The 'Tang'ible Enigma of Flavour

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UNIVERSITY OF OREGON

Graduate Student Seminar

21 May 2014

Jay Wacker

touched upon it

(and quit physics)

Wolfgang Altmannshofer

presented it in detail

This talk

a different perspective

Why copies?

Analogy 1


LETTHEREBEDOODLES.TUMBLR.COM


LETTHEREBEDOODLES.TUMBLR.COM


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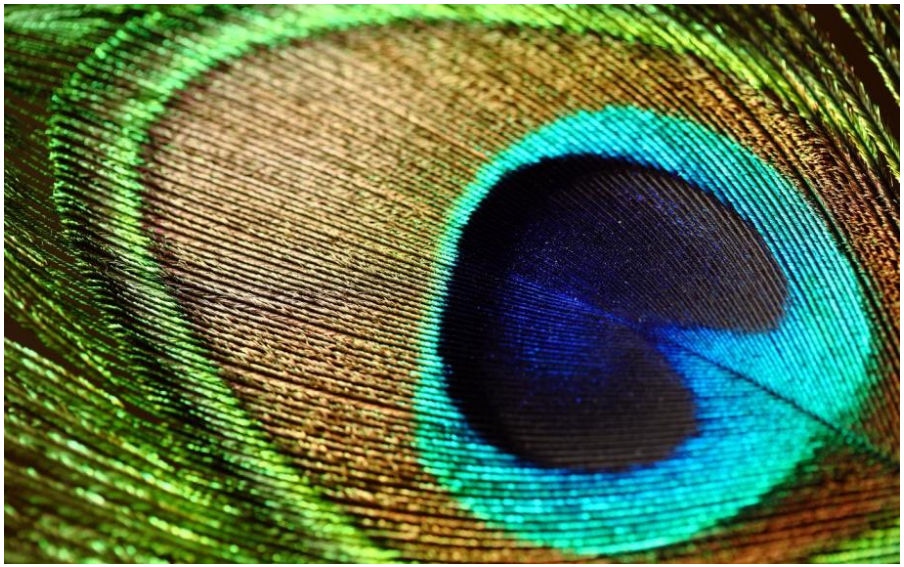
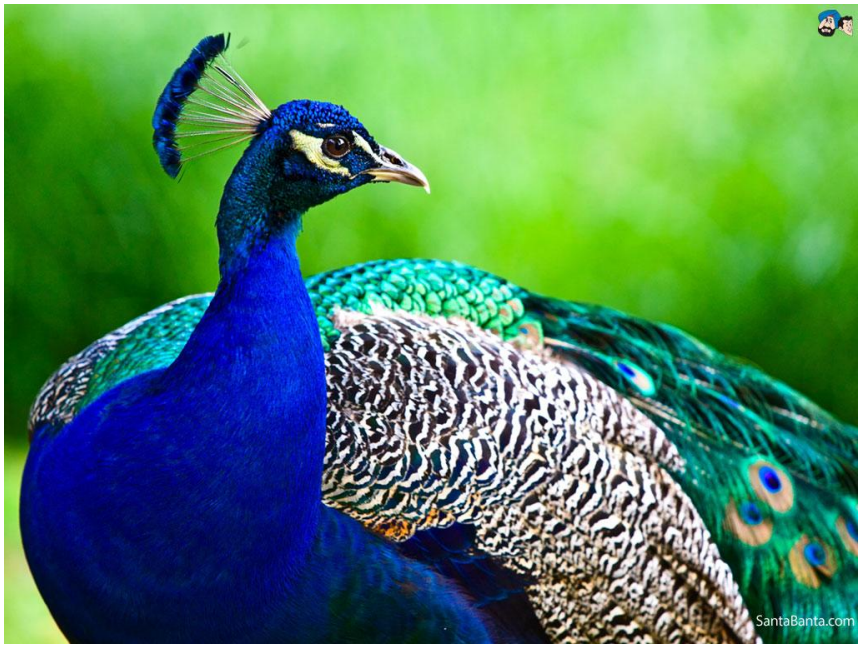
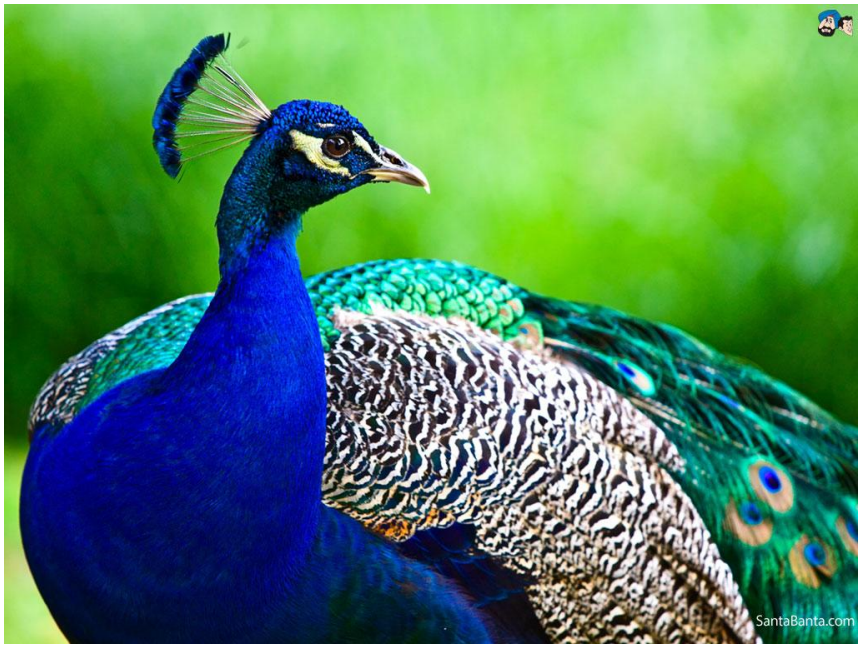
Analogy 11




SantaBanta.com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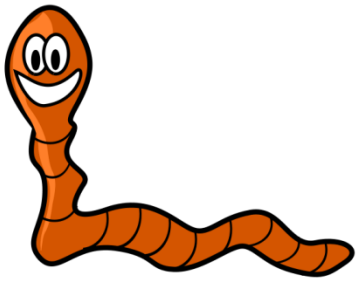
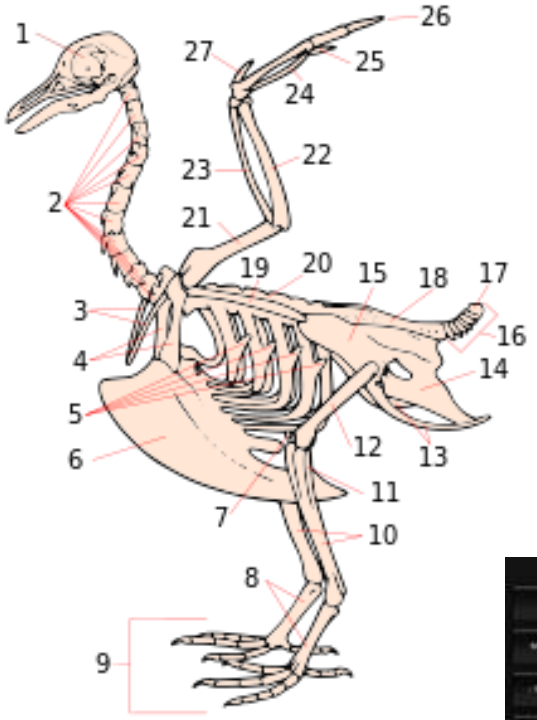
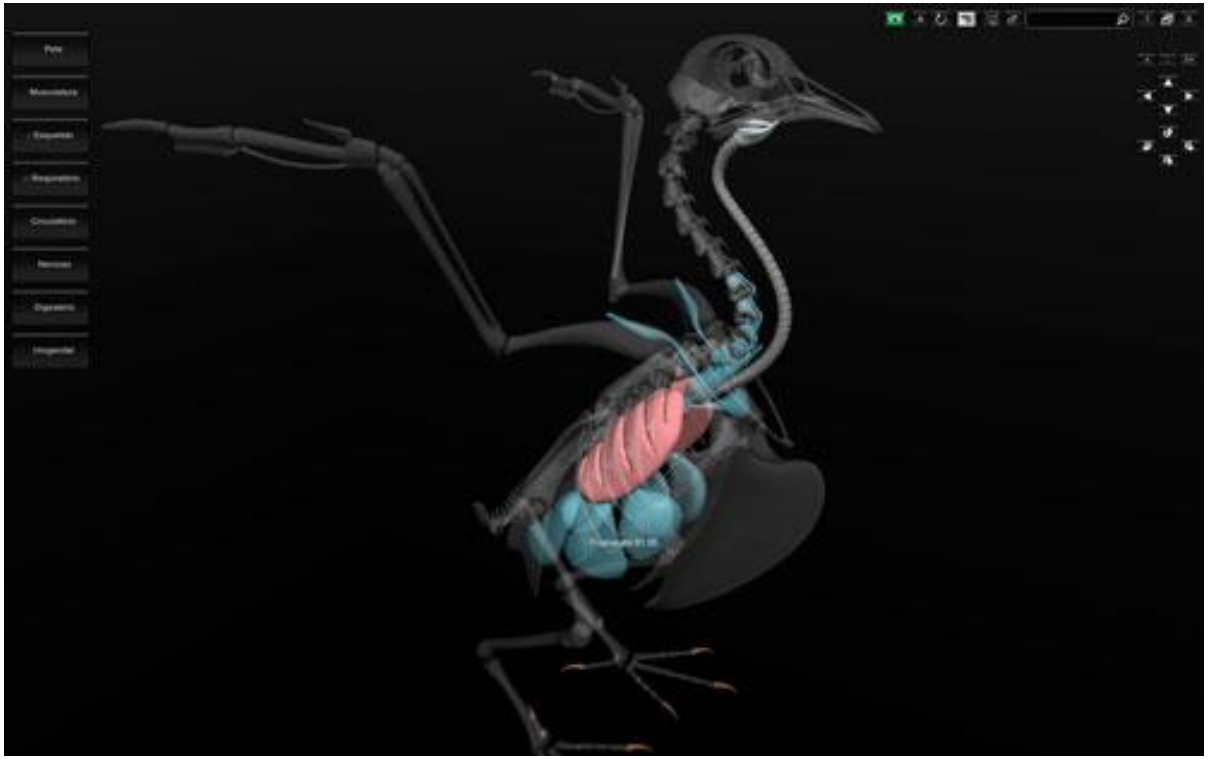
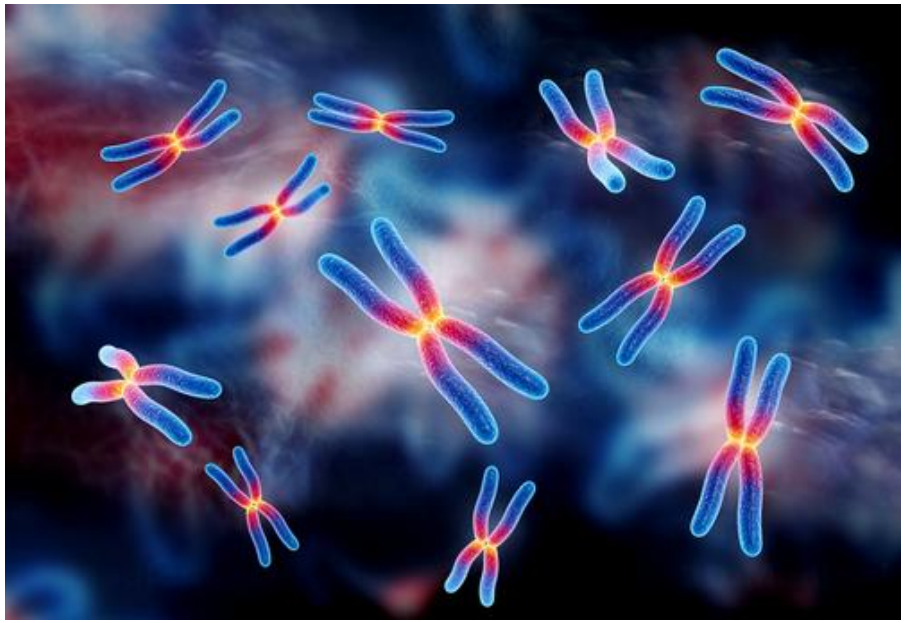




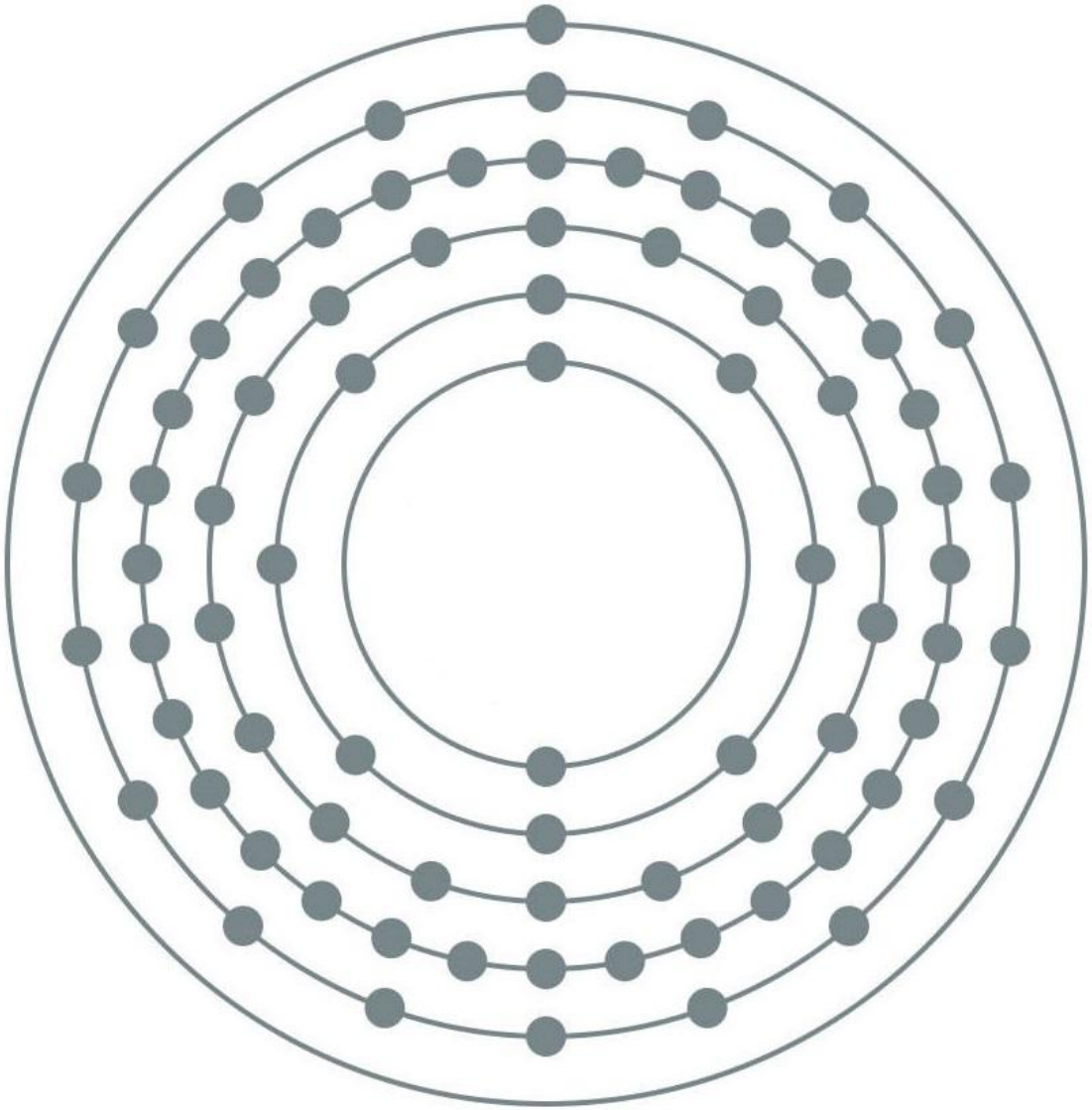
A little deeper





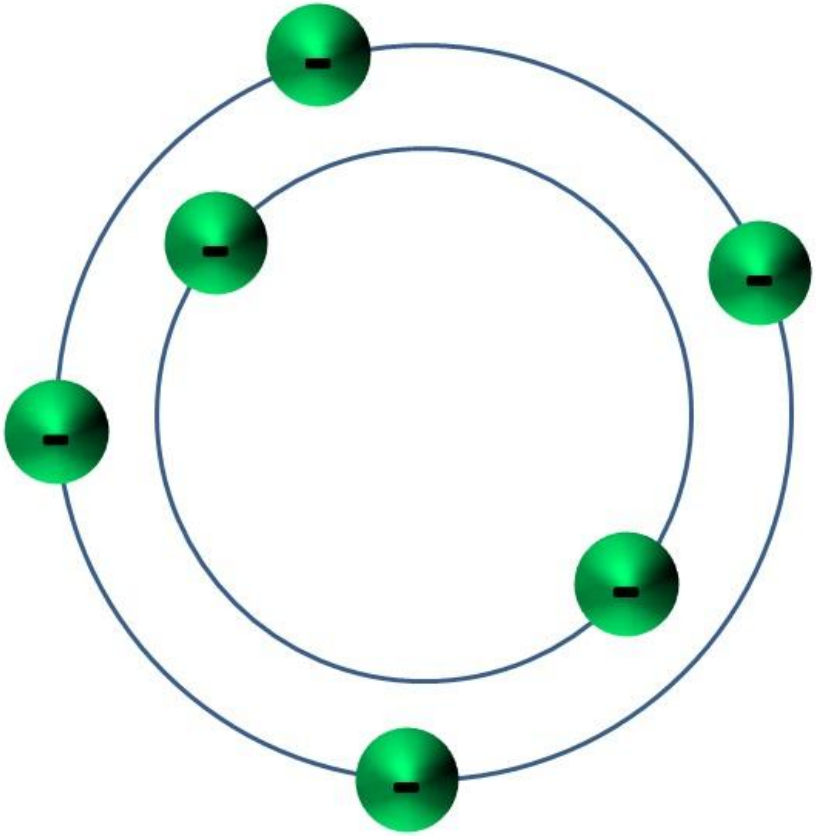
A lot deeper

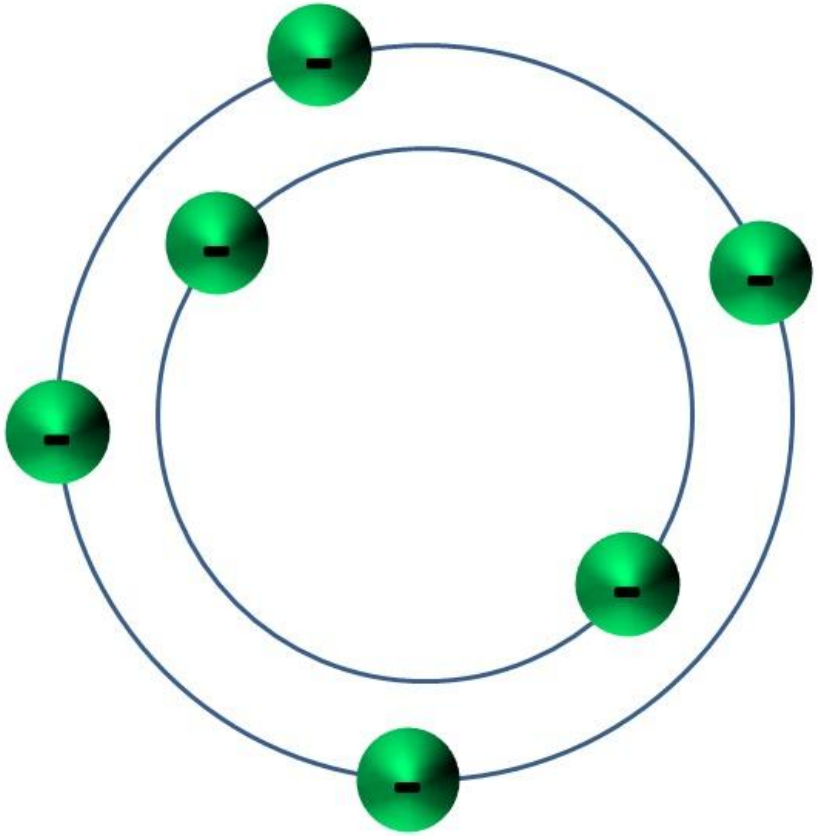
Analogy 111



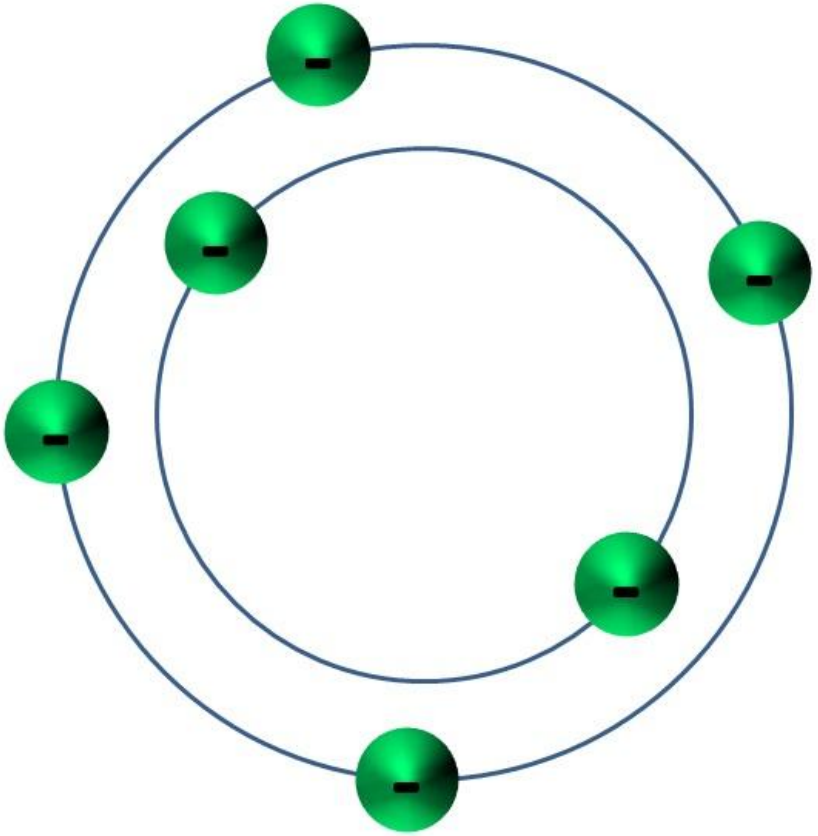
“Find Element 6”

“Find Element 6”



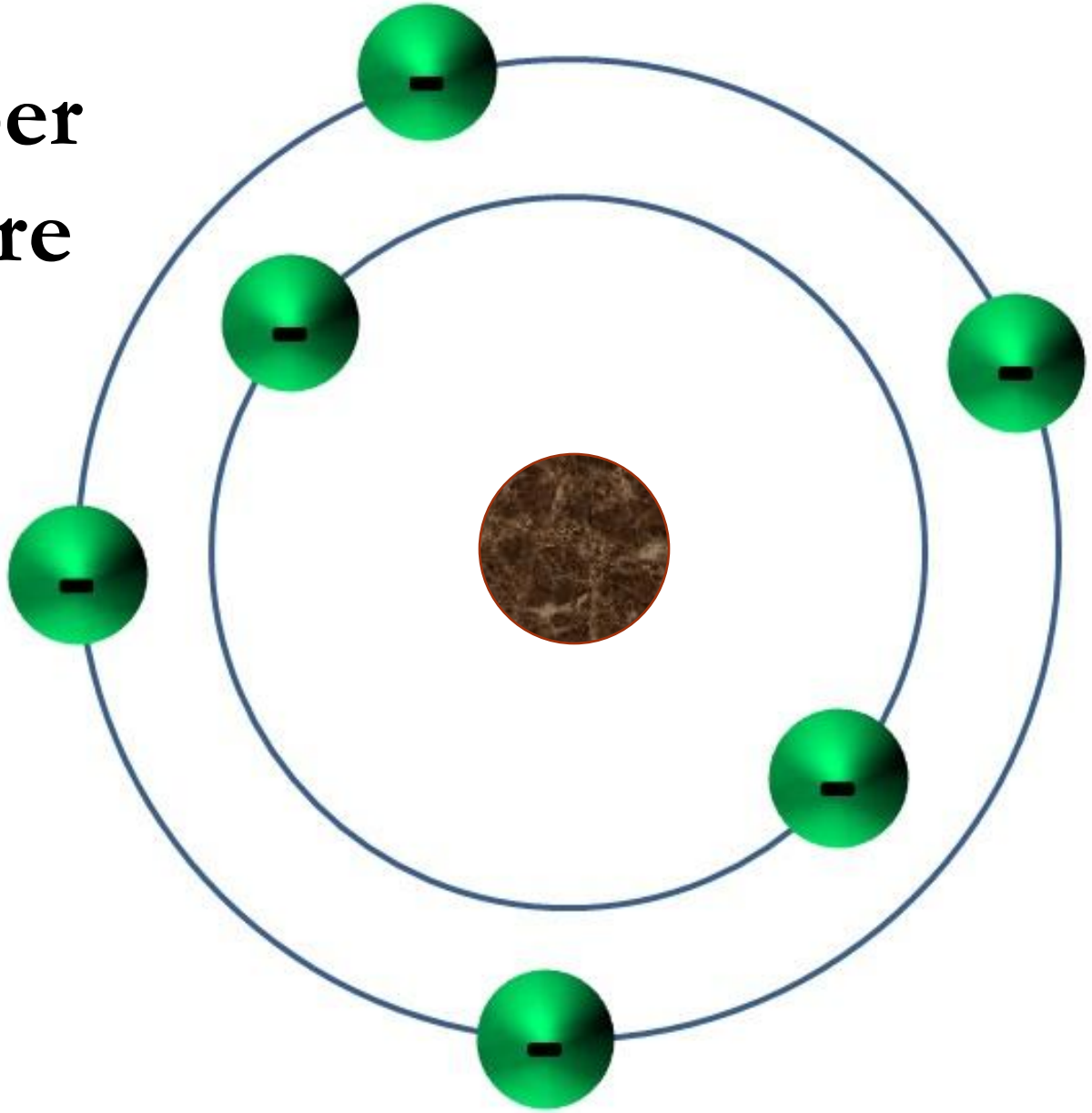


A = 13

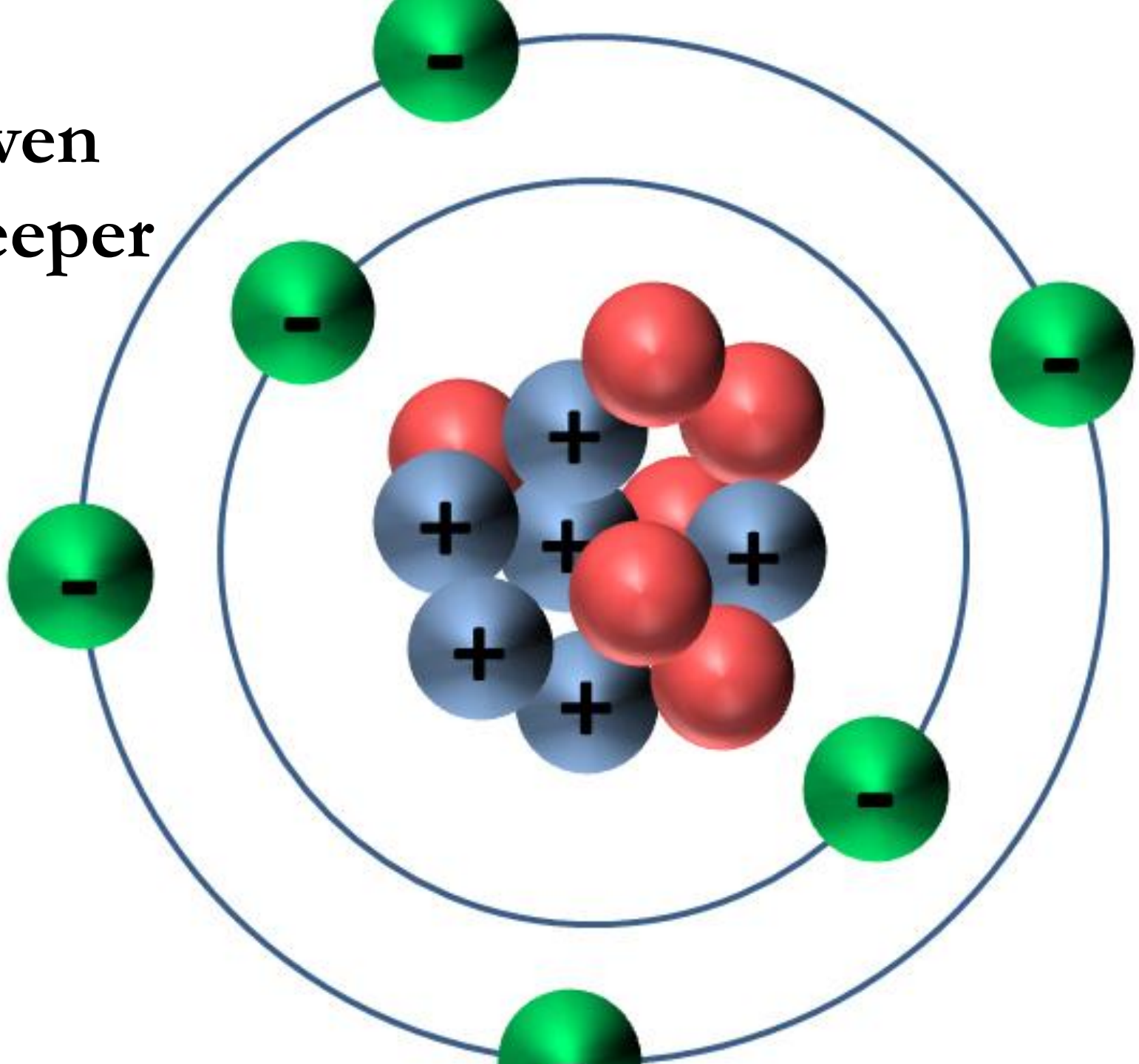


A = 12

Deeper picture



Even deeper



The analogies

Defining properties

(Near-)Copies

Probe at deeper lengths

Defining properties

(a) Fundamental particle

(b) Feels electromagnetism

(c) Neutral under strong force

Gauge invariance à la

$$\vec{A} \rightarrow \vec{A} + \vec{\nabla} f, \quad \phi \rightarrow \phi - \frac{\partial f}{\partial t}$$

Gauge invariance à la

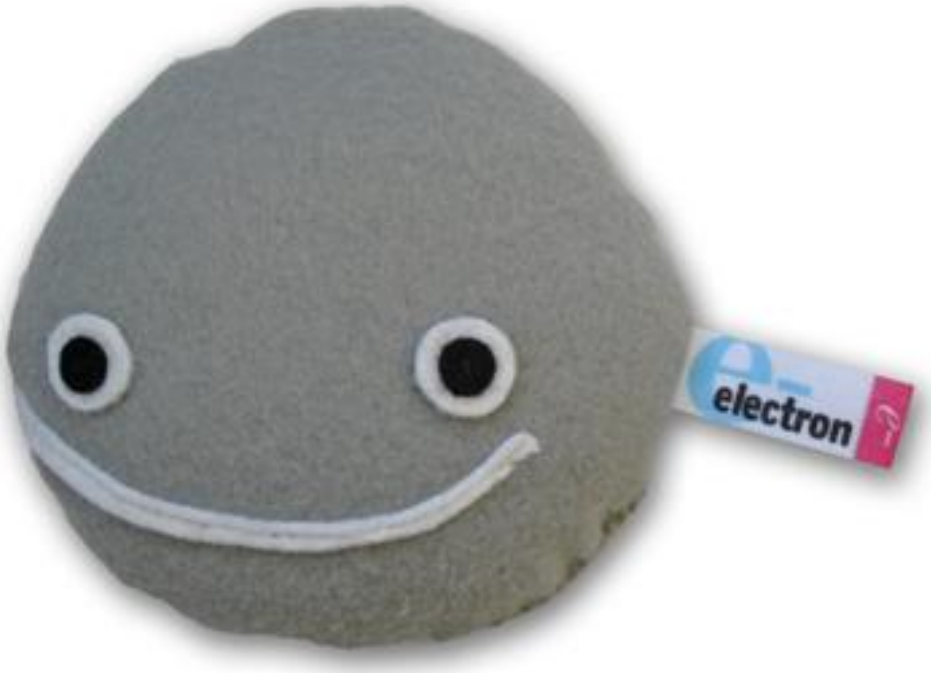
$$\vec{A} \rightarrow \vec{A} + \vec{\nabla} f, \quad \phi \rightarrow \phi - \frac{\partial f}{\partial t}$$

Q. E. D.

$$\psi(x) \rightarrow \psi(x) e^{i\alpha(x)}, \quad A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$$

ELECTRON

e^-



The **ELECTRON** is a fundamental subatomic particle carrying a negative charge. Its mass is 1/1000 that of the smallest atom. It participates in electromagnetic interactions, and is typically found orbiting the nucleus of an atom.

Acrylic felt with poly fill for minimum mass.

●○○○○○○○○○○○○

LIGHT HEAVY

$10.49

PLUS SHIPPING

GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK
NEUTRON DOWN QUARK TAU GLUON **ELECTRON** NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHY

The PARTICLE ZOO

"Quantum muodynamics"

MUON

μ

"Mu-meson"

The **MUON** is a short-lived, heavier version of the electron. It has the same negative charge, but is 200 times more massive than the electron.

Acrylic felt with poly bead fill for medium mass.

$10.49 PLUS SHIPPING

●●●●●●●○○○○○○

LIGHT HEAVY

"Who ordered that?"

- I. I. Rabi

GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK
NEUTRON DOWN QUARK TAU GLUON **MUON** NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHY
ARK PROTON NEUTRON DOWN QUARK TAU GLU
RK TAU NEUTRINO MUON UP QUARK PROTON N
ELECTRON UP QUARK DOWN QUARK TAU NEU

The PARTICLE ZOO

TAU

τ

The **TAU** is a short-lived ($3x10^{-13}$ second), heavier version of the muon and electron. It has the same negative charge, but is 3,478 times more massive than the electron.

Acrylic felt with gravel fill for maximum mass.

$10.49
PLUS SHIPPING

●●●●●●●●●●○○○
LIGHT HEAVY

GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON **TAU** NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON

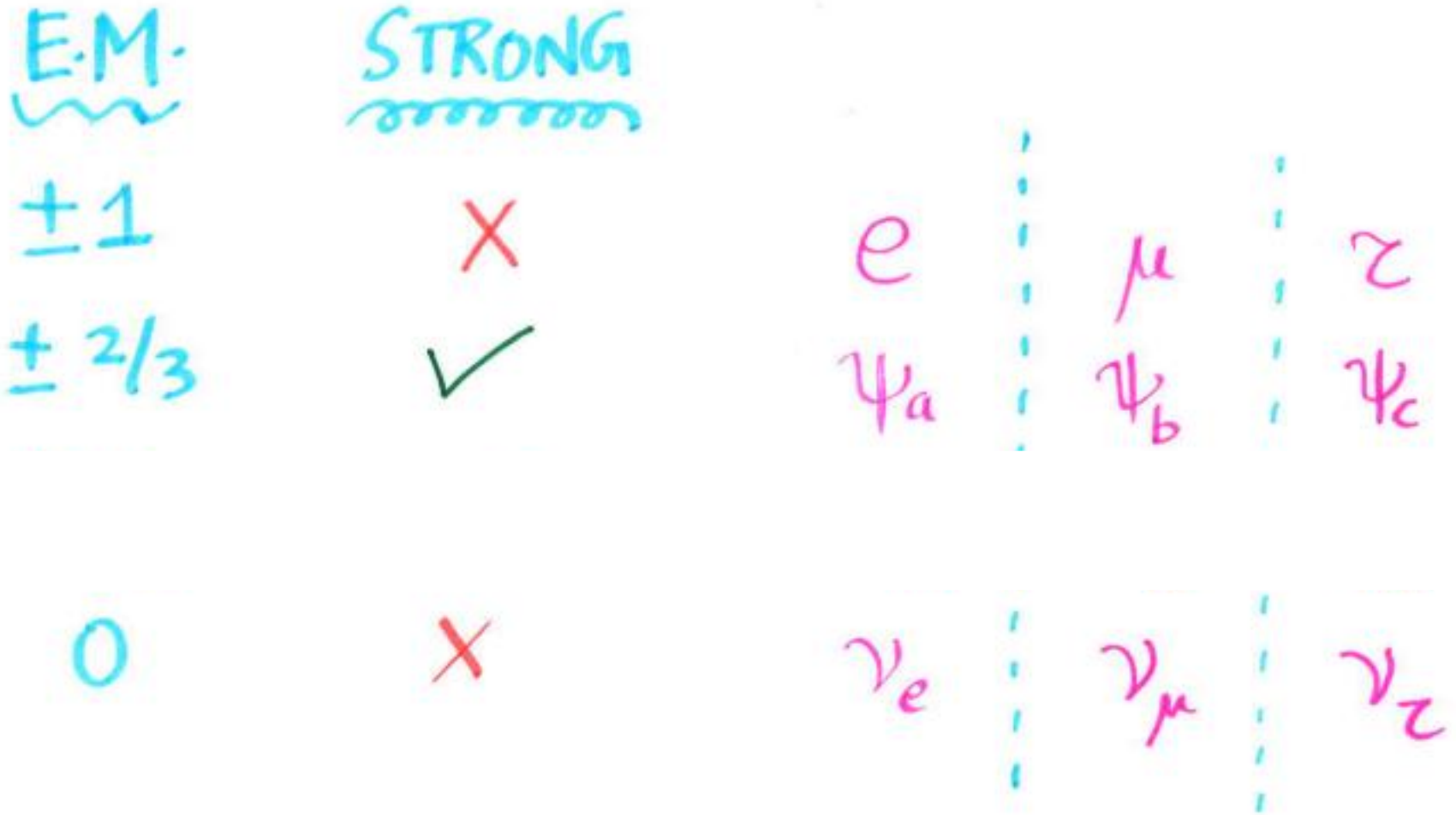
The PARTICLE ZOO

E.M.	STRONG			
± 1	X	e	μ	τ

Other defininings properties = other states

E.M.	STRONG			
± 1	X	e	μ	τ
0	X	ν_e	ν_μ	ν_τ

Other defininings properties = other states

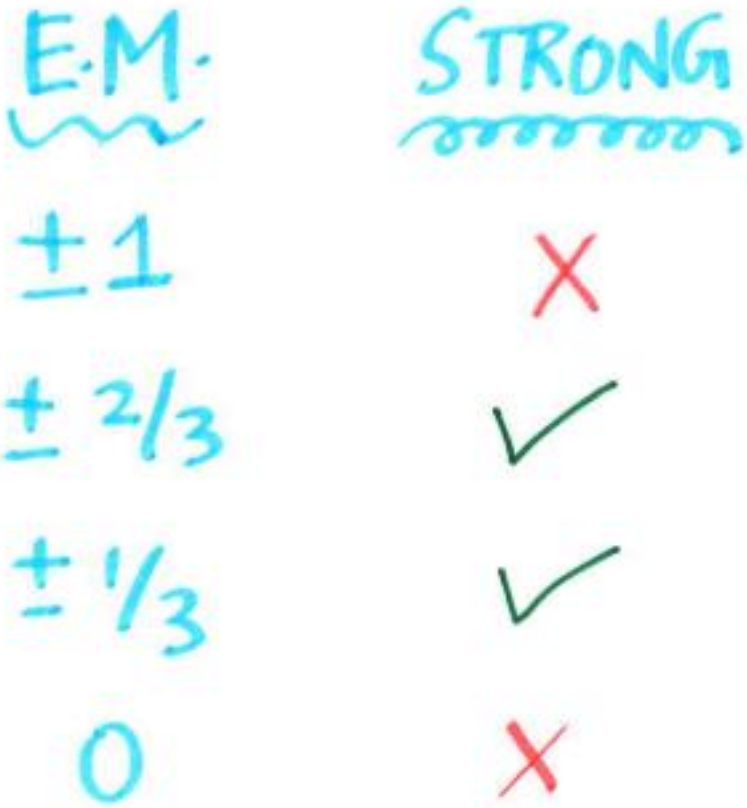


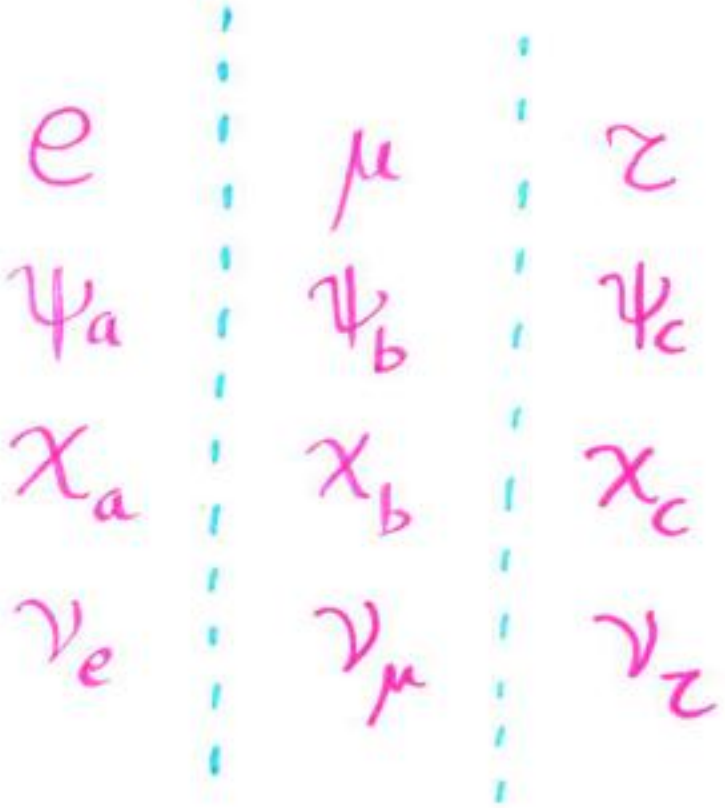
Other defining properties = other states

E.M.	STRONG
± 1	X
$\pm 2/3$	✓
$\pm 1/3$	✓
0	X

e	μ	τ
ψ_a	ψ_b	ψ_c
χ_a	χ_b	χ_c
ν_e	ν_μ	ν_τ

Other defining properties = other states





All fundamental fermions come in three families!

Why?!

Conundrum extends into new world below 10^{-18} m

HYPER-Q.E.D.

$$\psi(x) \to \psi(x) e^{i\alpha(x)}, \quad A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$$

WEINBERG

$$\psi(x) \to \psi(x) e^{i\alpha_k \frac{\sigma_k}{2}}, \quad A_\mu^k(x) \frac{\sigma^k}{2} \to$$

$$e^{i\alpha_k \frac{\sigma_k}{2}} \left[A_\mu^j(x) \frac{\sigma^j}{2} + \frac{i}{g} \partial_\mu \right] e^{-i\alpha_k \frac{\sigma_k}{2}}$$

"ELECTROWEAK"

HYPER-E.M.	WEINBERG	STRONG
$\pm 1/2$	✓	X
± 1	X	X
$\pm 1/6$	✓	✓
$\pm 2/3$	X	✓
$\pm 1/3$	X	✓

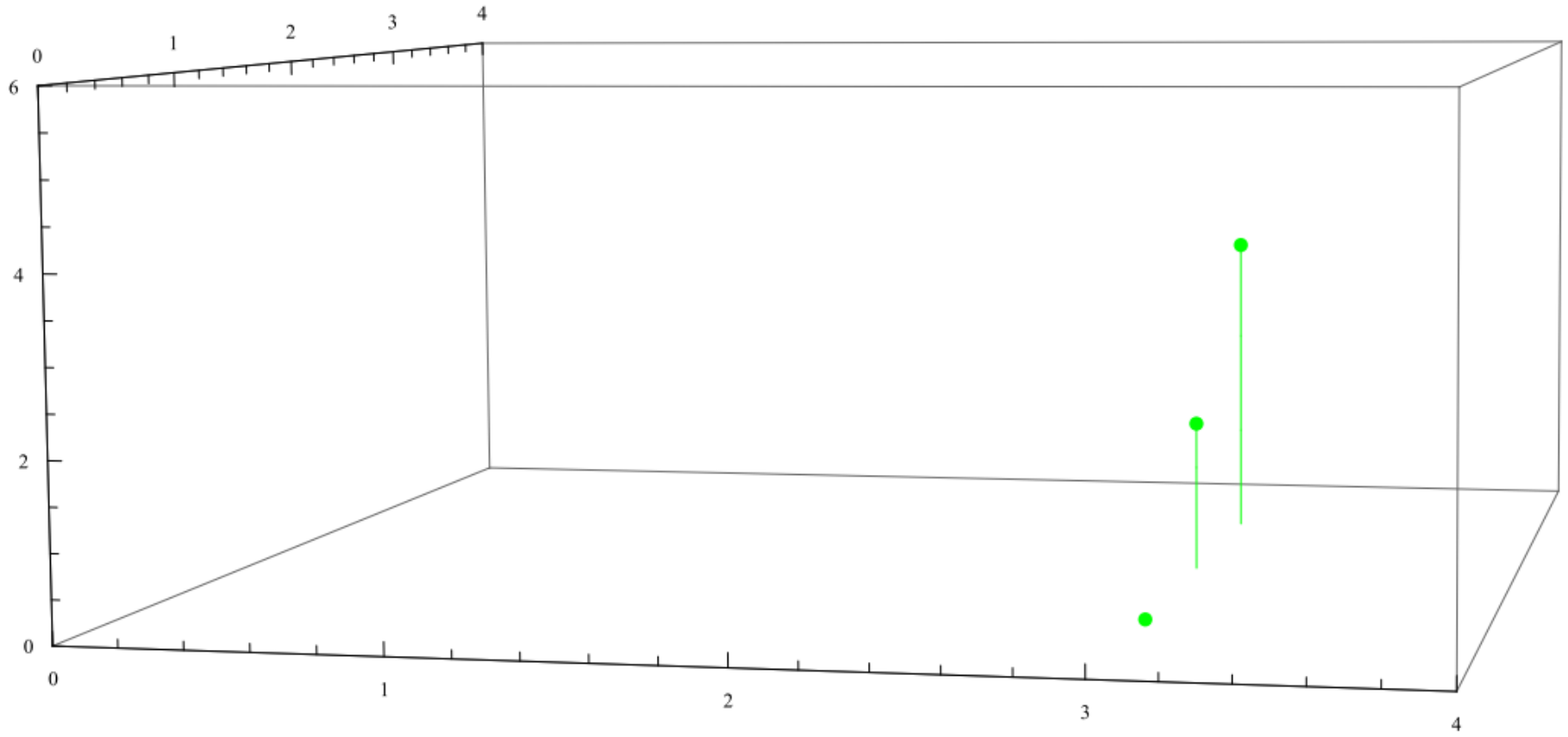
L_e L_μ L_τ

r_e r_μ r_τ

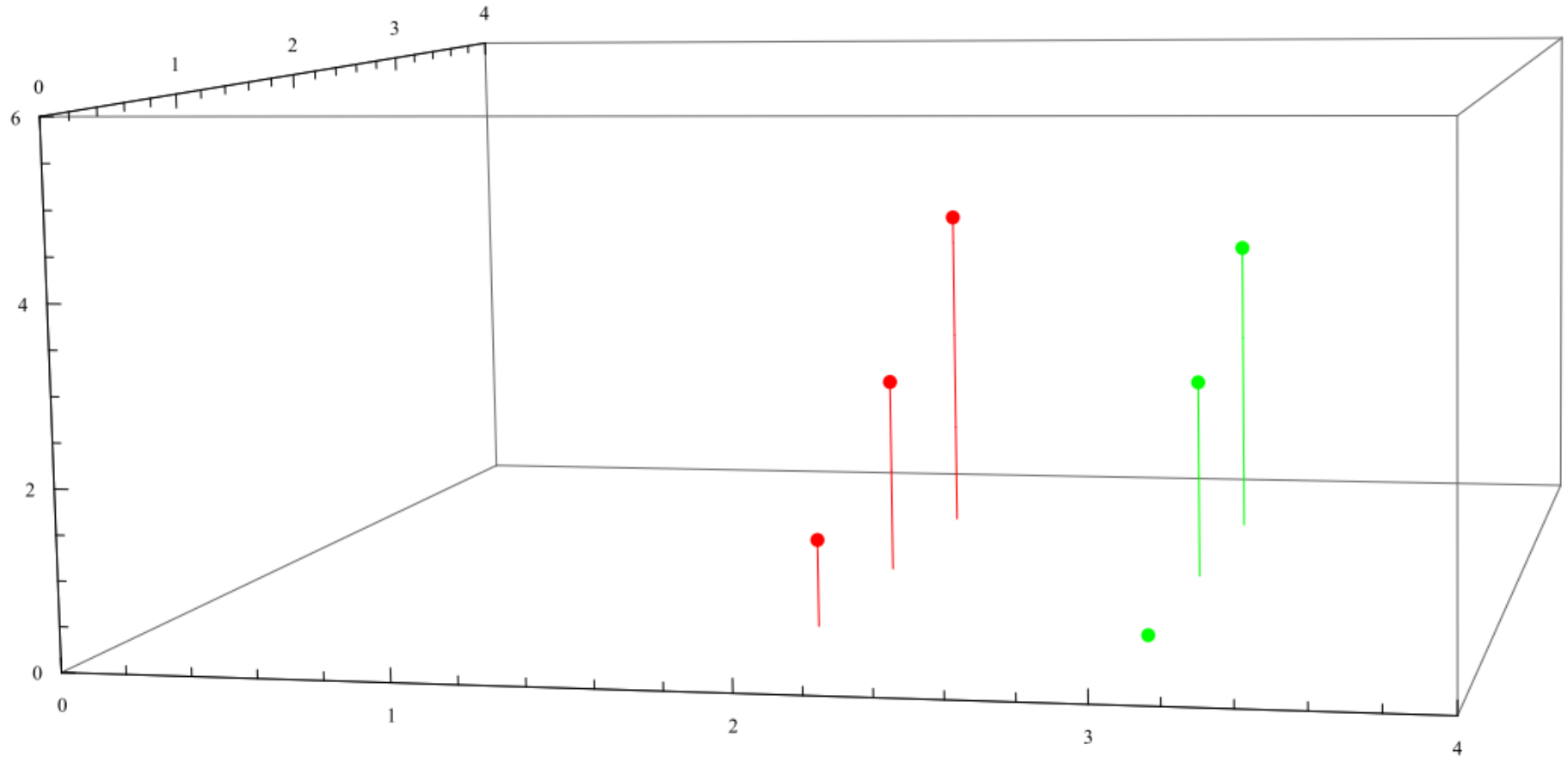
Q_a Q_b Q_c

Does the mass pattern give a clue?

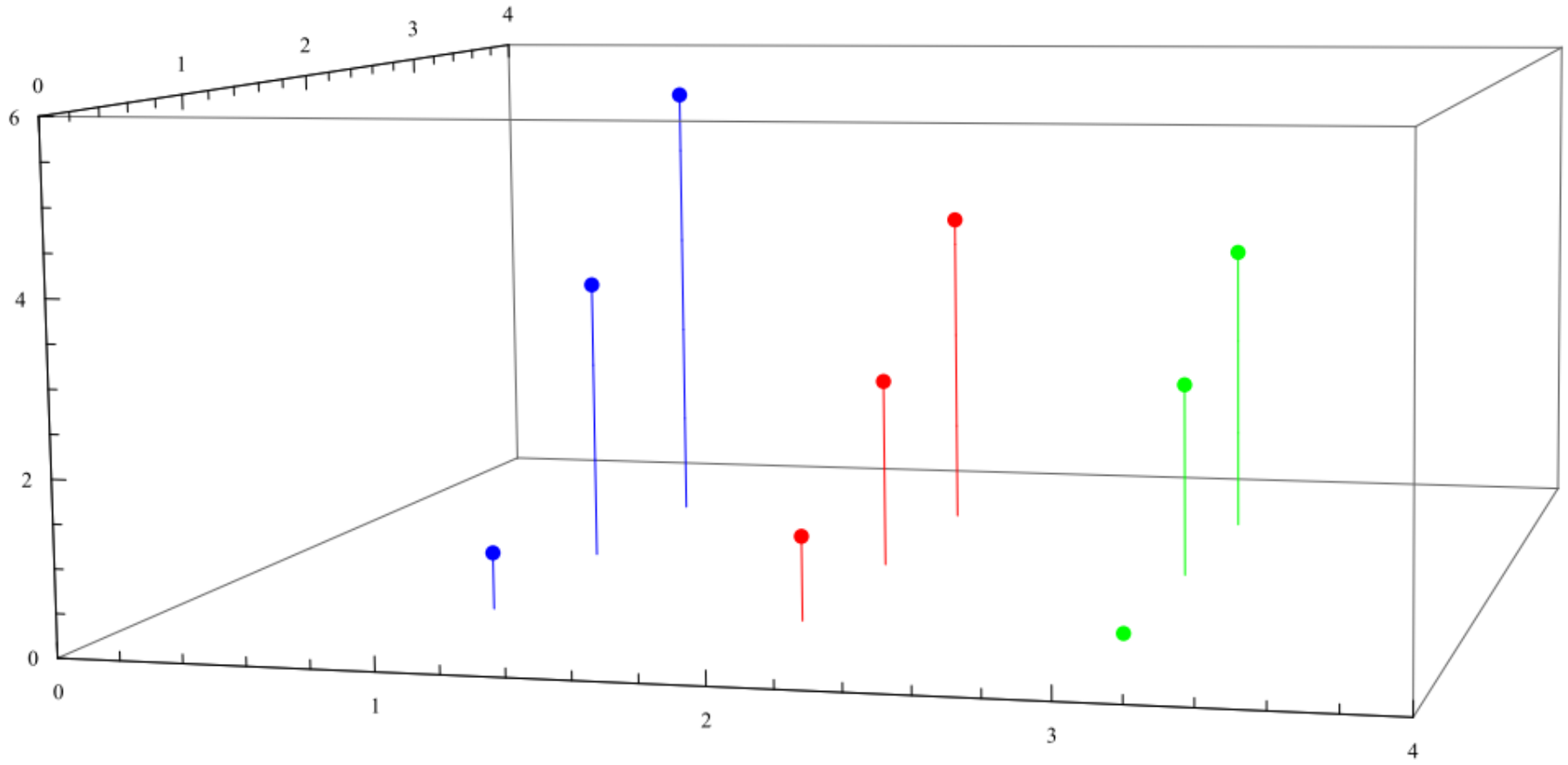
e, μ, τ

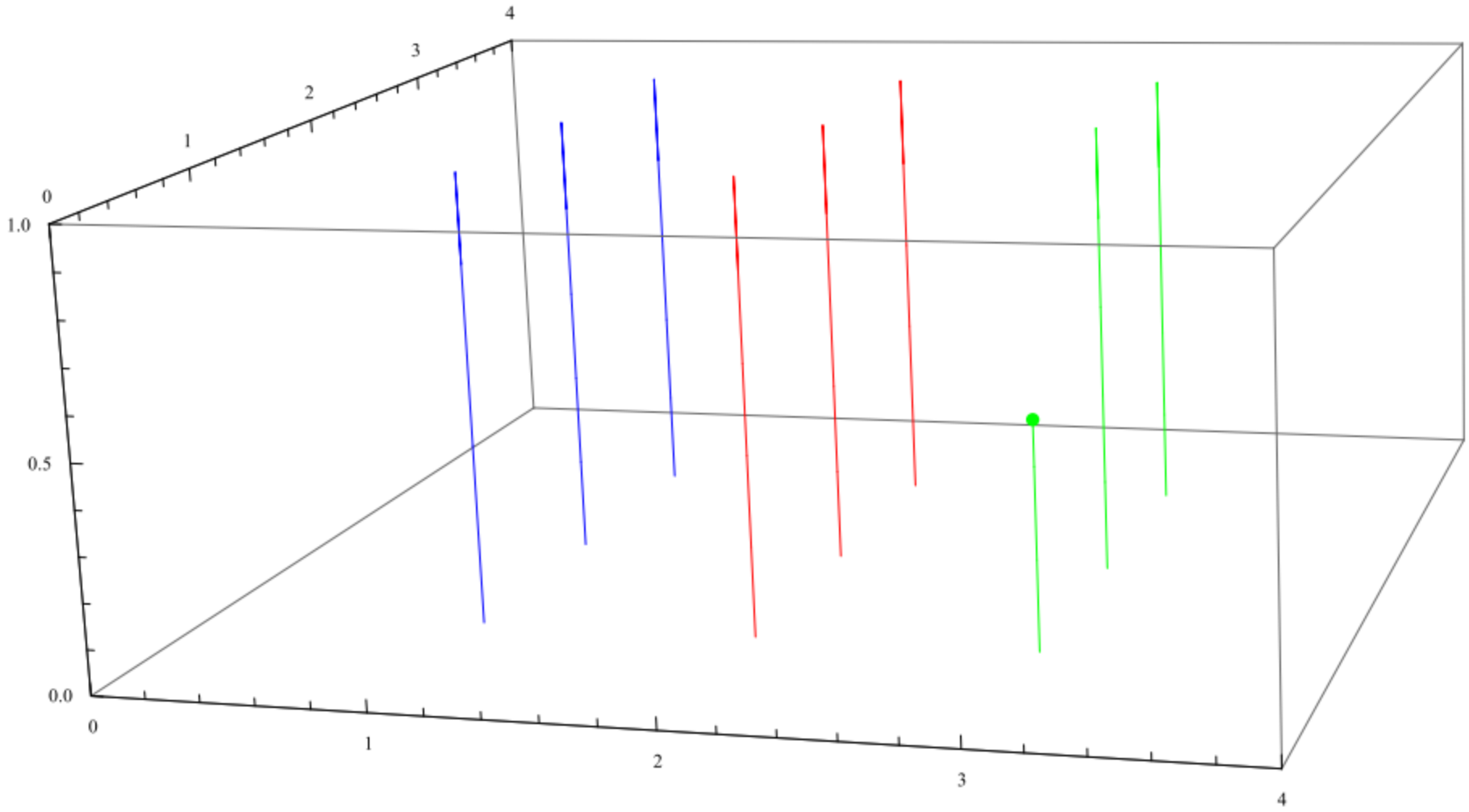


χ's



ψ's




4
3
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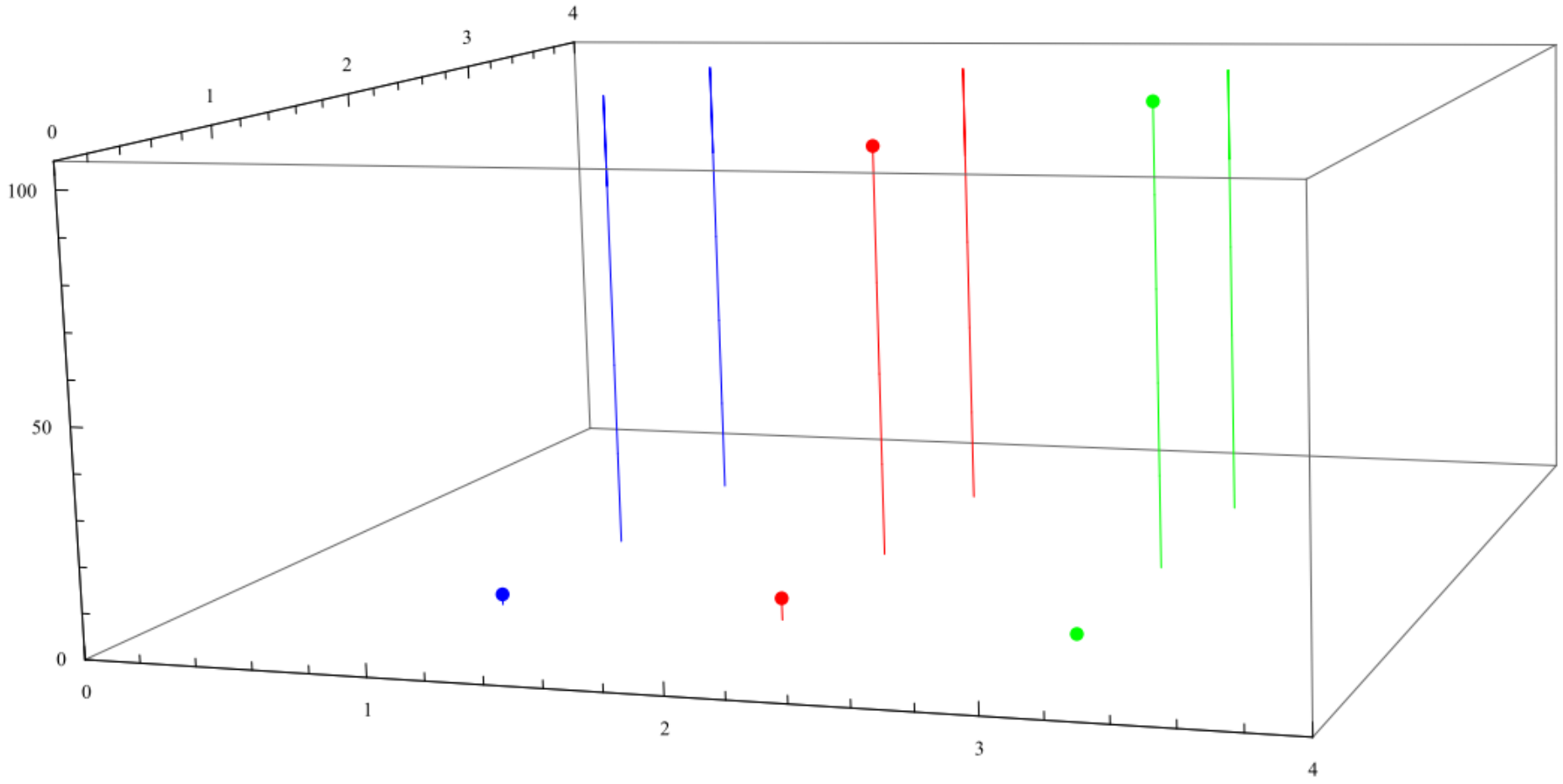
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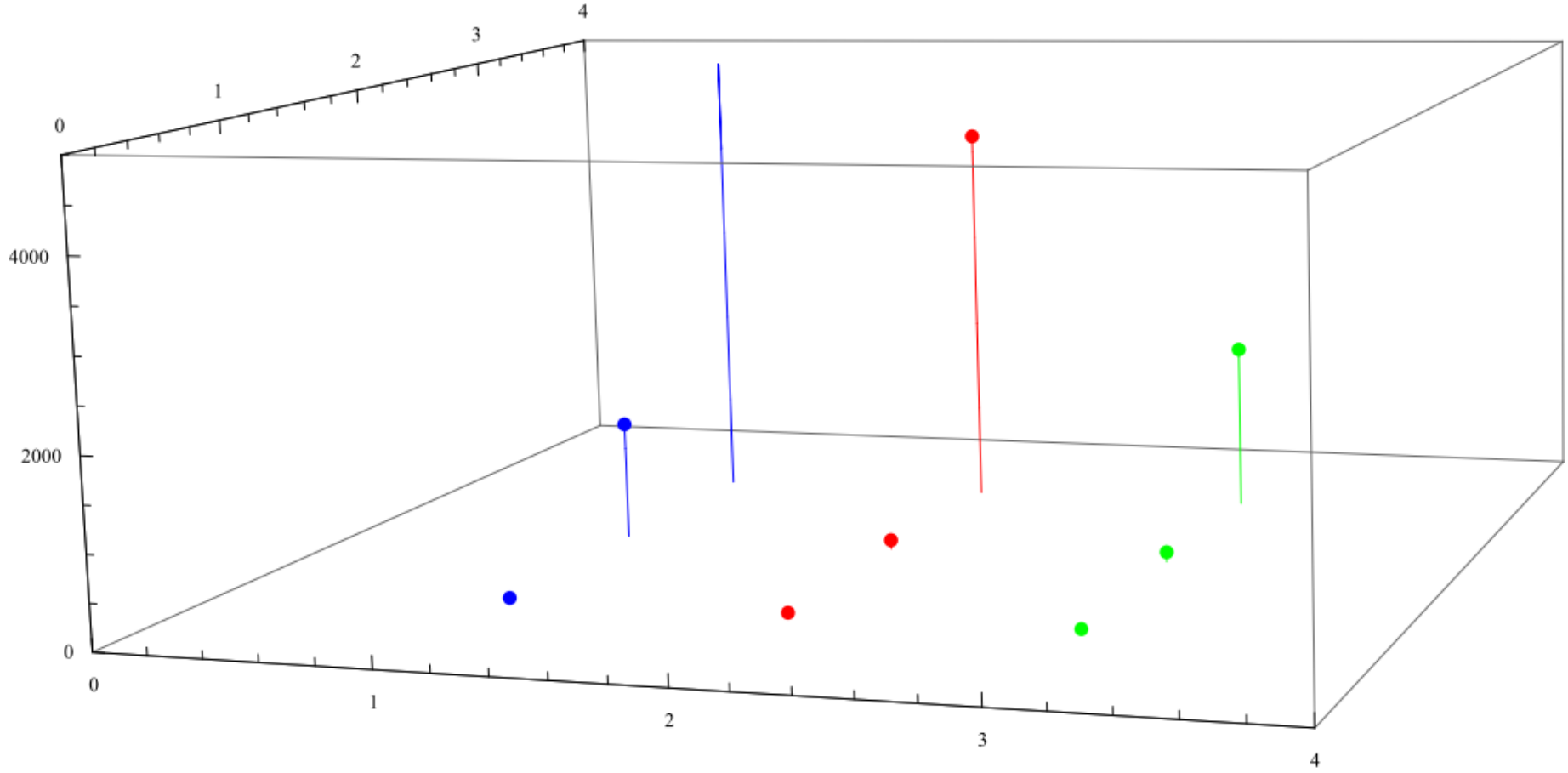
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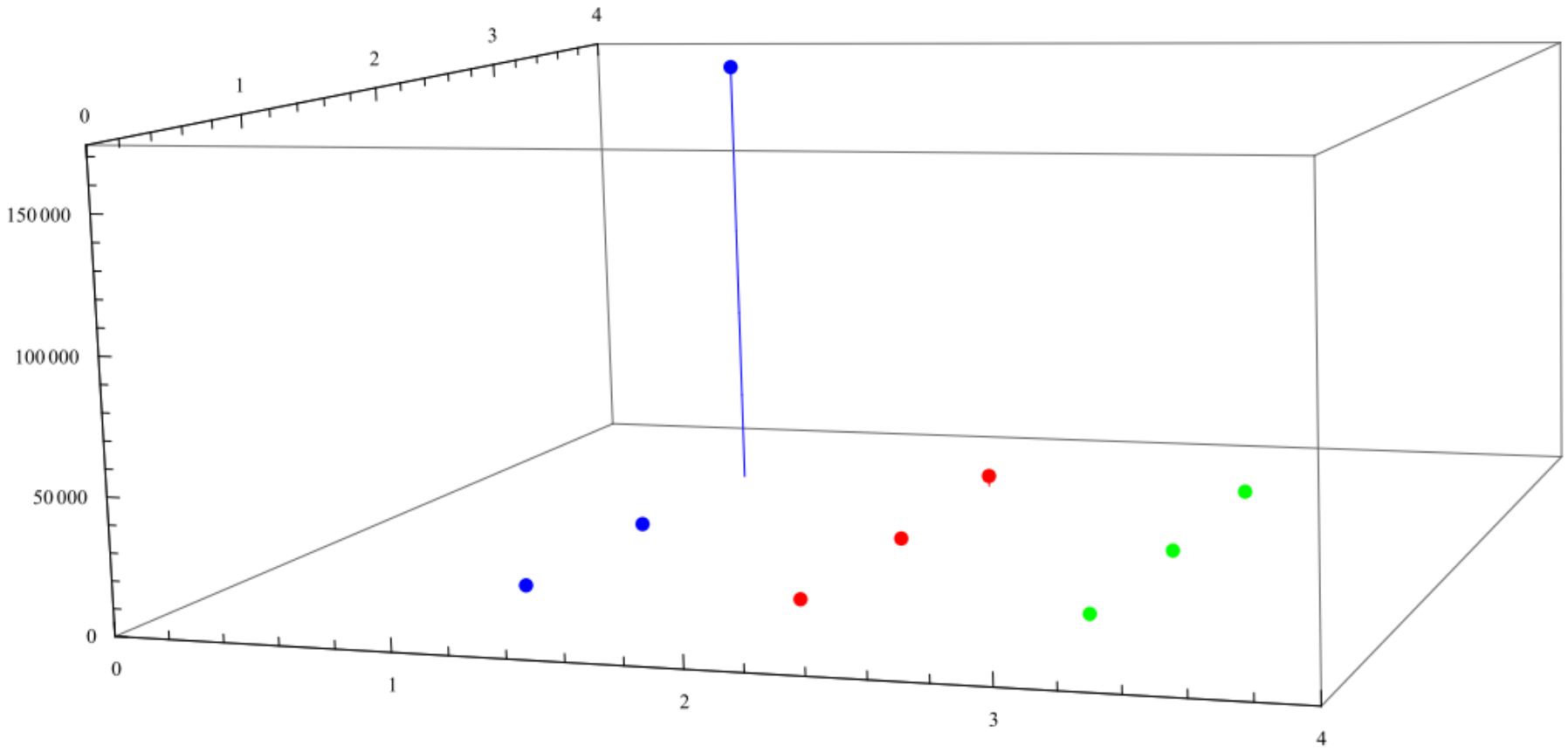

Ψ_3 – heaviest known elementary particle

$$|\psi_1\rangle = \underline{\star}\,|\psi_a\rangle + \overline{\star}\,|\psi_b\rangle + \boxed{\star}\,|\psi_c\rangle$$

$$|\psi_1\rangle = \underline{\star}\,|\psi_a\rangle + \overline{\star}\,|\psi_b\rangle + \boxed{\star}\,|\psi_c\rangle$$

$$|\psi_2\rangle = \underline{\bullet}\,|\psi_a\rangle + \overline{\bullet}\,|\psi_b\rangle + \boxed{\bullet}\,|\psi_c\rangle$$

$$|\psi_3\rangle = \underline{\heartsuit}\,|\psi_a\rangle + \overline{\heartsuit}\,|\psi_b\rangle + \boxed{\heartsuit}\,|\psi_c\rangle$$

$$|\psi_1\rangle = \underline{\star}\,|\psi_a\rangle + \overline{\star}\,|\psi_b\rangle + \boxed{\star}\,|\psi_c\rangle$$

$$|\chi_1\rangle = \underline{\star}\,|\chi_a\rangle + \overline{\star}\,|\chi_b\rangle + \boxed{\star}\,|\chi_c\rangle$$

$$|\psi_2\rangle = \underline{\bullet}\,|\psi_a\rangle + \overline{\bullet}\,|\psi_b\rangle + \boxed{\bullet}\,|\psi_c\rangle$$

$$|\chi_2\rangle = \underline{\bullet}\,|\chi_a\rangle + \overline{\bullet}\,|\chi_b\rangle + \boxed{\bullet}\,|\chi_c\rangle$$

$$|\psi_3\rangle = \underline{\heartsuit}\,|\psi_a\rangle + \overline{\heartsuit}\,|\psi_b\rangle + \boxed{\heartsuit}\,|\psi_c\rangle$$

$$|\chi_3\rangle = \underline{\heartsuit}\,|\chi_a\rangle + \overline{\heartsuit}\,|\chi_b\rangle + \boxed{\heartsuit}\,|\chi_c\rangle$$

$$|\psi_1\rangle = \underline{\star}\,|\psi_a\rangle + \overline{\star}\,|\psi_b\rangle + \boxed{\star}\,|\psi_c\rangle$$

$$|\chi_1\rangle = \underline{\star}\,|\chi_a\rangle + \overline{\star}\,|\chi_b\rangle + \boxed{\star}\,|\chi_c\rangle$$

$$|\psi_2\rangle = \underline{\circ}\,|\psi_a\rangle + \overline{\circ}\,|\psi_b\rangle + \boxed{\circ}\,|\psi_c\rangle$$

$$|\chi_2\rangle = \underline{\circ}\,|\chi_a\rangle + \overline{\circ}\,|\chi_b\rangle + \boxed{\circ}\,|\chi_c\rangle$$

$$|\psi_3\rangle = \underline{\heartsuit}\,|\psi_a\rangle + \overline{\heartsuit}\,|\psi_b\rangle + \boxed{\heartsuit}\,|\psi_c\rangle$$

$$|\chi_3\rangle = \underline{\heartsuit}\,|\chi_a\rangle + \overline{\heartsuit}\,|\chi_b\rangle + \boxed{\heartsuit}\,|\chi_c\rangle$$

$$\langle\psi_i|\psi_j\rangle = \delta_{ij} \qquad \langle\chi_i|\chi_j\rangle = \delta_{ij}$$

$$\langle \psi_i | x_j \rangle \neq 0 \,(!)$$

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$$\begin{bmatrix} \langle \psi_1 | x_1 \rangle & \langle \psi_1 | x_2 \rangle & \langle \psi_1 | x_3 \rangle \\ \langle \psi_2 | x_1 \rangle & \langle \psi_2 | x_2 \rangle & \langle \psi_2 | x_3 \rangle \\ \langle \psi_3 | x_1 \rangle & \langle \psi_3 | x_2 \rangle & \langle \psi_3 | x_3 \rangle \end{bmatrix}$$

$$\langle \psi_i | x_j \rangle \neq 0 \,(!)$$

$$\begin{bmatrix} \langle \psi_1|x_1\rangle & \langle \psi_1|x_2\rangle & \langle \psi_1|x_3\rangle \\ \langle \psi_2|x_1\rangle & \langle \psi_2|x_2\rangle & \langle \psi_2|x_3\rangle \\ \langle \psi_3|x_1\rangle & \langle \psi_3|x_2\rangle & \langle \psi_3|x_3\rangle \end{bmatrix}$$

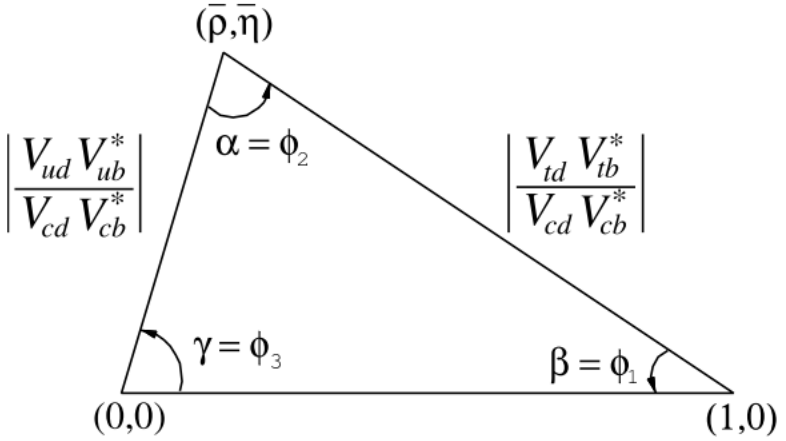
UNITARY MATRIX

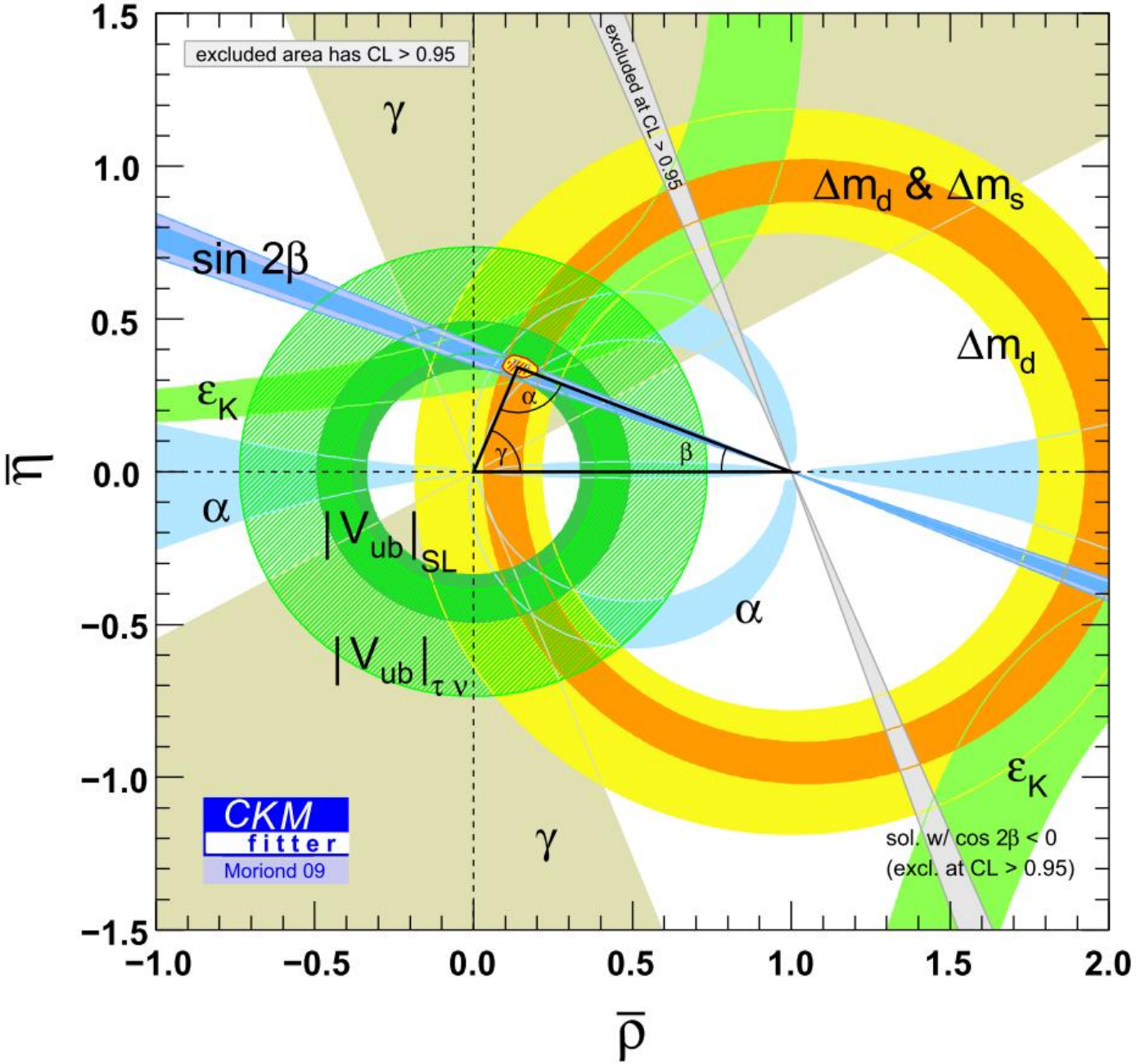
$U^\dagger U = I$

→ POWERFUL STATEMENT !

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

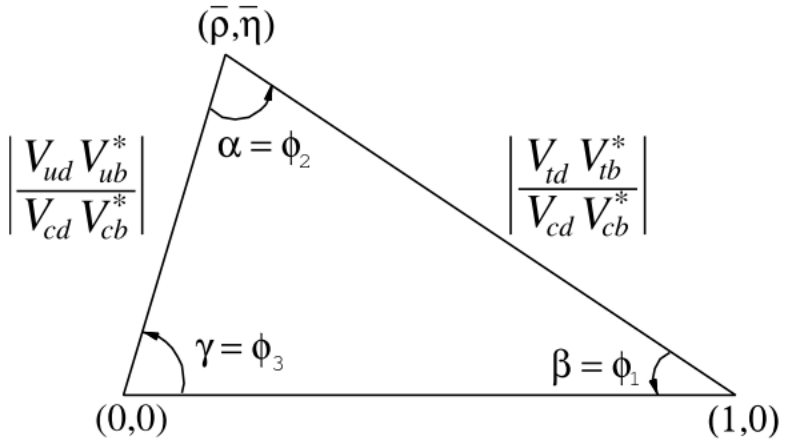



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
|V_ub|_SL
α
|V_ub|_τν
ε_K
CKM fitter
Moriond 09
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2+\frac{1}{2}A\lambda^4\left(1-2(\rho+i\eta)\right) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}+\mathcal{O}(\lambda^5)$$

$$\lambda = 0.2272 \pm 0.0010,\ A = 0.818^{+0.007}_{-0.017},\ \rho = 0.221^{+0.064}_{-0.028},\ \eta = 0.340^{+0.017}_{-0.045}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$$\begin{bmatrix} 1 & \lambda & A\lambda^3 \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3 & -A\lambda^2 & 1 \end{bmatrix}$$

$\lambda \sim 0.23$, $A \sim 0.81$

Lepton mixing matrix

$$\begin{bmatrix} 0.822 & 0.547 & -0.150 + 0.0381\mathrm{i} \\ -0.356 + 0.0198\mathrm{i} & 0.704 + 0.0131\mathrm{i} & 0.614 \\ 0.442 + 0.0248\mathrm{i} & -0.452 + 0.0166\mathrm{i} & 0.774 \end{bmatrix}$$

No easy parametrization,

no pattern

- Three (near-)replicas of matter
- No clear mass hierarchies
- ψ_3 ridiculously massive
- Approximate pattern in quark mixing
- No pattern in lepton mixing

- Three (near-)replicas of matter
- No clear mass hierarchies
- ψ_3 ridiculously massive
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+ Neutrinos [WTF is up with them?]

- Three (near-)replicas of matter
- No clear mass hierarchies
- ψ_3 ridiculously massive
- Approximate pattern in quark mixing
- No pattern in lepton mixing

+ Neutrinos [WTF is up with them?]

+ Why no CP violation in strong interaction?

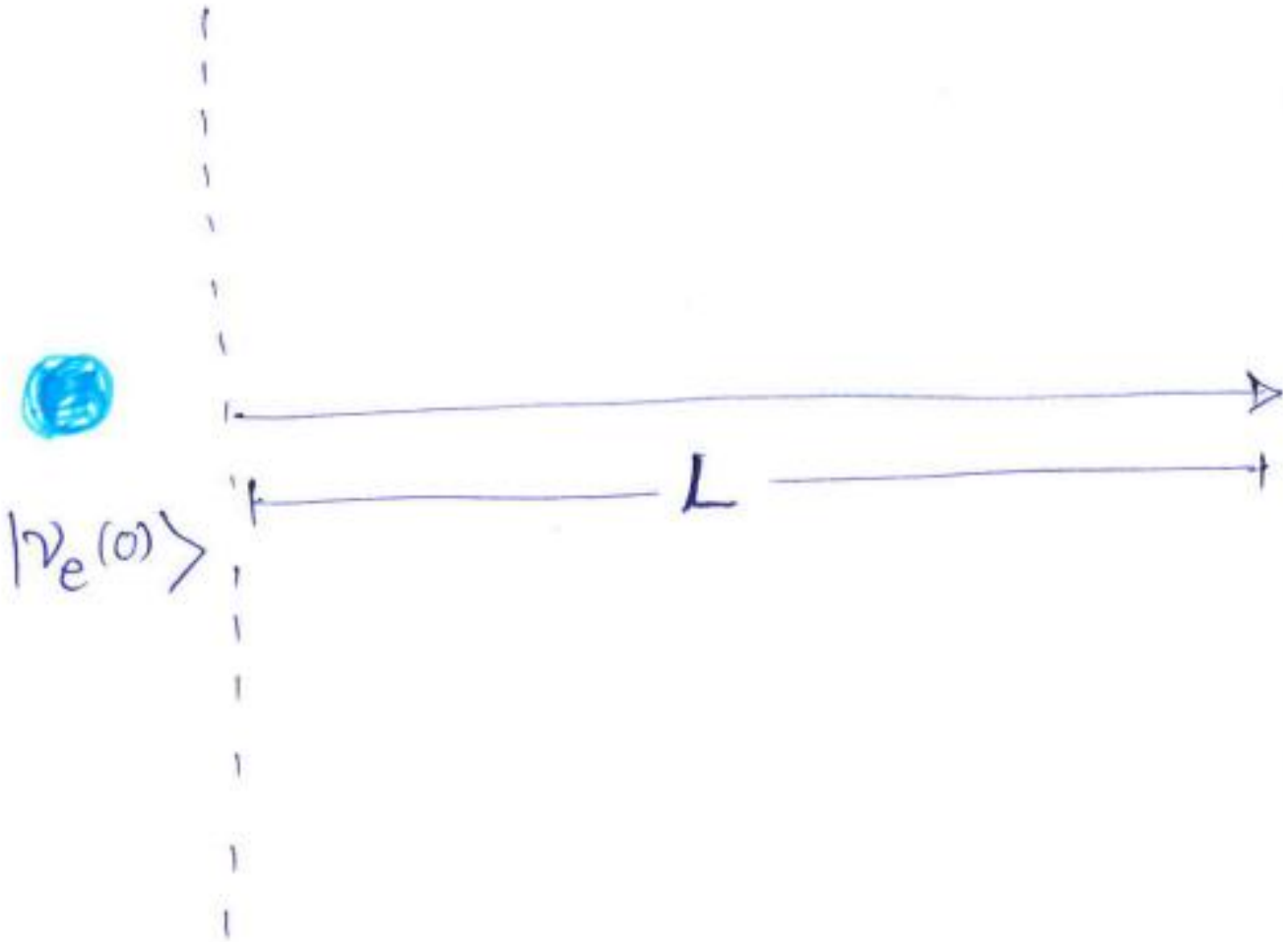
And that's the flavour puzzle

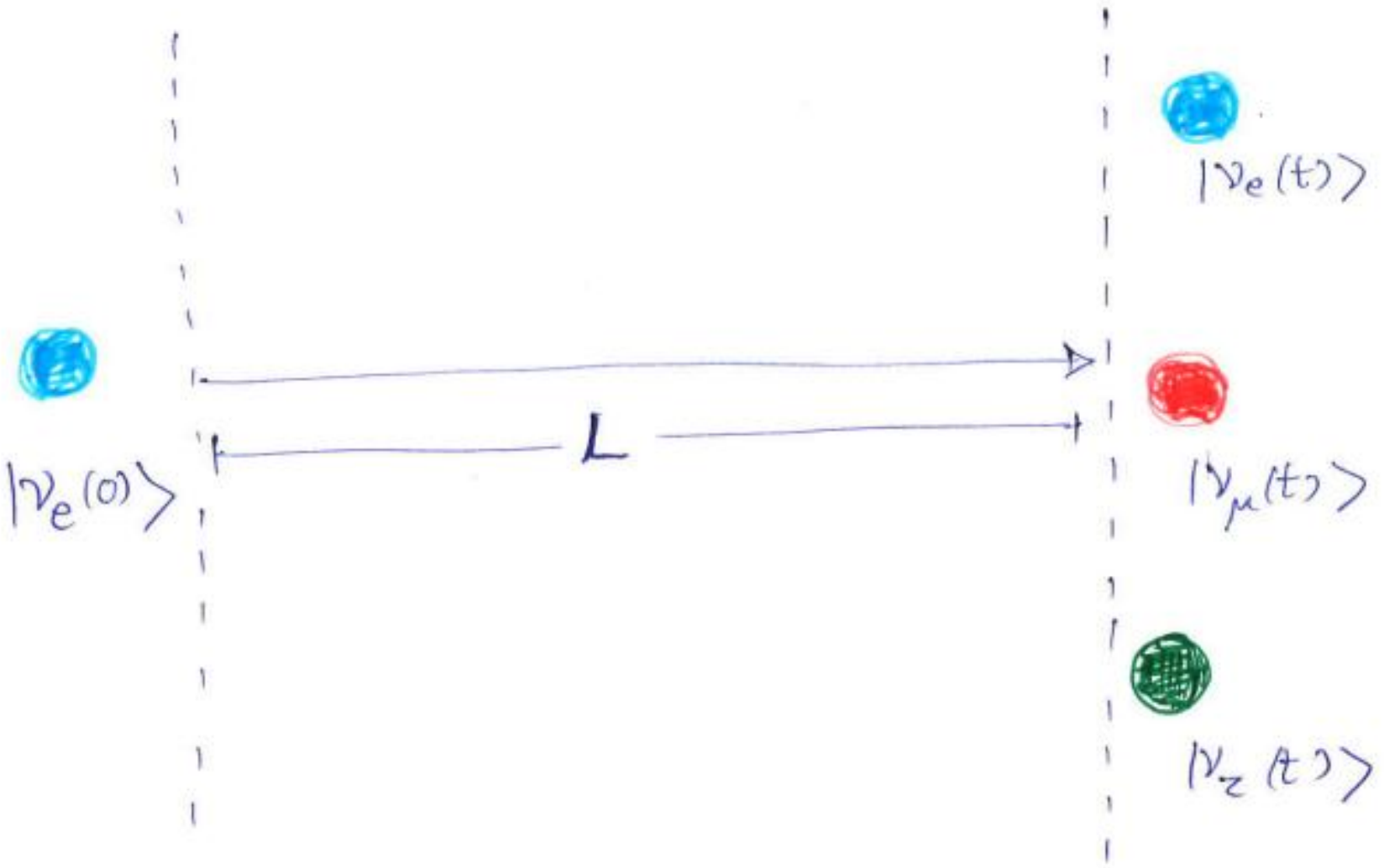
Has it *helped*?

Has it *helped*?

Yes – (i) in establishing neutrinos have mass

$|\nu_e(0)\rangle$


L
$|\nu_e(0)\rangle$


$|\nu_e(t)\rangle$
L
$|\nu_e(0)\rangle$
$|\nu_\mu(t)\rangle$
$|\nu_\tau(t)\rangle$

$$|\nu_e(0)\rangle = \alpha_1^e |\nu_1(0)\rangle + \alpha_2^e |\nu_2(0)\rangle + \alpha_3^e |\nu_3(0)\rangle$$

$$|\nu_e(0)\rangle = \alpha_1^e |\nu_1(0)\rangle + \alpha_2^e |\nu_2(0)\rangle + \alpha_3^e |\nu_3(0)\rangle$$

$$|\nu_{1,2,3}(t)\rangle = e^{-i m^2_{1,2,3} L/2E} |\nu_{1,2,3}(0)\rangle$$

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$$|\nu_{1,2,3}(t)\rangle = e^{-i m^2_{1,2,3} L/2E} |\nu_{1,2,3}(0)\rangle$$

AT OTHER END,

$$\alpha_1^e(t)\,|\nu_1(0)\rangle + \alpha_2^e(L)\,|\nu_2(0)\rangle + \alpha_3^e(L)\,|\nu_3(0)\rangle$$

$$= \beta_e |\nu_e(L)\rangle + \beta_\mu |\nu_\mu(L)\rangle + \beta_\tau |\nu_\tau(L)\rangle$$

$$|\nu_e(0)\rangle = \alpha_1^e |\nu_1(0)\rangle + \alpha_2^e |\nu_2(0)\rangle + \alpha_3^e |\nu_3(0)\rangle$$

$$|\nu_{1,2,3}(t)\rangle = e^{-i m^2_{1,2,3} L/2E} |\nu_{1,2,3}(0)\rangle$$

AT OTHER END,

$$\alpha_1^e(t)\,|\nu_1(0)\rangle + \alpha_2^e(L)\,|\nu_2(0)\rangle + \alpha_3^e(L)\,|\nu_3(0)\rangle$$

$$= \beta_e |\nu_e(L)\rangle + \beta_\mu |\nu_\mu(L)\rangle + \beta_\tau |\nu_\tau(L)\rangle$$

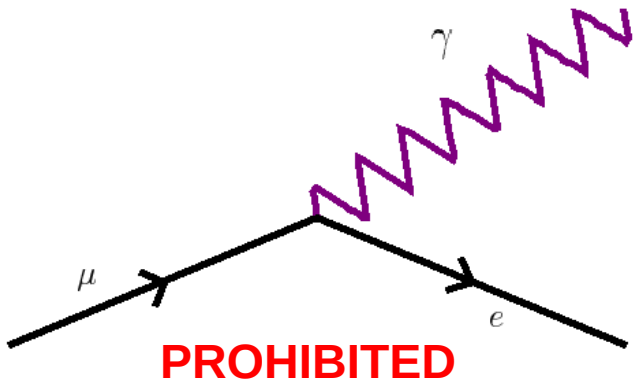
$$P(e \to \star) = |\langle \nu_e(0) | \nu_\star(L)\rangle|^2 = |\beta_\star|^2$$

Has it *helped*?

Yes – (i) in establishing neutrinos have mass

(ii) in probing for "new physics" ($< 10^{-18}$ m)

$\langle \psi_i | \psi_j \rangle = \delta_{ij}$ $\langle x_i | x_j \rangle = \delta_{ij}$ $\langle \psi_i | x_j \rangle \neq 0$



PROHIBITED

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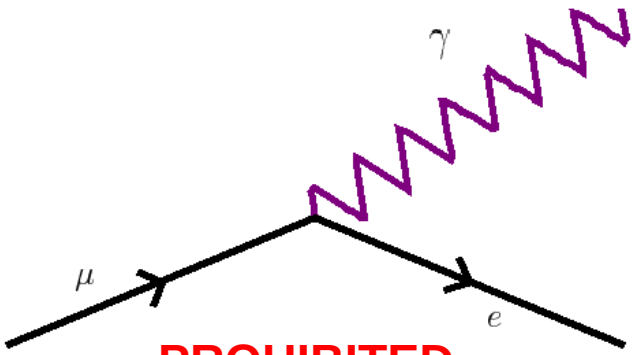

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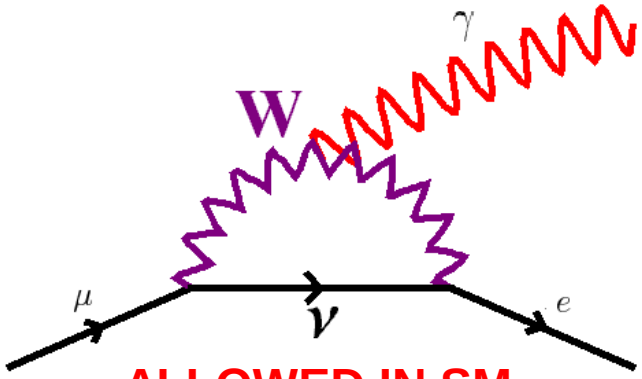
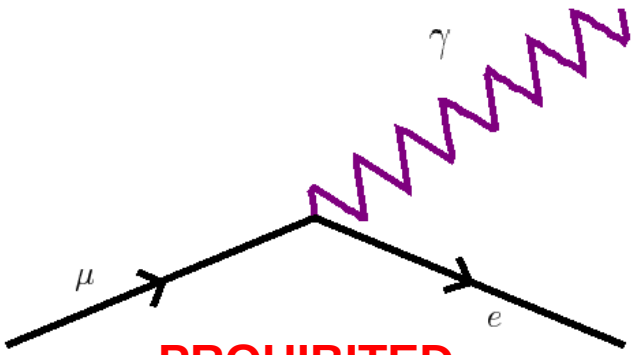


ALLOWED IN SM

SM prediction:
BR ~ 10^{-40}

$\langle \psi_i | \psi_j \rangle = \delta_{ij}$ $\langle \chi_i | \chi_j \rangle = \delta_{ij}$ $\langle \psi_i | \chi_j \rangle \neq 0$



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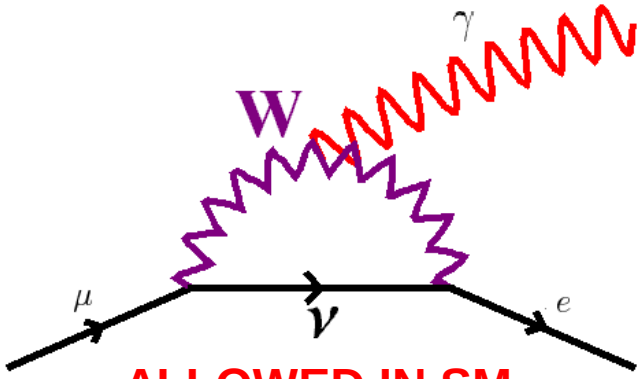
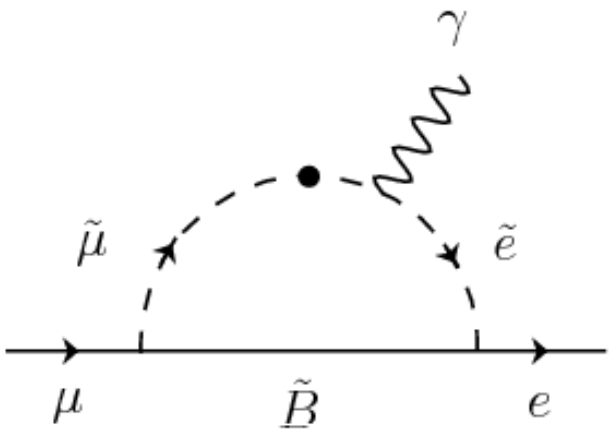


ALLOWED IN SM

SM prediction:
BR ~ 10^{-40}

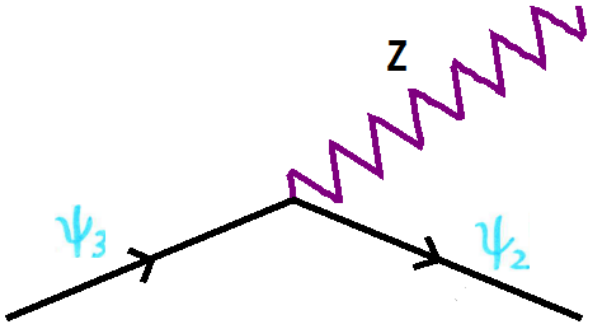


BEYOND SM

MEG Limit:
BR < 5.7 x 10^{-13}

LHC limits

$\langle \psi_i | \psi_j \rangle = \delta_{ij}$ $\langle \chi_i | \chi_j \rangle = \delta_{ij}$ $\langle \psi_i | \chi_j \rangle \neq 0$



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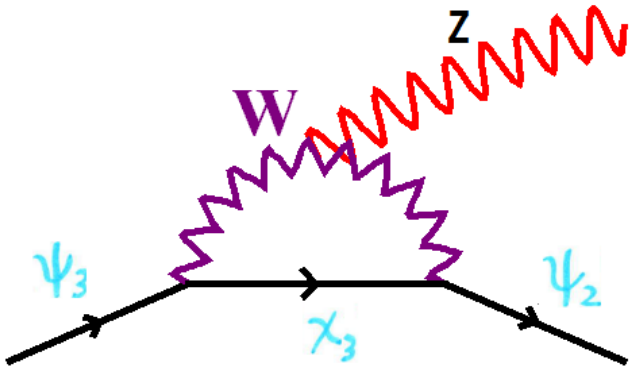


ALLOWED IN SM

SM prediction: BR ~ 10^{-14}

CMS: BR < 5 x 10^{-4} ; ATLAS: BR < 7.3 x 10^{-3}

Has it *helped*?

Yes – (i) in establishing neutrinos have mass

(ii) in probing for "new physics" ($< 10^{-18}$ m)

(iii) in constraining (=enhancing) imagination of model-builders

Wait, are you sure there's just three?

Guesses?

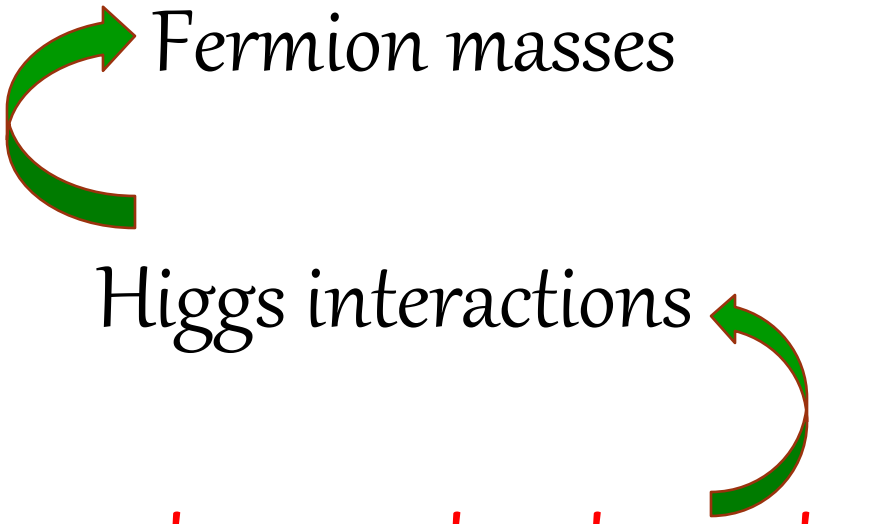
Guesses?

Microscopic phenomena

(0)

Something is profoundly sick
in our understanding of
quantum fields

(1)



[Disclaimer: Doesn't answer 'Why three?']

(1)

Perturbative expansion

Something in the ultraviolet

[Disclaimer: Doesn't answer 'Why three?']

(1)

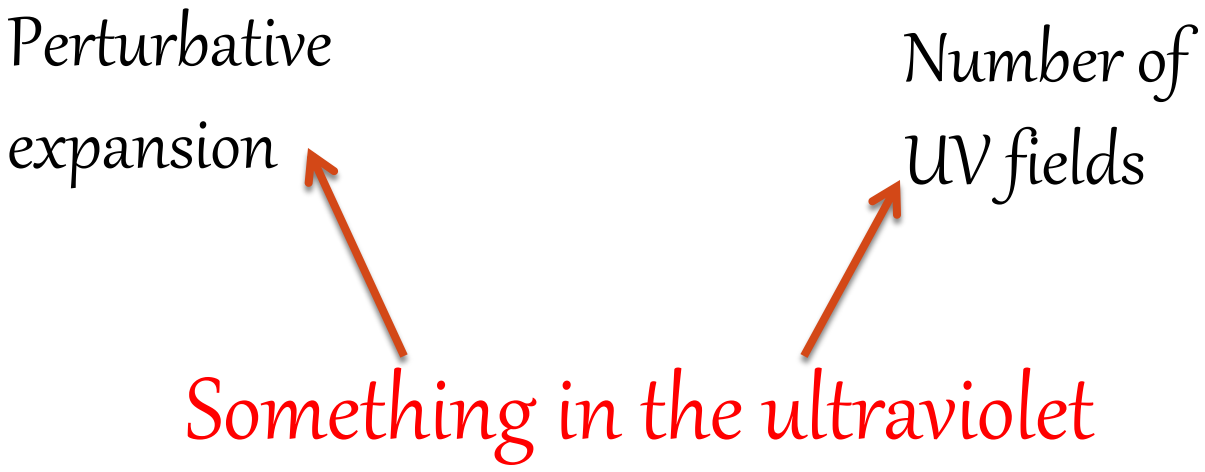
Matthew Baumgart
04.00 pm, June 03 2014
ITS Seminar Room

Perturbative expansion

Something in the ultraviolet

[Disclaimer: Doesn't answer 'Why three?']

(1)



[Disclaimer: Doesn't answer 'Why three?']

(2)

Symmetry principle

Flavour force

(1) and (2) keys that open just the flavour lock

(Sub)master keys?

(3)
Russian dolls

(3)

~~Russian dolls~~

(4)
Trinify

(5)
Strings

(6)
Anthropics?

(6)

Anthropics?

Nah.

How may we probe the mystery?

The LHC?

Bigger microscopes!

LORD OF THE RINGS

Physicists are discussing a proton-colliding machine that would dwarf the energy of its predecessors.

Very Large Hadron Collider (suggested)
100 km
100 TeV*

Large Hadron Collider
27 km
14 TeV

Tevatron (closed)
Circumference: **6.3 km**
Energy: **2 TeV**

*TeV, teraelectronvolt.

Final words

Flavour: 21 out of 26 Standard Model parameters.

12 fermion masses
+
03 quark mixing angles
+
01 quark CP violation phase
+
03 lepton mixing angles
+
01 lepton CP violation phase
+
01 strong CP violation phase

Where do these come from?

And **why three**?!

Quark names

http://xkcd.com/474/