An Introduction to Particle Physics

Summer Internship in Science & Technology
Summer Lecture Series

by J. L. Barrow
The University of Minnesota
May 28th, 2024

Fermilab

COSMIC QUESTIONS

HOW DID OUR UNIVERSE BEGIN?

Some 13.8 billion years ago our entire visible universe was contained in an unimaginably hot, dense point, a billionth the size of a nuclear particle. Since then it has expanded—a lot—fighting gravity all the way.

Inflation
In far less than a nanosecond a repulsive energy field inflates space to visible size and fills it with a soup of subatomic particles called quarks.
Age: 10^{-32} milliseconds
Size: Infinitesimal to golf ball

Early building blocks
The universe expands, cools. Quarks clump into protons and neutrons, the building blocks of atomic nuclei. Perhaps dark matter forms.
.01 milliseconds
0.1-trillionth present size

First nuclei
As the universe continues to cool, the lightest nuclei, of hydrogen and helium, arise. A thick fog of particles blocks all light.
.01 to 200 seconds
1-billionth present size

First atoms, first light
As electrons begin orbiting nuclei, creating atoms, the glow from our infant universe is unveiled. This light is as far back as our instruments can see.
380,000 years
.0009 present size

The "dark ages"
For 300 million years this cosmic background radiation is the only light. Clumps of matter that will become galaxies glow brightest.
380,000 to 300 million years
.0009 to 0.1 present size

Gravity wins: first stars
Dense gas clouds collapse under their own gravity—and that of dark matter—to eventually form galaxies and stars. Nuclear fusion lights up the stars.
300 million years
0.1 present size

Antigravity wins
After being slowed for billions of years by gravity, cosmic expansion accelerates again. The culprit: dark energy. Its nature: unclear.
10 billion years
.77 present size

Today
The universe continues to expand, becoming ever less dense. As a result, fewer new stars and galaxies are forming.
13.8 billion years
Present size

HOW WILL IT END?

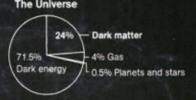
Which will win in the end, gravity or antigravity? Is the density of matter enough for gravity to halt or even reverse cosmic expansion, leading to a big crunch? It seems unlikely—especially given the power of dark energy, a kind of antigravity. Perhaps the acceleration in expansion caused by dark energy will trigger a big rip that shreds everything, from galaxies to atoms. If not, the universe may expand for hundreds of billions of years, long after all stars have died.

In the 20th century the universe became a story—a scientific one. It had always been seen as static and eternal. Then astronomers observed other galaxies flying away from ours, and Einstein's general relativity theory implied space itself was expanding—which meant the universe had once been denser. What had seemed eternal now had a beginning and an end. But what beginning? What end? Those questions are still open.

WHAT IS OUR UNIVERSE MADE OF?

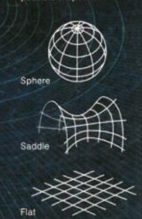
Stars, dust, and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy: an unknown energy field or property of space that counteracts gravity, providing an explanation for observations that the expansion of space is accelerating.

The Universe



Observable Universe
The universe began 13.8 billion years ago. Because it has been expanding ever since, the farthest observable edge is now 47 billion light-years away.

The Unknown Beyond
What we can't see. The possible shapes are:

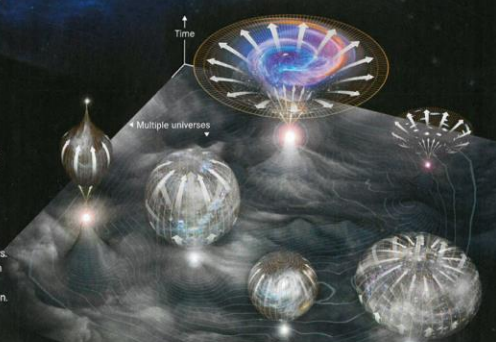


WHAT IS THE SHAPE OF OUR UNIVERSE?

Einstein discovered that a star's gravity curves space around it. But is the whole universe curved? Might space close up on itself like a sphere or curve the other way, opening out like a saddle? By studying cosmic background radiation, scientists have found that the universe is poised between the two: just dense enough with just enough gravity to be almost perfectly flat, at least the part we can see. What lies beyond we can't know.

DO WE LIVE IN A MULTIVERSE?

What came before the big bang? Maybe other big bangs. The uncertainty principle holds that even the vacuum of space has quantum energy fluctuations. Inflation theory says our universe exploded from such a fluctuation—a random event that, odds are, had happened many times before. Our cosmos may be one in a sea of others just like ours—or nothing like ours. These other cosmos will very likely remain forever inaccessible to observation, their possibilities limited only by our imagination.

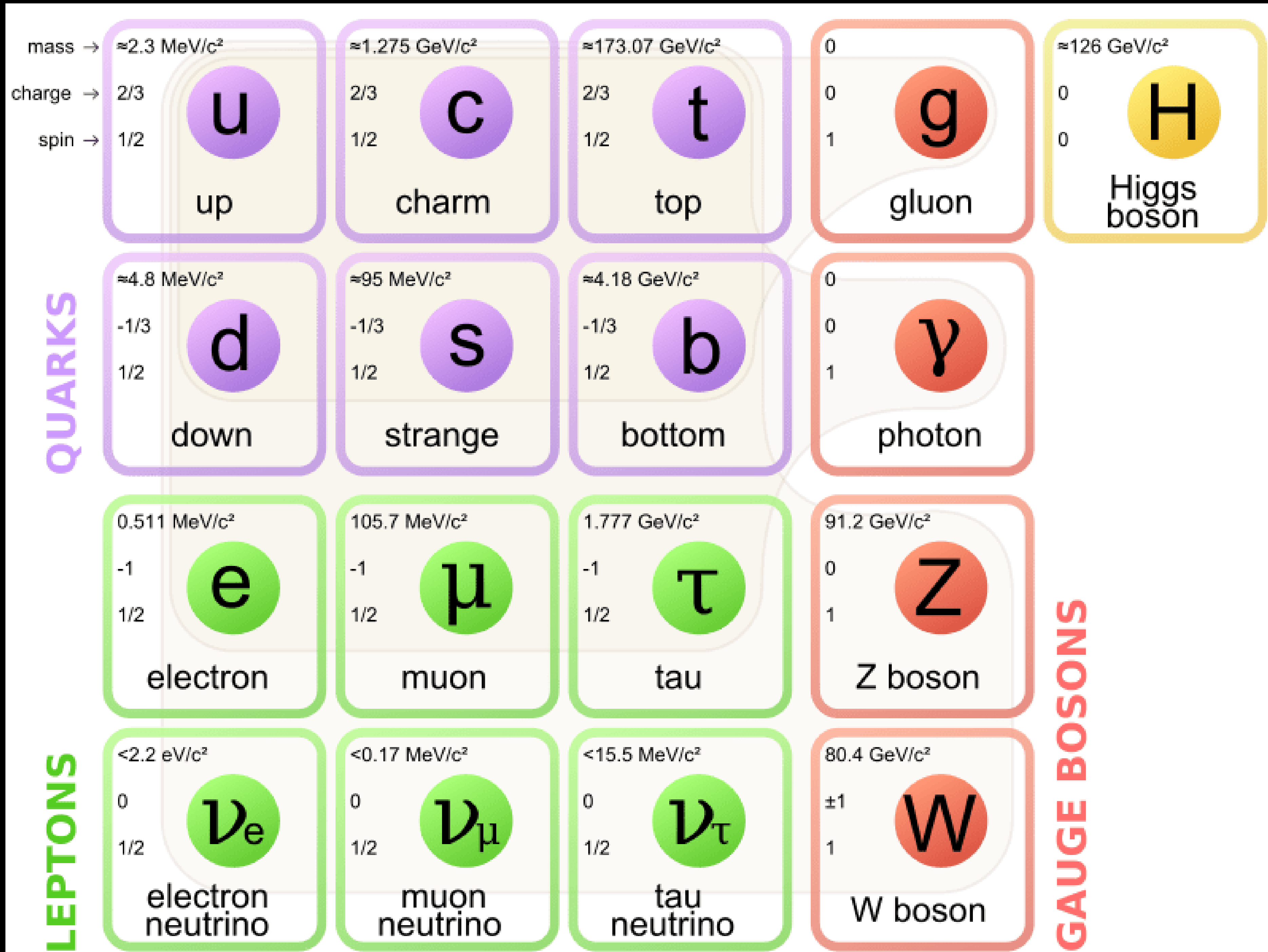


Fly through the universe on our digital edition.

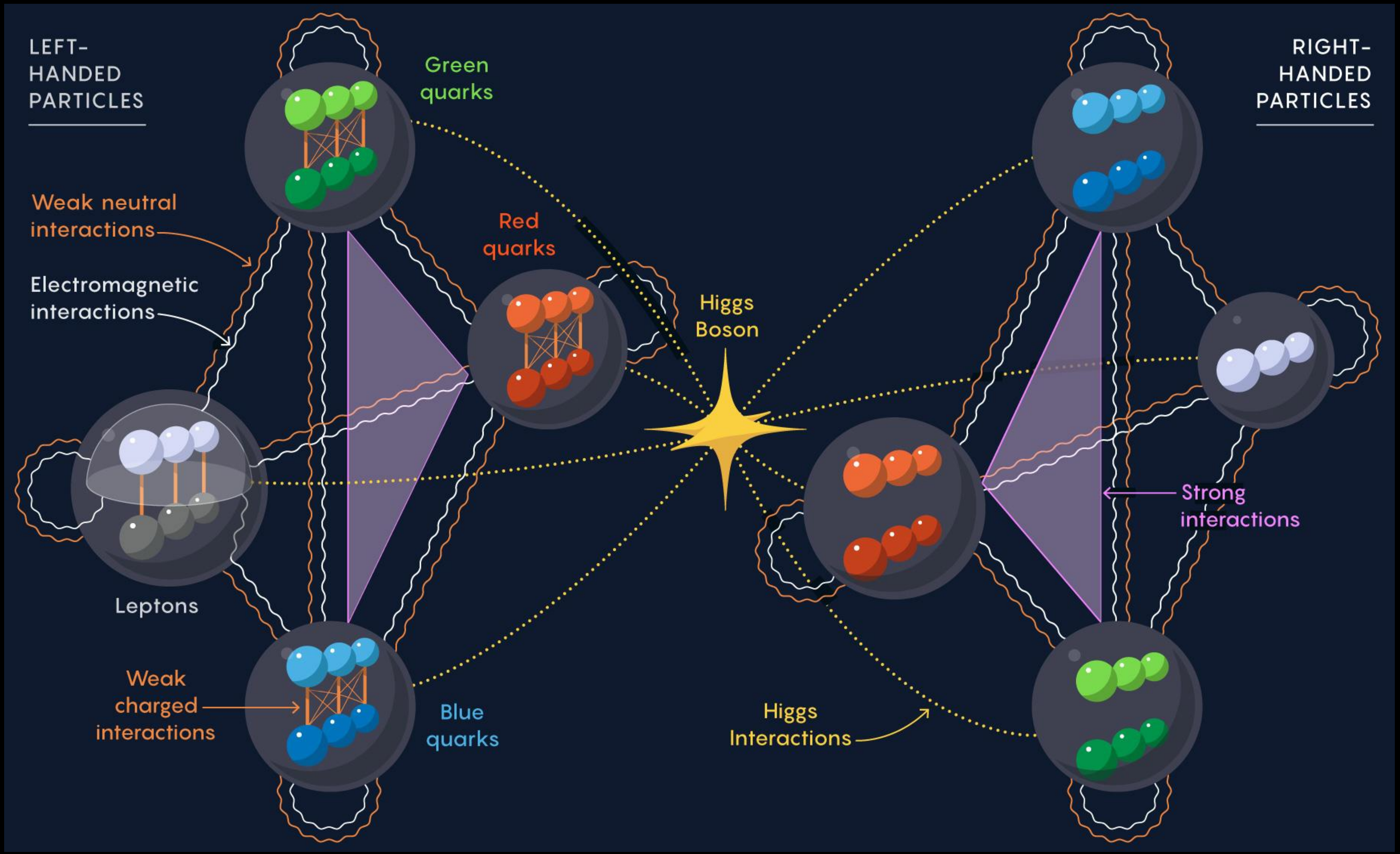
LAWSON PARKER, NGM STAFF; FANNA GEBREYESUS. ART: MOONRUNNER DESIGN

SOURCES: CHARLES BENNETT, JOHNS HOPKINS UNIVERSITY; MICHAEL S. TURNER, UNIVERSITY OF CHICAGO

The Standard Model of Particle Physics



Other Standard Model Representations

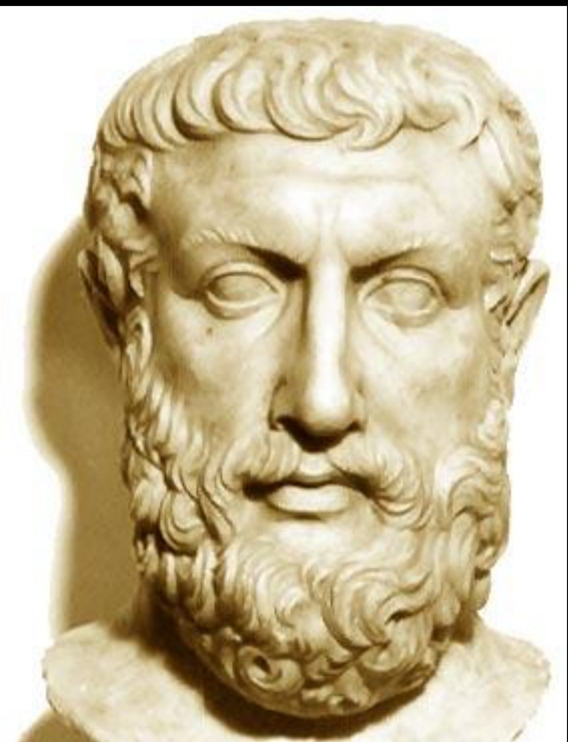


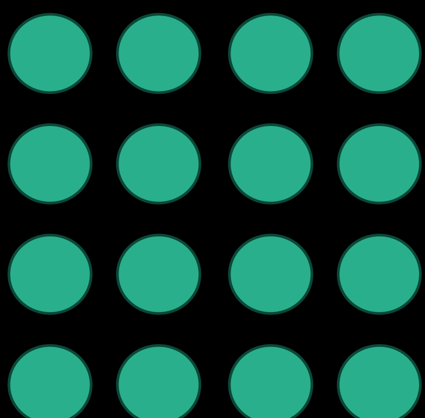
[Chris Quigg: A New Map of All the Particles and Forces | Quanta Magazine]

A Short History of *Partic*ular Understandings

(a whirlwind, ignoring many atomic and radioactive developments)

From Democritus to Newton





Democritus (~400 BCE)

- $\alpha\tau o\mu o\sigma$ "atomos" = "indivisible"
  - Matter cut through via its empty spots
  - Infinite in number
  - All made of similar material

Aristotle

- Four elements, "minima"
  - Lower limit on size of particles with properties

⋮

Newton

- Light as a "corpuscle"
  - Taken from Gassendi

Carl Sagan's *Cosmos*
Democritus' Idea of the Atom
Ancient Atomism-Stanford Encyclopedia of Philosophy
Philosophy of Science Timeline

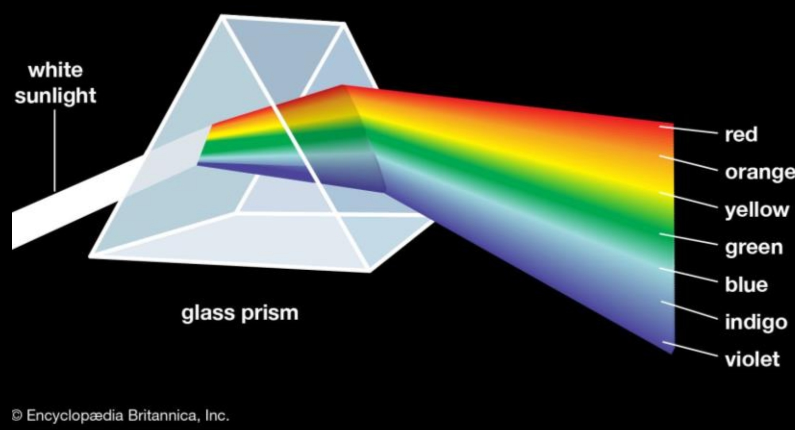
The Photon as a Wave

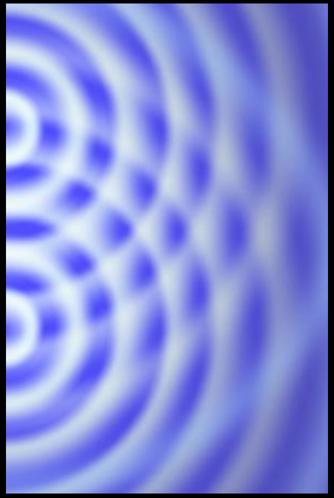
Renee Descartes (1637)
- Theory of refraction
  - Analogy of sound waves
  - Faster in medium—wrong

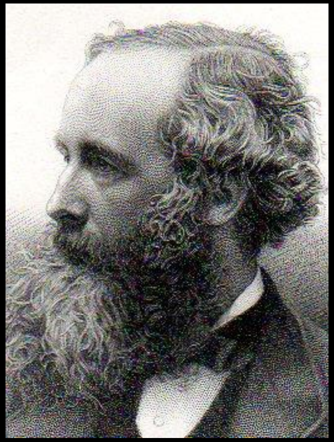
Christiaan Huygens (1678)
- Mathematical theory
  - “Luminous aether”
  - Predicted interference

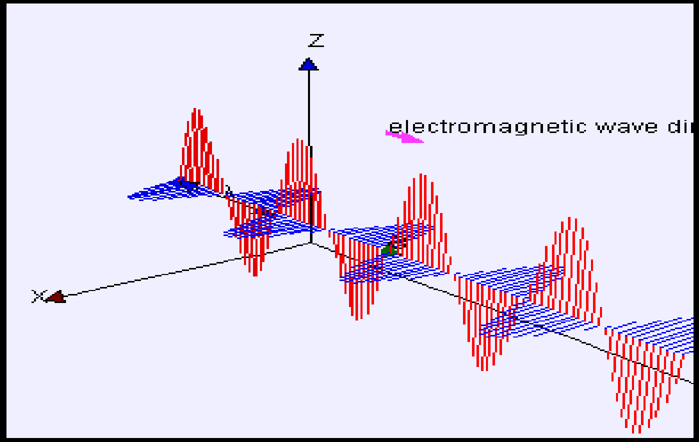
Thomas Young (~1800)
- First diffraction experiments
  - Colors as various wavelengths

James Clerk Maxwell
- Inspired by Faraday (1846)
  - Plane of polarization rotated when traveling through $\vec{B}$
- Maxwell’s Equations (1873)
  - Govern dynamics of electricity and magnetism
  - First unification of forces

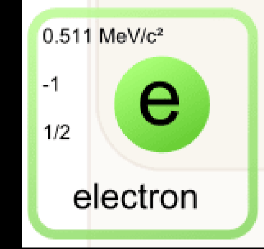


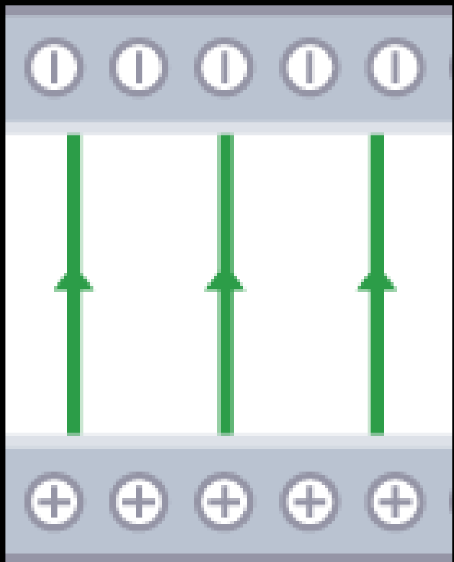




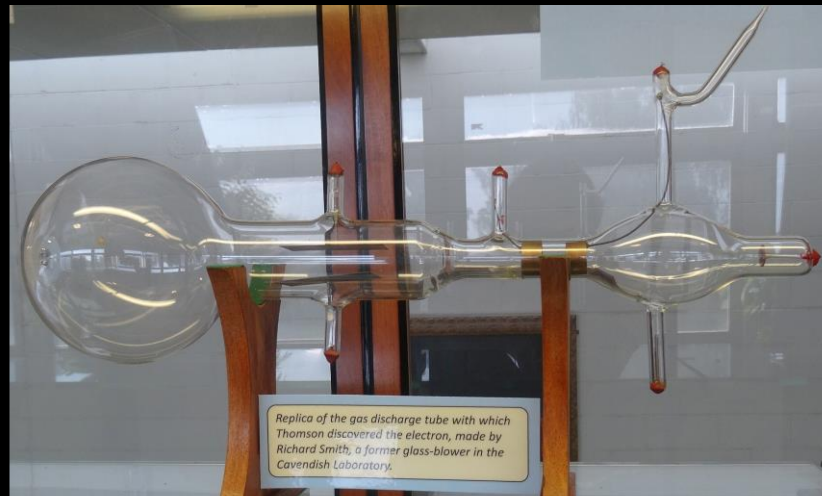


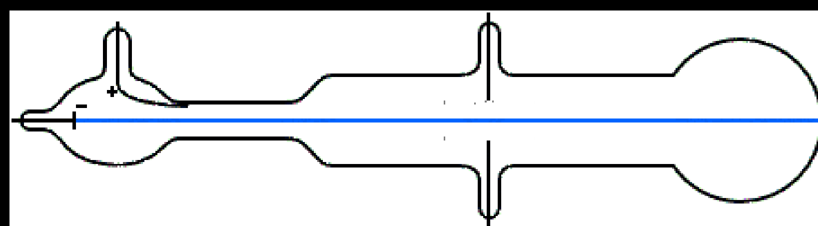
The Electron





Electric fields BBC Bitesize





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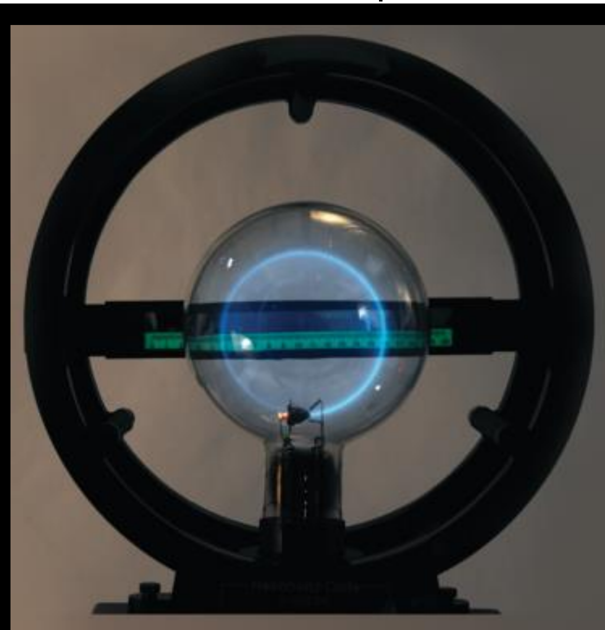


e/m Apparatus | PASCO

J. J. Thomson (1897)

- Investigated "cathode rays"
  - Deflected in $\vec{E}$
- Rays made into beam via slit
  - Passed between Al plates
    - Connected to battery voltage

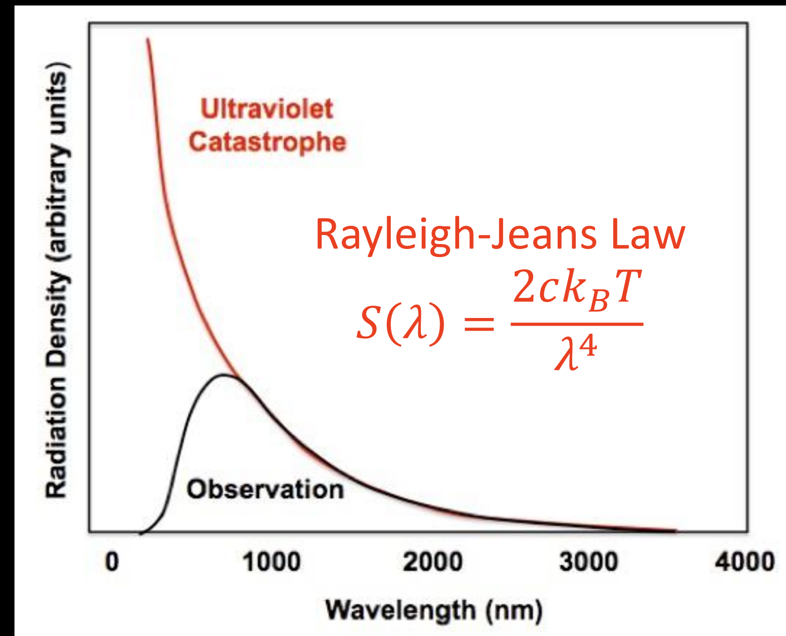
      $\vec{F} = q_e\vec{E} = m_e\vec{a}$
    - Deflection!
- Charge-to-mass ratio (e/m)
  - Used same apparatus: $\vec{E}$ & $\vec{B}$

    $$\vec{F} = q_e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$
  - Given curvature r:

$$\frac{q_e}{m_e} = \frac{\left|\vec{E}\right|}{B^2 r} = -1.7882 \times 10^{11}\,\frac{\mathrm{C}}{\mathrm{kg}}$$

The Planckian Revolution of the "Quanta"

- "Ultraviolet catastrophe" (1900)
  - Black body radiation explanation from equipartition theorem
  - Jeans law diverges at low λ
  - Infinite energy density



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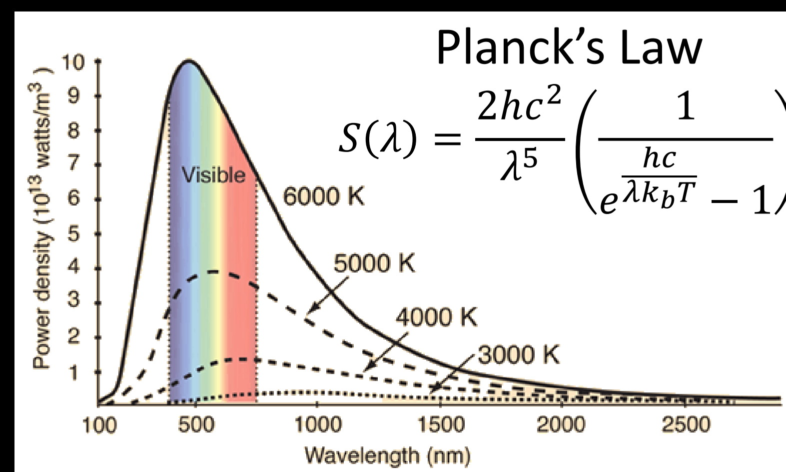
Max Planck

- Derived correct black body curve
- Assumed…
  - EM radiation emitted/absorbed as discrete energy *packets*

$$E_{quanta} = h\nu = h\frac{c}{\lambda}$$

  - Applied to partition function in similar statistical mechanics



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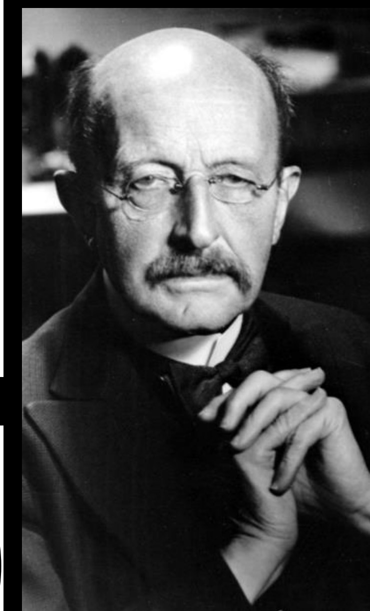

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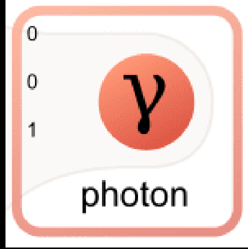
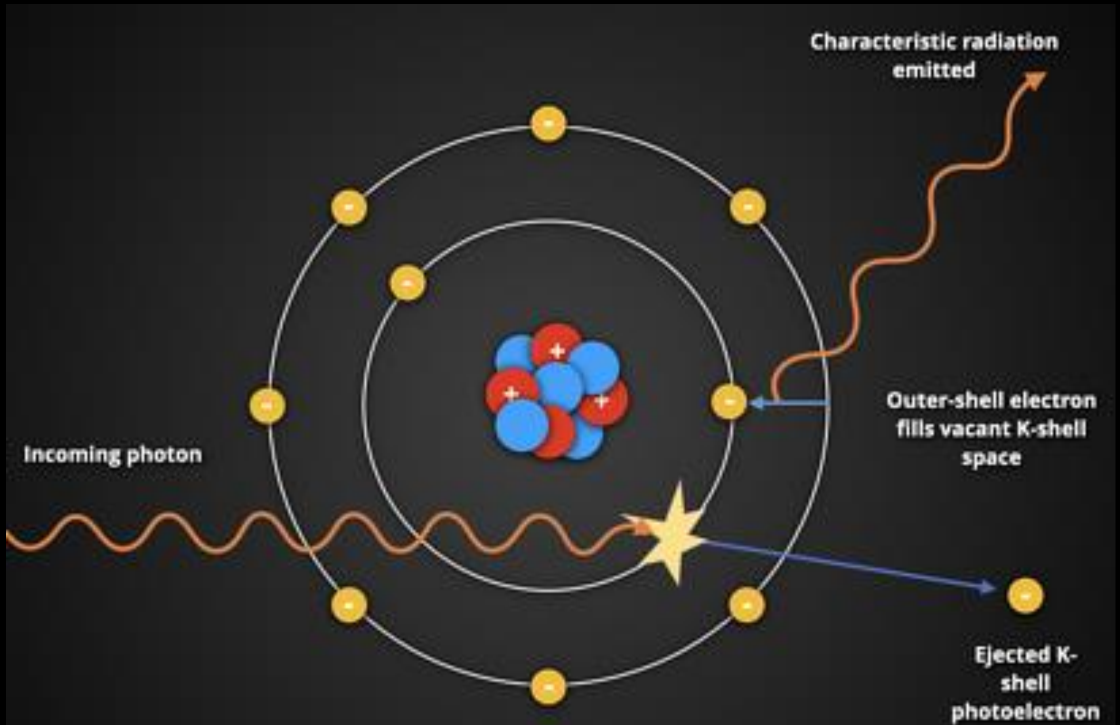
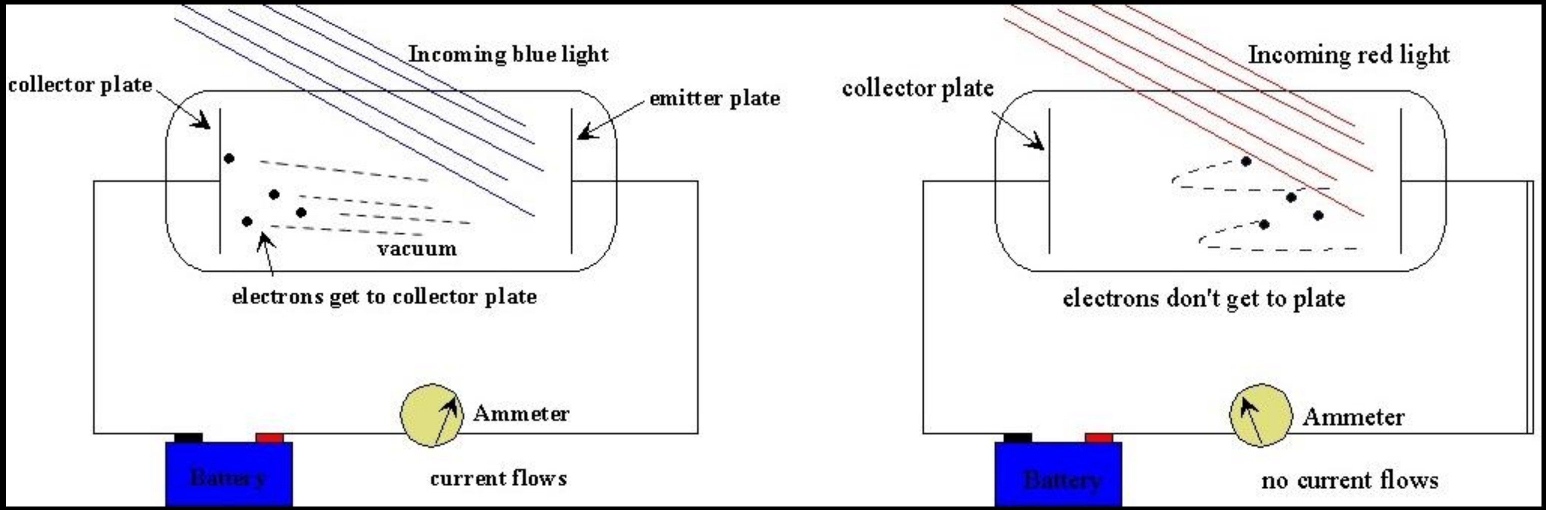
Lord Kelvin and the End of Physics, which he Never Predicted

The Photon as a Particle





~Bohr Model of the atom (1913)



Einstein (1905)

- Built on Thomson and Planck's work
- Photons (particles) have characteristic E_γ
  - Electron (particle) in material has certain "binding energy"
  - Must do *work* to remove from material
- Quantum effect
  - *All* absorbed…
  - …or *none* at all
  - If $E_\gamma < W$, no escape

$$K_{max} = h(\nu - \nu_o)$$

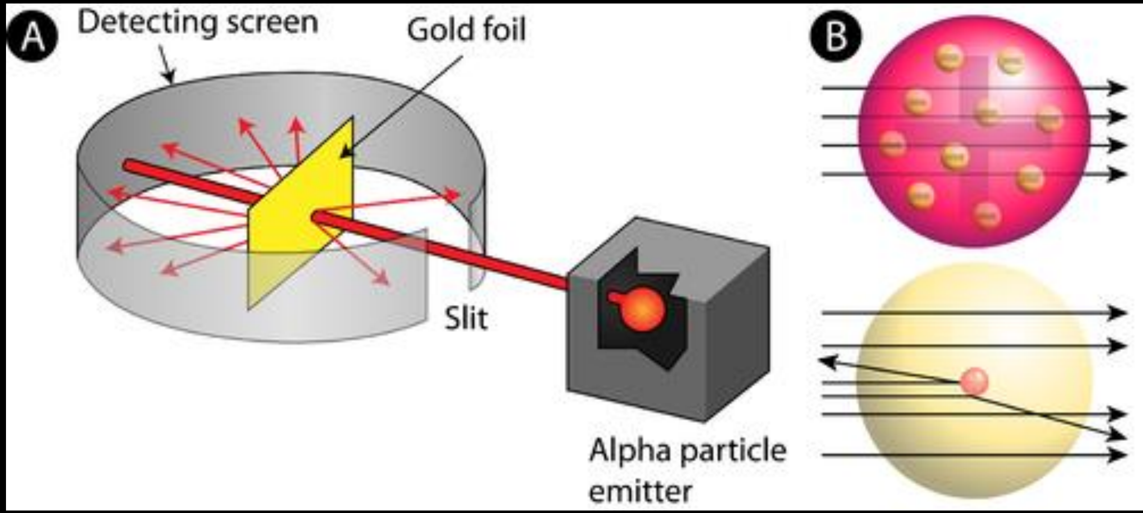
The Proton

Ernest Rutherford (1919)

- Renowned for α particle experiments
  - Discovered atomic nucleus (1911)
    - Alpha particle scattering on Au
- α particles are heavy, don't travel far
  - Activity beyond typical range of αs in air
    - Scintillation in a detector screen at long range
  - Found interaction occurring on N (enhanced)

$$^{14}\mathrm{N} + \alpha^{2+} \nrightarrow {}^{13}\mathrm{C}^{-} + \alpha^{2+} + p^{+}\left({}^{1}\mathrm{H}^{+}\right) \Rightarrow \boldsymbol{{}^{17}\mathrm{O}^{+} + p^{+}\left({}^{1}\mathrm{H}^{+}\right)}$$

  - Predicted 3 tracks, **saw 2**
    - 3: Scattering with proton kick out
    - 2: Absorption (and de-excitation)
      - **First nuclear reaction!**
- $\pi\rho\omega\tau o\nu$—"proton"—"first"
  - "Building block" of all matter
  - ~Integer multiples of $^{1}\mathrm{H}$ mass



The Neutron

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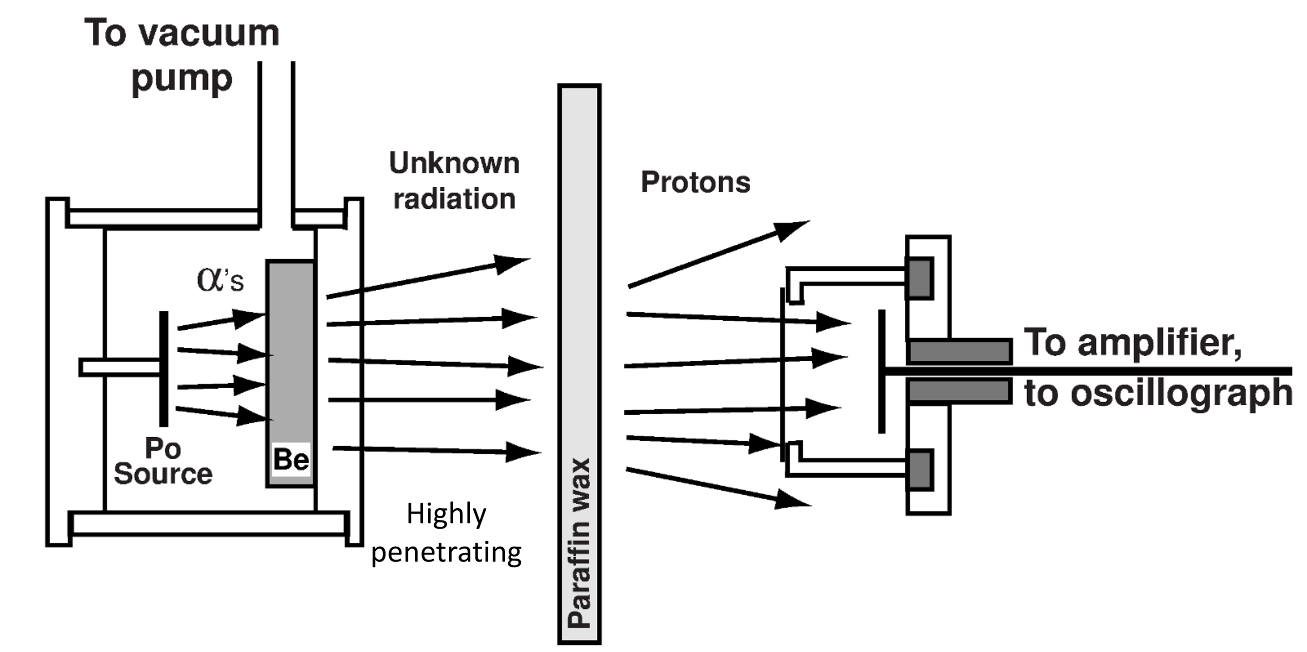

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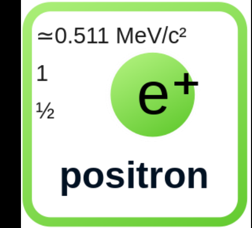
Irene Joliot-Curie & Frederic Joliot

- Polonium was highly radioactive
  - Marie & Pierre Curie (1898)
    $$^{210}\text{Po} \to \alpha + {}^{206}\text{Pb}$$
  - Known: an intense unknown radiation could be made via
    $$\alpha + {}^{9}\text{Be} \to \text{X}$$
  - They saw:
    $$\text{X} + \text{C}_\text{N}\text{H}_{\text{N}+2} \to p^+ \text{ (high energy)}$$
  - *They thought* $\text{X} = \gamma$ incorrectly, would have to be too high energy

James Chadwick (1932)

- *Predicted*: Rutherford (1920)
  - [Bakerian](#) Lecture at Royal Society
    - Reported $^{3}\text{X}^{2+}$, assumed $p^+ + e_n^-$
  - Had to be similar $m_\text{X} \sim m_p$
- Recoil experiments confirmed mass
  $$^{9}\text{Be} + \alpha \to {}^{12}\text{C} + n$$

The Positron & Dirac’s Revolution

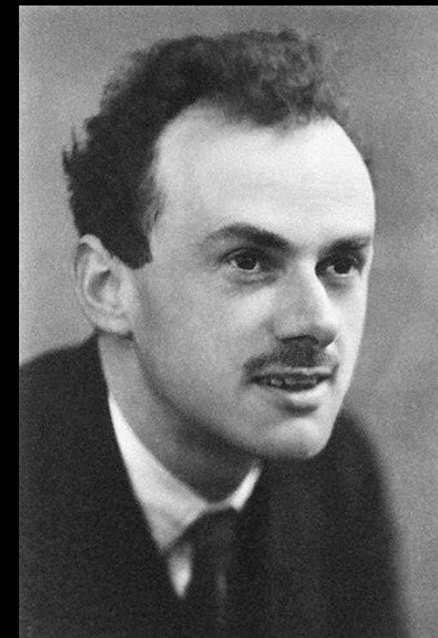


Paul Dirac (1928)

- Integrated special relativity & quantum mechanics
- Describes all spin-$\frac{1}{2}$ particles

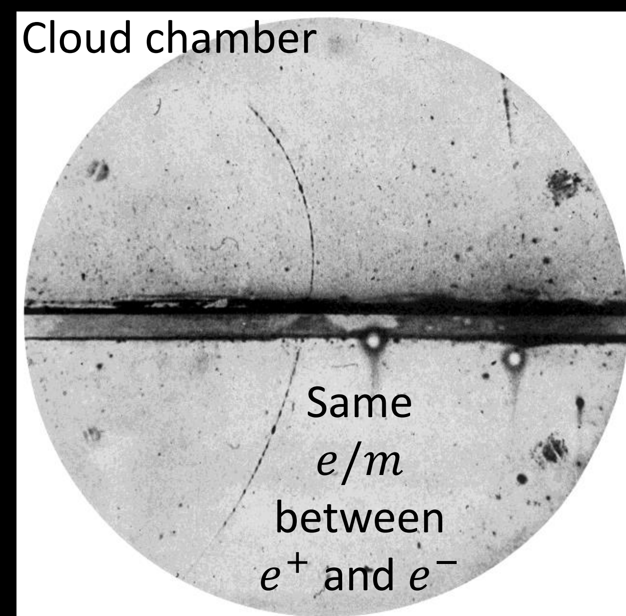
$$\left(i\hbar\gamma^{\mu}\partial_{\mu} - mc\right) = 0$$

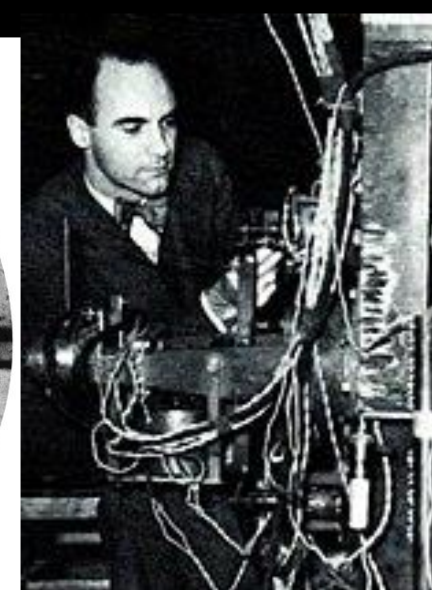
  - Built on Pauli’s theory of spins, make relativistic
  - Requires use of *bi*spinor vectors in equation
    - Requires four complex numbers, not only one as in Schrödinger
- Predicted new forms of matter:
  - Negative energy solutions…what do they mean physically?
  - Positive electron—not before seen…could it be the proton?
  - Oppenheimer: emphatically “no”, would imply instability of atom



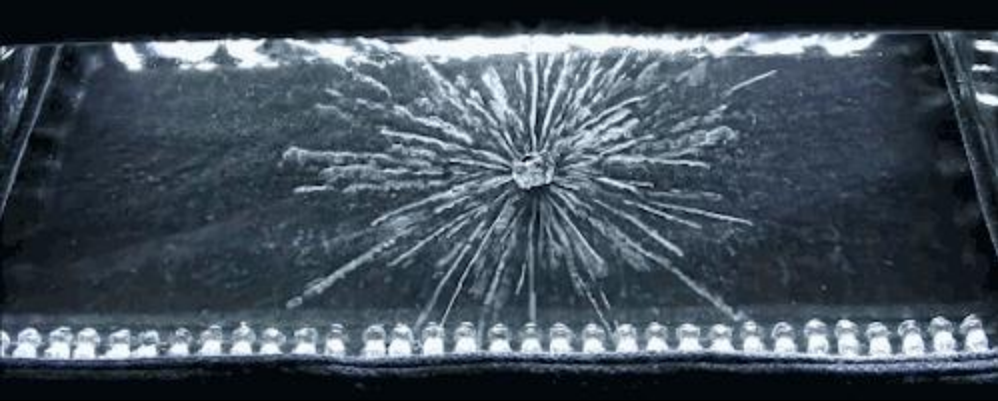
Carl Anderson (1932)—also discovered μ

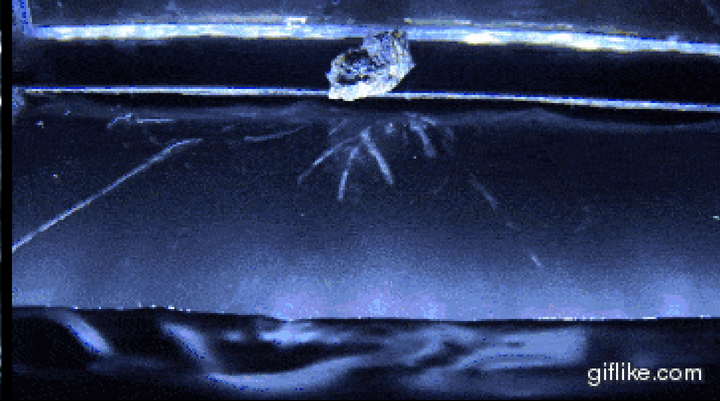
- Cosmic rays passing through cloud chamber with lead plate in a magnetic field
- Inspired by Caltech classmate C.-Y. Chao (1929)
  - Initial work was inconclusive and not followed up on
  - Positrons appear in Joliot-Curie photographic plates
  - Completed annus *mirabilis* at Cavendish, but waited to publish
  - “Positron” name taken by suggestion from *Phys. Rev.* editor
- Discovery of “antimatter”

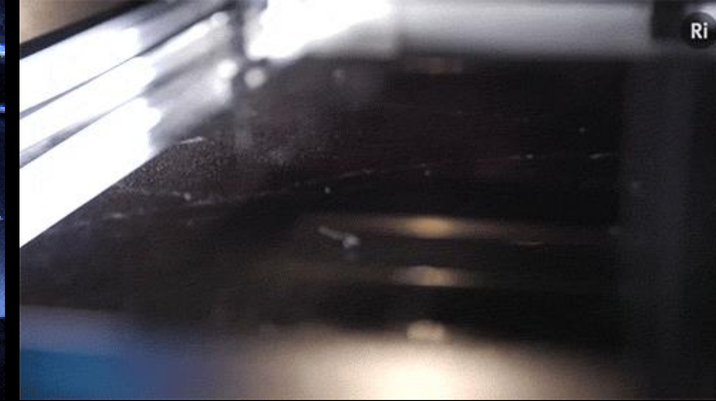




Dirac Interview (1982)   The Story of the Discovery of the Nucleus

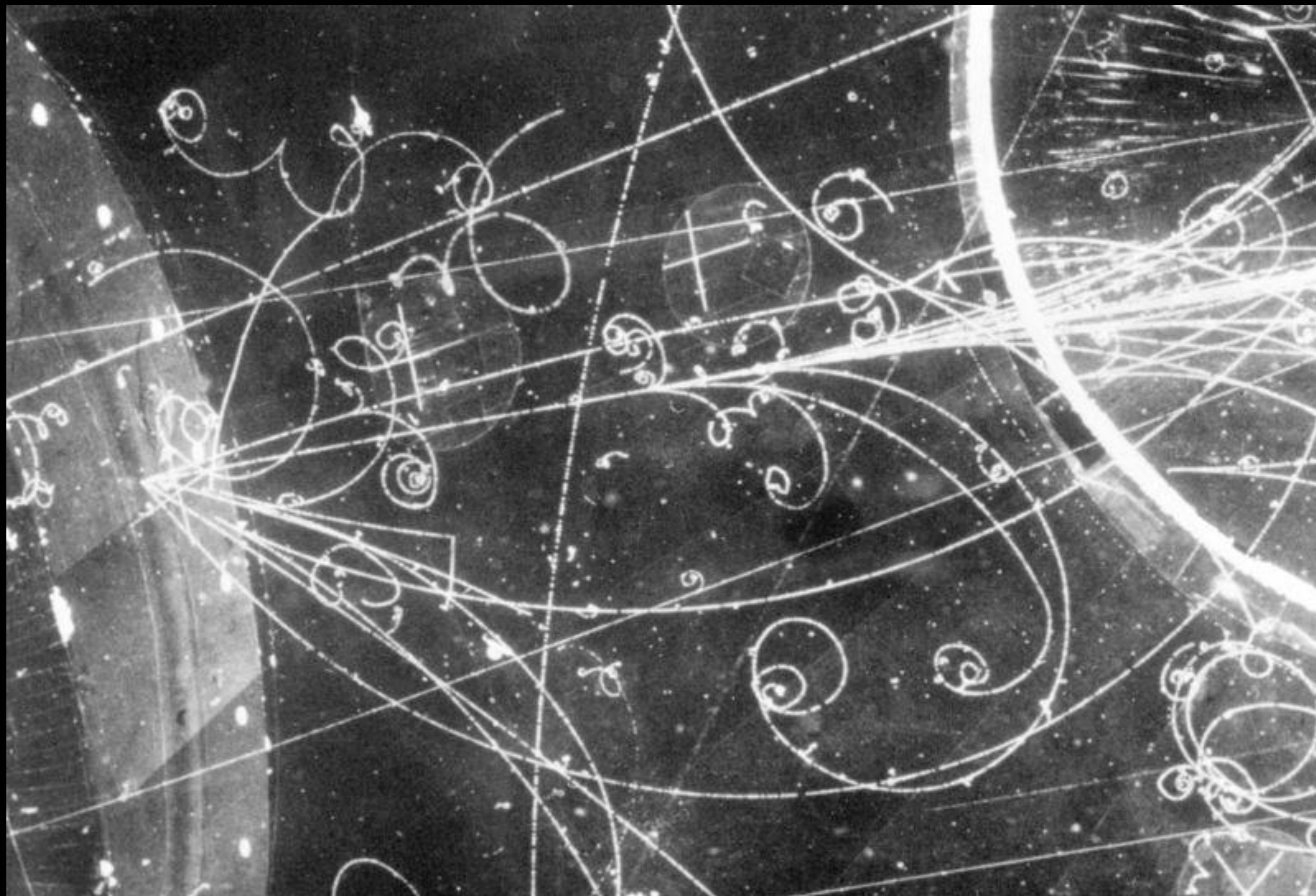




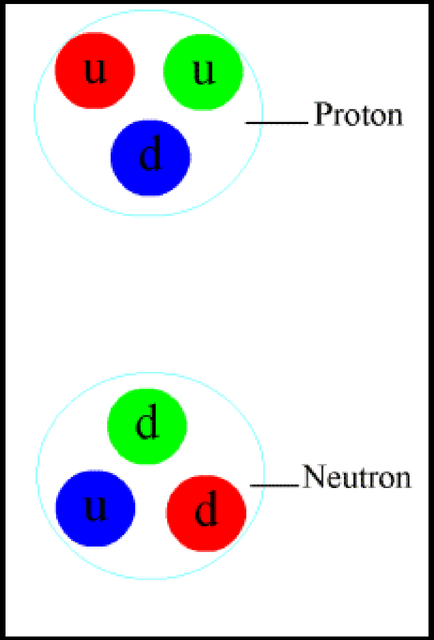


[Fermilab QuarkNet - How to Build a Cloud Chamber]

[How does a cloud chamber work?]



The Pion (and Kaon)

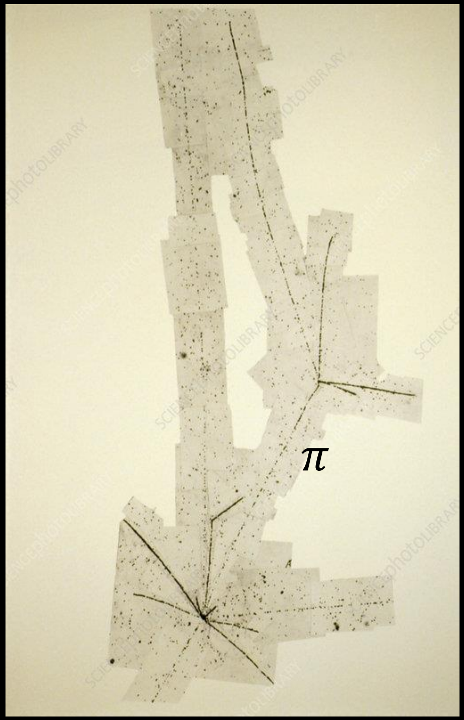


Predicted by Hideki Yukawa (1935)

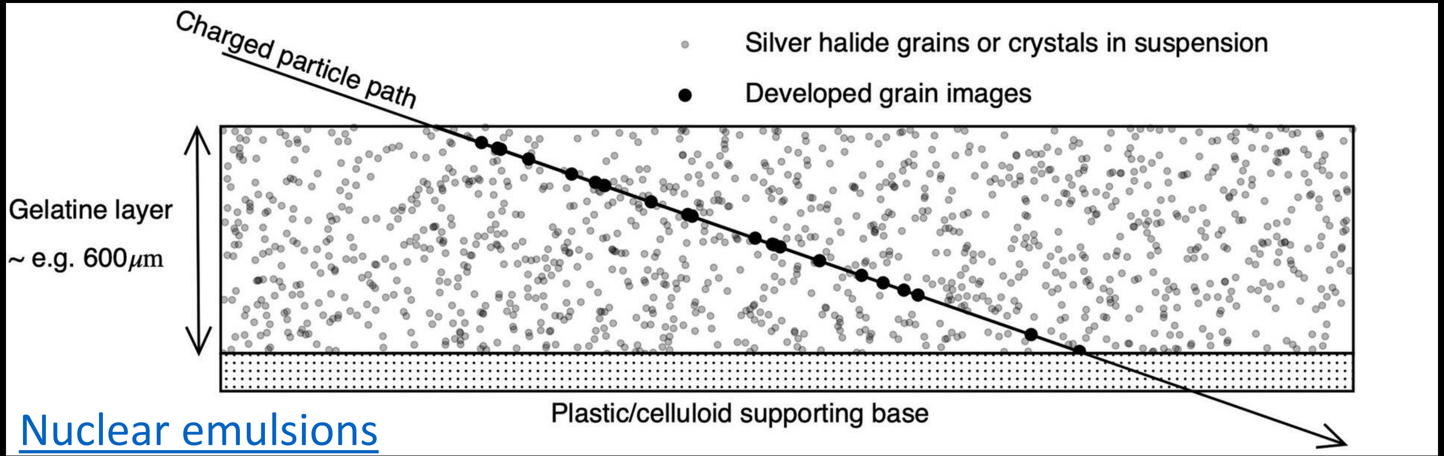
- Carriers of the *strong nuclear force*
  - $m_\pi \sim 100\mathrm{MeV/c^2}$ from size of nucleus
  - μ (previously "mu meson") was candidate

Cecil Powell (1947)

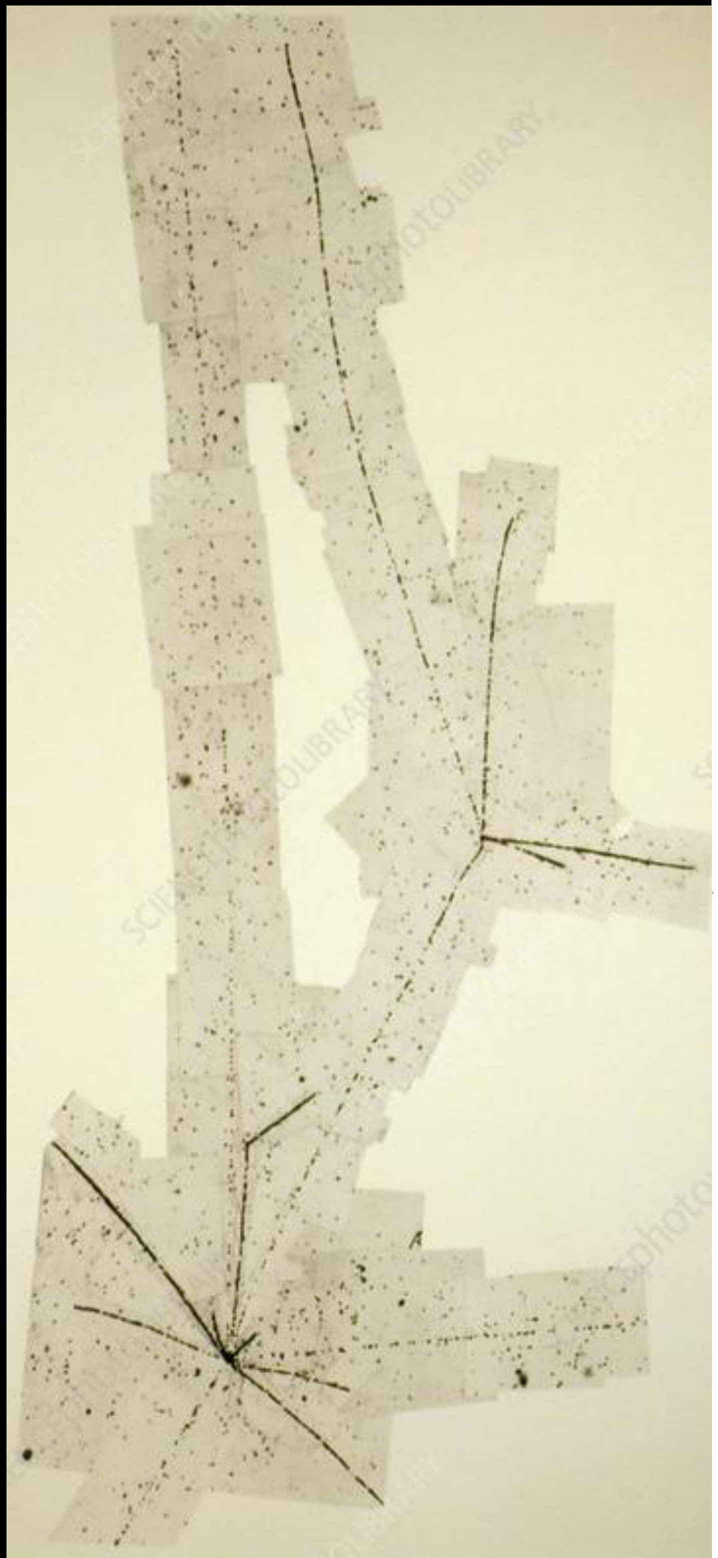
- Method w/photographic emulsions
  - Fine suspension (colloid) of insoluble light-sensitive crystals in gelatin (Nobel 1950)
- Exposed plates at high-altitude
  - Must utilize high energy cosmic rays

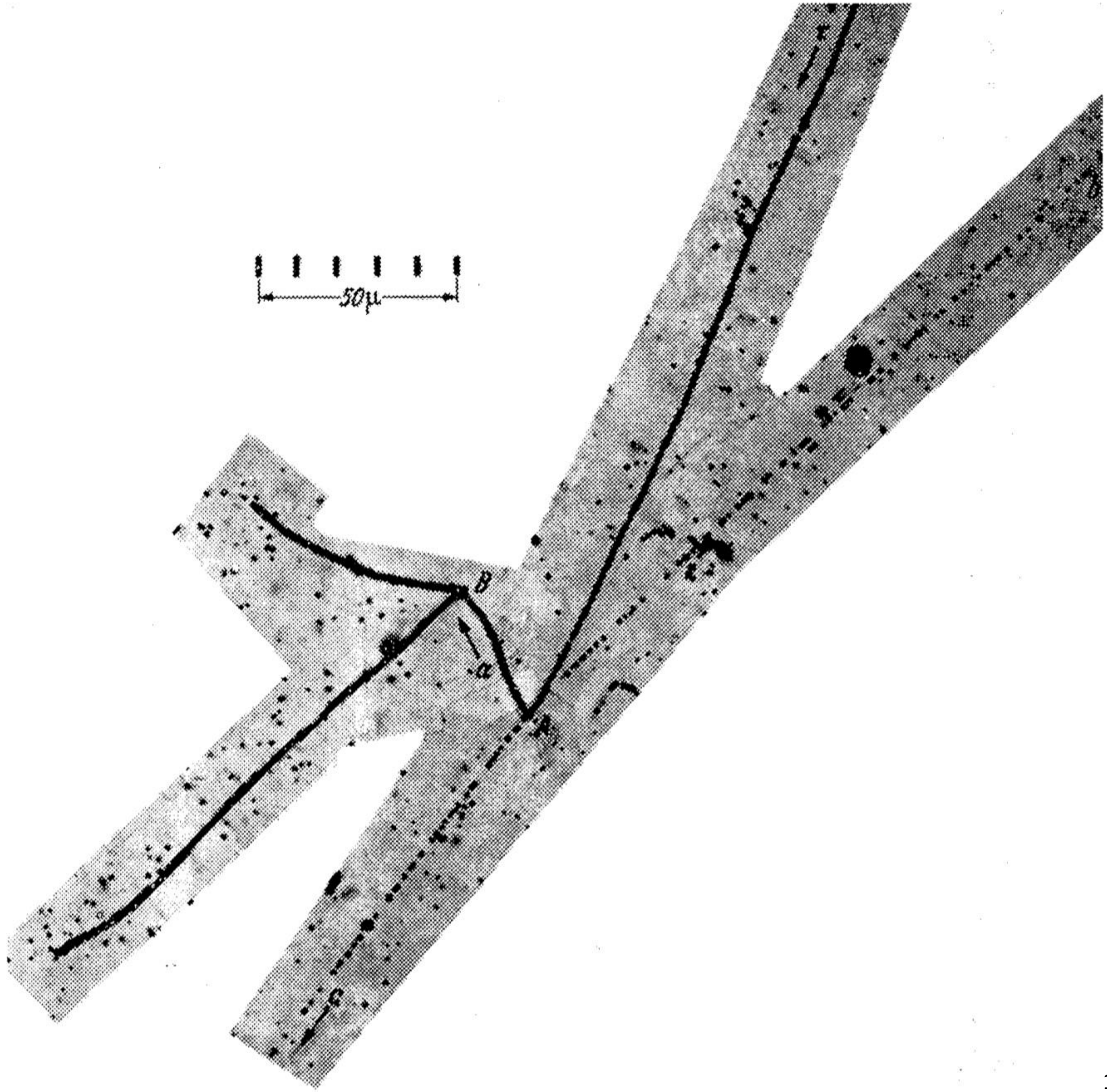


Emulsion photo of a cosmic ray pion



Nuclear emulsions

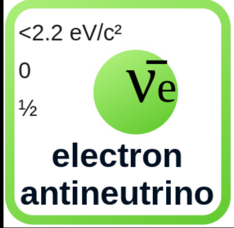




50μ
B
a
A
C

The Electron Neutrino (ν_e)

The Problem of β Decay



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β-decay of nuclei

- Instability of n
  - Decays to slightly lighter p
- Theorized to be ~2-body
  - Resulted in single value E_β

James Chadwick (1914)

- Observed cont. spectrum
  $\rightarrow E_\beta \subset (0, E_{max})$

Wolfgang Pauli (1930)

- Pred. light neutral particle
  - "Neutron"

Enrico Fermi (1931, 1933)

- "Little neutral one"–neutrino
- Landmark theory of β decay
  - Quantum mechanical
  - "Weak" processes hard to detect

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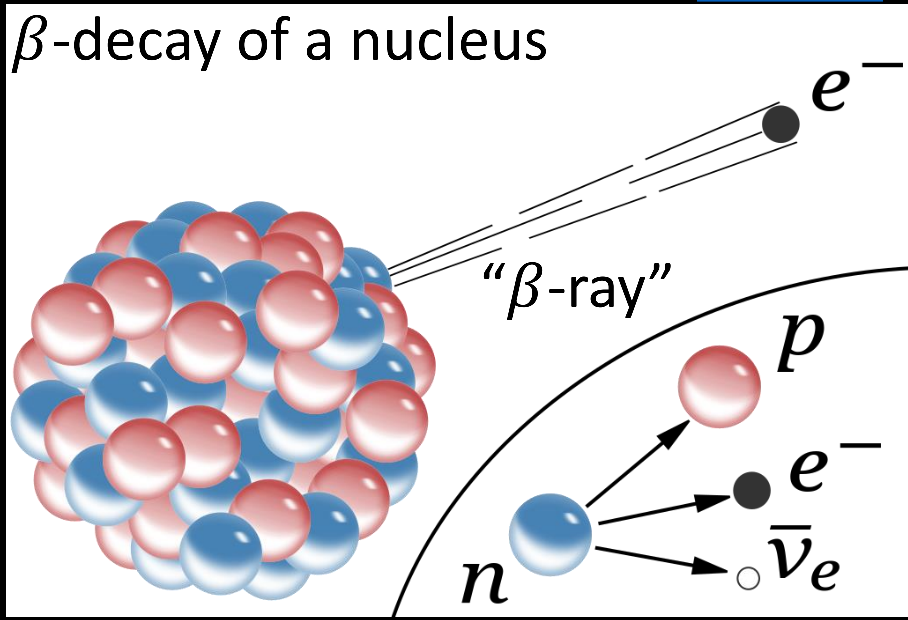

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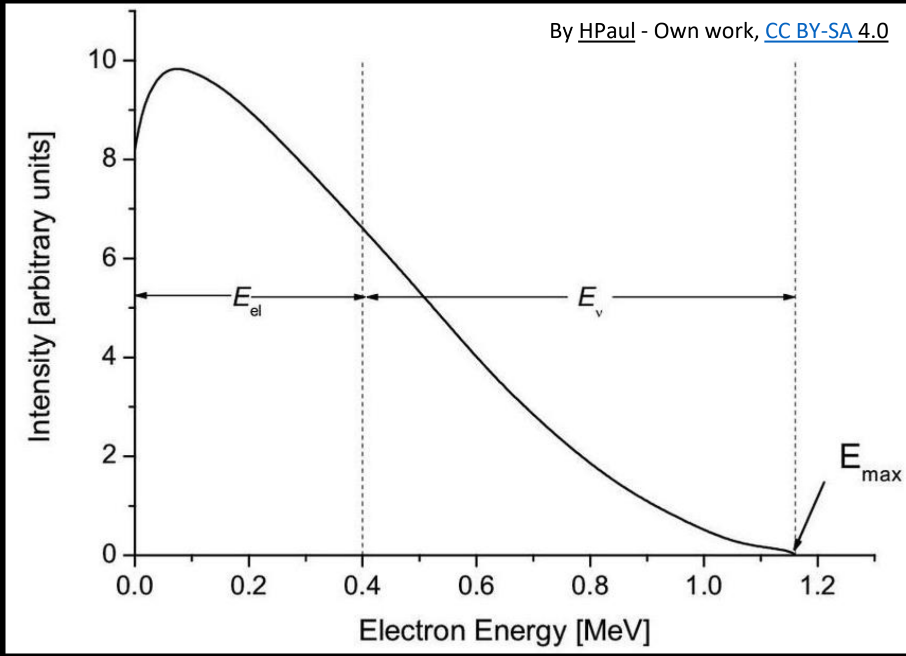
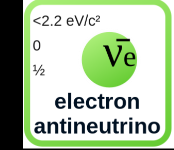


The Electron Neutrino (ν_e)

The Cowan & Reines Experiment



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From Fermi, one can begin predicting many possible reactions:

- β decay (known)

$$n \rightarrow p + e^- + \nu_e$$

- β capture (somewhat known)

$$e^- + p \rightarrow n + \nu_e$$

$$e^+ + n \rightarrow p + \bar{\nu}_e$$

- *Inverse* β decay (prediction)

$$\nu_e + n \rightarrow p + e^-$$

$$\boldsymbol{\bar{\nu}_e + p \rightarrow n + e^+}$$

  - The final of these offers tantalizing experimental possibilities
  - Coincidence of

$$e^+ + e^- \rightarrow \boldsymbol{2\gamma}$$

$$n + {}^{A}_{Z}\mathrm{N} \rightarrow {}^{A+1}_{Z}\mathrm{N}^* \rightarrow {}^{A+1}_{Z}\mathrm{N} + \boldsymbol{\gamma}$$

Cowan and Reines (1956)

- Used Savannah River nuclear plant
- Utilized 110 fast photomultiplier tubes
  - Water detector with dissolved cadmium
- Looked for coincidence of $2\gamma_F + \gamma_S$
  - Within $5\mu s$

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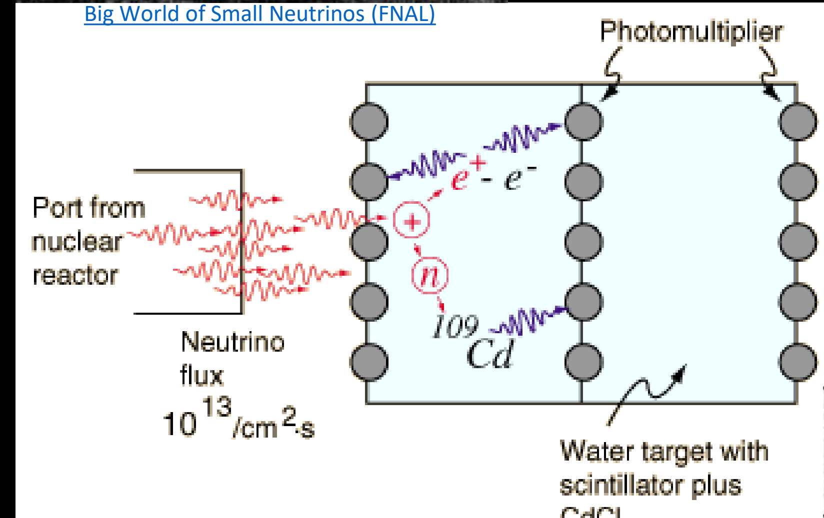
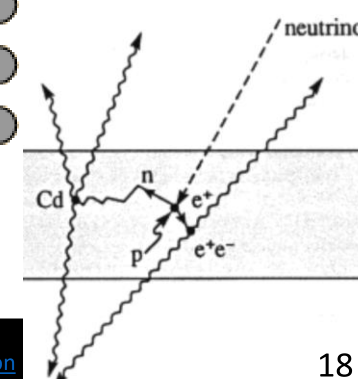
Big World of Small Neutrinos (FNAL)

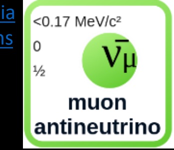


HyperPhysics: Cowan and Reines Neutrino Experiment

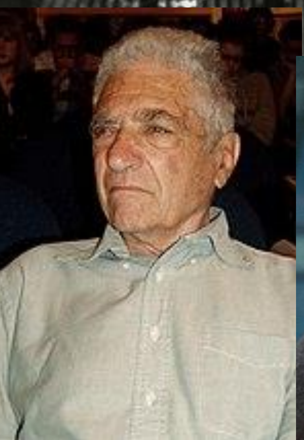


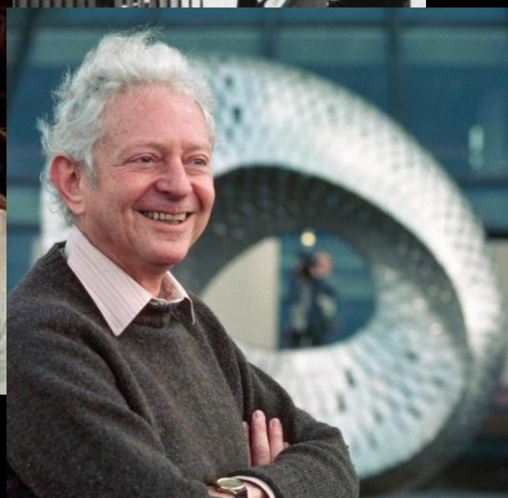
The Muon Neutrino (ν_μ)

Wikimedia Commons



Physics (APS) - Discovery of a 2nd Kind of Neutrino
From Brookhaven National Laboratory





By FNAL Public Domain

- Knowing charged pions decay weakly

$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$$

and similarly that muons decay via

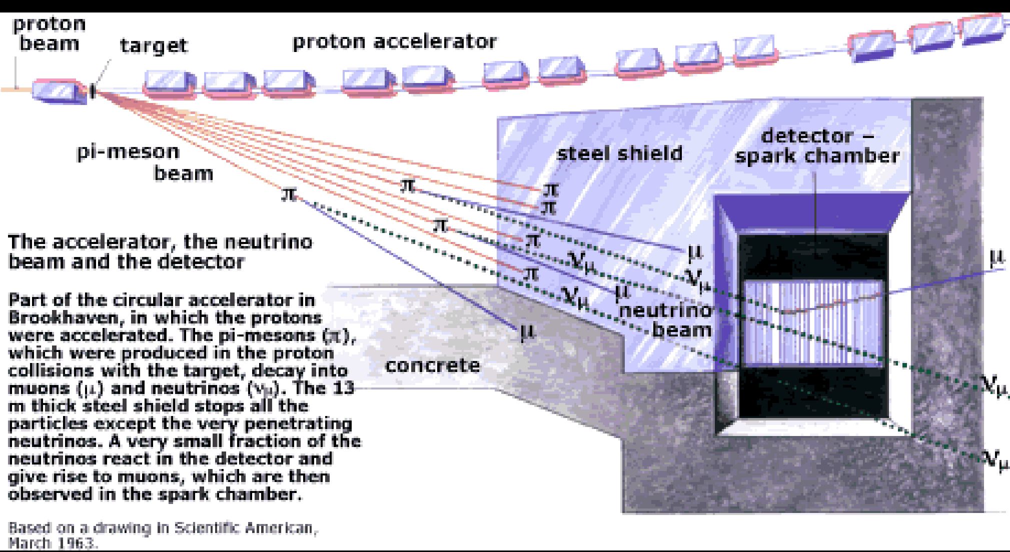
$$\mu^{\pm} \to \nu_\mu(\bar{\nu}_\mu) + e^{\pm} + \nu_e(\bar{\nu}_e)$$

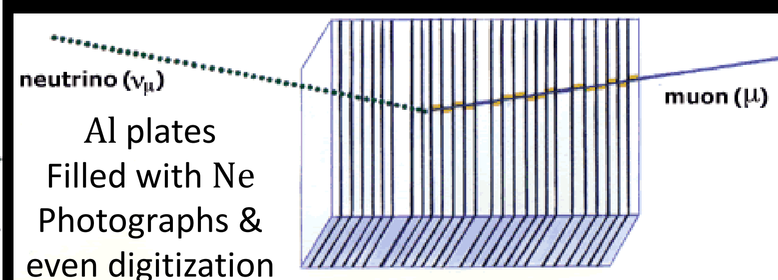
One can conceive of creating a ν beam

- Controlling upstream charged particles!

M. Schwarz, L. Lederman, J. Steinberger

- Created $\pi^{\pm}$ beam, impinged steel wall
  - Blocked most $\pi^{\pm}$ and $\mu^{\pm}$
  - Decayed quickly, made ν_μ predominately





A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.

The Nobel Prize in Physics 1988

The Quarks and Gluons (Partons)

Murray Gell-Mann (1961)

- Three-Quark Model (*a la Finnegan's Wake)*
- The Eightfold Way *(a la* Buddha)
    - $SU(3)$ flavor sym.—only a mathematical tool?
        - Mathematical group theory representation
        - Rotations of "flavor" via vector transformations

$$u \equiv \begin{pmatrix}1\\0\\0\end{pmatrix}, d \equiv \begin{pmatrix}0\\1\\0\end{pmatrix}, s \equiv \begin{pmatrix}0\\0\\1\end{pmatrix}$$

    - Spin-0 meson octet (later nonet)
    - Spin-$\frac{1}{2}$ baryon octet & spin-$\frac{3}{2}$ decuplet
        - Yielded prediction of the Ω^- baryon (1962→1964)

Electron scattering at SLAC (1969)

- Showed point-like objects within p
    - The proton is not elementary!

Richard Feyman (1969)

- "Partons" within hadrons ($p, n, \pi, \ldots$) *are real*

James Bjorken (1975)

- Partons *are* quarks & gluons
- Explains SLAC electron scattering data

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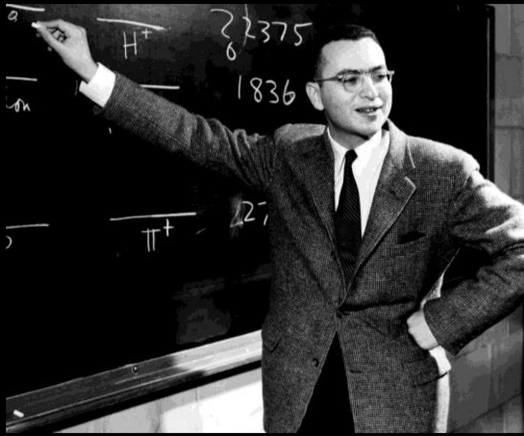

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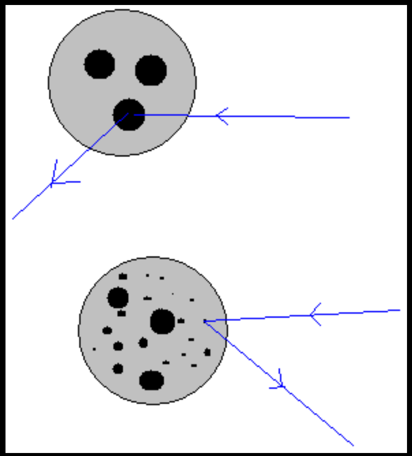

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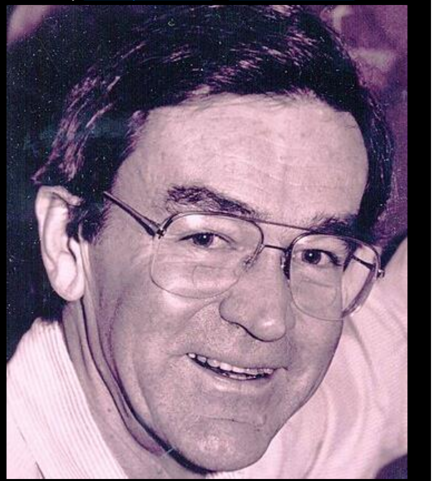
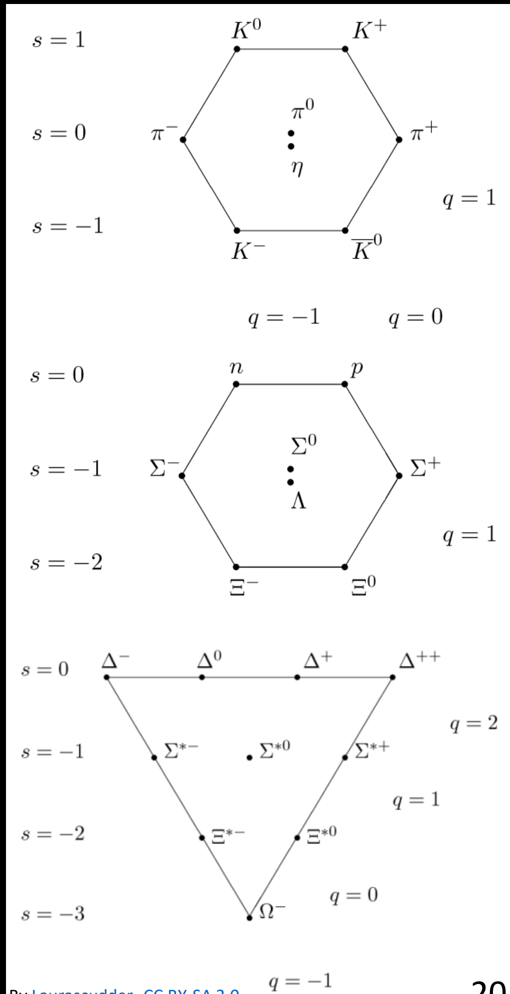


James Bjorken
Bjorken scaling



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The Quarks and Gluons (Partons)

Glashow, Iliopoulos, & Maiani (1970)

- GIM mechanism <u>*required*</u> *charm* quark
  - Arguments from unitarity beyond Cabibbo
    - Original Cabibbo matrix was only 4×4, needed more!
  - Charm predicted by Glashow and Bjorken (1964)

Kobayashi & Maskawa (1973)

- Two new flavors required
  - Bottom (beauty) & top (truth)
- Quark mixing via weak interactions

$$\begin{bmatrix} (d' & u') \\ (s' & c') \\ (b' & t') \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} (d & u) \\ (s & c) \\ (b & t) \end{bmatrix}$$

  - Use of Cabibbo angle for rotations (1963)

Richter (SLAC) and Ting (BNL)

- Discovery of J/ψ charmed meson
  - "November Revolution" of 1974

Lederman team at FNAL

- Bottom quark from Υ meson
  - Lifetime: 1.21×10^{-21}s

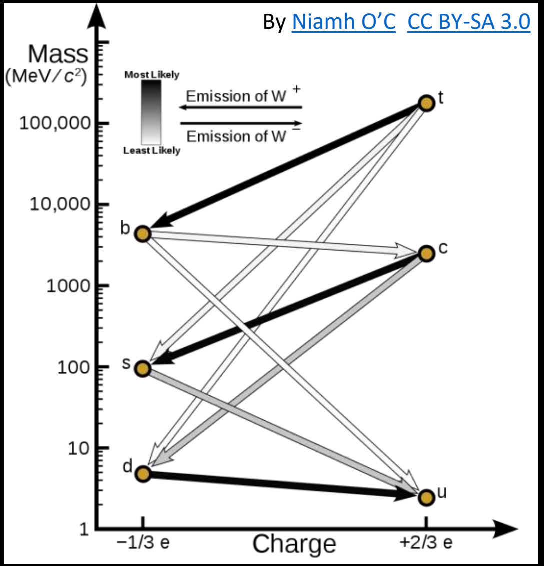
CDF & DO at FNAL Tevatron

- Top quark (1995)

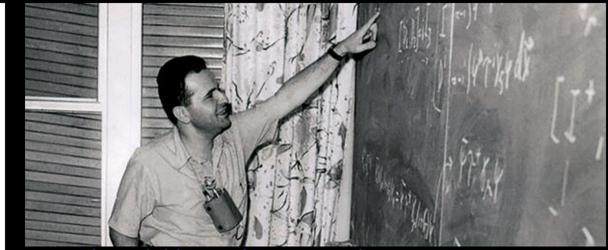
DESY three-jet events

- Gluon (1979)

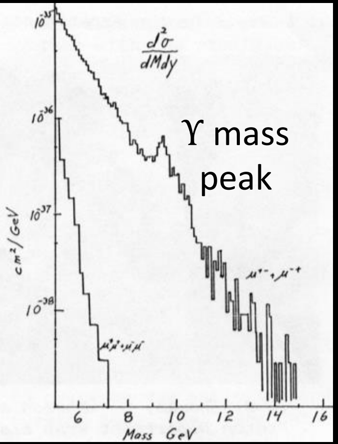
50 Years of the GIM Mechanism – CERN Courier
H.-J. He, J. Ellis, **J. Iliopoulos**, **S. L. Glashow**, V. Riquer & **L. Maiani**



By Niamh O'C CC BY-SA 3.0


The Cabibbo angle, 60 years later – CERN Courier


Nobel rewards for work on broken symmetry



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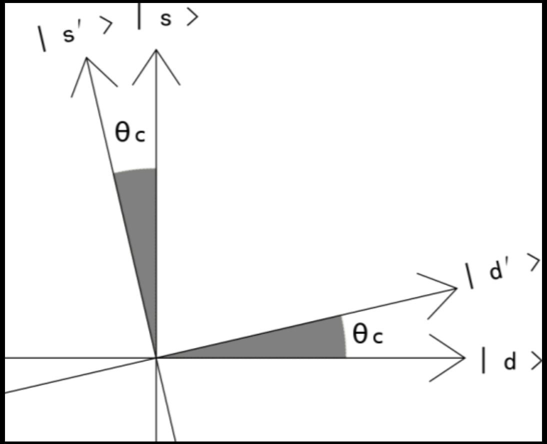
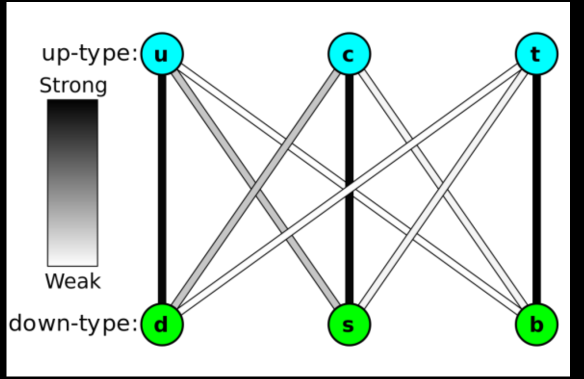
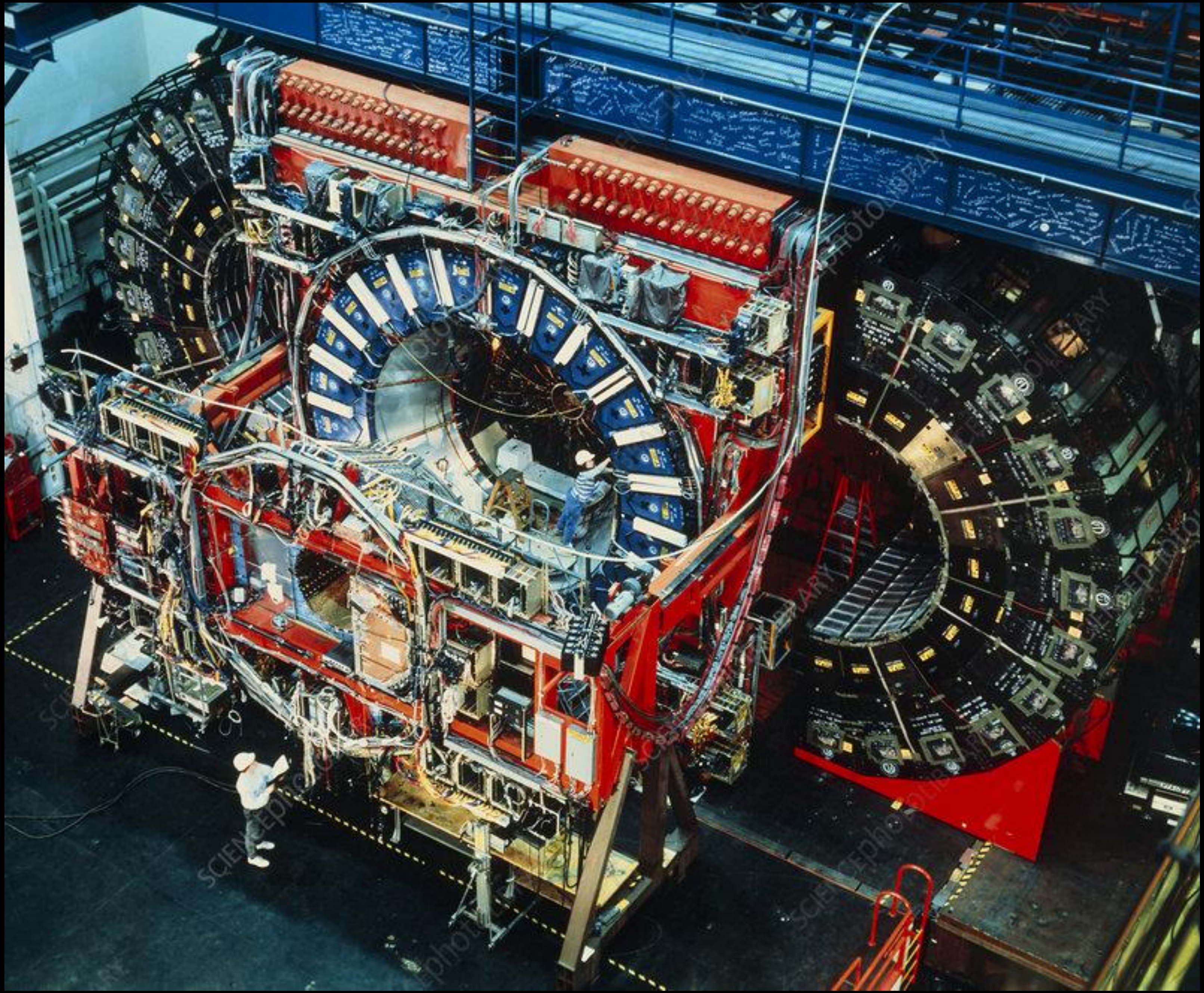


By Headbomb - Own work, Public Domain

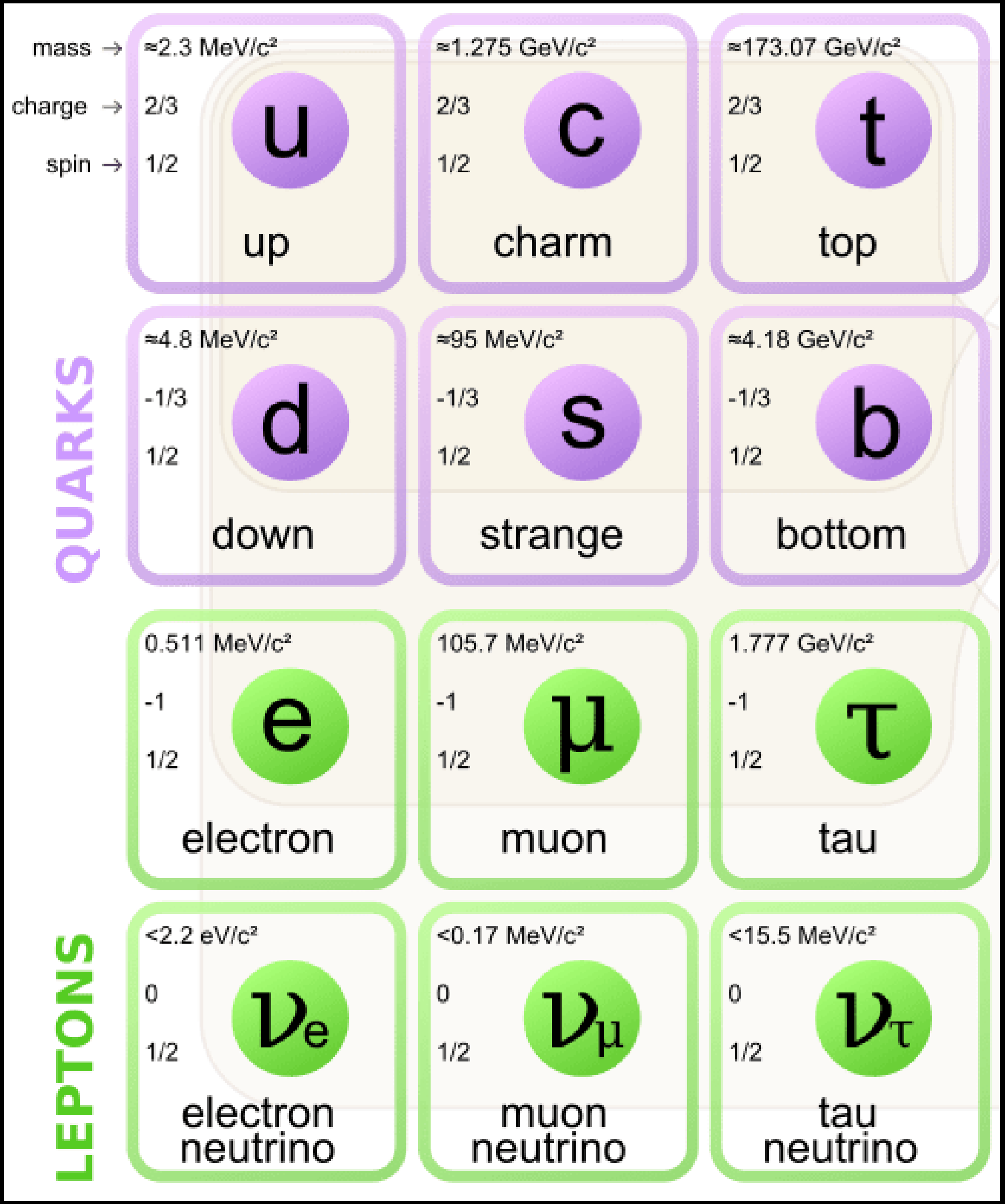


Derivative work, from public domain work



Collider Detector Facility (CDF) at Fermilab - Science Photo Library

Three Generations of Elementary Matter

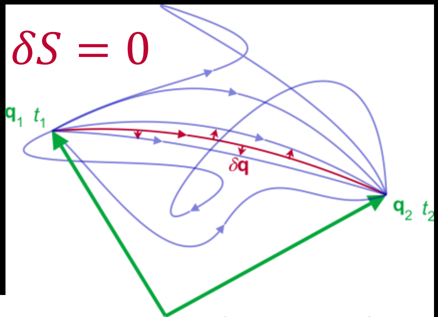


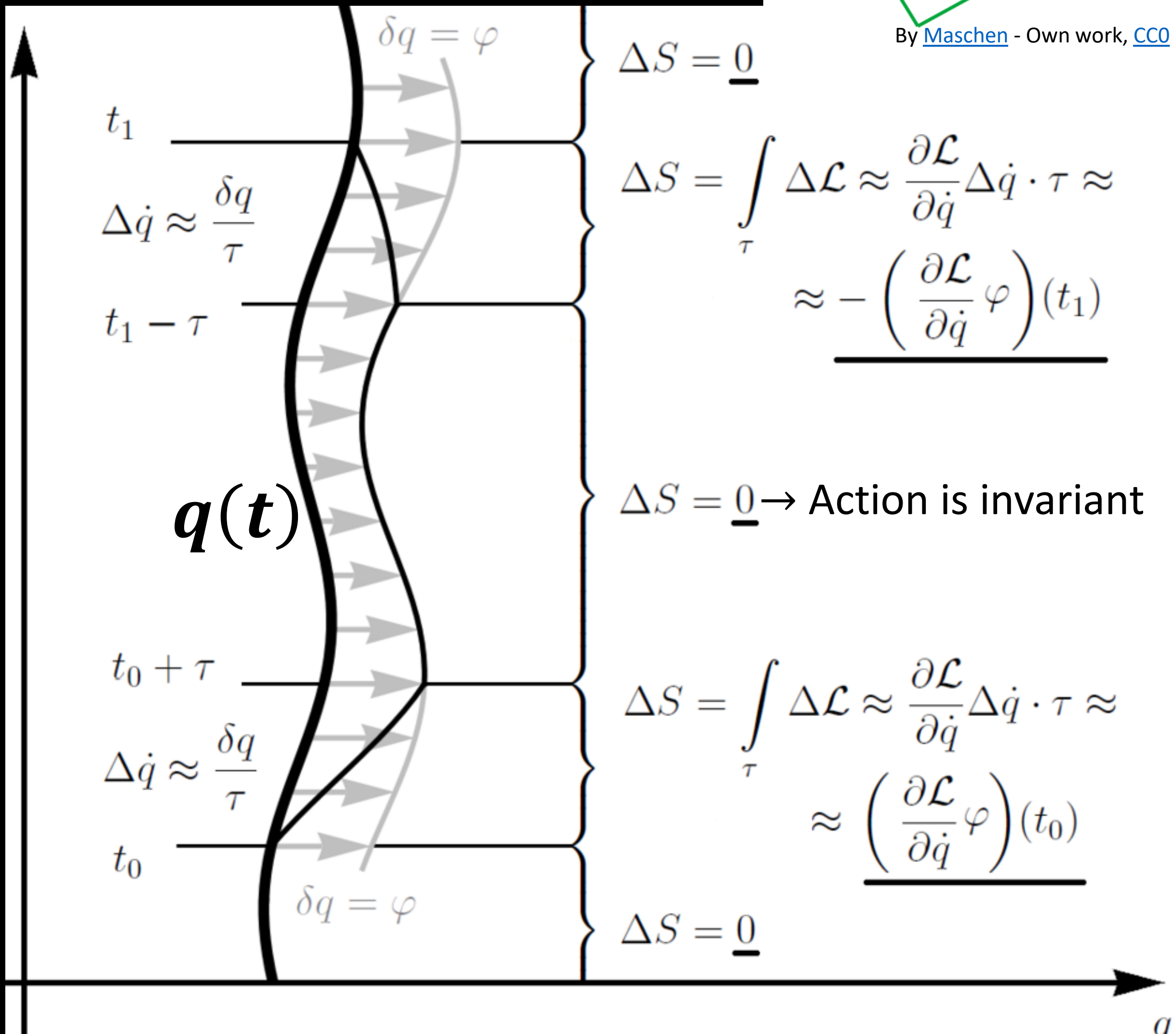
Putting it all together…

Quantum Field Theory

Symmetries & Conservation Laws

Lagrangian Mechanics
Hamilton's Principle
UCSD: The Physics of Noether's Theorem
Lagrangian Classical Field Theory
Path Integral Formulation of QM





"If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved…"

-W. J. Thompson, *Angular Momentum*

Consider a transformation in a single coordinate q

- Cont. symmetry:

$$\varphi: q(t) \rightarrow q(t) + \delta q(t)$$

where $q(t)$ is a trajectory

Examples in classical physics:

- **If symmetric in time…**
  - **Energy conserved!**
- **If symmetric in space…**
  - **Momentum conserved!**
- **Symmetric under rotations…**
  - **Ang. momentum conserved!**

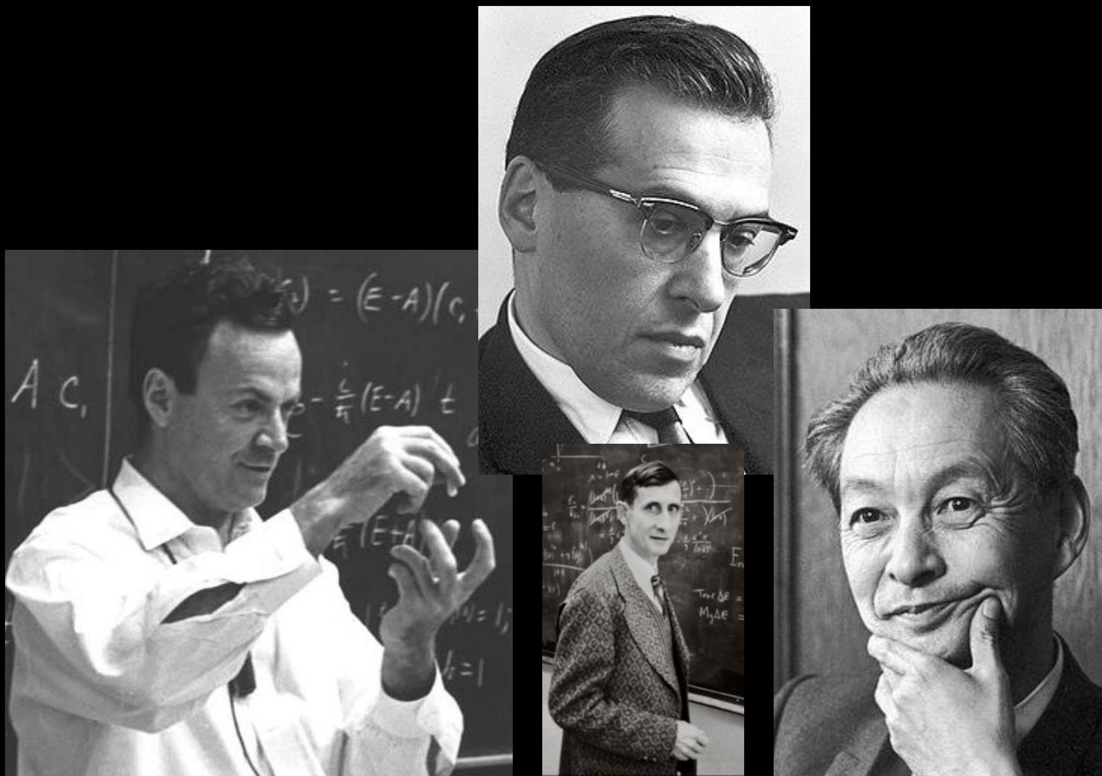
Used everywhere!

- Classical dynamics
- General relativity
- Quantum field theory

"Noether was the most significant creative mathematical genius thus far produced since the higher education of women began."
-Albert Einstein, *The New York Times*

Chris Quigg: A Century of Noether's Theorem
Chris Quigg Seminar
Don Lincoln: The Most Significant Genius

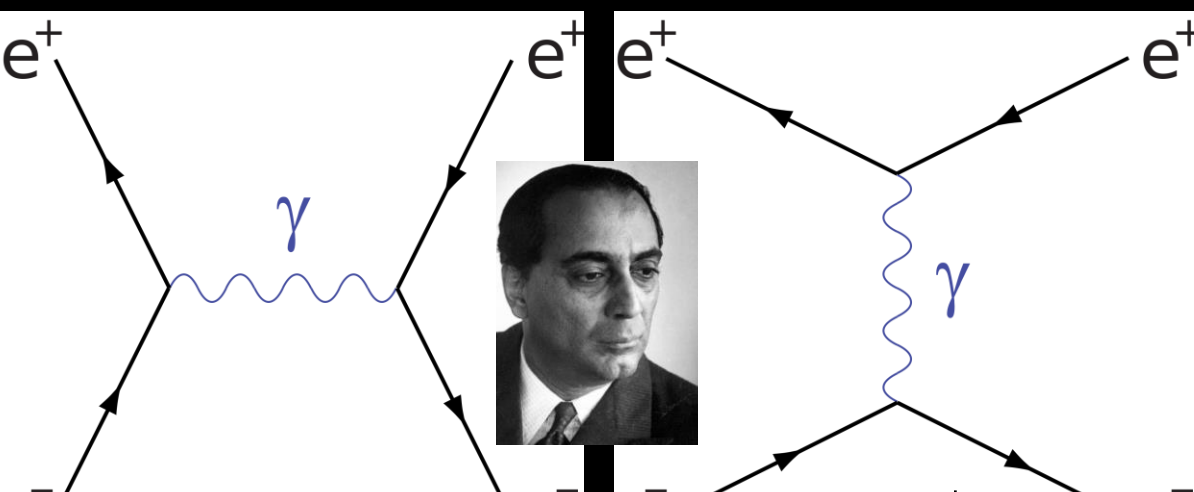
Quantum Electrodynamics: $U(1)$



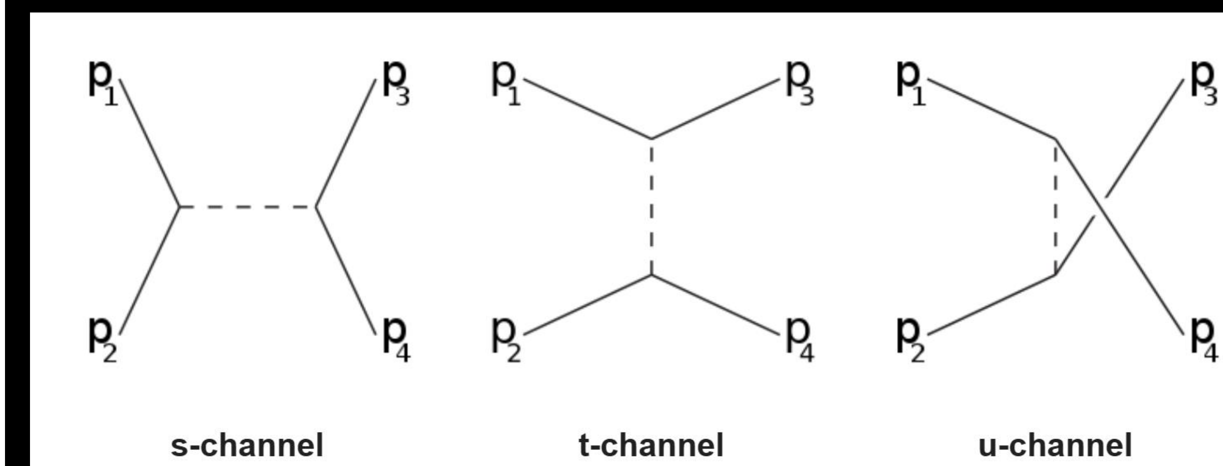
- Term due to Dirac
  - Quantization of EM field as harm. osc.
  - Creation and annihilation operators

- First full theory developed by Fermi
  - Worked to 1st order, diverged after
  - Bethe: 1st ideas of "renormalization"

- Schwinger, Tomanaga, Feynman
  - Feynman's math based on his diagrams
    - Unique, direct view of perturbation theory
    - Approaches were equivalent (Dyson series)
  - Attached physical meanings to infinities
- Template for all other QFTs
  - Conserved electric current

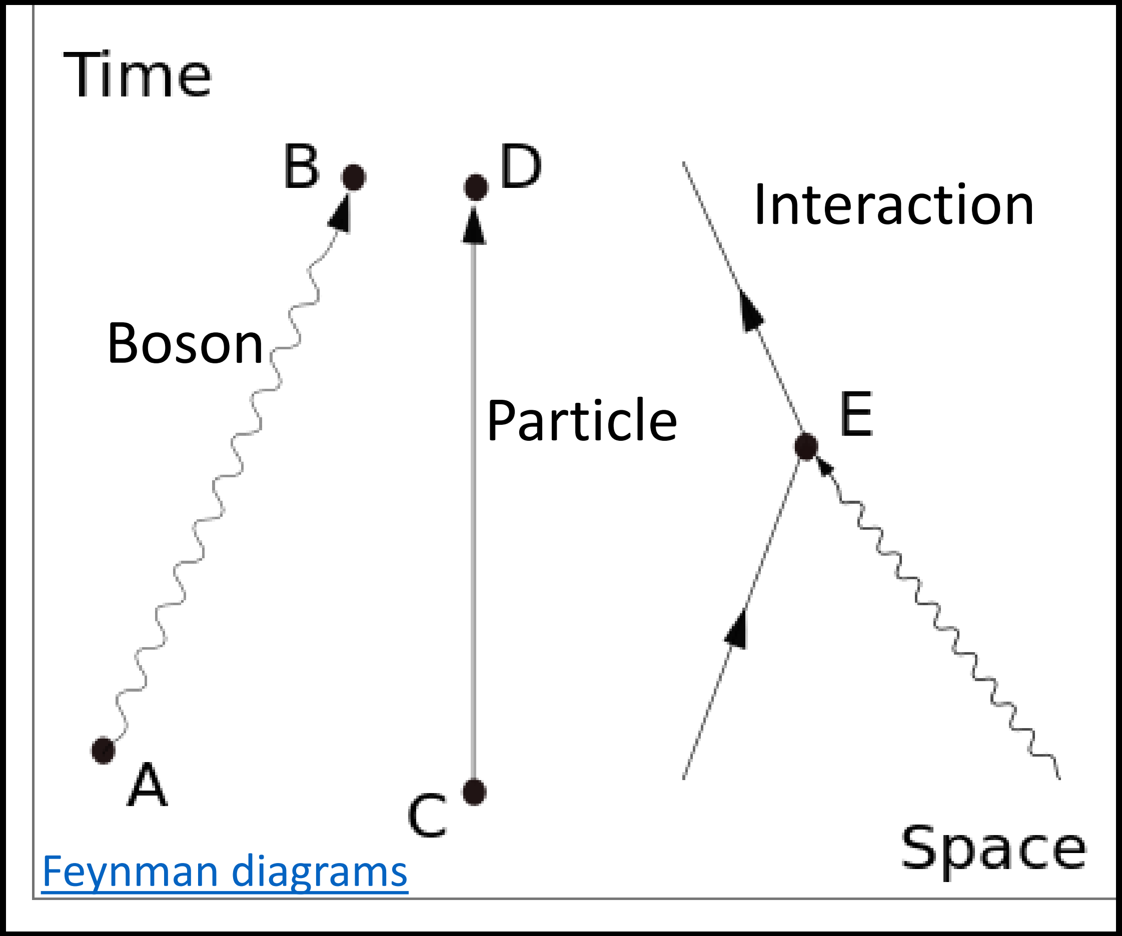


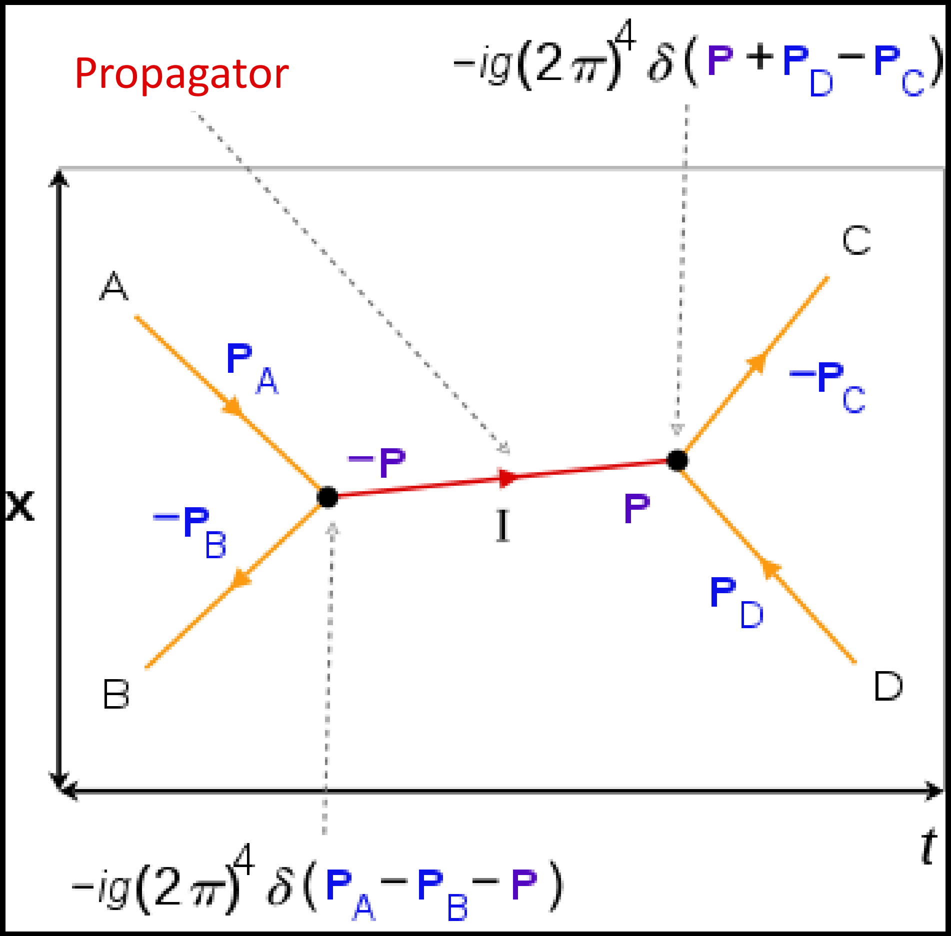
First $\sigma(e^+, e^-)$ from Bhabha



Mandelstam variables

Elements of Feynman Diagrams





Particle interactions mediated by (virtual gauge) bosons

- Vertex must be “dimension” $d = 4$ (generally true for all SM)
  - Particles (electrons, positrons in QED) are $d = \frac{3}{2}$
  - Bosons (photons in QED) are $d = 1$
  - Summing for interactions: $d = d_1 + d_2 + d_3 = \frac{3}{2} + \frac{3}{2} + 1 = 4 \Leftrightarrow \sim\phi^4$ theory

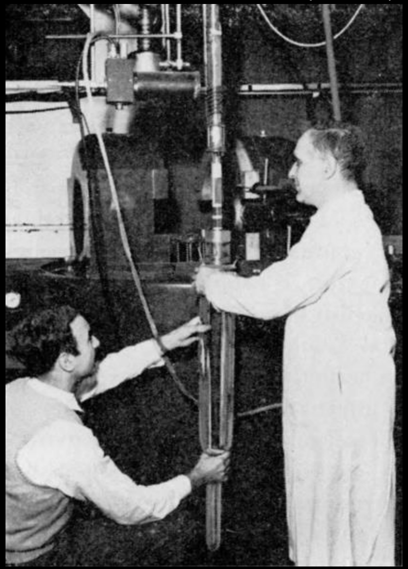
Electroweak Unification: $SU(2) \times U(1)$

Madame C. S. Wu

- Studied β decays of $^{60}\mathrm{Co}$

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + \mathrm{e}^- + \bar{\nu}_e + 2\gamma$$

  - Found *preferred* direction for outgoing γs
    - Unexpected! **Spatial parity is not conserved!**
    - Required a new view of weak & EM interactions *together* with a distinct handedness

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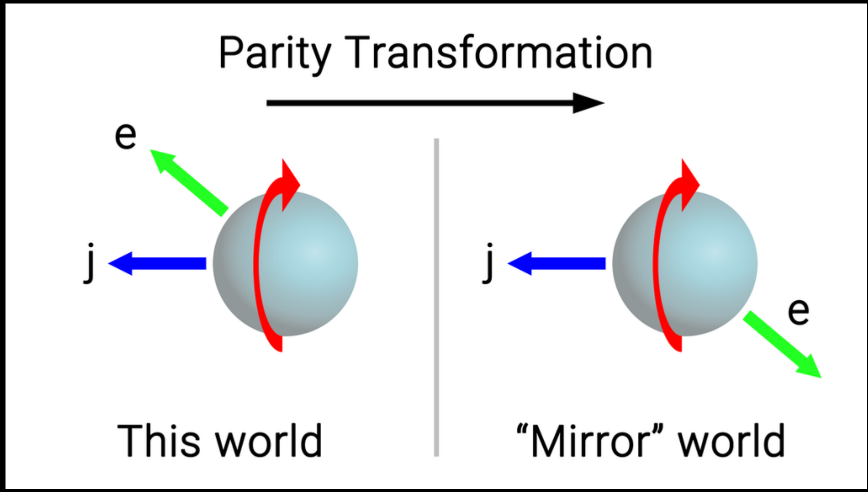
Glashow, Salam (1964), Weinberg (1967)

- Z boson predicted, but non-renormalizable
- Predicted massless photon, three massive bosons
- Found symmetries predicting masses of $W^\pm$ & Z bosons
  - Claimed was renormalizable
  - Incorporated spontaneous symmetry breaking
  - T'Hooft proved this
- Unified EM and weak interaction: $SU(2)_L \times U(1)_Y$
  - Conserved weak isospin and weak hypercharge Y



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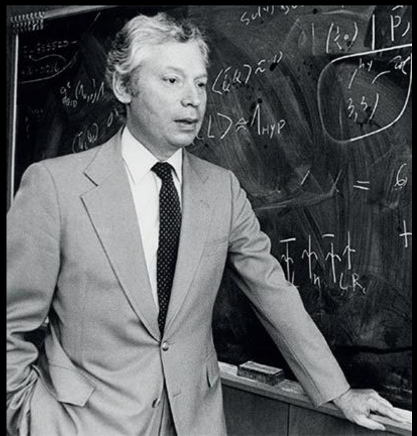
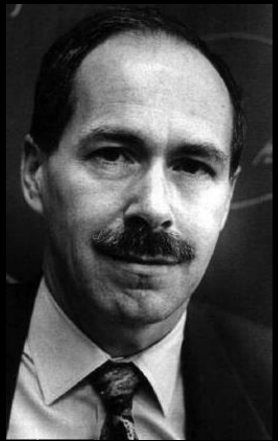
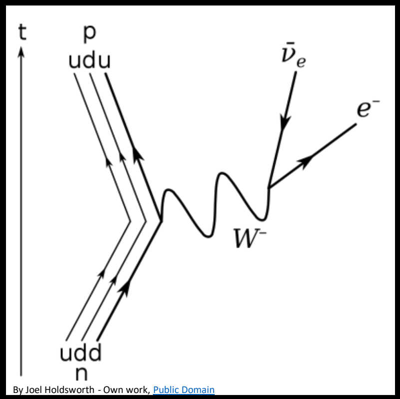
Dutch National Archives



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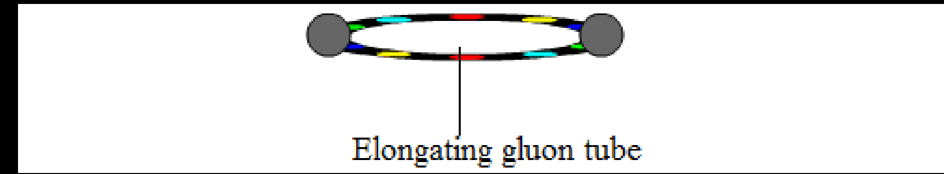
Unifying the Forces: Electroweak Theory

Electroweak Theory and the Origin of the Fundamental Forces

Quantum Chromodynamics: $SU(3)$

Strong (nuclear) interactions (of partons)

- "Strong": many infinities to deal with…
  - Short distance physics became untenable (Landau)
- Clues: Gell-Mann's work hadron structure
  - Particles were real, and strongly interacting
- Bjorken's work lead to new theories
  - "Color" & quark flavor as a conserved charges



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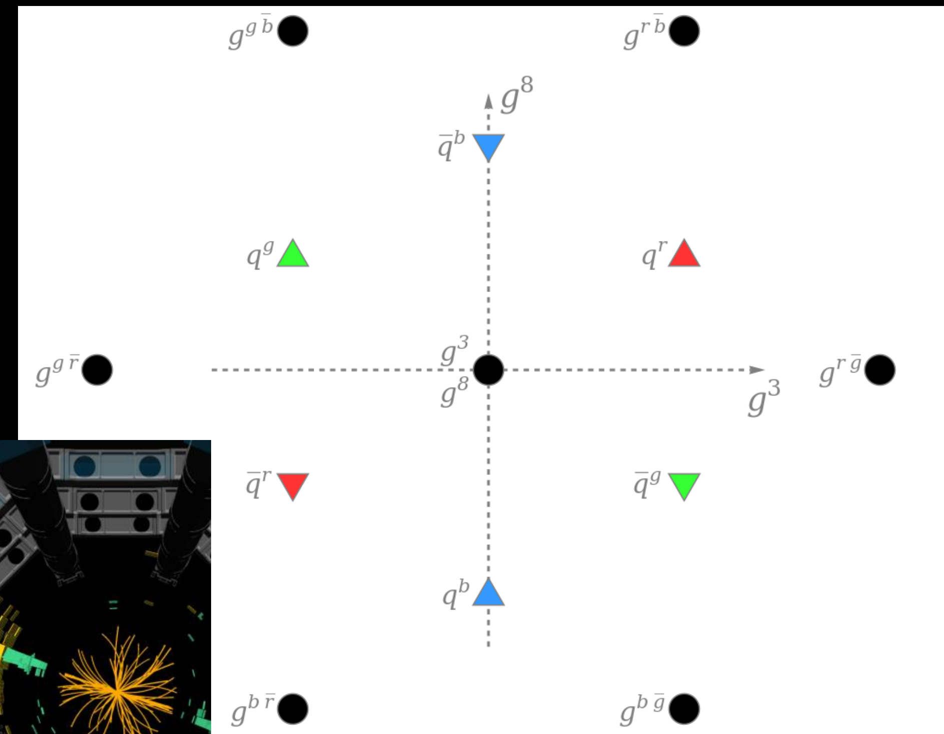

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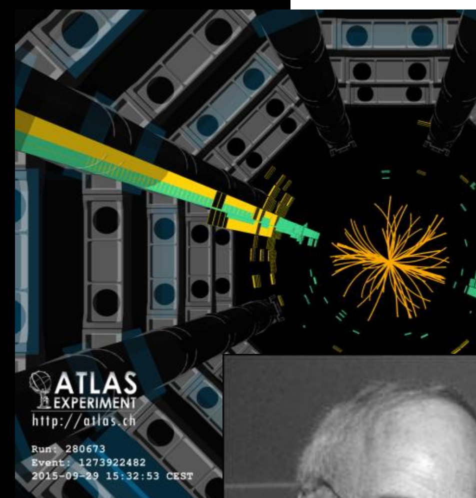
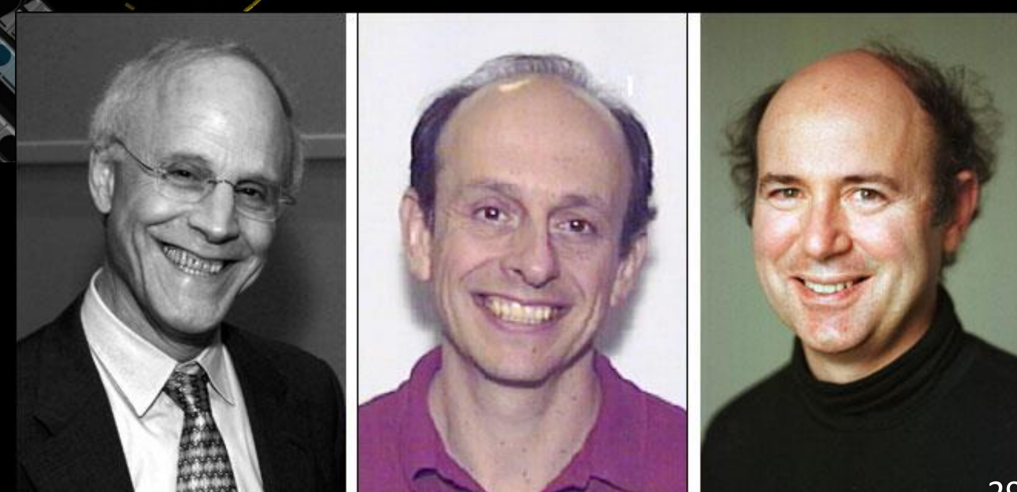


Fritzsh and Leutwyler (1973)

- Color as *source* of the strong field

Gross, Politzer, Wilczek (1973)

- Asymptotic freedom prevented Landau poles
  - Predicted color confinement
  - Can search for hadronization (jet production) in high-energy experiments
    - Lund string models



Altogether Now

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$ (U(1), SU(2) and SU(3) gauge terms)

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)}$$ (lepton dynamical term)

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right]$$ (electron, muon, tauon mass term)

Added Dirac

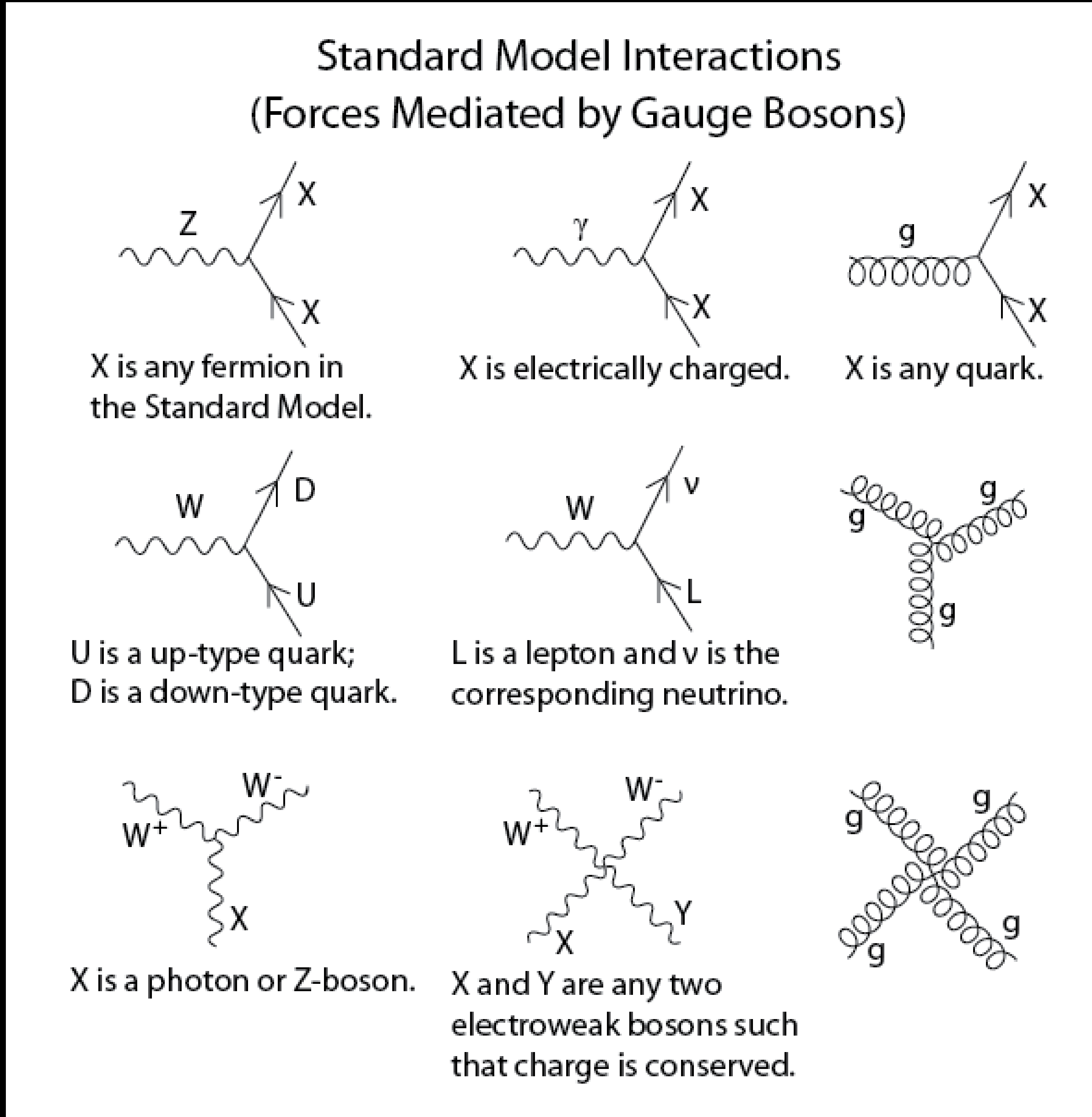
$$-\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right]$$ (neutrino mass term)

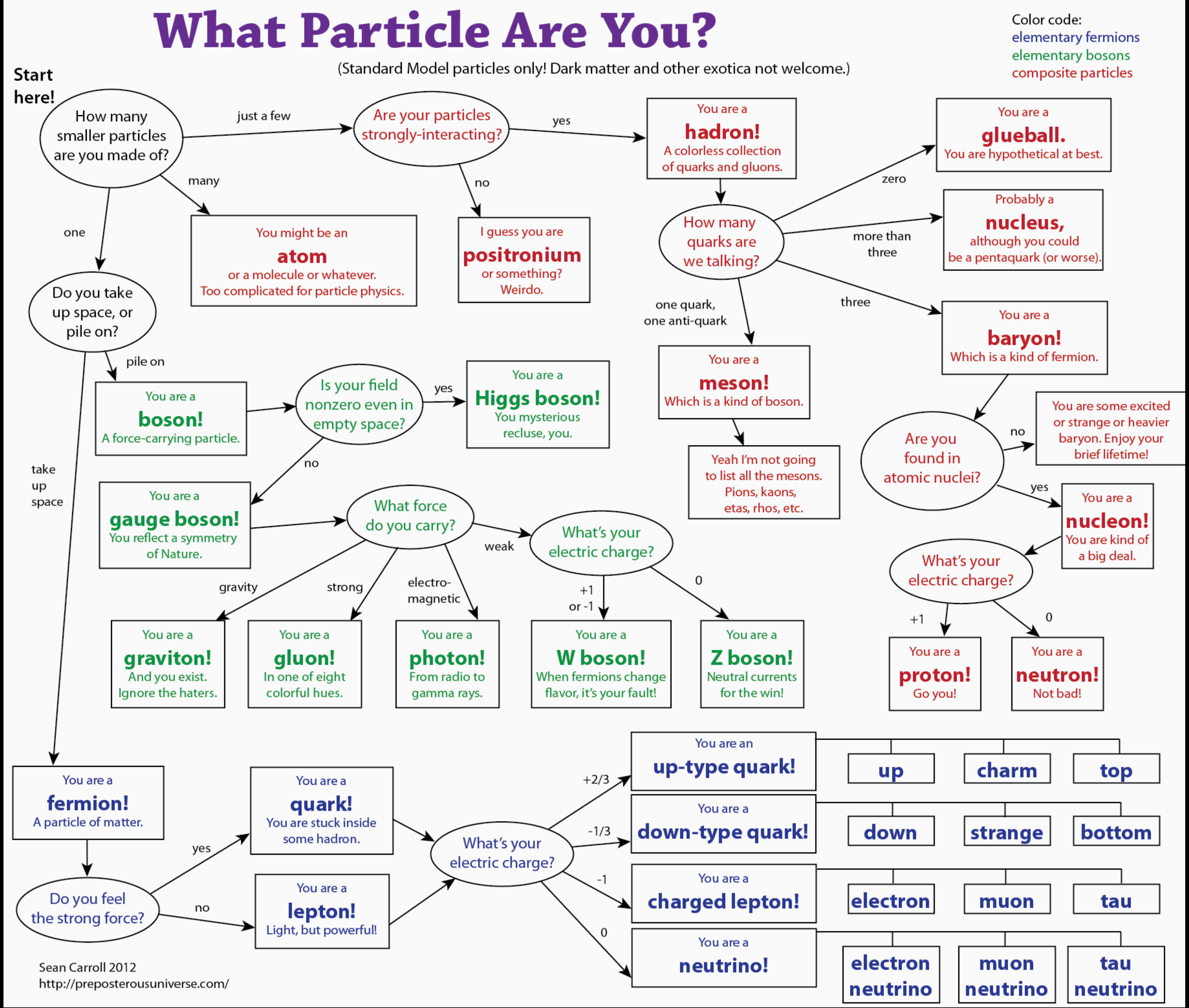
$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)}$$ (quark dynamical term)

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix} u_L \\ d_L \end{pmatrix}\right]$$ (down, strange, bottom mass term)

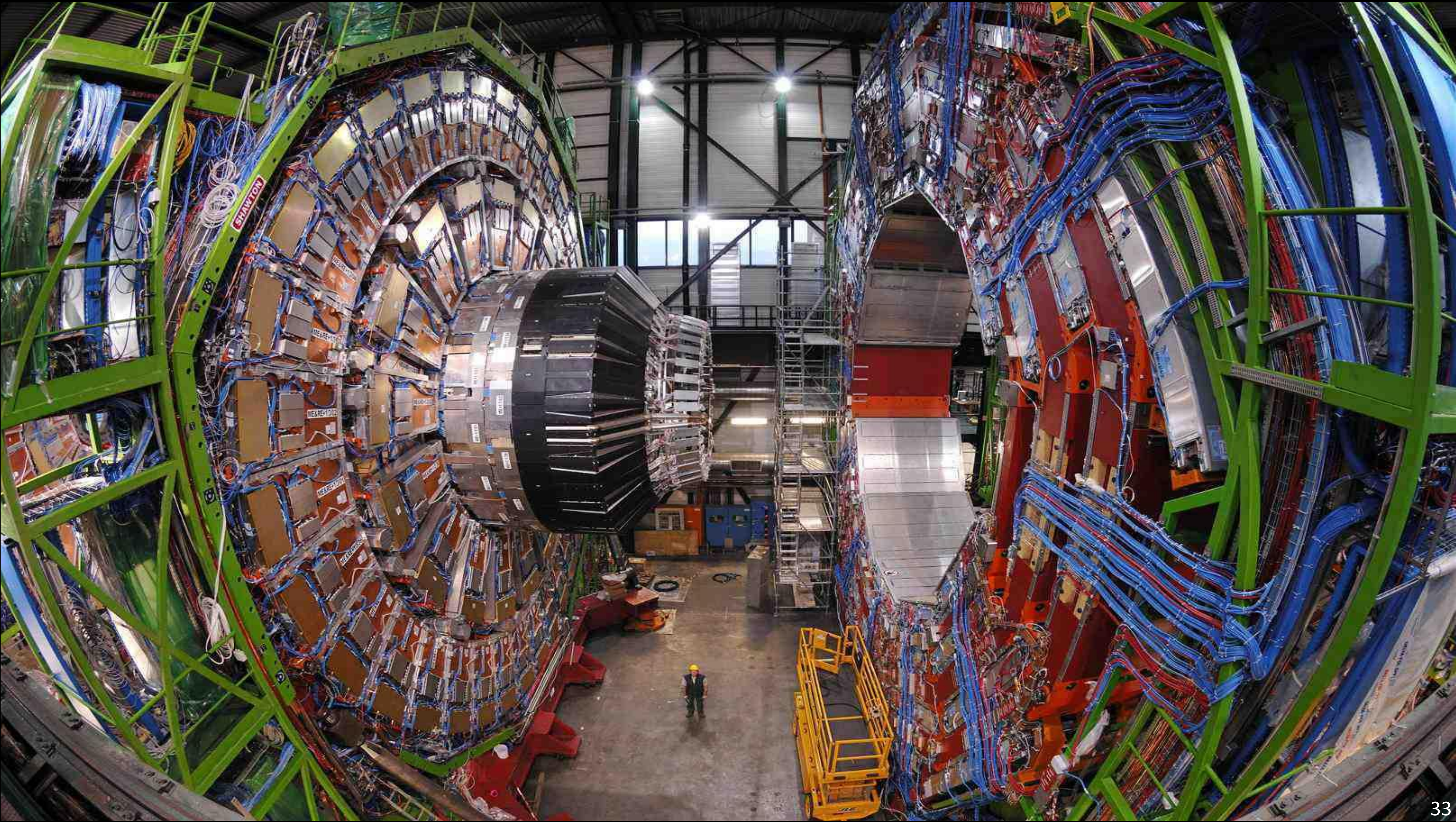
$$-\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]$$ (up, charmed, top mass term)

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$ (Higgs dynamical and mass term) (1)

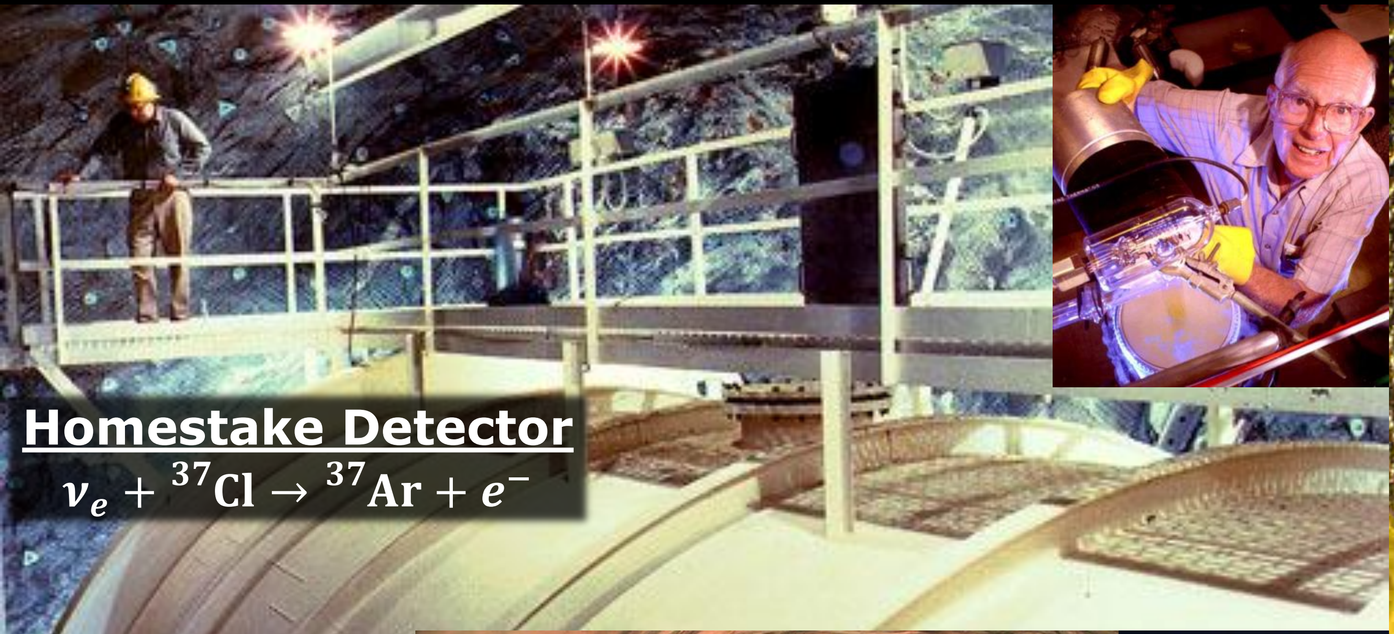

Standard Model Interactions
(Forces Mediated by Gauge Bosons)
Z
X
X
X is any fermion in the Standard Model.
γ
X
X
X is electrically charged.
g
X
X
X is any quark.
W
D
U
U is a up-type quark;
D is a down-type quark.
W
v
L
L is a lepton and v is the corresponding neutrino.
g
g
g
W-
W+
X
X is a photon or Z-boson.
W-
W+
Y
X
X and Y are any two electroweak bosons such that charge is conserved.
g
g
g
g


What Particle Are You?
(Standard Model particles only! Dark matter and other exotica not welcome.)
Color code:
elementary fermions
elementary bosons
composite particles
Start here!
How many smaller particles are you made of?
just a few
many
one
Are your particles strongly-interacting?
yes
no
You are a hadron! A colorless collection of quarks and gluons.
You might be an atom or a molecule or whatever. Too complicated for particle physics.
I guess you are positronium or something? Weirdo.
How many quarks are we talking?
zero
more than three
three
one quark, one anti-quark
You are a glueball. You are hypothetical at best.
Probably a nucleus, although you could be a pentaquark (or worse).
You are a baryon! Which is a kind of fermion.
You are a meson! Which is a kind of boson.
Yeah I'm not going to list all the mesons. Pions, kaons, etas, rhos, etc.
Are you found in atomic nuclei?
no
yes
You are some excited or strange or heavier baryon. Enjoy your brief lifetime!
You are a nucleon! You are kind of a big deal.
What's your electric charge?
+1
0
You are a proton! Go you!
You are a neutron! Not bad!
Do you take up space, or pile on?
pile on
take up space
You are a boson! A force-carrying particle.
Is your field nonzero even in empty space?
yes
no
You are a Higgs boson! You mysterious recluse, you.
You are a gauge boson! You reflect a symmetry of Nature.
What force do you carry?
gravity
strong
electro-magnetic
weak
What's your electric charge?
+1 or -1
0
You are a graviton! And you exist. Ignore the haters.
You are a gluon! In one of eight colorful hues.
You are a photon! From radio to gamma rays.
You are a W boson! When fermions change flavor, it's your fault!
You are a Z boson! Neutral currents for the win!
You are a fermion! A particle of matter.
Do you feel the strong force?
yes
no
You are a quark! You are stuck inside some hadron.
You are a lepton! Light, but powerful!
What's your electric charge?
+2/3
-1/3
-1
0
You are an up-type quark!
up
charm
top
You are a down-type quark!
down
strange
bottom
You are a charged lepton!
electron
muon
tau
You are a neutrino!
electron neutrino
muon neutrino
tau neutrino
Sean Carroll 2012
http://preposterousuniverse.com/

Still Searching for What's Next

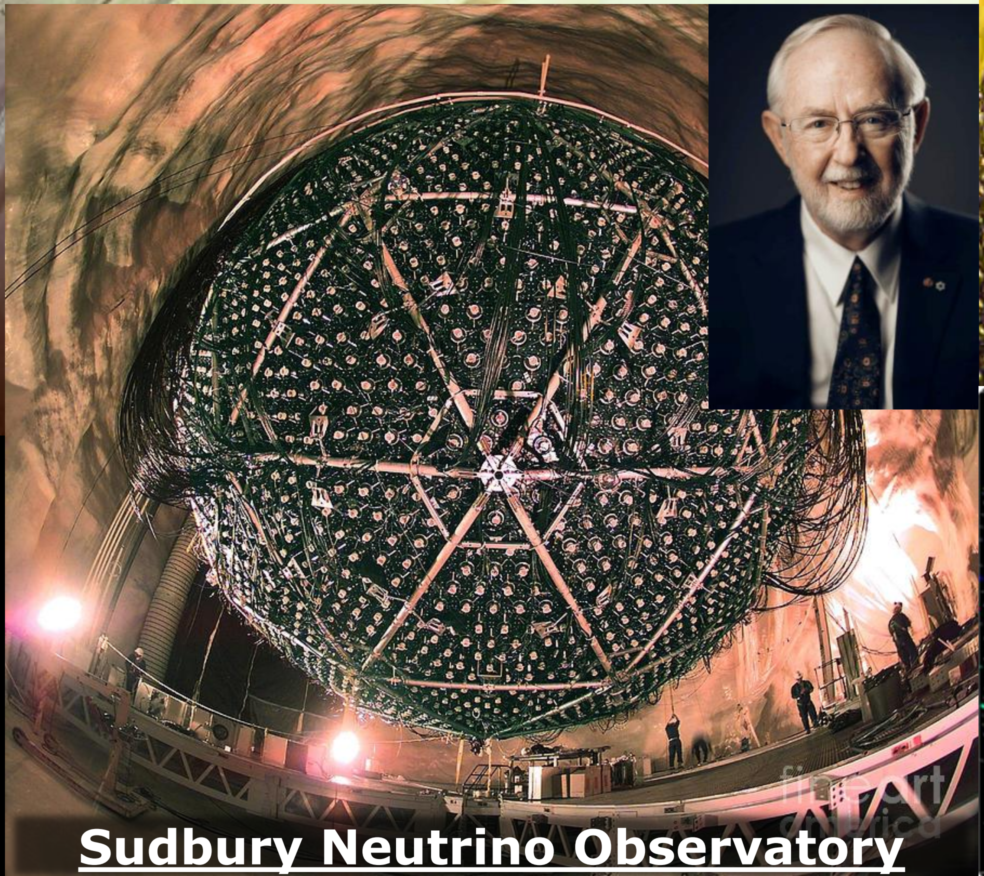


Neutrino Oscillations



Homestake Detector

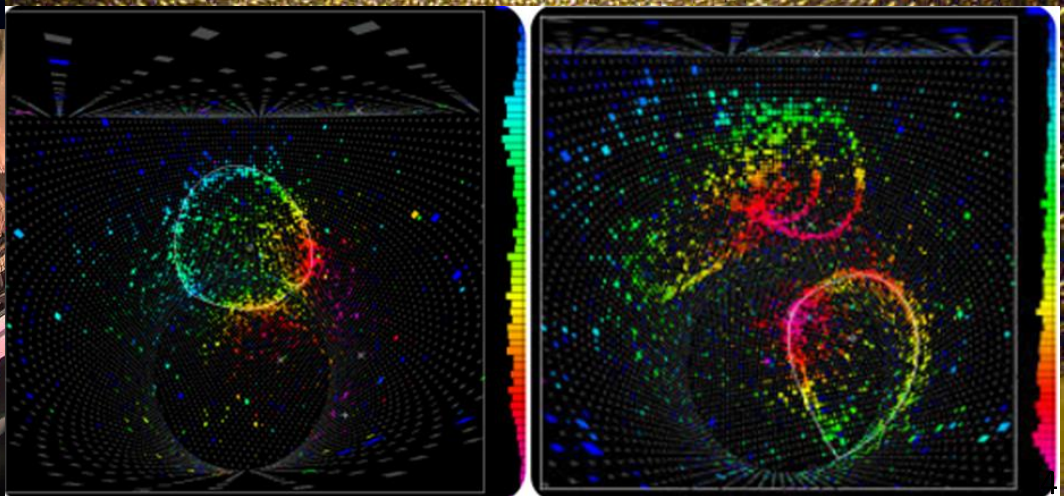
$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$



Sudbury Neutrino Observatory

2002 Nobel Prize in Physics
2015 Nobel Prize in Physics

Super-Kamiokande

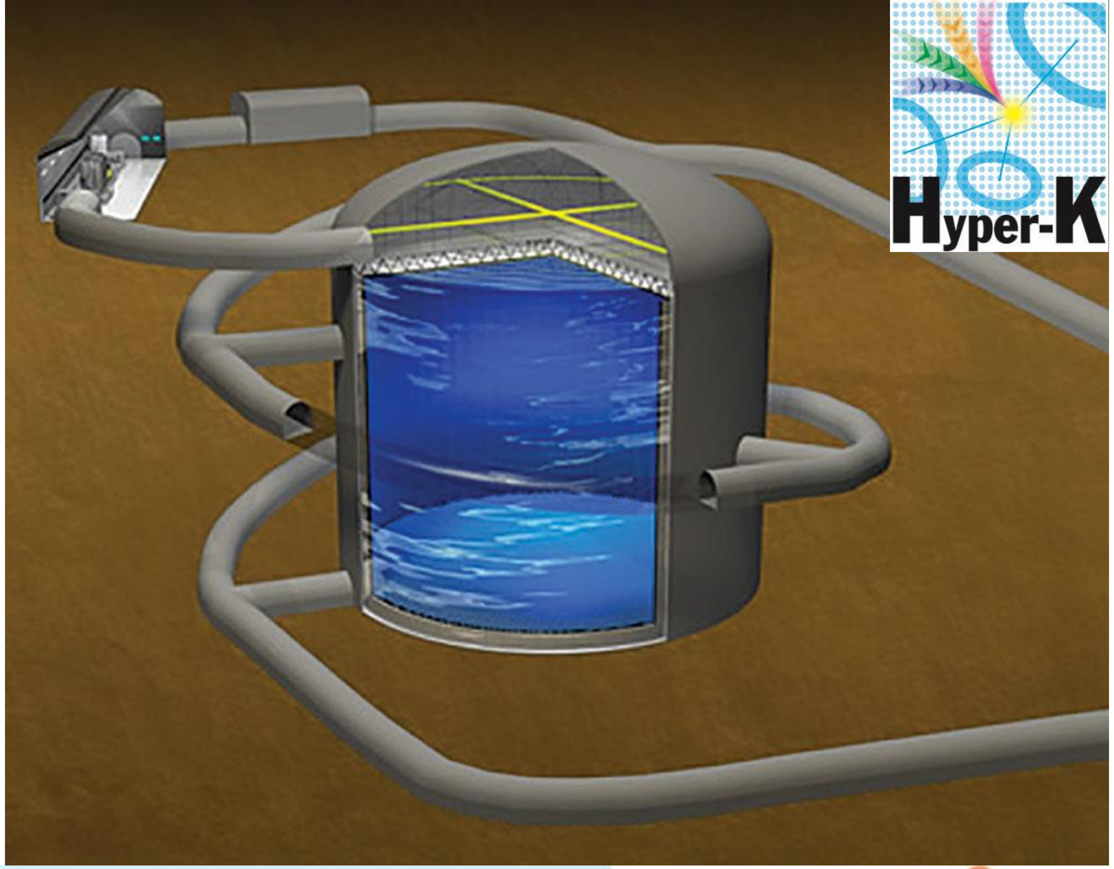


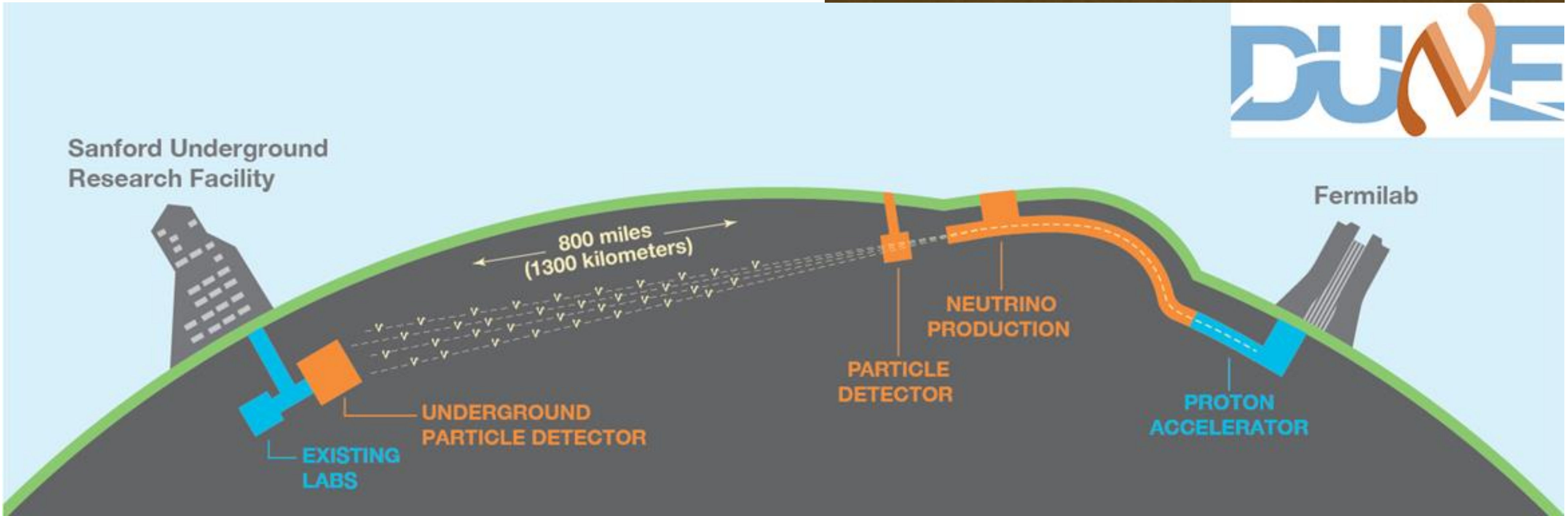
Thank-you!

Questions?

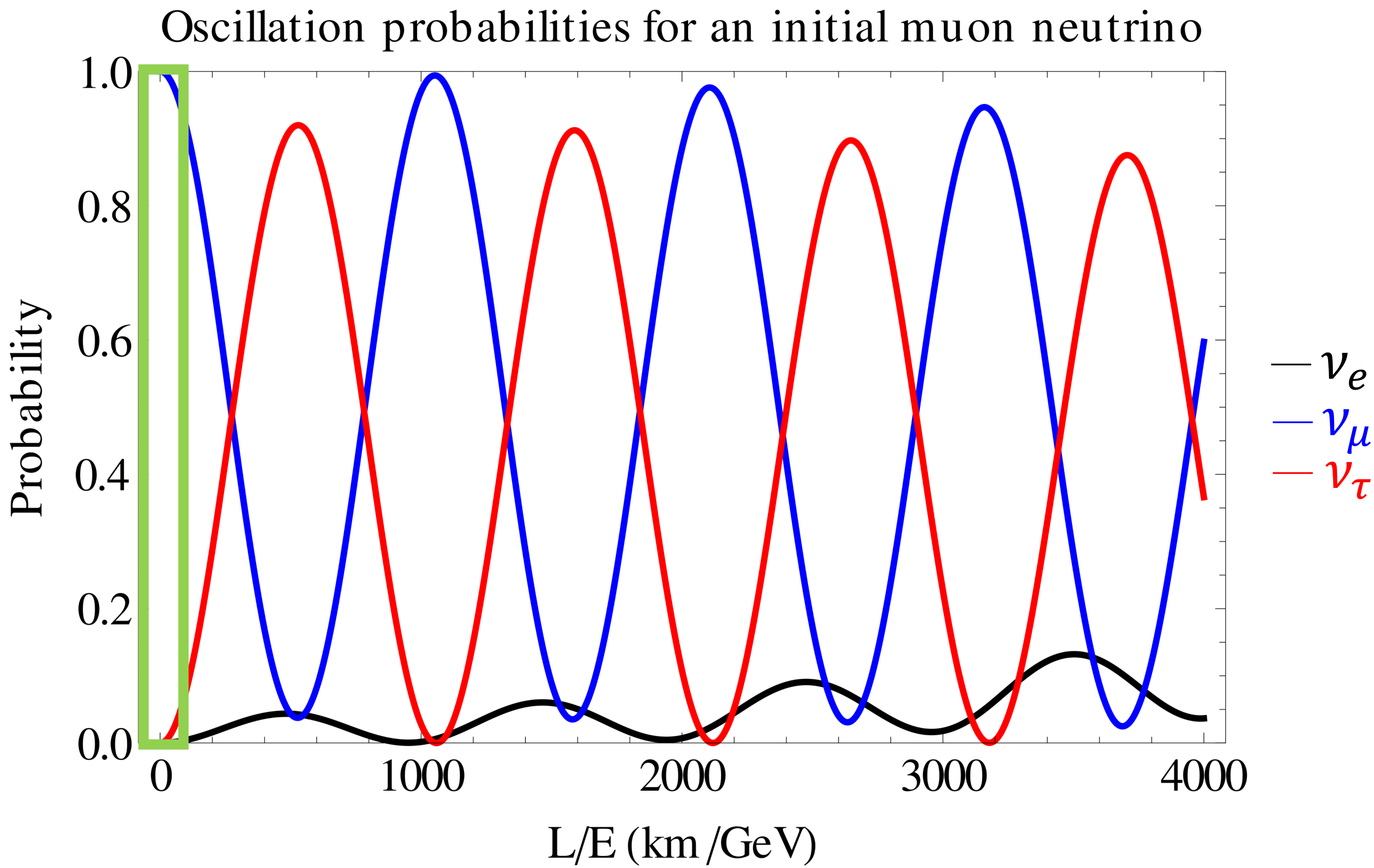
Future Experimental ν Physics

- Goal:
  - Extract ν oscillation parameters
- Implications
  - Leptogenesis, cross sections, τ production, BSM, Non-Standard Interactions
- Challenges
  - Broadband ν spectra
  - Unknown initial ν energy





$$P_{\nu_\alpha \to \nu_\beta}(E_{\nu,\text{true}}, L) \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_{\nu,\text{true}}}\right)$$

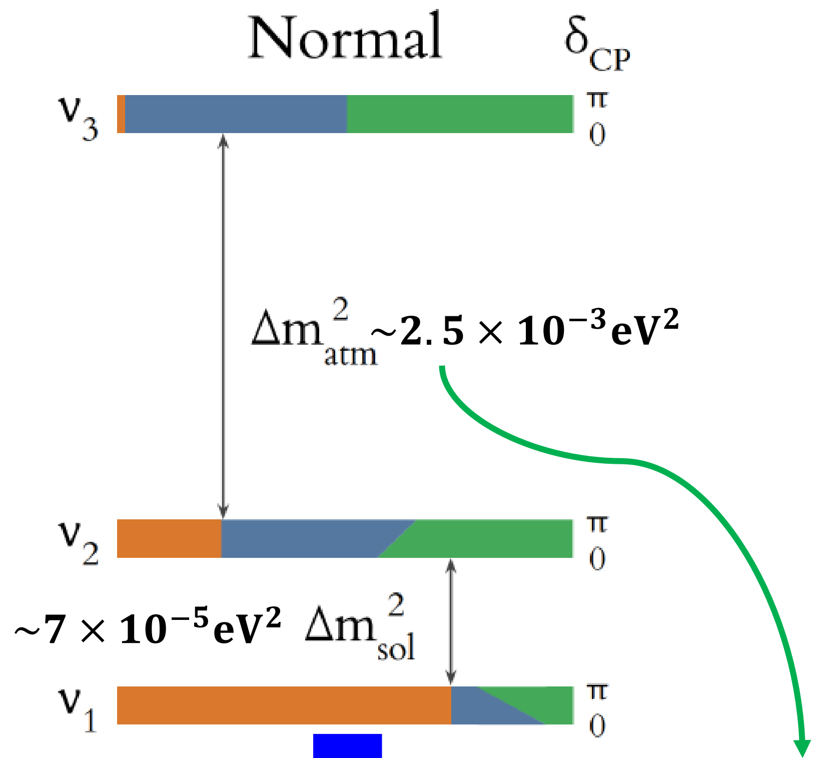


Wiki

Neutrino Oscillations: 3-Flavor Mixing

- Evidence of oscillations from solar, atmospheric and many other ν experiments

- Massive states are active mixtures of flavor states
  - **Three**-flavor model parameterized by the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix**



$$\Delta m^2 \equiv m_\alpha^2 - m_\beta^2$$

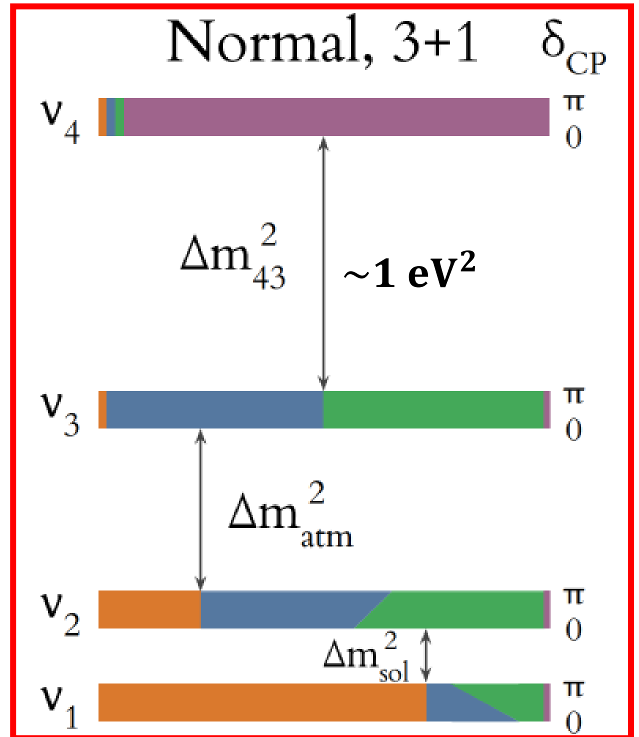
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

2015 Nobel Prize in Physics

PDG
NuFit
Phys. Rev. Lett. 81, 1562 (1998)
Phys. Rev. Lett. 87, 071301 (2001)
Phys. Rev. Lett. 89, 011301 (2002)
R. S. Jones' thesis

Neutrino Oscillations: 4-Flavor Mixing

- Massive states are mixtures of flavor states
  - **Four**-flavor model parameterized by the **extended $3+1$ mixing matrix**
  - 3 active, 1 sterile
- All ν flux is conserved!
  - Energy dependent effects
  - 4th ν_s can lead to:
    - Excess $\nu_e \rightarrow \nu_s$ disapperance
    - Excess $\nu_\mu \rightarrow \nu_s$ disappearance
    - Excess $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ appearance

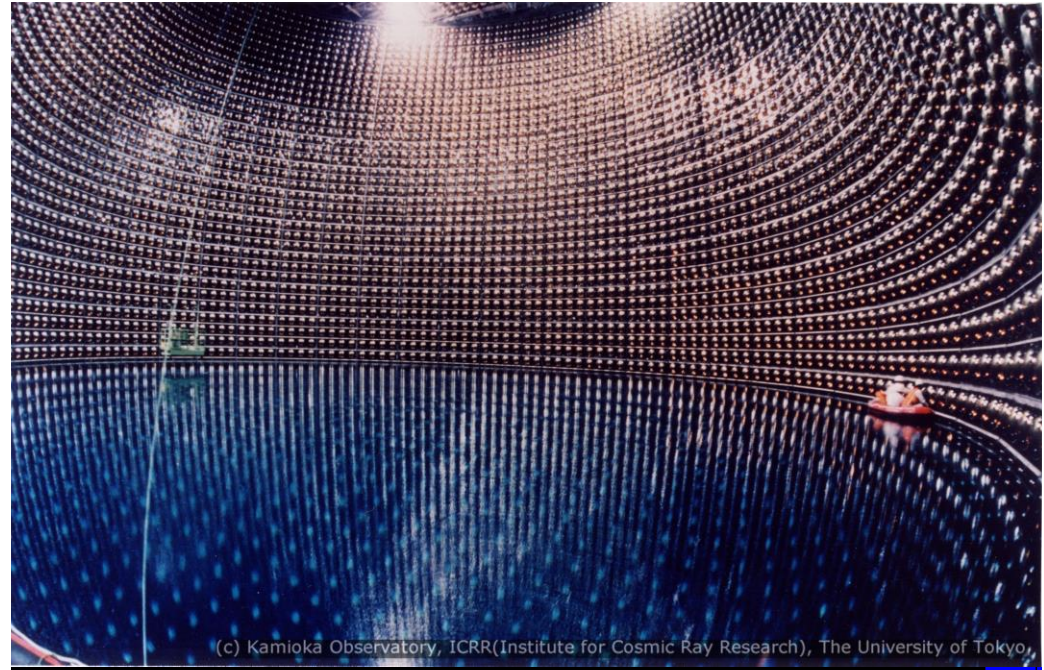


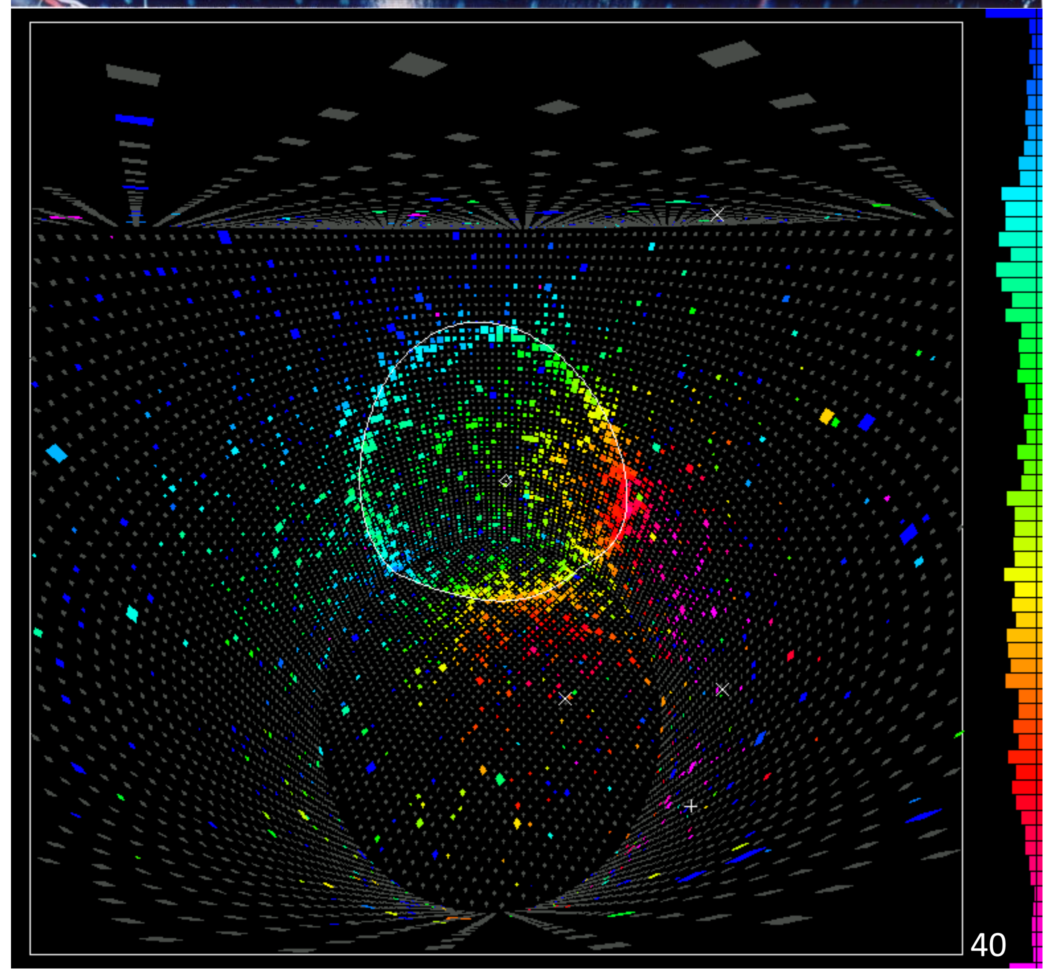
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \mathbf{U^{BSM}_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$P_{\nu_\alpha \rightarrow \nu_\beta}(E_{\nu,\,\mathrm{true}}, L) \approx \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E_{\nu,\,\mathrm{true}}}\right)$$

Water Cherenkov Detectors

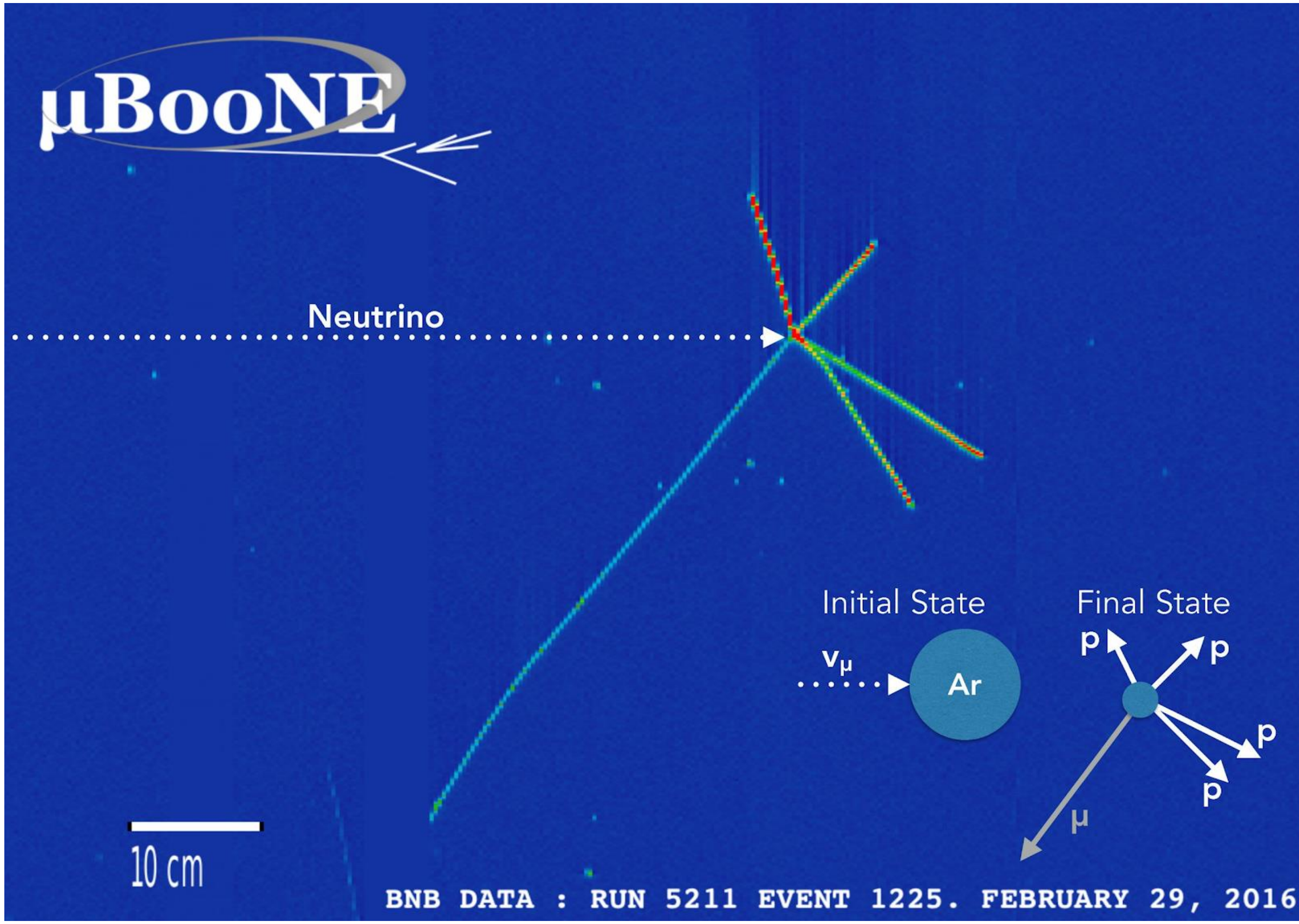
- Super & Hyper-Kamiokande's technology
  - Well understood, battle tested
  - Huge masses, statistics
- Oxygen as main nuclear target
  - "Simple" symmetric nucleus
- Reconstruct particle momenta from Cherenkov rings
  - High proton thresholds
  - Lack of γ/e separation power





Liquid Argon Time Projection Chambers

- DUNE's technology
- Argon as target
  - Complex nucleus
- Ionization of LAr for track reconstruction
  - Low proton thresholds
  - $dQ/ds \sim dE/ds$ for calorimetry
  - γ/e separation power



Animation from Bo Yu (BNL)