

3 VERY SMALL QUESTIONS

ABOUT OUR
VERY BIG UNIVERSE

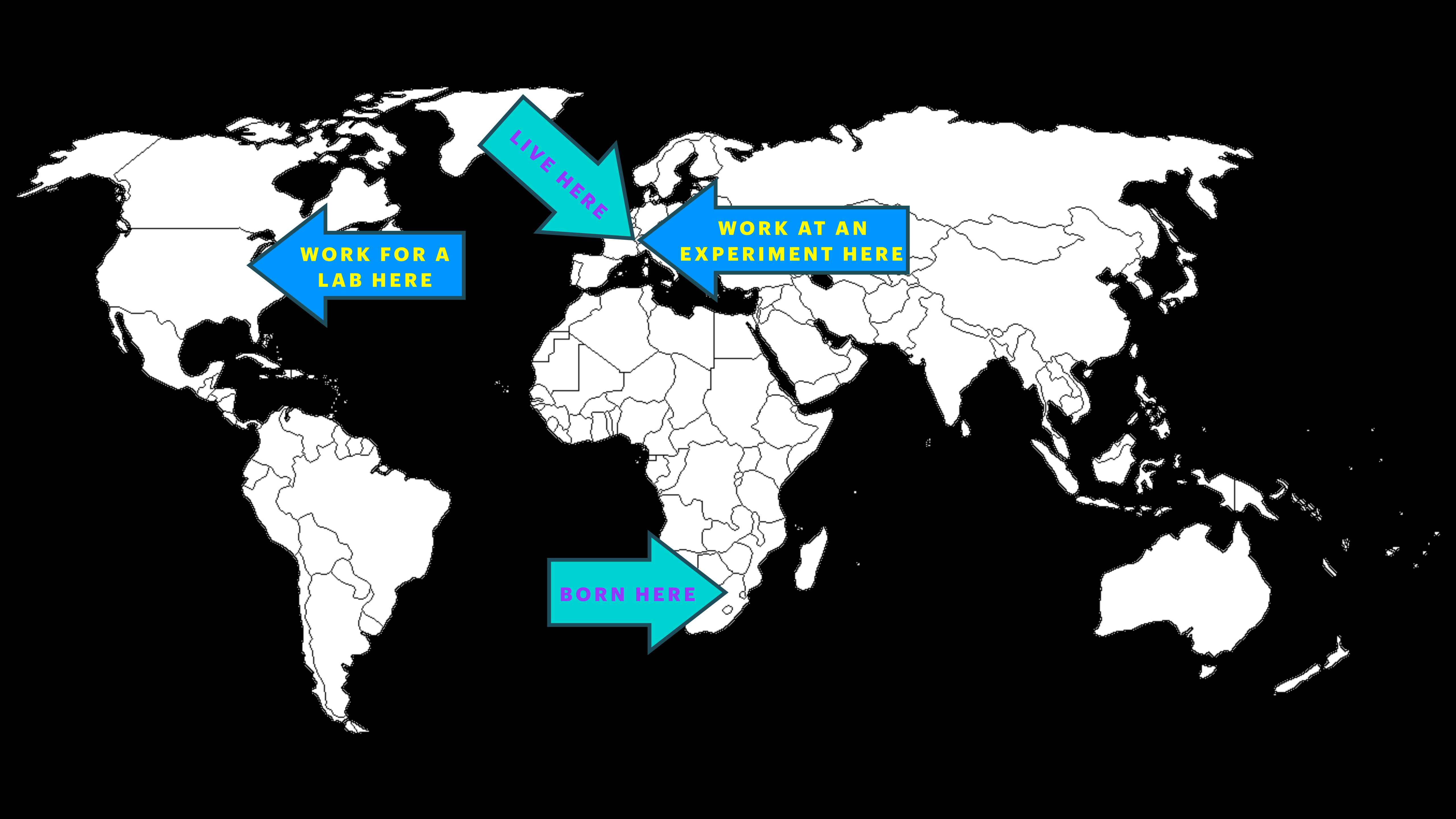
An introduction to particle physics



@Claire_Lee 

Dr. Claire Lee (she/her)

Particle Physicist at Fermilab



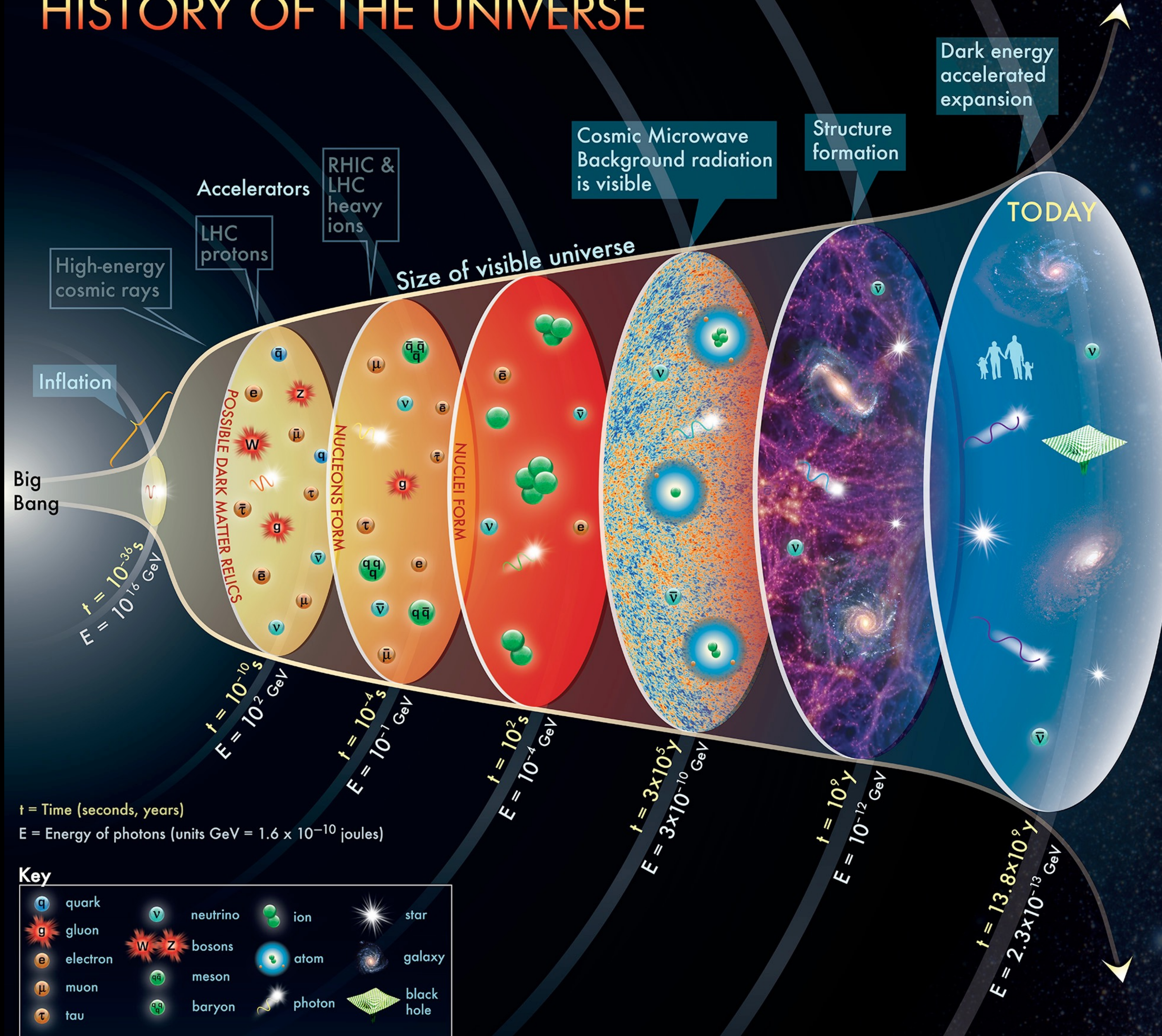
LIVE HERE

WORK AT AN
EXPERIMENT HERE

BORN HERE

WORK FOR A
LAB HERE

HISTORY OF THE UNIVERSE



t = Time (seconds, years)
 E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Key

quark	neutrino	ion	star
gluon	bosons	atom	galaxy
electron	meson	photon	black hole
muon	baryon		
tau			

The concept for the above figure originated in a 1986 paper by Michael Turner.

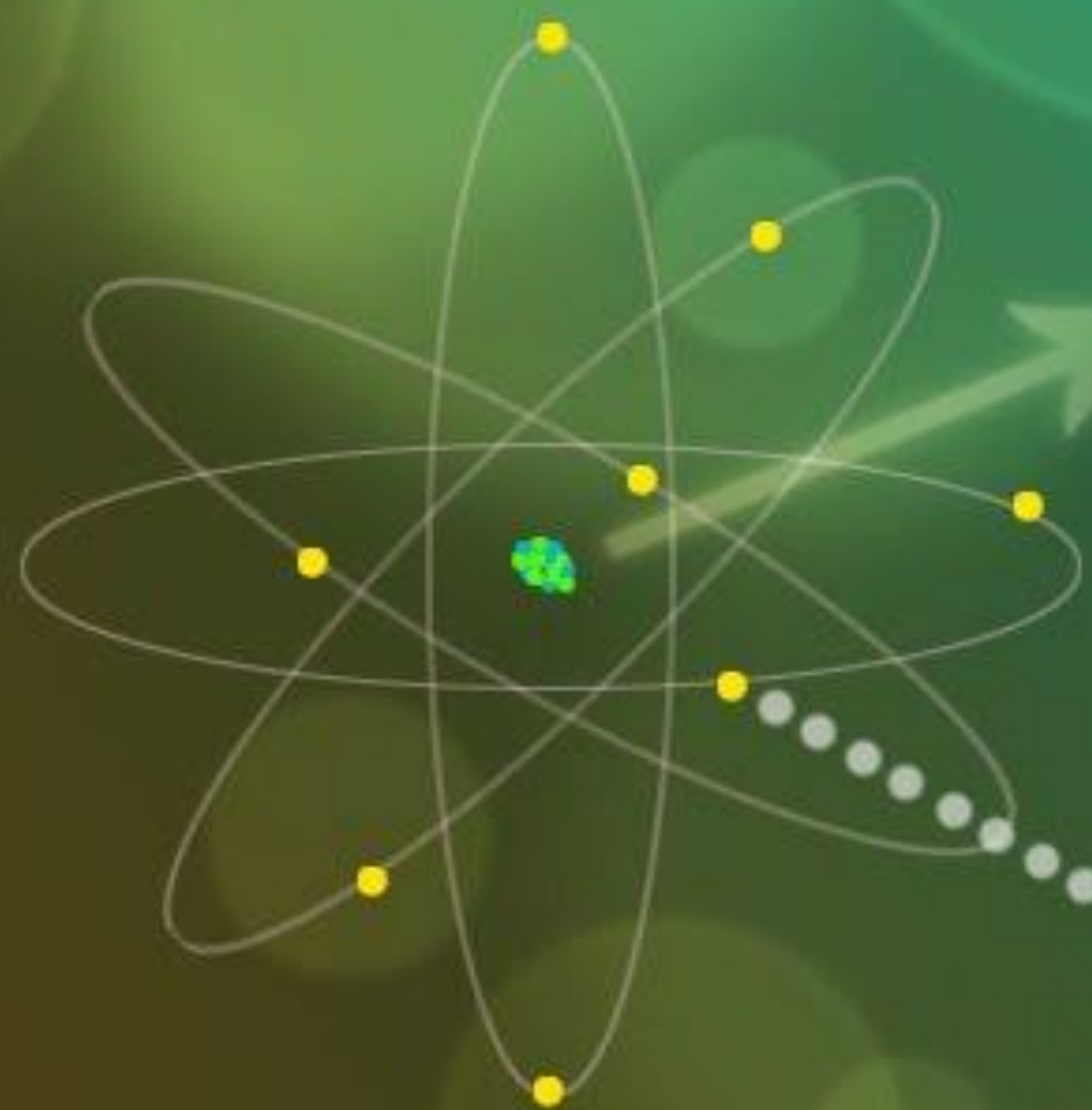
**WHAT PIECES DO
YOU NEED TO
BUILD THIS
UNIVERSE
& HOW DO THEY
FIT TOGETHER?**



SUBATOMIC PARTICLES

.....
BOSON | FERMION | HADRON | LEPTON | MESON | BARYON

ATOM



NUCLEUS



PROTON



Quark

Proton

Neutron

Electron
(Lepton)

d

u

s

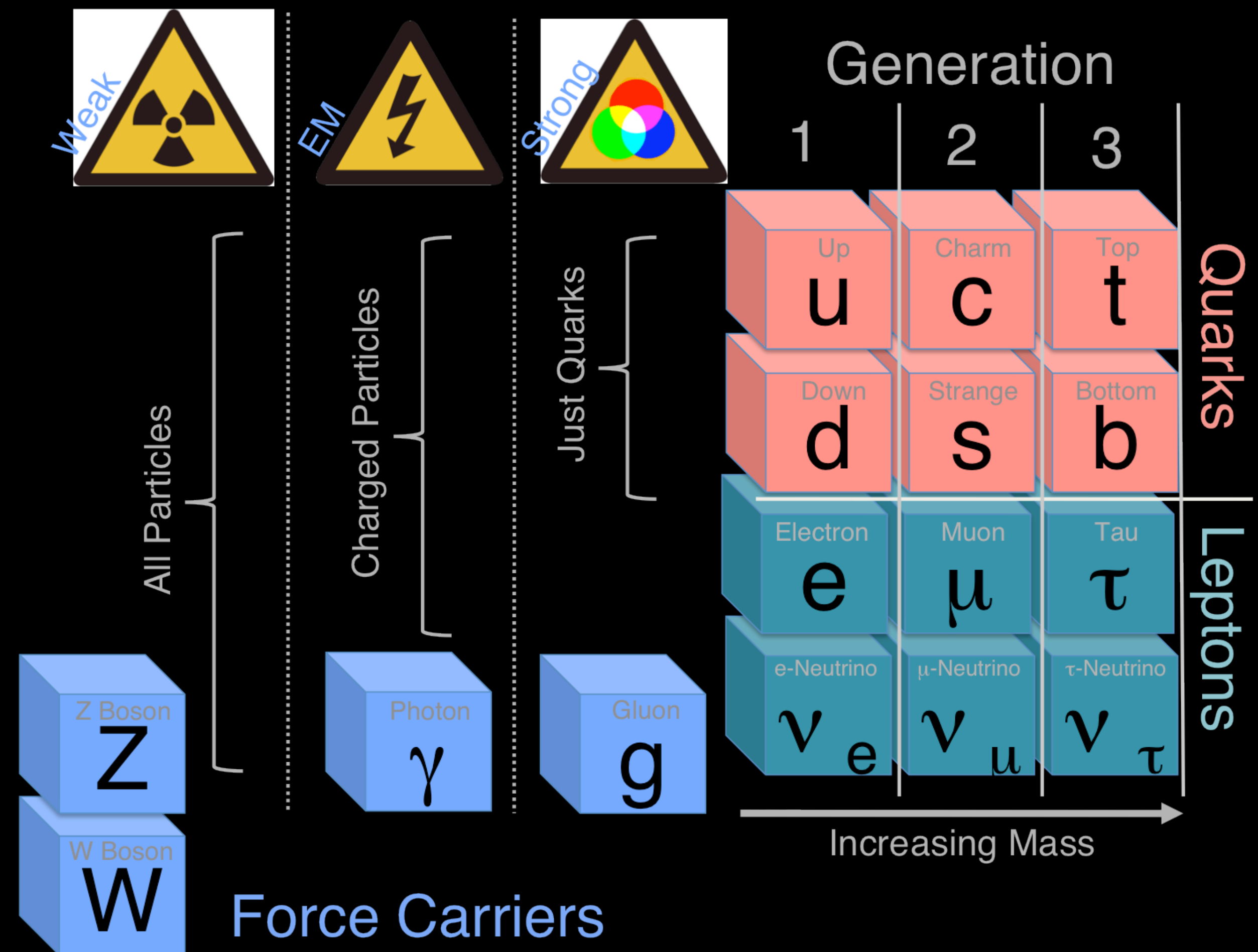
Quarks

Not to scale! Most of an atom is actually empty space!

FORCES AND PARTICLES

(AT LHC ENERGIES)

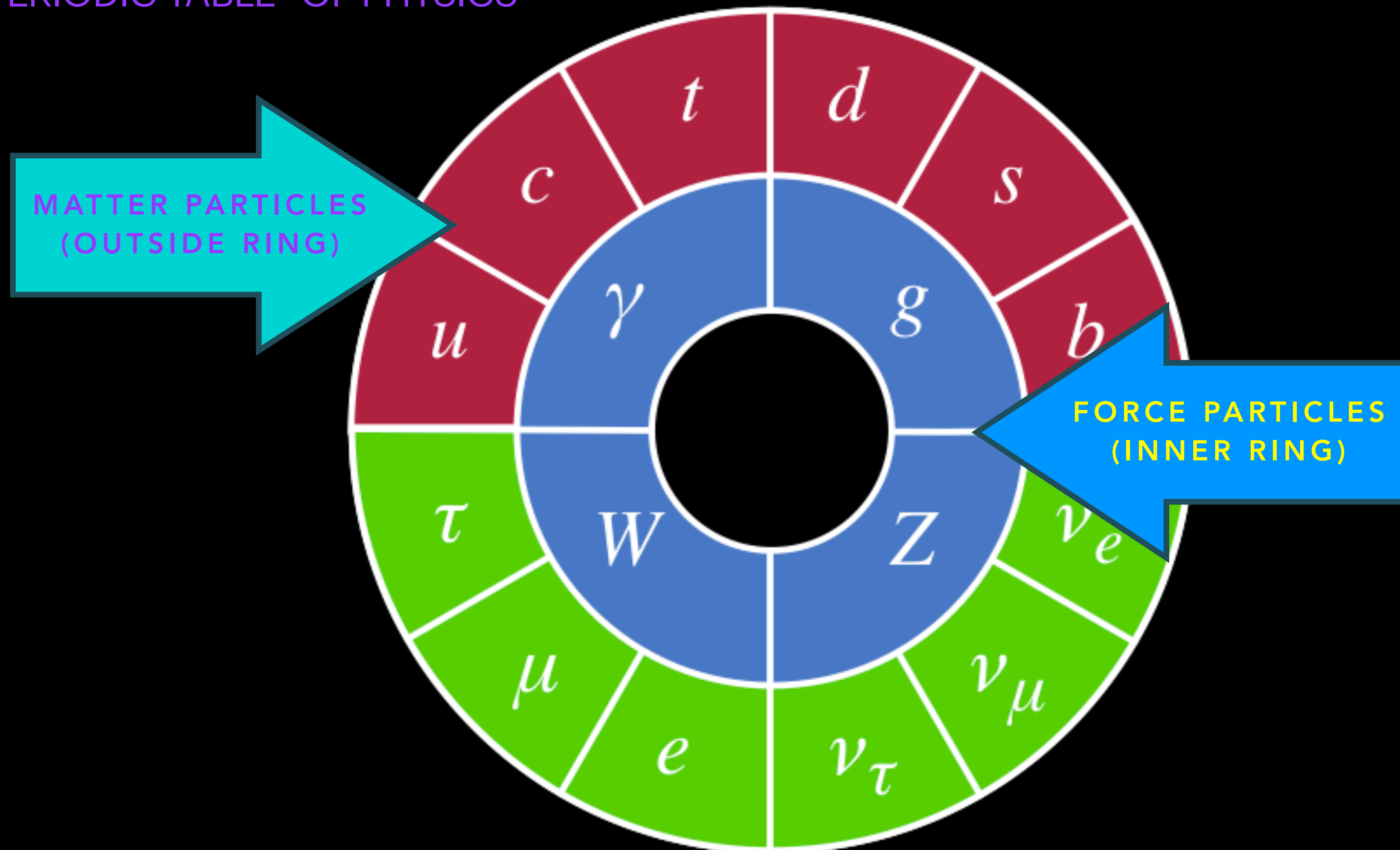
- A force is another way of saying “an interaction”
- The range of a force depends on the mass of the particle that carries that force
- Most interactions we experience in daily life are based on the electromagnetic force



THE STANDARD MODEL OF PARTICLE PHYSICS

IT'S THE "PERIODIC TABLE" OF PHYSICS

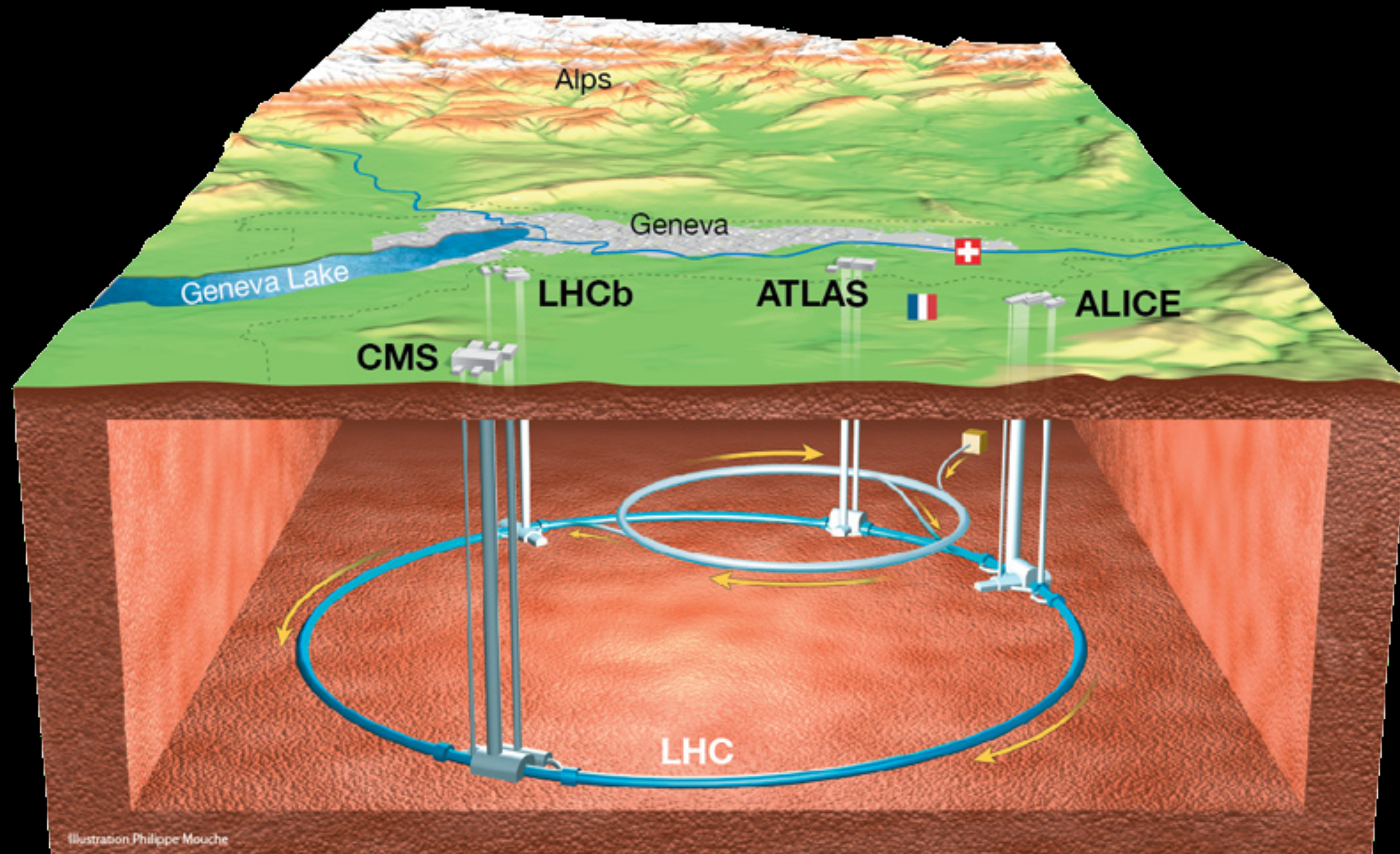
(PRE 2012)



HOME OF THE LARGE HADRON COLLIDER

THE WORLD'S LARGEST PARTICLE ACCELERATOR

- 27 km tunnel 100m underground with more than 9000 magnets
- Sends protons round & round at 99.99999991% of the speed of light, and smashes them together millions of times per second



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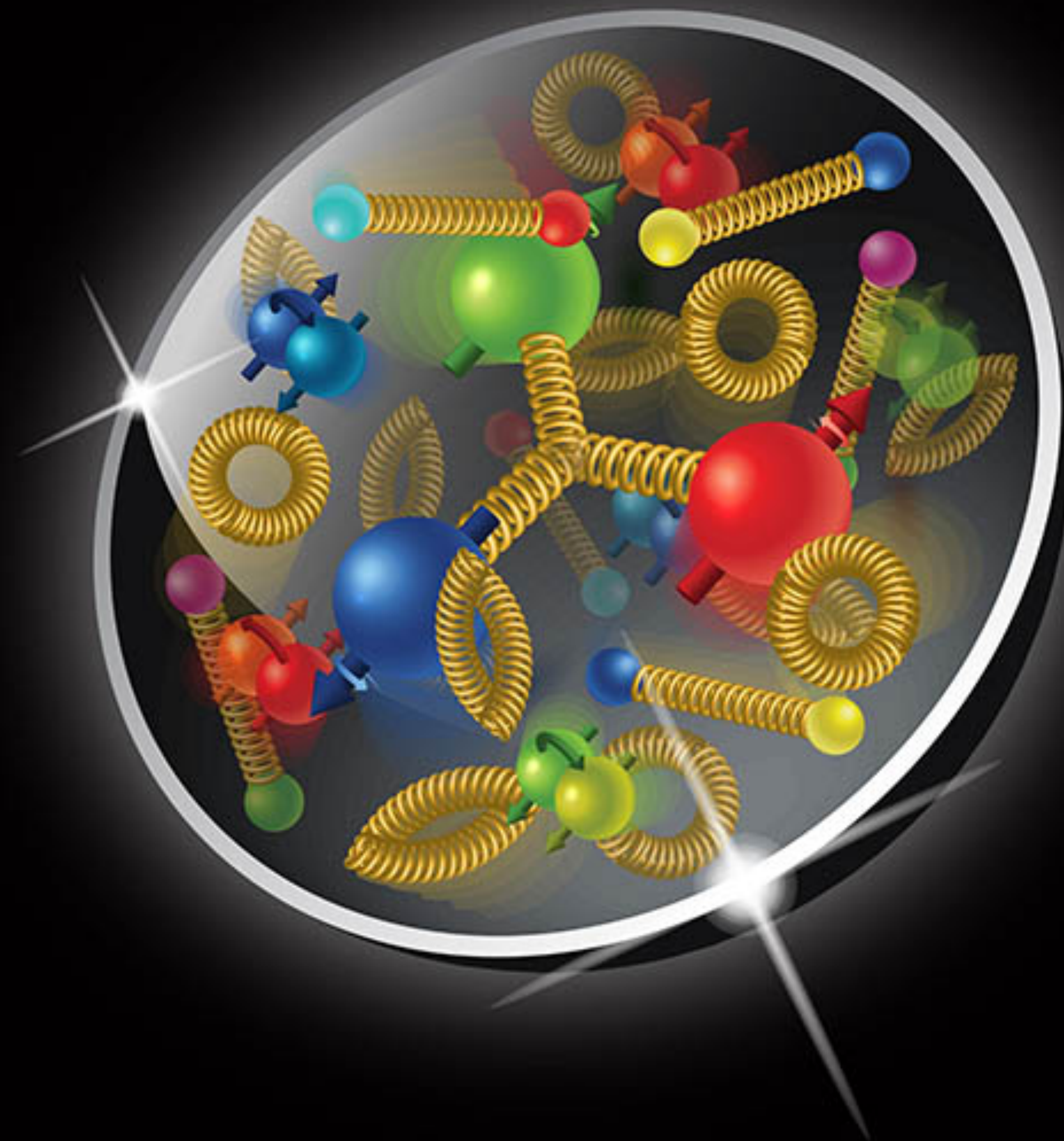


INSIDE A PROTON

(AT LHC ENERGIES)

- The three “valence” quarks
- “Sea” quarks: quark-antiquark pairs popping in and out of existence
- Gluons holding them all together

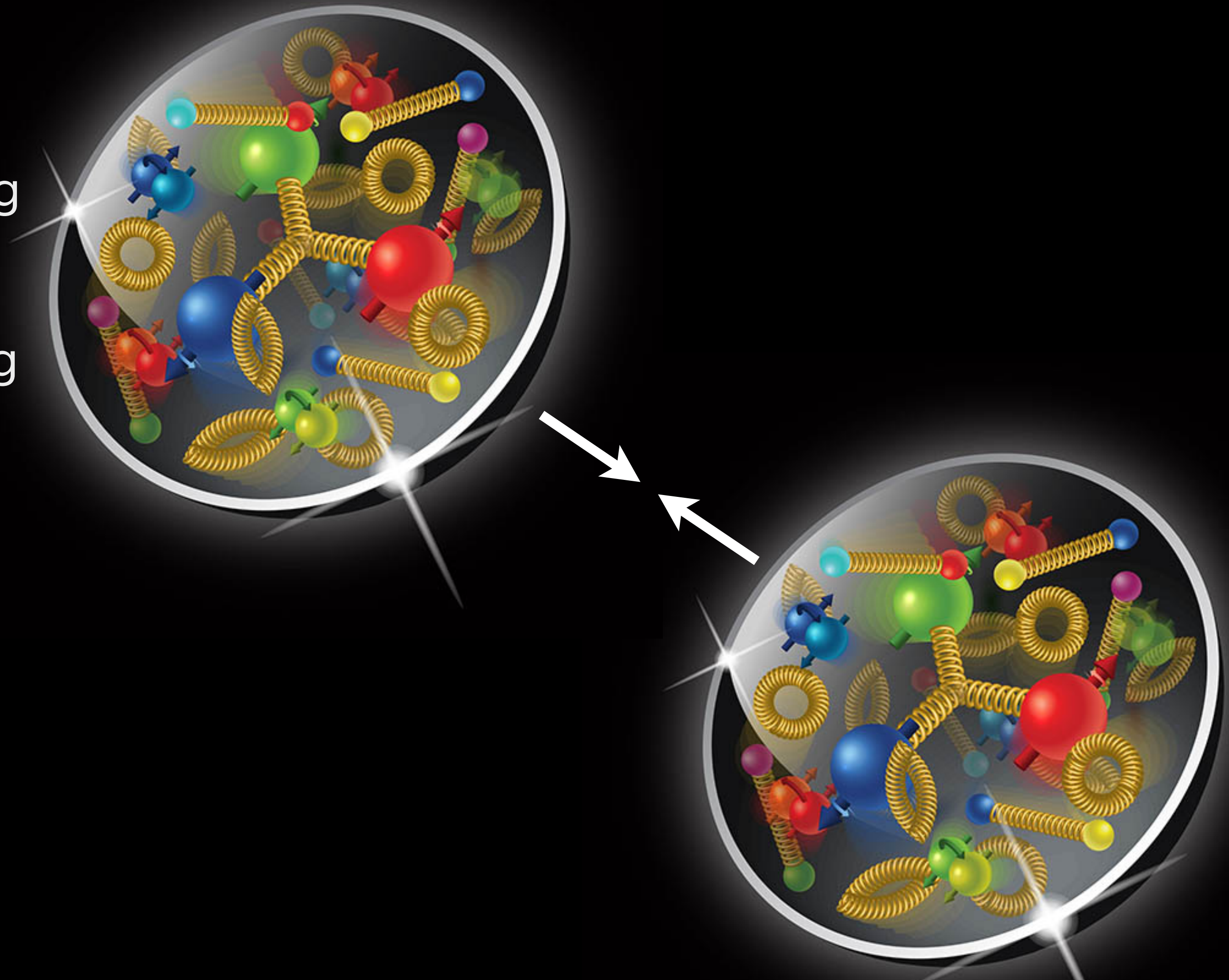
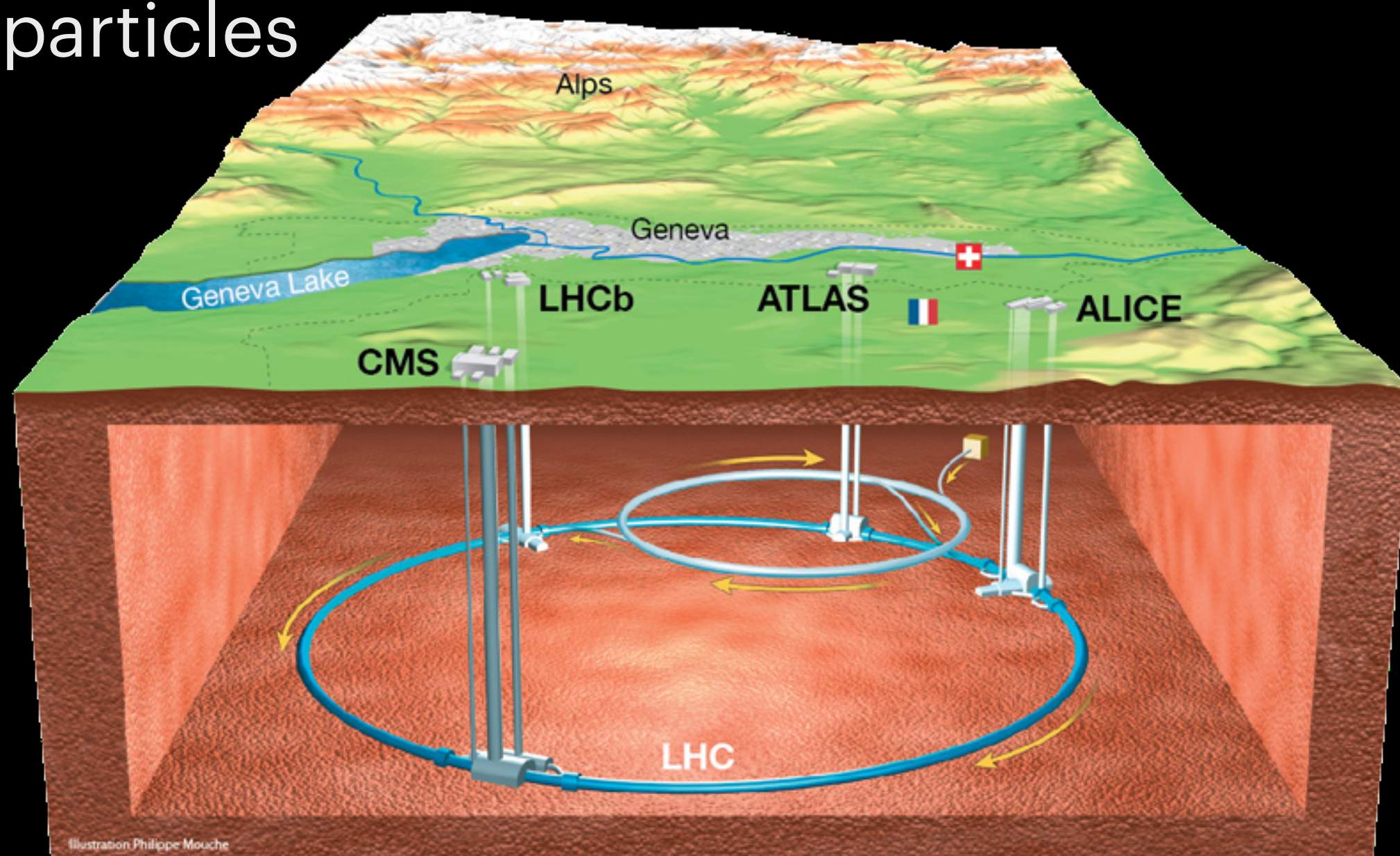
- Ideal discovery machine!

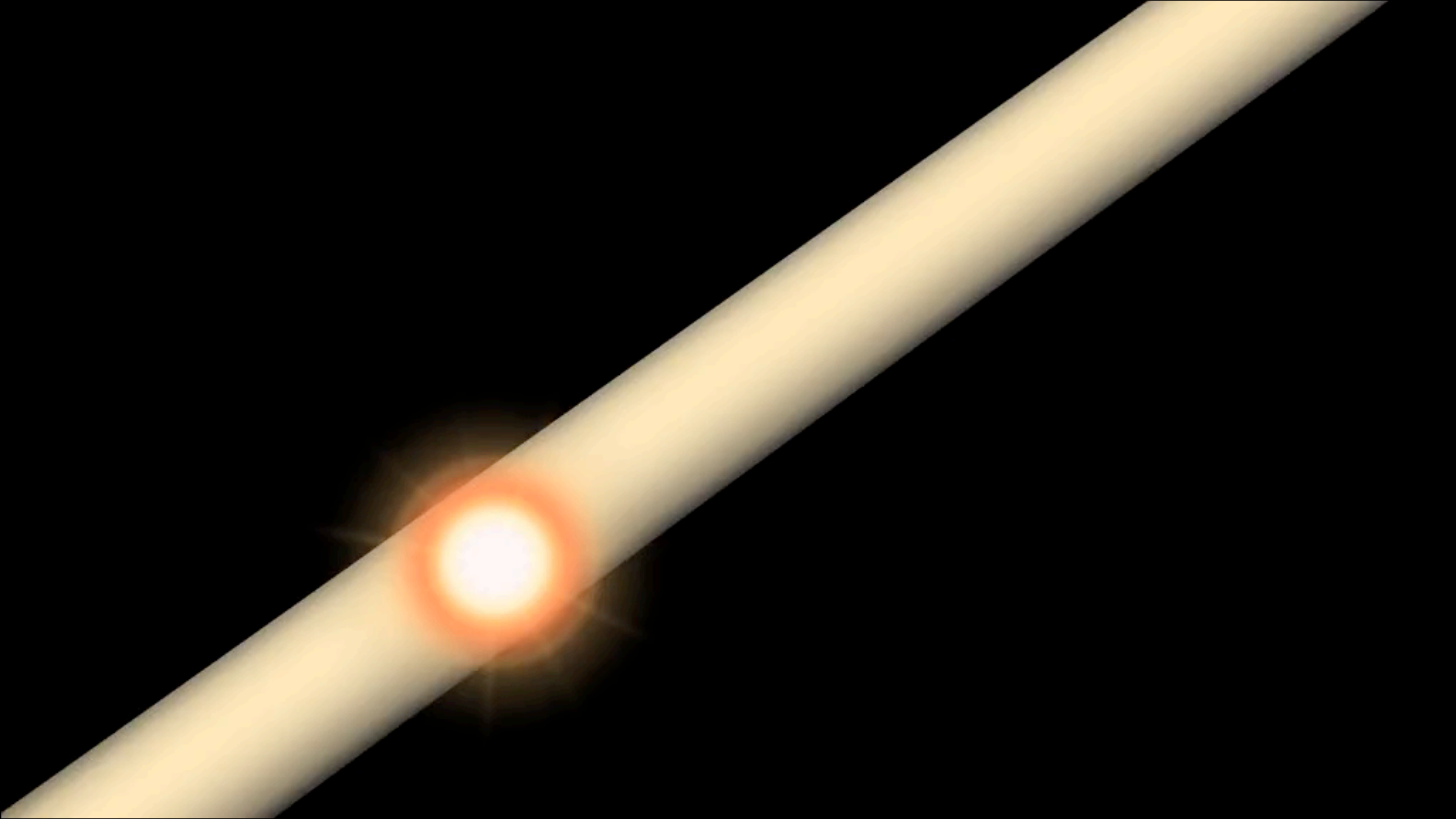


THE LHC

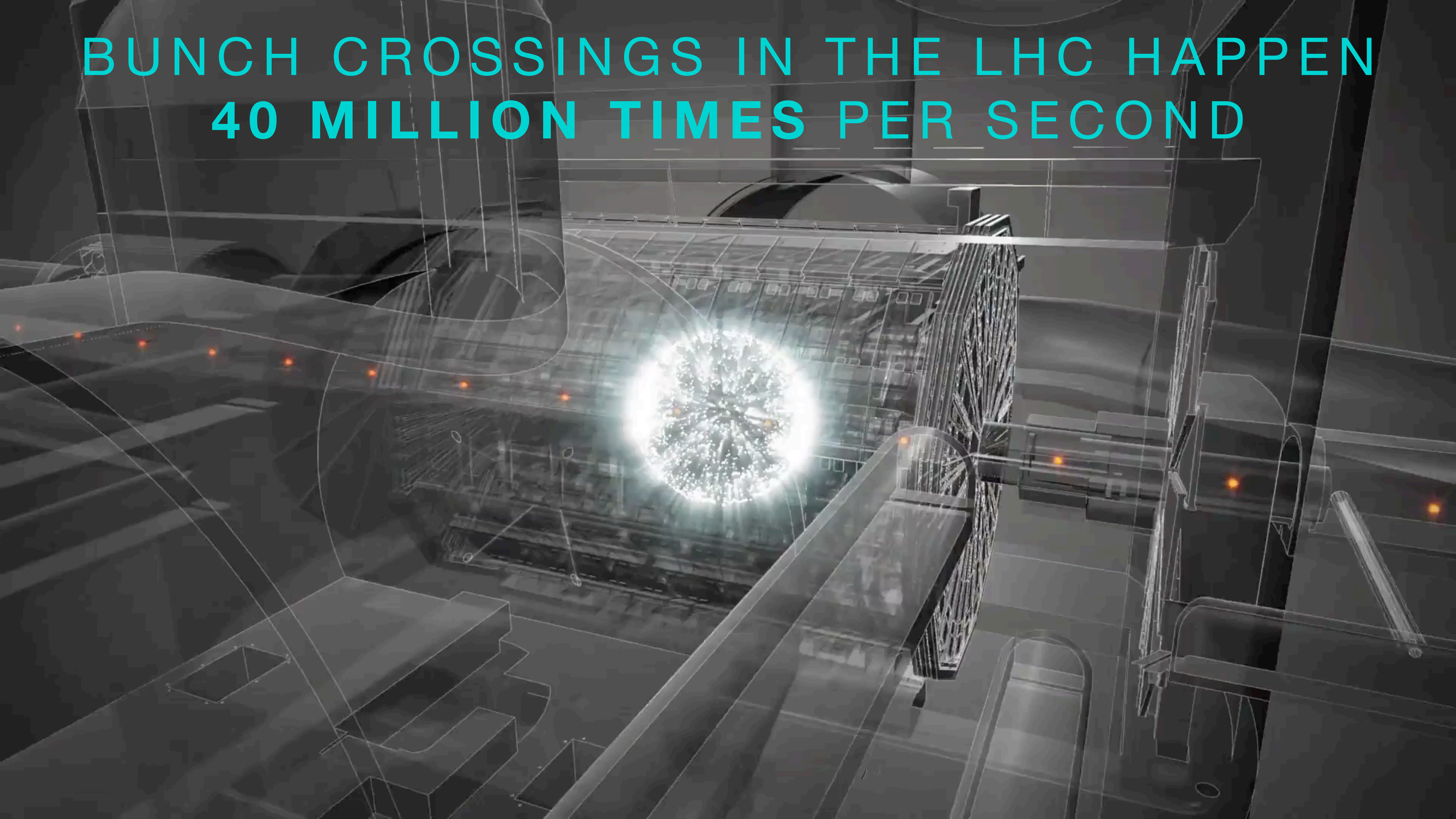
A PARTICLE FACTORY

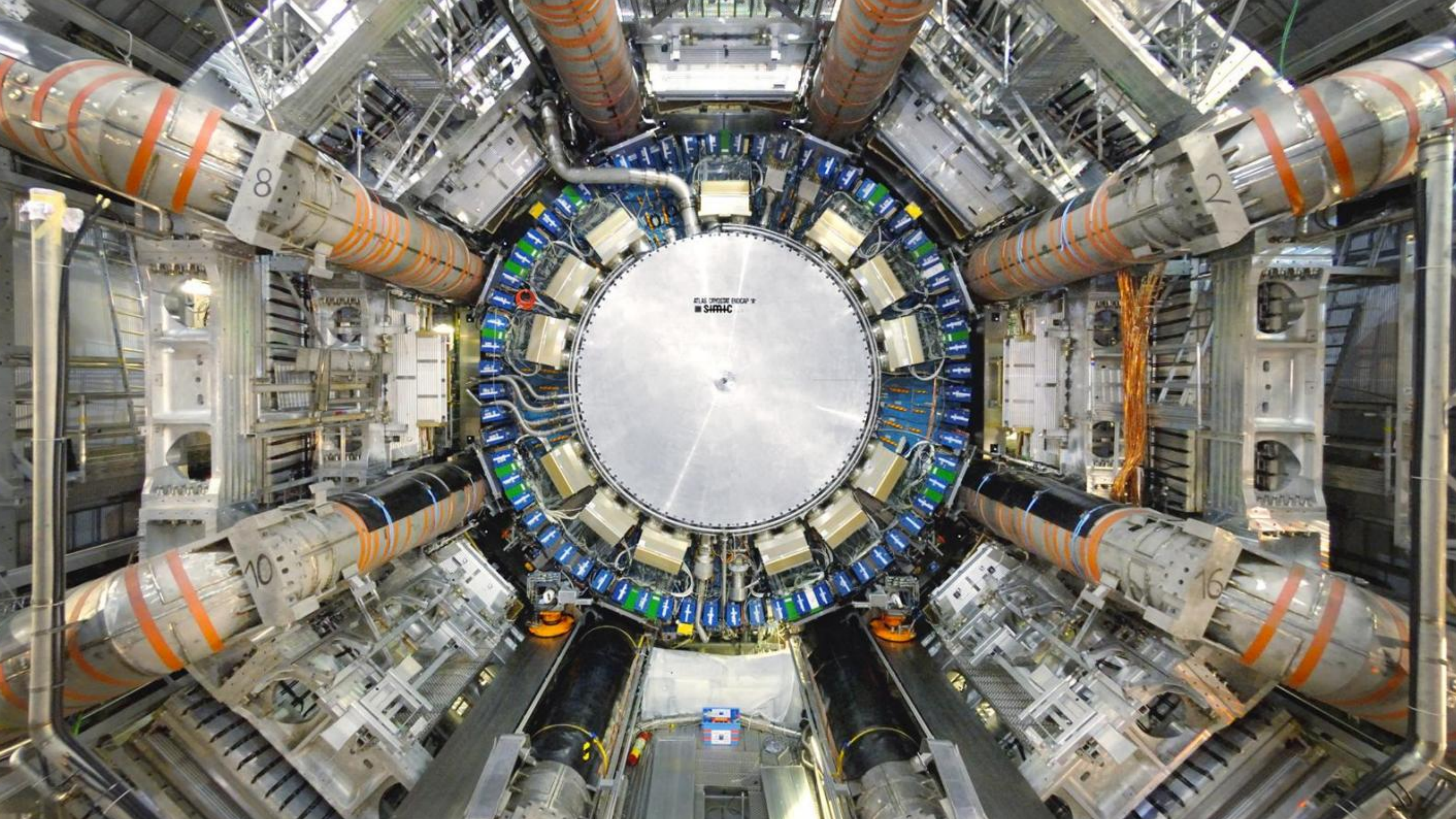
- Bunches of protons collide every 25 nanoseconds at 4 points around the LHC ring
- At each of these points is a huge detector specially designed to “catch” all the outgoing particles

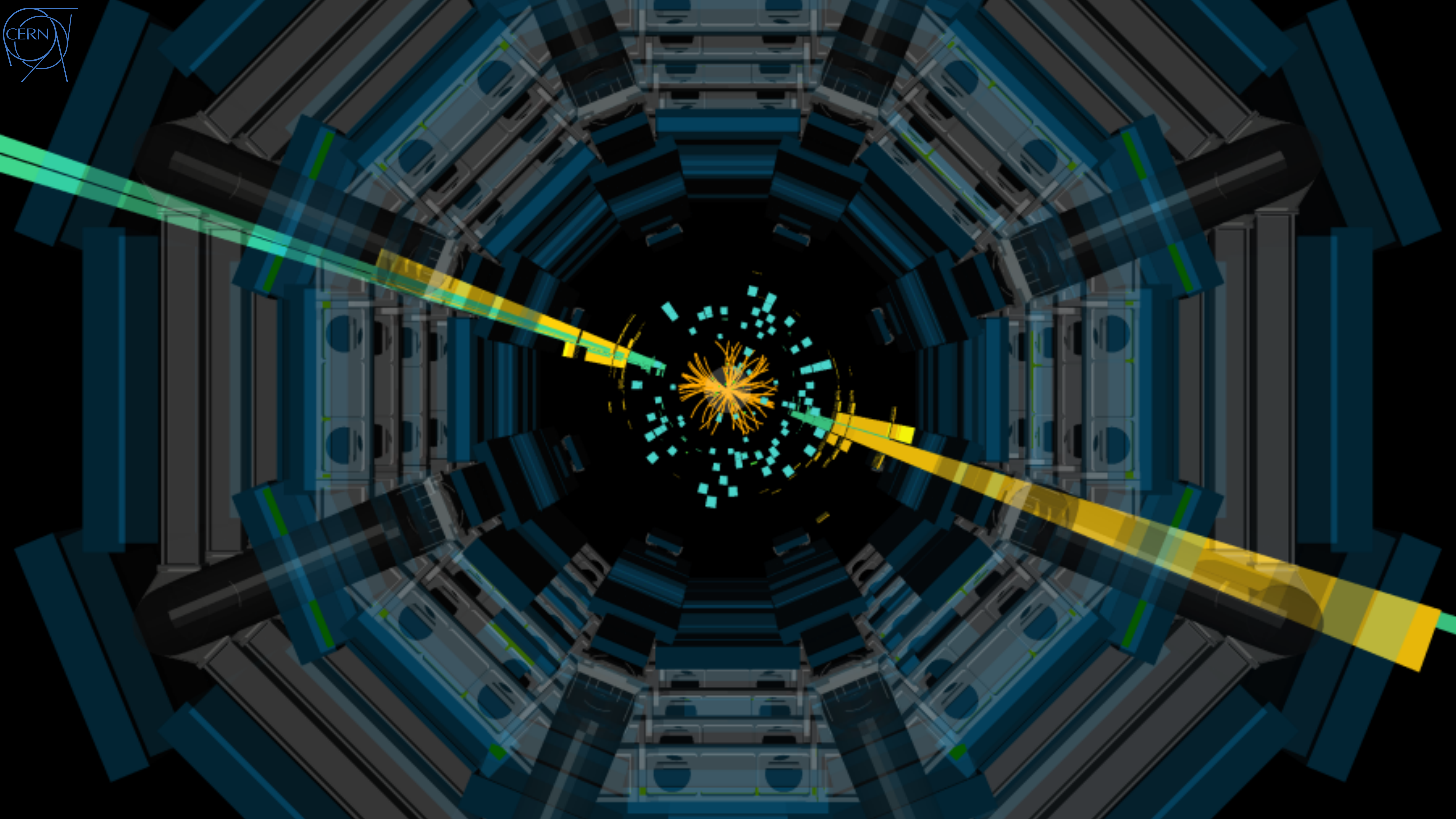


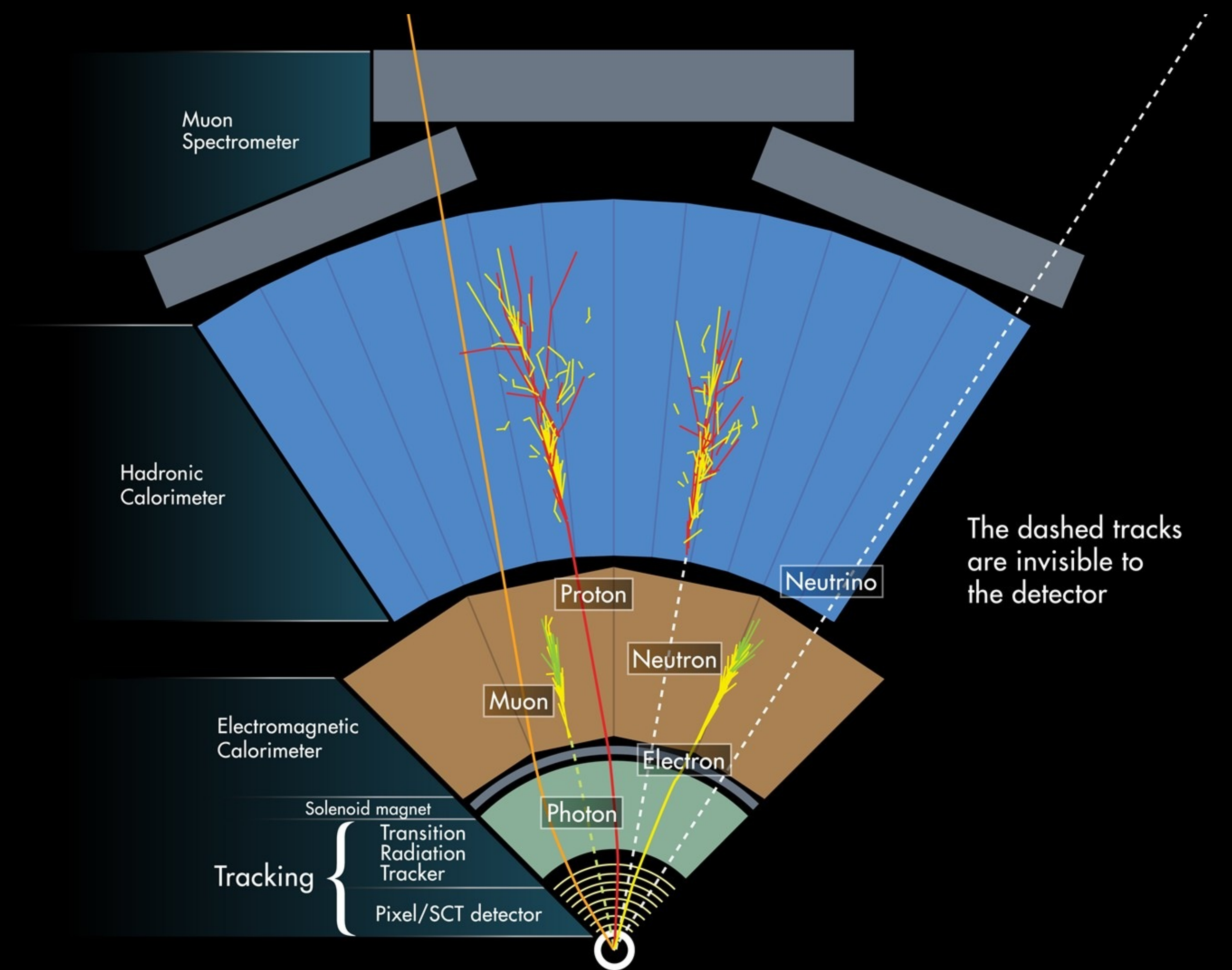


**BUNCH CROSSINGS IN THE LHC HAPPEN
40 MILLION TIMES PER SECOND**









Muon Spectrometer

Hadronic Calorimeter

Electromagnetic Calorimeter

Tracking {
Solenoid magnet
Transition Radiation Tracker
Pixel/SCT detector

Proton

Neutron

Muon

Electron

Photon

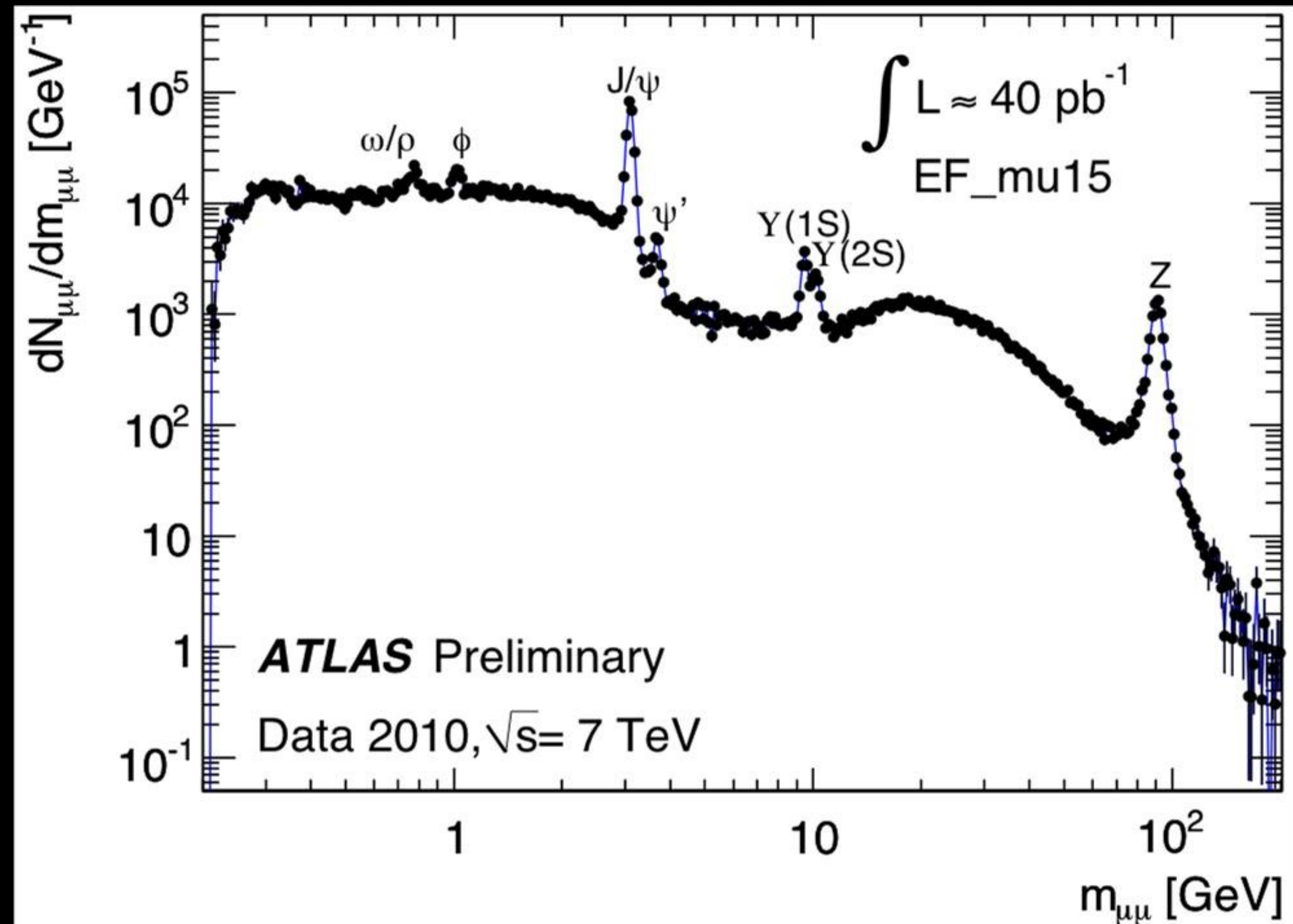
Neutrino

The dashed tracks are invisible to the detector

FIRST THINGS FIRST

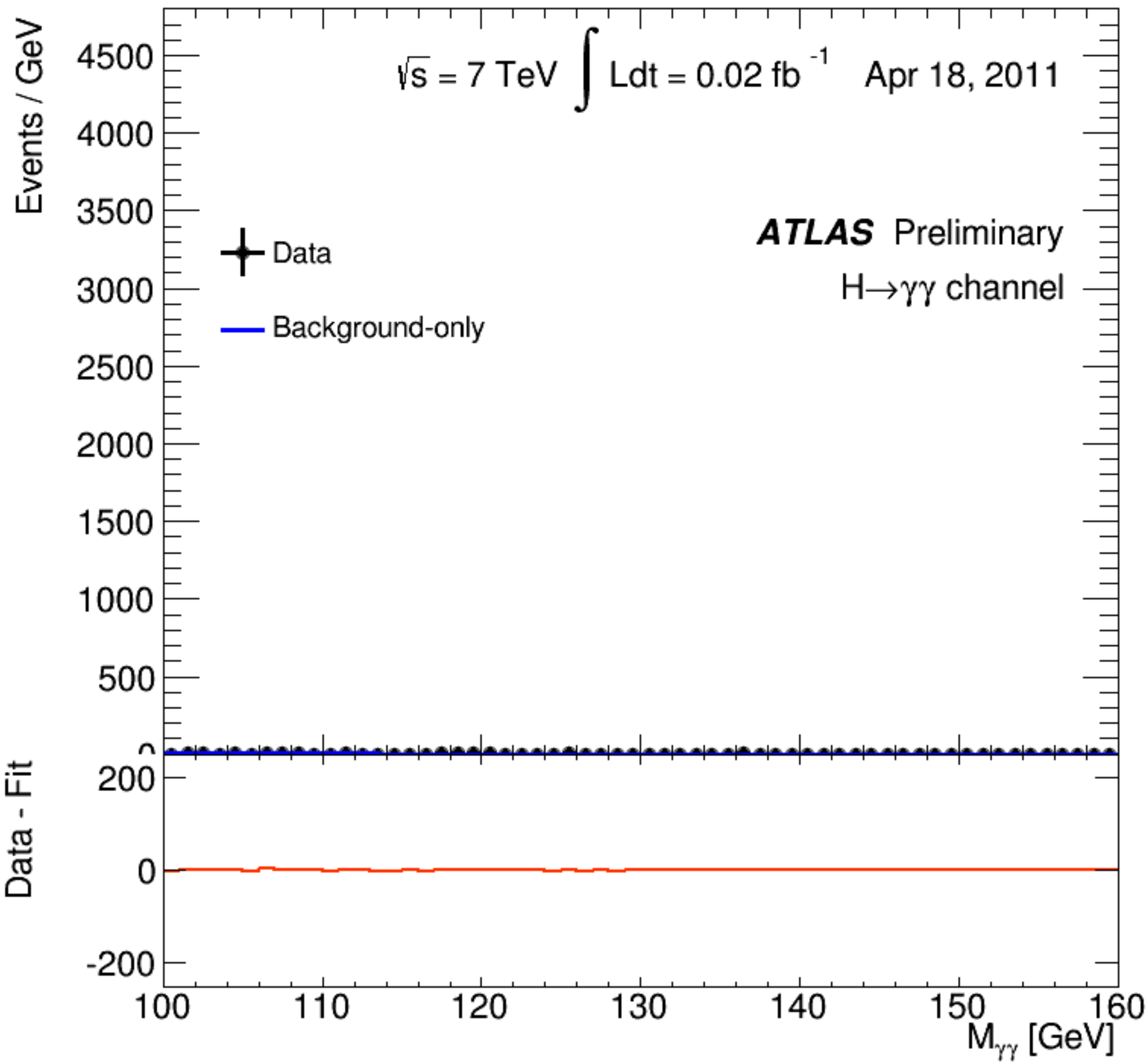
MAKING SURE THE DETECTOR WORKS WELL

- Basically every particle physics data plot ever:
 - x-axis: range of something we're measuring (like mass)
 - y-axis: how many times the something has happened
 - Smooth curve shows the background (random stuff)
 - Spikes show a particle!

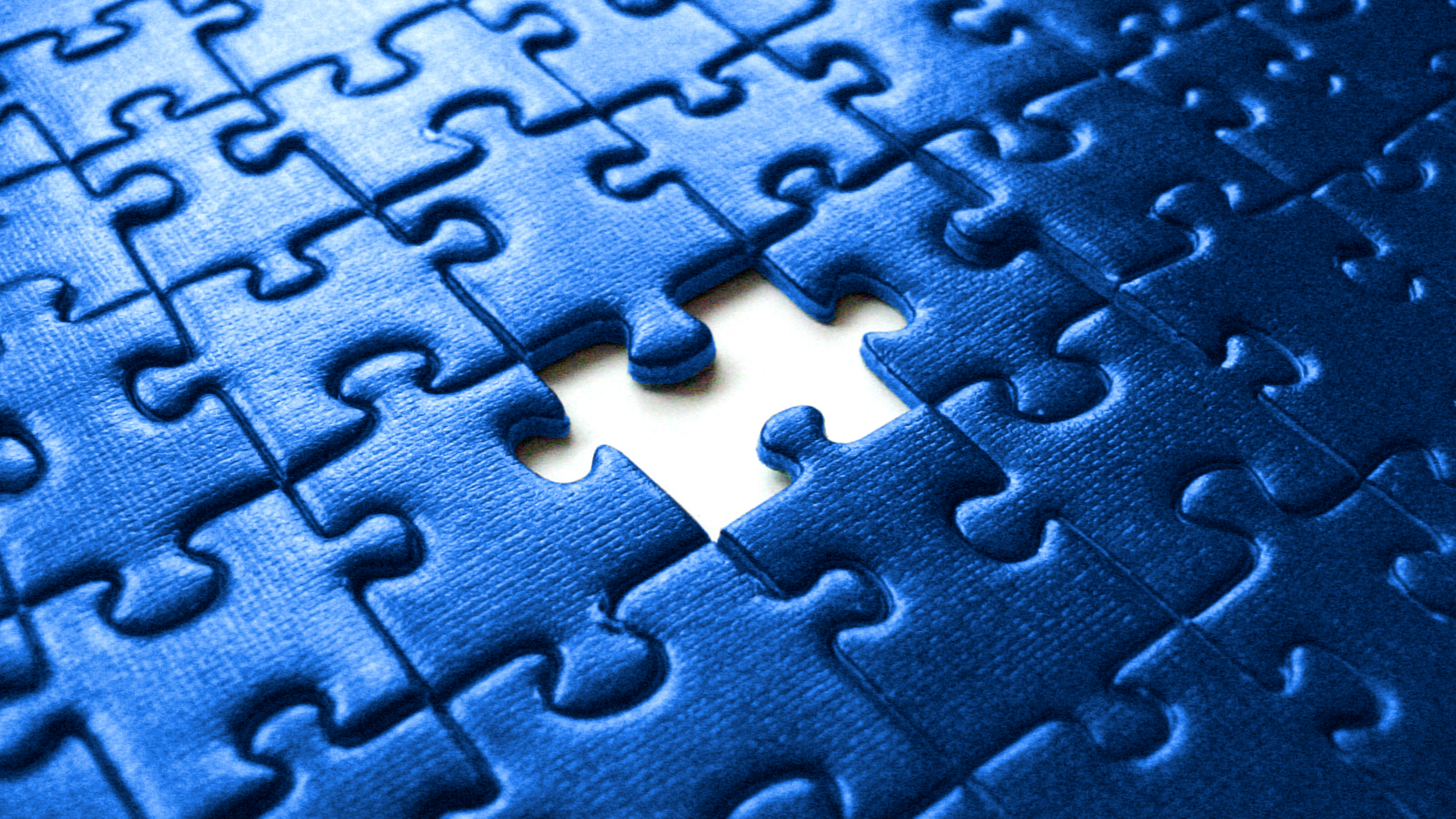


SO HOW DO WE FIND A HIGGS?



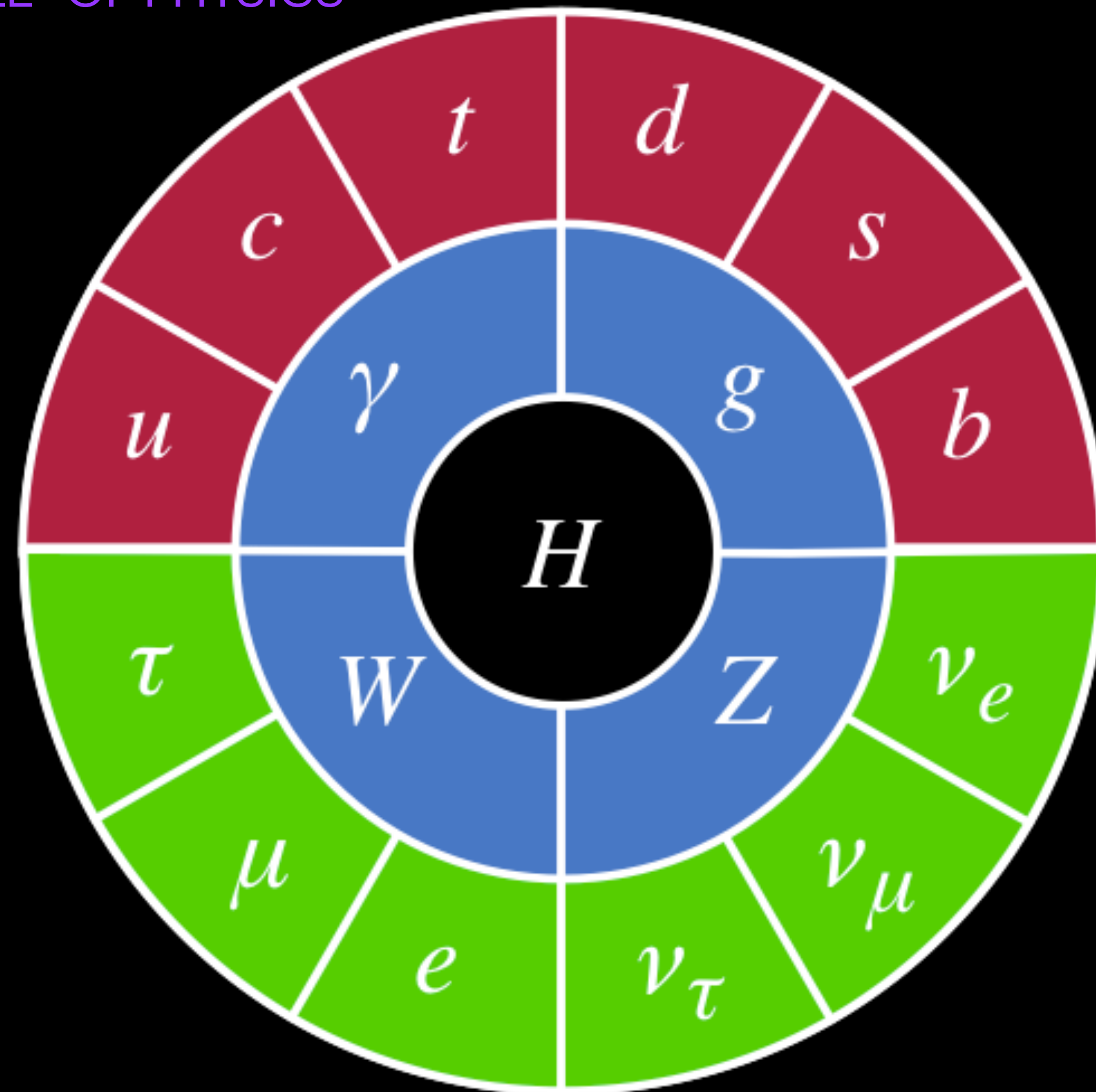


COMBINED MASS OF 2 PHOTONS



THE STANDARD MODEL OF PARTICLE PHYSICS

IT'S LIKE THE "PERIODIC TABLE" OF PHYSICS



THE FORMULA OF THE UNIVERSE

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\
 & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)] - ig s_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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{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] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + \\
 & m_d^\lambda) d_j^\lambda + ig s_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
 & \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + \\
 & (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\
 & \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \\
 & \frac{ig}{2\sqrt{2}} \frac{m_\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
 & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \\
 & \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\lambda (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \\
 & \frac{g}{2} \frac{m_\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{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) + ig s_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^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
 & igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
 & \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \\
 & \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

F OR D: FORCE
PARTICLES

Ψ : MATTER
PARTICLES

Φ : HIGGS BOSON

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\Psi} \not{D} \Psi + \text{h.c.} \\ & + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

DESCRIBES THE FORCES

HOW FORCES ACT ON MATTER

HOW PARTICLES GET MASS

HOW THE HIGGS WORKS

THE COMPOSITION OF THE UNIVERSE

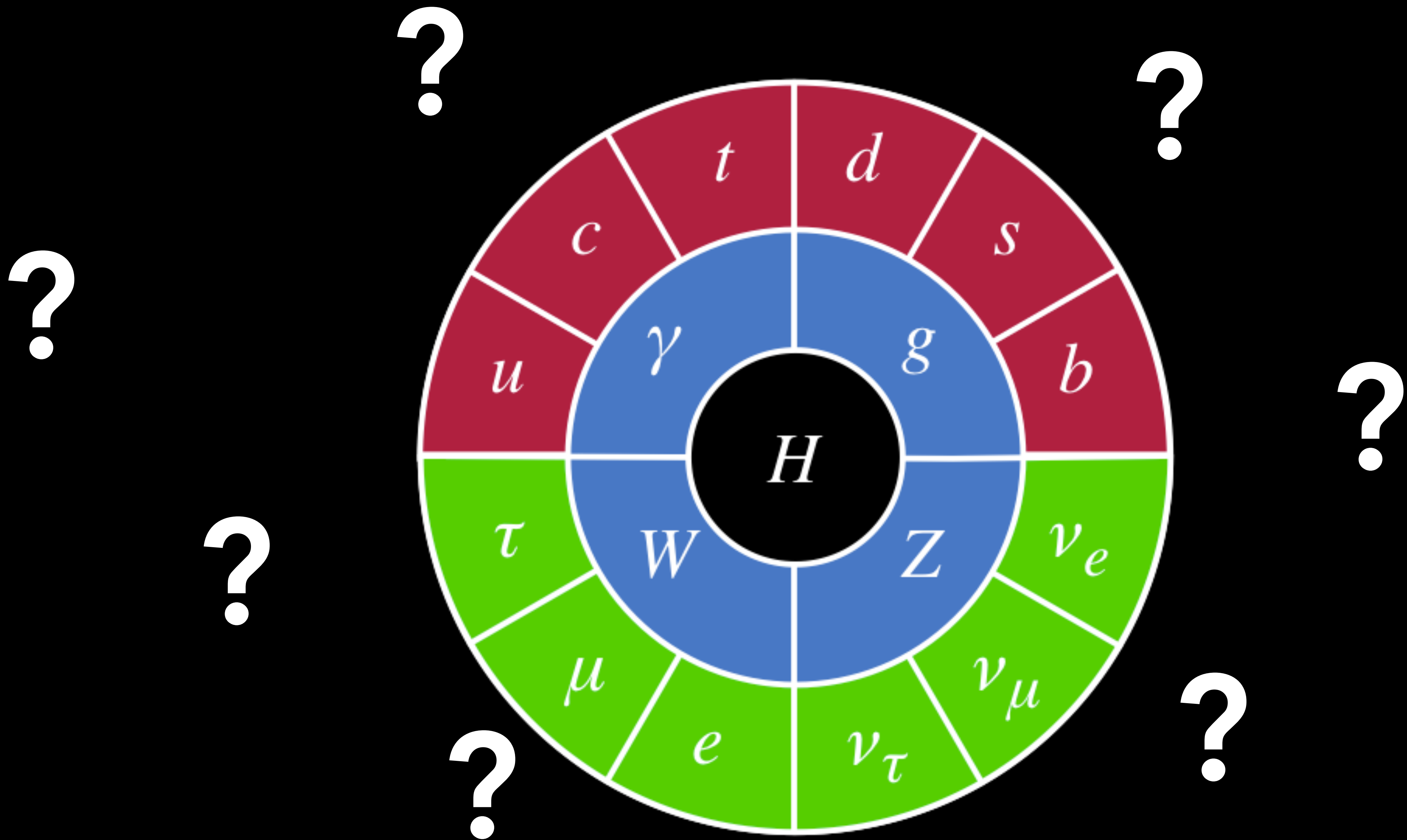
DARK M.

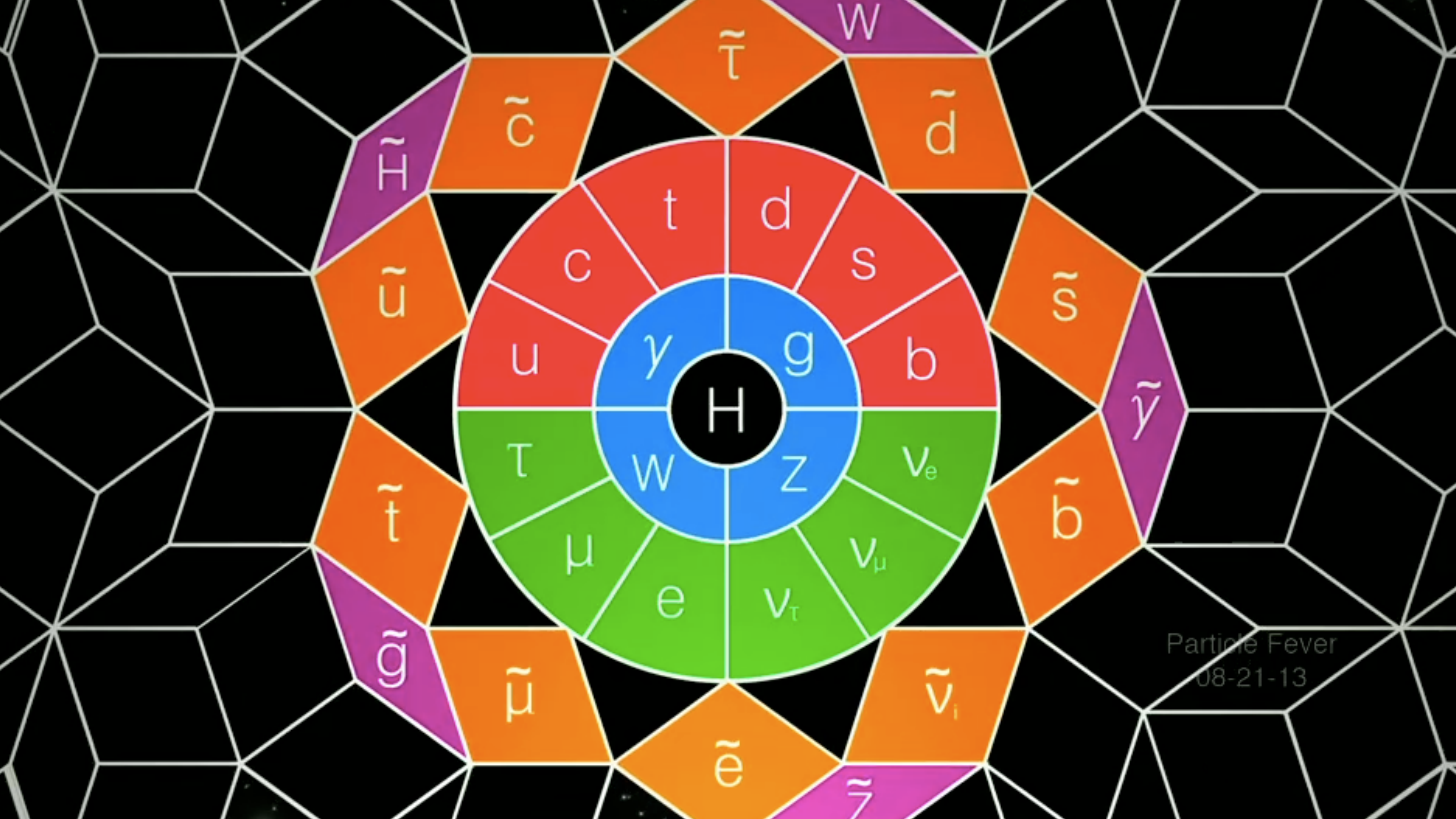
NORMAL MATTER

5 %

ENERGY

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi}\not{\partial}\psi + \text{h.c.} \\ & + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$





Particle Fever
 08-21-13

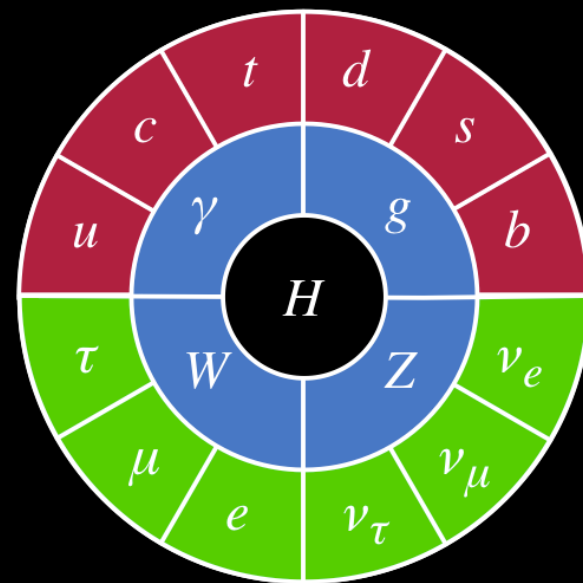


**WHAT PIECES DO
YOU NEED TO
BUILD THIS
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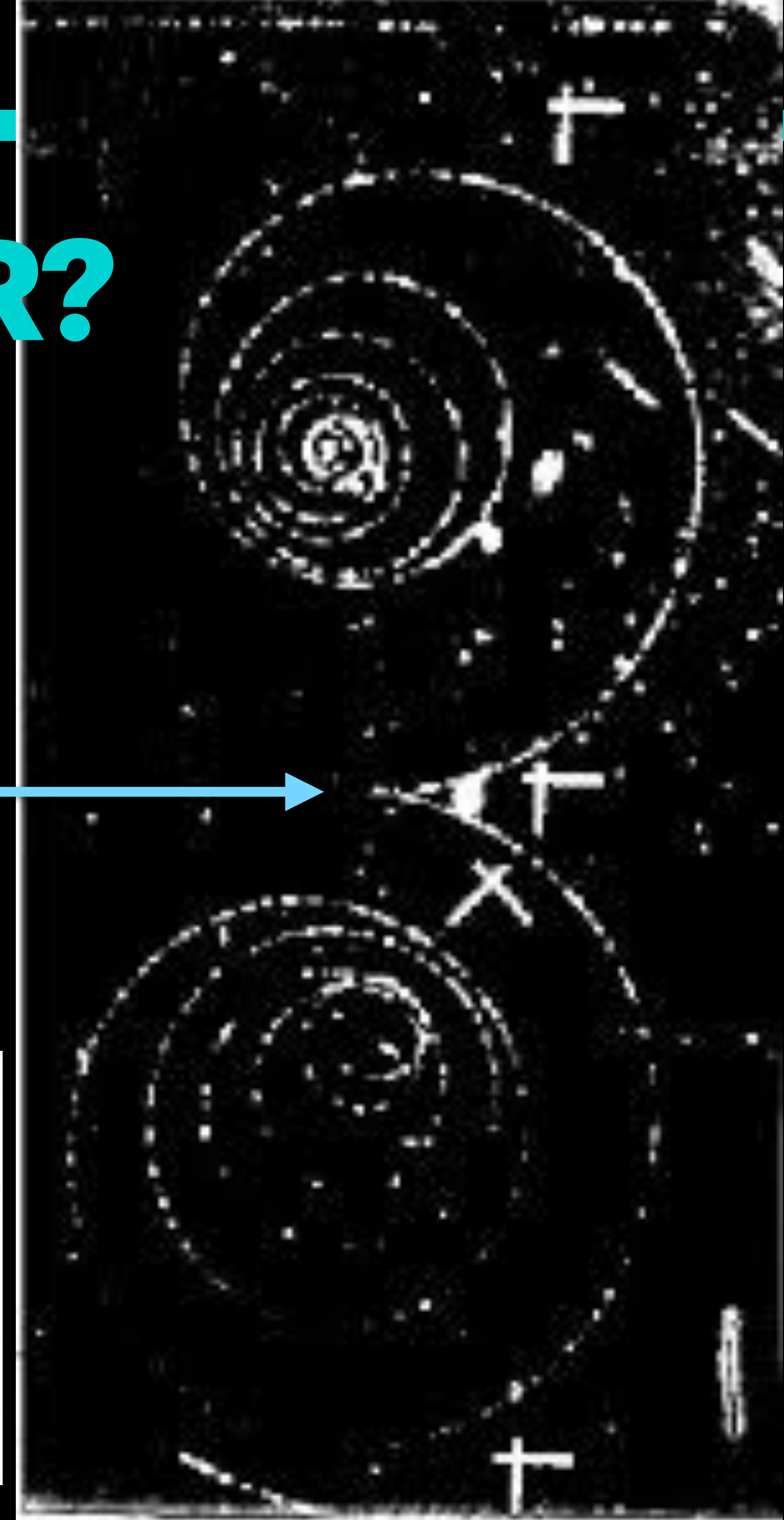
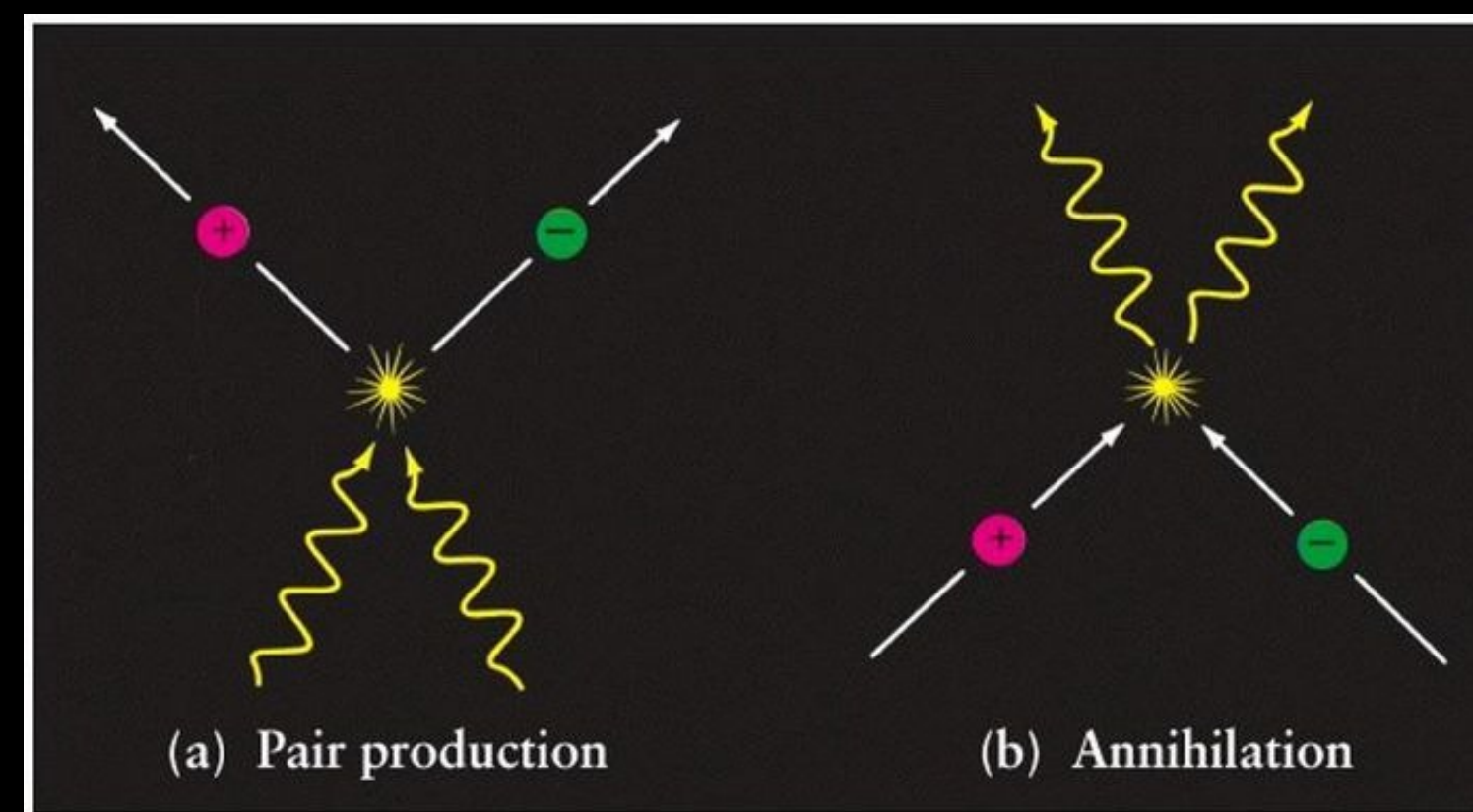
**WHAT ARE THE REST
OF THE PIECES?**

WHAT'S THE (ANTI)MATTER?

- Despite popular fiction giving the impression otherwise, antimatter is perfectly normal, everyday stuff!
- Basically, it's the same as normal matter, but with opposite charge
- and we make it all the time in our experiments!



Bubble chamber photo showing an electron and positron (anti-electron) pair being created and spiralling off in opposite directions



Antimatter

Antimatter

Matter

THE ANTIMATTER PROBLEM

Matter

Antimatter

Antimatter

Matter

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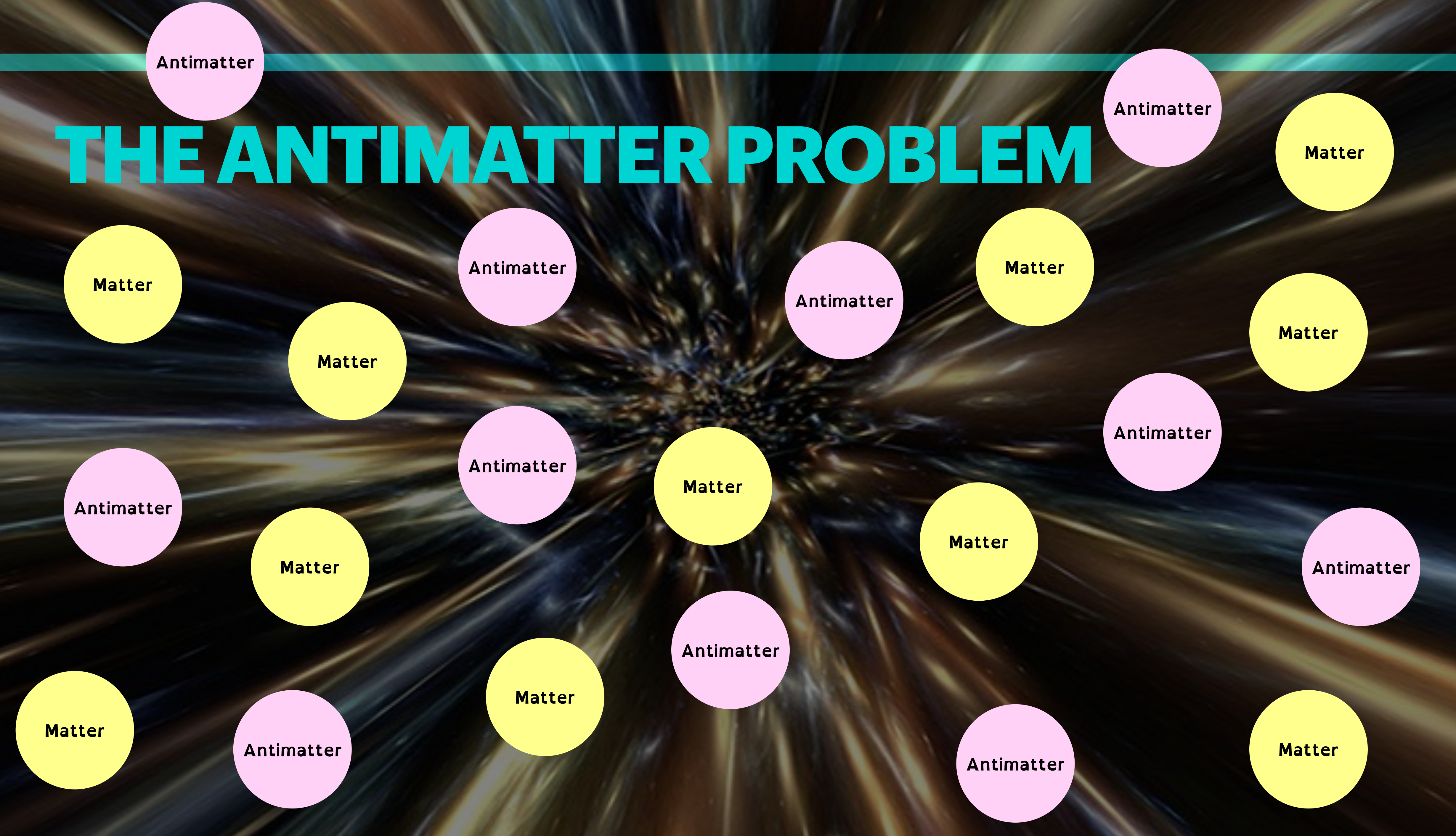
Matter

Matter

Antimatter

Matter

Antimatter



Antimatter

Antimatter

Matter

THE ANTIMATTER PROBLEM

Matter

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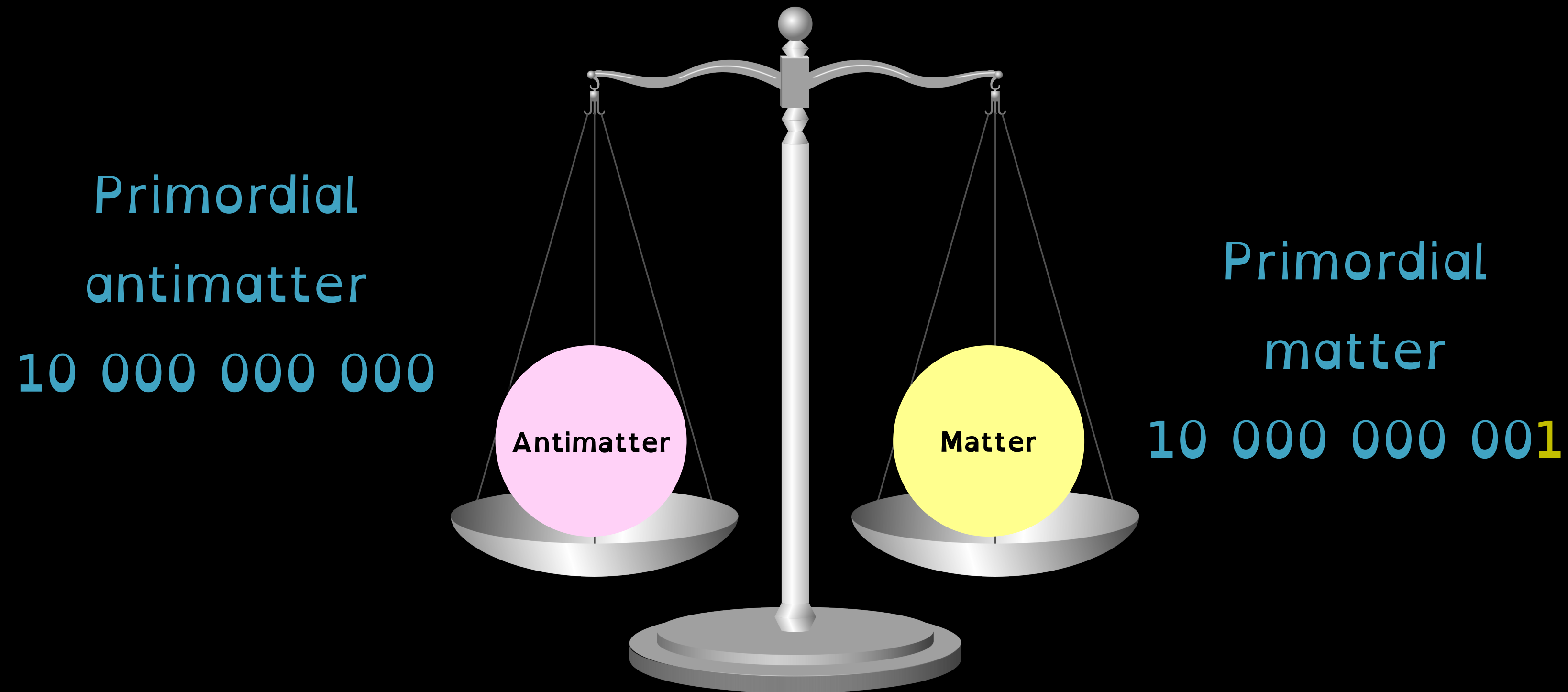
Matter

Antimatter

Matter

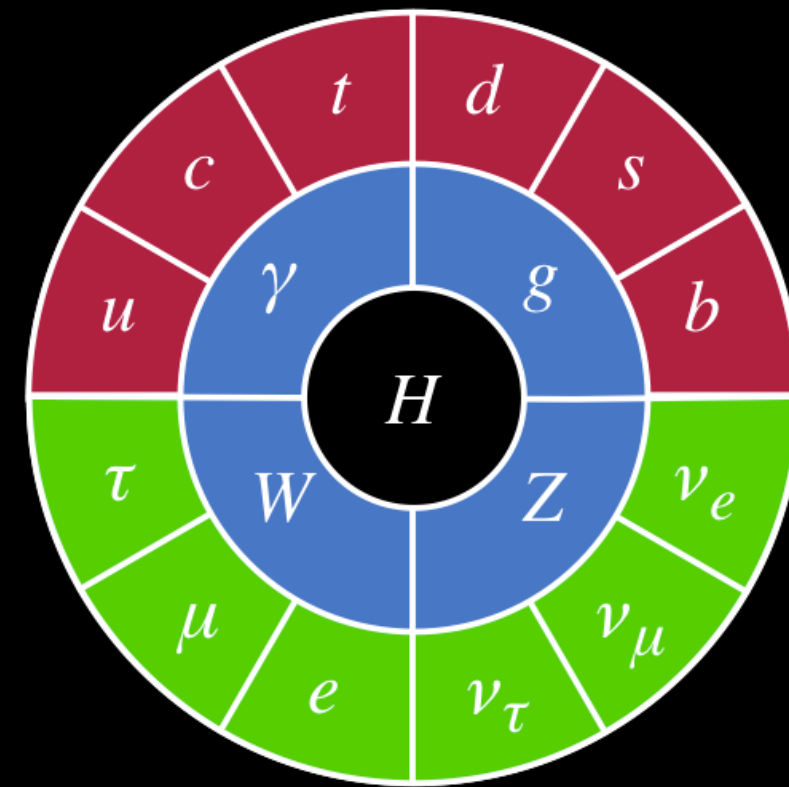
THE ANTIMATTER PROBLEM

THE PROBLEM WITH ANTIMATTER IS THERE ISN'T ENOUGH OF IT AROUND THESE DAYS



NEUTRINOS

WEIRD LITTLE THINGS

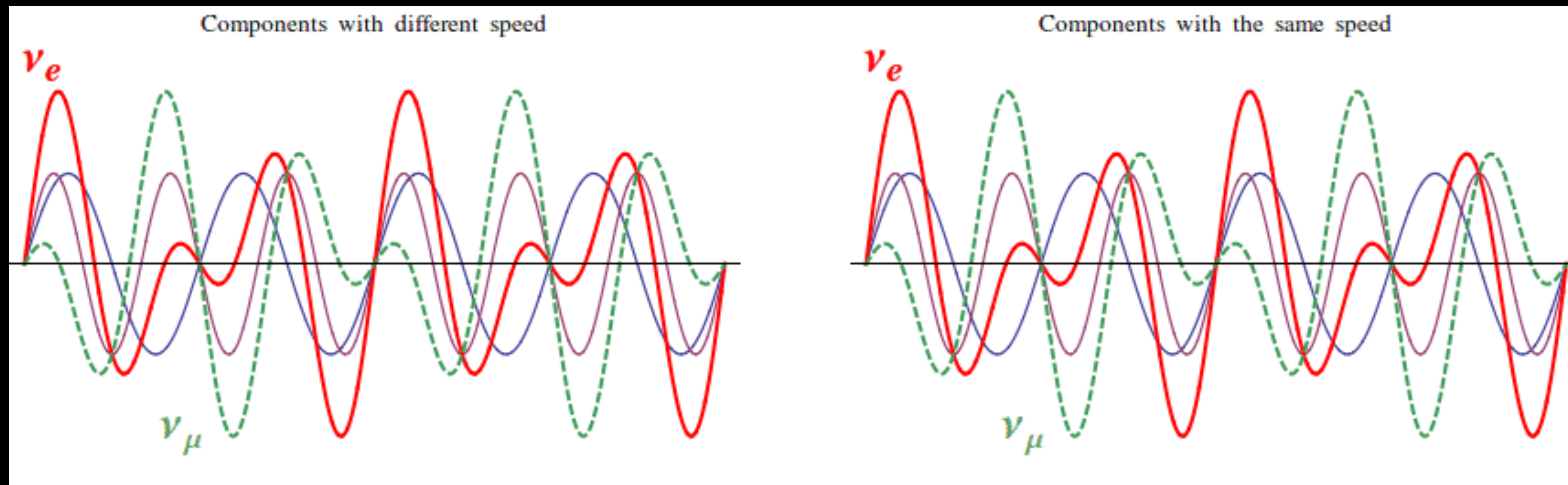
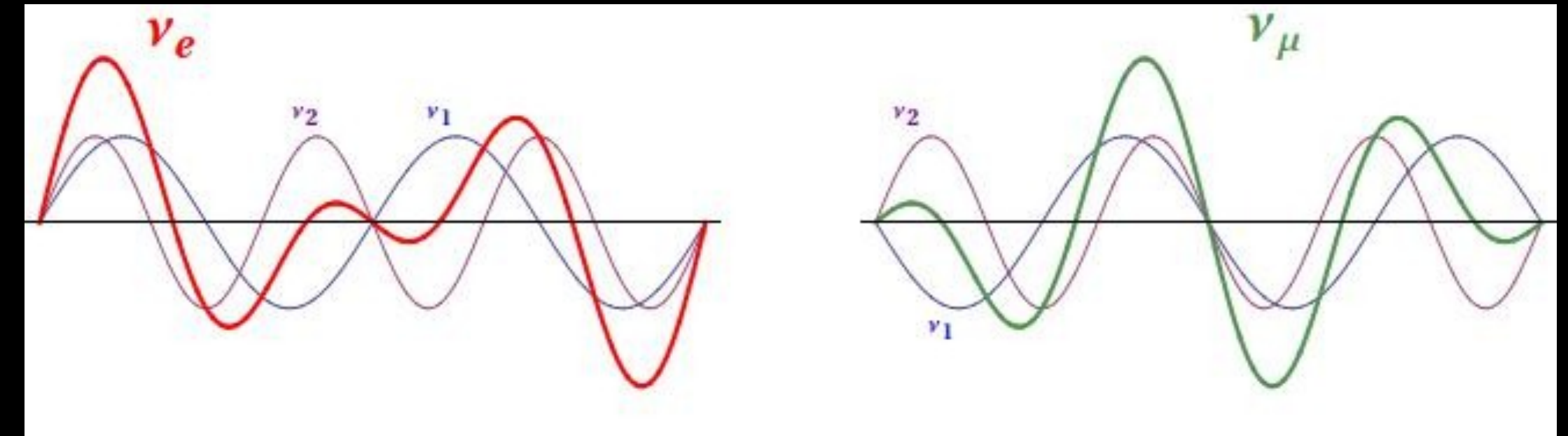


- Neutrinos are almost, but not quite, massless
- Each type of neutrino is made up of 3 different components in different quantities - kind of like three different cocktails, each with the same 3 ingredients, just in different quantities
- But the *really* special thing about neutrinos is that they change into other types of neutrino (or “oscillate”) as they travel



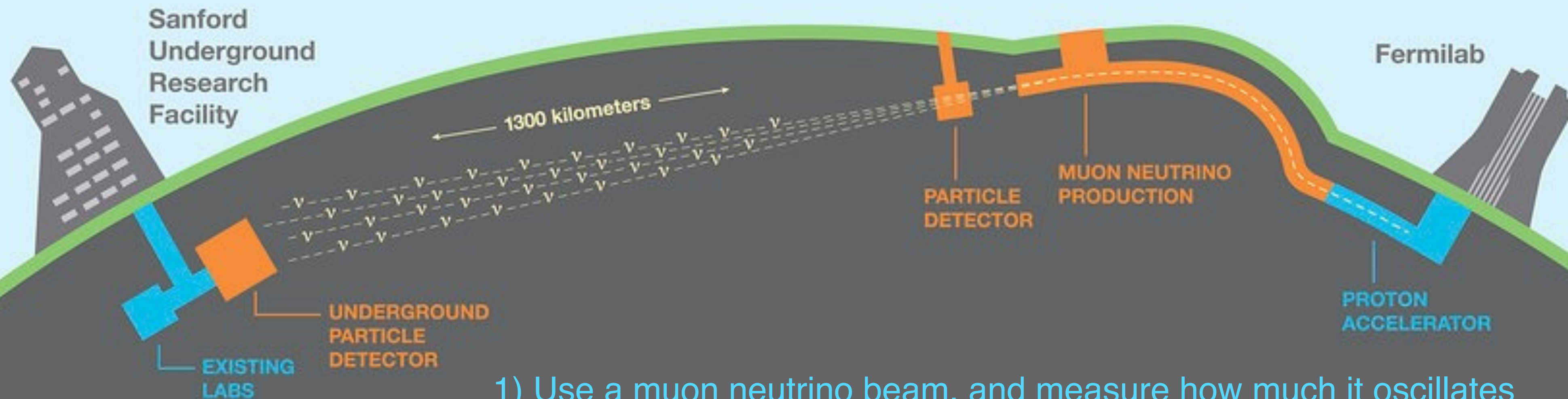
NEUTRINOS... OSCILLATE!

- The *special* thing about neutrinos is that they change into other types of neutrino (or “oscillate”) as they travel
- Do neutrinos and antineutrinos oscillate the same?

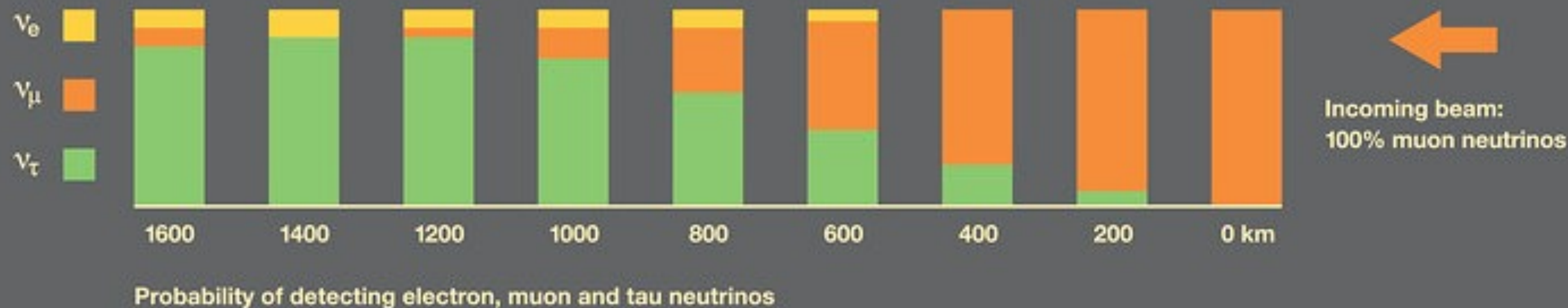


Currently being built!

Deep Underground Neutrino Experiment



- 1) Use a muon neutrino beam, and measure how much it oscillates
- 2) Then use a muon antineutrino beam, and make the same measurement
- 3) Compare the two measurements!



If neutrinos and antineutrinos oscillate at different rates, this could explain the matter/antimatter asymmetry in the universe!

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**WHY DO WE EVEN
HAVE THESE PIECES
AT ALL?**

**WHAT ARE THE REST
OF THE PIECES?**



NEUTRINOS.FNAL.GOV AND WWW.HOME.CERN



@CLAIRE_LEE