

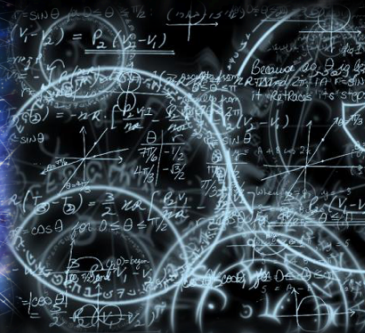
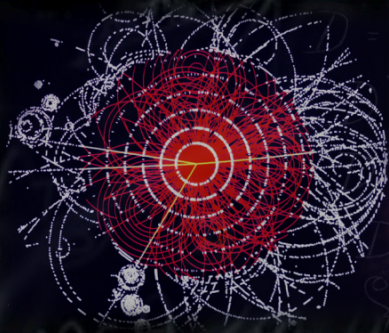
# Introdução à Física de Partículas

Introduction to particle Physics

(4/4)

FILIPE JOAQUIM

IST Dep. de Física e CFTP, Lisboa, Portugal

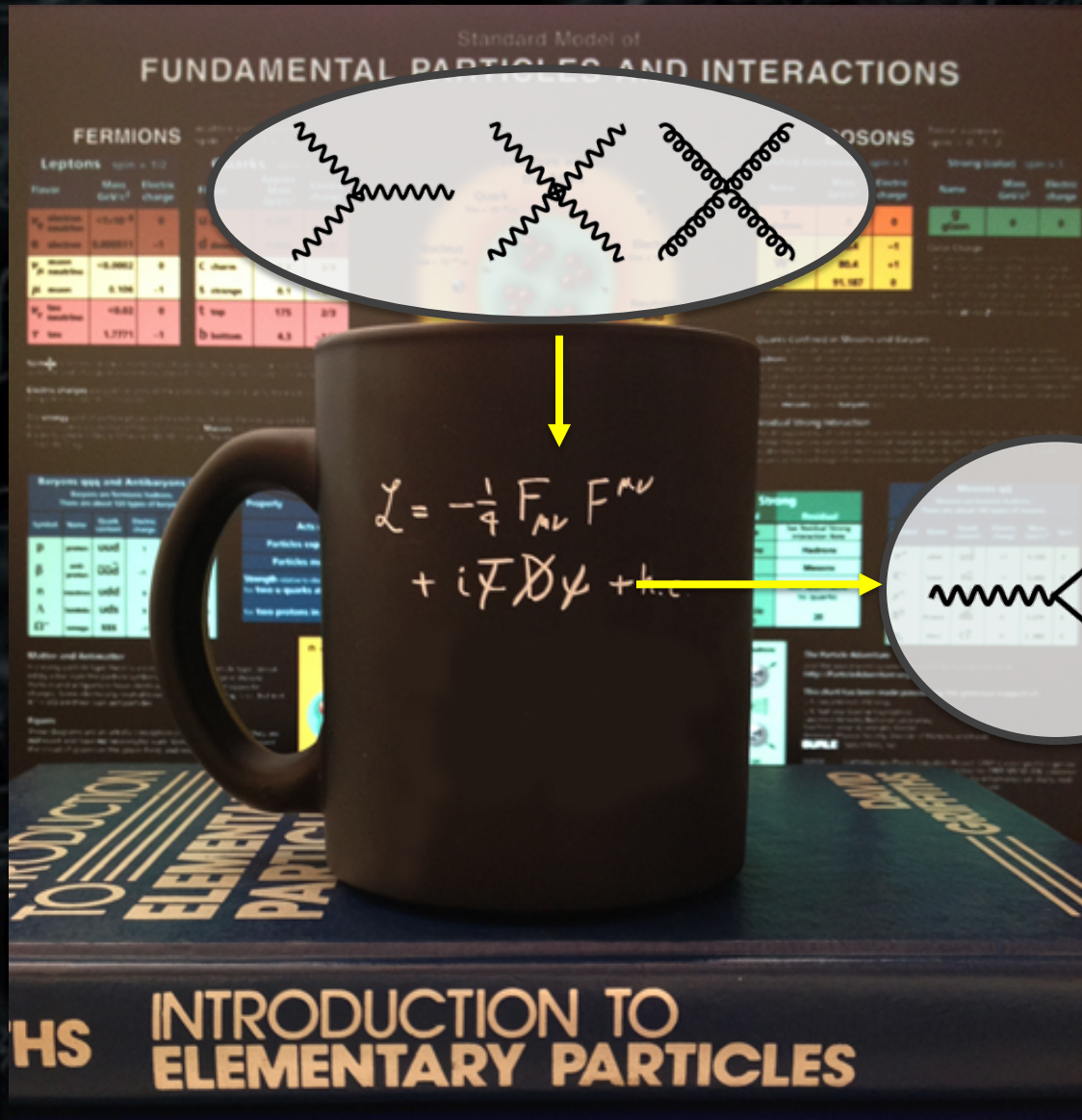


Escola de Professores no CERN em Língua Portuguesa 2017

CERN Portuguese Language Teachers Programme 2017

3 – 8 Setembro, CERN, Genebra







1964

## O mecanismo ABEGHHK'tH

Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble and 't Hooft



Como funciona então o mecanismo ABEGHHK'tH?

## O CAMPO DE HIGGS...



Standard Model of  
**FUNDAMENTAL PARTICLES AND INTERACTIONS**

**FERMIONS** spin = 1/2

**Leptons** spin = 1/2

Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	< 0.17	0
$\bar{\nu}_e$ antineutrino	0.000011	-1
$\nu_\mu$ muon neutrino	< 0.0002	0
$\bar{\nu}_\mu$ antineutrino	0.106	-1
$\nu_\tau$ tau neutrino	< 0.02	0
$\bar{\nu}_\tau$ antineutrino	1.7771	-1

**Quarks** spin = 1/2

Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
u up	0.002	2/3
d down	0.005	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

Structure within the Atom

**BOSONS** spin = 1

**Unified Electroweak** spin = 1

Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^-$	80.4	-1
$W^+$	80.4	+1
$Z^0$	91.187	0

**Strong (color)** spin = 1

Name	Mass GeV/c <sup>2</sup>	Electric charge
$g$ gluon	0	0

Quarks Confined in Mesons and Baryons

**Mesons** spin = 0

Symbol	Quark content	Electric charge
$\pi^+$	u $\bar{d}$	+
$\pi^0$	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	0
$\pi^-$	$\bar{u}d$	-
$K^+$	u $\bar{s}$	+
$K^0$	$\frac{1}{\sqrt{2}}(u\bar{d} + d\bar{u})$	0
$K^-$	$\bar{u}s$	-
$K_S^0$	$\frac{1}{\sqrt{2}}(d\bar{s} + s\bar{d})$	0
$K_L^0$	$\frac{1}{\sqrt{2}}(d\bar{s} - s\bar{d})$	0
$\eta$	$\frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$	0
$\eta'$	$\frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$	0

**Baryons** spin = 1/2

Symbol	Quark content	Electric charge
$p$	uud	+
$\bar{p}$	$\bar{u}\bar{u}\bar{d}$	-
$n$	udd	0
$\bar{n}$	$\bar{u}\bar{d}\bar{d}$	0
$\Lambda$	uds	0
$\Sigma^+$	uus	+
$\Sigma^0$	uds	0
$\Sigma^-$	dds	-

**Strong**

Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$\Delta^+$	uuu	uuu	+	1.116	3/2
$\Delta^0$	uud	uud	0	1.116	3/2
$\Delta^-$	udd	udd	-	1.116	3/2
$\Sigma^+$	uus	uus	+	1.116	1/2
$\Sigma^0$	uds	uds	0	1.116	1/2
$\Sigma^-$	dds	dds	-	1.116	1/2

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i\bar{\psi} \not{D} \psi + h.c.$$

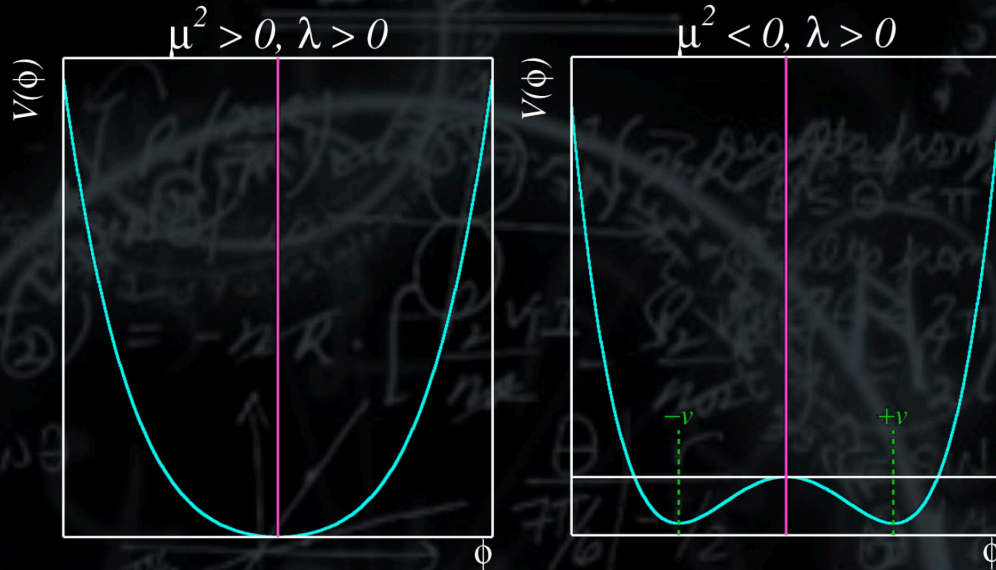
$$+ \chi_i Y_{ij} \chi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

HS INTRODUCTION TO ELEMENTARY PARTICLES



# O MECANISMO DE HIGGS



$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

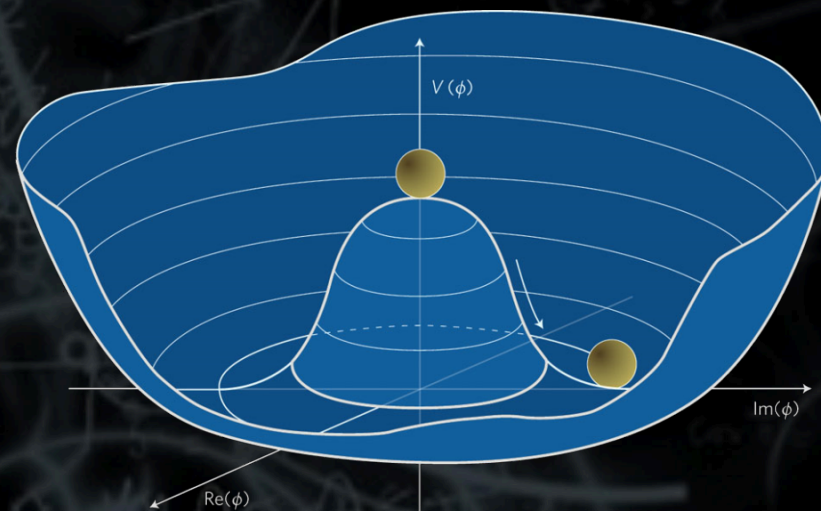
$$\text{"NO VÁCUO"}: v = \sqrt{-\frac{\mu^2}{2\lambda}}$$

Essencial para o mecanismo de Higgs funcionar.

A simetria é quebrada espontaneamente!!

Os bósons de gauge (W e Z) e os fermiões adquirem massa!

E... O FOTÃO PERMANECE SEM MASSA!!!





# PRÉMIO NOBEL DA FÍSICA 2013



The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

## The Nobel Prize 2013 in Physics



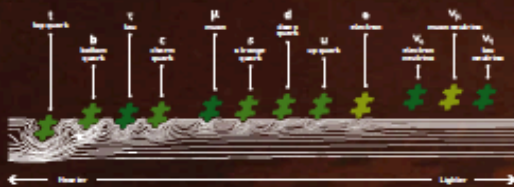
# Here, at last!

François Englert and Peter W. Higgs are jointly awarded the Nobel Prize in Physics 2013 for the theory of how particles acquire mass. In 1964, they proposed the theory independently of each other (Englert did so together with his now-deceased colleague Robert Brout). In 2012, their ideas were confirmed by the discovery of a so-called Higgs particle, at the CERN Laboratory outside Geneva in Switzerland.

The awarded mechanism is a central part of the Standard Model of particle physics. This description of how the world is constructed according to the Standard Model, everything – from flowers and people to stars and planets – consists of just a few building blocks, matter particles which are governed by forces mediated by force particles. And the entire Standard Model also rests on the existence of a special kind of particle, the Higgs particle.

The Higgs particle is a vibration of an invisible field that fills up all space. Even when our universe was empty, this field is there. Had it not been there, nothing of what we know

would exist because particles acquire mass only in contact with the Higgs field. Englert and Higgs proposed the existence of the field on purely mathematical grounds, and the only way to discover it was to find the Higgs particle. The Nobel Laureates probably did not imagine that they would get to see the theory confirmed in their lifetime. To do so required an enormous effort by physicists from all over the world. Almost half a century after the proposal was made, on July 4, 2012, the theoretical prediction could claim its biggest triumph, when the discovery of the Higgs particle was announced.



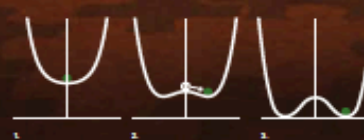
↑  
The Field

Matter particles acquire mass in contact with the invisible field that fills the whole universe. Particles that are not affected by the Higgs field do not acquire mass, those that interact weakly become heavy, and those that interact strongly acquire mass from the field, and if a suddenly disappeared, all matter would collapse as the suddenly massless electrons disintegrated at the speed of light. The weak force carriers, W and Z particles, get their masses directly through the Higgs mechanism, while the origin of the neutrino masses still remains unclear.

→  
Broken Symmetry

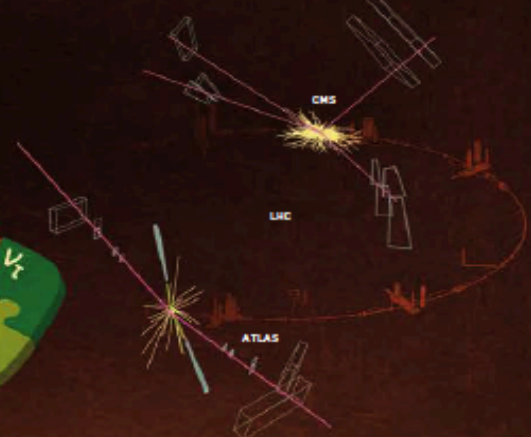
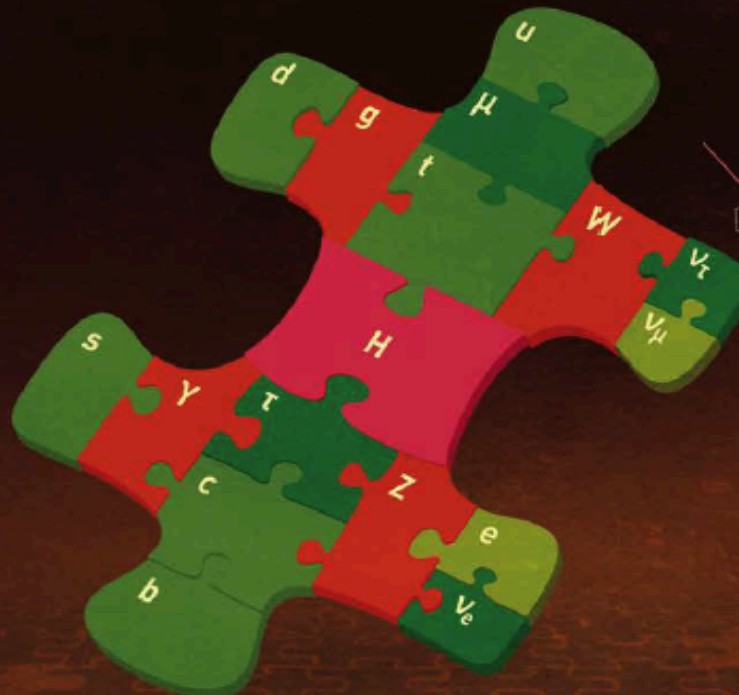
The Higgs mechanism relies on the concept of spontaneous symmetry breaking. Our universe was probably born asymmetrical [1], with a zero value for the Higgs field in the lowest energy state – radioactive. But less than one billionth of a second after the Big Bang, the symmetry was broken spontaneously as the lowest energy state moved away [2] from the asymmetrical zero-point. Since then, the value of the Higgs field in the vacuum state has been non-zero [3].

Potential energy of the Higgs field



←  
The Puzzle

The Higgs particle [4] was the last missing piece in the Standard Model puzzle. But the Standard Model is not the final piece in the cosmic puzzle. One of the reasons for this is that the Standard Model only describes visible matter, accounting for one sixth of all matter in the universe. To find the rest – the mysterious so-called dark matter – is one of the reasons why scientists continue to chase unknown particles at CERN.



ATLAS

In the collision, a short-lived Higgs particle is created, which decays into two muons [tracks in red] and two electrons [tracks in green].

CMS

A short-lived Higgs particle is created in the collision and decays into two muons [tracks in red] and two electrons [tracks in green].

The Particle Collider LHC

Protons – hydrogen nuclei – travel at almost the speed of light in opposite directions inside the circular tunnel, 27 kilometres long. The LHC (Large Hadron Collider) is the largest and most complex machine ever constructed by humans. In order to find a trace of the Higgs particle, two huge detectors, ATLAS and CMS, are capable of seeing the protons collide over and over again, 40 million times a second.



←  
François Englert

Belgian citizen. Born 1932 in Eschbaek, Belgium. Professor emeritus at Université Libre de Bruxelles, Brussels, Belgium.

←  
Peter W. Higgs

British citizen. Born 1929 in Newcastle upon Tyne, United Kingdom. Professor emeritus at University of Edinburgh, United Kingdom.

**FURTHER READING:** More information on the Nobel Prize in Physics 2013: <http://www.nobelprize.org> <http://www.nobelprize.org/Prizes/2013> <http://www.nobelprize.org/Prizes/2013/Physics> <http://www.nobelprize.org/Prizes/2013/Physics/Englert.html> <http://www.nobelprize.org/Prizes/2013/Physics/Higgs.html> <http://www.nobelprize.org/Prizes/2013/Physics/Higgs.html>

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# O MECANISMO DE HIGGS

Algumas previsões da teoria:

$$M_Z \cos \theta_W = M_W, \quad \sin^2 \theta_W = 1 - M_W^2 / M_Z^2$$

$$M_W^2 \sin^2 \theta_W = \frac{e^2}{4\pi\sqrt{2} G_F}$$

Os bósons W e Z foram descobertos no CERN em 1983.

$$M_W = 80.385 \pm 0.015 \text{ GeV}$$

$$M_Z = 91.1876 \pm 0.086 \text{ GeV}$$



O detector gargamelle

**O prêmio Nobel da Física foi atribuído a Rubbia e Van De Meer em 1984;**

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"



# O NOBEL PARA O MODELO PADRÃO



O prêmio Nobel da Física foi atribuído a Glashow, Weinberg e Salam em 1979;



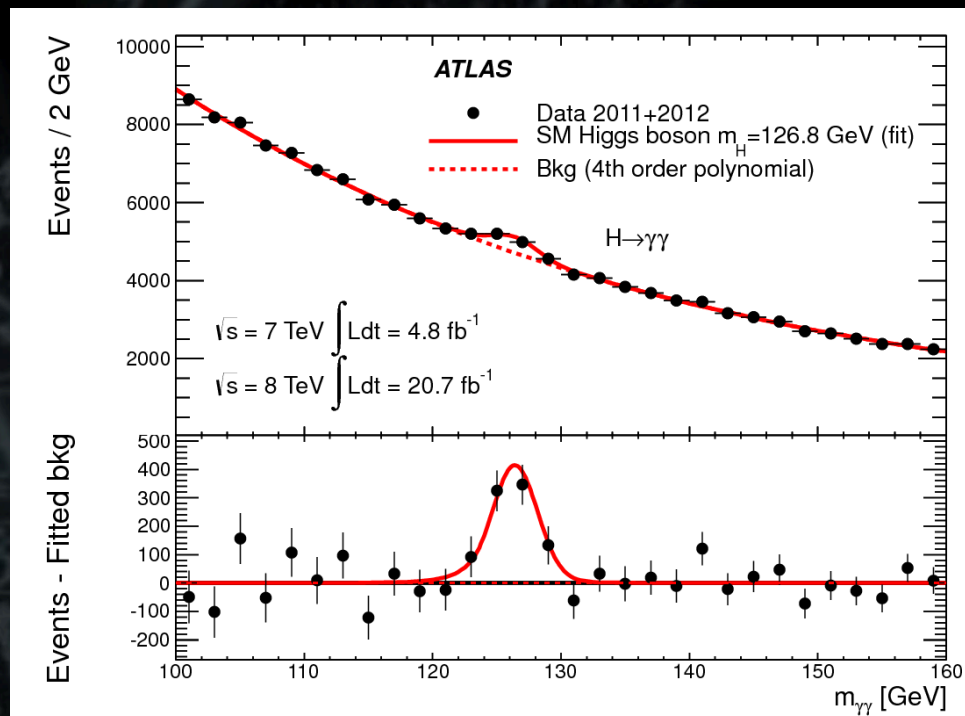
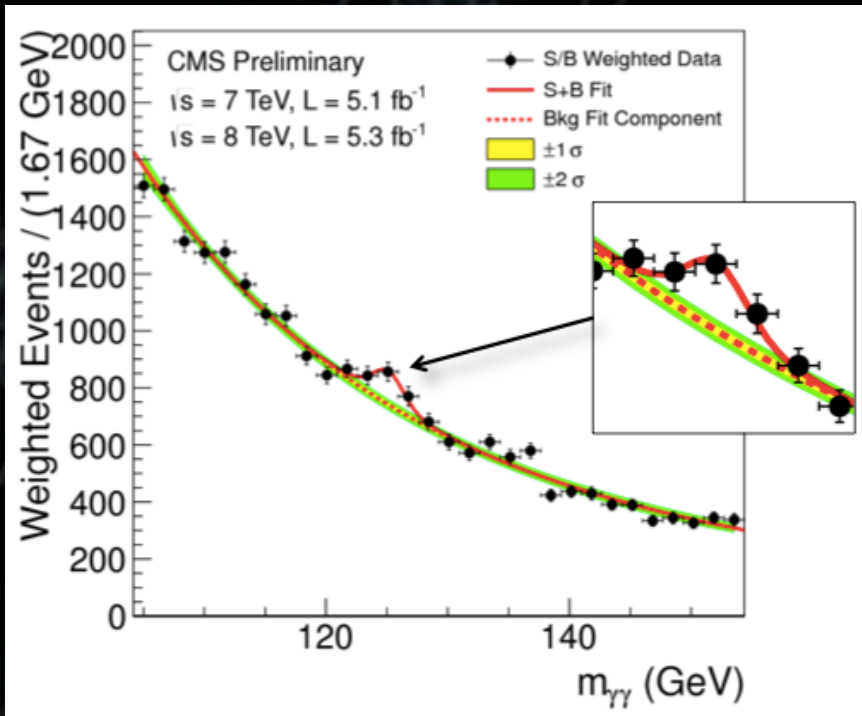
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, the prediction of the weak neutral current".

Até ao dia 4 de Julho de 2012 não se sabia nada sobre o que estava por detrás da quebra de simetria electrofraca.

## Até que...



# BORN ON THE 4TH OF JULY



“The discovery of a particle consistent with the Higgs boson opens the way to more detailed studies, ... , and is likely to shed light on other mysteries of our Universe.”

Rolf Heuer, CERN D.G., Press Release July 4, 2012

“We are reaching into the fabric of the Universe at the level never done before... We are in the edge of a new exploration.”

Joe Incandela, CMS spokesperson, Press Conference, July 4, 2012



# O ACONTECIMENTO CIENTÍFICO MAIS MEDIÁTICO

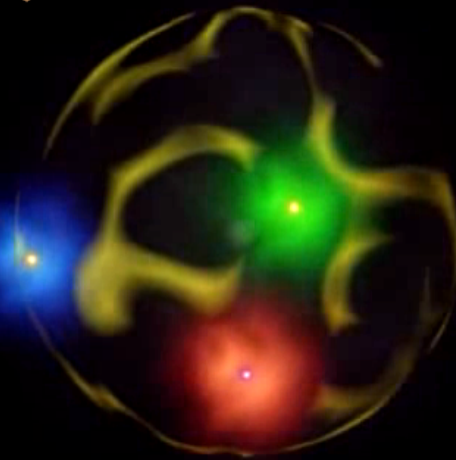




# "ENTÃO A MASSA VEM TODA DO HIGGS?"

Protão  $p = uud$ :  $2 m_u + m_d = 11 \text{ MeV}$

$$m_p = 938 \text{ MeV}$$



Só 1% da massa do protão é devida à massa em repouso dos quarks, ou seja...

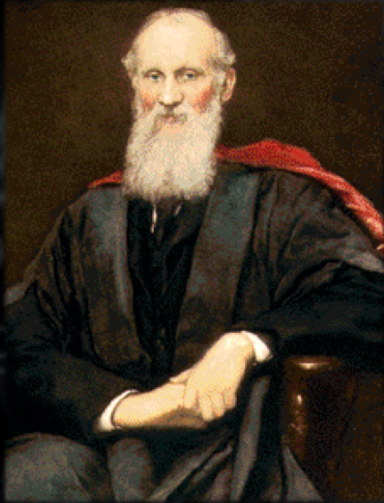
Apenas uma infima parte da massa é devida ao mecanismo de Higgs...

# E AGORA?



# “Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light”

Lord Kelvin, 27 de Abril 1900



## As núvens negras de Kelvin

Incapacidade de detectar o Éter e a  
“Catástrofe ultra-violeta”

A Física estaria limitada à medição de quantidades conhecidas com grande precisão...

**Kelvin não podia estar mais enganado...**

**Stephen Hawking (1998)**

*“Com a descoberta iminente do bosão de Higgs não há nada fundamentalmente novo a ser descoberto. Tudo o que há a fazer é medir com mais precisão.”*

**REPETIÇÃO DA HISTÓRIA?**

**STEPHEN  
HAWKING**

AUTOR DE  
BREVE  
HISTÓRIA  
DO TEMPO

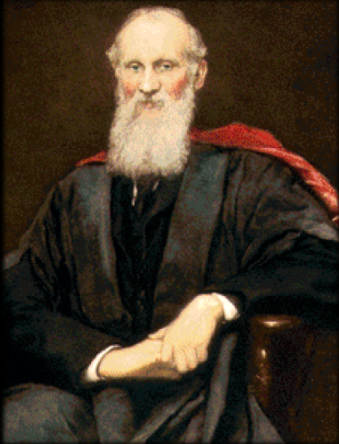


**O FIM  
DA FÍSICA**

COMPANHIA  
grãfica

# O QUE DIRIA KELVIN AGORA?

“Twentieth first-Century Clouds over the electroweak theory”



“A beleza e a clareza da teoria electrofraca está obscurecida por algumas núvens”

## As núvens do Pedro:

- Matéria escura e energia escura
- Porque existe mais matéria que anti-matéria no Universo?
- Porquê 3 famílias?;
- Problema da Hierarquia;
- Porque é que as massas das partículas elementares são o que são;
- Porque é que os neutrinos são muito mais leves do que os leptões carregados e os quarks;
- Será que as 3 (ou 4) forças se unificam a alguma escala?;
- Será que as partículas elementares são mesmo elementares?;



# PORQUE FÍSICA PARA ALÉM DO MP?

## EVIDÊNCIAS EXPERIMENTAIS PARA A EXISTÊNCIA DE NOVA FÍSICA



### Assimetria matéria-antimatéria

O MP falha em explicar porque razão existe um excesso de matéria no Universo ou “porque estamos de facto aqui!”

#### FERMIÕES

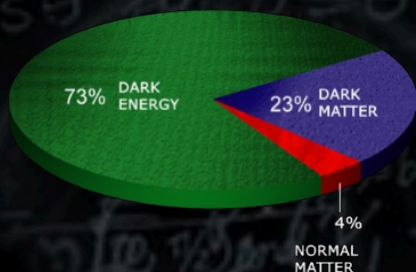
Leptões $spin = 1/2$			Quarks $spin = 1/2$		
Sabor	Massa $GeV/c^2$	Carga Eléctrica	Sabor	Massa Aprox. $GeV/c^2$	Carga Eléctrica
$\nu_L$ neutrino* mais leve	$(0-2) \times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electrão	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_M$ neutrino* intermédio	$(0.009-2) \times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muão	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_H$ neutrino* pesado	$(0.05-2) \times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

### Massas de neutrinos

No MP os neutrinos não têm massa, mas de facto hoje sabemos que estas partículas são massivas (com uma massa muito menor que os restantes fermiões).

### Problema da matéria escura

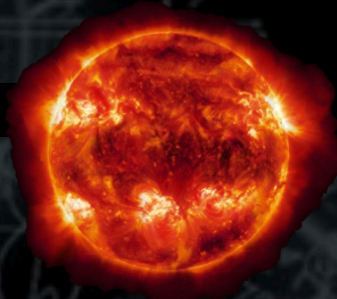
23% do budget de energia do Universo surge sob a forma de matéria escura. O MP não tem um candidato para a matéria escura.



# 1964: MISTÉRIO DOS NEUTRINOS DESAPARECIDOS



Bachall



$$N_{\nu_e} \longrightarrow N'_{\nu_e}$$

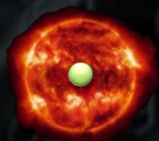


Davis

$$\frac{N'_{\nu_e}}{N_{\nu_e}} = \frac{1}{3}$$

- O número de neutrinos que saem do Sol está mal calculado, OU
- A experiência está errada.

## OSCILAÇÕES DE NEUTRINOS



$$\nu_e \rightarrow \nu_\mu$$

$$P = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

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







# Chameleons of space



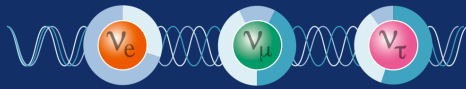
Takaaki Kajita in Japan and Arthur B. McDonald in Canada were key scientists in two large research groups that discovered that neutrinos change identities, which requires that neutrinos have mass. The discovery has changed our understanding of the innermost workings of matter and may prove crucial to our view of the universe.

The discovery of neutrino identity changes has resolved a neutrino puzzle that physicists had wrestled with for decades. Compared to theoretical calculations of the number of neutrinos, up to two-thirds of them were missing in measurements performed on Earth. The two research groups discovered that the neutrinos had changed identities, which led to the conclusion that neutrinos must have some mass, however small. This discovery was historic for particle physics, as its Standard Model requires neutrinos to be massless. This new physics is now needed.

between cosmic radiation and the Earth's atmosphere. Others are produced in nuclear reactions inside the Sun. Thousands of billions of neutrinos stream through our bodies every second. The combined weight of neutrinos is estimated to be roughly equal to that of all visible stars in the universe.

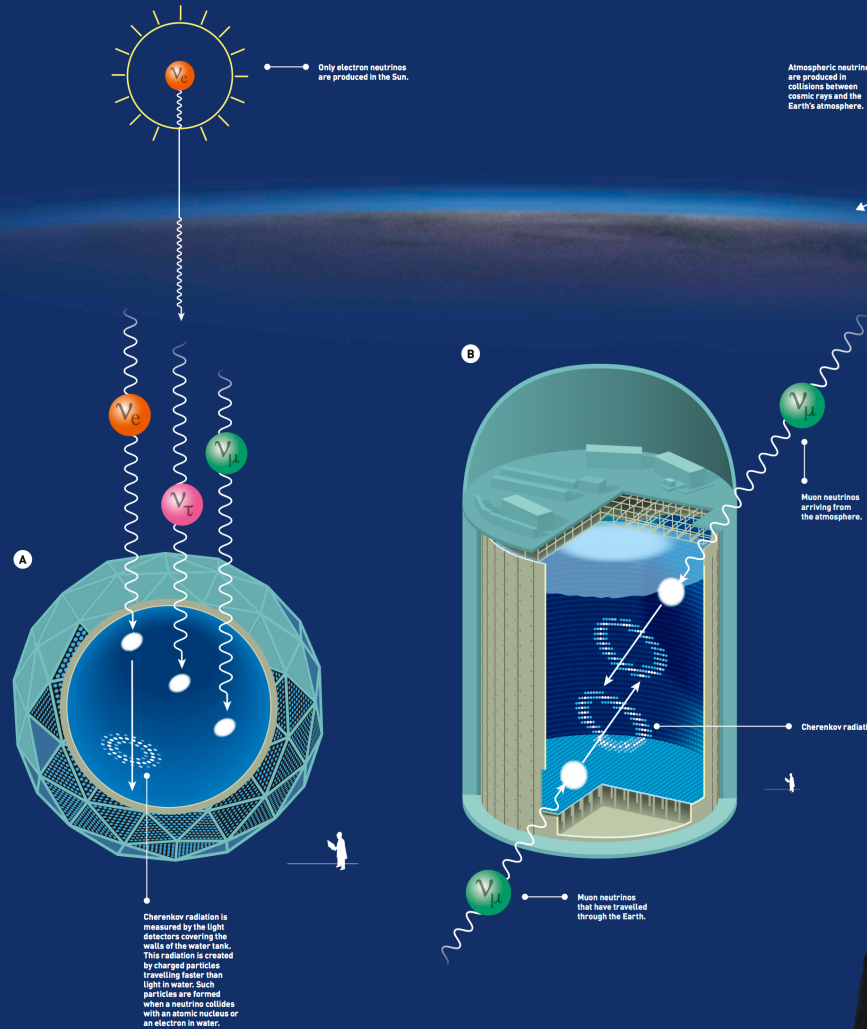
Hardly anything can stop the neutrinos; they are amongst nature's most elusive elementary particles. Experiments are continuing to uncover the all but hidden world of neutrinos. New discoveries about their deepest secrets are expected to change our current understanding of the history, structure and future of the universe.

There are three types of neutrinos: electron, muon and tau neutrinos. Each type is a mixture, a quantum superposition of three mass states.



**Neutrino oscillations**  
Neutrinos change identities as they travel through space. Quantum physics is required to explain this magic, where the neutrinos are represented by superposed waves that correspond to neutrino states with different masses. When the neutrinos travel, these waves go out of phase and are superposed in

different ways. The superposition in any given location yields the probability of which type of neutrino is most likely to be found there. These probabilities vary from one location to another – oscillate – and the neutrinos appear in their various identities. This is only possible if neutrinos have mass.

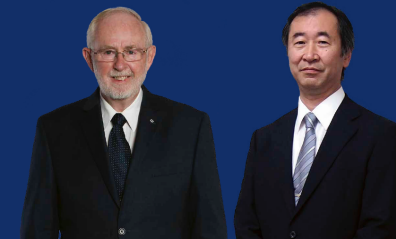


**A Sudbury Neutrino Observatory**  
The detector measured neutrinos from the Sun. Its tank, filled with heavy water, was placed two kilometres under the surface of the Earth. Signals from all three types of neutrinos were registered in the tank. The sum of the neutrinos corresponded to what was expected, but there were not enough electron neutrinos – they must have changed identity.

**B Super-Kamiokande**  
The detector measured atmospheric neutrinos. Its tank, filled with water, was placed one kilometre under the surface of the Earth. The muon neutrinos that arrived straight at Super-Kamiokande from the atmosphere were more numerous than those that arrived at the detector after passing through the Earth. The muon neutrinos that travelled further thus had time to change identity and become another type of neutrino.

**Arthur B. McDonald**  
Canadian citizen. Born 1943 in Sydney, Canada. Professor Emeritus at Queen's University, Kingston, Canada.

**Takaaki Kajita**  
Japanese citizen. Born 1959 in Higashimatsuyama, Japan. Director of Institute for Cosmic Ray Research and Professor at University of Tokyo, Kashiwa, Japan.



**FURTHER READING** More information on the Nobel Prize in Physics 2015: <http://www.nobelprize.org> **BOOKS:** ● **Jayawardhana, R.** (2013) *Neutrino Hunters: The Thrilling Chase for a Ghostly Particle to Unlock the Secrets of the Universe*, Scientific American/Farrar, Straus and Giroux. ● **Clois, F.** (2010) *Neutrino*, Oxford University Press. **POPULAR SCIENCE ARTICLES:** ● **Hath, P. D.** (2005) High Energy Neutrinos from the Cosmos, *http://nobelprize.org* ● **Bahcall, J. N.** (2004) Solving the Mystery of the Missing Neutrinos, *http://nobelprize.org* ● **McDonald, A. B., Klein, J. R. and Warke, D. L.** (2003) Solving the Solar Neutrino Problem, *Scientific American*, Vol. 288, no. 4, April. ● **Karara, E., Kajita, T. and Totsuka, Y.** (1999) Detecting Massive Neutrinos, *Scientific American*, Vol. 281, no. 2, August.

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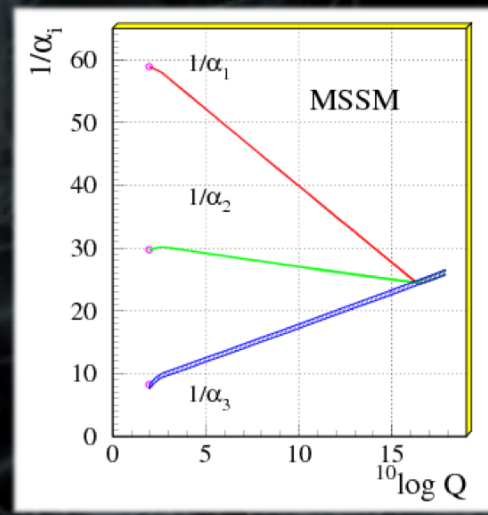
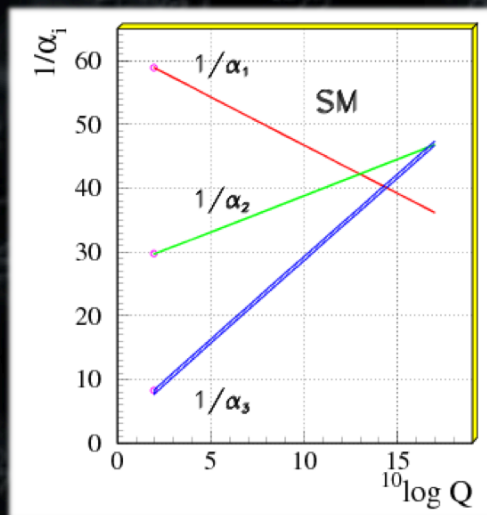
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# UNIFICAÇÃO DAS INTERAÇÕES FUNDAMENTAIS

## UNIFICAÇÃO DAS INTERAÇÕES FUNDAMENTAIS

Propriedade	Interação Gravítica	Interação Fraca (Electrofraca)	Interação Electromagnética	Interação Forte
Actua em:	Massa – Energia	Sabor	Carga Eléctrica	Carga de cor
Partículas afectadas:	Todas	Quarks, Leptões	Electricamente carregadas	Quarks, Gluões
Partículas mediadoras:	Gravitão (ainda por observar)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluões
Intensidade a {	$10^{-41}$	0.8	1	25
	$3 \times 10^{-41}$	$10^{-4}$	1	60

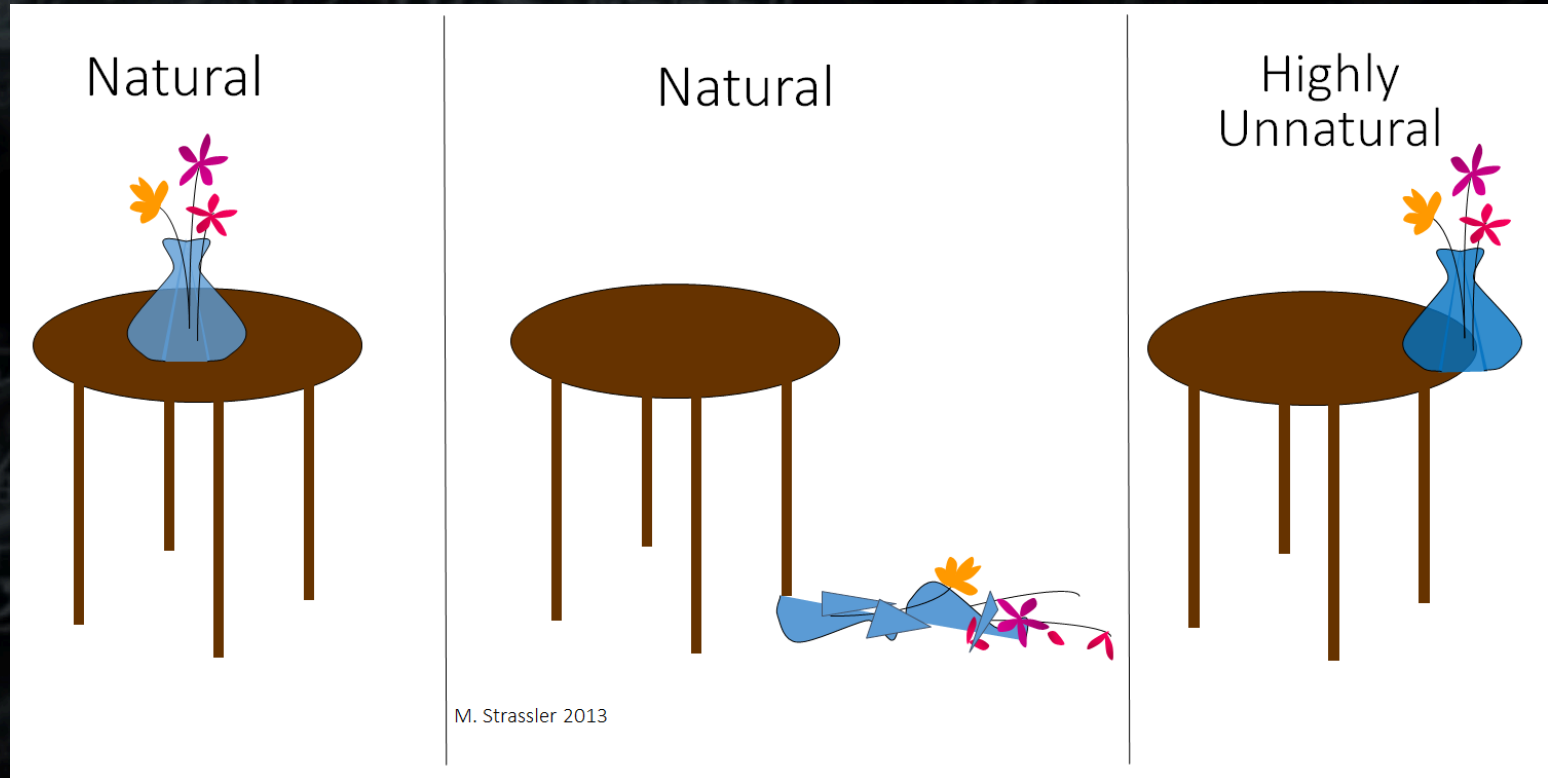
SE O MP FOR VÁLIDO ATÉ À ESCALA DE PLANCK AS 3 (4) FORÇAS FUNDAMENTAIS UNIFICAM-SE OU NÃO?







# PROBLEMA DA HIERARQUIA DE ESCALAS





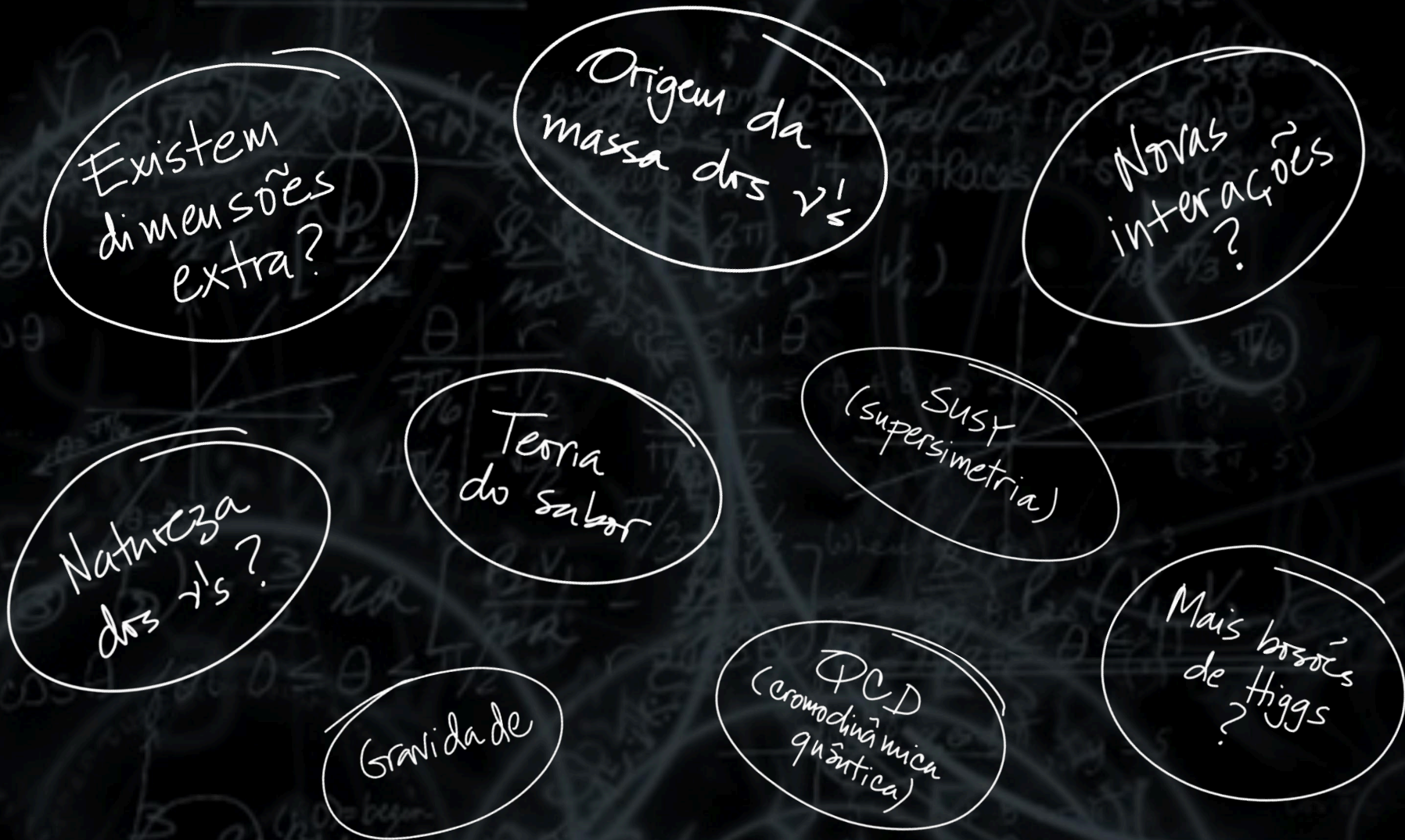
# SOLUÇÃO PARA O PROBLEMA DA HIERARQUIA

The image shows two Feynman diagrams representing the solution to the hierarchy problem. The first diagram on the left is a solid blue circle with a top vertex labeled  $t$  and a bottom vertex labeled  $\bar{t}$ . Two external lines, each labeled  $h^0$ , enter from the left and exit to the right, with a coupling constant  $\lambda$  at each vertex. The second diagram on the right is a dashed blue circle with a top vertex labeled  $\tilde{t}$  and a bottom vertex labeled  $\tilde{\lambda}$ . Two external lines, each labeled  $h^0$ , enter from the left and exit to the right. A large white plus sign is between the two diagrams, and a large white equals sign followed by a zero is to the right of the second diagram.

$$\text{Se } \tilde{\lambda} = -\lambda^2$$

# SUSY

# PORQUE FÍSICA PARA ALÉM DO MP?



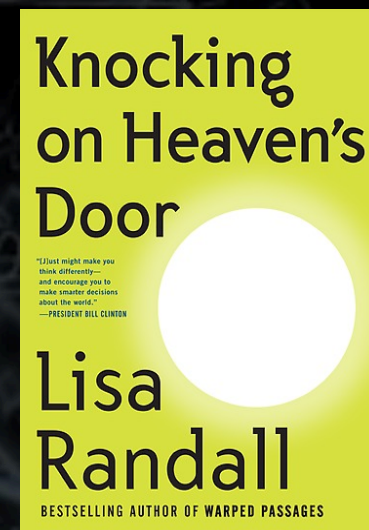
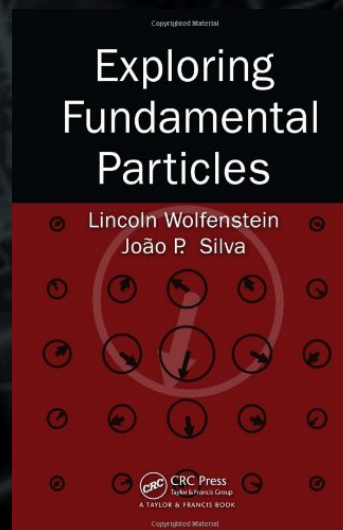
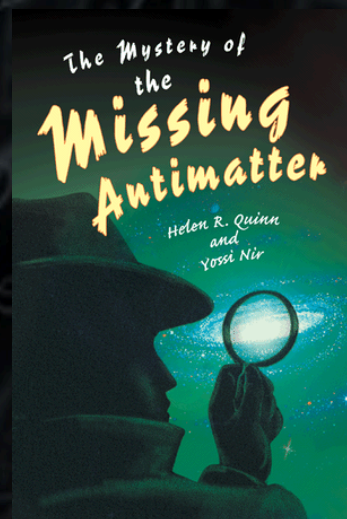
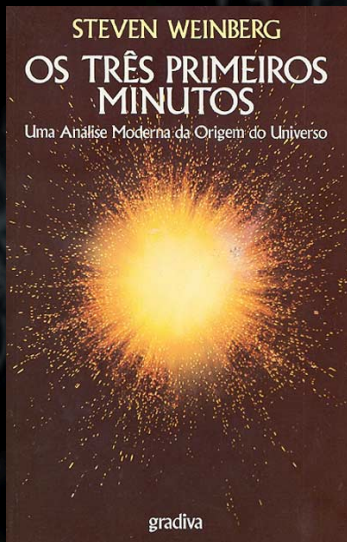




“We are reaching into the fabric of the Universe at the level never done before... We are in the edge of a new exploration.”

Joe Incandela, CMS spokesperson, Press Conference, July 4, 2012

# ALGUNS LIVROS (Os mais actuais em inglês)





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