The
‘God Particle’
God(%#$!) Particle
Hug Bison
Higgs Boson
BEH Scalar
and Beyond

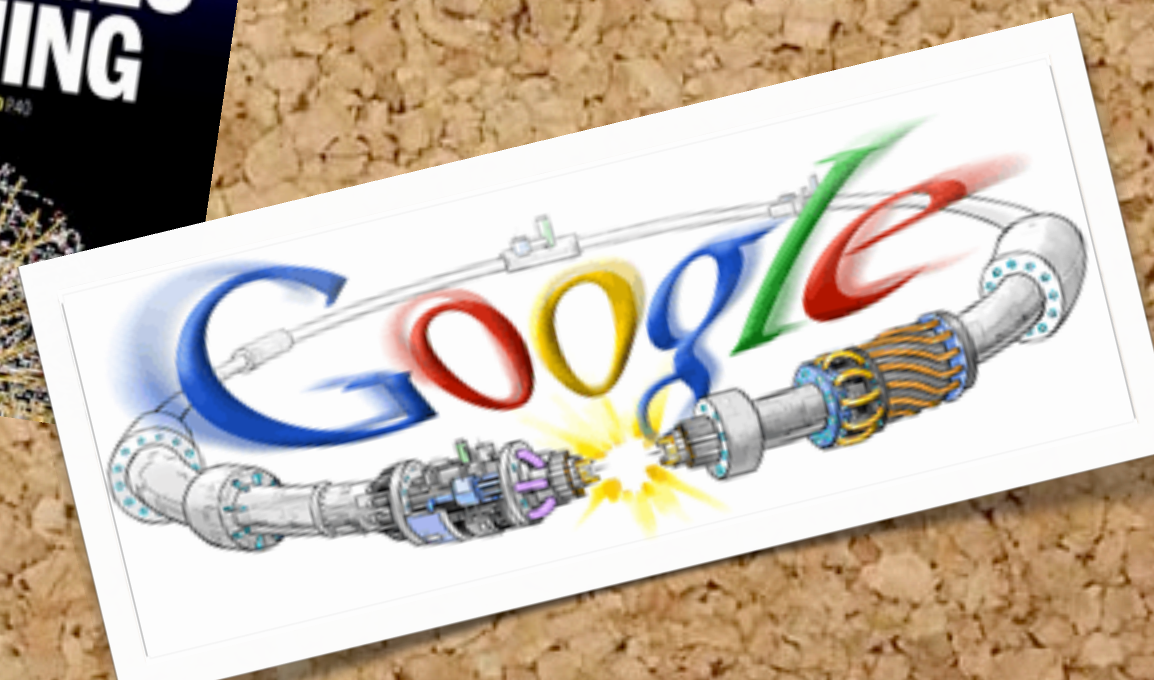
Colin Gay, UBC Physics

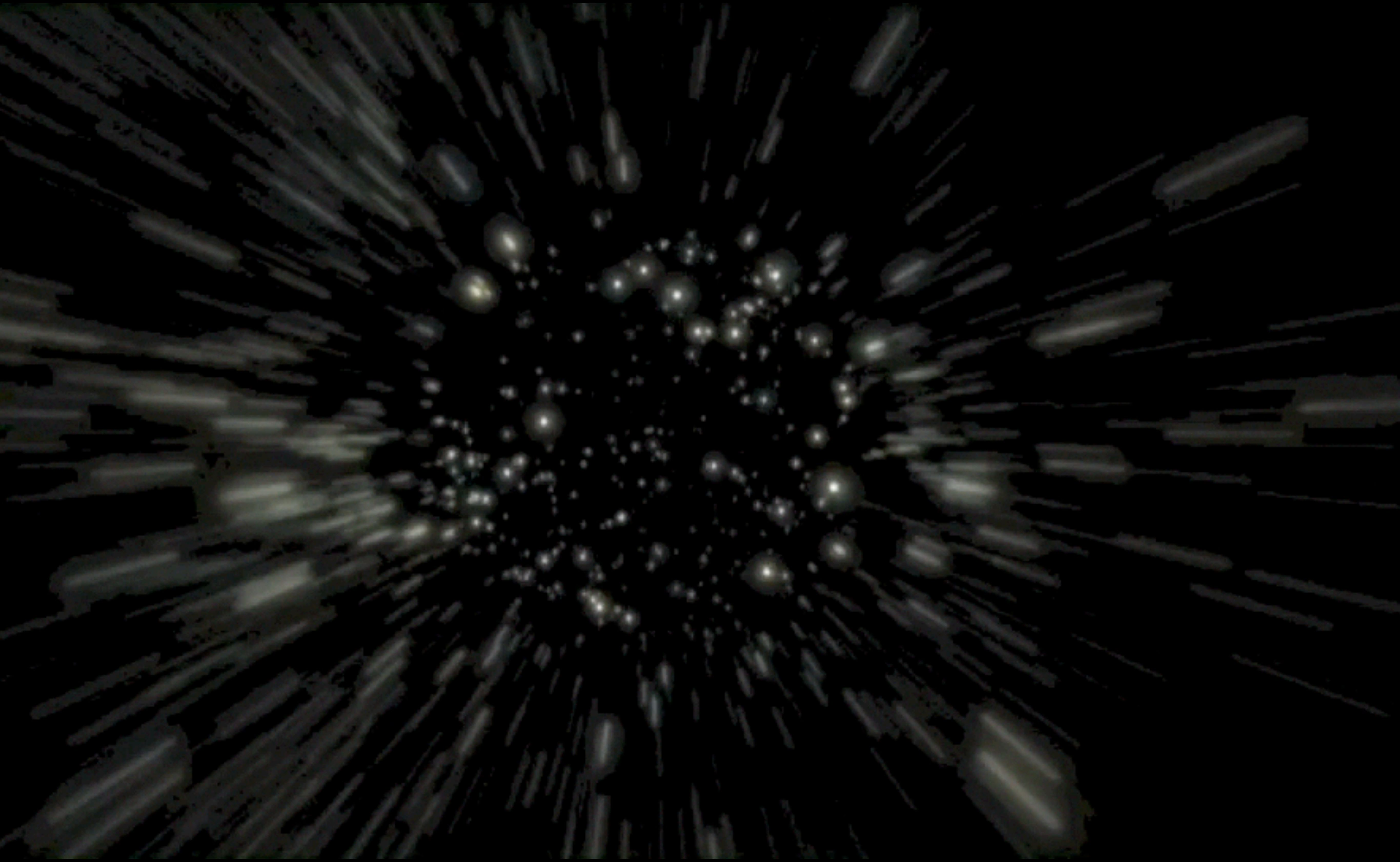
"There is either a violation of probability or some new physics," Dr. Ellis said.

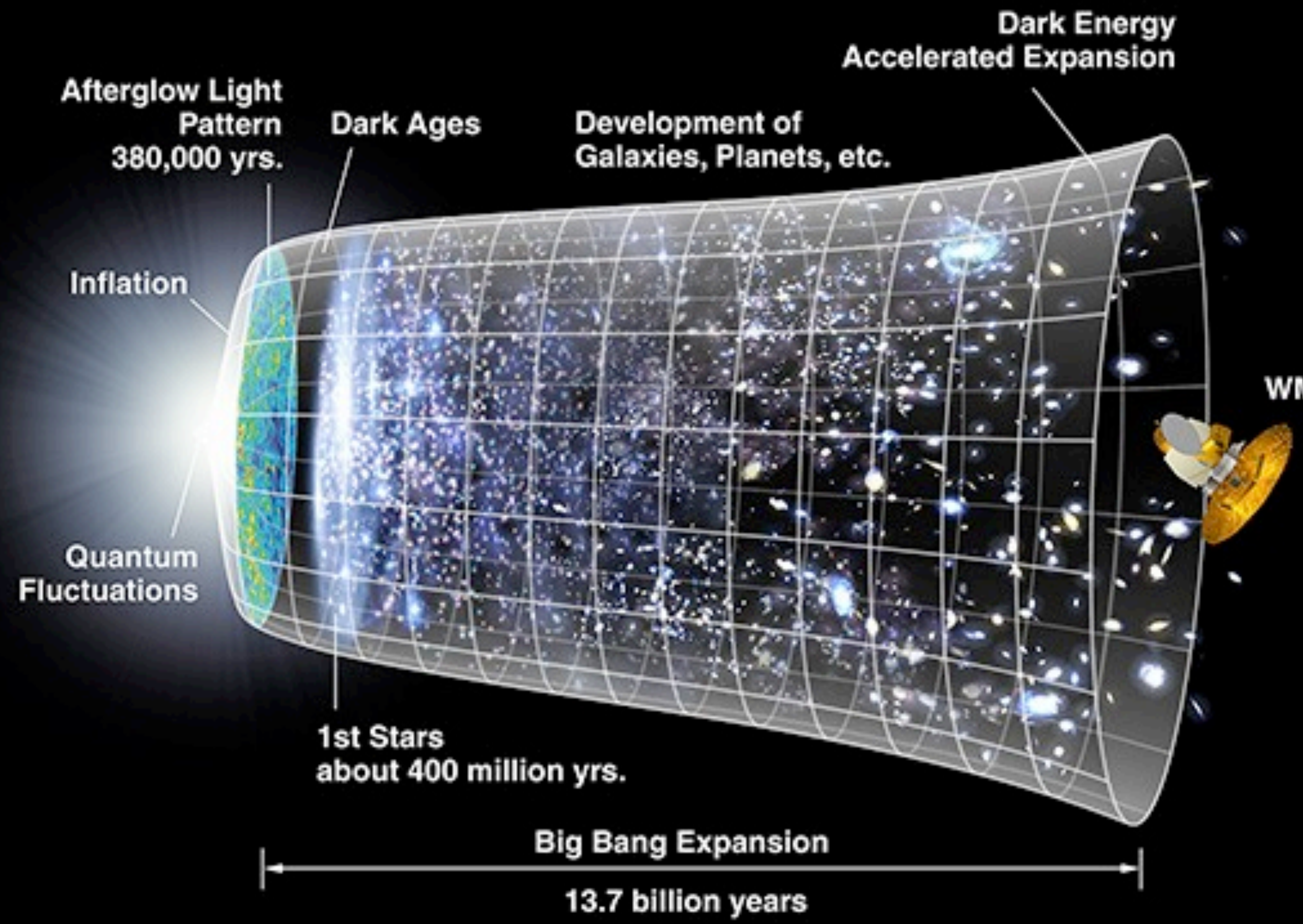
"If you see nothing," said a CERN physicist, John Ellis, "in some sense then, we theorists have been talking rubbish for the last 35 years."

"If the Higgs or something like it doesn't exist," Dr. Arkani-Hamed said, "then some very basic things like quantum mechanics are wrong."

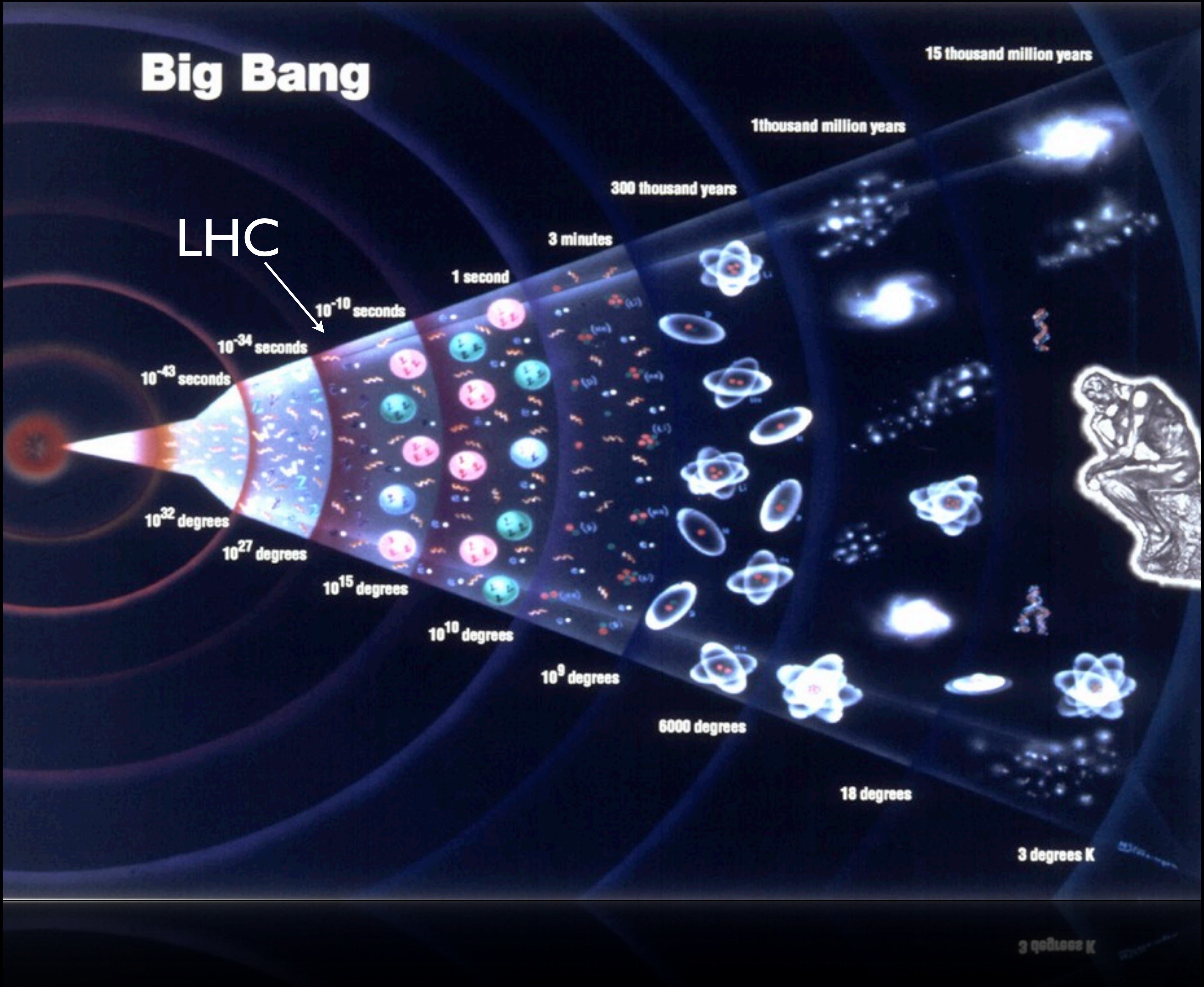
That collider in Switzerland didn't create a universe-gobbling black hole. So far.
-NY Times



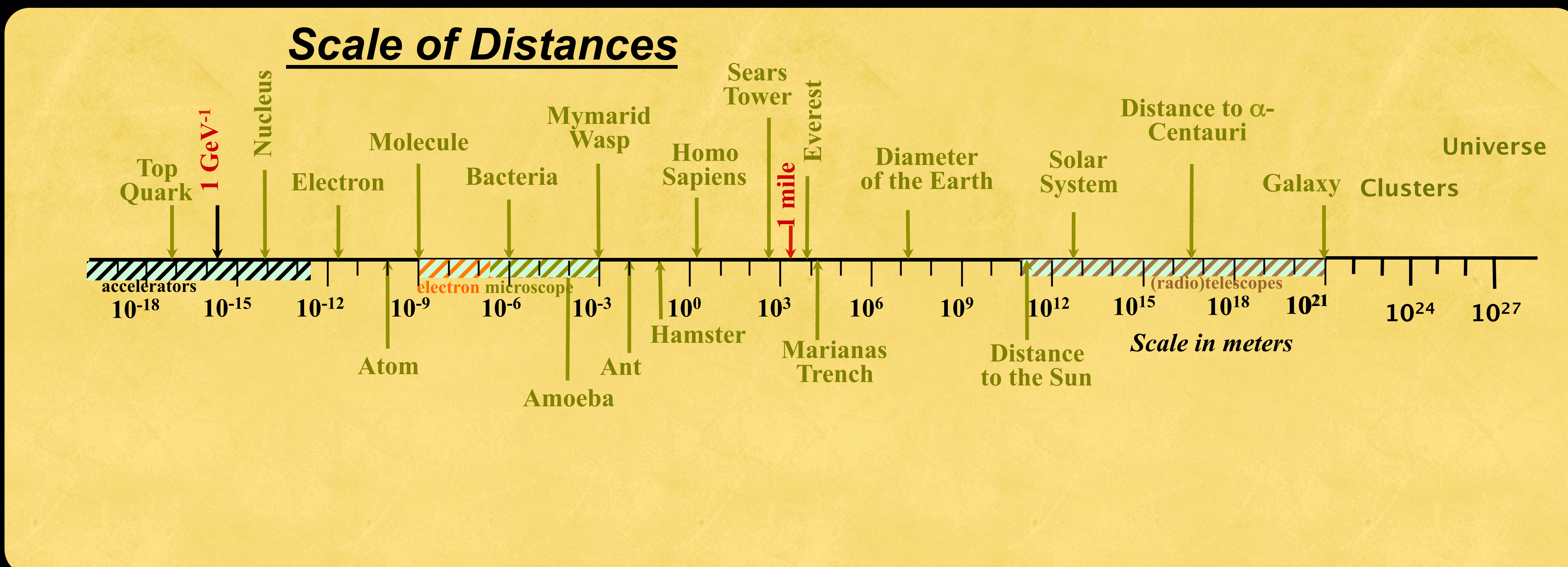




History of the Universe

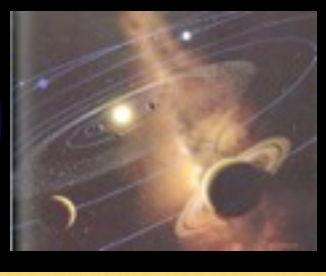
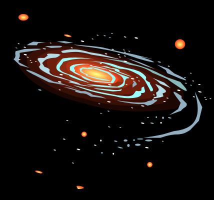
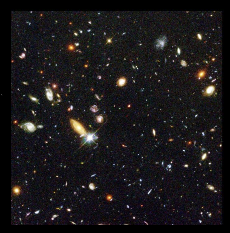
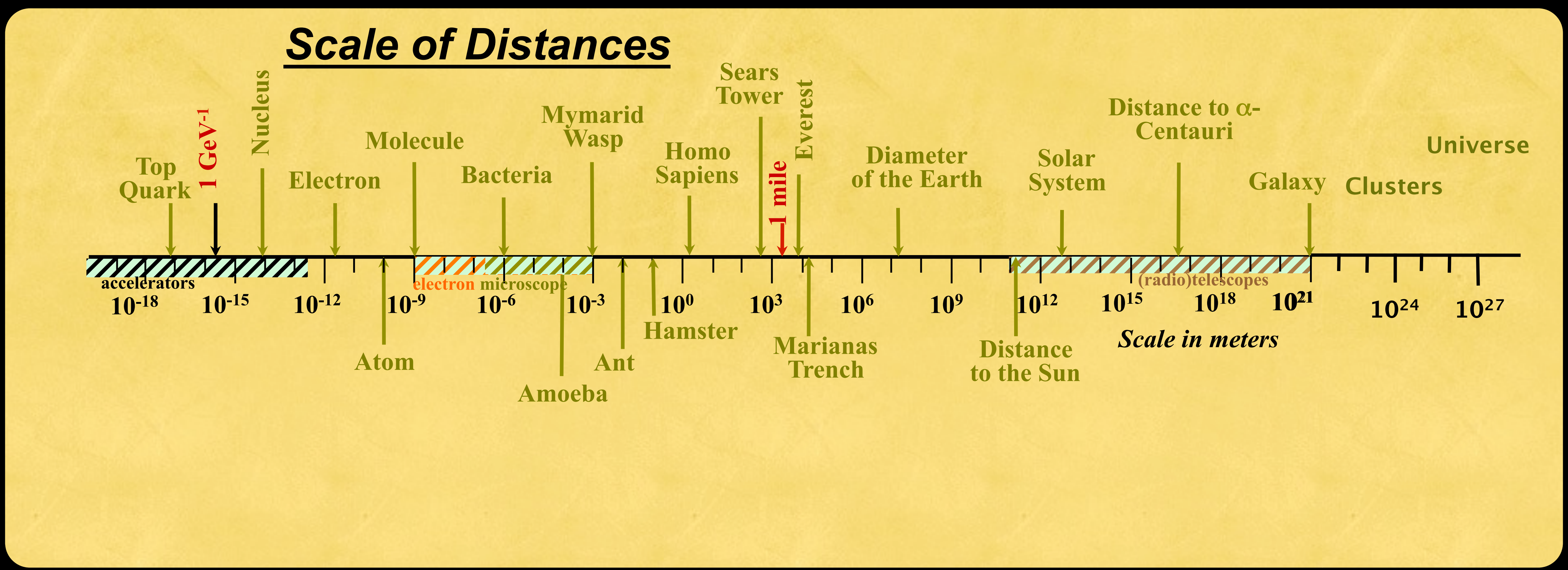


Big Bang
LHC
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^-10 seconds
10^-34 seconds
10^-43 seconds
10^32 degrees
10^27 degrees
10^15 degrees
10^10 degrees
10^9 degrees
6000 degrees
18 degrees
3 degrees K



Accelerators let us probe to very small distance scales



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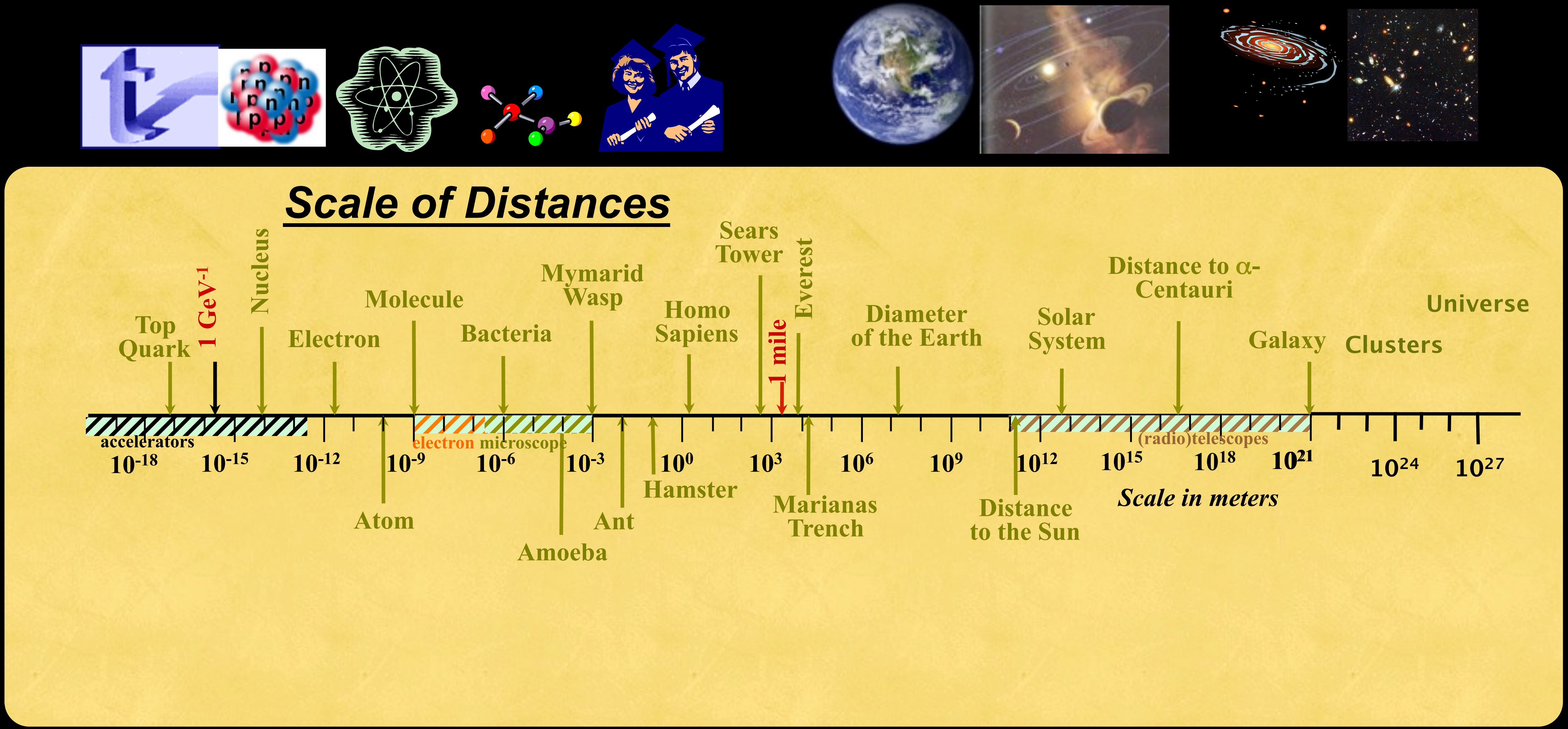

Accelerators let us probe to very small distance scales

What is Particle Physics?

What is Particle Physics?

Particle Physics tries to answer 2 basic questions

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Particle Physics tries to answer 2 basic questions

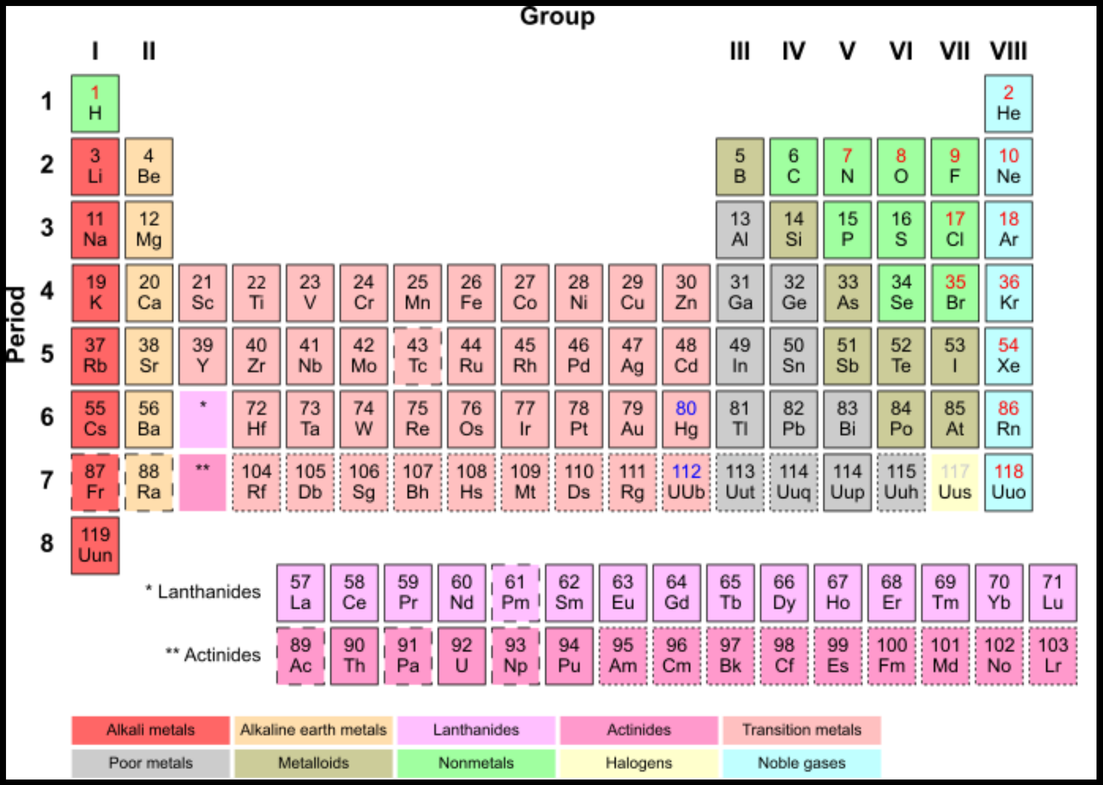
WHAT is the Universe made of?

What is Particle Physics?

Particle Physics tries to answer 2 basic questions

WHAT is the Universe made of?

HOW do these building blocks interact?

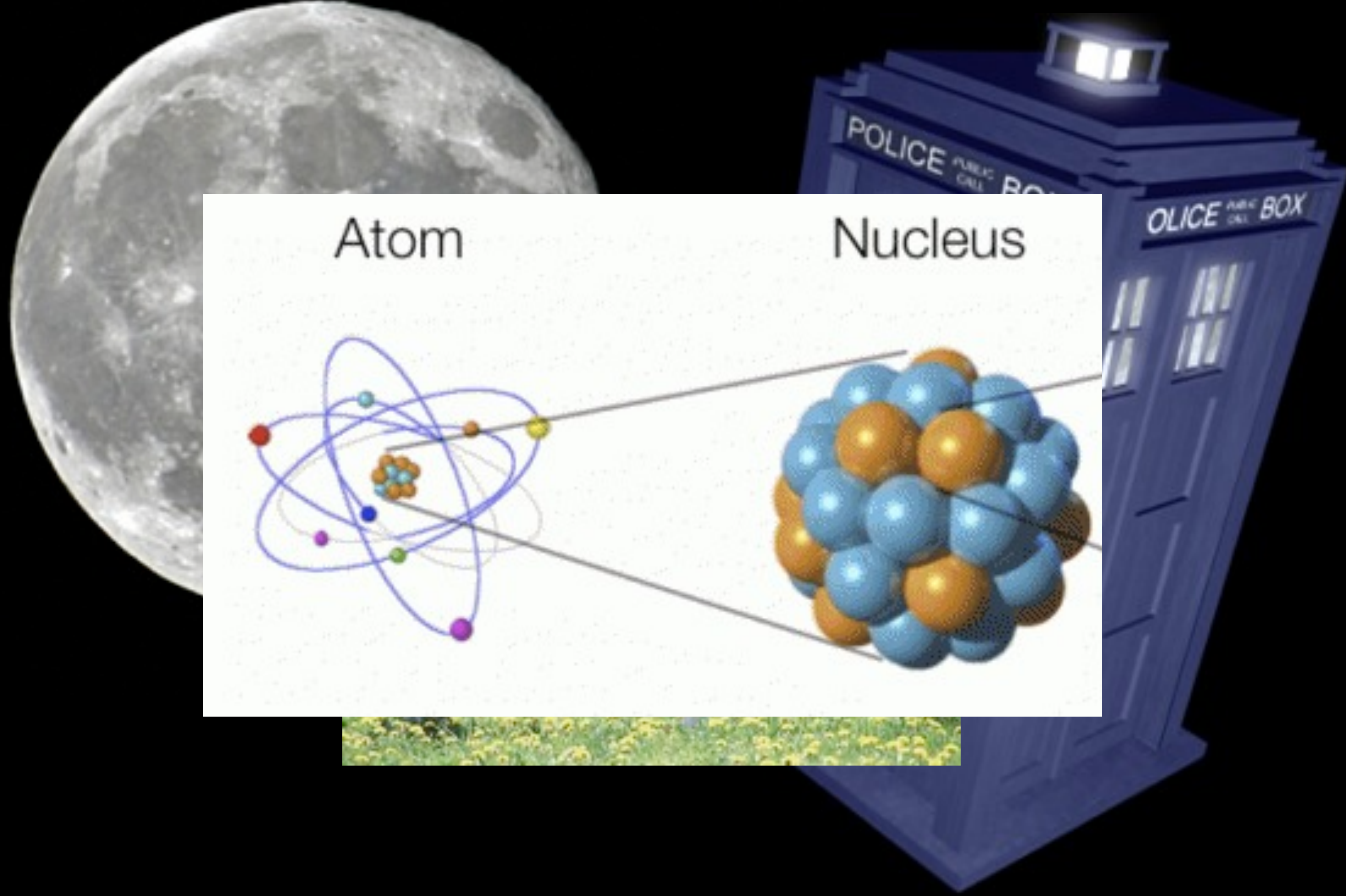


Group

Period	I	II											III	IV	V	VI	VII	VIII
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 UUb	113 Uut	114 Uuq	114 Uup	115 Uuh	117 Uus	118 Uuo
8	119 Uun																	

* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Alkali metals	Alkaline earth metals	Lanthanides	Actinides	Transition metals
Poor metals	Metalloids	Nonmetals	Halogens	Noble gases



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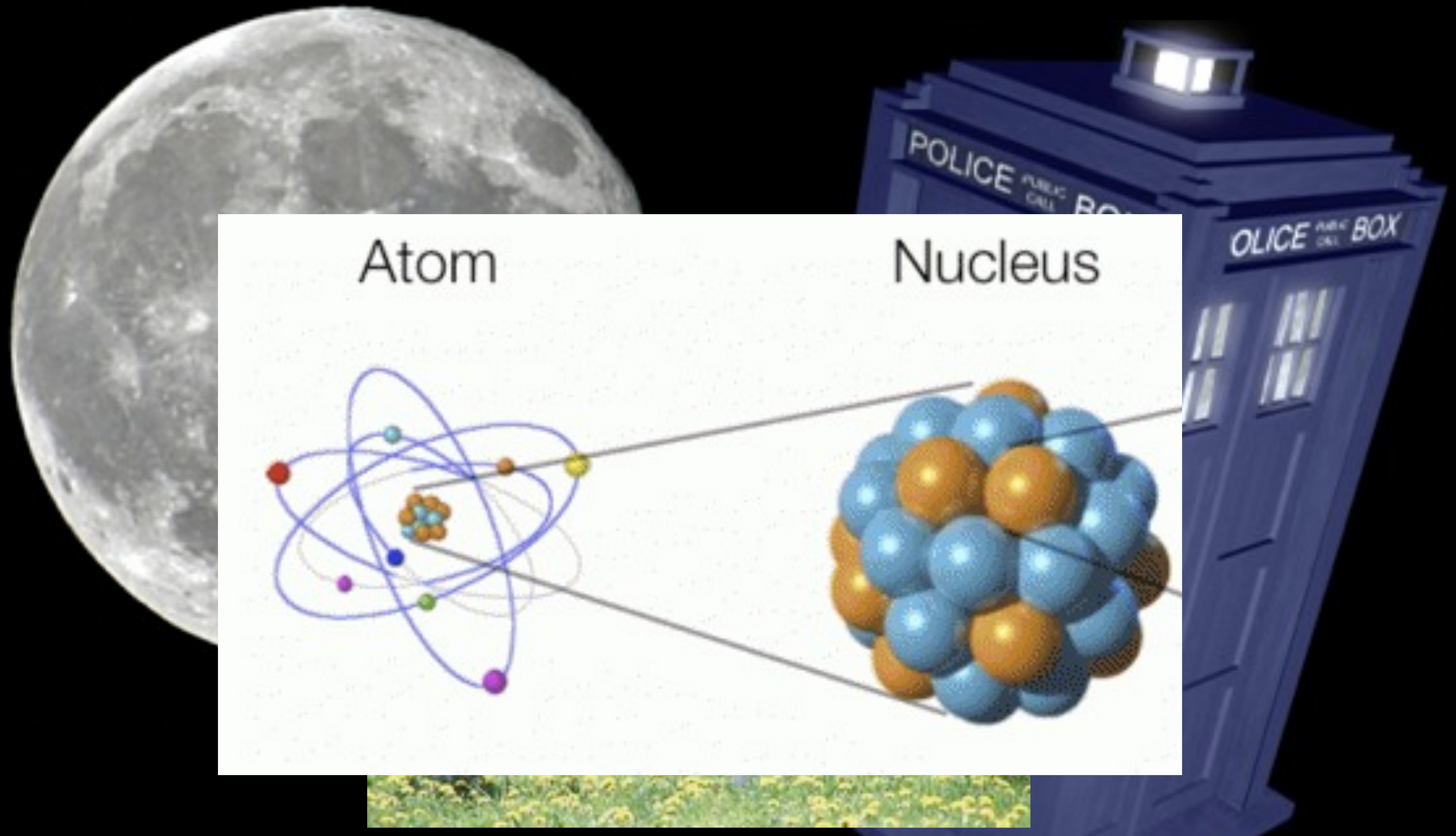
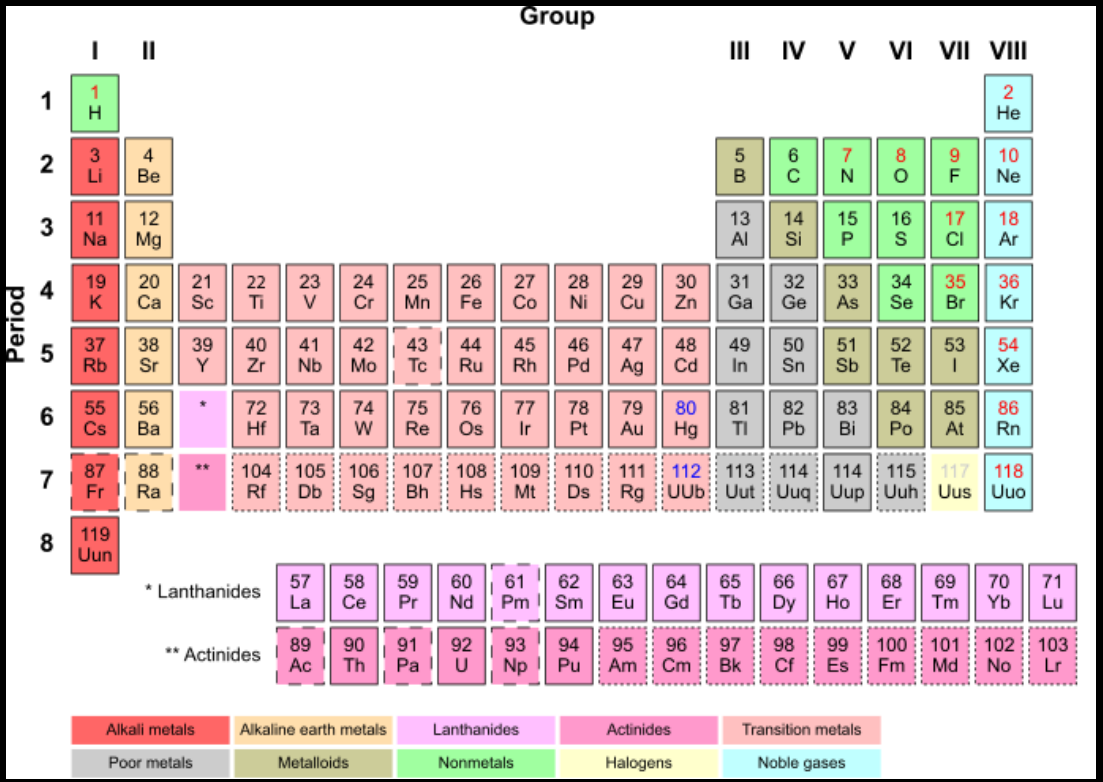
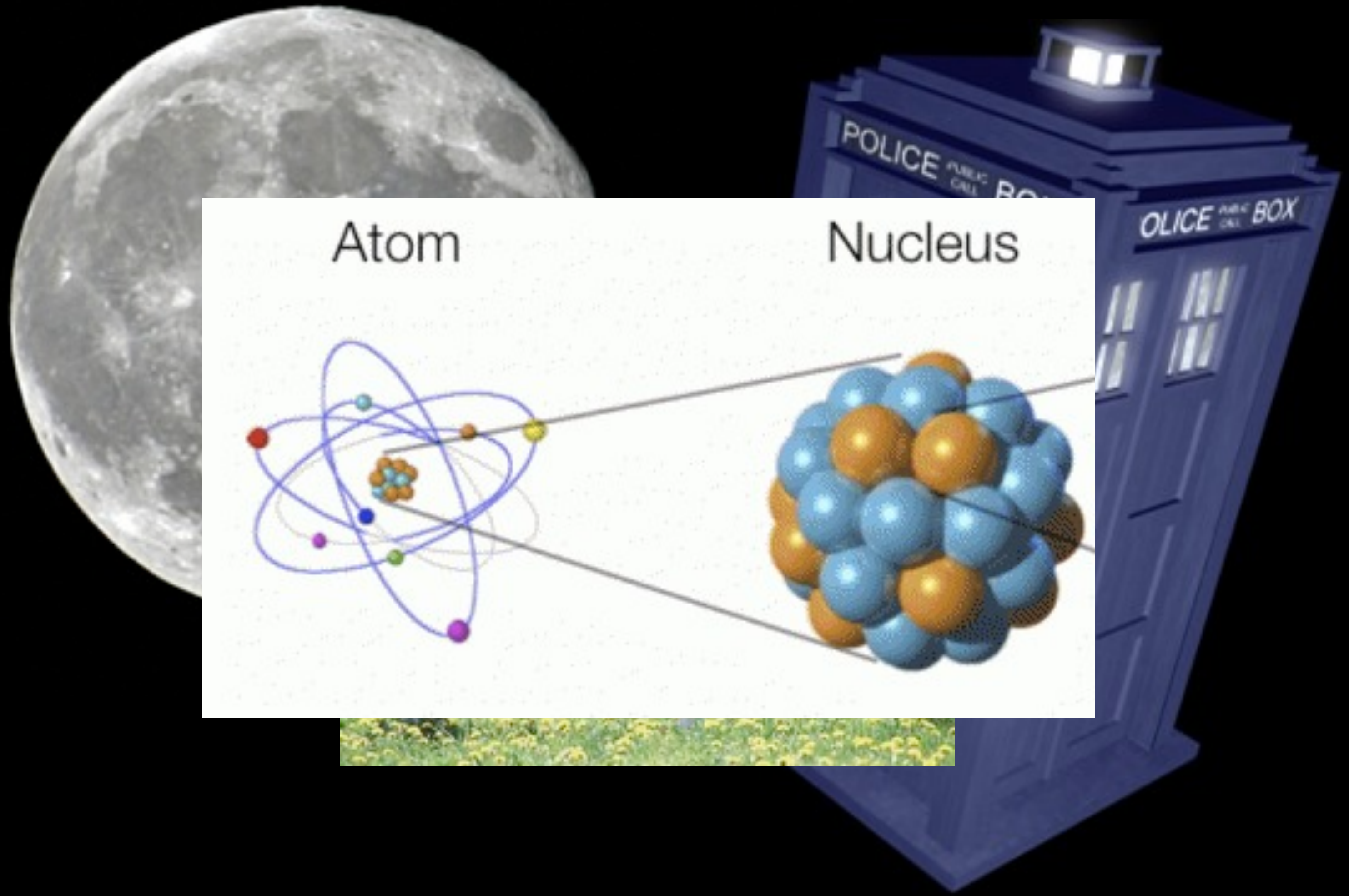




By 1930s we knew how it all worked -- Everything is made out of atoms, and every atom in the periodic table is just different combinations of *protons*, *neutrons* and *electrons* – just 3 basic building blocks of the whole, complicated Universe



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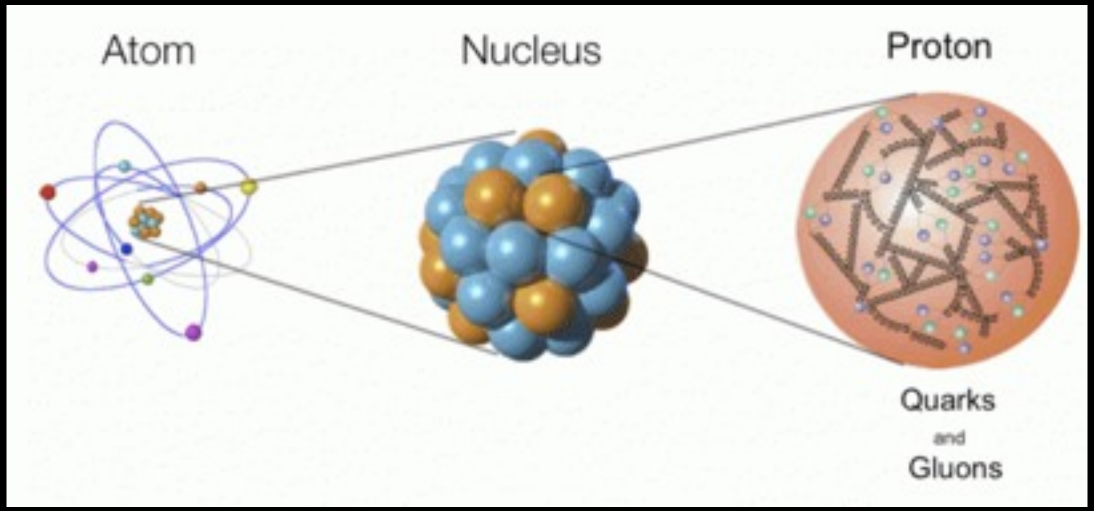
We should have stopped here....

In 1969, we built machines that could look inside protons and discovered quarks



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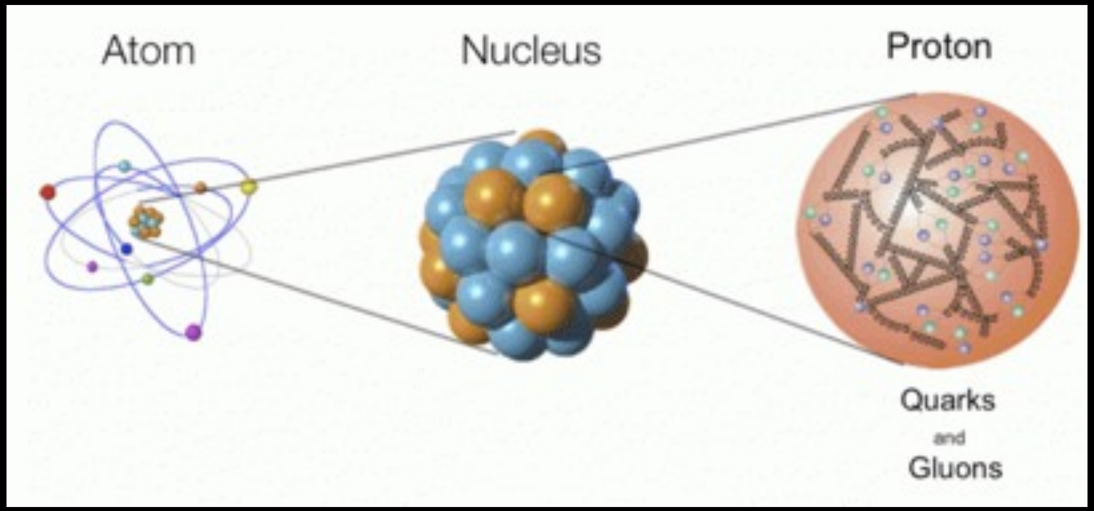

Eventually a total of 6 types of quarks were discovered, between 1969 and 1994 from the very light ‘up’ and ‘down’ quarks ending with the very heavy ‘top’ quark

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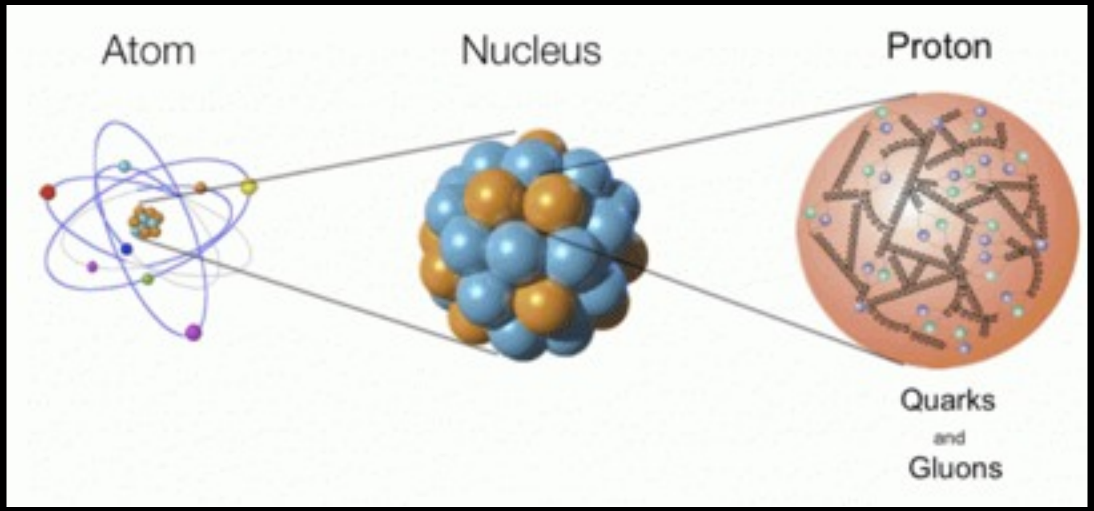

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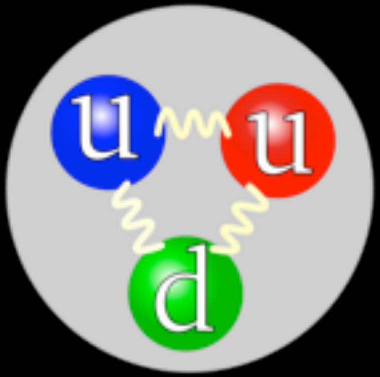
Proton = (uud)

Neutron = (udd)



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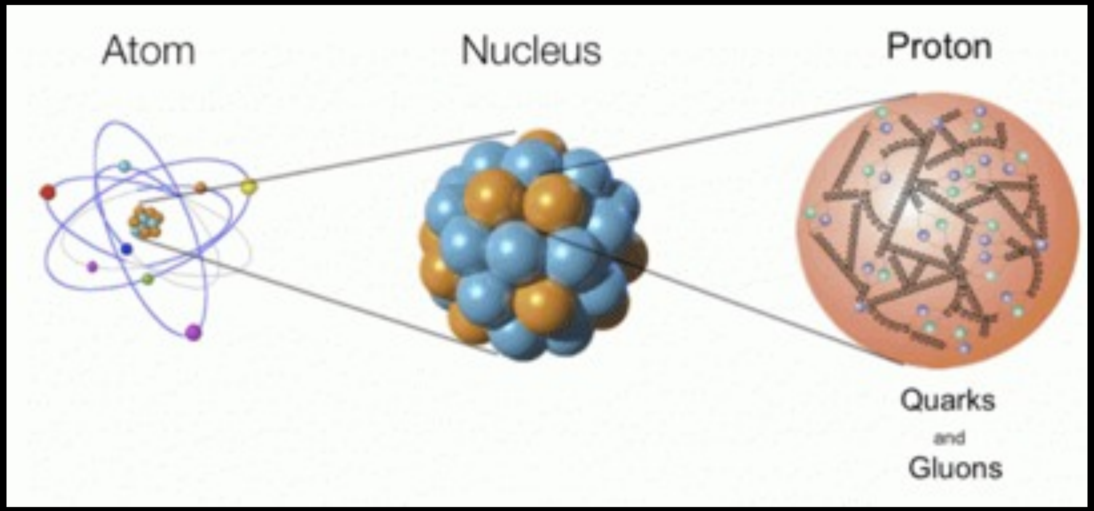

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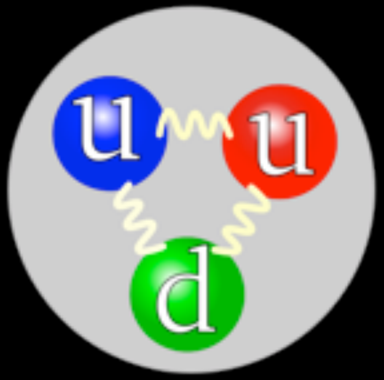

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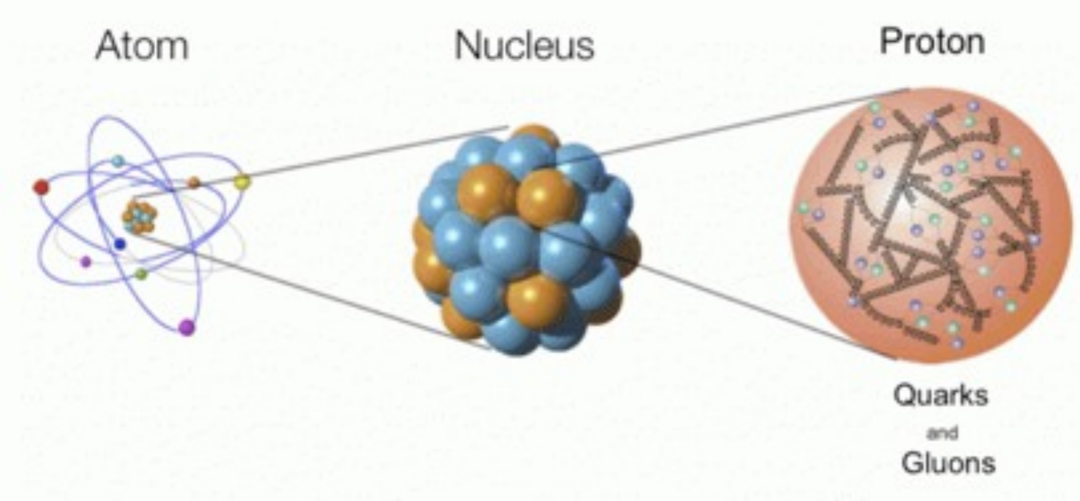

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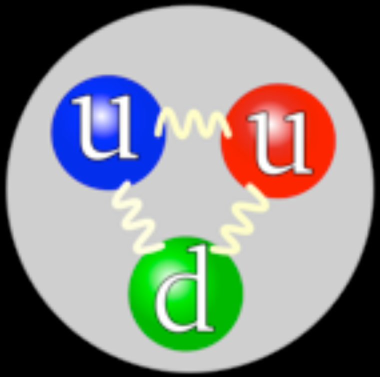
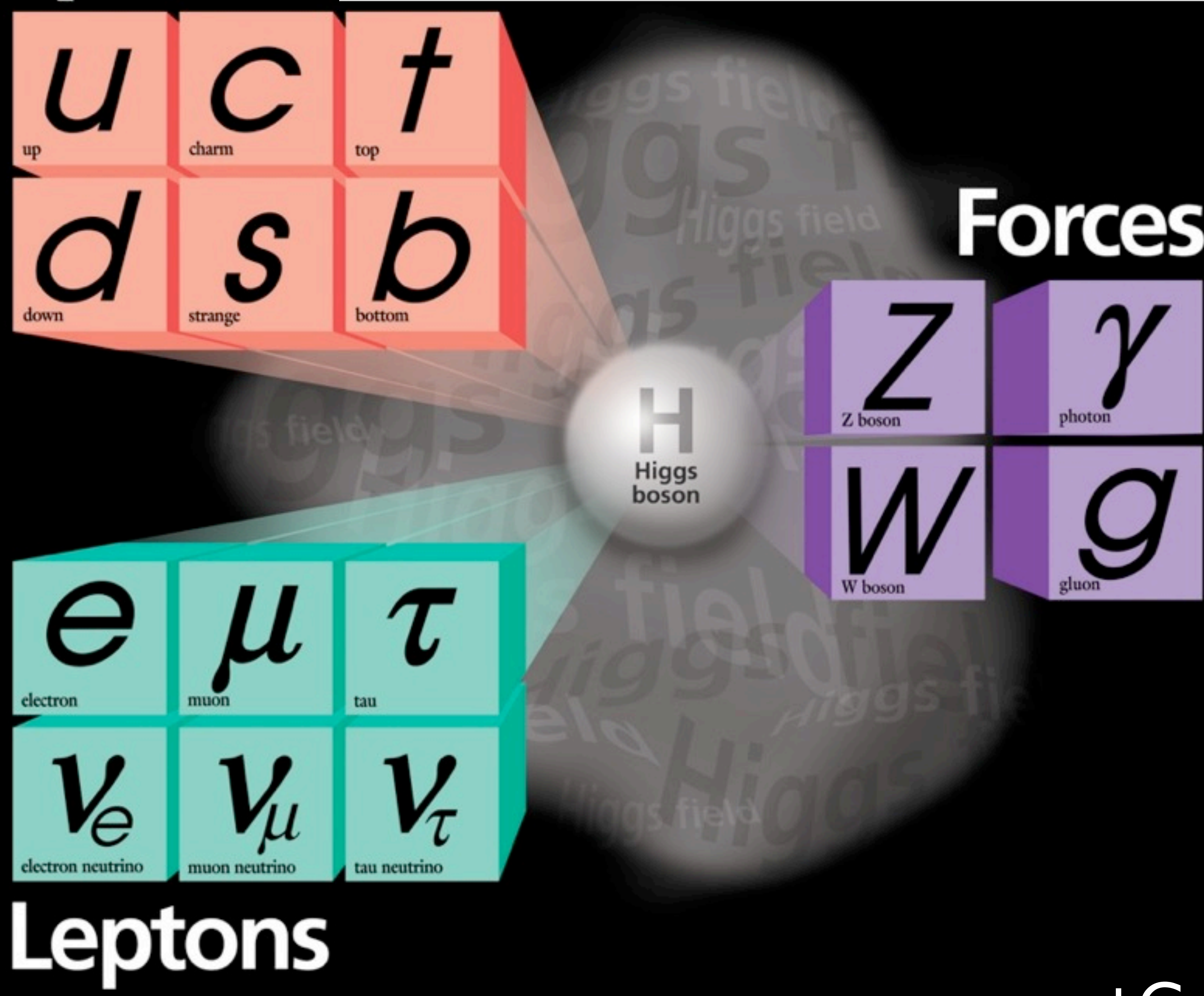


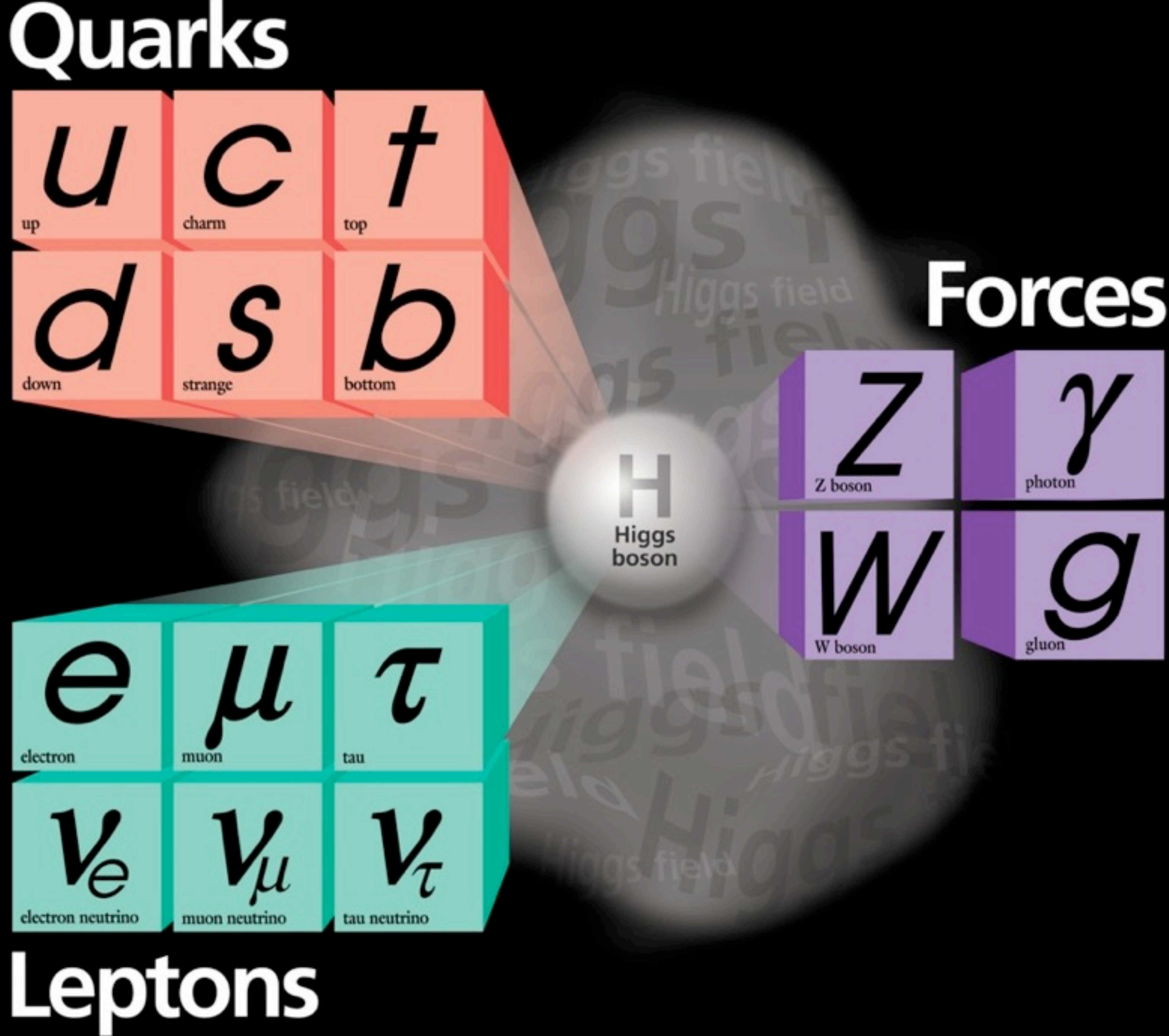
Each quark comes with 3 possible "strong charges" just like electric charge

These were fancifully named Red, Green, Blue, and called "colour" charge. Not that they really are coloured, it's just a name, like "positive" and "negative"

The Standard Model



+Gravity ...


Quarks
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Forces
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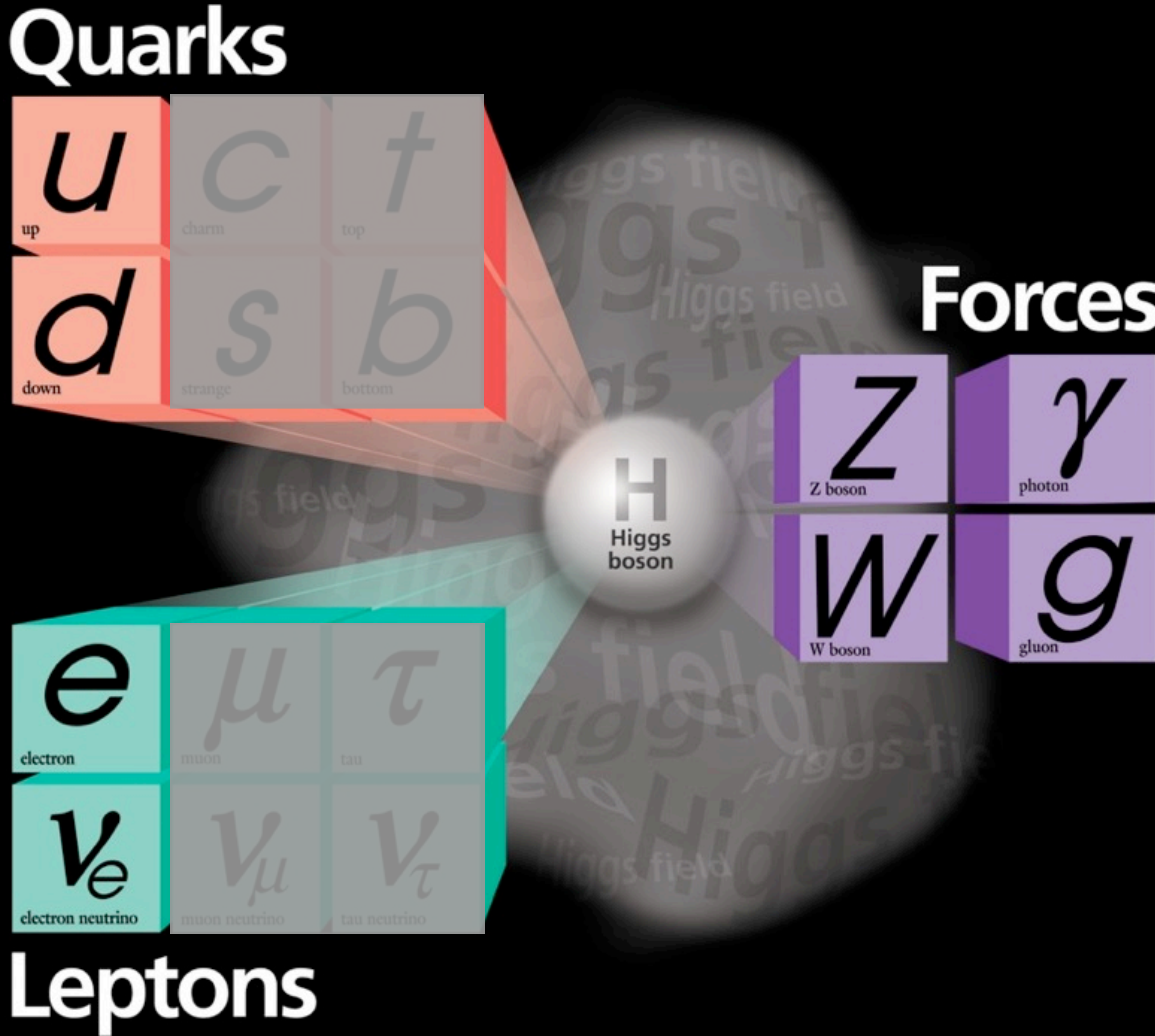
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons
Higgs field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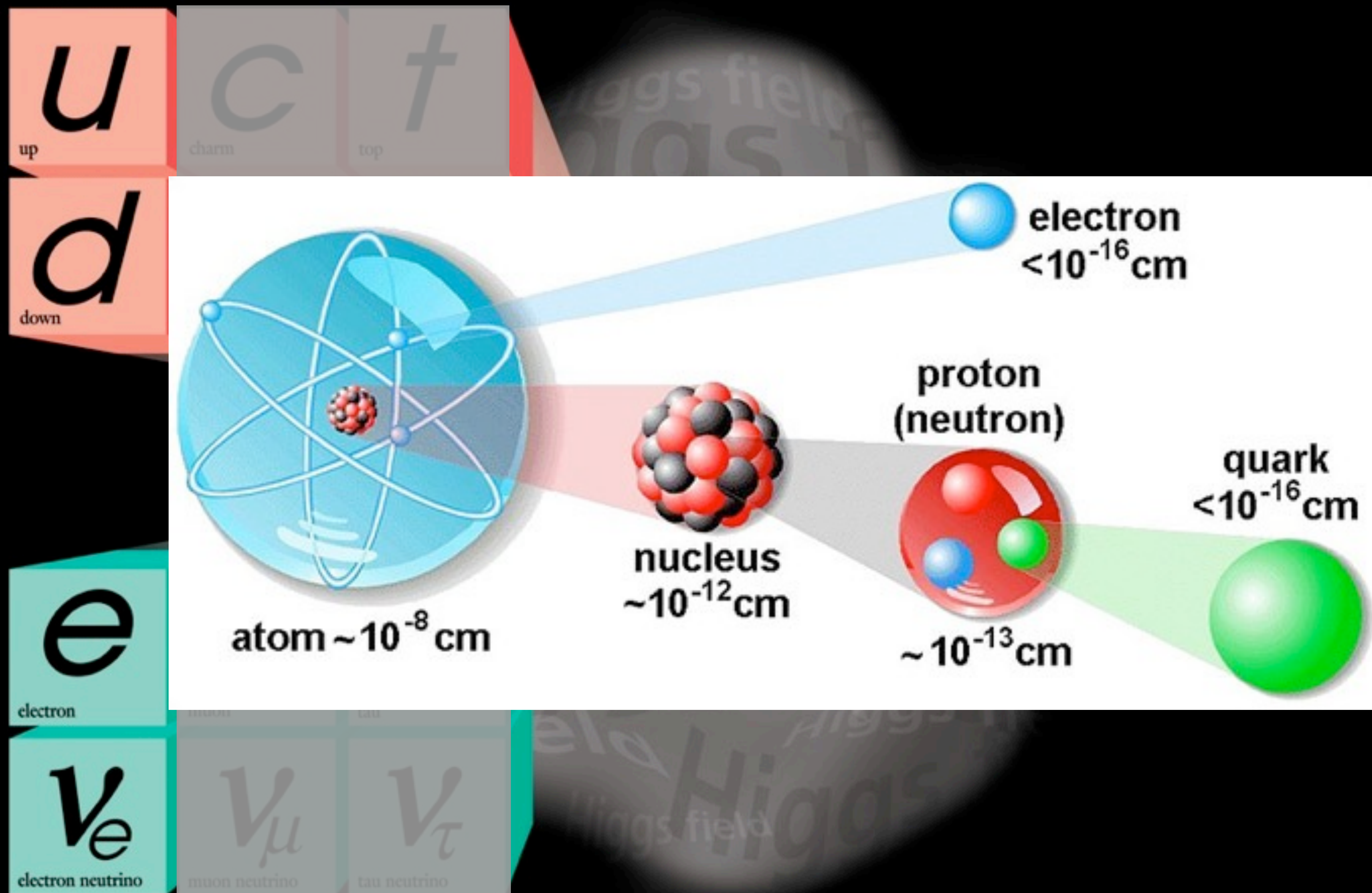

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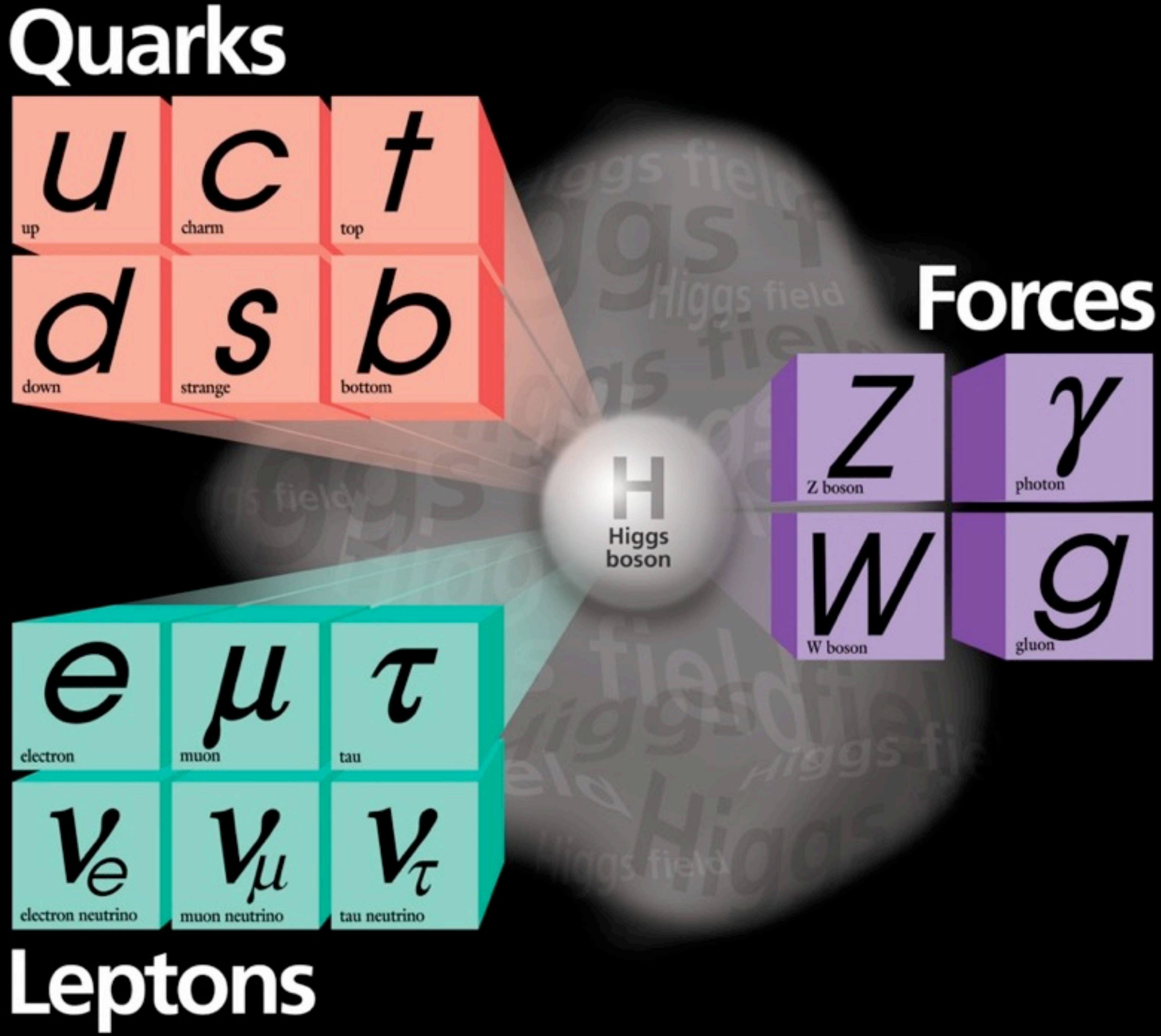

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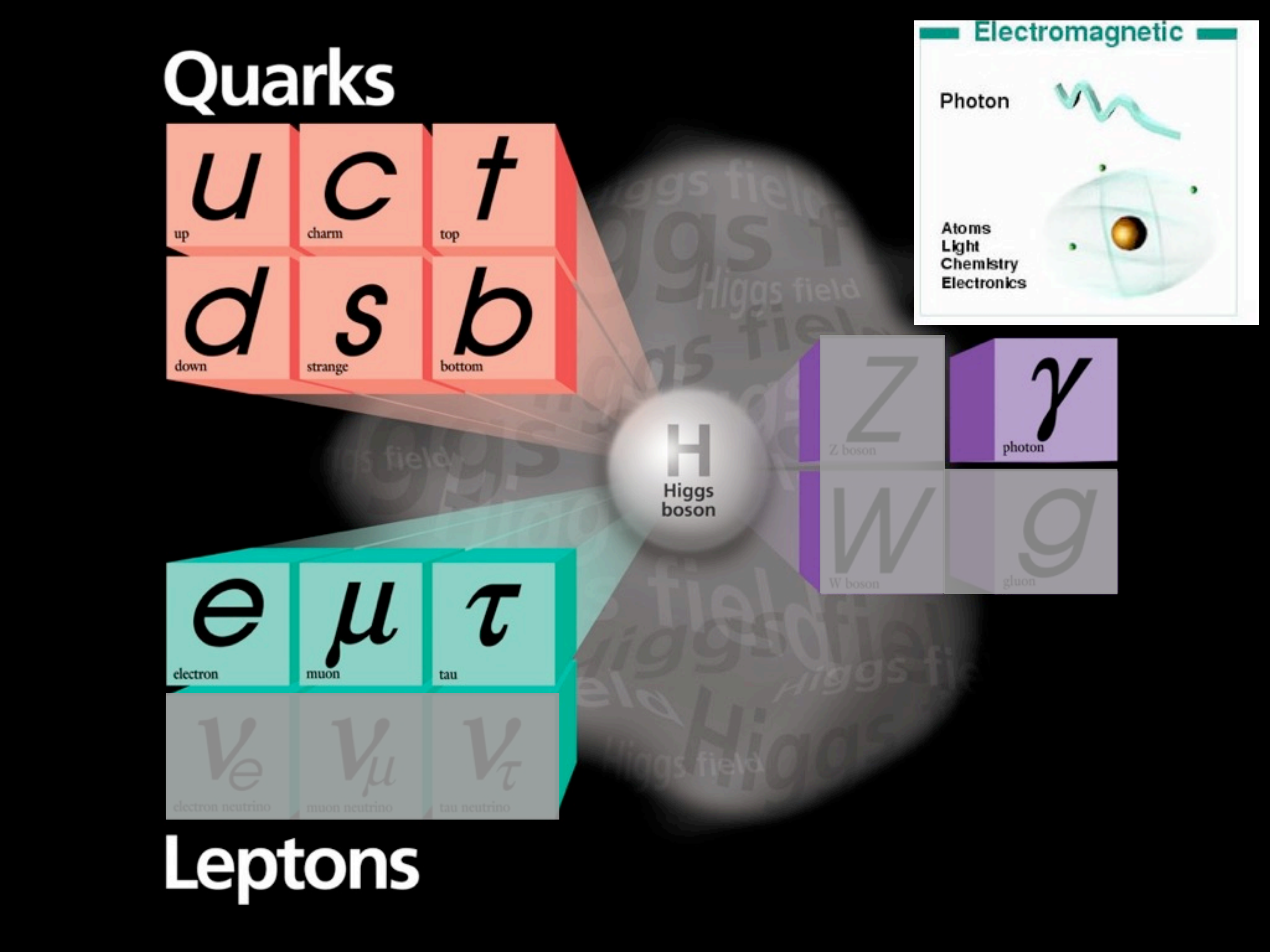

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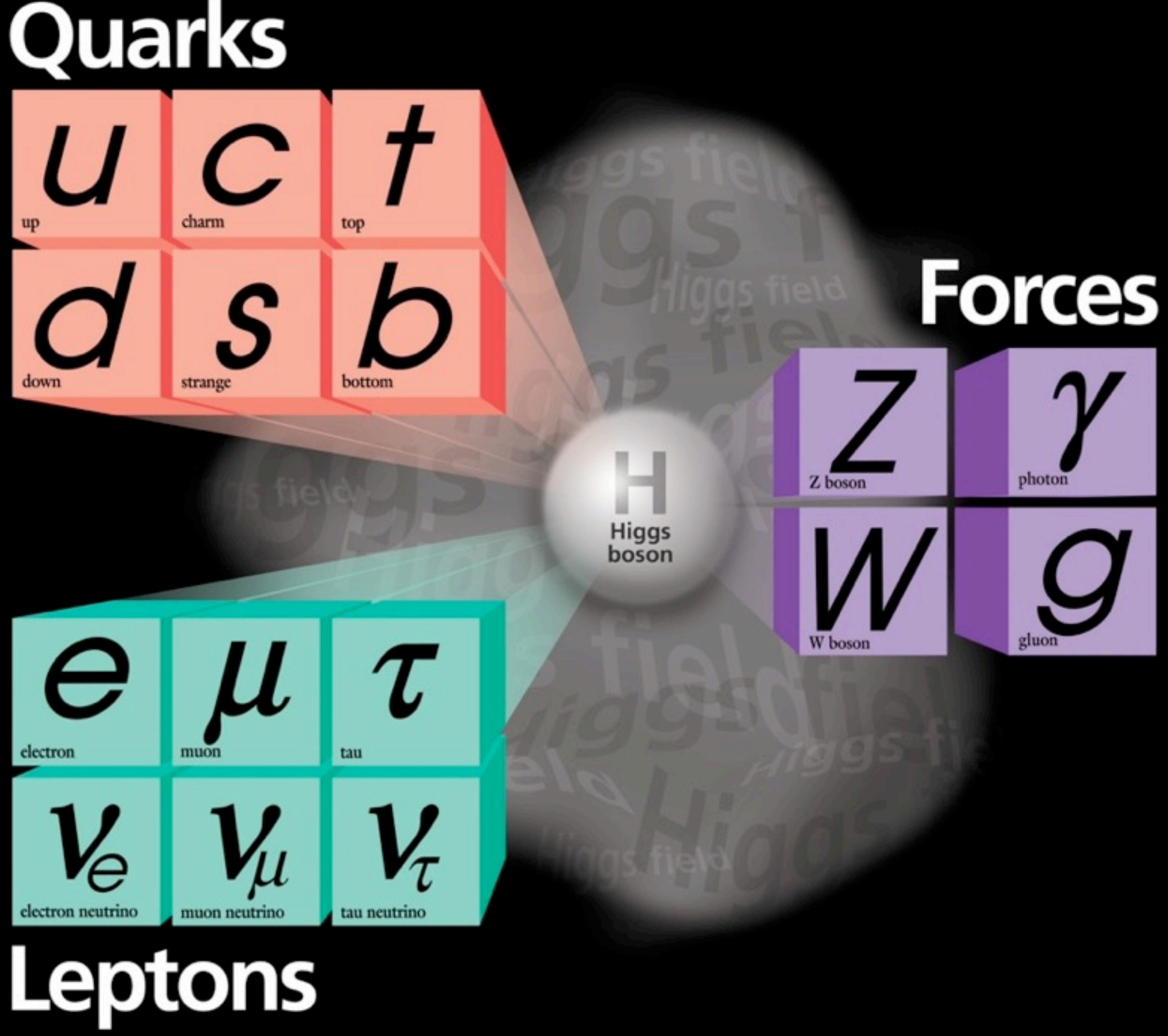

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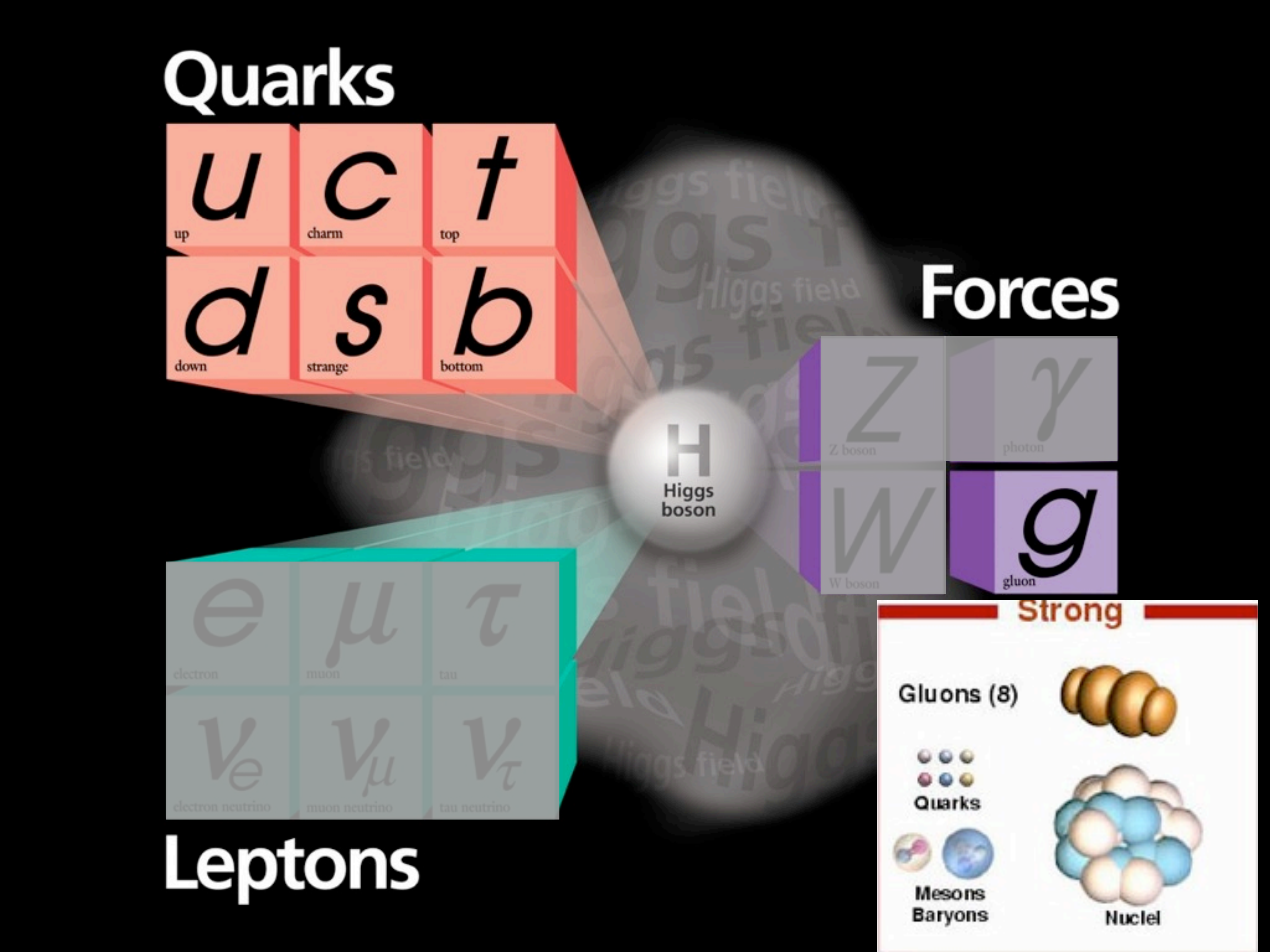
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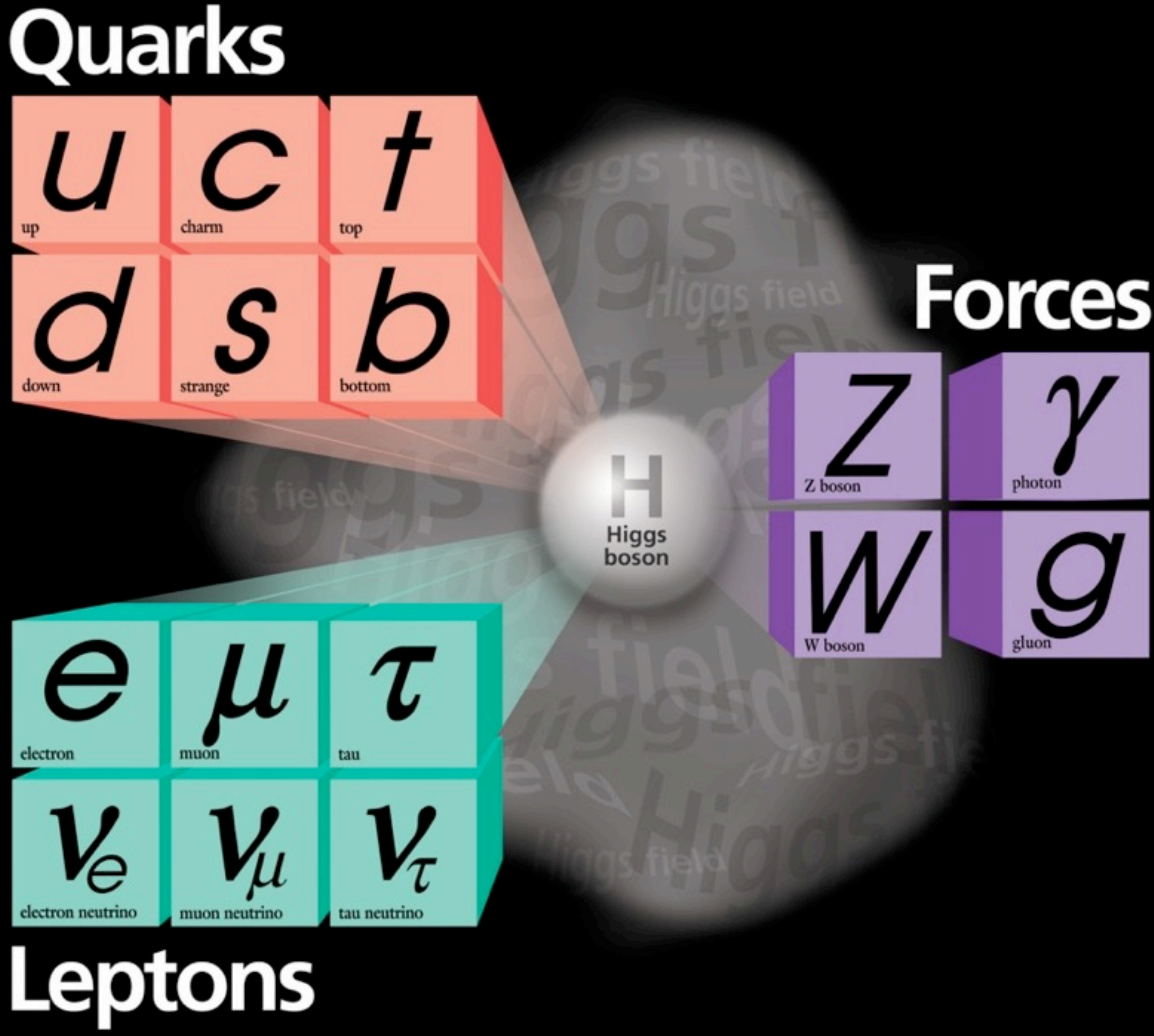
Leptons
Strong
Gluons (8)
Quarks
Mesons
Baryons
Nuclei



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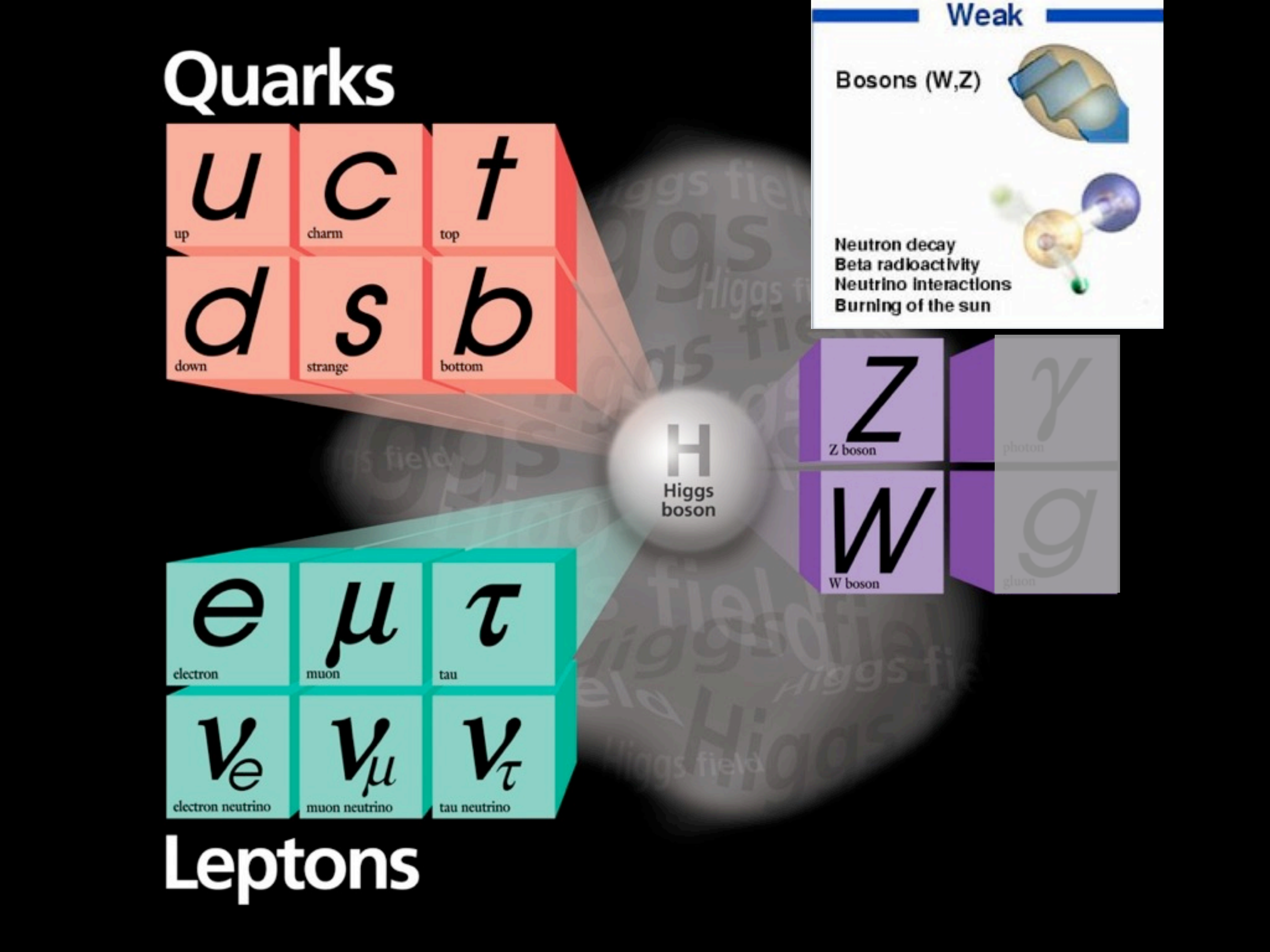
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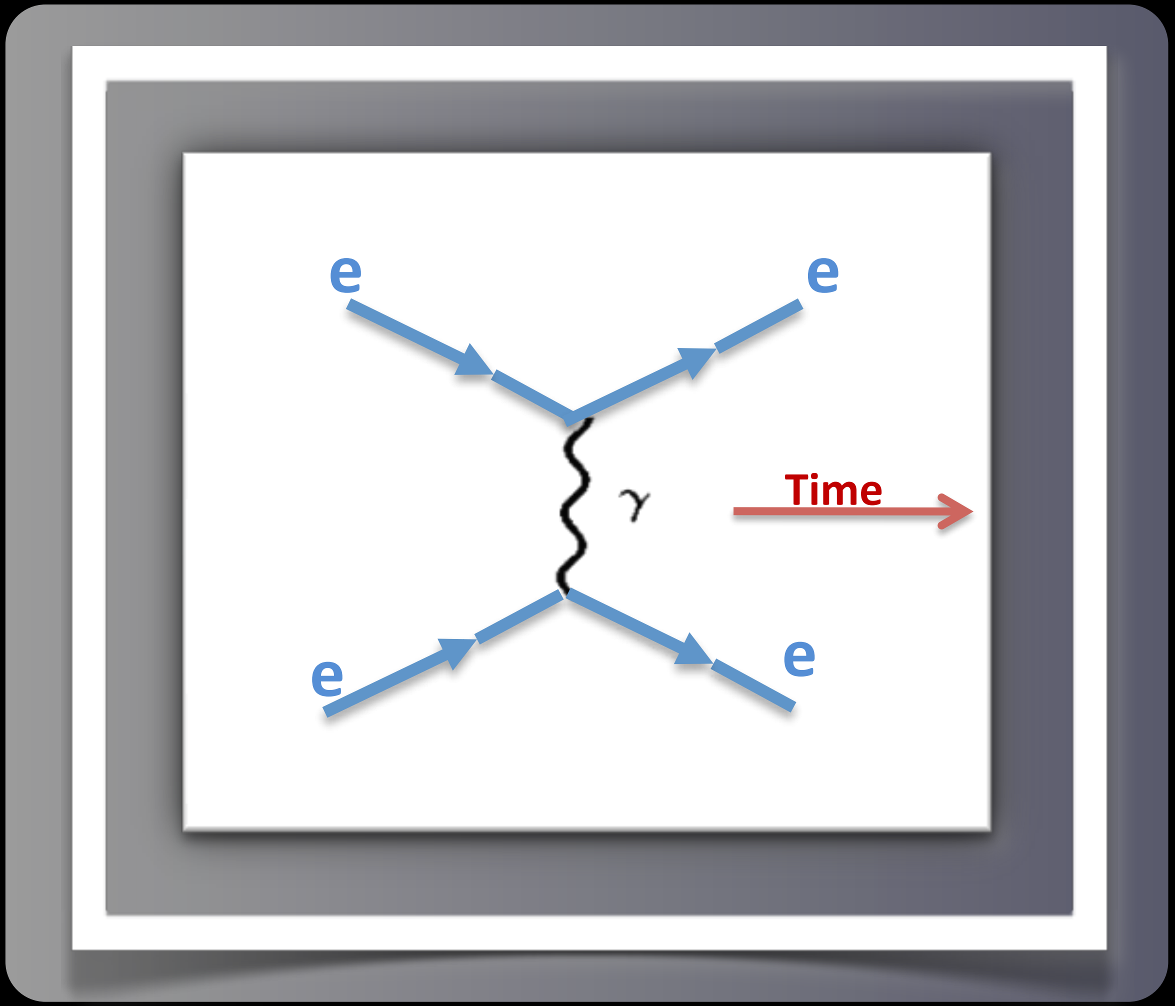
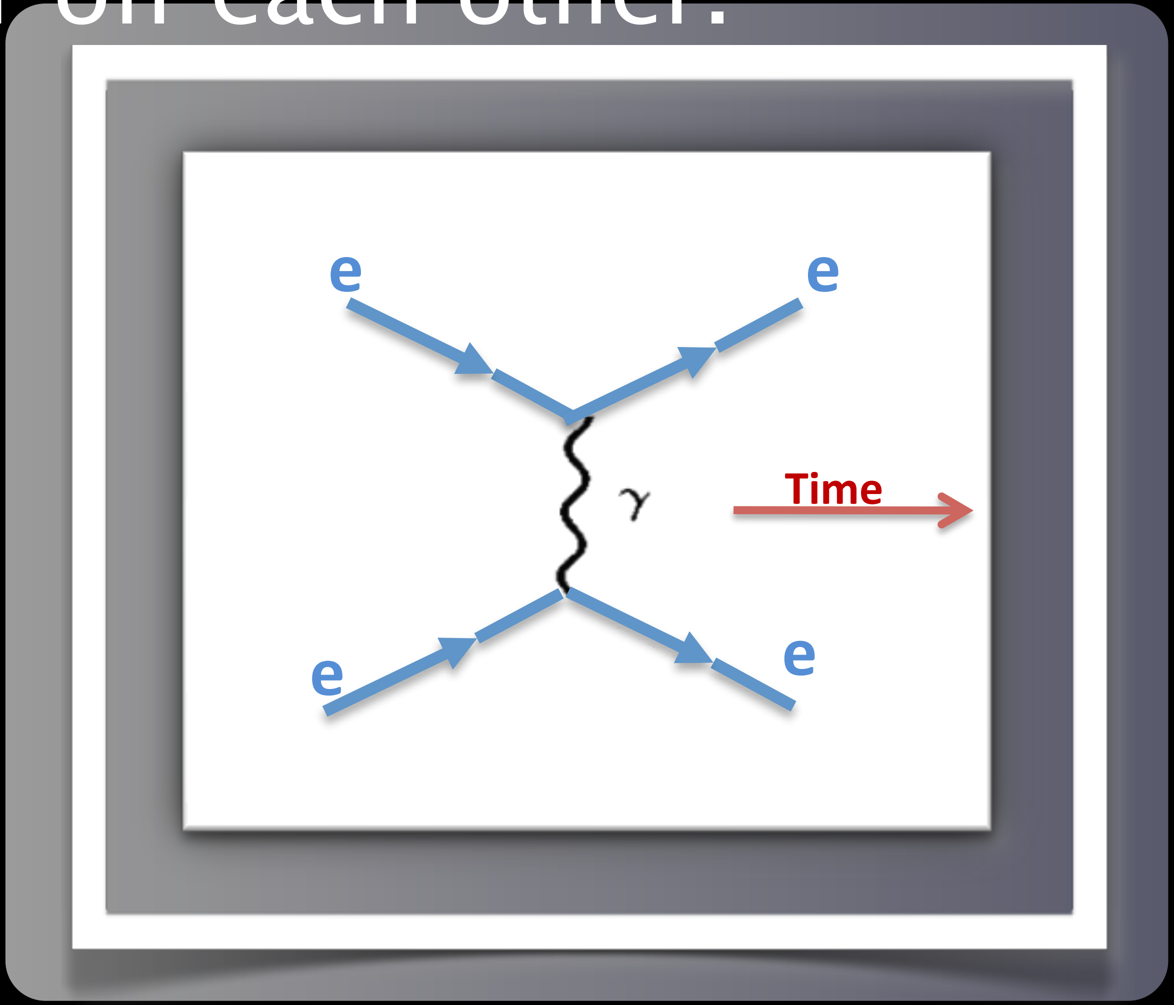
Weak
Bosons (W,Z)
Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

To represent forces/interactions, we draw diagrams, invented by Feynman, which show the elements of the process



In this example, an electron “emits” a photon, which carries momentum to the other electron, causing them to scatter off each other.



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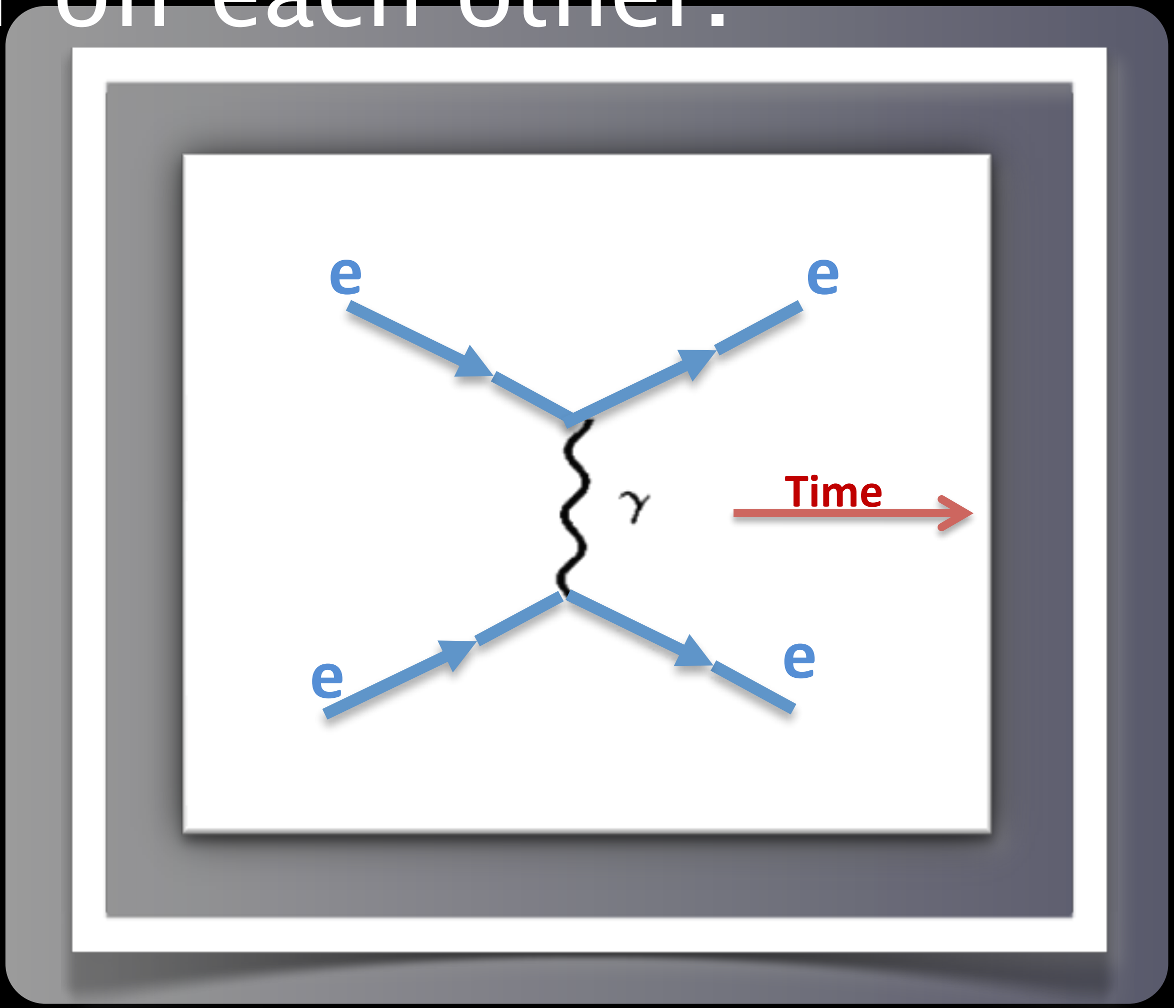
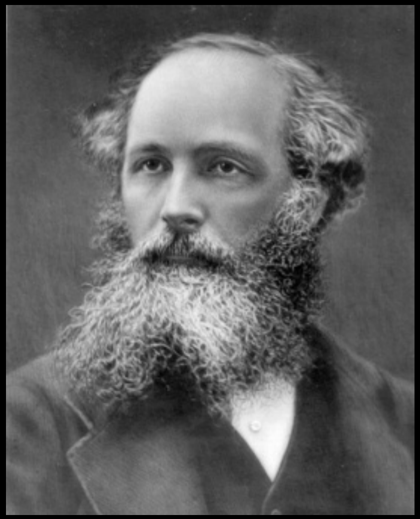


Q: How do we know what forces exist (or equivalently -- what particles can be exchanged) and what are their properties?

Forces and Symmetries

Newton



Maxwell

Forces and Symmetries

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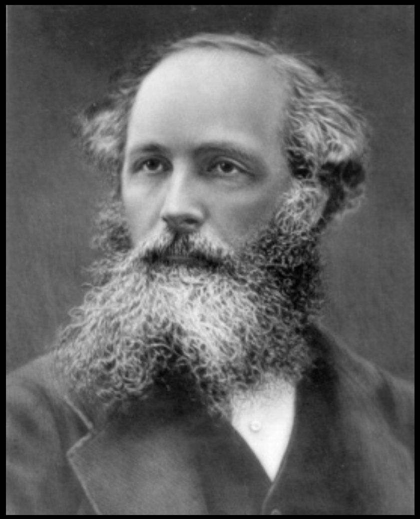

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1. Observe a force (eg gravity, electromagnetism)

Forces and Symmetries

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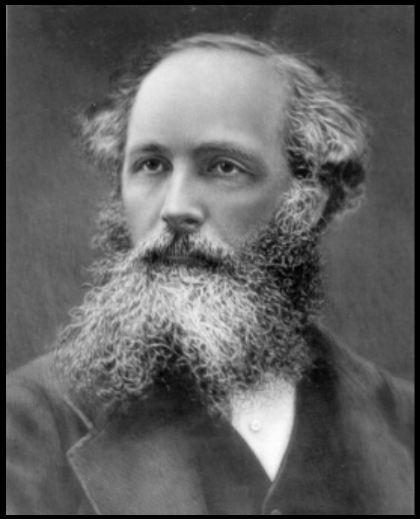

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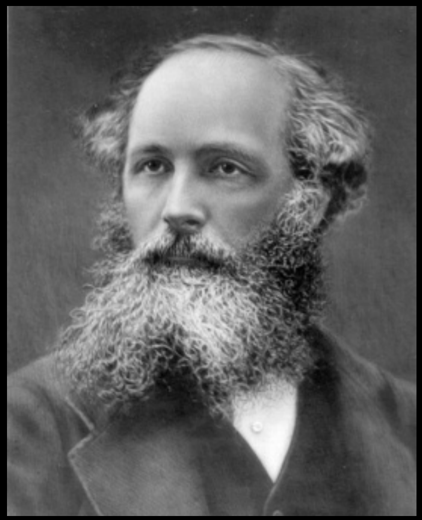

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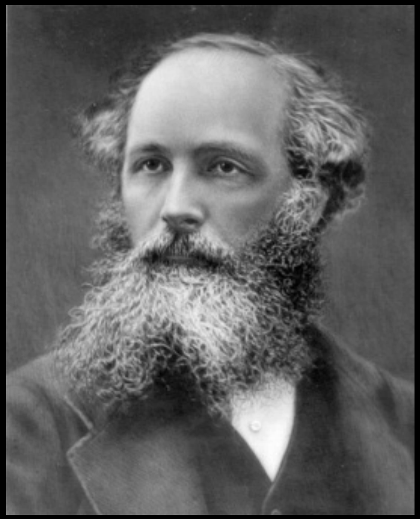

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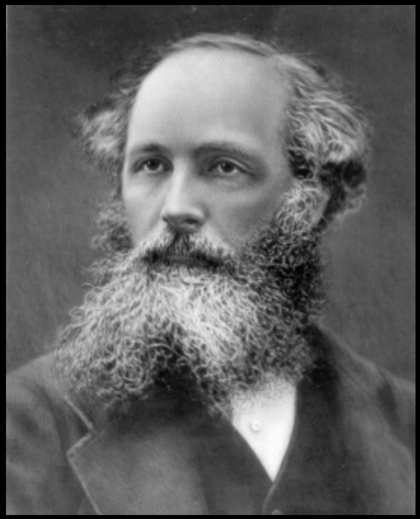
Forces and Symmetries

Newton



Maxwell

1. Observe a force (eg gravity, electromagnetism)
   - Measure some properties
   - Guess at governing equations ($1/r^2$ law, Maxwell's equations …)
   - Test experimentally

2. Modern: Special kind of *symmetry* causes certain forces to be *required*

Symmetry

Symmetry

Rotate through 90°

Object is the same

but only for special values

$1 \times 90^\circ$

$2 \times 90^\circ$

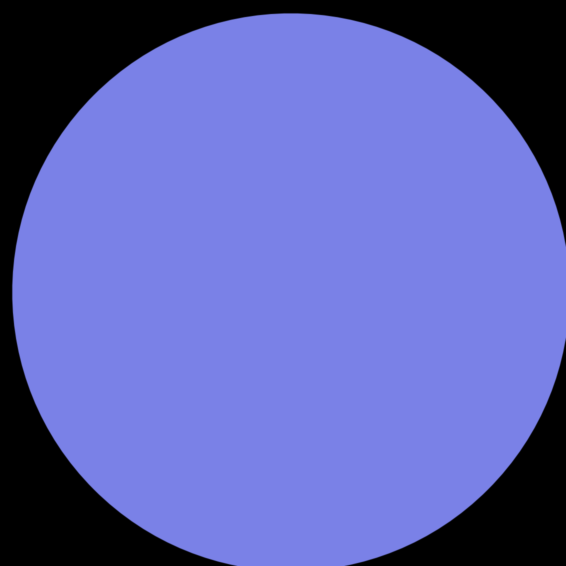
$3 \times 90^\circ$

....

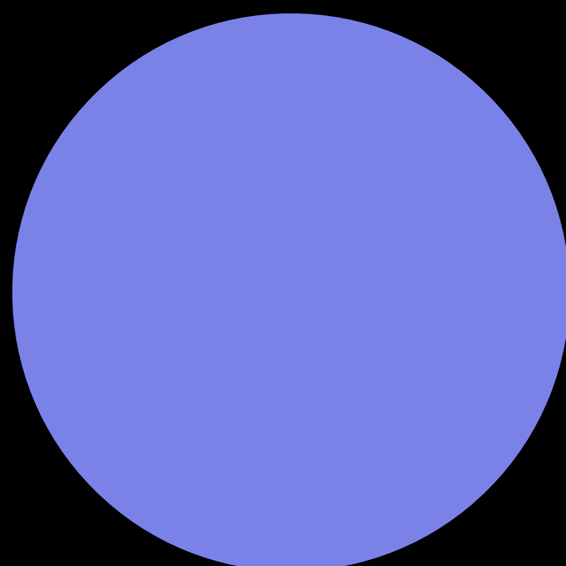
Not for *any* value

eg 36.2°

Continuous Symmetry



Continuous Symmetry



Rotate through *any* angle

Object is the same

for *any* value

36.2°

82.1°

...

Symmetries and Laws

We apply this thinking but:

The “Object” is now “The Laws of Physics”

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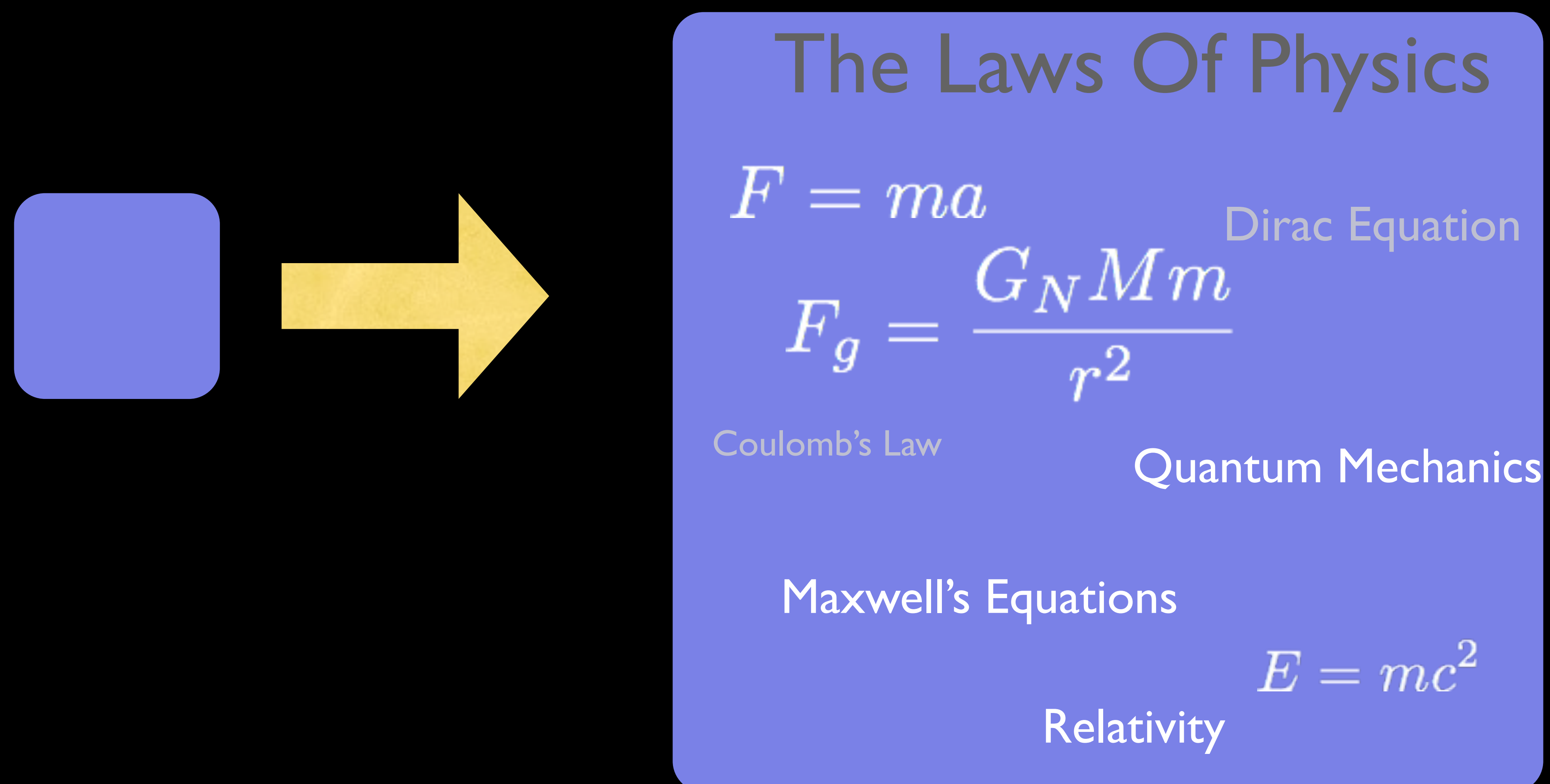

The 2nd Coolest Thing I Know about Physics

The Laws Of Physics

$F = ma$

Dirac Equation

$$F_g = \frac{G_N M m}{r^2}$$

Coulomb's Law

Quantum Mechanics

Maxwell's Equations

$E = mc^2$

Relativity

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They are the same here

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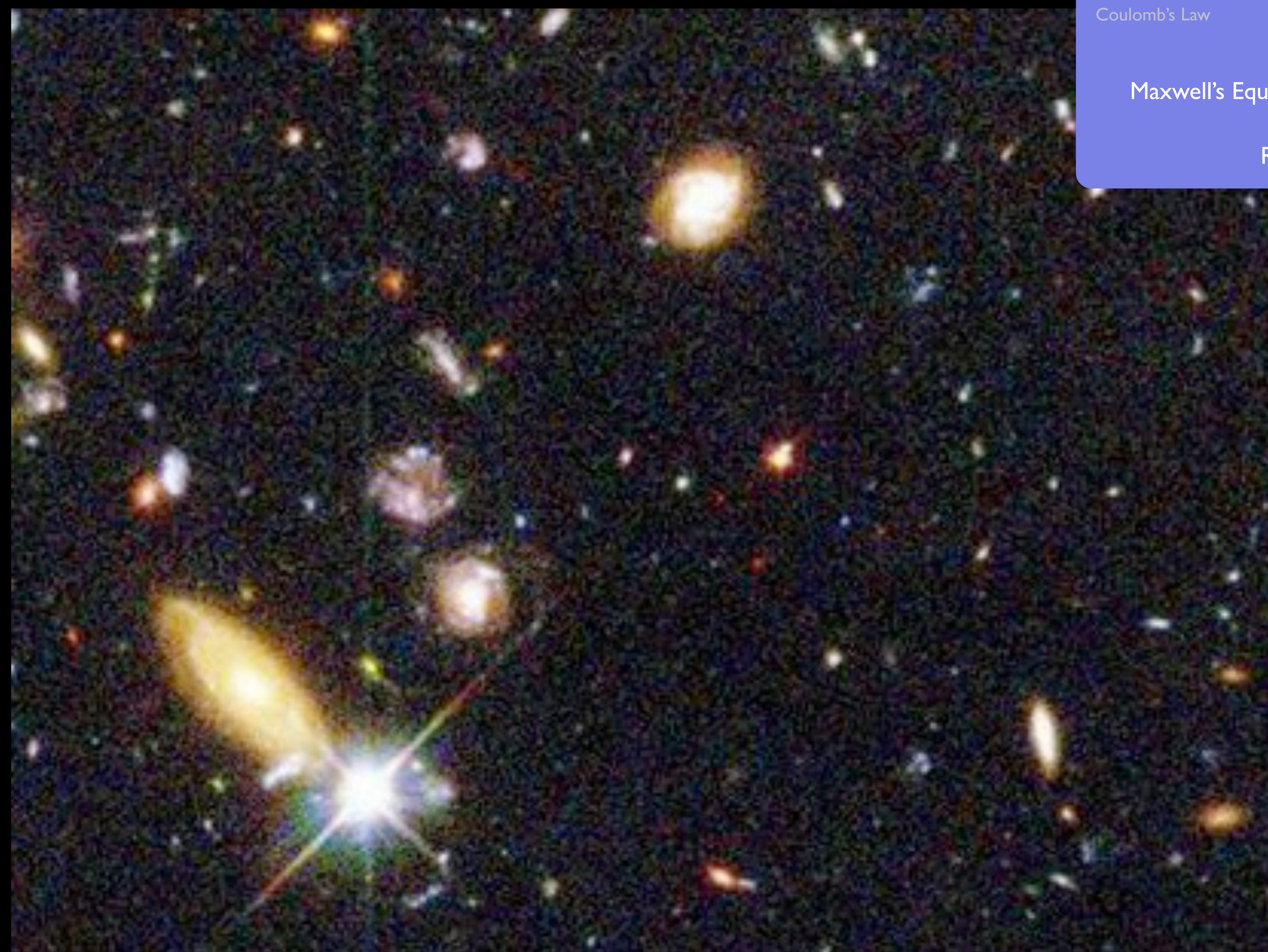

So ....????

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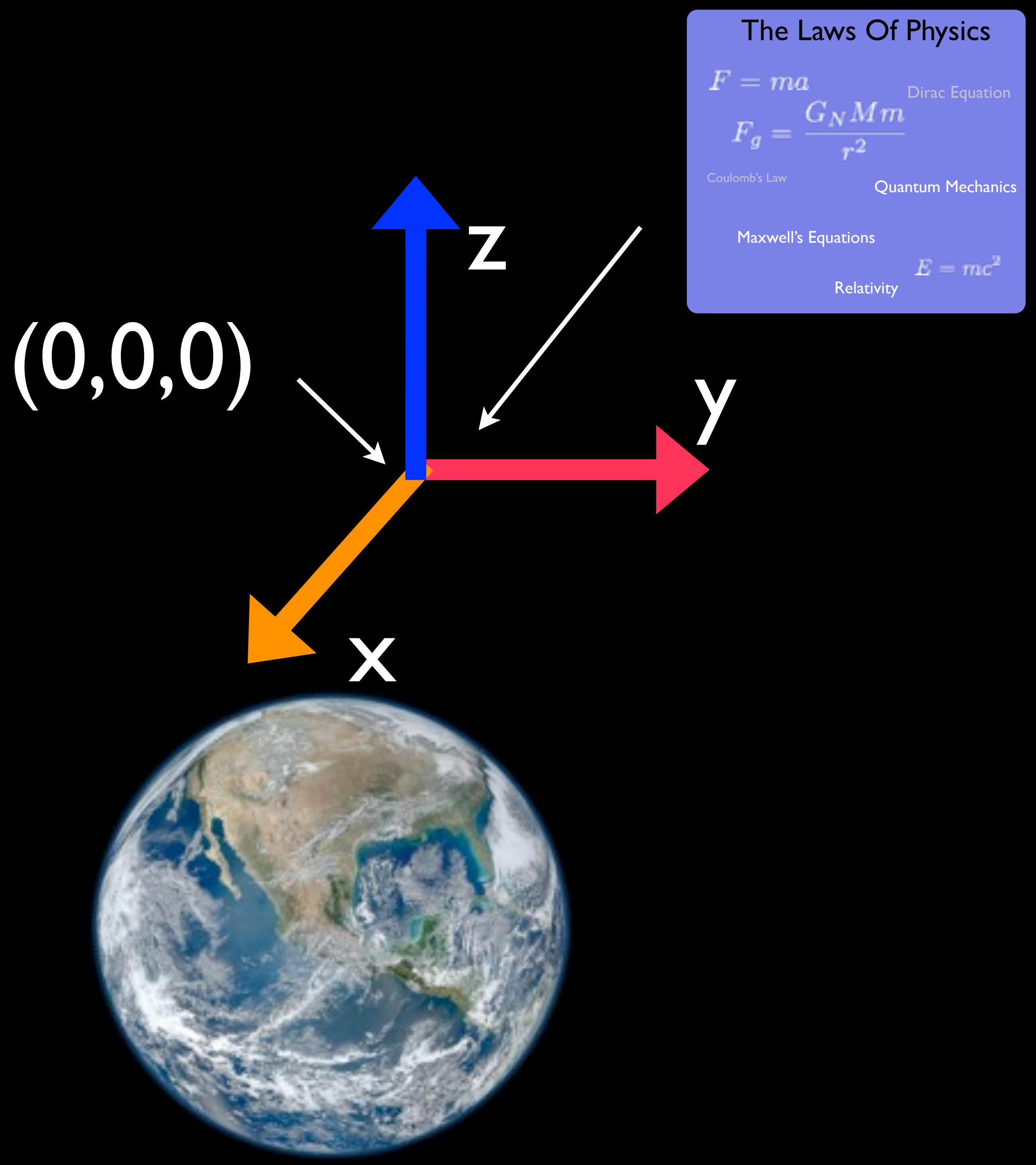

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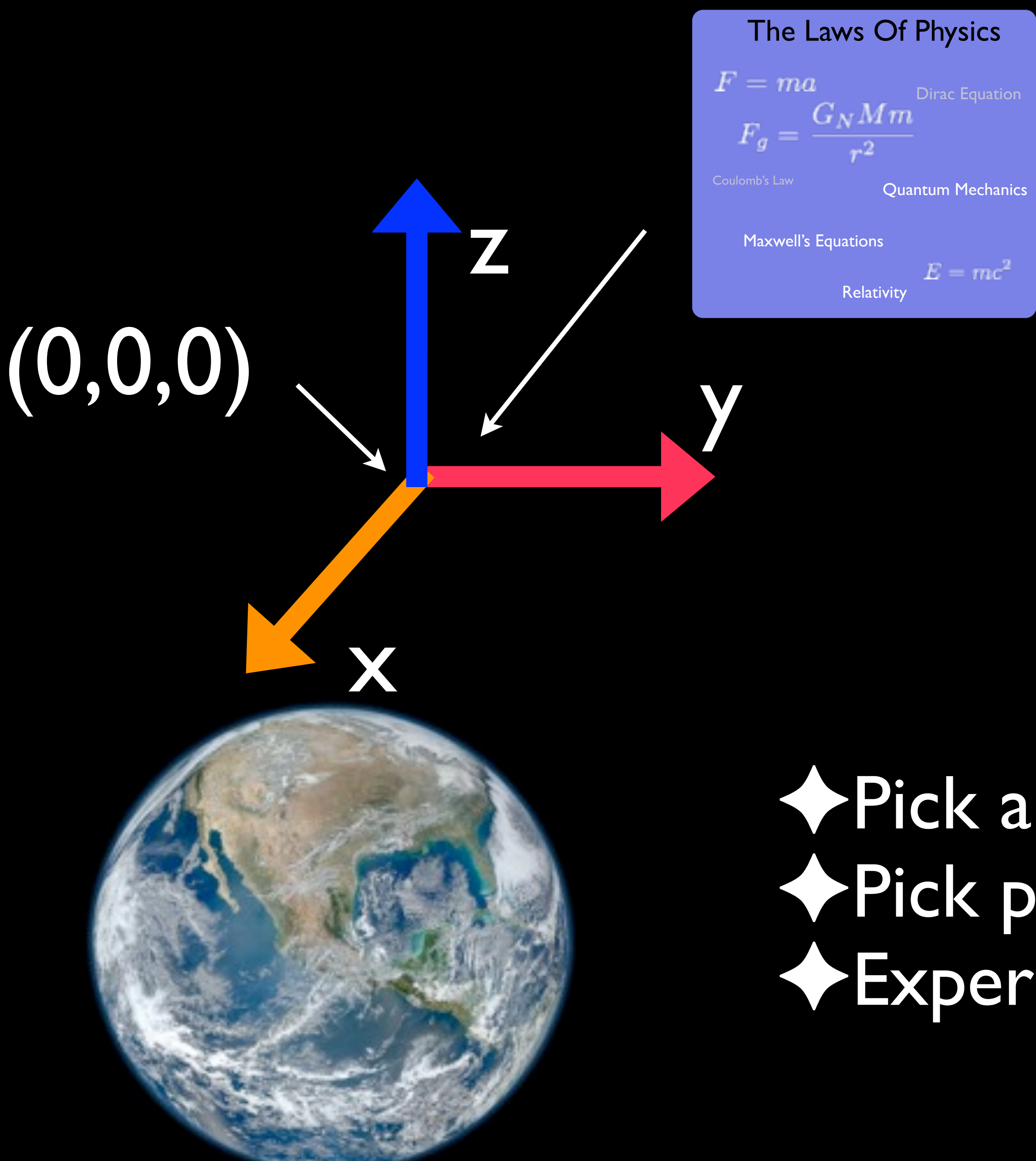
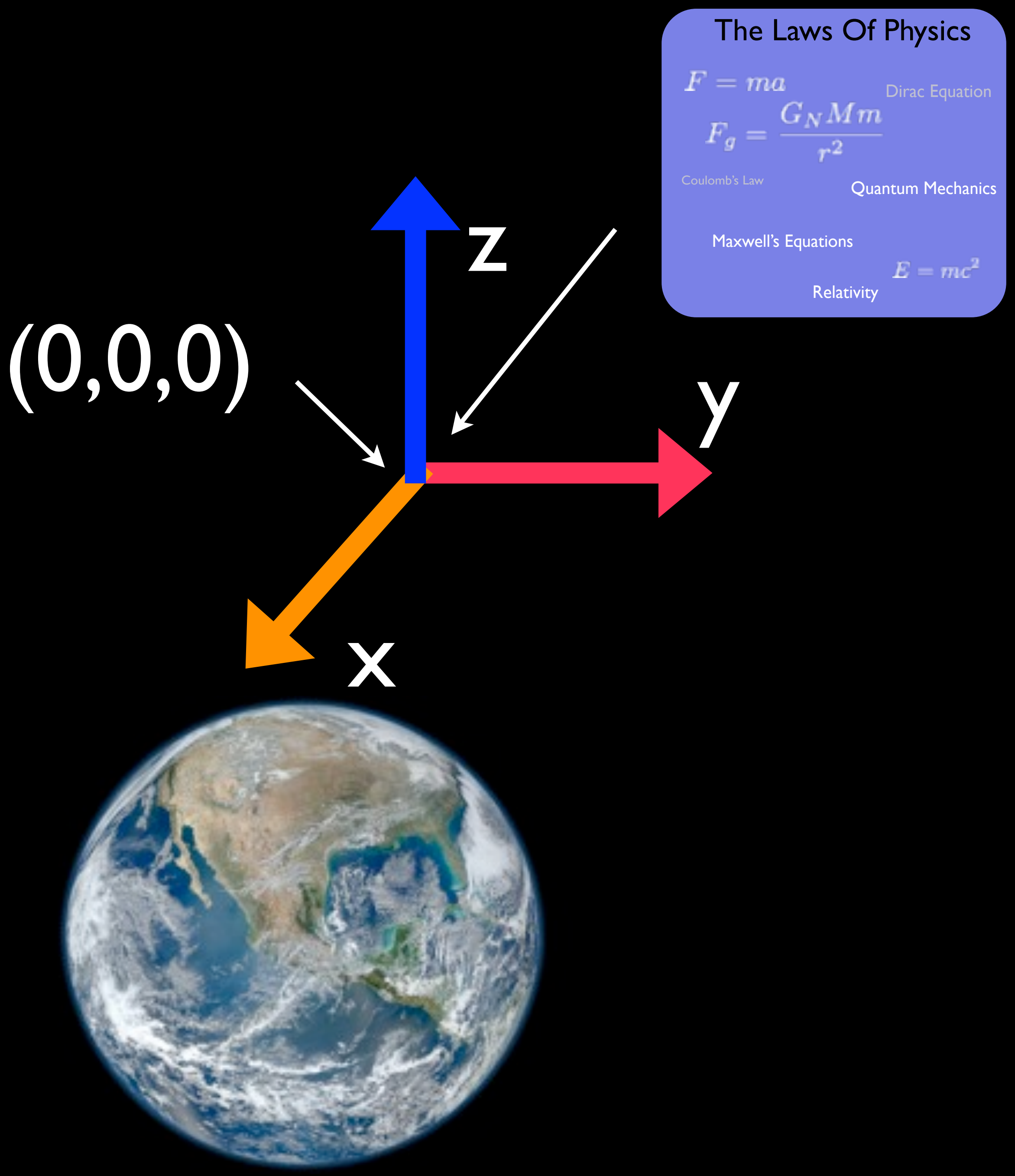
Relativity
z
(0,0,0)
y
x

So ....????



- ✦Pick a coordinate system (3 directions)
- ✦Pick point from which to measure distances
- ✦Experiment and determine Laws of Physics



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✦*Move the* point from which to measure distances (keeping all else the same)

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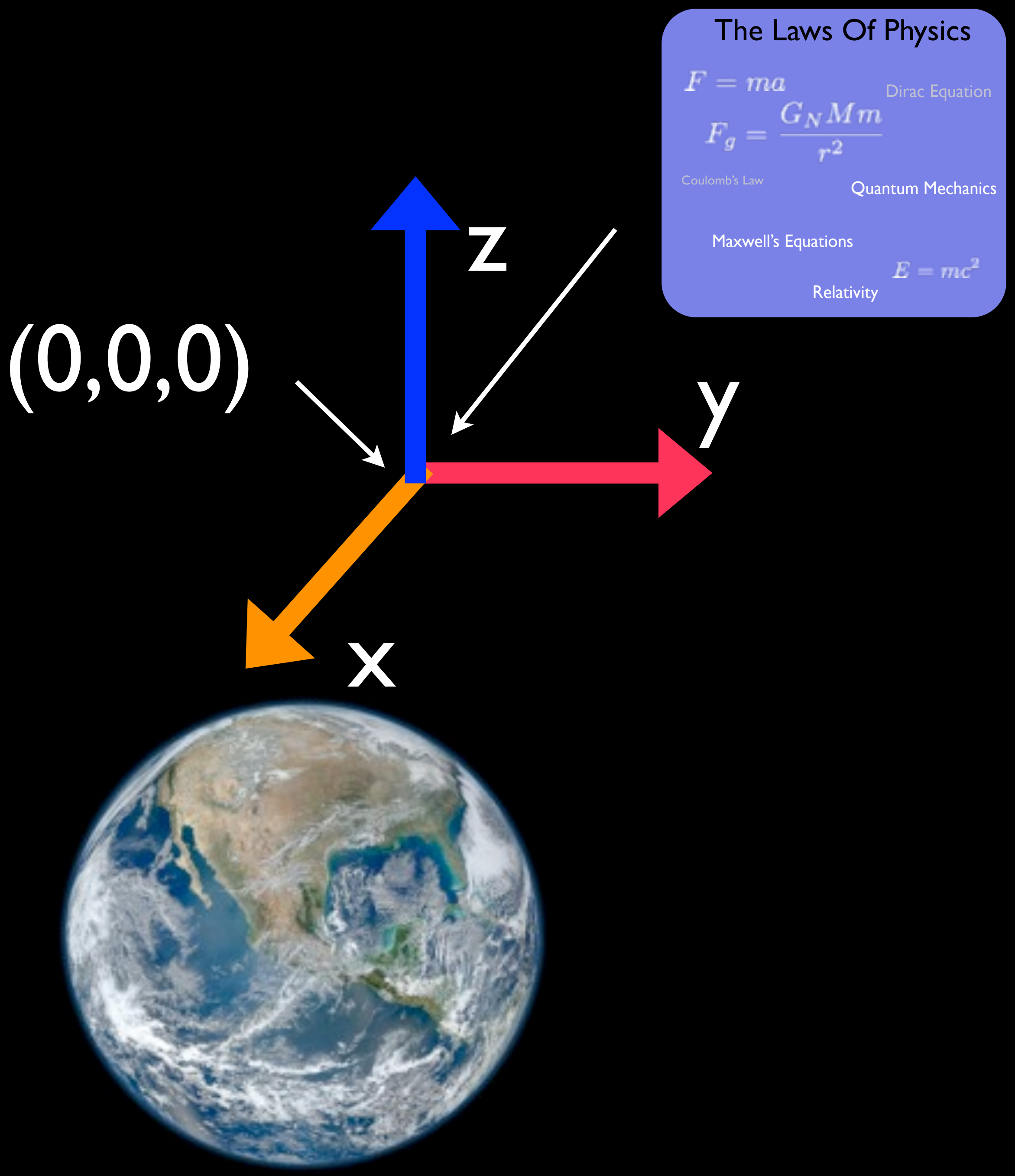

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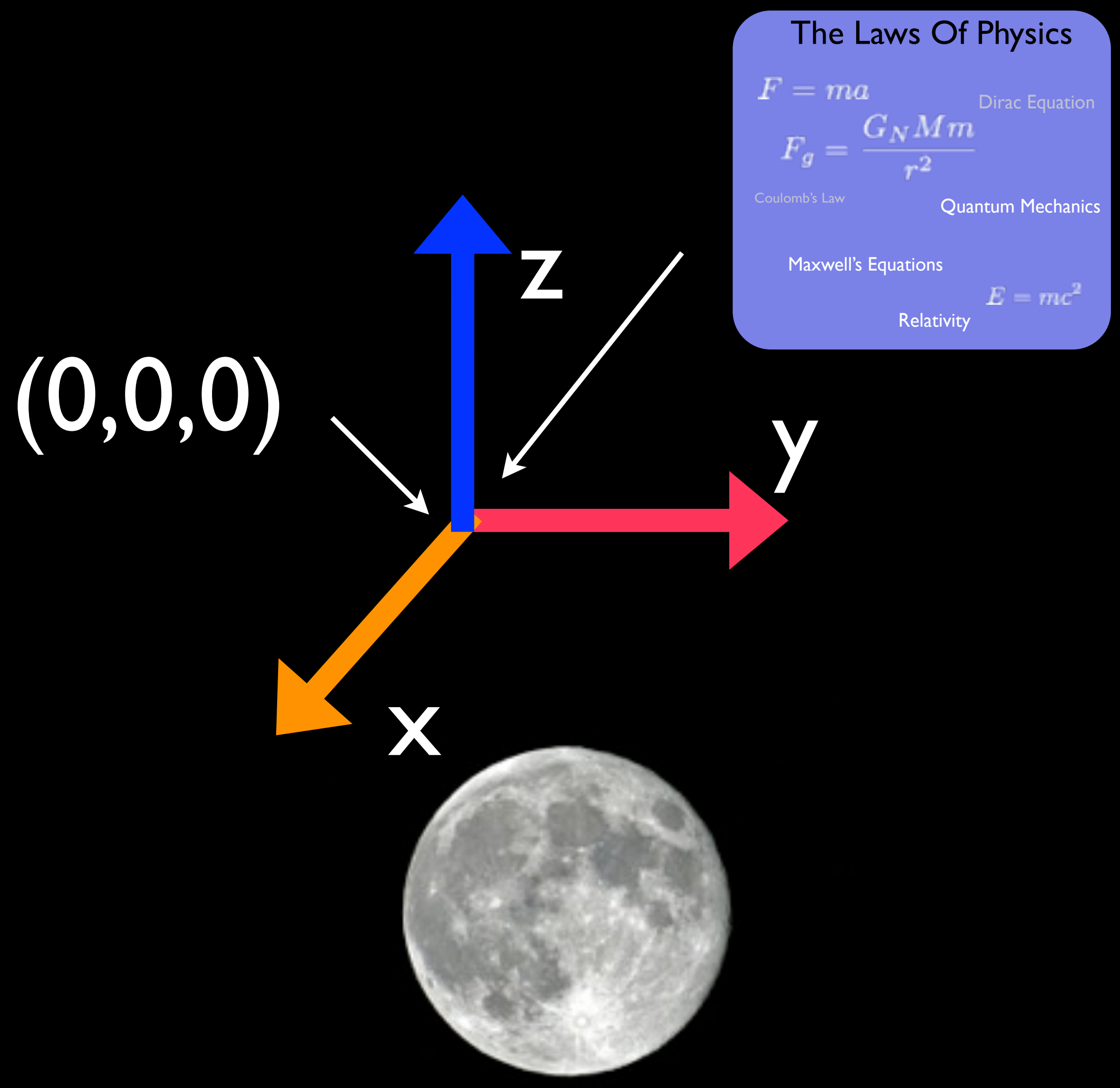

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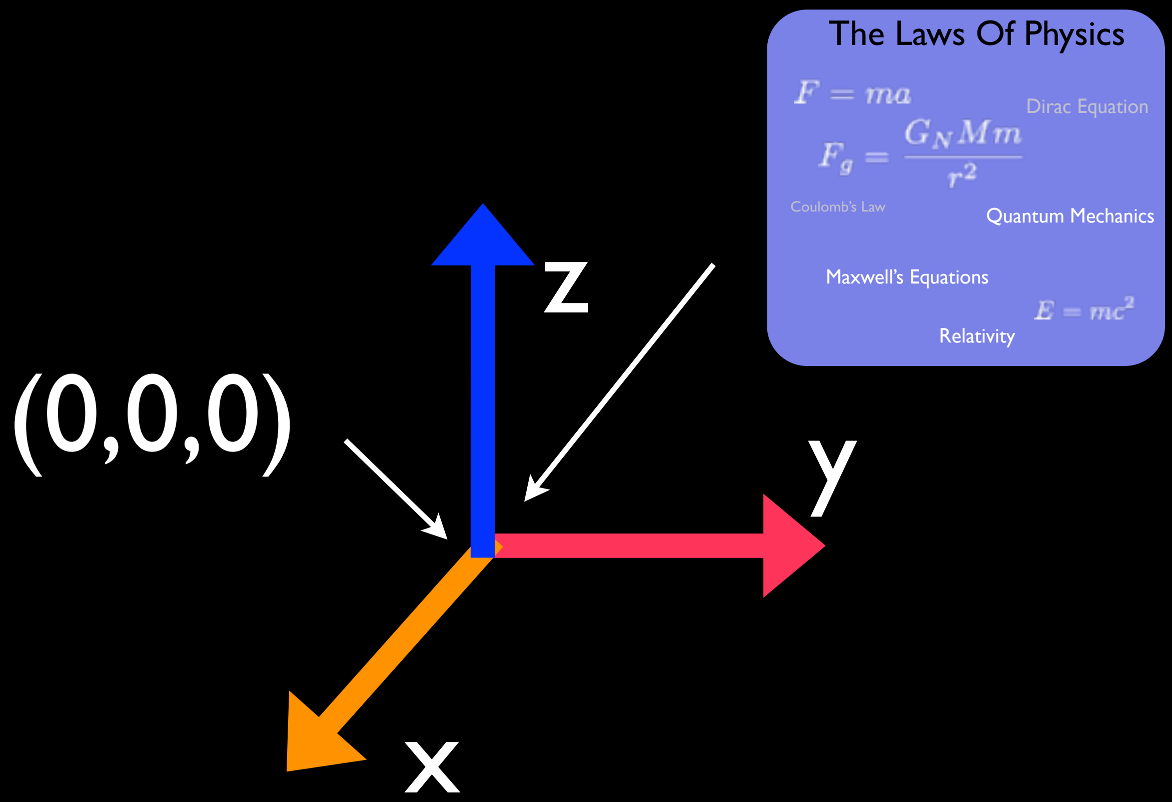

Obvious?

- The Laws of Physics don't depend on where we measure them
- Not that eg the *strength* of gravity is the same on the moon as Earth
- But, the *mathematics* of gravity is the same

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- This is a form of a *symmetry!*
- We can move the coordinate system we use to measure the object = "Laws of Physics", and it is the same (invariant) no matter where we move our coordinates
- Amazingly, this causes the Law of Inertia, or Conservation of Momentum (momentum = mass x velocity)

Symmetry and Force

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- Start with an empty Universe with one particle of mass *m*
- There are no forces -- particle just moves freely (Law of Inertia)
- Write down the physics equation the particle follows, that is consistent with both Relativity and Quantum Mechanics (this equation is called the Dirac Equation)

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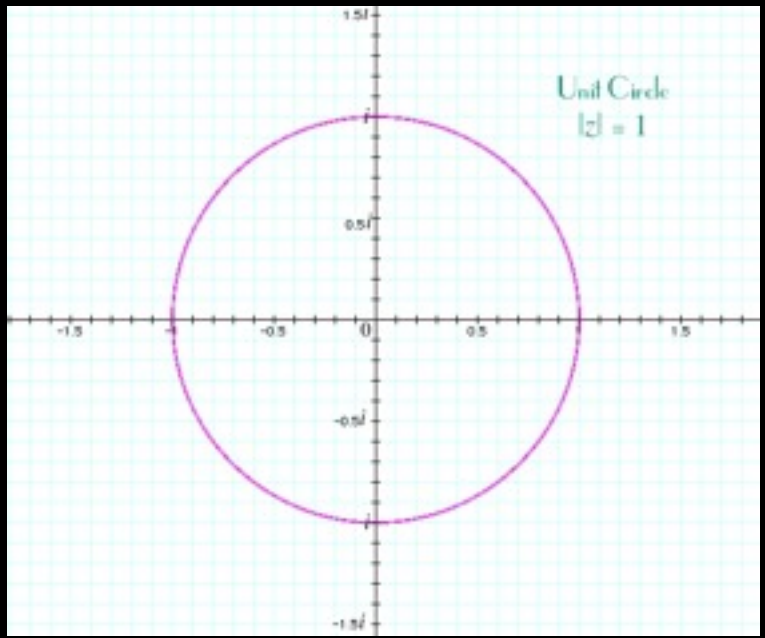
- It’s just like picking a direction by choosing a point on a circle



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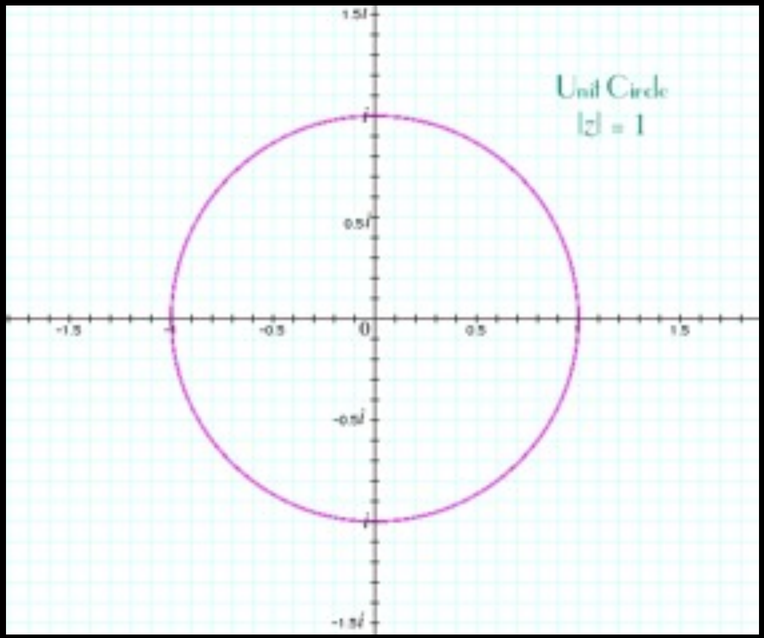
- It's just like picking a direction by choosing a point on a circle
- The physics is "symmetric" if you rotate



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- Like if you had a map and picked what you called 'North' differently all over the map (but still expected all your directions to work!)
- But it turns out this doesn't work. So we ask -- what do we have to add to make it work?

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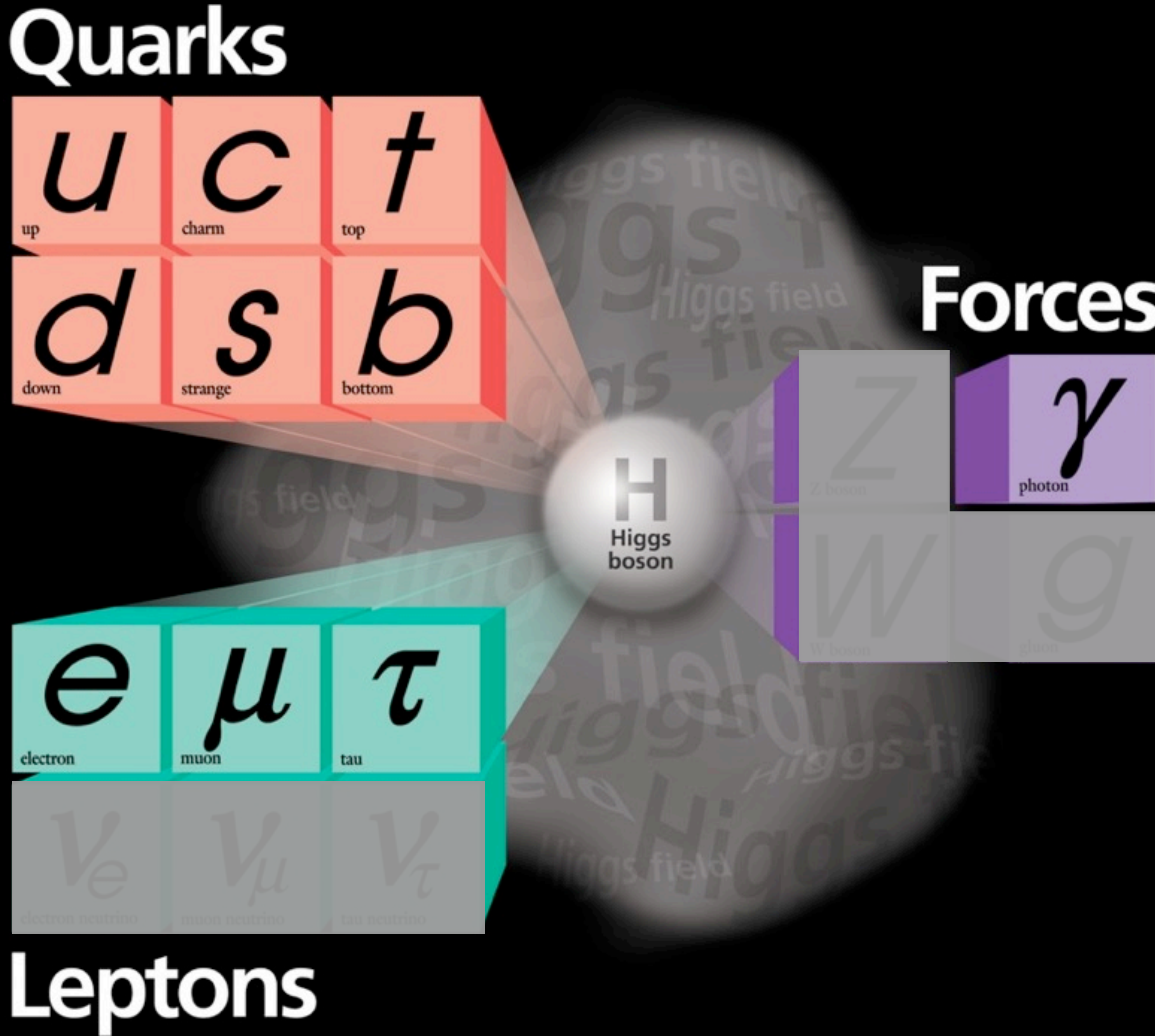
- All this only works if the new particle has mass = 0


Quarks
u
up
c
charm
t
top
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s
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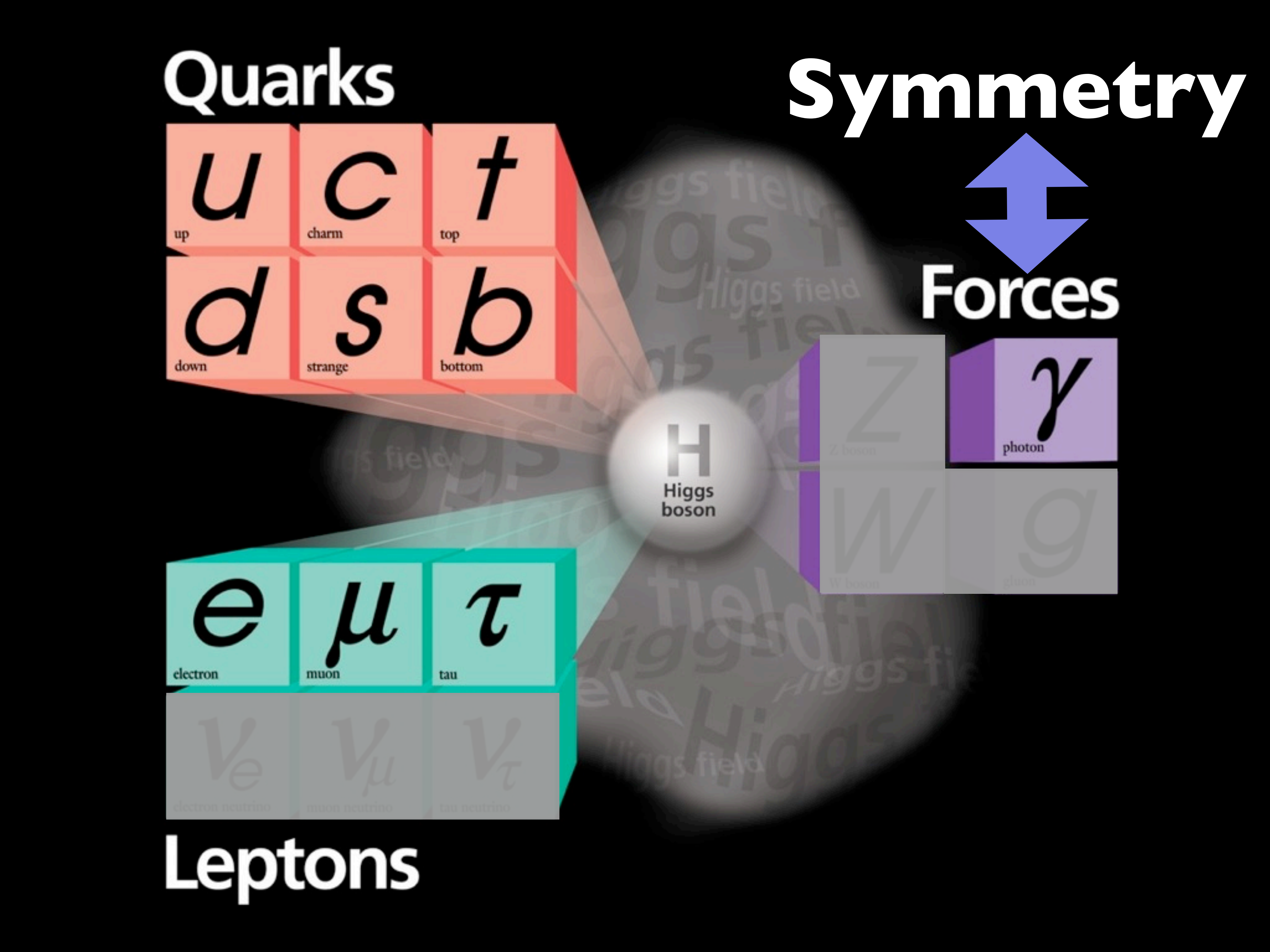
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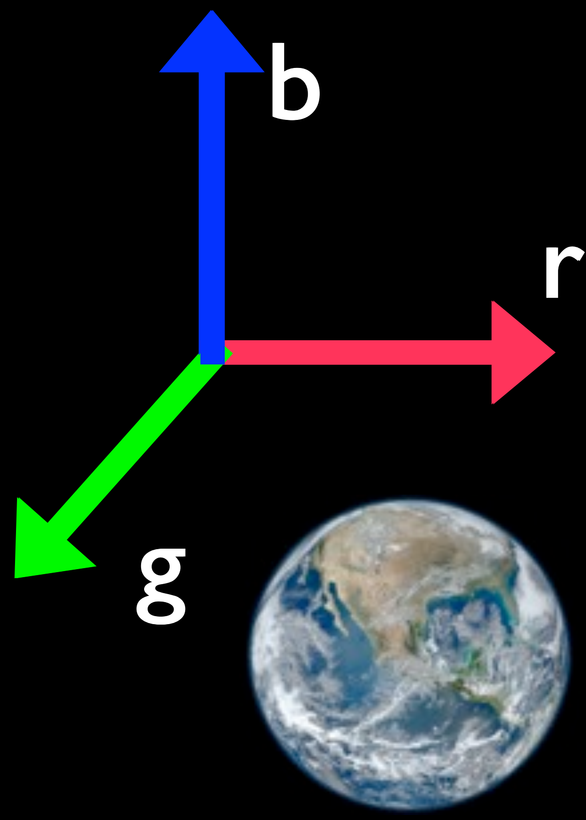
Strong Force

- Now we do the same with the strong force
- It has 3 “charges” which we call Red, Green, Blue (just to help remember)



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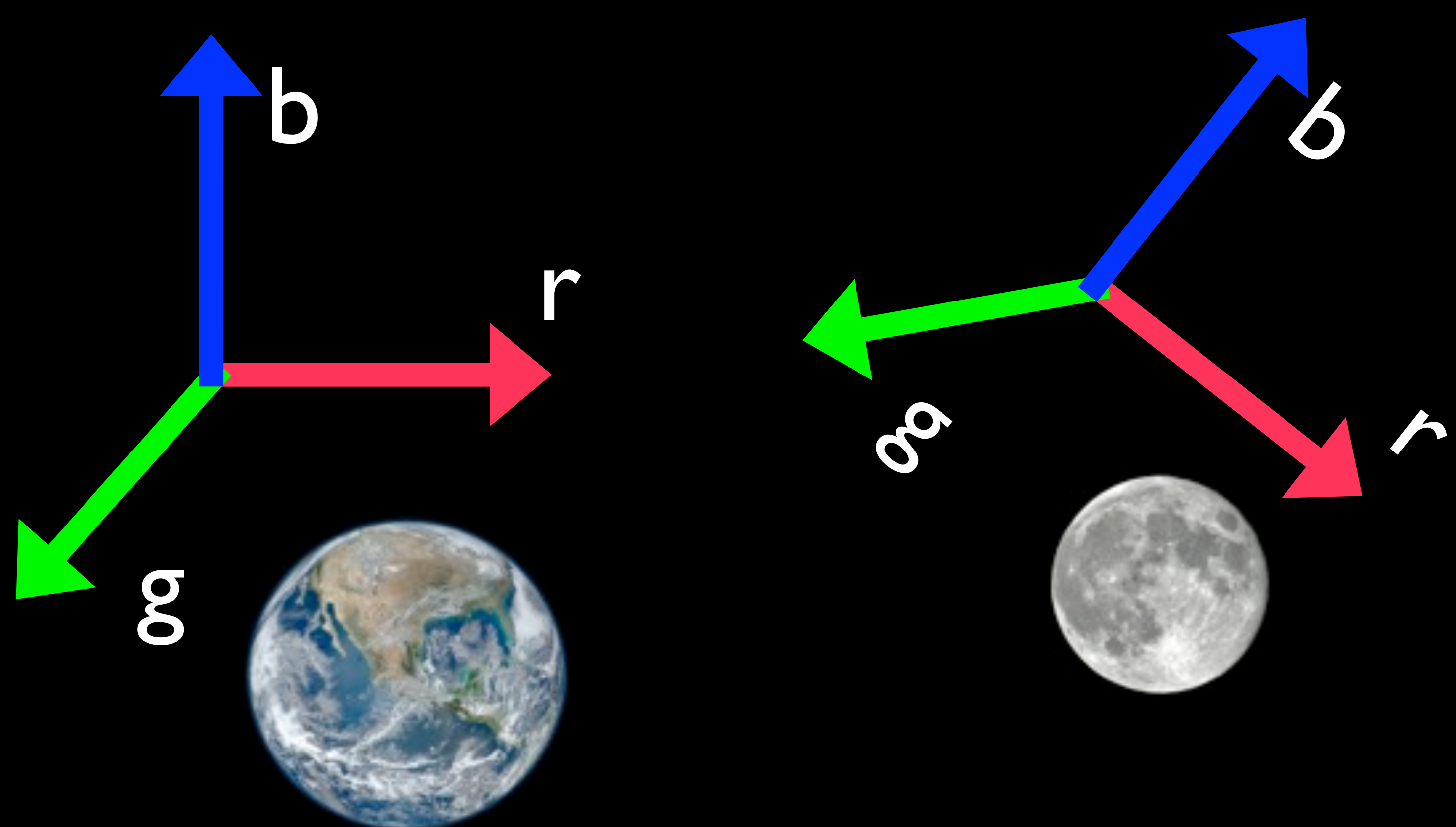

Require that we can pick any "direction" we want for the R, G, B definitions and that the Laws of Physics are unchanged

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- All 8 new particles must be massless

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- Disaster #2: It turns out we have to set the mass of *every* particle in the Universe to 0! But all the quarks and leptons have non-zero mass.
- This is not good ...

Remarkable Recovery

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- Everything really *is* massless
- Add a new particle type -- Higgs Boson
- Interactions with the H make particles *seem* to have mass

The Papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 19

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

2013 Nobel Prize -- Higgs and Englert

SideBar: Mass

- Remember: Mass is not the same as weight

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- In space, you are *weightless (*zero gravity), but not *massless*

Cmdr. Hadfield on the Space Station

SideBar: Mass

- Remember: Mass is not the same as weight
- In space, you are *weightless (*zero gravity), but not *massless*
- How would you measure the mass of something?

Cmdr. Hadfield on the Space Station

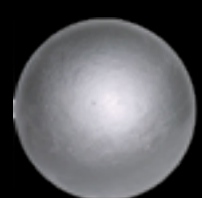
In space, these would all just float in front of me

Shot Put

Beach Ball

Pea

But if I wiggle them back and forth, they are different



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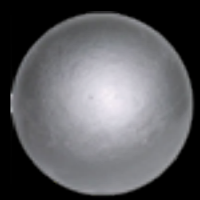
Pea

Because F=ma (Force = mass x acceleration)
it is harder to move the shot put than the pea



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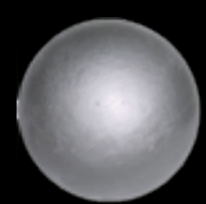


Shot Put

Beach Ball

Pea

Hard to move
Large Mass

Easy to move
Small Mass

Very Easy to move
Very Small Mass

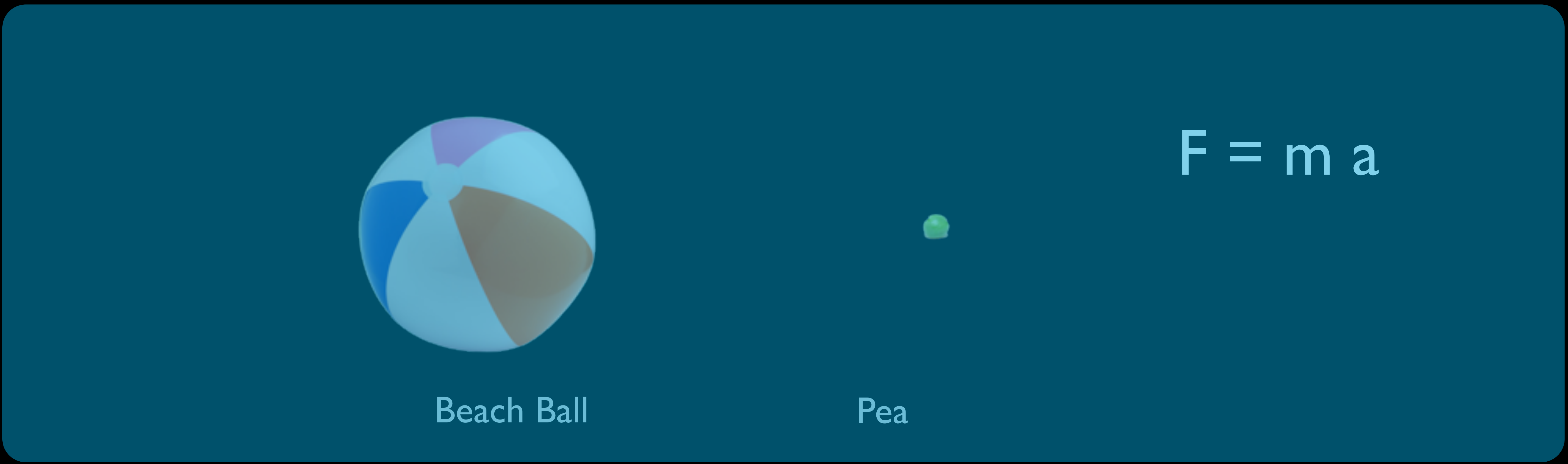
Now, imagine my space station is filled with water

Beach Ball

Pea

$$F = m\ a$$

Now, imagine my space station is filled with water



Very Hard to move
Very Large Mass?

Very Easy to move
Very Small Mass

Now, imagine my space station is filled with water

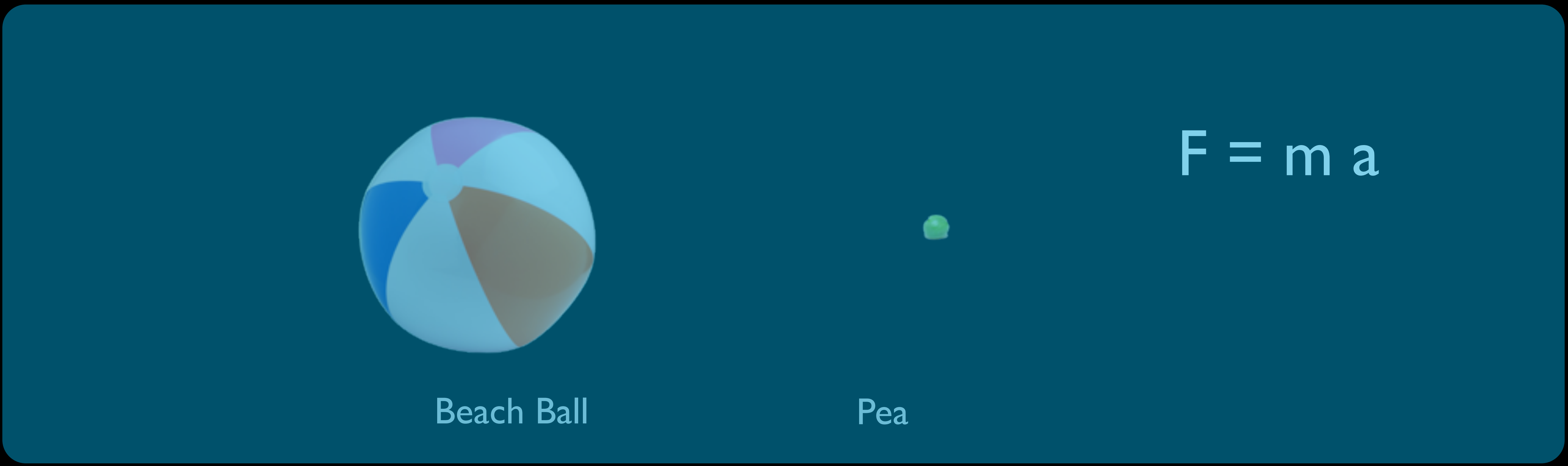
$$F = m\,a$$

Very Hard to move
Very Large Mass?

Very Easy to move
Very Small Mass

The Beach Ball *interacts* more strongly with the water than the pea and so is harder to move (needs more Force)

Now, imagine my space station is filled with water



Very Hard to move
Very Large Mass?

Very Easy to move
Very Small Mass

The *interaction* with the surrounding medium makes the ball seem heavy now

Generating Mass

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Generating Mass

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- The stronger this interaction the harder it is to move
- Harder to move = “heavier”
- Mass is a mirage, heavier particles just interact more strongly with the Higgs field!

- That analogy has some flaws -- e.g. why doesn’t the Higgs field end up slowing down everything moving, like water would?
- The Higgs field, even in completely empty vacuum, has a strange property

Ground States

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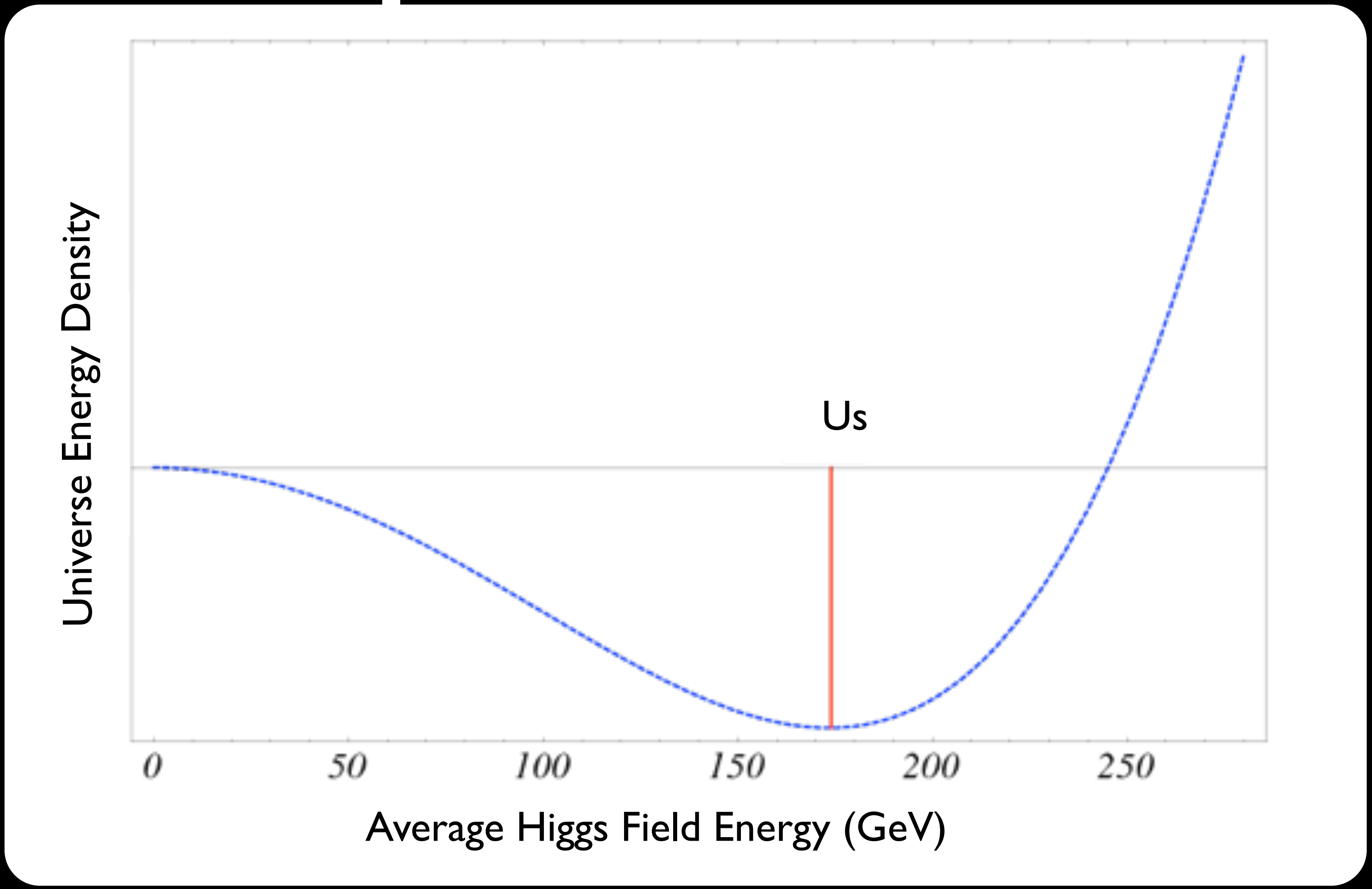
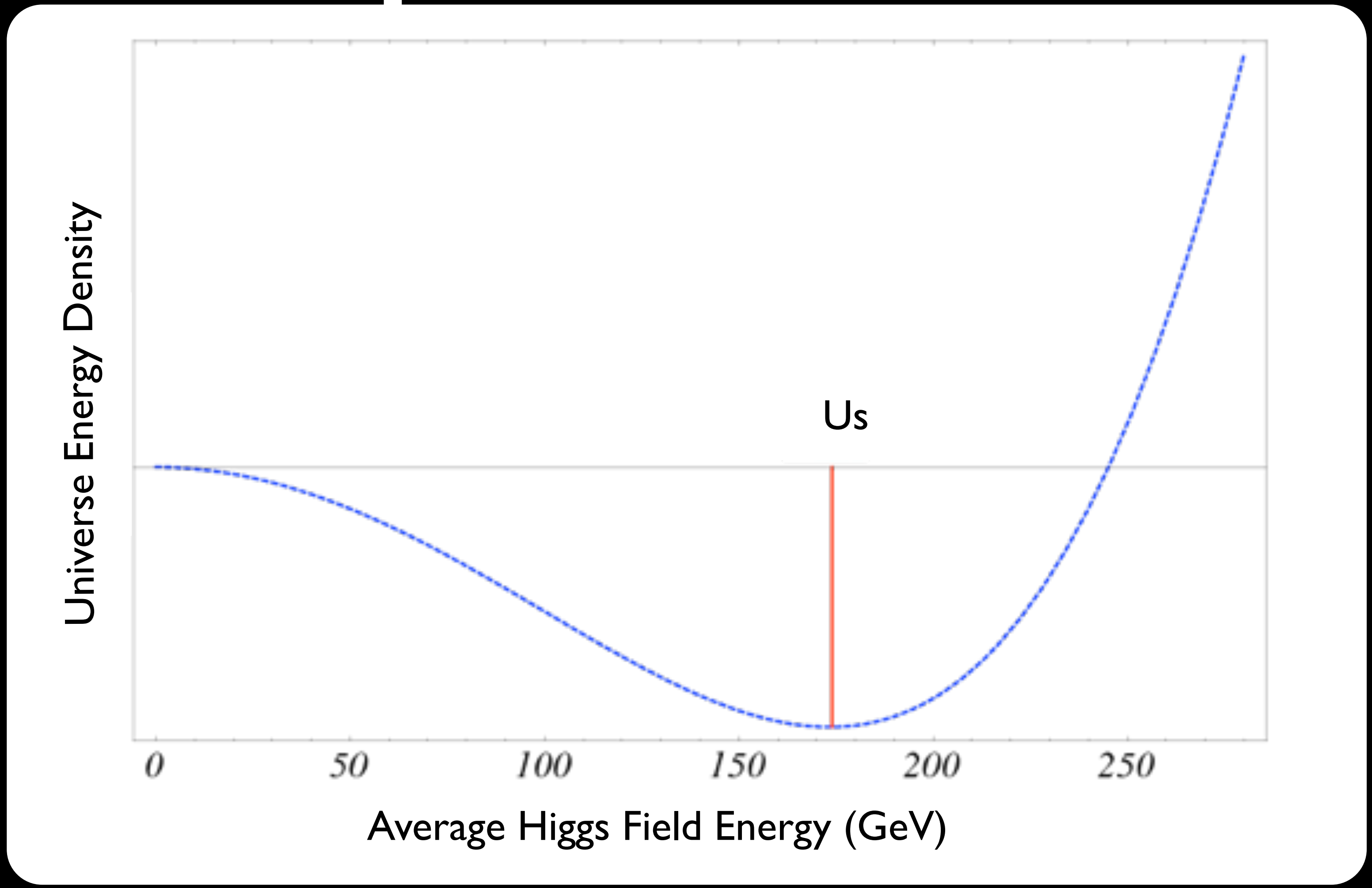
- In the vacuum of empty space (lowest energy state), the average value of the electromagnetic field, for example, is zero
- If we add energy into the electromagnetic field, we increase the total energy of the system (obvious, right?)

Higgs in Space



Higgs in Space

- The Higgs field *doesn't* act this way



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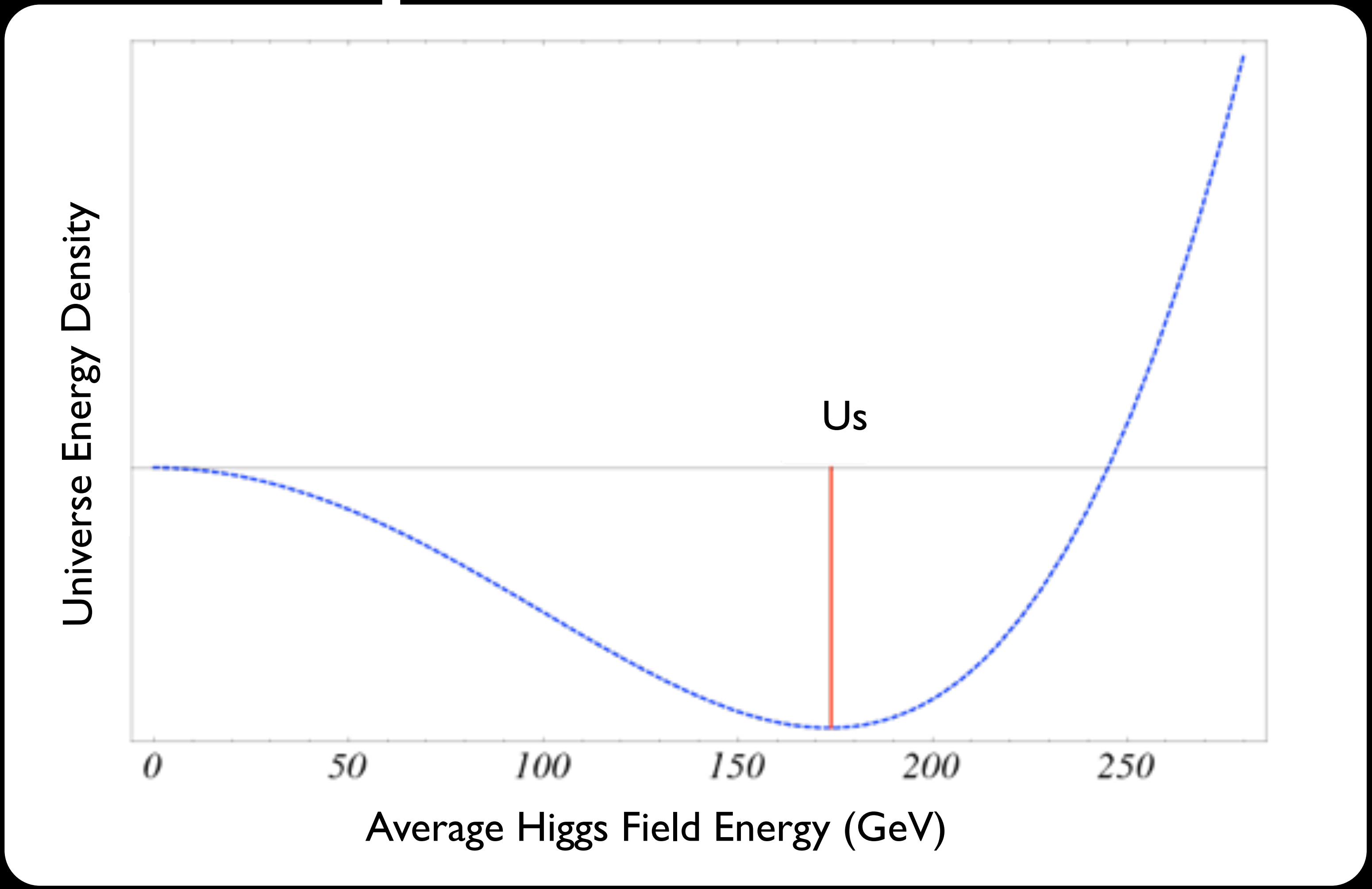

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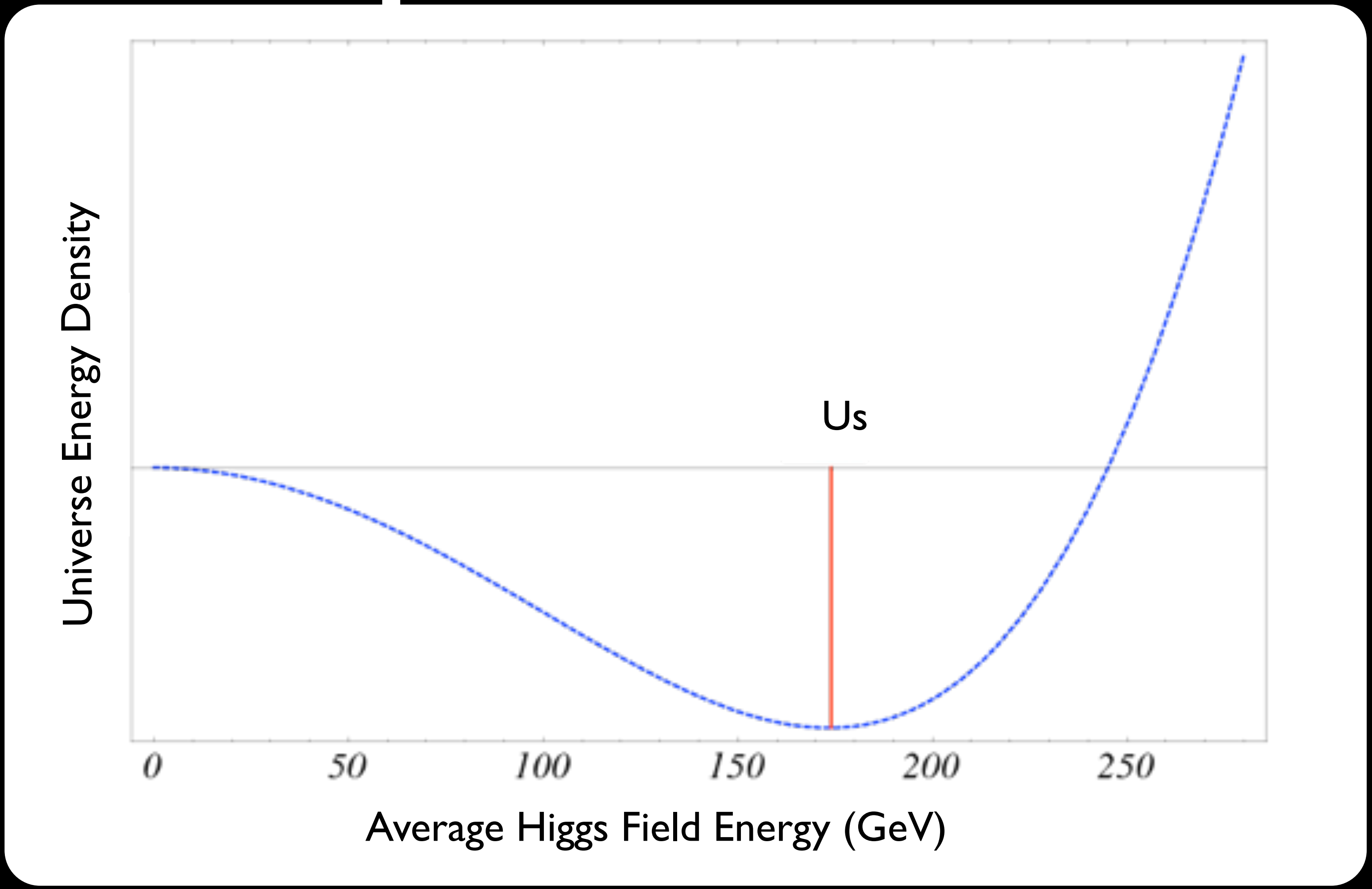

- The Higgs field *doesn't* act this way
- As you increase the average field energy from zero, the total energy of the vacuum goes *down* not up, at least to a certain point
- The most stable, lowest energy configuration has a non-zero average Higgs field energy everywhere

Making Particles

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Making Particles

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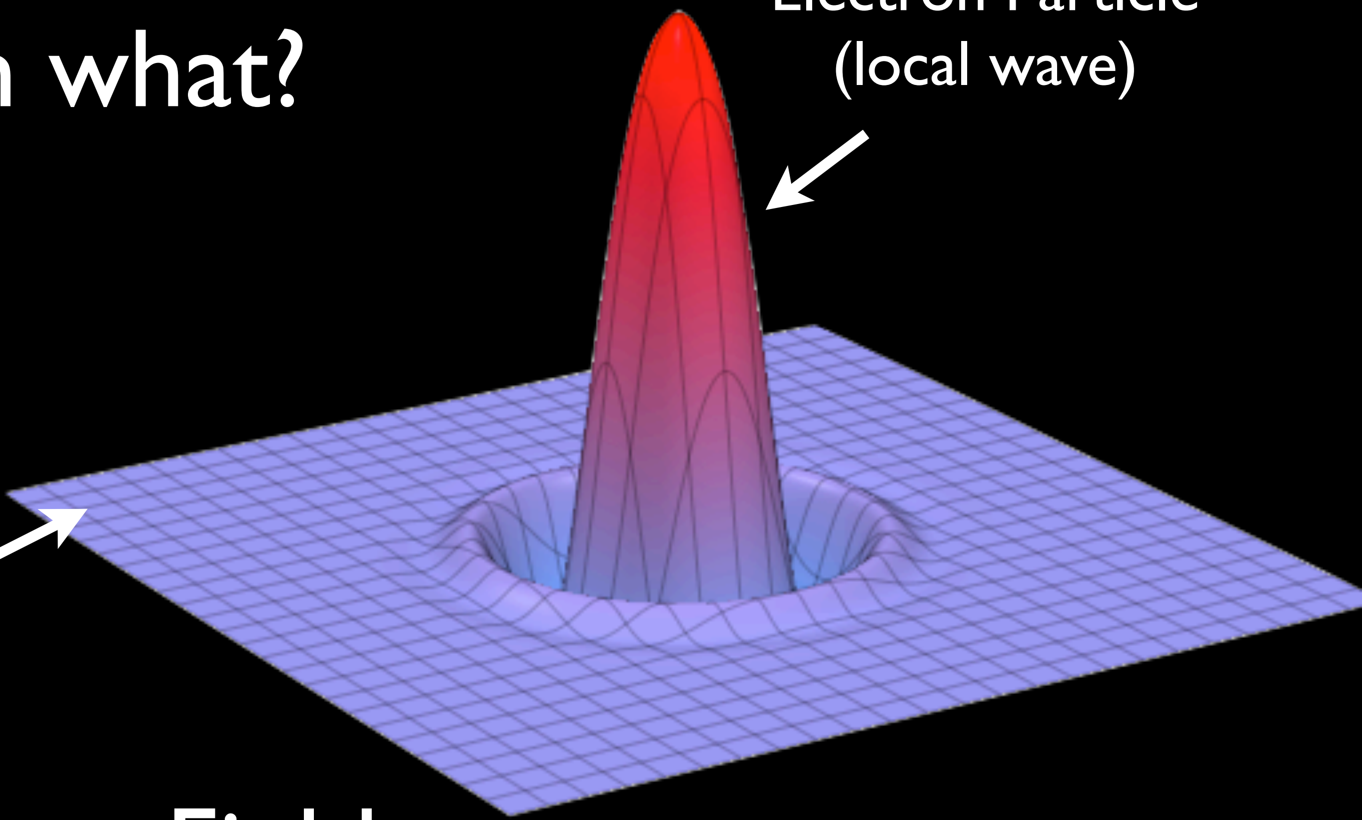

- Electron = wave in Electron Field
- *Costs energy to make*

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- We have to pay for the energy of this interaction
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- No matter how little energy we put into the motion of the electron wave, we always have this minimum cost

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- Each elementary particle type can have a different strength of the amount it interacts with the Higgs Field
  - (strength of interaction) x (average Higgs Field Energy)
- Which just means a different minimum energy is needed to make any wave in that particle's field
- Which means a different apparent mass

Any Evidence?

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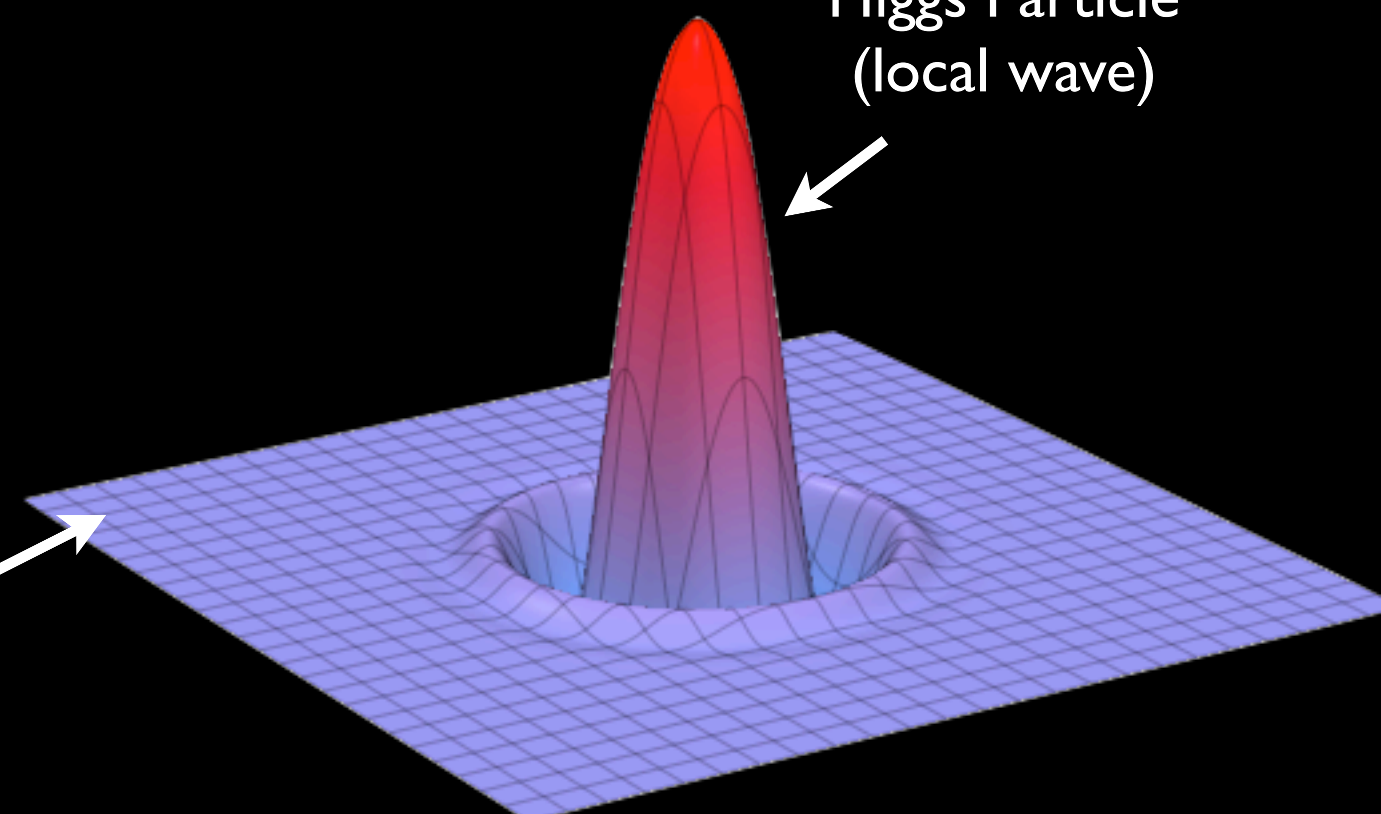

- Higgs *Particle* = wave in Higgs *Field*

(vanishes 1 billionth of a billionth of a billionth of a second after you make it)

Seeing Higgs Particles

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- But we need *enough energy* to create the excitation, and it is *very rare to excite the field* ... it interacts most strongly with heavy particles, and our usual accelerators use electrons or protons (ie up and down quarks) which are very light

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- This is the challenge that the LHC has finally solved -- high energy and high repetition rate of collisions

Trouble with the Higgs

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- The problem is -- the Higgs makes no sense!

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- If you work out the math of what it's mass should be we need an unnatural cancellation between two unrelated numbers in the theory to get anything sensible

The problem

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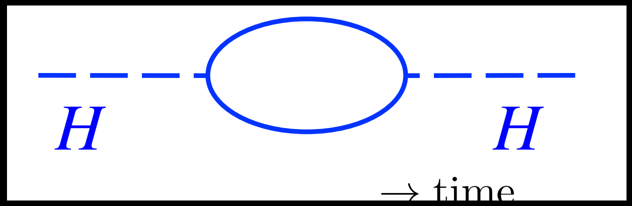

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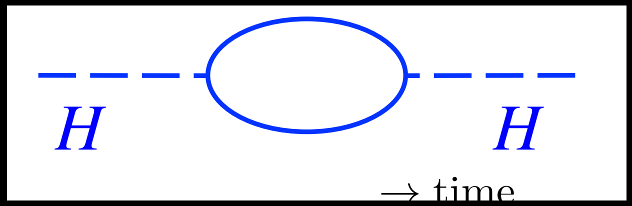

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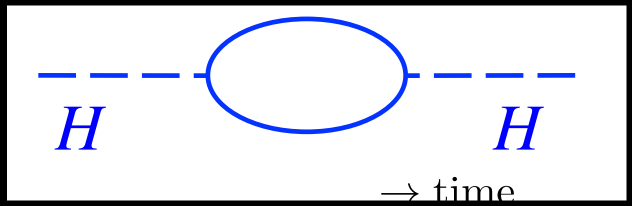

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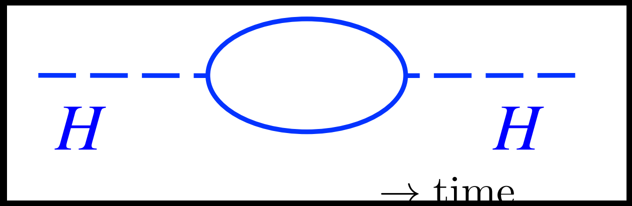

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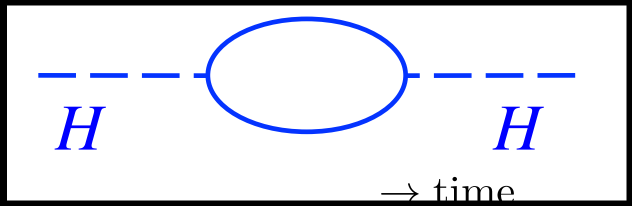

- The Higgs is actually all these things at once -- the "Higgs in itself" and all the other particles it can fluctuate into
- It's properties, such as it's *mass* get contributions from all of these states at once
- It turns out the contributions from these loop fluctuations are *enormous*, and so must be offset by the "Higgs in itself" mass to get anything sensible

Coincidences?

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- Total Eclipse: Angular size of moon = angular size of Sun (to within ~2.5%)

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- Total Eclipse: Angular size of moon = angular size of Sun (to within ~2.5%)
- 987654321/123456789 = 8.000000073
- For the Higgs mass to be near 125 GeV (about 125 times the mass of the proton, where we think we have found it)

We need 2 unrelated numbers in our theory to be equal to about 32 decimal places!

Such as:

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Such as:

$a=8.92746351424283546746251659684702 4$

$b=8.927463514242835467462516596847025$

We need 2 unrelated numbers in our theory to be equal to about 32 decimal places!

Such as:

a=8.92746351424283546746251659684 7024

b=8.927463514242835467462516596847025

But: These numbers aren’t so close for *any reason at all!*

We need 2 unrelated numbers in our theory to be equal to about 32 decimal places!

Such as:

a=8.927463514242835467462516596847024

b=8.927463514242835467462516596847025

It is just a coincidence

Without which the universe wouldn't be here anymore

Trust me!

- This *naturalness problem* is so extreme because the particles in the loop fluctuations can have very large energy -- all the way up to the energy at which gravity becomes strong and must play a role -- about 10^{15} times higher than the energy we can make at our current accelerators

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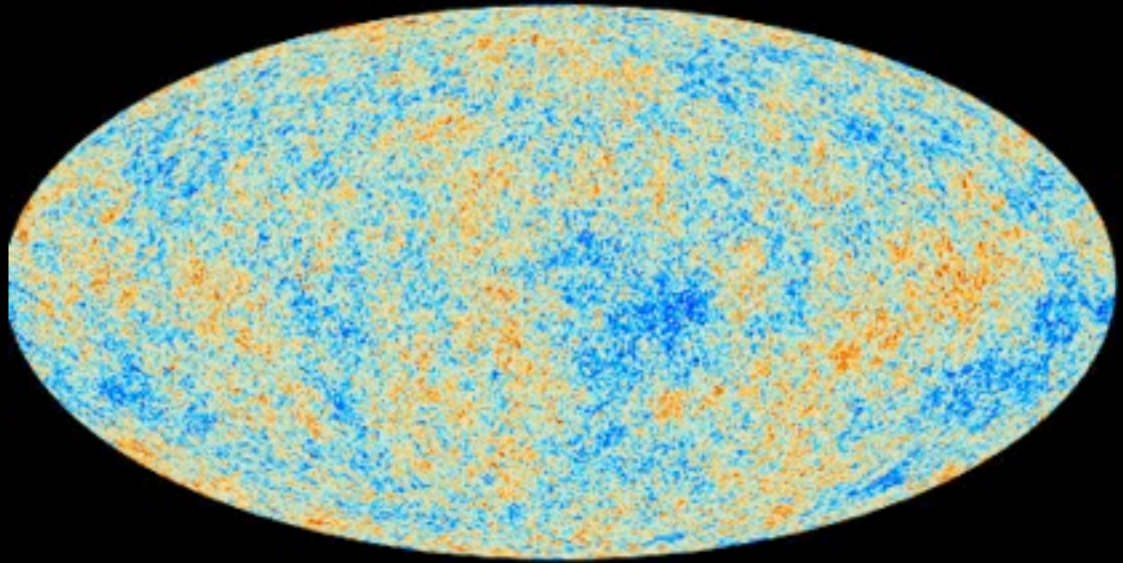
- Way out #1 -- Add some new physics!
- Way out #2 -- Make gravity strong sooner
- Way out #3 -- Make lots of universes

Dark Matter

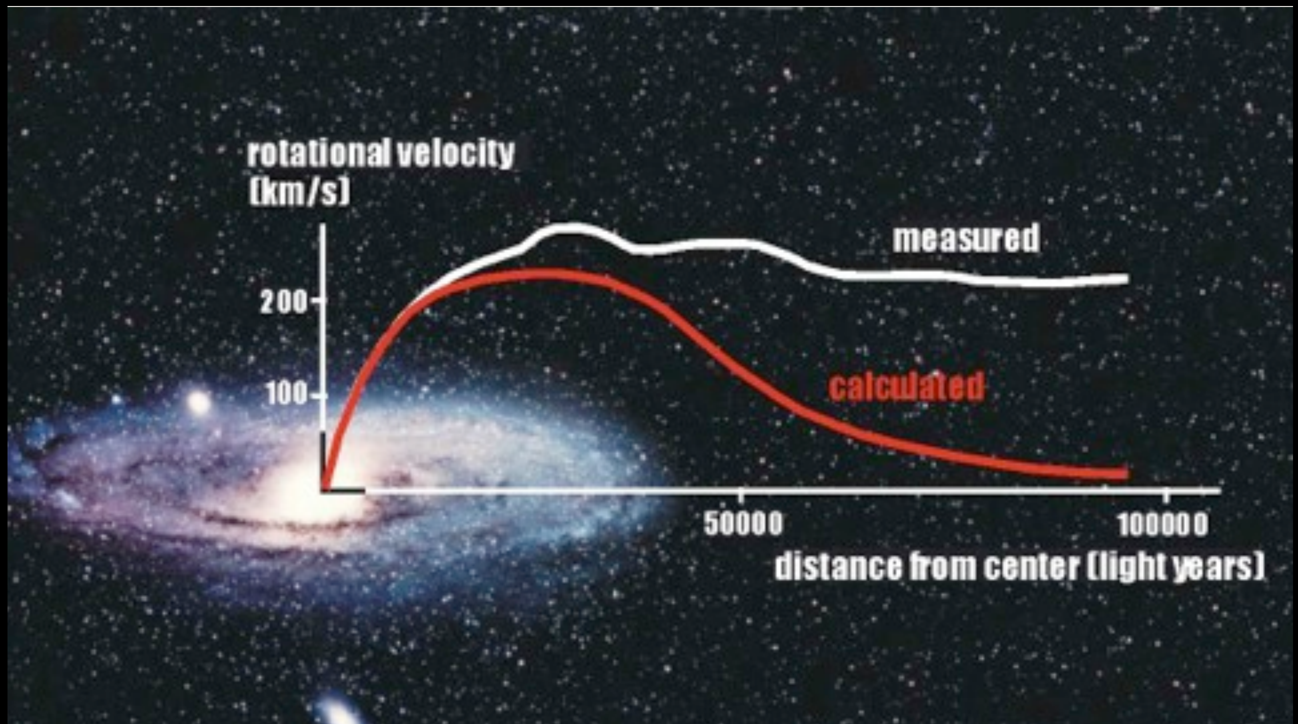
- Cosmic microwave background
- Galaxy Rotation Curves
- Galactic Cluster motion
- Lensing
- Big Bang Nucleosynthesis
- Supernova redshifts
- .....

Point to most of the universe being Dark Matter (and Dark Energy)

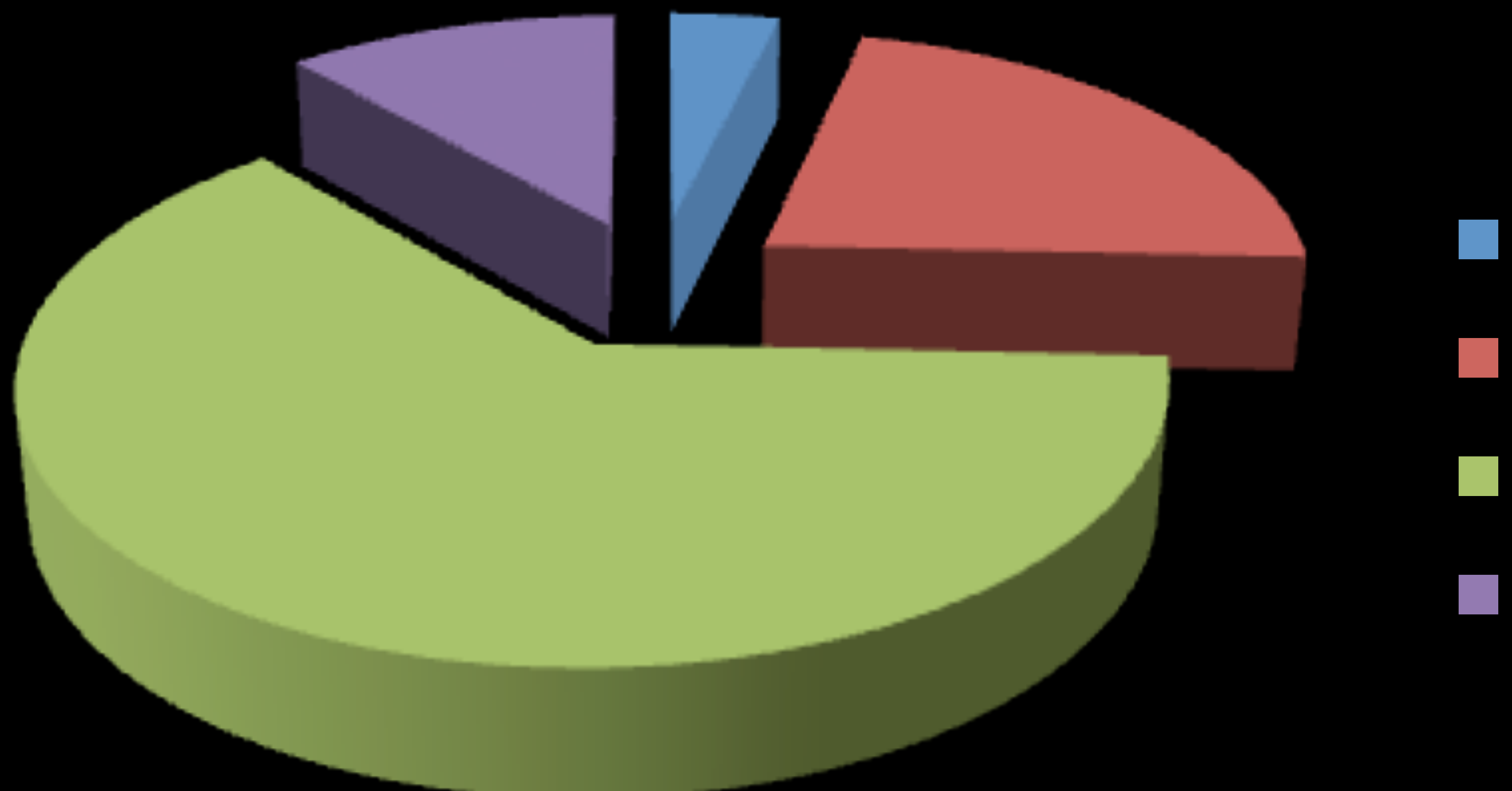
Two Galaxy Clusters Collide



Planck temperature map



What’s in the Universe?



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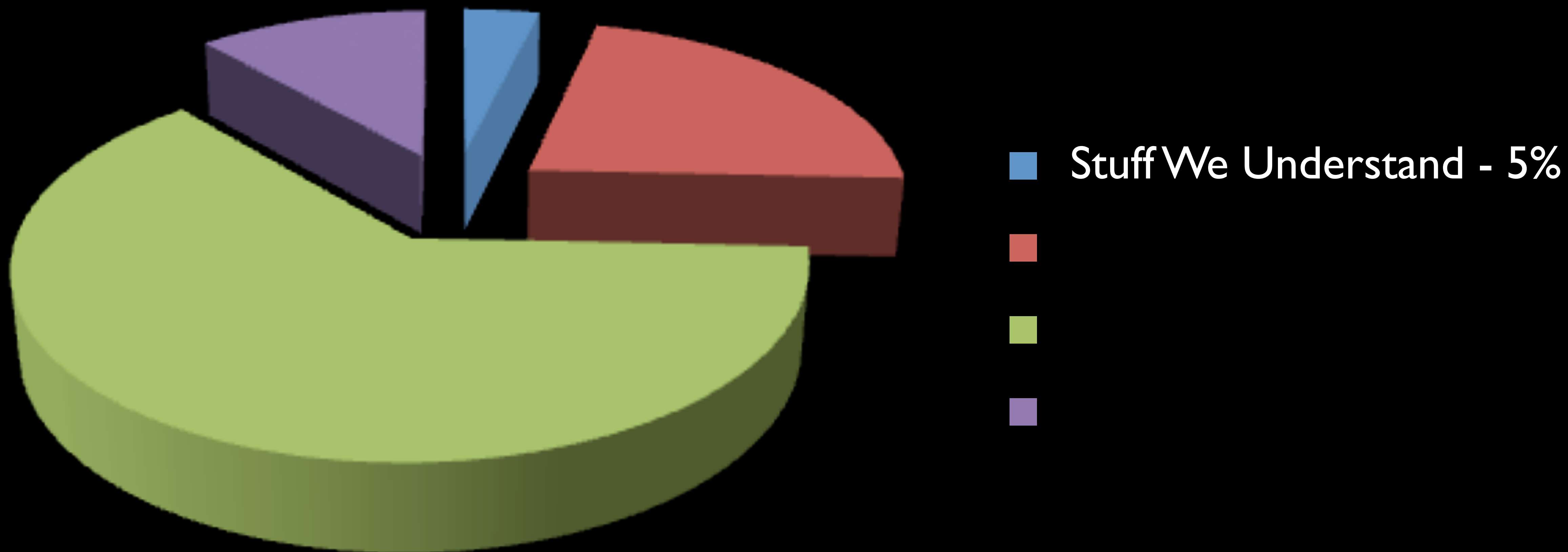

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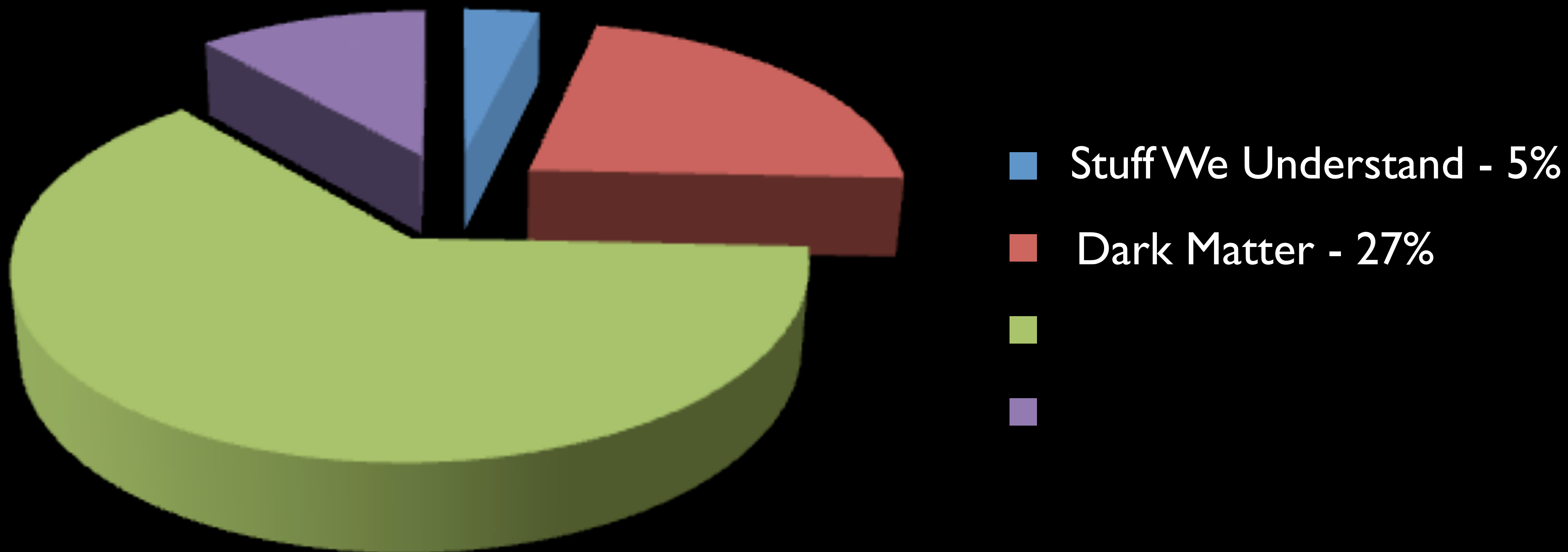

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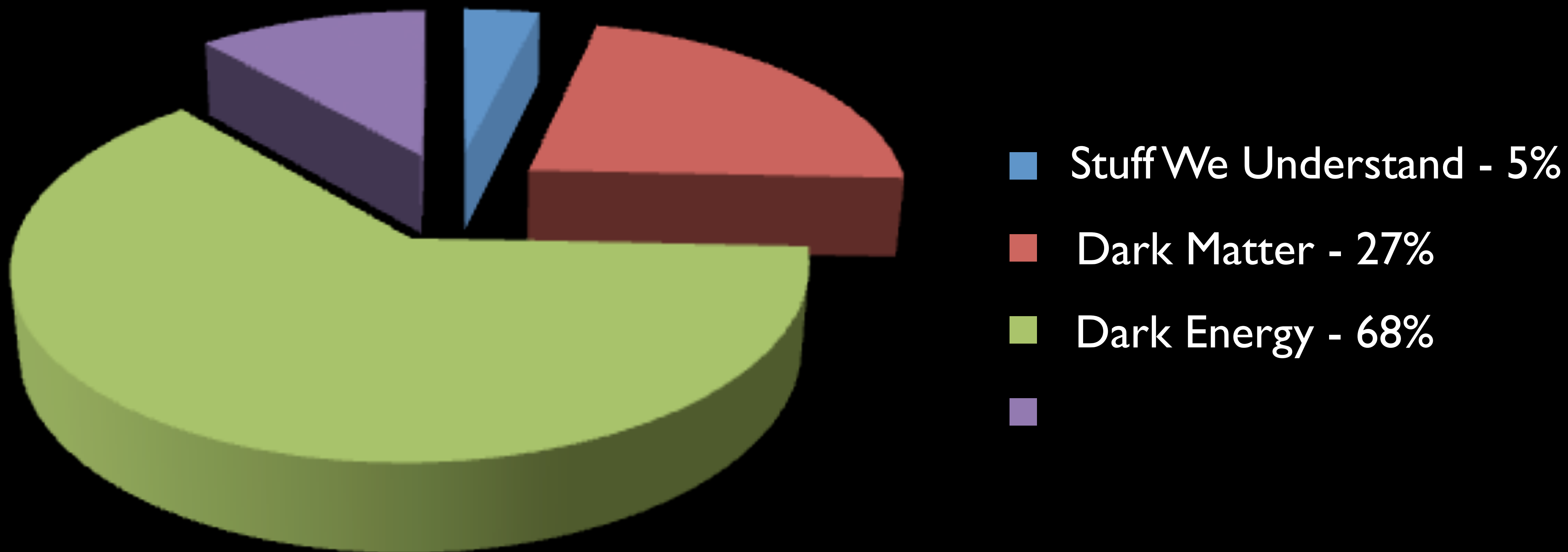

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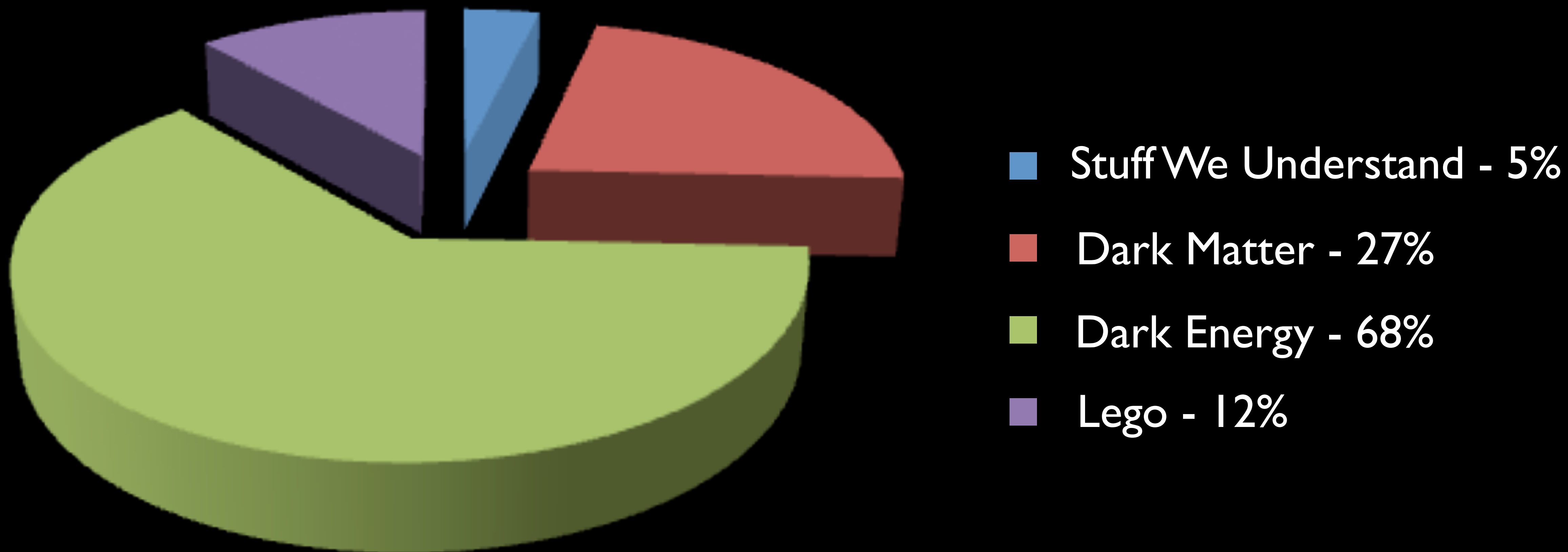

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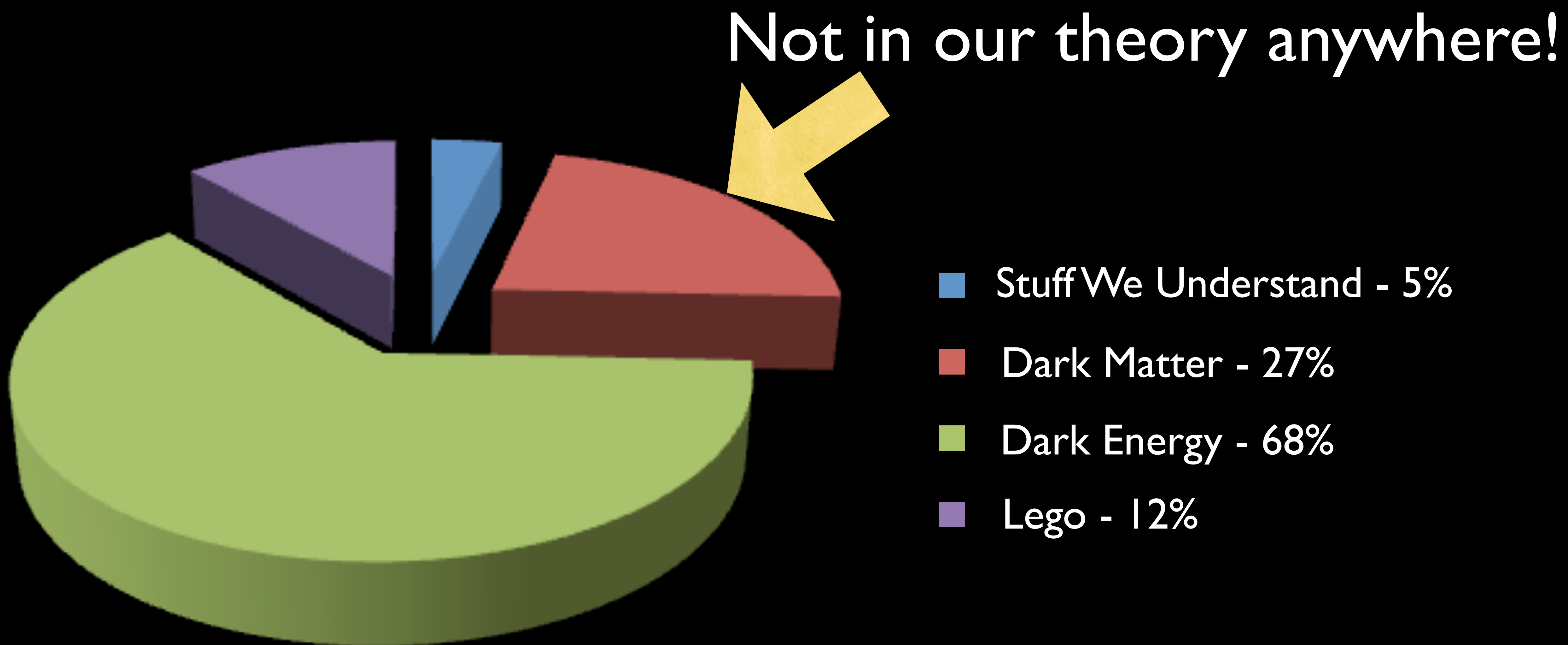
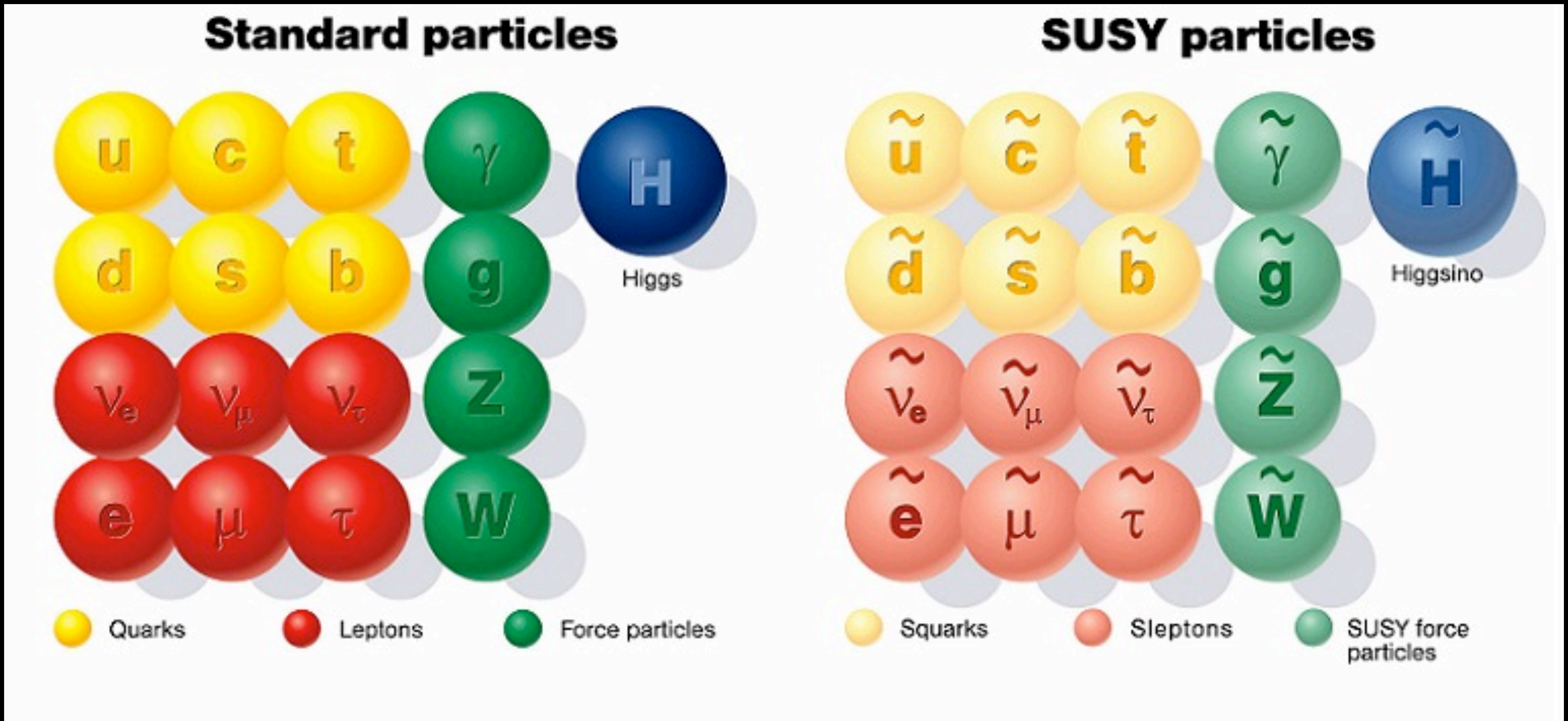
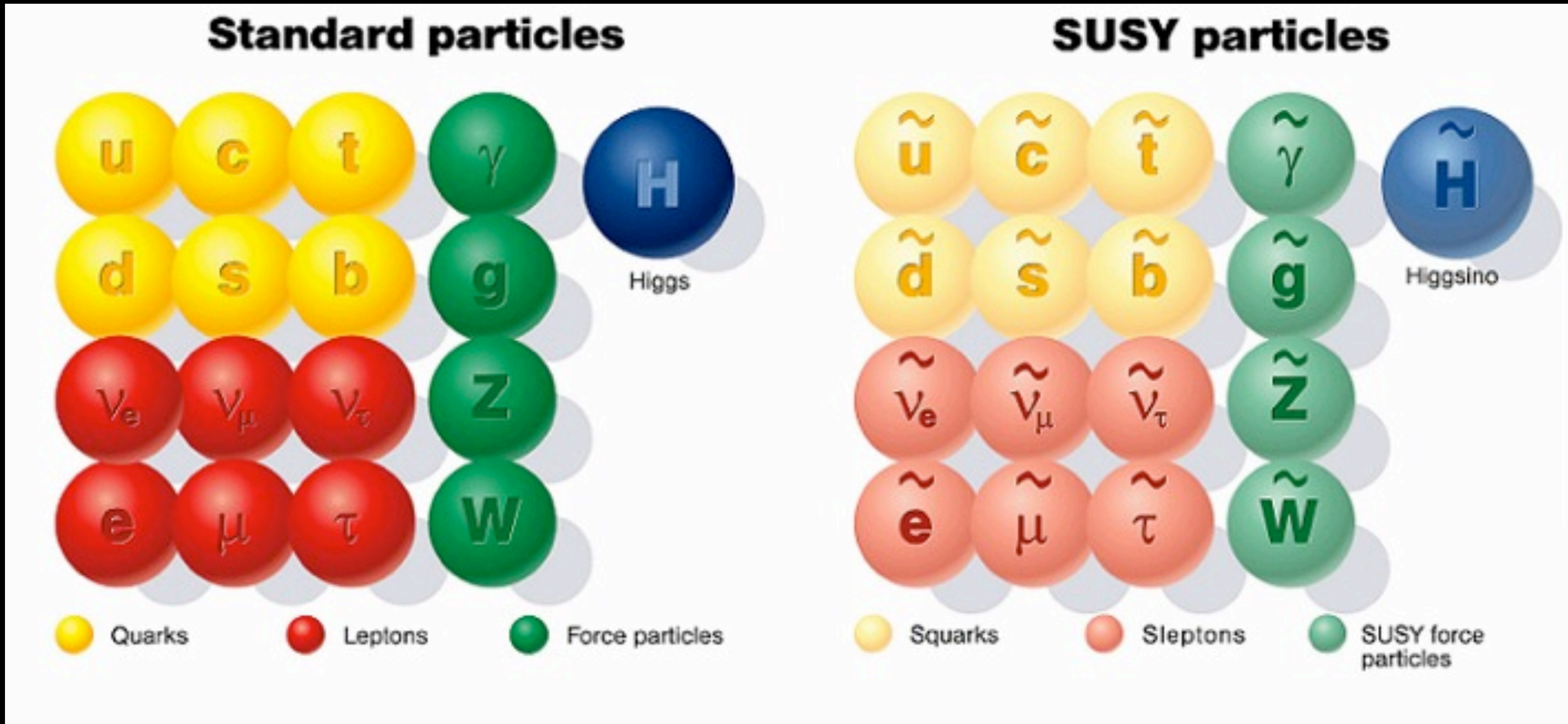


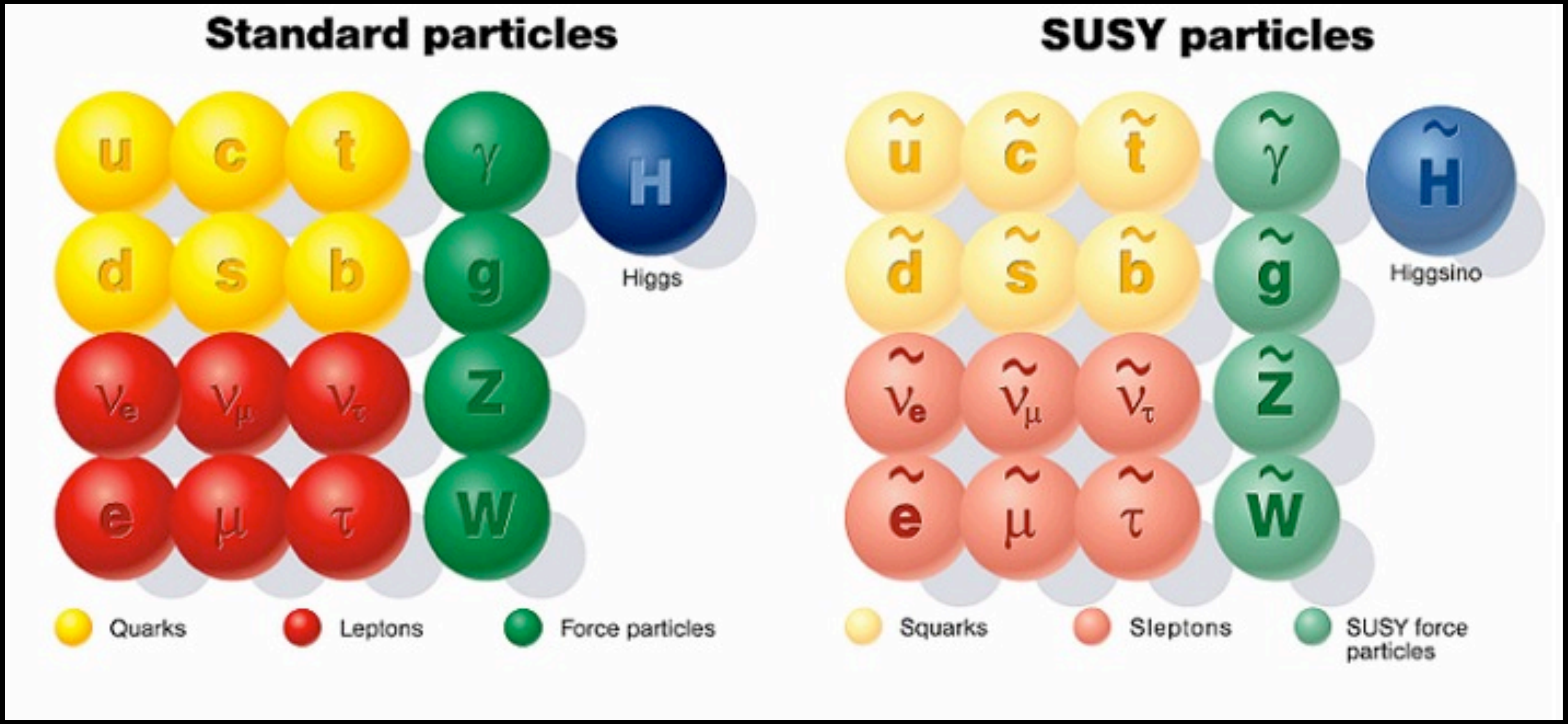
Easy -- just add “s” or “ino”!



Supersymmetry



Many like this model because:



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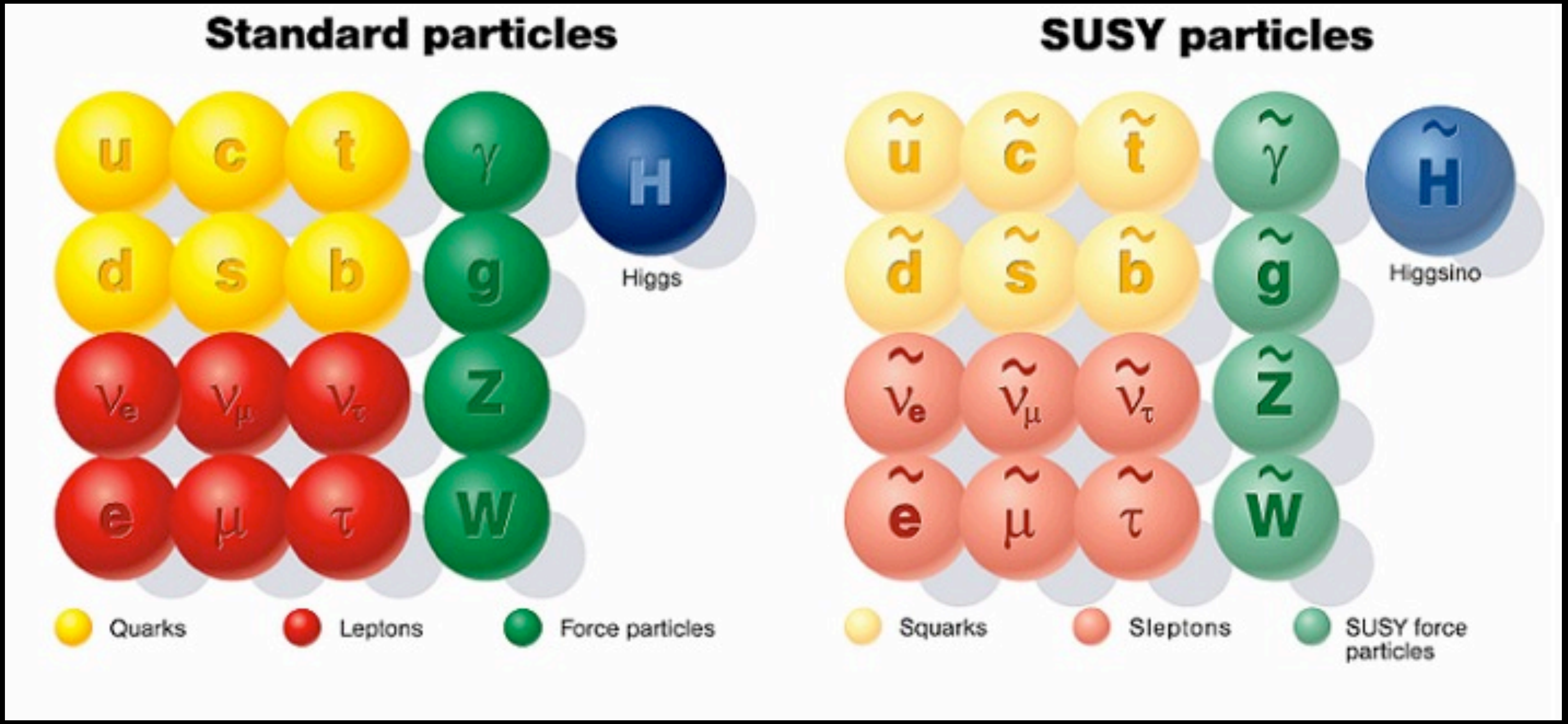
The SUSY particles fix the absurd cancellation needed in the Higgs mass



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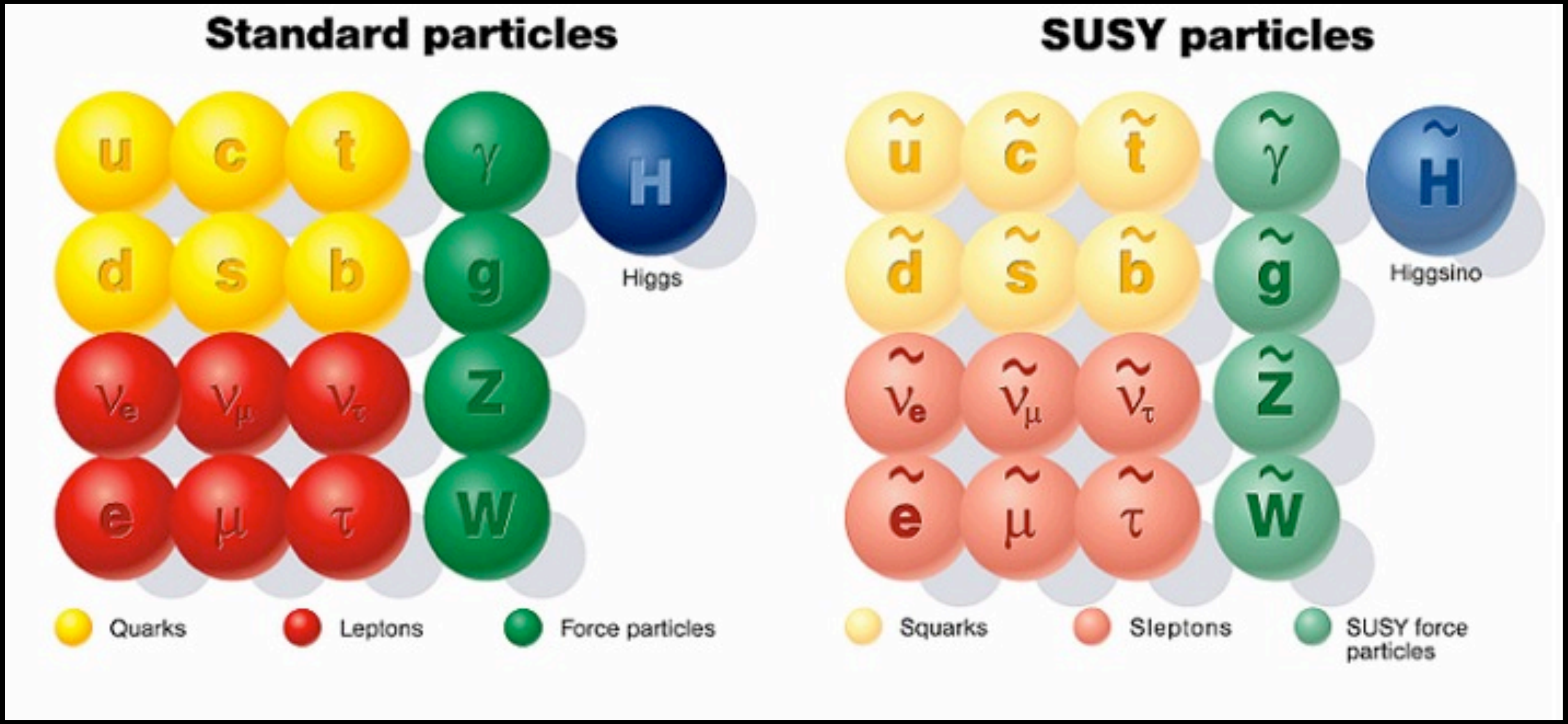
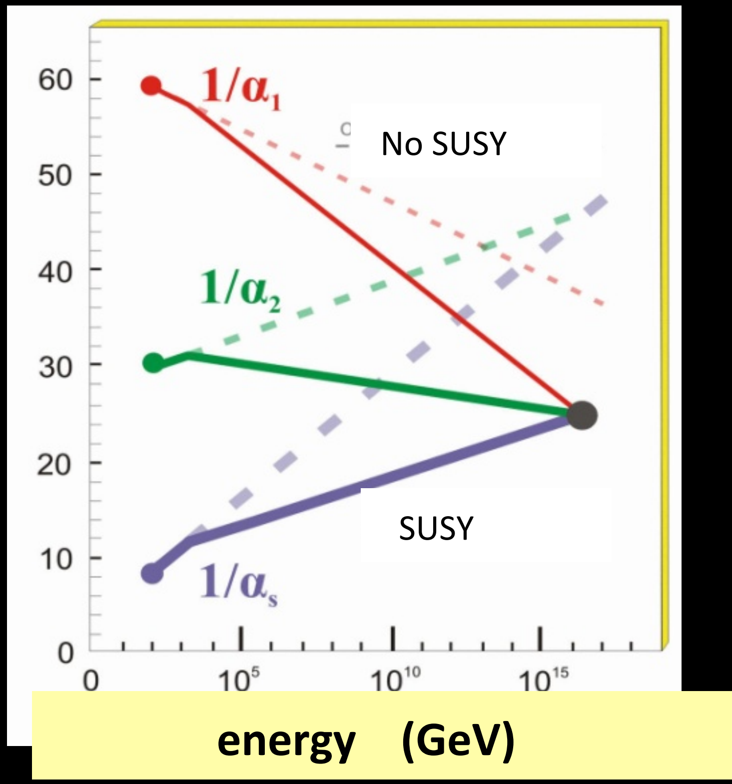
The lightest neutral particle would be Dark Matter -- and Cosmological data suggest it is right at a mass that the LHC will produce



Hint of Grand Unification



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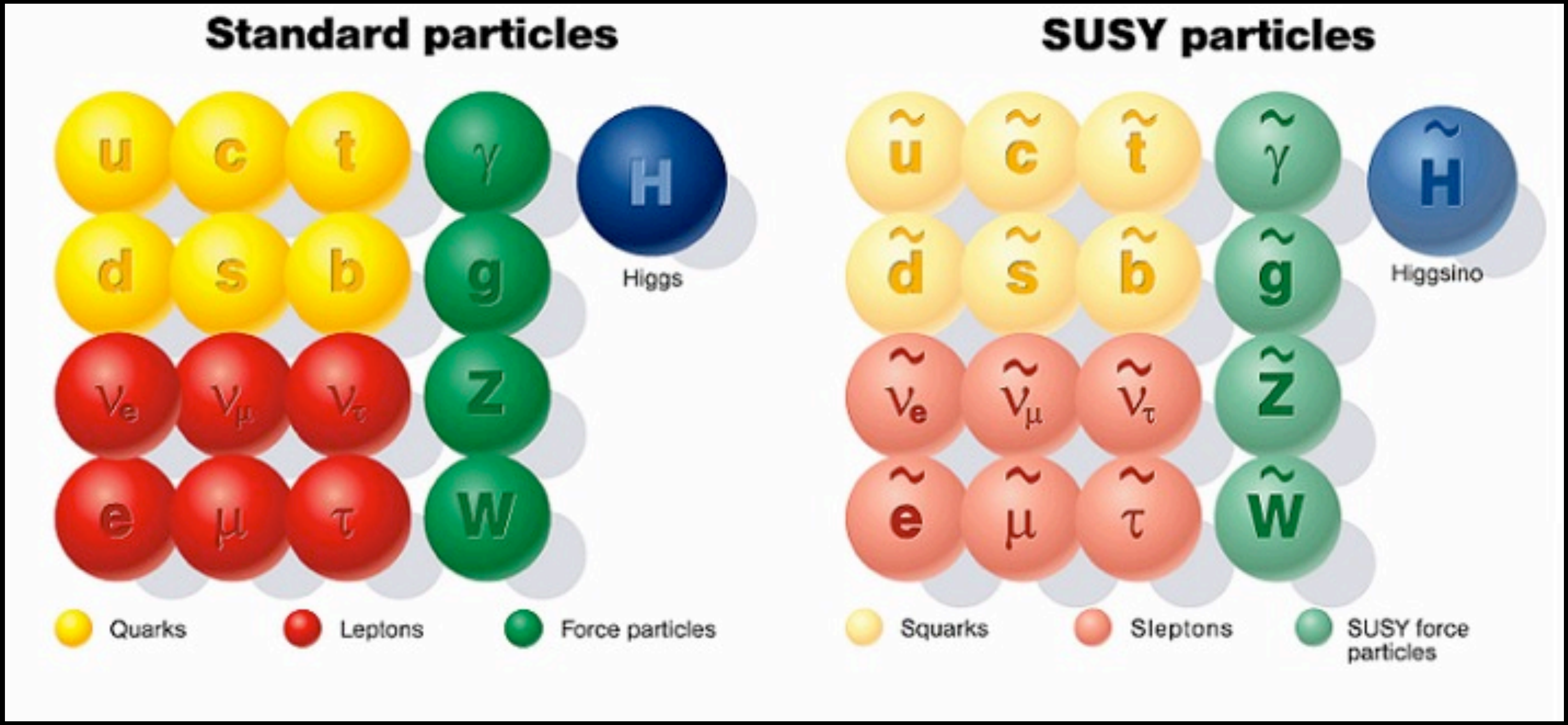

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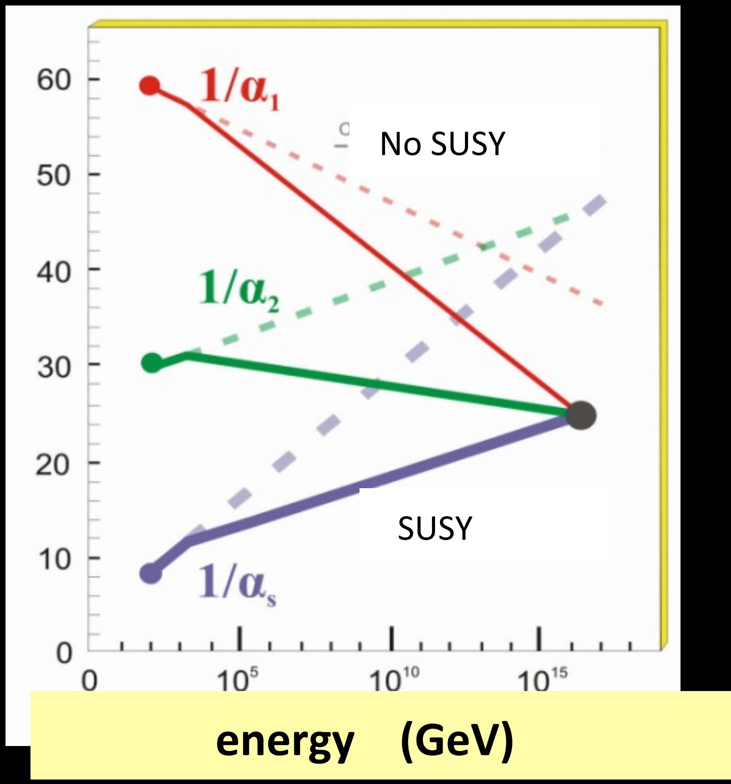
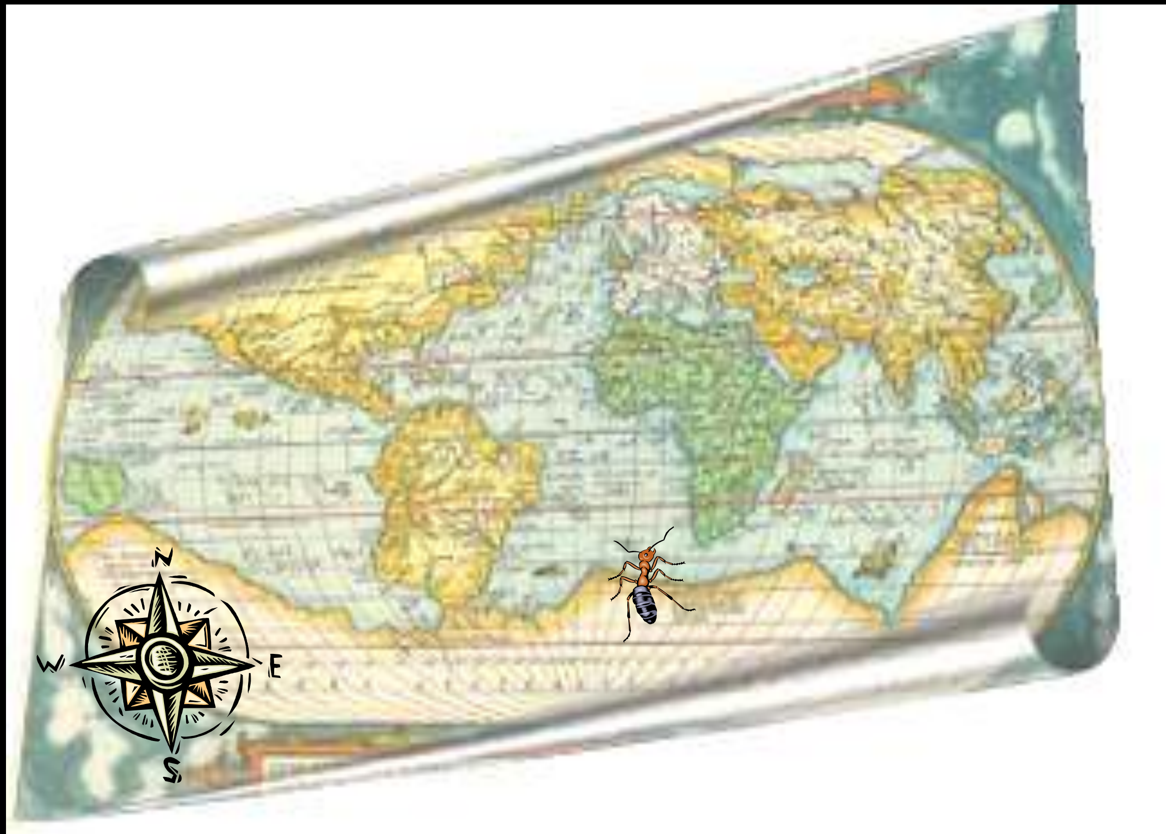
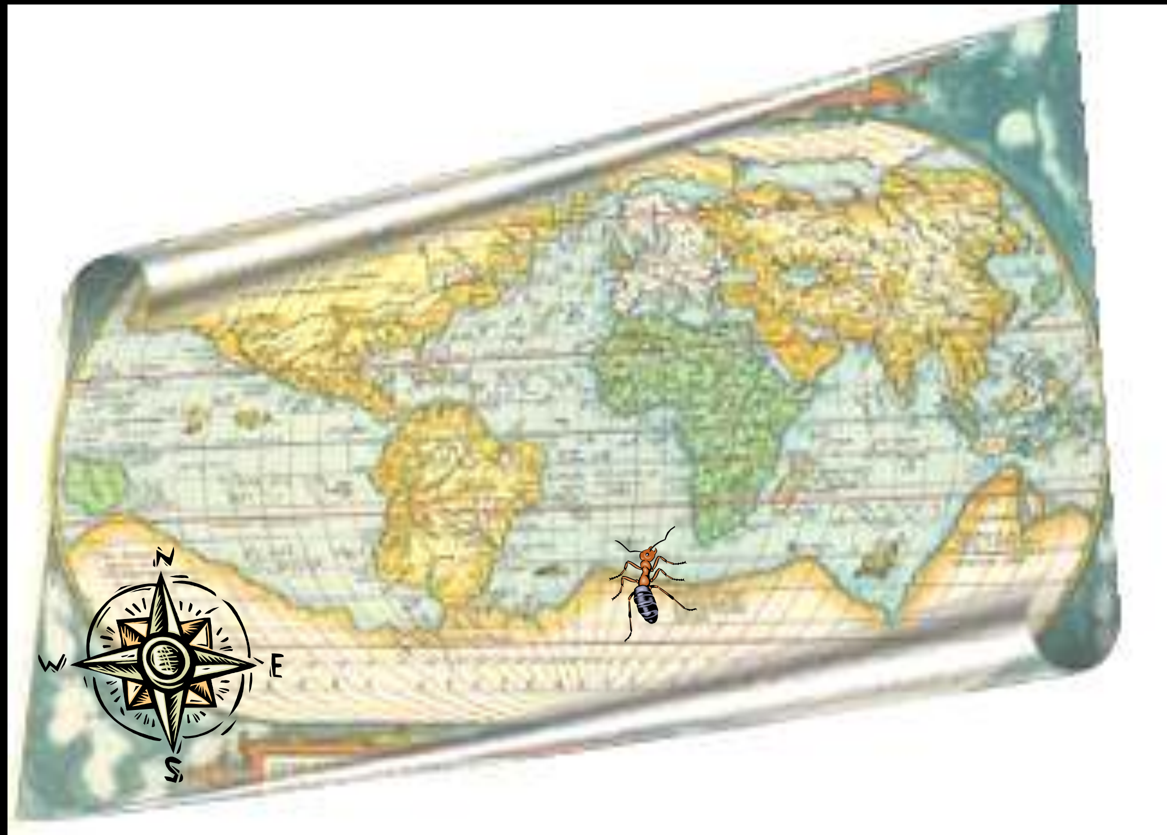


Twice as many particles to discover!
Job security!



To a bug living on this map, the “World” has 2 large dimensions and one small (0.1mm thick paper) It’s “World” is essentially 2-dimensional --the 3rd is too small to see

Extra Dimensions



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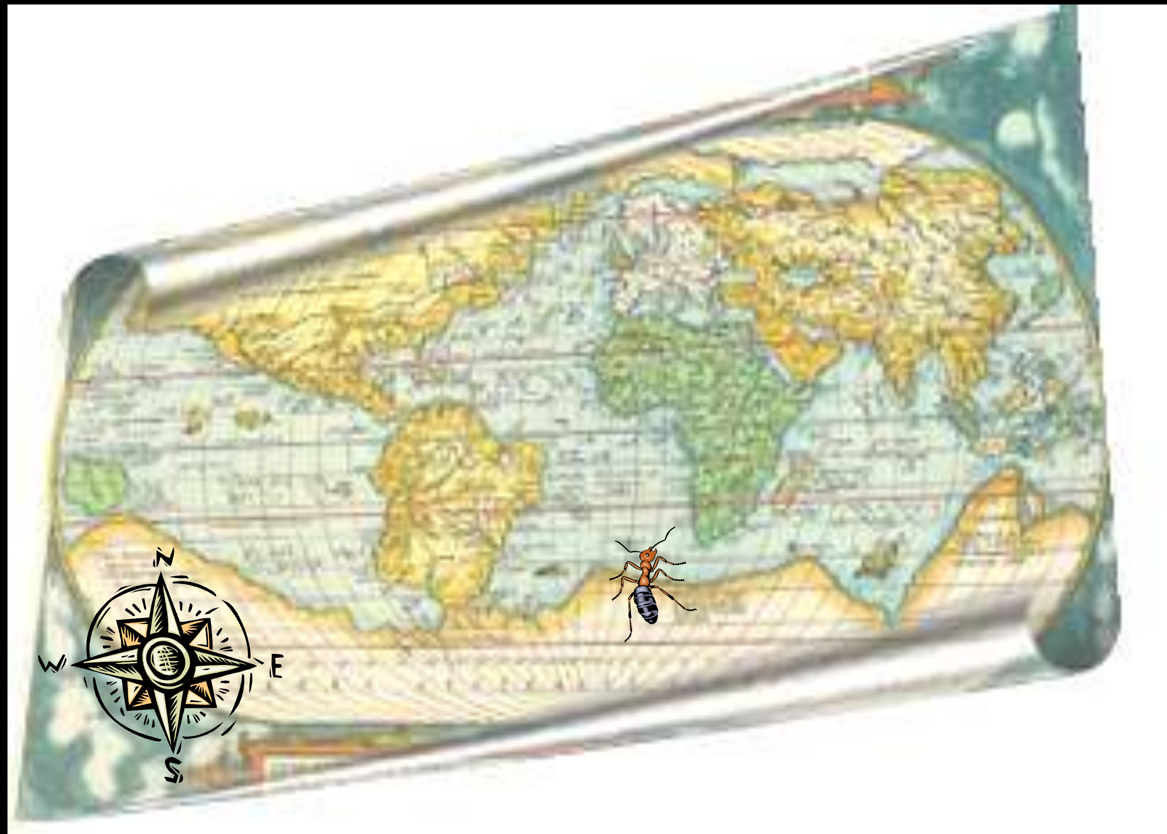

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... until they build

a microscope that can see things smaller than 0.1mm

Now they see the world is really 3-dimensional!

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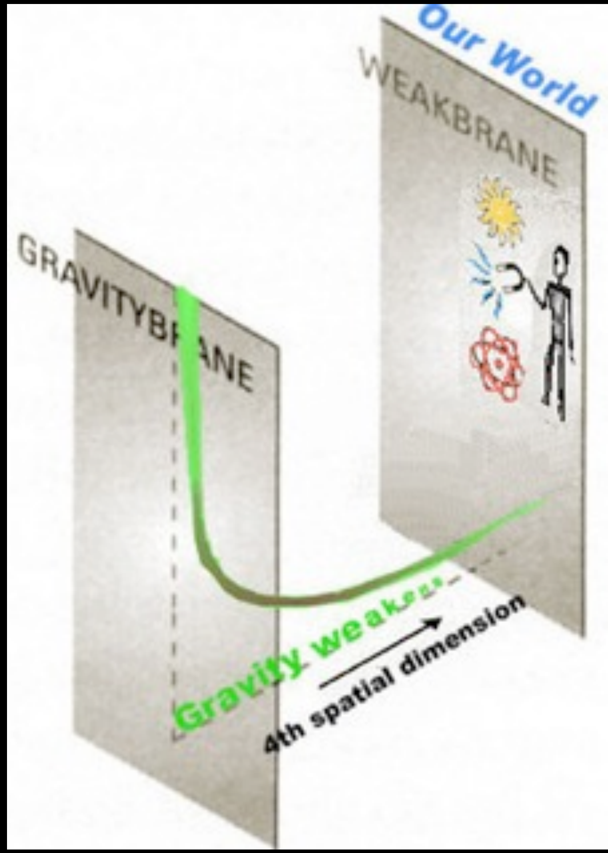
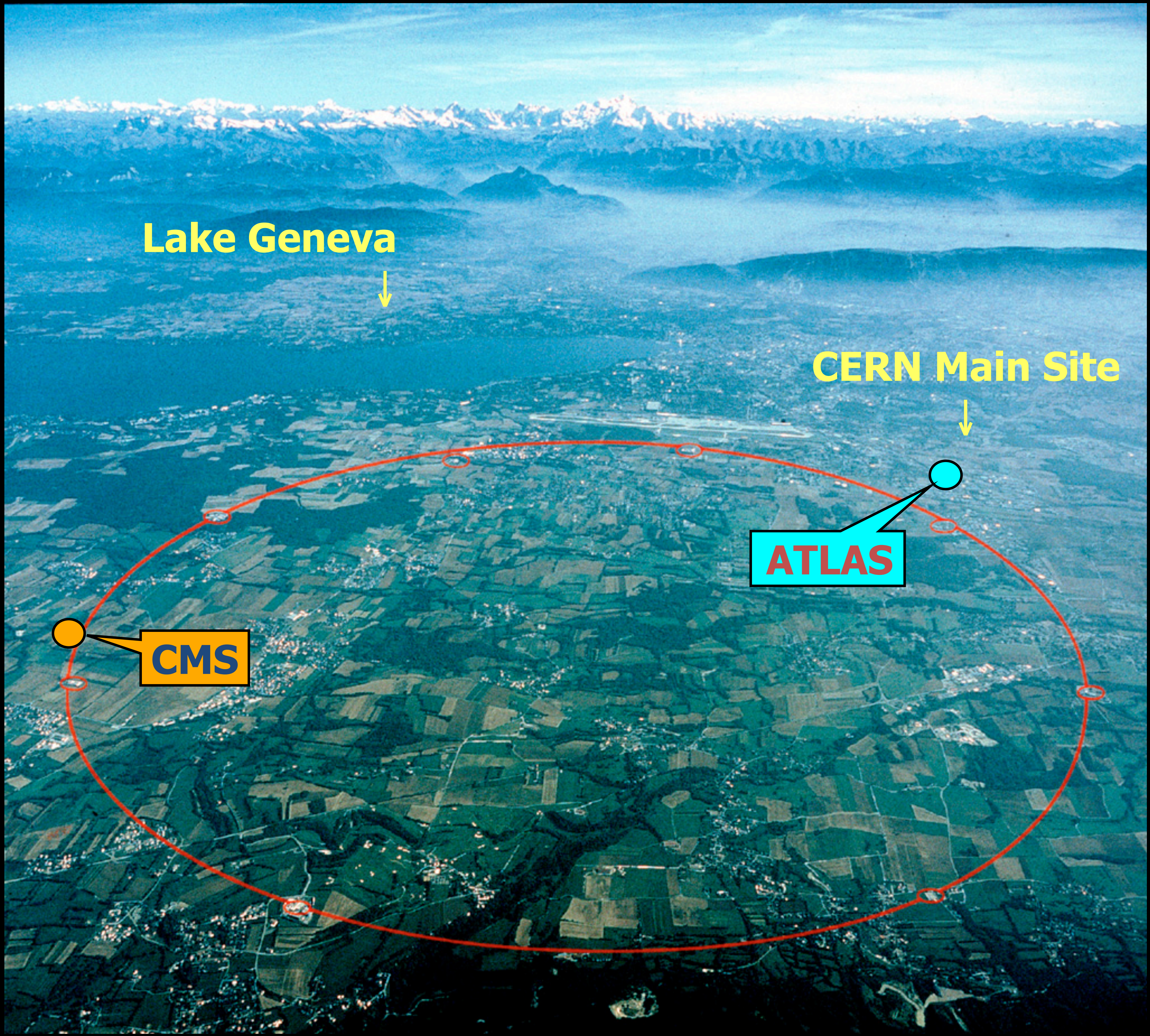
10^{-19} m = ??



The Machine

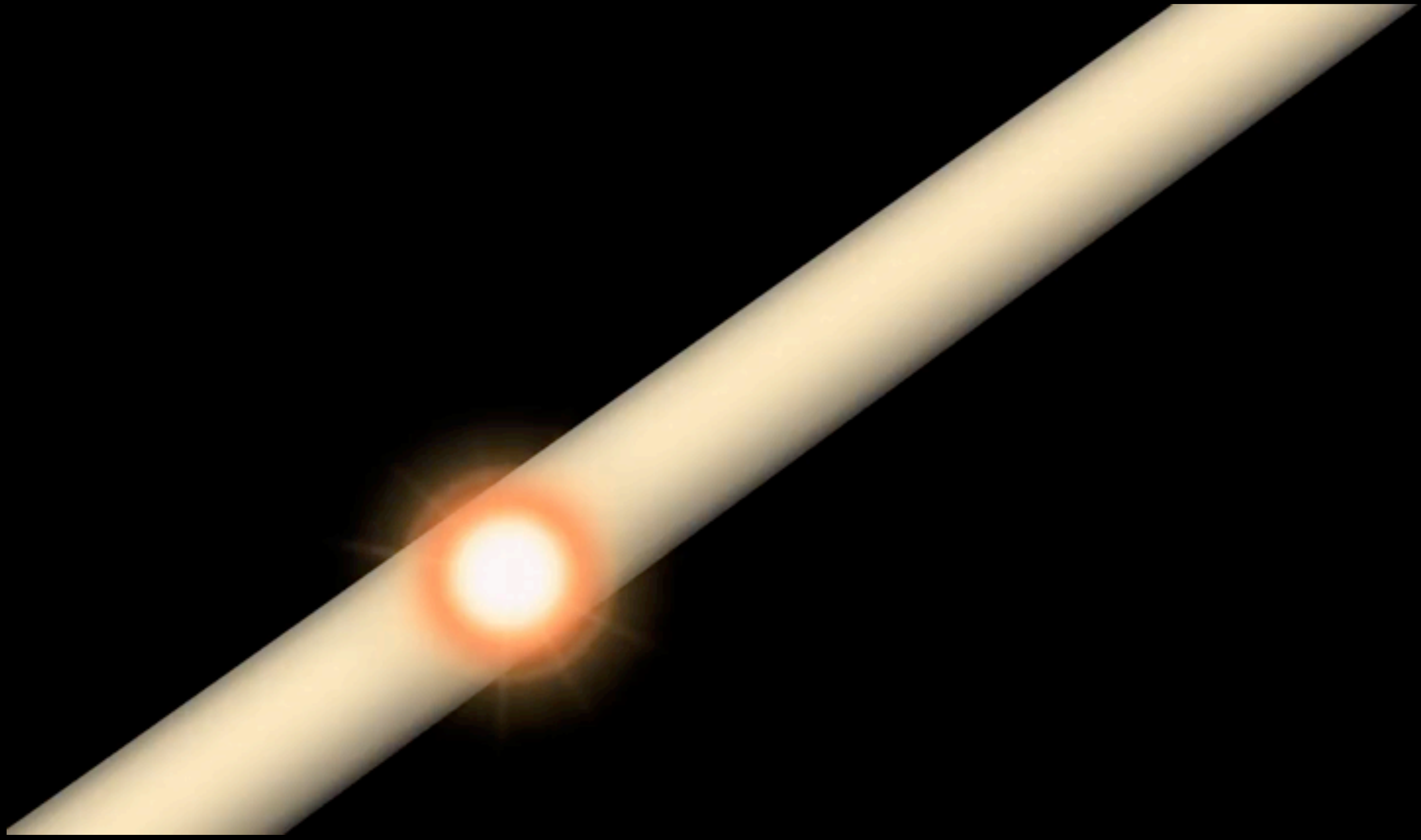
The Large Hadron Collider

- A Proton-Proton Collider
- 27 km around
- Energy = 14 TeV (7 times Fermilab)
- 100,000 times hotter than the Sun
- Proposal in 1983!
- Colder than space
- Creates conditions of 1 billionth of a second after the Big Bang
- ~10 Billion $

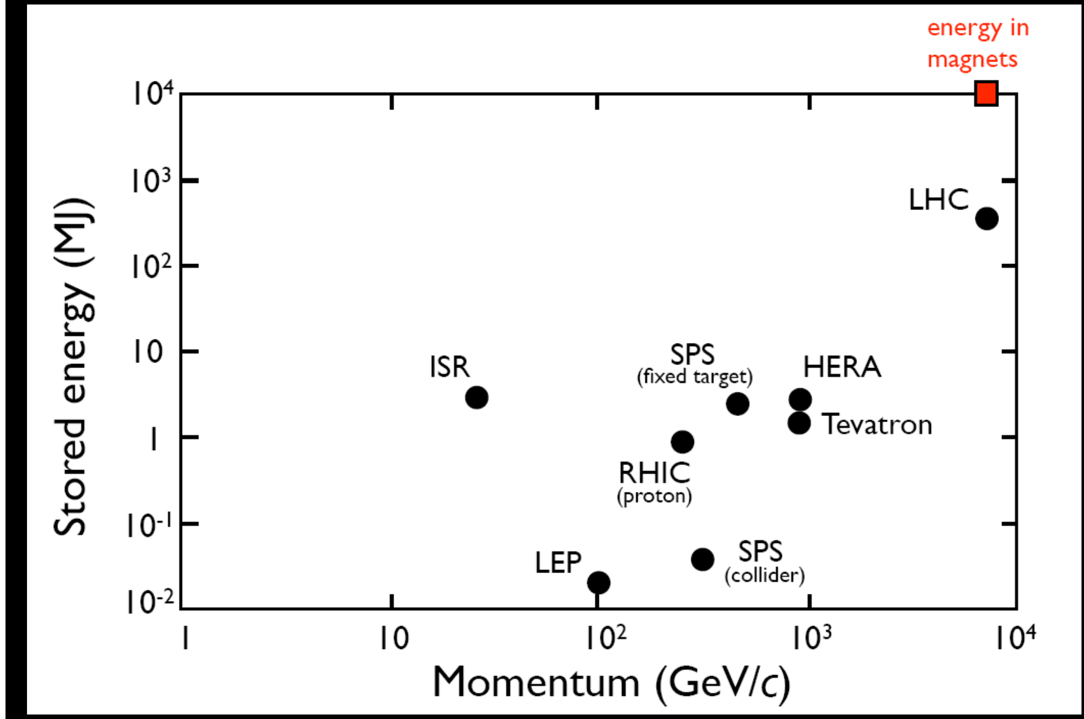


LHC Tunnel 2003

After LEP was ripped out



LHC Accelerator



Enough Energy to melt 12 tons of copper

Or, like driving your car into our detector at 2,500 km/h

$25M / year electrical bill

Energy of the LHC

- Biology, chemistry, art, architecture – move atoms around to create (very interesting) new *arrangements*, but underneath, you are moving existing atoms around

Methane Oxygen

$$CH_4 + 2O_2$$

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C H H H H

Methane Oxygen

$$CH_4 + 2O_2$$

C H H H H O O O O

Methane Oxygen

$CH_4 + 2O_2$

H H H H O O

➡ CO_2

Methane Oxygen

$CH_4 + 2O_2$

$\rightarrow CO_2 + H_2O + H_2O$

Methane Oxygen

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→ $CO_2 + H_2O + H_2O$

- Particle physicists create *brand new* objects that weren't there before -- all through the magic of

$$E = mc^2$$

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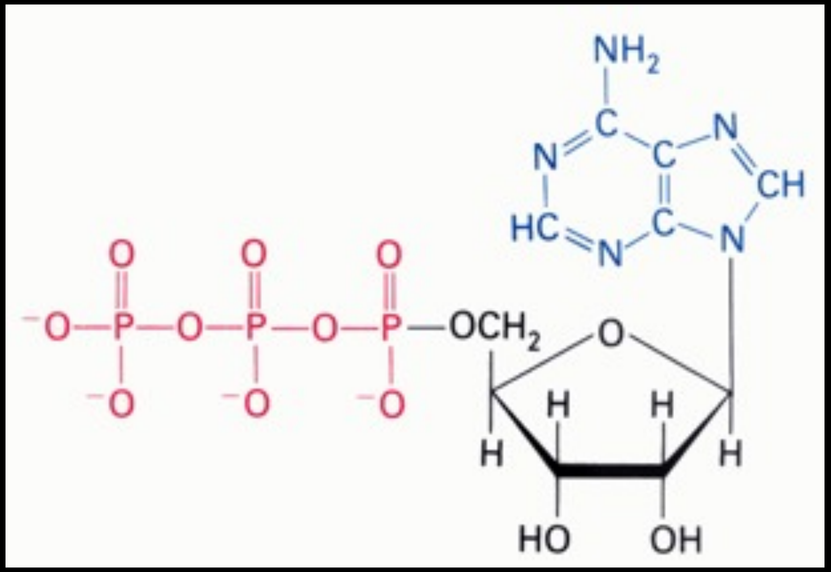
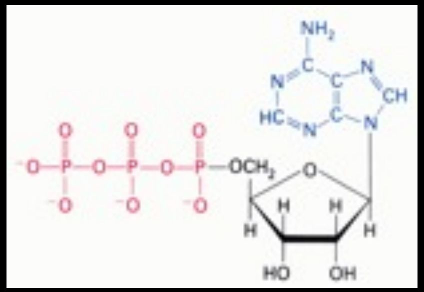
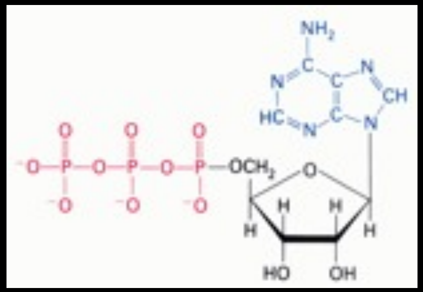
- Most of these fun new objects quickly decay back into regular boring matter -- that's how we're going to see them

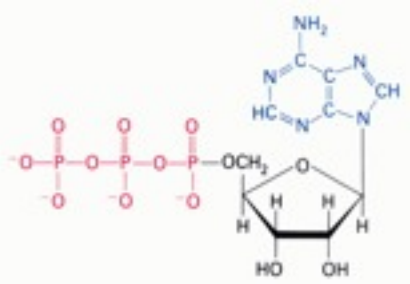





france


NH2
OCH2
HO
OH

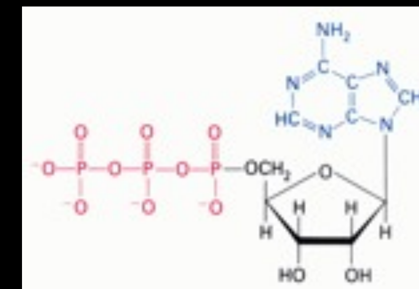

UNION



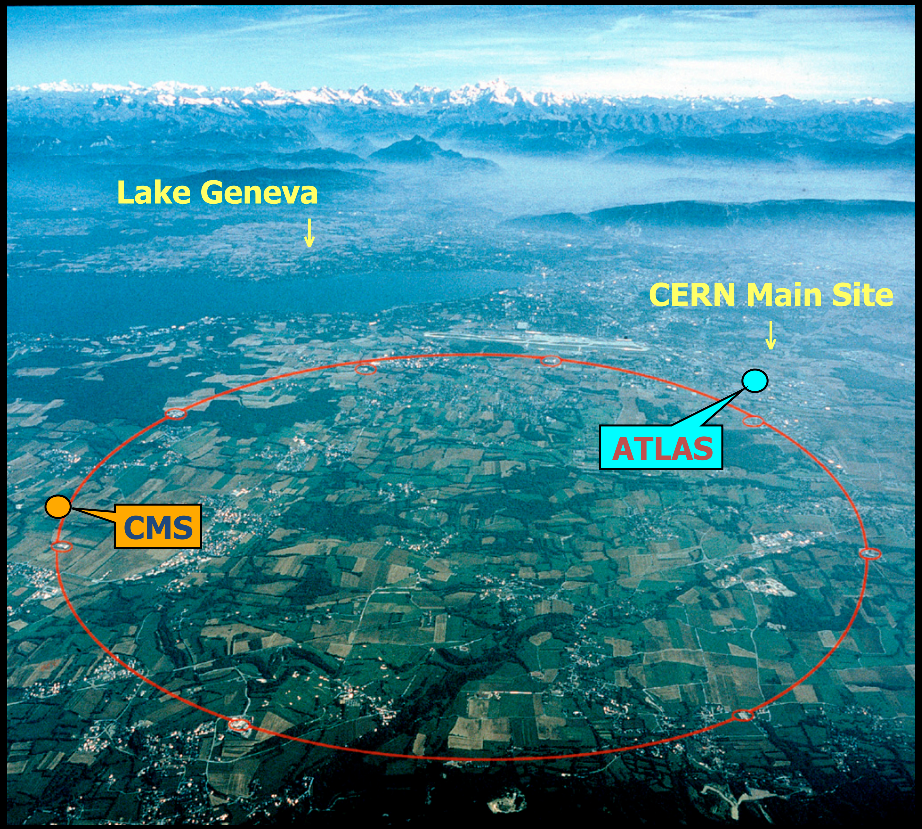

UNION

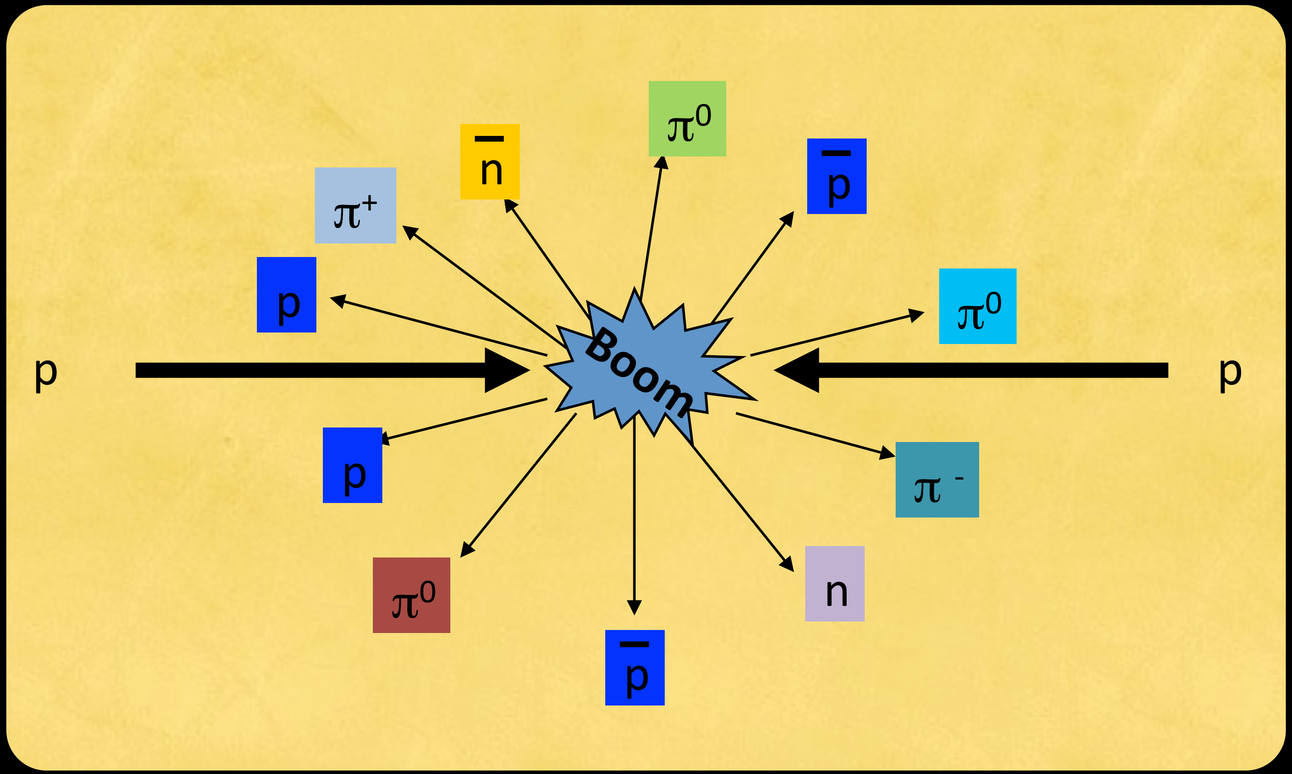

TWENTY






Energy changes form but total amount is constant

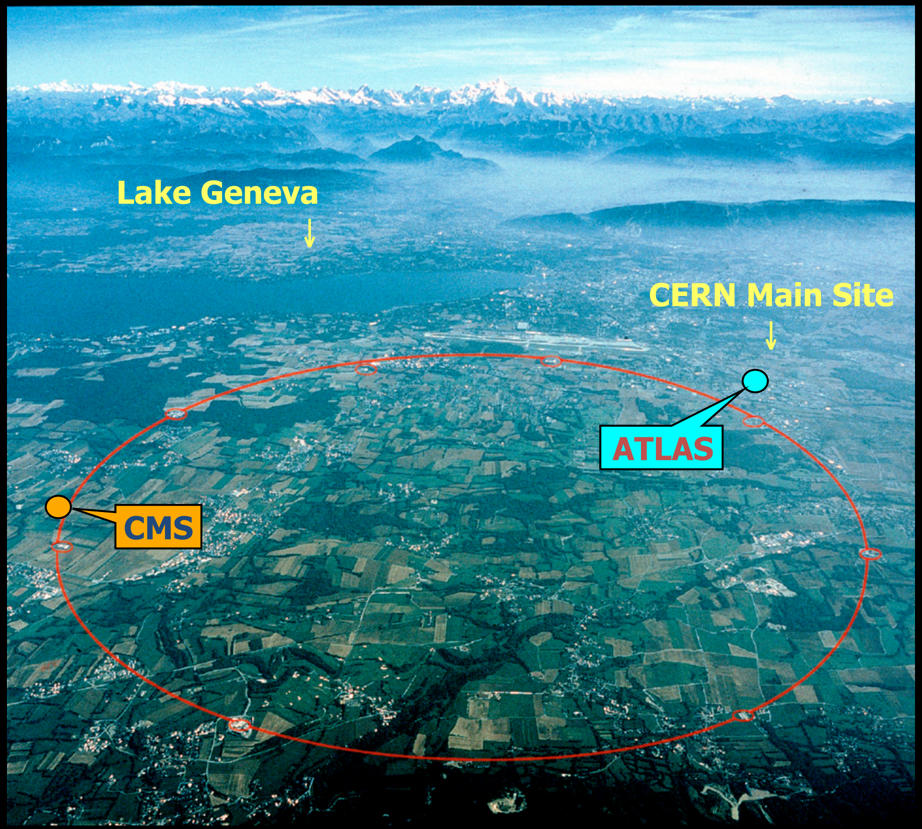


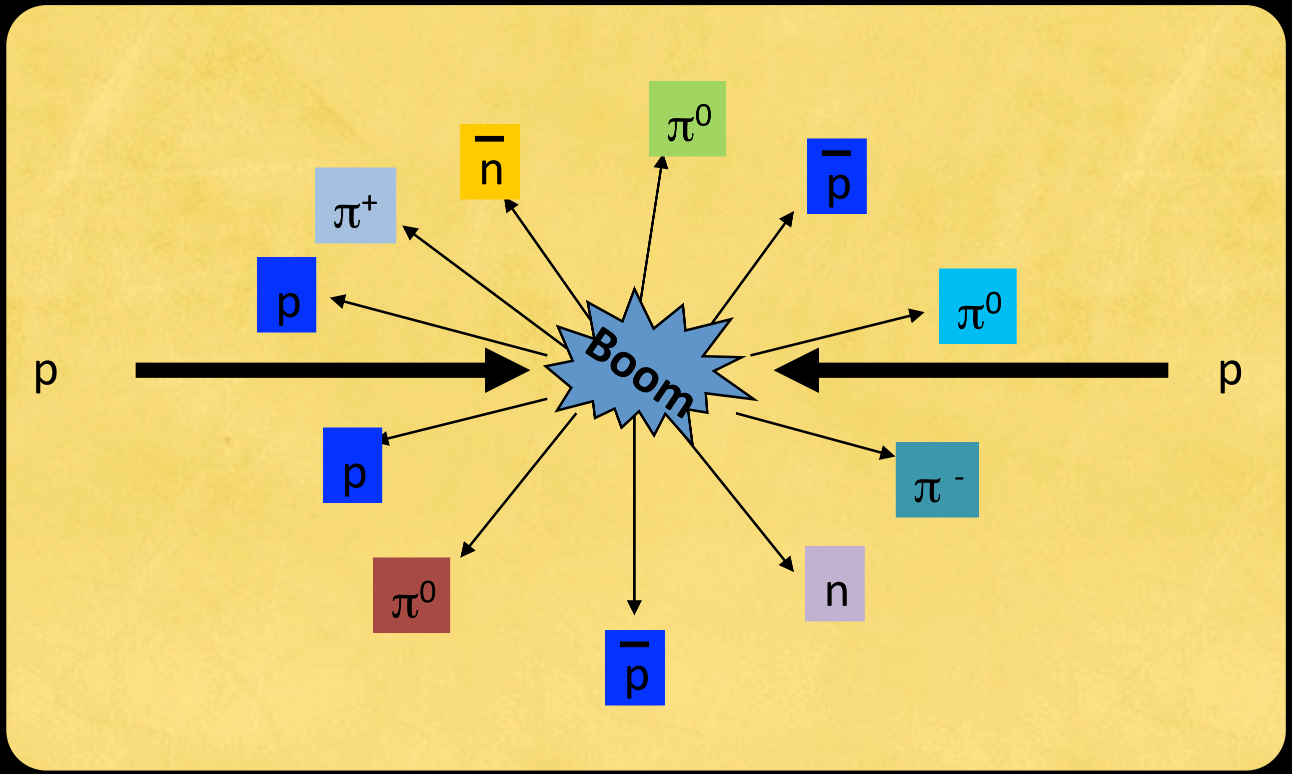


Energy of motion of highly accelerated protons

$$E = mc^2$$

Turned into mass of new particles that were common 1 billionth of a second after the Big Bang





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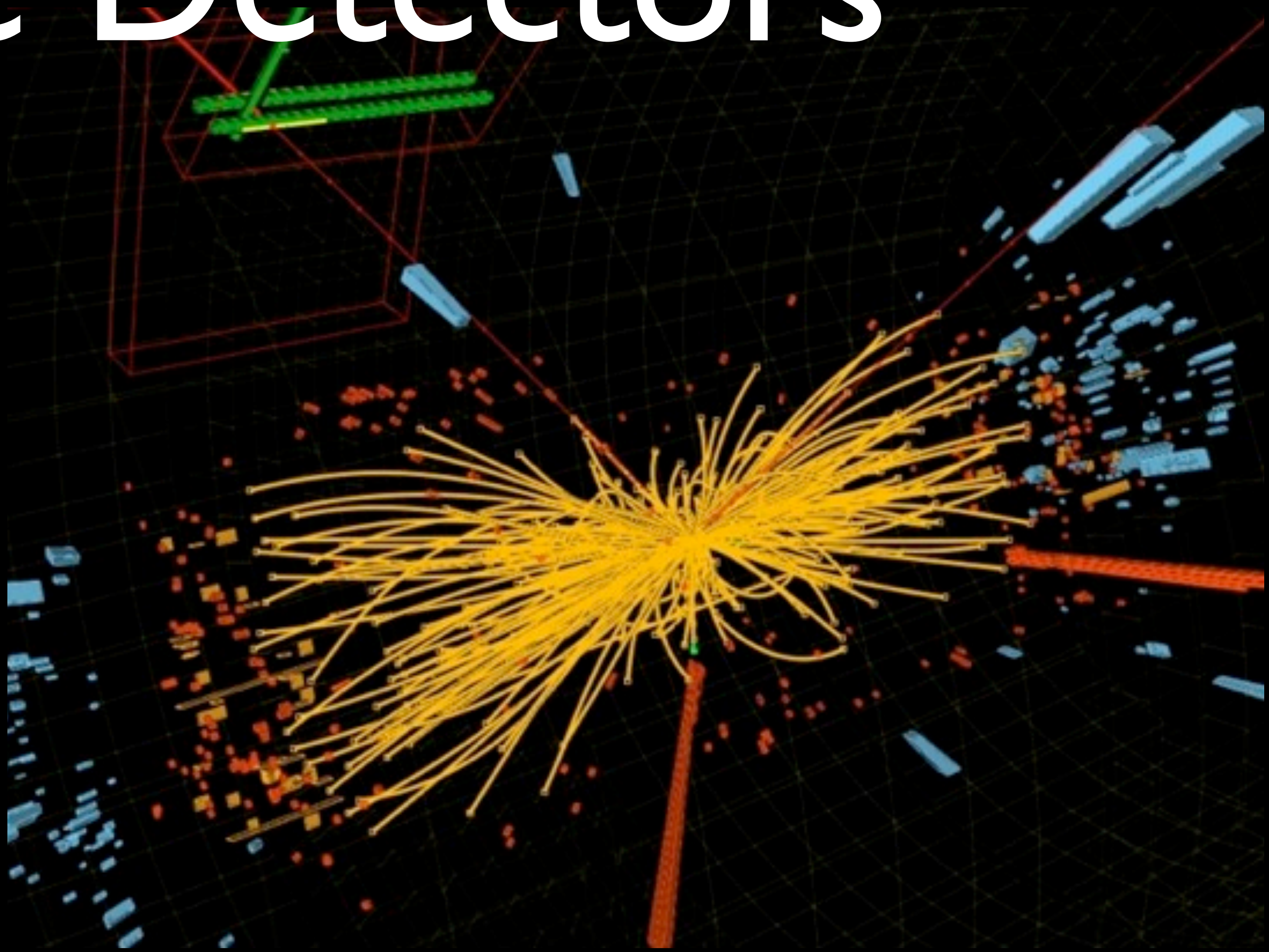
Most of these collisions are actually rather boring -- need to repeat a lot!

The Detector

Particle Detectors

Want a device that can measure:



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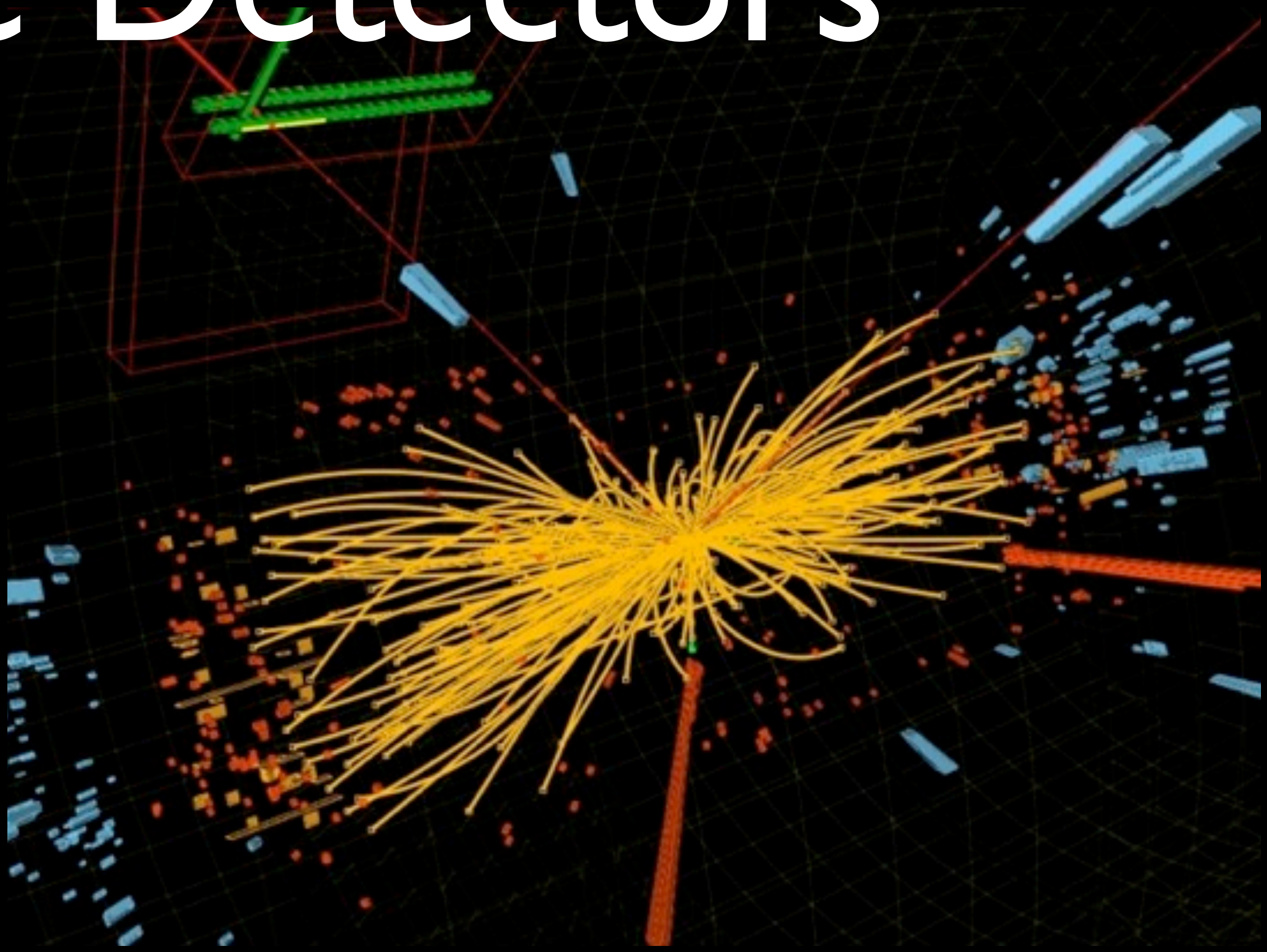

Trajectories of all particles produced collision

Particle Detectors

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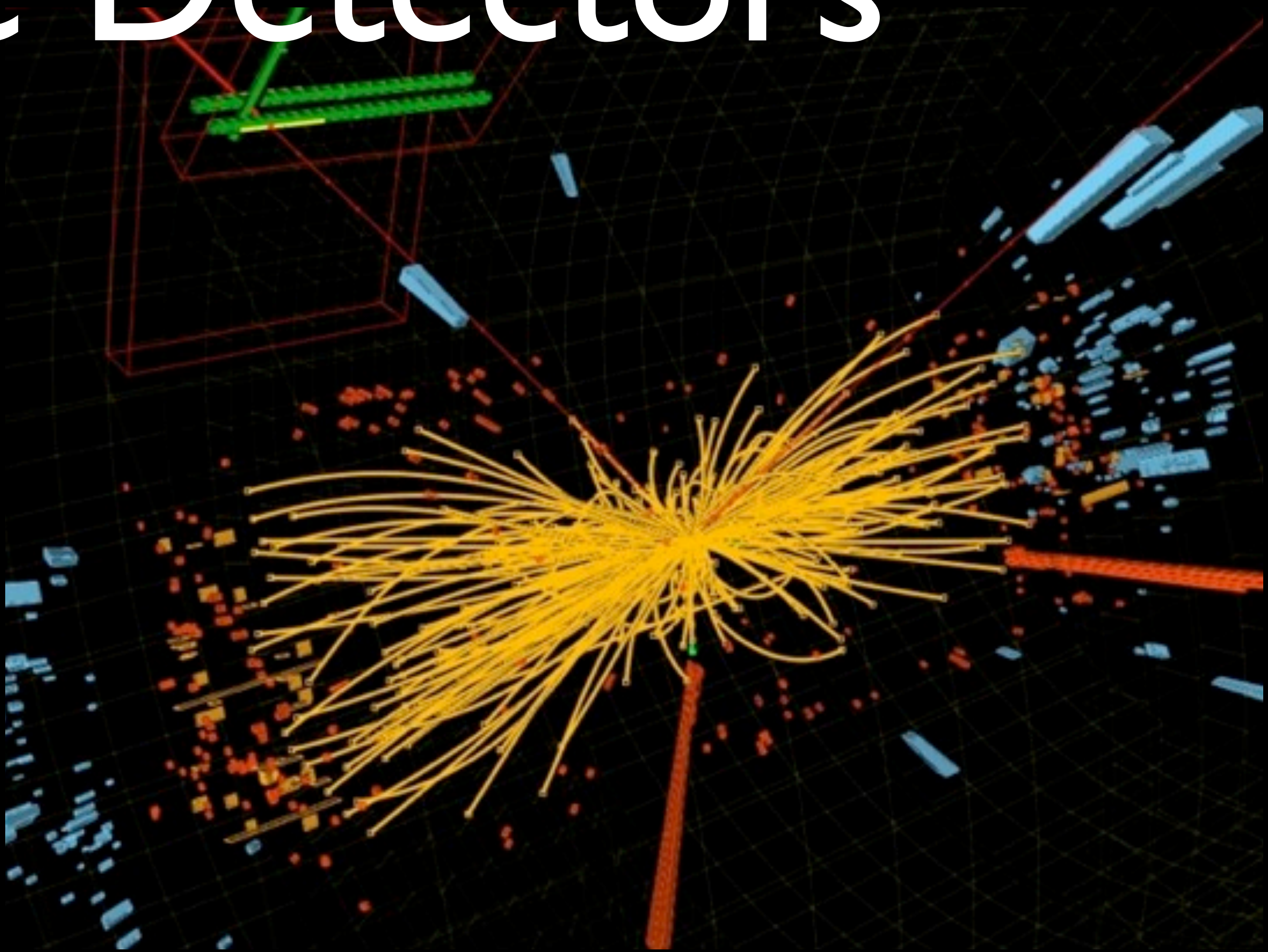

Trajectories of all particles produced collision

Energy and momentum of all these particles

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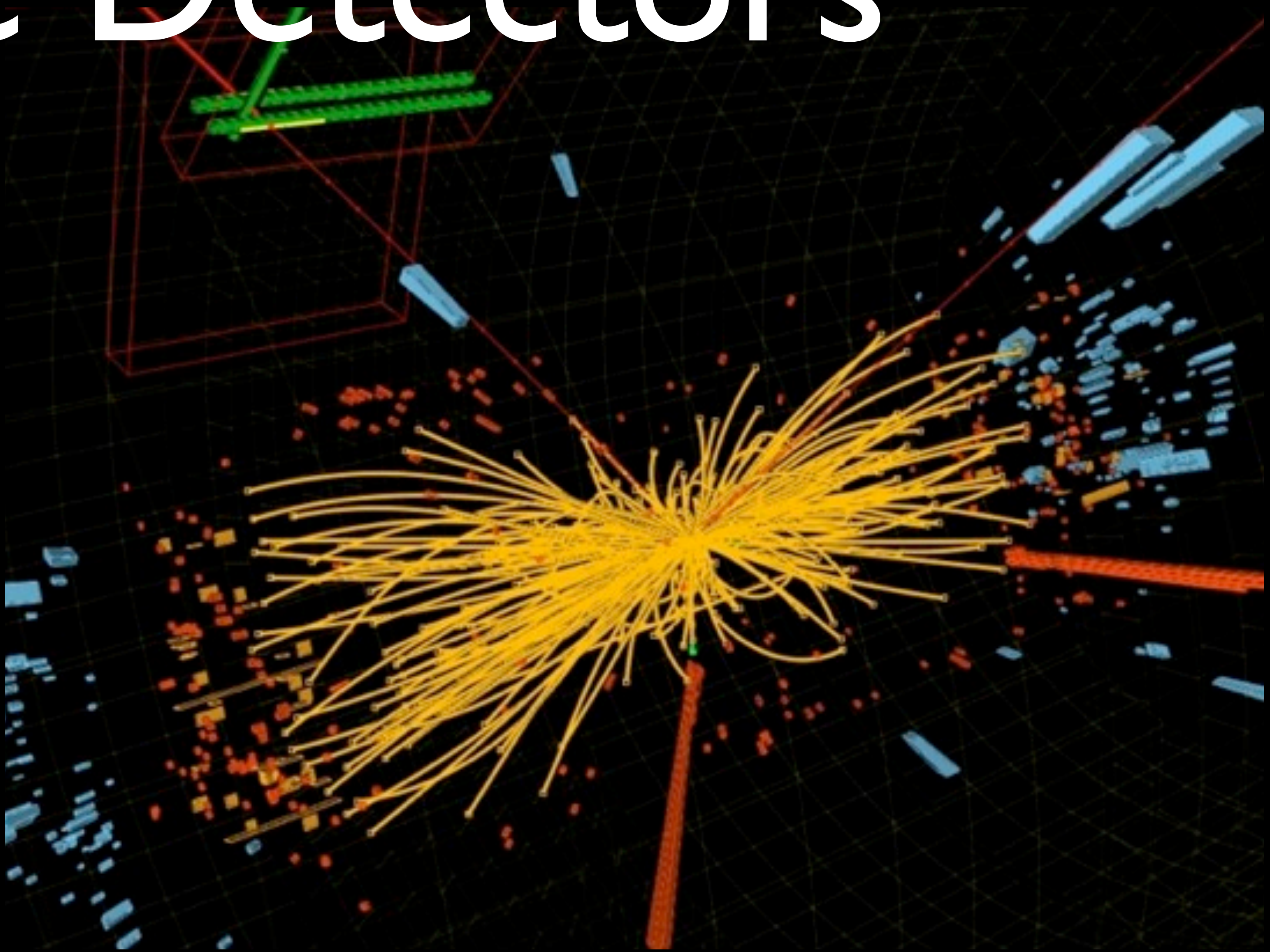
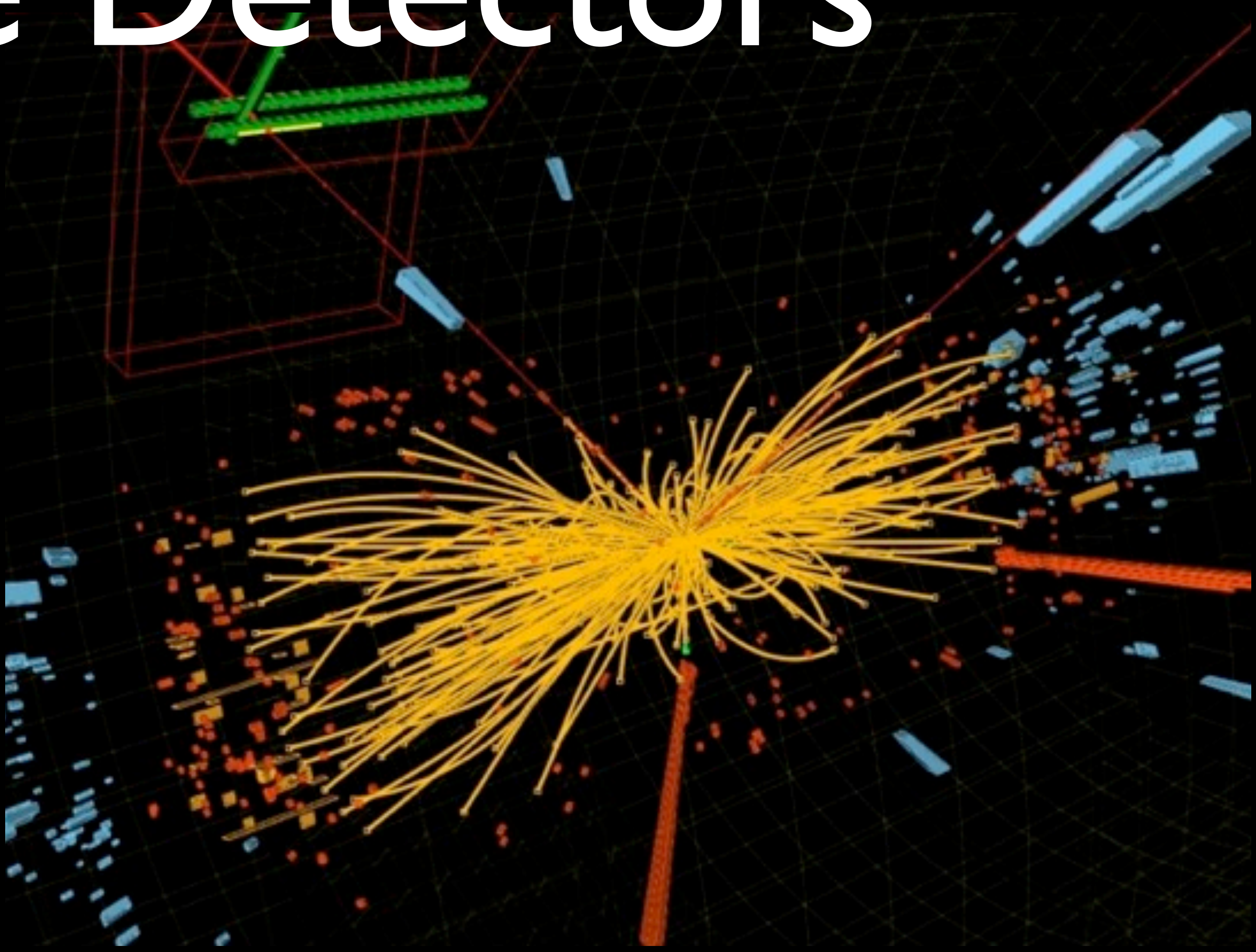


Trajectories of all particles produced collision

Energy and momentum of all these particles

What type each of all these particles are

Particle Detectors



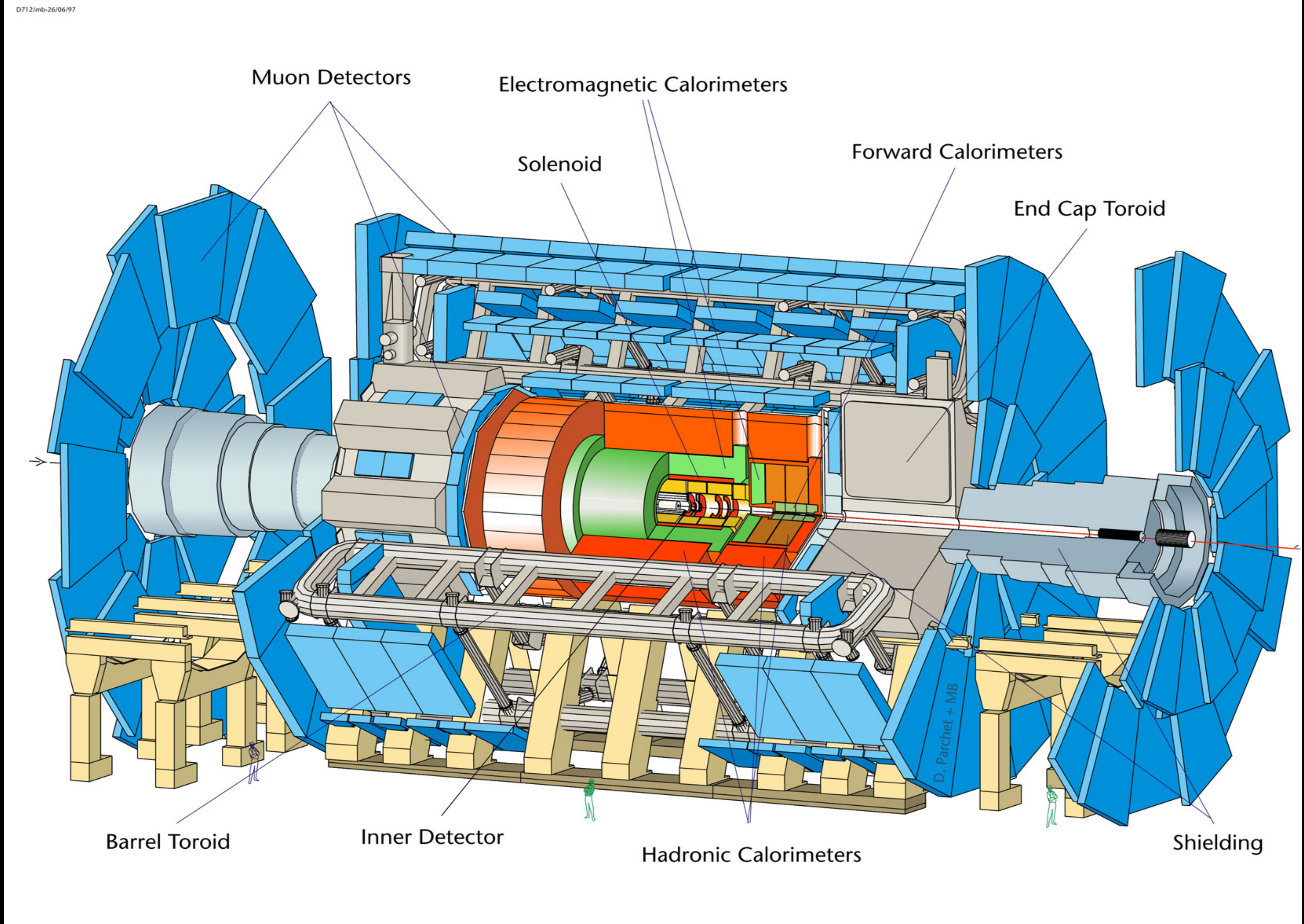
Want a device that can measure:

Trajectories of all particles produced collision

Energy and momentum of all these particles

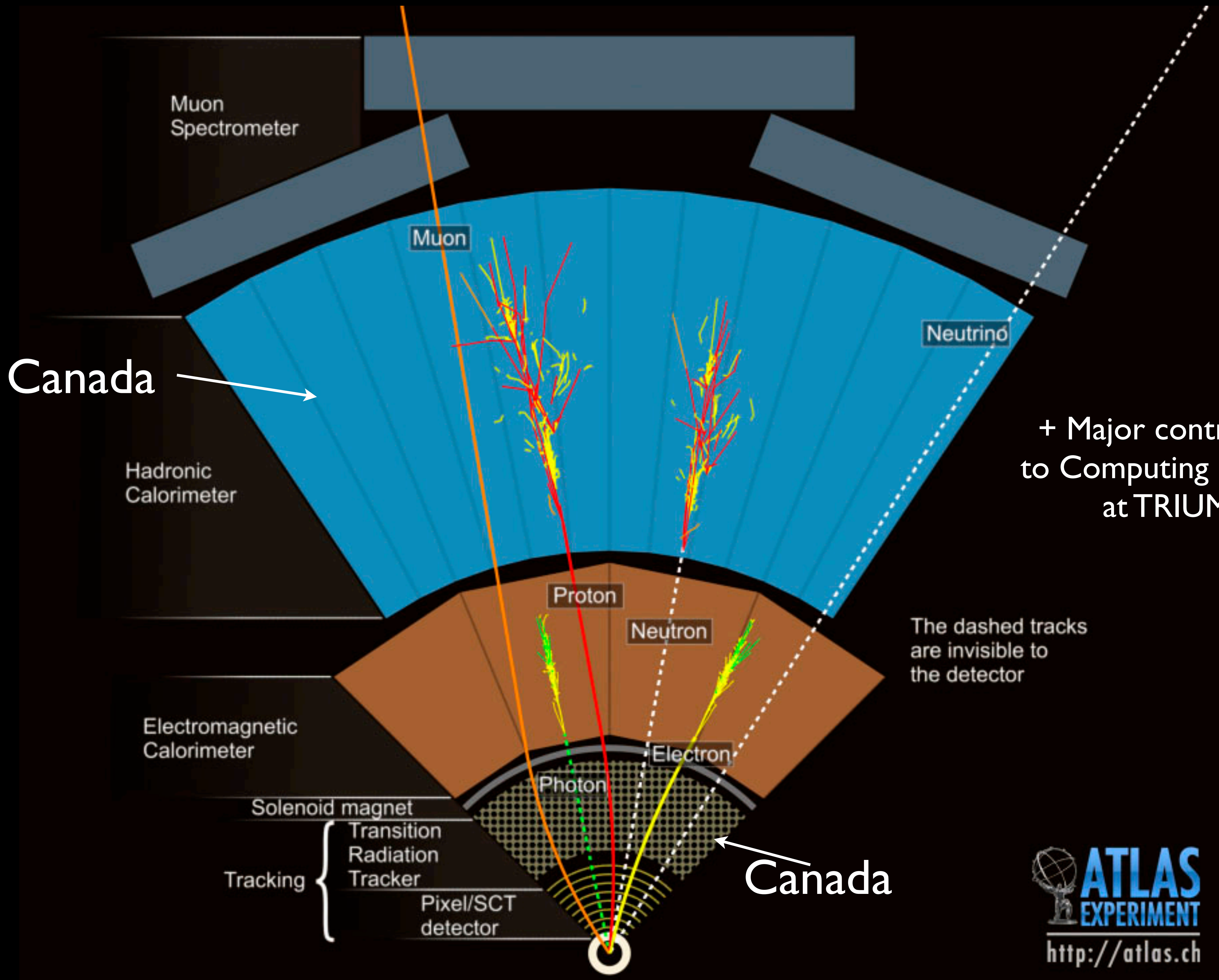
What type each of all these particles are

We do this with a huge, multi-layer device, with different layers specializing in different aspects



Diameter
25 m
Barrel toroid
length 26 m
Endcap end-wall chamber
span 46 m
Overall weight
7000 Tons

ATLAS



+ Major contribution to Computing ("Tier 1" at TRIUMF)

ATLAS Facts

7000 tons
46m long, 25m diameter
100M+ channels of electronics (taking data 40M times per second)
3,000 km of cables

Real time data handled by electronics is enormous – just the part built by UBC crunches 2 Tb/s of data, 24/7
Like checking, compressing, fixing and formatting a medium-sized hard drive worth of data every second, for 10 years.

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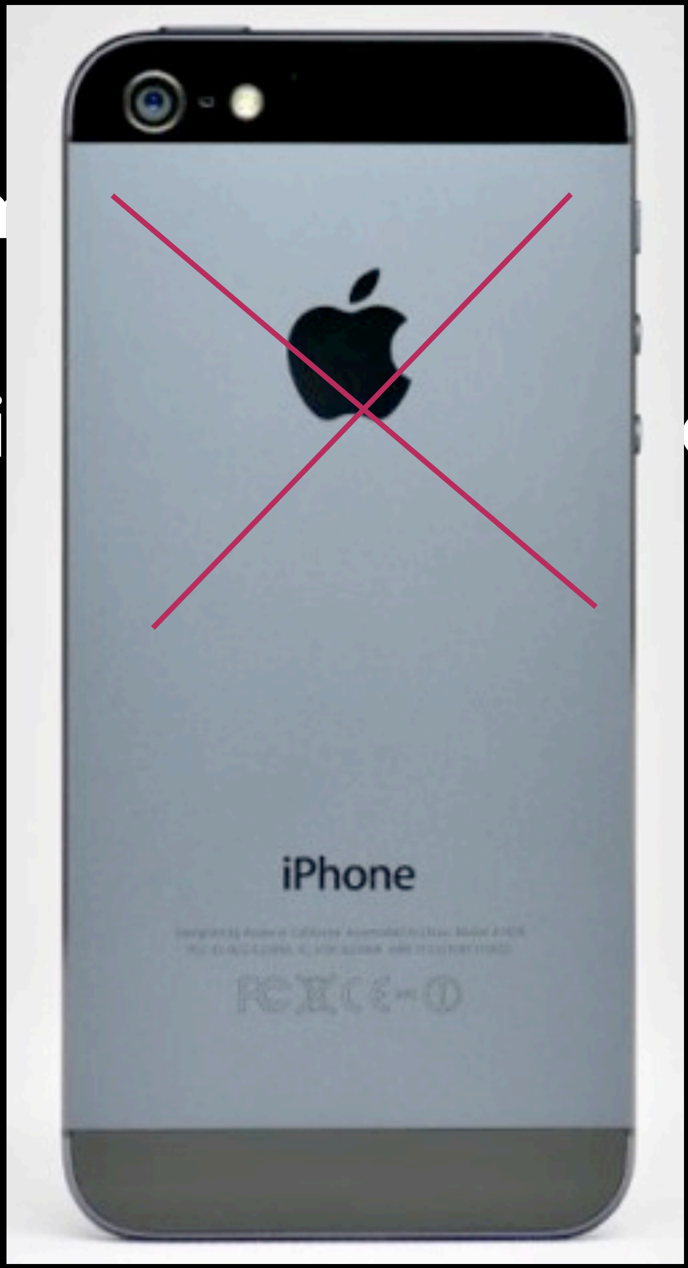
Like checking, compressing, fixing and formatti d hard drive worth of data every second, for 1



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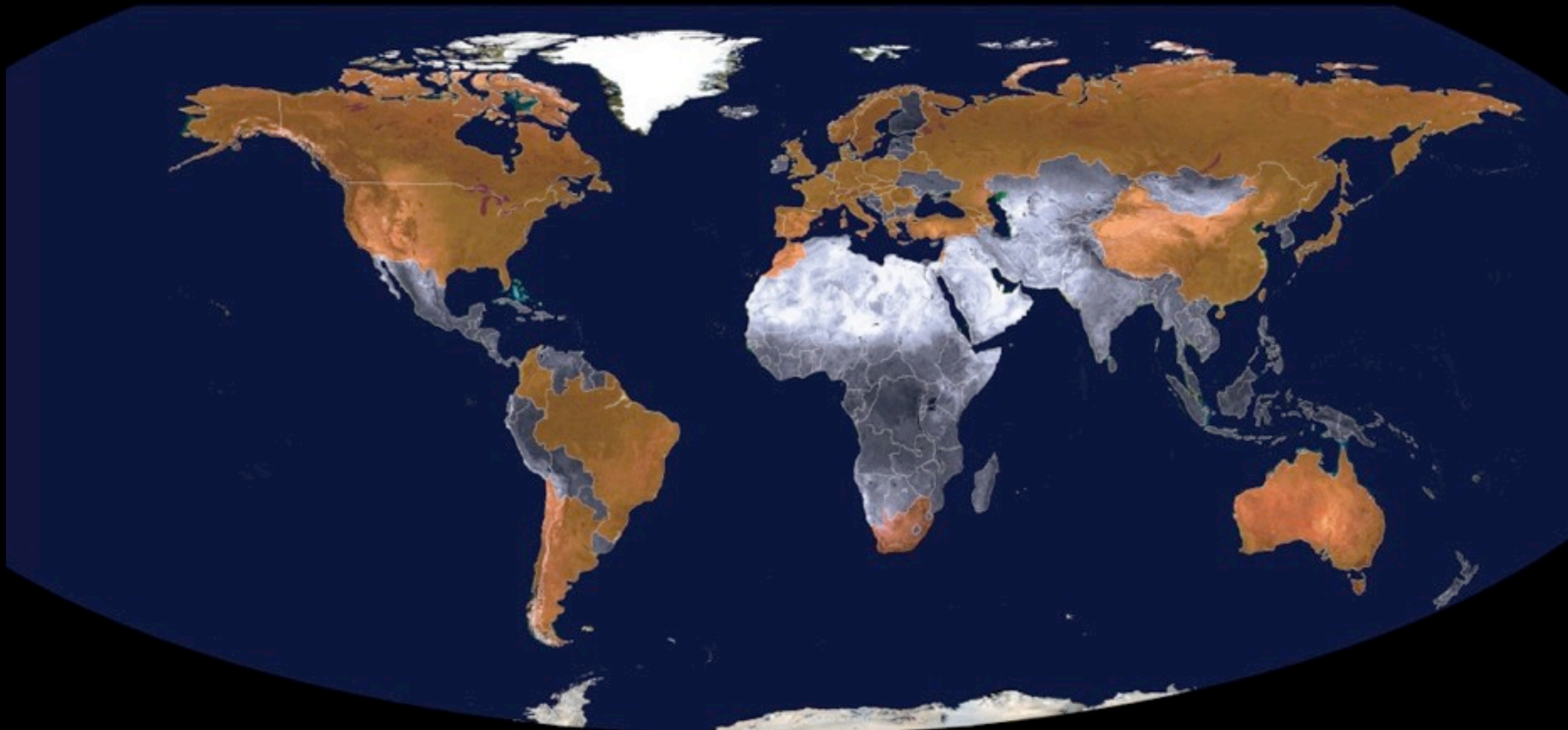
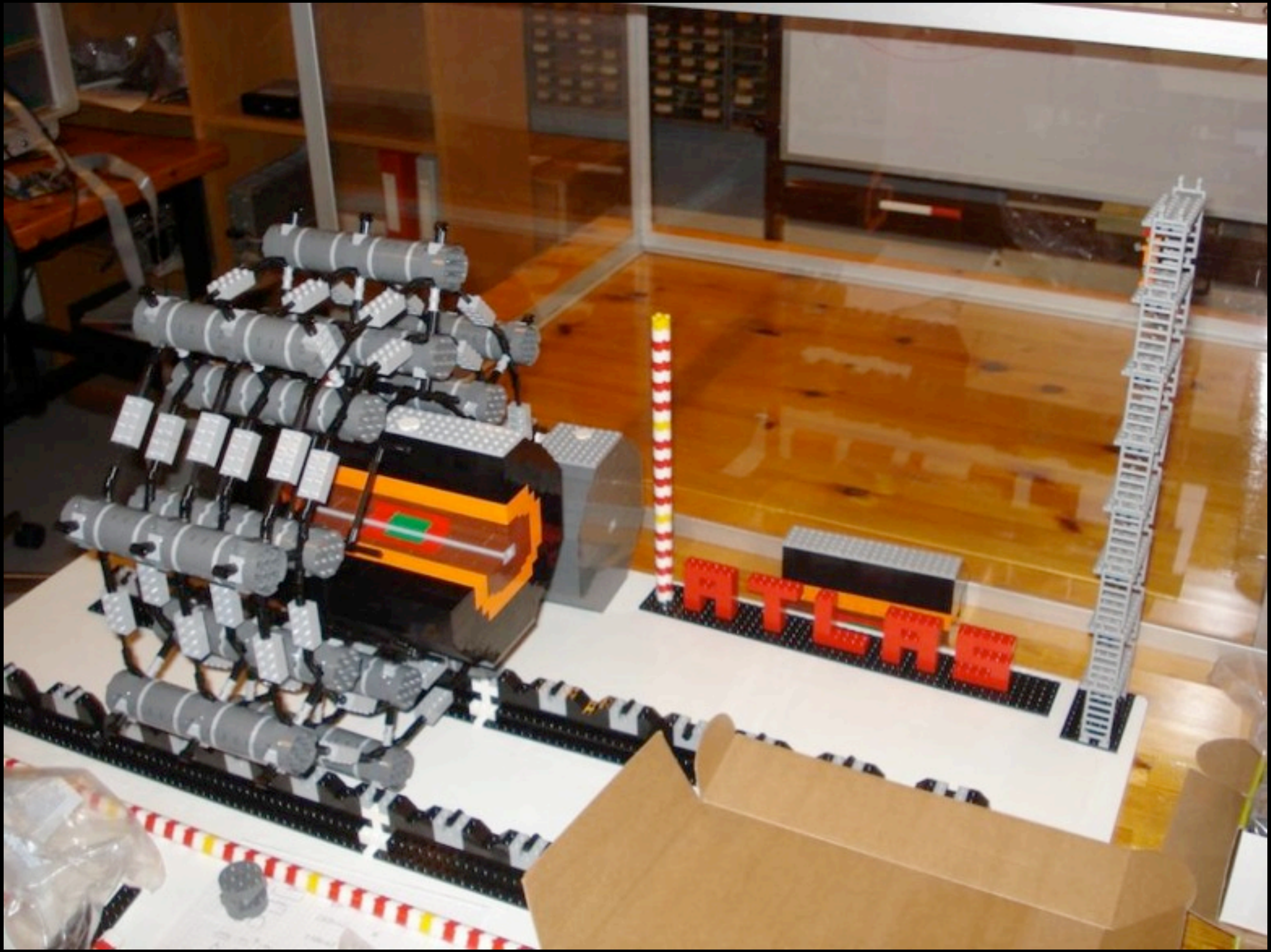
ATLAS Collaboration



Argentina	Chile	Greece	Portugal	Sweden
Armenia	China	Israel	Romania	Switzerland
Australia	Columbia	Italy	RussianFederation	Taiwan
Austria	Czech Republic	Japan	Serbia	Turkey
Azerbaijan	Denmark	Morocco	Slovak Republic	United Kingdom
Belarus	France	Netherlands	Slovenia	United States of America
Brazil	Georgia	Norway	South Africa	*CERN*
Canada	Germany	Poland	Spain	*JINR*

Building ATLAS



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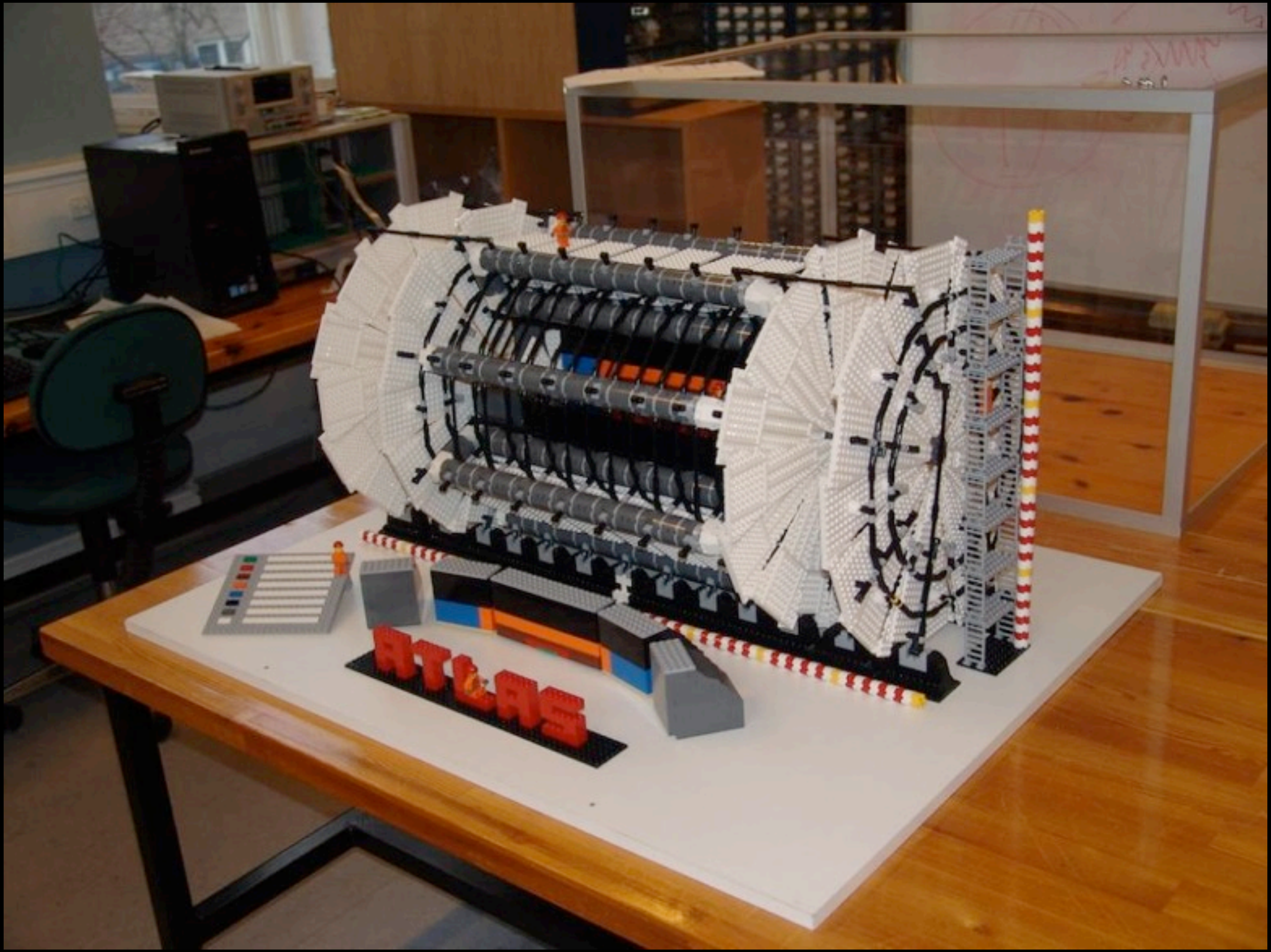
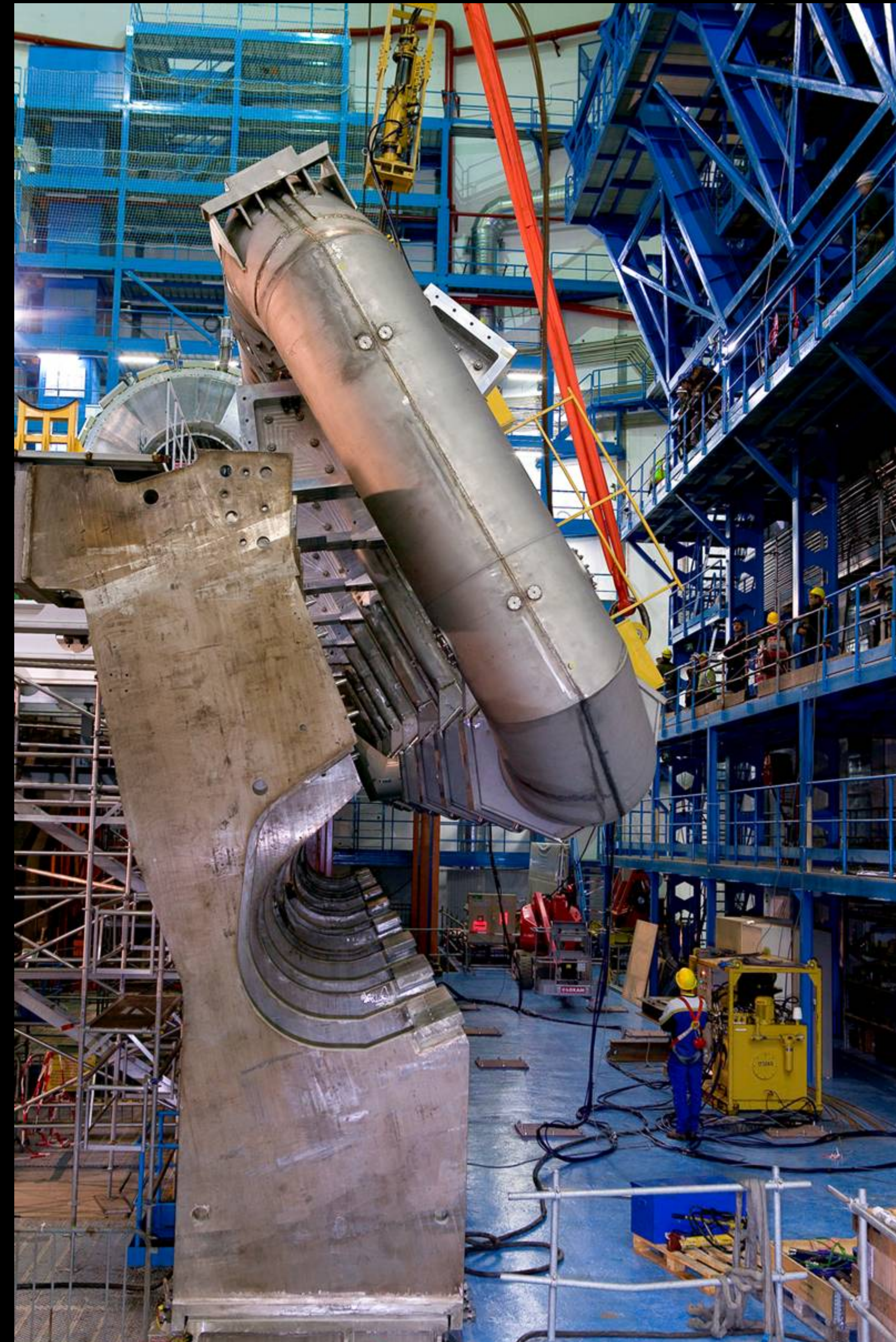
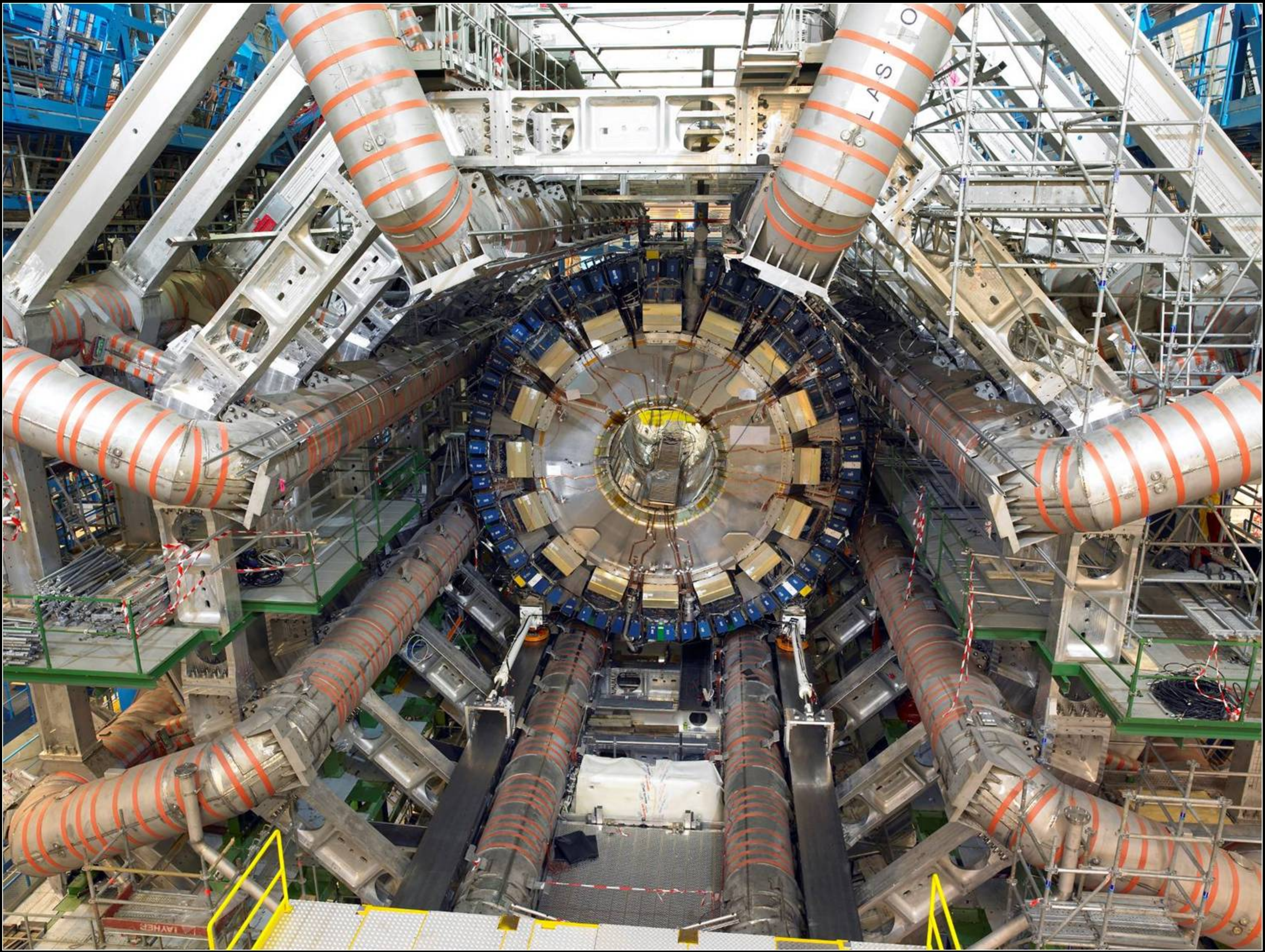


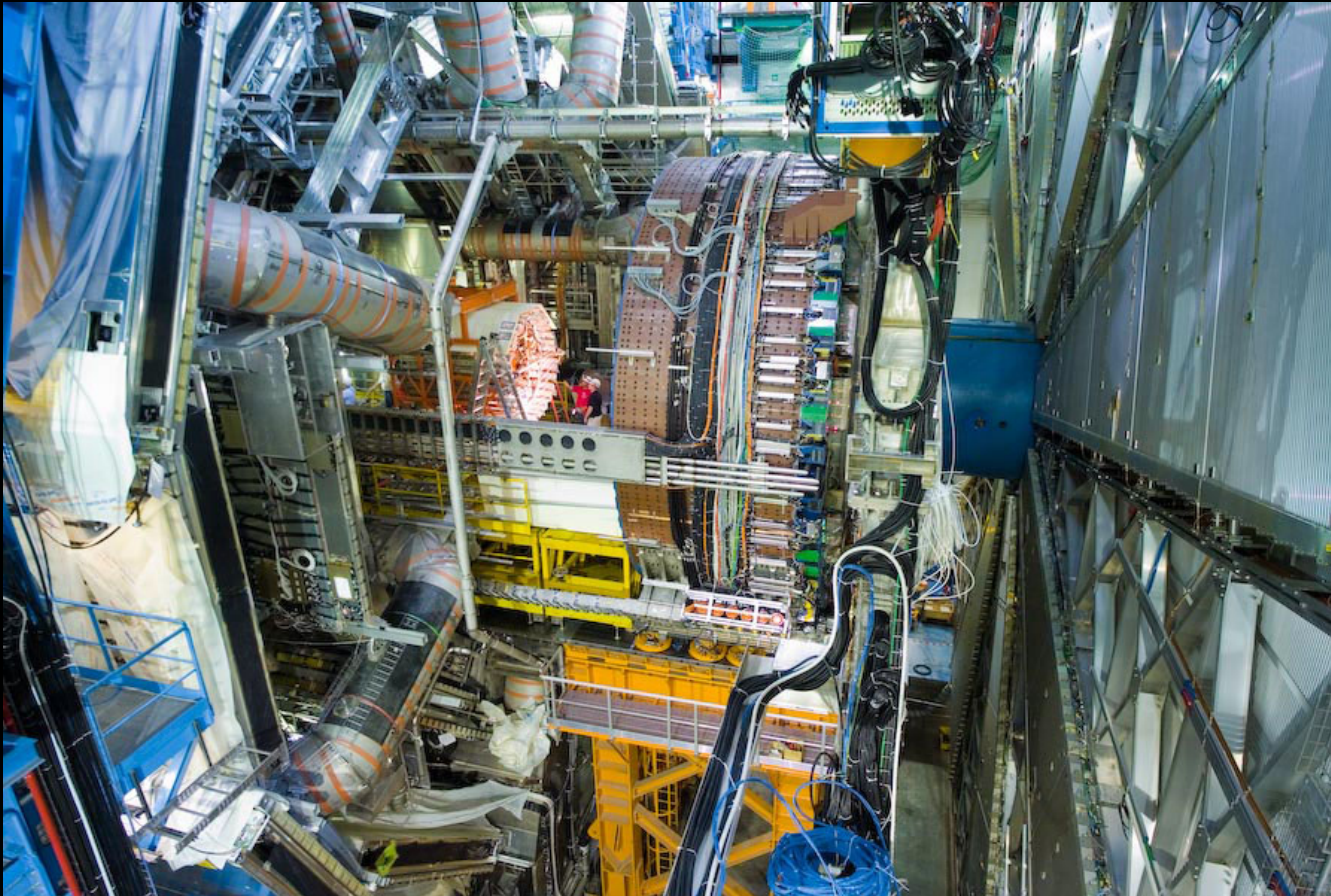
Building ATLAS


LHC Point 1 - UX15 Cavern - Formwork low beta shielding - 2003-02-06 - CERN ST-CE


A

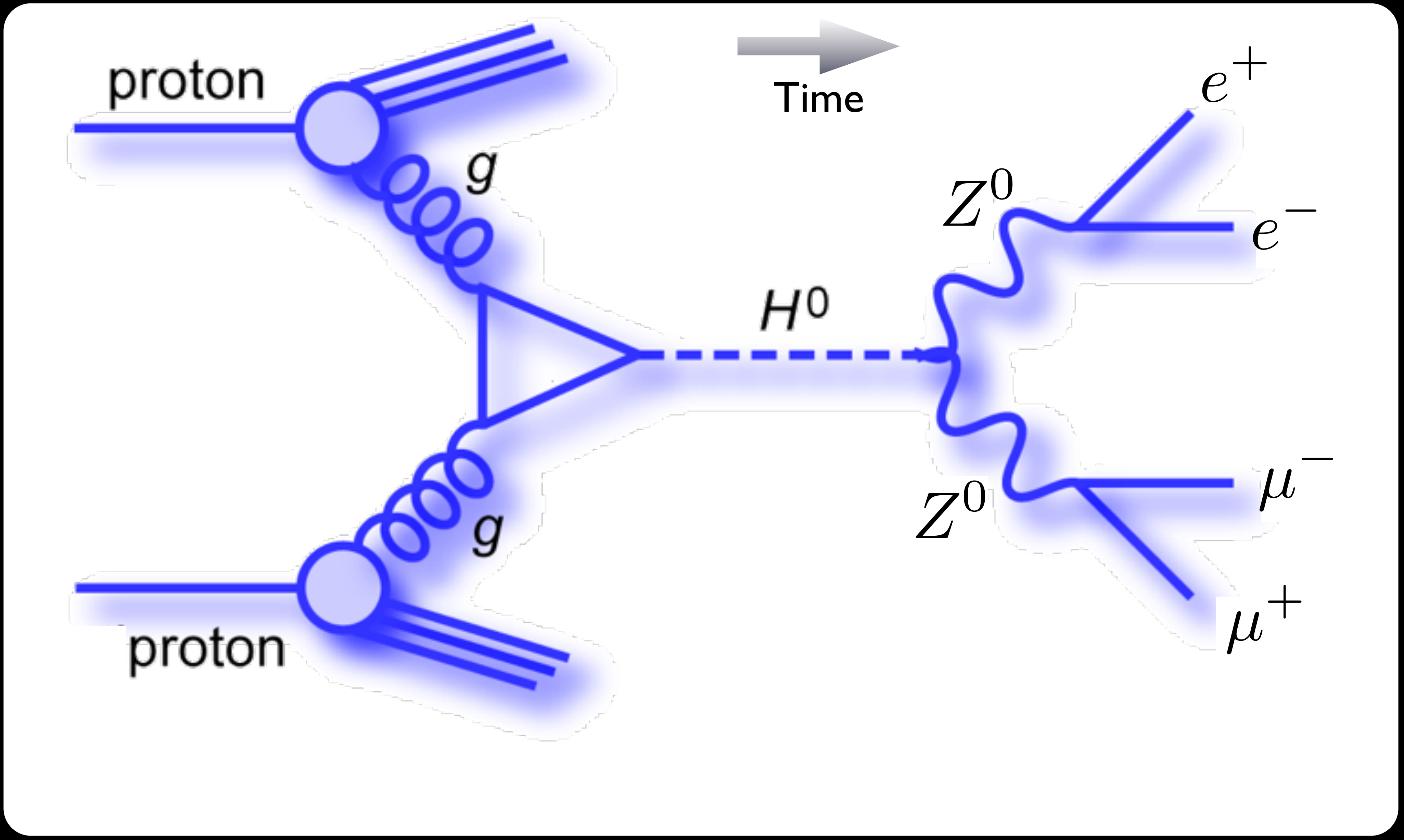


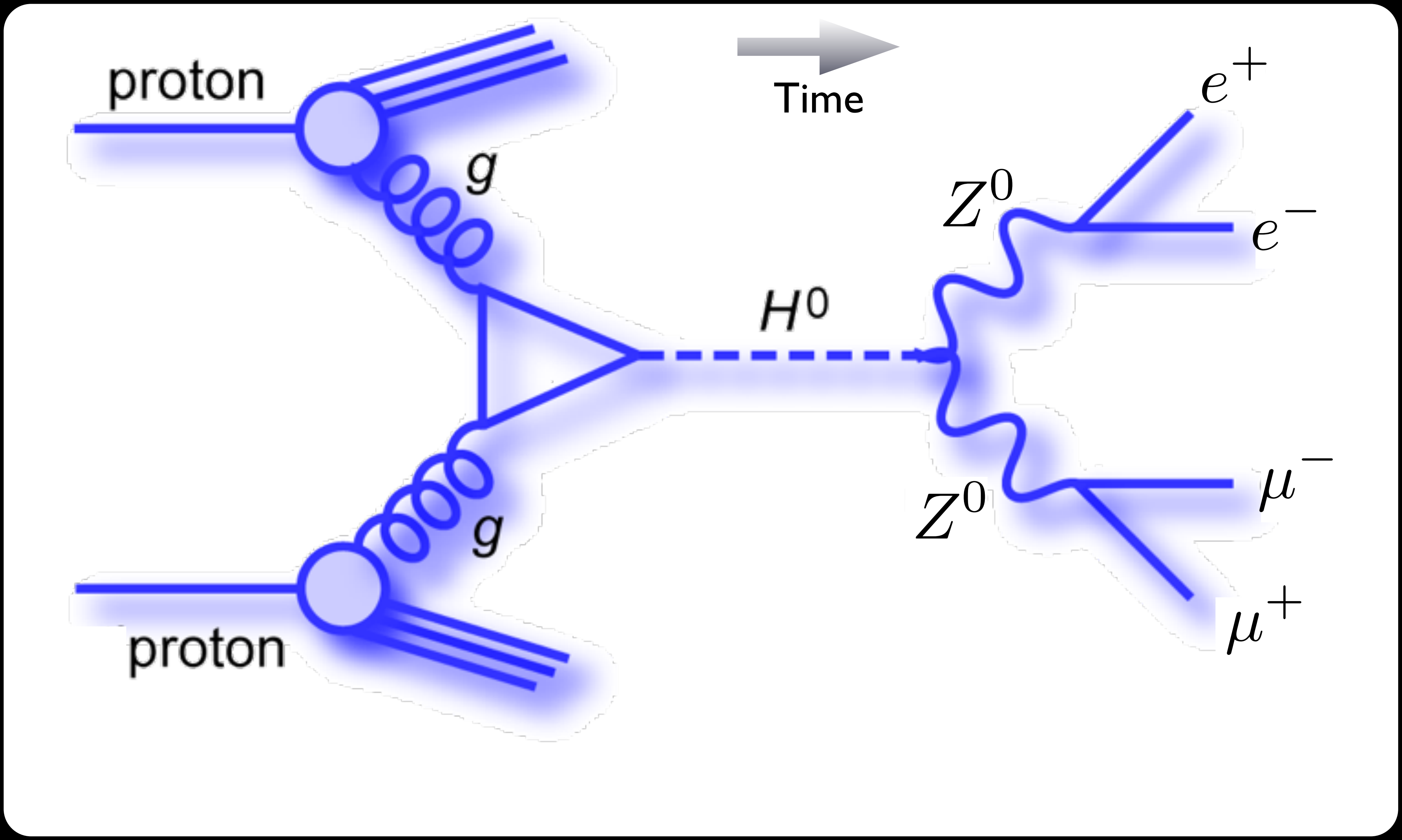


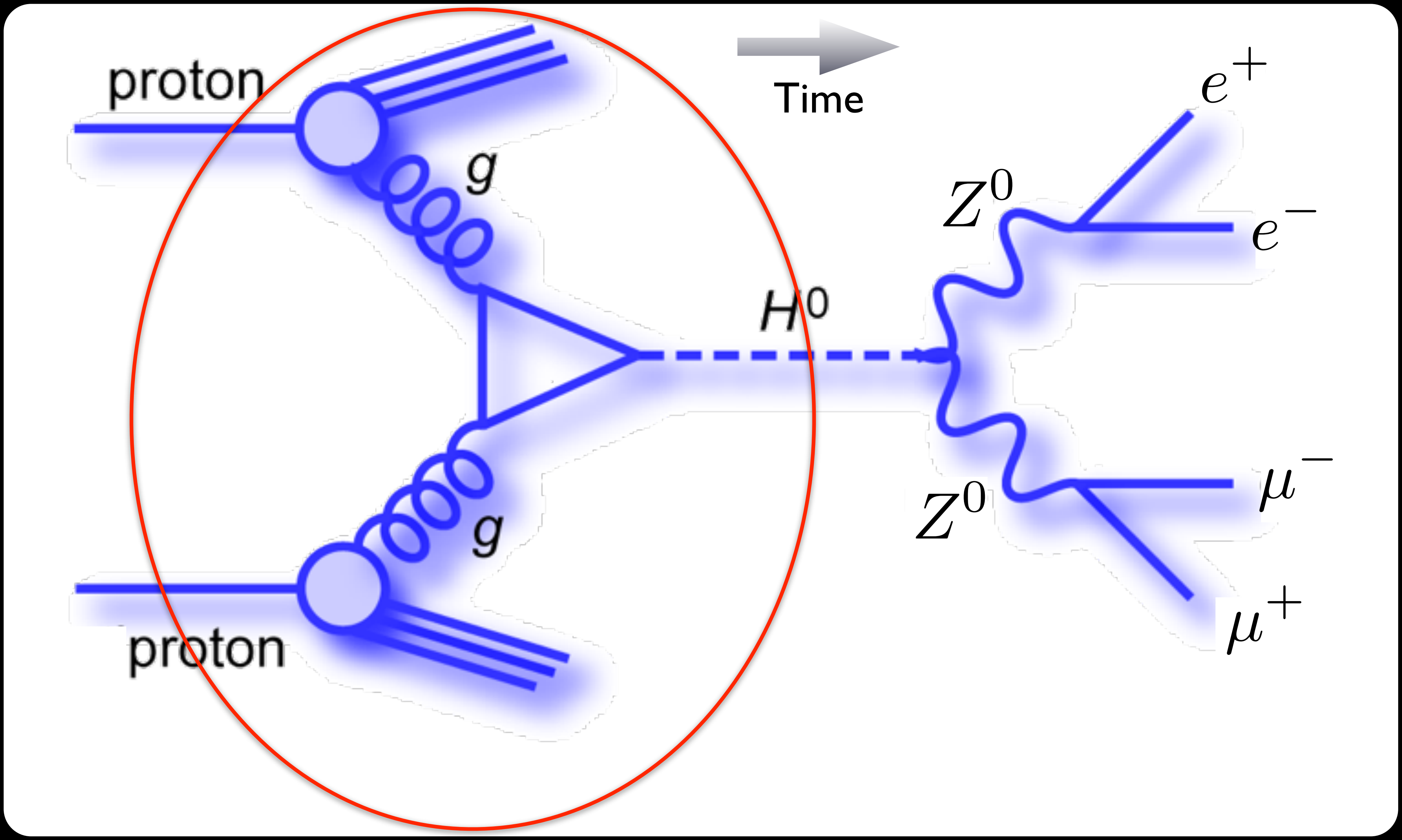



Looking for the Higgs

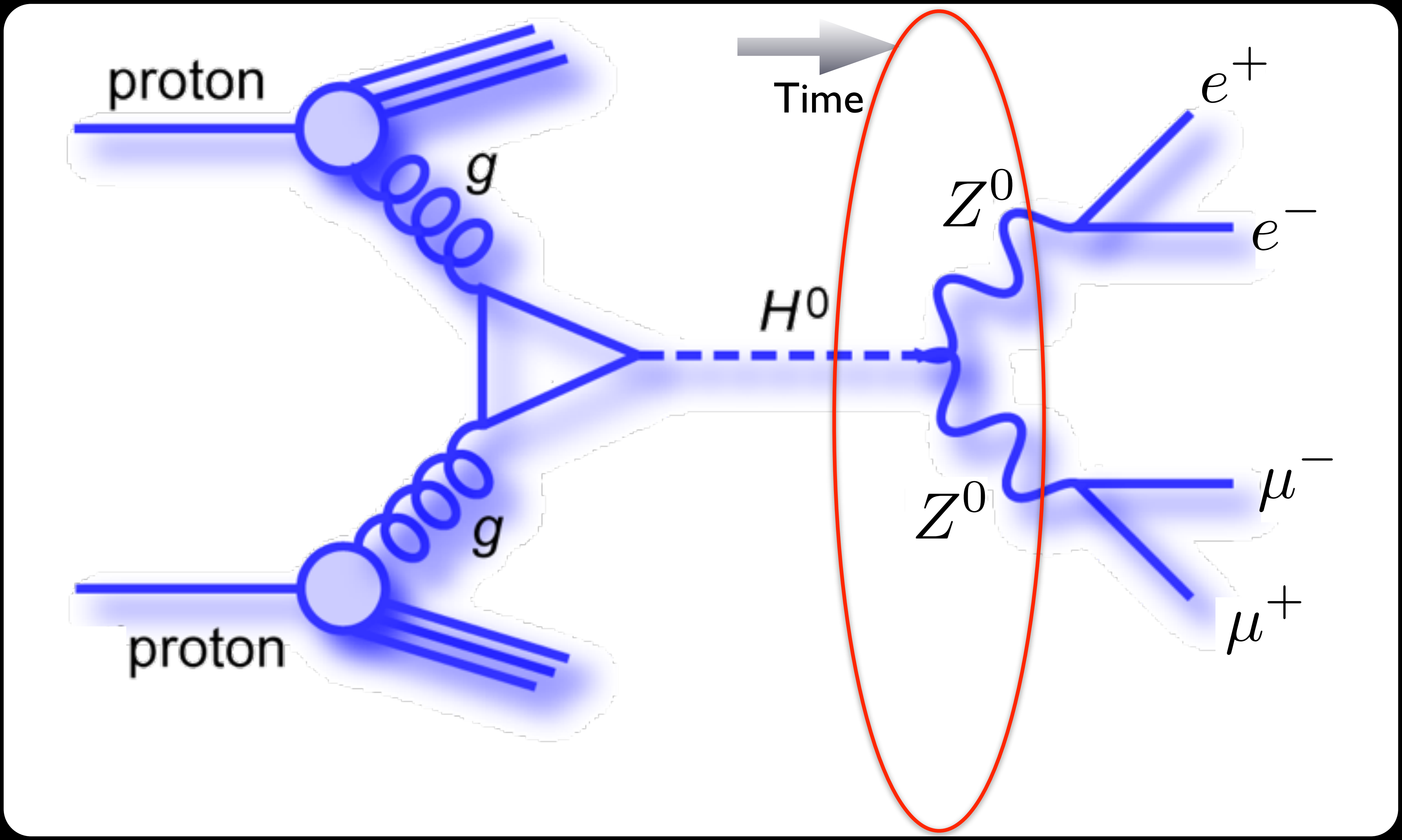
How to find the Higgs



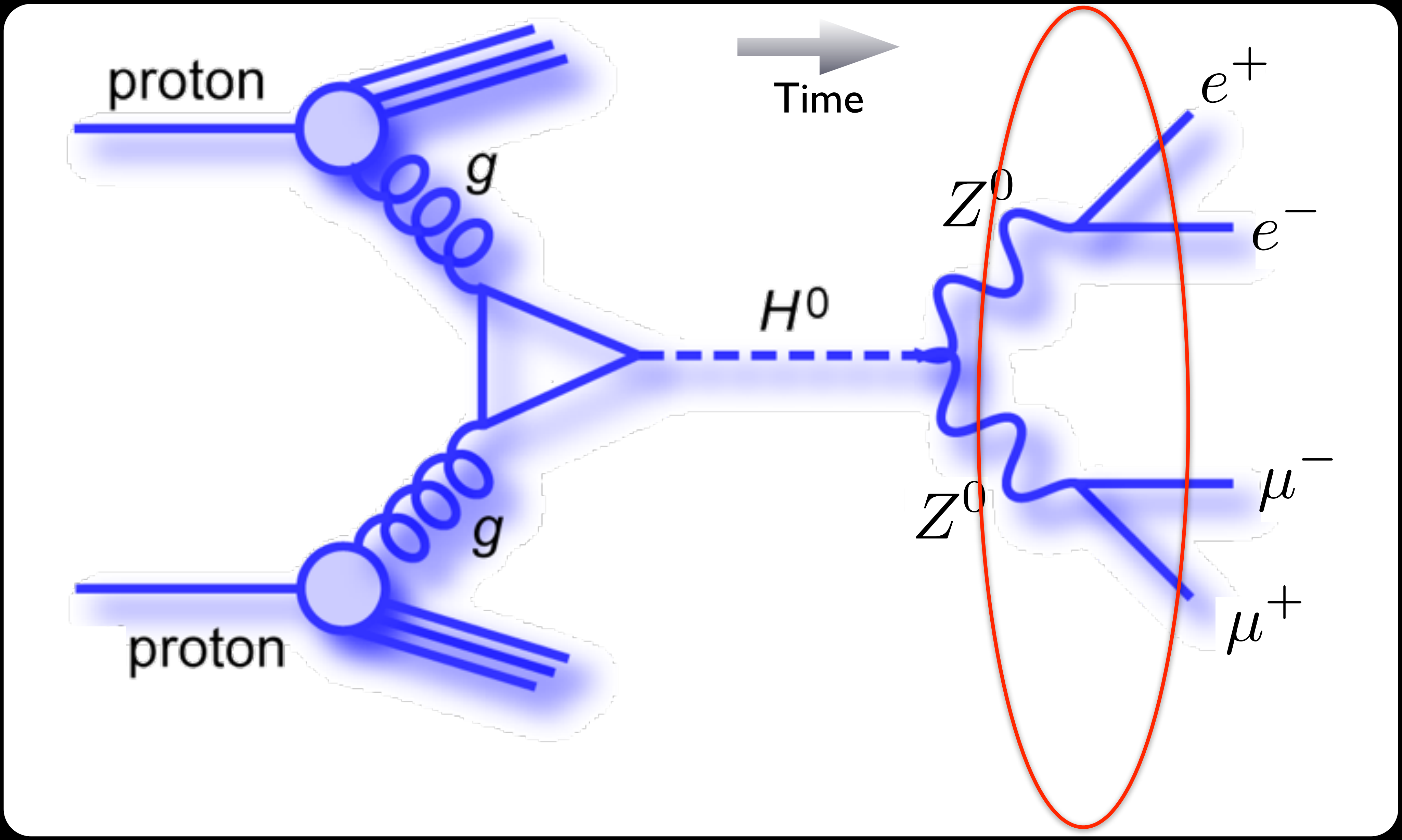

Time
proton
g
H^0
Z^0
e^+
e^-
μ^-
μ^+
Z^0
g
proton



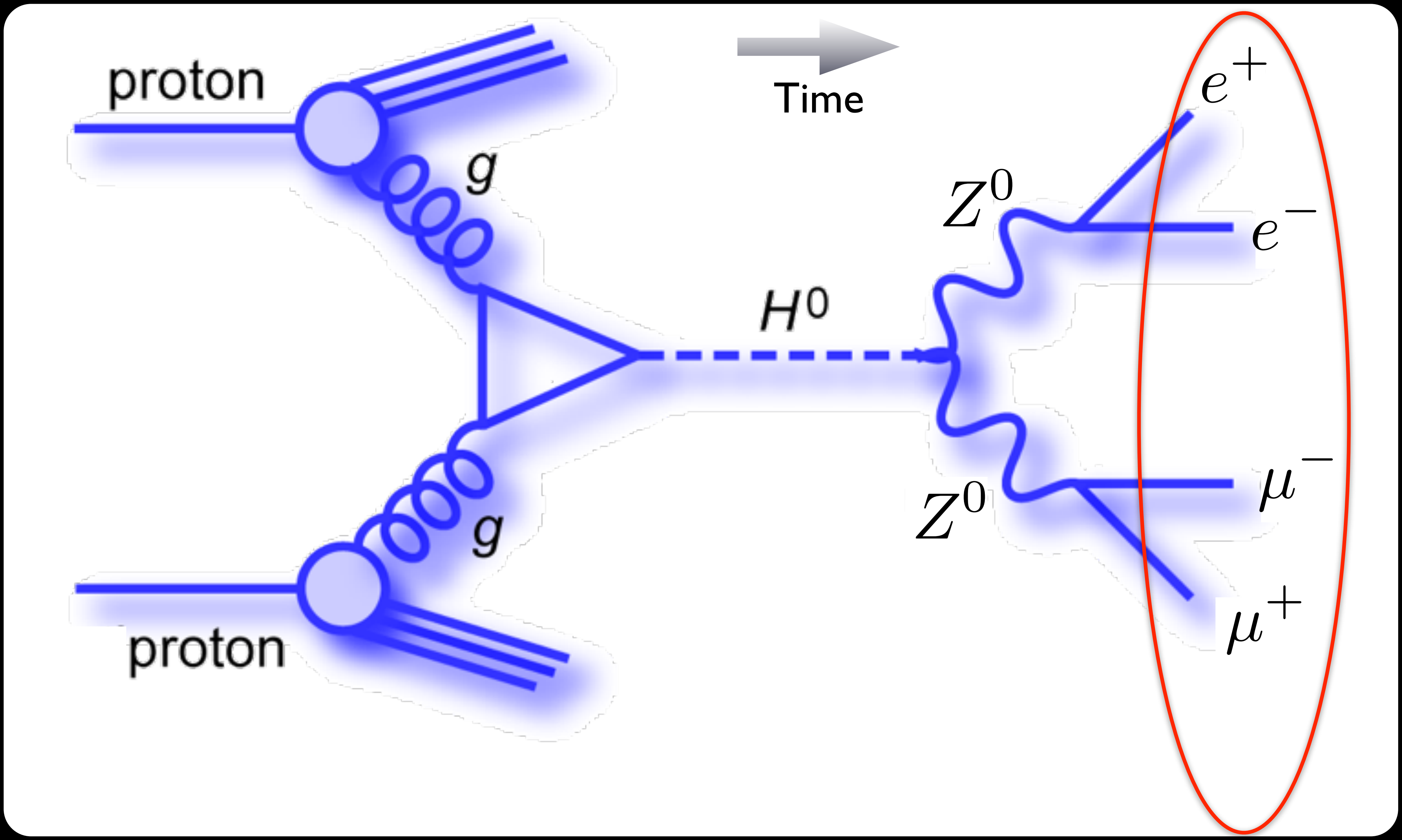
Make some Higgs
(LHC
High Energy
Huge rate of
attempts)



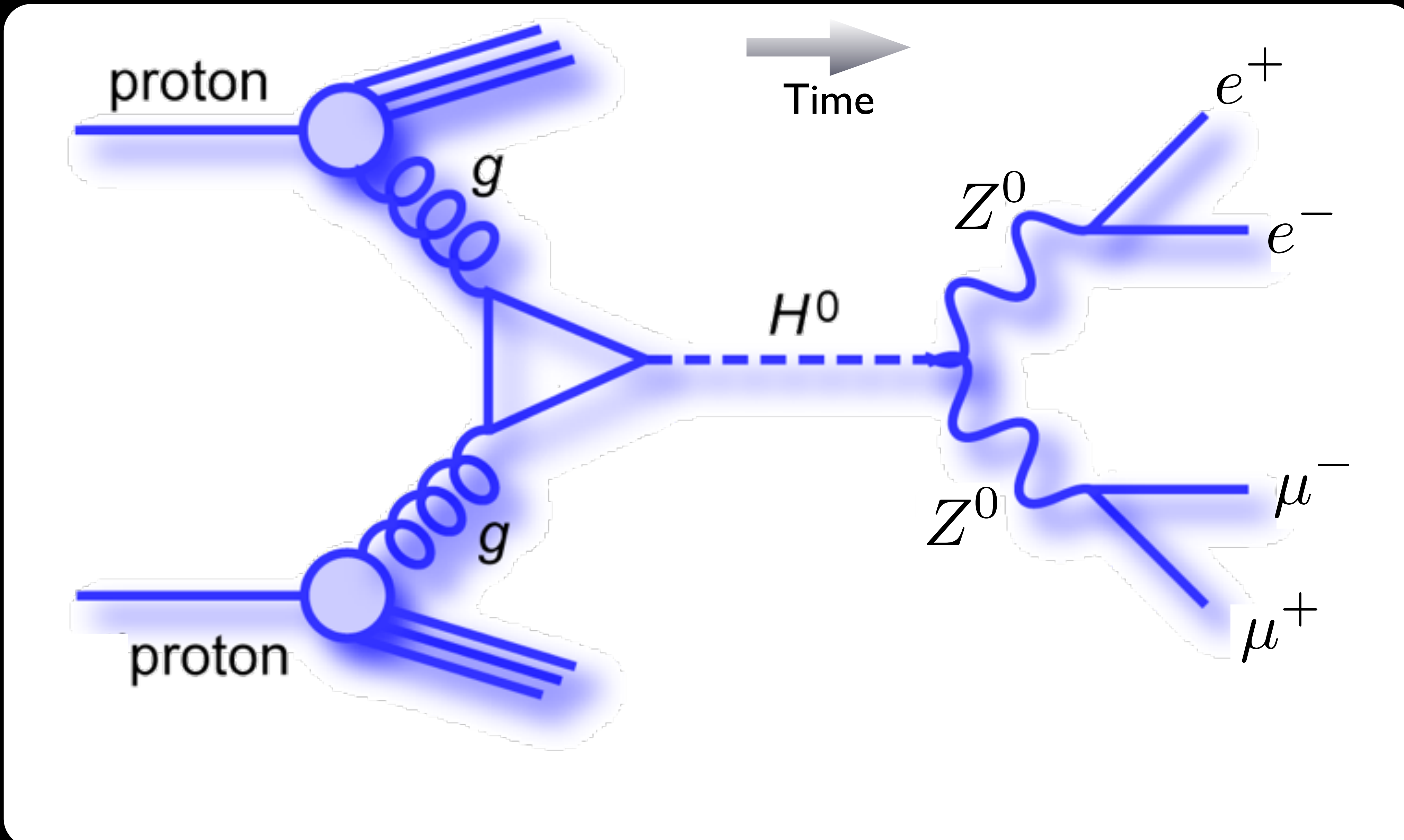
It immediately decays (into ZZ in this case)



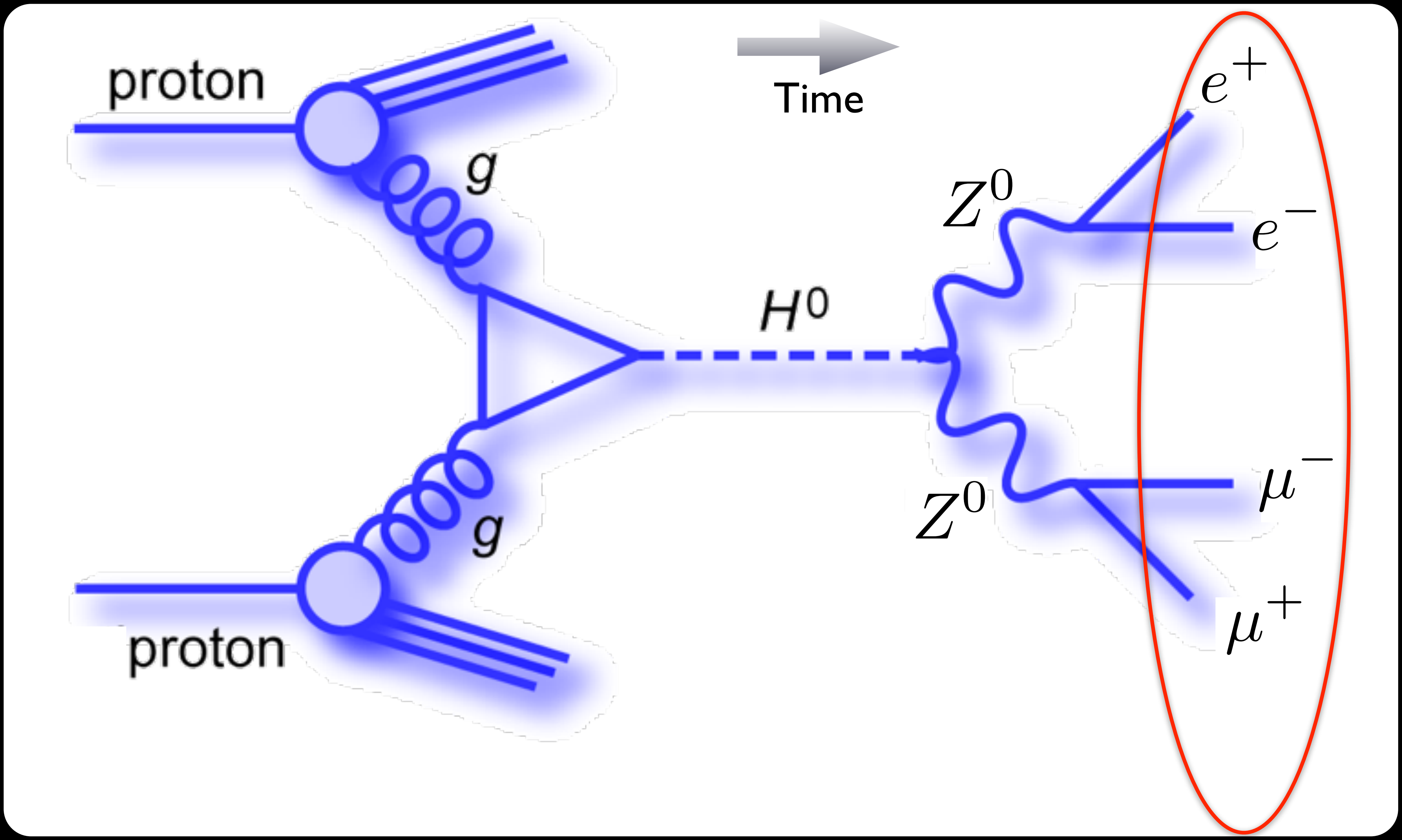
These particles decay



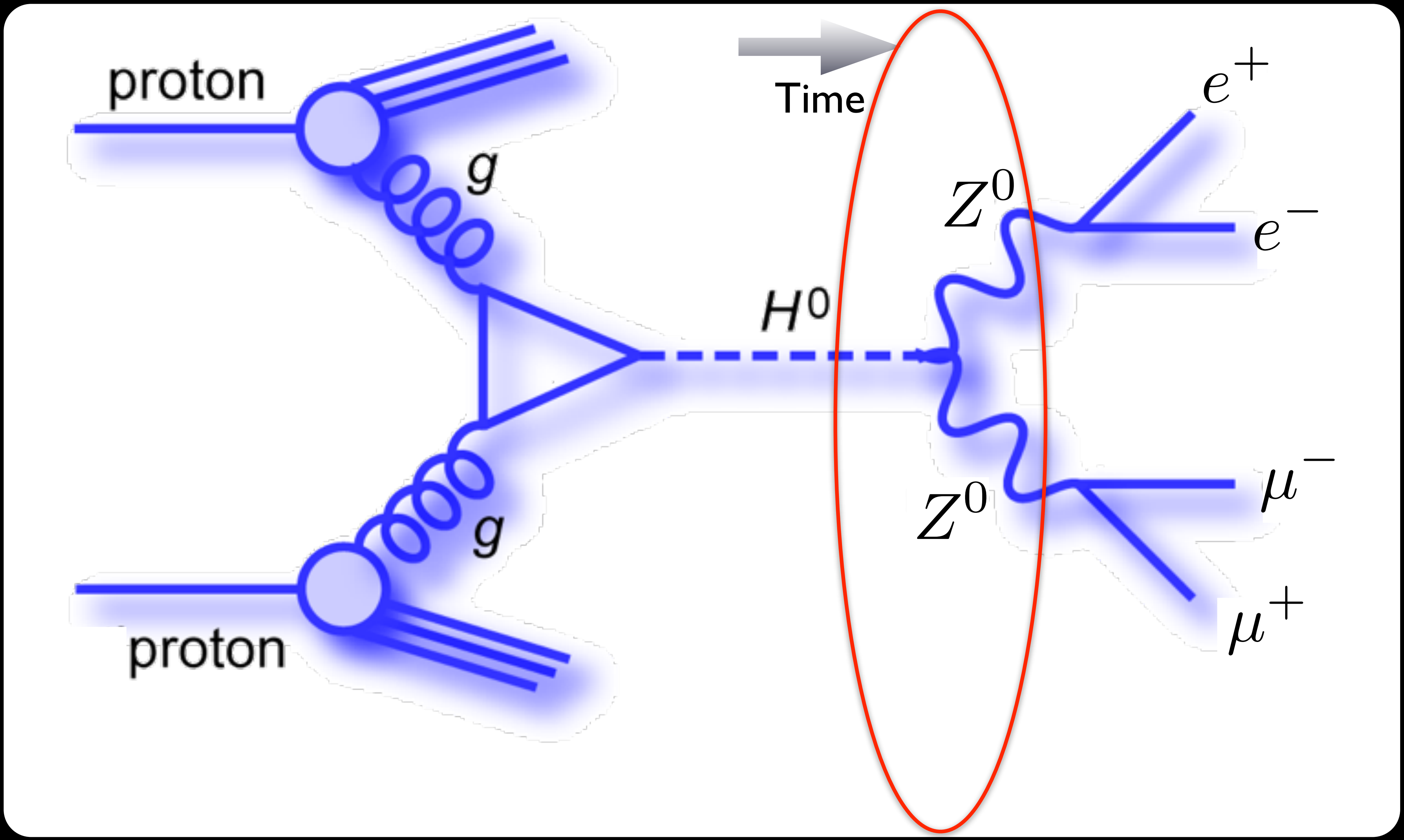
Into these,
which we see in
our detector
(ATLAS)



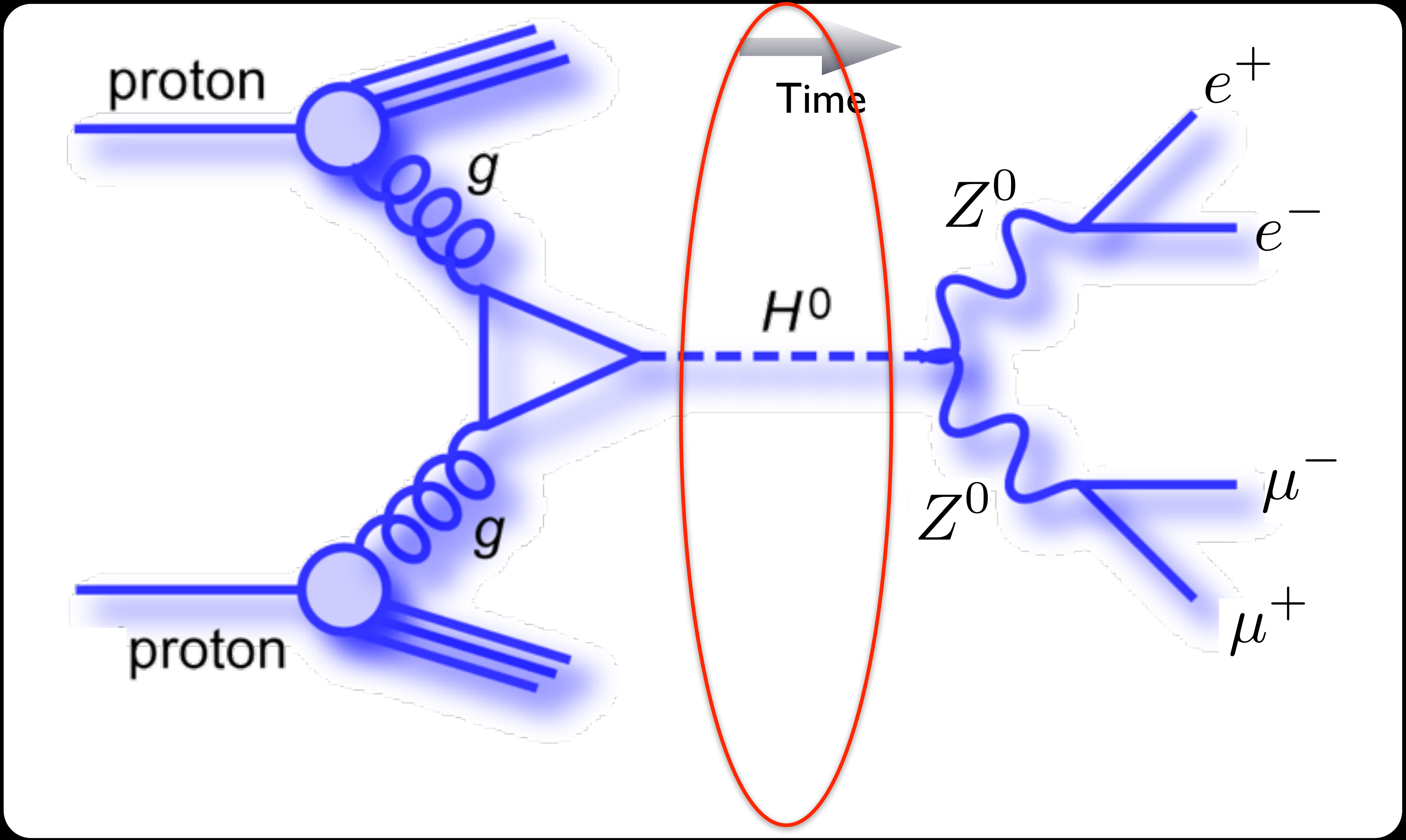
proton
g
Time
e^+
Z^0
e^-
H^0
μ^-
Z^0
g
proton
μ^+



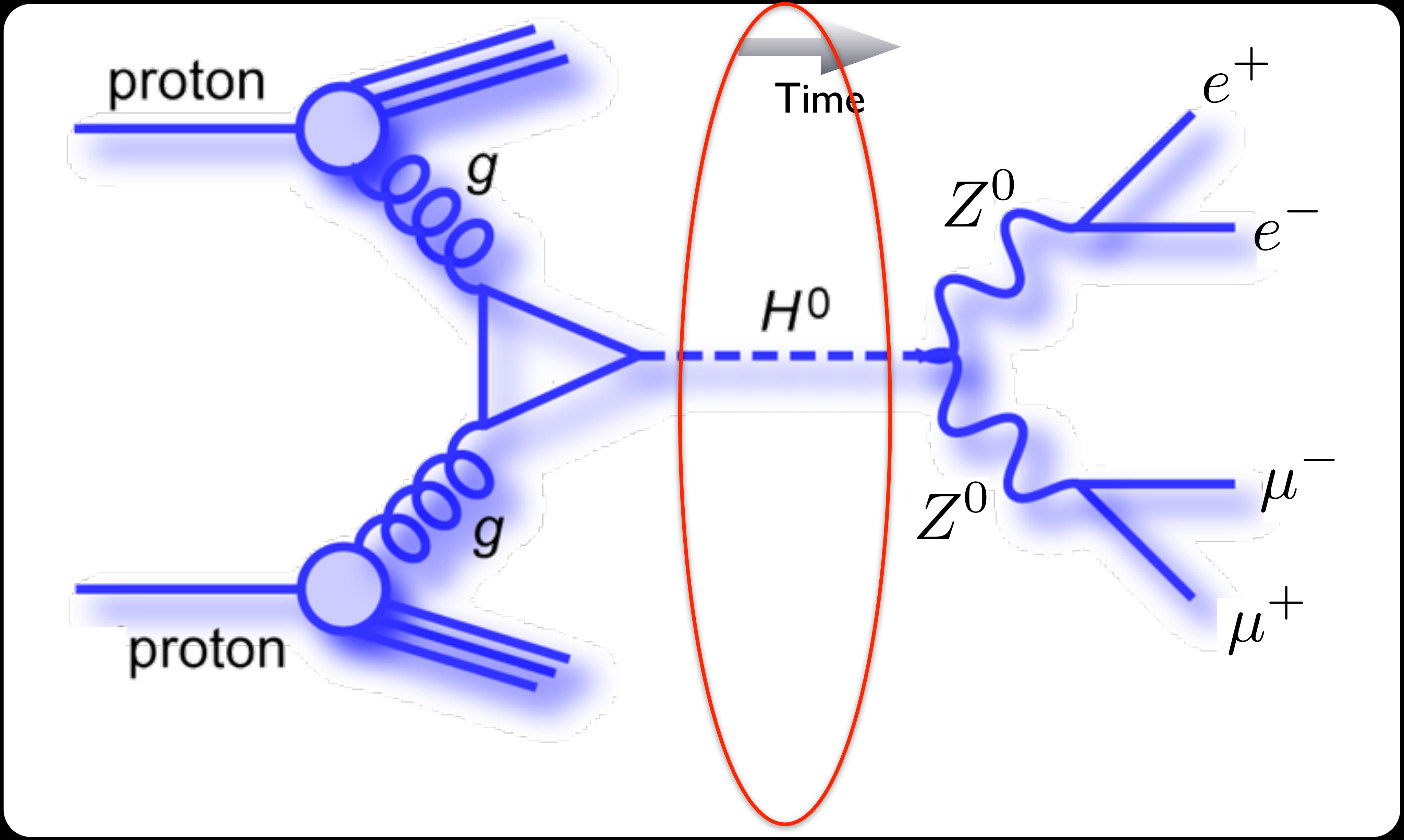
Measure the Energy and Momentum of these



To get the
Energy and
Momentum of
these

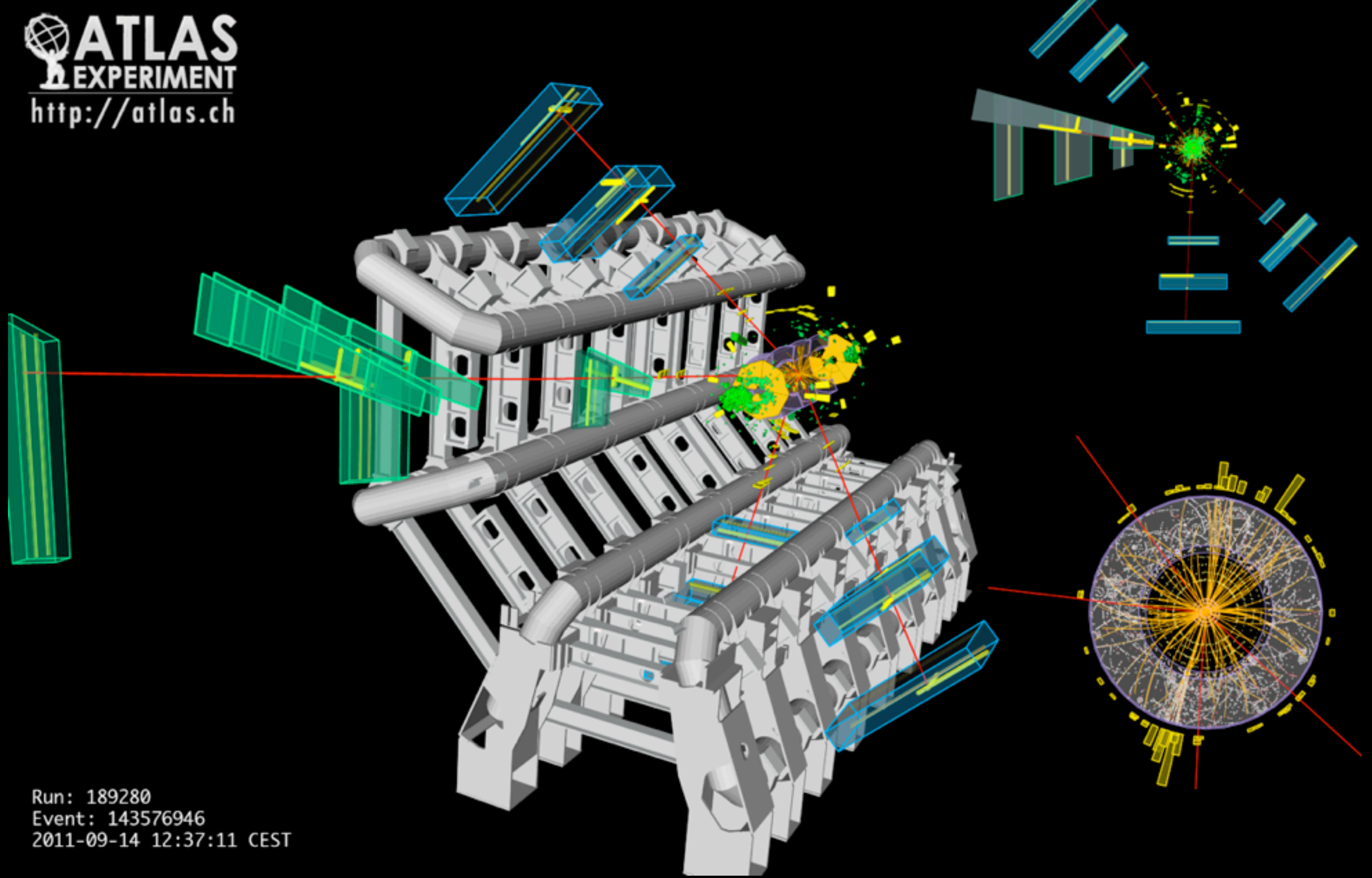


Gives us the
Energy and
Momentum of
the H



Gives us the Energy and Momentum of the H

Let's us calculate the Higgs Mass



Of course, complications

How many?

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It’s hard to make Higgs Particles

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Might expect 15 H->ZZ events all of last 2 years

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Don’t want to miss the
few good ones!

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Events that just have random combinations of particles will have masses spread out over a wide range (called Background events)

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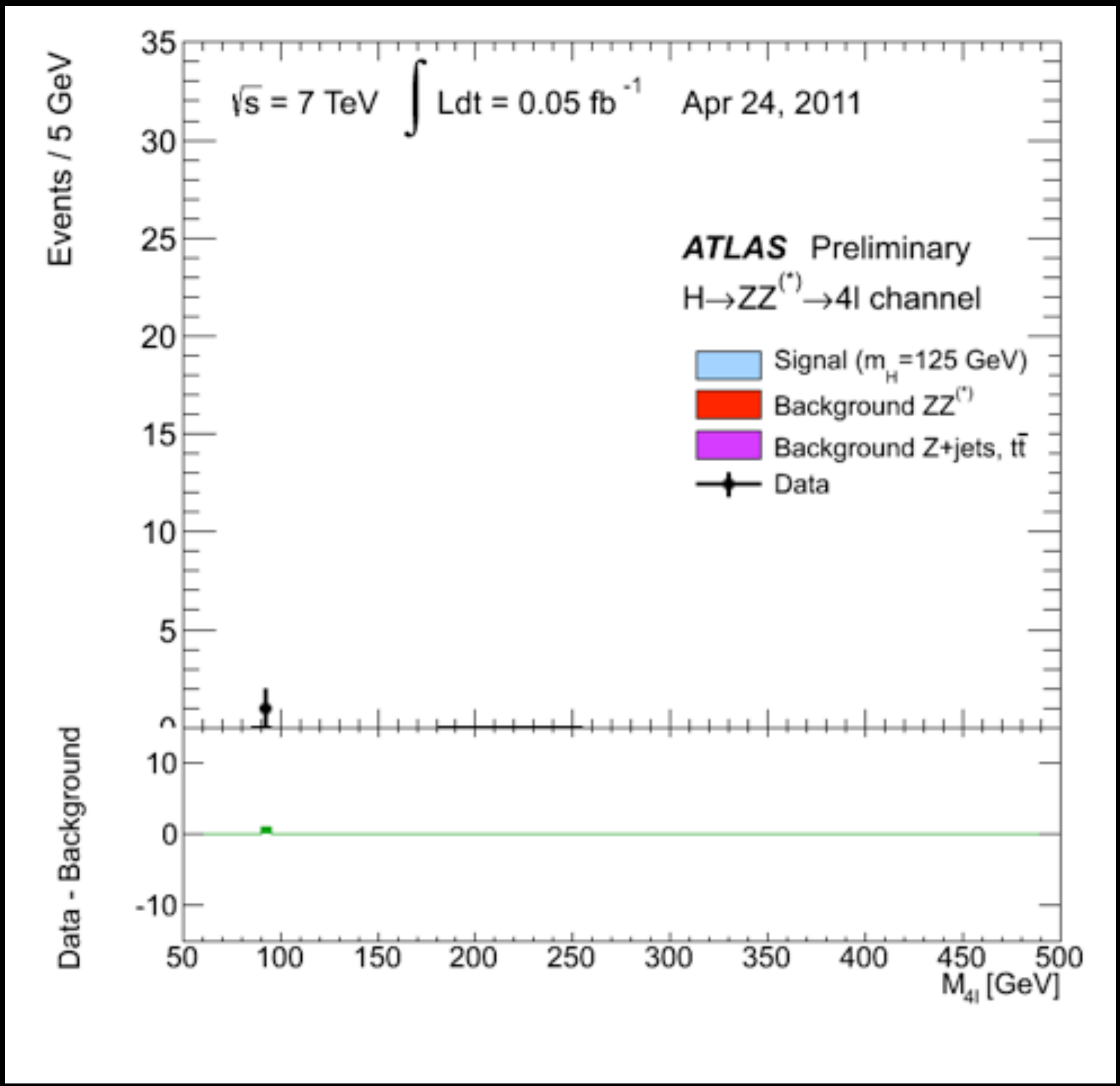

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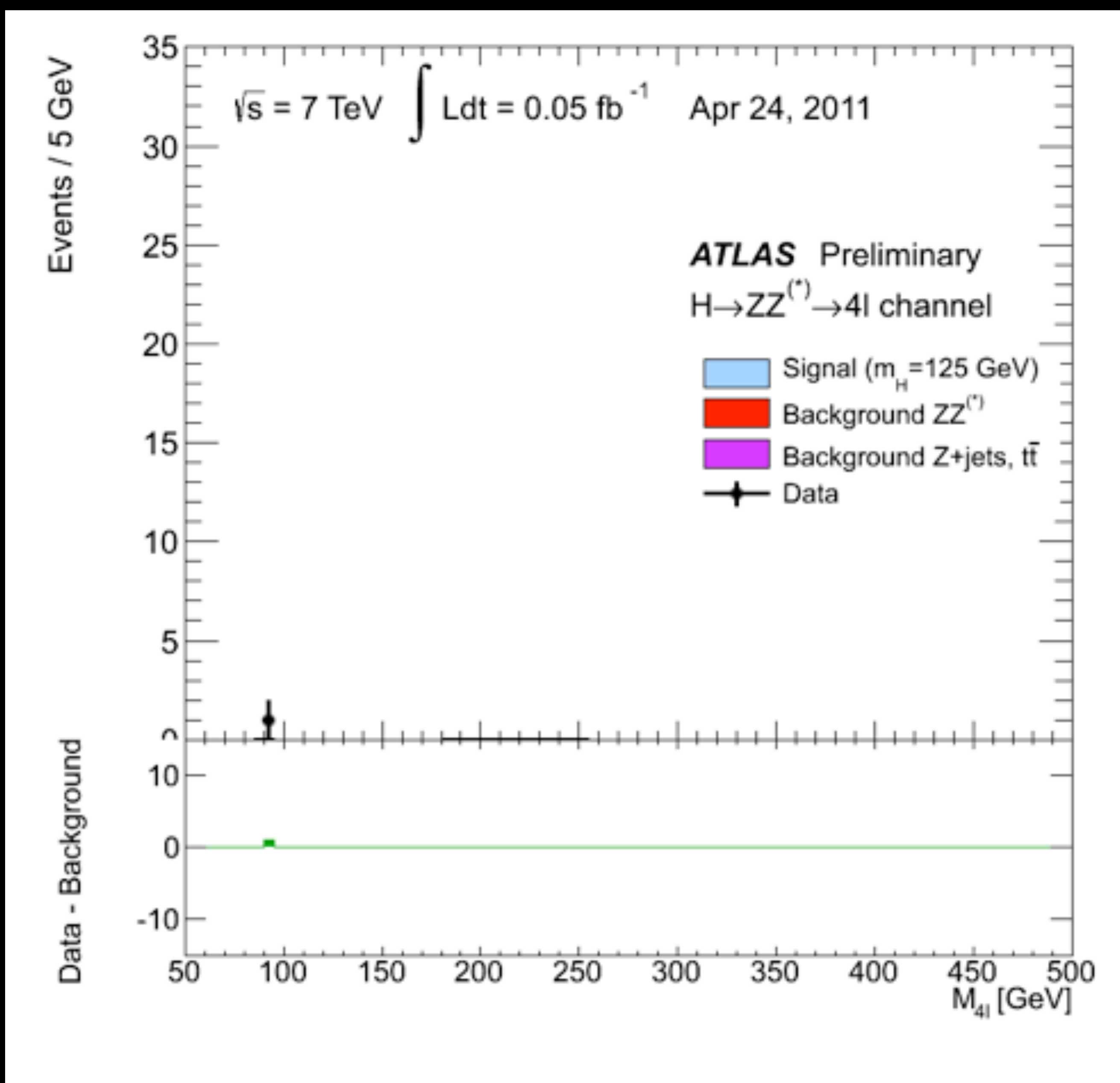

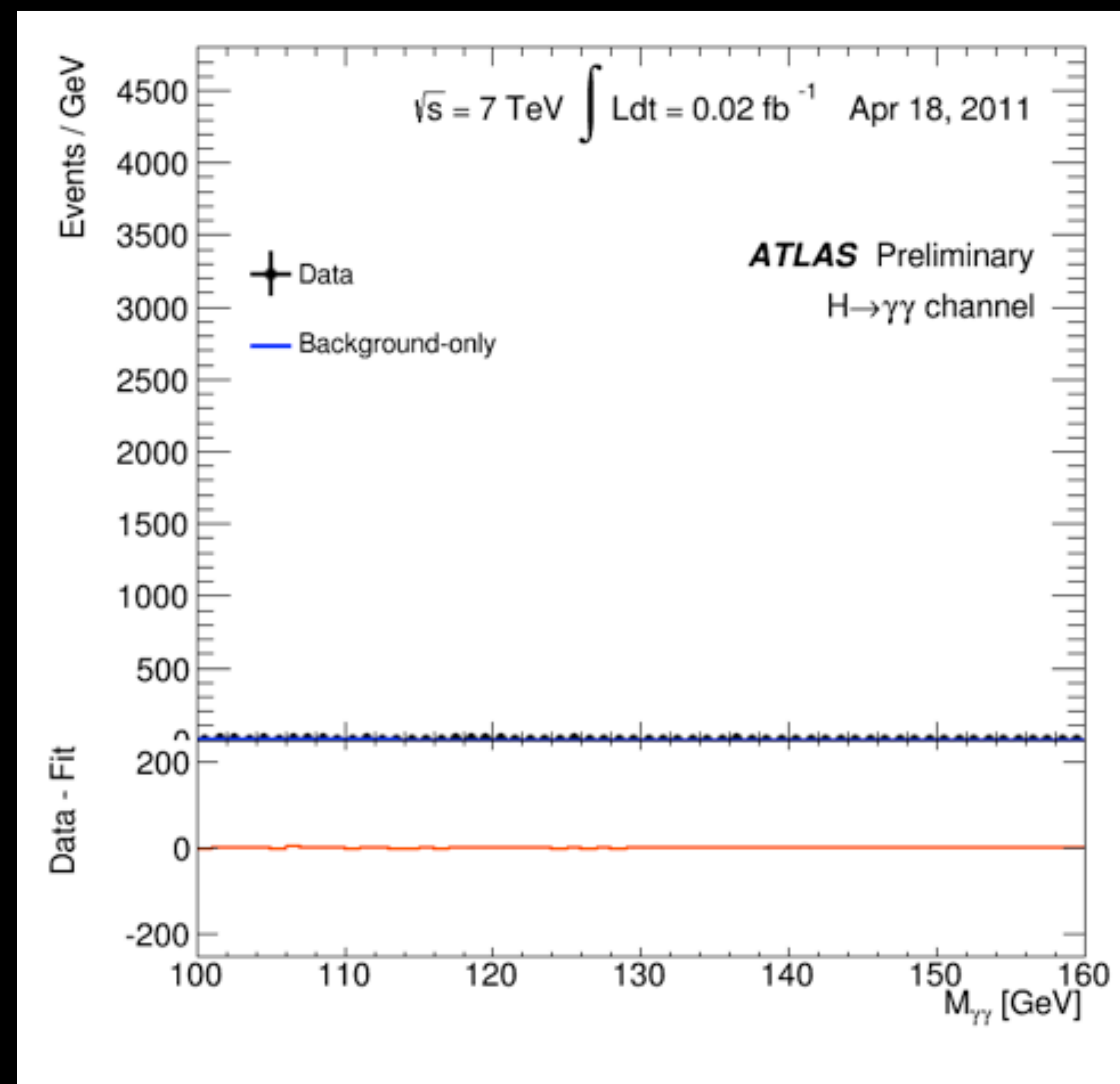

We were all pretty excited!

Both ATLAS and the other similar experiment, CMS, observe a particle consistent with being the Higgs Boson, ie an excitation of the Higgs Field that is responsible for giving elementary particles their apparent mass

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Can also think of this as a discovery of a new force, that is of different origin than all the others

But remember, the Higgs Boson, and the Standard Model, without some additional new physics, has deep theoretical problems ...

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Maybe the new particles in these models are too heavy to make with our current accelerator? $E = mc^2$

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Lot’s of fun other ideas to look for ...

Big Questions for Particle Physics

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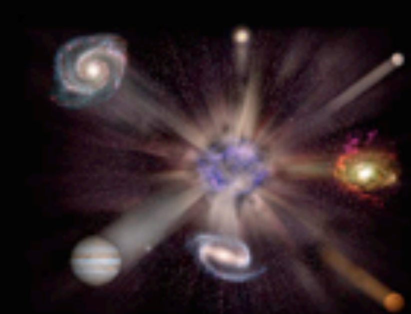
Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Big Questions for Particle Physics

Particle Accelerators
(looking at the very small)

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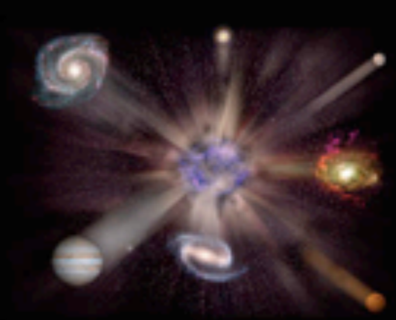

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Cosmology (looking at the very big)

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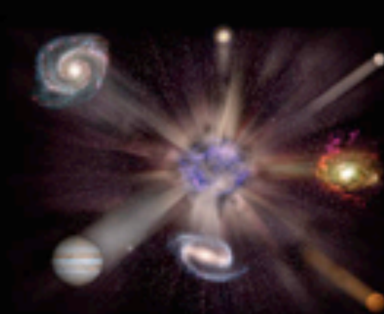

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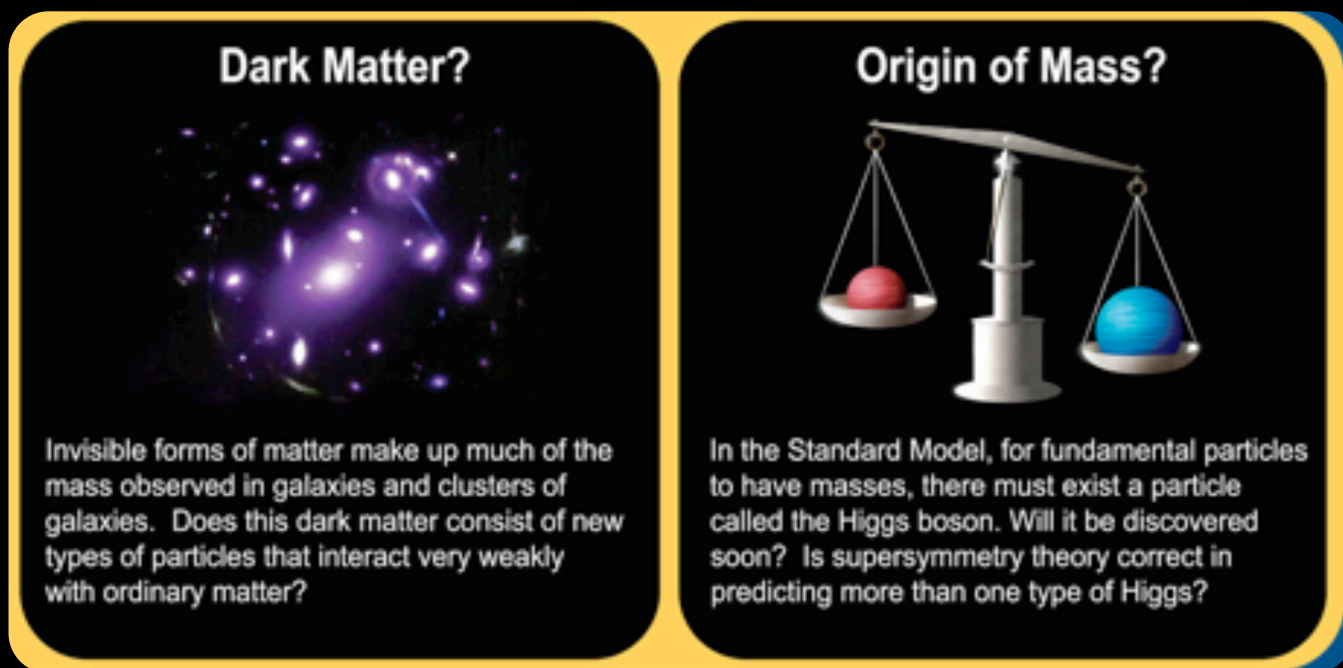

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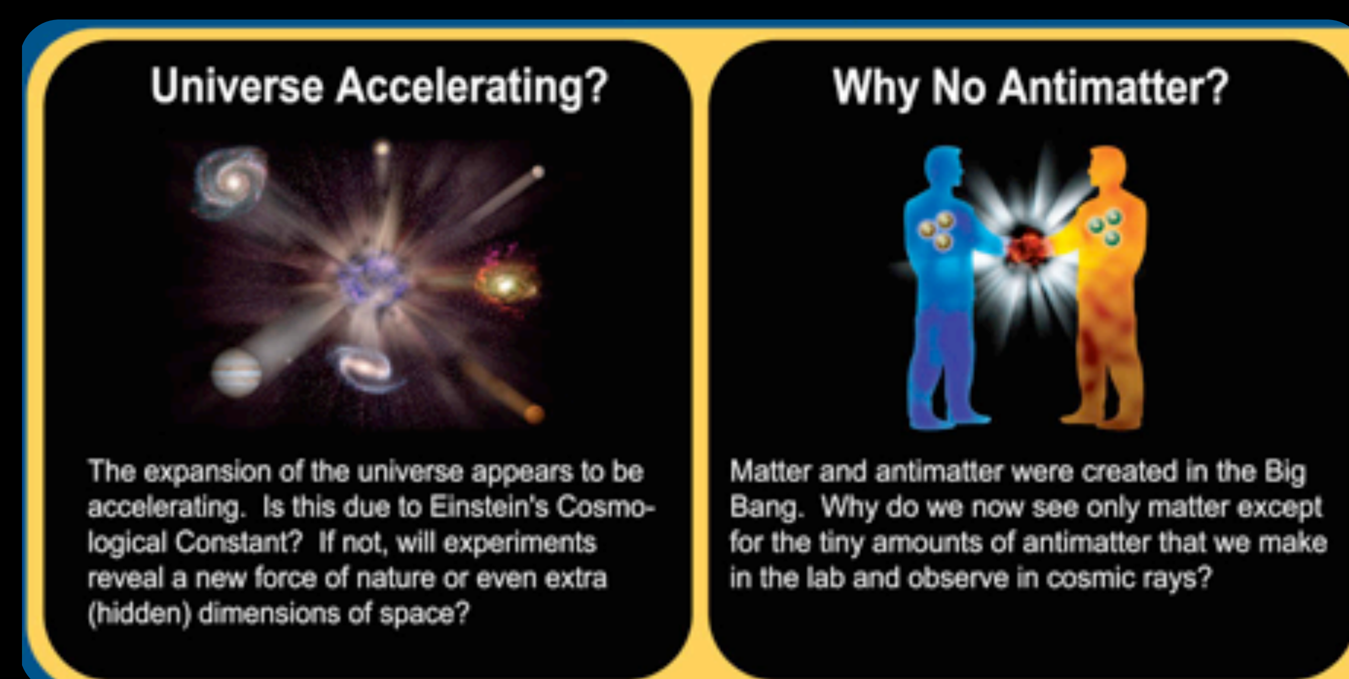

Cosmology
(looking at the very big)

But that's another talk ...