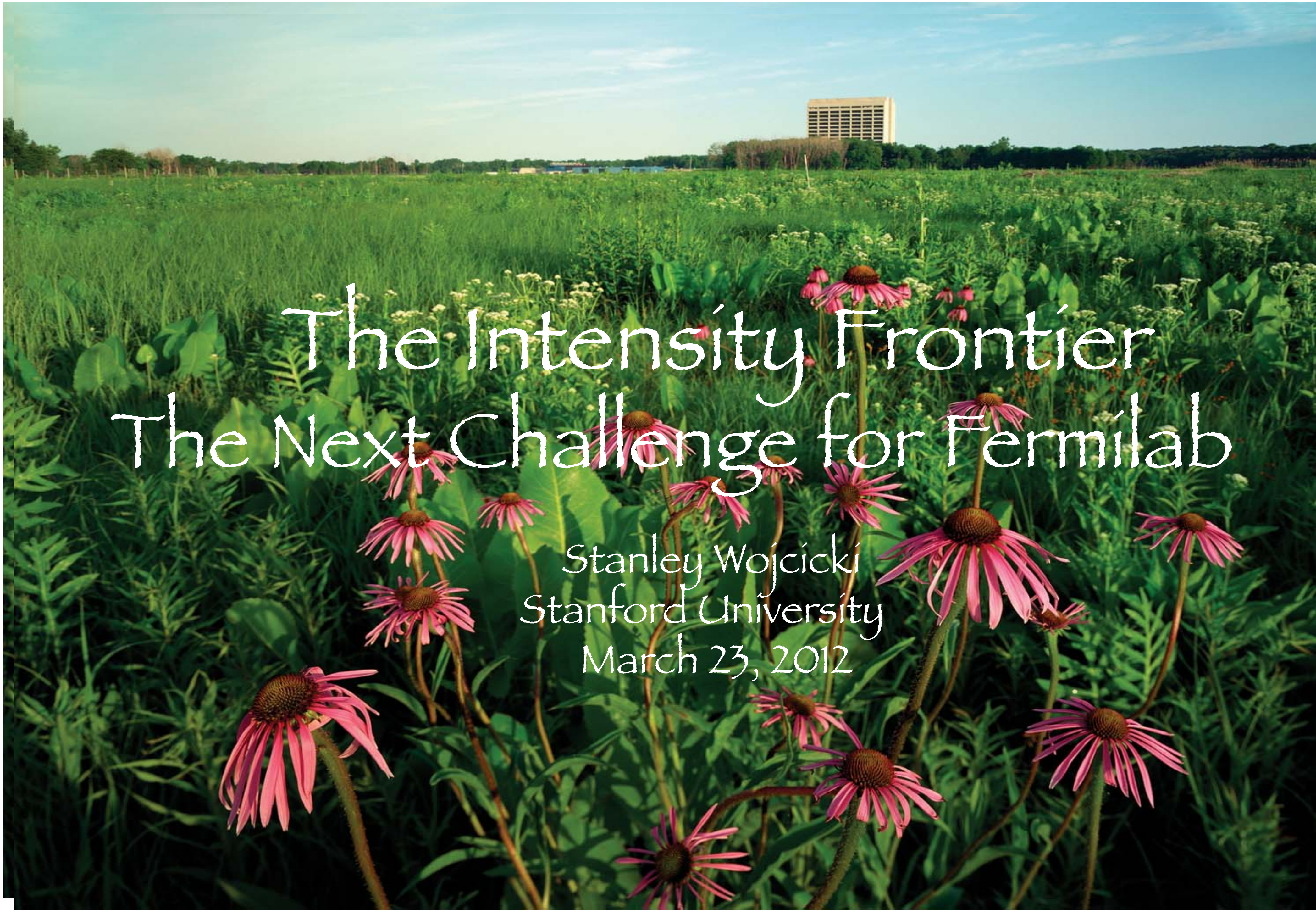
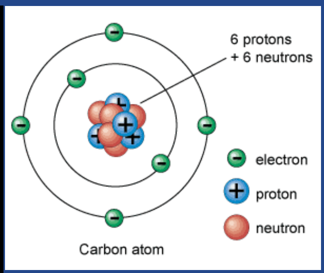


The Intensity Frontier
The Next Challenge for Fermilab

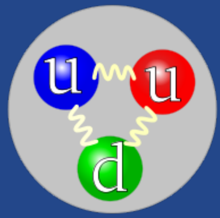
Stanley Wojcicki
Stanford University
March 23, 2012

Our world is DIVERSE

very large



very small



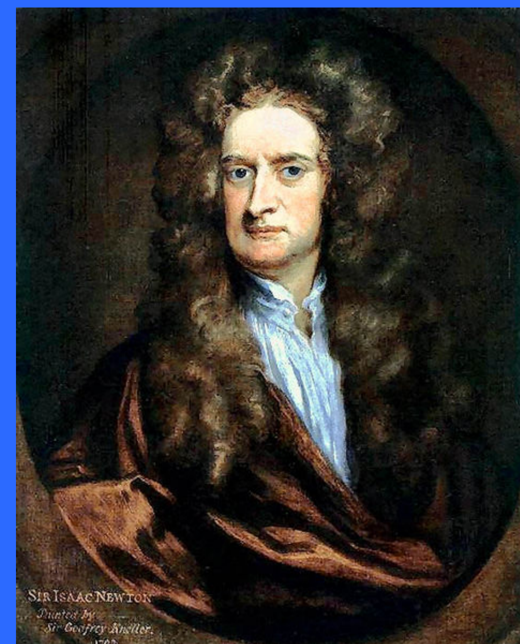
Our goal is SIMPLIFICATION

For both Constituents and the Forces

All of Physics on a T-shirt (Leon L.)

Truth is ever to be found in simplicity, and not in the multiplicity and confusion of things. He is the God of order and not of confusion.

Sir Isaac Newton



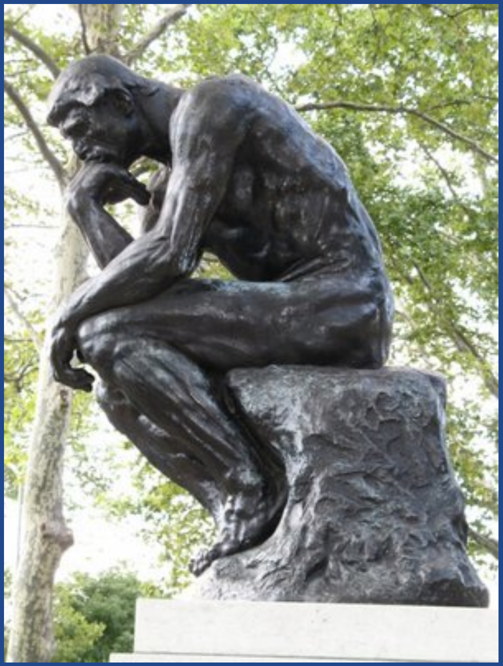
THE GRAND QUESTIONS

What is the world made of ?

What holds it together ?

Where do we come from?

Why are we "us" and not "anti-us"?



THE FUNDAMENTAL CONSTITUENTS

In 1920 there were 3 elementary particles:
proton (p^+), electron (e^-), photon (γ)

In 1955 there were about 20 (+ their antiparticles):
p, e, γ and also: n, μ, ν, π, K, τ, θ, χ, Λ, Σ, Ξ ...

And starting in the 1960's there was even a greater explosion

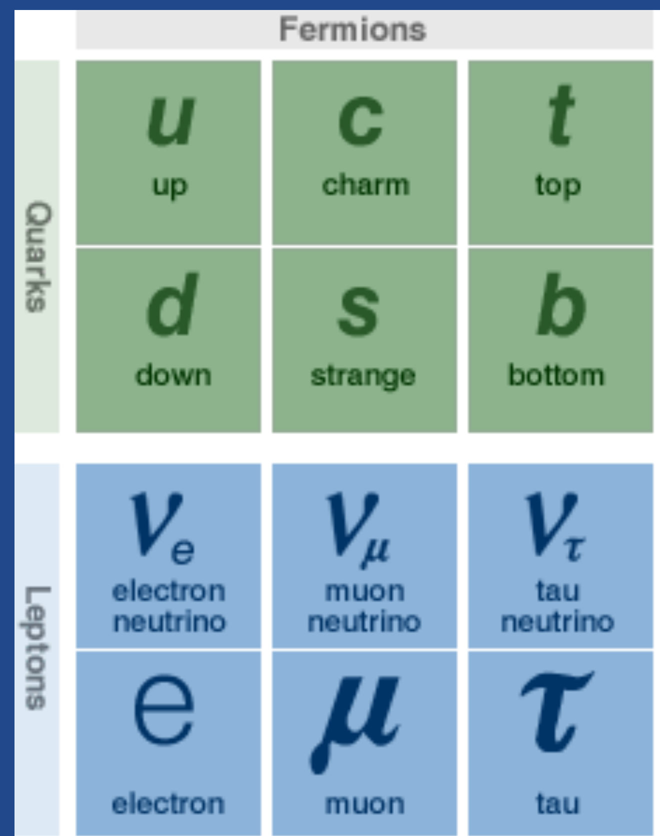
CAN SO MANY PARTICLES BE ALL ELEMENTARY?

If I could remember the names of all these particles, I'd be a botanist.

Enrico Fermi

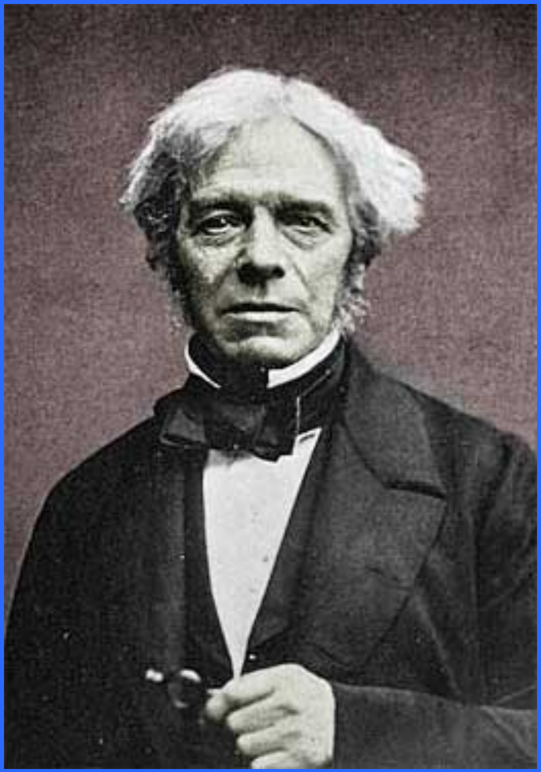
THE FUNDAMENTAL CONSTITUENTS WHAT WE BELIEVE TODAY

1) Quarks and Leptons are fundamental
2) They may be point particles or little strings
3) There are at least 6 of each, maybe more



I have long held an opinion, amounting almost to conviction, in common, I believe, with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin.

Michael Faraday



THE FIRST UNIFICATION

Isaac Newton (1642 - 1727)

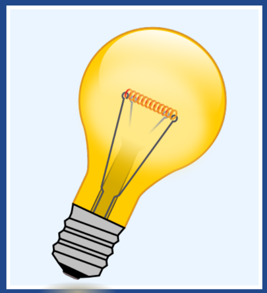
Celestial Gravity

Terrestial Gravity

They are the same

THE SECOND UNIFICATION

James Clark Maxwell (1831 - 1879)

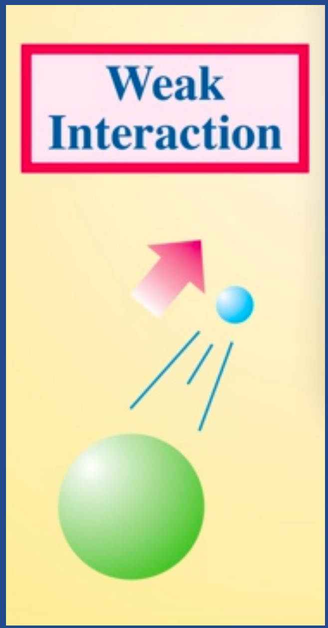


≈

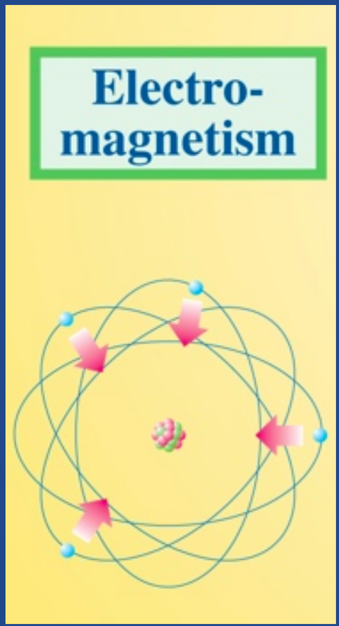
Electricity and magnetism are different manifestations of the same phenomenon

THE THIRD UNIFICATION

S. Glashow, A. Salam, S. Weinberg (1967-68)



Responsible for neutron decay, radioactivity in reactors

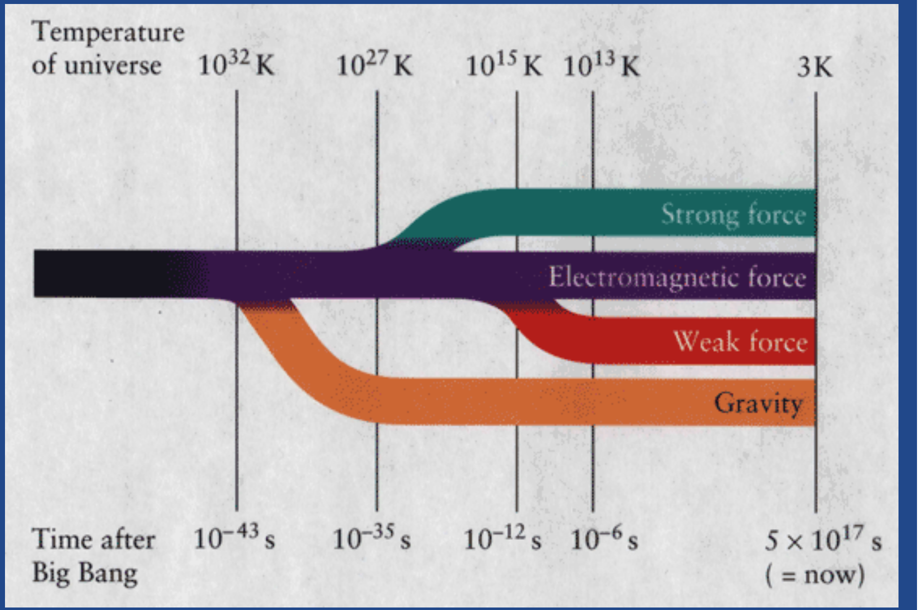


Holds atoms together; Responsible for electricity, magnetism

Weak + Electromagnetic → Electroweak

THE NEXT UNIFICATION (S) ?

The Grand Unified Theory (GUT) ?
The String Theory ?



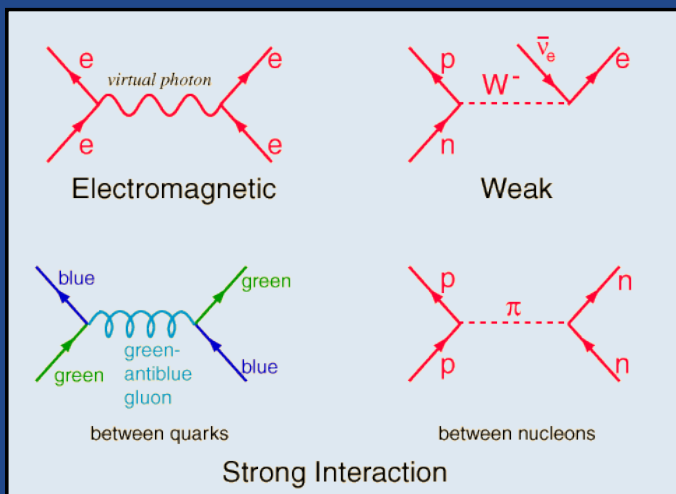
THE FAMILIAR FORCES

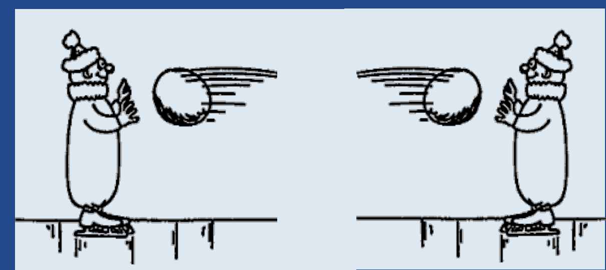
Push (contact) Pull (contact)

But there are also forces at a distance
Examples: Gravity, Magnetism

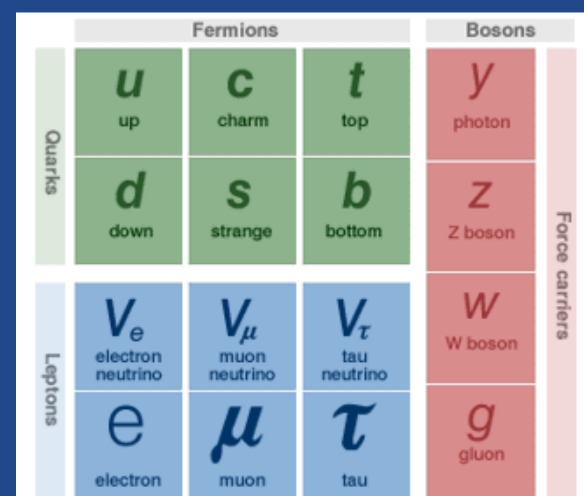
THE FORCES IN PARTICLE PHYSICS

How do we describe them?





Exchange Force (repulsive)



Exchange Forces
Exchanged particle can be heavy
It is virtual

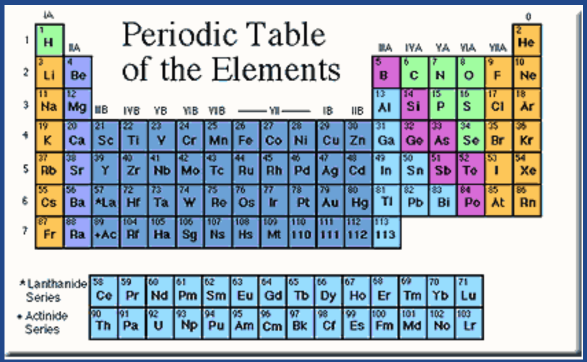
Uncertainty Principle: $\Delta E \Delta t \geq \hbar$

The Standard Model

THE STEPS TOWARDS KNOWLEDGE

Example: Chemical Elements

1. Observation (New Data):
   Hydrogen, Carbon, Copper, Mercury, Gold...



2. Classification:
   Periodic Table

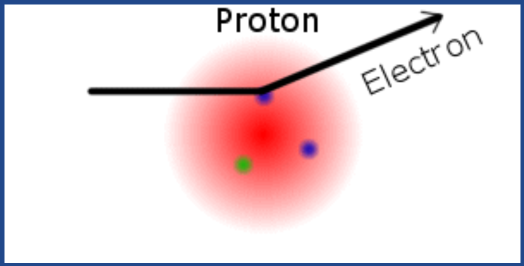
3. Understanding (Why?):
   Quantum Mechanics, Spin...

WHERE ARE WE IN PARTICLE PHYSICS?

1. Observation :

Many Particles, Similarities

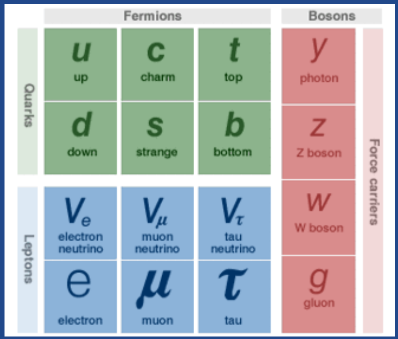
Structure in the Proton



2. Classification:

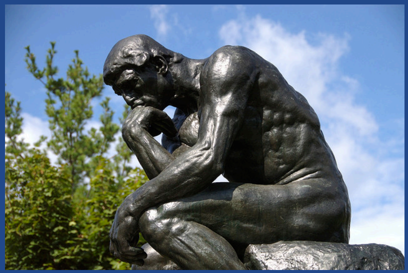
Quarks, Leptons,

Force Carriers → SM



3. Understanding:

Many Questions Need Answers

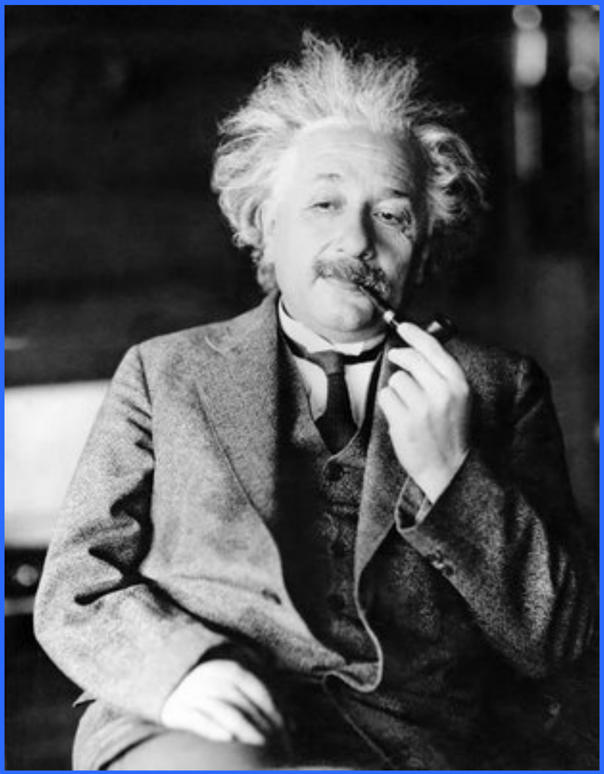


FEW DETAILED QUESTIONS

Why 3 families of quarks and leptons?
Do all forces become one?
Why are the masses of quarks so different?
Why are neutrino masses so small?
What happened to anti-matter?
How will Standard Model break down?
What is dark matter?
What is dark energy?
Are quarks and leptons little strings?

A theory is more impressive the greater the simplicity of its premises, the more diverse the things it relates, and the more extended its area of applicability.

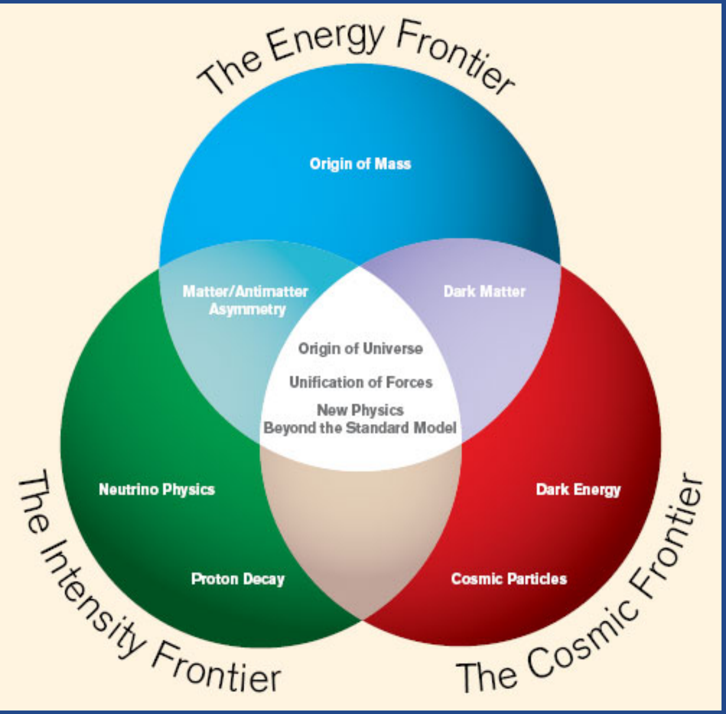
Albert Einstein



THE 3 FRONTIERS OF PARTICLE PHYSICS

Colliders, Tevatron → LHC

External beam
fixed target



Telescopes
Satellites
Balloons
Large Arrays

Intensity Frontier experiments can be sensitive to mass scales >> LHC

ENERGY AND INTENSITY FRONTIERS

Direct and Indirect Measurements

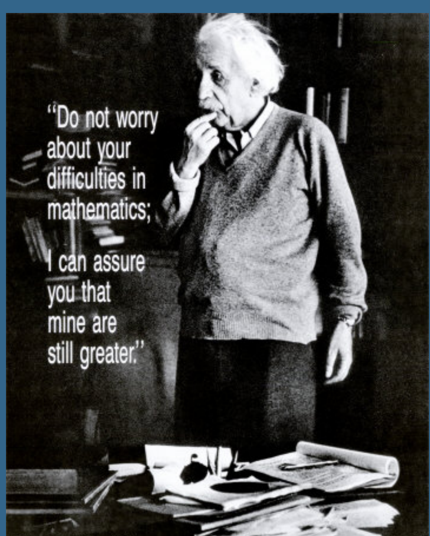
Real particles created from energy
Requires high energy

$$E = mc^2$$

Virtual particles exist for a short time
Requires high intensity

$$\Delta E \, \Delta t \geq \hbar$$

Albert Einstein

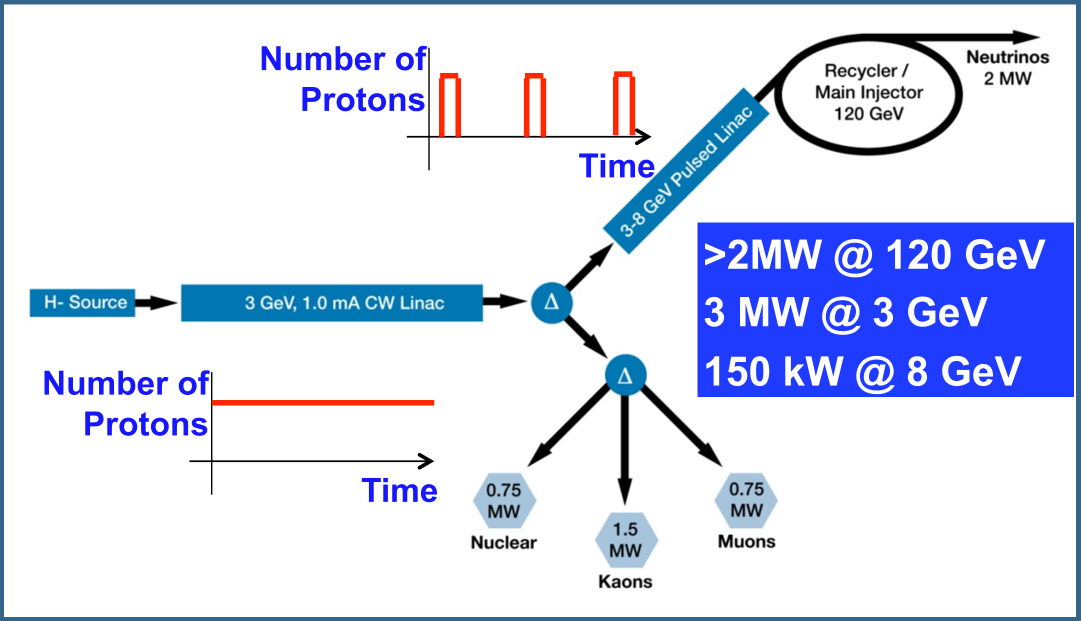


Werner Heisenberg

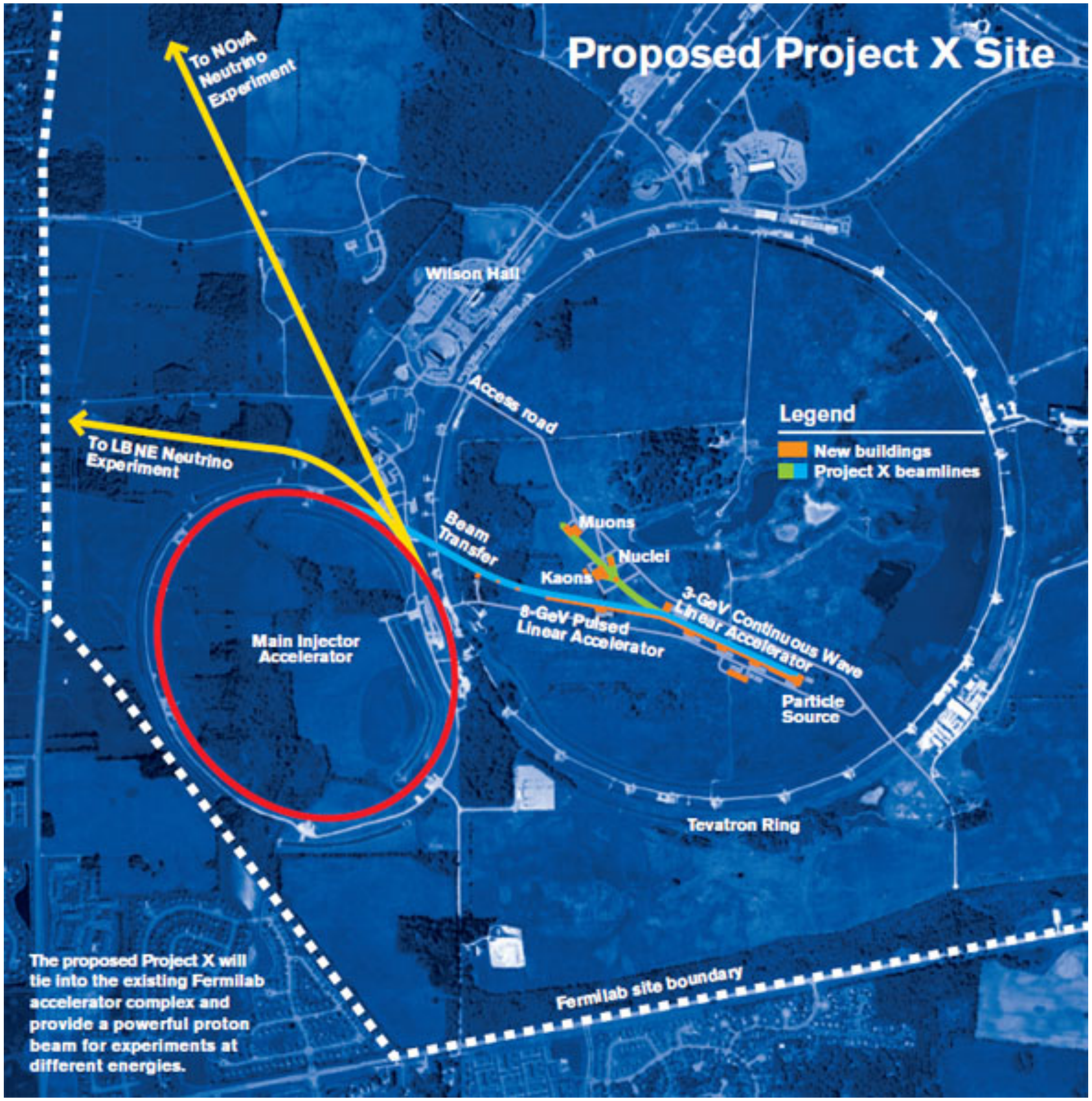
FROM 300 Kw TO 2.2 Mw

1. Upgrade of an existing fixed target complex from 300 Kw to 700 Kw

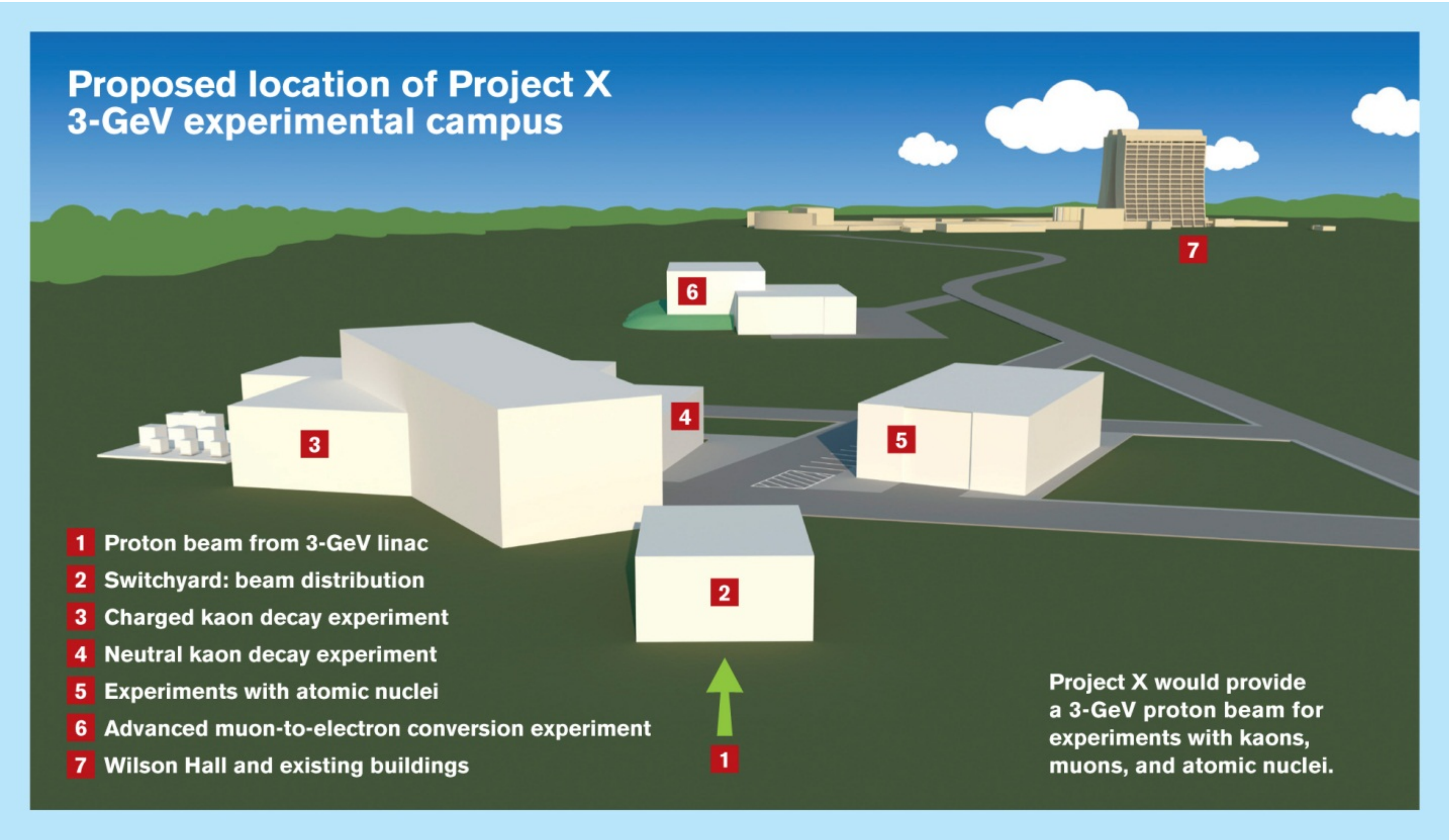
2. Construction of a new accelerator complex - Project X



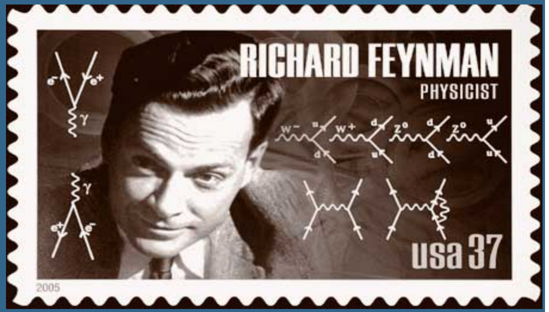
PROPOSED LOCATION OF PROJECT X



PROJECT X EXPERIMENTAL CAMPUS

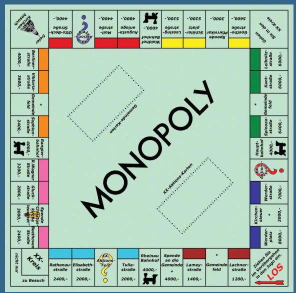


FEYNMAN DIAGRAMS



Method for Calculating Particle Properties and the Rates for Their Interactions and Decays

Allows Visualization of the Process



Rules are Simpler than in Monopoly:

1. Each diagram is composed of vertices, internal lines, external lines

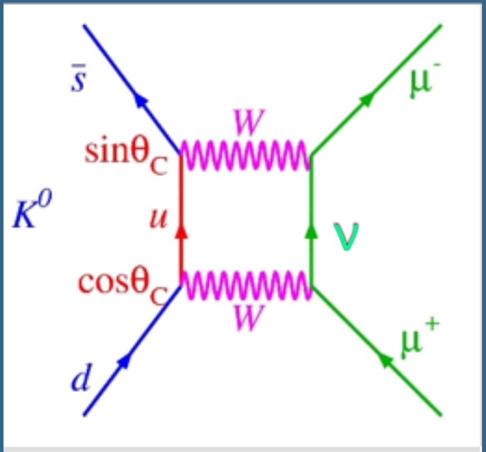
2. Each of these contributes a factor to the amplitude for this diagram

3. Add up all the diagrams and square the sum

AN EXAMPLE (Feynman and Indirect Expt)

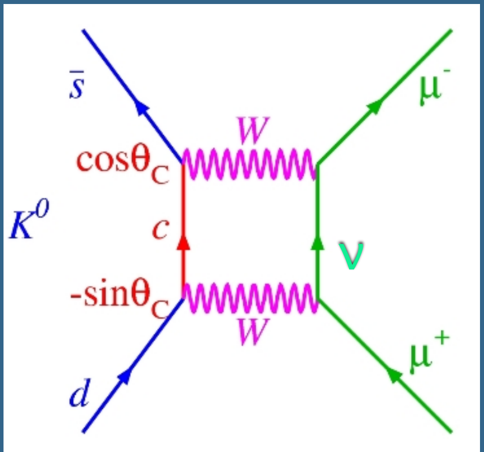
A decay $K^0 \rightarrow \mu^+\mu^-$

The "box" diagram on the right describes a mechanism for this decay



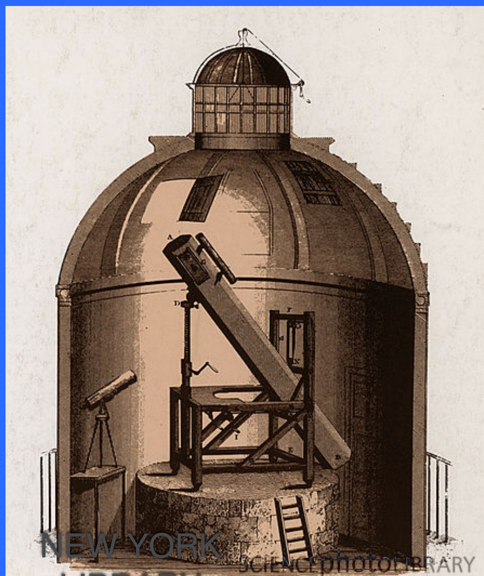
But the prediction for this rate based on this diagram did not agree with the experiment

Theory and experiment could be reconciled if one postulated additional diagram with a new quark

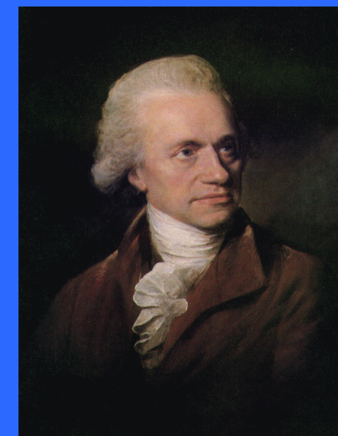


Few years later, required quark, charm, was discovered

ANOTHER EXAMPLE - FROM ASTRONOMY



In 1781 William Herschel discovered the 7th planet, eventually named Uranus, using the 15cm telescope he had constructed himself.



But there was a problem: Uranus trajectory in the sky did not follow the expectation from Newton's law

Two possible explanations were put forward:

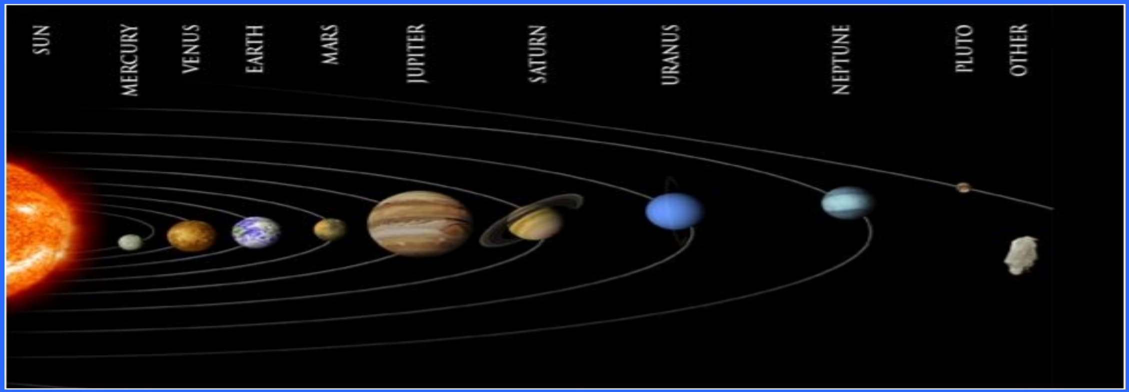
a) Newton's law was not rigorously true

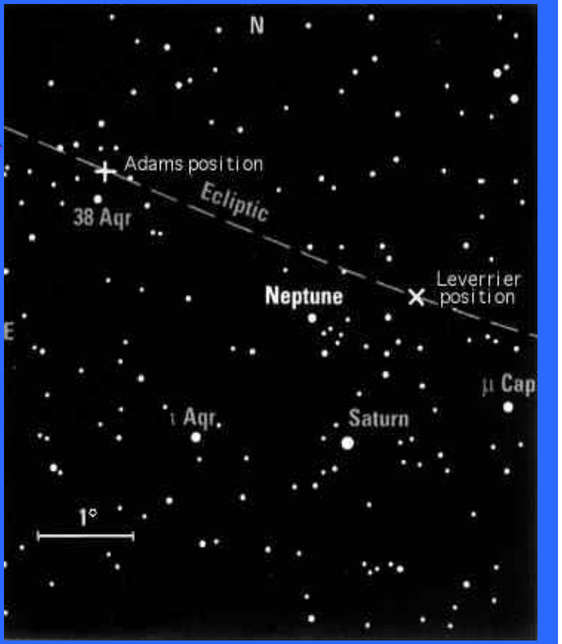
b) There was another perturbing planet

Urbain LeVerrier (France) and John Adams (UK) espoused the planet idea and calculated its location.

LeVerrier asked Johann Galle at the Berlin Observtory to look for a planet in the suggested sky area.

In 1846 Galle found the planet (named Neptune) within 1° of LeVerrier 's prediction. LeVerrier got credit for the discovery.





NEWTON WAS RIGHT AFTER ALL

DIFFERENT MEASUREMENTS

precision measurements
or
rare (forbidden) processes

interactions or decays
or
particle properties

	interactions, decays	particle properties
precision measurements	$K^0 \rightarrow \pi^0 \nu\nu$	μ g-2
rare (forbidden) processes	$\mu \rightarrow e$ capture	electric dipole moments

+ NEUTRINO INTERACTONS

Question: What are spin and magnetic moment?

Answer: Fundamental properties of particles, like mass or charge

Classical analogue: spinning top that is charged

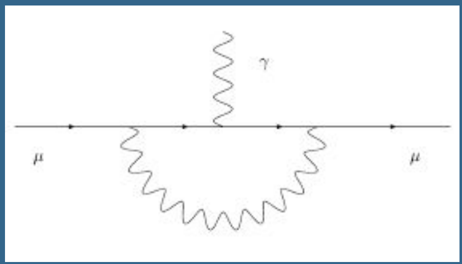
Ratio of spin and magnetic moment is called g factor

For charged leptons (e, μ, τ), g is close to 2 and its deviation from 2 (g-2) can be both measured and calculated very precisely (<1 ppm)

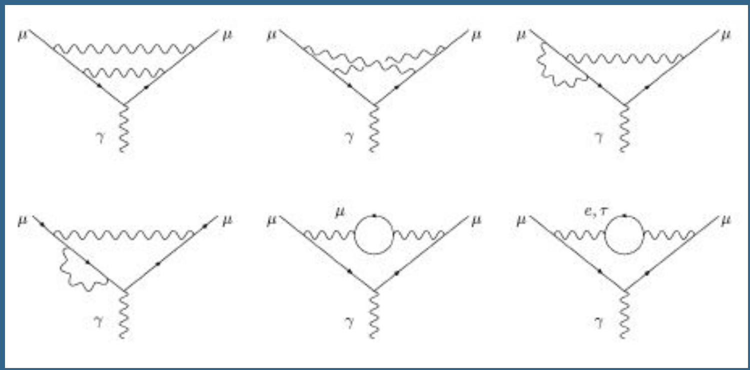
$$g_{\mu}^{exp} = 2.00233184178(128)$$

MUON g-2 (THEORY)

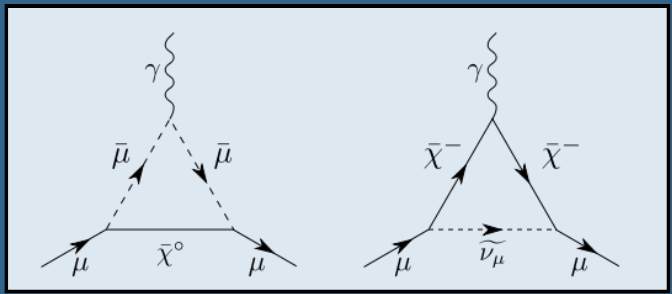
Muon g-2 can be calculated very precisely
Thus disagreement between theory and experiment might be an indication of new physics



Leading diagram



Higher order diagrams

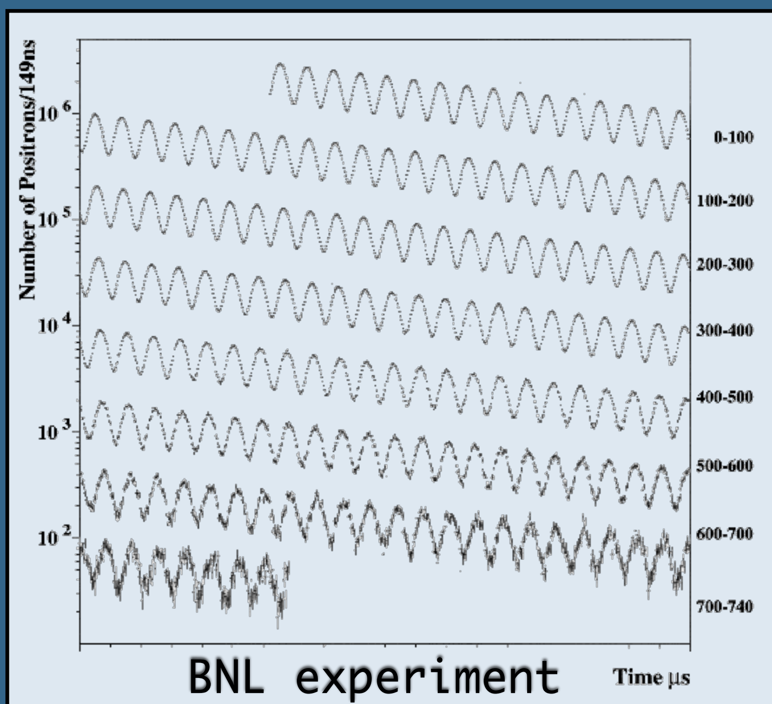


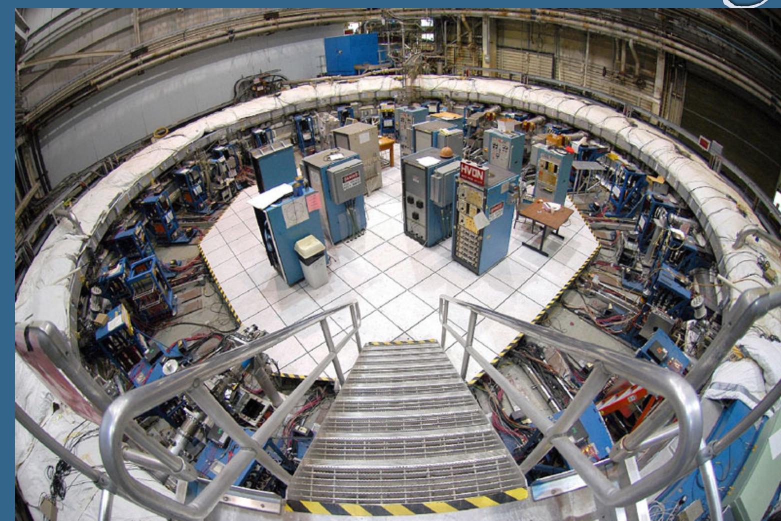
Possible diagram from new physics (supersymmetry)

MUON g-2 (EXPERIMENT)

Protons on target → pions → $\pi \to \mu\nu$ → store μ in ring

Observe muon spin rotation through muon decays to electrons



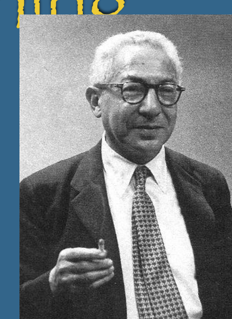


Frequency(f) = no. of cycles/time

$$g-2 \propto f/B$$

"Never measure anything but frequency"

I.I.Rabi



Need lots of muons

MUON CAPTURE (mu2e)

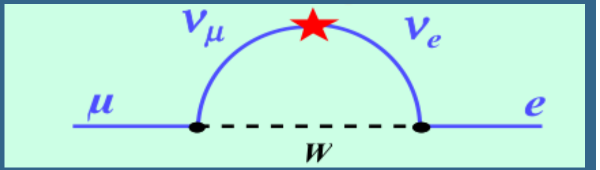
What happens when μ^- stops in matter?

a) It can decay: $\mu^- \rightarrow e^-\nu\nu$

b) It can be captured by the nucleus: $\mu^- + p \rightarrow n + \nu$

Can it transform itself into an electron?

Yes, but VERY rarely. In SM, $\sim 10^{-52}$



Only SM diagram possible

Excellent candidate for looking for New Physics

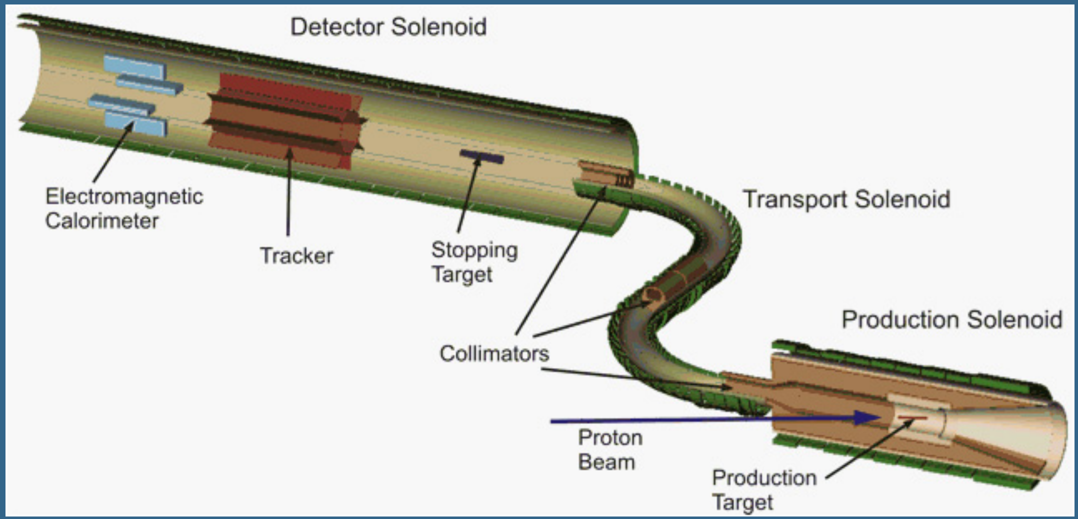
Current experimental limit: $\sim 10^{-12}$
Can one do significantly better than that?

Most New Physics models predict a rate for muon conversion to electrons of $\sim 10^{-16} - 10^{-13}$

To reach 10^{-16} need a lot of muons, $\sim 10^{19}$

This requires LOT of protons and sophisticated apparatus

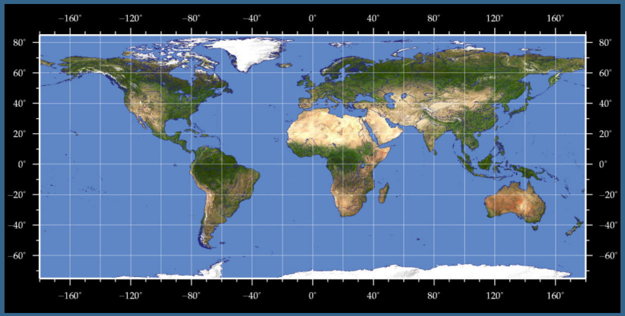
Compare to about 5×10^{19} (?) grains of sand on all the world's beaches



DECAY MODE: $K^0 \to \pi^0 \nu \nu$

Standard Model prediction: $BR \sim .2 \times 10^{-10}$

There are today about 7×10^9 people in the world



The New Physics can increase this decay rate

Very difficult experimentally; not seen yet

neutral → neutral + neutral + neutral

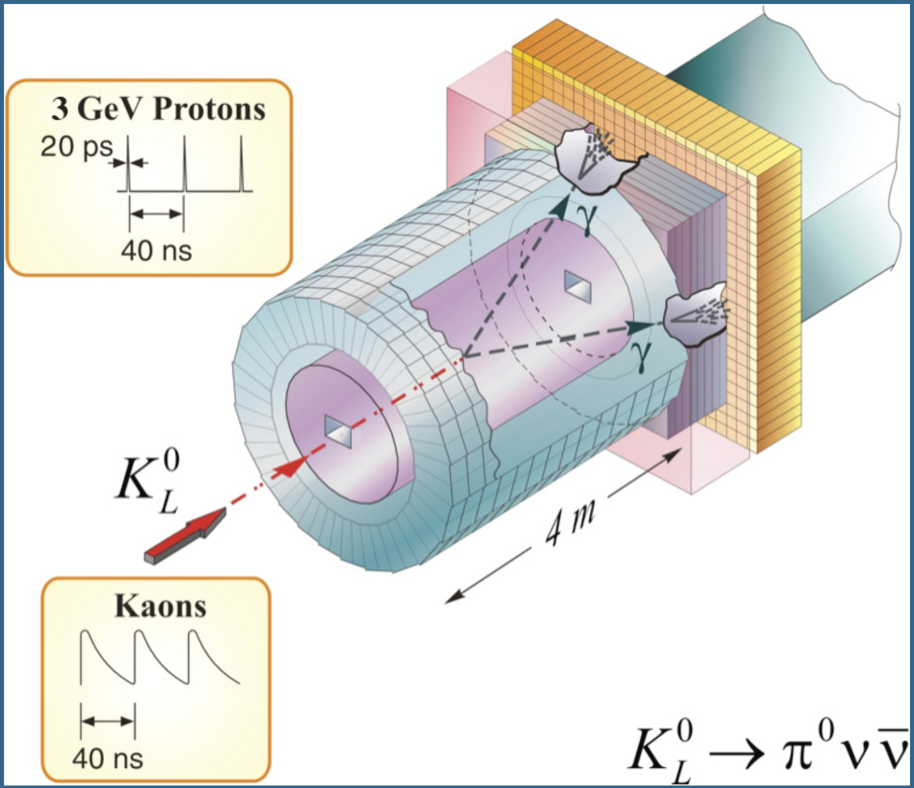
Hence no visible tracks

To achieve required precision need high intensity

Need to make small K° beam to have good direction precision

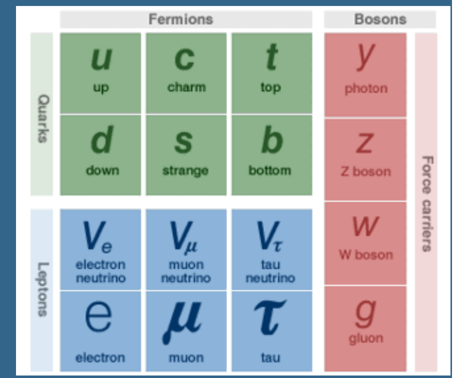
Also good photon detection and measurement

Strive for 10% measurement of BR



All of this requires high intensity

NEUTRINOS



They are fundamental and ubiquitous

10^{14} go through each one of us every sec

They are produced in nature:

in the sun, in cosmic rays, in the earth, in the oceans,...take 99% of energy in supernovas

They are also produced by humans:

in reactors, by the accelerators, in medical isotopes

They are unique and important but ill understood

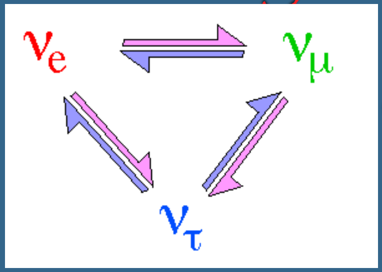
They may be responsible for our existence

WE MUST STUDY THEM

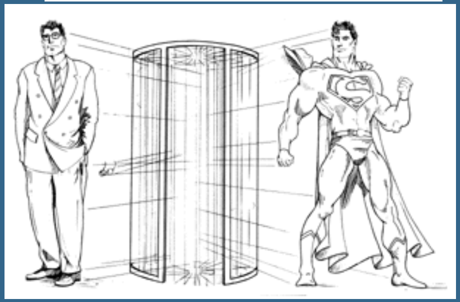
NEUTRINOS ARE WEIRD

They hardly interact with matter: Out of ~100,000 all but one will get through 450 miles of earth (like a hot knife through butter)

As they move along they change from

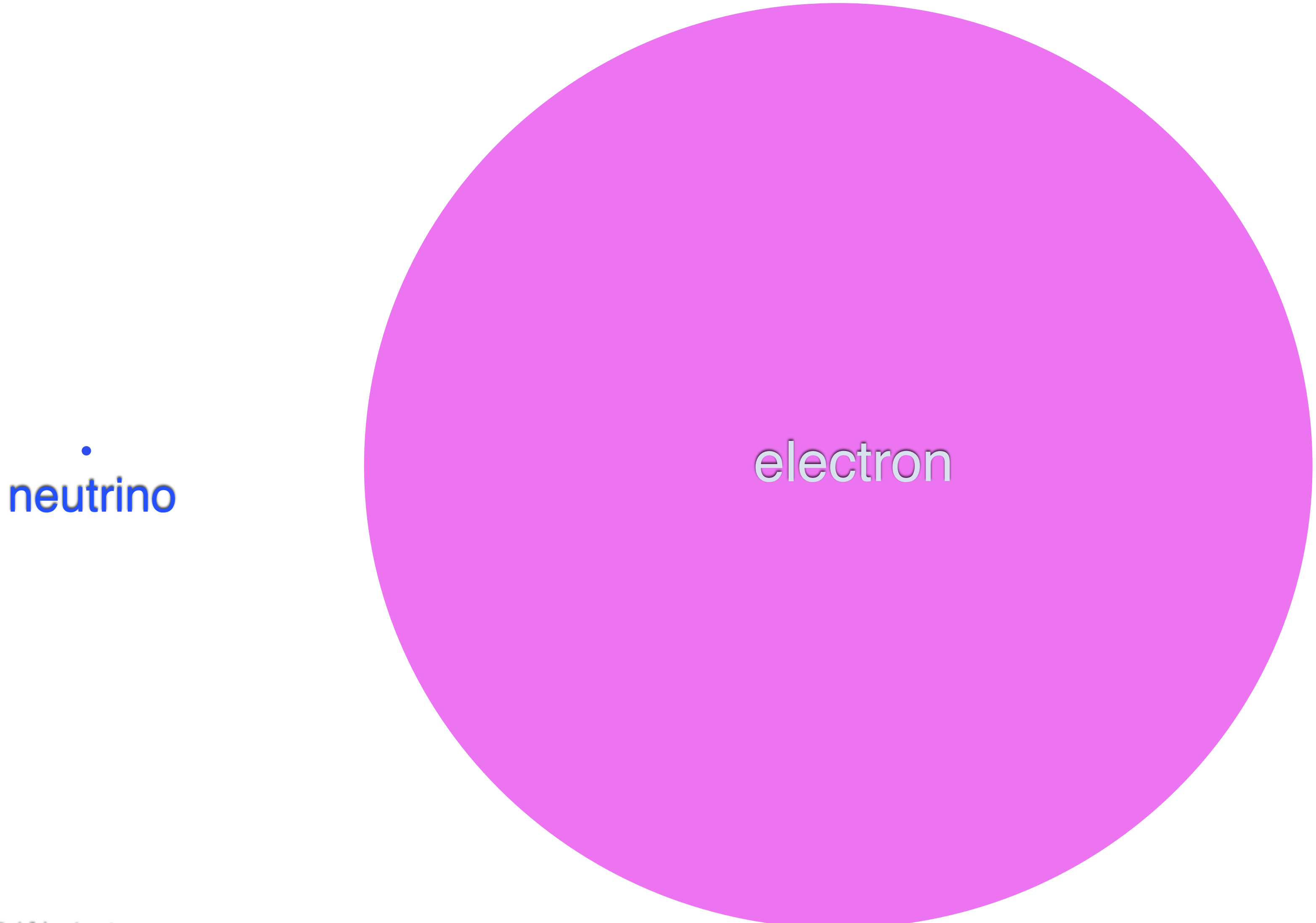


one flavor to another, eg. $\nu_\mu \rightarrow \nu_\tau$ and back again

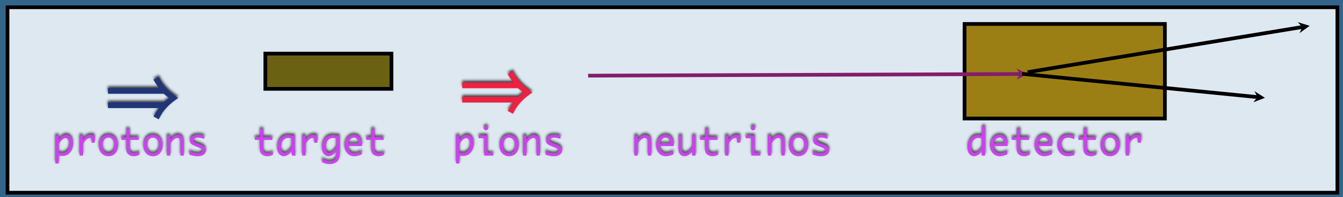


Neutrino masses are tiny; their mass is no more than one millionth the mass of an electron

NEUTRINO AND ELECTRON MASSES COMPARED



NEUTRINO EVENT RATES



No of events will be proportional to: x-section x detector mass x flux x time

Thus for precise measurement we need:

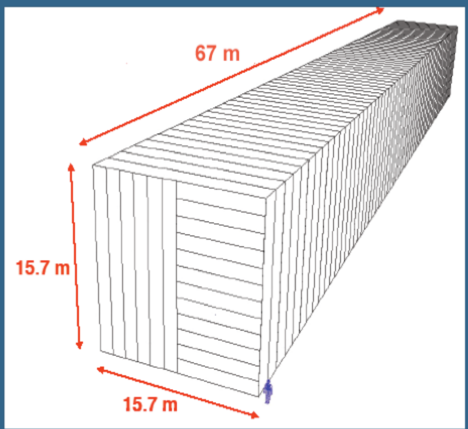
large detector mass
large ν flux ie. intense proton beam

AERIAL VIEW OF POTENTIAL FERMILAB NEUTRINO PROGRAM

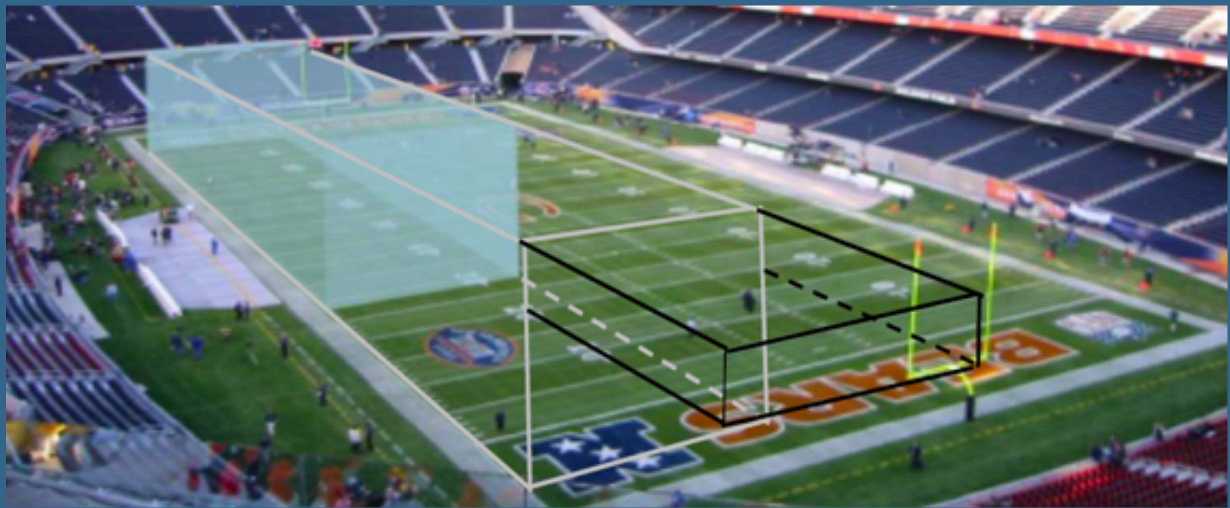
Principal Goals of future neutrino program:

a) Mass hierarchy: which ν is heaviest
b) Study of matter-antimatter symmetry
c) Search for more ν's, unexpected

AN EXAMPLE: NOνA EXPERIMENT



385,000 extrusions



14,700 tons, 810 km away, to start in 2013

CONCLUDING REMARKS

Since its beginning, some 40 years ago, Fermilab has dominated the high energy frontier in particle physics

This torch has now passed to CERN and LHC

The richness and diversity of currently planned program on the intensity frontier should keep Fermilab at the forefront of particle physics for many years to come


ONE GLORIOUS ERA IS
COMING TO AN END


ANOTHER ONE, EQUALLY PROMISING, IS JUST AROUND THE CORNER
THANK YOU FOR YOUR ATTENTION
I want to acknowledge help and use of graphics from R.Bernstein, R.Tschirhart, S.Holmes and Y.K.Kim