Neutrinos, Higgs & Flavour

João Penedo, CFTP/IST

19 May 2023

8th mini-school
on Particle and Astroparticle Physics
Oeiras 15 - 20 . MAY . 2023

FCT Fundação para a Ciência e a Tecnologia
DF DEPARTAMENTO DE FÍSICA TÉCNICO LISBOA
CFTP Centro de Física Teórica de Partículas
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QREN QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
COMPETE PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

Fields: Neutrinos, Higgs & Flavour

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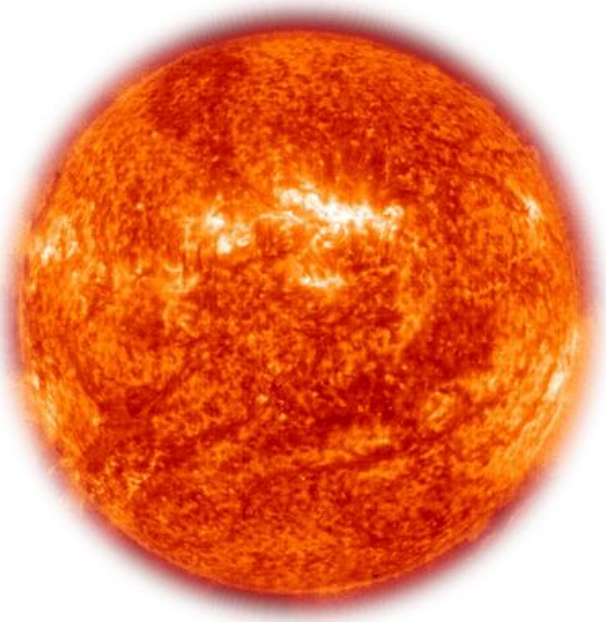
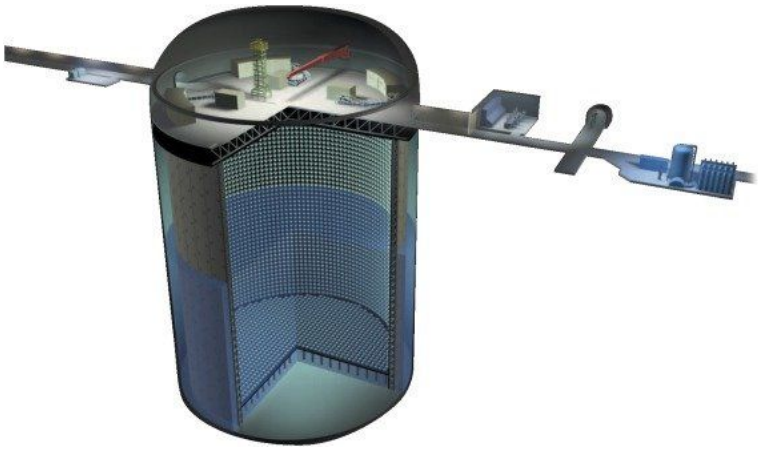
Neutrinos

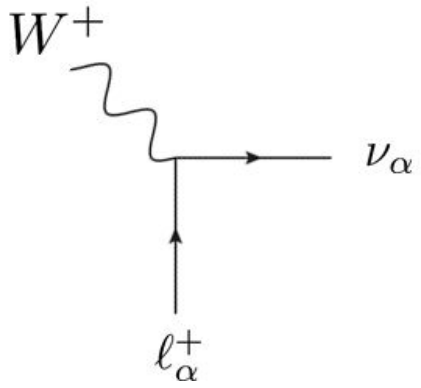
Neutrinos



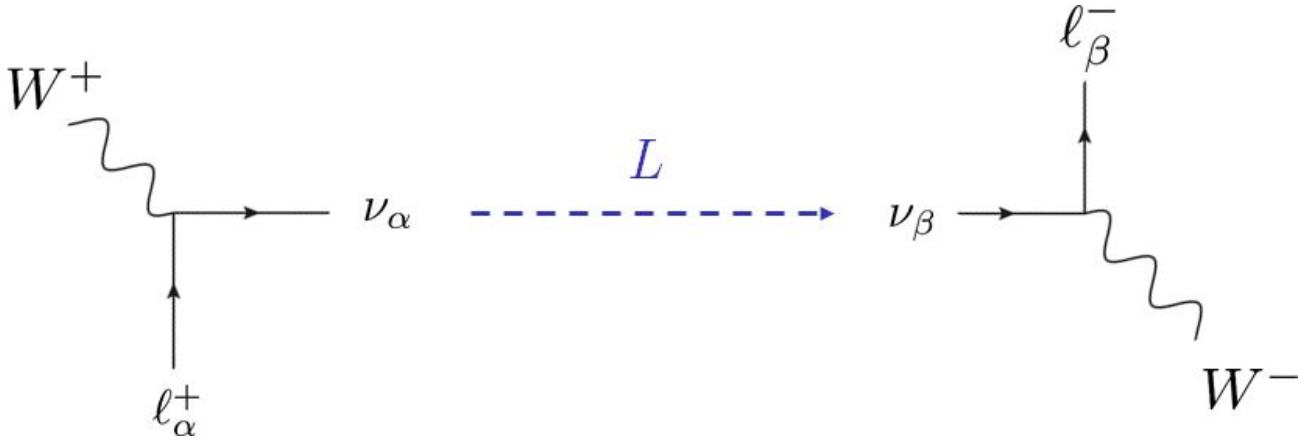


$$\sim \; 70\,000\,000\,000 \;\; \mathrm{cm}^{-2} \; \mathrm{s}^{-1}$$

Neutrinos

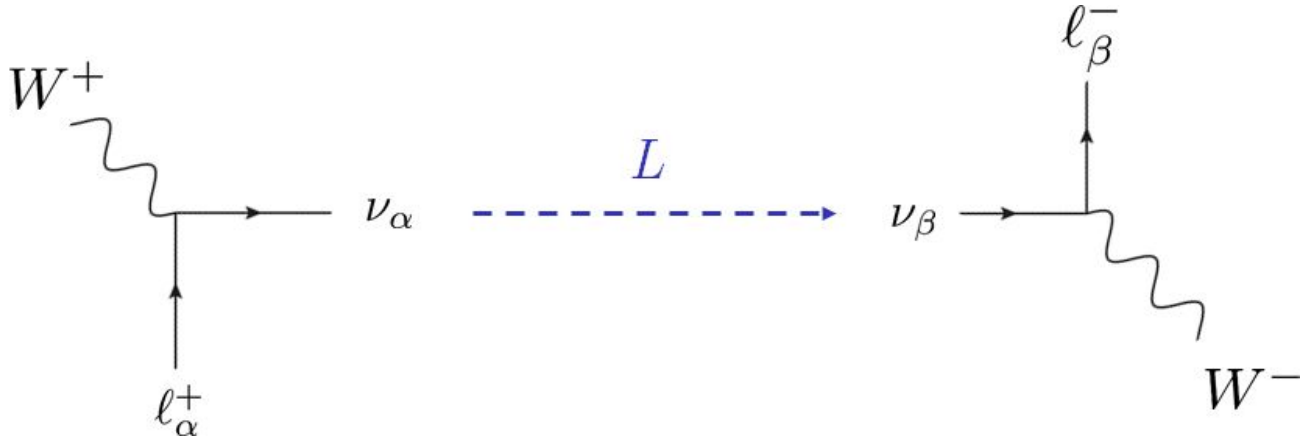


Neutrinos



$$|\nu_\alpha\rangle = (U_{\mathrm{PMNS}})^*_{\alpha k}\,|\nu_k\rangle$$

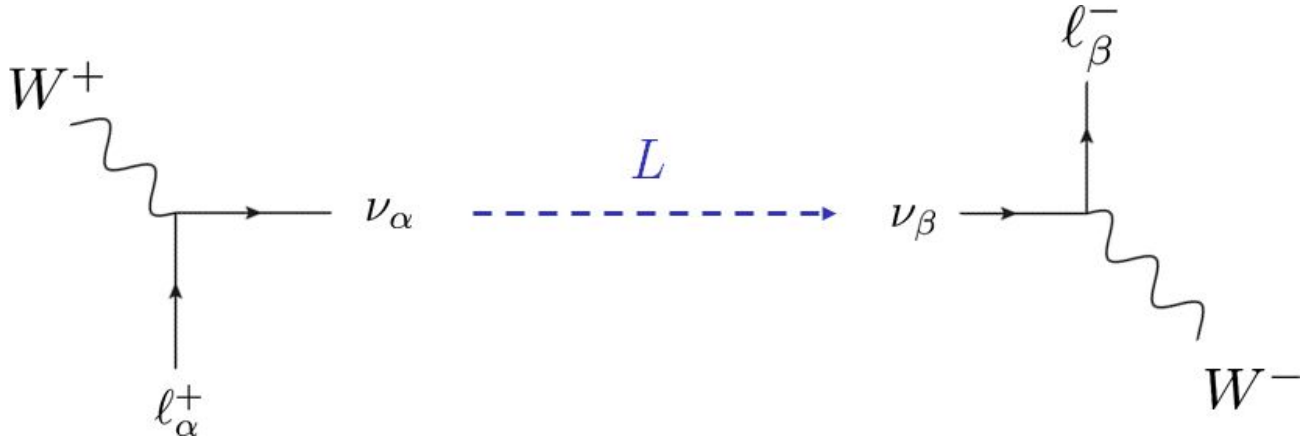
Neutrinos



$$|\nu_\alpha\rangle = (U_{\mathrm{PMNS}})^*_{\alpha k}\,|\nu_k\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = (U_{\rm PMNS})^*_{\alpha k}\,(U_{\rm PMNS})_{\beta k}\,(U_{\rm PMNS})_{\alpha j}\,(U_{\rm PMNS})^*_{\beta j}\,\exp\left(-i\frac{\Delta m^2_{kj}L}{2E}\right)$$

Neutrinos



$$|\nu_\alpha\rangle = (U_{\rm PMNS})^*_{\alpha k}\,|\nu_k\rangle$$

$$U_{\mathrm{PMNS}}$$

Matter vs. antimatter

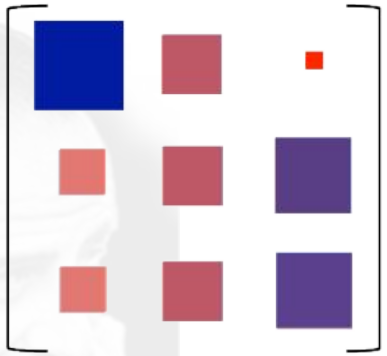
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric *angle*
θ_{23} ~ 40°-50°

Reactor *angle*
θ_{13} ~ 9°

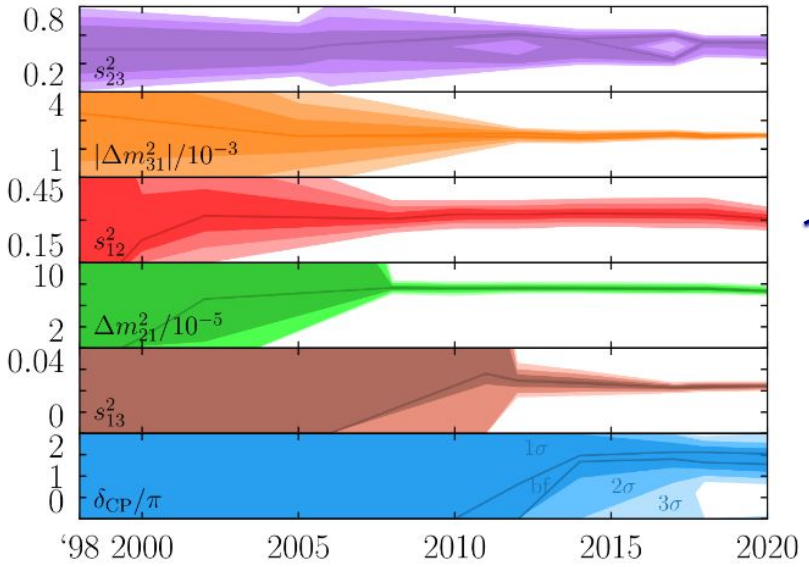
Solar *angle*
θ_{12} ~ 33°

$\simeq$



(in magnitude)

From: Wenjie Wu, CERN neutrino platform week 2023



Snowmass NF01 Topical Report, *arXiv:2212.00809*

NOvA

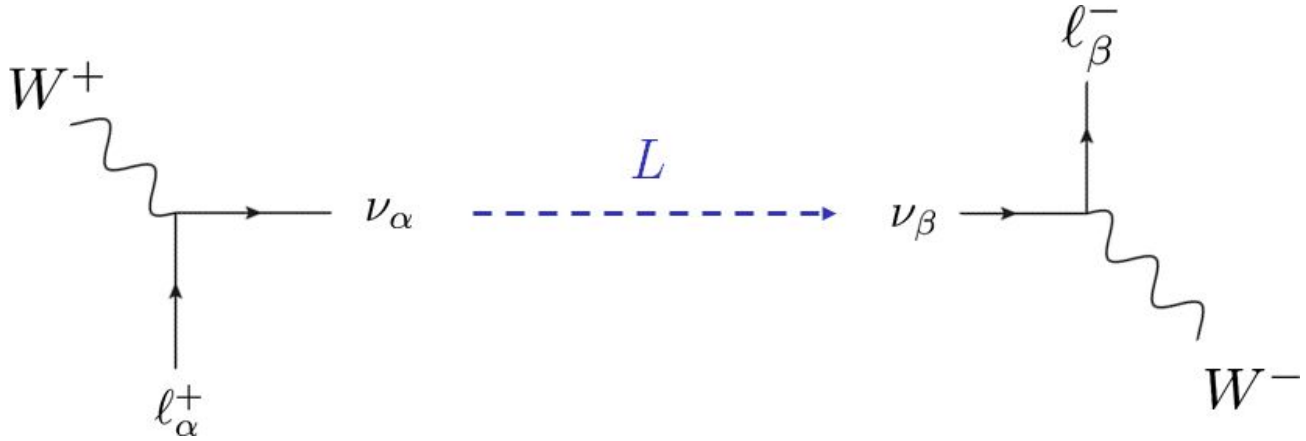
T2K

Hyper-K

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

$$P(\nu_\alpha \to \nu_\beta) = (U_{\rm PMNS})^*_{\alpha k}\,(U_{\rm PMNS})_{\beta k}\,(U_{\rm PMNS})_{\alpha j}\,(U_{\rm PMNS})^*_{\beta j}\,\exp\left(-i\frac{\Delta m^2_{kj}L}{2E}\right)$$

Neutrinos

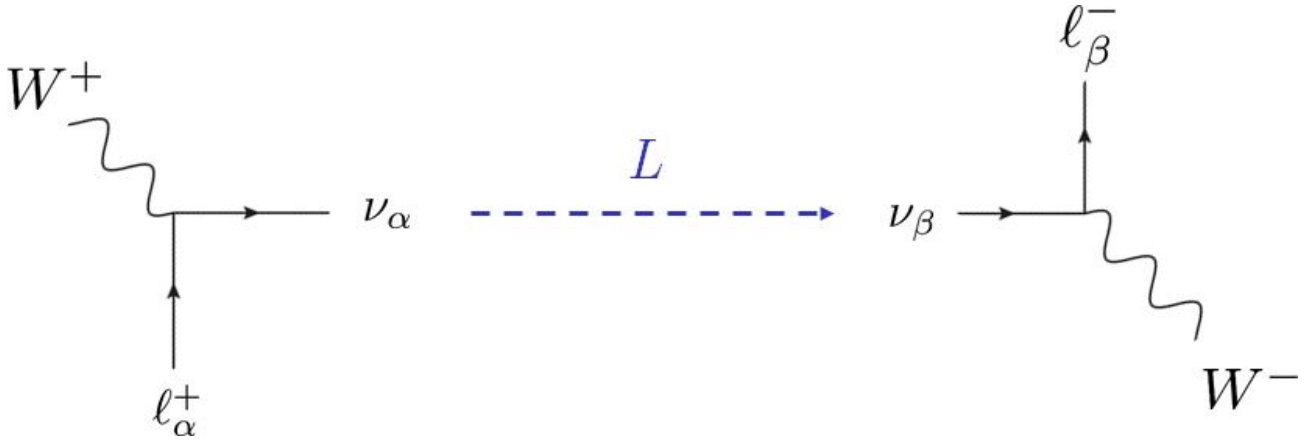


$$|\nu_\alpha\rangle = (U_{\rm PMNS})^*_{\alpha k}\,|\nu_k\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = (U_{\text{PMNS}})^*_{\alpha k} (U_{\text{PMNS}})_{\beta k} (U_{\text{PMNS}})_{\alpha j} (U_{\text{PMNS}})^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{kj} = m^2_k - m^2_j$$

Neutrinos



$$|\nu_\alpha\rangle = (U_{\text{PMNS}})^*_{\alpha k} |\nu_k\rangle$$

for Particle Physics since 1960

for Particle Physics since 1960

?

for Particle Physics since 1960

?

Neutrinos, Higgs & Flavour

Higgs

The Higgs boson

Gotcha!

The hunt for physics's most elusive quarry is over

Jul 7th 2012 | From the print edition

Higgs

The Higgs boson

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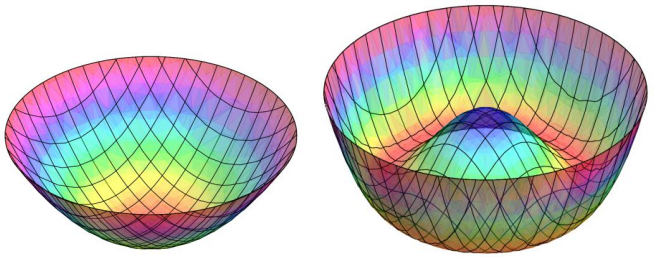

From: A.M.Coutinho
Master Thesis

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Higgs

The Higgs boson

Gotcha!

The hunt for physics's most elusive quarry is over

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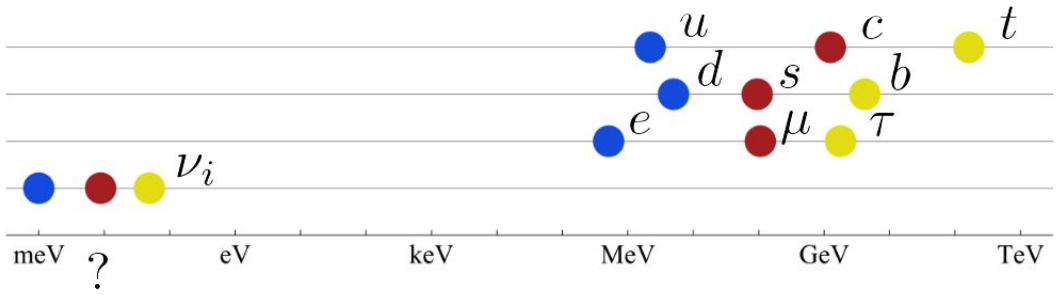
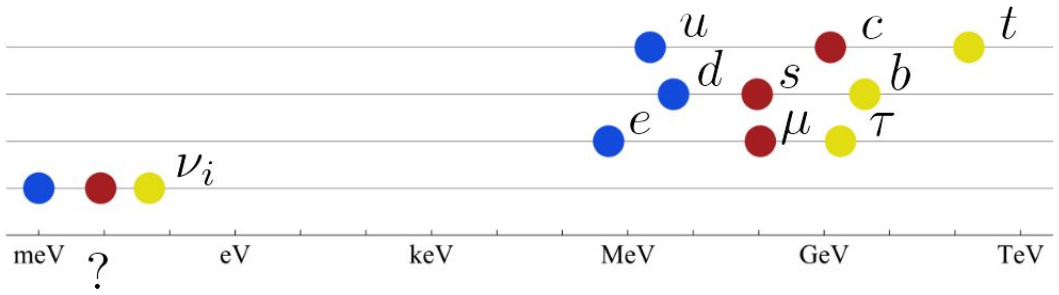
$$\rho = \frac{\sum_{i=1}^{n} \left[I_i \left(I_i + 1 \right) - \frac{1}{4} Y_i^2 \right] v_i}{\sum_{i=1}^{n} \frac{1}{2} Y_i^2 v_i}$$

Neutrinos, Higgs & Flavour



From: A.Toorop PhD Thesis

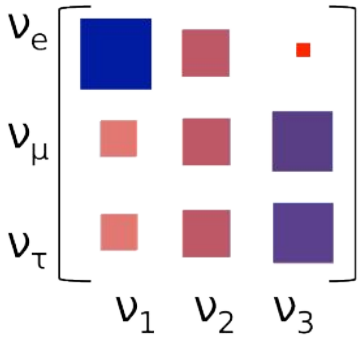
Flavour



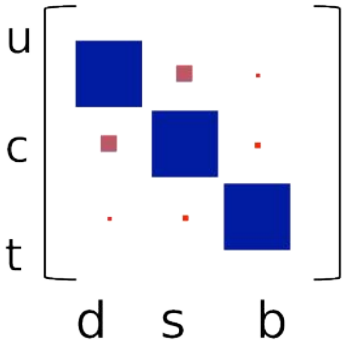
From: A.Toorop PhD Thesis

Flavour

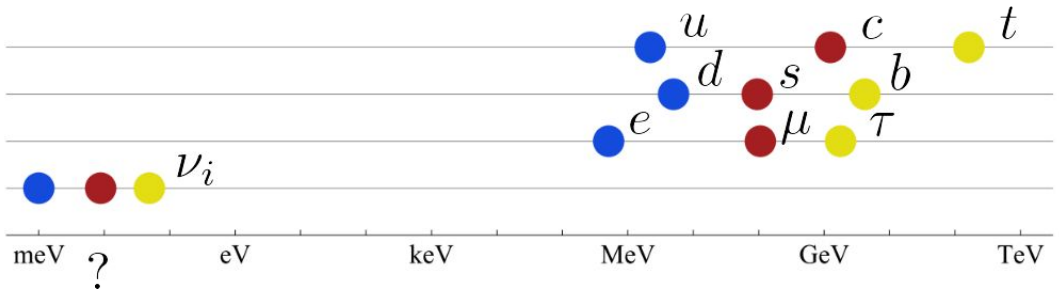
$U_{\mathrm{PMNS}} \sim$



$V_{\mathrm{CKM}} \sim$



From: P.Novichkov Discrete 2018 slides

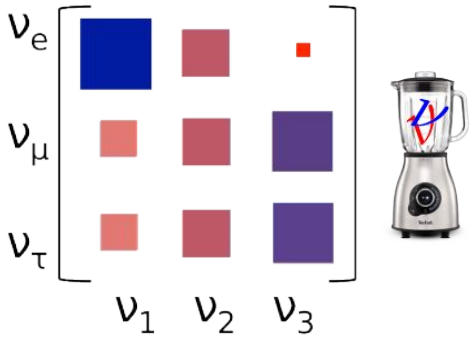


From: A.Toorop PhD Thesis

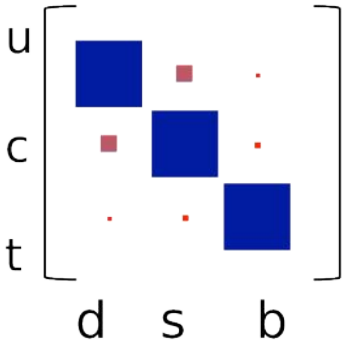
From: I. Varzielas / F. Joaquim slides

Flavour

$U_{\mathrm{PMNS}} \sim$



$V_{\mathrm{CKM}} \sim$



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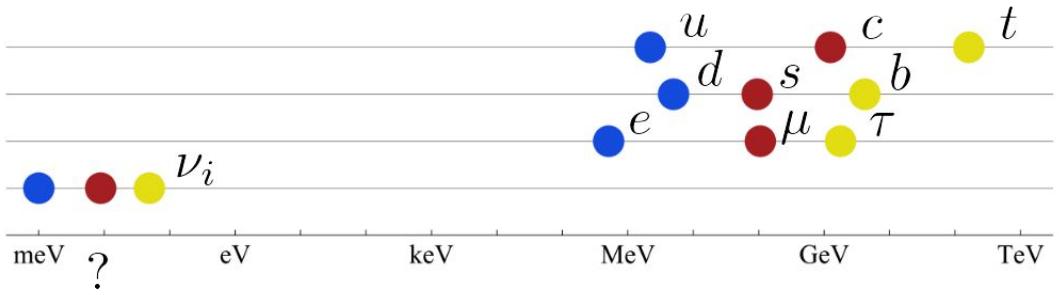

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Flavour

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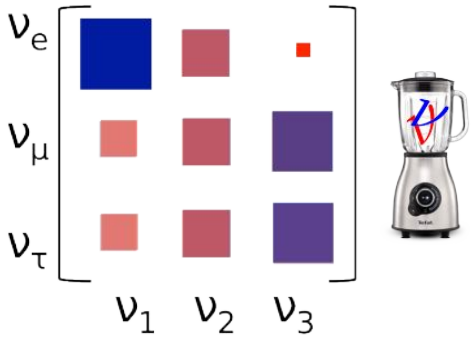
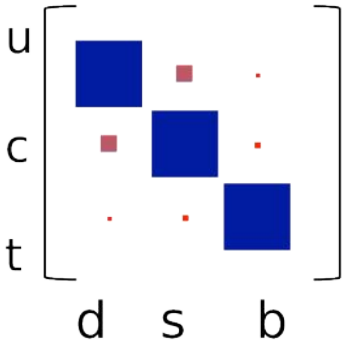
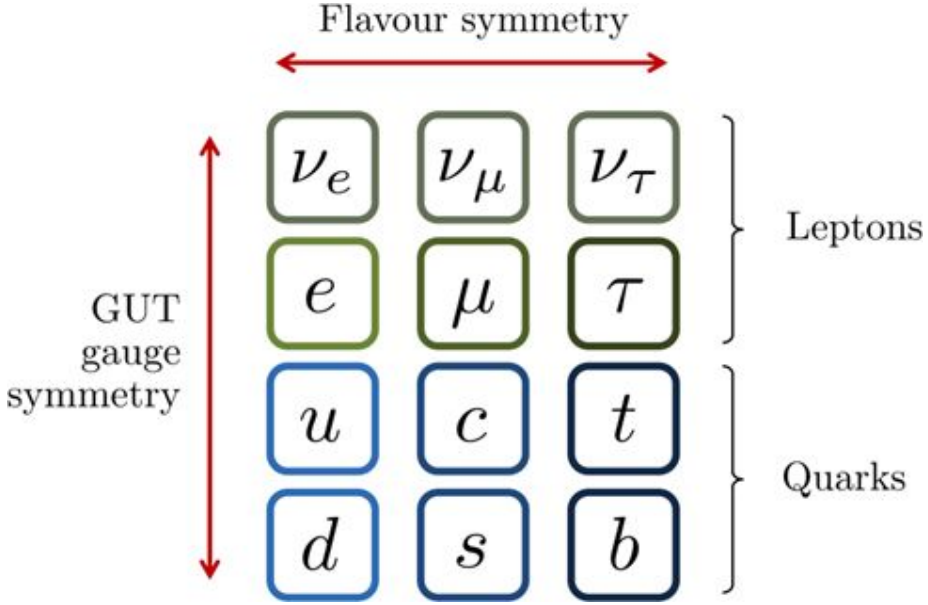


$V_{\mathrm{CKM}} \sim$





From: P.Novichkov Discrete 2018 slides

Neutrinos, Higgs & Flavour

Neutrinos, Higgs & Flavour

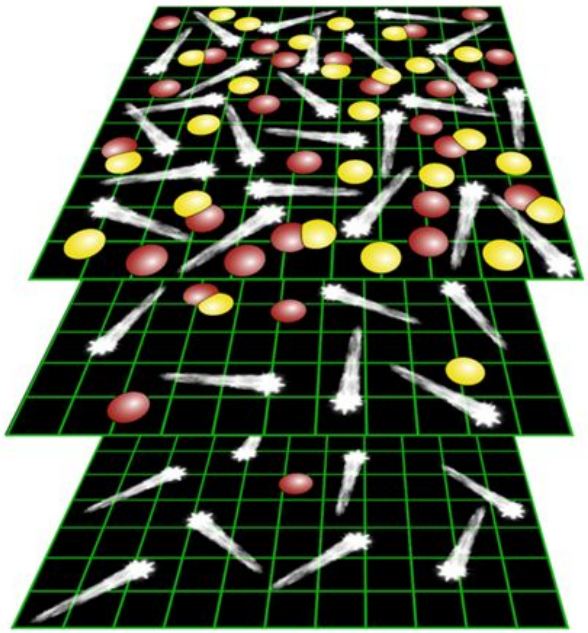
Motivated by a common question:

Why are we here?

$$n_B \equiv n_b - n_{\overline{b}}$$

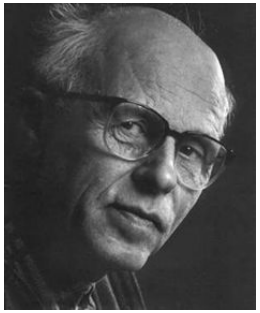
$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\overline{b}}}{n_\gamma} \approx \frac{n_b}{n_\gamma}$$

$$\eta = (6.21 \pm 0.16) \times 10^{-10}$$



From: A.Toorop PhD Thesis

$30\,000\,000$ *vs.* $30\,000\,001$ (at $t = 1$ s)



B Violation
C and CP violation
Departure from thermal equilibrium

Neutrinos, Higgs & Flavour

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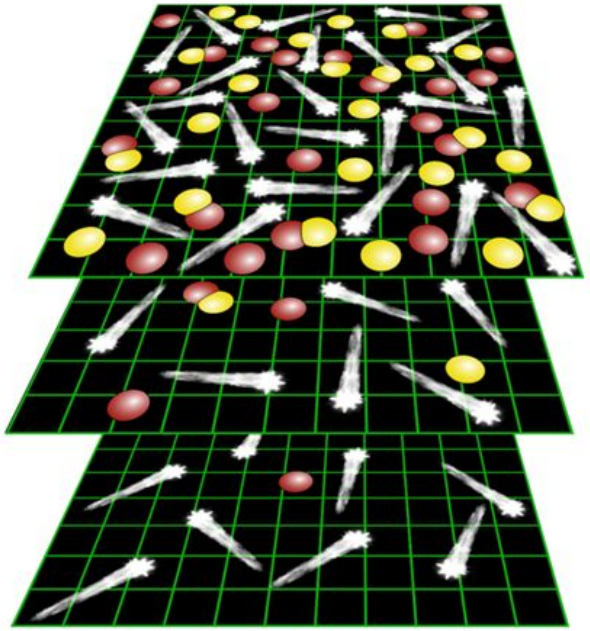

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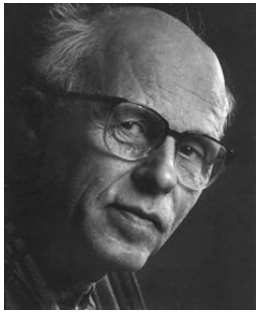
$30\,000\,000$ *vs.* $30\,000\,001$ (at $t = 1$ s)



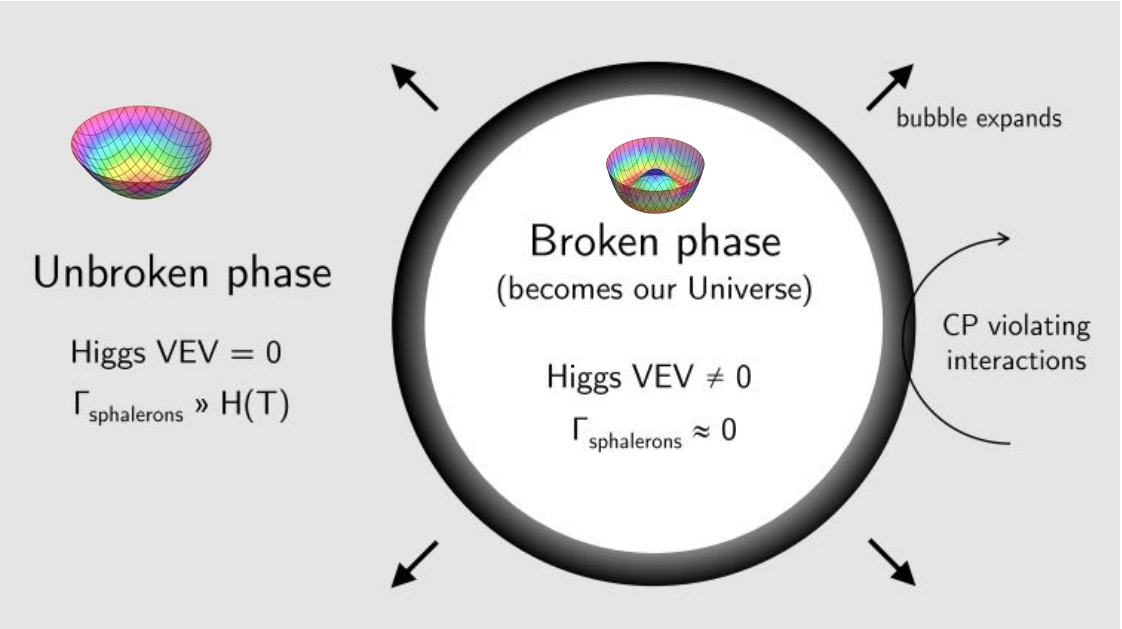
B Violation ✓

C and CP violation ✗

Departure from thermal equilibrium ✗

Neutrinos, Higgs & Flavour

Problem in the Standard Model



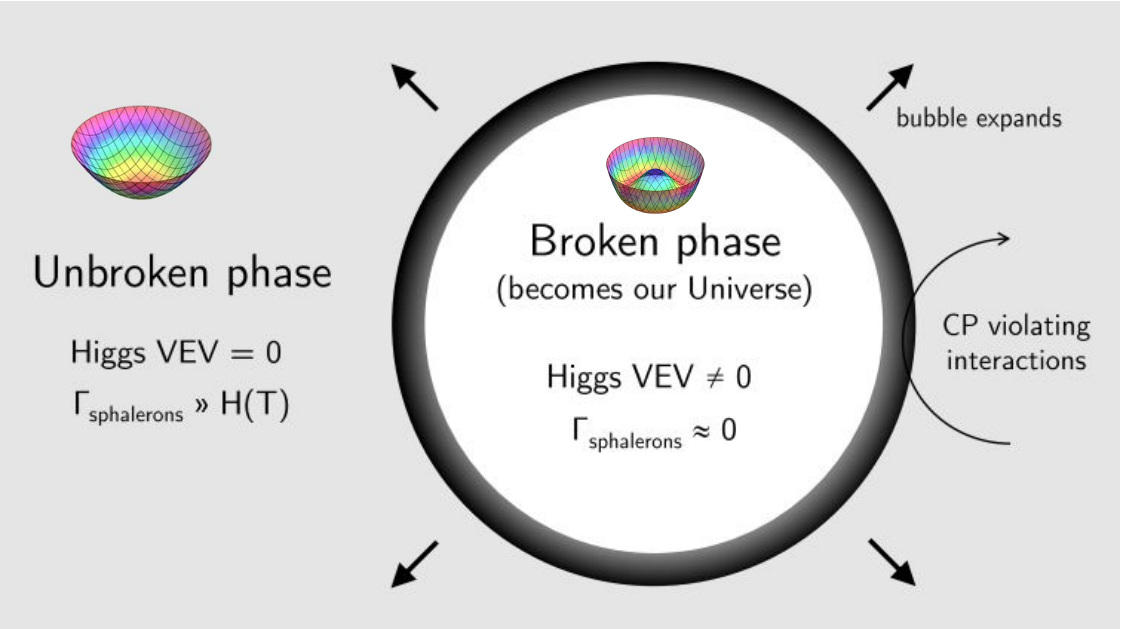
B Violation ✓
C and CP violation ✓
Departure from thermal equilibrium ✓

Neutrinos, Higgs & Flavour

Solution using Higgses:

Electroweak baryogenesis

(see e.g. 1704.08911)



Citation: K. Nakamura *et al.* (Particle Data Group), JPG **37**, 075021 (2010) (URL: http://pdg.lbl.gov)

LIGHT UNFLAVORED MESONS
($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u}-d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \to \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	(2.00 ± 0.25) $\times 10^{-4}$		30
$e^+\nu_e$	[b]	(1.230 ± 0.004) $\times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	(7.39 ± 0.05) $\times 10^{-7}$		70
$e^+\nu_e\pi^0$		(1.036 ± 0.006) $\times 10^{-8}$		4
$e^+\nu_e e^+e^-$		(3.2 ± 0.5) $\times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$		< 5 $\times 10^{-6}$	90%	70

DARK MATTER

$J =$?

Mass $m =$?
Mean life $\tau =$?

DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
?	?	?	?

From: A.Ibarra ICTP Summer School talk

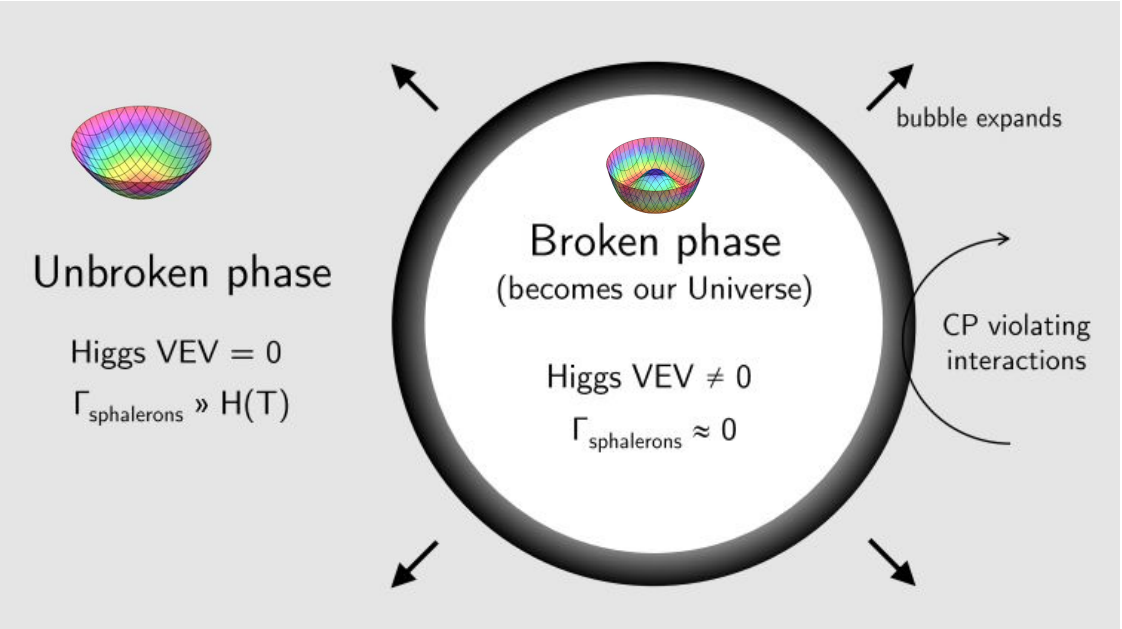
B Violation ✓
C and CP violation ✓
Departure from thermal equilibrium ✓

Neutrinos, Higgs & Flavour

Solution using Higgses:

Electroweak baryogenesis

(see e.g. 1704.08911)

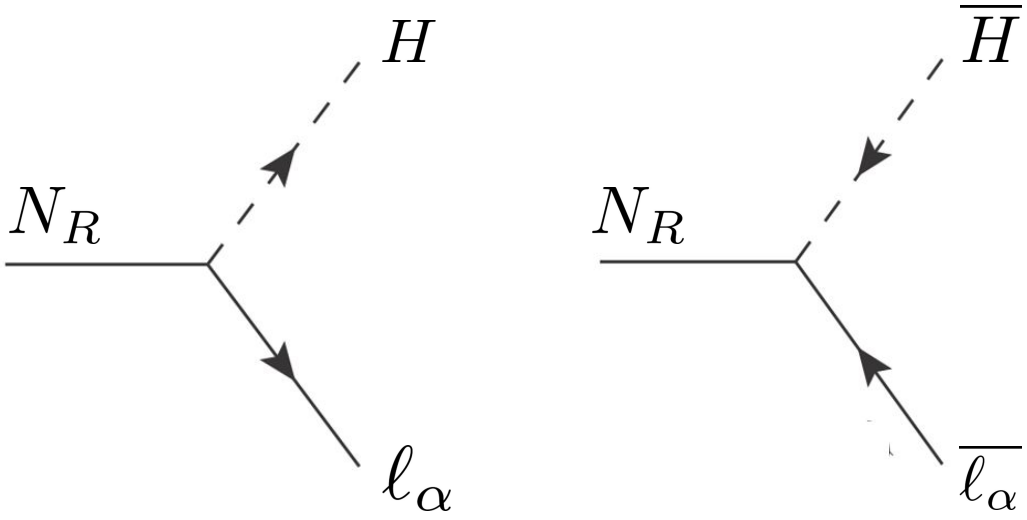


B Violation ✓
C and CP violation ✓
Departure from thermal equilibrium ✓

Neutrinos, Higgs & Flavour

Solution using neutrinos:

Leptogenesis

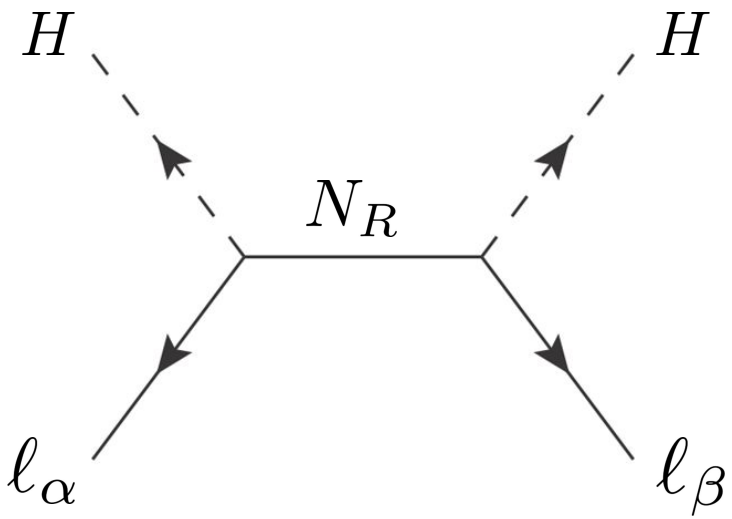


B Violation ✓
C and CP violation ✓
Departure from thermal equilibrium ✓

Neutrinos, Higgs & Flavour

Solution using neutrinos:

Leptogenesis
& type I seesaw



$$\mathbf{M}_\nu = -\left(\mathbf{Y}_N\right)^T \frac{v^2}{\mathbf{M}_N} \mathbf{Y}_N$$

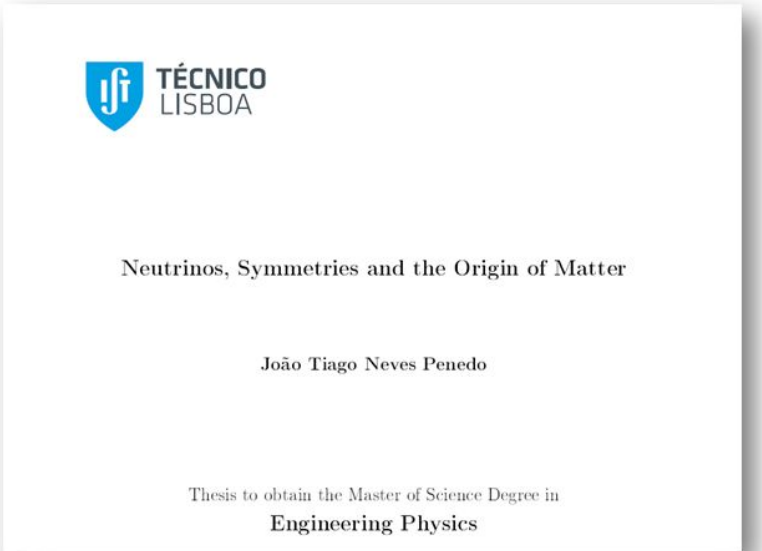
B Violation ✓
C and CP violation ✓
Departure from thermal equilibrium ✓

Neutrinos, Higgs & Flavour

$$\frac{1}{\Gamma_{\Delta_i}}\left(\Gamma(\Delta_i^* \to \ell_\alpha\,\ell_\beta) - \Gamma(\Delta_i \to \overline{\ell_\alpha}\,\overline{\ell_\beta})\right)$$

Solution using all 3:

Flavoured
Leptogenesis
w/ type II seesaw



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Neutrinos, Symmetries and the Origin of Matter

João Tiago Neves Penedo

Thesis to obtain the Master of Science Degree in
Engineering Physics

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*How do fermions get **mass**?*

*How to explain the **baryon asymmetry** of the Universe?*

*What is the nature of **Dark Matter**?*

*How do **neutrinos** get mass?*

*Is there an extended **Higgs sector**?*

*What is the role of **flavour symmetries**?*

and many more...

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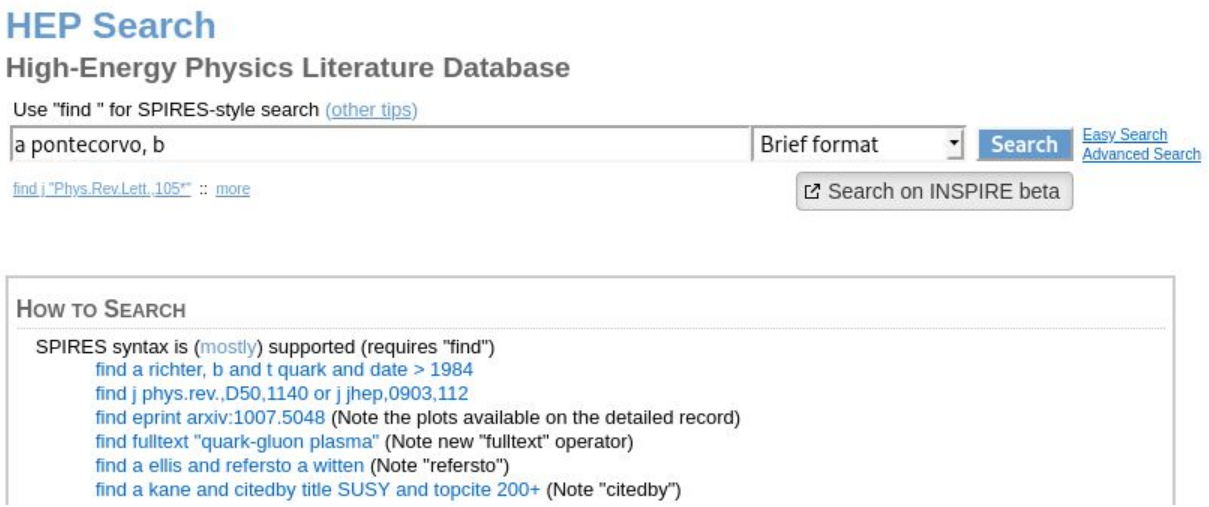

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	Citeable papers	Published only
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Number of citations:	9250	9250
Citations per paper (average):	134.1	136.0
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Breakdown of papers by citations:

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Famous papers (250-499)	0	0
Very well-known papers (100-249)	7	7

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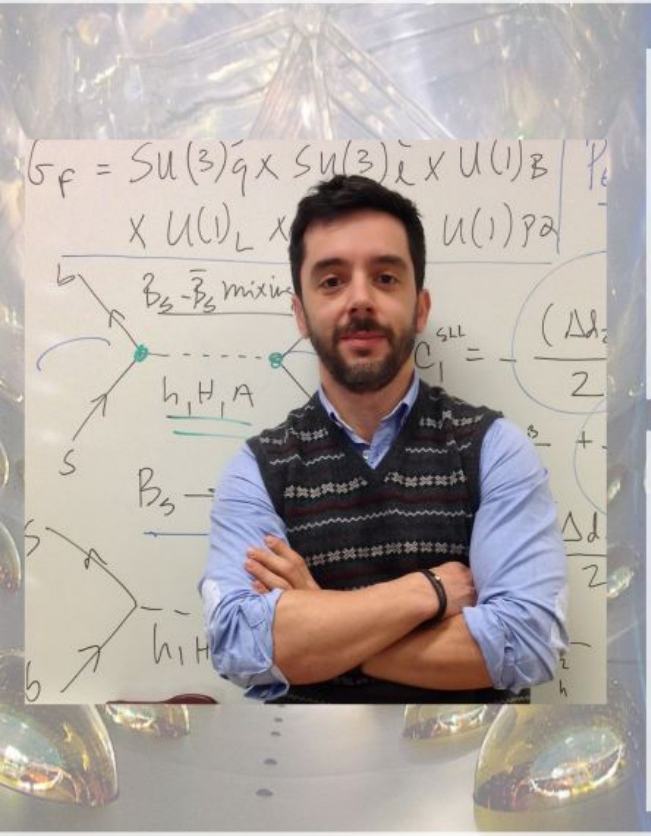

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