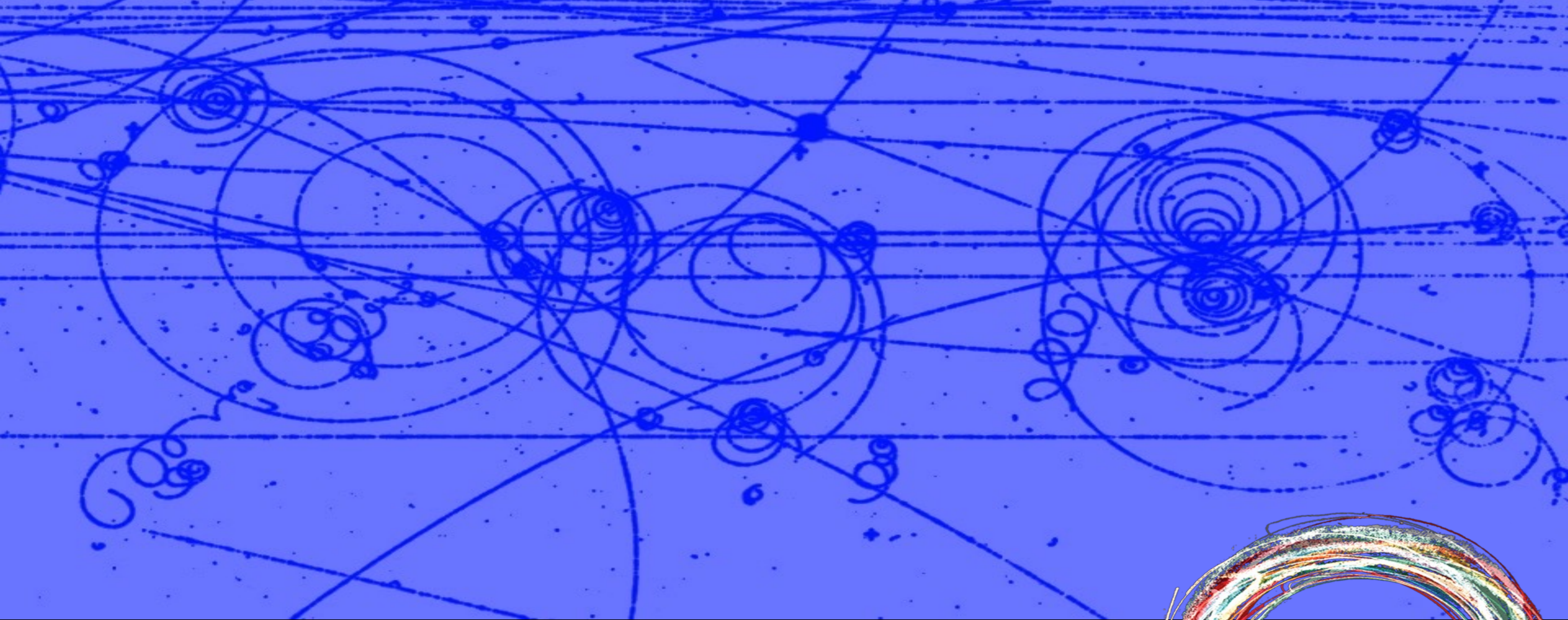


LECTURE 2
THE PARTICLE ZOO

PHY 493 / 803

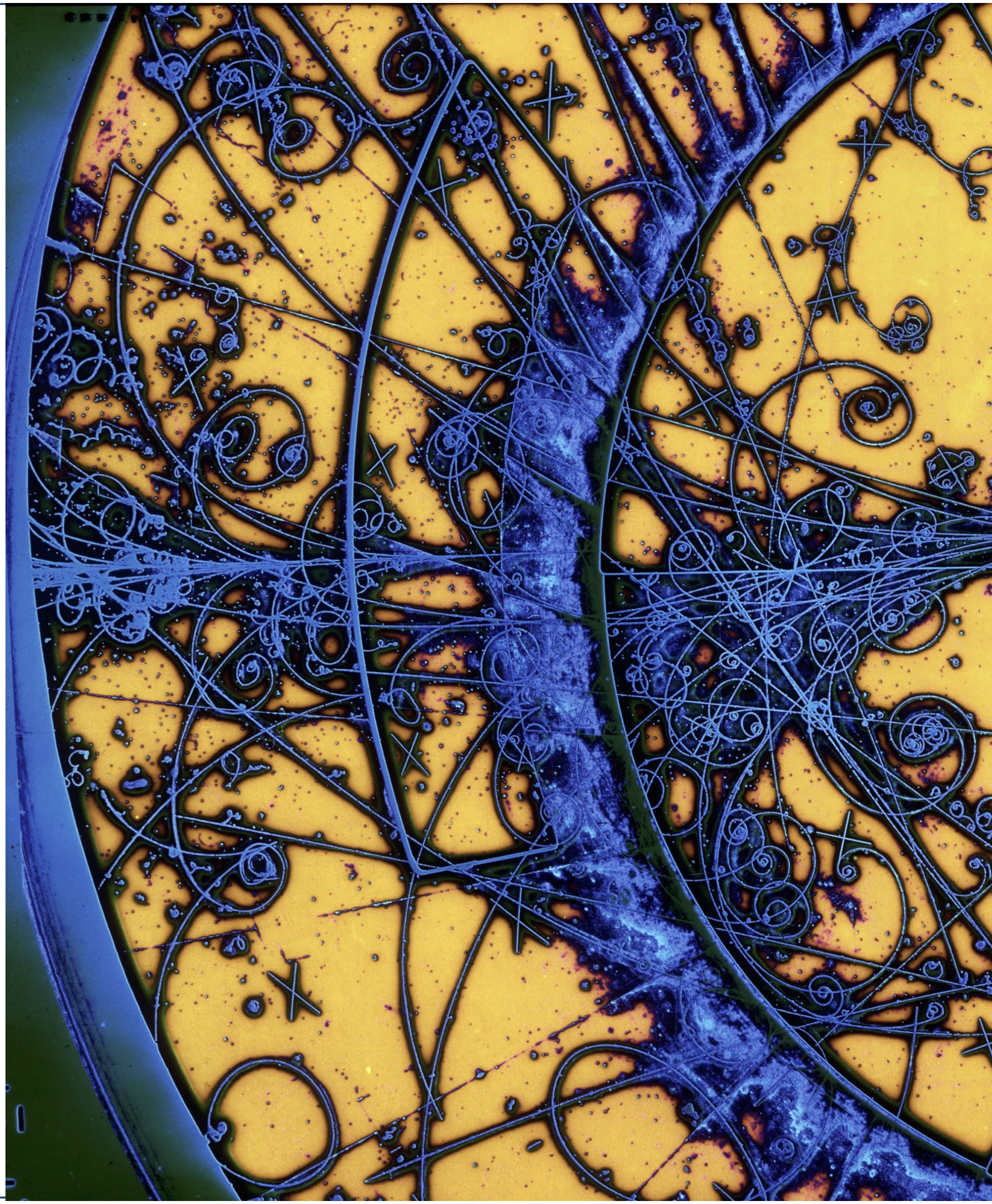
Announcements

1. Syllabus, slides from last time posted on combined 493/803 D2L page. First homework will be posted by the end of the week.

2. Quizzes nominally on Fridays, starting next week, except for weeks when there are exams.

3. There will be a TA for the course. Contact information is in the syllabus. Please reach out to him with questions about the homework/grading. He does not have fixed office hours, but you can schedule a meeting. Please copy me on any email communication with him.

4. Reading for this week: Ch 1 of Griffiths



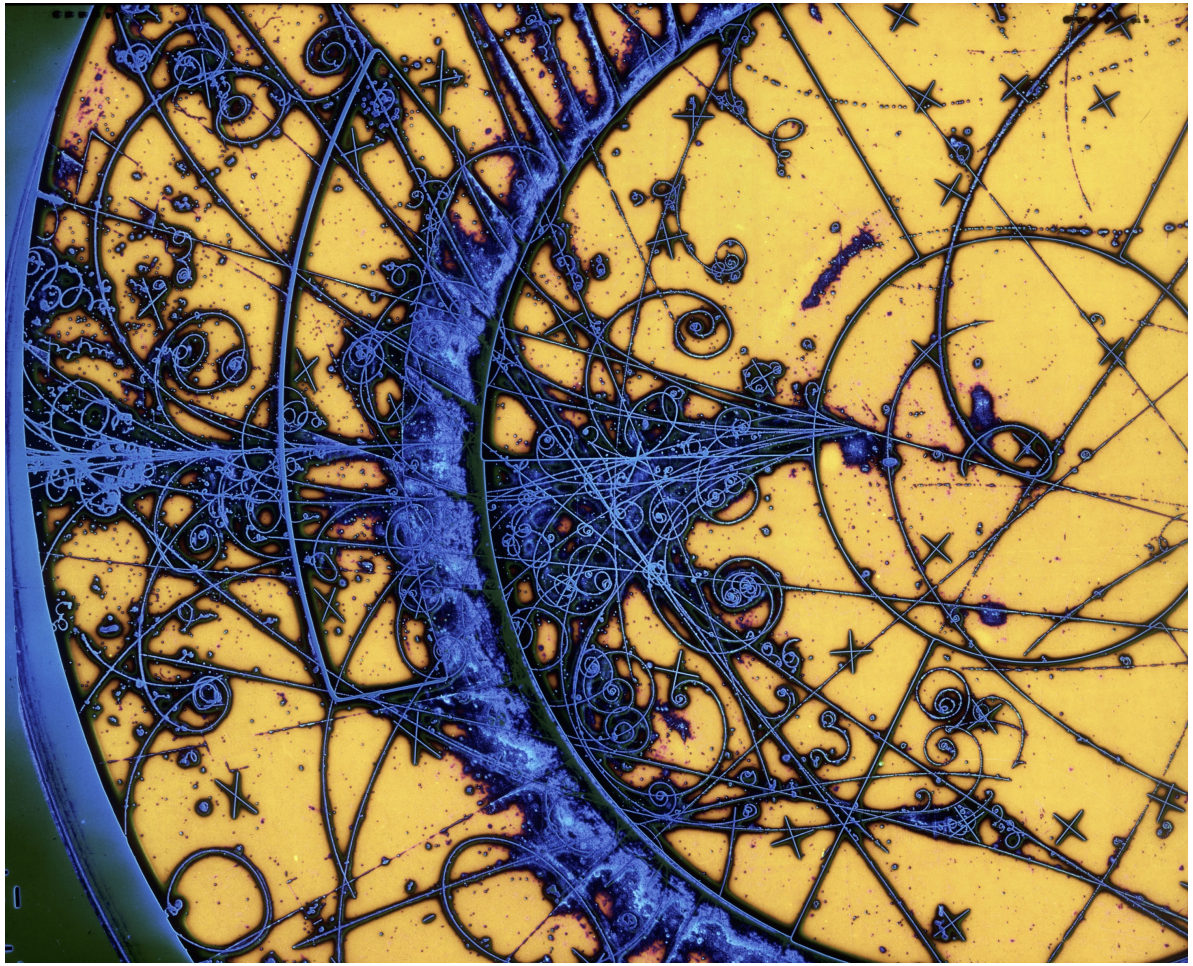
Recap / Up Next

Last time:

Introductions & Overviews

This time:

- Particles!
- Fundamentals: units, concepts
- Some history, two important cases
    1. Discovery of the electron
    2. Discovery of the nucleus



Particle Physics

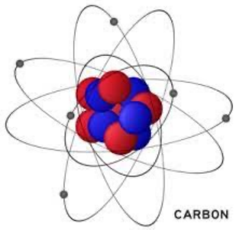
- What are the fundamental components of our universe?

What is a tree made of?

A: branches, leaves, trunk

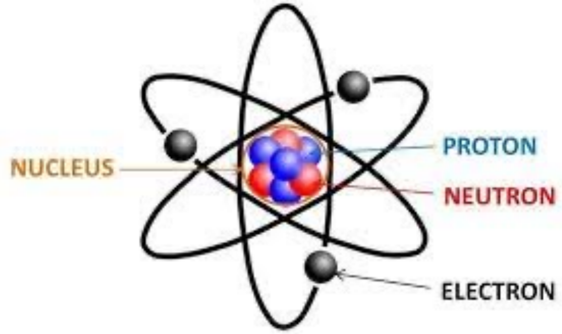
What are those made of?

A: Molecules (H2O), atoms (C, O), etc



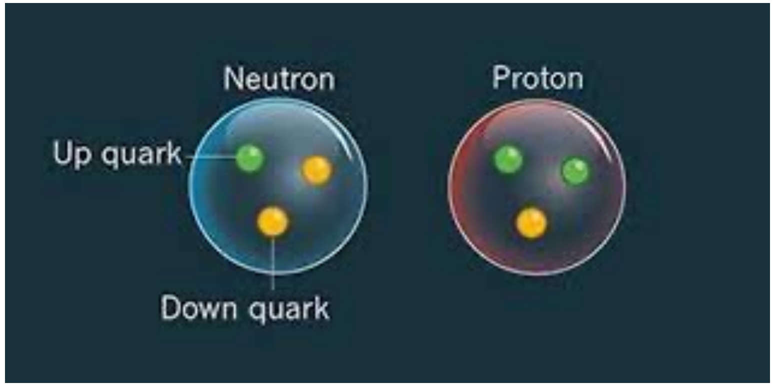
What are those made of?

A: protons, neutrons, electrons

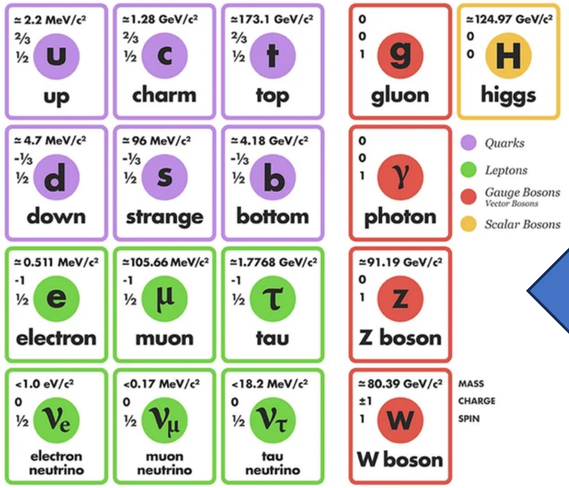


What are those made of?

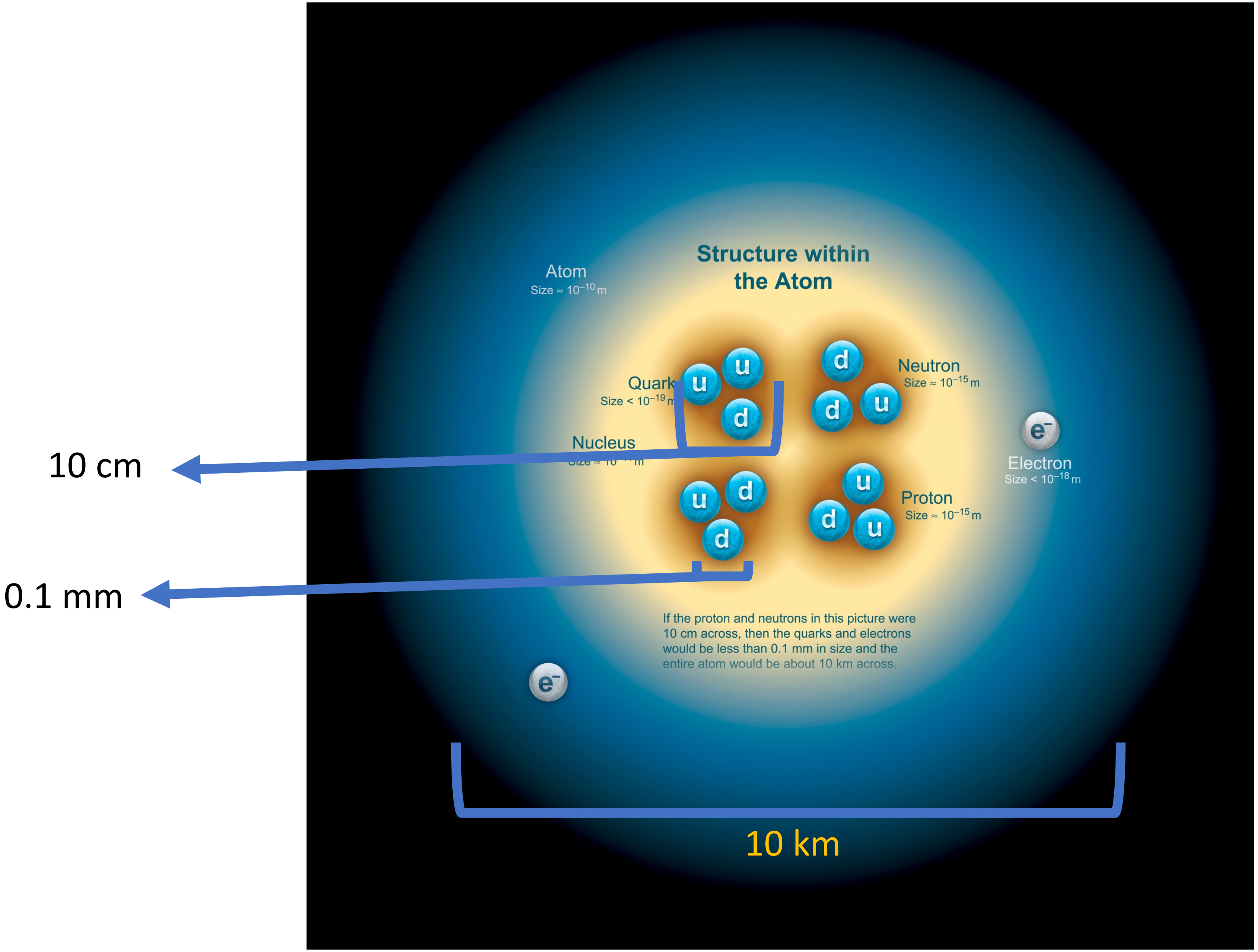
A: quarks
(electrons, so far as we know are fundamental)



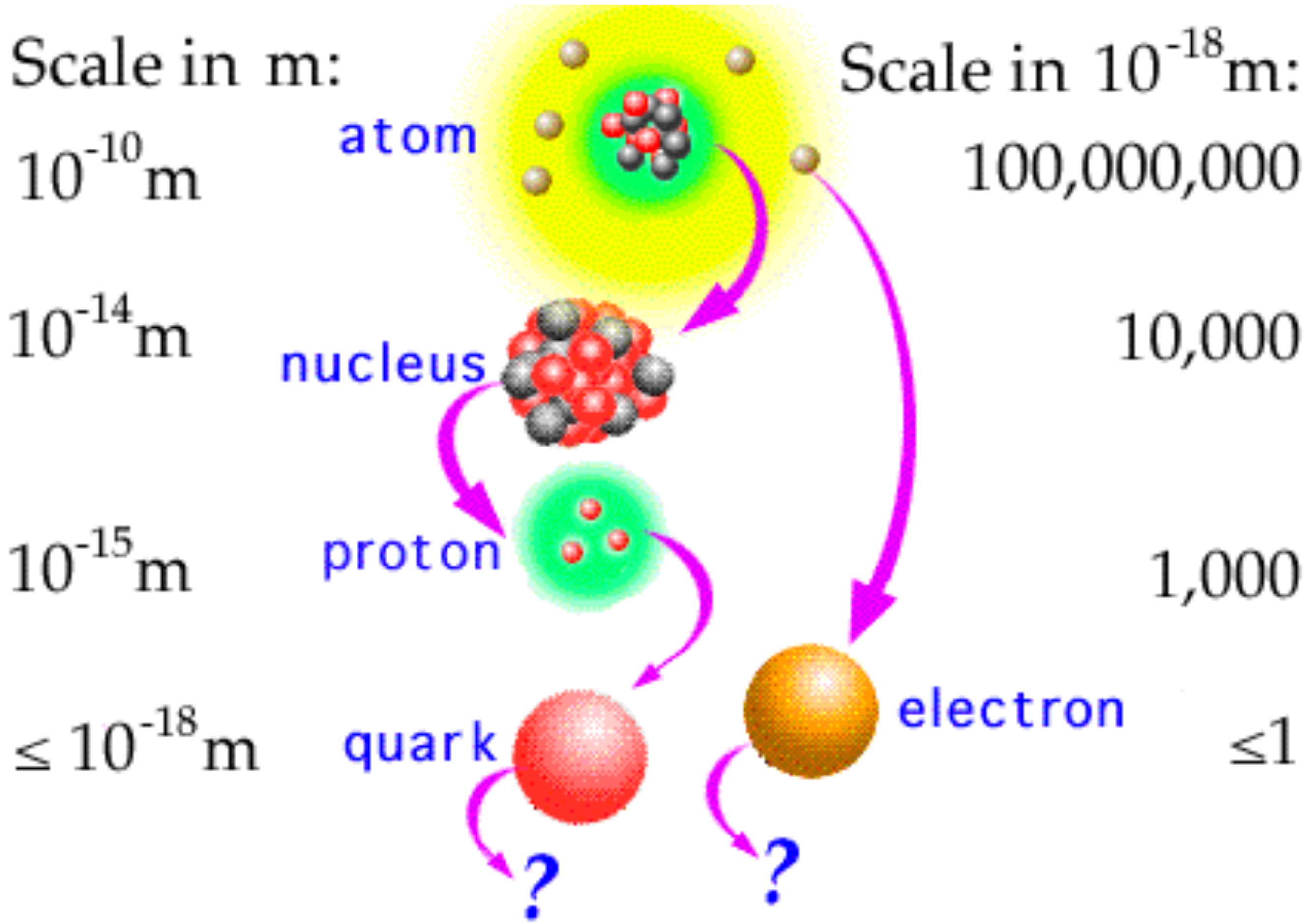
Currently Known Particles



Particle physics distances: Picture not to scale

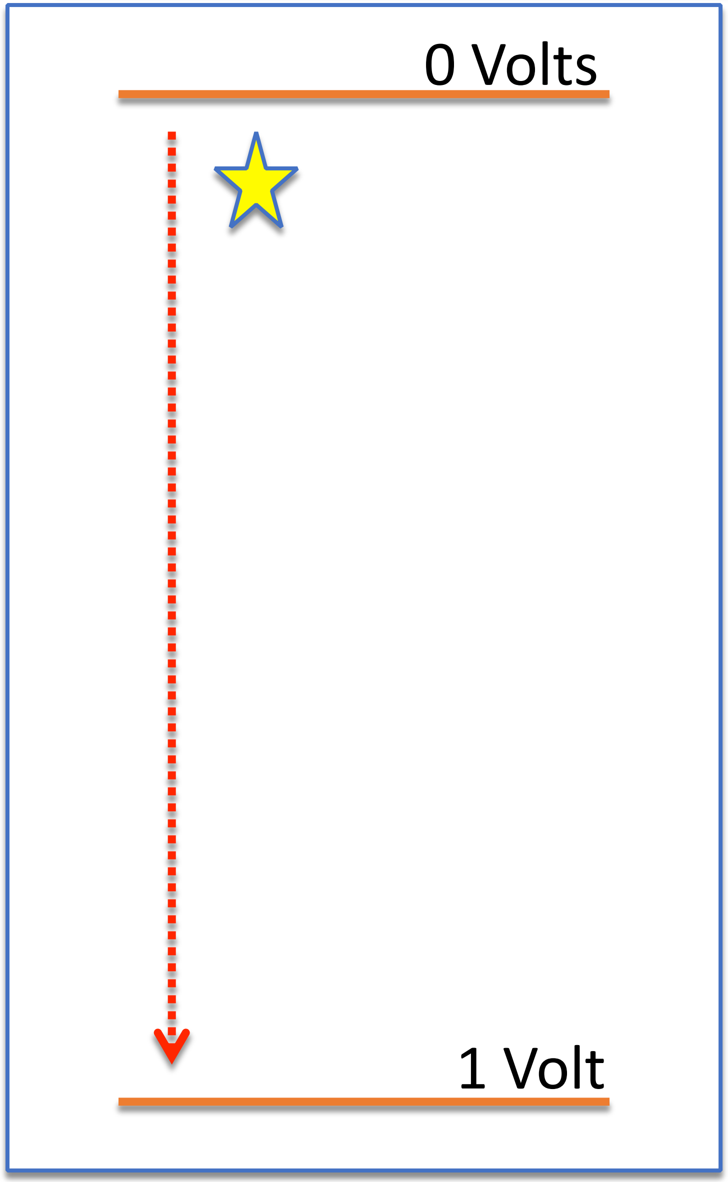


Small Distances



Since these are so tiny when it comes to meters/other standard units, we use "particle physics" units to describe these scales

High Energy Physics Units



Drop an electron through a 1 Volt potential and it will gain an energy of 1 electron-Volt (1 eV).

What matters here is the charge, not the particle.

$$E = qV$$

q= charge
V= voltage

$$1\text{eV} = 1.602 \times 10^{-19}\text{J}$$

Units!

- Distances : fm (femtometer or fermi) = 10^{-15} m = 10^{-13} cm
- Cross section : b (barn) = 10^{-28} m^2 = 10^{-24} cm^2, mb = 10^{-3} b
- Energy : 1 eV = energy required to raise the electric potential of an electron by one volt
  = 1.6×10^{-19} (C) × 1(V)
  = 1.6×10^{-19} (J, in S.I. unit)
  1 keV = 10^3 eV, 1 MeV = 10^6 eV, 1 GeV = 10^9 eV
- Mass : 1 MeV/c^2 = 1.78×10^{-30} (kg), (S.I. unit)
  At rest: $E=mc^2$, so $m=E/c^2$
- "Natural" units (particle physics) : $h = c = 1$ (for simplicity)
- Mass unit (nuclear physics) : 1 u = Mass(^{12}C)/12 = 931.5 MeV/c^2

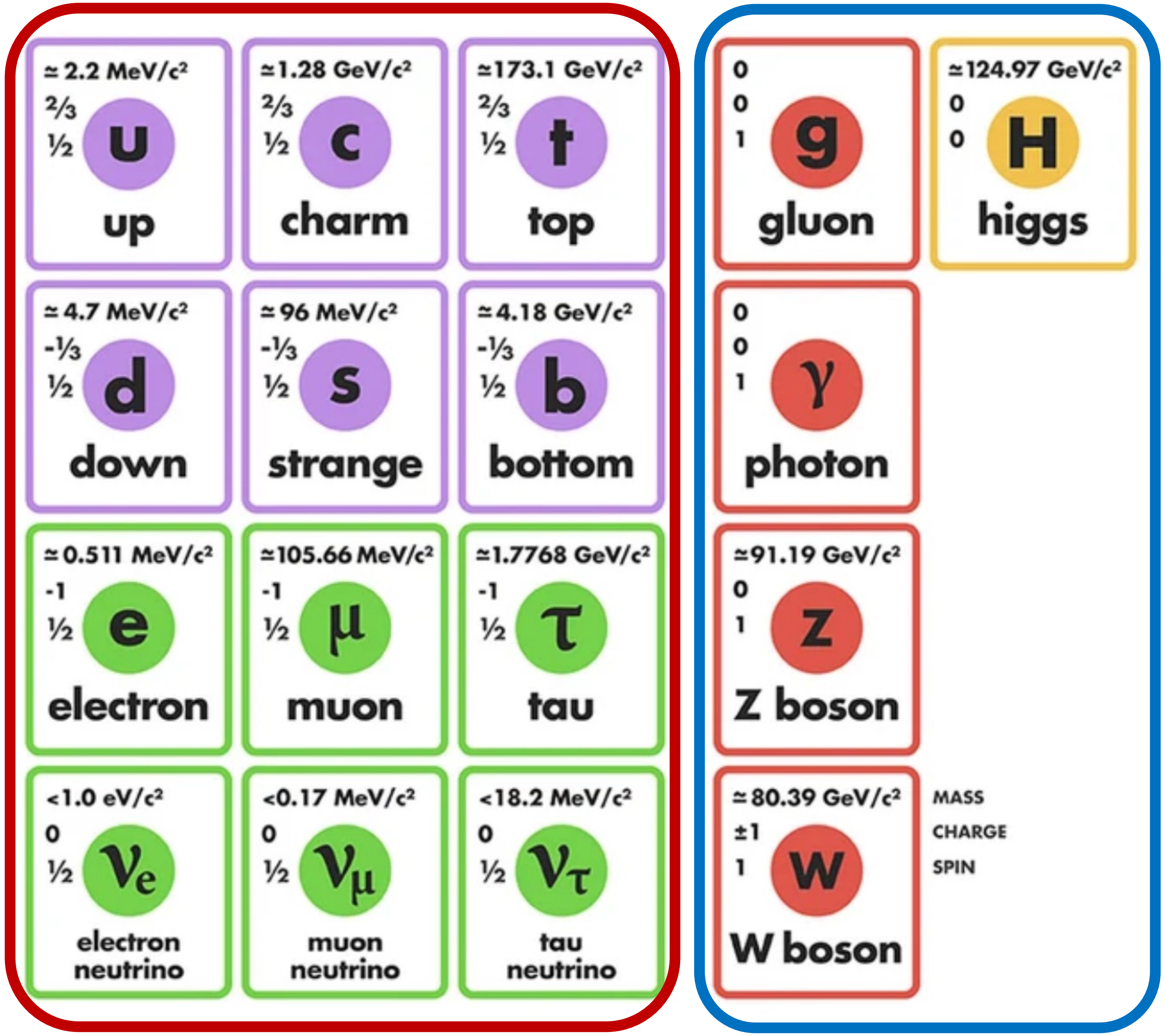
mili=10^{-3}
micro=10^{-6}
nano=10^{-9}
pico=10^{-12}
femto=10^{-15}

What are the particles?

Matter:
(Fermions)

Quarks

Leptons



Force Carriers

(Bosons)

Matter Constituents: Fermions

Leptons spin =1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_μ	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_τ	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

1st Generation

2nd Generation

3rd Generation

Leptons :

- Elementary particles in the standard model.
- All have spin = 1/2
- Do not interact through the strong force.
- charged leptons interact via EM force as well

Matter Constituents: Fermions

Quarks :

- fundamental constituents of matter, but always appear in bound states
- All have spin = 1/2
- Fractional electric charge
- Interact through strong, weak, and EM forces

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge	
u up	0.002	2/3	1st Generation
d down	0.005	–1/3	
c charm	1.3	2/3	2nd Generation
s strange	0.1	–1/3	
t top	173	2/3	3rd Generation
b bottom	4.2	–1/3	

Matter Constituents: Fermions

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, …

	Leptons spin =1/2			Quarks spin =1/2		
	Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
1st Generation	ν_e	$(0-2)\times10^{-9}$	0	**u** up	0.002	2/3
	e electron	0.000511	–1	**d** down	0.005	–1/3
2nd Generation	ν_μ	$(0.009-2)\times10^{-9}$	0	**c** charm	1.3	2/3
	μ muon	0.106	–1	**s** strange	0.1	–1/3
3rd Generation	ν_τ	$(0.05-2)\times10^{-9}$	0	**t** top	173	2/3
	τ tau	1.777	–1	**b** bottom	4.2	–1/3

Leptons :
Elementary particles
in the standard model.
Do not interact through the strong force.
All have spin = 1/2

Quarks :
Strongly interacting particles
fundamental constituents of matter,
but always appear in bound states
All have spin = ½, fractional electric charge

Force Carriers: Bosons

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

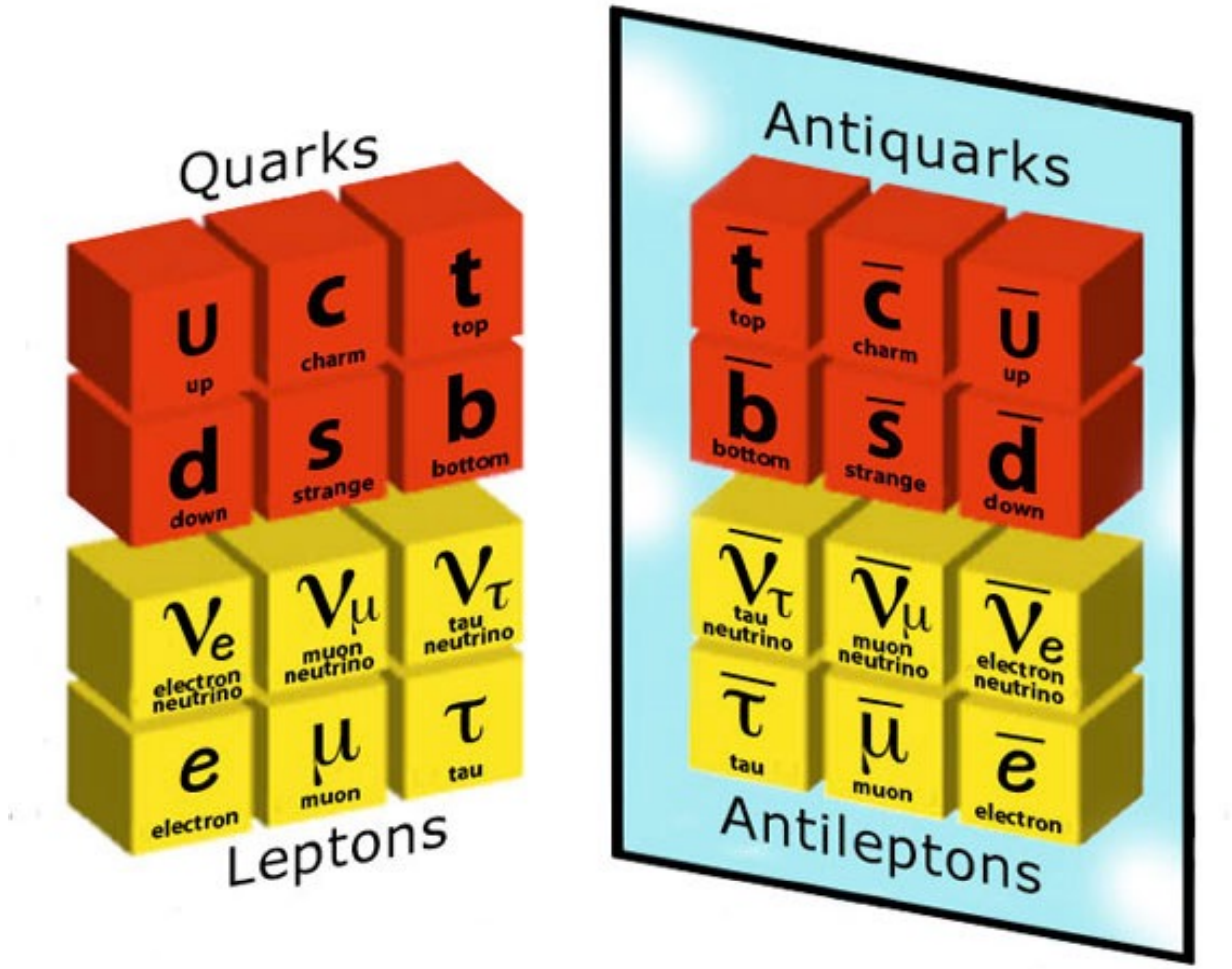
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

There is a little more to the story…

Not just one gluon

What else is there…?

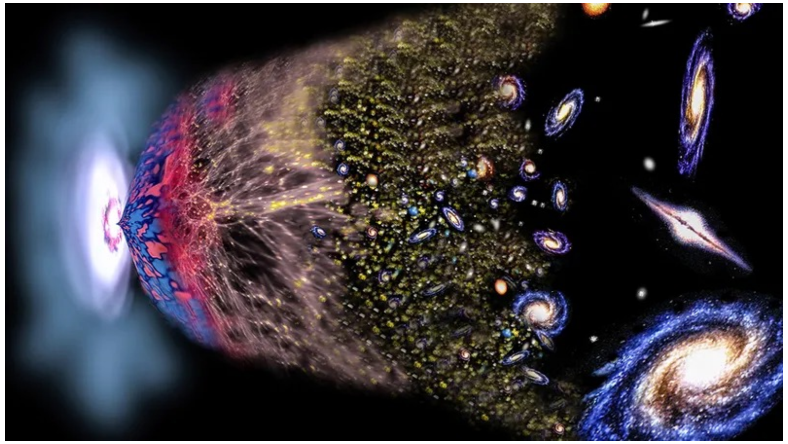
Anti-Particles



Anti-Particles: Big Picture Physics

Assume the universe began in an electrically neutral state.

To create matter all we need is energy (big bang):



Then, a neutral boson (eg. Z), can decay into a fermion/anti-fermion (matter/anti-matter) pairs)!

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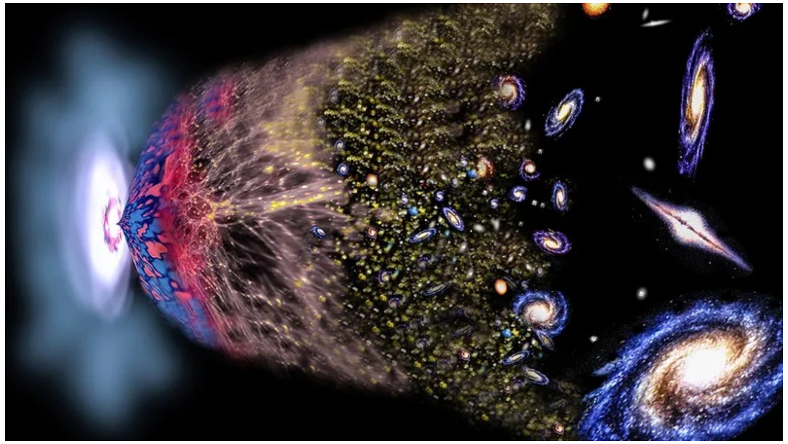


Then, a neutral boson (eg. Z), can decay into a fermion/anti-fermion (matter/anti-matter) pairs)!

BUT:

Q: Where did the neutral boson come from?

A matter particle is needed to emit it!

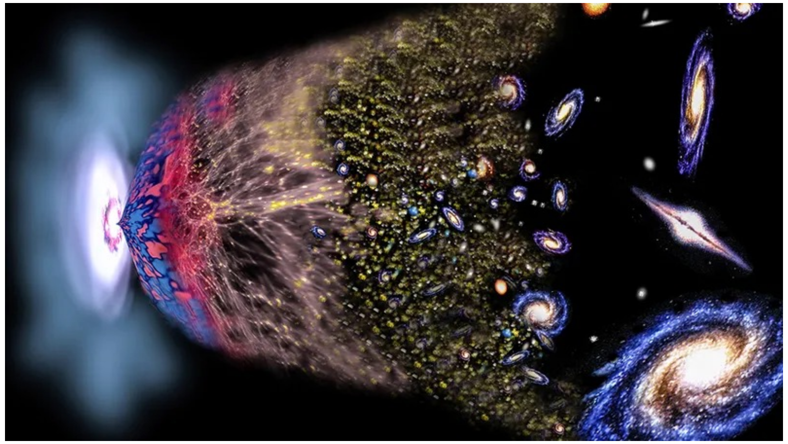
Q: Where did the matter particle come from?

Decay product of a neutral boson!

Anti-Particles: Big Picture Physics

Assume the universe began in an electrically neutral state.

To create matter all we need is energy (big bang):



Then, a neutral boson (eg. Z), can decay into a fermion/anti-fermion (matter/anti-matter) pairs)!

….So, let’s say that there was a fluctuation in the early universe that led to the boson

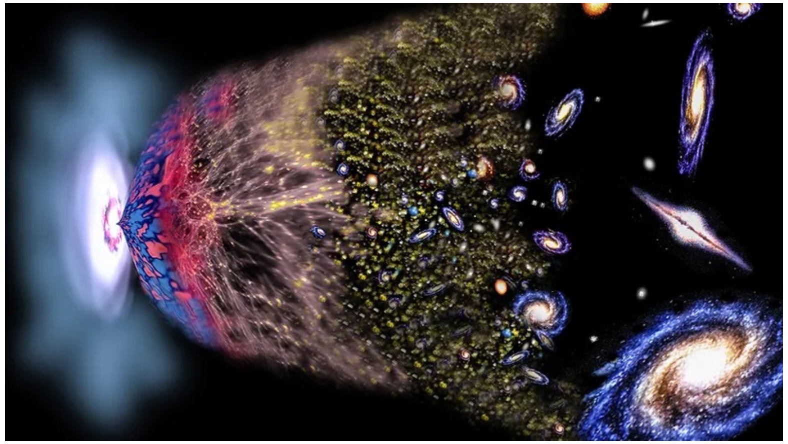
But, we are still left with a problem….

Anti-Particles: Big Picture Physics

Assume the universe began in an electrically neutral state.

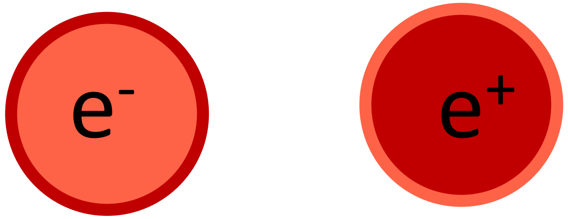
To create matter all we need is energy (big bang):

Then, a neutral boson (eg. Z), can decay into a fermion/anti-fermion (matter/anti-matter) pairs)!



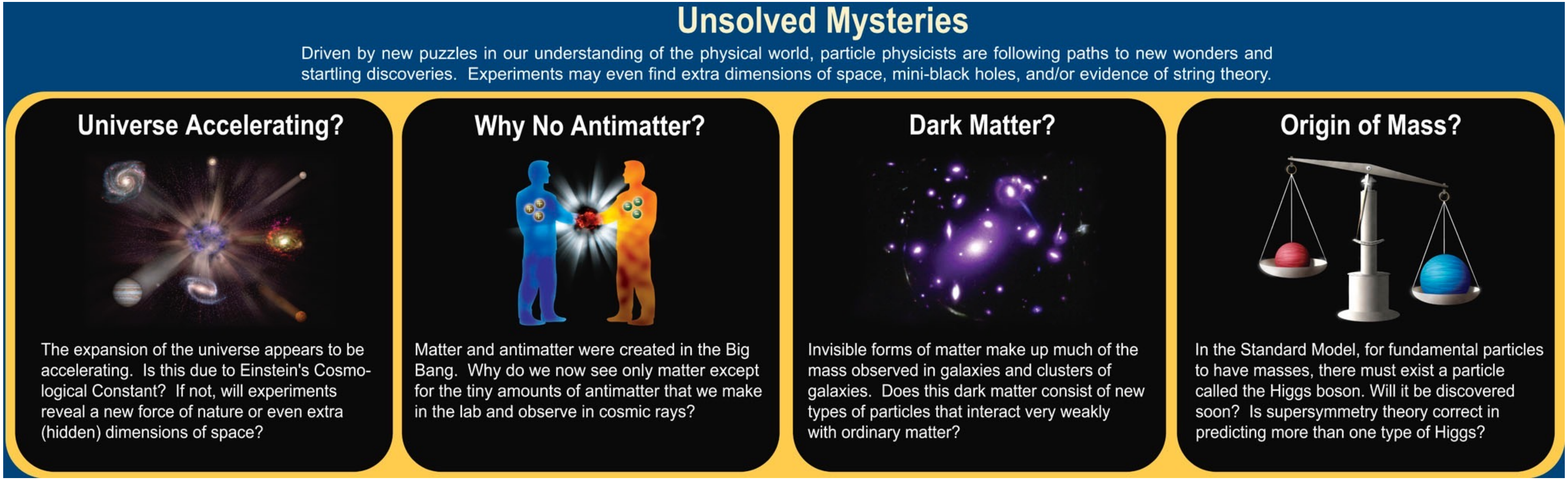
….And, let's say that there was a fluctuation in the early universe that led to the boson

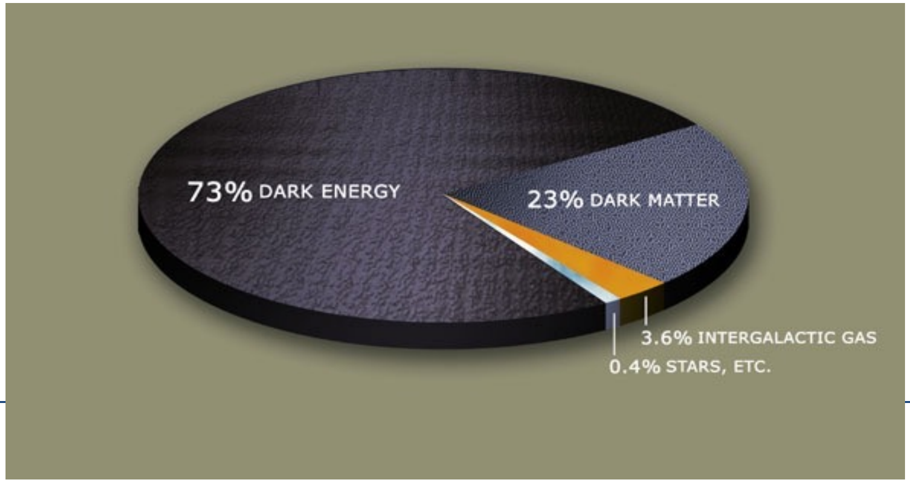
BUT: matter is created with antimatter for charge conservation.



1. Why didn't the anti-matter recombine back to neutral particles?
2. We are made of matter, so where did the anti-matter go?

Unsolved Mysteries





Anti-Particles

- Particles have near-identical anti-particle partners:
  - Differ only in sign of ***most*** quantum numbers
- **Example comparison:**

e^- vs. e^+

1. Mass: same
2. Spin: same
3. Magnitude of electric charge: same
4. Sign of electric charge: different

More on this when we talk about symmetries and solve the Dirac equation later in this class

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  - Differ only in sign of ***most*** quantum numbers
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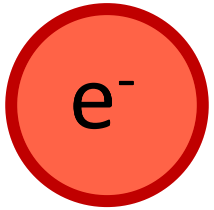
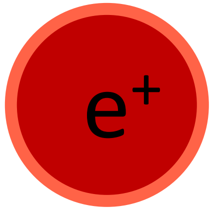


vs.



1. Mass: same
2. Spin: same
3. Magnitude of electric charge: same
4. Sign of electric charge: different

More on this when we talk about symmetries and solve the Dirac equation later in this class

- Neutral particles (photon, Z) are their own anti-particles

- But composite neutral particles don't follow this convention:
  - neutron = 2 down quarks + 1 up quark
  - anti-neutron = 2 anti-down quarks + 1 anti-up quark

Quantum Numbers: Leptons

Particle	Charge	Le	Lμ	Lτ
Electron	-1	+1	0	0
Muon	-1	0	+1	0
Tau	-1	0	0	+1
Electron Neutrino	0	+1	0	0
Muon Neutrino	0	0	+1	0
Tau Neutrino	0	0	0	+1

Anti-Particle	Charge	Le	Lμ	Lτ
Anti-Electron	+1	-1	0	0
Anti-Muon	+1	0	-1	0
Anti-Tau	+1	0	0	-1
Electron Anti-Neutrino	0	-1	0	0
Muon Anti-Neutrino	0	0	-1	0
Tau Anti-Neutrino	0	0	0	-1

"Lepton Number"

L_e= electron number

L_μ= muon number

$L\tau$ = tau number

Convention: anti-particle is the positively charged one

Quantum Numbers: Quarks

Particle	Charge	Baryon	U	D	C	S	T	B
Up	+2/3	+1/3	1	0	0	0	0	0
Down	-1/3	+1/3	0	-1	0	0	0	0
Charm	+2/3	+1/3	0	0	+1	0	0	0
Strange	-1/3	+1/3	0	0	0	-1	0	0
Top	+2/3	+1/3	0	0	0	0	+1	0
Bottom	-1/3	+1/3	0	0	0	0	0	-1

Anti-Particle	Charge	Baryon	U	D	C	S	T	B
Anti-Up	-2/3	-1/3	-1	0	0	0	0	0
Anti-Down	+1/3	-1/3	0	1	0	0	0	0
Anti-Charm	-2/3	-1/3	0	0	-1	0	0	0
Anti-Strange	+1/3	-1/3	0	0	0	+1	0	0
Anti-Top	-2/3	-1/3	0	0	0	0	-1	0
Anti-Bottom	+1/3	-1/3	0	0	0	0	0	+1

C = charm
S = strange
T = Top
B = Bottom

Other Quantum Numbers

- **Spin:**
  - ½ for fermions (quarks and leptons)
  - 1 for photon, W, Z,
  - 0 for Higgs
- **T_3 = weak isospin**
  - Photon and Z boson are a mixture of $T_3 = 1$ and $T_3 = 0$
  - Higgs interactions have undefined weak isospin T_3
  - -1/2 for charged leptons, +1/2 for neutrinos, flipped for anti-particles
  - quarks: +1/2 for u, c, t and -1/2 for d, s, b. Flipped for anti-particles
- **I_3= strong isospin**
  - Undefined for W+/-: couple to quarks in different generations
  - Other bosons have strong isospin $I_3 = 0$
  - 0 for leptons

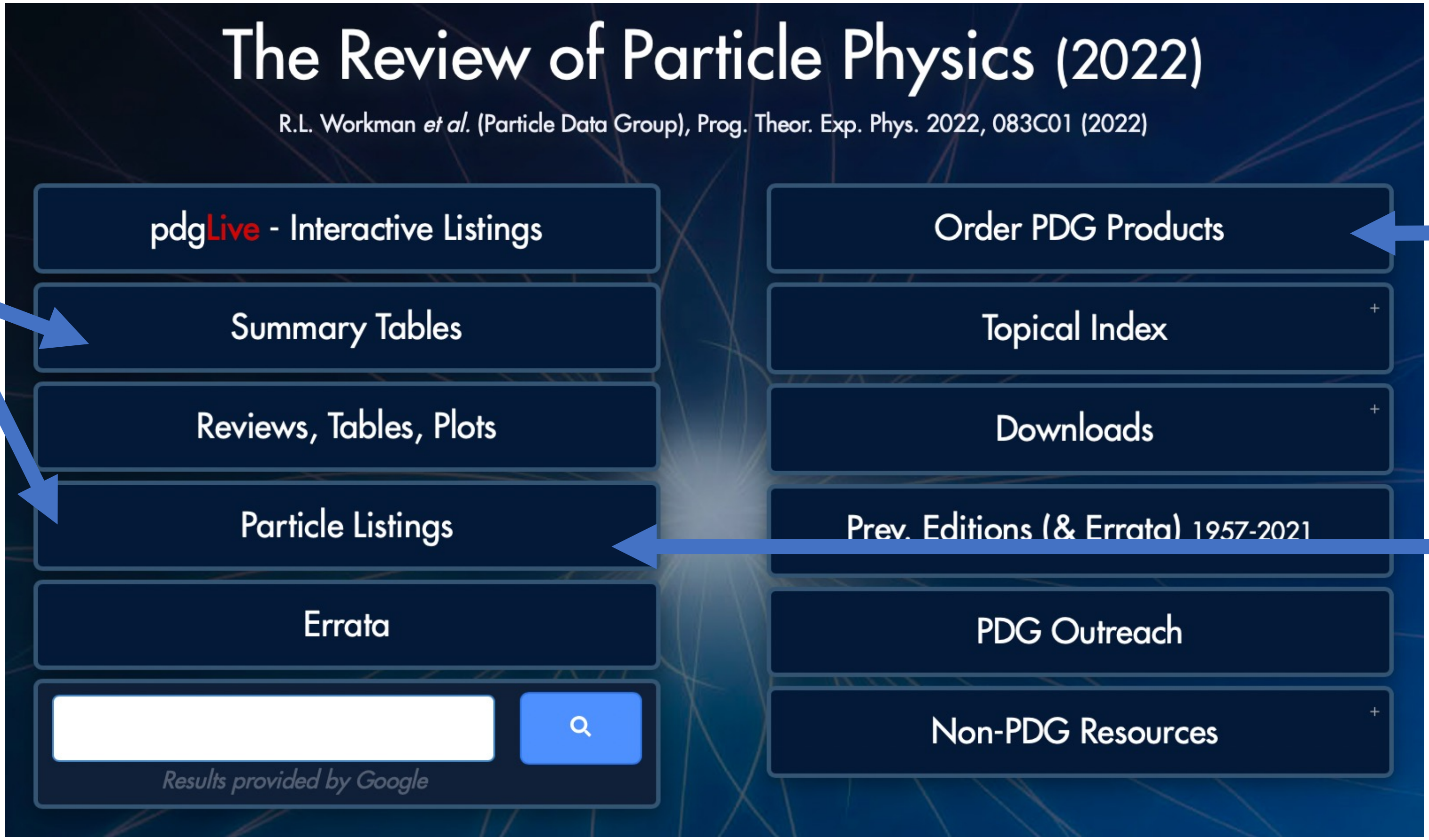
We will discuss these more when we get to "symmetries", for now, just know they exist

Useful Resource: Particle Data Book

Particle Physics:

http://pdg.lbl.gov

Particle data (mass, charge, etc)



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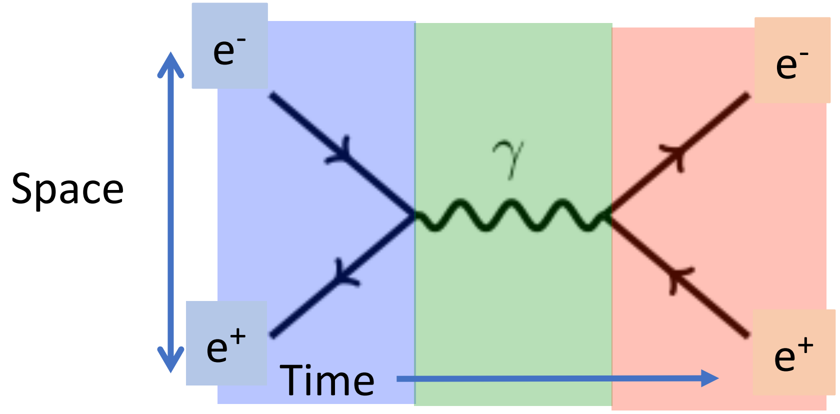
(Or it's all available online here)

Review articles and Tools/Formulas

Quantum Number Examples

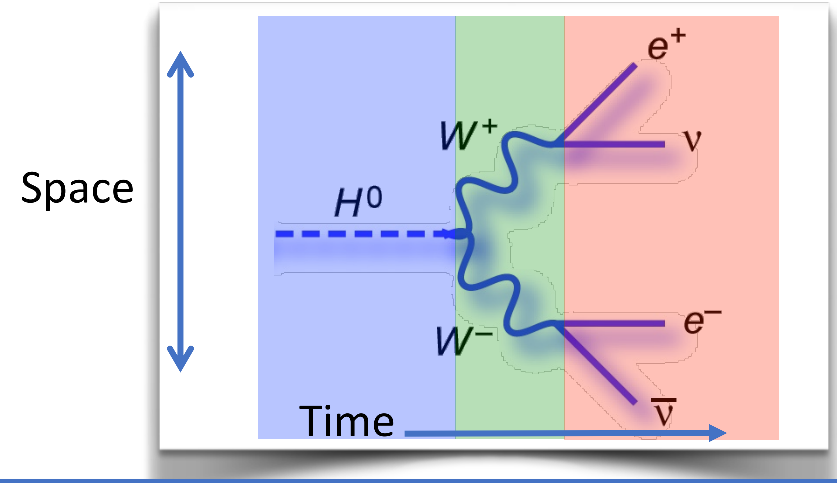


<u>Initial State (e^+, e^-):</u>
Electron Number: **$L_e = -1 + 1 = 0$**
Total charge: **$Q = -1 + 1 = 0$**

<u>Propagator (photon):</u> **$L_e = 0$, $Q=0$**

<u>Final State (e^+, e^-):</u> **$L_e = 0$, $Q=0$**

Quantum Number Examples



Initial State (Higgs boson):

All lepton numbers: **$L_{e/\mu/\tau} = 0$** Total charge: **$Q = 0$**

Propagator (W^+,W^-): **$L_{e/\mu/\tau} = 0$** **$Q = +1 -1 = 0$**

Final State ($e^+\nu$, $e^-\bar{\nu}$): **$L_e = -1 + 1 + 1 - 1 = 0$** **$Q = + 1 - 1 = 0$**

Quarks, Gluons & Color

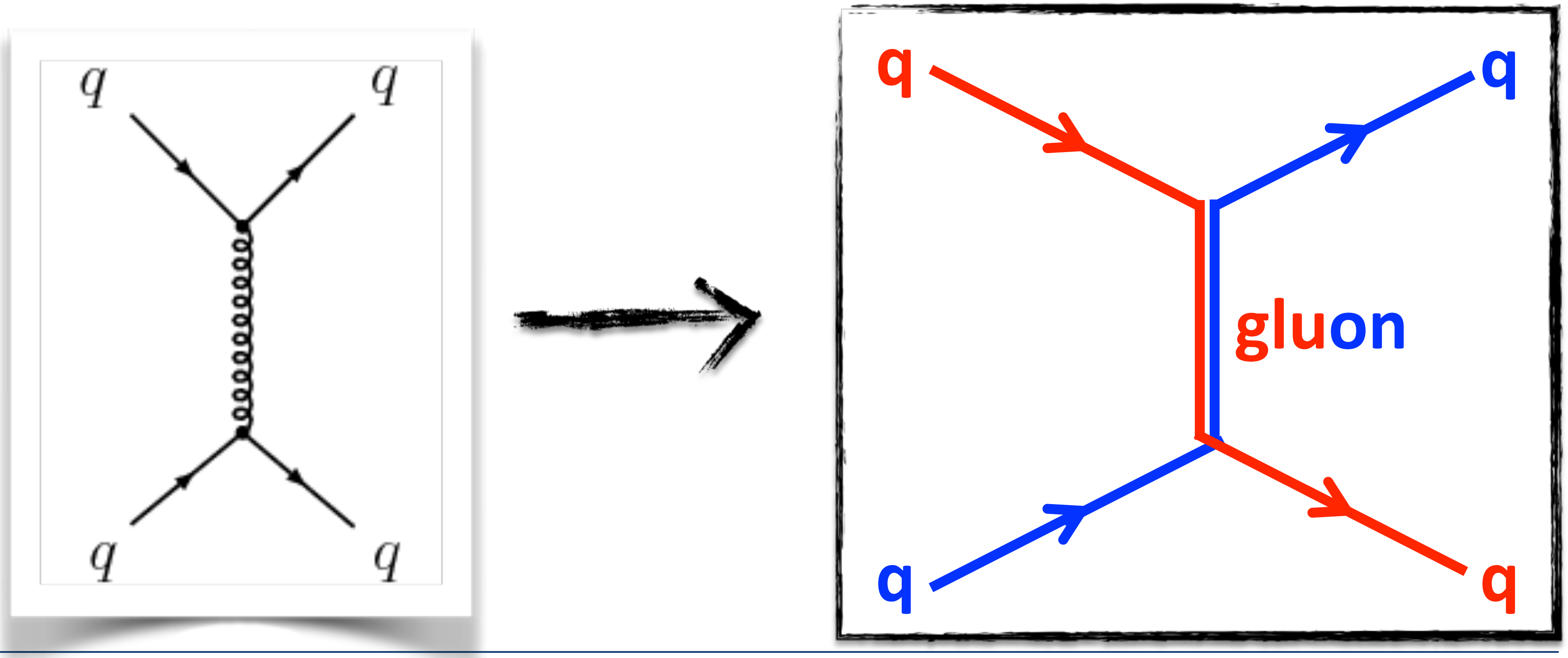
A very important quantum number for quarks & gluons is COLOR.

- Plays the role of electric charge in quark/gluon interactions.

Unlike the single electric charge quantum, there are three colors

- Arbitrarily called RED, GREEN, & BLUE.
- The name has **nothing** to do with real color.

Red	Green	Blue



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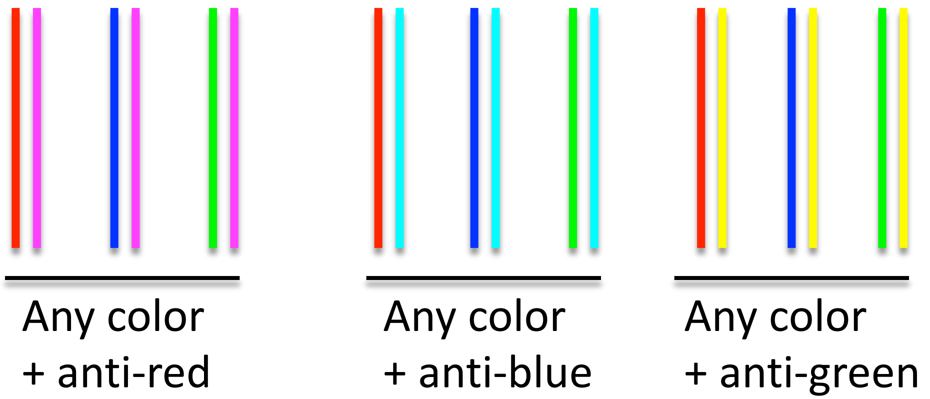
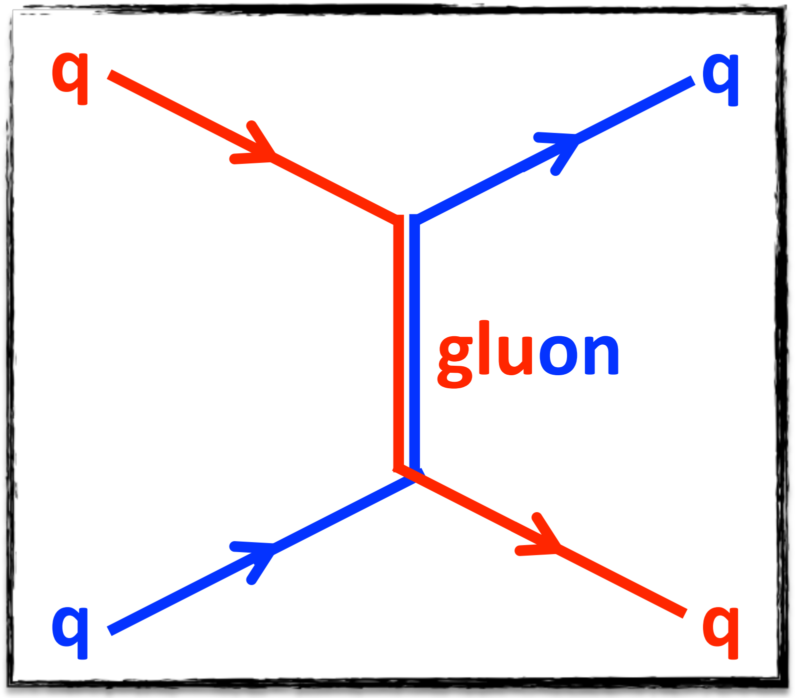
So, it turns out that gluons themselves have color quanta

- They carry two colors at once!
- 9 possible pairings, but only 8 exist (more on this when we talk about QCD)





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Red	Green	Blue

A further complication is that bare color is not observed in nature

- Every particle must exist as a "color singlet" (*or be purely colorless*)

Color	Red	Green	Blue
Anti-Color	Anti-Red	Anti-Green	Anti-Blue

Mesons: 2-quark bound states

Red	Green	Blue
Anti-Red	Anti-Green	Anti-Blue

Hadrons: 3-quark bound states

Red	Green	Blue
Anti-Red	Anti-Green	Anti-Blue

Quarks, Gluons & Color

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Color	Red	Green	Blue
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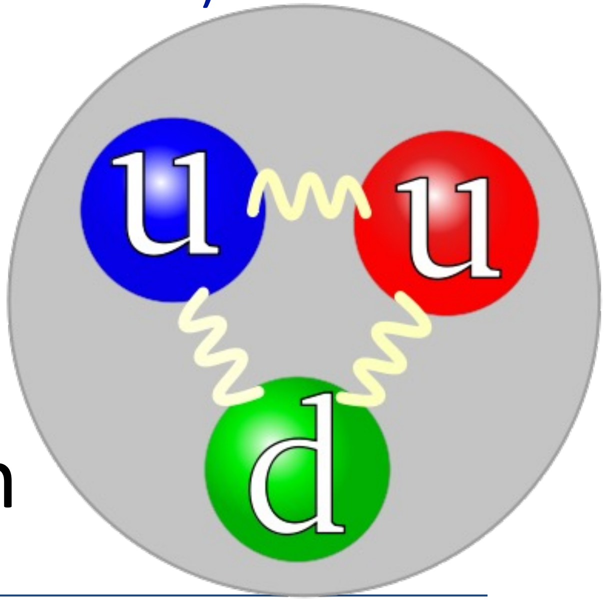
Proton



Mesons (not a complete list!)

Mesons $q\bar{q}$ Mesons are bosonic hadrons There are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Baryons (not a complete list!)

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. There are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Particle Decays

Question: With so many particles out there, why are we made out of ONLY up/down quarks and electrons??

Two-Part Answer:

1 - Particles can decay into other, lighter particles provided…

2- Energy and momentum conservation are satisfied (*also several other conserved quantum numbers*)

Particle Decay Example

Top Quark, M=175 GeV

Bottom Quark
M=5 GeV

W boson
M=80 GeV

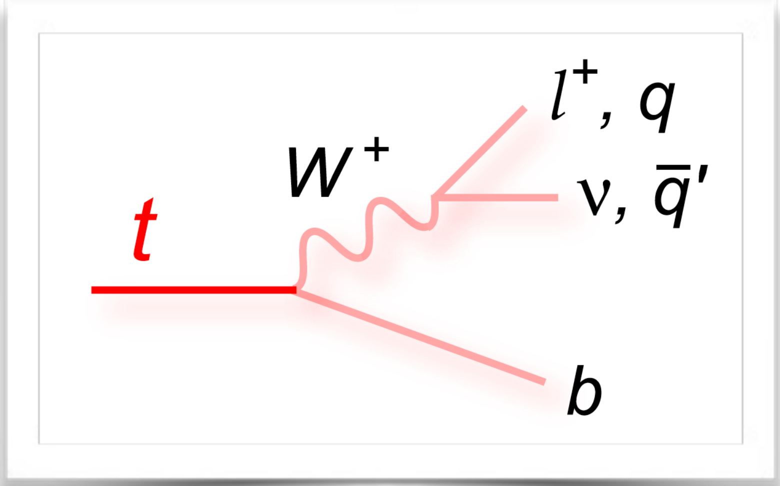
$E^2 = m^2 + p^2$

+ 90 GeV Energy
(175-80-5=90)

Electron
M=0.5 MeV

Neutrino
M<0.5 eV

+ 79.9 GeV Energy
(80-ε=79.9995)



Ultimately, 169.9 GeV of energy is liberated and the final state particles can no longer decay because there are no lighter particles to decay into.

> Caution: Many quantities are conserved, not just energy! Charge, color, baryon number, lepton number, etc. Don't be fooled by this simple example.

Also: the bottom quark can decay, but let's worry about that detail later in the course!

Quantum Numbers: Bosons

Particle	Charge	Spin	T_3	I_3
Photon	0	1	0 or 1	0
W^+	+1	1	+1	undefined
W^-	-1	1	-1	undefined
Z^0	0	1	0 or 1	0
Gluon	0	1	0	0
Higgs	0	0	~0	0

- T_3 = weak isospin
  - Photon and Z boson are a mixture of $T_3 = 1$ and $T_3 = 0$
  - Higgs interactions have undefined weak isospin T_3
- I_3= strong isospin
  - Undefined for W+/-: couple to quarks in different generations
  - Other bosons have strong isospin $I_3 = 0$

Quantum Numbers: Leptons

Particle	Charge	Spin	Le	Lμ	Lτ	T_3
Electron	-1	½	+1	0	0	-½
Muon	-1	½	0	+1	0	-½
Tau	-1	½	0	0	+1	-½
Electron Neutrino	0	½	+1	0	0	+½
Muon Neutrino	0	½	0	+1	0	+½
Tau Neutrino	0	½	0	0	+1	+½

Anti-Particle	Charge	Spin	Le	Lμ	Lτ	T_3
Anti-Electron	+1	½	-1	0	0	+½
Anti-Muon	+1	½	0	-1	0	+½
Anti-Tau	+1	½	0	0	-1	+½
Electron Anti-Neutrino	0	½	-1	0	0	-½
Muon Anti-Neutrino	0	½	0	-1	0	-½
Tau Anti-Neutrino	0	½	0	0	-1	-½

Note that due to convention the anti-particle is the positively charged one

Quantum Numbers: Quarks

Particle	Charge	Spin	Baryon	C	S	Top	Be	T_3	I_3
Up	+2/3	½	+1/3	0	0	0	0	+½	+½
Down	-1/3	½	+1/3	0	0	0	0	-½	-½
Charm	+2/3	½	+1/3	+1	0	0	0	+½	***0***
Strange	-1/3	½	+1/3	0	-1	0	0	-½	***0***
Top	+2/3	½	+1/3	0	0	+1	0	+½	***0***
Bottom	-1/3	½	+1/3	0	0	0	-1	-½	***0***

Anti-Particle	Charge	Spin	Baryon	C	S	Top	Be	T_3	I_3
Anti-Up	-2/3	½	-1/3	0	0	0	0	-½	-½
Anti-Down	+1/3	½	-1/3	0	0	0	0	+½	+½
Anti-Charm	-2/3	½	-1/3	-1	0	0	0	-½	***0***
Anti-Strange	+1/3	½	-1/3	0	+1	0	0	+½	***0***
Anti-Top	-2/3	½	-1/3	0	0	-1	0	-½	***0***
Anti-Bottom	+1/3	½	-1/3	0	0	0	+1	+½	***0***