the standard model!

splash 2019
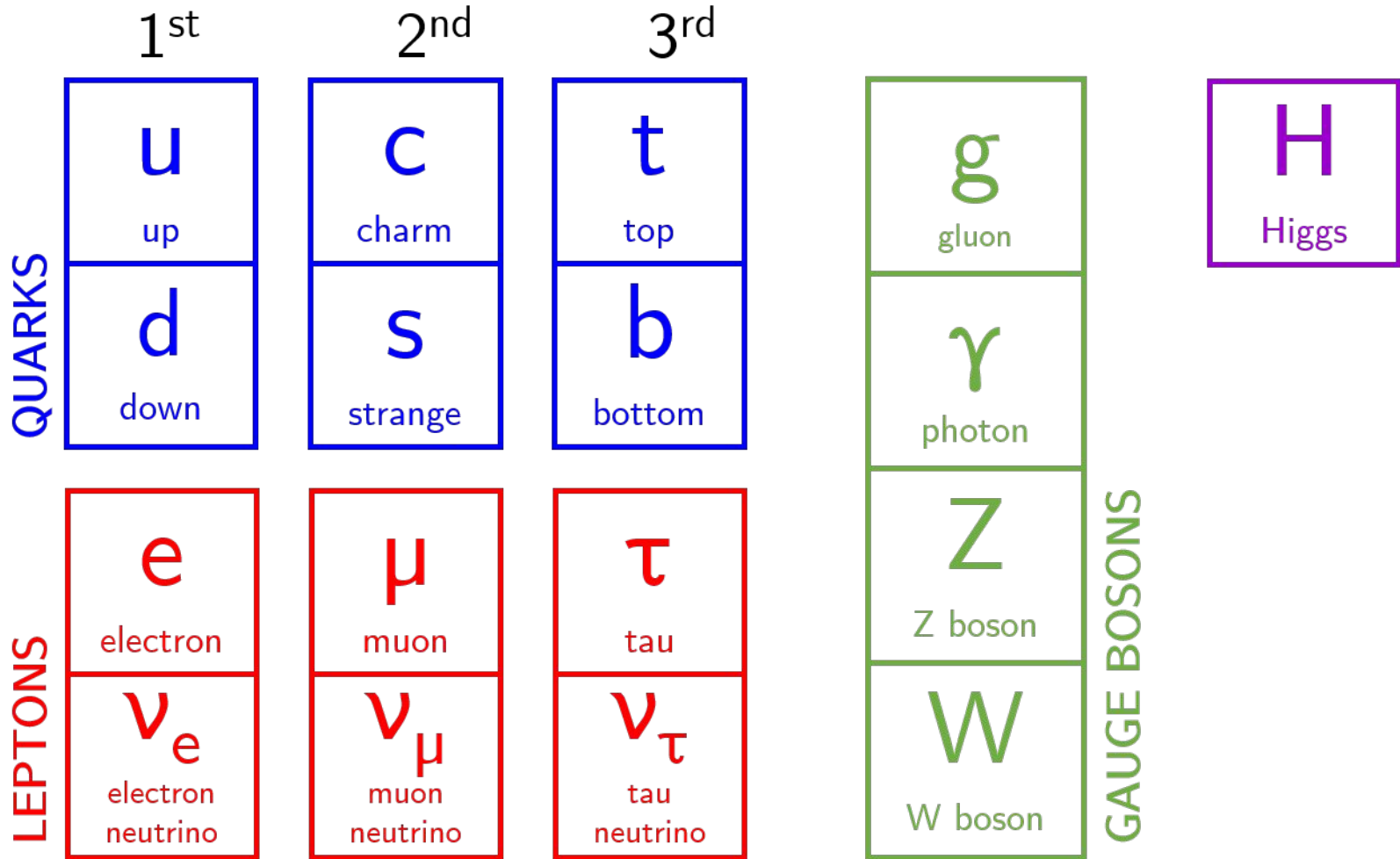
$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h -$$
$$g\alpha_h M(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) -$$
$$\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H -$$
$$\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\tfrac{1}{4}g^2 W^+_\mu W^-_\mu(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-) -$$
$$\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s \lambda^a_{ij}(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial +$$
$$m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa -$$
$$\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) +$$
$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu \bar{X}^0 X^- -$$
$$\partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu \bar{Y}X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu \bar{X}^- X^0 -$$
$$\partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu \bar{X}^+ X^+ -$$
$$\partial_\mu \bar{X}^- X^-) + igs_w A_\mu(\partial_\mu \bar{X}^+ X^+ -$$
$$\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) +$$
$$\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) +$$
$$\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).$$

the standard model
(according to some people)
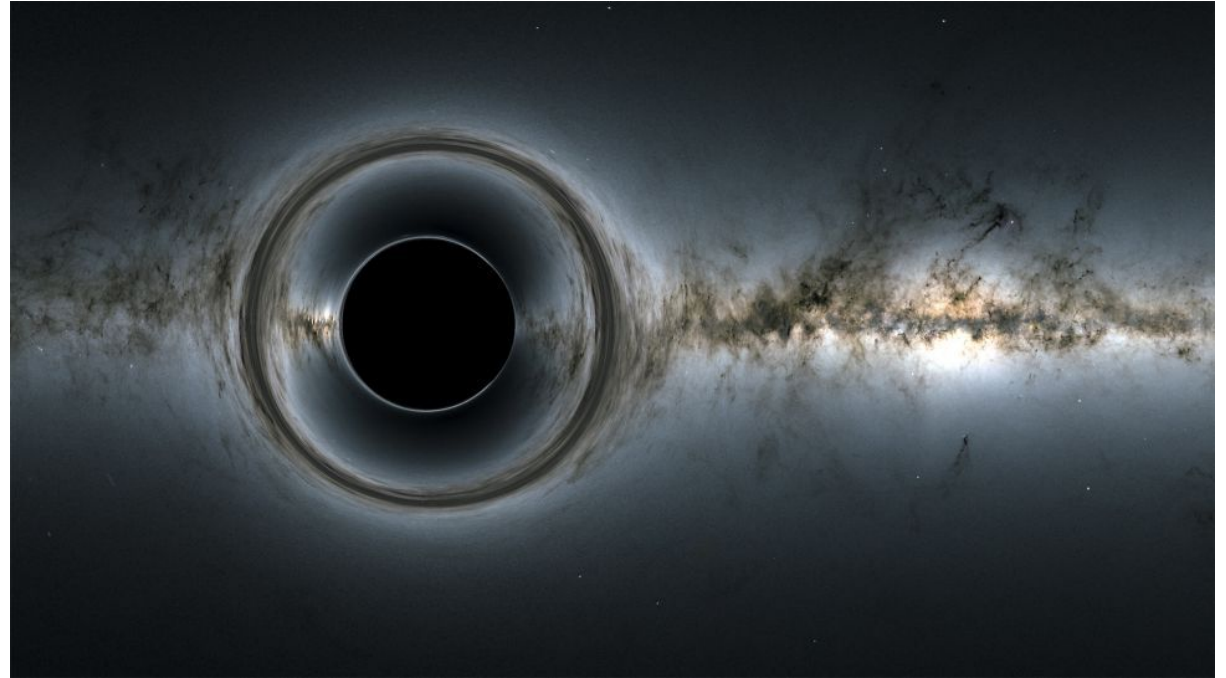
the standard model
(according to other people)

	1st	2nd	3rd		
QUARKS	u up	c charm	t top	g gluon	H Higgs
	d down	s strange	b bottom	γ photon	
LEPTONS	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	**GAUGE BOSONS**

	1st	2nd	3rd

QUARKS

u	c	t
up	charm	top
d	s	b
down	strange	bottom

LEPTONS

e	μ	τ
electron	muon	tau
ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

GAUGE BOSONS

g
gluon
γ
photon
Z
Z boson
W
W boson

H
Higgs

there are four fundamental forces.
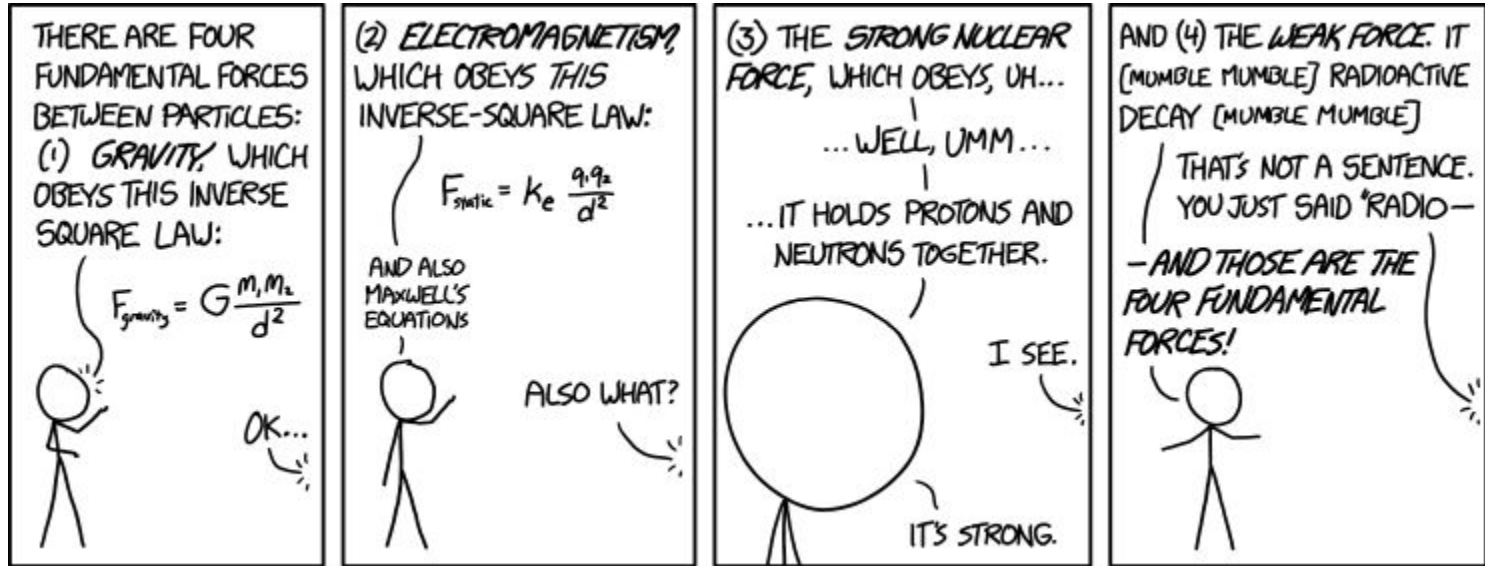
there are four fundamental forces.

#1   gravity

there are four fundamental forces.

#1   gravity

#2   electromagnetism

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#1   gravity

#2   electromagnetism
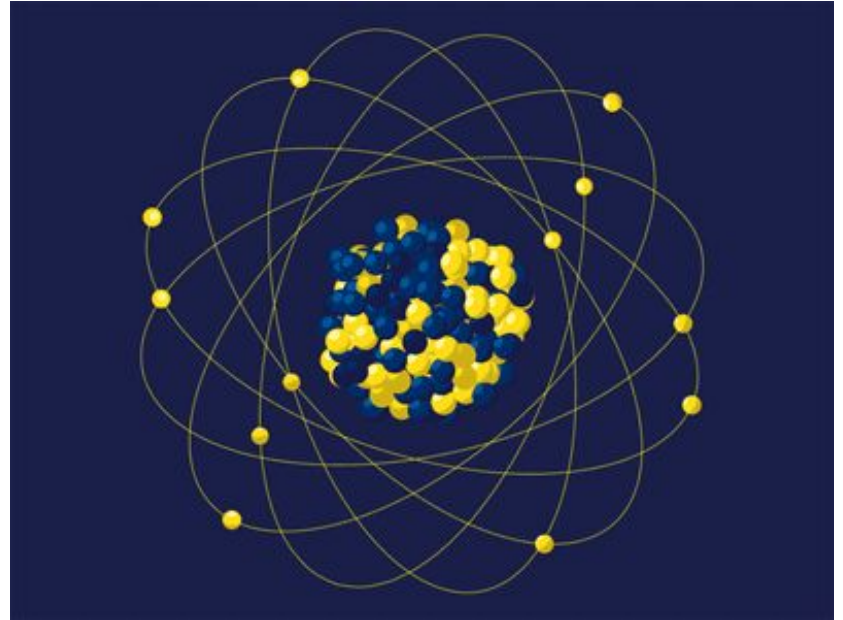
#3   strong force

there are four fundamental forces.

#1   gravity

#2   electromagnetism

#3   strong force

#4   weak force

the electromagnetic force is controlled by photons.

- ○ magnets, electrical current, light...
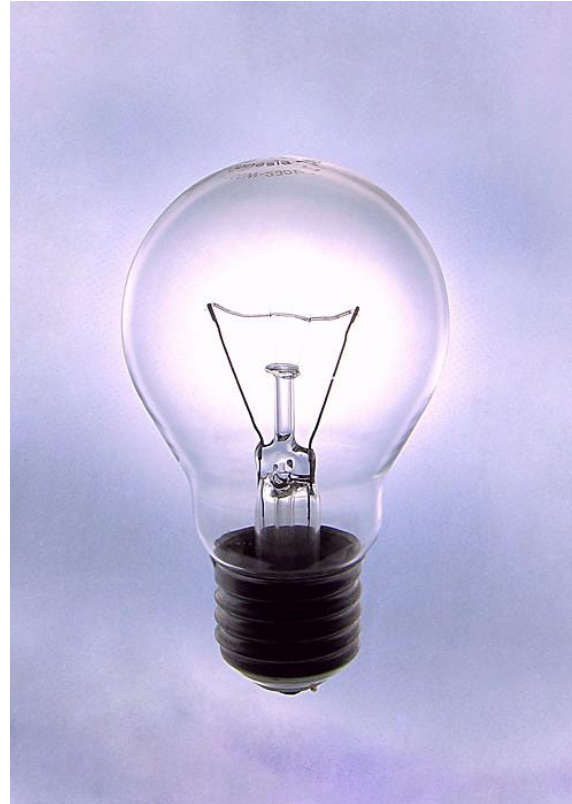
the strong force is mediated by gluons.

- ○ Holds together nuclei
- ○ Literally named after glue

the weak force is controlled by the W and Z bosons.

- radioactive decay
- doesn't form bound states, unlike gravity, electromagnetism, and the strong force (really more of an interaction)

gravity is... controlled by... uh...

1st 2nd 3rd

QUARKS

| u up | c charm | t top |
| d down | s strange | b bottom |

LEPTONS

| e electron | μ muon | τ tau |
| ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino |

GAUGE BOSONS

g gluon

γ photon

Z Z boson

W W boson

H Higgs
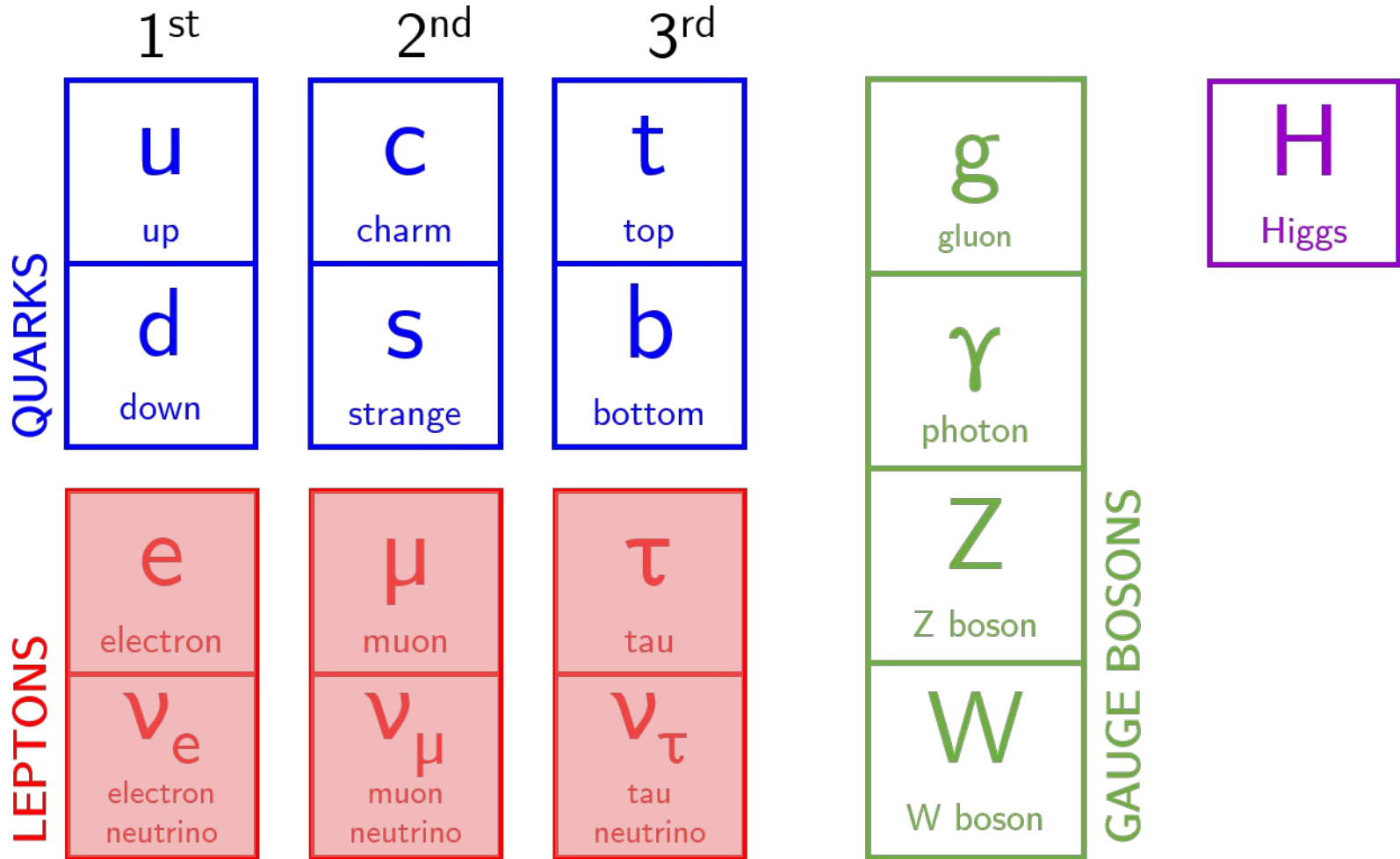
leptons are particles *unaffected* by the strong force.

there are **6 flavors** of lepton

    electron, muon, tau, and three types of neutrino

there are **charged** and **neutral** leptons

    charged leptons combine with things (c.f. atoms)

muons and **taus** decay rapidly into other leptons

    only seen in cosmic rays and particle accelerators

how do you observe muons and taus?

Incoming Cosmic Ray

KEY

P	Proton	e	Electron
n	Neutron	μ	Muon
π	Pion	γ	Photon

primary cosmic ray from interstellar space interacts with air nucleus

how do you observe muons and taus?

primary cosmic ray from interstellar space interacts with air nucleus
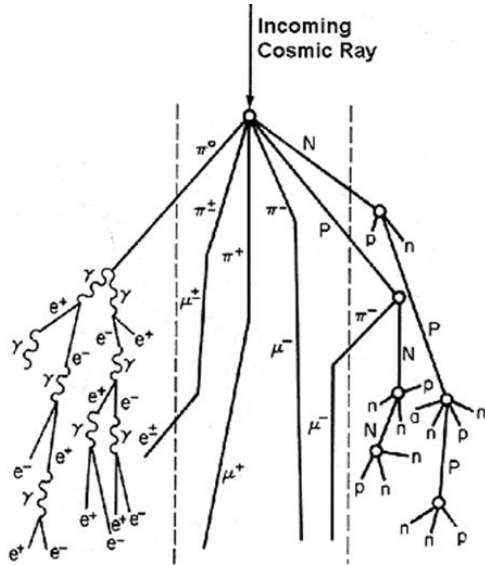
generates a cascade of high-energy interactions, producing hadrons

KEY

P	Proton	e	Electron
n	Neutron	μ	Muon
π	Pion	γ	Photon

how do you observe muons and taus?

primary cosmic ray from interstellar space interacts with air nucleus

generates a cascade of high-energy interactions, producing hadrons

something made of quarks

how do you observe muons and taus?

primary cosmic ray from interstellar space interacts with air nucleus

generates a cascade of high-energy interactions, producing hadrons

cosmic rays that we measure are leptons (and gamma rays)

how do you observe muons and taus?
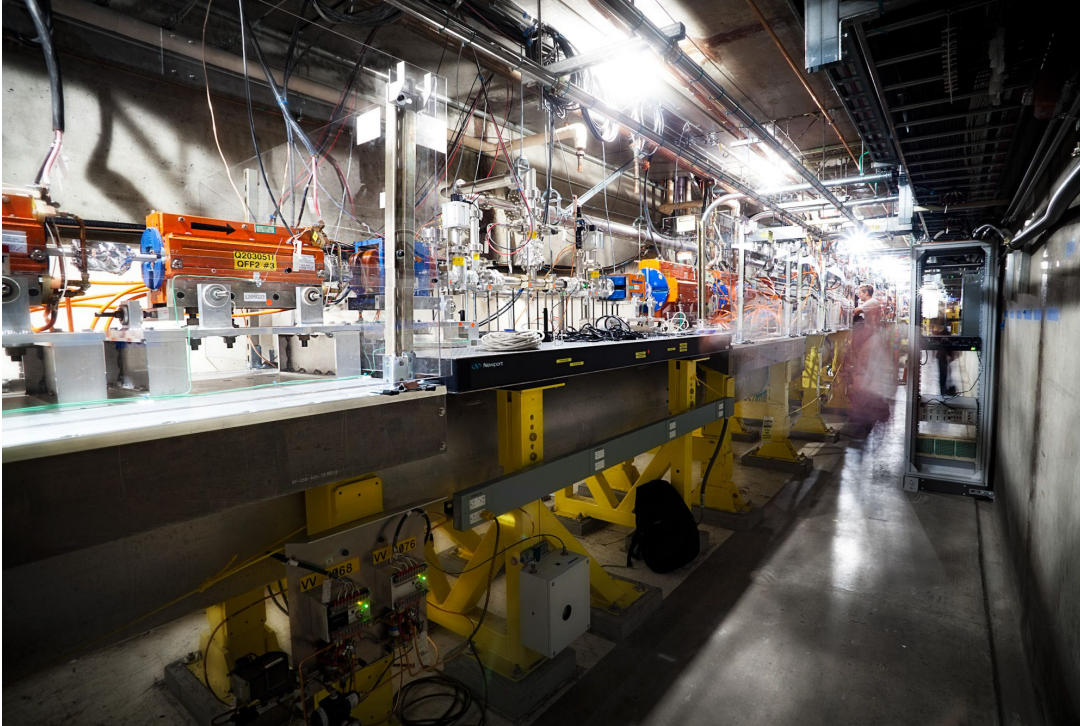
smash things together!
$$e^+ + e^- \longrightarrow \tau^+ + \tau^-$$

SLAC beamline.

the og lepton is the electron

j j thomson discovered them
    cathode ray experiment found really light, charged particles

they're (shocker!!) in atoms
    understanding electrons in **hydrogen** $\rightarrow$ quantum mechanics

de broglie suggested that **matter can be waves**
    verified with electrons!
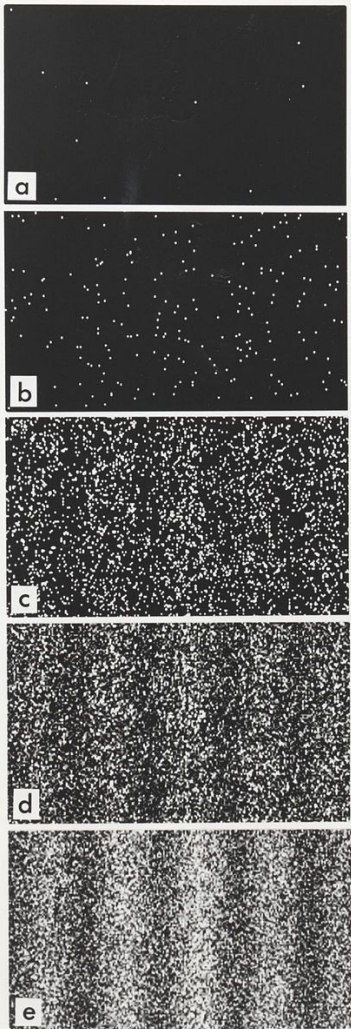
Above: The Jefferson Lab electron accelerator.

Left: The double-slit experiment, with electrons!

neutrinos are the most abundant massive particles!

1000 trillion neutrinos pass through your body every second!
they come in three flavors and they're neutral
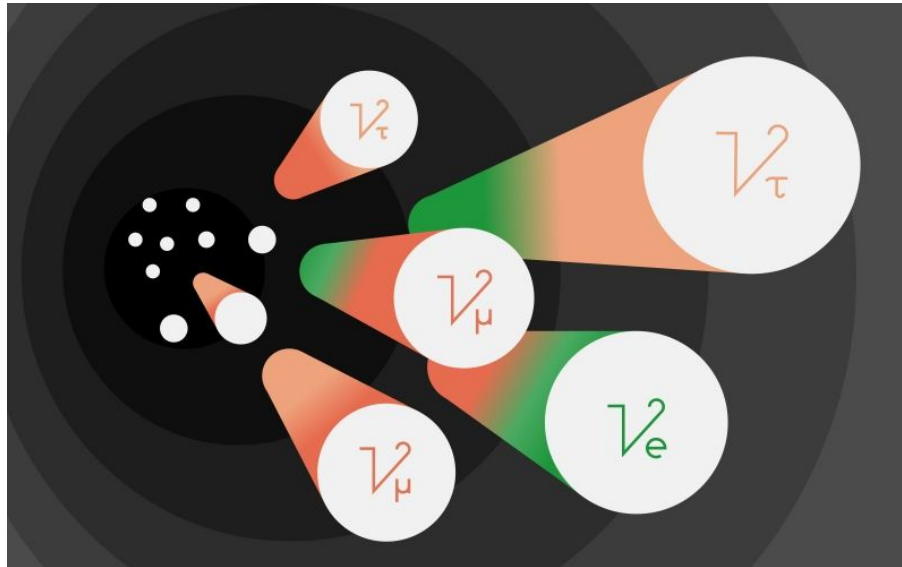
neutrinos are the most abundant massive particles!

1000 trillion neutrinos pass through your body every second!
    they come in three flavors and they're neutral

neutrinos are difficult to detect because they rarely interact
    they interact via **the weak force**
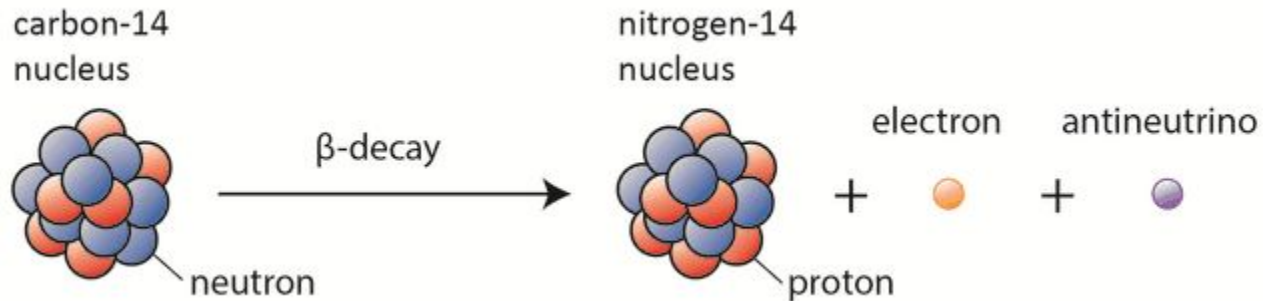
neutrinos are the most abundant massive particles!

1000 trillion neutrinos pass through your body every second!
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neutrinos are difficult to detect because they rarely interact
they interact via **the weak force**

we know there's **new physics** involved with neutrinos!
it turns out they have mass! although this mass is really tiny

where do neutrinos come from?

nuclear reactors: fission produces neutrinos
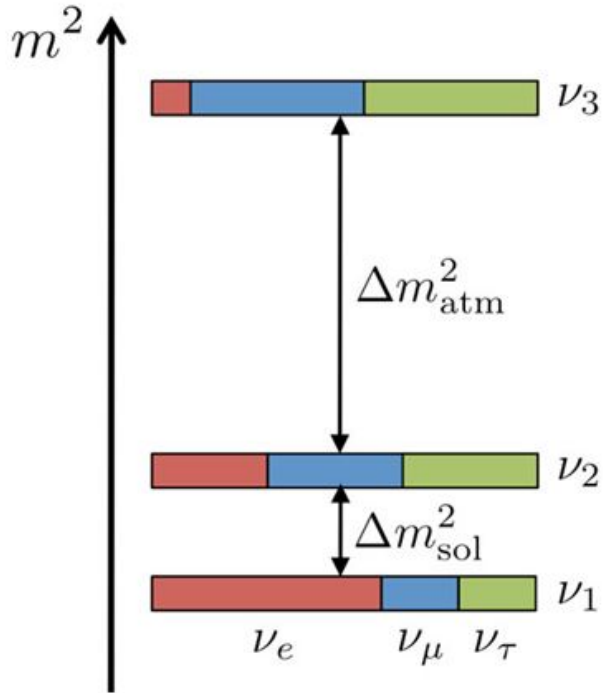
accelerators: we make neutrino beams!

cosmic rays: decays produce neutrinos

interstellar space: the big bang, supernovae, black holes?

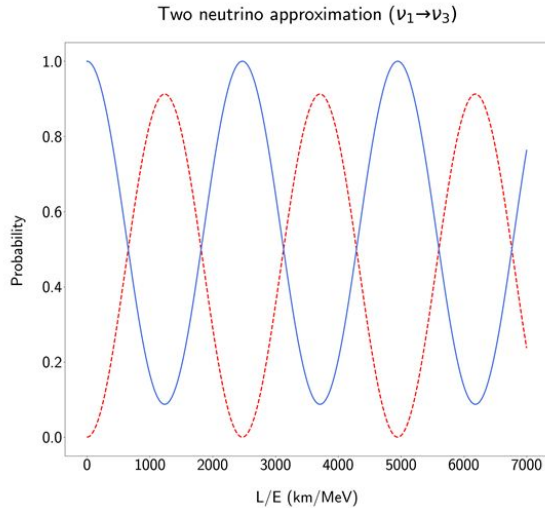**the sun:** fusion produces neutrinos — but they seemed to vanish

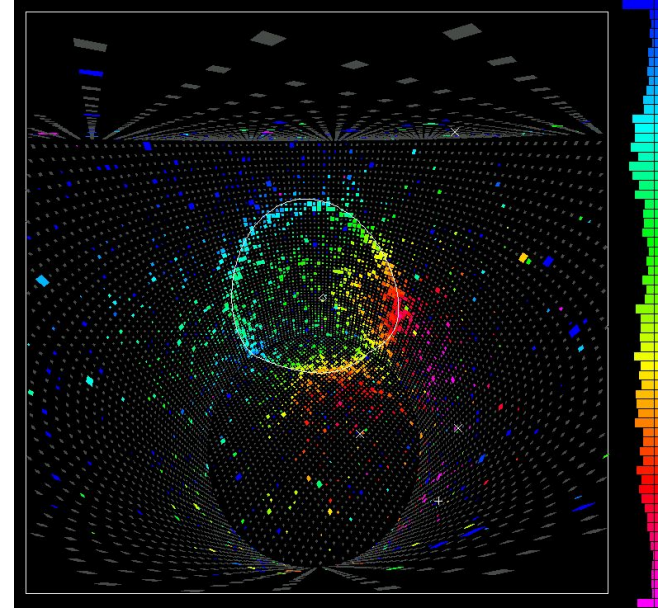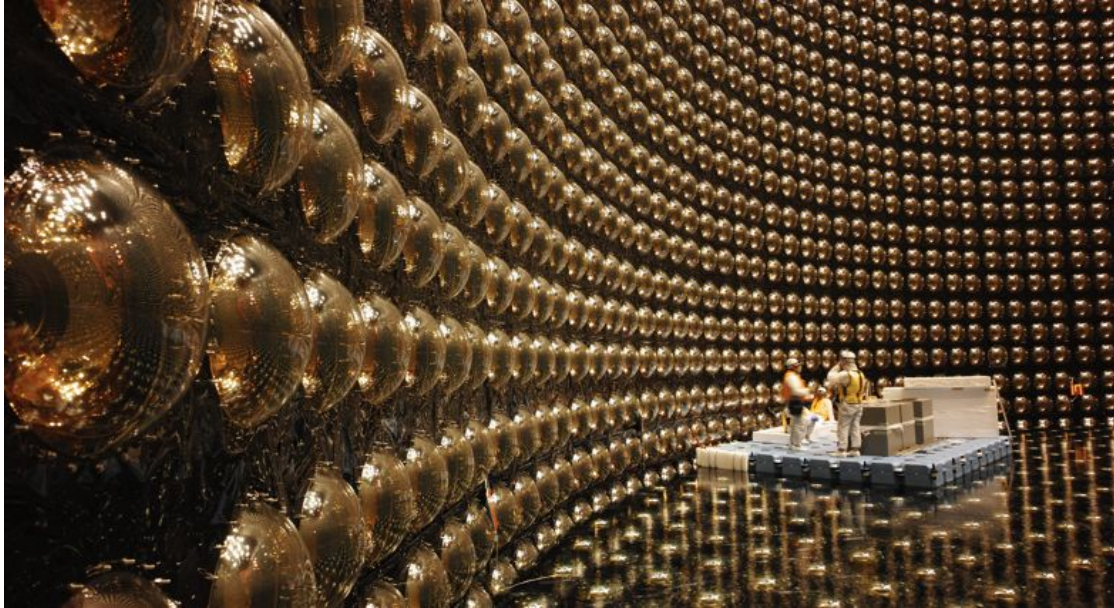|	1st	2nd	3rd	
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GAUGE BOSONS

H
Higgs
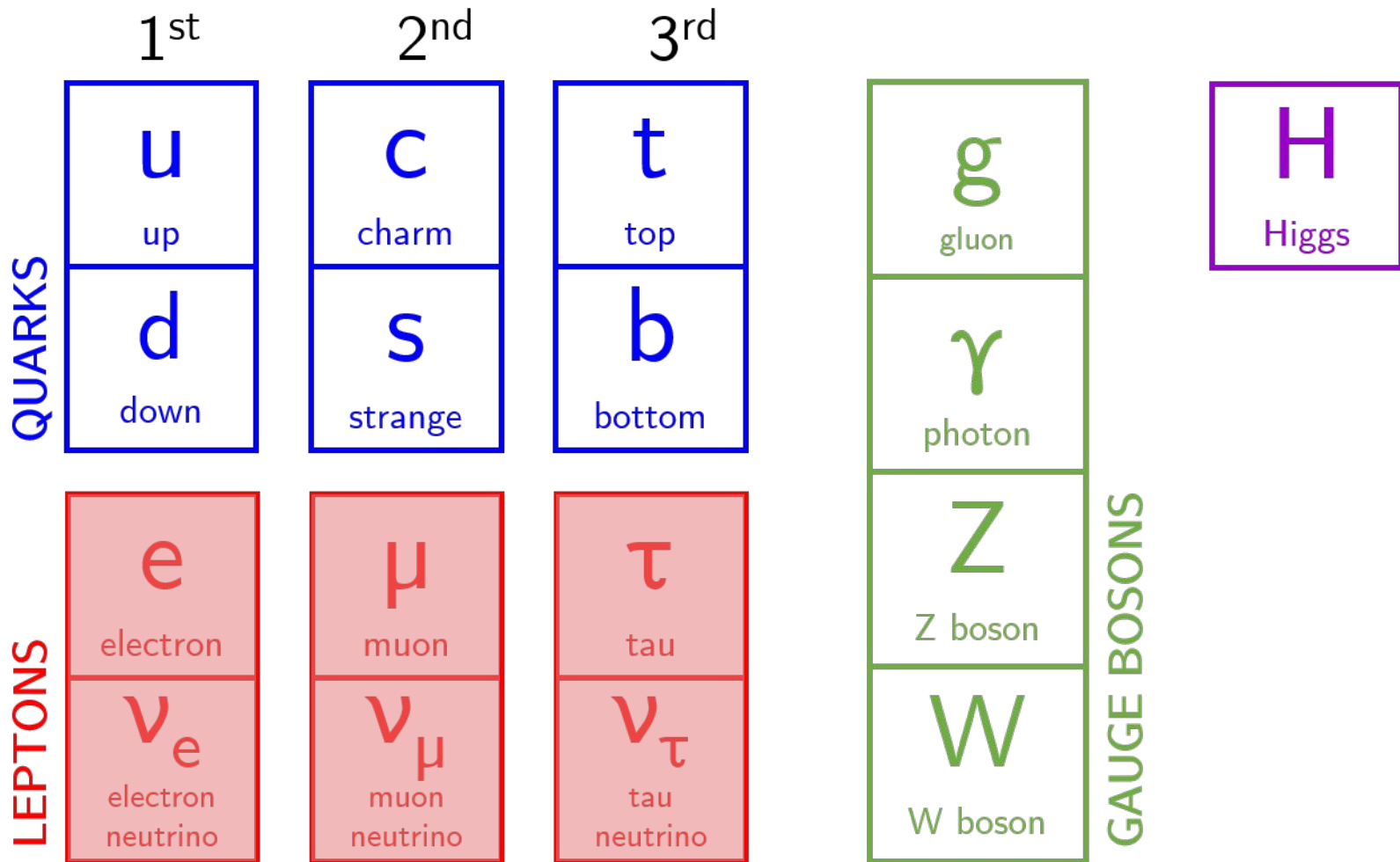
flavor isn't the best way to talk about neutrinos!
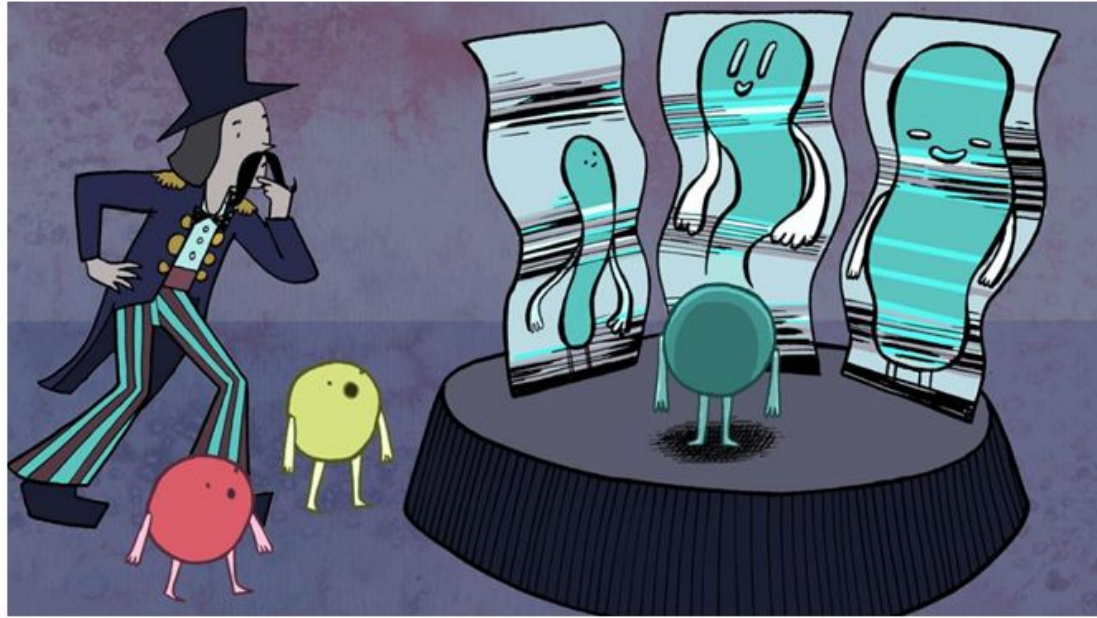
the upshot is that flavor changes.

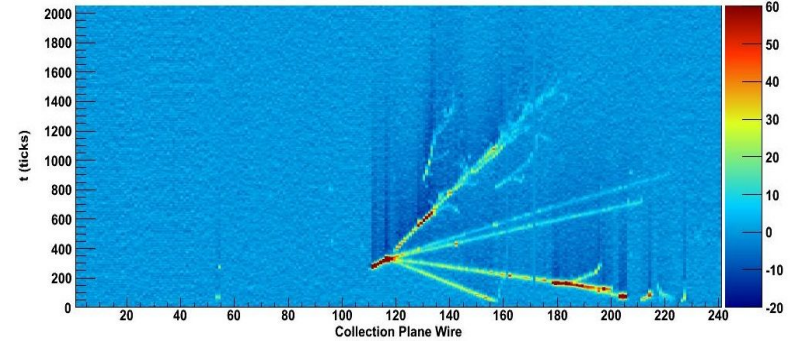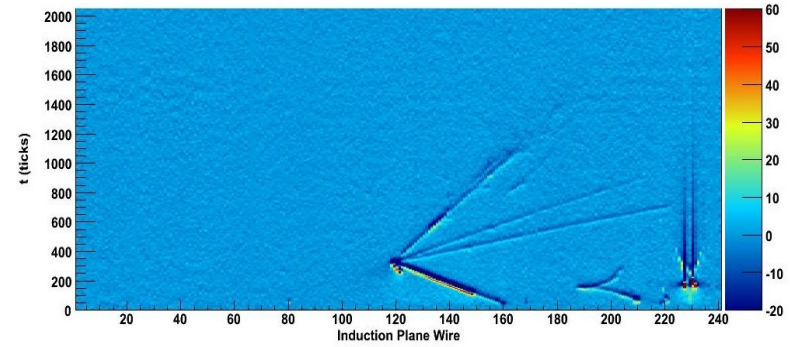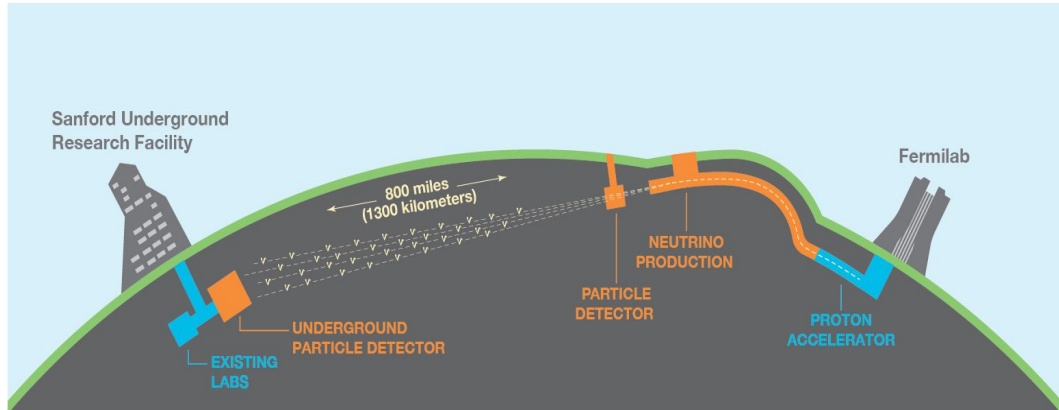$$P(\nu_\alpha \to \nu_\beta) = \underbrace{\sin^2 2\theta}_{\text{ampl.}} \underbrace{\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}_{\text{freq.}}$$
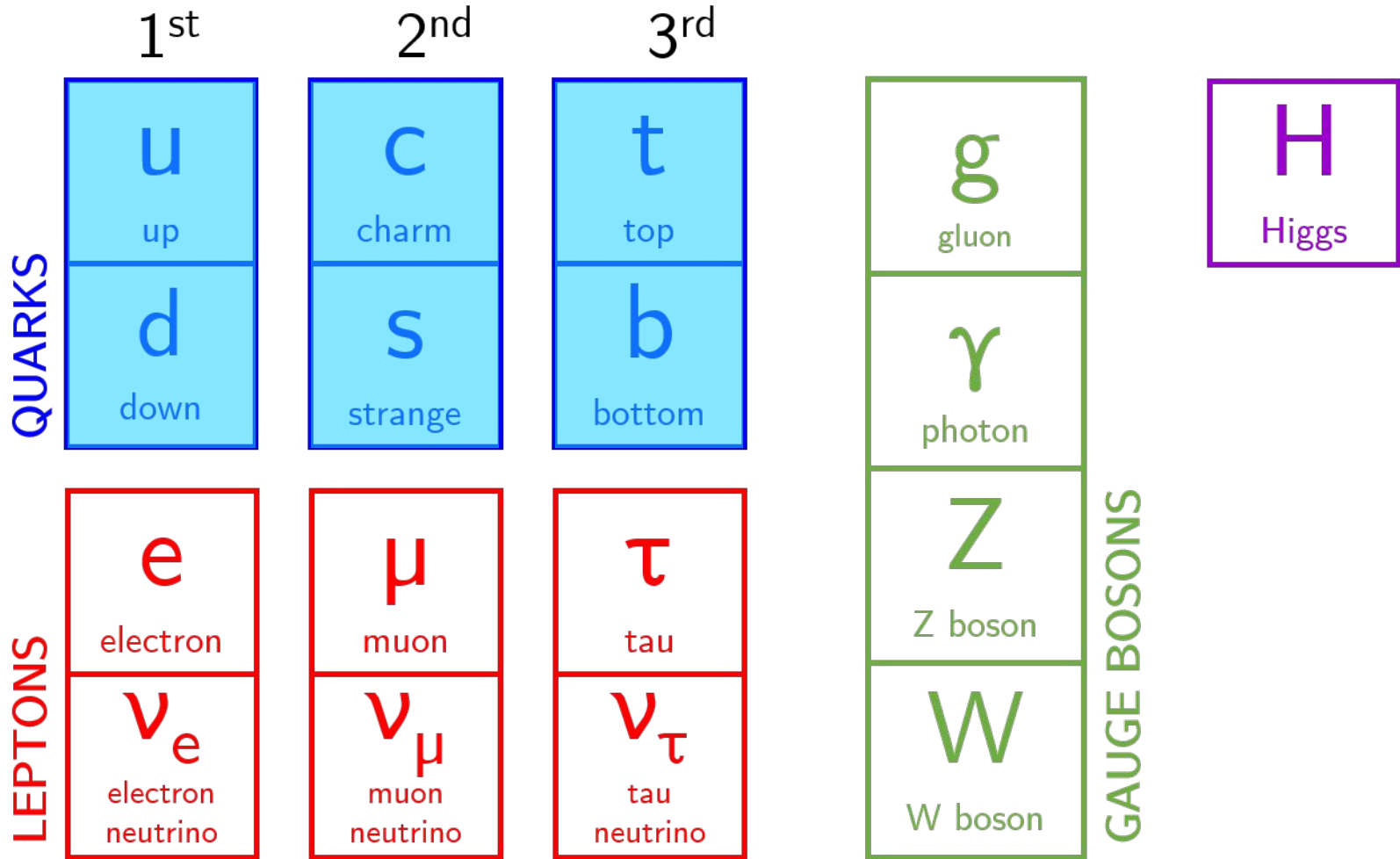

Two neutrino approximation ($\nu_1 \to \nu_3$)

oscillation experiments today

oscillation experiments today

neutrinos might be their own antiparticle!

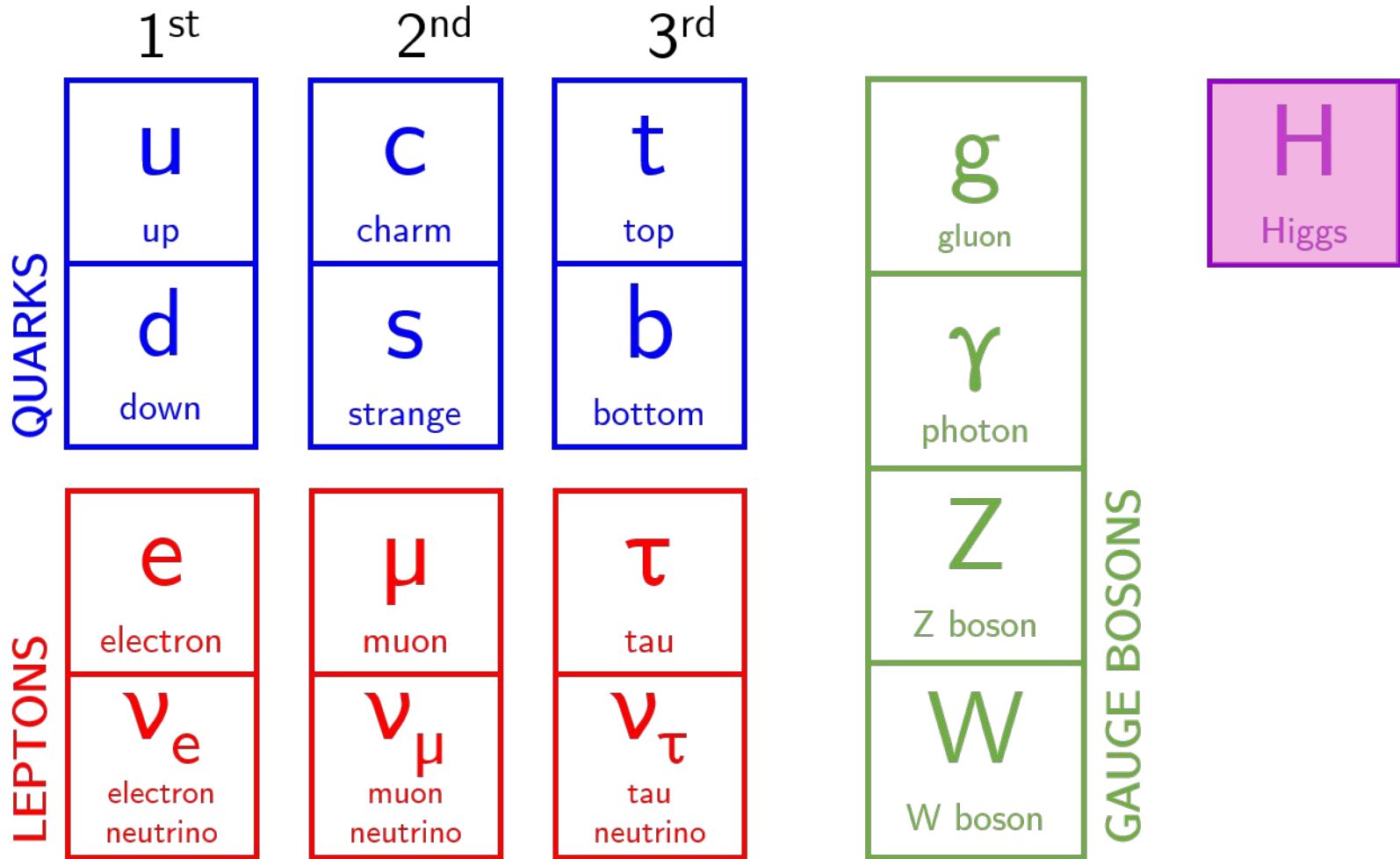|	1st	2nd	3rd		
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Quarks

there are **6 flavors** of quark
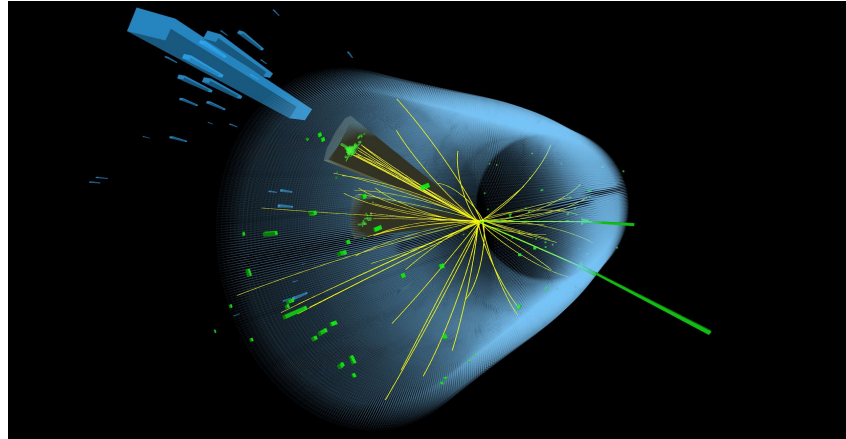
   up, down, strange, charm, top, bottom

they can change their flavor using the weak force

The Higgs Boson

is secretly **everywhere** always, giving mass to **quarks, leptons,** and **W and Z gauge bosons**
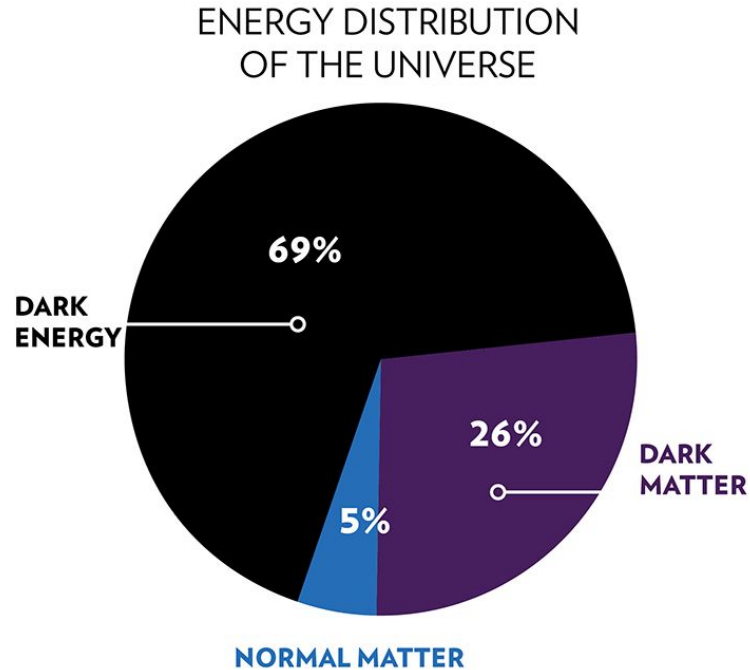
discovered at the large hadron collider in 2012!

How to Build a Universe

1. add a dash of antiparticles
2. glue together quarks to get neutrons and protons, then atoms, then stars and solar systems and people....
3. ???

but the standard model isn't the final word in physics...

ENERGY DISTRIBUTION
OF THE UNIVERSE

69%

DARK
ENERGY

26%

DARK
MATTER

5%

NORMAL MATTER

dark matter

dark energy

Theories of Everything