Imaging fundamental processes

Understanding the Visible Universe
DESY Zeuthen Jan. 18, 2019

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1. **Setting the Stage**
2. **The road to fundamental particles**
3. **The players and rules in the game of the Standard Model**
4. **Exploring the micro world: assembling the Standard Model**
5. **The realm of gravity**
6. **Prospects and conundrums**

I. Introduction: Setting the Stage

- The Fundamental laws of physics emerge from the very smallest and very largest scales in the observable universe.

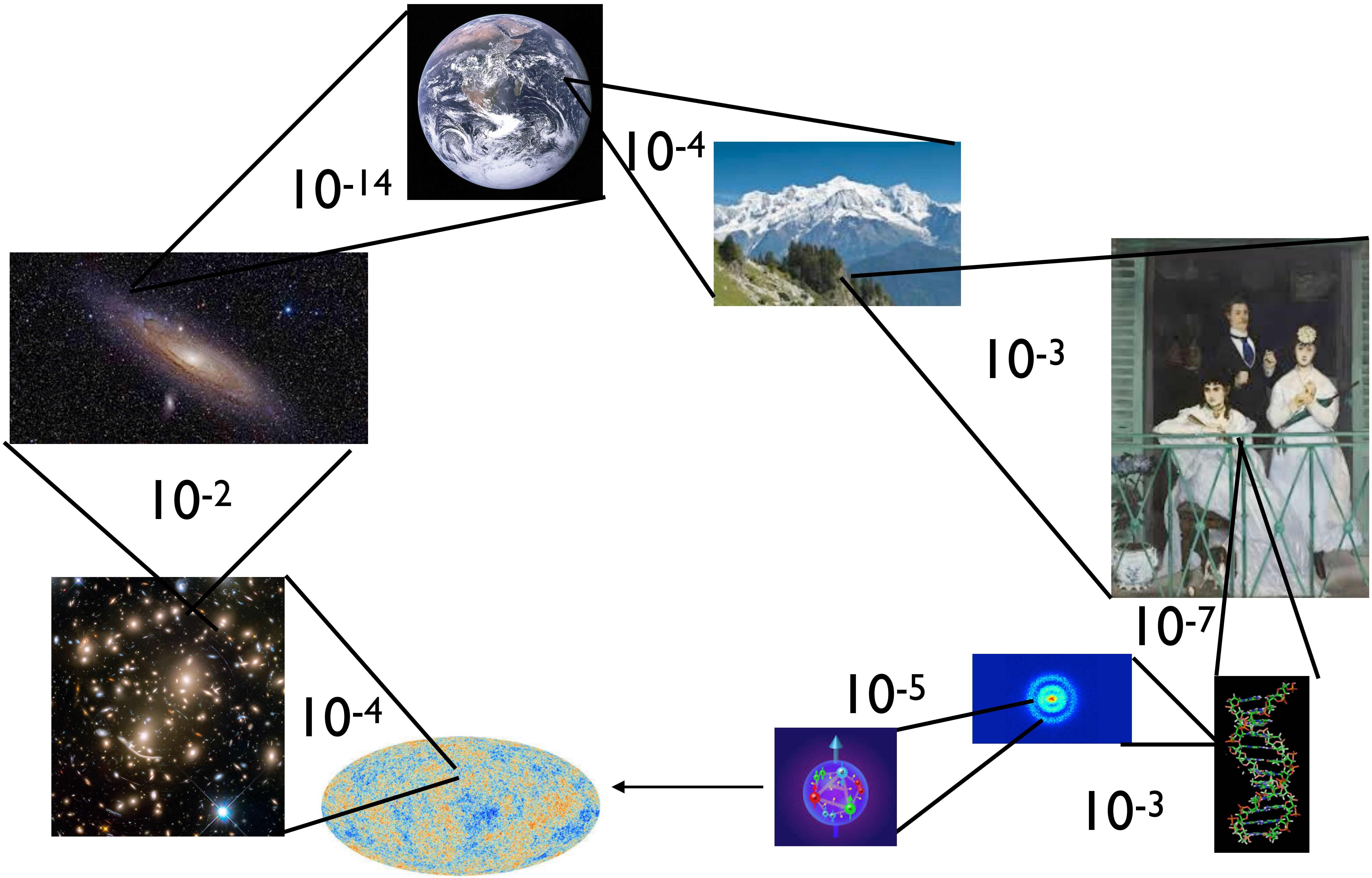
- These laws are mathematical in nature, but are amenable to visualization.

What can be seen

The visible universe	10^{27} meters
Galaxy clusters	10^{23}
Galaxies	10^{21}
Stars	10^{9}
Earth	10^{7}
Human	1
Atoms	10^{-10}
Nuclei	10^{-15}
The micro frontier	10^{-19}

At each scale, identifiable objects and phenomena.
In all we can see, matter follows
the same laws of persistence and transformation.

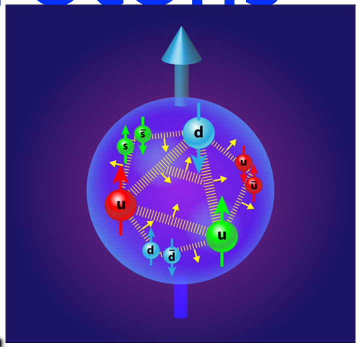
Comparing some "scales" of what we see



The broad story. Once upon a time . . . the "Big Bang"

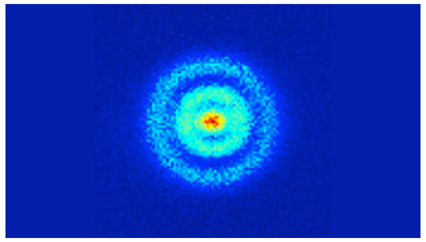
The universe appears, very hot and expanding.

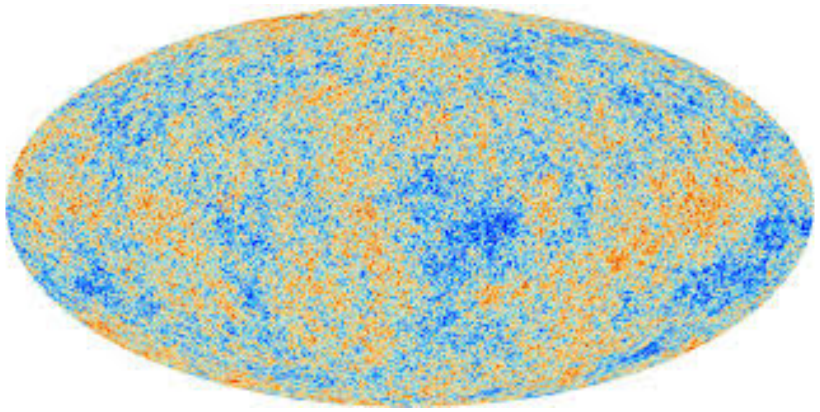
After a short time, it is composed of photons, protons and other stable particles.



In a few minutes, light nuclei appear.

At 300,000 years, electrons bind to atoms.

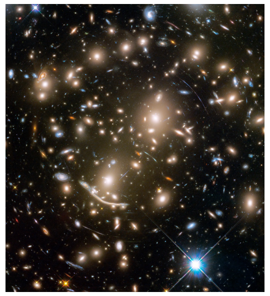




The universe was then very uniform, with only tiny inhomogeneities (1 in 100,000). Even now we see the light that's left over.

Over billions of years, gravitational attraction magnifies these tiny variations into stars & galaxies

and galaxy clusters.



Meanwhile, stars create heavier elements.

Life appears.

And eventually, humanity has a look .

What are things made of?
What holds them together?
What makes them change?

How to proceed? Here's a suggestion from Newton, "Query 31" of *Optics:*

" . . . we may proceed from Compounds to Ingredients, and from Motions to the Forces producing them; and in general, from Effects to their Causes, and from particular Causes to more general ones, till the Argument end in the most general."

In a sense, this says it all, although the meanings of some words have changed since Newton's time.

We want a "theory" — a systematic explanation on which we may base predictions of how matter and energy evolve under conditions accessible to human ingenuity, and of what deeper examinations of the far universe will reveal.

A turning point in the history of knowledge was Heinrich Hertz's creation of conditions under which electromagnetic radiation could be produced and detected.

This was in direct response to an existing theory, the synthesis of a century of thought and experiment by James Clerk Maxwell.

Hertz on “Maxwell Theory” (1892):

``To the question, `What is Maxwell's theory?' I know of no shorter or more definite answer than the following: Maxwell's theory is Maxwell's system of equations. "

This talk will present one way of visualizing:

- What our current best equations say,
- how that knowledge came to be,
- how it illuminates the history of the universe,
- and why it must be incomplete.

Summary (part I)

- The Fundamental laws of physics emerge from the very smallest and very largest scales in the observable universe.

- These laws are mathematical in nature, but are amenable to visualization.

I. Introduction: setting the stage

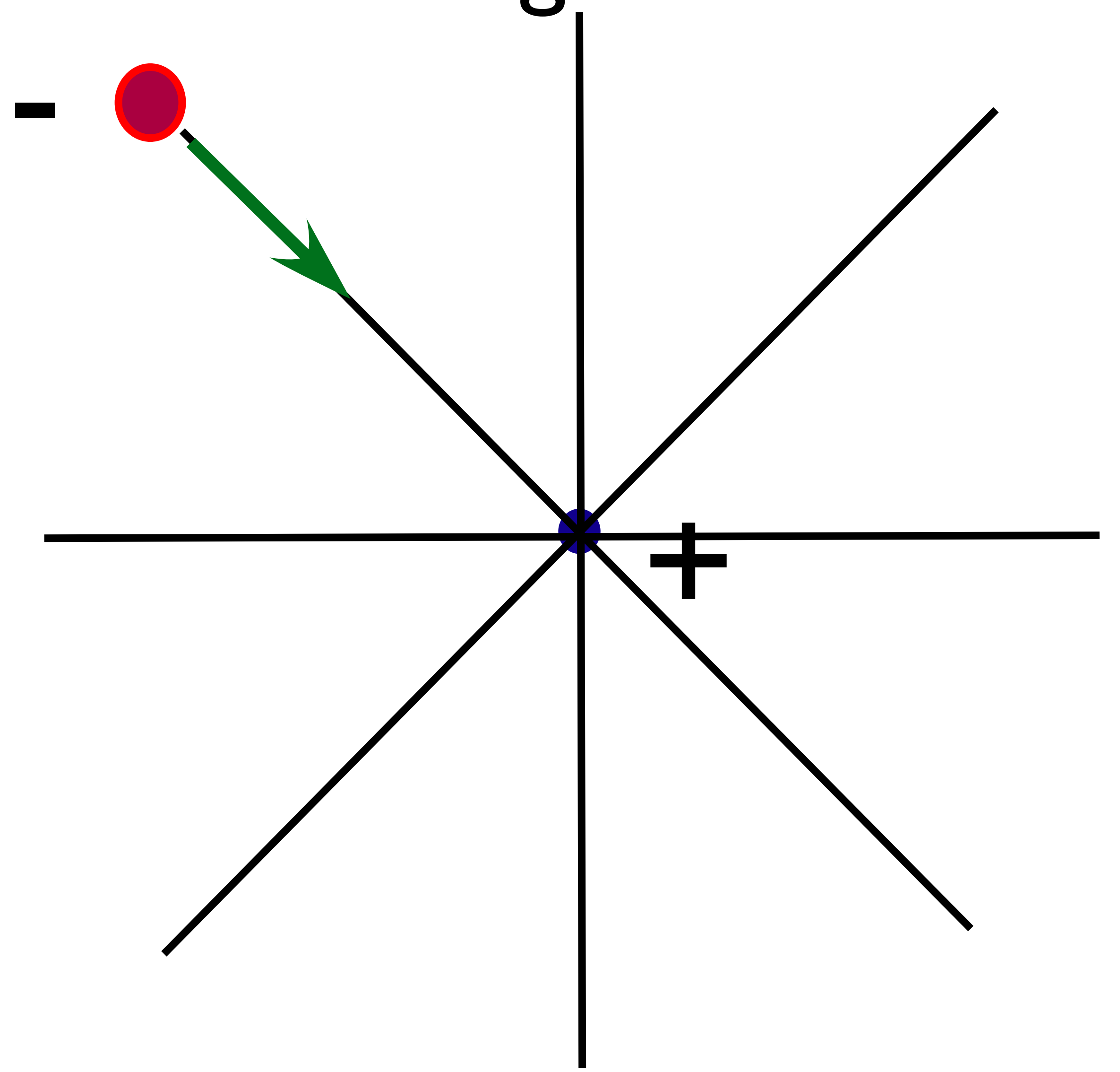
II. THE ROAD TO FUNDAMENTAL PARTICLES

- The 19th Century saw the unification of electricity and magnetism (E&M), and the realization that light is a wave of these fields together.
- E&M was the first gauge field theory, characterized by transverse waves and charge conservation.
- The density of photons is proportional to the square of the E&M wave amplitude.
- Light and electrons can both be described as particles with wave-like properties, but light is created and absorbed “at a point”

The 19th C, in brief

- From John Dalton, 1810: multiple proportions (like H_2O)
- From Amedeo Avogadro, 1811: a hypothesis, equal pressure in two gases implies equal NUMBERS (!) of molecules (but the number is unknown).
- Michael Faraday: mass/charge for hydrogen ion.
- Lodschmidt, 1865: first estimate of Avogadro's number.
- J.J.Thompson, 1897: discovery of the electron
- And from Maxwell, 1865:
- light and electromagnetism . . . starting with "+ & -".

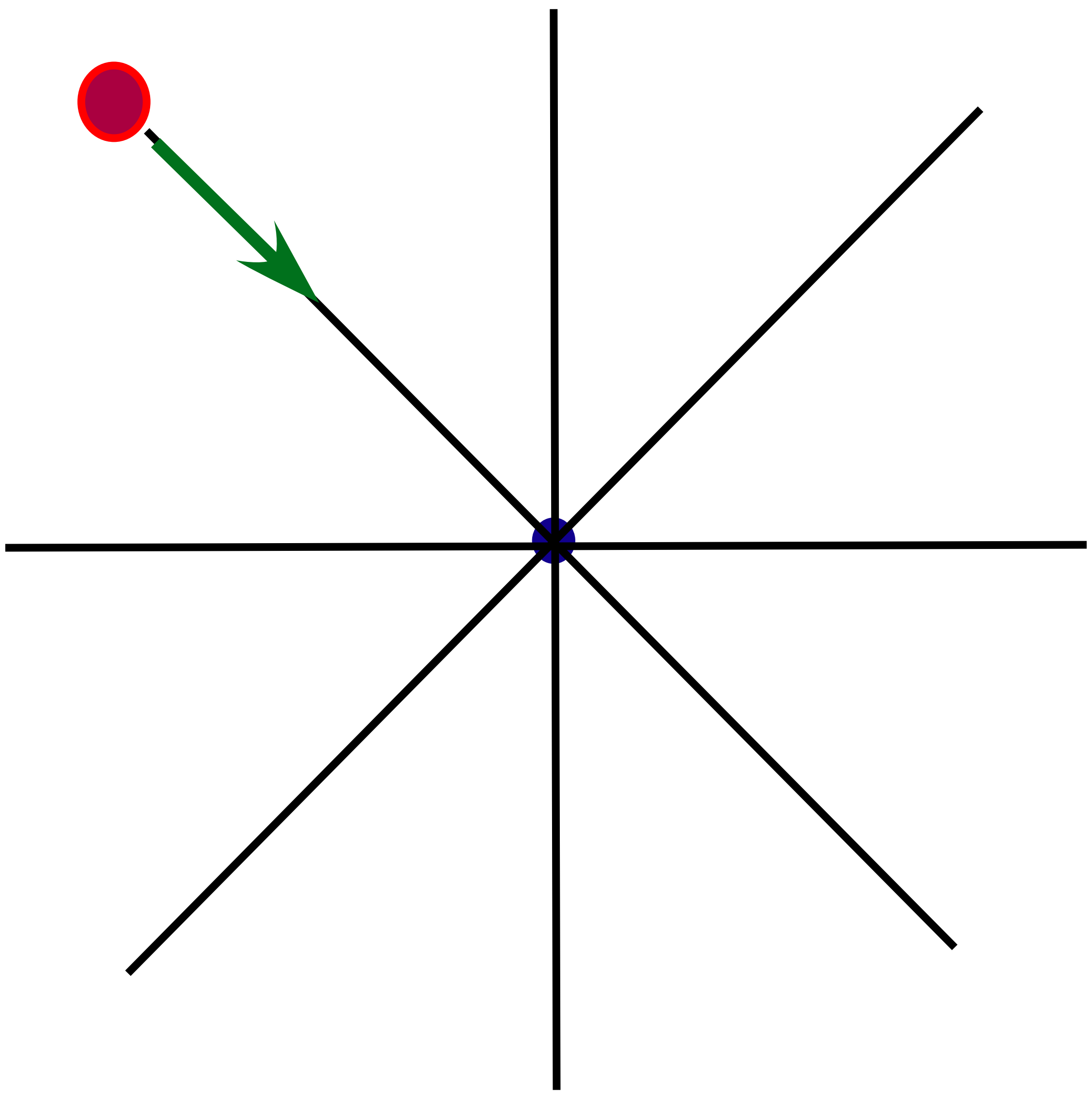
Lines of force around an immovable plus charge guide nearby minus charges.

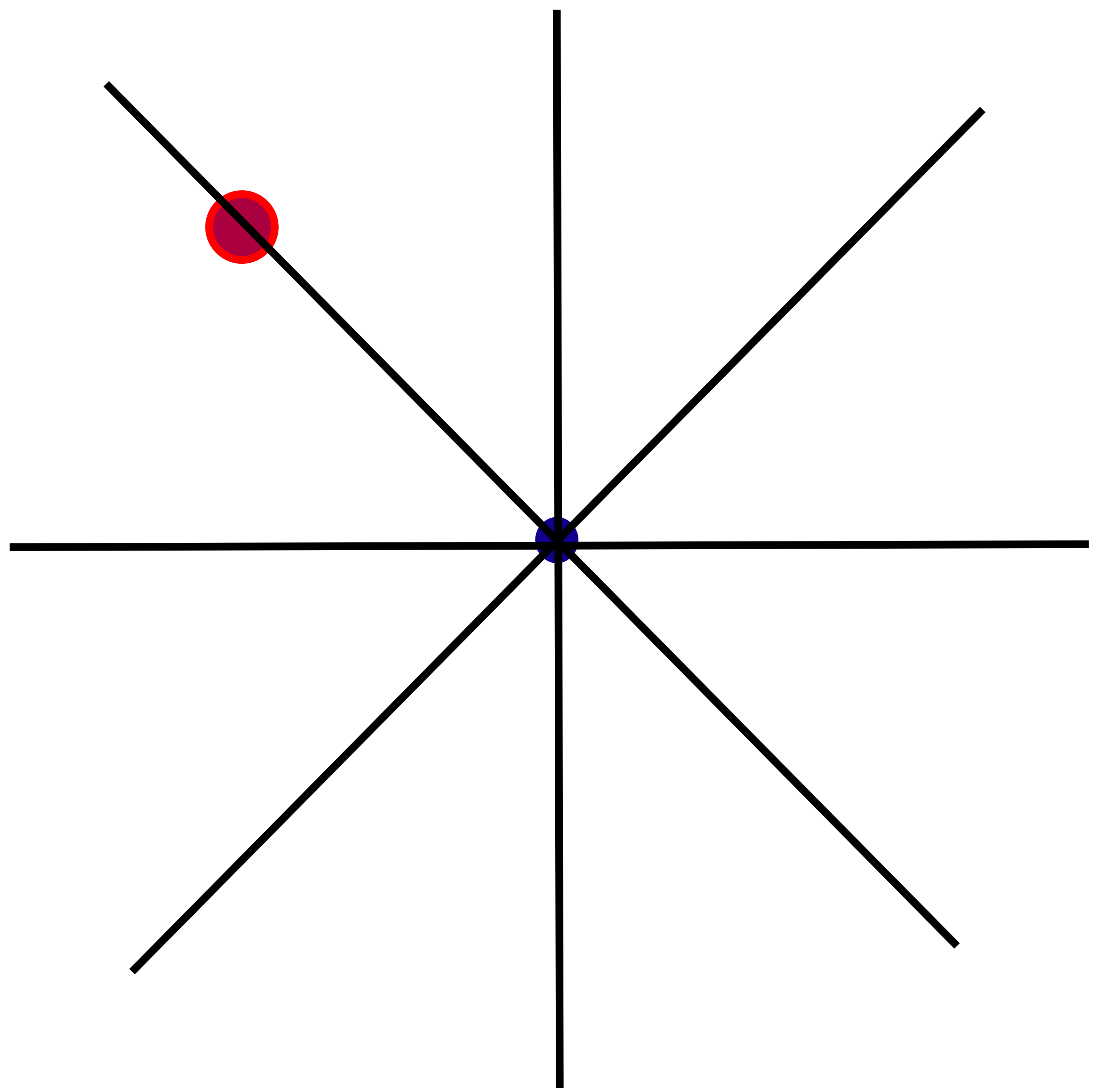


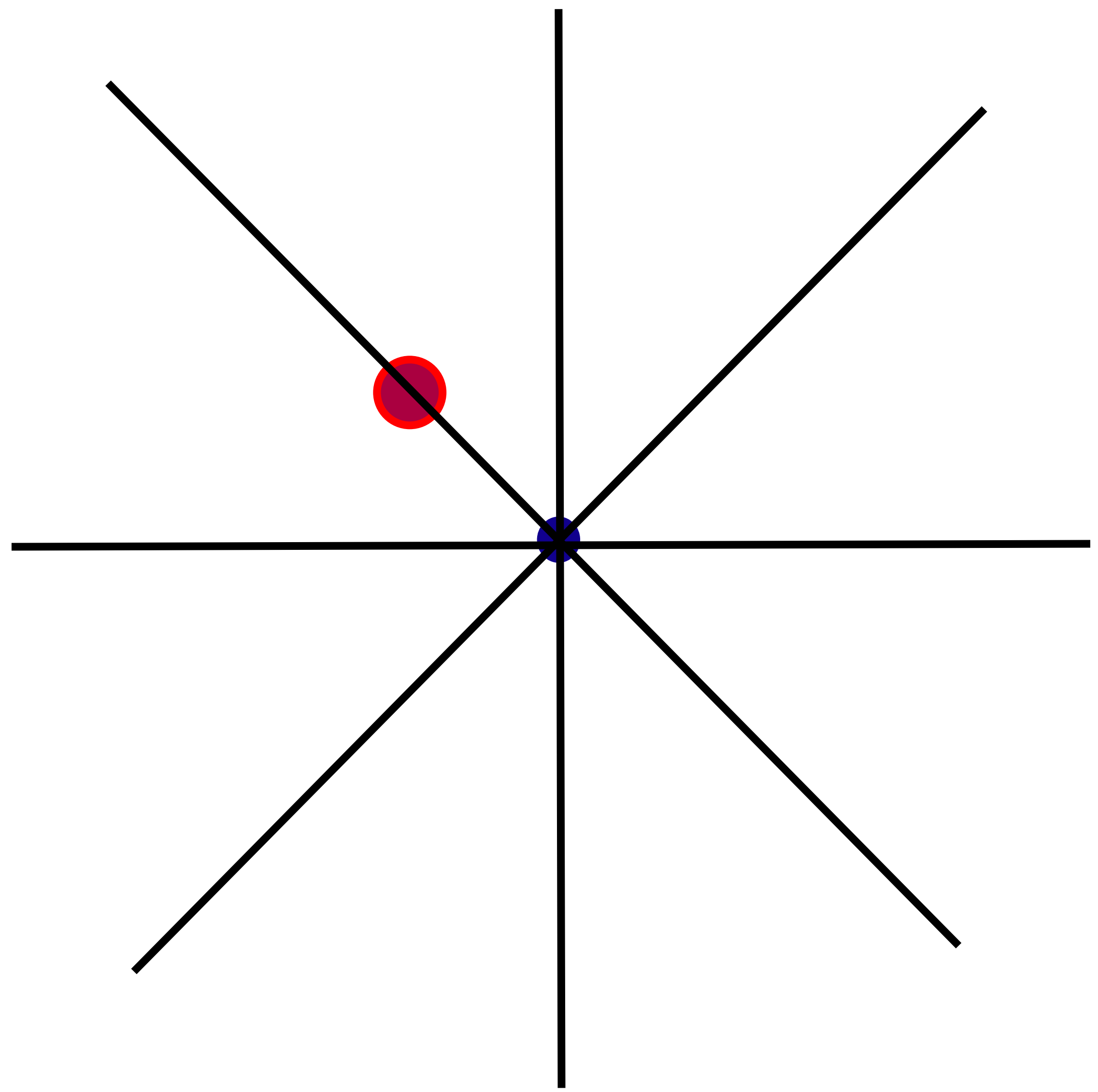
Michael Faraday, William Thomson, 1830--1860

Something seems to be in between.

It's not "action at a distance".





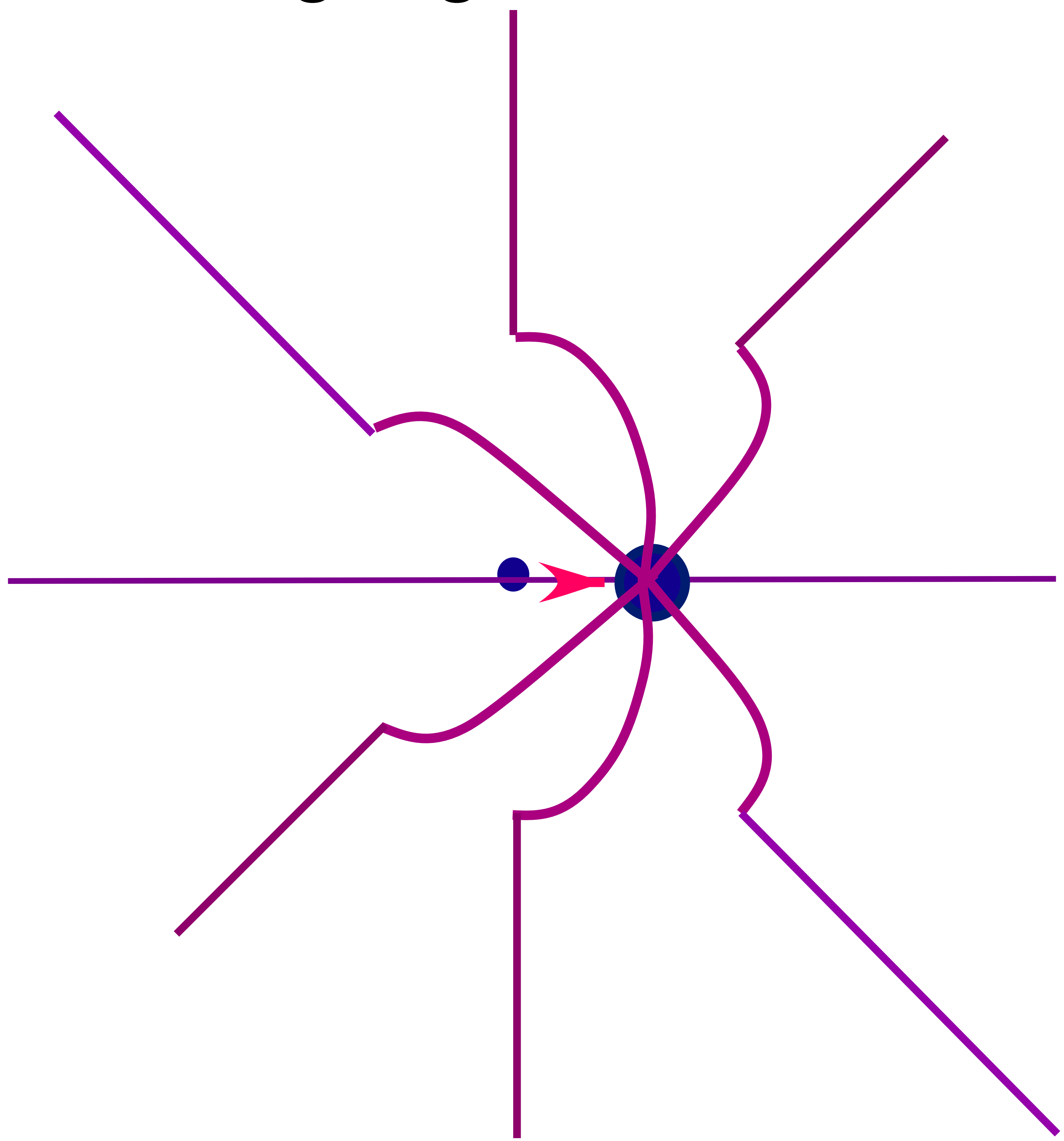


Do these “lines of force” correspond to something real ?

Faraday, Thomson & Maxwell: yes.

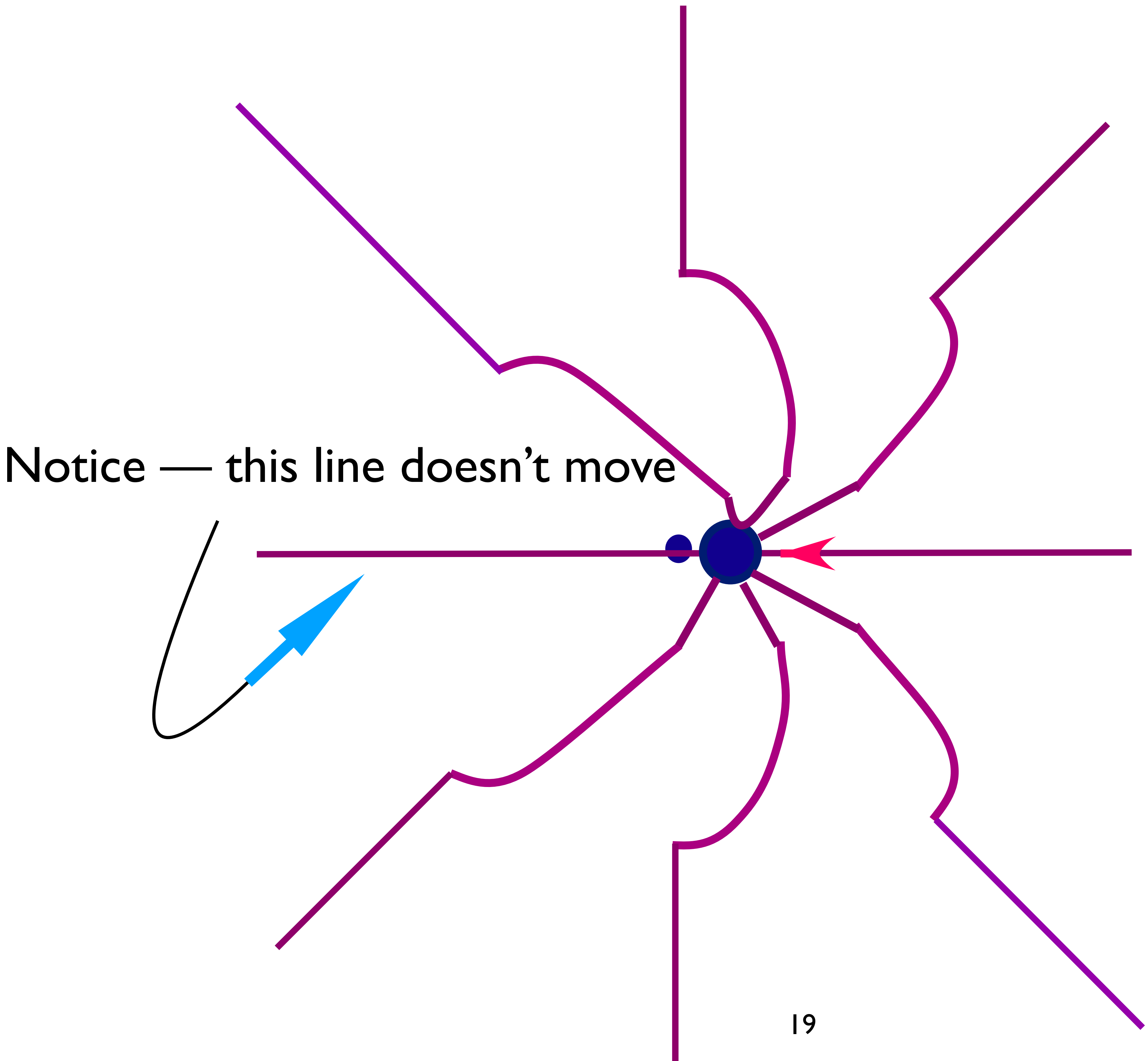
The **electric field.**

Move the charge right . . .

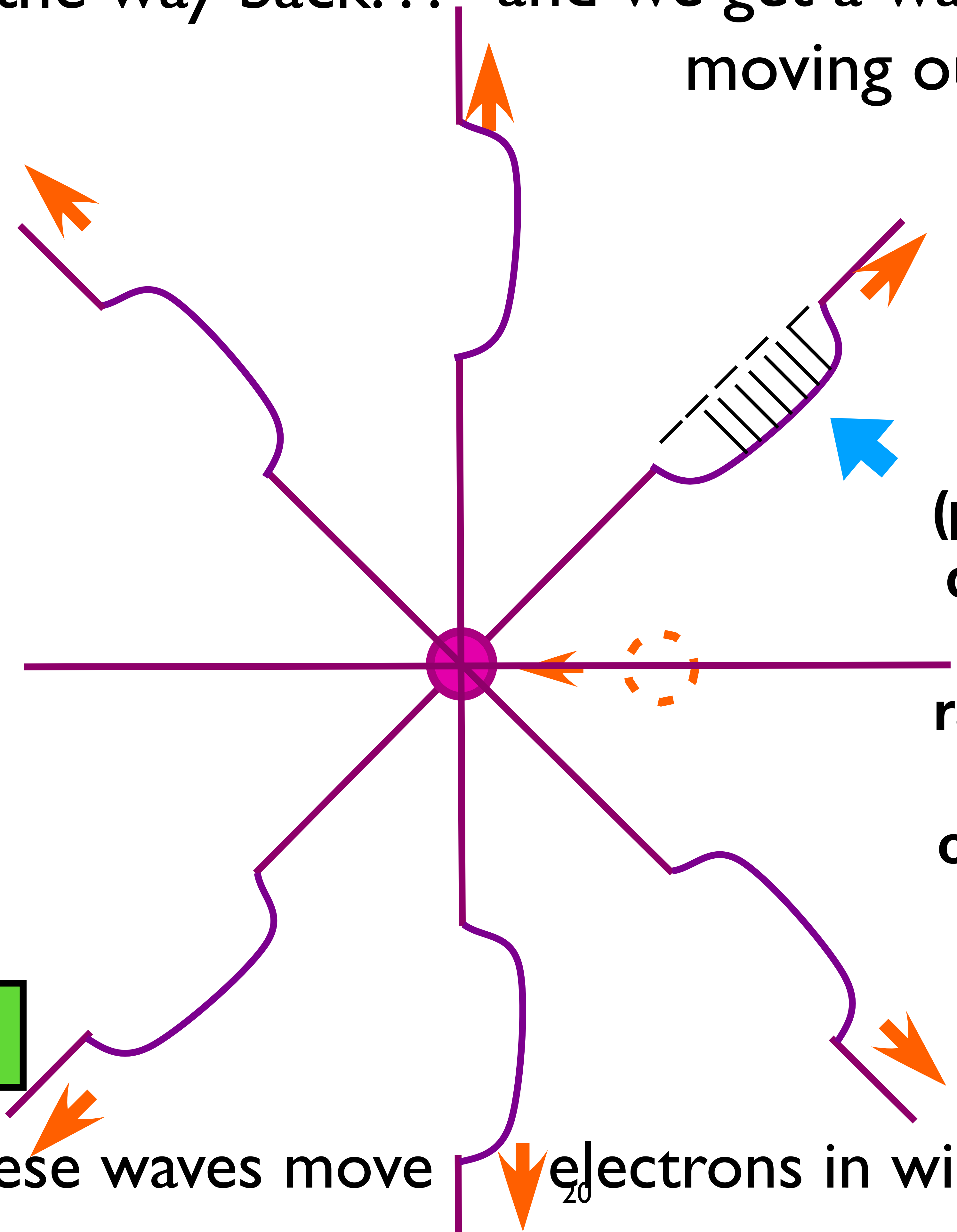


And the lines follow. . .

And back. Lines start to move back



All the way back... and we get a wave in the lines moving outward.



“Transverse” (perpendicular) displacement. and no radiation in the direction the charge moves.

Hertz:

These waves move electrons in wires... Radio !

What Maxwell Found

When the wave moves out, a magnetic field appears along with it. "Radiation". In fact:

Electric force measured by a constant k
Magnetic force measured by a constant μ

Speed of light: c = 300,000 km/sec

$$\boxed{c^2 = k/\mu}$$

c squared = (Electric constant) / (Magnetic constant)

Unification of forces

ELECTROMAGNETISM AS THE FIRST GAUGE THEORY

- Maxwell's waves are all "transverse", vibrating perpendicular to their direction of motion.

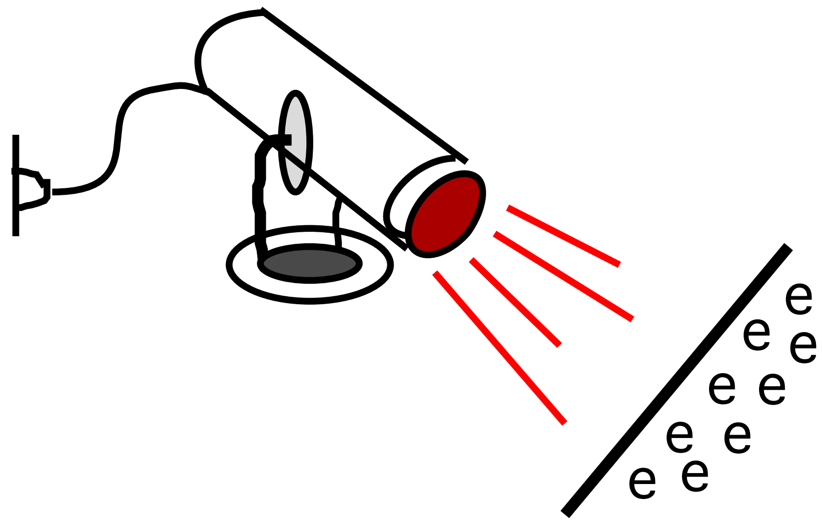
- The absence of waves in the direction a charge oscillates is connected to the conservation of electric charge.

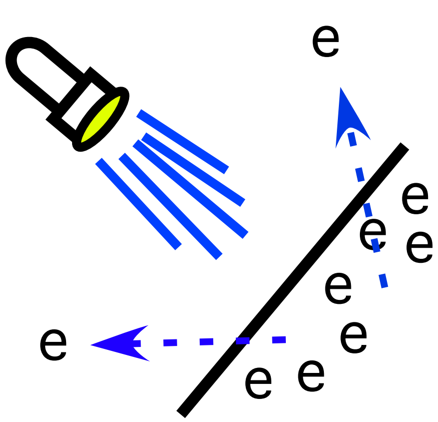
- Theories with charge conservation and only transverse waves are "gauge theories". Electromagnetism was the first.

- The energy carried by waves is proportional to the square of the fields:

$$\boxed{\text{Energy density} = \text{constant x (Electric field)}^2}$$

Meanwhile, around 1888, in his wave experiments, Hertz noticed: The Photoelectric Effect





Even a little blue light knocks electrons out of metals.
Even intense red light doesn't knock them out at all.

Einstein (1905):

- Waves are the correct description of light for "time averages", but the "creation and conversion of light" requires a particle description.

- Light waves consist of a collection of photons. Electrons are only knocked out by one photon at a time, and blue photons have more energy than red.

To be more precise . . .

$\boxed{\text{Photon energy} = h \times (\text{frequency of the wave}) = h\nu}$

h = Planck constant

h / 1 sec. = 6.6×10^{-34} (Joule = 1 Watt x 1 sec)

or about
250,000,000,000,000,000 photons per second
for every watt of a light bulb (visible light).

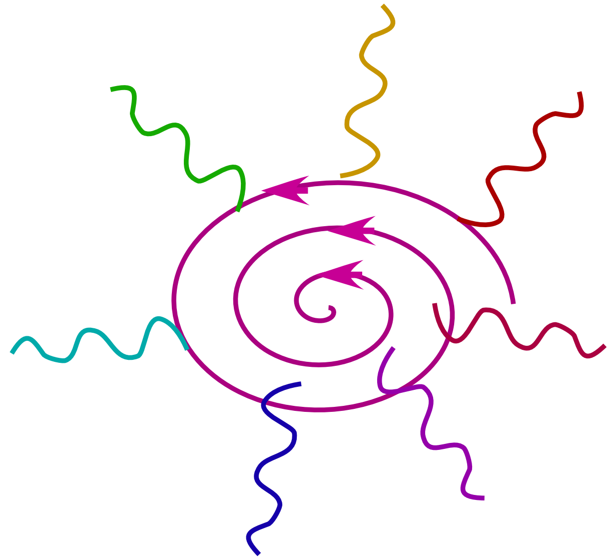
$$\boxed{\textbf{Photon density} = \frac{\textbf{Energy density of wave}}{\textbf{Energy for one photon}}}$$

$$\boxed{\textbf{Photon density} = \frac{\textbf{constant} \times (\textbf{Field})^2}{h\nu}}$$

- And that's not all . . . not only the photon of light, but **the electron is also a wave.**

- A picture like this was necessary once the atomic nucleus was discovered (Rutherford et al.). Here's why:

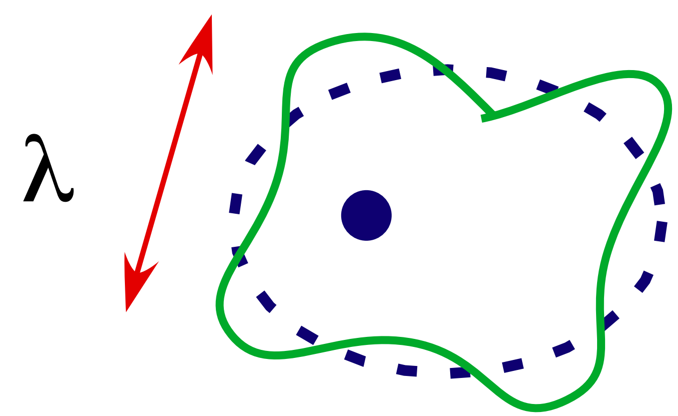
- We've seen that oscillating charges radiate. In E&M, atoms would collapse in a burst of light, as all electrons spiral into the nucleus. Luckily, this is not observed in nature.



Solution: 1909 . . . 1926

Bohr -- de Broglie -- Heisenberg -- Schroedinger

Electrons are waves too !



Electrons don't spiral in, because the waves can't fit !

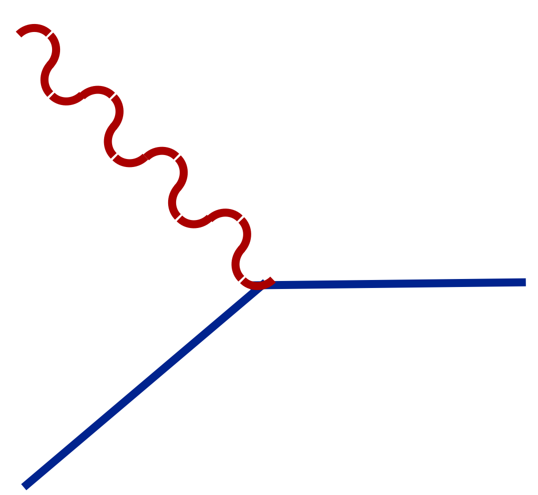
$\lambda = h / p$, the "de Broglie wavelength"

Quantum Mechanics

The waves of light and electrons have a reality all their own. They exist as themselves in space, with no intermediary "ether". They are called collectively, "fields", yet they interact as particles.

When described in terms of particles, one electron is ejected from a metal when it absorbs one photon "at a point"

like this:



In summary (Part II)

- The 19th Century saw the unification of electricity and magnetism (E&M), and the realization that light is a wave of these fields together.

- E&M was the first gauge field theory, characterized by transverse waves and charge conservation.

- The density of photons is proportional to the square of the E&M wave amplitude.

- Light and electrons can both be described as particles with wave-like properties, and light is created and absorbed “at a point”.

III. THE PLAYERS AND RULES OF THE STANDARD MODEL

- The visible world is mostly matter and force particles organized into gauge quantum field theories (QFTs), one of which is Quantum Electrodynamics (QED).

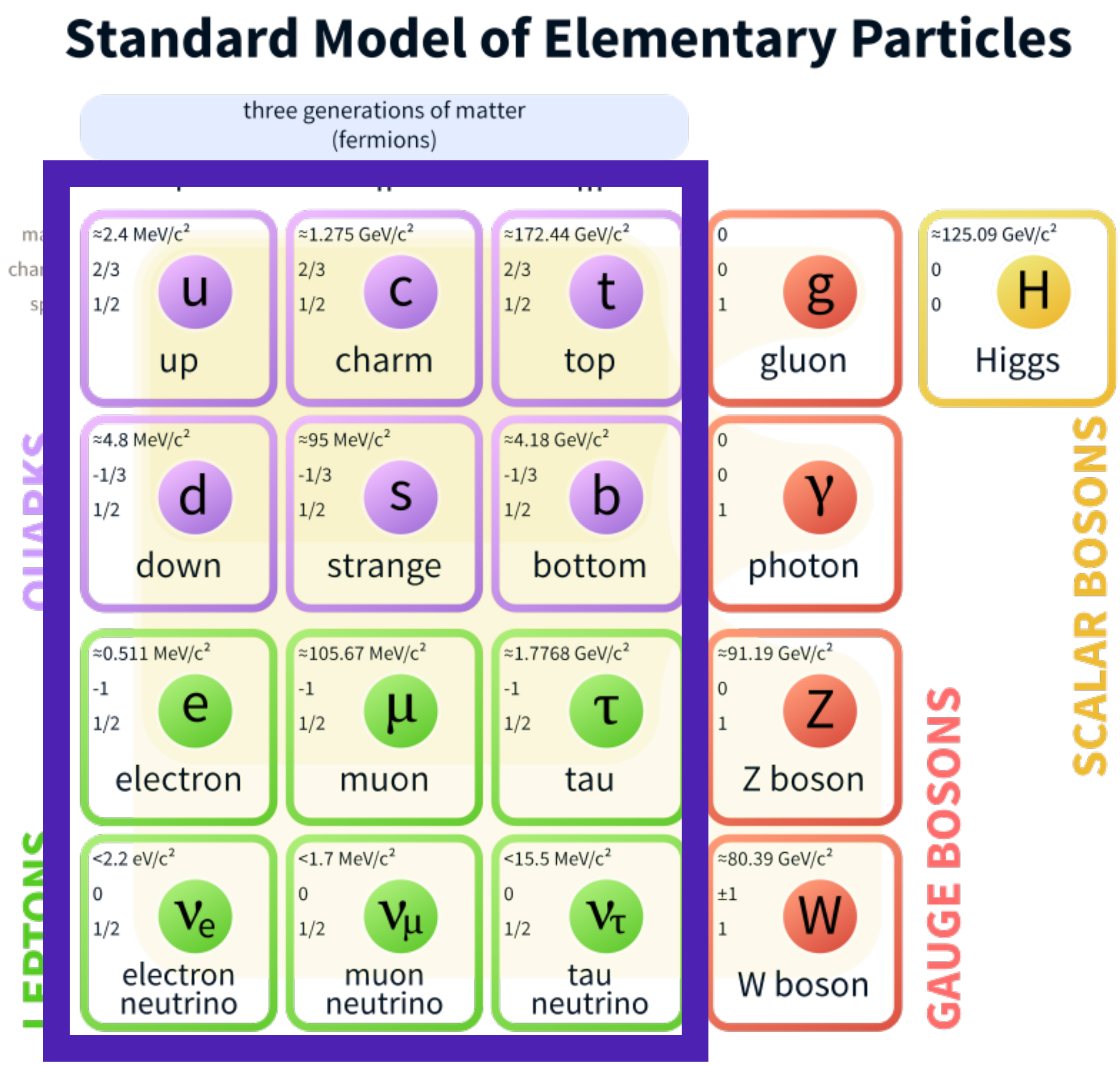
- QFTs give sets of rules to compute the probability of finding one set of particles from another by passing through virtual states. The strength of an interaction may change with momentum or distance scales.

- In the Standard Model, no more than four particles meet at a point.

- Under normal conditions, heavy unstable particles exist only in short-lived virtual states, but can be produced in scattering experiments.

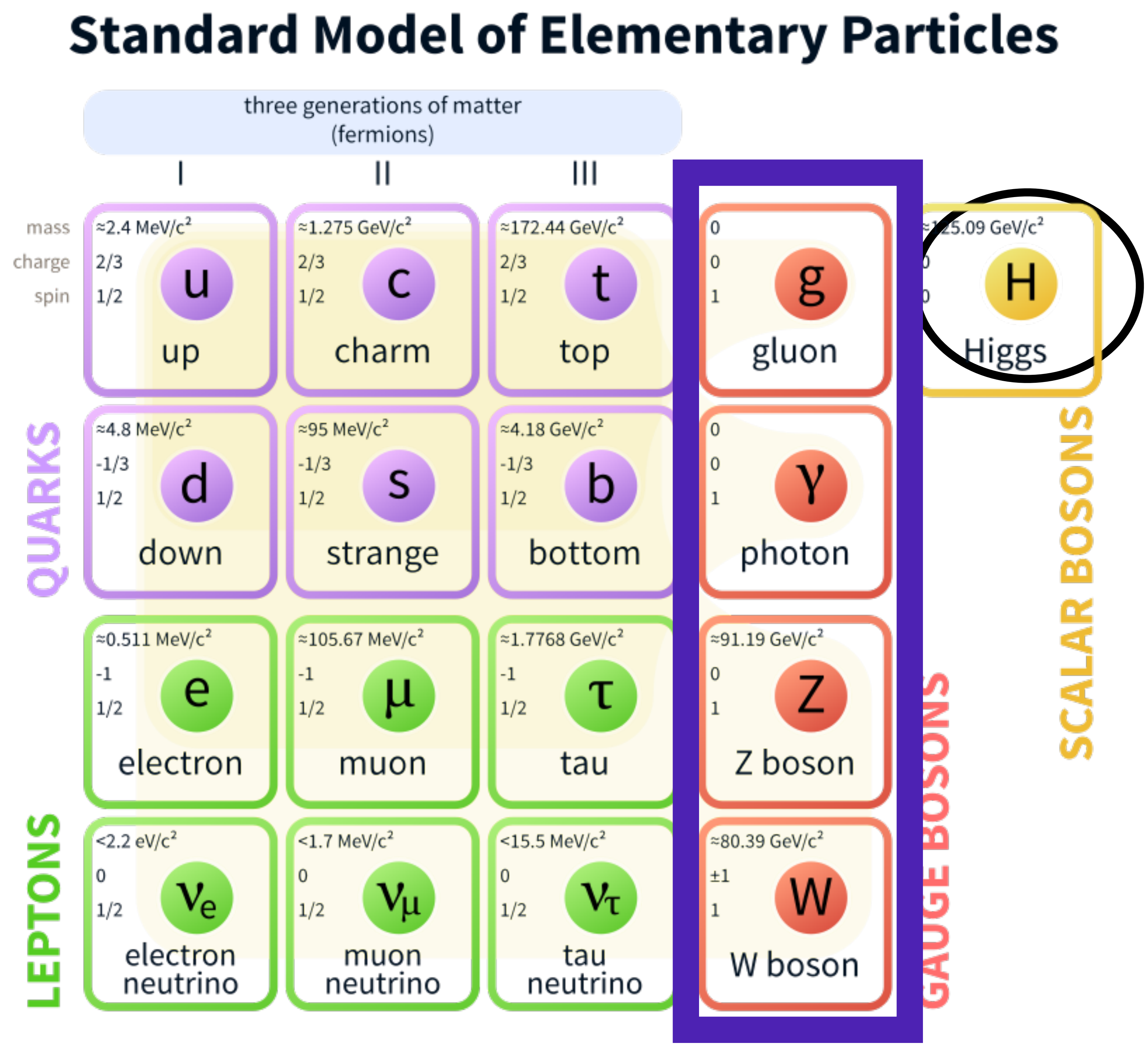
The Players (1)

Fermions: the “matter” of the universe
(the stuff that gets pushed around by the forces)



The Players (2)

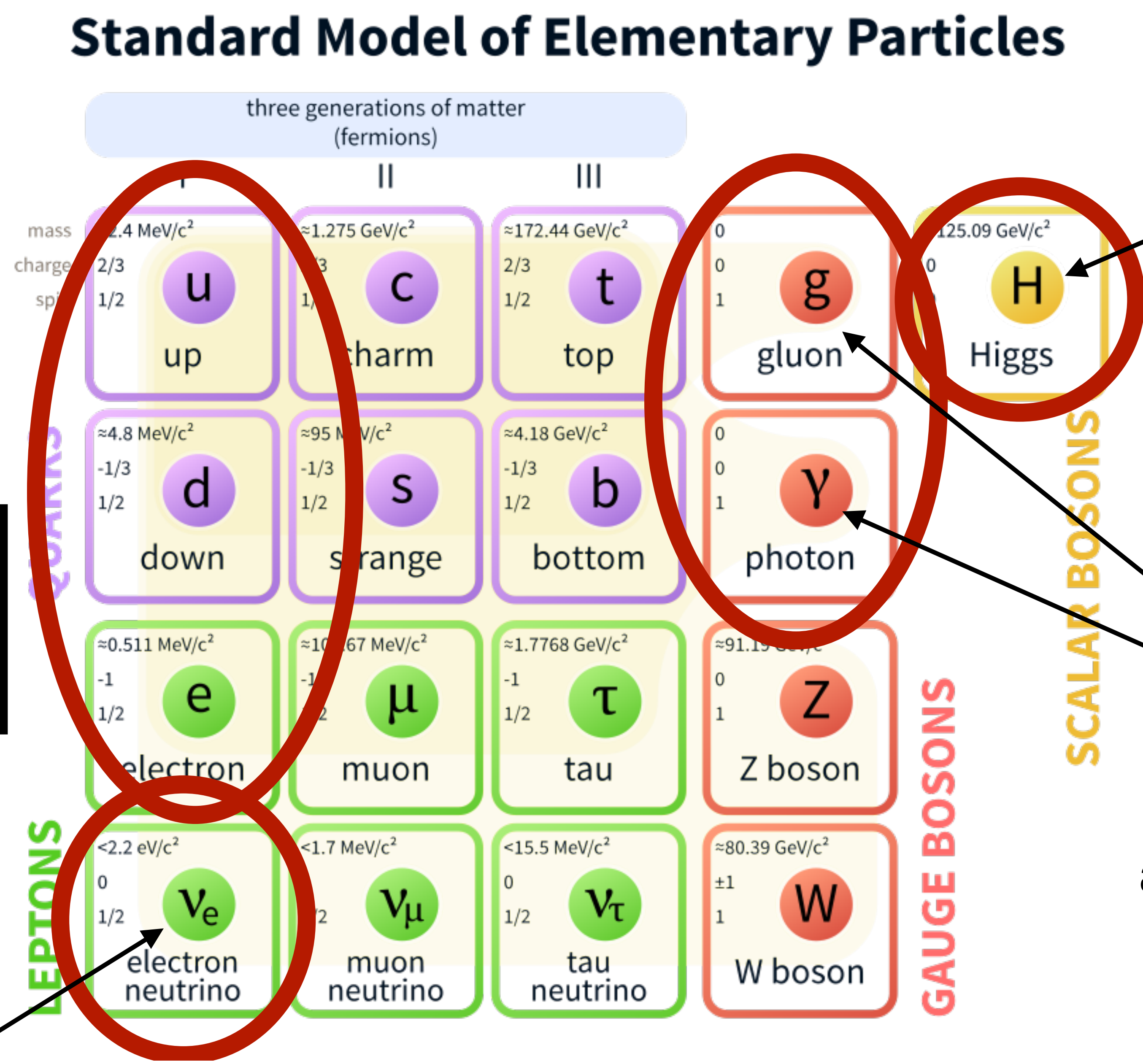
2. Bosons: The force-carrying (vector) particles, and the Higgs boson



The“everyday” particles.

Everything we see contains these

(uud) forms a proton, (udd) a neutron.



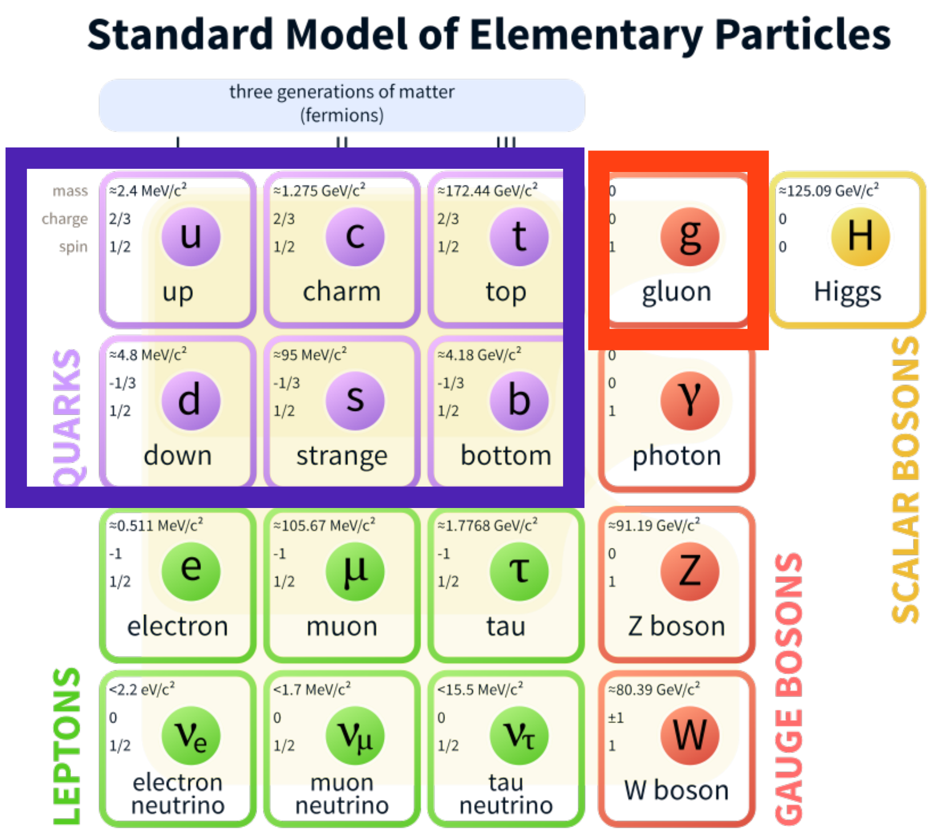
Literally everywhere but unseen

Supply the forces that hold nuclei and atoms together

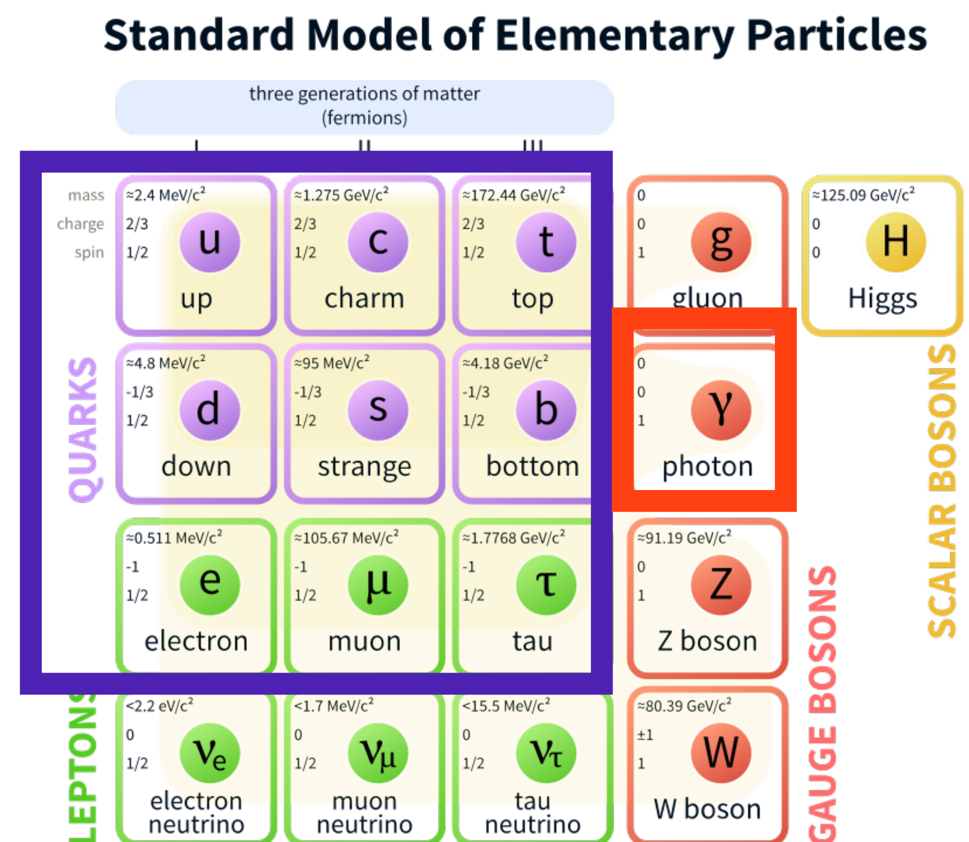
Don’t usually see them but they’re all over the place

FORCES

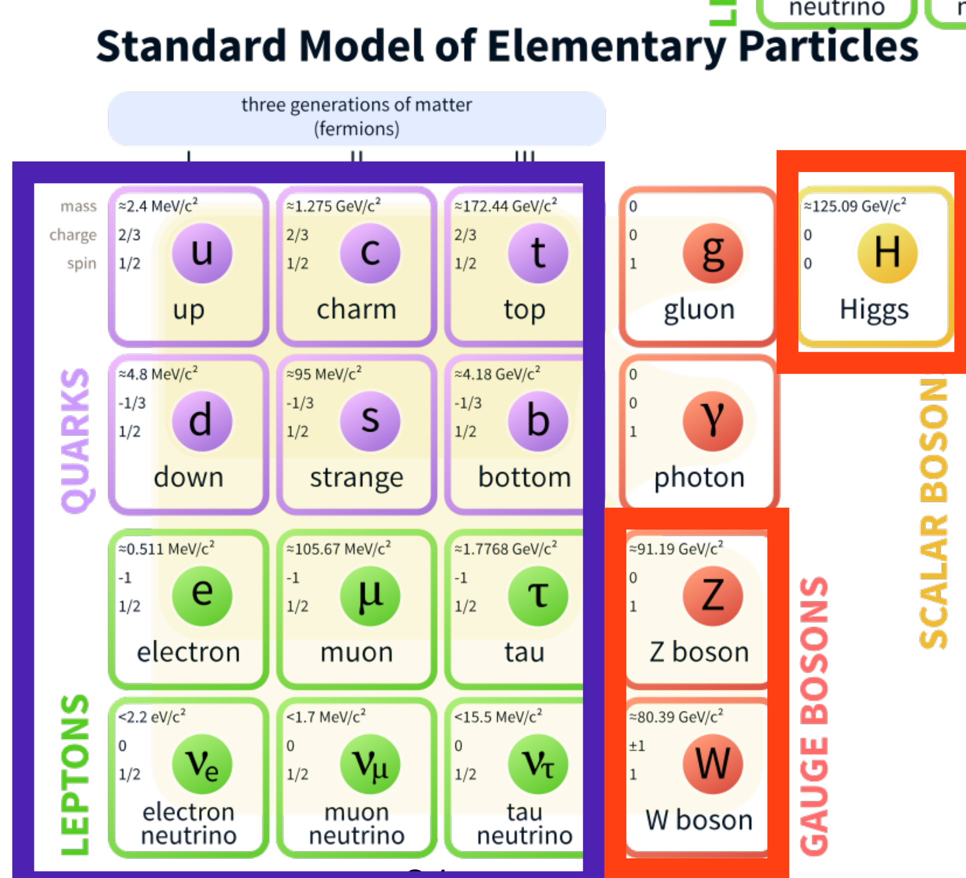
The strongly interacting fermions & their gluon (QCD):



The charged fermions & their photon (QED):



All the fermions experience the weak force:



The Rules: Equations that govern the visible universe.

For ΔT a small time:

("Likelihood" for a new list of particles at time $T + \Delta T$)

=

(ΔT) x [rule for changing the list] x (Lists of particles at time T)

(Schroedinger equation)

Rules act on any list of fermions and bosons

that we represent as

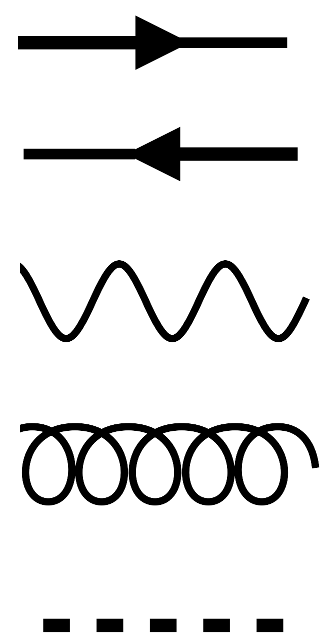
Quark or lepton

Anti-quark or anti-lepton

Photon or weak boson

Gluon

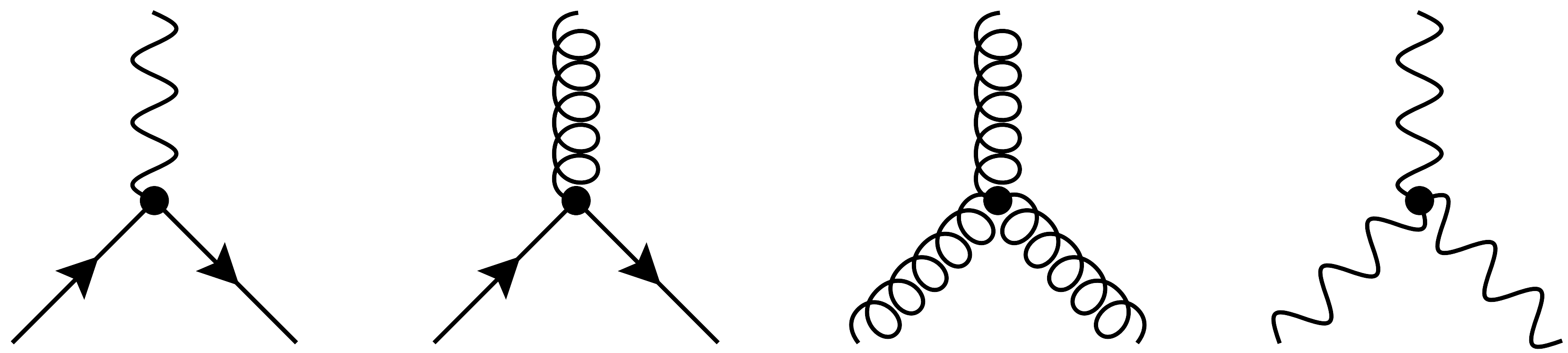
Higgs boson



The list of particles is a possible configuration of the field(s) associated with those particles

Here are the rules for the electromagnetic, strong and weak forces. They are each proportional to a "charge": electric: e, strong: g_s, or weak: g_W.

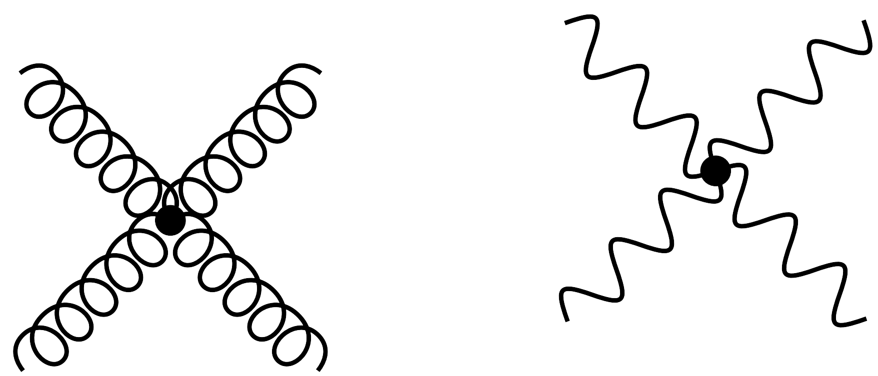
Rules for three particles



charge e **charge g_s** **charge g_s** **charge g_W**

Rules for four particles

Yang-Mills theories (1954) for the strong and weak interactions - charged vector particles.

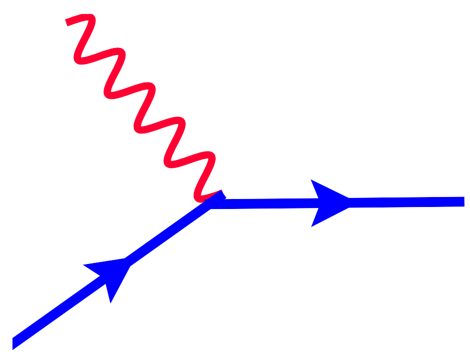


charge $(g_s)^2$ **charge $(g_W)^2$**

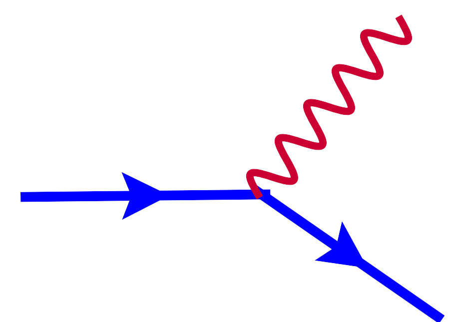
All time directions are allowed.

Here’s how it works:

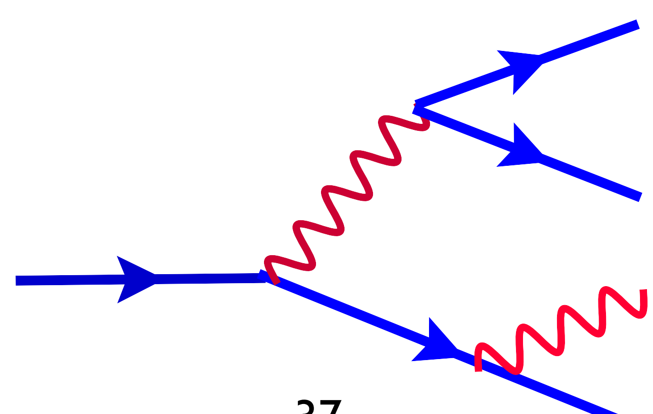
There is a kind of restlessness in nature: every single particle is constantly trying to unwind a whole new world out of itself, and at the same time to ravel it back up, always through simple steps that increase or decrease the number of particles by one or two.



or



And it keeps going on and on.

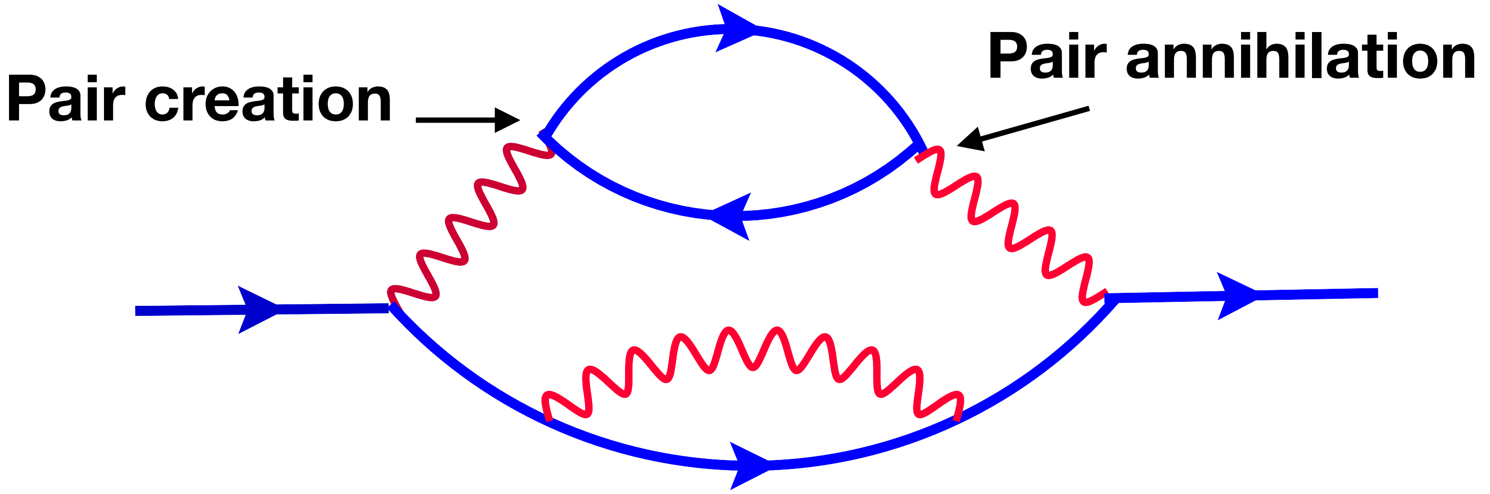


But, sadly, for an isolated electron, all of these states have energy greater than the electron's energy, by some amount, say ΔE.

These are called ``virtual states", and they live only for a time of about

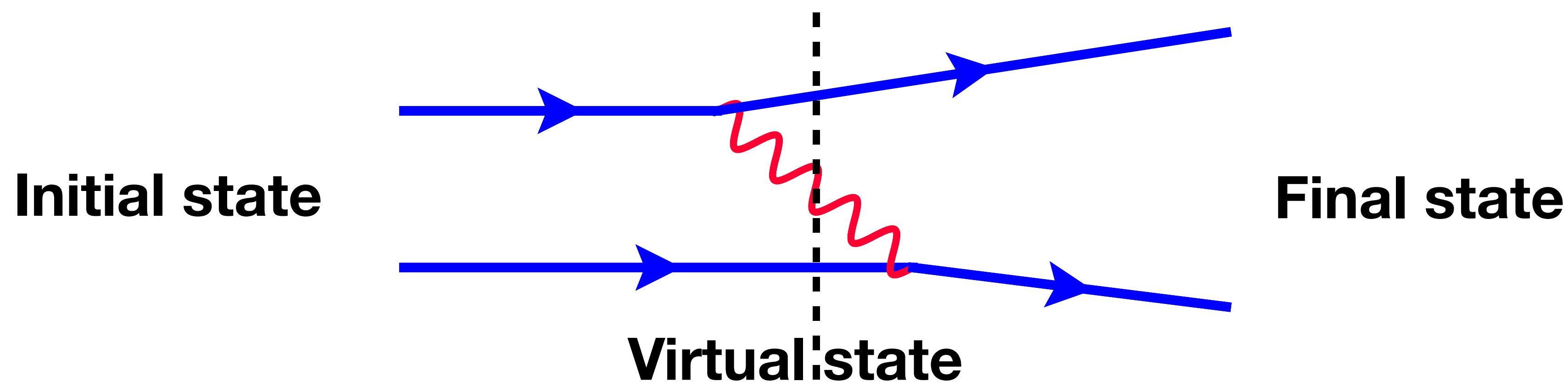
$$T = h/\Delta E$$

before they are wound back in, like

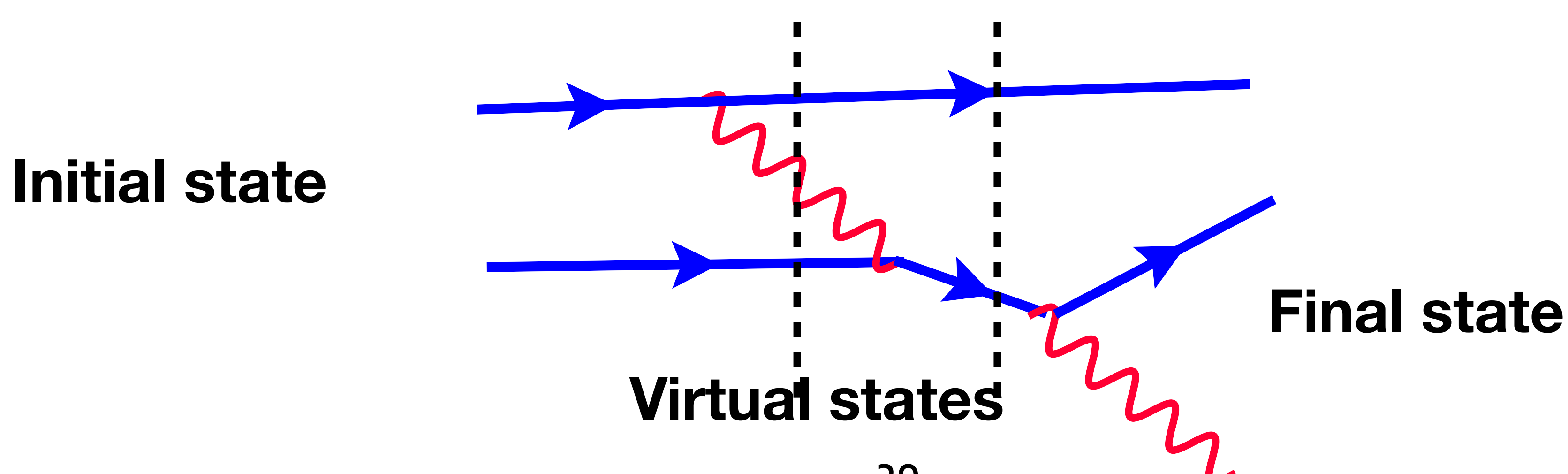


And no matter how hard it tries, each particle in isolation returns always to itself, only to start all over again.

But starting with two particles in a state, together they have enough energy to produce new states by spending short amounts of time in a series of virtual states. “Scattering”.

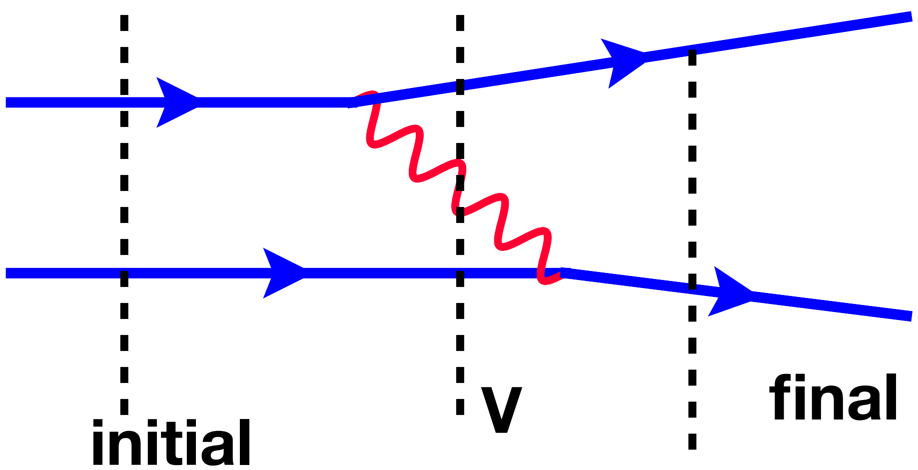


The higher their energy, the more states they can bring about. This is how things happen . . . for example, X-rays are made by adding another virtual state.



From pictures to predictions

For each process given by a picture, there are rules to calculate a wave height, or "amplitude" (Feynman). The amplitude is just a number, found like this:

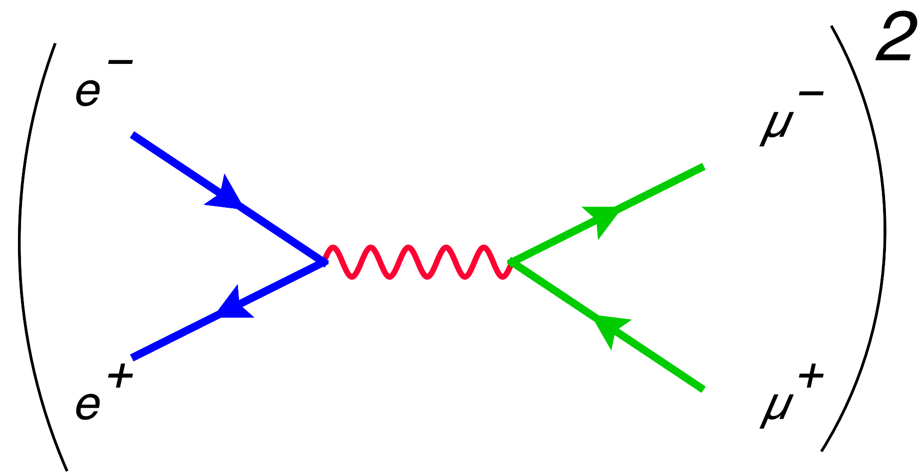


$$= \quad e^2 \left(\frac{\Delta T_V}{h} \right) \quad \mathbf{x} \quad \textbf{(factors of particle energy)}$$

$$\Delta T_A = \frac{h}{E_V - E_{initial}}$$

The probability for any process to happen is proportional to the SQUARE of the amplitude, just as the density of photons in a wave is proportional to the square of the Electric field.

For example, the amplitude that corresponds to the creation of a muon-antimuon pair from an electron-positron pair in a head-on collision, the probability is given by

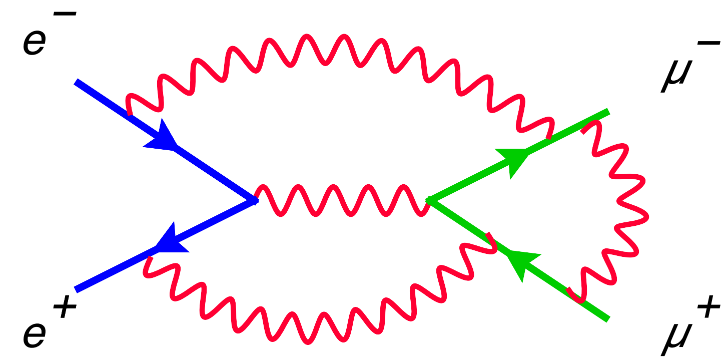


$= e^4/8\pi$ when the muon is in the same direction as the electron
$= e^4/16\pi$ when the muon is produced at right angles to the electron

Simple!

But it gets more complicated quickly with more virtual states.
Because e is small, however, this prediction is pretty accurate.

- In principle, we should calculate all “paths” (diagrams) like:



- In the ideal case (QED is pretty ideal) only “low orders in the coupling” are necessary — because the relevant “e” is small. Such an approximation is called “perturbative” and we’re talking about “perturbative QFT” here.

- For the calculations necessary to establish the Standard Model, perturbation theory is essential.

- “Non-perturbative’ analyses of QFT are also indispensable — including those built on numerical simulations. For some topics, like the confinement of quarks, they are absolutely necessary.

- The rates at which new states arise are given for each transformation by the charge of each vertex.

- The hallmark of quantum mechanics is that the system explores every single way of getting from the first state (which we can prepare) to the last state (when we detect what' comes out)… all diagrams are needed.

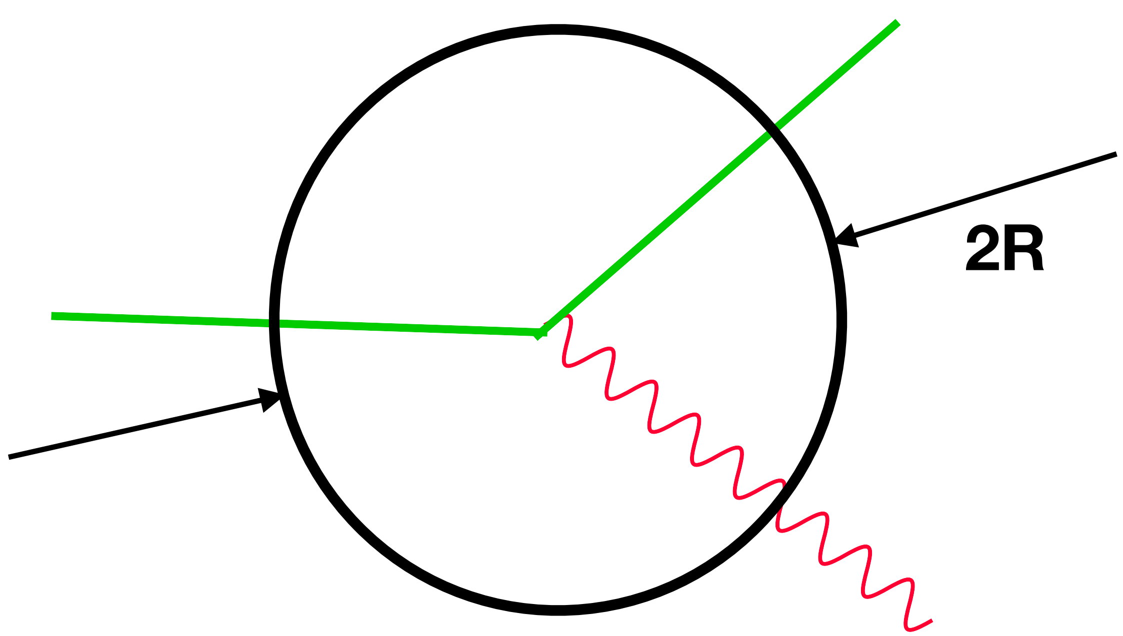
- And if there is enough energy, we can get to any final state that the rules of transformation (vertices) can bring us to.

- Quantum mechanics tells us only the probabilities for what we will find, because all paths are explored at the same time.

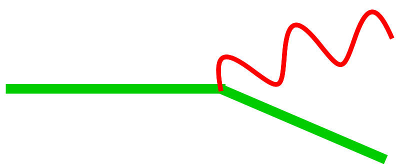
This is quantum field theory.

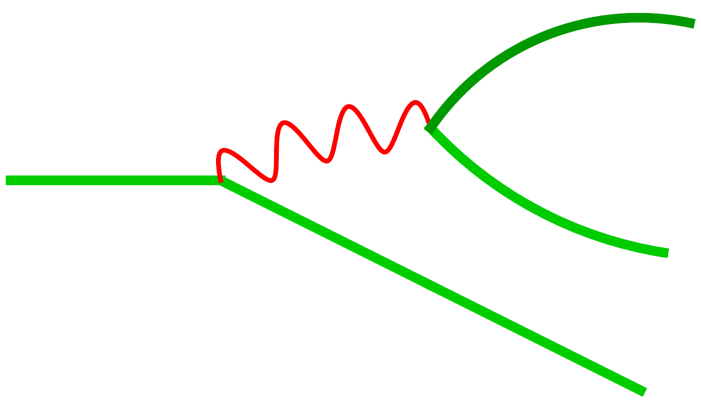
There is no limit to how short a time virtual states might live — no limit to the energy they might have.

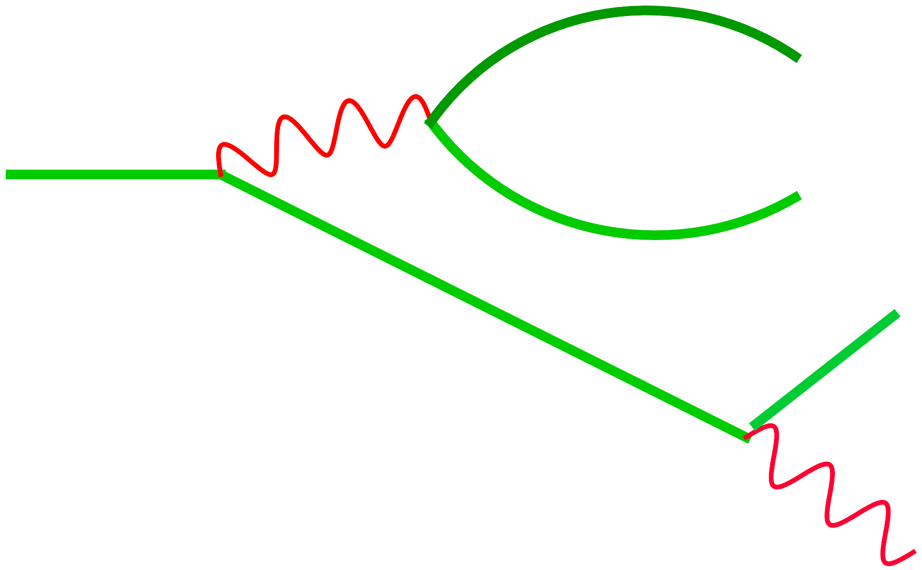
So the closer you look at an interaction, the more you will find. Look inside a radius R, and find not only

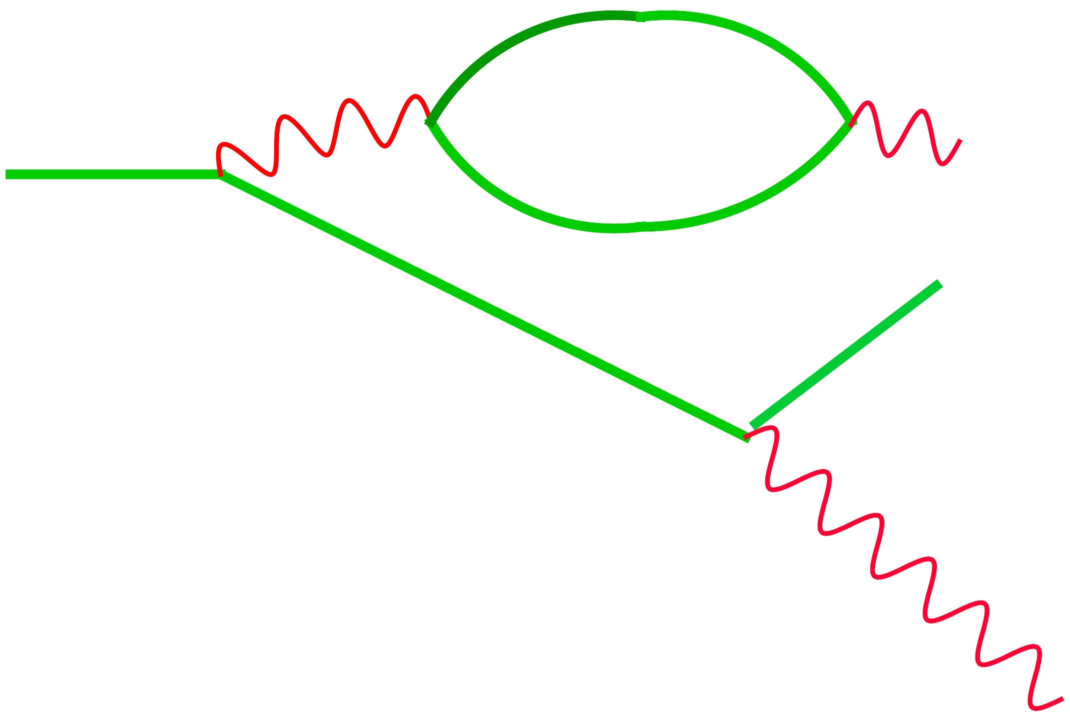


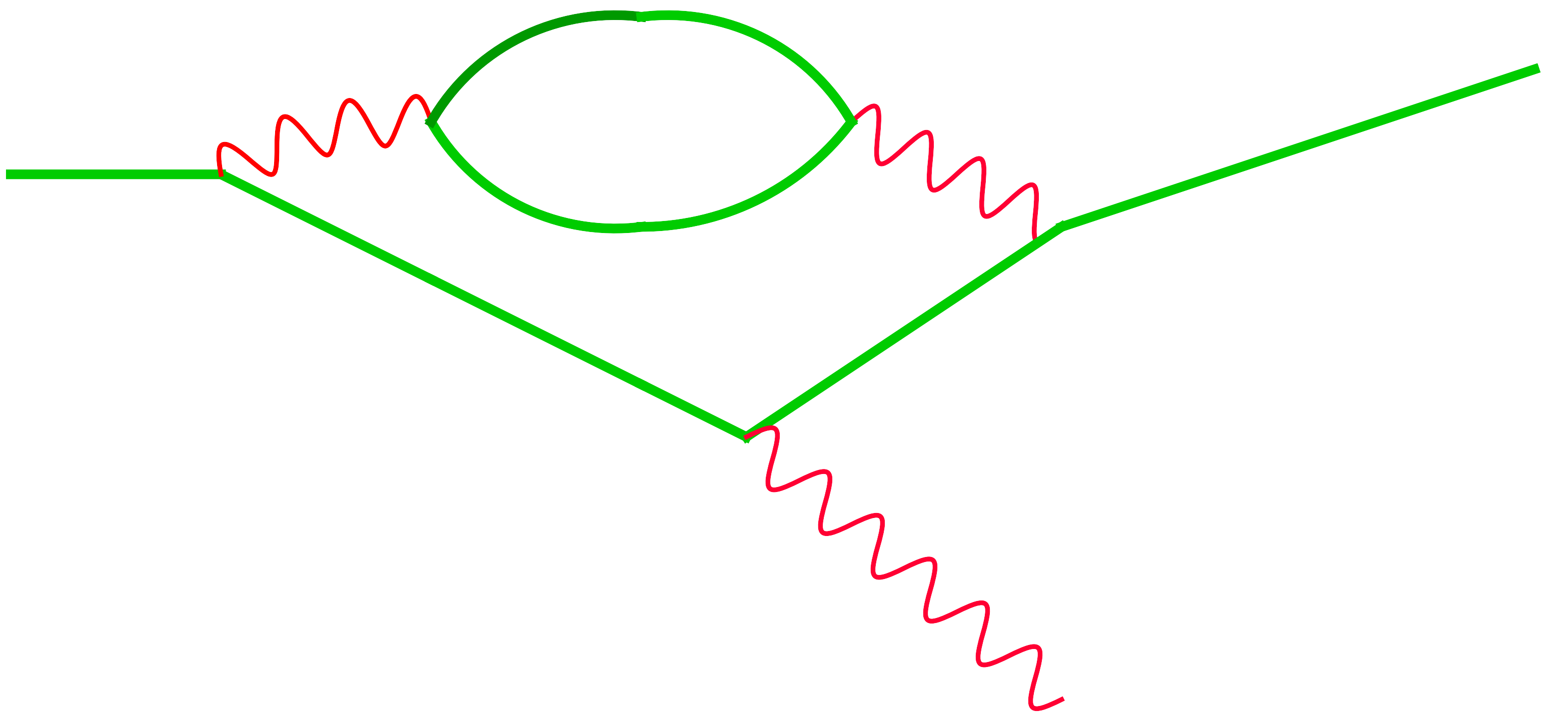
but also . . .



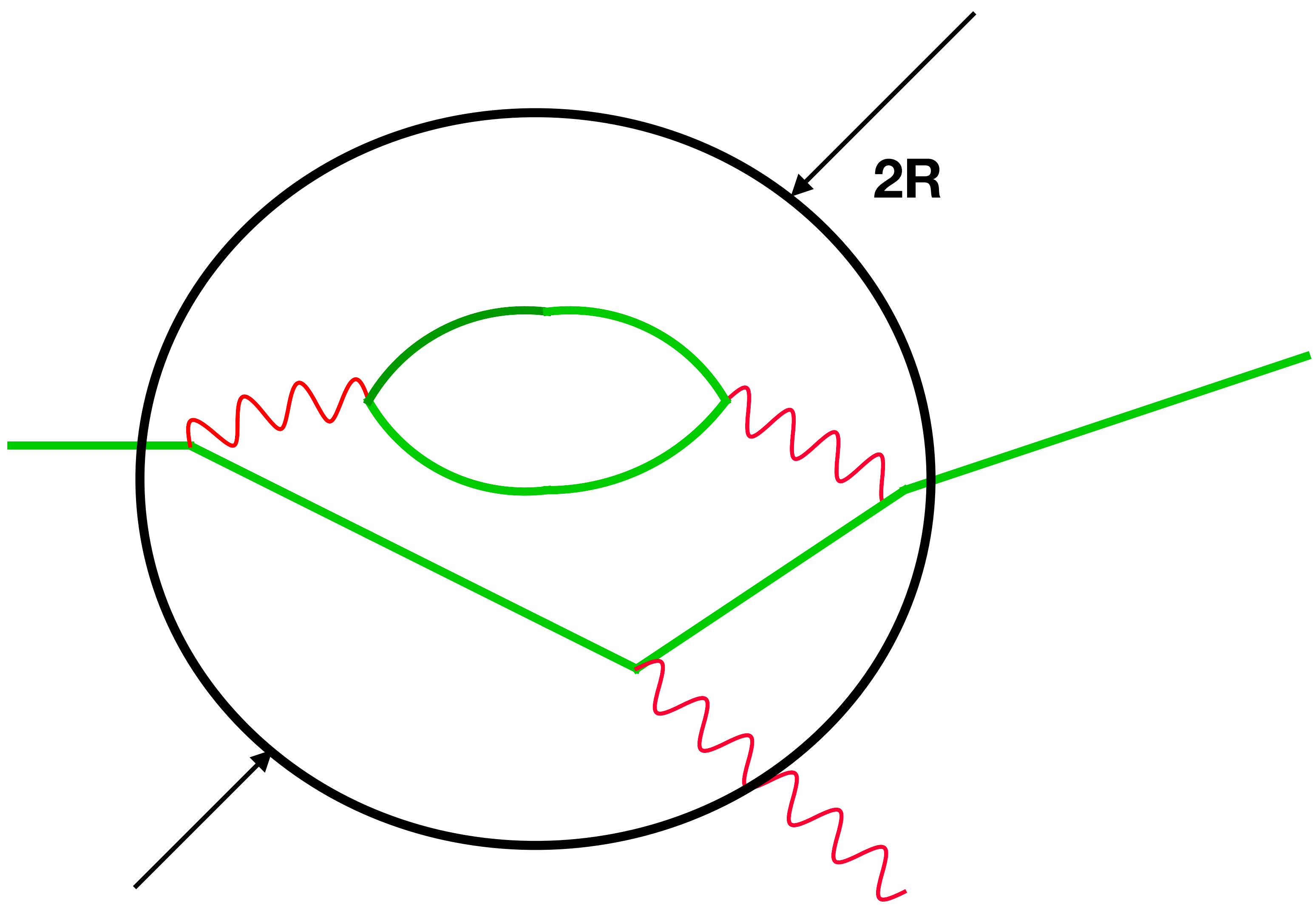








We can actually calculate how all these diagrams depend on R. This is called the "running coupling" and is usually given as a function of the de Broglie wavelength that corresponds to radius R: $\alpha(p=h/\lambda)$ [$\alpha=e^2/4\pi$]. For QED this technique is not such a big effect, but it is very important for the strong interactions.



Explanation and prediction: QED and beyond

— At large scales, photons “pile up” to give macroscopic fields and their waves.

— At small scales, time development is in terms of photons, electrons and other particles.

— At the boundary of large and small — an atom is the result of a steady exchange of photons between the nucleus and its electrons (and between the electrons, too).

— Scattering experiments give images of QFT “in action”, and probabilities for outcomes can be computed. The higher the momentum transfer, the shorter the distances probed.

— Given a new set of rules, unseen fields and particles can be, and have been, predicted. This is how the Standard Model was discovered.

- Theories that work like this are an elite group! All those seen so far have transverse waves only for force particles (gauge theories). No more than four particles at a vertex. “Renormalizable”.

- Otherwise, so many high energy virtual states are produced that the calculations require introduction of an endless set of new vertices and couplings.

- These are often useful for approximate calculations, but they are not “fundamental” in the sense that they can be written as a finite set of rules.

- But in the long run, “effective” may be what we have . . .

Early history of the universe revisited:

- Originally, all particles mixed freely. Decays were balanced by production, but as the universe expanded and cooled, high energy collisions ceased.

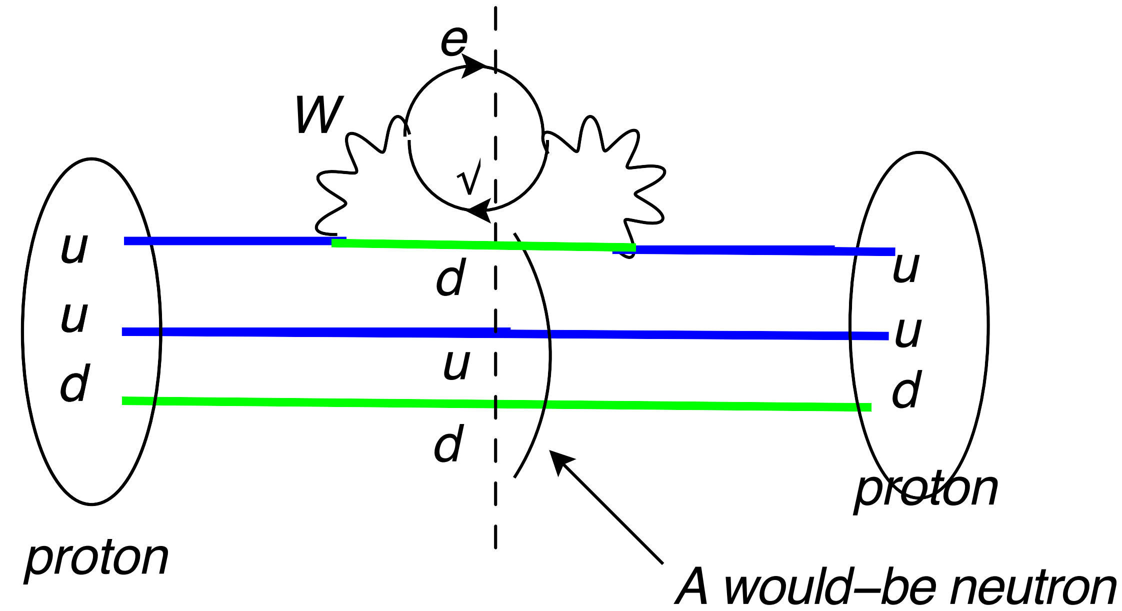
- **Because of their weak interactions, 2nd and 3rd generation quarks and charged leptons, W, Z and H bosons decayed and were not replaced.**

- They are now found only in short-lived virtual states, from which they can only emerge with sufficient energy or over short times.

- Stable quarks and gluons retreated to the tiny volumes of protons and neutrons, surrounded at great relative distances by electrons and photons.

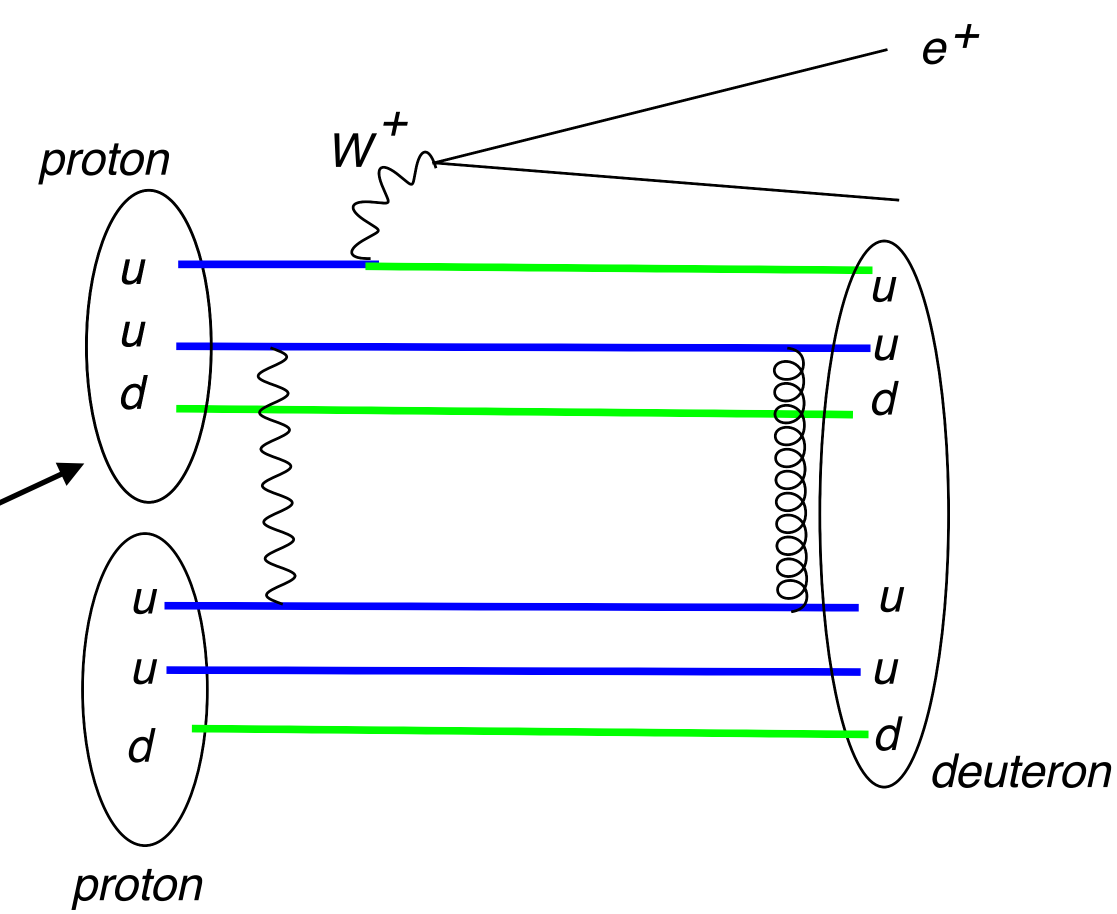
- Neutrinos streamed outward freely for the most part.

One really important ways the W's emerge from virtual states: first step in stellar fusion:



In isolation the proton is completely stable against decay into a neutron

But at high density in stars, two protons can share energy and form a deuteron, the first step in the "pp" cycle.



In summary (part III)

- The visible world is mostly matter and force particles organized into gauge quantum field theories (QFTs), one of which is Quantum Electrodynamics (QED).

- QFTs give sets of rules to compute the probability of finding one set of particles from another by passing through virtual states. The strength of an interaction may change with momentum or distance scales.

- In the Standard Model, no more than four fields meet at a point.

- Under normal conditions, heavy unstable particles exist only in short-lived virtual states, but can be produced in scattering experiments.

IV. Exploring the Micro World: Assembling the Standard Model

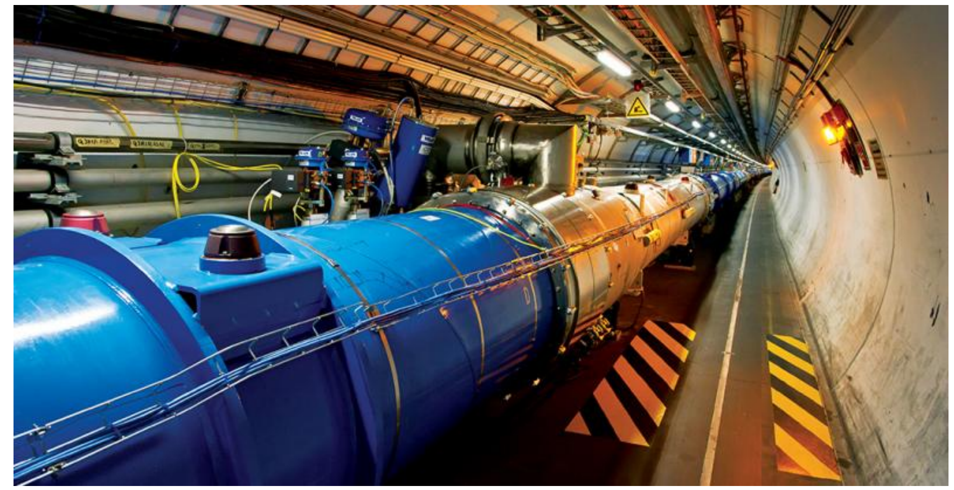
- An accelerator is a machine for efficiently producing virtual states, bringing life to particles that normally hide inside the nucleus or slumber in the flickering world of virtual states.

- It does this by colliding particles at velocities approaching the speed of light. The states produced depend on the particles they accelerate.

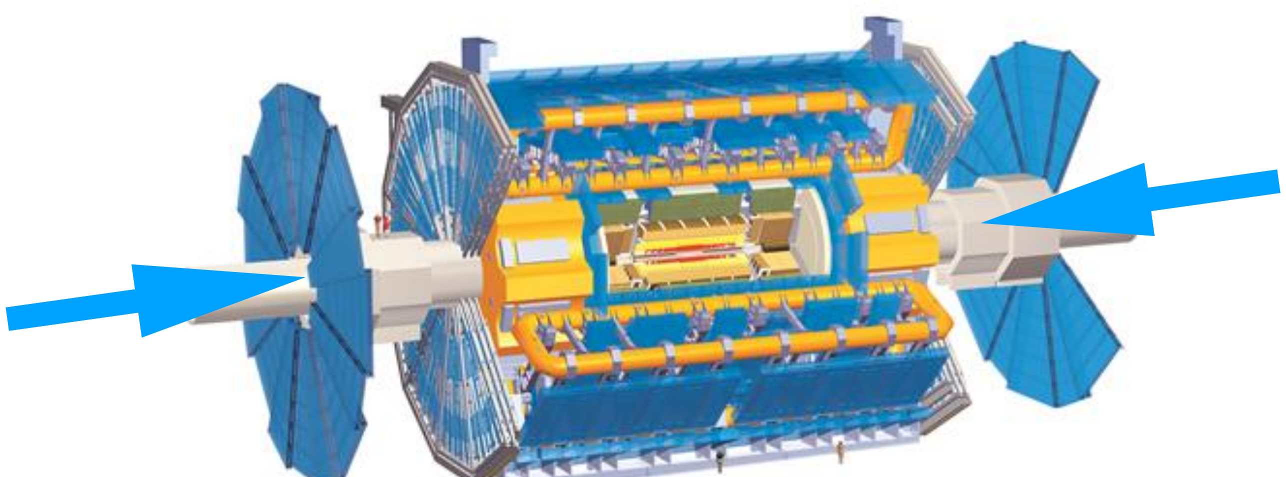
- The strong force is "asymptotically free". It confines quarks to nucleons, yet still allows us to detect their interactions through particle jets.

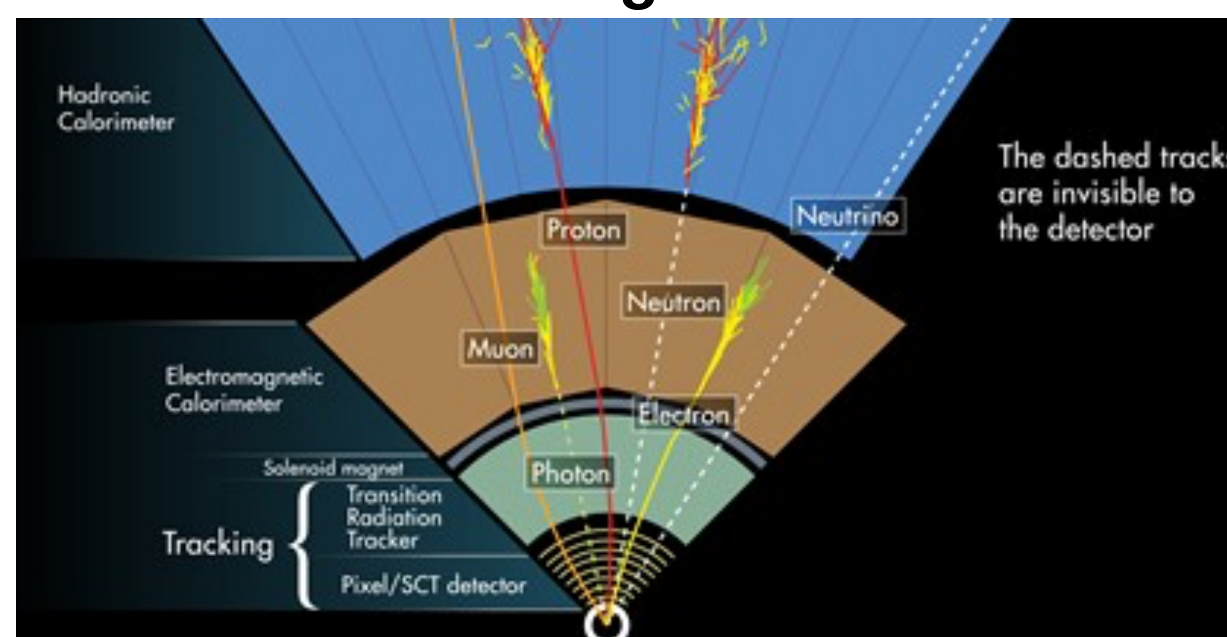
- The mass of visible matter comes from the Higgs particle and from the strong force.

Accelerators: e.g. LHC at CERN (2010 - present) proton-proton collisions with up to 13,000 m_{proton} "available energy"

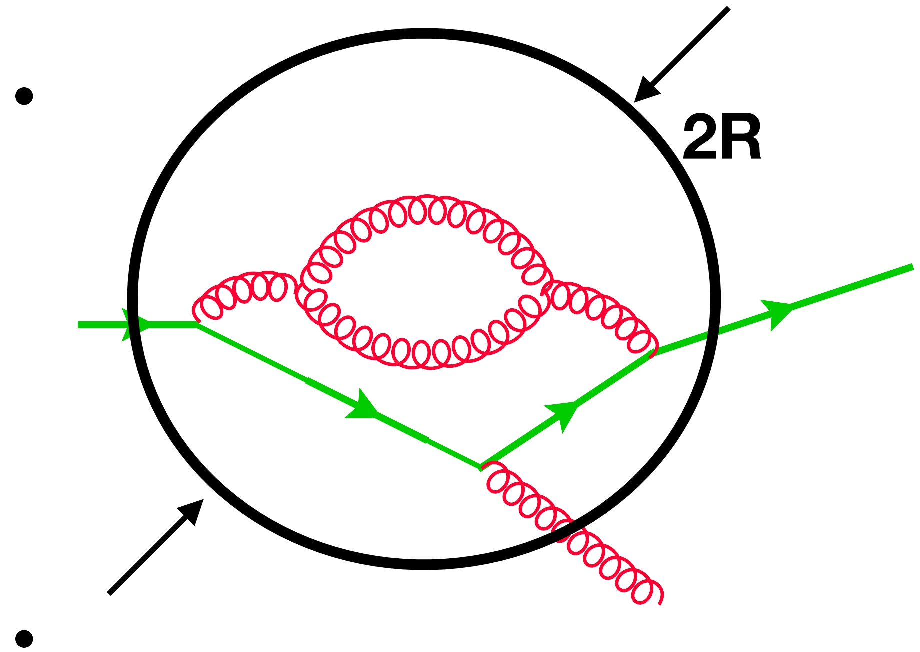


When the particles reach the chosen energy in each ring, they are guided into an "interaction region". Colliding particles pass through virtual states and/or produce unstable particles. The final states of newly-created particles flow into detectors that surround the interaction regions.





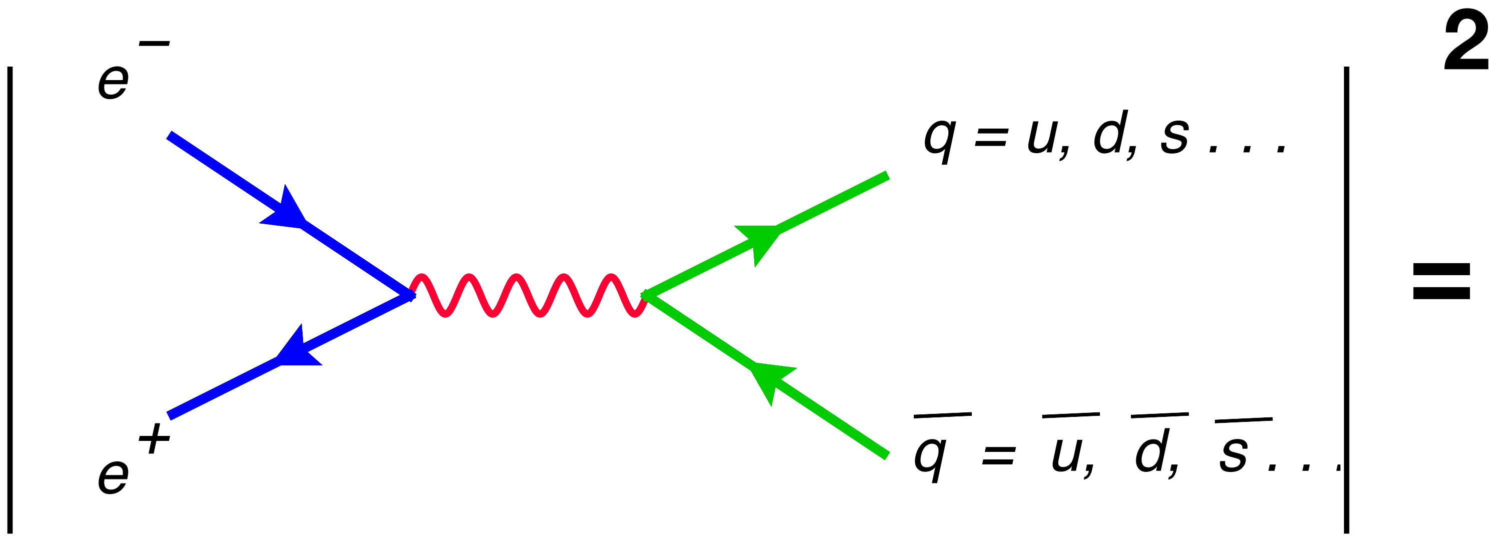
Quarks have a "strong charge" with which they couple to gluons. And each of the u,d,s . . . quarks **come in 3 different types (colors).** In the Standard Model **there is no way to tell colors apart!**

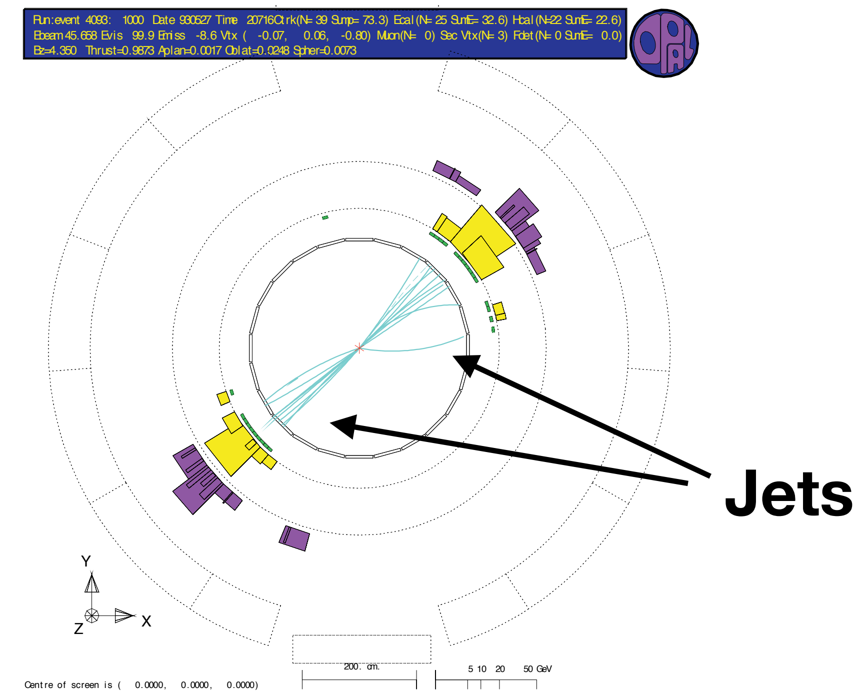


Because of the color charge — g_s decreases as R decreases — or as momentum increases. But at momentum $p = h/R_{proton}$ it gets very large. Together, this is called:

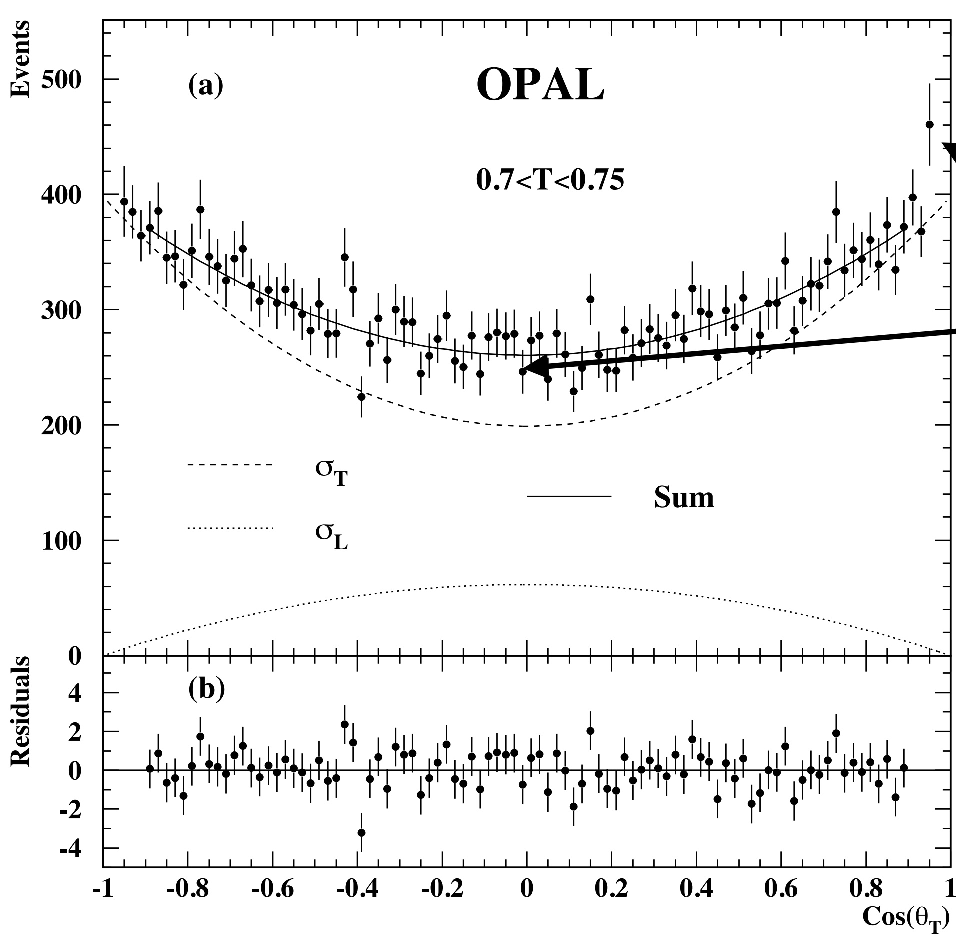
Asymptotic Freedom — Neither gluons nor quarks are ever found in isolated particles that have a net color ("confinement"). That's why protons have 3 quarks. But at short distances, we can still use perturbation theory.

Electron-positron collisions: we “see" quarks with particle jets.





With the same angular dependence as for “e^+e^- to muons”



Twice as many jets in the e^- direction as at right angles to e^-

And 3 times the probability:
3 colors for each quark flavor.

Why do particle jets remember quarks?

Long-lived virtual states are reached only with **small momentum transfers** at vertices.

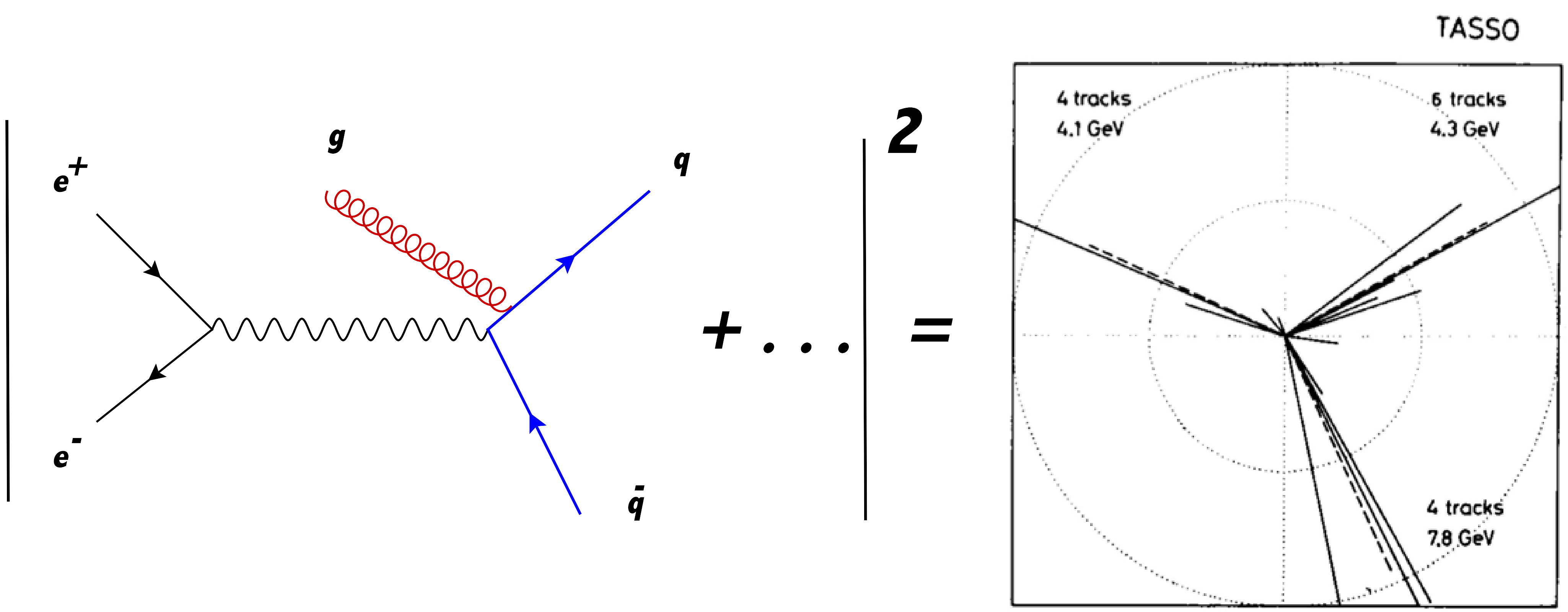
These transitions respect the **flow of energy**.

If we sum over all states with the same energy flow, corrections associated with long-lived virtual state (“large ΔT”s) cancel, and the probability depends only on what happens at short times, where asymptotic freedom makes the coupling small. This property of jets is sometimes called **infrared safety**.

With electron-positron beams, jet probabilities are calculable from first principles.

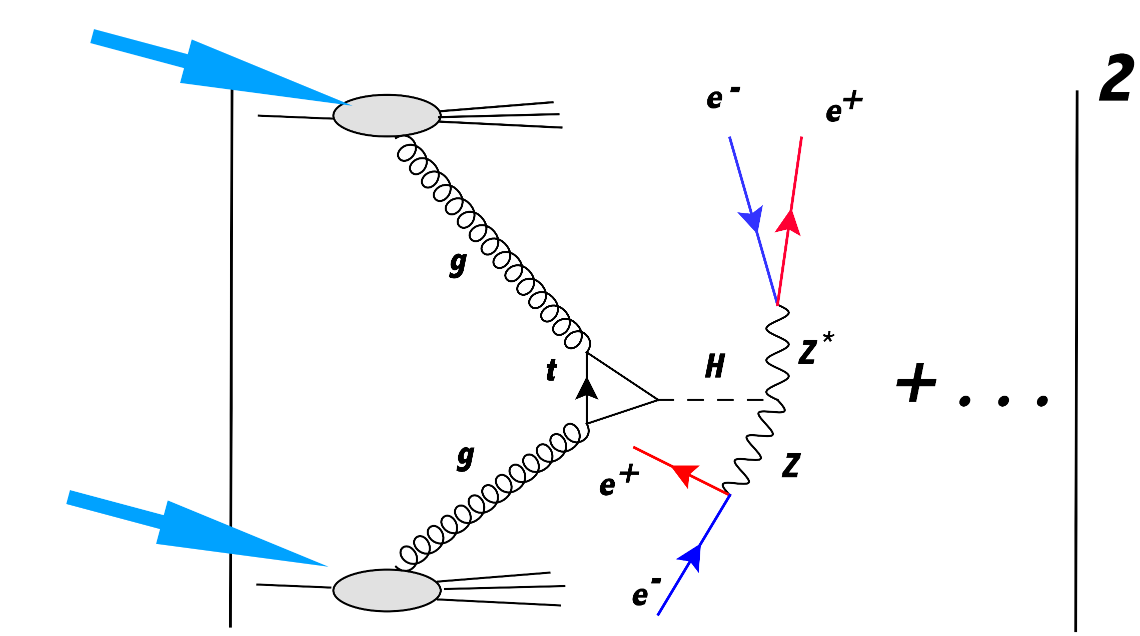
1979 (Petra accelerator, DESY Hamburg)

Using jets to find the gluon. Seeing the gauge boson of the strong interactions (QCD)



(a)

- At HERA, electron-proton scattering finds fractionally-charged quarks, then antiquarks, then confirms the force transmitted by transverse gluons. It measured "parton distributions", which show how quarks and gluons share the momentum of protons.
- At the LHC, the entire Standard Model comes to life in two figures:



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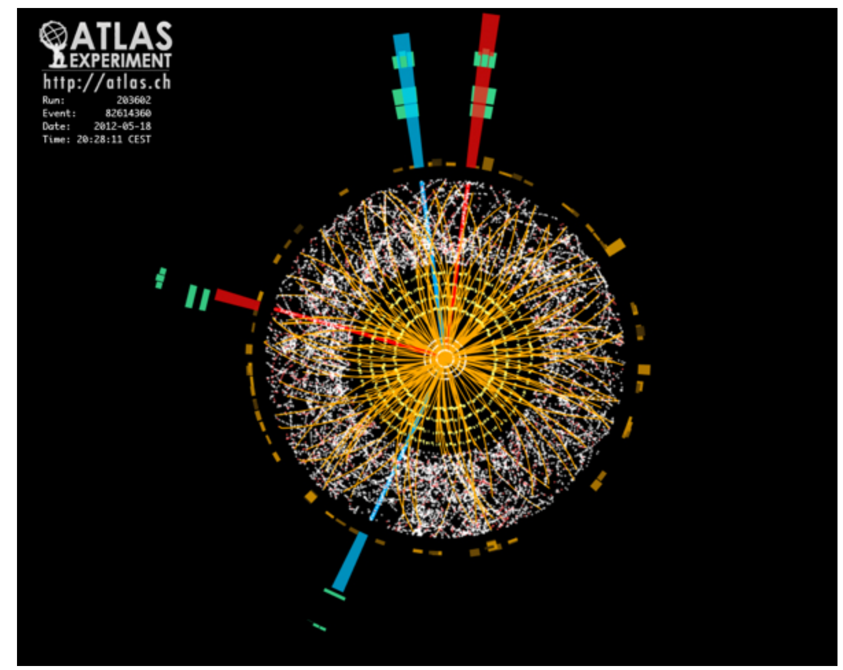

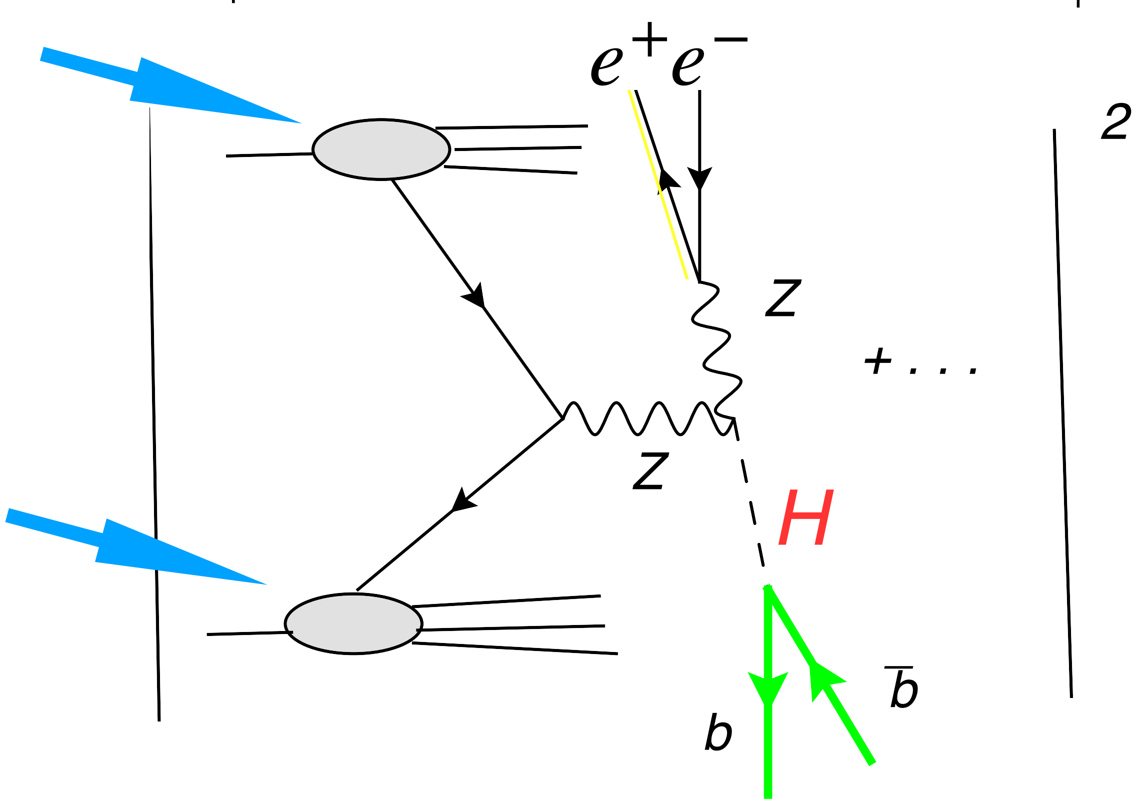

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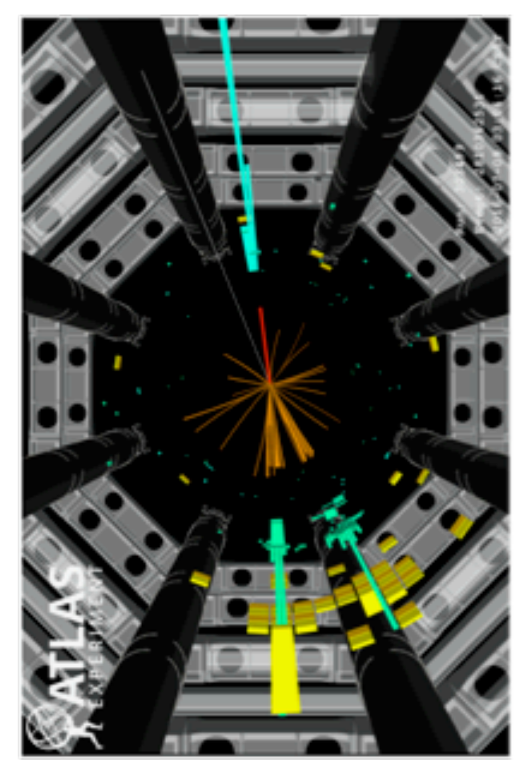


Particle masses in the Standard Model

- The Brout-Englert-Higgs-Guralinik-Hagen-Kibble mechanism starts with four “scalar” fields (no spin). Three combine with weak vector bosons to give them mass. The W+, W- and Z are no longer purely transverse, but they remain gauge bosons.

- The fourth field fills space, providing masses to all particles that feel the weak force. Waves in this field are the Higgs boson, and they interact with fermions with a coupling proportional to each individual mass.

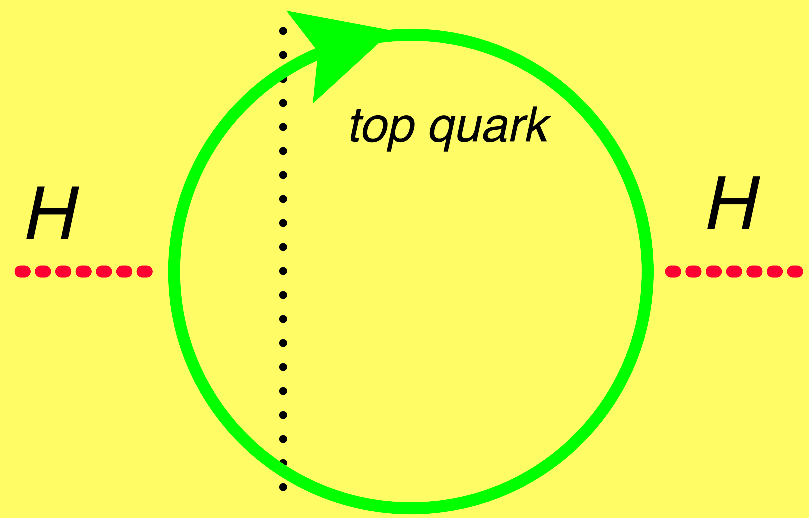
- For protons, neutrons and other physical particles made up of quarks and gluons, most of their observed mass is due to the strong gluon fields inside the particles themselves. By “weight”, this is most of the visible mass in the universe.

- The transverse nature of gauge theory bosons helps stabilize fermion and vector boson masses.

- The mass of the Higgs particle, however, is a special case. The mass is:

- mass = classical mass + quantum corrections.

- The quantum corrections are from virtual states like:



- In the SM, every virtual state contributes to the Higgs mass by an amount proportional to the momenta of the particles in that state, **without limit**, a result described as "unnatural".

- It is possible that there is a cancellation between different virtual states, but this requires new particles. These particles haven't been found yet.

In summary (Part IV)

- An accelerator is a machine for efficiently producing virtual states, bringing life to particles that normally hide inside the nucleus or slumber in the flickering world of virtual states.

- It does this by colliding particles at velocities approaching the speed of light. The states produced depend on the particles they accelerate.

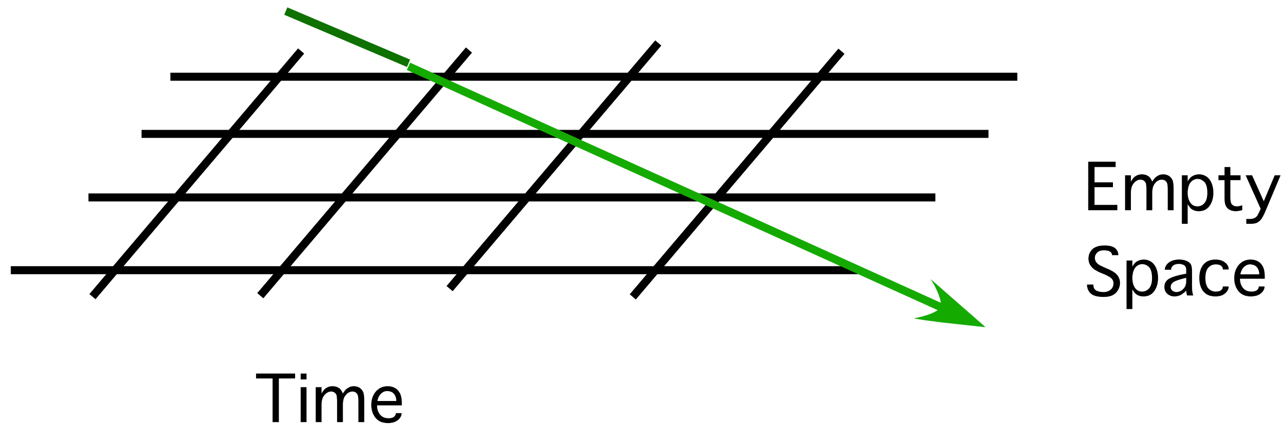
- The strong force is "asymptotically free". It confines quarks to nucleons, yet still allows us to detect their interactions through particle jets.

- The mass of visible matter comes from the Higgs particle and from the strong force.

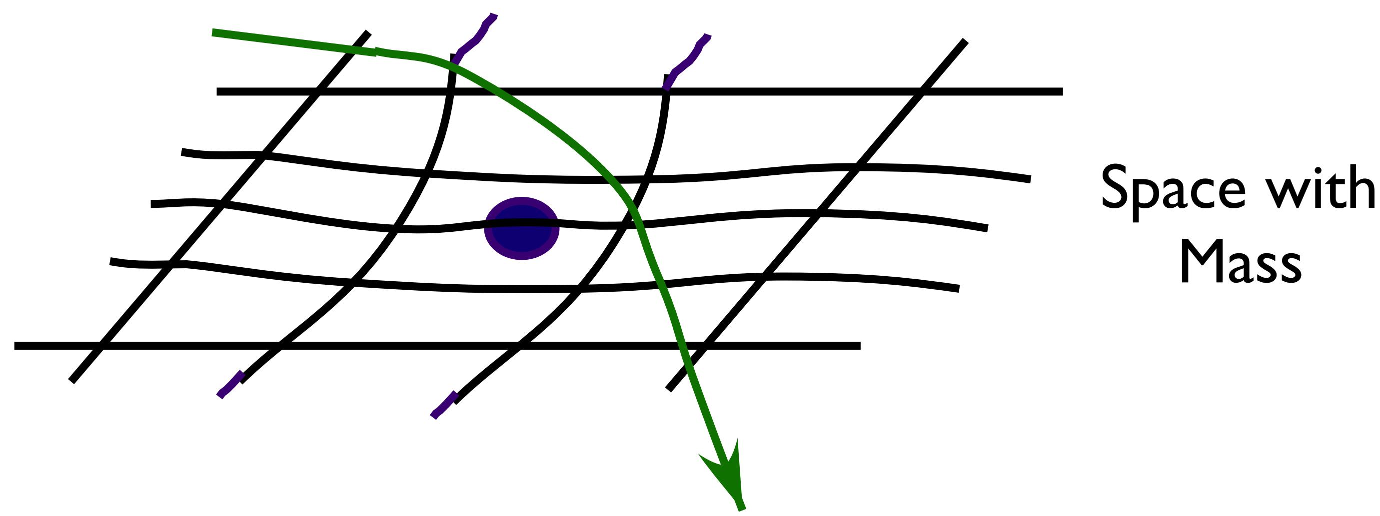
V. The Realm of Gravity

- At the largest scales, gravity is a gauge theory, with transverse waves.
- These are waves in and of space, coupled to all energy, including their own.
- Gravity's highly nonlinear interactions make it different.
- These interactions have been seen in waves observed by LIGO.
- Cosmological observations point to sources of gravity beyond the Standard Model.

Gravity is just the shortest distance in curved space-time

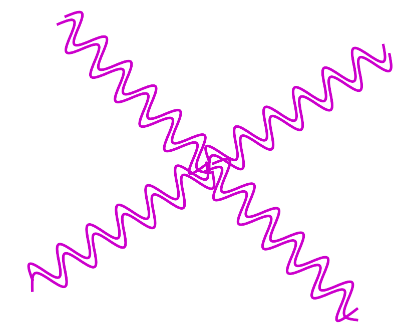


The future is where the "geodesic" goes.



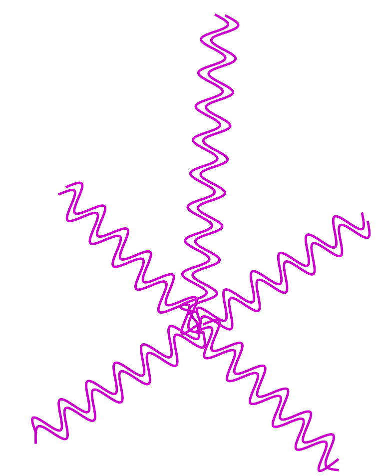
Gravity itself has waves

And they are transverse. Classically, they are complicated but can be computed numerically.



The "problem" is that gravity couples to energy and momentum.

When we have a vertex with four gravitons, it contributes to the energy.



The graviton has to couple to it again, and therefore, we get a vertex with five gravitons. And so on.

Thus, the quantum mechanics of gravity won't follow the pattern found in the Standard Model.

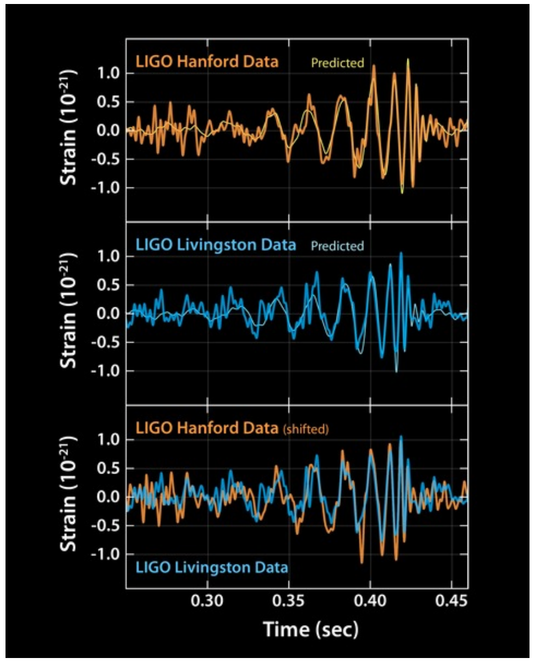
Gravitational waves have now been seen!

LIGO

They have come from the merging of black holes and more recently (also VIRGO) neutron stars

The signal is a wave with rising frequency.

It must be computed numerically, and it is dependent on high-level interactions.



A little about big subjects in the cosmos.

- How structure forms in the universe and behaves in galaxies requires sources of gravity from more matter than we can see. This is described as "**Dark matter**", which could participate in the weak force of the Standard Model, but could be invisible, except for gravity.

- **Dark matter could readily appear in extensions of the Standard Model, and many experiments are searching on earth for dark matter with weak interactions. The unprecedented surveys of stars may help map it out through subtle gravitational lensing.**

- From changes in the expansion rate on cosmic scales, the universe appears to be accelerating.

- Today, the exploration of a "**dark energy**" is through surveys of the formation and distribution of distant galaxies and supernovae. Many are underway, and many are planned.

In summary (part V)

- At the largest scales, gravity is a gauge theory, with transverse waves.

- These are waves in and of space, coupled to all energy, including their own.

- Gravity's highly nonlinear interactions make it different.

- These interactions have been seen in waves observed by LIGO.

- Cosmological observations point to sources of gravity beyond the Standard Model.

VI. Prospects and conundrums

- **The SM has been extraordinarily successful.**

- **At present there is no generally accepted contradiction in the data, although there are potential discrepancies, mostly associated with the 2nd and 3rd generations of quarks or leptons. There is good reason to believe that ongoing experiments will clarify these exceptions.**

- **Should one or more exceptions turn out to be a sign of "new physics", it is possible that the SM can be generalized in the same general form — a new set of particles, a new gauge theory, a profound symmetry between matter and forces ("supersymmetry").**

So What Gives us Pause?

Our story is of the "visible universe"

But there is that which we cannot "see" directly.
<u>Dark matter</u>, which appears to have been created alongside the matter of the Standard Model, and which pulls upon us with its gravity. We can "see" its effects indirectly though the motion among and inside galaxies. Perhaps it shares weak interactions, but we don't know yet.

<u>Dark Energy</u>, which appears to come into existence as the universe expands. Its influence is at the cosmic scale, seeming to accelerate the expansion.

Oddly, the stories of the Standard Model itself would produce an equivalent of dark energy, but at a scale much, much larger than what we observe!

There is a lot that we do not understand . . .
But, perhaps in that we should rejoice!
And really, it is only one of many questions.

- The SM is a tremendous success of human insight and inventiveness, but it remains unsatisfying to many.

- Its essential drawback is its "dimensionless" numbers — the three couplings: g_s, g_W, e, and the ratios of fermion masses, encoded in their couplings to the Higgs particle. Such "pure numbers" are elegant, but arbitrary.

- And then — why 3 generations, why three heavy gauge bosons, why 3 colors for quarks? All these seem to point to an underlying reality, which we haven't yet touched experimentally, although there are plenty of ideas. It could be string theory, or another formalism that can find a common ground for the transverse waves of gravity and those of the SM.

The story we've shared here is based on a particle description of quantum field theory, and that has been at the heart of the establishment of the SM. The eventual resolution of today's questions may have to come from different approaches.

At the same time, the particle approach has been spectacularly successful in bridging a wide range of scales, from the wavelength of light, 10^{-7} m to 10^{-19} m at the LHC.

When first invented, quarks were sometimes thought of as a mnemonic to organize what physical hadrons could form — but when we looked for them, they were there!

- **Perhaps an additional advance as profound as the creation of quantum mechanics will be necessary to bridge the gap fully.**

- **But we should also remember how far humanity has come since the unification of electricity and magnetism. Astonishing developments may yet be on the horizon, or even here already, in a form we are about to recognize.**

Let's keep looking for answers.