Prof. Heather Logan
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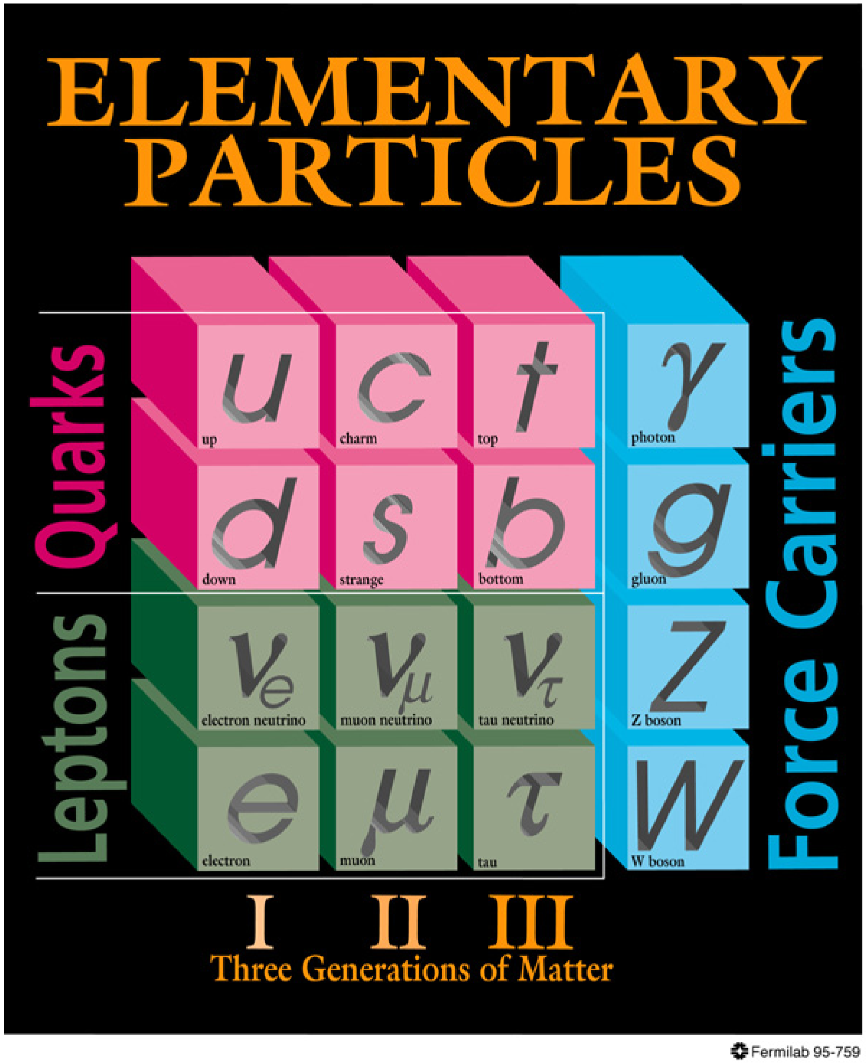
Carleton University

We know a lot about the structure of matter.



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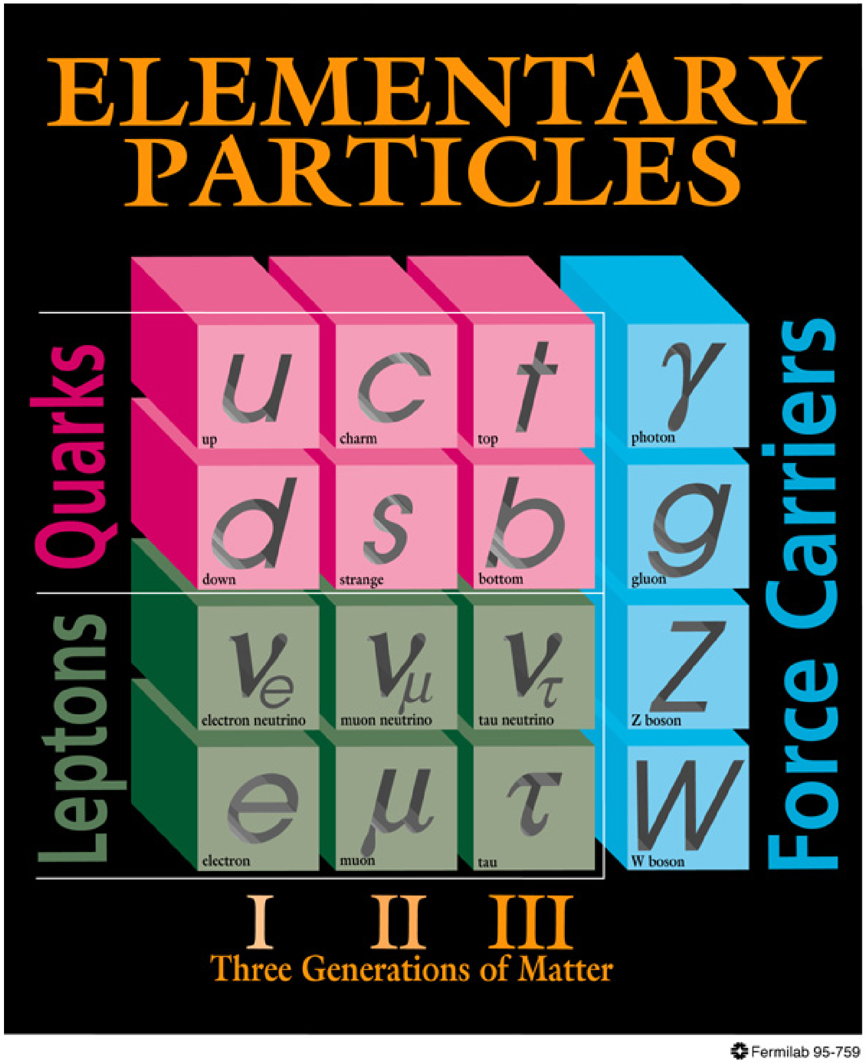


But...

What are all these particles?

How do they fit in to the modern understanding of matter at the smallest scales?

Where are the gaps in our knowledge?

The best way to answer these questions is to answer another:

How did we learn what we know?

In this talk I will focus on the matter (rather than the forces)

although the two really go hand-in-hand

There are two big themes that underlie the history of our discoveries:

1) the advance of technology that enabled each new experiment to be done

2) the advance of theory (built on our past experiments) that let us interpret the results of new experiments

Since I am a theorist, I'll focus a lot on item 2. :)

The original indivisible building block

Democritus (and Rutherford's atom) on a Greek 100-drachma note

Idea of indivisible "atoms" moving in a void came from Greek philosopher Democritus and his mentor Leucippus, 400's BCE.

- Consistent with observation of mixing and separation of substances, ability of fluids to change shape.

- Different features (sizes, shapes, attachment-points) for different substances.

But there was no way to test the idea in those days:

- The needed experimental technology didn't exist yet

- No framework of "physics" to even pose the questions

  e.g., no Newton's laws, ideal gas law, ...

So nothing much happened for the next 2200 years.

Chemistry and the birth of the modern atom

Chemistry was becoming industrially useful (mining, etc).
Idea (and technology) to measure quantities of reagents.

$\rightarrow$ Stoichiometry (Richter 1792)

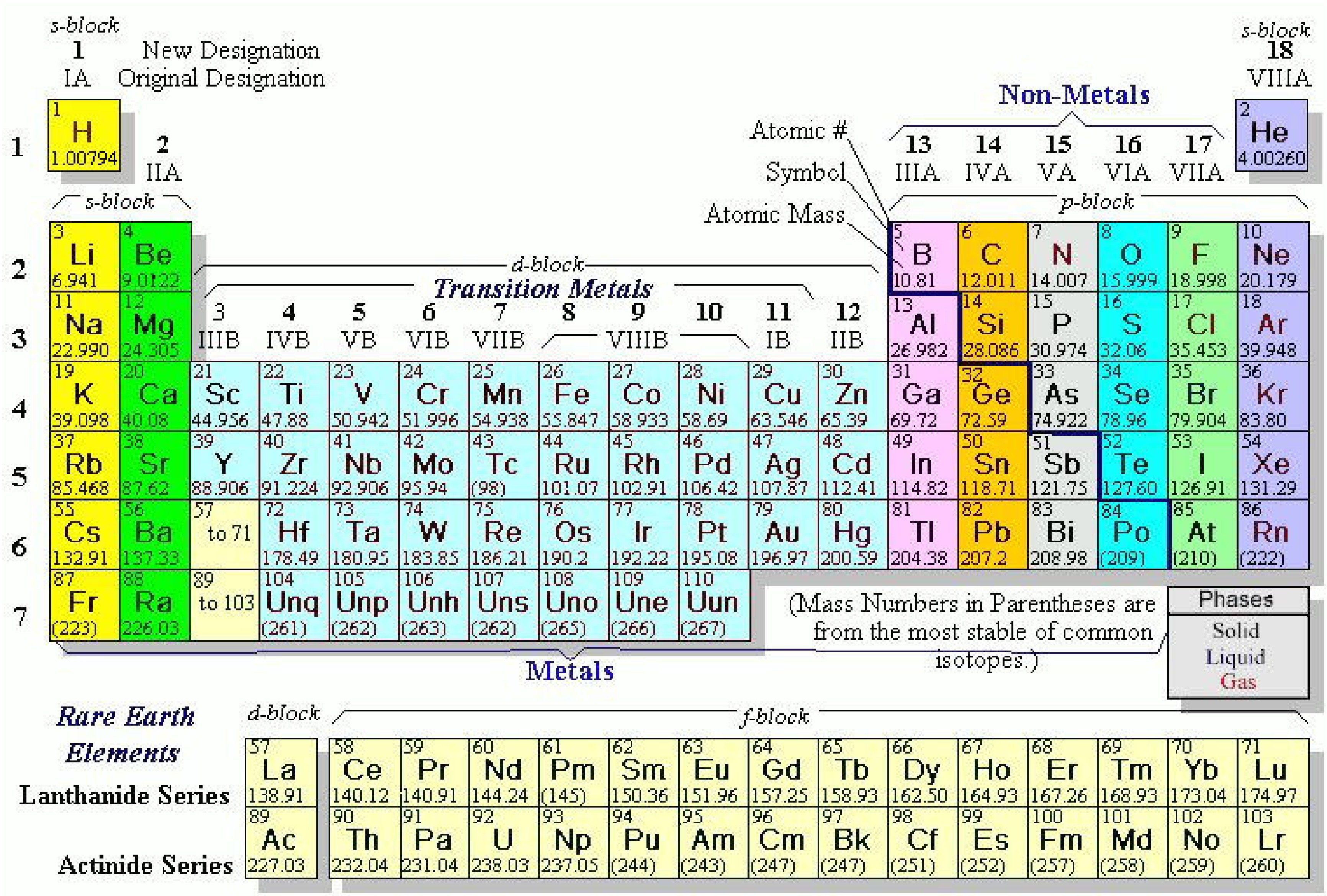
- Ratio of weights of compounds consumed in a chemical reaction is always the same. $2\,H_2 + O_2 \rightarrow 2\,H_2O$

Ideal gas law (Clapeyron 1834) $PV = nRT$

- At constant pressure and temperature, volume of a gas "counts the molecules" (Avogadro 1811).

Could start measuring the masses of different atoms relative to each other.

Periodic table of the elements (Mendeleev 1869)



Systematization of knowledge:
- Arranged known elements in order of their atomic mass
- Columns group the elements that have similar chemical properties

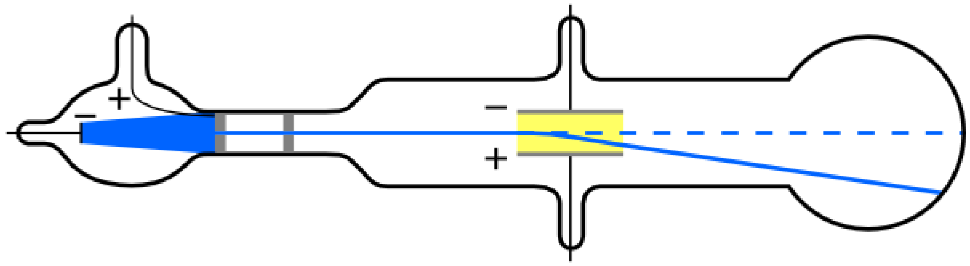
Definition of “atomic number”
- Later understanding in terms of number of electrons

Gaps in the table: some elements were “missing”!
- Predicted new elements and their properties
$\rightarrow$ subsequently discovered!

The key here was the combination of careful measurements and development of quantitative theoretical models.

Quantitative = giving numerical predictions

Atoms are divisible (J.J. Thomson 1897)



"Cathode rays", emitted from an anode at high (negative) voltage had been known for several years.

Are they "rays"? Are they particles? Thomson's key measurements:
- cathode rays deflected by an electric field → negatively charged
- measurement of these particles' charge-to-mass ratio Q/m

***** video *****

Discovery that cathode rays consisted of particles: the electron!

2000 times lighter than a hydrogen atom: some kind of subatomic particle. Now known as electrons!

Magnetic deflection: force depends on charge, speed, and magnetic field $F = QvB$ (many people, late 1800s)

Causes circular motion: radius of circle depends on force, speed, and mass $F = \frac{mv^2}{R}$ (Newton 1600s)

Set two forces equal and do some algebra:

$$QvB = \frac{mv^2}{R} \quad \longrightarrow \quad \frac{Q}{m} = \frac{v}{BR}$$

How do we measure v? Use electric deflection to cancel magnetic deflection! Turn up voltage until $F = QE$ (Coulomb 1783) exactly balances $F = QvB$ – that is, $QE = QvB$.

Solve for v: $v = \frac{E}{B}$

Put it all together: $\frac{Q}{m} = \frac{E}{B^2R}$

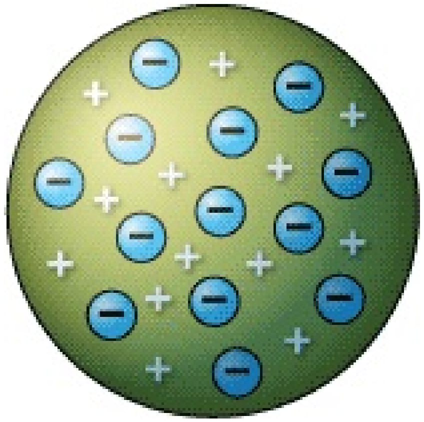
We know E and B and can measure R, so we can find Q/m!

- Atoms have (negatively charged) electrons in them

- Atoms are net neutral

- There must be some positively charged stuff in the atom too.

Plum pudding model (Thomson)

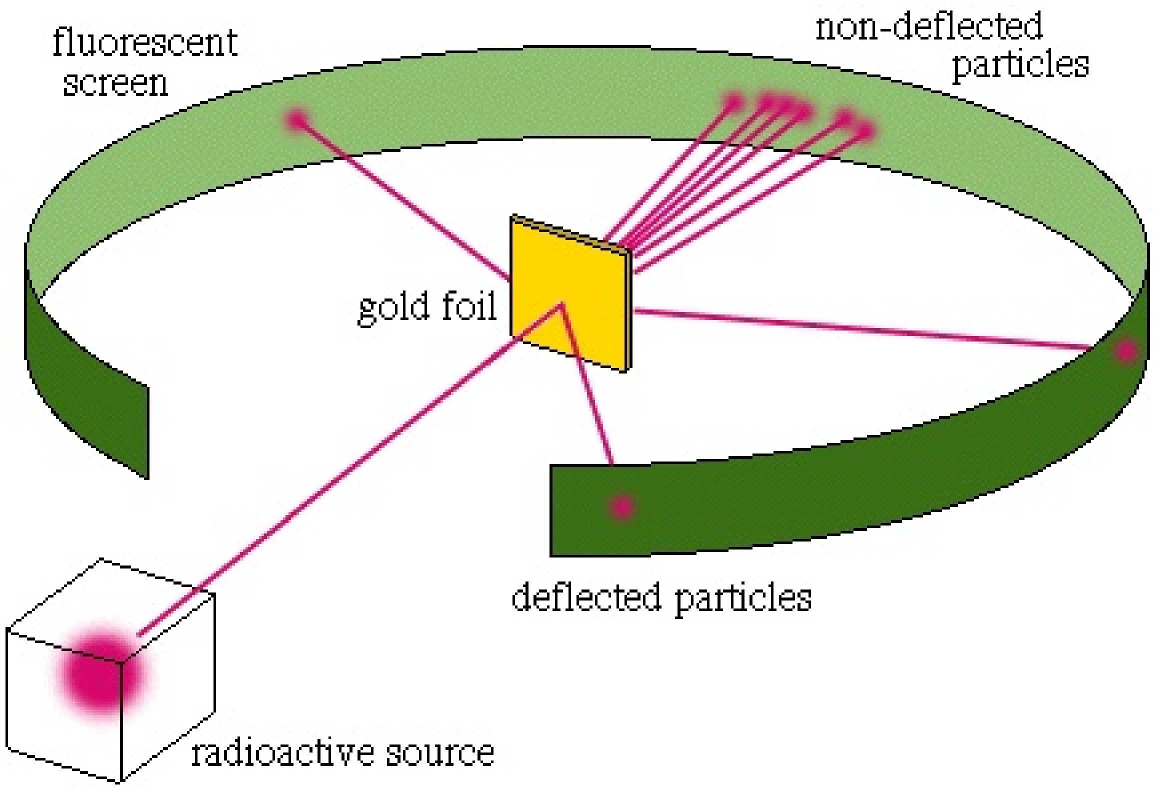


But how do you test this? Atoms are too small to see.

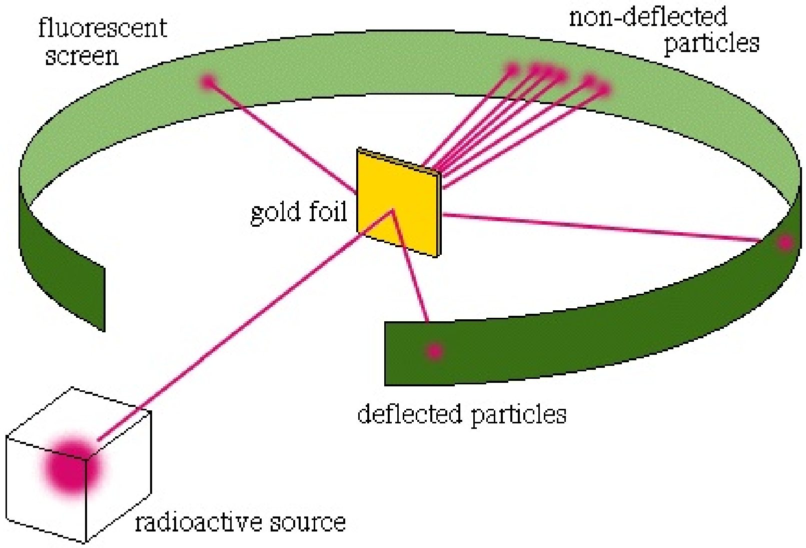
Answer: shoot stuff at it!

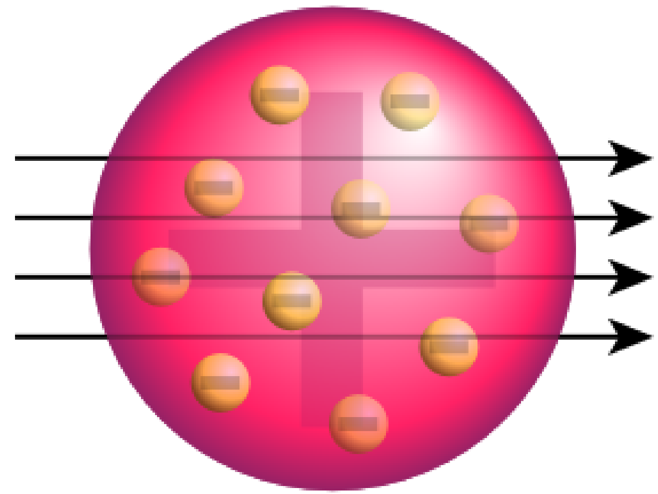
Radioactive elements had been discovered by then: use a source that emits alpha particles.

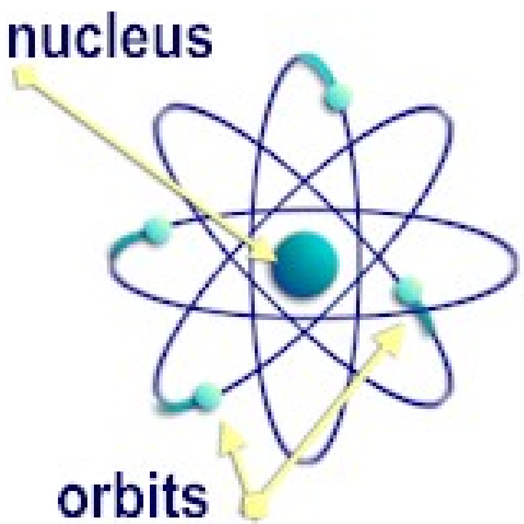
"Rutherford scattering" experiment (done 1909 by Geiger & Marsden, working under Rutherford's direction)

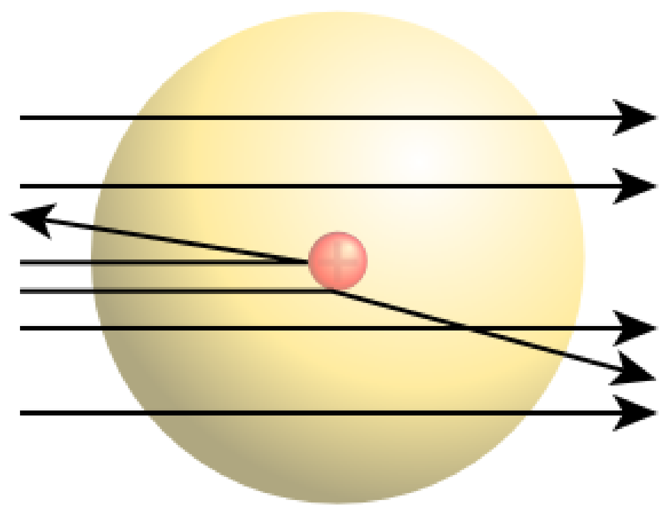


Surprising thing was the large-angle deflections.



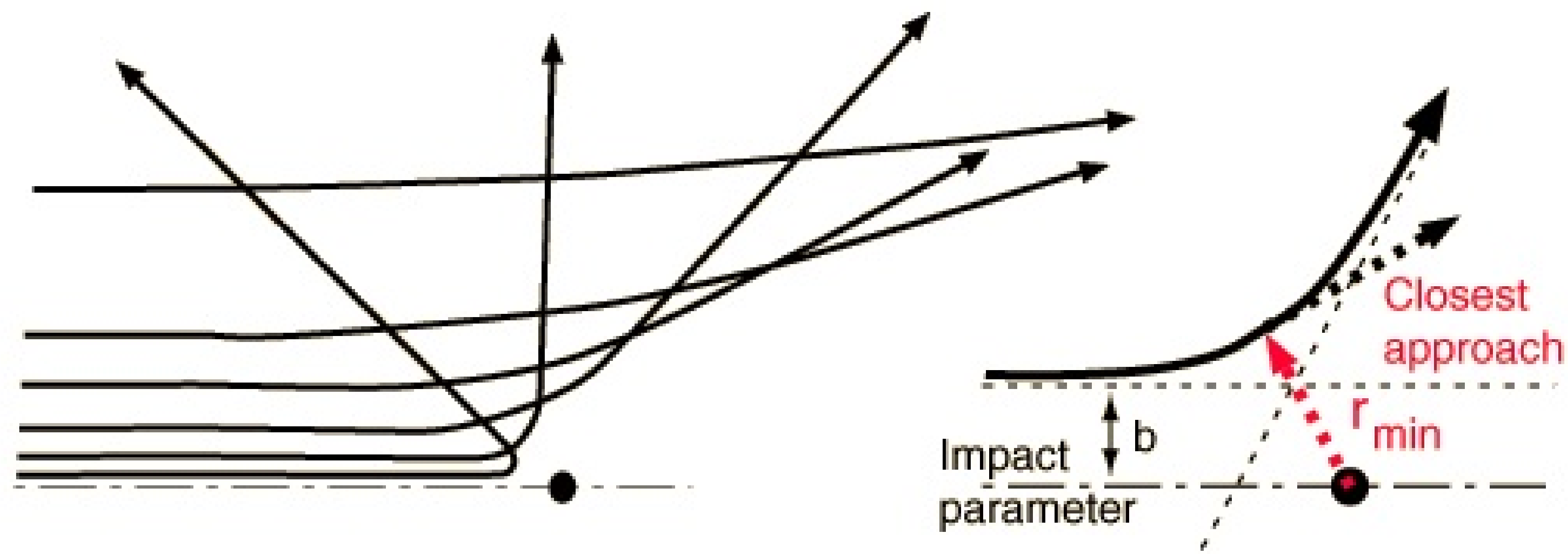


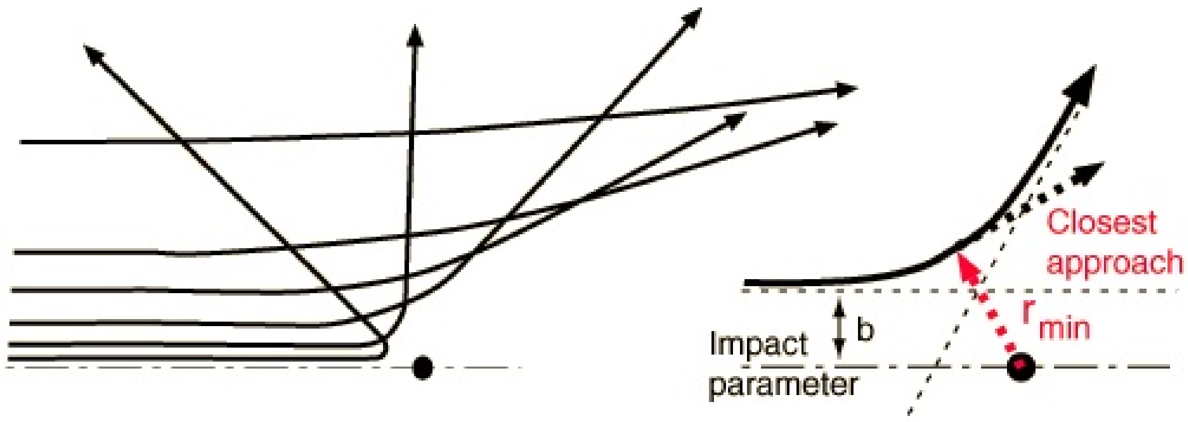




Experiment done 1909, but theoretical interpretation only worked out by Rutherford in 1911.

Understand this using scattering theory: an established idea in classical mechanics.





- Hypothesize the force law from the target:
  Coulomb force in this case, $\vec{F} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}\hat{r}$
- Pick a value for the "impact parameter"
- Figure out projectile motion using $\vec{F} = m\vec{a}$
- Predict the scattering angle θ

- Average over the impact parameter: gives a "count density" as a function of angle.

- Compare to experiment to test the force law hypothesis!

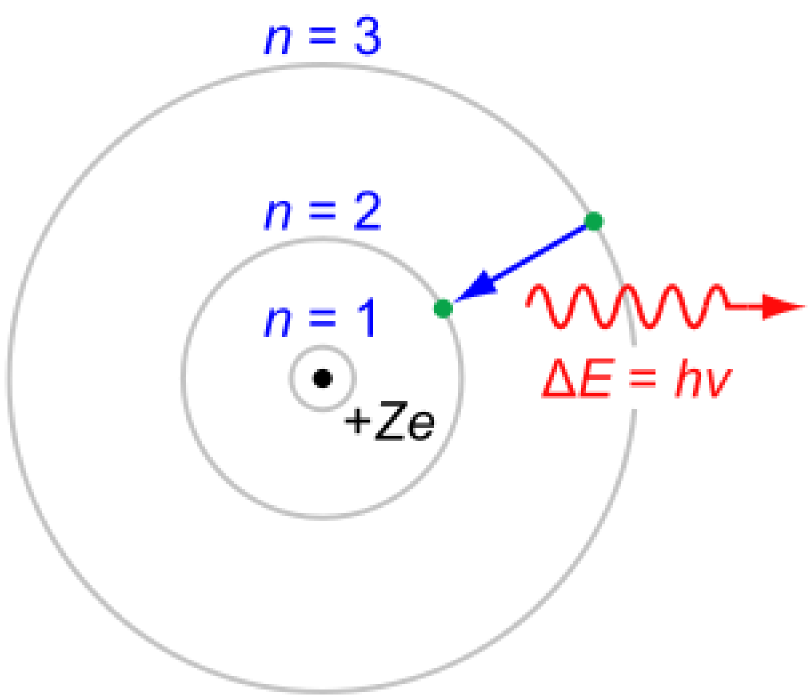
To make things more general, divide out the number of projectiles per square centimetre per second.

This gives what's called a differential cross section (a function of scattering angle in this case): expected number of events per unit angle per unit incoming beam flux.

- Predicted by the underlying interaction hypothesis
- Can be tested quantitatively in a scattering experiment

This concept is absolutely central in modern particle physics experiments.

1920s: quantum mechanics was developed.



"Orbitals" for electrons
+ Pauli Exclusion Principle

→ explanation for periodic structure of periodic table

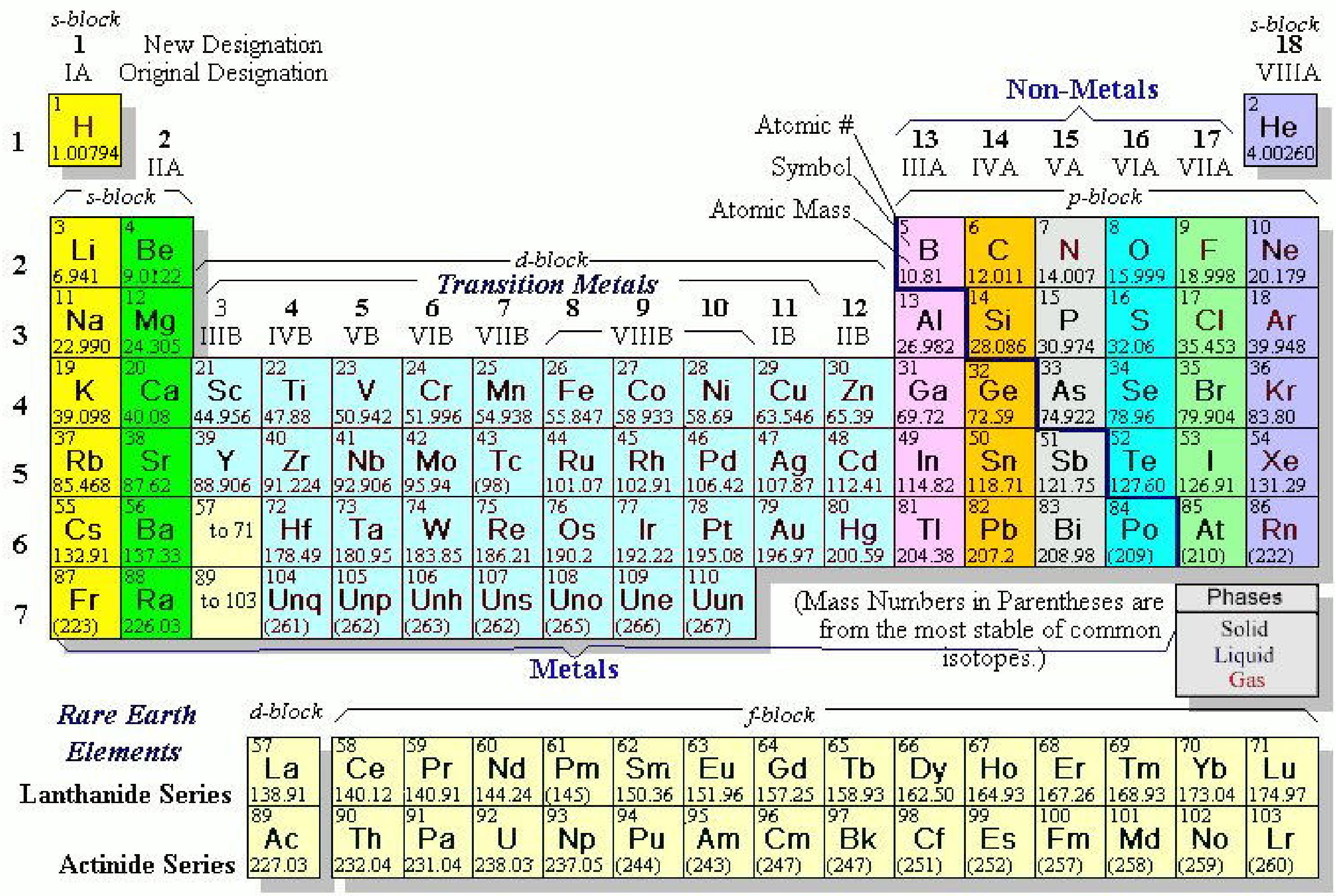
Also high-precision predictions for spectroscopy, understanding of geometric structure of molecules/crystals, foundation for modern electronics, ...

That is a talk for another day.

The upshot here is that quantum mechanics gives a mathematical framework for doing the theory to compare to experiments.

(Quantum Field Theory: basis of all modern particle physics.)

The substructure of the nucleus



Atomic mass increases faster than atomic number

- Hydrogen, atomic number = 1, atomic mass = 1
- Helium, atomic number = 2, atomic mass = 4
- Lithium, atomic number = 3, atomic mass = 7

Initially it was thought that the nucleus contained just protons and electrons.

Now we know that's not true: nucleus is made of protons and neutrons, a new type of particle.

Discovered as a new type of radiation that you could blast off of nuclei. Again, this was from careful measurements of the properties of the radiation by many people.

Theoretical synthesis by Chadwick (1932), based on:

- how the new radiation is absorbed by other materials, like lead, in a way that was inconsistent with it being gamma rays;

- how it is not deflected by electromagnetic fields, so it can't be electrically charged like electrons or alpha particles;

- how it can kick protons out of hydrogen-containing materials, like billiard ball scattering: deductions about its mass.

By now it's the 1930s and we have all the basic ingredients of ordinary matter. (or do we?)

People got interested in how protons and neutrons interact in the nucleus.
- Protons repel each other: what keeps them together?
- If there's a new force, it has to be short-range: can prove from quantum mechanics that this means that the force-carrier has to have mass!

Predict the mass from the range of the nuclear force, inferred from size of nucleus (Yukawa 1935)
- should be about 200x the electron mass
- new particle should interact with nucleons (by definition)
- should be able to change a neutron into a proton – this would explain beta decay

Called the "mesotron" (meso = middle, -tron like in neutron, electron). Purely theoretical prediction!

And sure enough, in 1936 a new particle was discovered!

- Discovered by looking at cosmic rays going through a cloud chamber

- Mass 207 times the electron's, measured using a magnetic field and Thomson's Q/m method

A triumph of theory!
... except that it did not interact with the nuclear force. D'oh!

It was actually the muon, a particle exactly like the electron only 207 times heavier!

– "Who ordered that?!?"

(I.I. Rabi; discovered nuclear magnetic resonance)

Discovery of Yukawa's actual particle, the pion, came in 1947.

Again from cosmic rays, hitting photographic emulsions placed on top of mountains in the Pyrenees and the Andes.

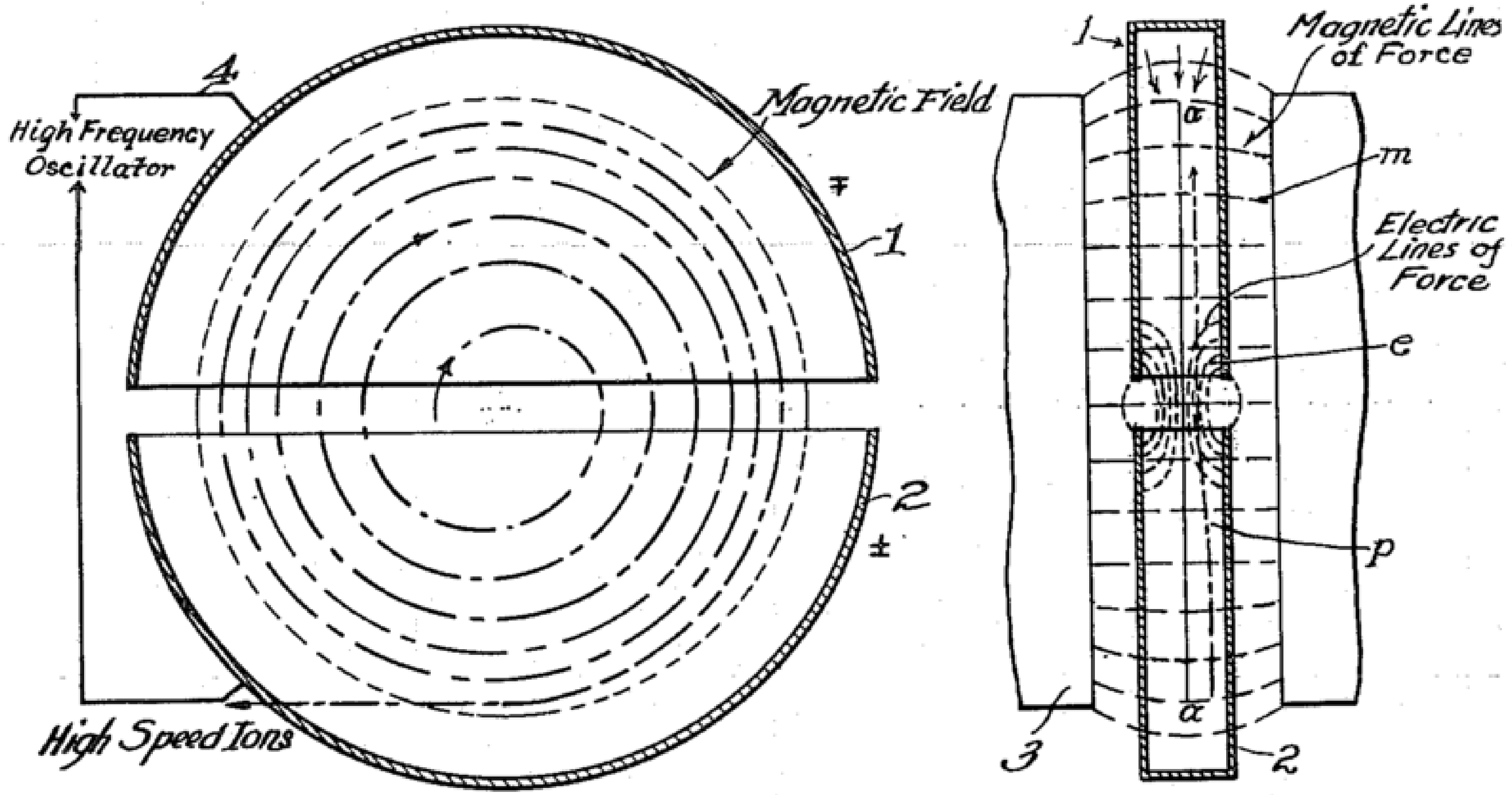
This time it really was the pion predicted by Yukawa.

But humanity was running up against the limits of natural radiation sources for experiments.

Need a new tool for experiments!

Chacaltaya (Bolivia): 5,421 m (17,785 ft)—very little atmosphere above it, lots of cosmic rays get through!

The cyclotron

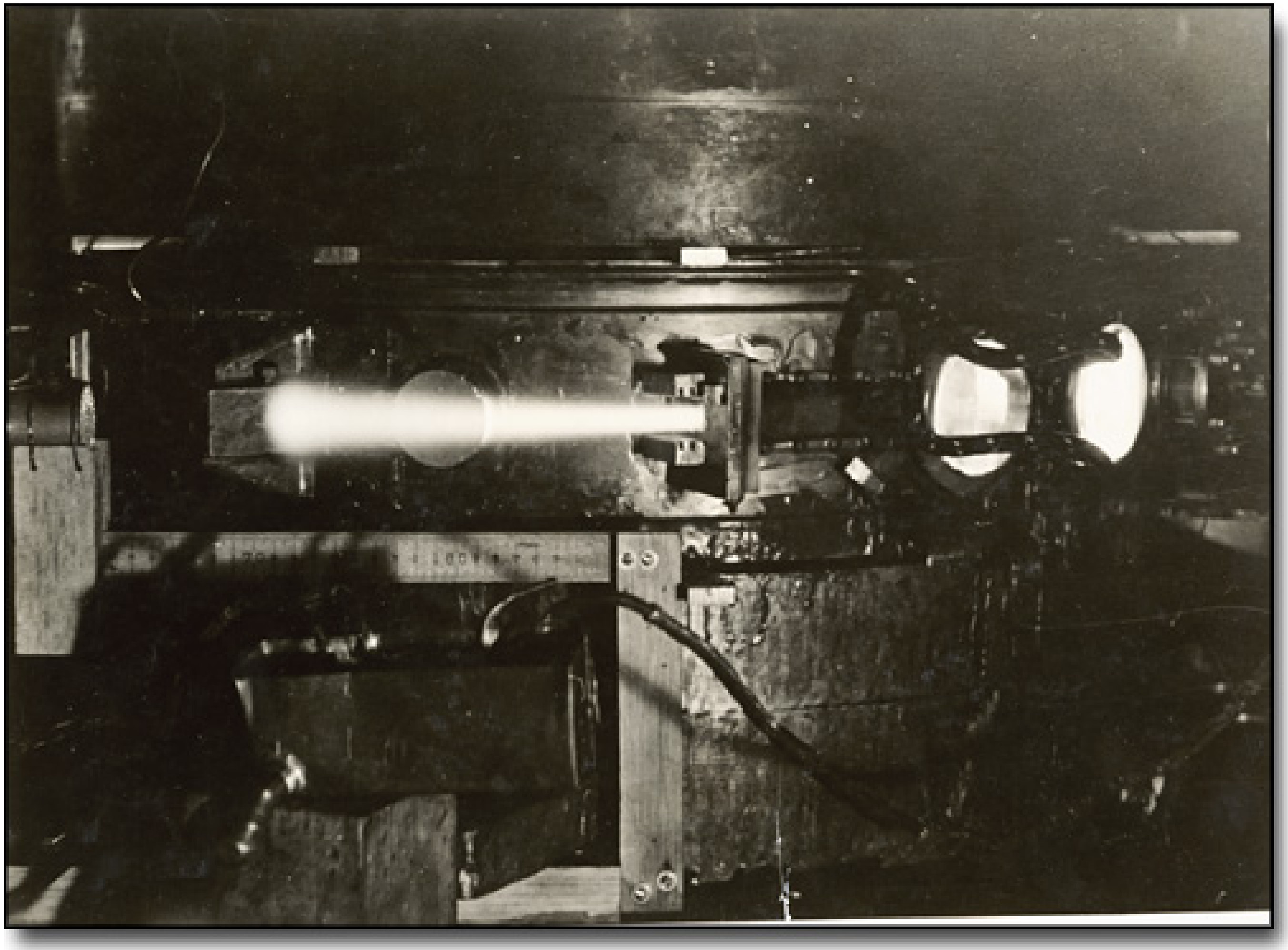


***** animation *****

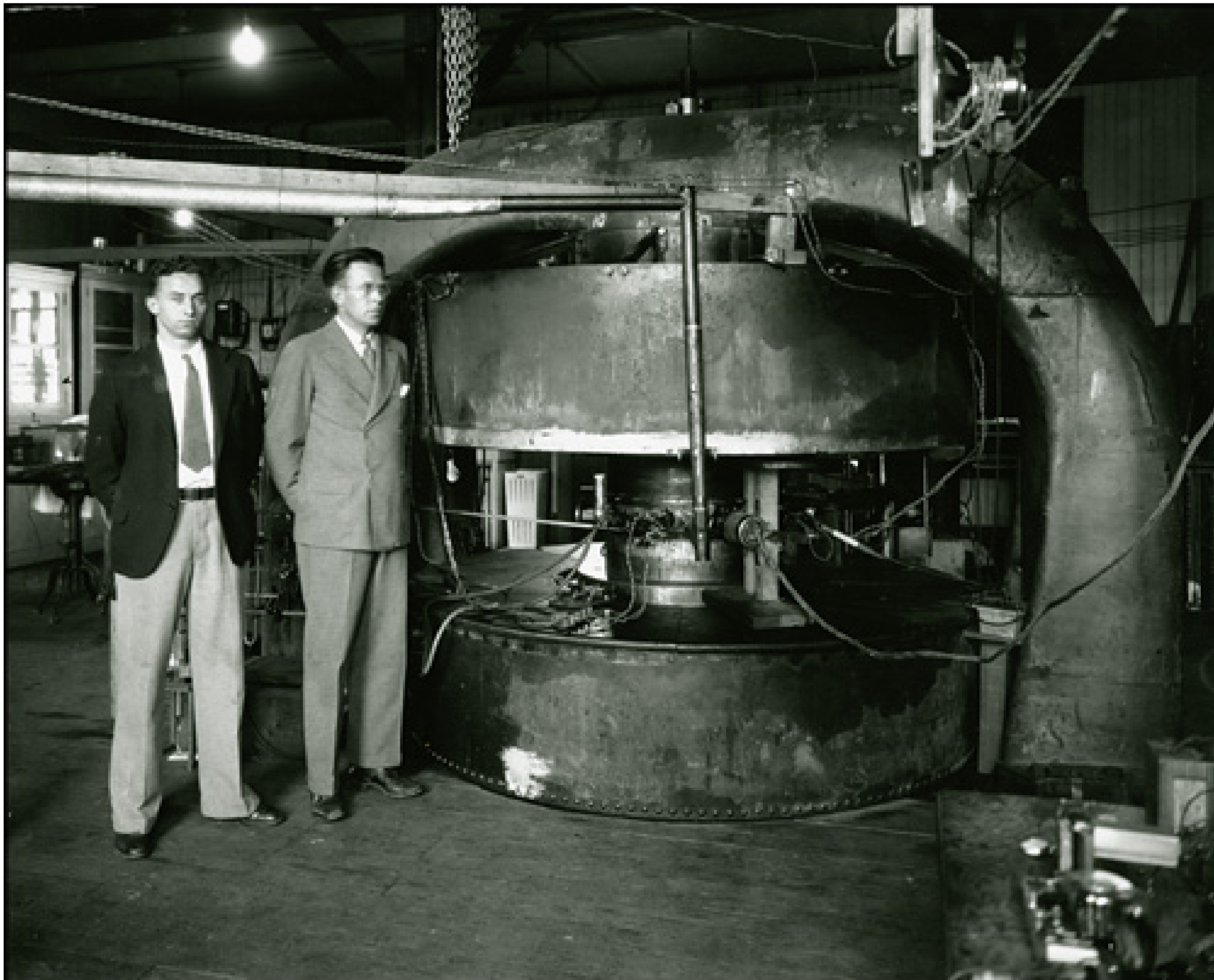
Cyclotron invented 1931 by E.O. Lawrence (U.C. Berkeley)

Prototype model for the first one was quite small, made of random bits of metal, glass, and wax (!)

Lawrence then proceeded to build bigger and better cyclotrons for the next 2 decades.

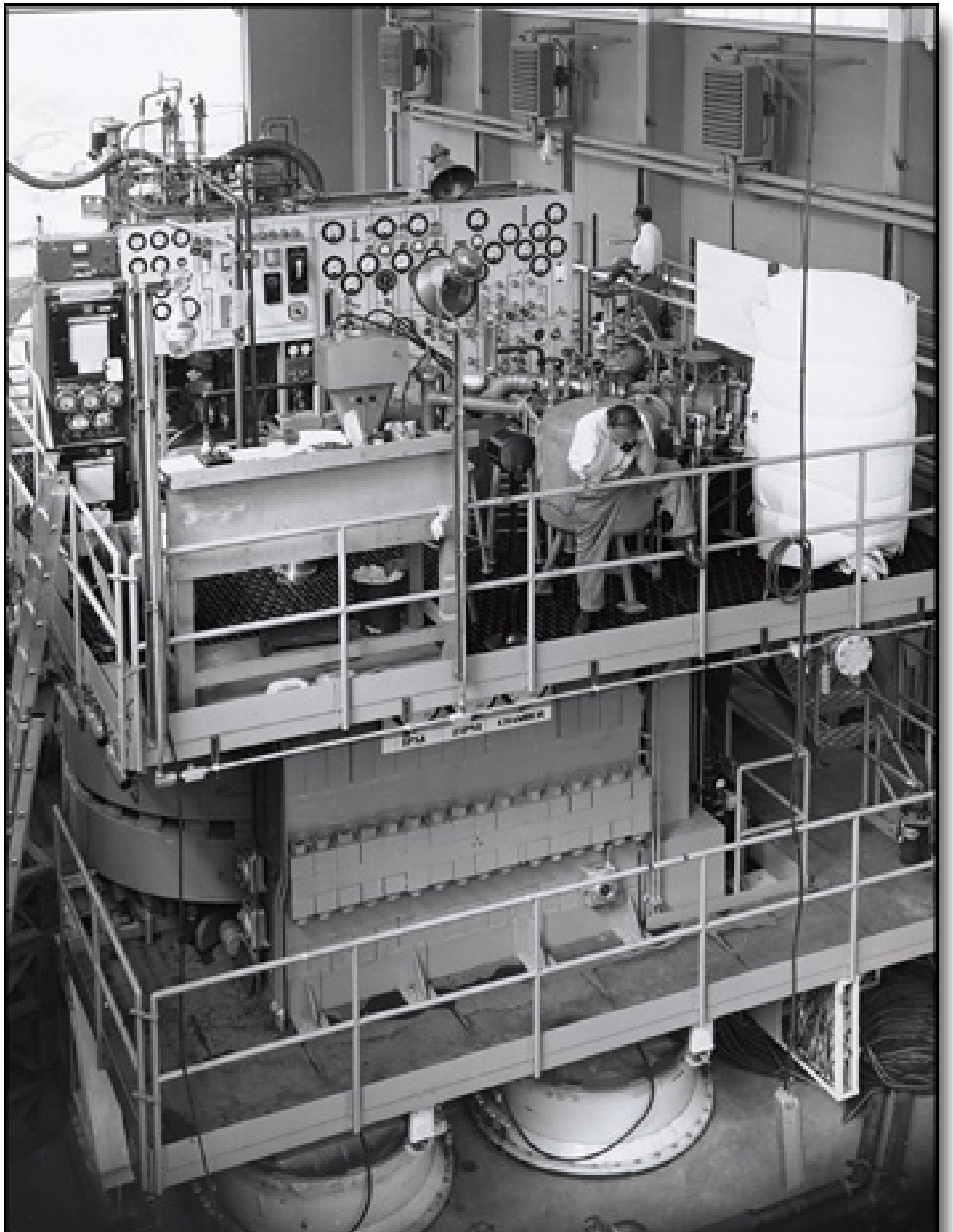


11-inch cyclotron (1931), with air glow of the beam



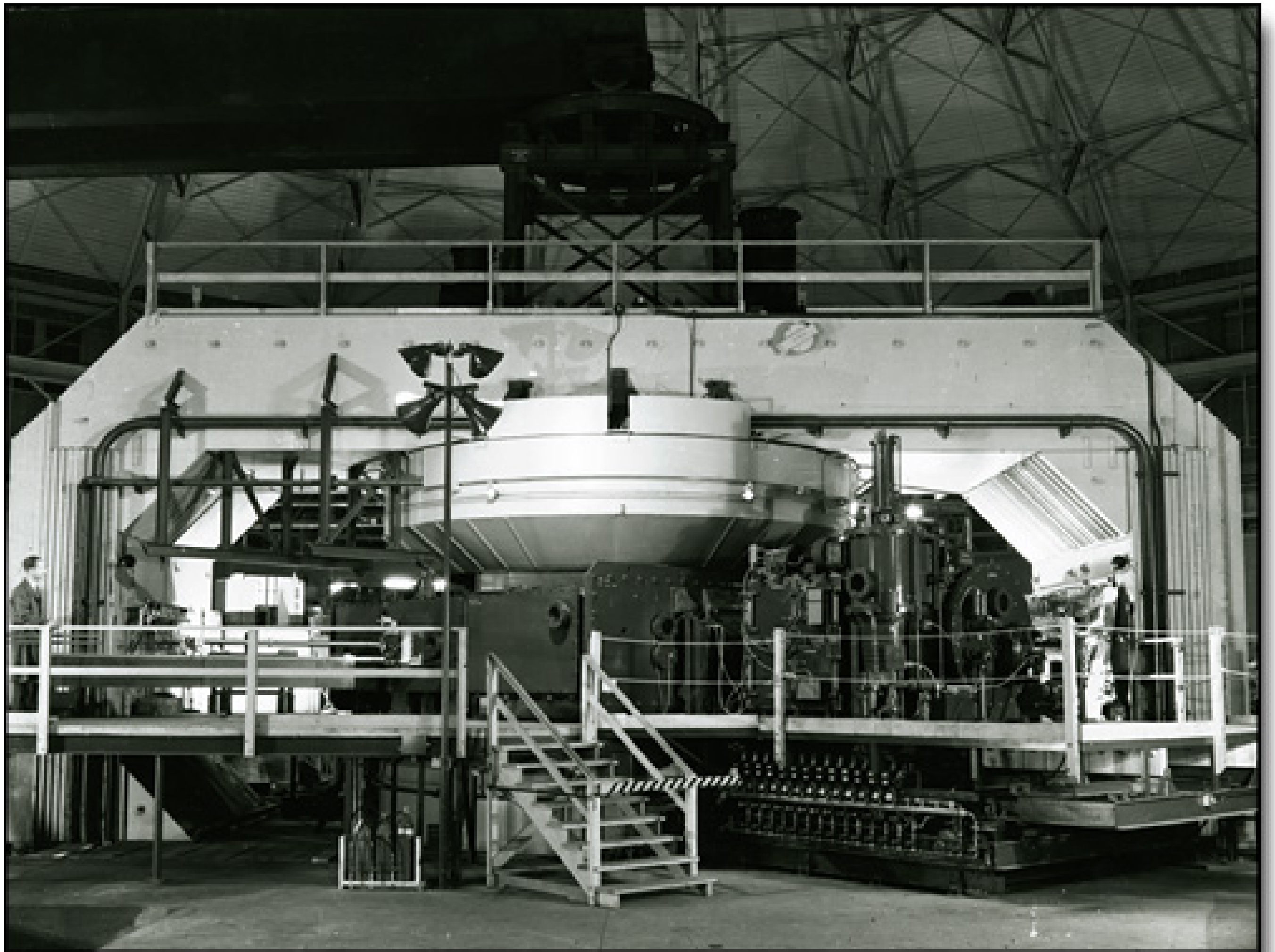
27-inch cyclotron (1932) with Lawrence and a colleague

Lawrence at work on the 37-inch cyclotron (1937)



60-inch cyclotron (1939)

Eventually turned over to making medical isotopes

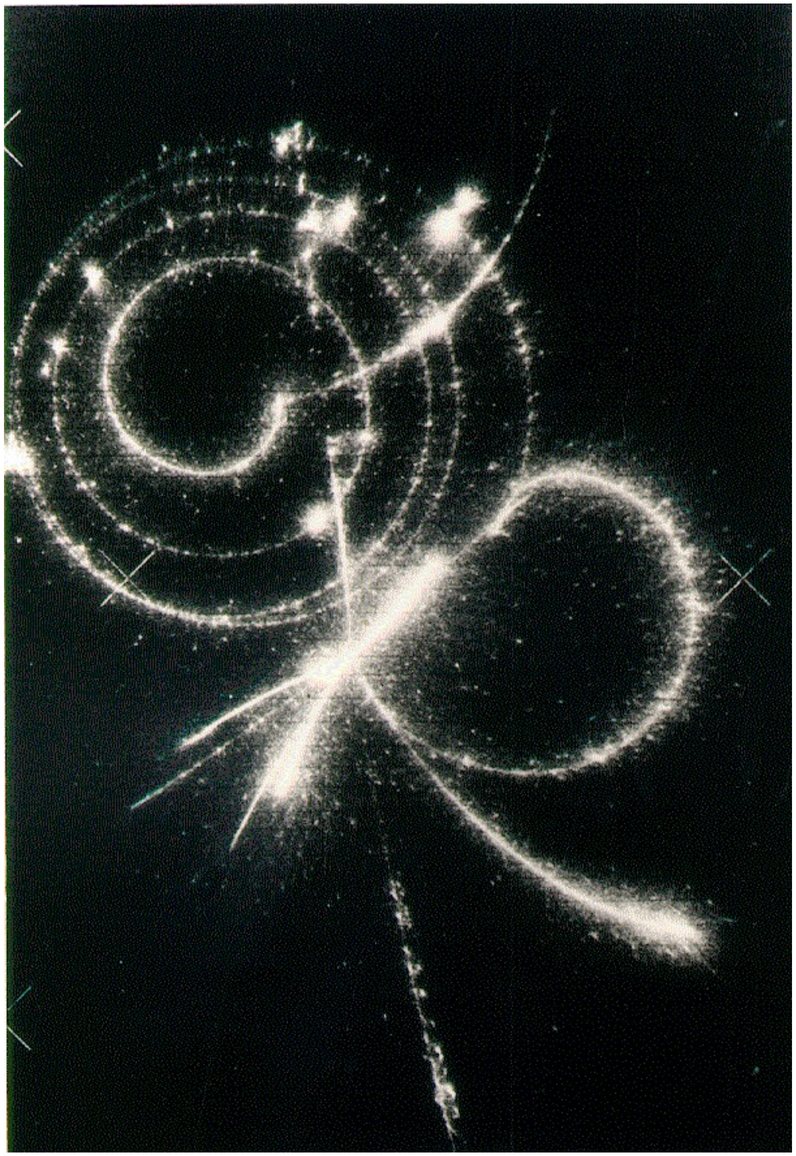


184-inch (4.7 m) cyclotron under construction (ca. 1940).

This was used to artificially produce pions and cement their discovery in 1948 (1 year after pion discovery in cosmic rays) by bombarding carbon with alpha particles.

The world's biggest cyclotron is at TRIUMF in Vancouver, still doing cutting-edge nuclear physics research.

(Shown here under construction in 1972)



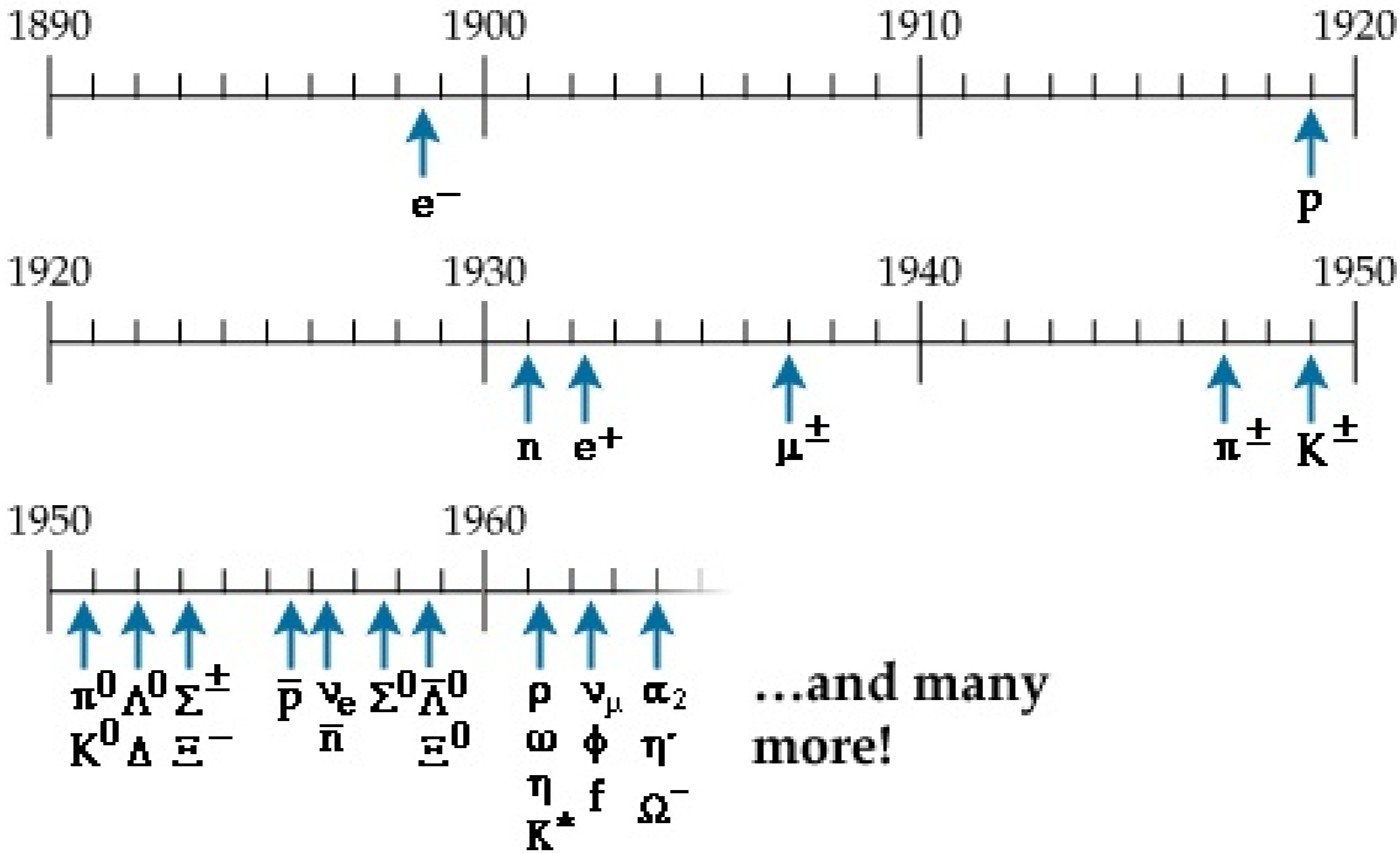
With a way to produce pions in the lab, their properties could be more carefully studied.

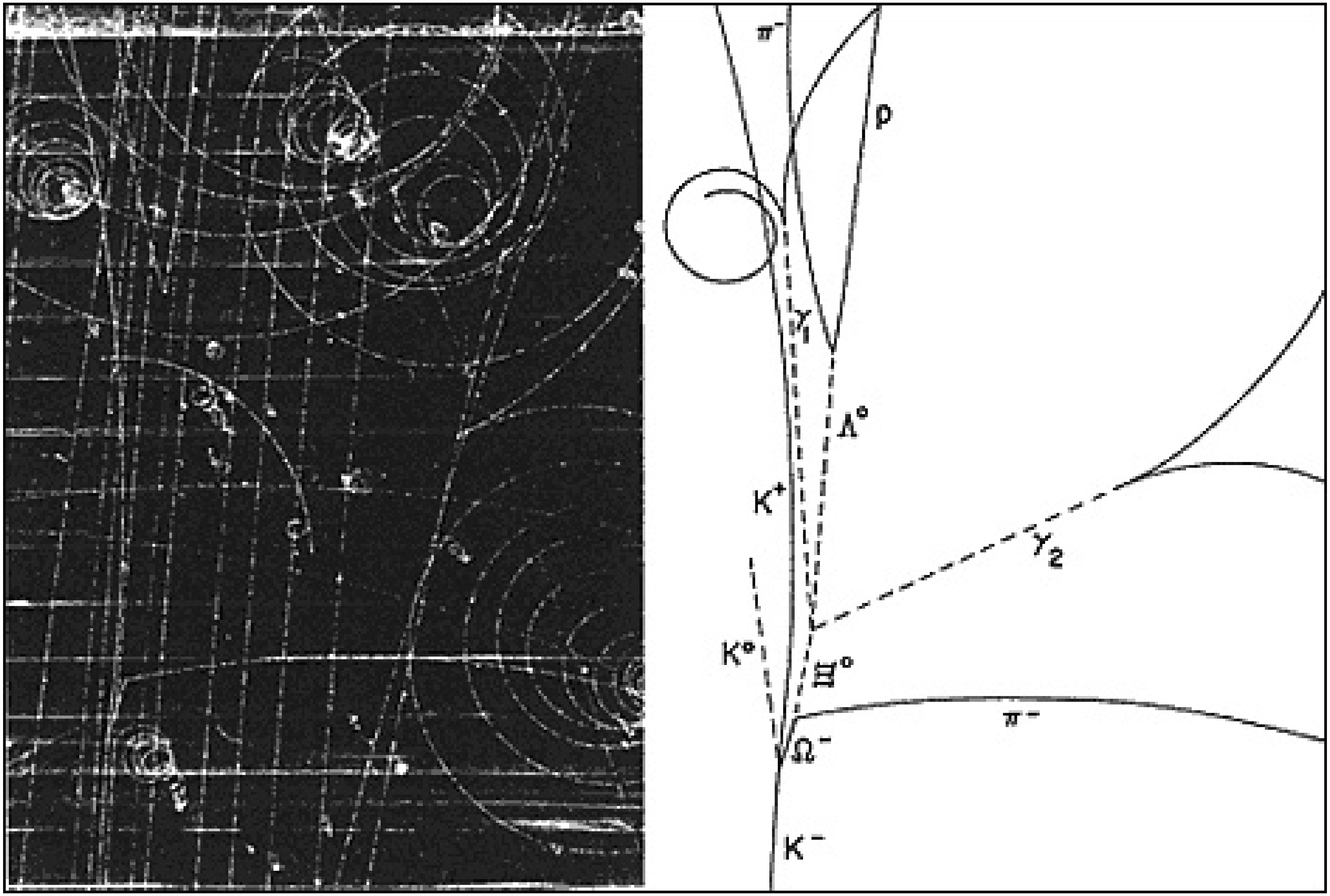
Shown here is the decay chain of a pion:

pion $\rightarrow$ muon $\rightarrow$ electron

(Seen here in a streamer chamber – a type of gaseous detector)

Birth of the "industry" of particle physics





Particles were identified by photographing their tracks in a bubble chamber or a cloud chamber

This was done by hand! Very slow process, but there was not a lot of data in those days, and you didn't need to worry as much about "background events"—just one unique new event was enough to discover a new particle.

Question: Why are the tracks spirals?

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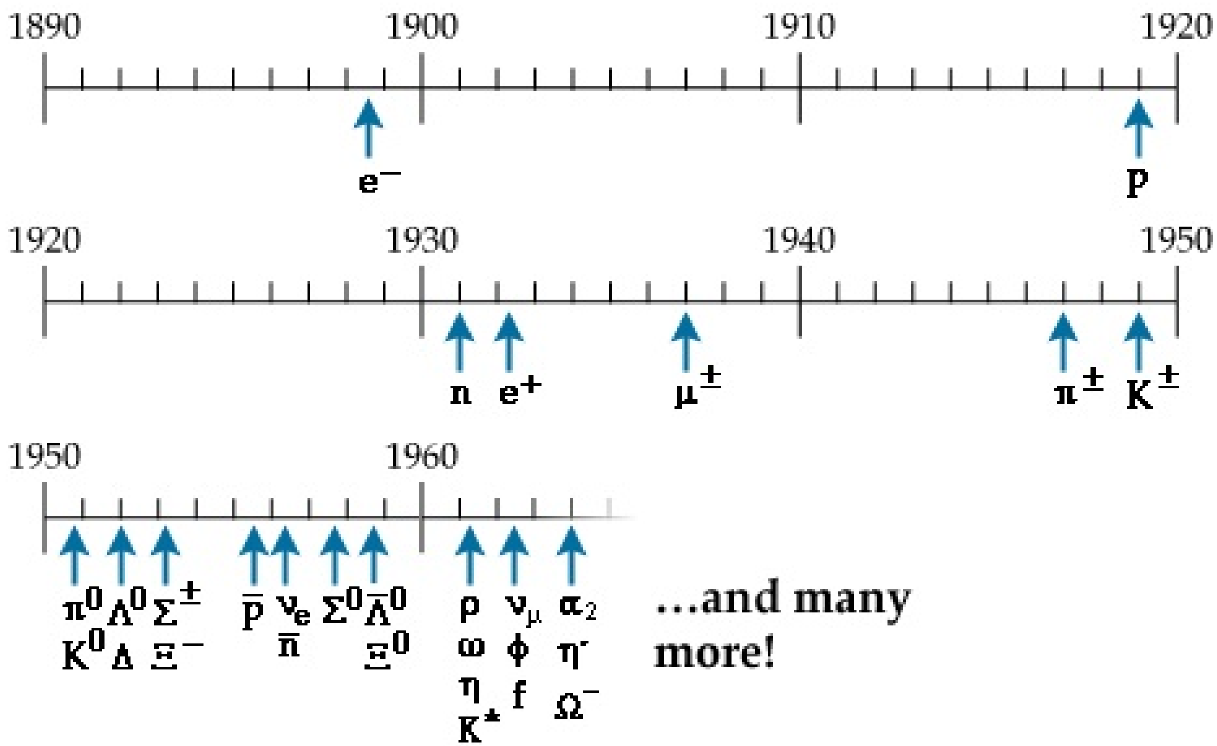
Hint: Remember that charged particles will move in a circle in a magnetic field: $R = \frac{mv}{QB}$



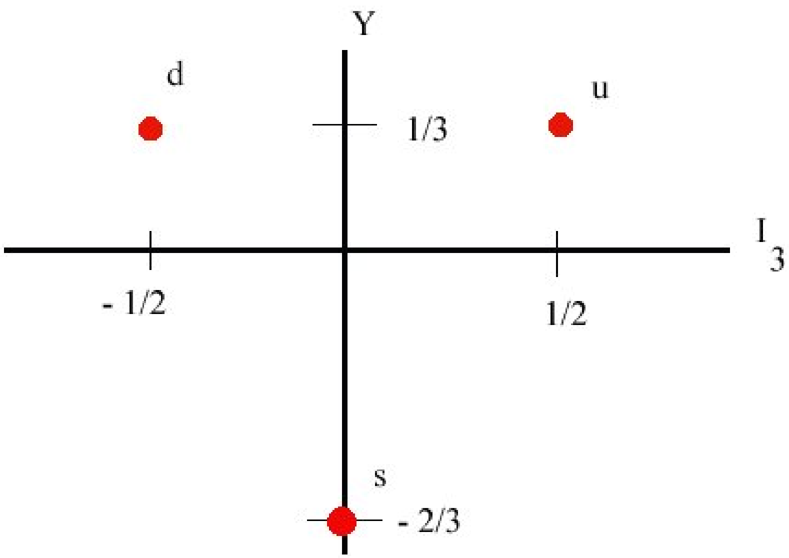
By the 1960's, things were a mess.

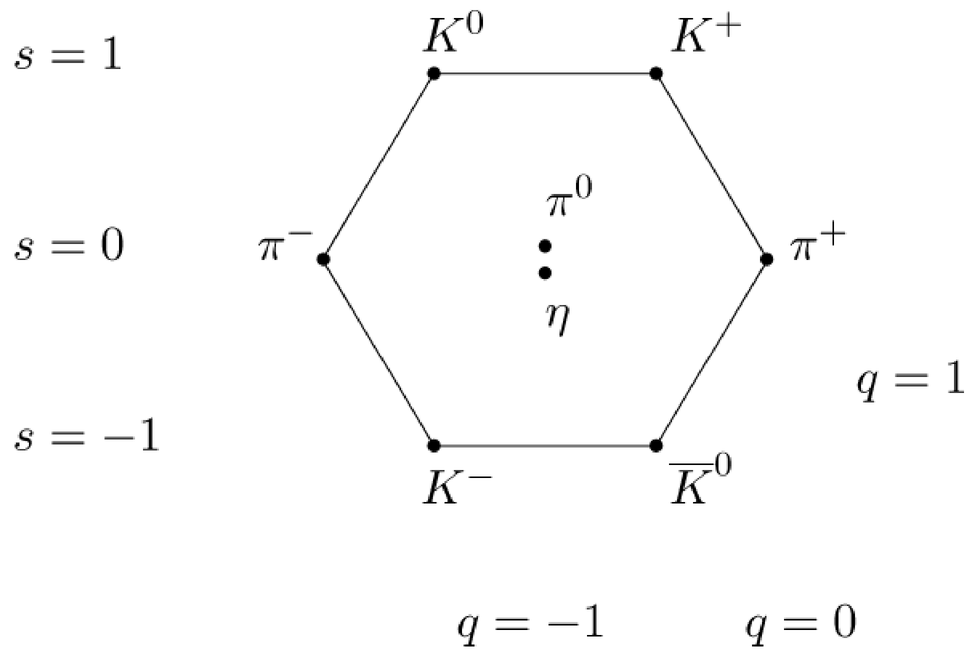
Willis Lamb (1955, Nobel Prize lecture for atomic fine structure) joked that he had heard it said that "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine."

In bad need of a "periodic table of the particles"!

Gell-Mann's eight-fold way (1962): the invention of quarks

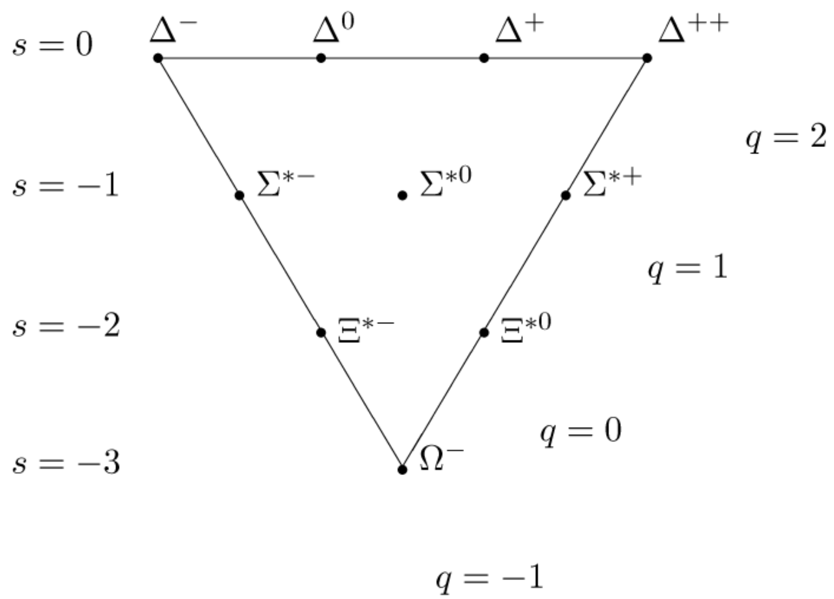
The theory behind this rests on group theory.
Invent 3 quarks (a "triplet"), and a "symmetry" among them.
Put together 1 quark and 1 antiquark: a meson.
8 ways to do it ("octet"):

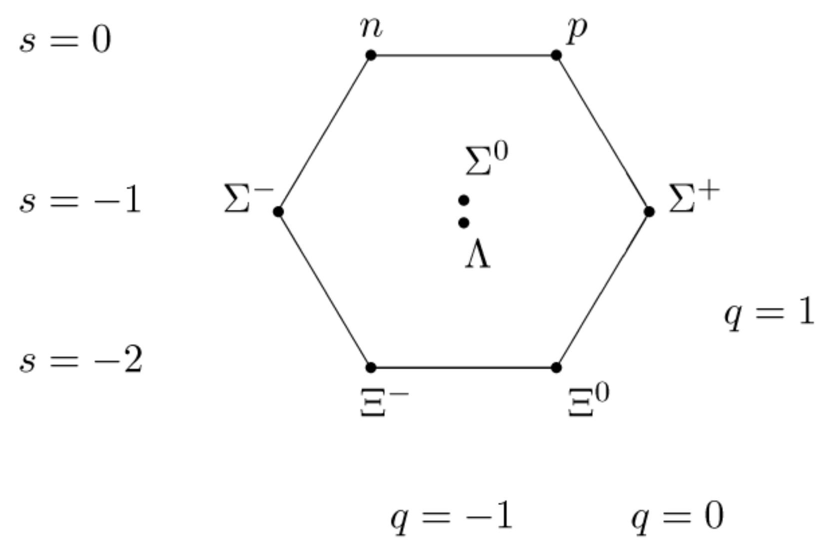




(plus one symmetric "singlet" combination, the $f_0(600)$ or σ meson)

Put together 3 quarks: a baryon. Different spin combinations let you make different quark combinations: total spin 3/2 or 1/2:

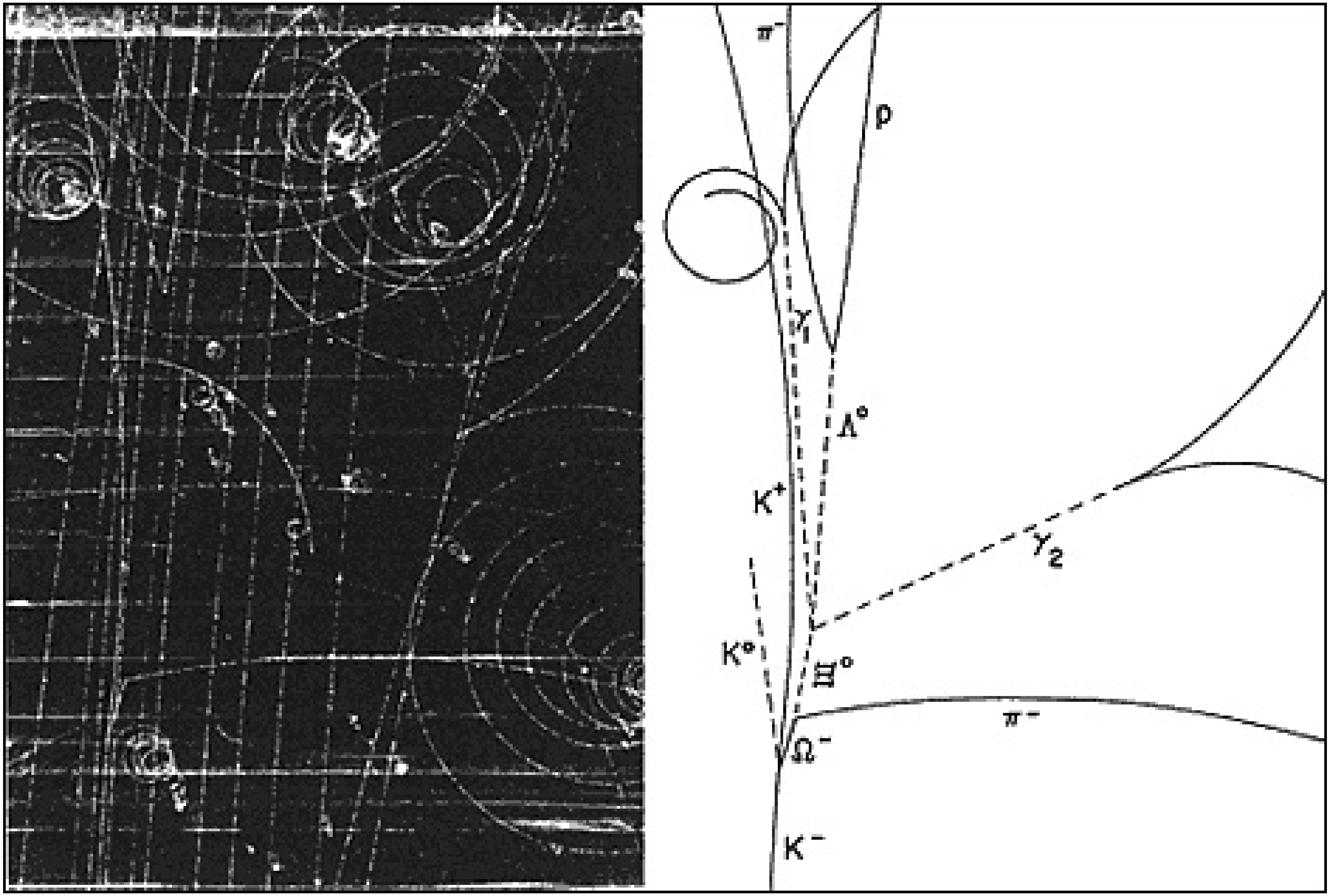




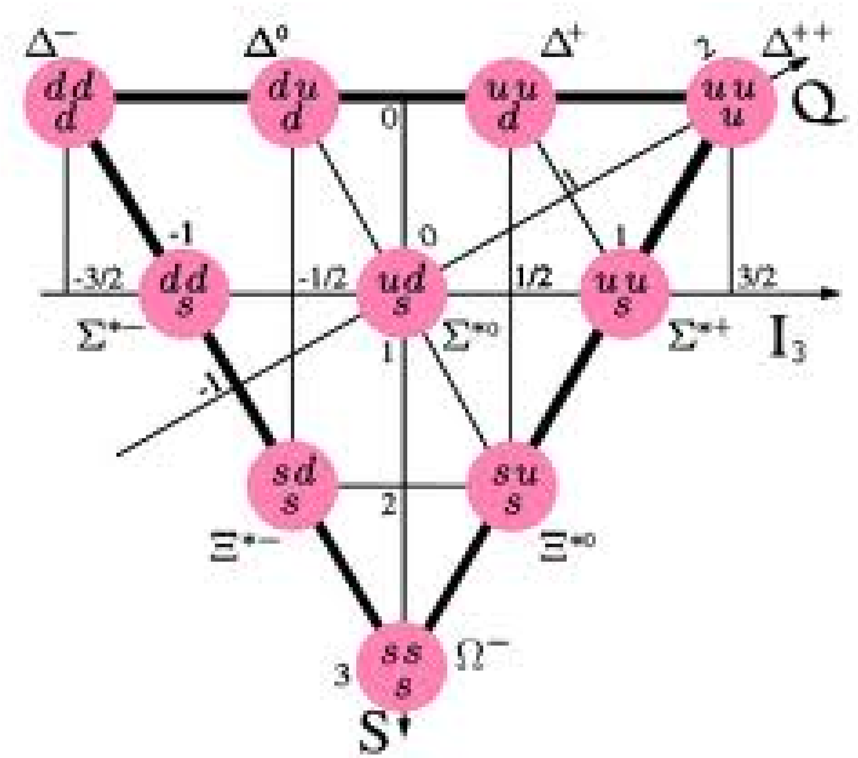
Everything fit! Gell-Mann's diagrams agreed with measured particle properties!

And just like Mendeleev and the periodic table, there was a gap: the Ω^-, the bottom point of the triangle on the left.

Theoretical prediction 1962; experimentally discovered 1964!



First bubble chamber photo of the Ω^-, Brookhaven, 1964



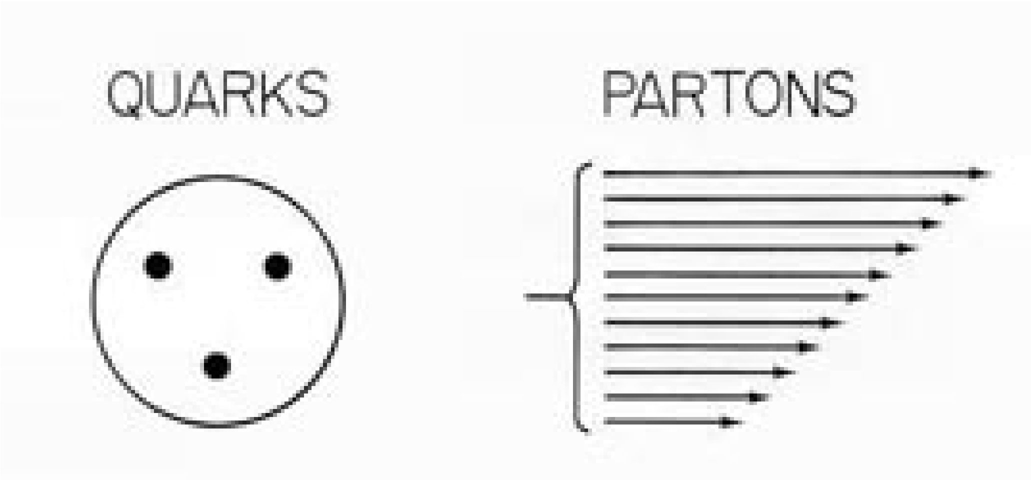
Ω^- discovery had great theoretical significance:

- 3 strange quarks: all the same
- spin 3/2: all 3 quarks must have the same spin
- but quarks are fermions and Pauli Exclusion Principle says they can't be in the same quantum state!

→ Concrete evidence for a new quantum number: "colour".

Quark idea was also proposed in a different form by Feynman: Look for substructure in mesons and baryons in the same way as Rutherford did.

Scattering experiments were giving evidence for hard, point-like sub-particles: Feynman called them "partons".



These ideas (quarks and partons) are just different pictures of the same physics. Both are useful in modern times:

We classify composite particles using the quark model, and we predict the outcome of particle collisions (like at the LHC) using the parton model.

At that point things were still kind of a mess.

- The hadrons (mesons + baryons) and some of their properties were understood using the quark model

- Weak interactions were still a huge question mark.

There were 4 known leptons: e^-, ν_e, μ^-, ν_μ

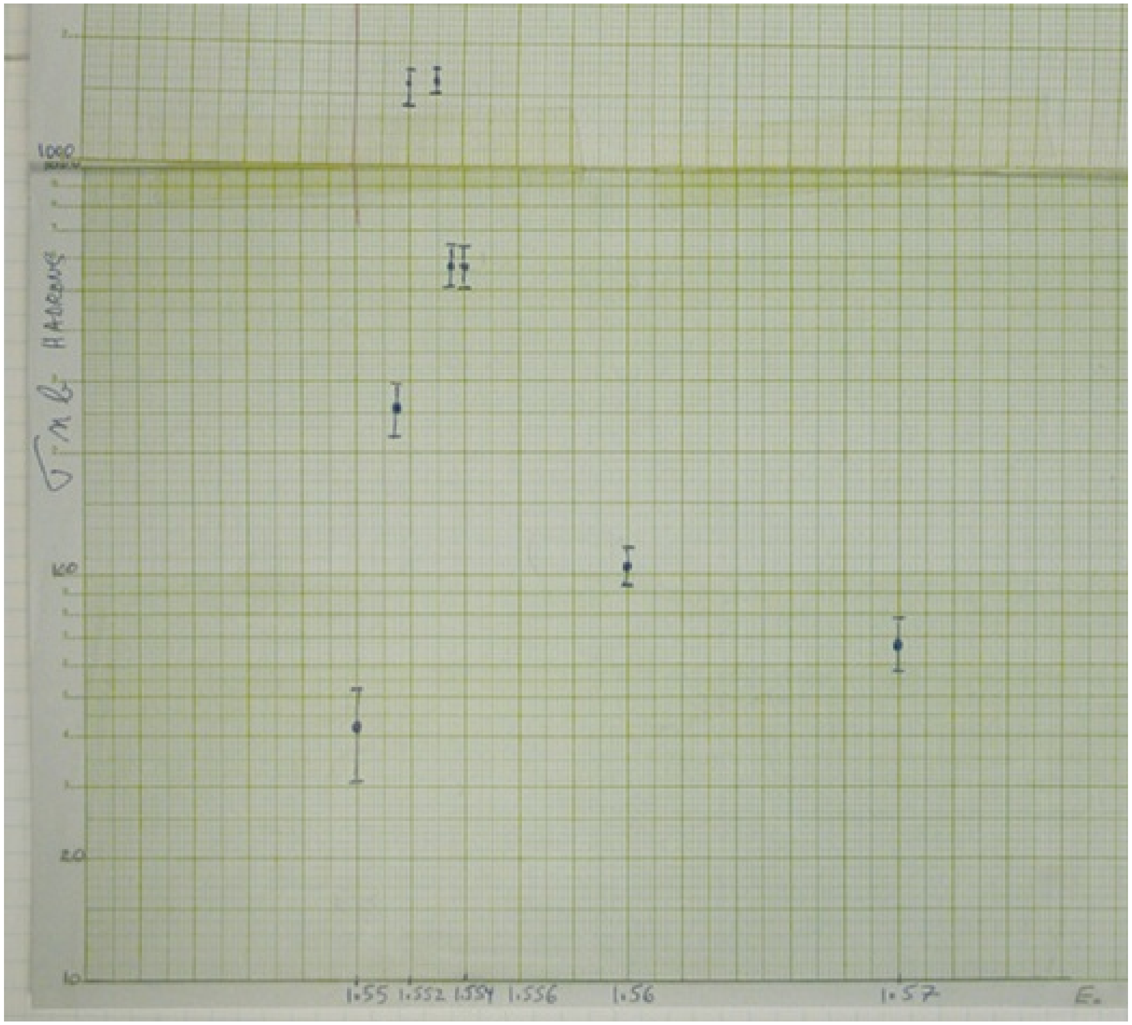
There were 3 known quarks: u, d, s

There were a whole pile of empirically-determined "selection rules" telling you which reactions hadrons liked to do.

The Standard "Electroweak" Model had actually been proposed, as had a 4th quark (charm, 1970) but these were ones of many theorized possibilities. There just wasn't enough data yet.

The November revolution (1974)

What do you do when you're colliding e^- and e^+, you tweak up the beam energy, and your count rate suddenly increases by a factor of 400?



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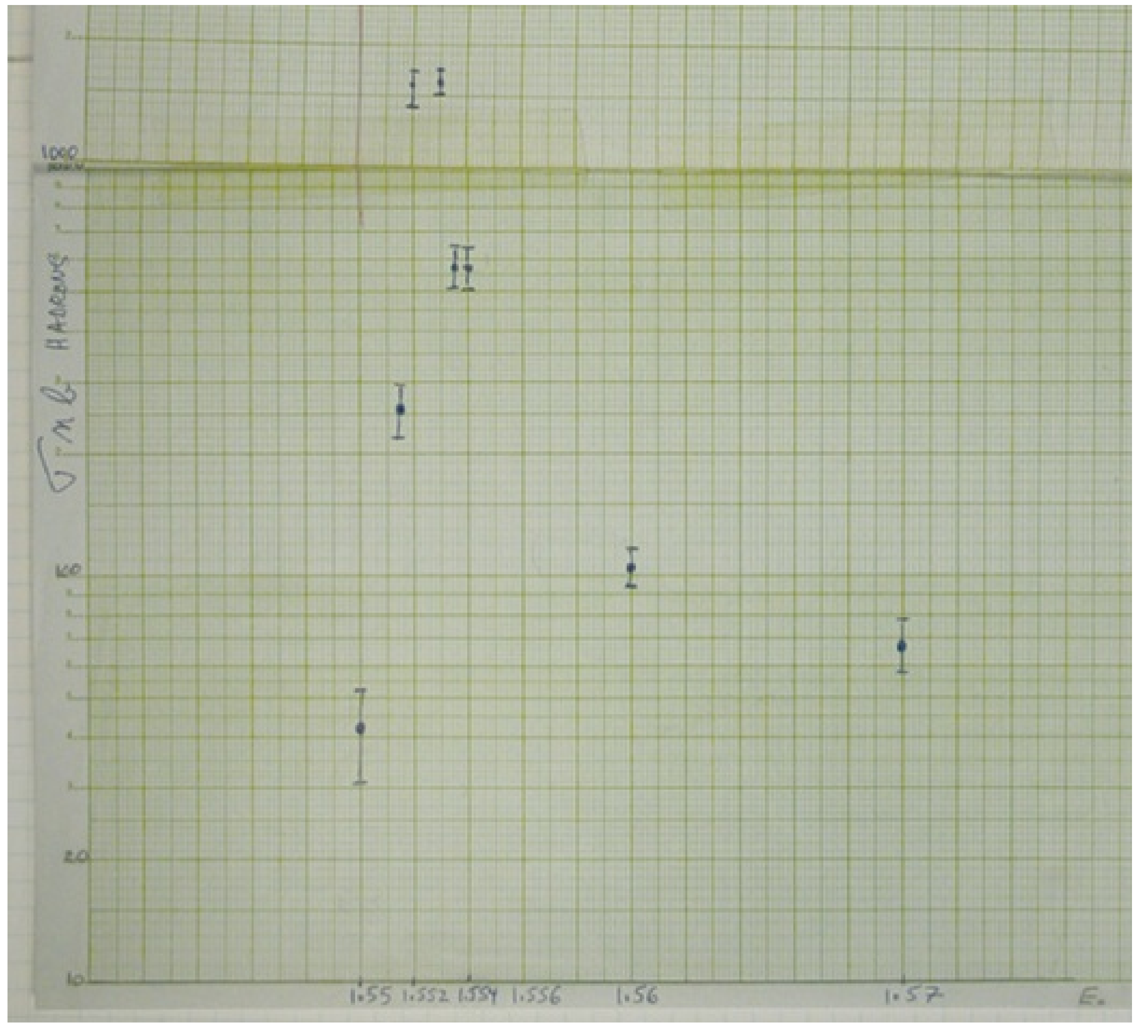
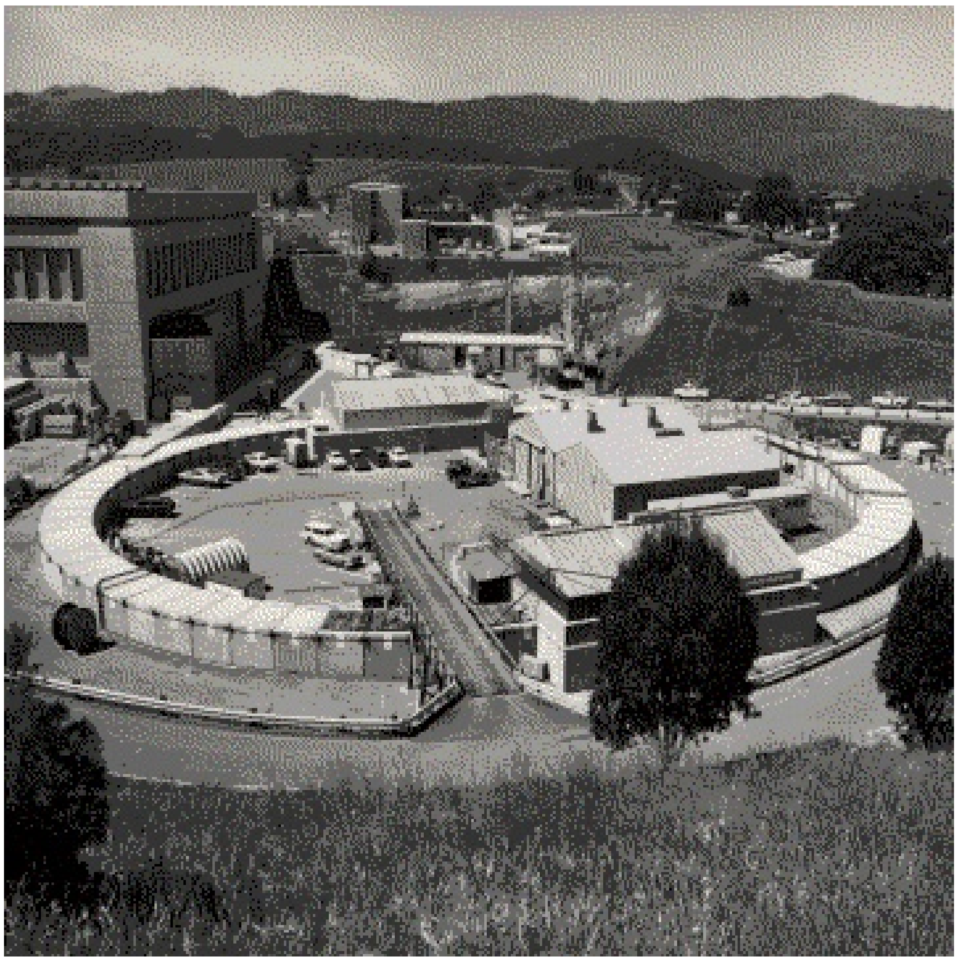


Answer:
call your friends immediately!

The November revolution (1974)

Near-simultaneous discovery at SLAC and Brookhaven of a spectacular new particle.



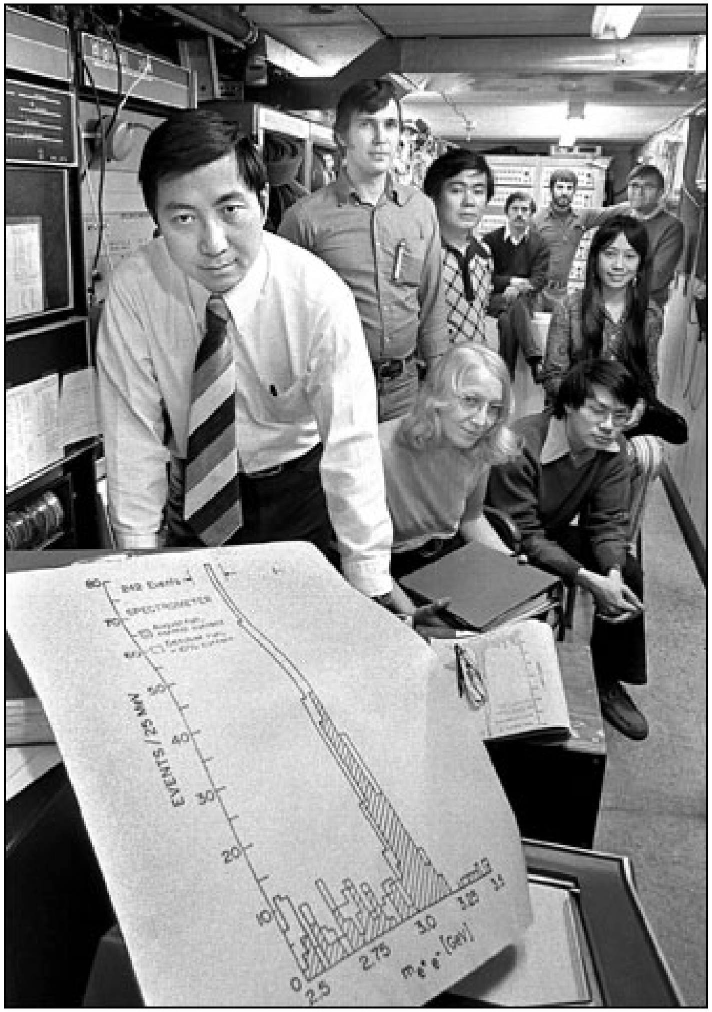
Electron-positron collider experiment at SLAC, called SPEAR

Saw a huge increase in the scattering rate for $e^+e^- \rightarrow$ hadrons, at a very specific e^+e^- combined energy.

Called the new particle ψ (psi)

The November revolution (1974)

Near-simultaneous discovery at SLAC and Brookhaven of a spectacular new particle.



Brookhaven: energetic proton beam on a fixed target; look at stuff produced

Saw lots of events where something decayed to an e^+e^- pair, with a very specific parent particle mass.

Called the new particle J

Now this particle is called the J/ψ. It is a charm-anticharm bound state.

There is a 4th quark!

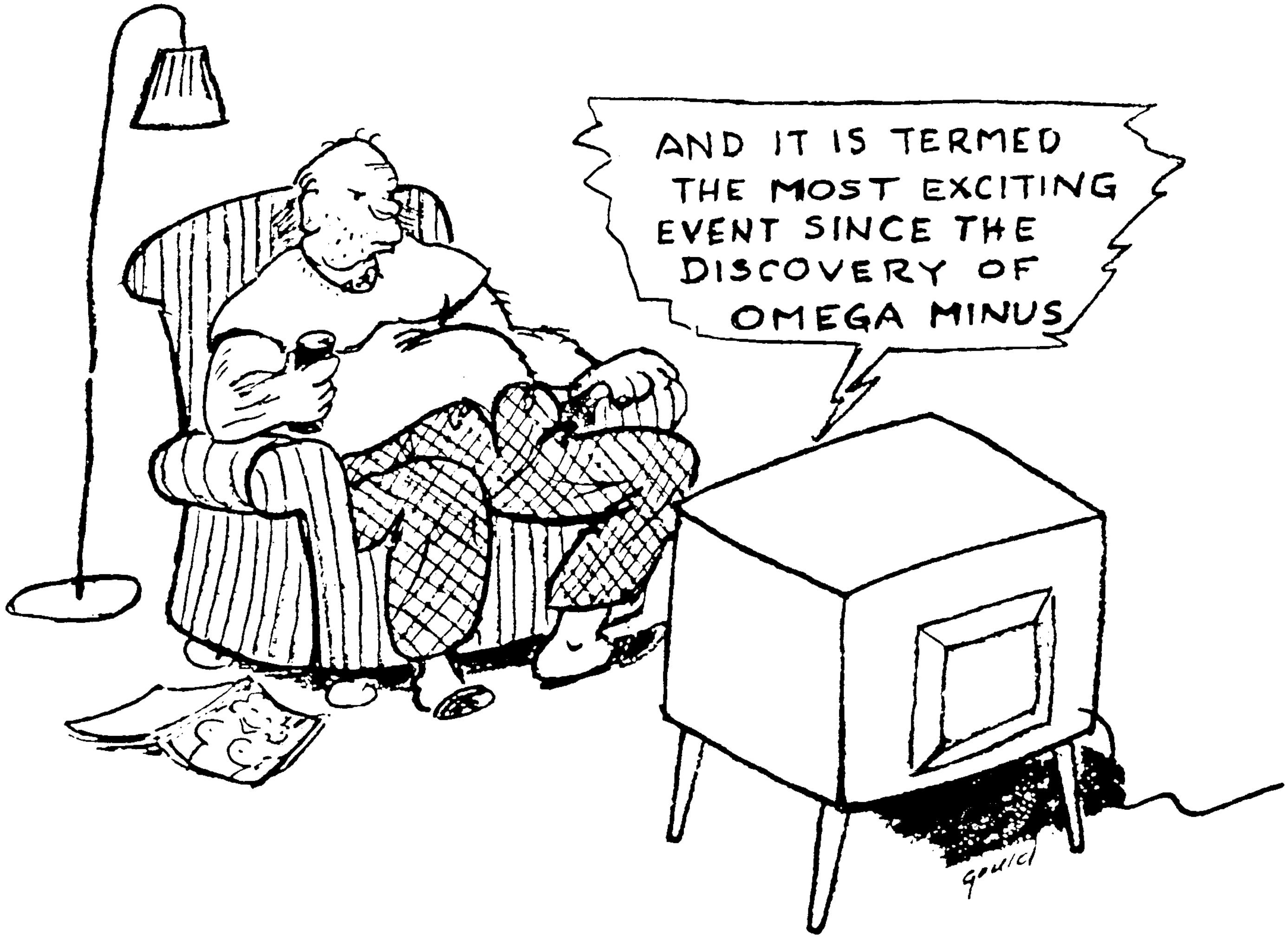
This was fantastic for theory. Suddenly everything fell into place.

$$\underbrace{\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}}_{\text{Leptons}} \qquad \underbrace{\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}}_{\text{Quarks}}$$

- Shows how to make a working theory of the weak interactions

Weinberg, Salam 1967; Glashow, Iliopoulos, Maiani 1970; but these were just 2 of many proposals without data

Notice how this particle was discovered: a scattering resonance; a mass peak. Not a track in a cloud chamber: it decays too fast.


AND IT IS TERMED THE MOST EXCITING EVENT SINCE THE DISCOVERY OF OMEGA MINUS

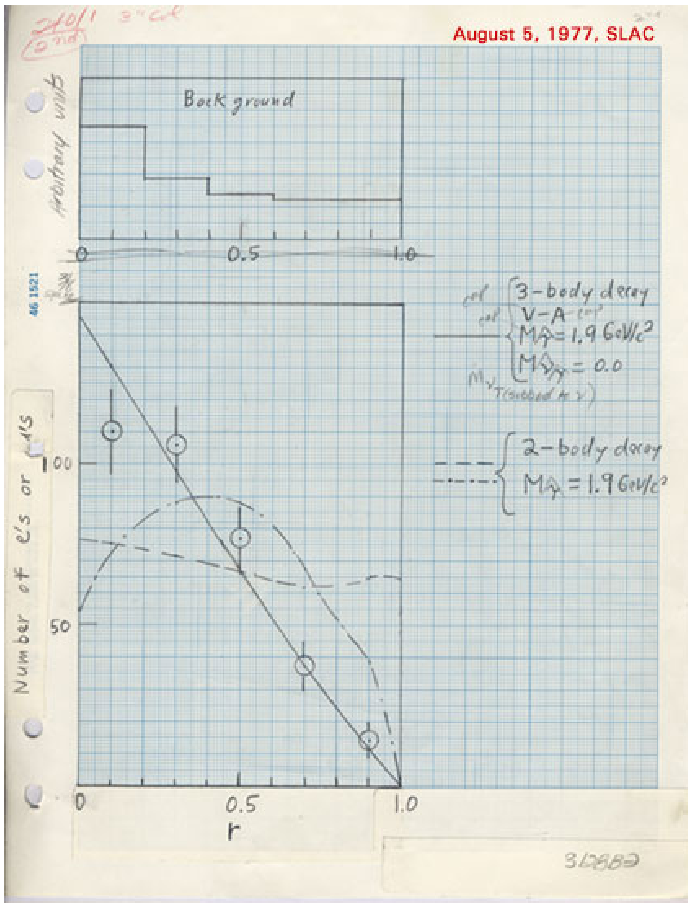
The development of a proper theory of weak interactions gave theorists something much more solid to work with.

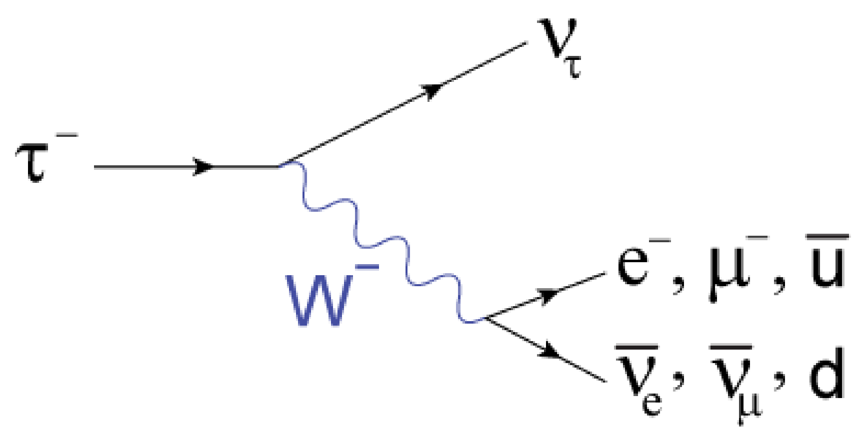
Observed tiny non-conservation effect in “charge conjugation $\times$ parity” symmetry had prompted the proposal of a 3rd generation of quarks (Kobayashi & Maskawa, 1973 – pre–November-revolution!)

Now expermientalists set out to look for them.

Tau lepton discovery

Anomalous events at SPEAR, 1974-77 (Martin Perl):
angular distribution of decay products gave the needed hint.





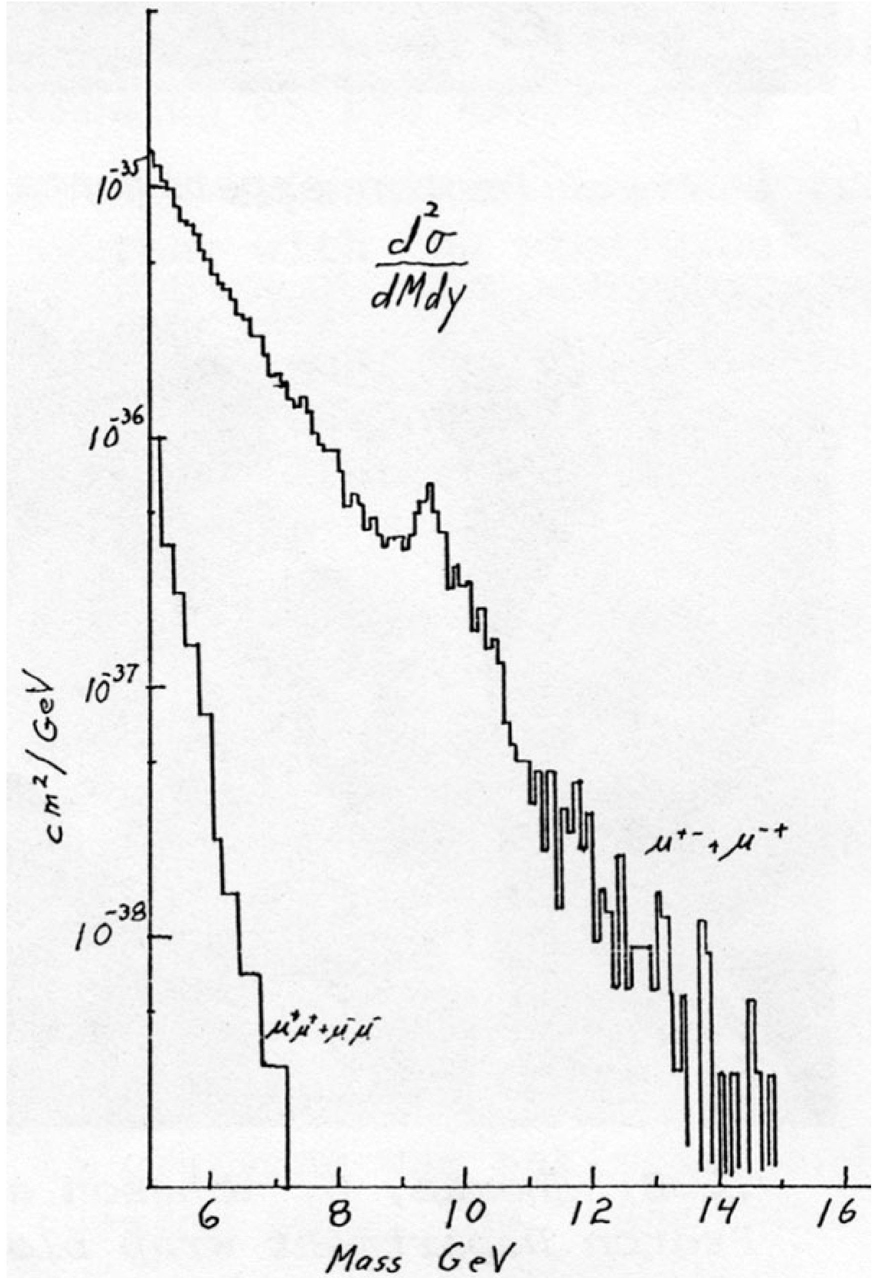
Bottom quark discovery

Dedicated search at Fermilab:
(Lederman 1977)

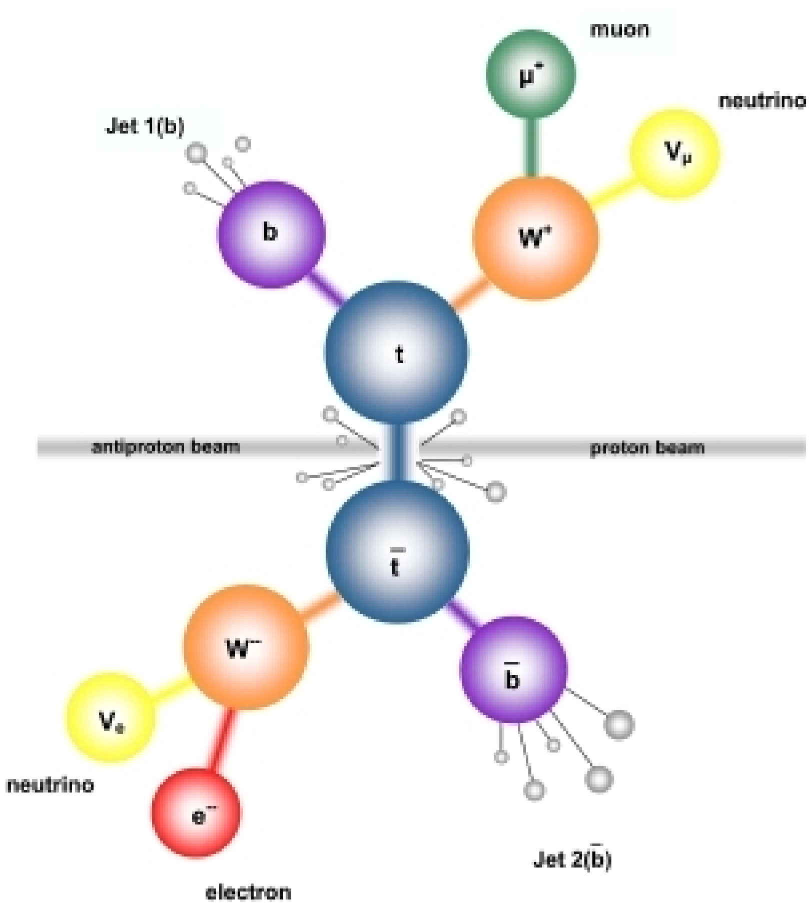
High-energy proton beam onto a fixed target.

Look at energies of the leptons produced in new particle decays.

Bottom–anti-bottom bound state: the sibling of the J/ψ.



Top quark discovery (Fermilab, 1995)

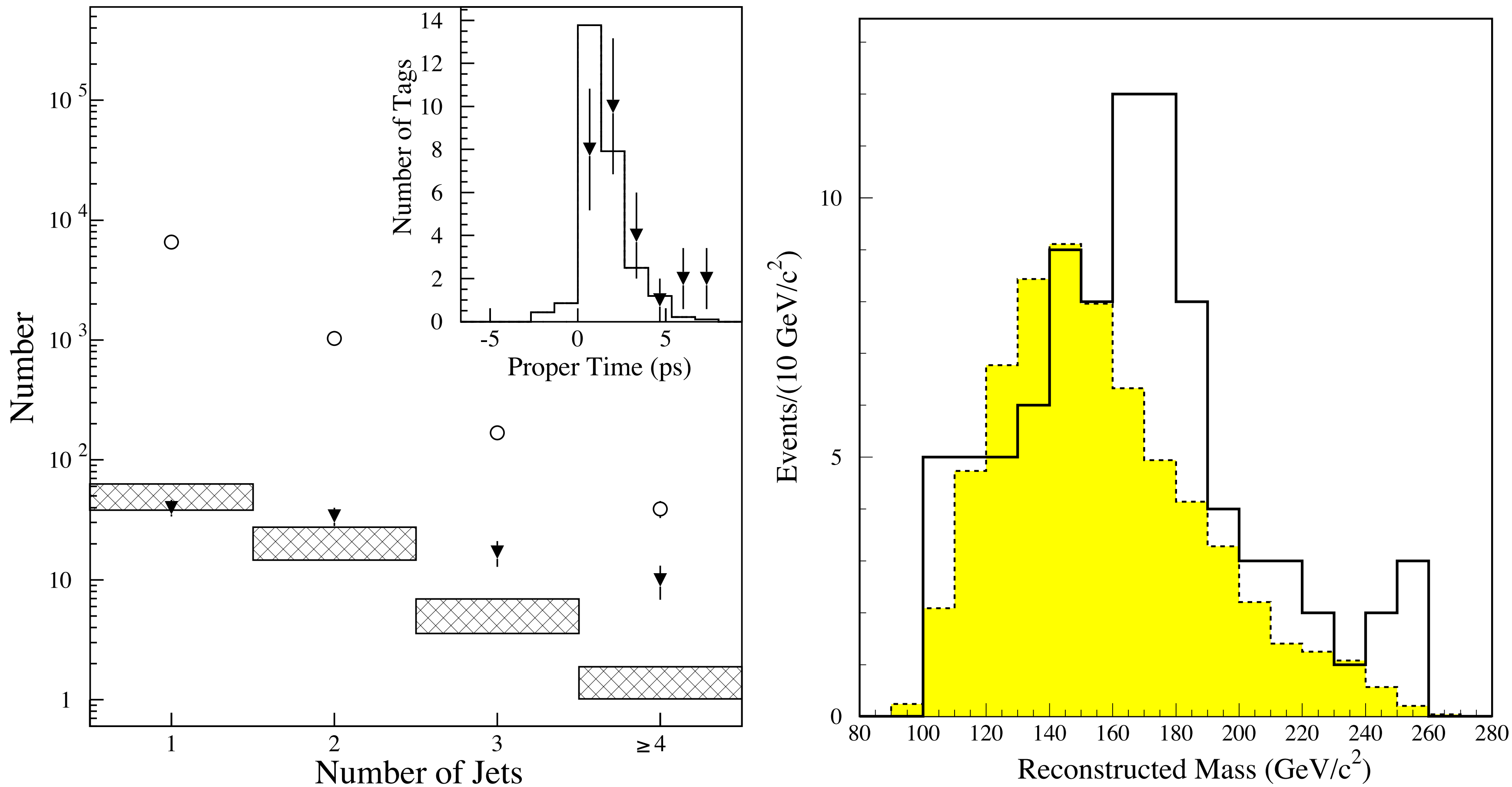


Top quark is super-heavy:

Need very high energy beam collisions to produce them

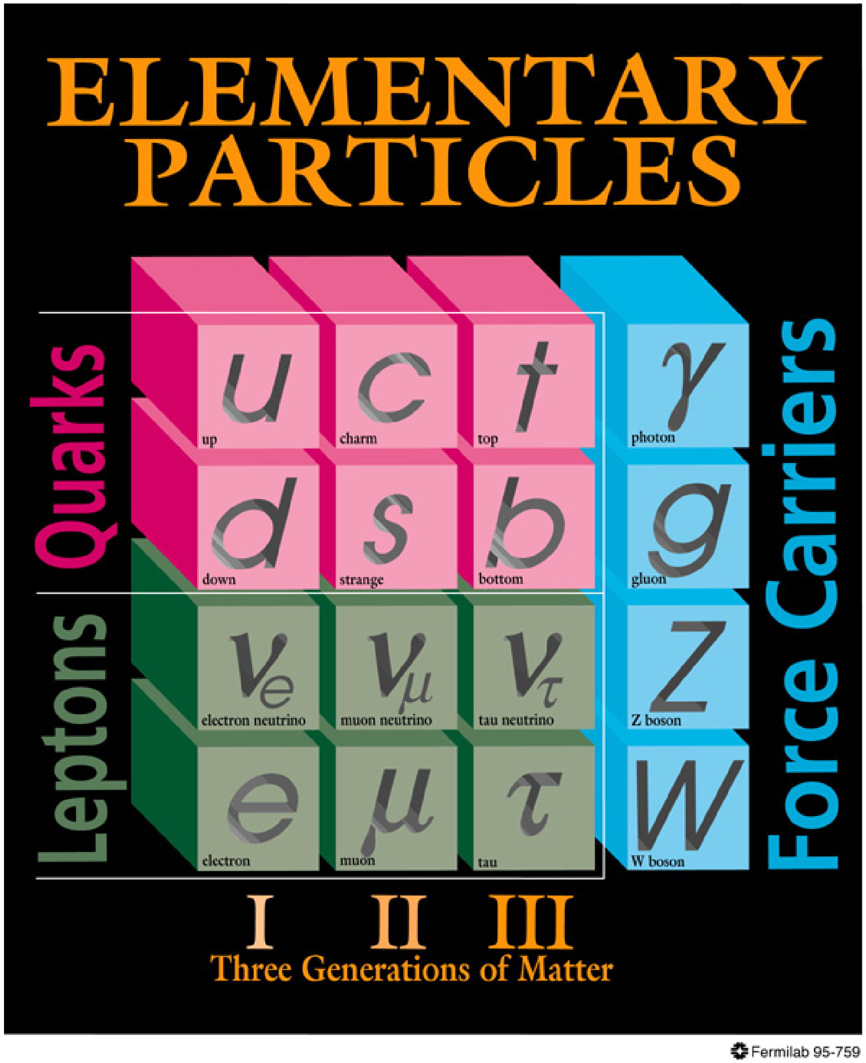
Decays are messy and complicated: lots of backgrounds!

Top quark discovery (Fermilab, 1995)



Techniques much more sophisticated: multiple particle final states, "cuts" on differential cross section.
See an excess of events → have to understand their properties.

At last we have all the matter we know!



I have completely glossed over:

- Neutrinos

- Force carriers: gluon, $W^{\pm}$, Z^0

- Super-high-precision measurements of Z^0 properties (which give many hints about what other particles are *not* there)

- The Higgs and why we're looking for it

Where we are now

The Standard Model lets us make detailed, concrete, high-precision theoretical predictions.
Most of these predictions are really well tested at this point.

Last untested area of SM: why the $W^{\pm}$ and Z^0 have mass.
(Higgs mechanism?)

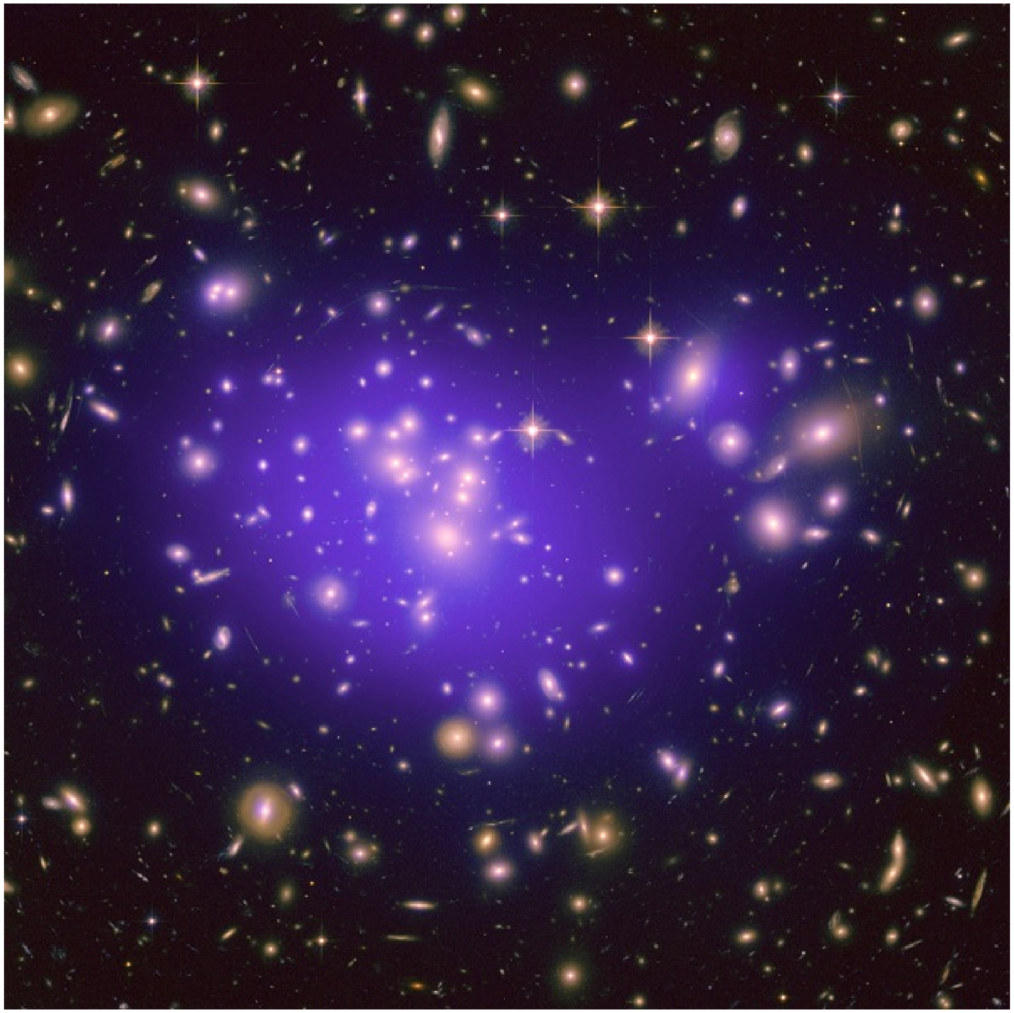
Last major theoretical problem of SM: $W^{\pm}$ and Z^0 masses should get humongous corrections from virtual particles, but we don't see that: something cancels it off. (supersymmetry?)

Also, we don't know why there are 3 generations, why there are quarks and leptons, why they have those particular masses, charges, etc, why there are weak and strong forces, ...

We'll try to answer these questions with a new generation of experiments at even higher energies: the Large Hadron Collider.

But the biggest mystery is the huge amount of

matter we don't know!



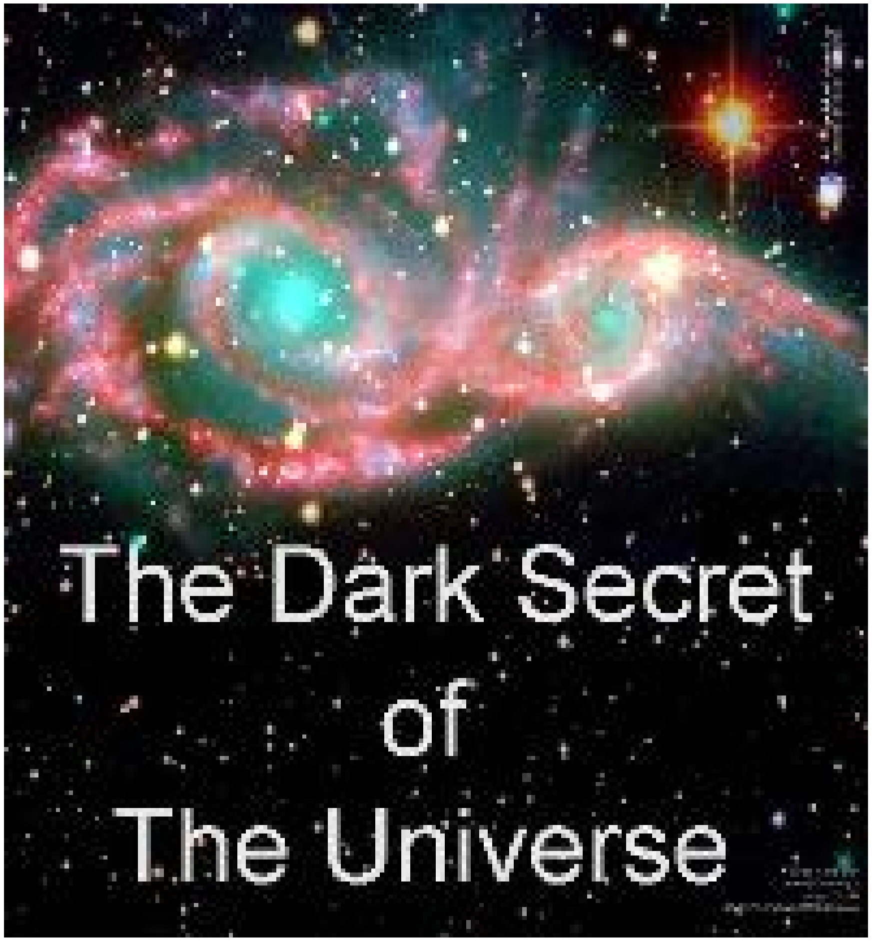
There is about 6x more gravitating mass out there than can be explained by ordinary matter.

We have no idea what it is.

We call it dark matter.

← false colour image of a galaxy cluster, as seen by gravitational lensing: the blue is the reconstructed mass distribution.

Talk by Prof. Kevin Graham



Thursday November 23
7:00–8:30 p.m.
Room 360, Tory Building

An experimental physicist will describe how we discovered that the universe is predominantly made of dark matter and the ways in which we are trying to understand what dark matter is.