Exploring the Energy Frontier

our journey to understanding nature

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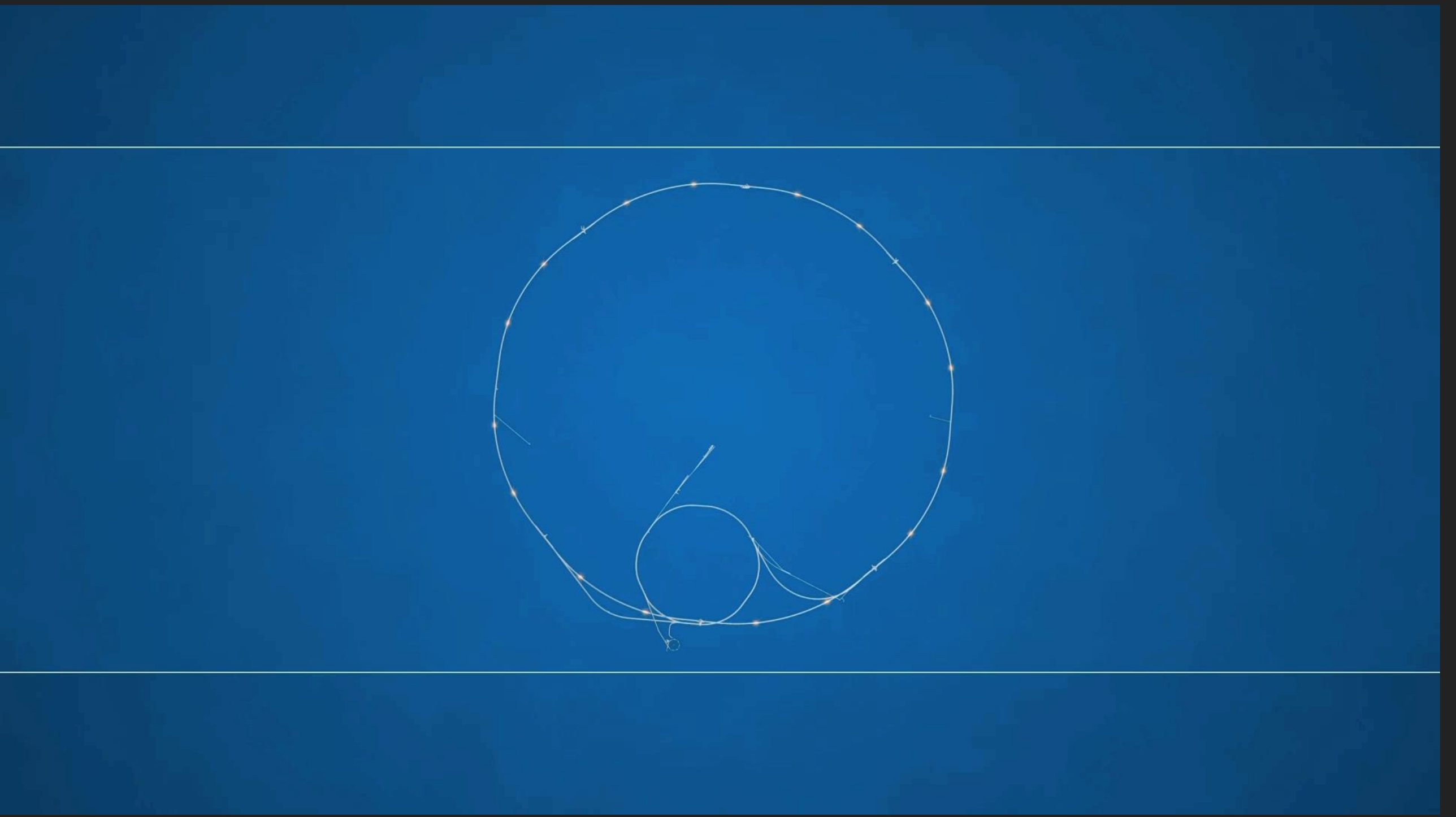
ATLAS EXPERIMENT

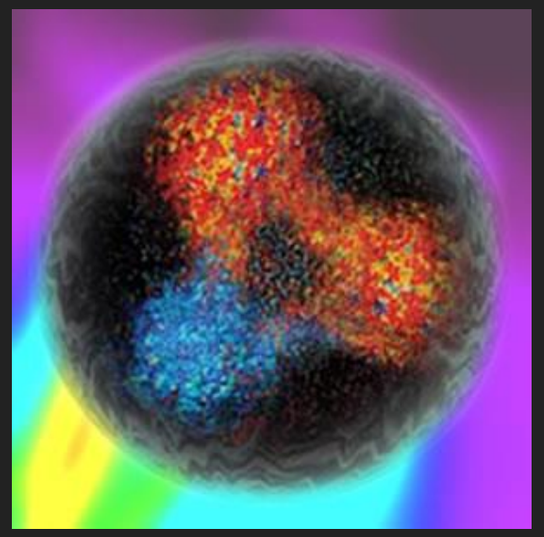
The LHC collides protons millions of times a second!

At the highest ever energy (13 TeV!)



THE LARGE HADRON COLLIDER

The LHC accelerates some of the smallest objects in the universe



up to almost the fastest speeds possible in the universe *(speed of light)*

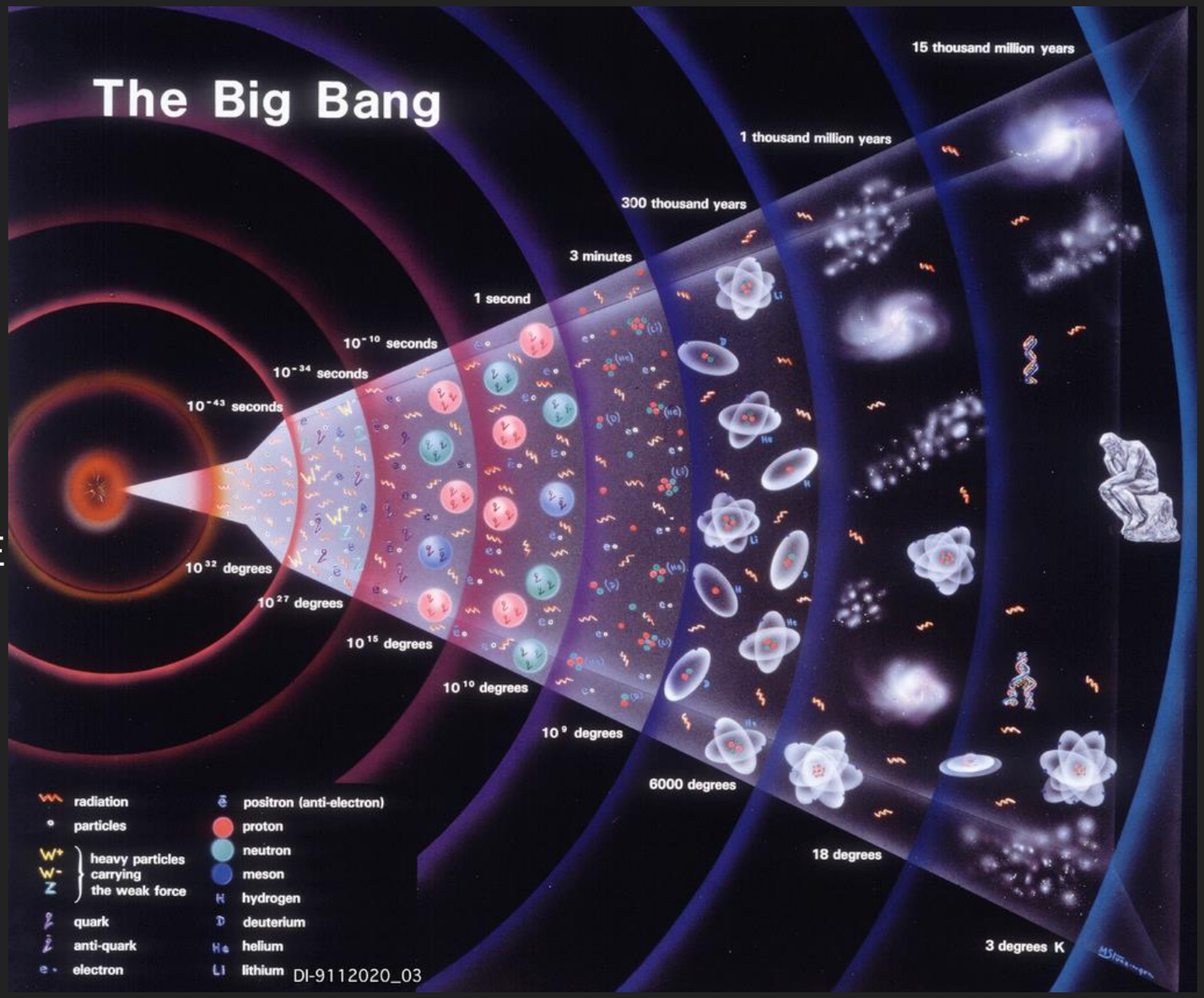
Using magnets 1.9 K (-271.3°C), colder than outer space!

WHY do we smash protons together at high energies millions of times a second?

WHY do we smash protons together at high energies millions of times a second?

HOT

DENSE

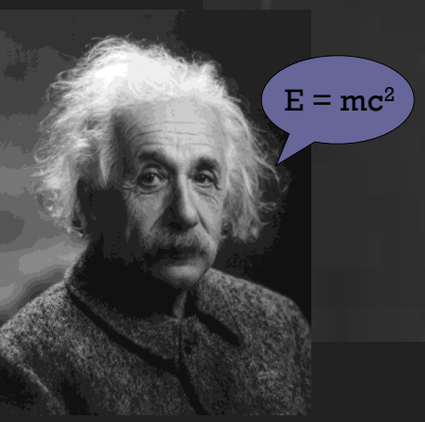


COOL

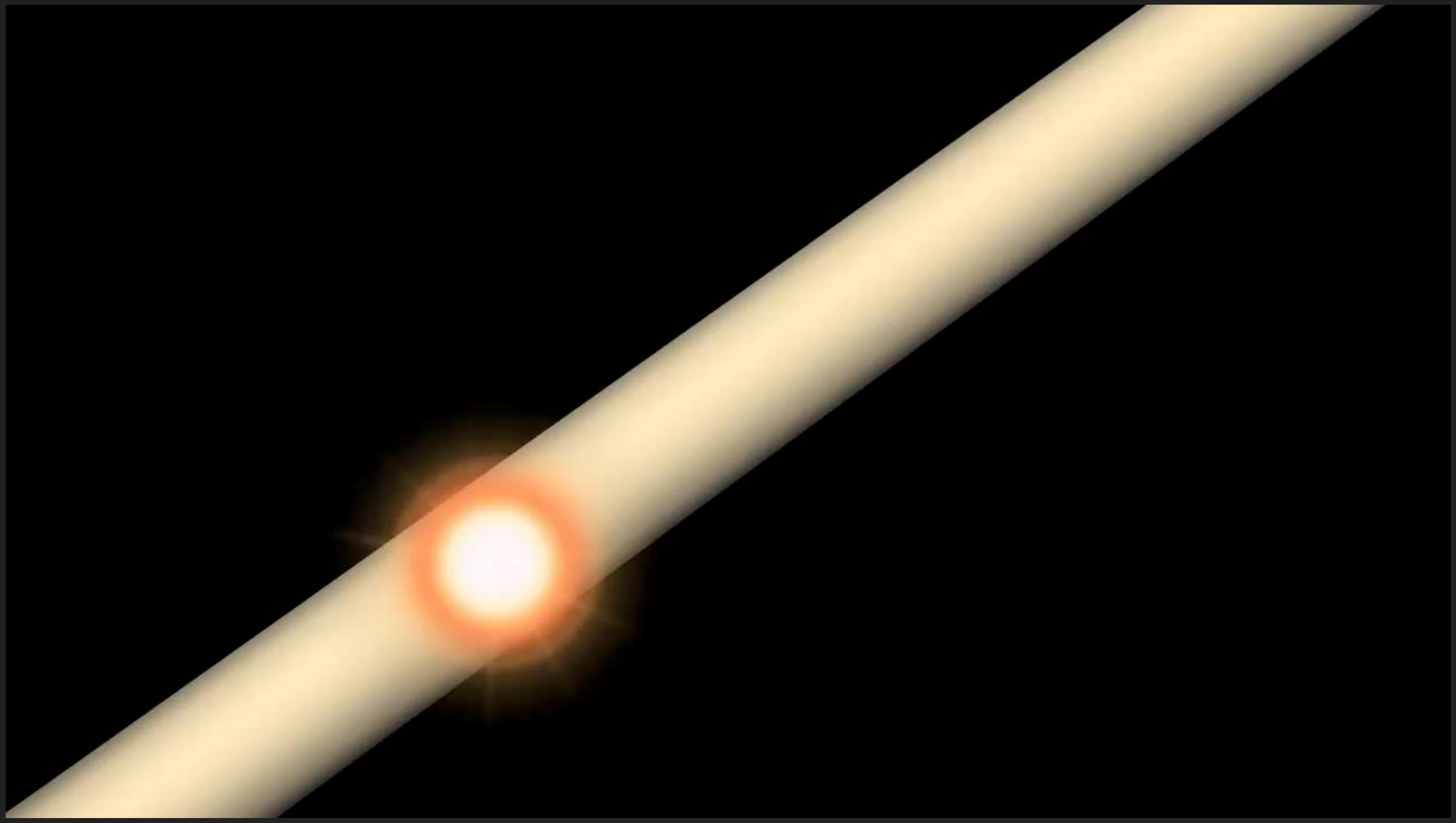
EXPANDED

WHY do we smash protons together at high energies millions of times a second?

- ✓ RARE particles (like Higgs, or particles we haven’t found yet) are not made very often – so we need MANY collisions to collect a large enough sample



HOW DO WE STUDY PARTICLE PHYSICS?



WHAT DOES A PARTICLE PHYSICIST DO?

Questions we ask:

- Where did everything come from?
- What is everything made out of?
- How does it work (interact)?

Physicists are ambitious!

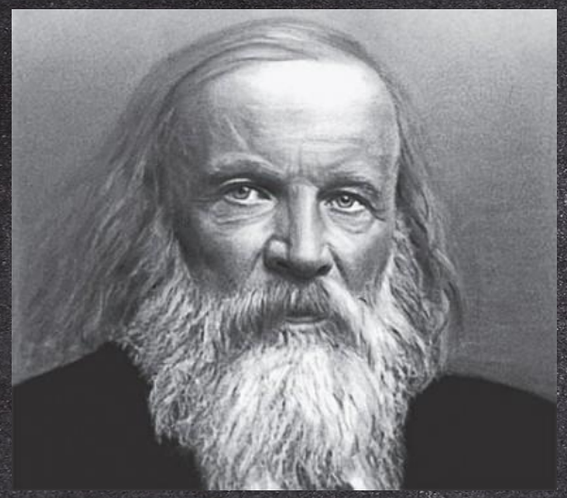
Turn 20th century Lord Kelvin (maybe) said that Physics was basically finished ☺

Only some decimal places to be sorted out!

Along came Quantum Mechanics

Special and General Relativity

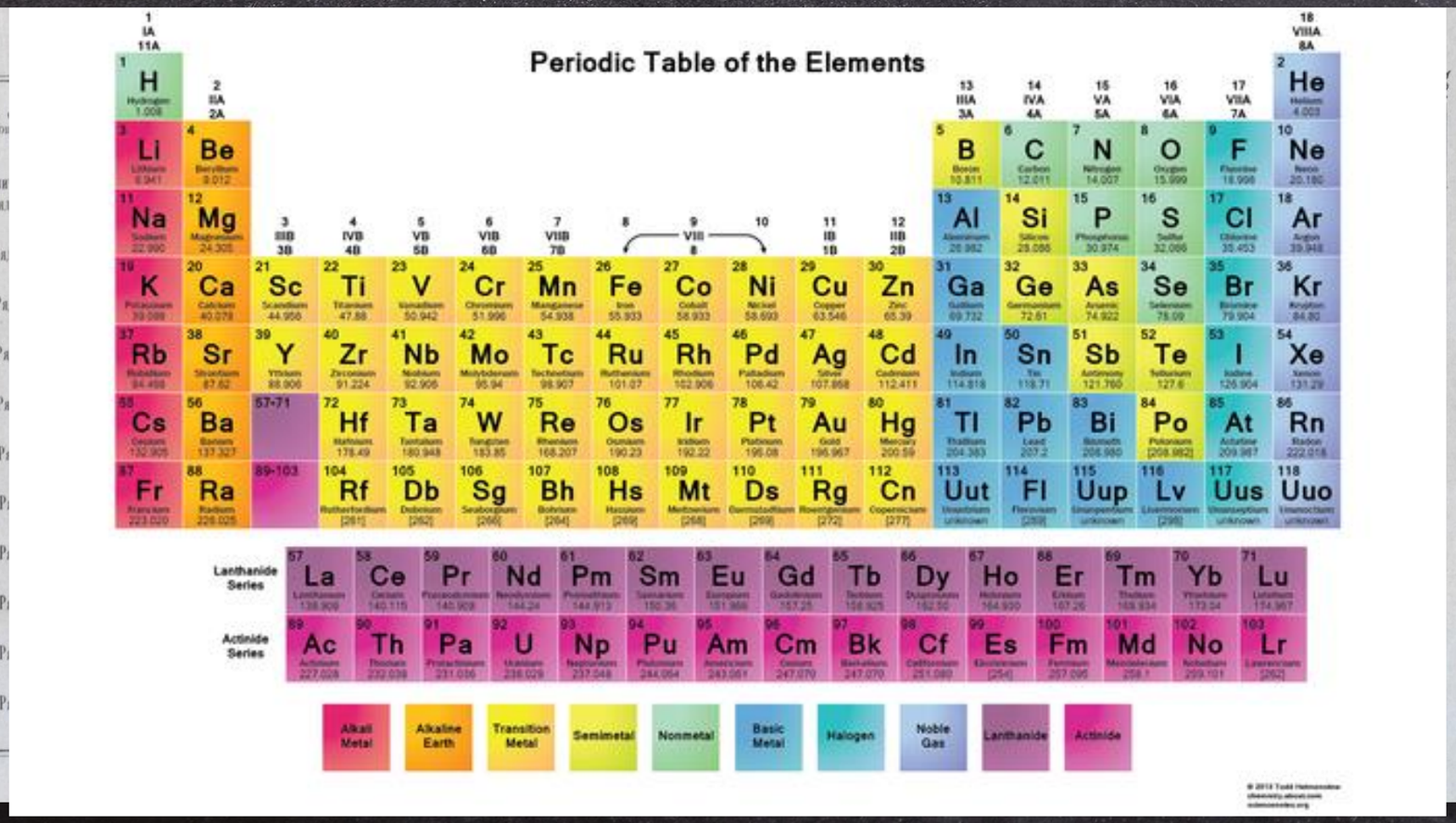
Quantum Field Theory that led to our Standard Model of Particle Physics



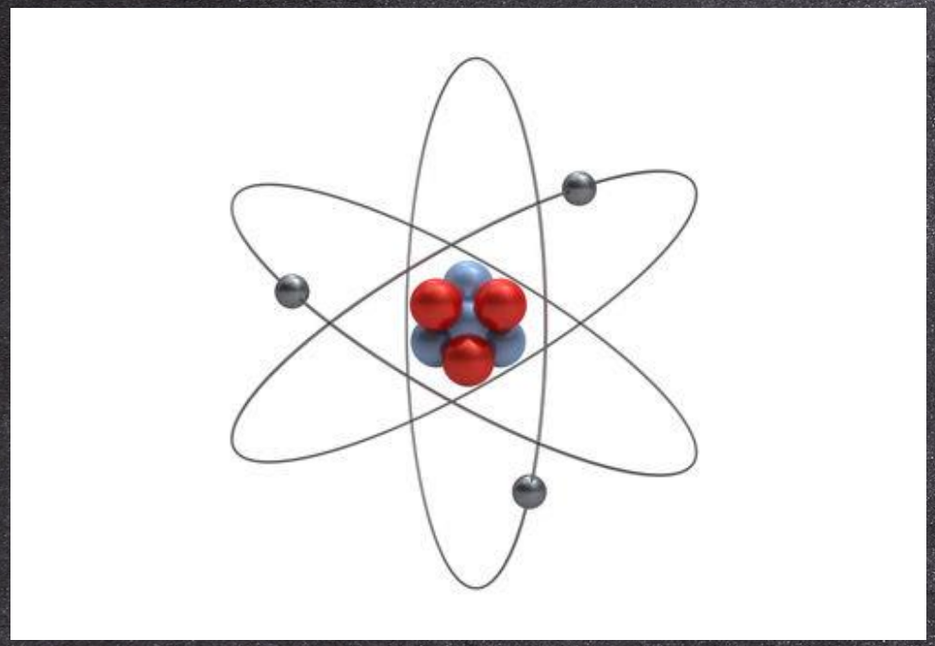
In 1869 Russian chemist Dimitri Mendeleev published the **periodic table**, arranging chemical elements by atomic mass.

~ **80 elements** – WHY SO MANY?

Is there a simpler structure?



WHAT IS EVERYTHING MADE OF?



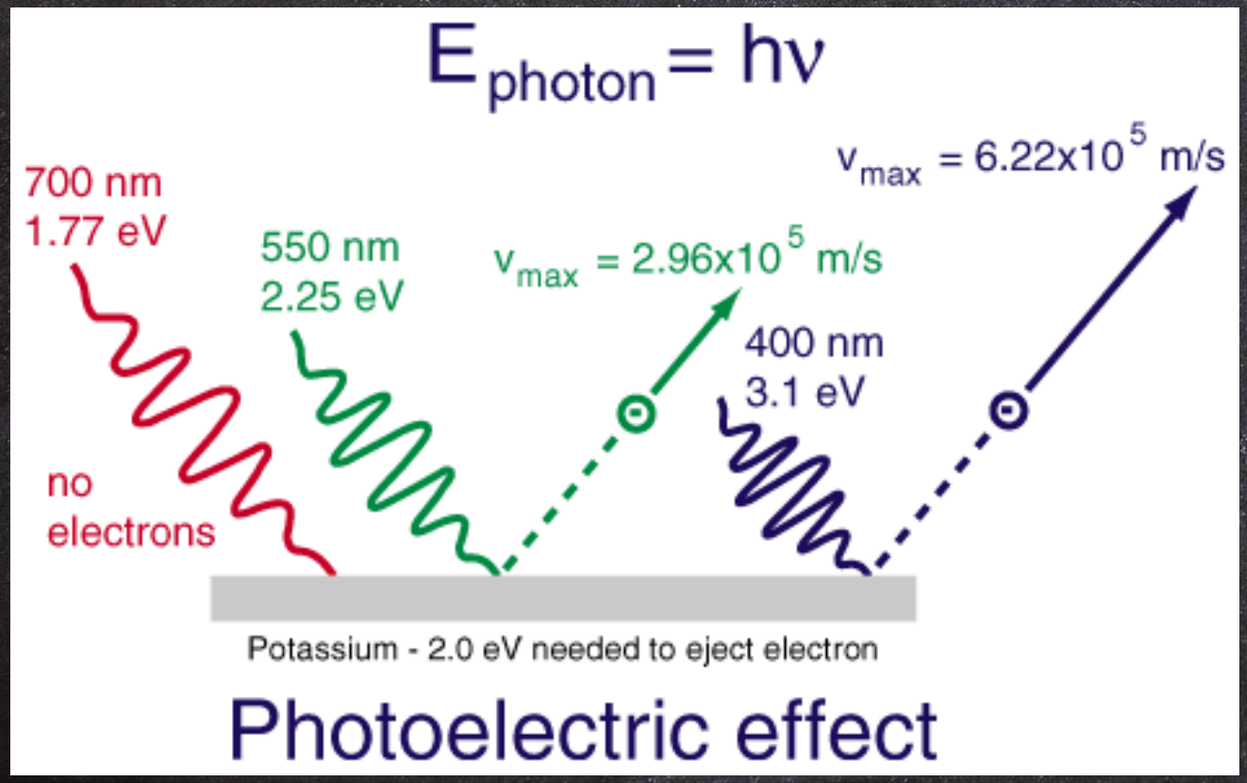
Proton

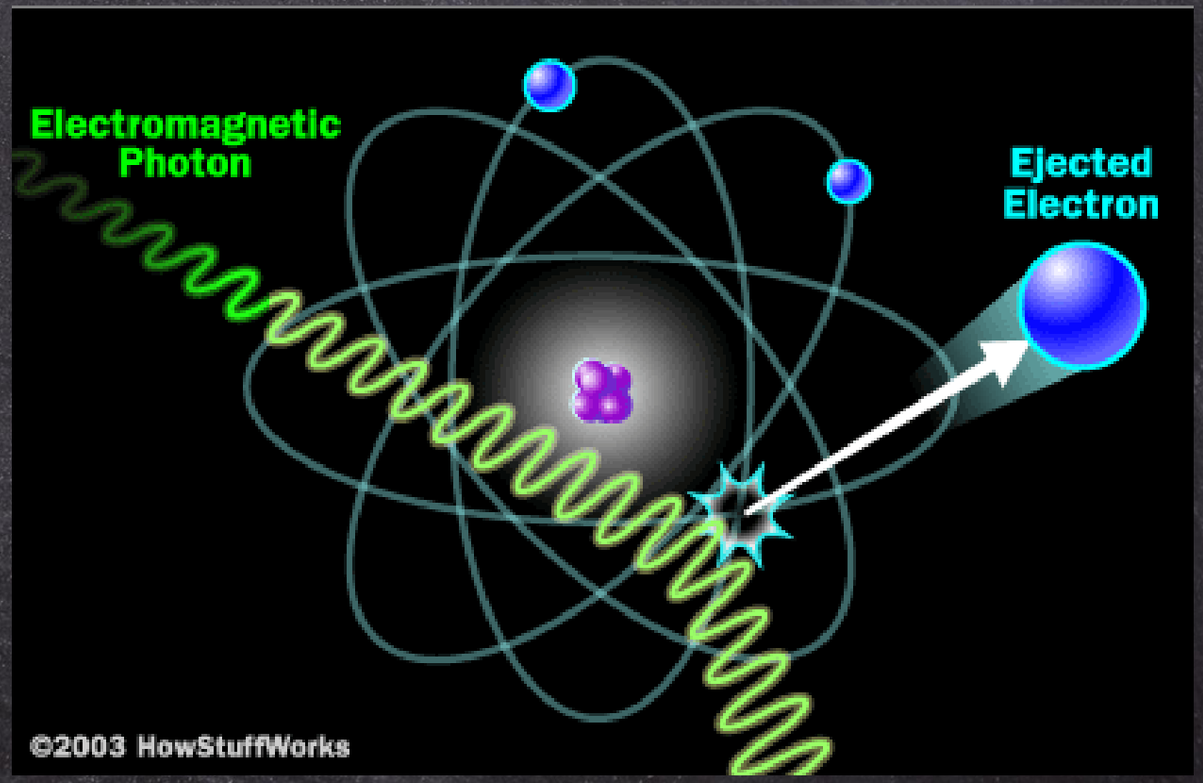
Neutron

Electron

- 1897 electron discovered by J.J. Thompson
- 1911 nucleus of the atom discovered by Ernest Rutherford, and nucleus of hydrogen a proton
- 1932 neutron discovered by James Chadwick

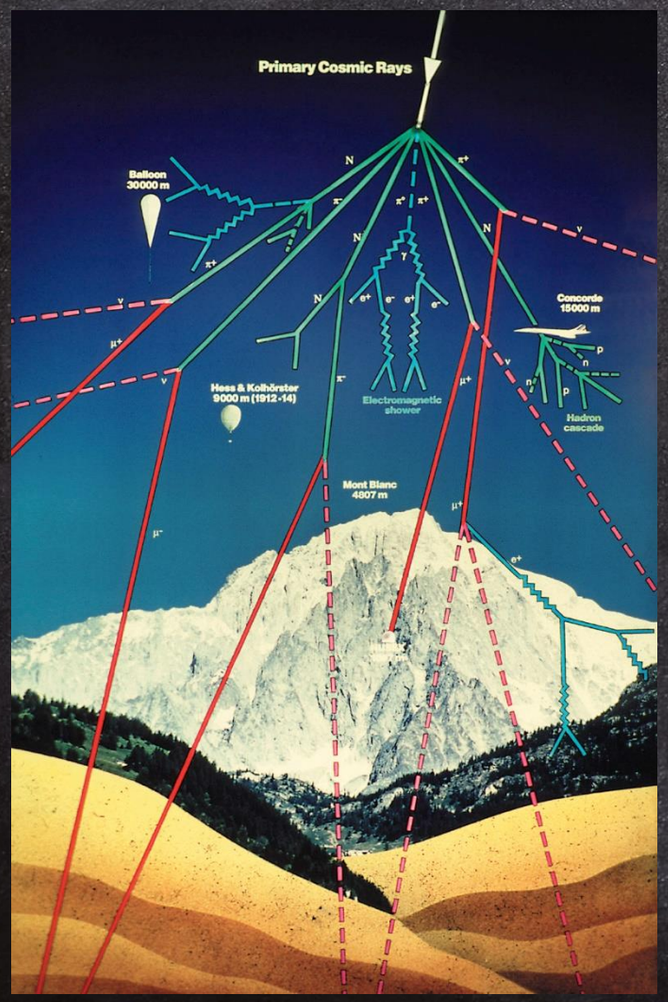
- Photon – particle of the electromagnetic force suggested by Einstein in 1905
- Electromagnetic waves could only exist as discrete wave packets – light quantum or photon





However other particles not part of the atom seemed to appear!

- 1932 positron detected (predicted by Dirac in 1928)
- 1934 neutrinos established in theory – detected in 1956



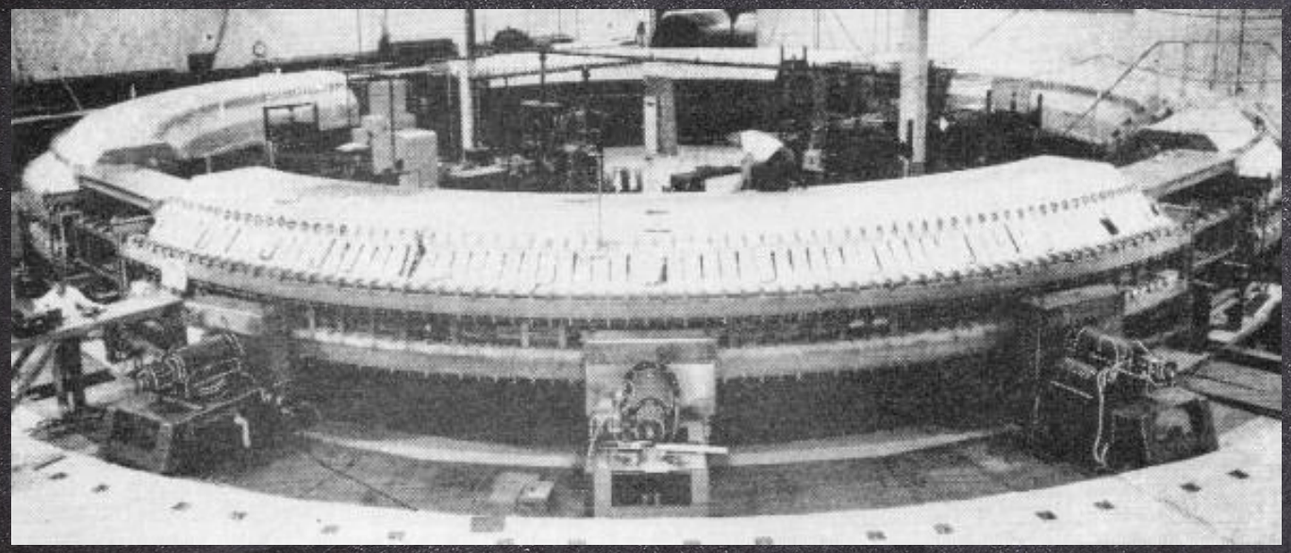
- 1937 muons were discovered in cosmic rays

Who ordered that?

- 1947 pions (a type of meson) were also discovered!!

Things were getting out of hand!
What were all these particles?

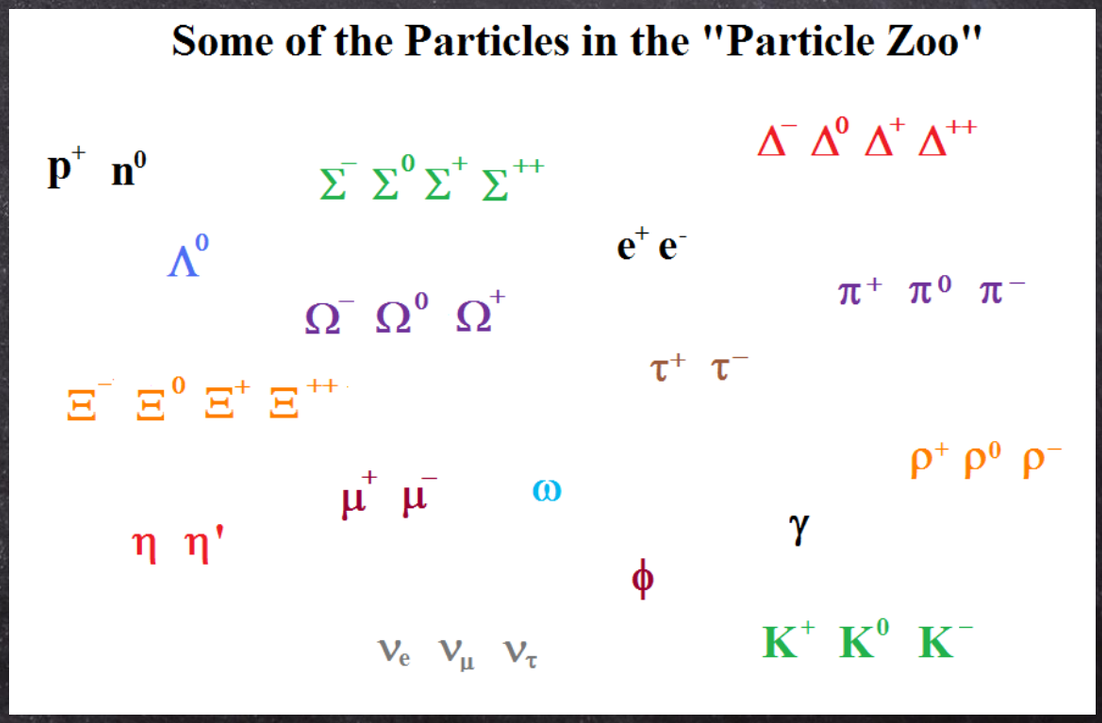
Atom smashers (1950s)



The Brookhaven Cosmotron, at
1.3 – 3.3 GeV accelerator

Plethora of NEW particles started coming out of these atom smashes!

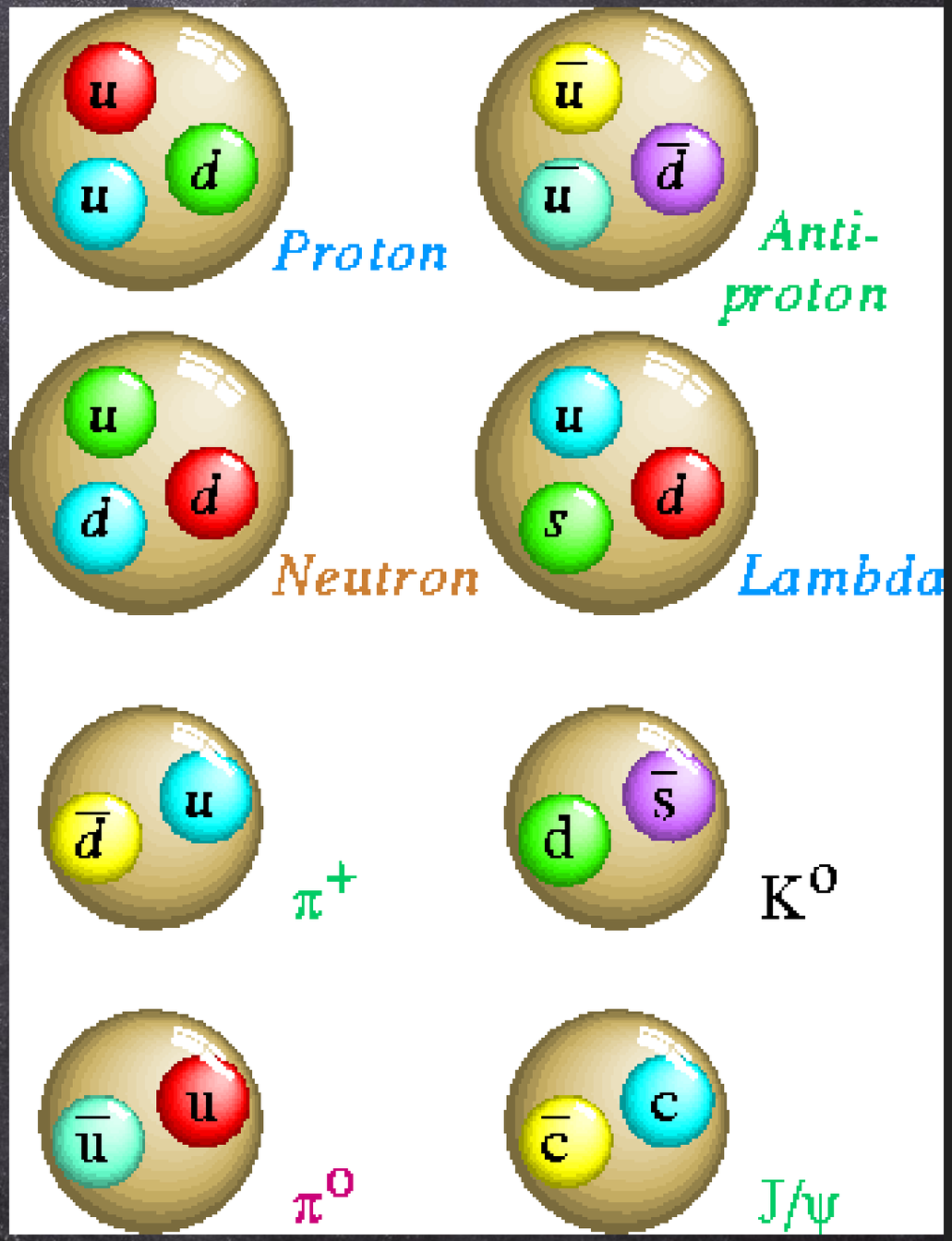
Sigma particles, rho particles, Delta particles, kaons, Lambda…



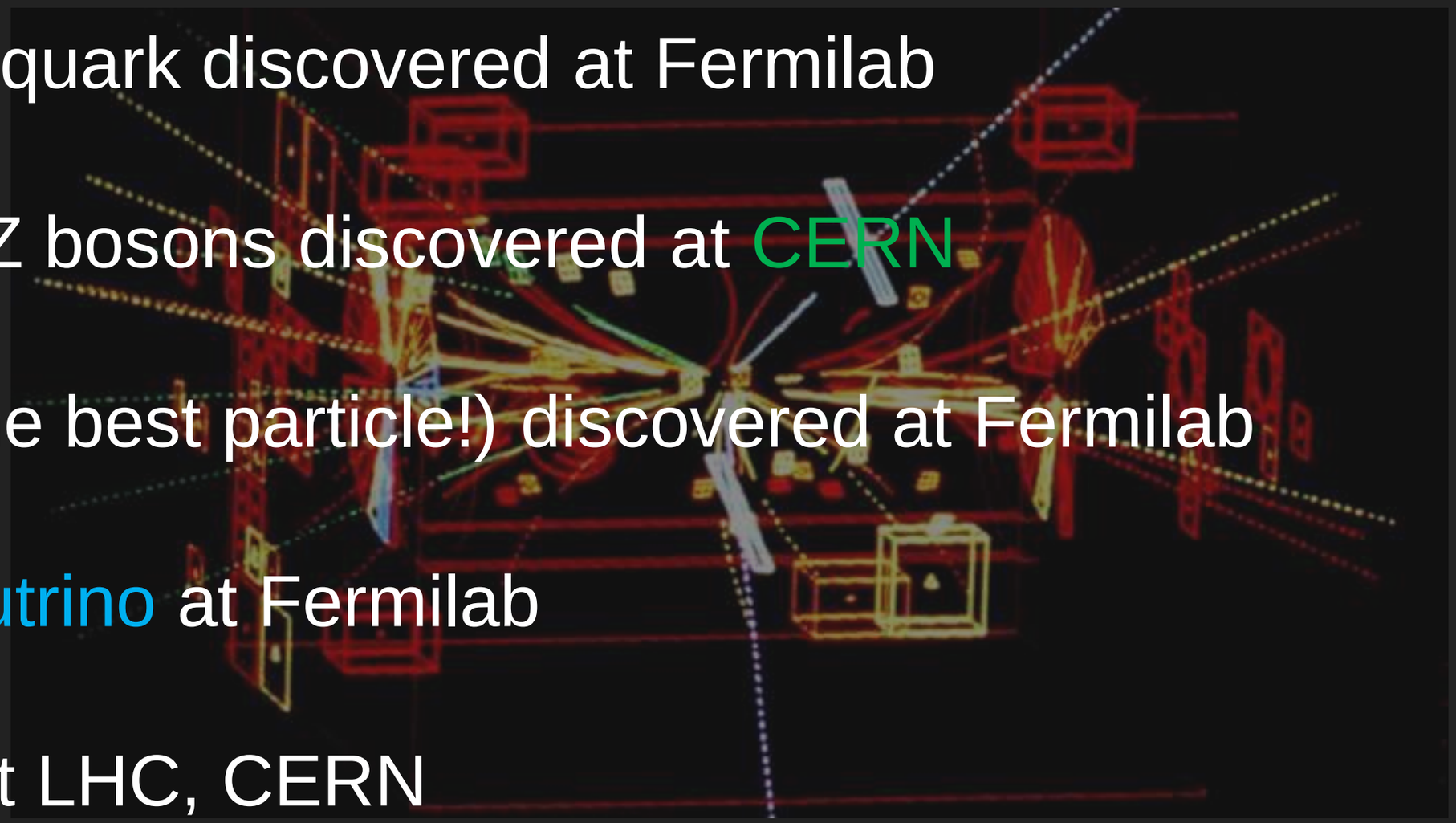
BREAK THROUGH!!!

1960s Murray Gell-Mann of Caltech said hadrons are composed of more fundamental particles which he called quarks.

The word comes from a line in *Finnegans Wake*, a book written by James Joyce.



DISCOVERY: Bottom, Top, WZ, HIGGS!



1977 Bottom quark discovered at Fermilab

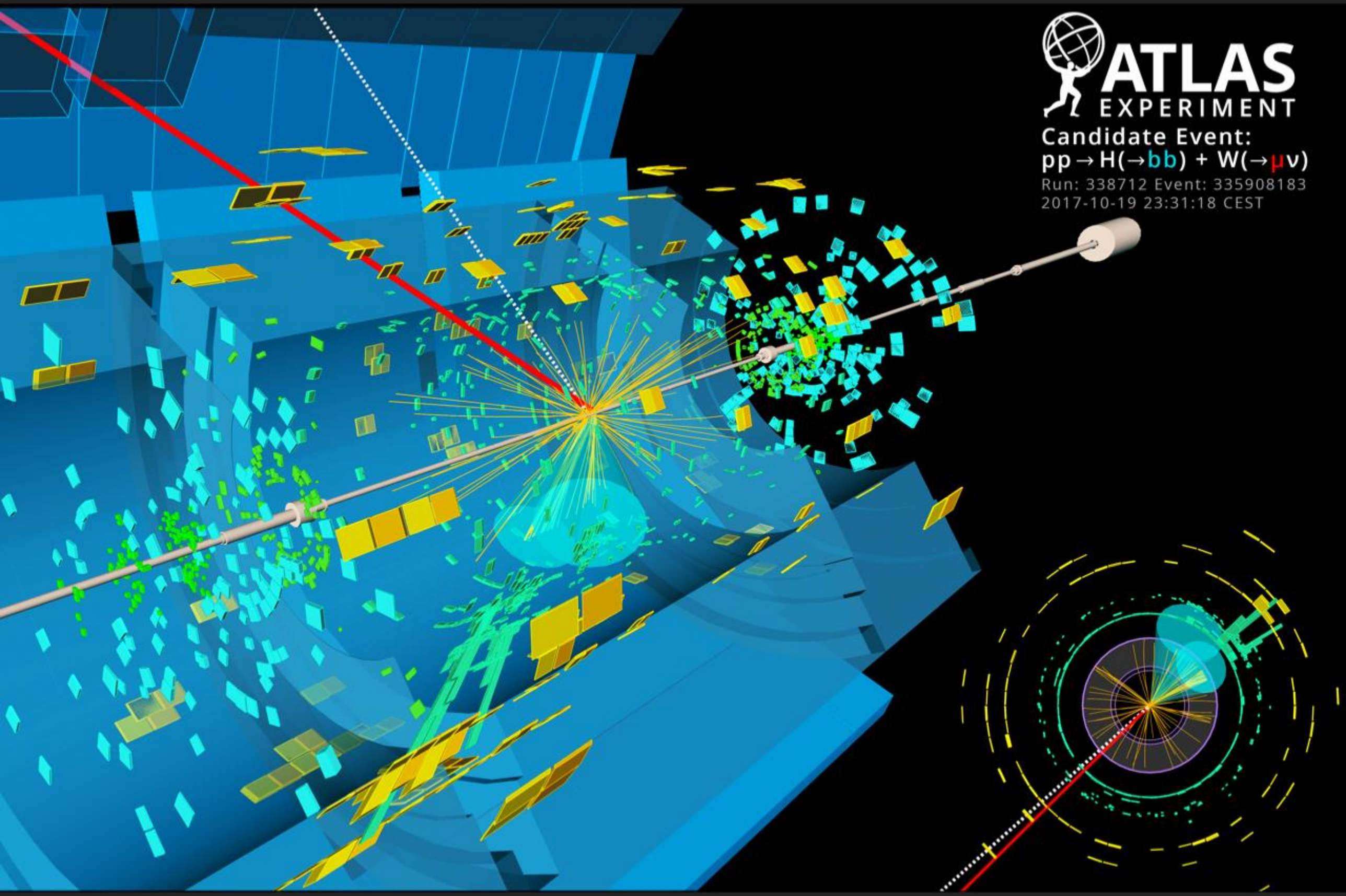
1983 W and Z bosons discovered at CERN

1995 TOP (the best particle!) discovered at Fermilab

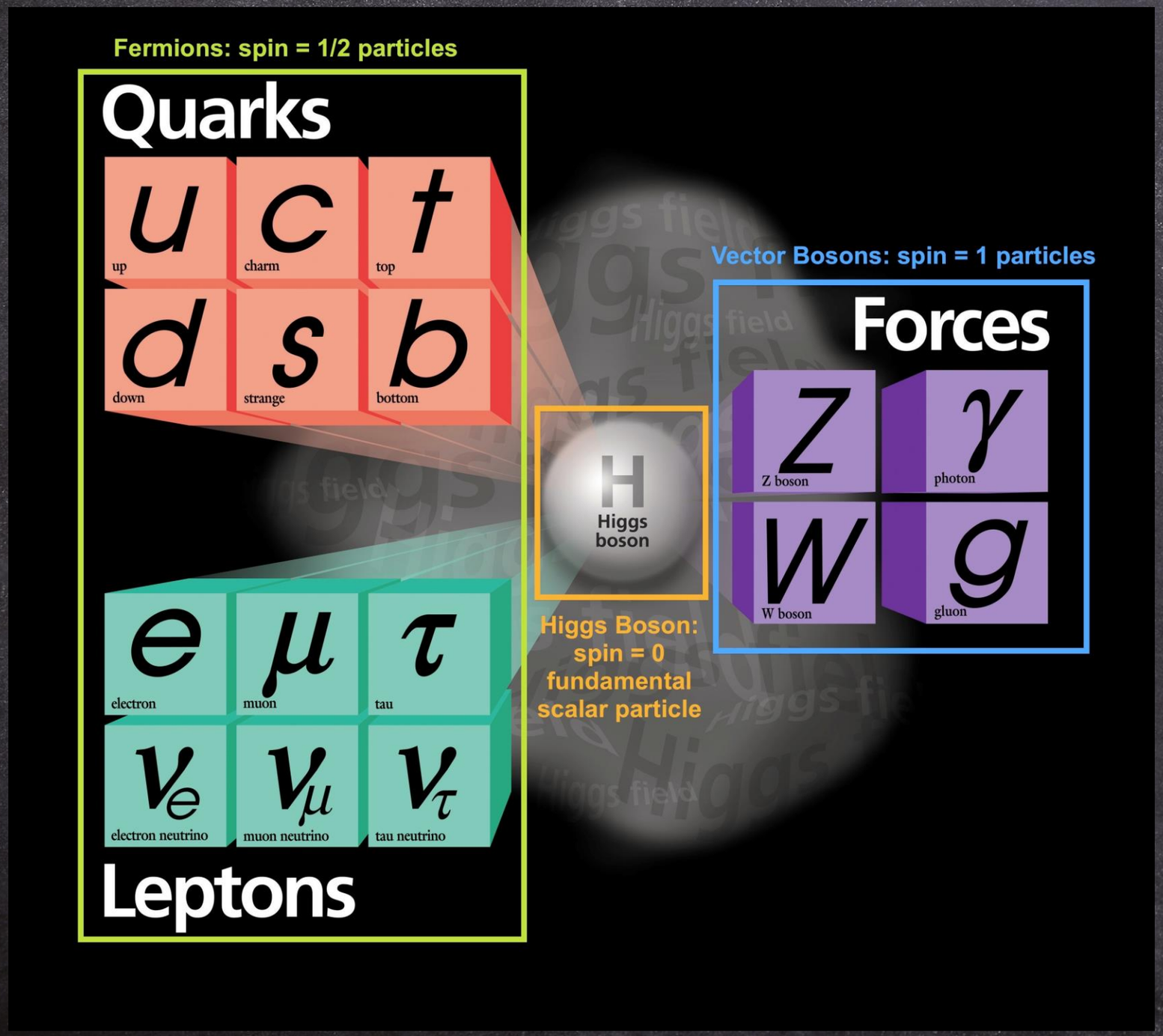
2000 Tau neutrino at Fermilab

2012 Higgs at LHC, CERN

WHAT IS EVERYTHING MADE OF?



STANDARD MODEL

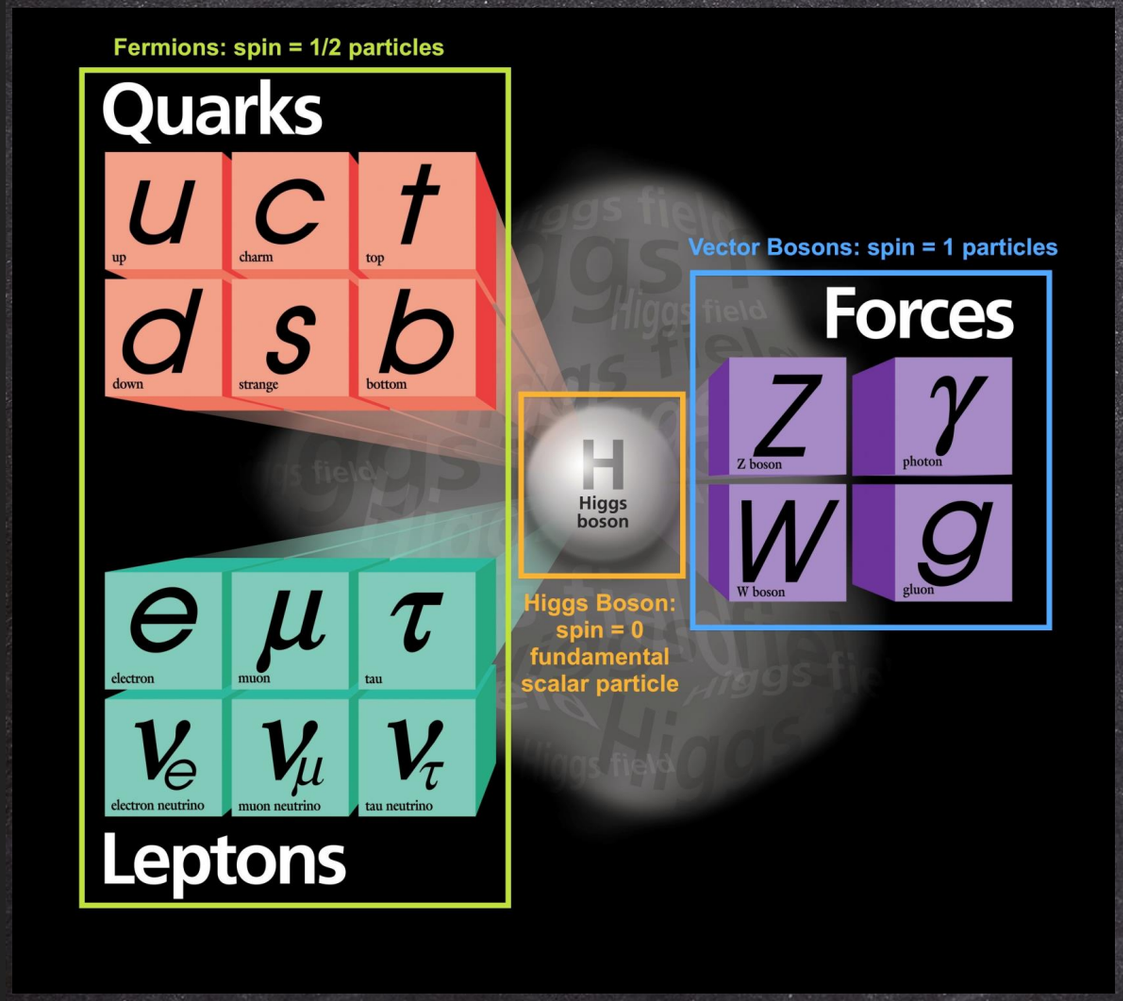


WE STILL HAVE NO IDEA WHY THE STANDARD MODEL WORKS SO WELL!!!

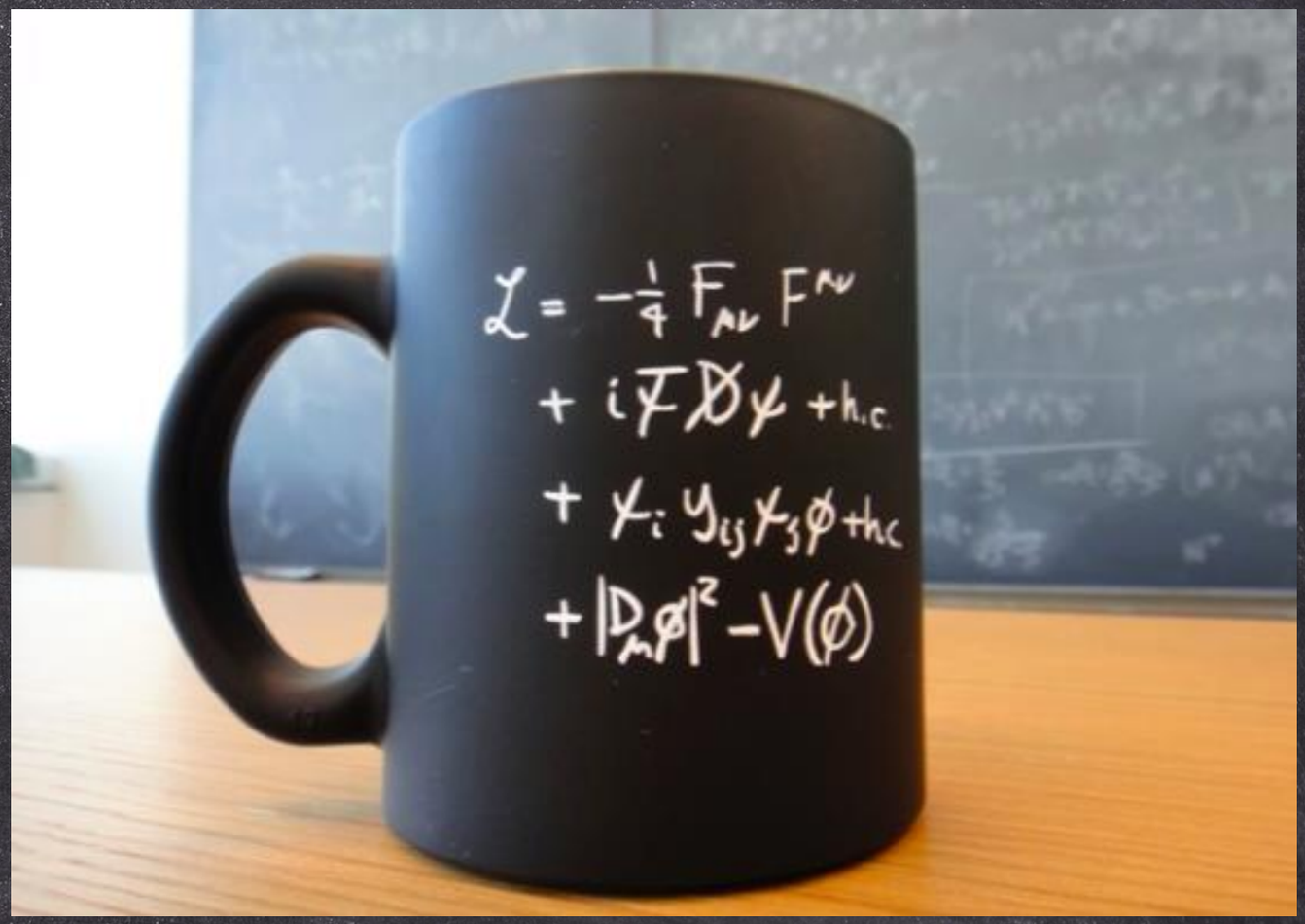
WHAT IS EVERYTHING MADE OUT OF AND HOW TO THINGS INTERACT

STANDRAD MODEL OF PARTICLE PHYSICS

FUNDAMENTAL PARTICLES



RULES OF HOW THEY INTERACT



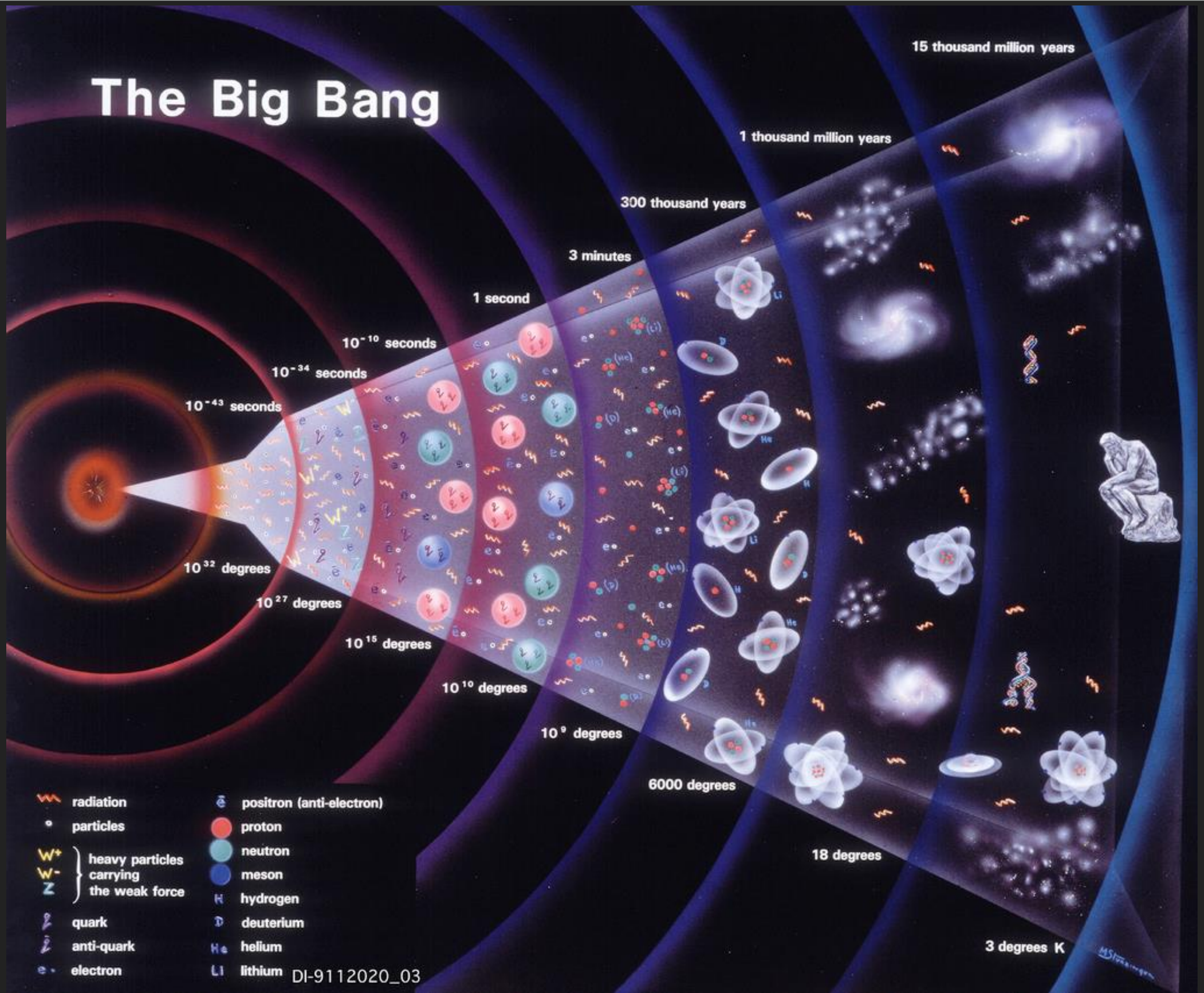
$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu 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 (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) - 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(\tfrac{1}{c_w}Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\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 \right) - \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) .$$

STANDARD MODEL HD!

WHAT IS EVERYTHING MADE OUT OF?

If the Universe were a game of chess, the theories of the forces (such as the EM force) would dictate the way the pieces (or particles) would move..

- Each particle / chess piece has its own properties so we know what it ‘looks’ like
- With particle physics, how they move/interact is dependent of the rules of the Standard Model


The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10⁻¹⁰ seconds
10⁻³⁴ seconds
10⁻⁴³ seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+
W-
Z
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium
DI-9112020_03

WHAT ARE WE LOOKING FOR?

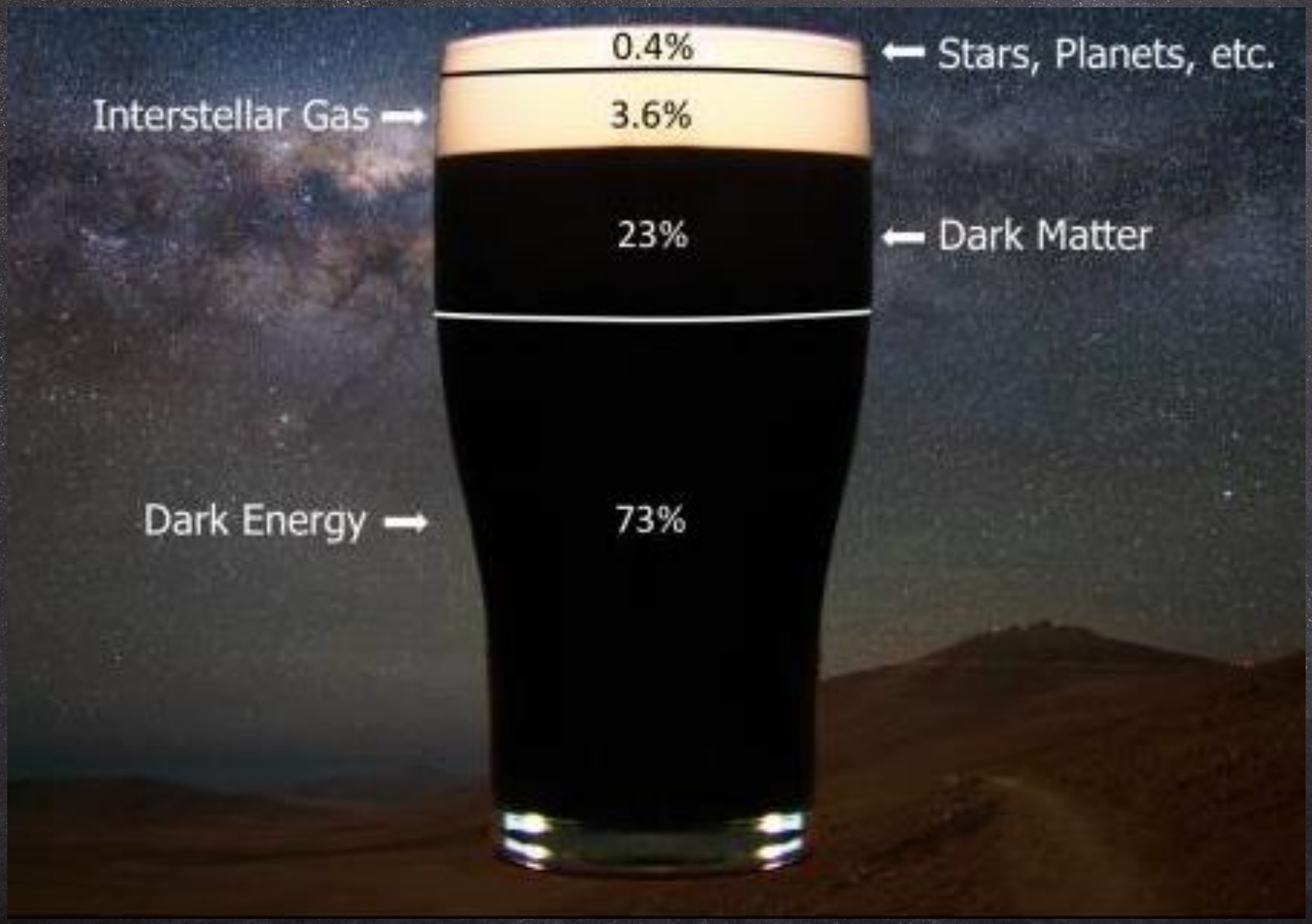
THERE MUST BE NEW PHYSICS AT HIGHER ENERGIES

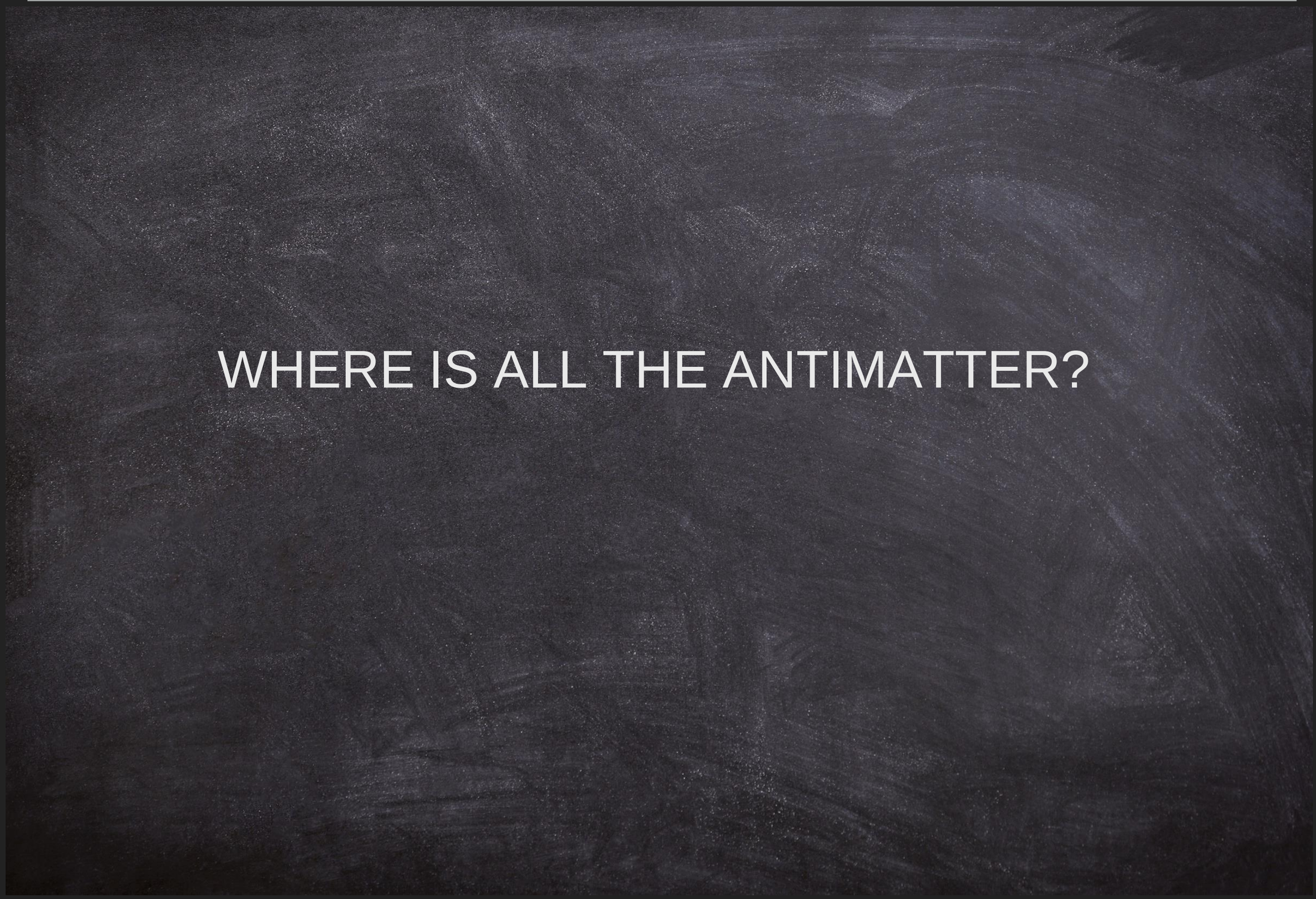
– solve hierarchy problem ☺

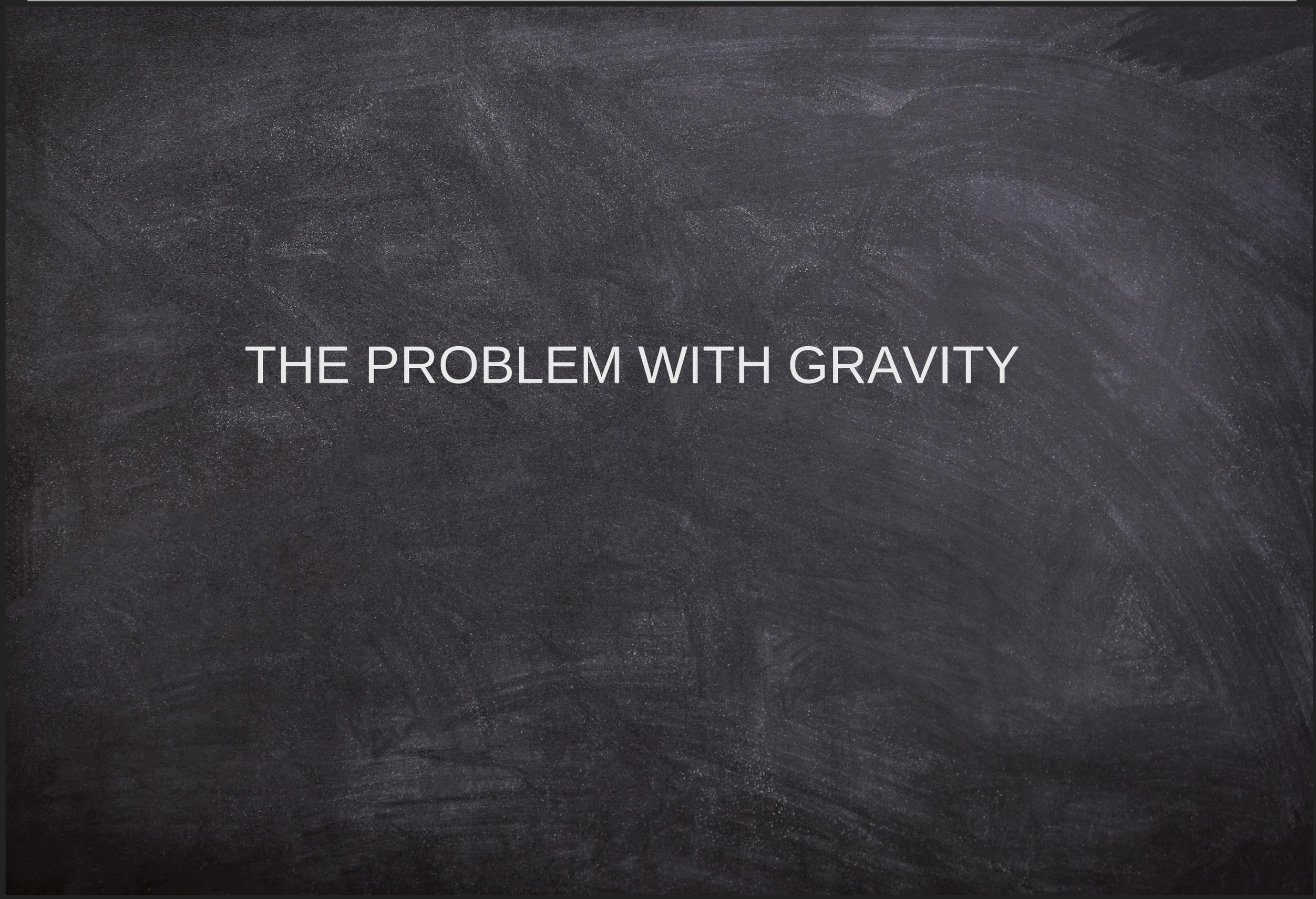
THERE ARE UNSOLVED MYSTERIES!!!

- ✓ DARK MATTER – DARK ENERGY
- ✓ MATTER – ANTIMATTER ASYMMETRY
- ✓ GRAVITY – HOW DOES IT FIT IN?

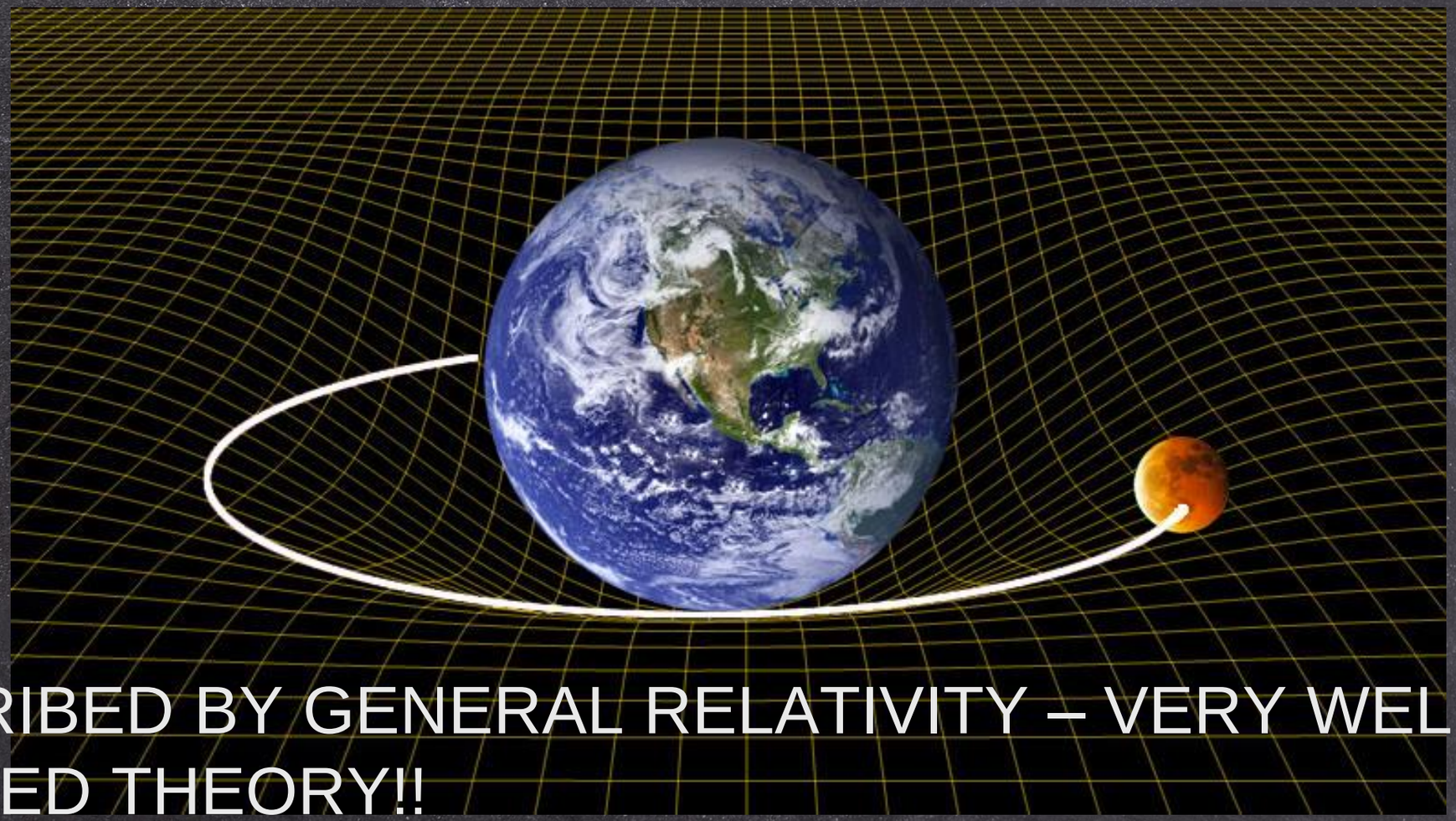
THE DARK UNIVERSE




WHERE IS ALL THE ANTIMATTER?


THE PROBLEM WITH GRAVITY

THE PROBLEM WITH GRAVITY



DESCRIBED BY GENERAL RELATIVITY – VERY WELL VERIFIED THEORY!!

WE CURRENTLY CANNOT DESCRIBE GRAVITY IN THE STANDARD MODEL – IT'S TOO WEAK, WE CAN'T QUANTIZE IT :(

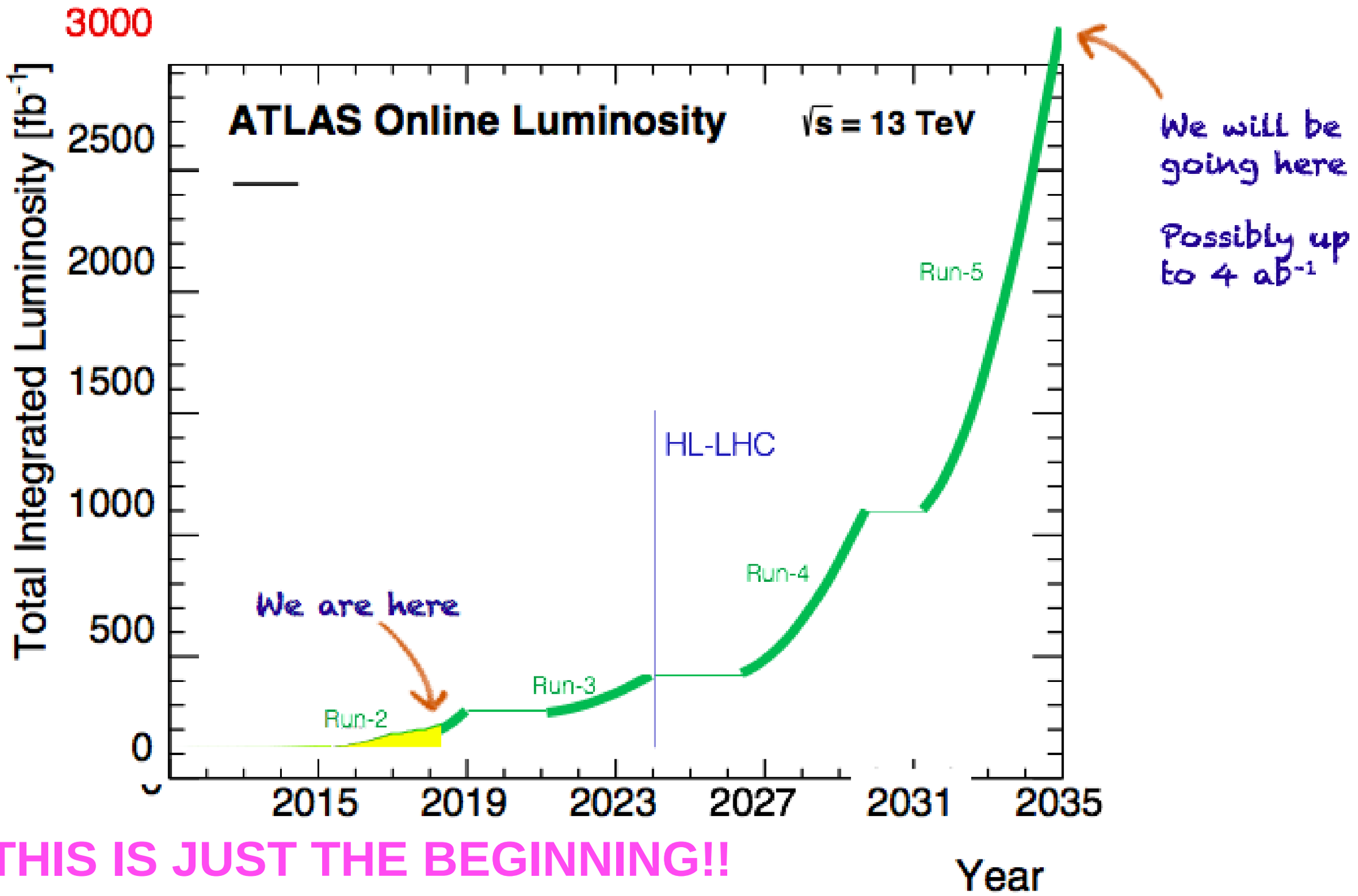
A LOT TO DO..

WE HAVE BUILT AN AMAZING MACHINE THAT IS RUNNING AT UNPRECENDENTED RATES AND ENERGIES !

WE HAVE THOUSANDS OF SCIENTISTS, ENGINEERS, AND TECHNICIAN ALL OVER THE WORLD, WORKING TOGETHER WITH A COMMON GOAL!

WE HAVE TOOLS WE NEVER HAD BEFORE!

- MACHINE LEARNING / DEEP LEARNING
- GRID AND CLOUD COMPUTING
- CUTTING EDGE TECHNOLOGY, ELECTRONICS, HARDWARE



THIS IS JUST THE BEGINNING!!

EXCITING TIME TO BE STUDYING PHYSICS!

- 100 years ago scientists thought physics was almost complete, look how far we have come
- Who knows what the next 100 years of investigation will bring, along with advances in technology and tools

The unanswered questions we have about our Universe tell us…

we have just scratched the surface, there is a deeper and more connected theory that describes matter, space and time

There is so much more to learn

Watch this space .

We are at the beginning of a tremendous journey, with thousands of scientists utilizing and developing cutting edge technology!

We are on the brink of a new way of understanding matter space and time.