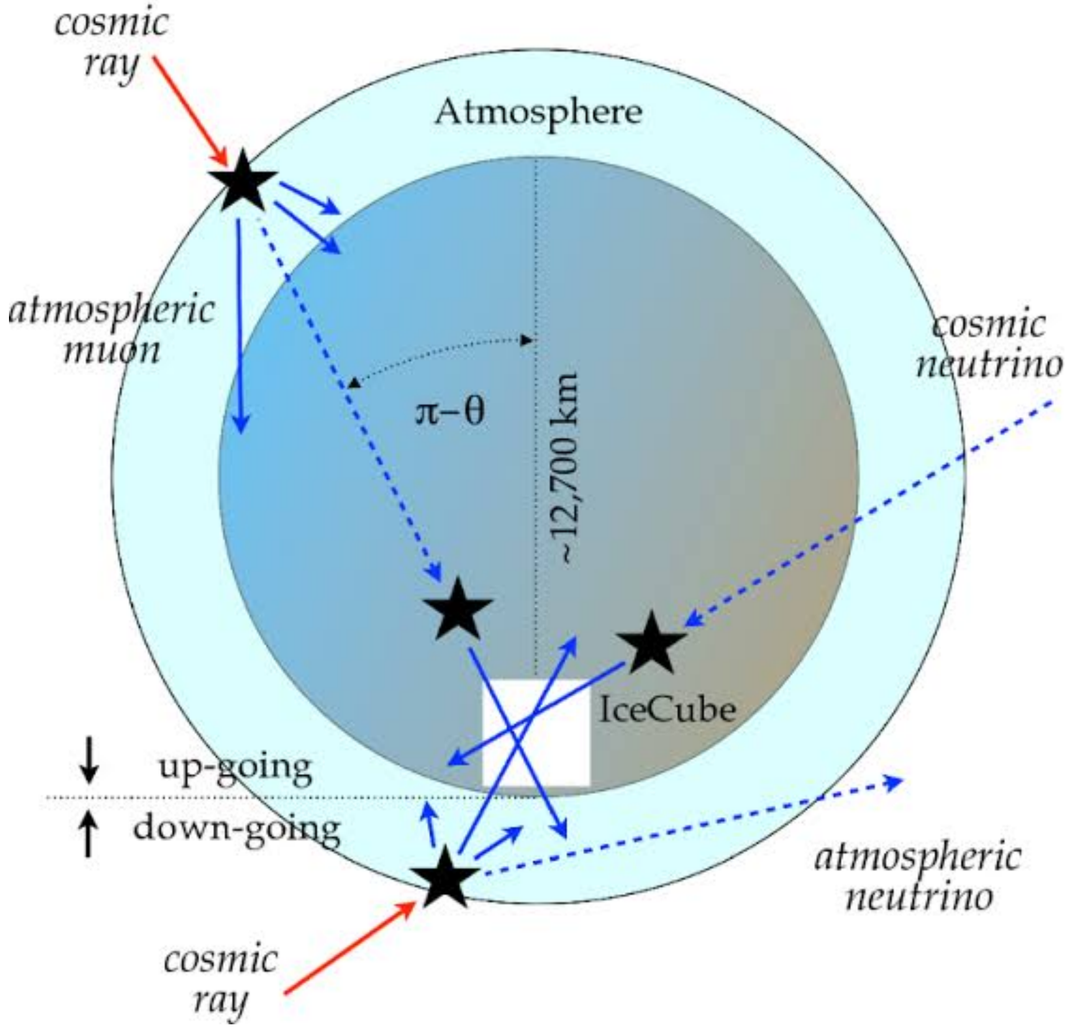
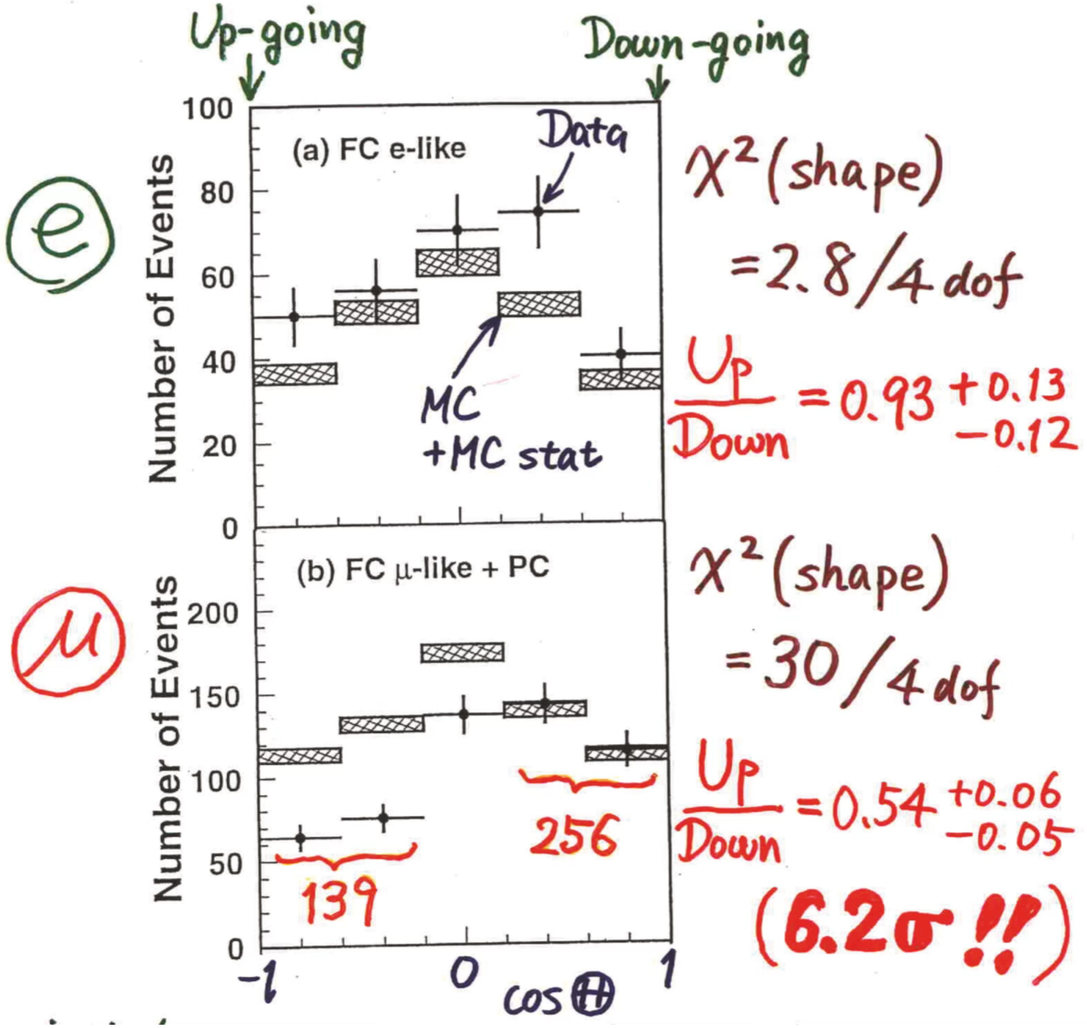


Neutrinos na atmosfera



Zenith angle dependence (Multi-GeV)



Oscilação de neutrinos

Nobel Prize in Physics 2015

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Takaaki Kajita

Prize share: 1/2

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Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Oscilação de neutrinos

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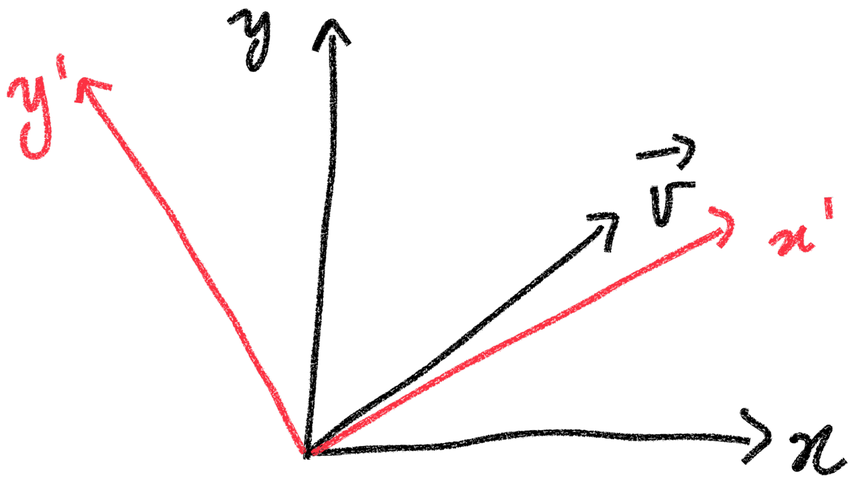
Introdução simples ao fenômeno de oscilação

Bases em álgebra linear



$$\vec{v} = v_1 \hat{i} + v_2 \hat{j}$$
$$= v_1' \hat{i}' + v_2' \hat{j}'$$

Introdução simples ao fenômeno de oscilação

Neutrinos

Base de sabor

$$|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle$$

Base de massa

$$|\nu_1\rangle, |\nu_2\rangle, |\nu_3\rangle$$

Introdução simples ao fenômeno de oscilação

Neutrinos

Base de sabor

$$|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle$$

Produzidos nas interações

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Introdução simples ao fenômeno de oscilação

Neutrinos

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$$|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle$$

Produzidos nas interações

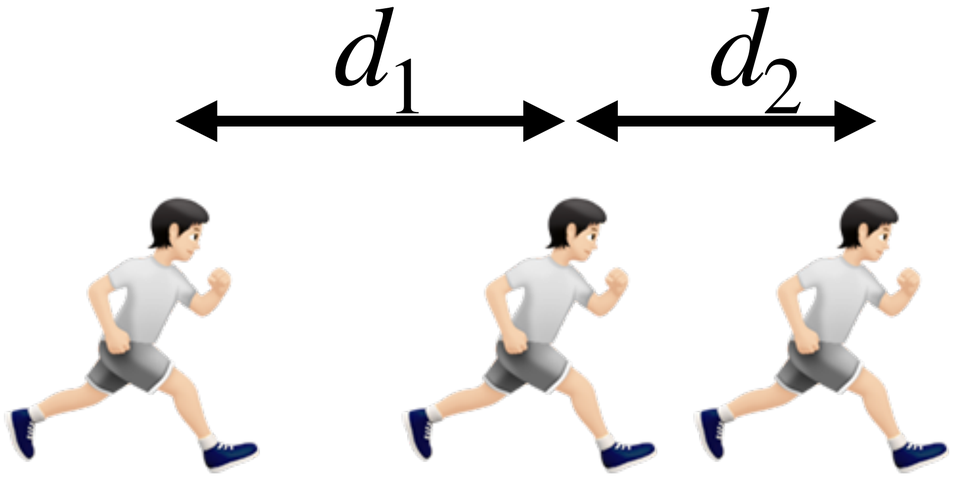
Base de massa

$$|\nu_1\rangle, |\nu_2\rangle, |\nu_3\rangle$$

Estados que propagam

Introdução simples ao fenômeno de oscilação

Introdução simples ao fenômeno de oscilação



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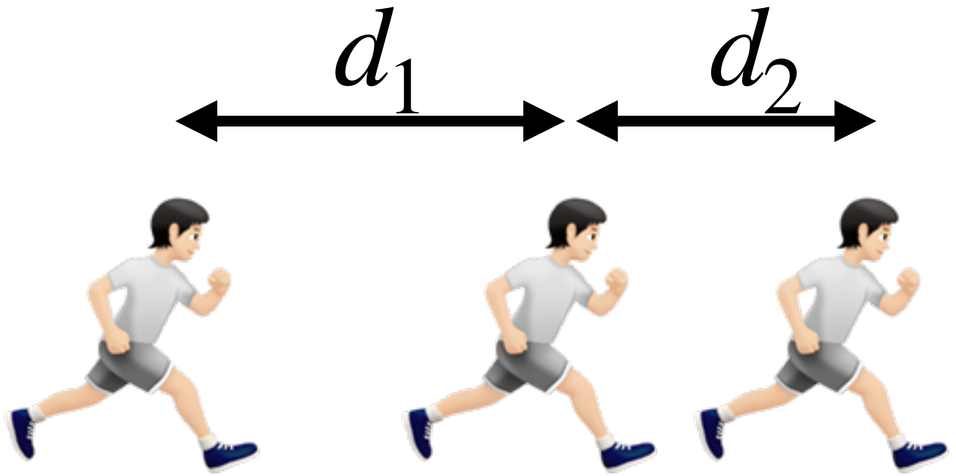

$$|\nu_\mu\rangle$$

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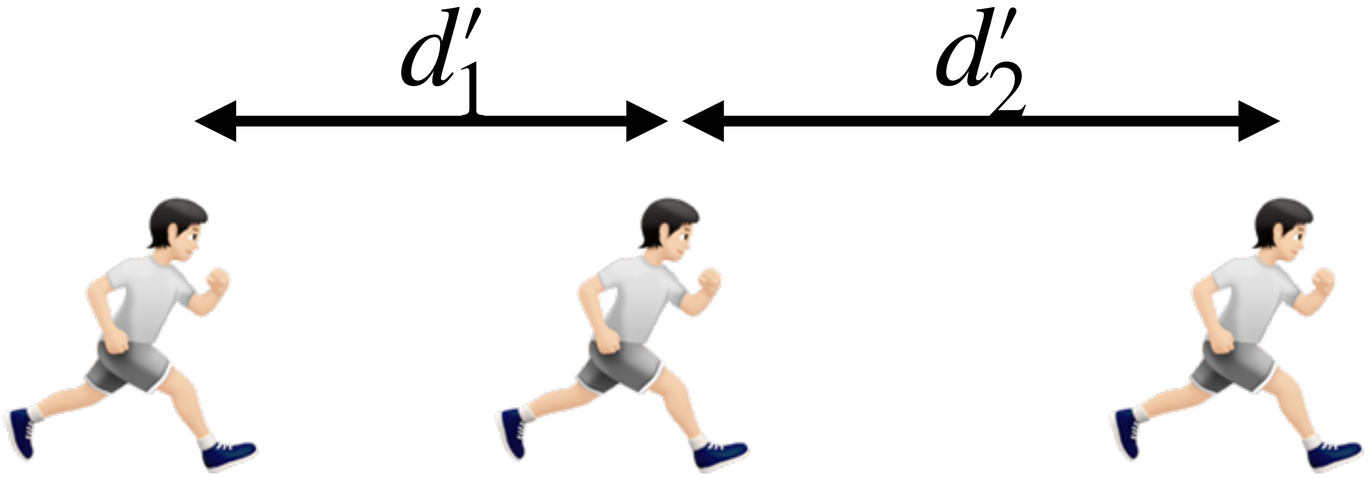

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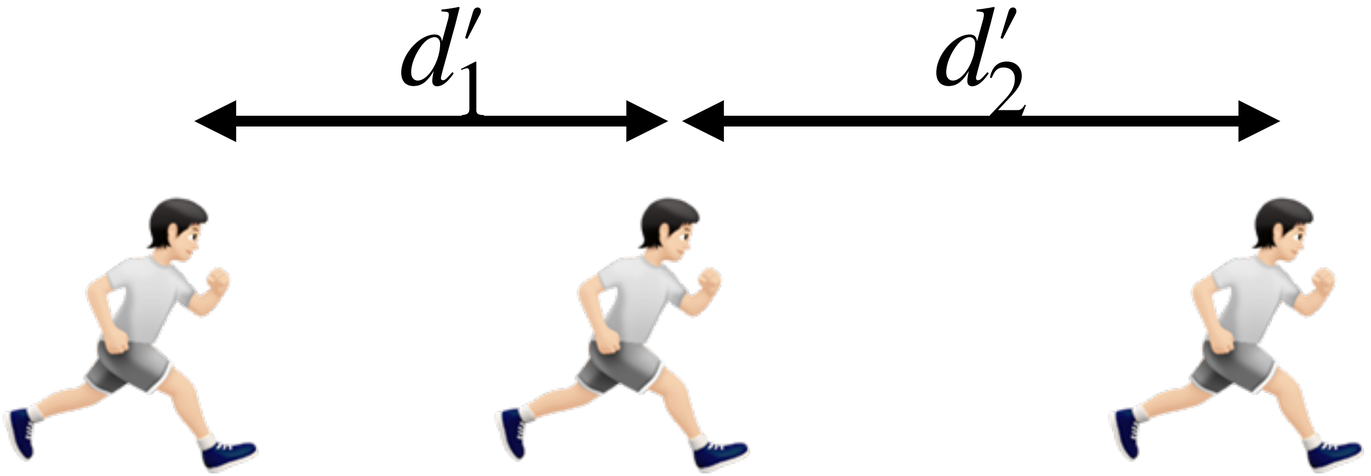

$$|\nu_e\rangle$$

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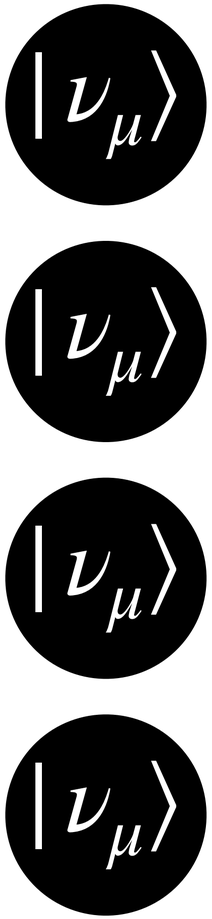

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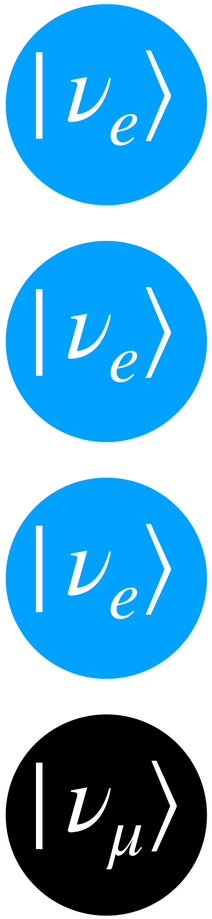

Introdução simples ao fenômeno de oscilação

Mecânica quântica (2 gerações)

$$|\nu_\mu\rangle = U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle$$

Evolução temporal

$$|\nu_\mu\rangle = U_{\mu 1} e^{-iE_1 t}\,|\nu_1\rangle + U_{\mu 2} e^{-iE_2 t}\,|\nu_2\rangle$$

Probabilidade

$$\mathscr{P}_{\nu_\mu \to \nu_\mu}(t) = |\,\langle \nu_\mu\,|\,\nu_\mu\rangle\,|^2 = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Introdução simples ao fenômeno de oscilação

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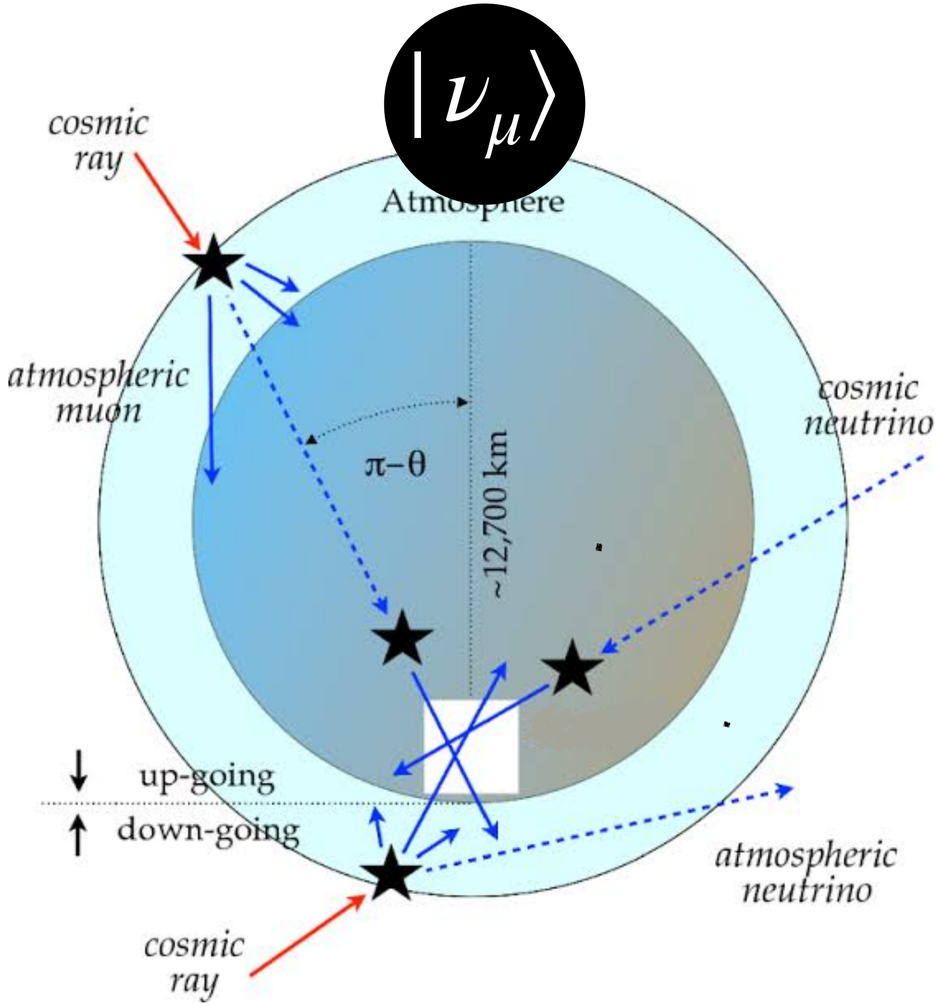
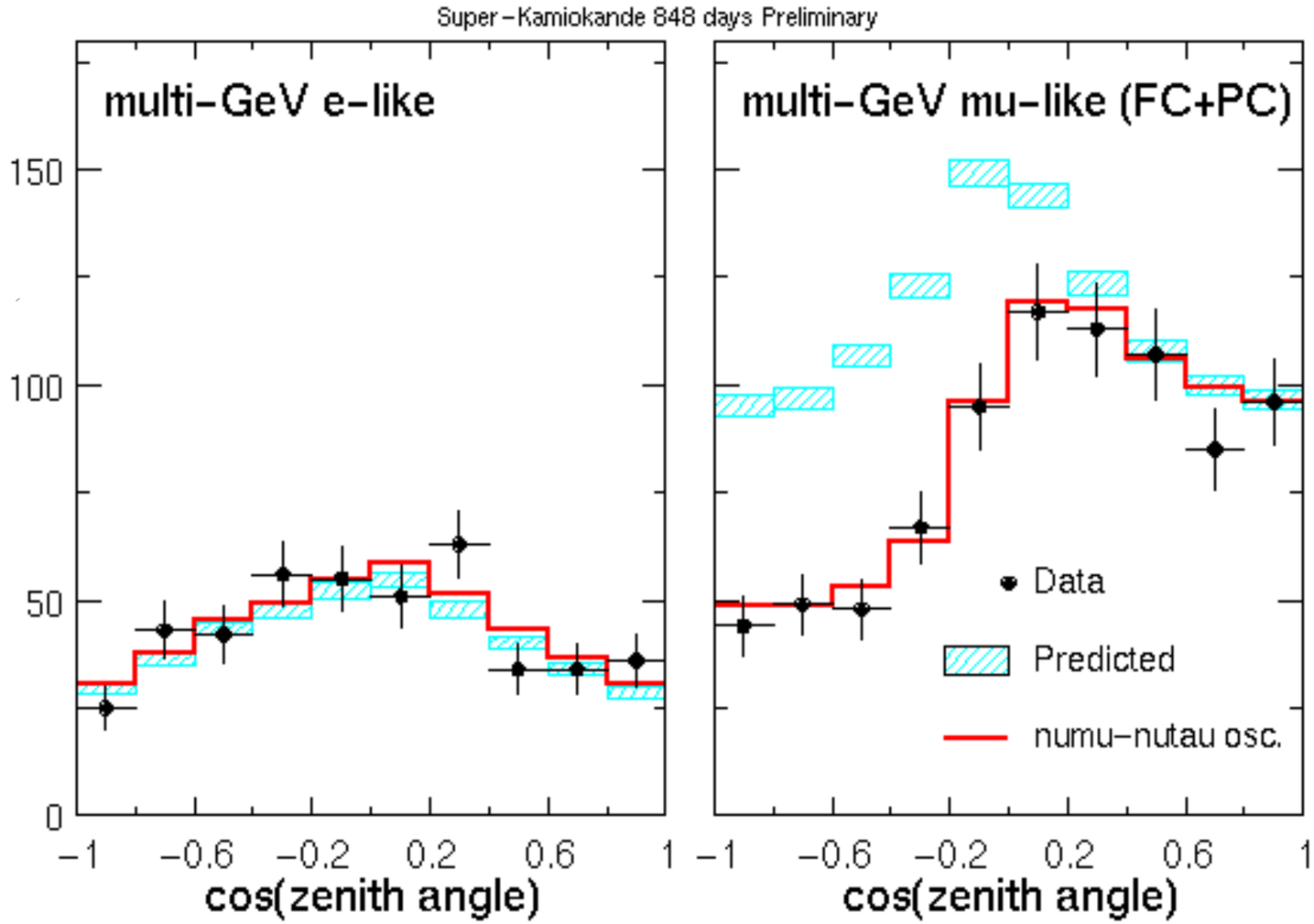
$$\Delta m^2 = m_2^2 - m_1^2$$

Introdução simples ao fenômeno de oscilação





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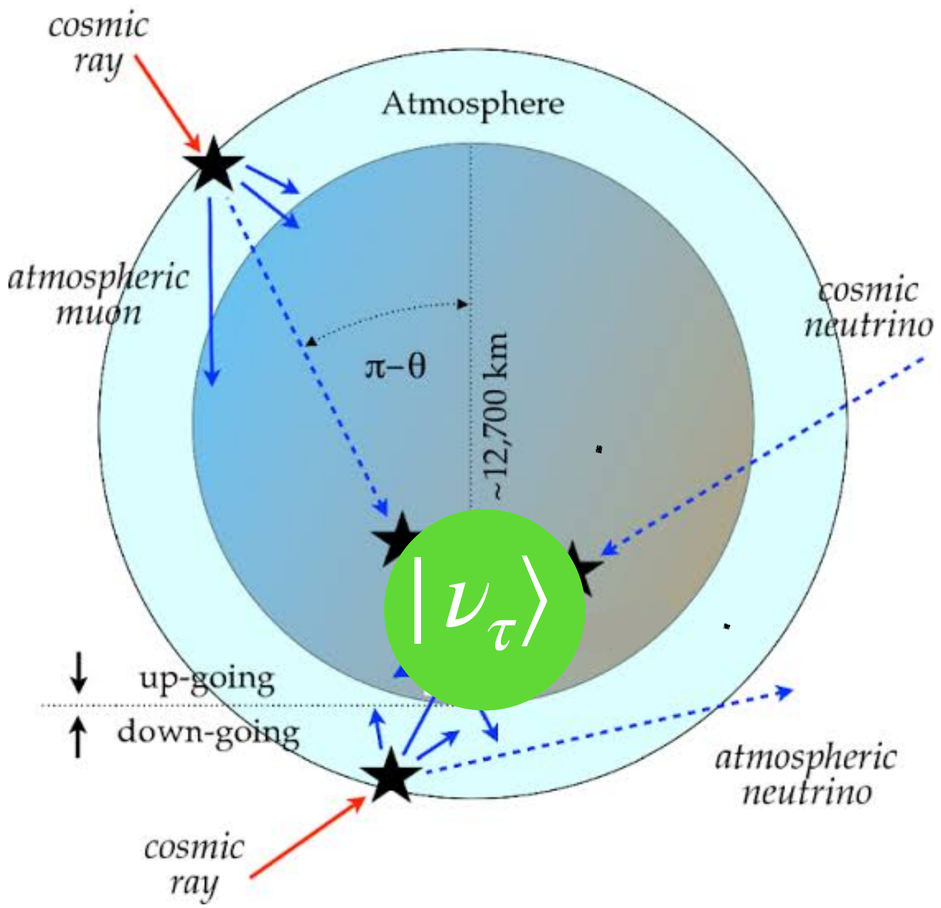

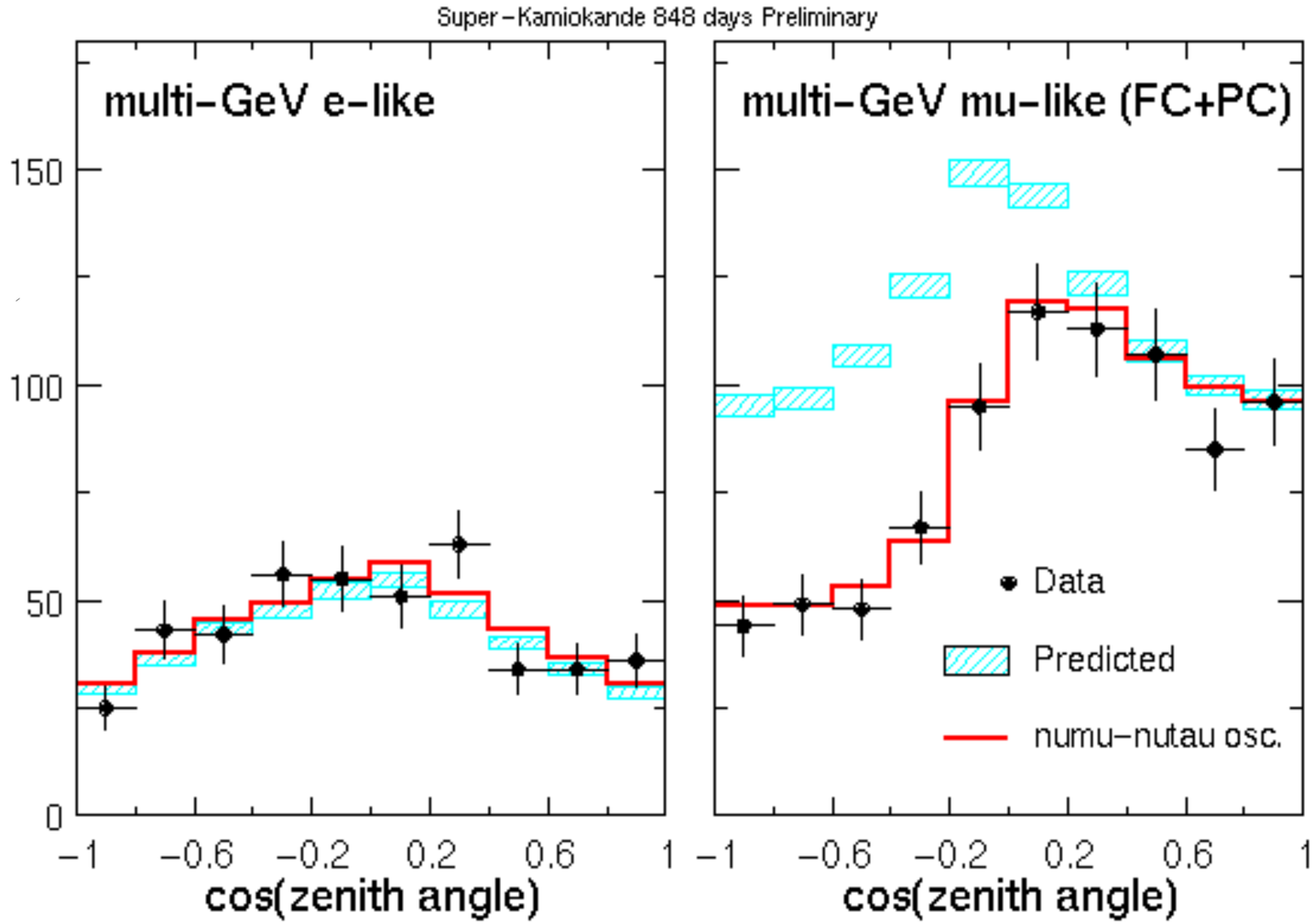

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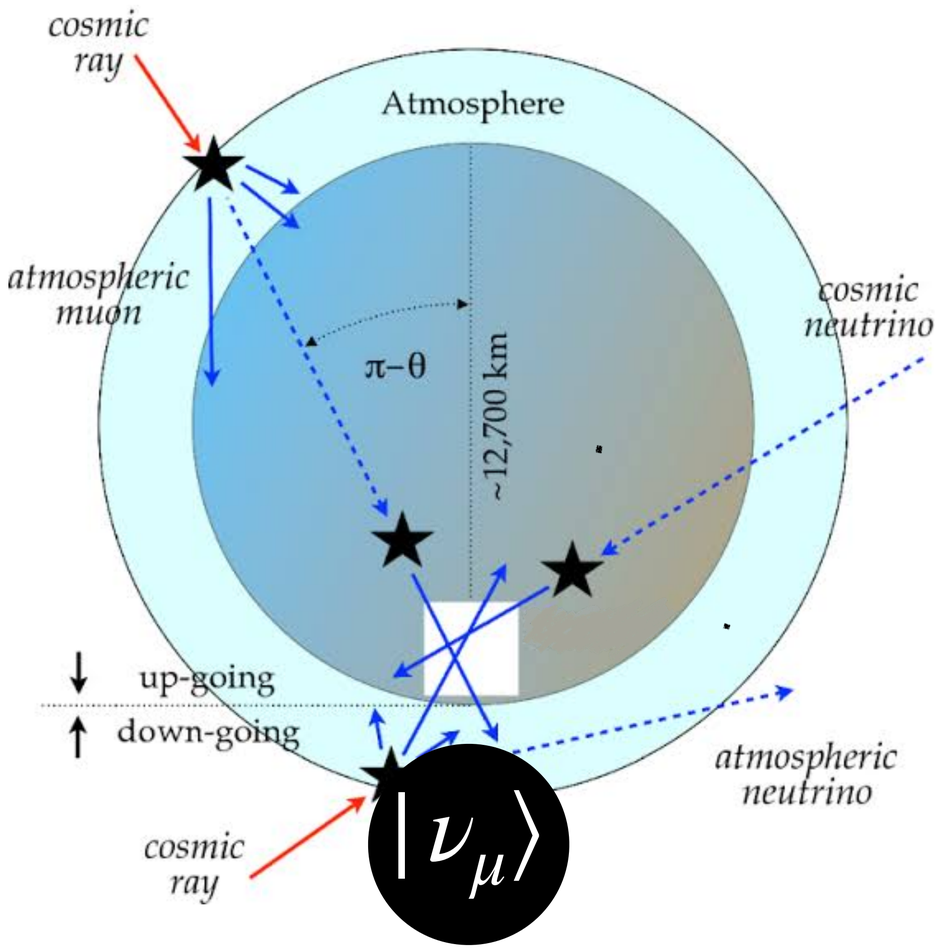
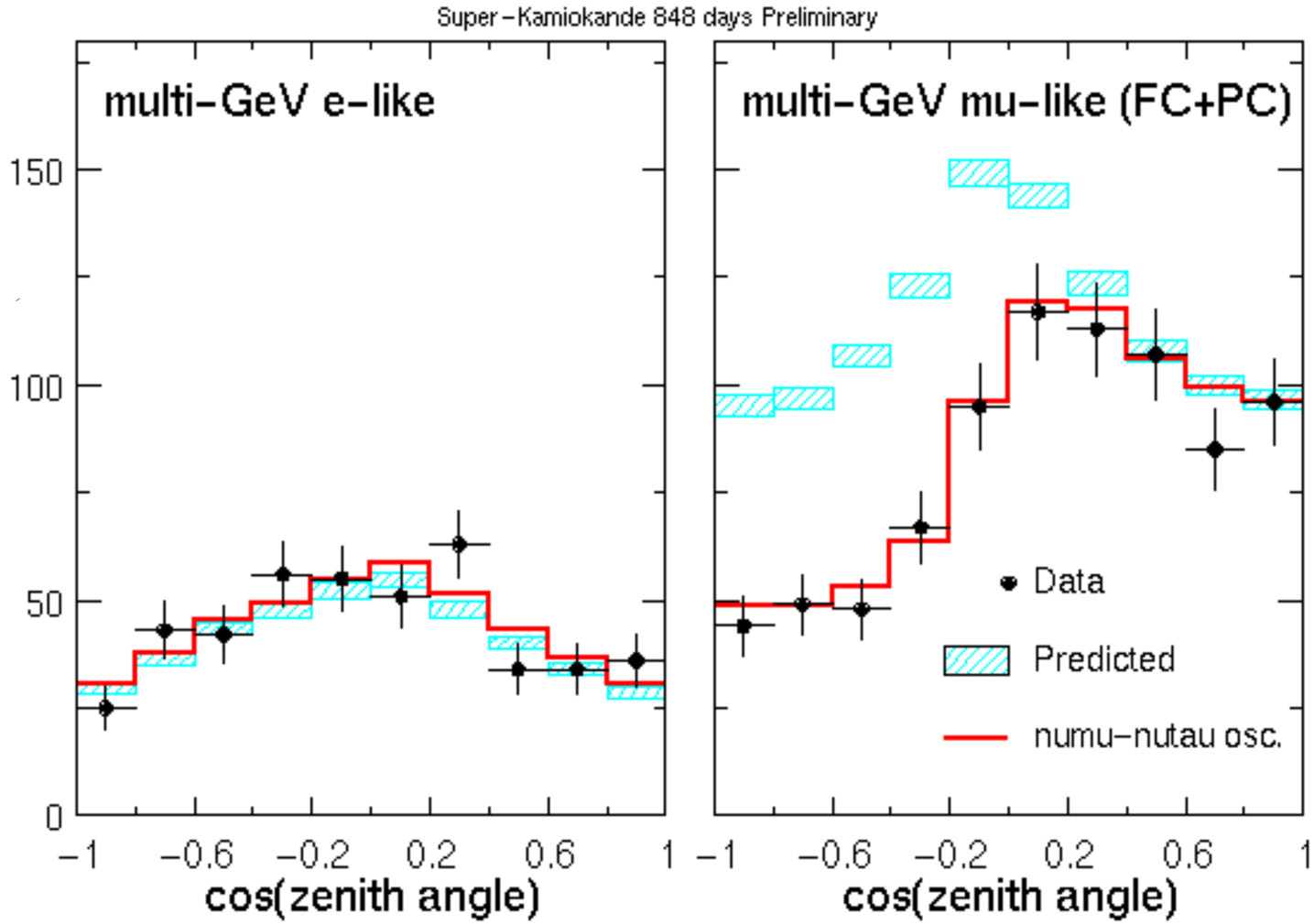
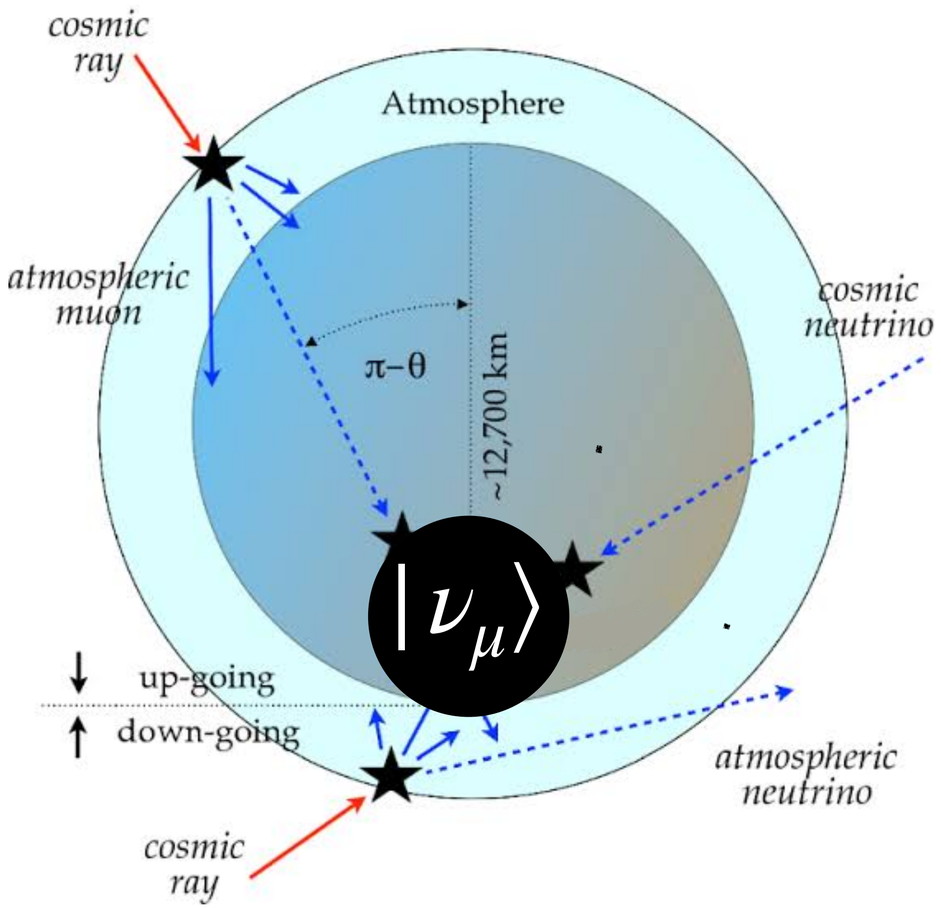
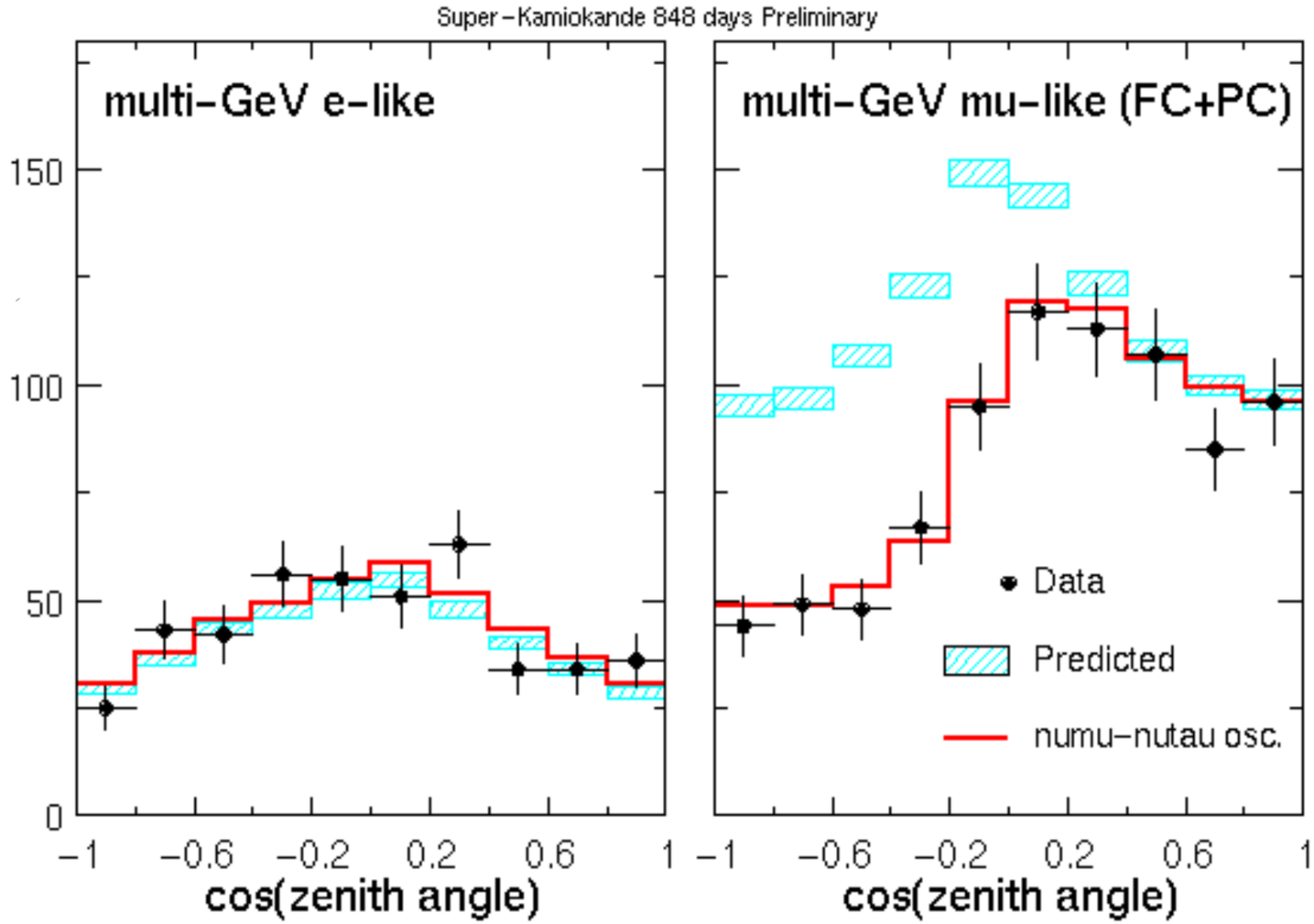




Introdução simples ao fenômeno de oscilação





Solução do problema solar

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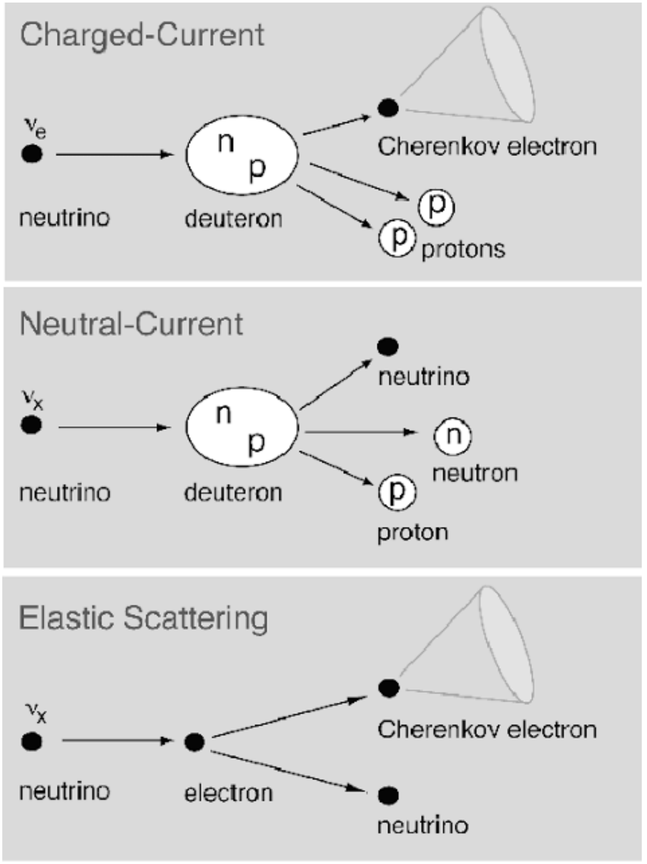
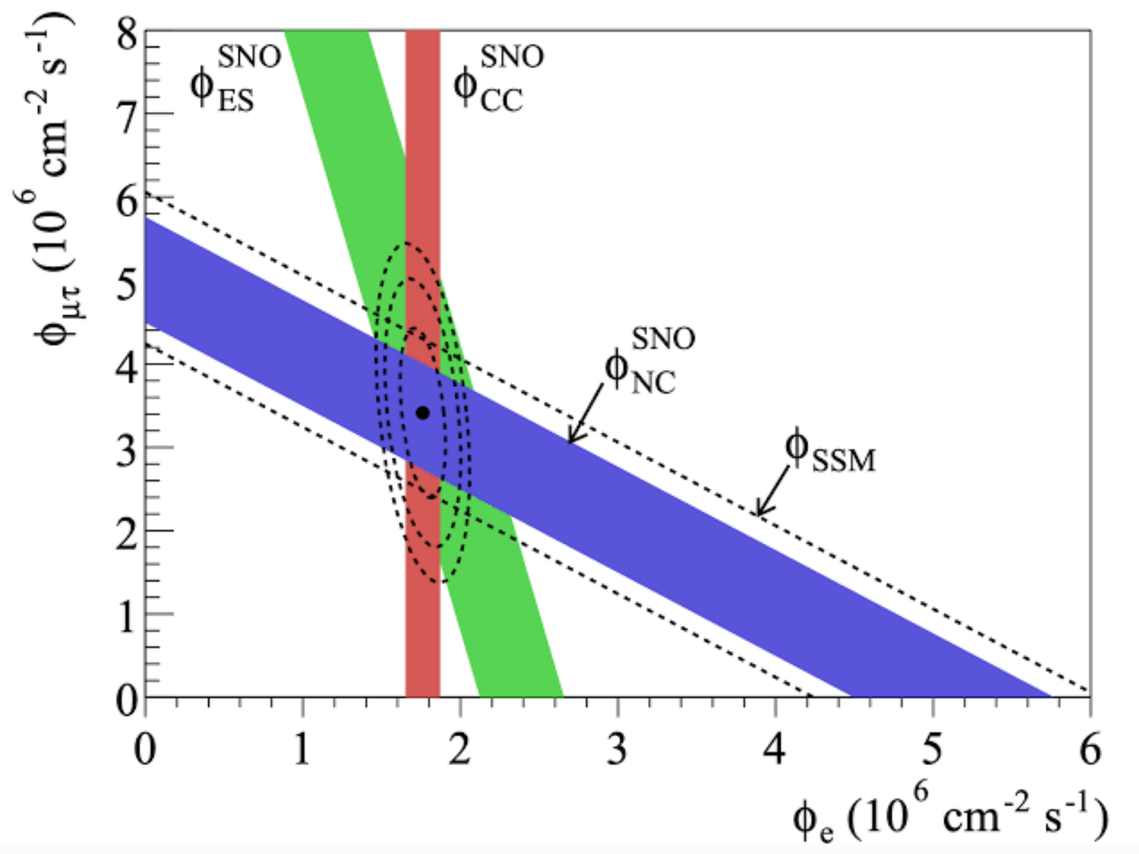
Todos neutrinos chegam. Nós só estávamos medindo neutrinos do elétron.





Experimento SNO

Solução do problema solar

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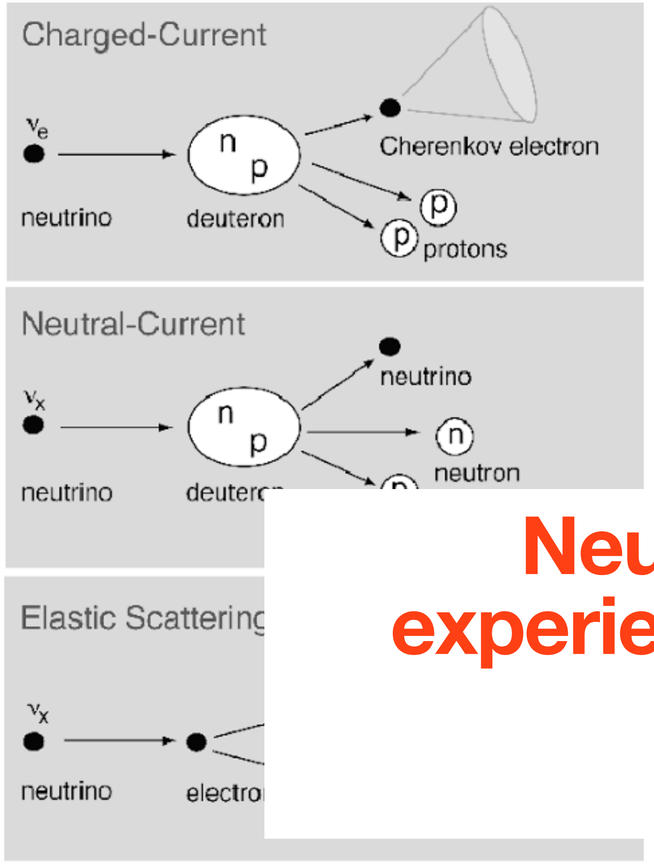
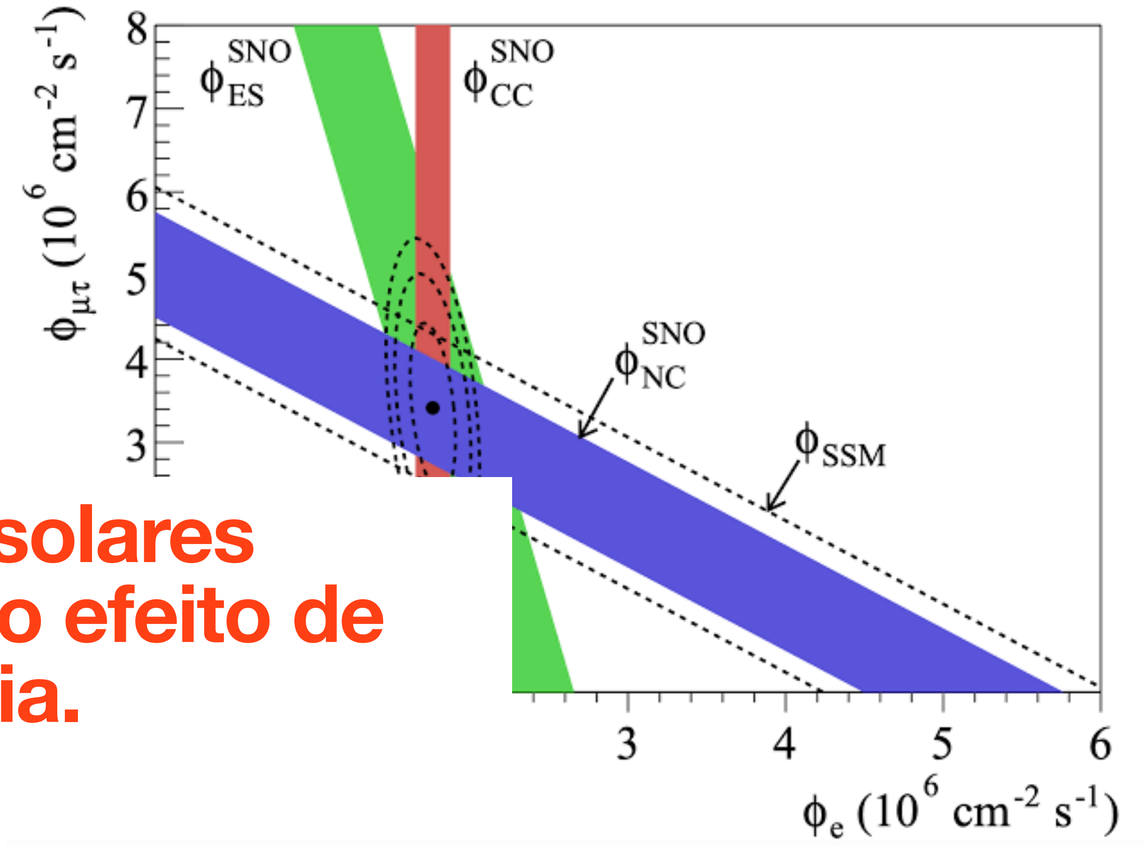
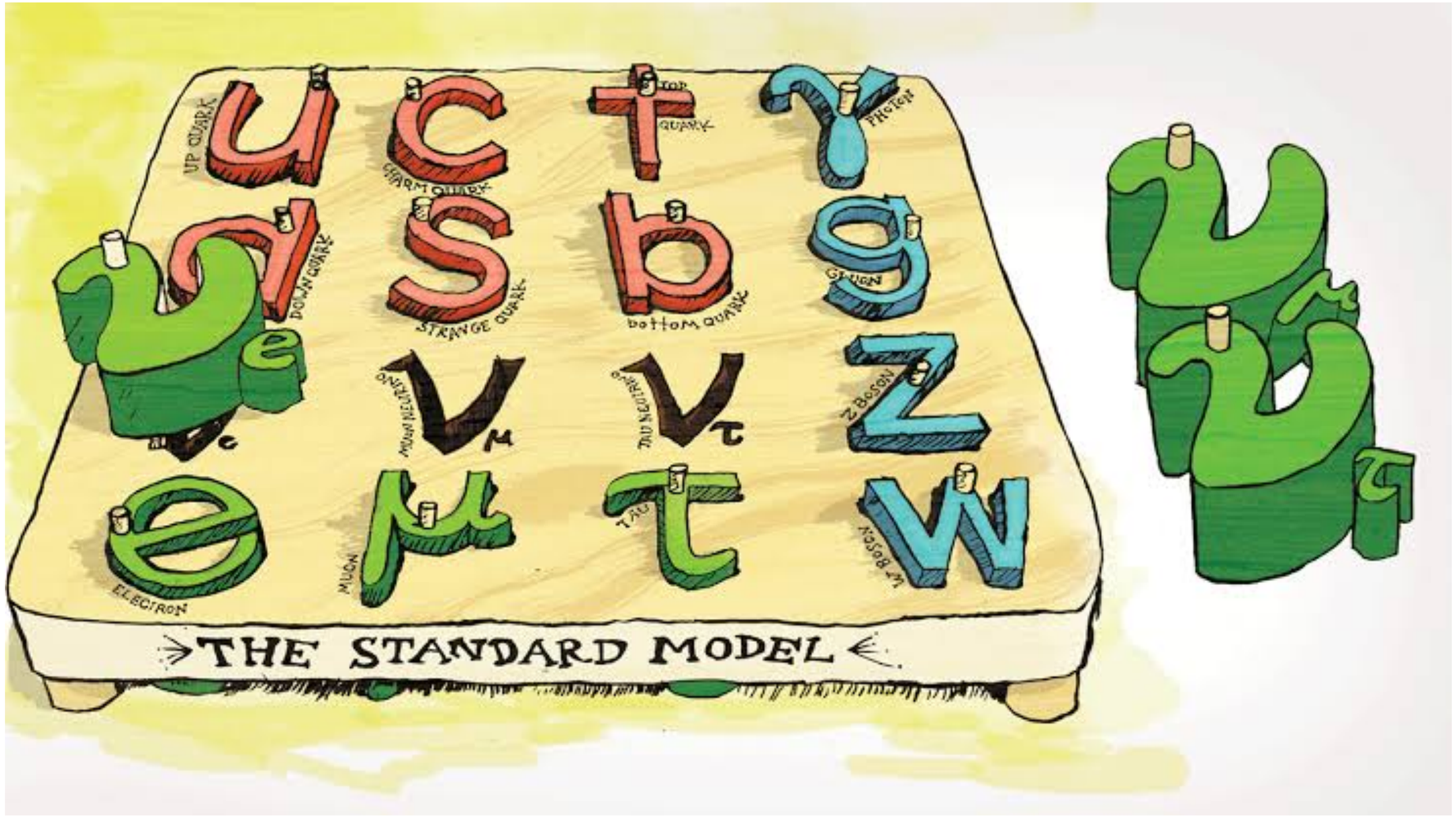


Neutrinos solares experienciam o efeito de matéria.



Experimento SNO

Agora podemos entender o porque



Predição do Modelo Padrão:

Neutrinos são partículas sem massa

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Processos envolvendo neutrinos nos guiaram para construir o modelo padrão. Neutrinos agora podem nos guiar para ir além dele!

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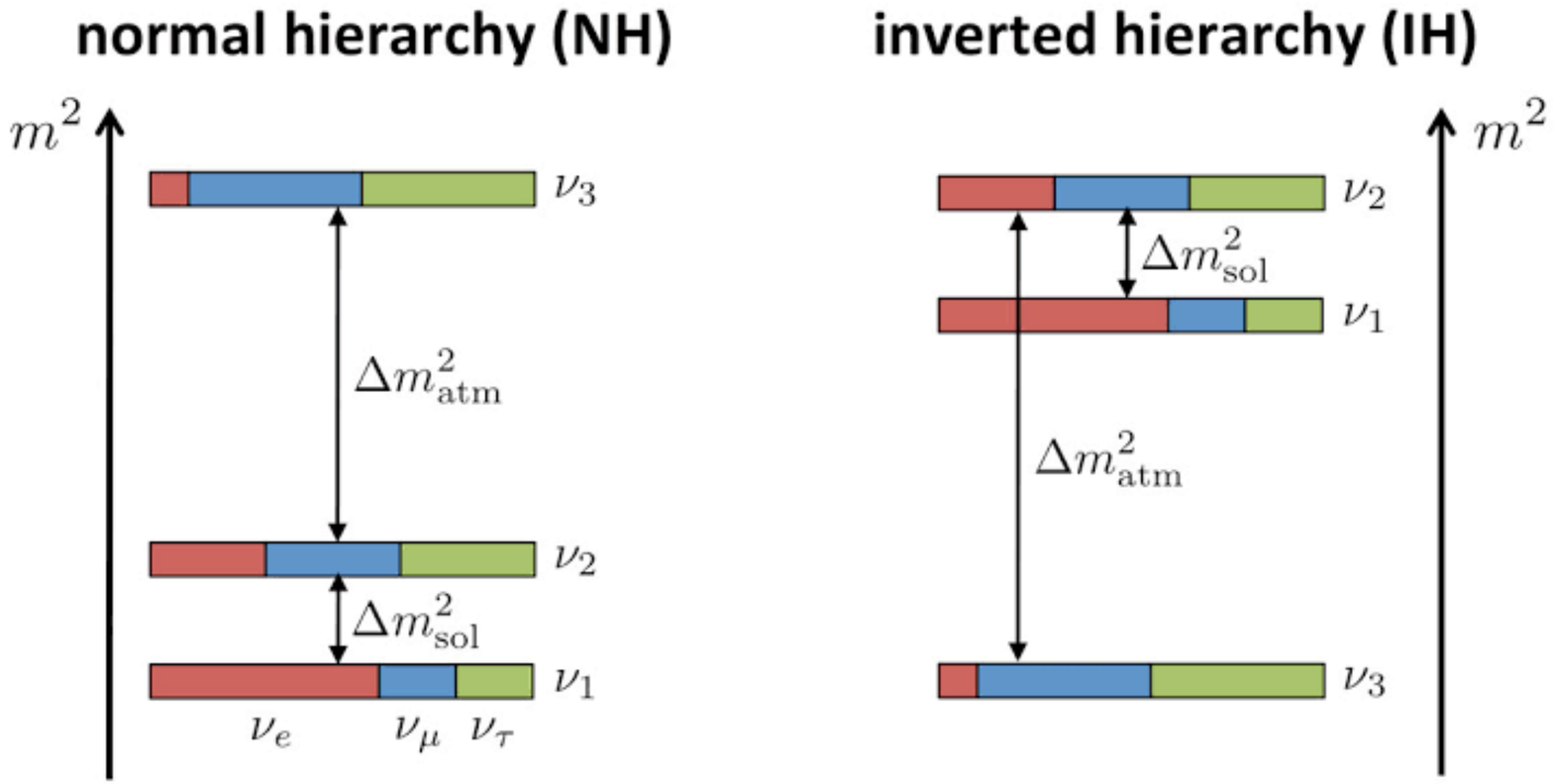
Oportunidades de trabalho!

Criatividade + horas de dedicação + sorte

Ainda não sabemos muitas coisas sobre neutrinos



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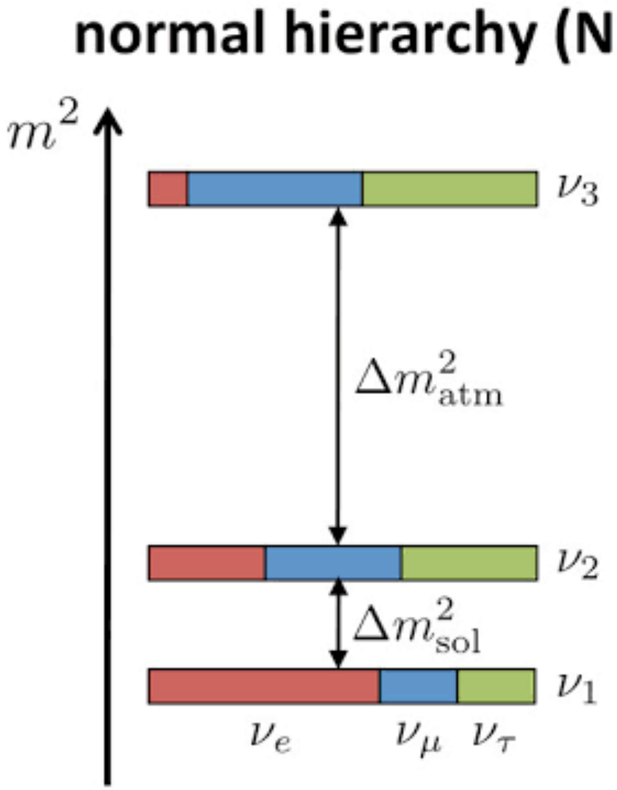

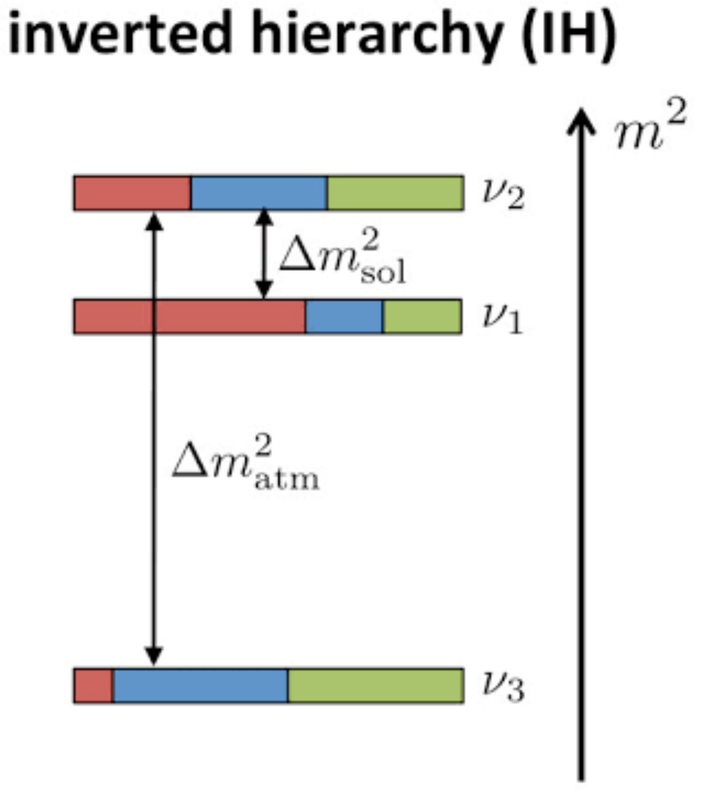

Massa absoluta?

Medir todos parâmetros de oscilação

Exemplos que tenho trabalhado

Como explicar a origem da massa dos neutrinos?

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Novas partículas?

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Explorar o setor eletrofraco do Modelo padrão.

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Novas partículas?

Conectar com outros problemas em aberto?

Explorar o setor eletrofraco do Modelo padrão.

Exemplos que tenho trabalhado

Interface com outras áreas de pesquisa?

Searches for massive neutrinos with mechanical quantum sensors

Daniel Carney, Kyle G. Leach, David C. Moore

The development of quantum optomechanics now allows mechanical sensors with femtogram masses to be controlled and measured in the quantum regime. If the mechanical element contains isotopes that undergo nuclear decay, measuring the recoil of the sensor following the decay allows reconstruction of the total momentum of all emitted particles, including any neutral particles that may escape detection in traditional detectors. As an example, for weak nuclear decays the momentum of the emitted neutrino can be reconstructed on an event-by-event basis. We present the concept that a single nanometer-scale, optically levitated sensor operated with sensitivity near the standard quantum limit can search for heavy sterile neutrinos in the keV-MeV mass range with sensitivity significantly beyond existing constraints. We also comment on the possibility that mechanical sensors operated well into the quantum regime might ultimately reach the sensitivities required to provide an absolute measurement of the mass of the light neutrino states.

Exemplos que tenho trabalhado

Could SBND-PRISM probe lepton flavor violation? #8

Gustavo F.S. Alves (Sao Paulo U.), Renata Zukanovich Funchal (Sao Paulo U.), Pedro A.N. Machado (Fermilab) (May 1, 2024)

Published in: *Phys.Rev.D* 110 (2024) 3, 3 • e-Print: 2405.00777 [hep-ph]

pdf links DOI cite claim reference search 3 citations

Limits on W_R from Meson Decays #9

Gustavo F.S. Alves (Sao Paulo U. and Fermilab), Chee Sheng Fong (ABC Federal U.), Luighi P.S. Leal (Sao Paulo U.), Renata Zukanovich Funchal (Sao Paulo U.) (Jul 10, 2023)

Published in: *Phys.Rev.Lett.* 133 (2024) 16, 16 • e-Print: 2307.04862 [hep-ph]

pdf links DOI cite claim reference search 7 citations

Exploring the Neutrino Sector of the Minimal Left-Right Symmetric Model #10

Gustavo F.S. Alves (U. Sao Paulo (main)), Chee Sheng Fong (ABC Federal U.), Luighi P.S. Leal (U. Sao Paulo (main)), Renata Zukanovich Funchal (U. Sao Paulo (main)) (Aug 15, 2022)

e-Print: 2208.07378 [hep-ph]

pdf cite claim reference search 4 citations

Mass reconstruction of heavy neutral leptons from stopped mesons #6

Gustavo F.S. Alves (Sao Paulo U. and Fermilab), P.S. Bhupal Dev (McDonnell Ctr. Space Sci.), Kevin J. Kelly (Texas A-M), Pedro A.N. Machado (Fermilab) (Sep 6, 2024)

Published in: *Phys.Rev.D* 111 (2025) 1, 1 • e-Print: 2409.04394 [hep-ph]

pdf links DOI cite claim reference search 2 citations

Does the Sun have a dark disk? #7

Gustavo F.S. Alves (Fermilab and Sao Paulo U.), Susan Gardner (Kentucky U.), Pedro Machado (Fermilab), Mohammadreza Zakeri (Kentucky U.) (Jun 5, 2024)

Published in: *Phys.Rev.D* 111 (2025) 8, 083057 • e-Print: 2406.03607 [hep-ph]

pdf links DOI cite claim reference search 1 citation

Measuring the weak mixing angle at SBND #5

Gustavo F.S. Alves (Sao Paulo U. and Fermilab), Antonio P. Ferreira (Sao Paulo U. and Fermilab), Shirley Weishi Li (Fermilab and UC, Irvine), Pedro A.N. Machado (Fermilab), Yuber F. Perez-Gonzalez (Durham U., IPPP) (Sep 11, 2024)

e-Print: 2409.07430 [hep-ph]

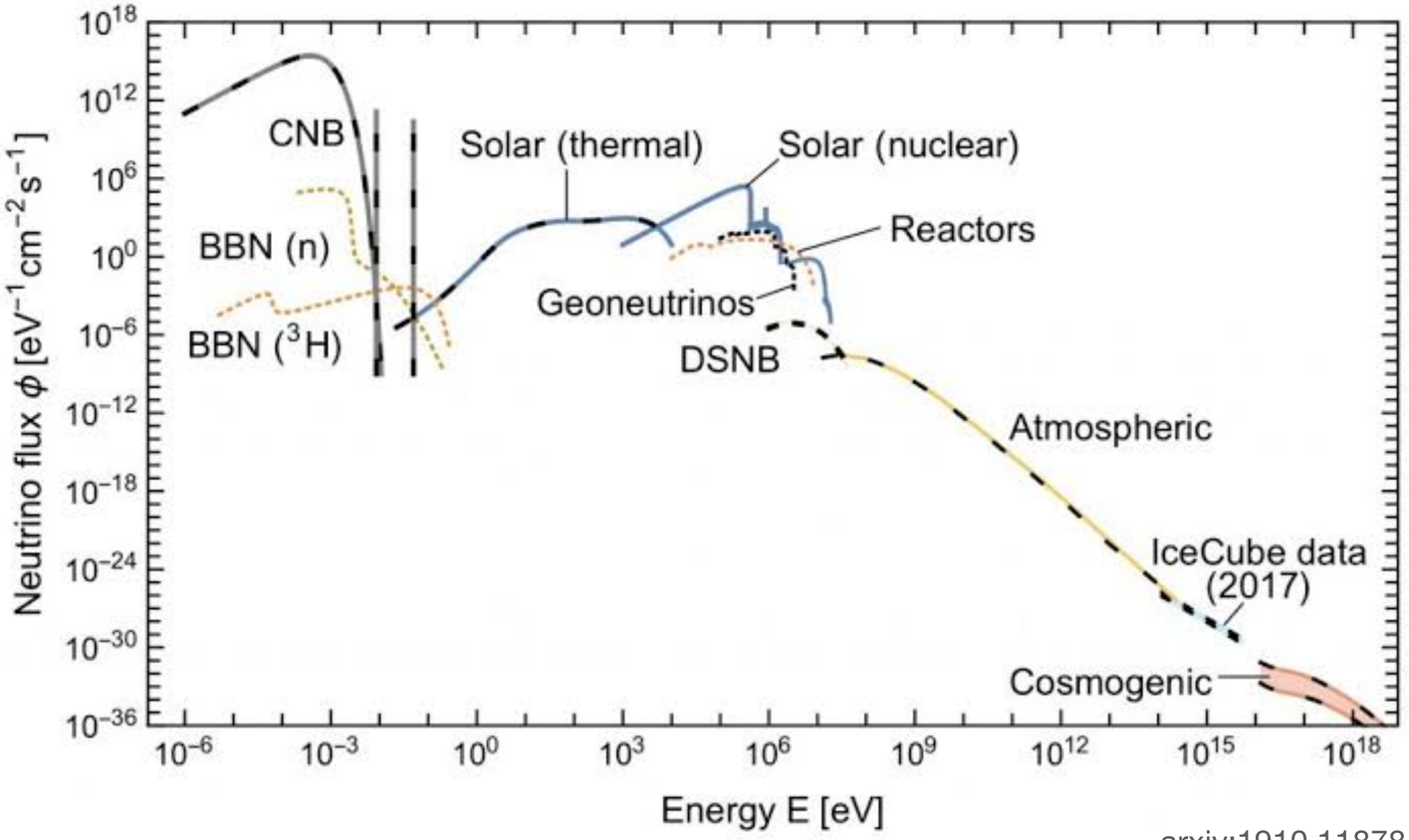
pdf links cite claim reference search 5 citations

Física de neutrinos é uma área quente!

Neutrinos são a segunda partícula mais abundante do universo.

Física de neutrinos é uma área quente!

Produzidos em diferentes energias, cobrindo 24 ordens de magnitude!



arxiv:1910.11878

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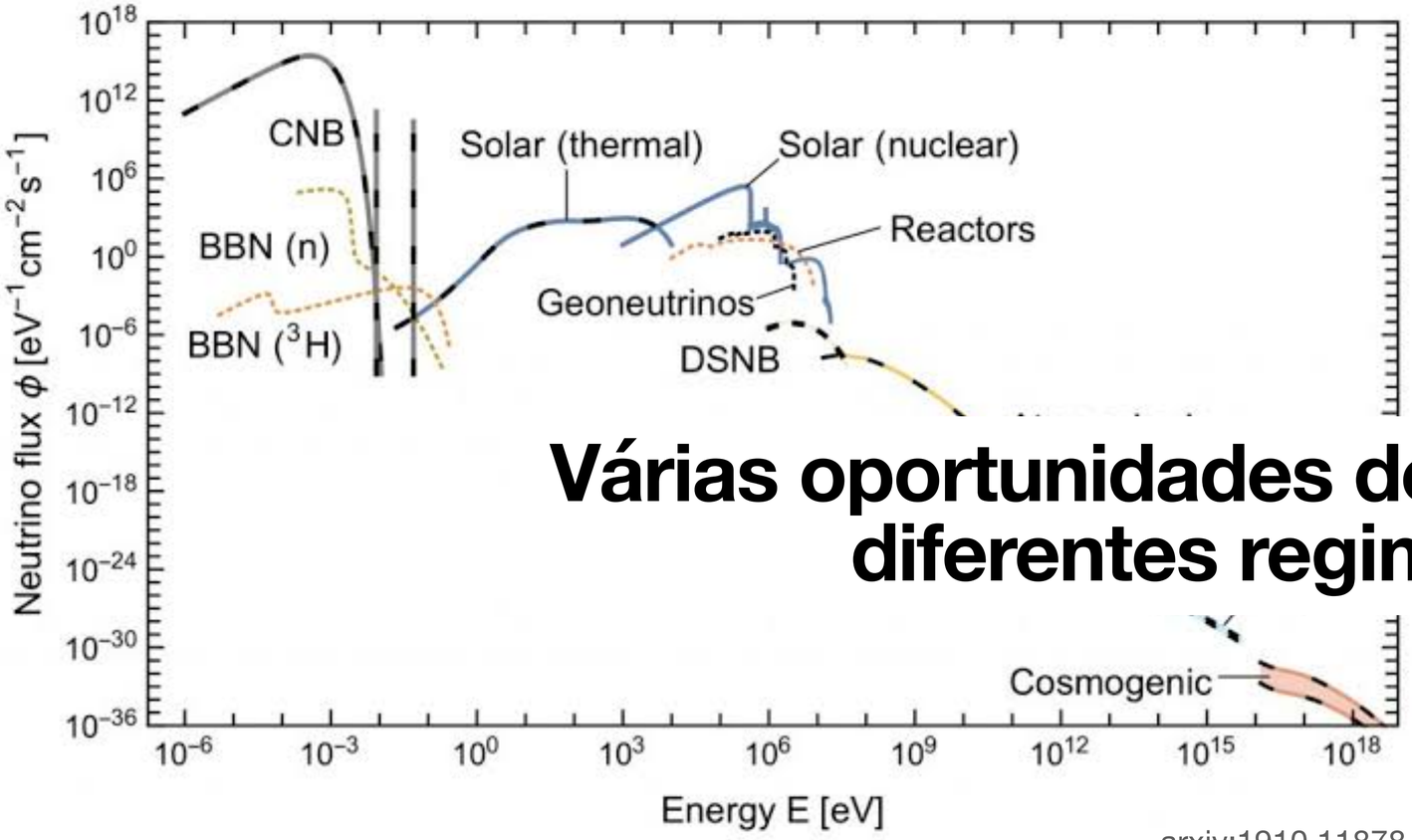


Várias oportunidades de estudo em diferentes regimes!

arxiv:1910.11878

Física de neutrinos é uma área quente!

Podemos estudar a terra

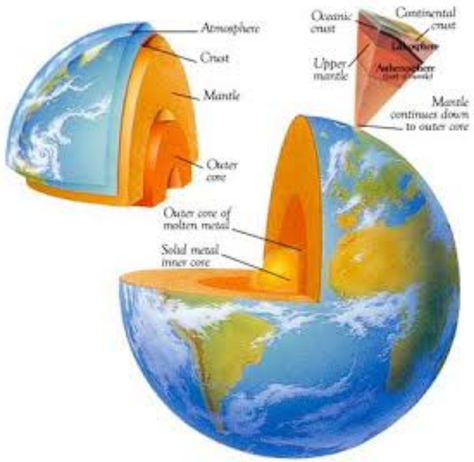
What are Geoneutrinos?

the antineutrinos produced by natural radioactivity in the Earth

radioactive decay of uranium, thorium and from potassium-40 produces antineutrinos

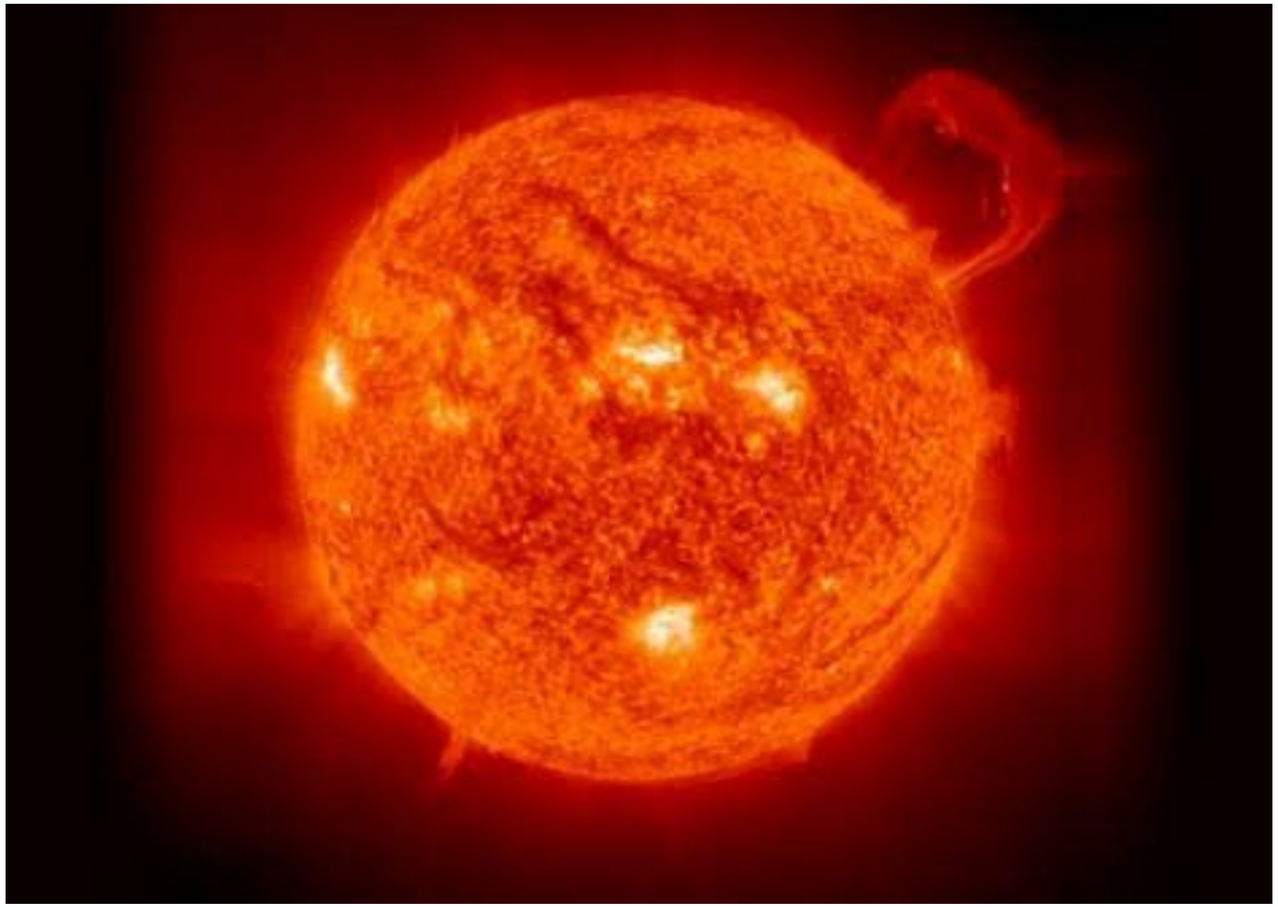
$\overline{\nu}_e$

assay the entire Earth by looking at its "neutrino glow"



July 21, 2008 M. Chen OCPA Underground Science Image by: Colin Rose, Dorling Kindersley 2

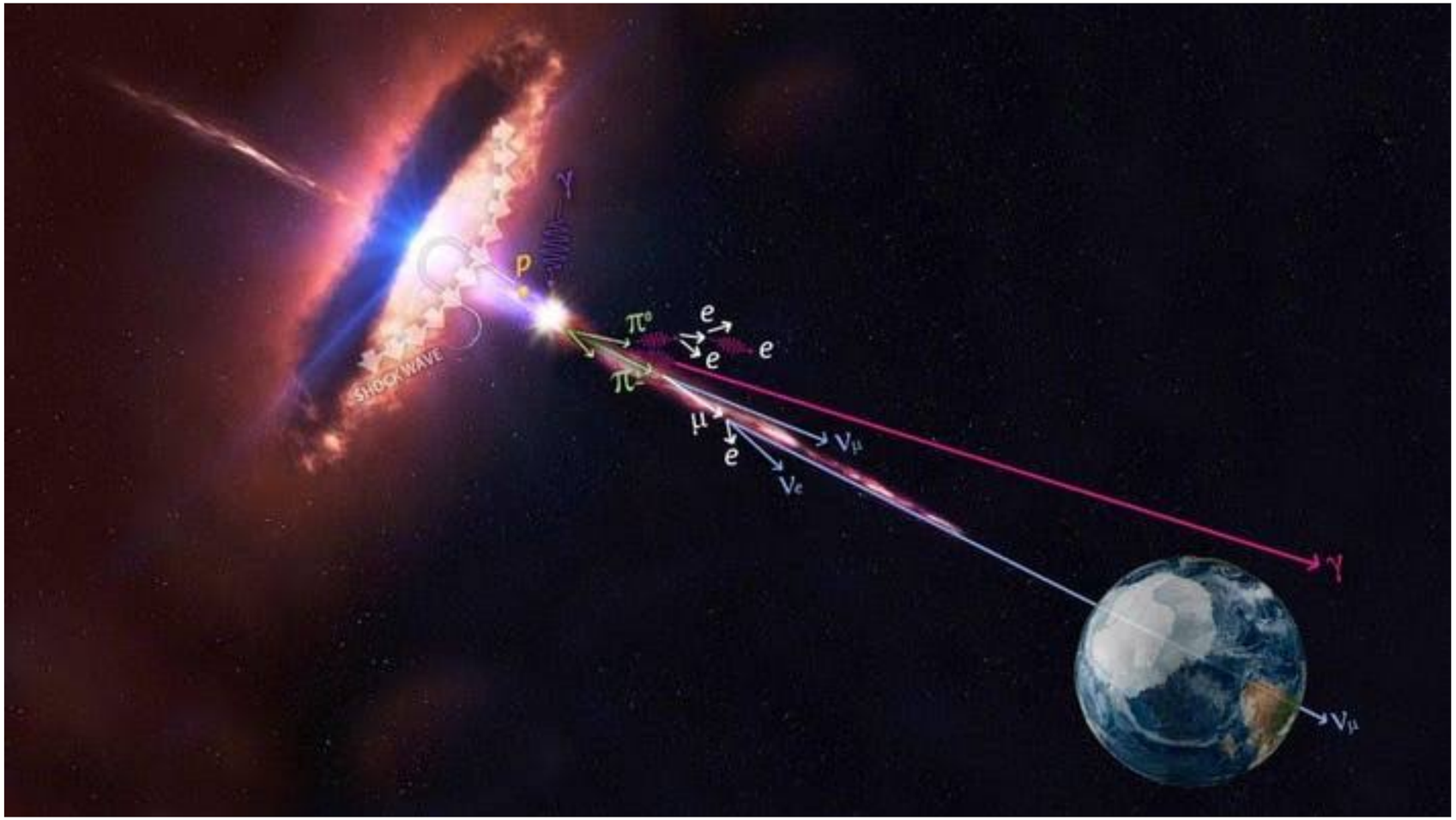
Física de neutrinos é uma área quente!



Podemos estudar o interior do Sol!

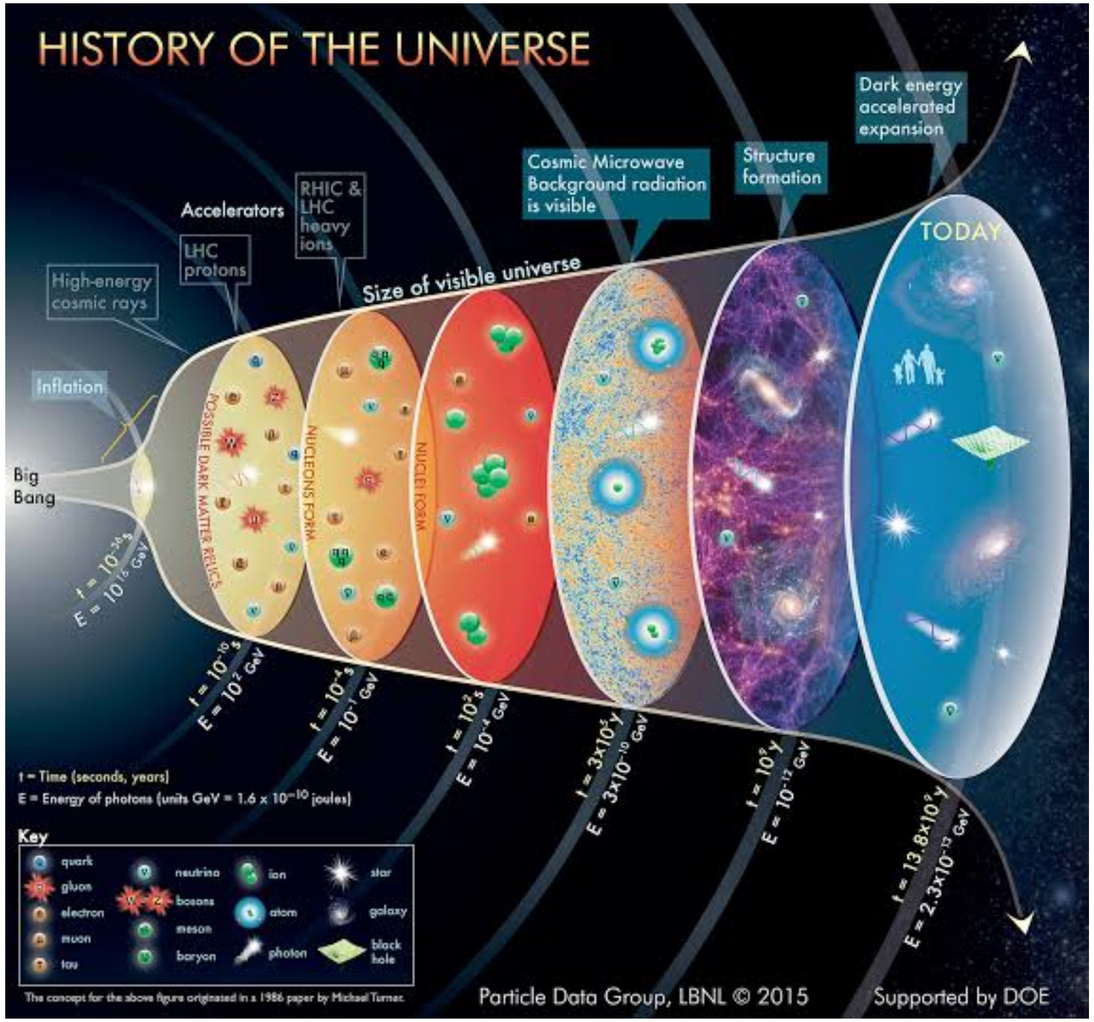
Física de neutrinos é uma área quente!

Amplamente produzidos nos eventos mais energéticos do universo



Física de neutrinos é uma área quente!

Desempenham um papel importante na evolução do universo



Física de neutrinos é uma área quente!

Article | Open access | Published: 12 February 2025

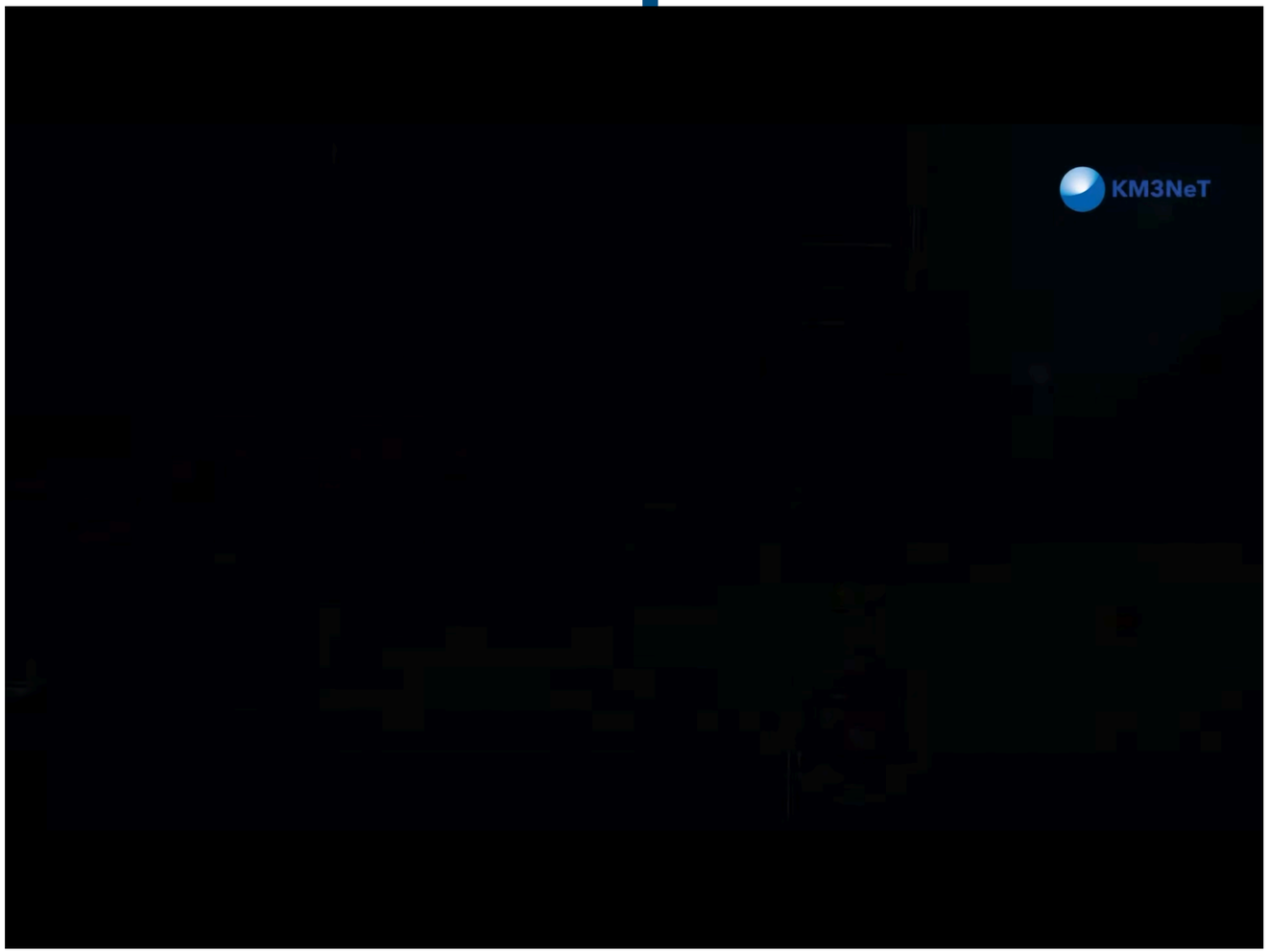
Observation of an ultra-high-energy cosmic neutrino with KM3NeT

The KM3NeT Collaboration

Nature **638**, 376–382 (2025) | Cite this article

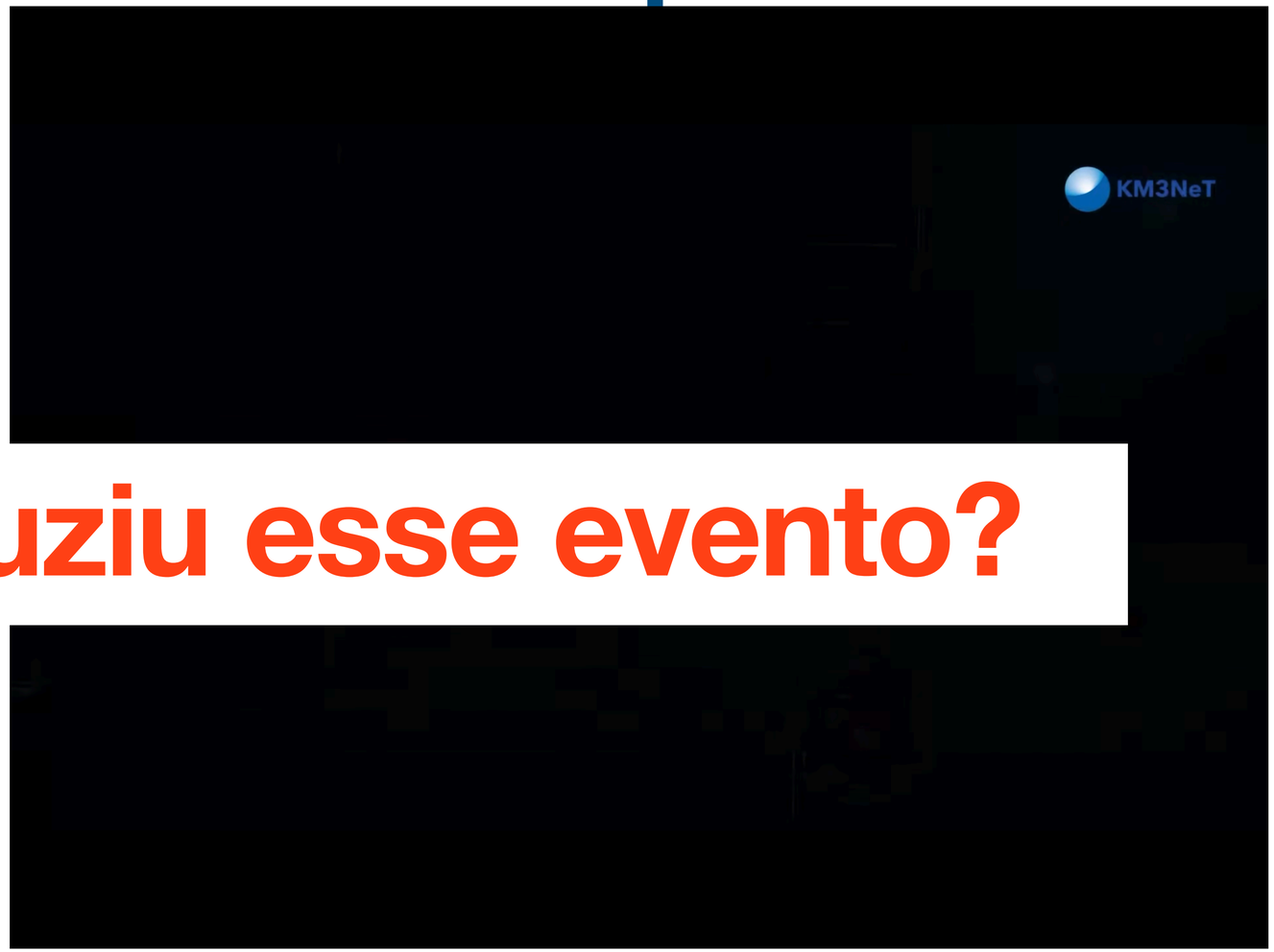
133k Accesses | **33** Citations | **1632** Altmetric | Metrics

Física de neutrinos é uma área quente!



“The signal of the most energetic elementary particle ever observed.”

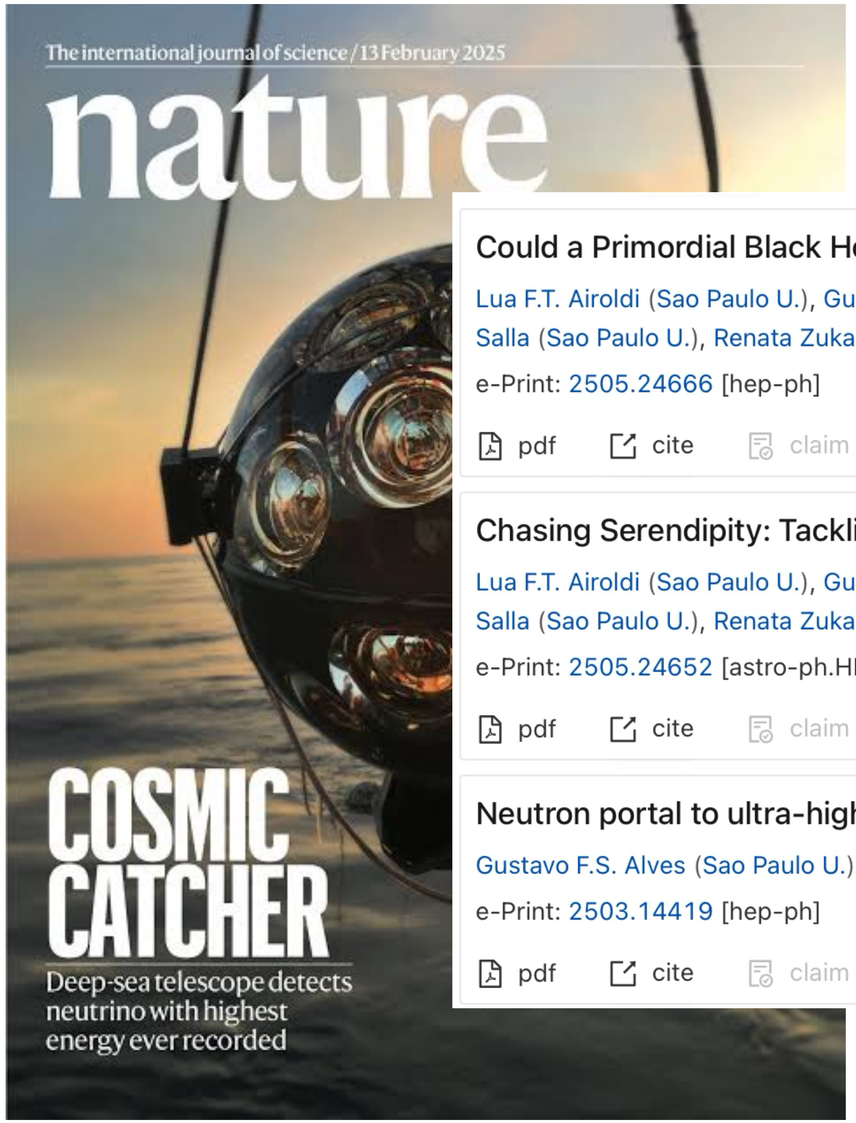
Física de neutrinos é uma área quente!



O que produziu esse evento?

“The signal of the most energetic elementary particle ever observed.”

Física de neutrinos é uma área quente!



Could a Primordial Black Hole Explosion Explain the KM3NeT Event? #1

Lua F.T. Airoldi (Sao Paulo U.), Gustavo F.S. Alves (Sao Paulo U.), Yuber F. Perez-Gonzalez (Madrid, IFT), Gabriel M. Salla (Sao Paulo U.), Renata Zukanovich Funchal (Sao Paulo U.) (May 30, 2025)

e-Print: 2505.24666 [hep-ph]

pdf cite claim reference search 6 citations

Chasing Serendipity: Tackling Transient Sources with Neutrino Telescopes #2

Lua F.T. Airoldi (Sao Paulo U.), Gustavo F.S. Alves (Sao Paulo U.), Yuber F. Perez-Gonzalez (Madrid, IFT), Gabriel M. Salla (Sao Paulo U.), Renata Zukanovich Funchal (Sao Paulo U.) (May 30, 2025)

e-Print: 2505.24652 [astro-ph.HE]

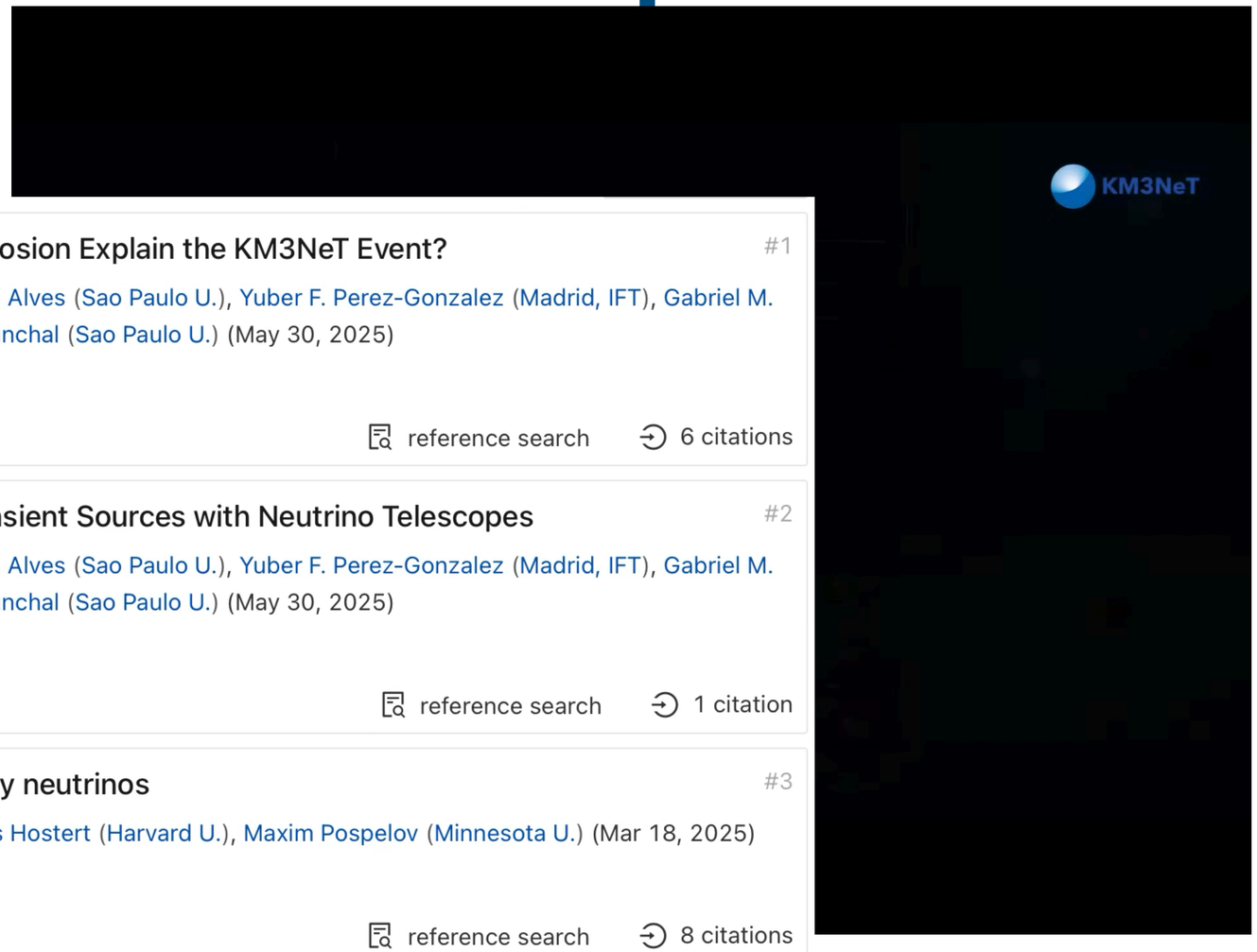
pdf cite claim reference search 1 citation

Neutron portal to ultra-high-energy neutrinos #3

Gustavo F.S. Alves (Sao Paulo U.), Matheus Hostert (Harvard U.), Maxim Pospelov (Minnesota U.) (Mar 18, 2025)

e-Print: 2503.14419 [hep-ph]

pdf cite claim reference search 8 citations



"The signal of the most energetic elementary particle ever observed."

Física de neutrinos é uma área quente!

The JUNO (Jiangmen Underground Neutrino Observatory) experiment, a major neutrino research facility in China, is scheduled to begin operating in the latter half of 2025. Its primary goal is to determine the neutrino mass ordering by measuring the energy spectrum of reactor neutrinos with high precision, according to Science News. The experiment is lo-

Uma das perguntas mais velhas da humanidade

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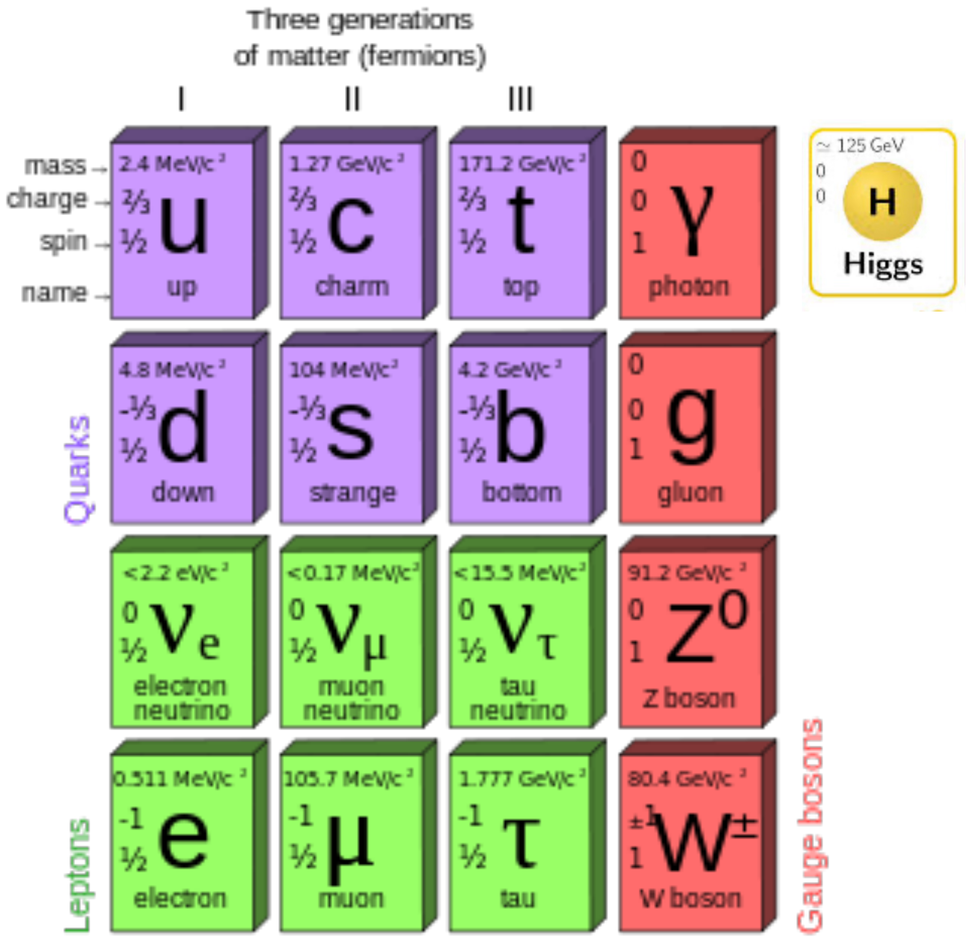
Do que as coisas são feitas?

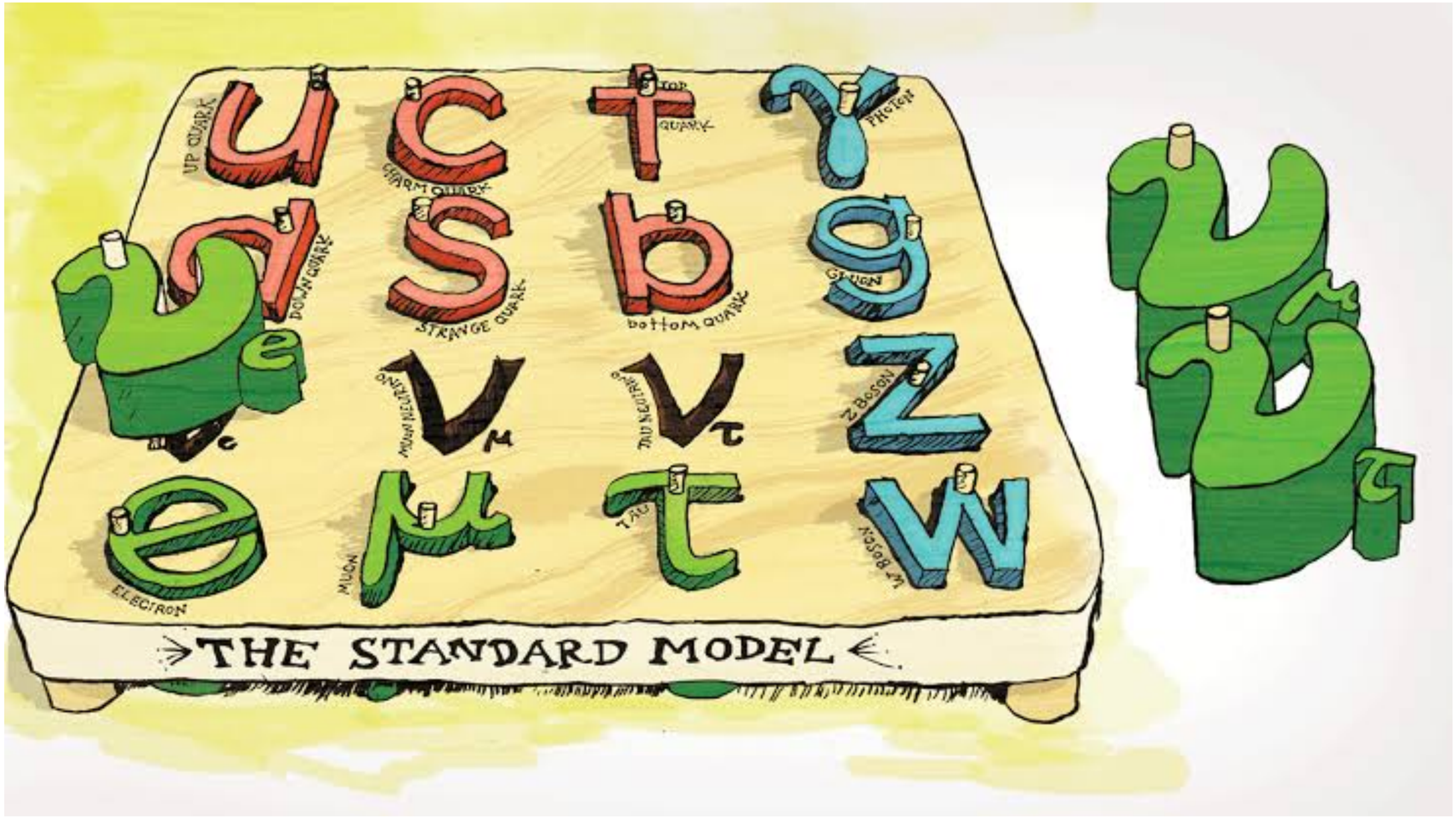
Uma das perguntas mais velhas da humanidade

Do que as coisas são feitas?

Nossa melhor resposta até o momento:



Neutrinos são fundamentais para progredir nessa caminhada!



Neutrinos são fundamentais para progredir nessa caminhada!

Obrigado!