

Little, Neutral, Mysterious: An Introduction to Neutrino Physics

The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Enrico Fermi Institute, University of Chicago



Andrew T. Mastbaum

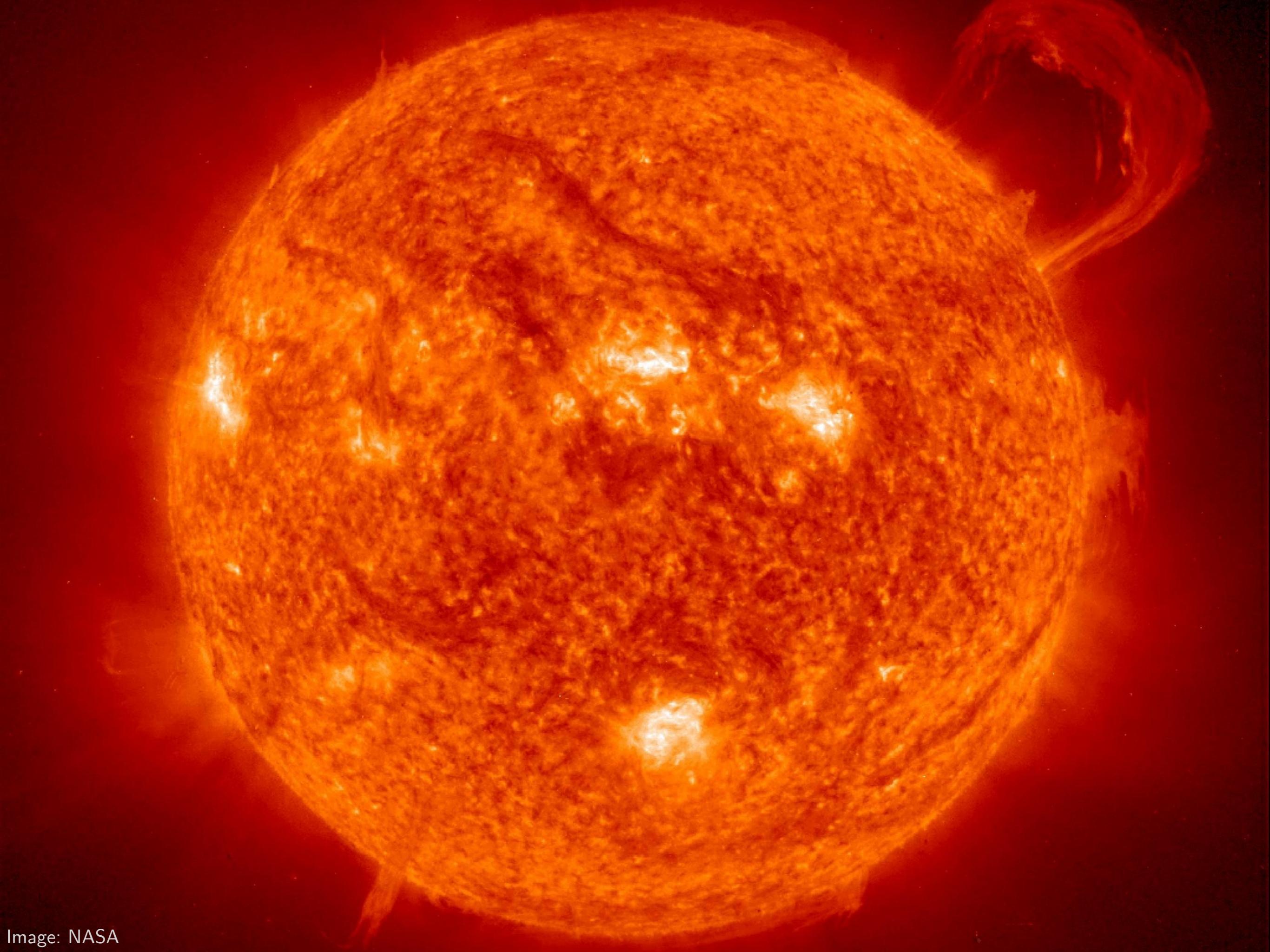
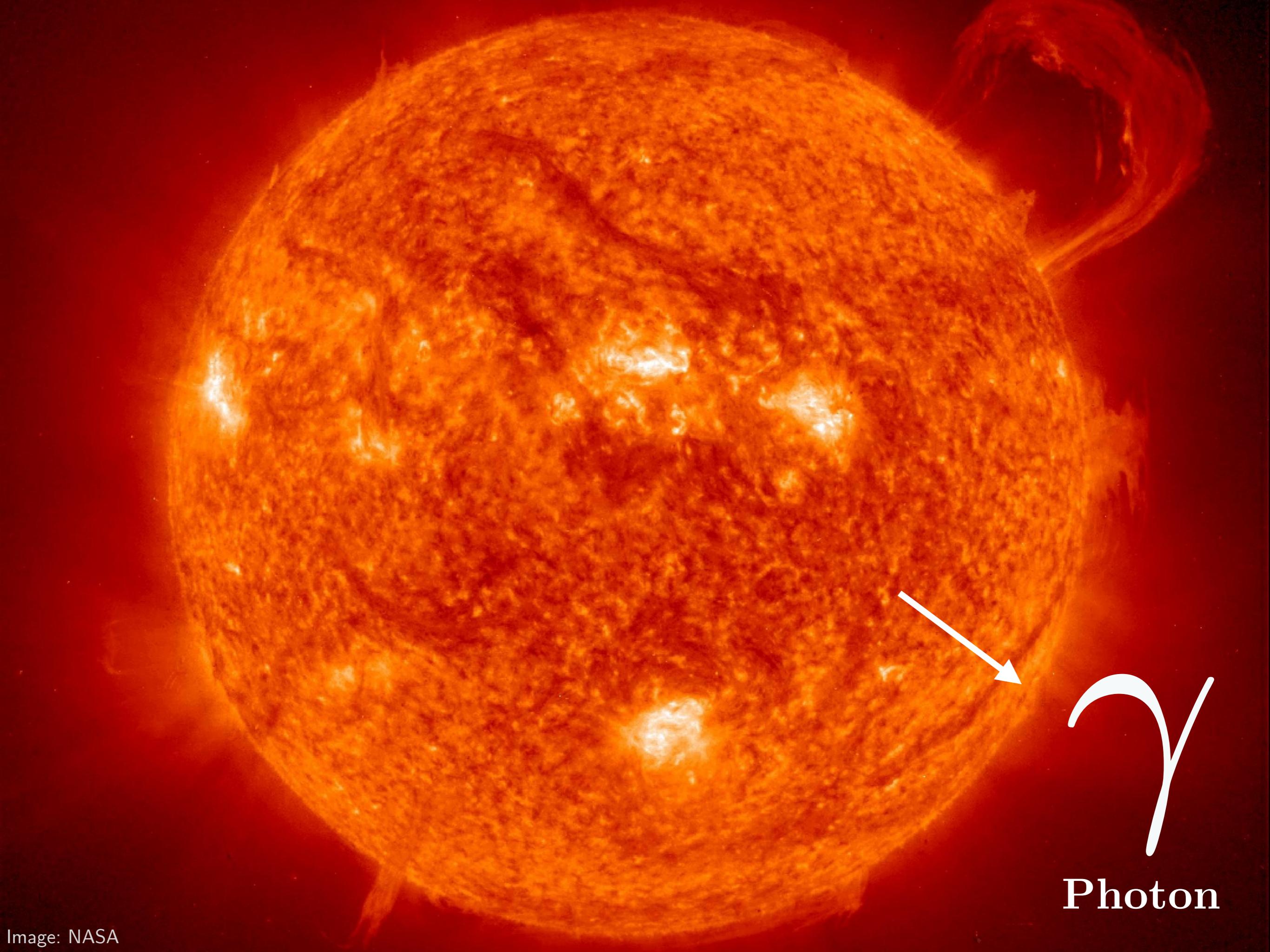
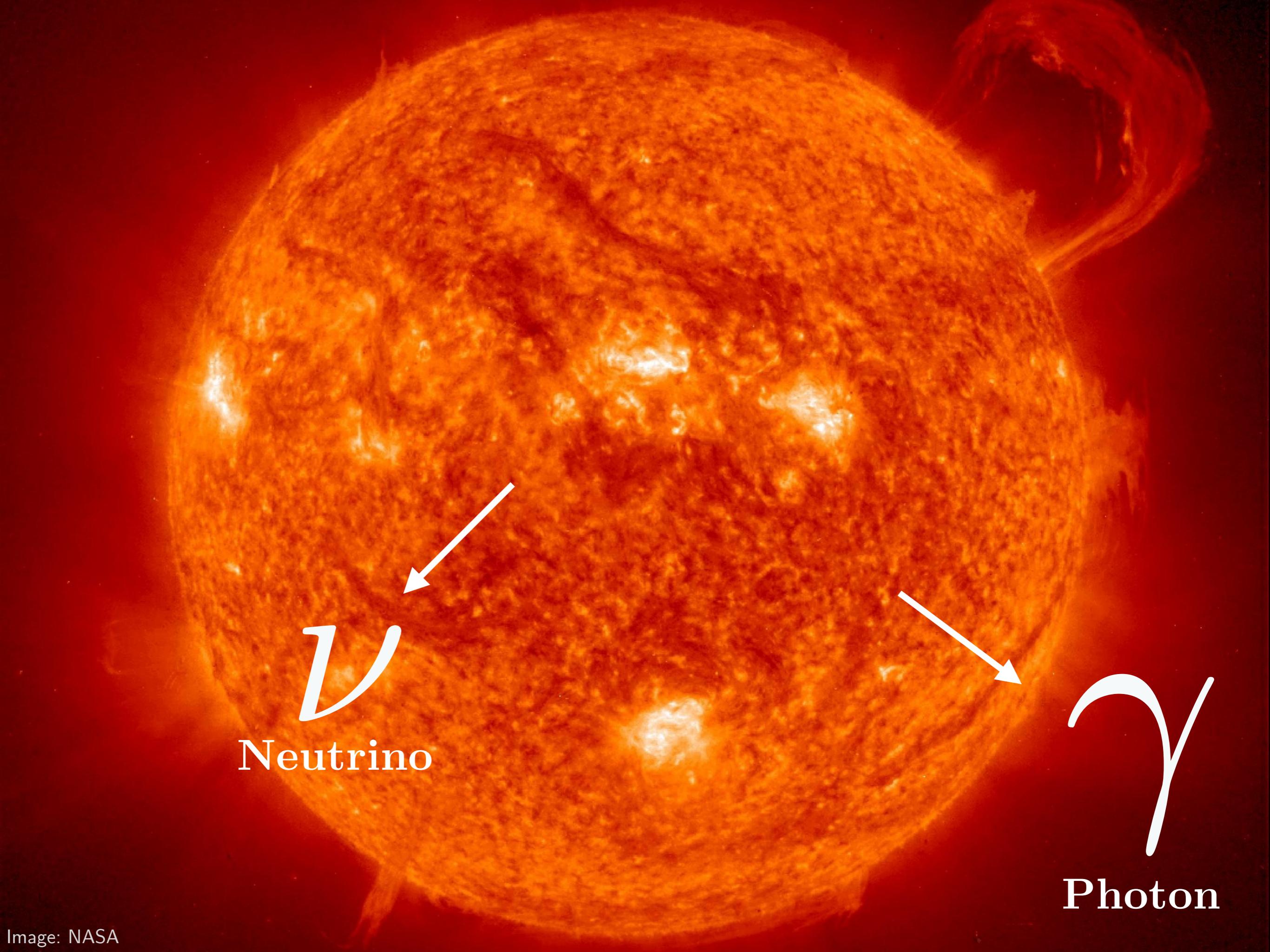


Image: NASA



Photon

 ν

Neutrino

 γ

Photon

Internal structure:

inner core
radiative zone
convection zone

Subsurface flows

Photosphere

ν

Neutrino

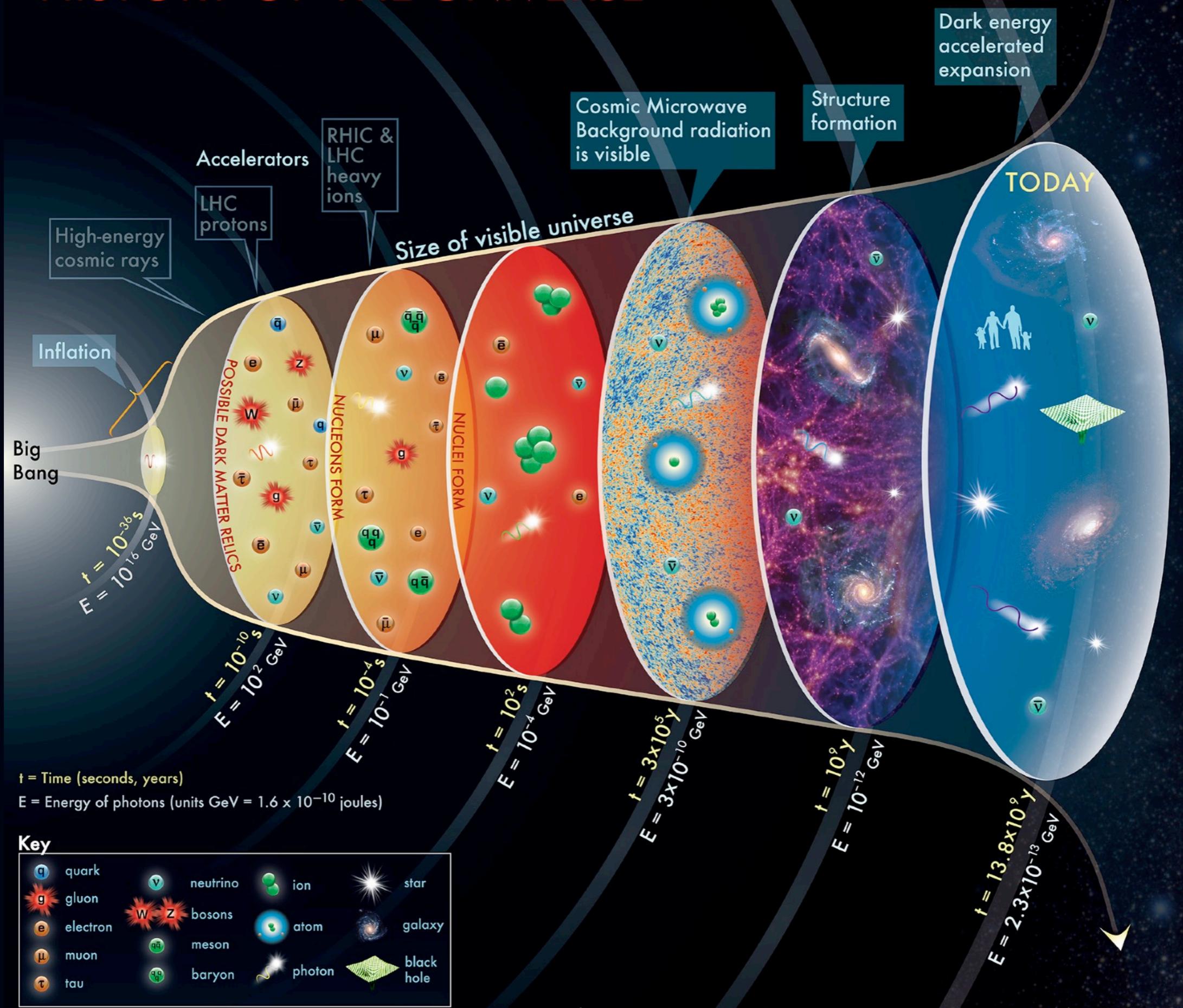
γ

Chromosphere

Corona

Photon

HISTORY OF THE UNIVERSE

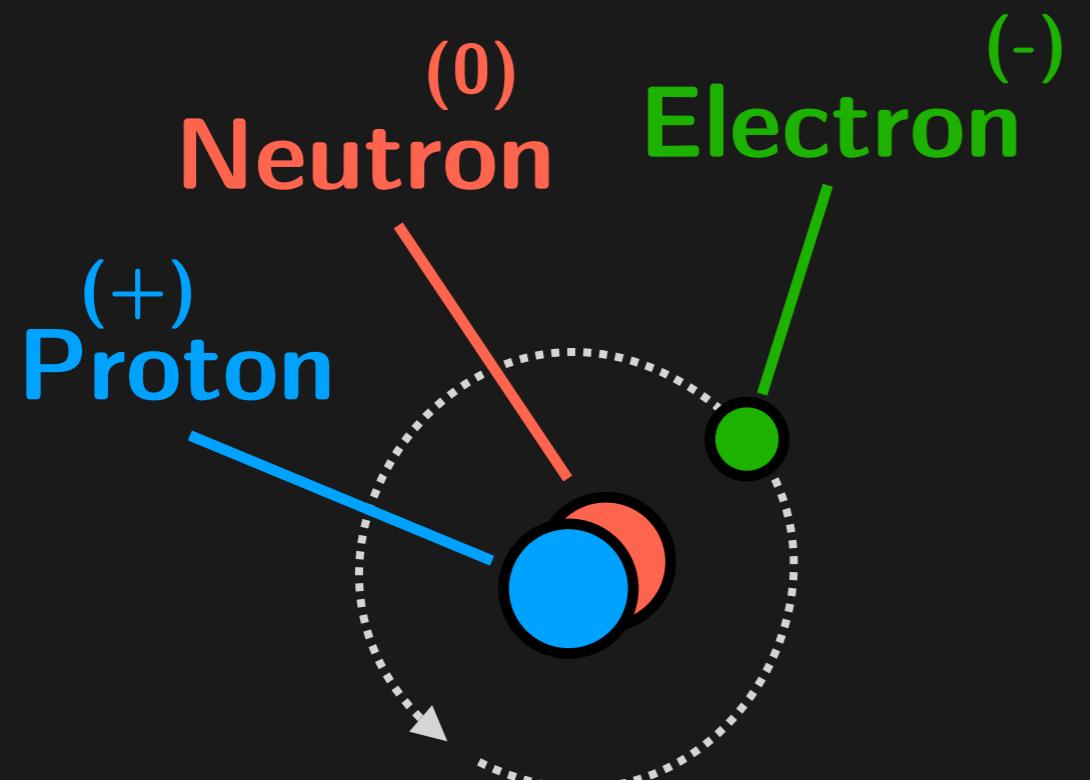


The concept for the above figure originated in a 1986 paper by Michael Turner.

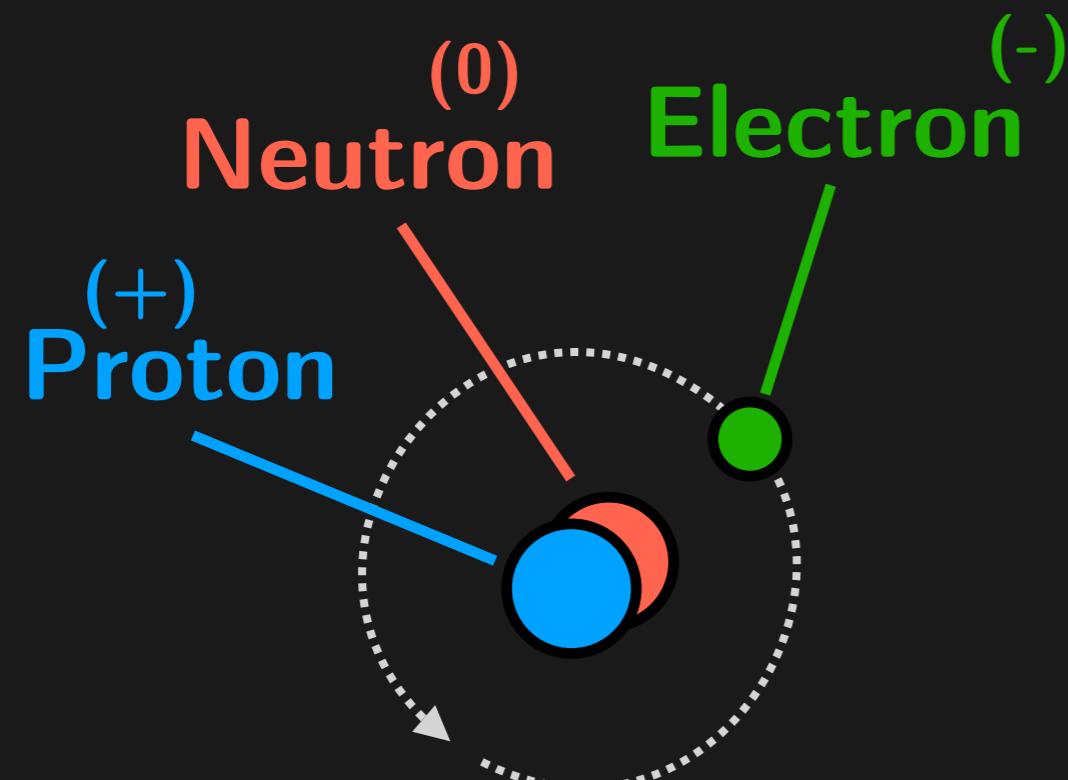
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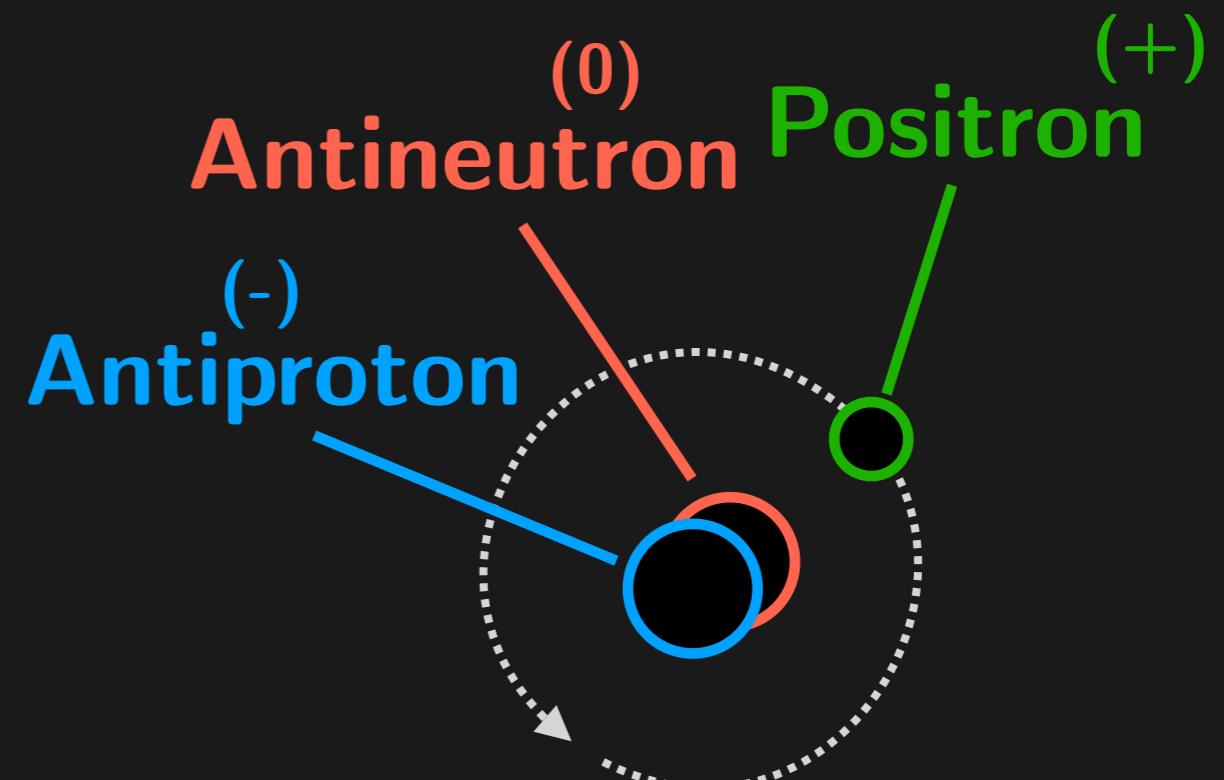
"MATTER"



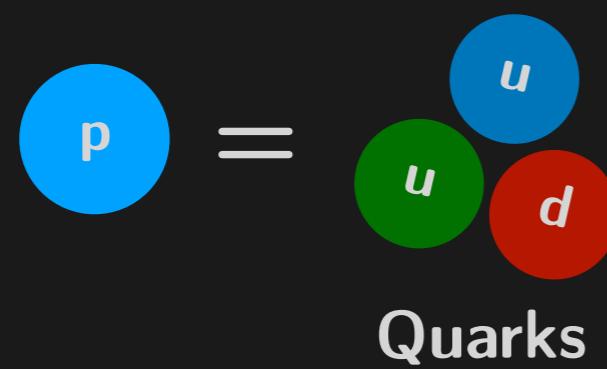
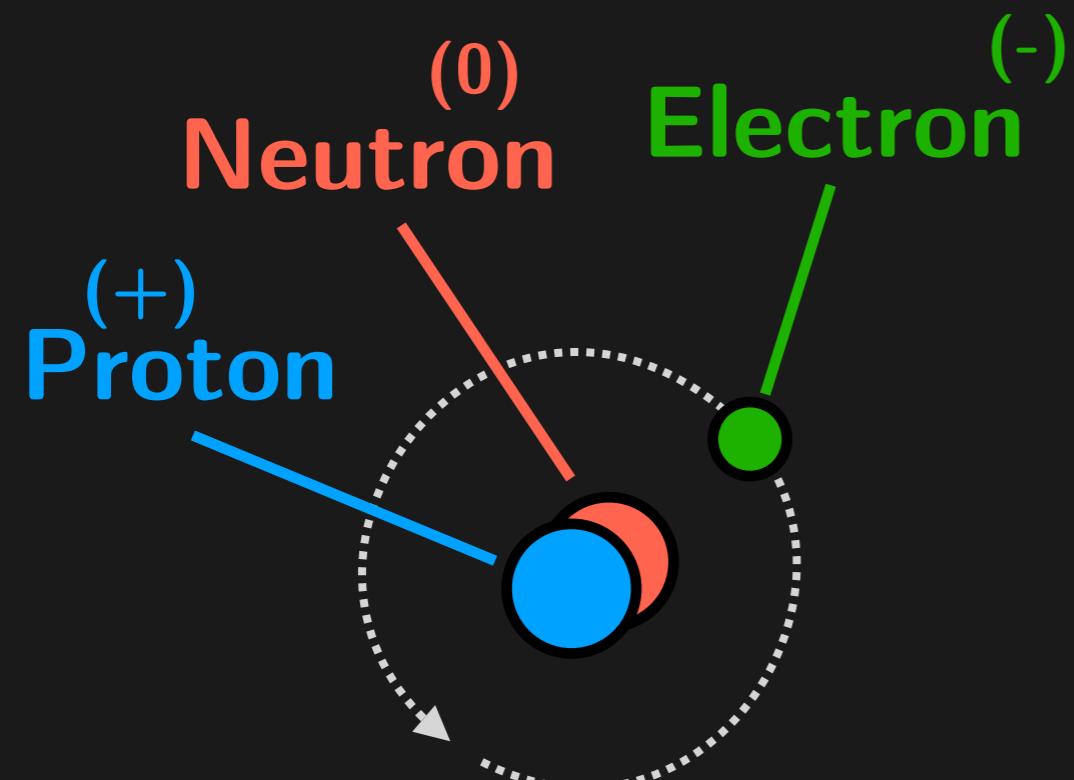
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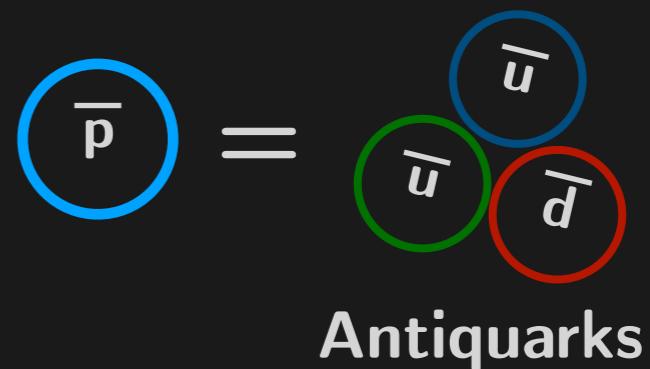
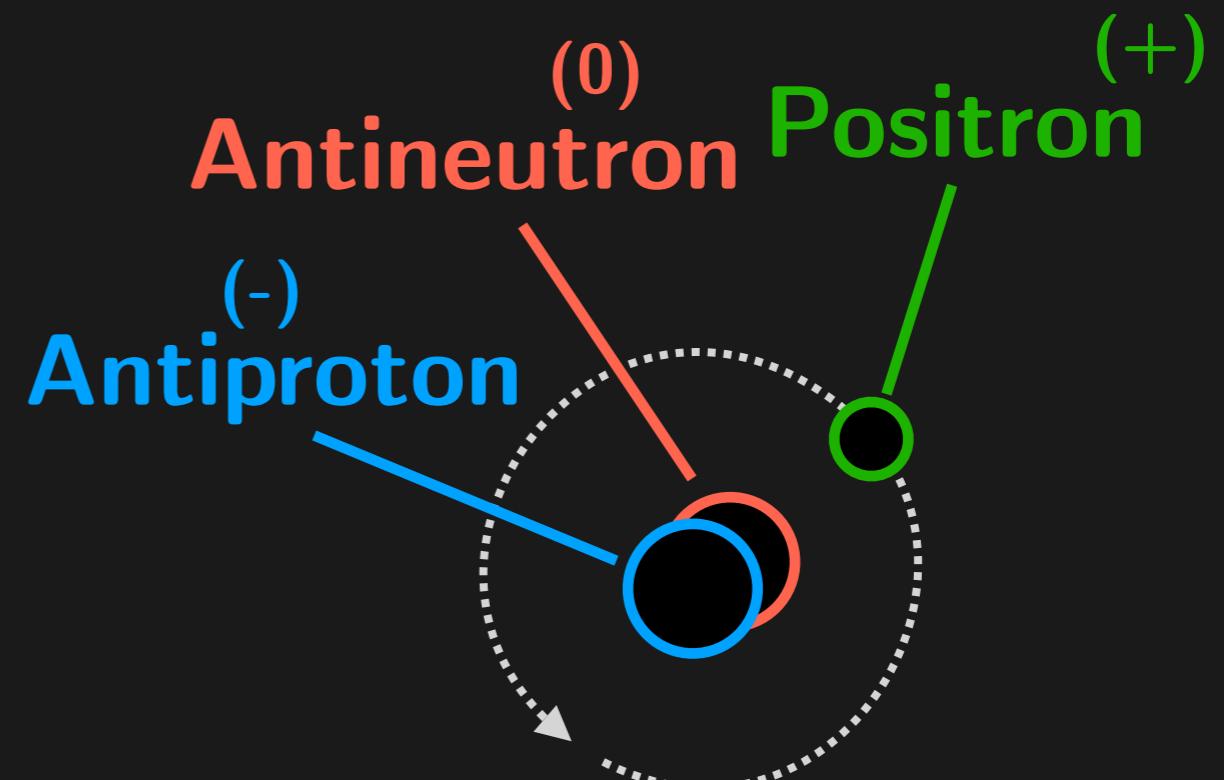
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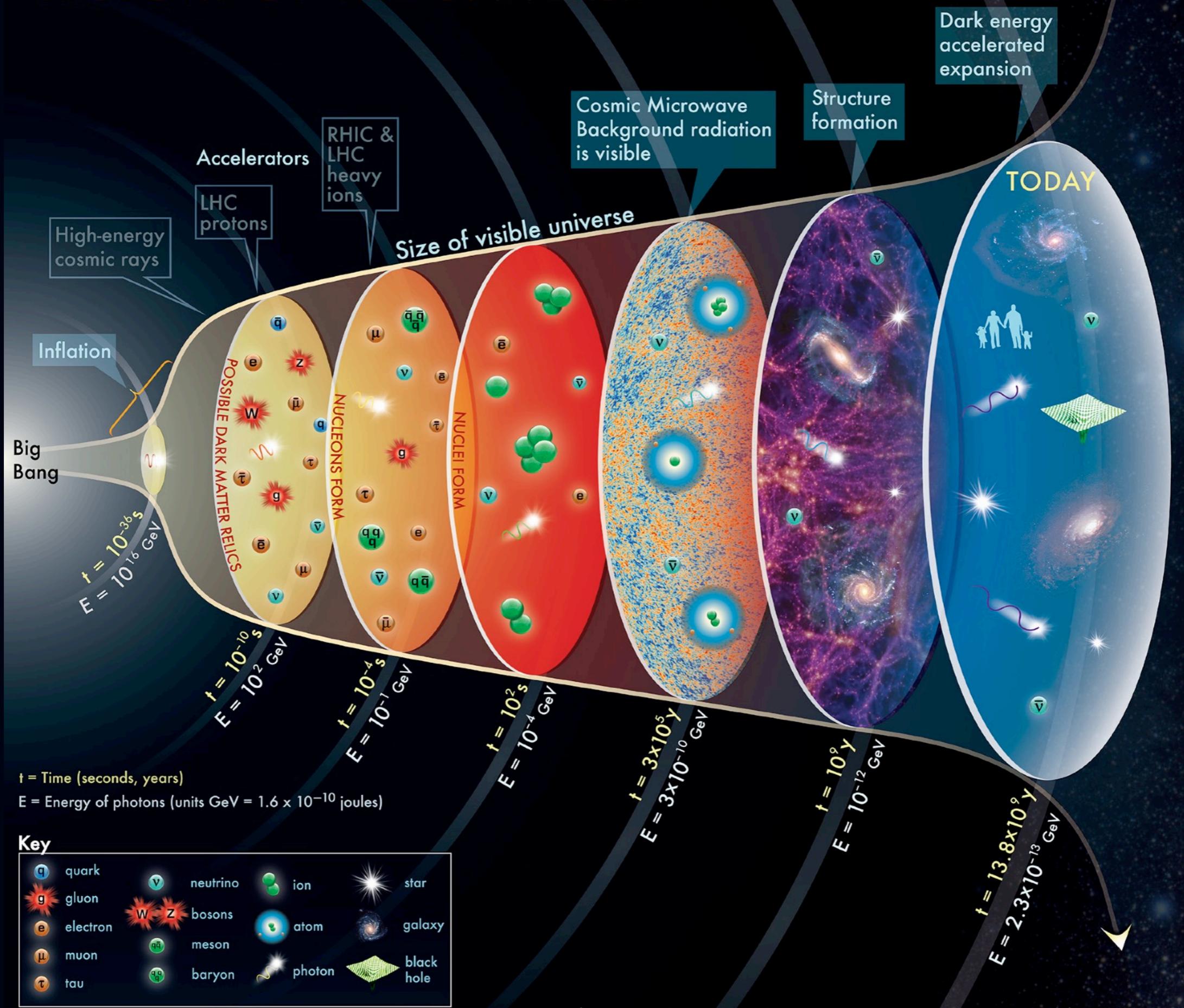
"MATTER"



"ANTIMATTER"



HISTORY OF THE UNIVERSE



The concept for the above figure originated in a 1986 paper by Michael Turner.

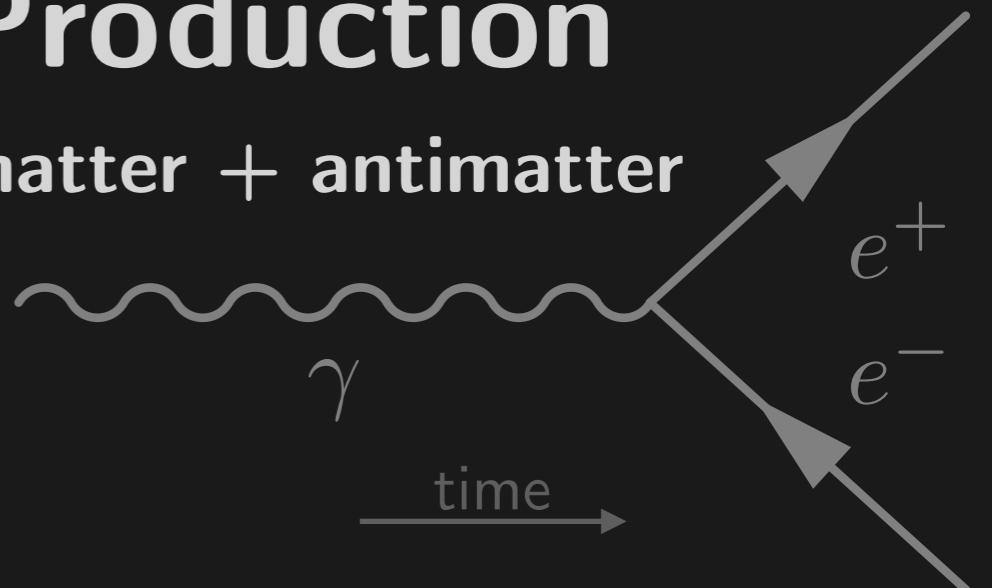
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$$E = mc^2$$

Pair Production

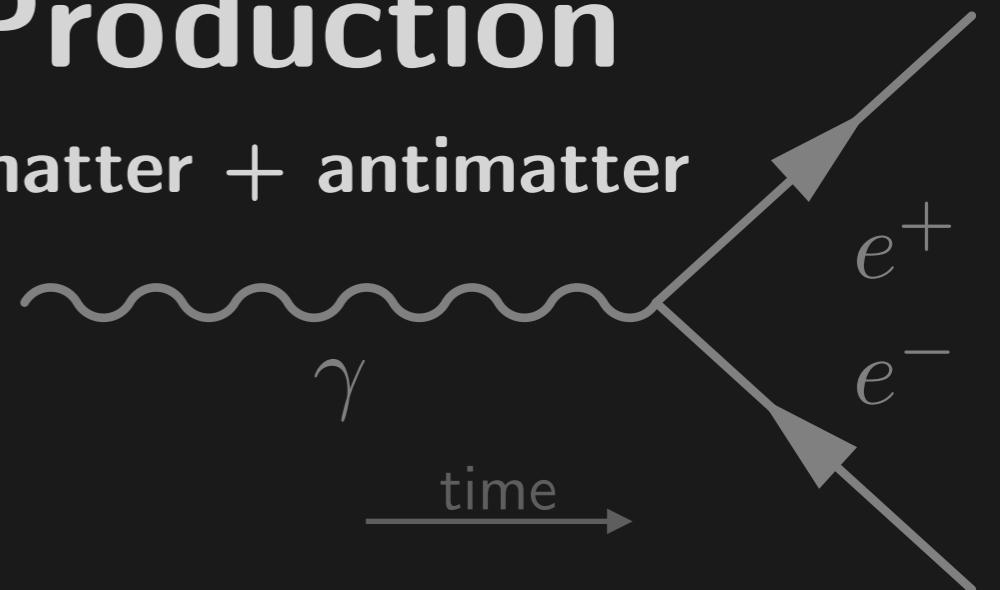
energy → matter + antimatter



$$E = mc^2$$

Pair Production

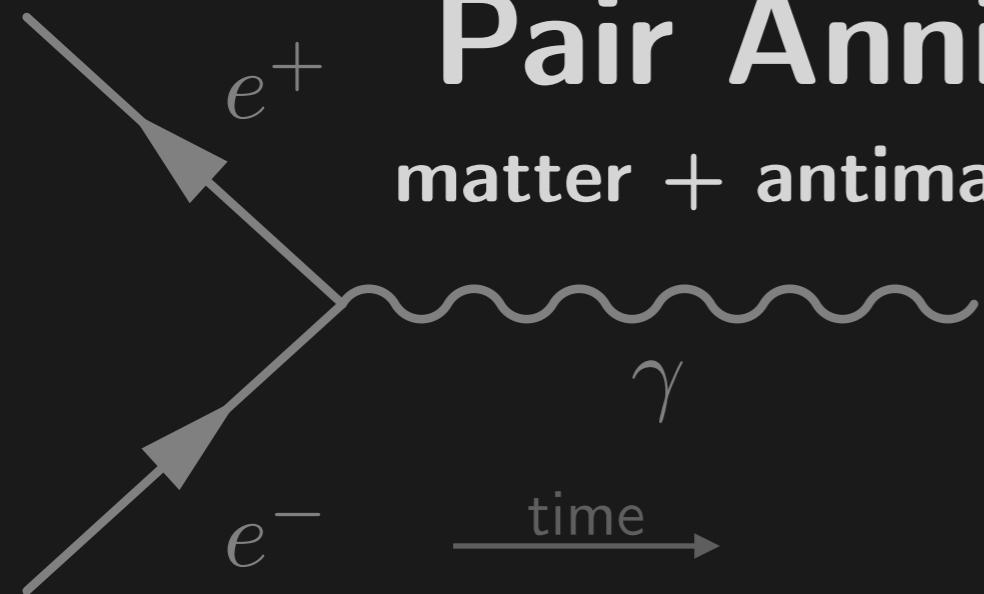
energy \rightarrow matter + antimatter

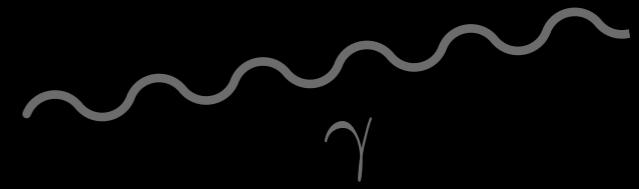
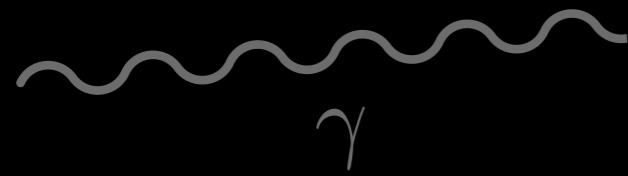
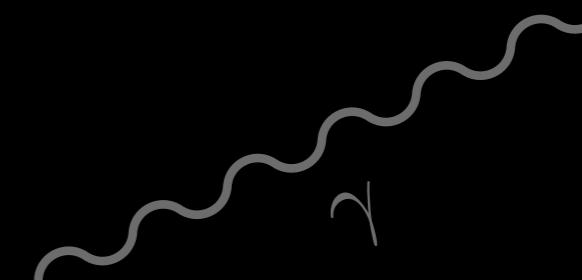
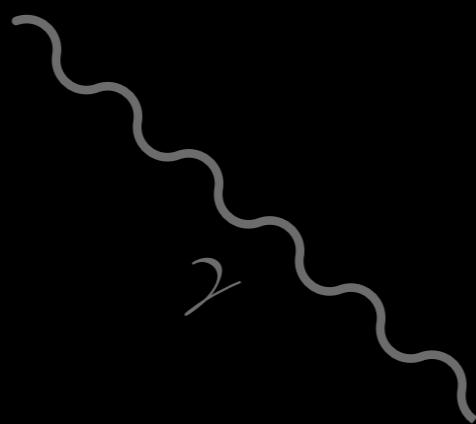
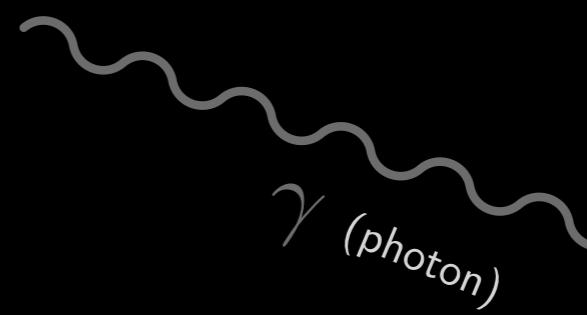
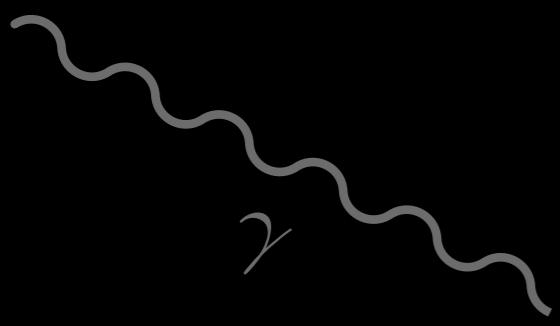


$$E = mc^2$$

Pair Annihilation

matter + antimatter \rightarrow energy





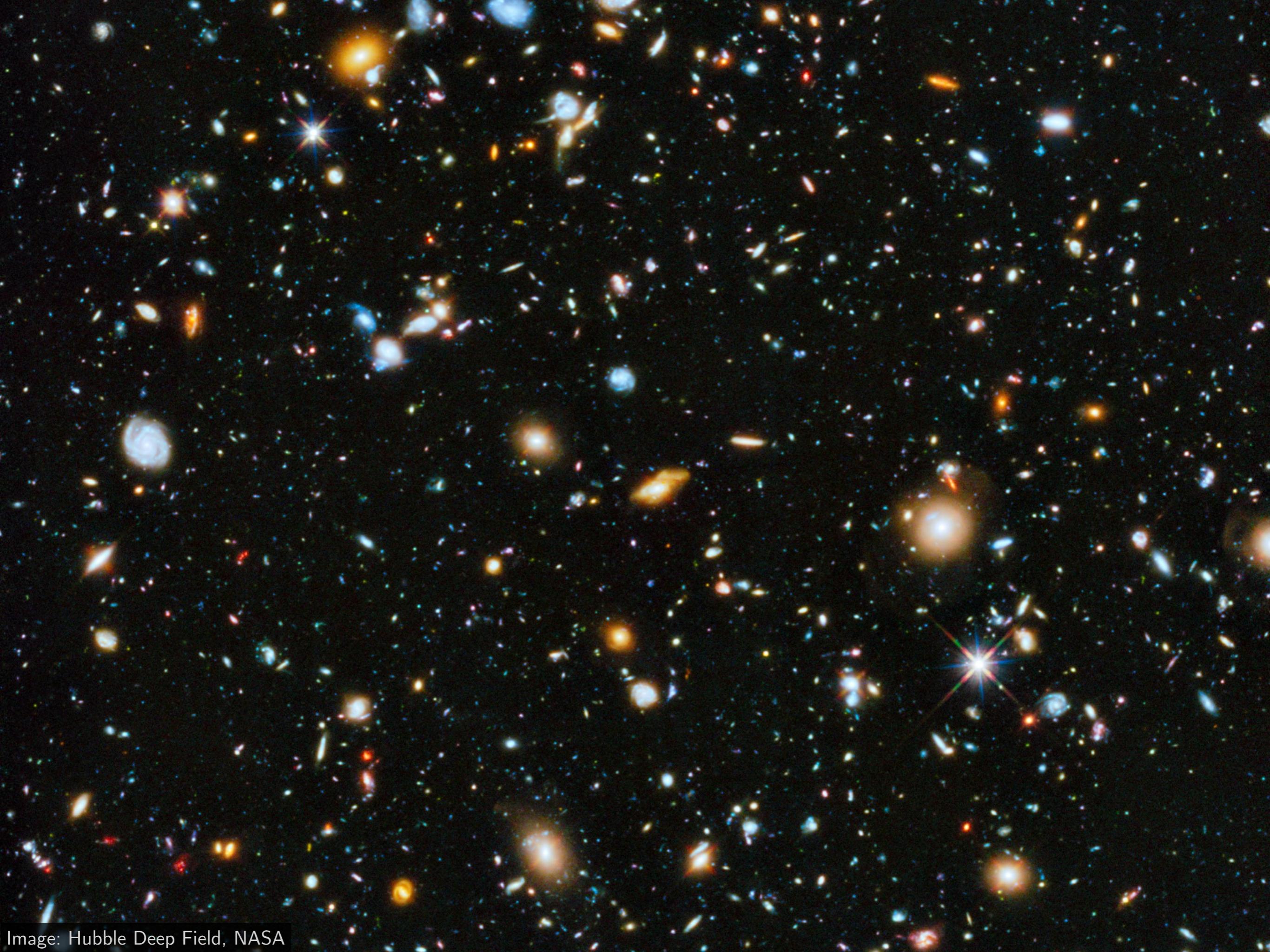
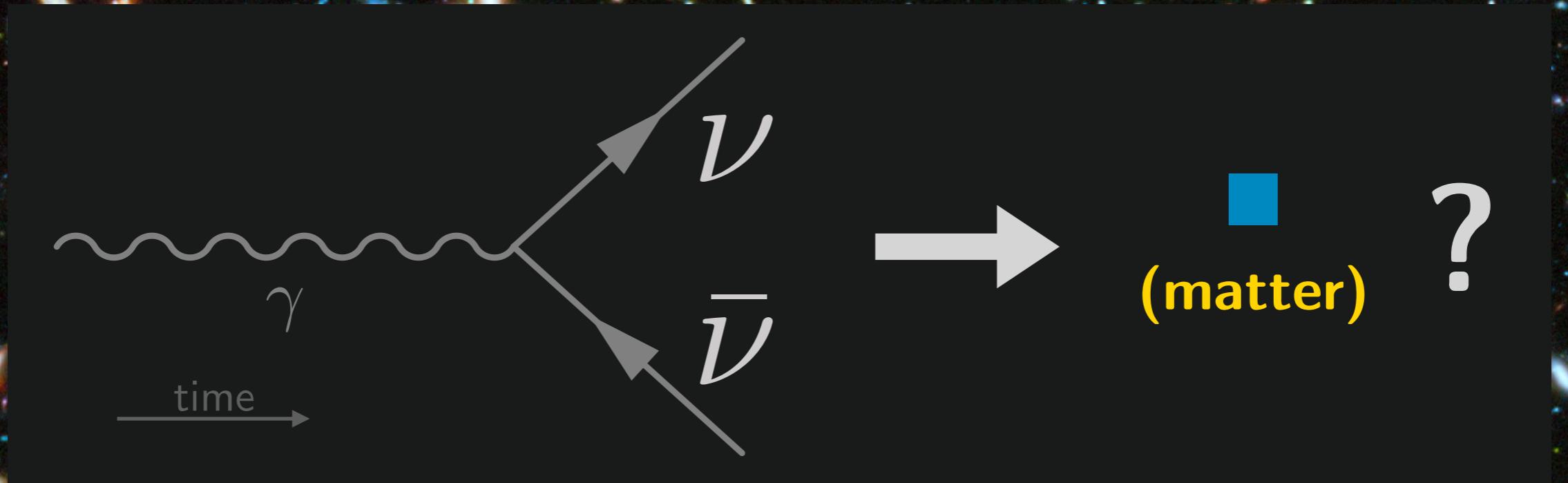


Image: Hubble Deep Field, NASA



v

Astrophysics & Cosmology

Image: NASA

Origin of the Universe

Image: Hubble Deep Field, NASA

V

Nuclear Testing and Reactors

Image: NRC

Elementary Particle Physics

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The Physics of Neutrinos: Progress and Puzzles

The 87th Compton Lecture Series

Goals

I hope you leave this series with an understanding of...

- What neutrinos are and how they fit into our model of physical interactions
- Major experimental efforts ongoing in neutrino physics
- Open questions in neutrinos and particle physics
- Neutrinos as *objects of study* in their own right, and neutrinos as *messengers* of other interesting physics

The Physics of Neutrinos: Progress and Puzzles

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Agenda (subject to change)

March 31	Little, Neutral, Mysterious: An Introduction to Neutrino Physics
April 7	Neutrinos from the Sun
April 14	Neutrinos from Space
April 21	Neutrinos from Reactors
April 28	Neutrino Cosmology
May 5	How Many Neutrinos Are There, Anyway?: Sterile Neutrino Searches
May 12	Why Are We Here?: Long-Baseline Neutrino Physics and CP
May 19	How Little Is Little?: Neutrino Mass
May 26	<i>No lecture</i>
June 2	Where We Are, Where We're Going

v

I. Discovery



Nuclear Decays

When Things Fall Apart



Pierre & Marie Curie

Alpha Decay

Nucleus emits an "alpha" (two protons, two neutrons)
 $(A, Z) \rightarrow (A - 4, Z - 2) + \alpha$



Beta Decay

Nucleus emits an electron ("beta")
 $(A, Z) \rightarrow (A, Z + 1) + \beta$



Gamma Decay

Nucleus emits a photon ("gamma")
 $(A, Z) \rightarrow (A, Z) + \gamma$

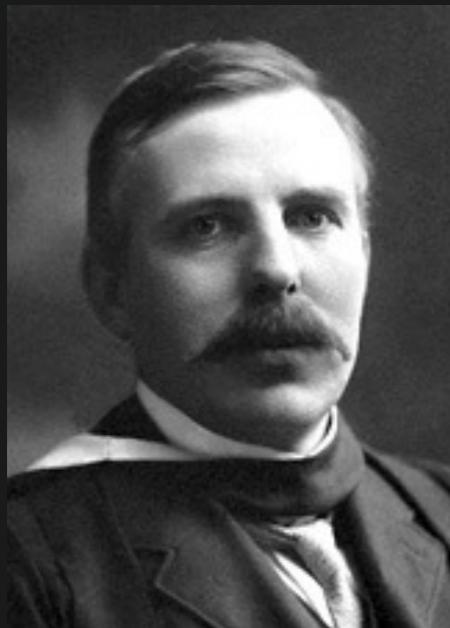


Trouble with Beta Decays

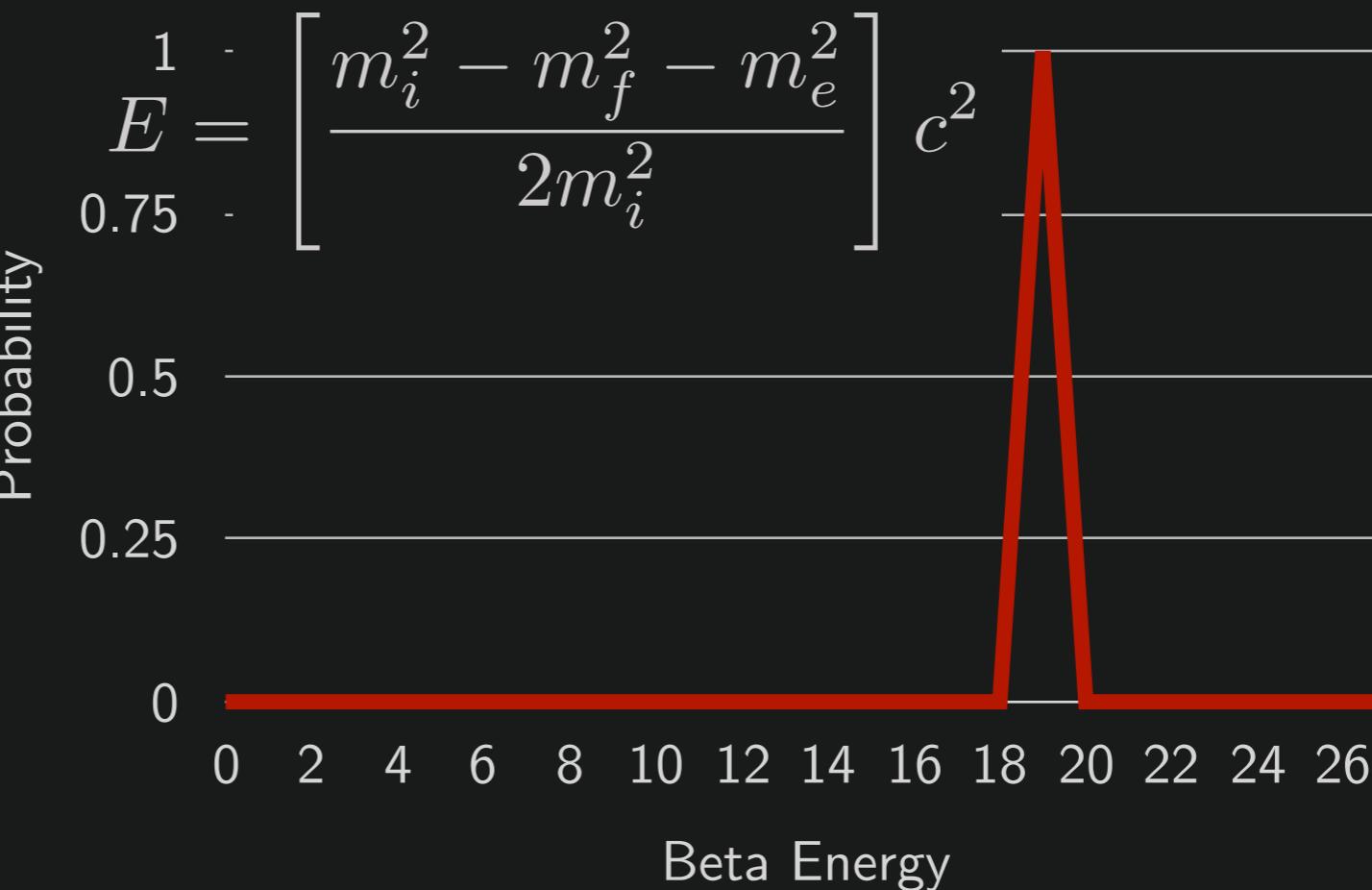
c. 1927



James Chadwick



Ellis Drummond



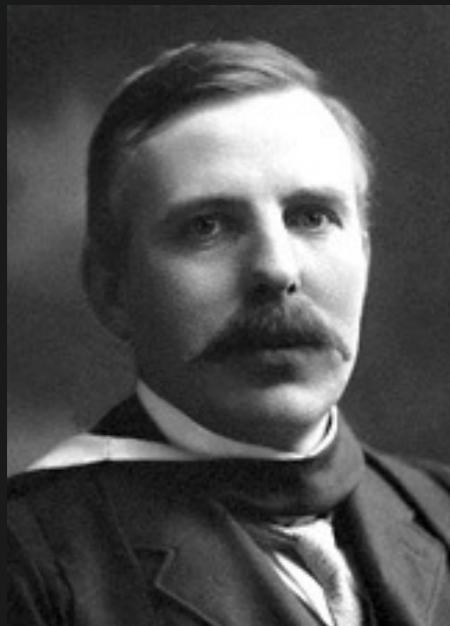
Expected beta decay spectrum

Trouble with Beta Decays

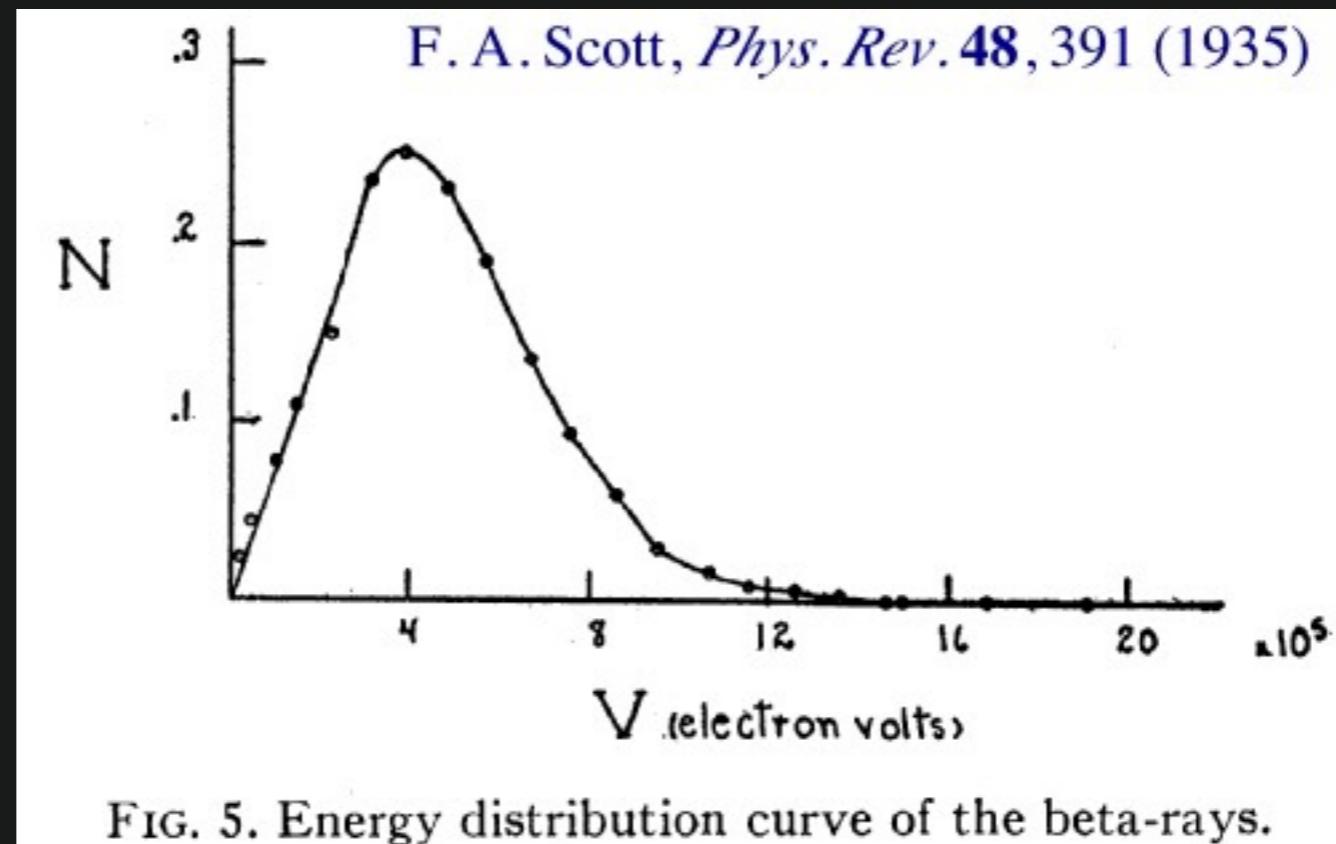
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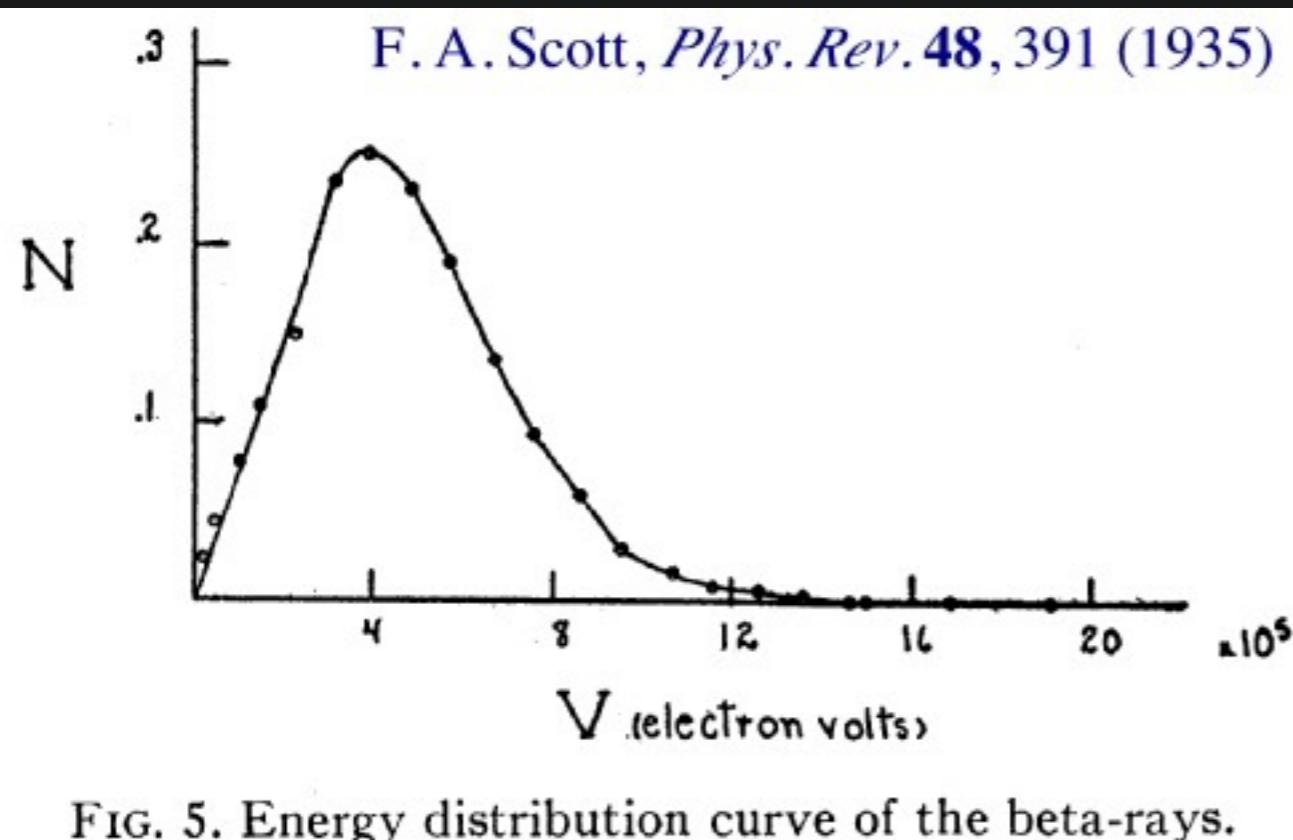
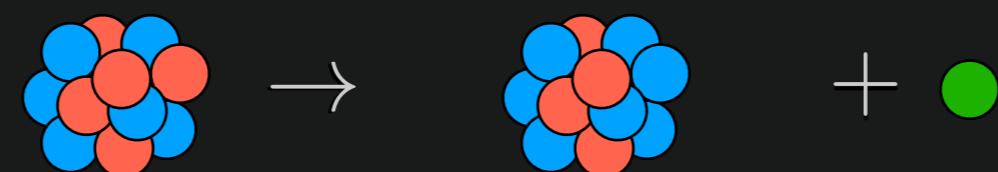
Measurement of beta decay spectrum

Trouble with Beta Decays

c. 1927

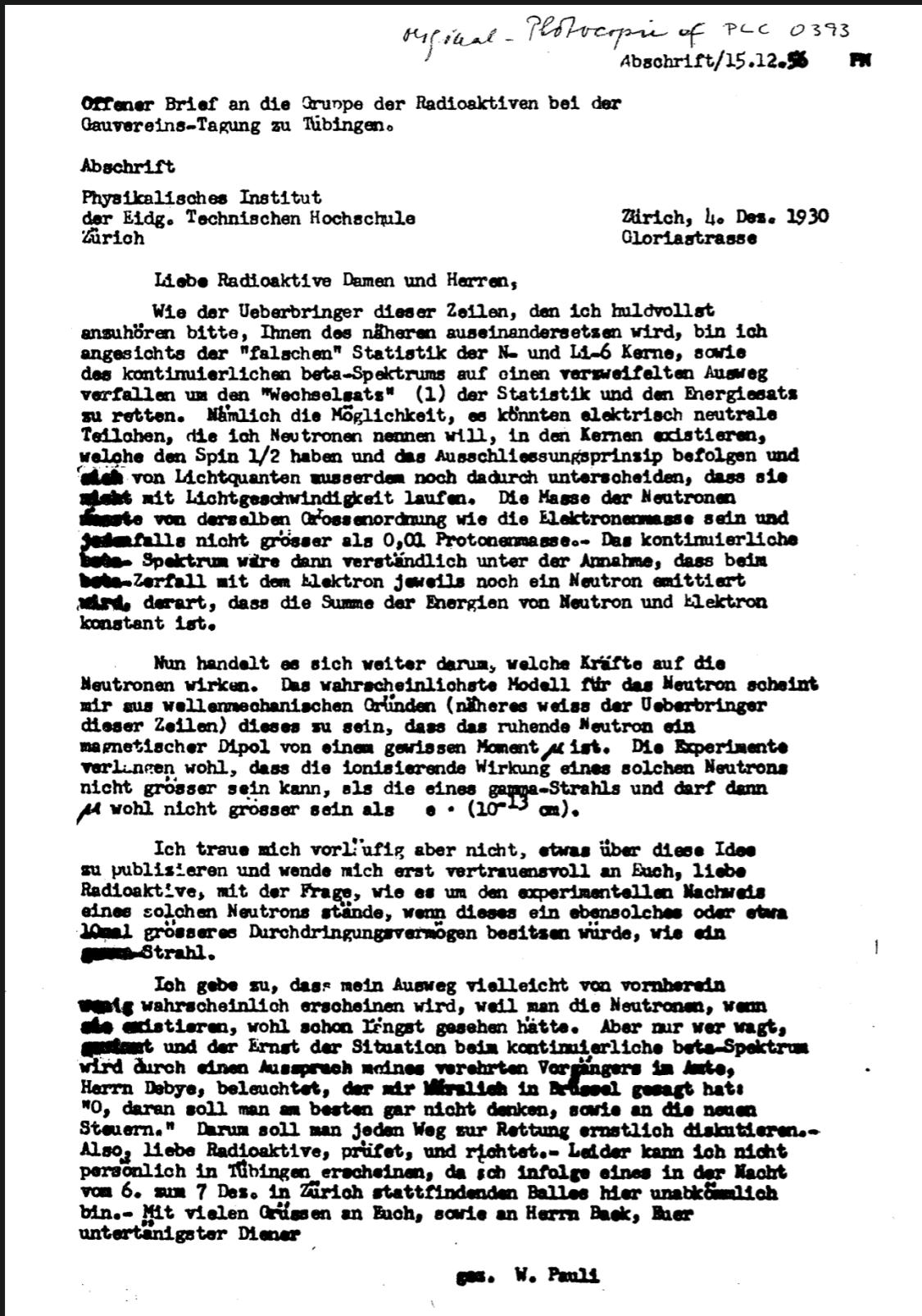
Beta Decay

Nucleus emits an electron ("beta")
 $(A, Z) \rightarrow (A, Z + 1) + \beta$



Option 1: Energy just disappears.
Energy isn't conserved in the universe, physics goes back to the drawing board.

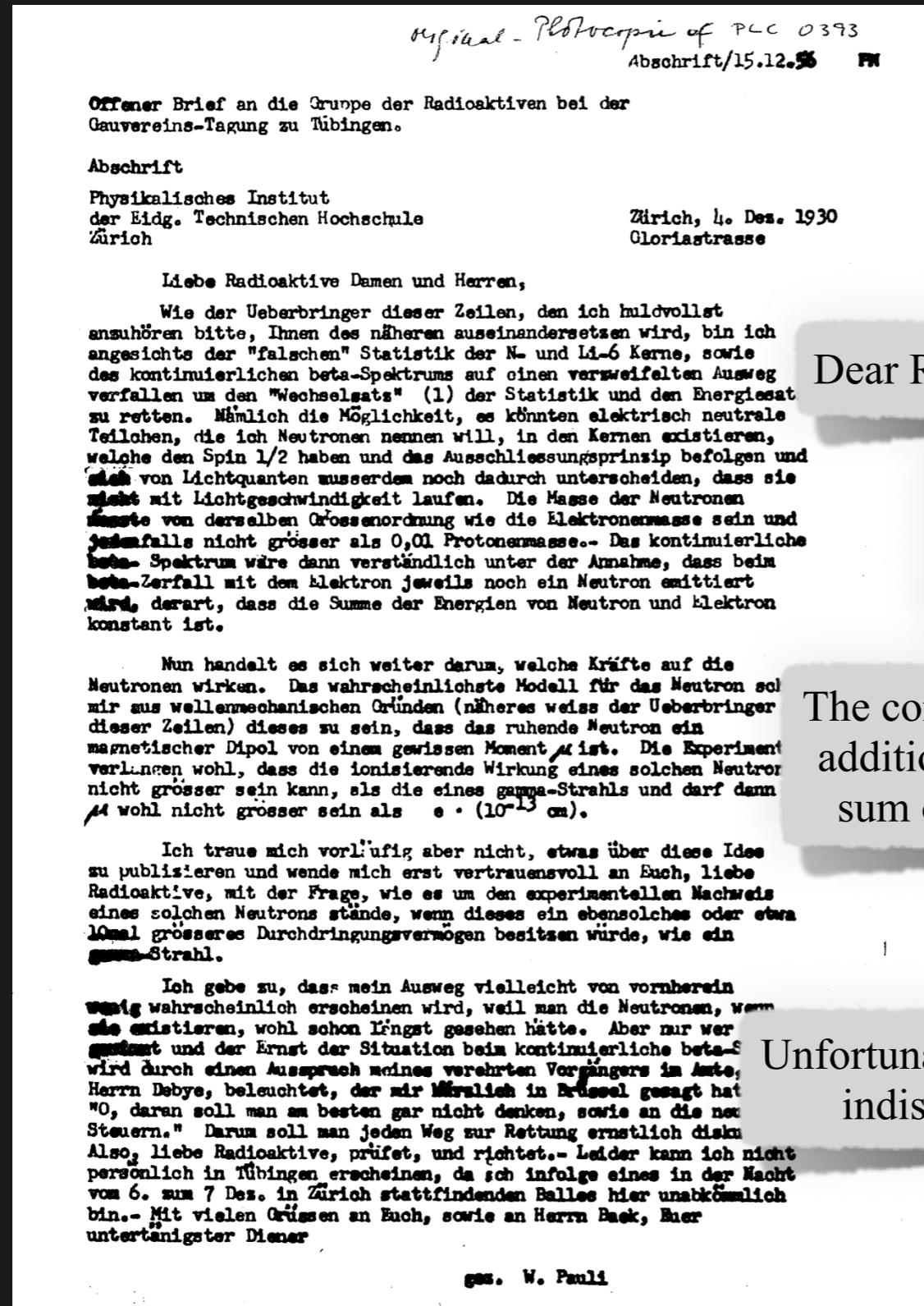
Dear Radioactive Ladies and Gentlemen....



Wolfgang Pauli
December 1930



Dear Radioactive Ladies and Gentlemen....



Wolfgang Pauli
December 1930



Dear Radioactive Ladies and Gentlemen,

I have hit upon a **desperate remedy** ... there could exist electrically-neutral particles [emitted in beta decay] ...

The continuous beta spectrum would then make sense ... in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

I do not dare to publish anything

Unfortunately, I cannot personally appear ... since I am indispensable here in Zürich because of a ball



"I have done a terrible thing today by proposing a particle that cannot be detected; it is something no theorist should ever do."

— Wolfgang Pauli, 1930

Trouble with Beta Decays

Beta Decay

Nucleus emits an electron ("beta")
 $(A, Z) \rightarrow (A, Z + 1) + \beta + \bar{\nu}_e$

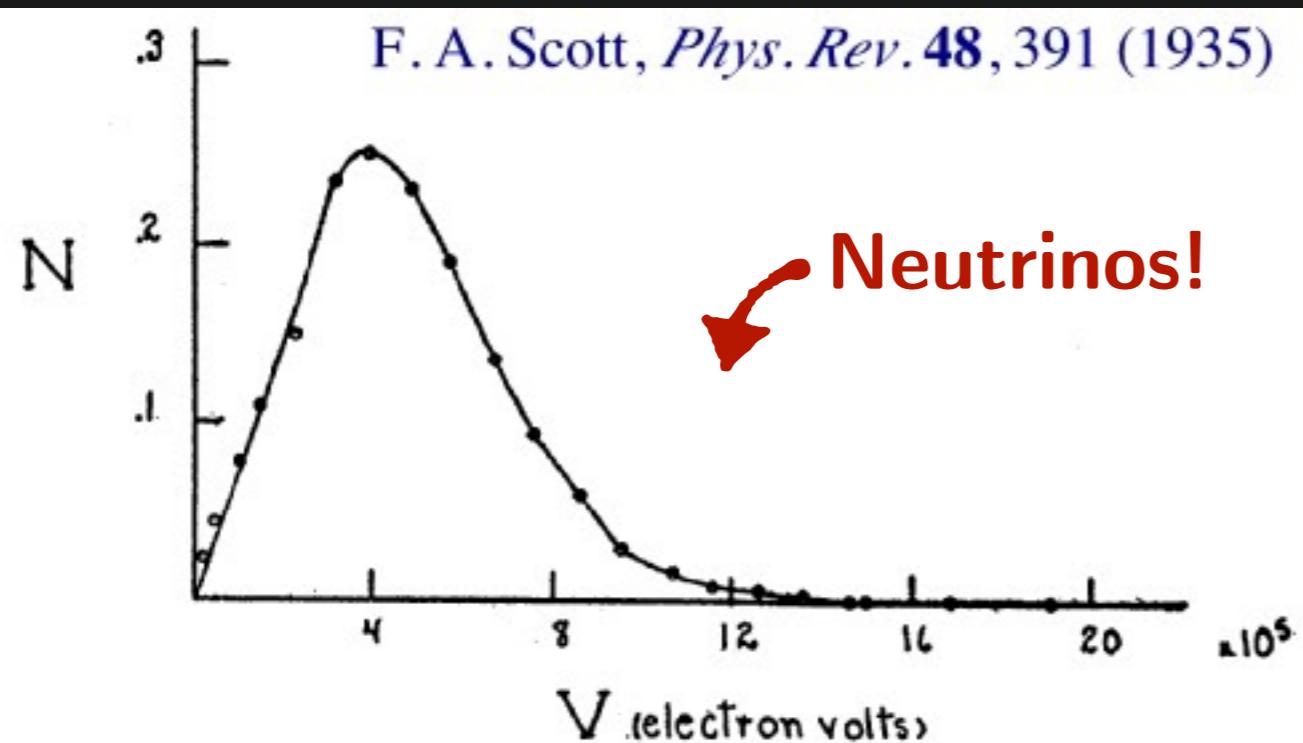
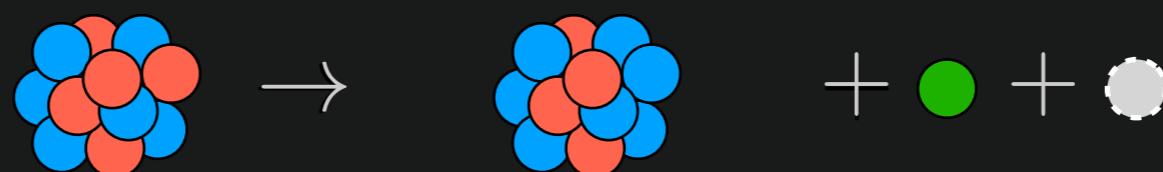


FIG. 5. Energy distribution curve of the beta-rays.

Option 1: Energy just disappears.

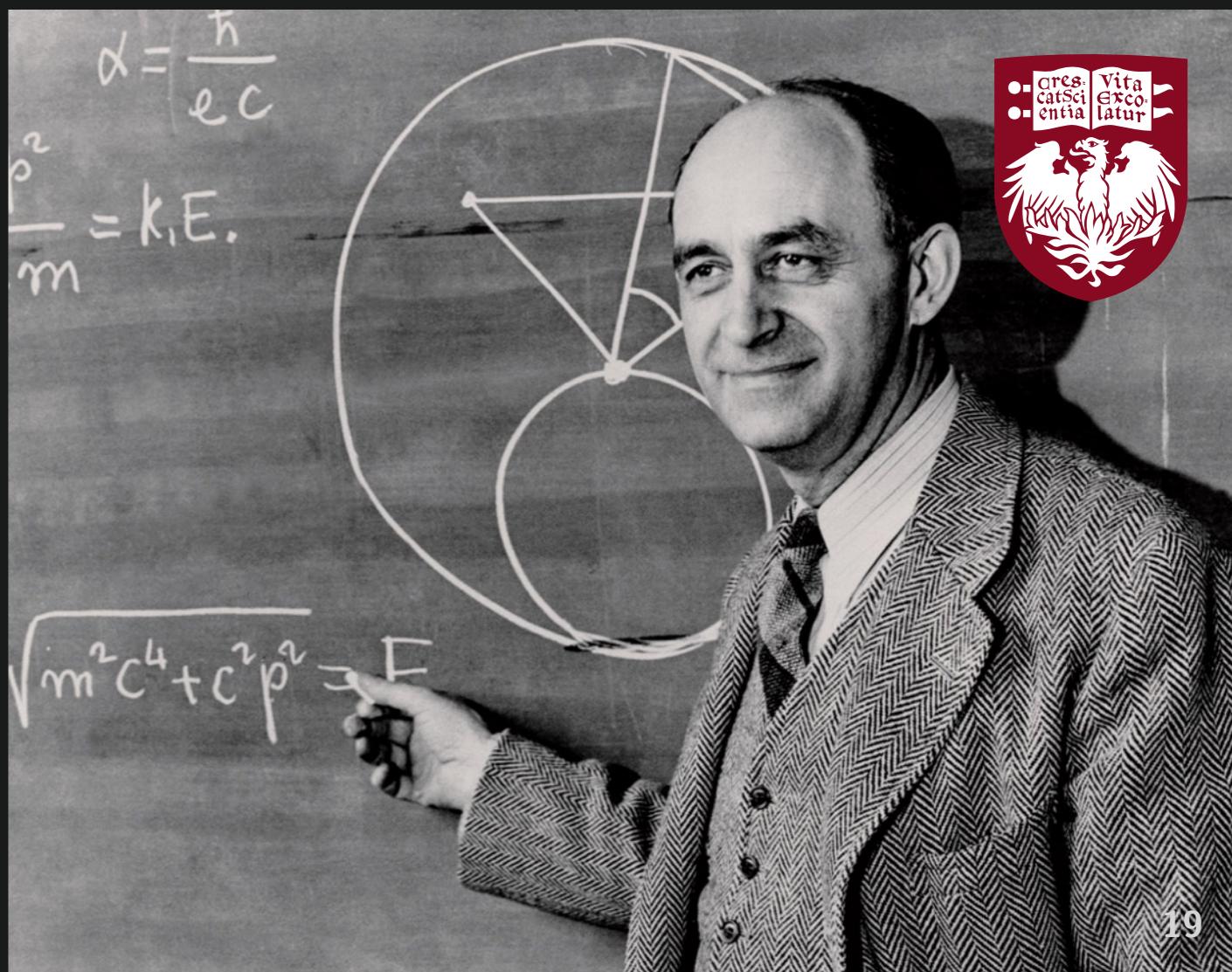
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Option 2: Some invisible participant is carrying some energy away.

We invent a new decay product which shares the energy and somehow evades detection.

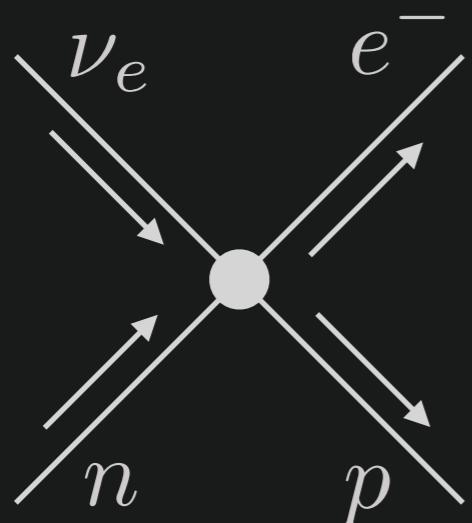
1934: Fermi's Theory

Enrico Fermi works out a theory of beta decay, with a neutral particle carrying away energy.



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Enrico Fermi works out a theory of beta decay, with a neutral particle carrying away energy.



$$M \sim G_F (\bar{u}_p \gamma^\mu u_n)(\bar{u}_e \gamma_\mu u_\nu)$$

$$\lambda_{i \rightarrow f} = \frac{2\pi}{\hbar} |M|^2 \rho$$

AMERICAN JOURNAL OF PHYSICS VOLUME 36, NUMBER 12 DECEMBER 1968

Fermi's Theory of Beta Decay*

FRED L. WILSON
6666 Chetwood #295, Houston, Texas 77036
(Received 13 March 1968; revision received 19 August 1968)

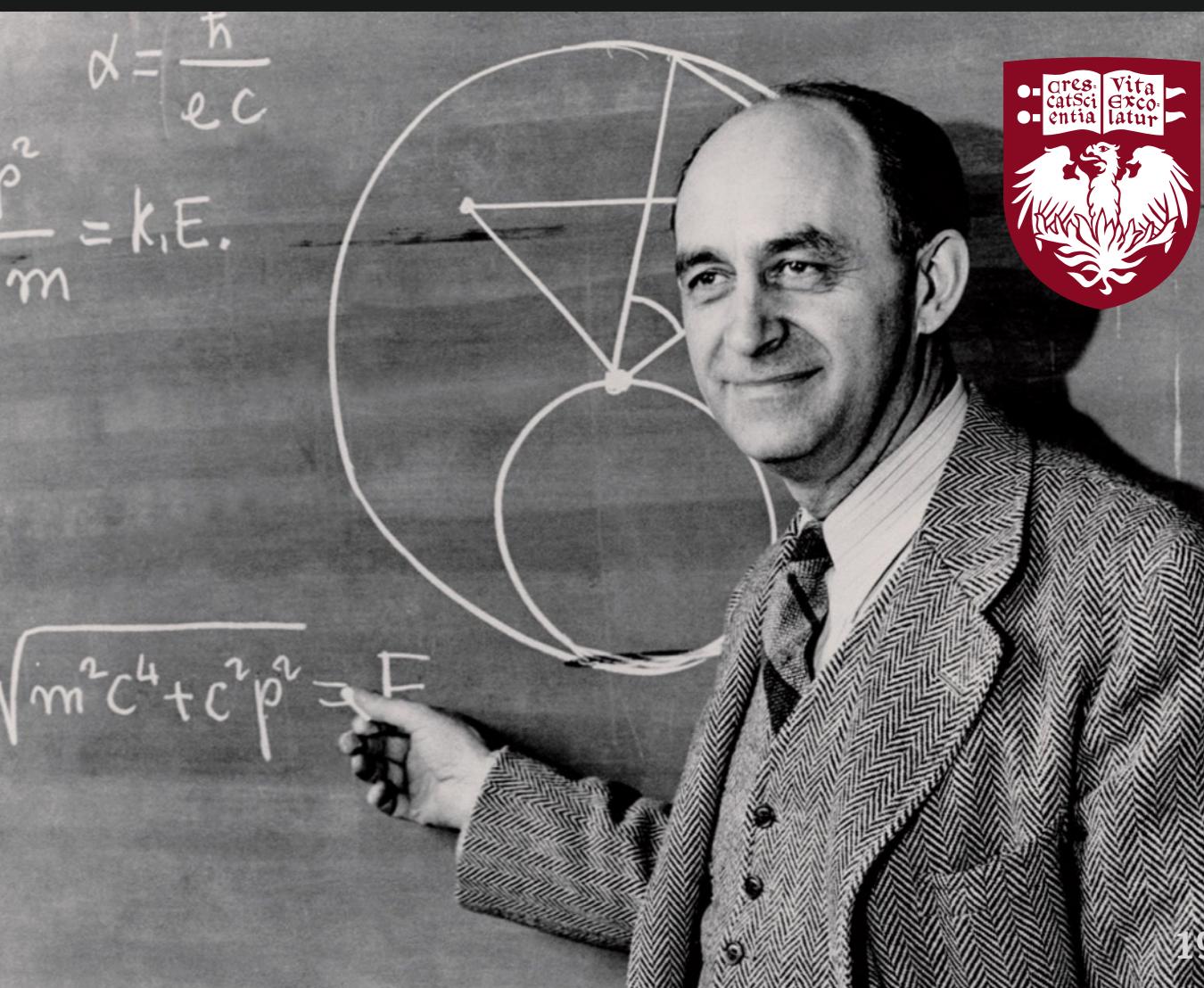
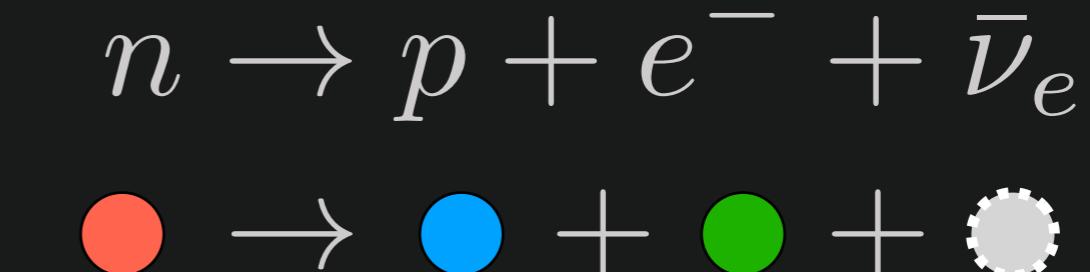
A complete English translation is given of the classic Enrico Fermi paper on beta decay published in *Zeitschrift für Physik* in 1934.

INTRODUCTION

In 1934, Enrico Fermi, then a professor of theoretical physics at the University of Rome, Italy, proposed his clear and simple description of β decay. He assumed the existence of the neutrino which Pauli had suggested to preserve the principle of conservation of energy, and he treated the ejection of electrons and neutrinos from a nucleus by a method similar to the radiation theory of photon emission from atoms. Fermi derived quantitative expressions for the lifetime

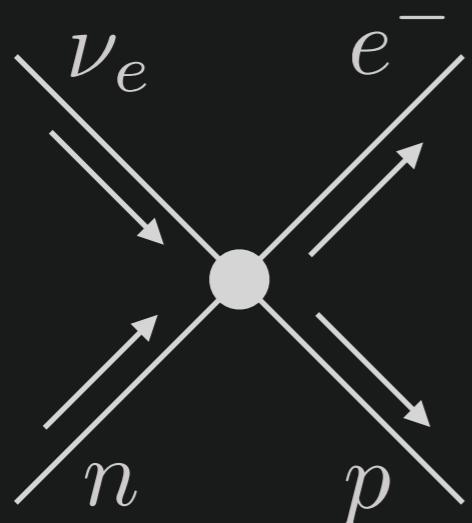
To appreciate the impact produced by Fermi's theory of β decay on modern physics, one may note that it is rather amazing what varieties of observed phenomena (and what thicknesses of the *Physical Review*) are based on his one paper on the subject. For example, the experiment proposed by Yang and Lee in 1956 to test conservation of parity, involved the properties of β decay of ^{60}Co .

With his paper on β decay, Fermi brought to a close his purely theoretical studies and became



1934: Fermi's Theory

Enrico Fermi works out a theory of beta decay, with a neutral particle carrying away energy.



$$M \sim G_F (\bar{u}_p \gamma^\mu u_n)(\bar{u}_e \gamma_\mu u_\nu)$$

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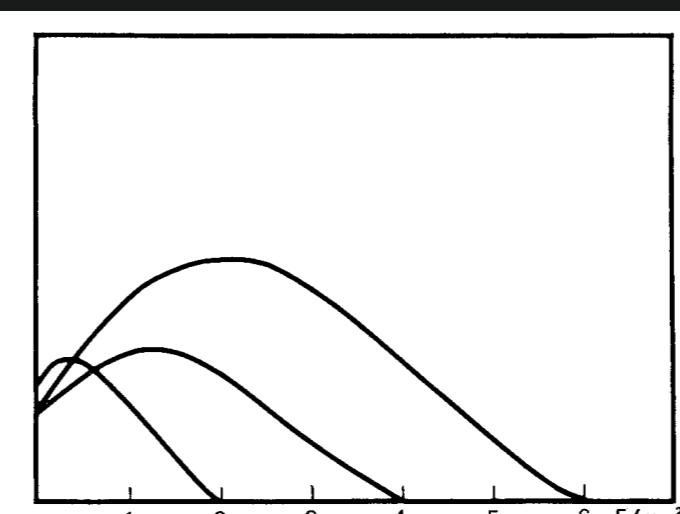
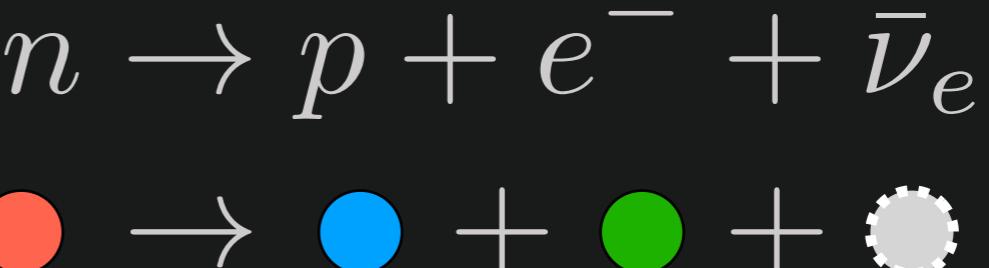
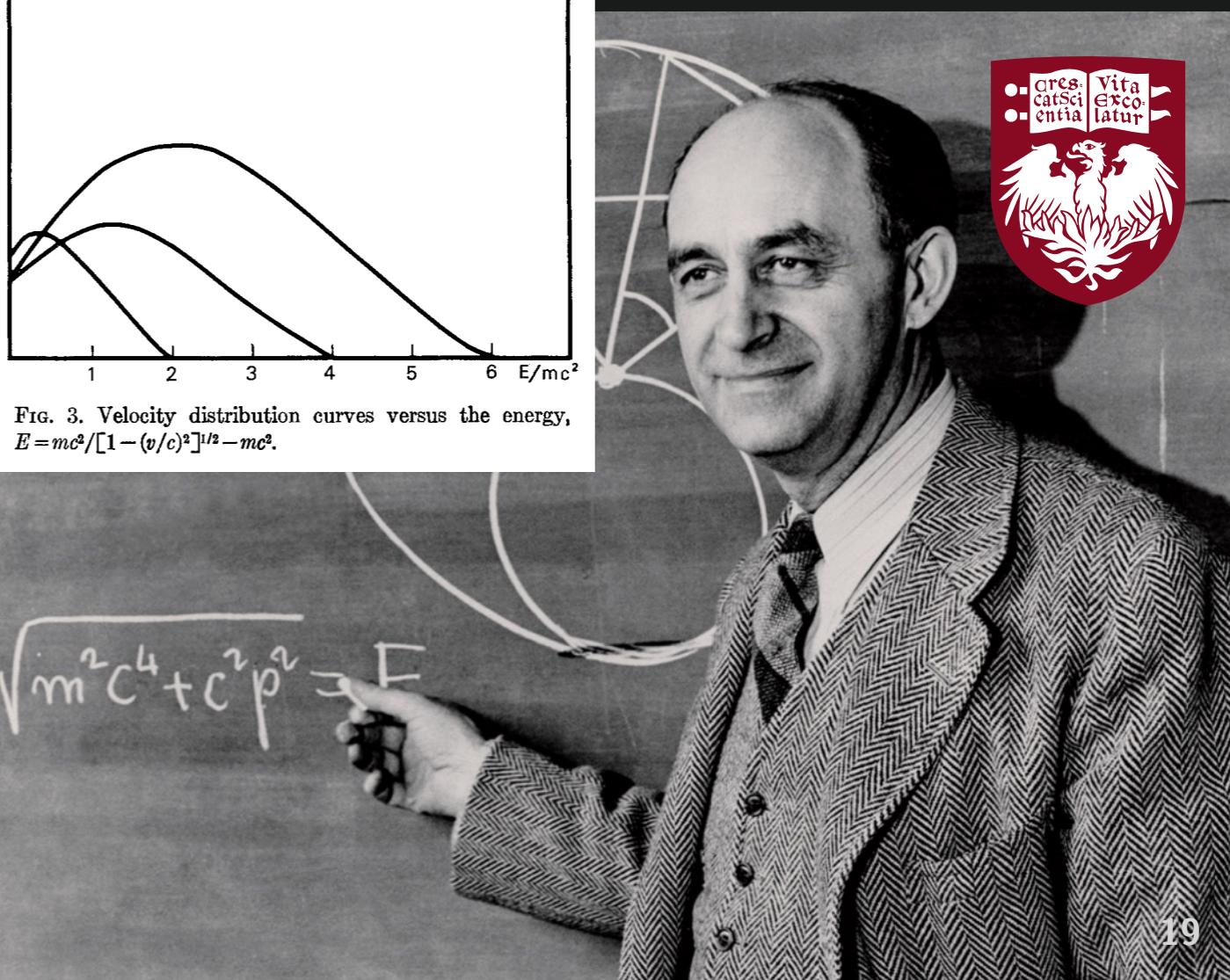


FIG. 3. Velocity distribution curves versus the energy, $E = mc^2/[1 - (v/c)^2]^{1/2} - mc^2$.



1934: Fermi's Theory

Hans Bethe & Rudolf Peierls
calculate the neutrino cross section



1934: Fermi's Theory

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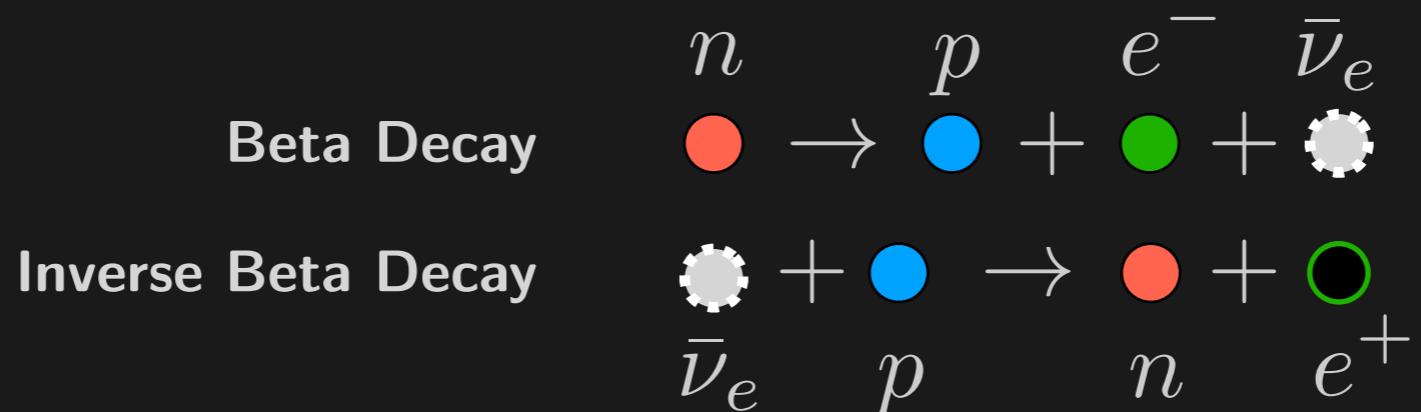


1934: Fermi's Theory

Hans Bethe & Rudolf Peierls
calculate the neutrino cross section



Hans Bethe



532 © Nature Publishing NATURE APRIL 7, 1934

The following comparison of the structure given by Badami and by me for the line $\lambda 5639\cdot7$ ($6s\ ^3P_2 - 6p\ ^3S_1$) shows to what extent the hollow cathode patterns are more clearly resolved:

	0 (6)	205 (5)	450 (4)	584 (4)	760 (1)	$\text{cm.}^{-1} \times 10^{-3}$			
Badami	0	205	450	584	760				
Tolansky	0 (10)	71 (8)	217 (9)	319 (3)	399 (3½)	477 (6)	605 (5)	728 (1½)	$\text{cm.}^{-1} \times 10^{-3}$

It is seen that Badami's values are those which would arise from the blending of components due to excessive line width.

Full details with analysis will be communicated elsewhere shortly.

S. TOLANSKY.

Astrophysics Department,
Imperial College of Science,
London, S.W.7.
March 3.

¹ J. S. Badami, *Z. Phys.*, **79**, 206; 1932.

The "Neutrino"

THE view has recently been put forward¹ that a neutral particle of about electronic mass, and spin $\frac{1}{2}\hbar$ (where $\hbar = h/2\pi$) exists, and that this 'neutrino' is emitted together with an electron in β -decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics². Both the emitted electron and neutrino could be described either (a) as having existed before in the nucleus or (b) as being created at the time of emission. In a recent paper³ Fermi has proposed a model of β -disintegration using (b) which seems to be confirmed by experiment.

According to (a), one should picture the neutron as being built up of a proton, an electron and a neutrino, while if one accepts (b), the roles of neutron and proton would be symmetrical⁴ and one would expect that positive electrons could also sometimes

first case, one of the two nuclei (Rb) is known to emit β -rays. In each of the last two cases one of the two isobares is stated to be exceedingly rare and its identification might be due to experimental error. The other three cases actually lie close together and have medium weight. A particular case of isobares are proton and neutron. Since all experimentally deduced values of the neutron mass lie between 1.0068 and 1.0078, they are certainly both stable even if the mass of the neutrino should be zero.

The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst them would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1.

The cross section σ for such processes for a neutrino of given energy may be estimated from the lifetime t of β -radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

$$\sigma = A/t$$

where A has the dimension cm.^2 sec. The longest length and time which can possibly be involved are \hbar/mc and \hbar/mc^2 . Therefore

$$\sigma < \frac{\hbar^3}{m^3 c^4 t}$$

For an energy of 2.3×10^6 volts, t is 3 minutes and therefore $\sigma < 10^{-44} \text{ cm.}^2$ (corresponding to a penetrating power of 10^{16} km. in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

With increasing energy, σ increases (in Fermi's model³ for large energies as $(E/mc^2)^2$) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.

If the neutrino contains no interaction with



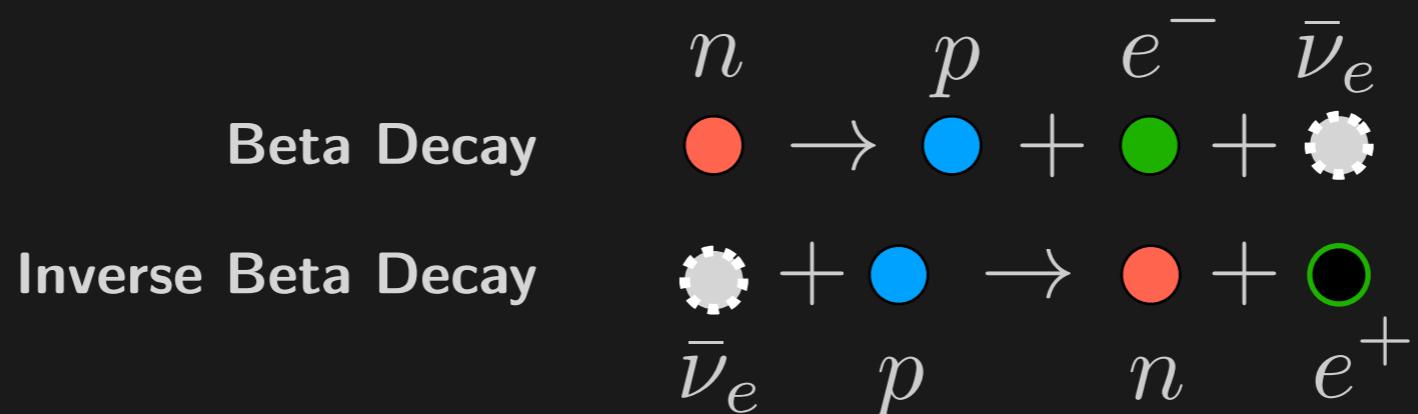
Sir Rudolf Peierls

1934: Fermi's Theory

Hans Bethe & Rudolf Peierls
calculate the neutrino cross section



Hans Bethe



532 © Nature Publishing NATURE APRIL 7, 1934

The following comparison of the structure given by Badami and by me for the line $\lambda 5639\cdot7$ (6s 3P_2 — 6p 3S_1) cathode patterns

Badami	0 (6)
Tolansky	0 (10) 71 (8)

It is seen that would arise from to excessive line Full details wi elsewhere shortly.

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¹ J. S. Badami, *Z. Phys.*, **79**, 206; 1932.

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The "Neutrino"

THE view has recently been put forward that there exists a neutral particle of about electronic mass $\frac{1}{2}h$ (where $h = h/2\pi$) exists, and that this is emitted together with an electron in β -decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics¹. Both the emitted electron and neutrino could be described either (a) as being emitted together with an electron in β -decay, or (b) as being emitted together with an electron in β -decay. Recent disintegration experiments² conclude that there is no practically possible way of observing the neutrino. According to Fermi's theory, even if one accepts (b), the roles of neutron and proton would be symmetrical³ and one would expect that positive electrons could also sometimes

For an energy of $2\cdot3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.² (corresponding to a penetrating power of 10^{16} km. in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

—one can observe the process if one accepts (a). Fermi's theory, however, is based on the assumption that the neutrino is highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.



Sir Rudolf Peierls

1934: Fermi's Theory

Hans Bethe & Rudolf Peierls
calculate the neutrino cross section



Hans Bethe



Claim: A neutrino will go through 1000 light years of matter!

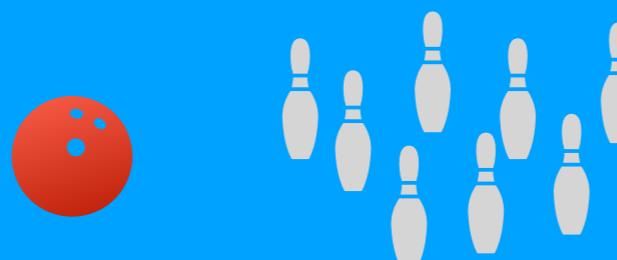
But...



Rudolf Peierls

event rate \sim number of neutrinos \times probability of interaction

$$R \text{ [1/s]} = N_{\text{targets}} \times \Phi \text{ [cm}^{-2}/\text{s}] \times \sigma \text{ [cm}^2] \times \epsilon$$



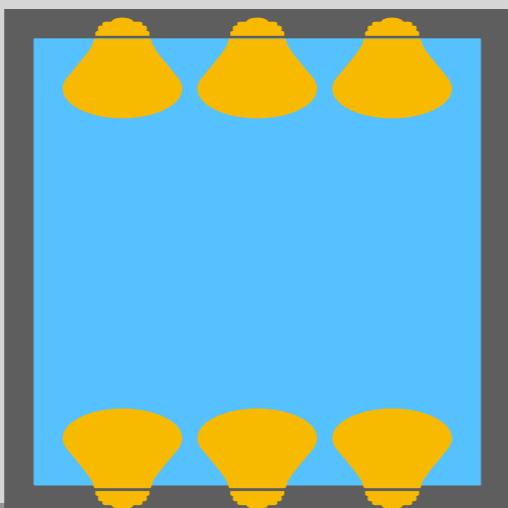
According to Fermi's theory, the cross section of a neutrino interaction is as highly as being built up of a proton, an electron and a neutrino, while if one accepts (b), the roles of neutron and proton would be symmetrical⁴ and one would expect that positive electrons could also sometimes

as highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.

If the first claim is true, interaction with

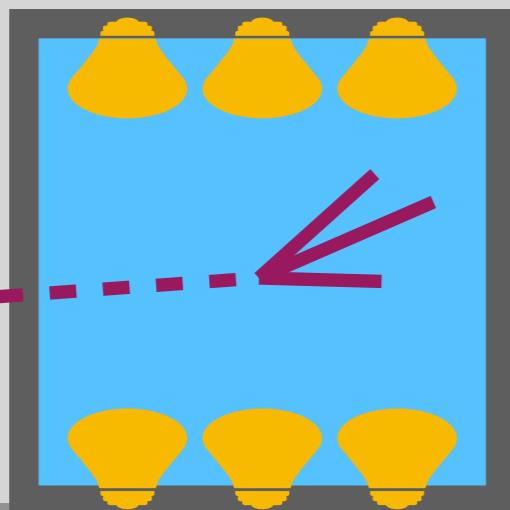
Neutrino Department

**Elementary
Particle Detector**



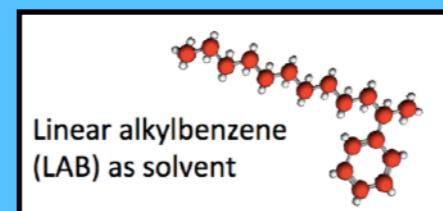
Neutrino Department

Elementary Particle Detector



Scintillator

Produces light when charged particles go through

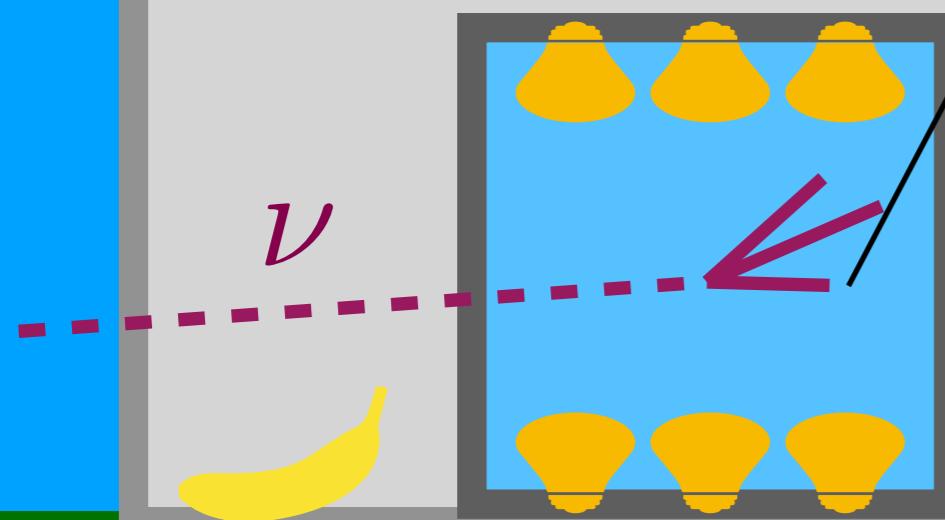


uni-mainz.de



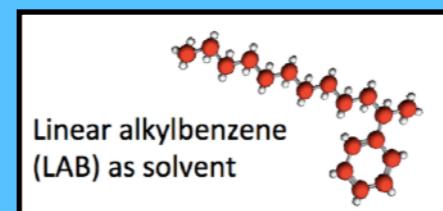
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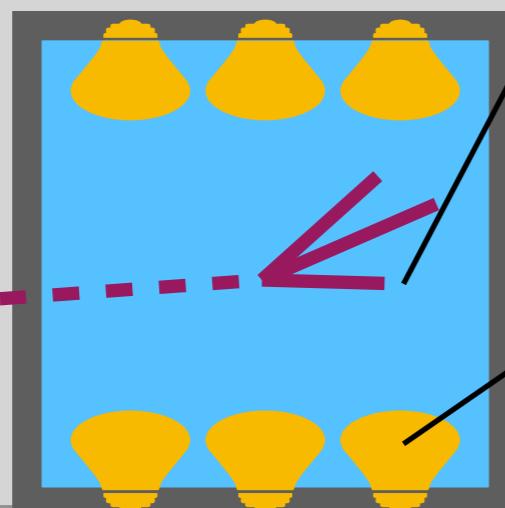


uni-mainz.de



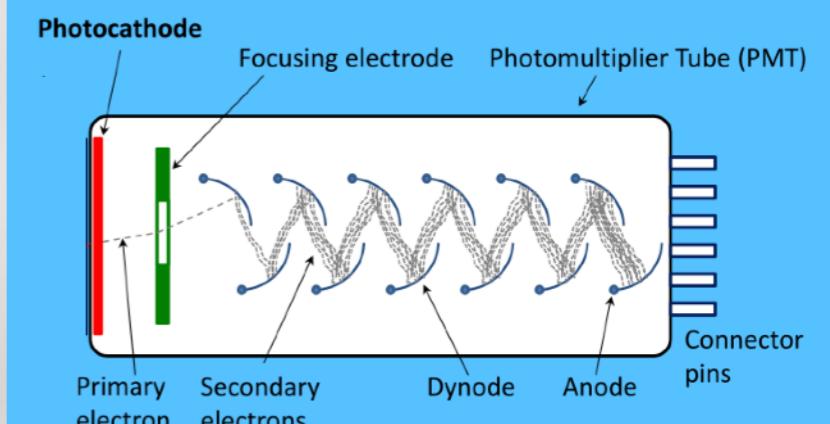
Neutrino Department

Elementary Particle Detector



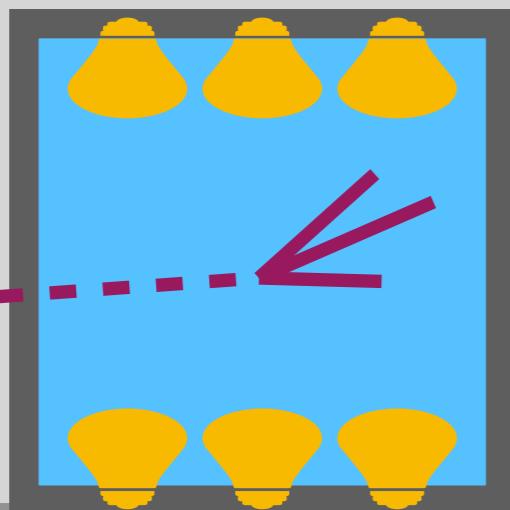
Photomultiplier Tube

An ultra-sensitive light detector



Neutrino Department

Elementary Particle Detector

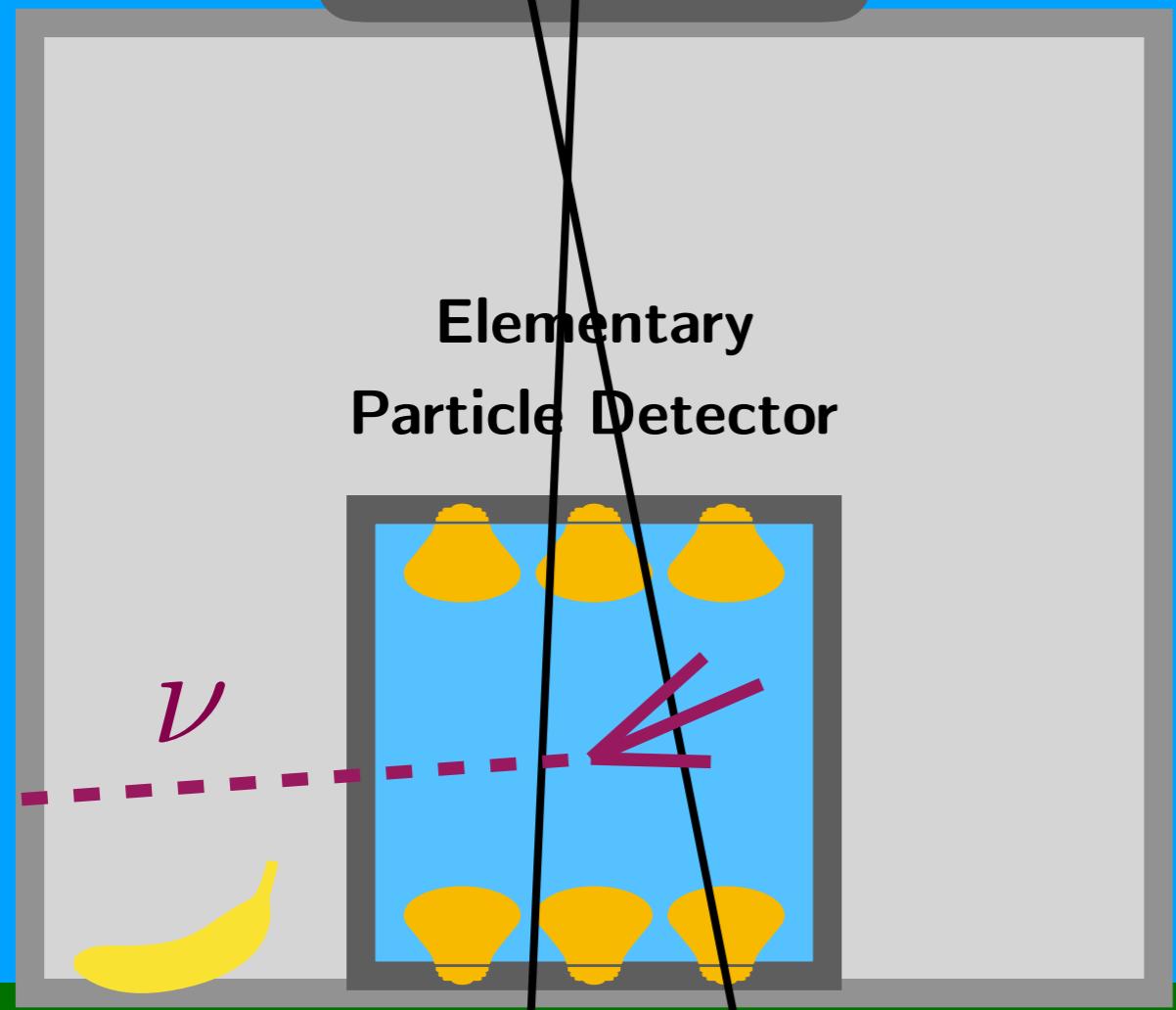


Cosmic
Rays

Neutrino Department

**Elementary
Particle Detector**

ν

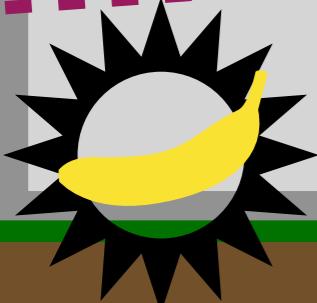


Cosmic
Rays

Neutrino Department

**Elementary
Particle Detector**

ν

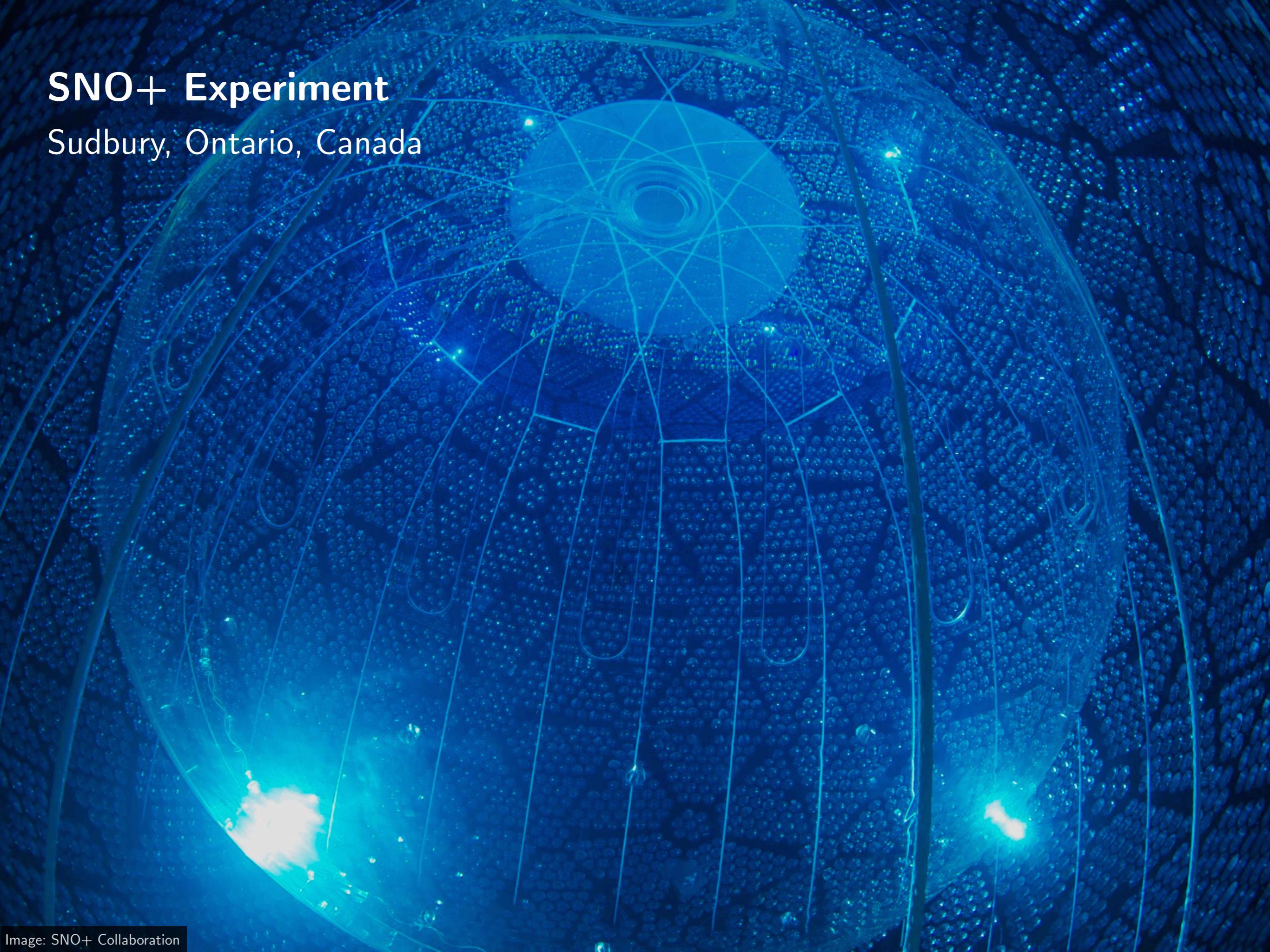


Natural
Radioactivity



SNO+ Experiment

Sudbury, Ontario, Canada



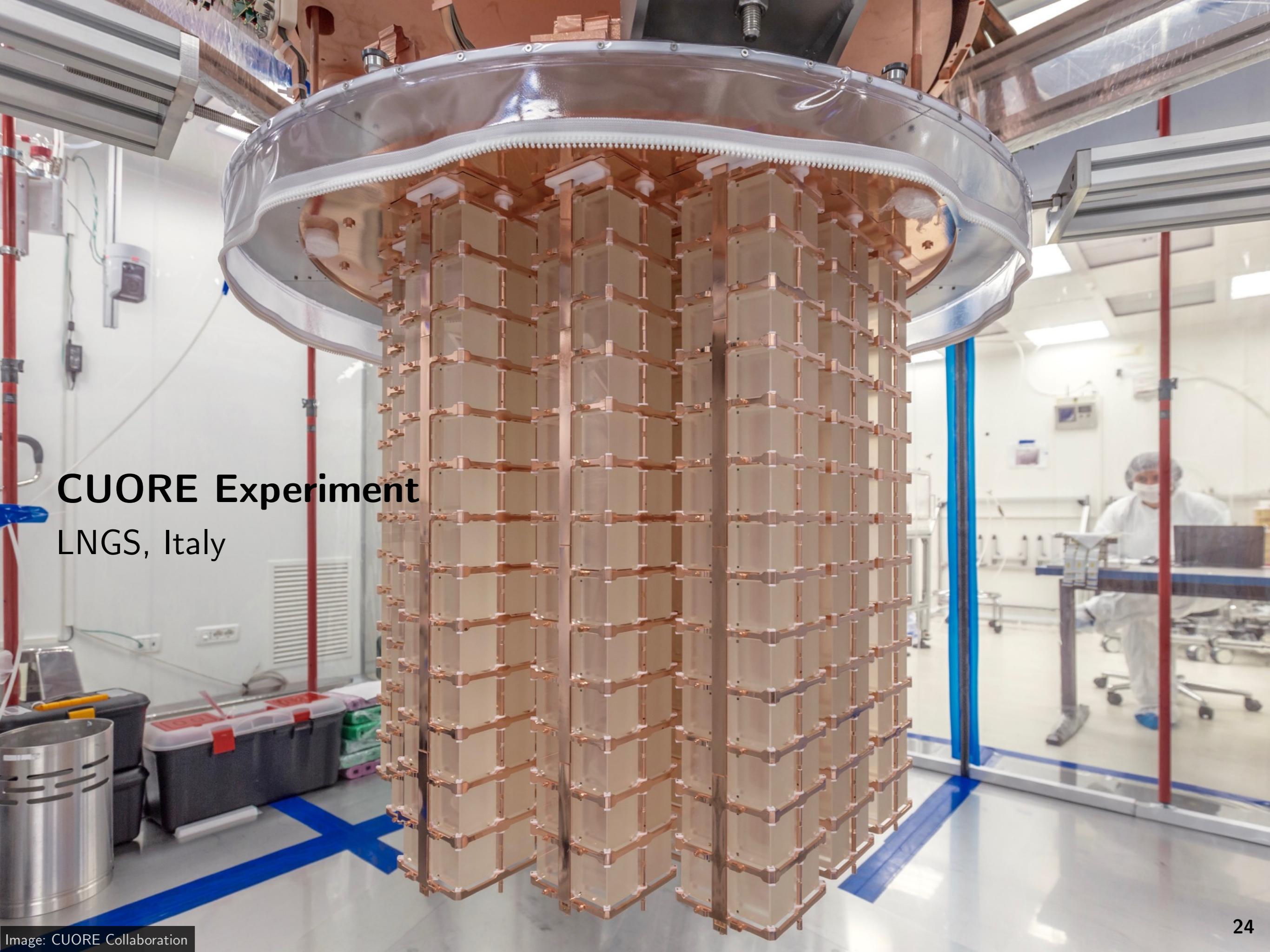


Deep Underground Neutrino Experiment, Prototype Detector

CERN, Switzerland

CUORE Experiment

LNGS, Italy





"Herr Auge"
Los Alamos, NM, 1953

Liquid Scintillator

Photomultiplier Tubes

Hunting the Neutrino

Plan A: Project Poltergeist



Hanford Team 1953

Los Alamos Science 25 (1997)

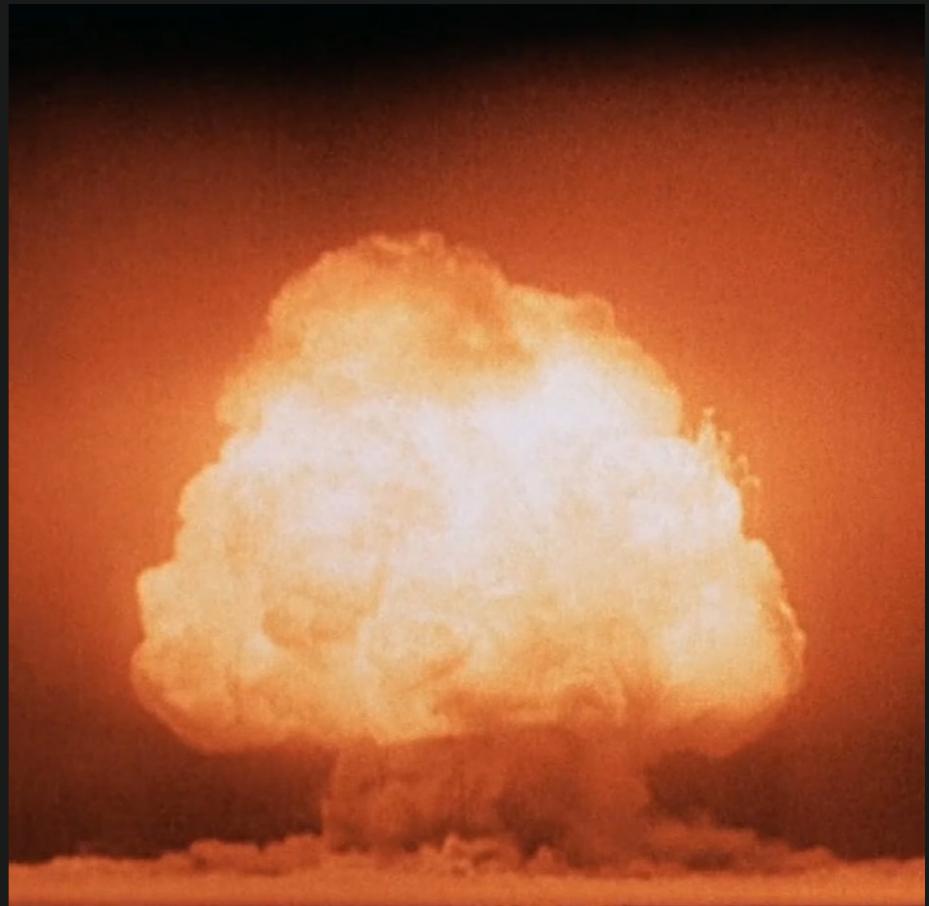
Hunting the Neutrino

Plan A: Project Poltergeist



Hanford Team 1953

Los Alamos Science 25 (1997)



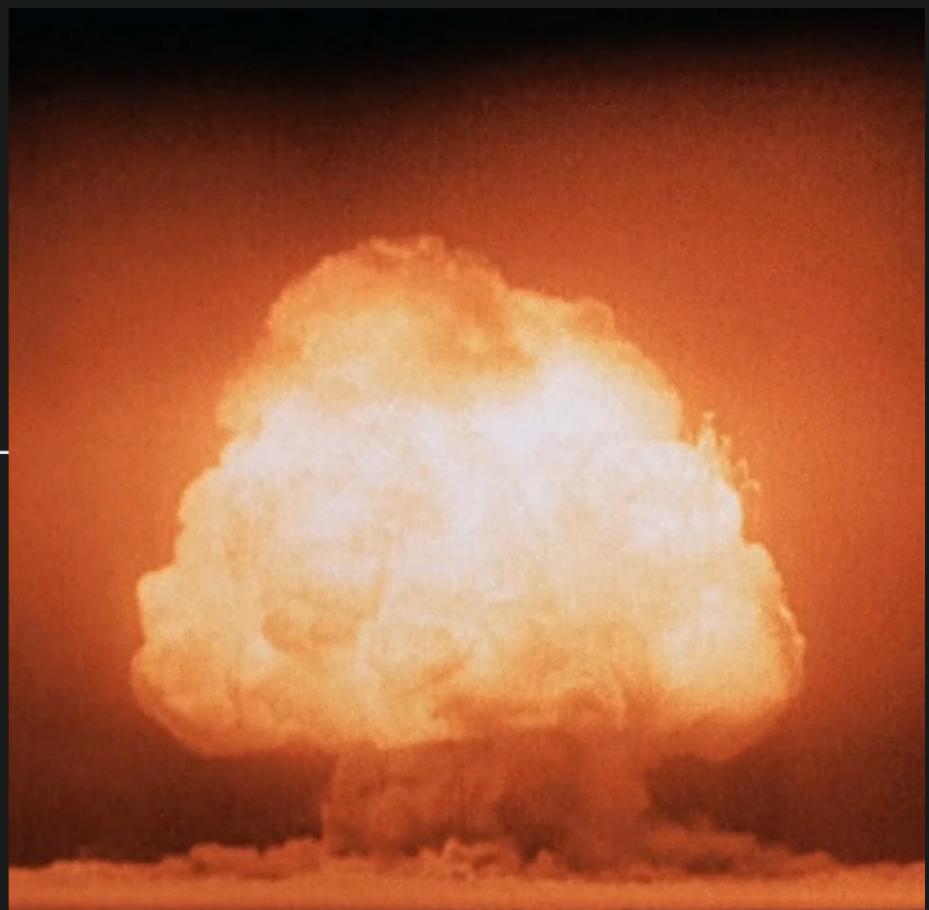
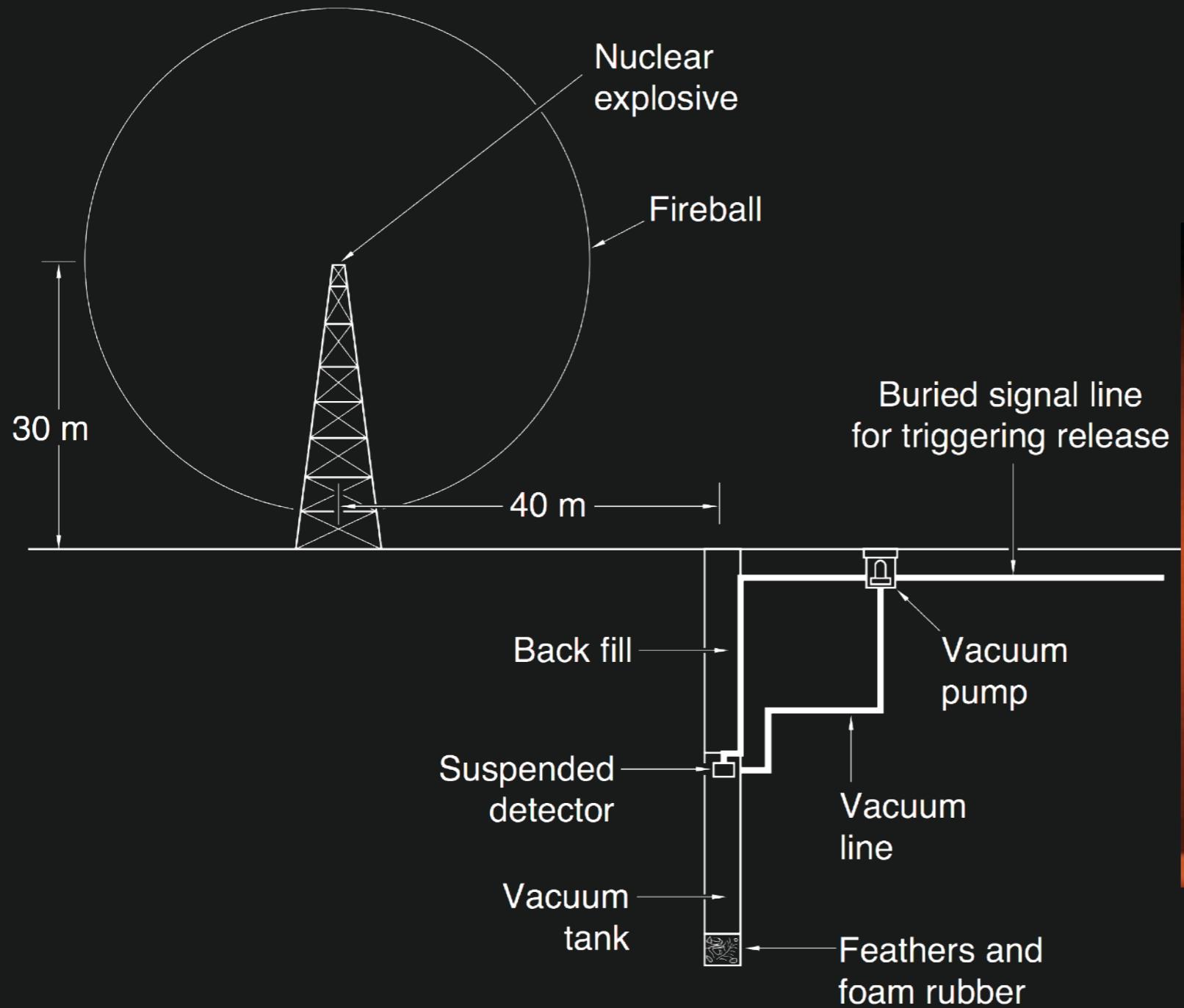
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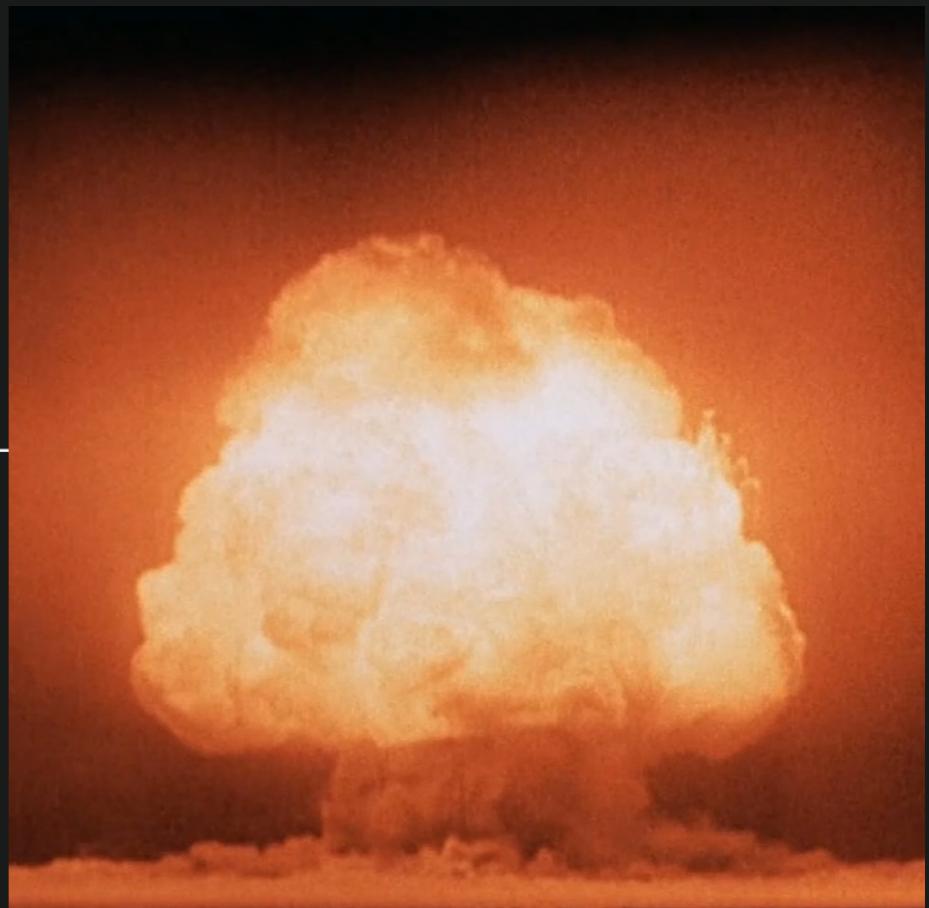
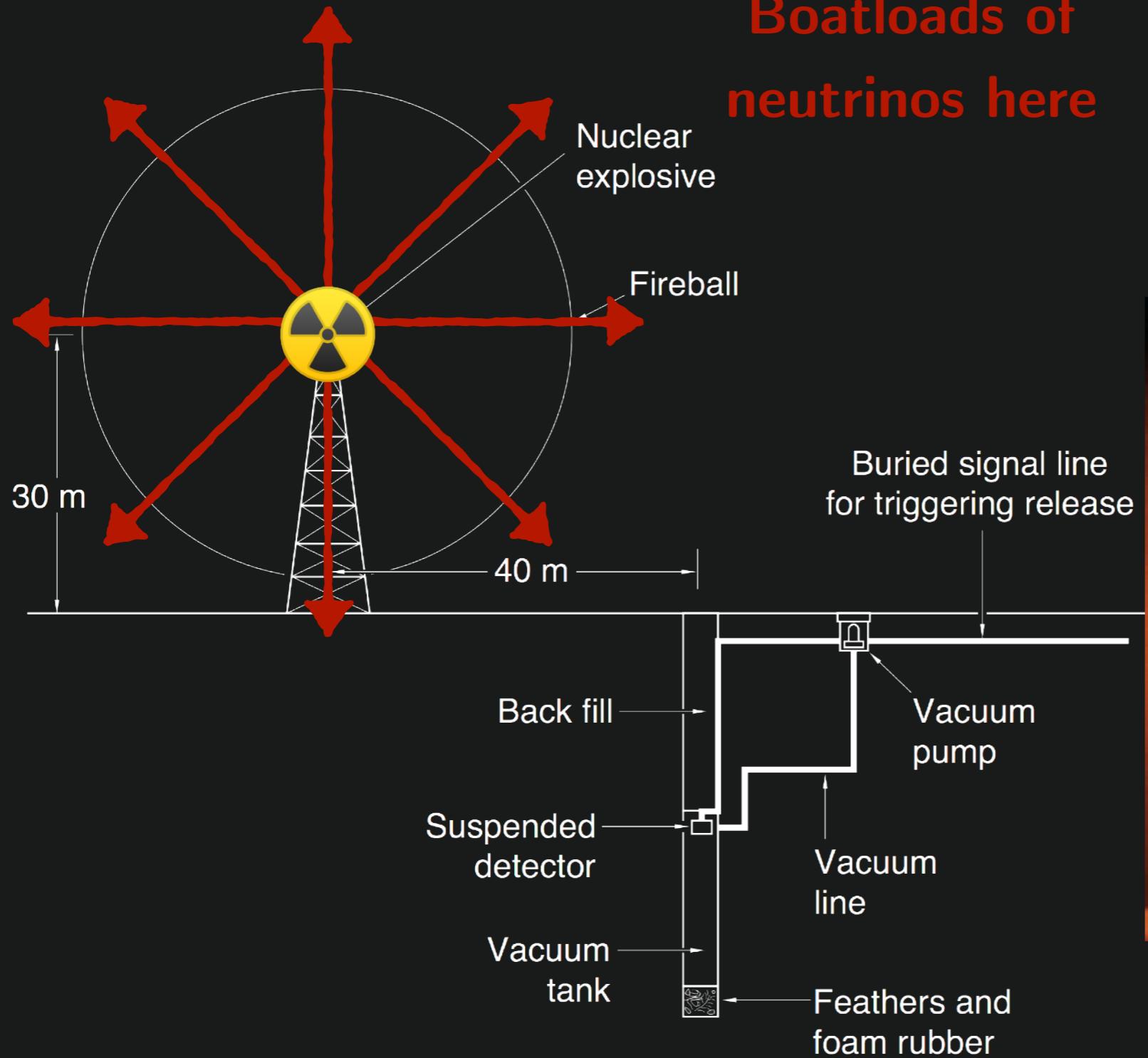
Hunting the Neutrino

Plan A: Project Poltergeist



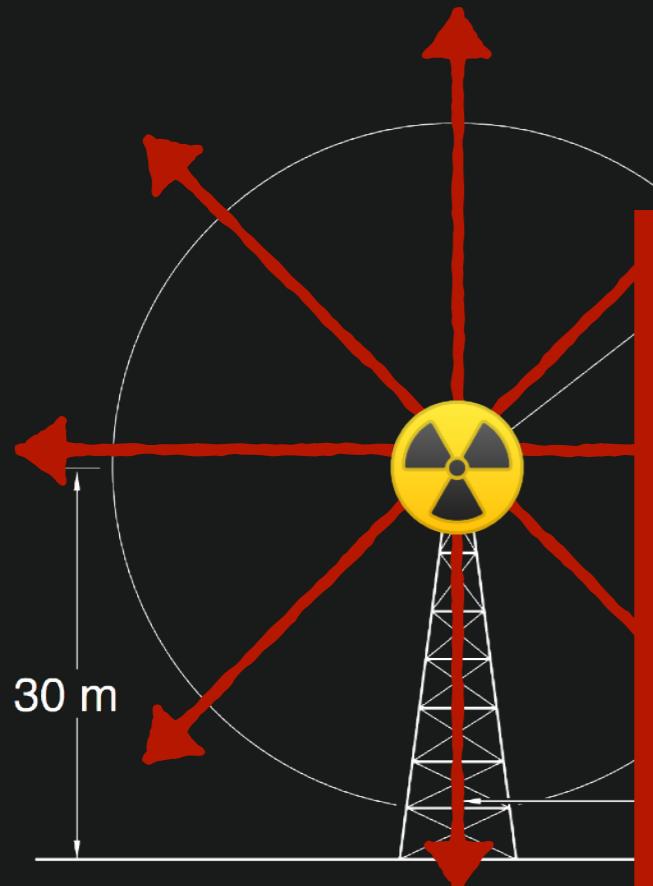
Hanford Team 1953

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Hunting the Neutrino

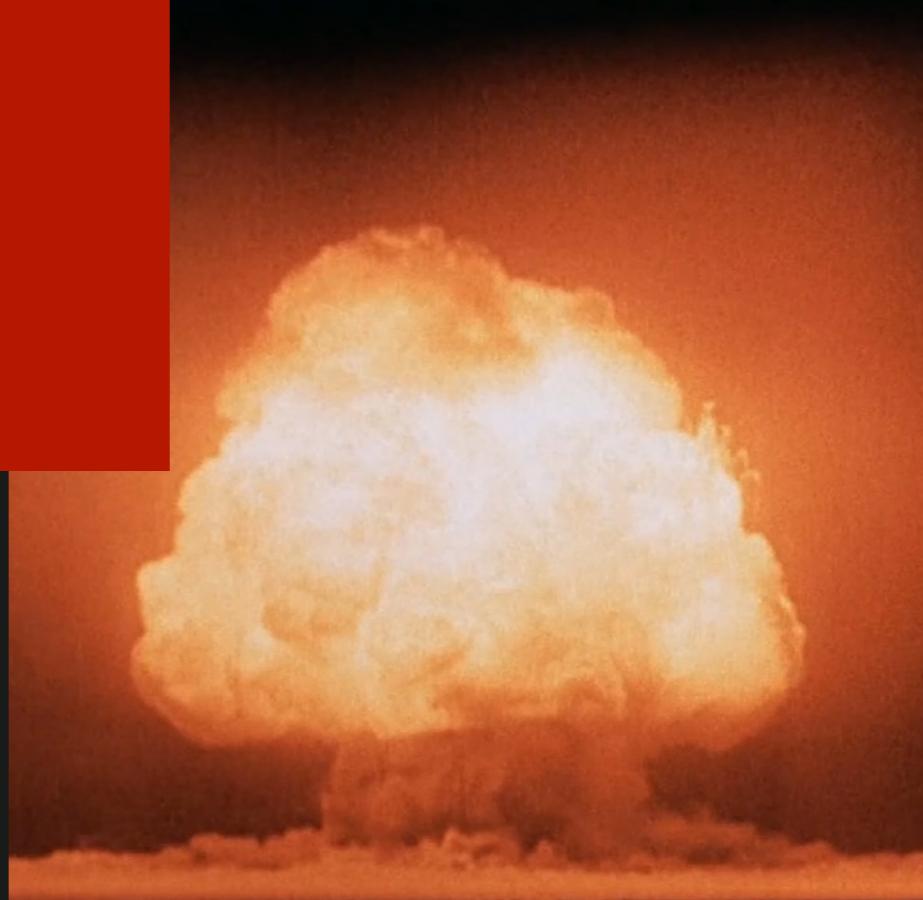
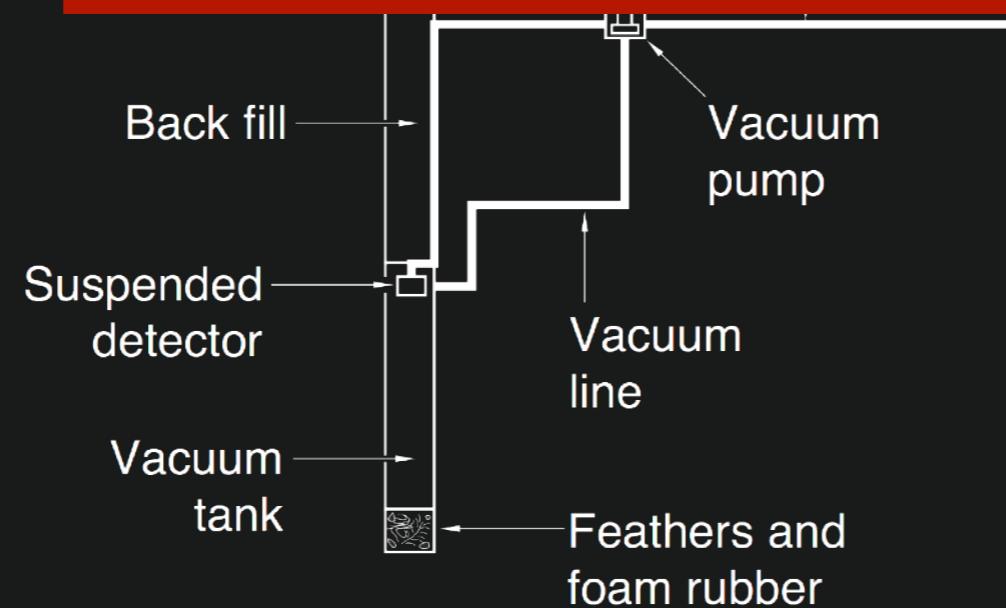
Plan A: Project Poltergeist



Boatloads of
neutrinos here

Nope.

An "interesting" idea, but....
there's a better way.



Nuclear Reactors

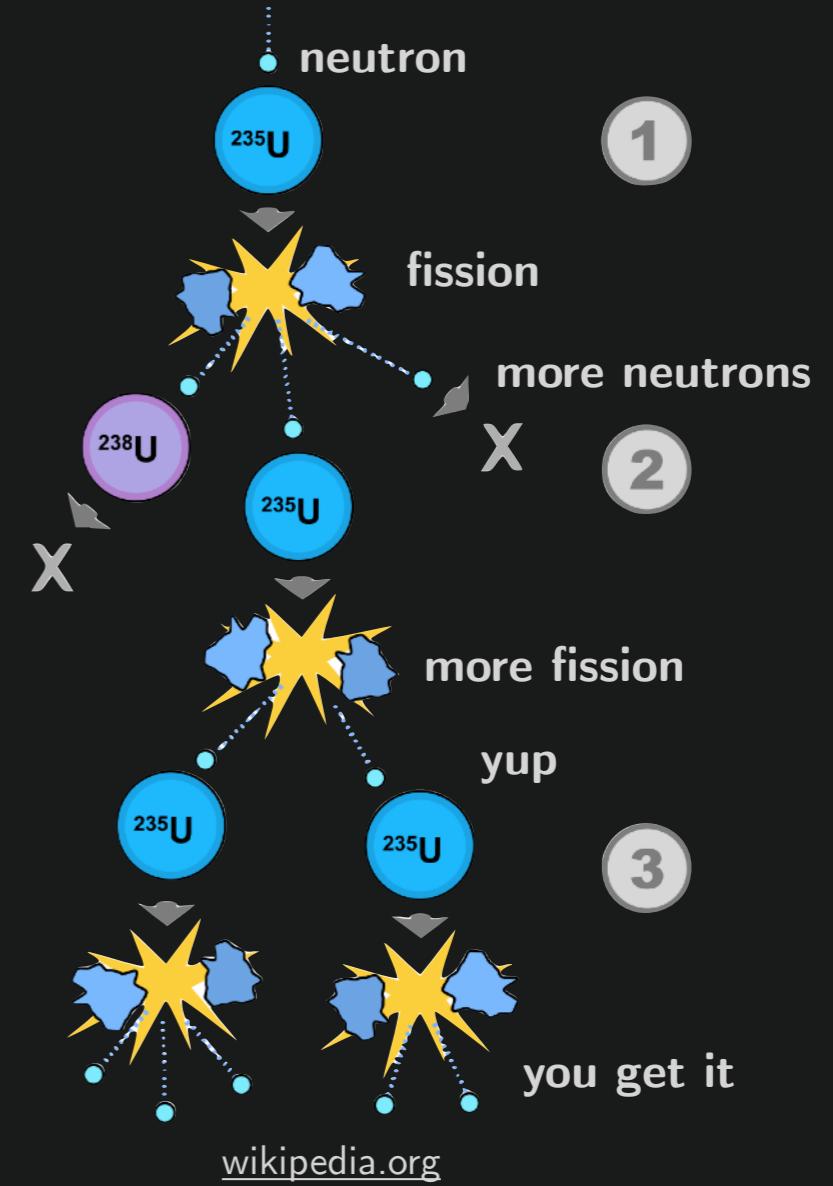
A Bit of UChicago History!



Lise Meitner & Otto Hahn
Laboratory R&D, c. 1938



CP1 Cake, UChicago EFI, 2017



Enrico Fermi Nuclear Plant
Commercial Use, 1958 - present



Photo from 2011

CC BY 2.0, DOE SRS



Savannah River Site, SC
US Department of Energy
July 1956

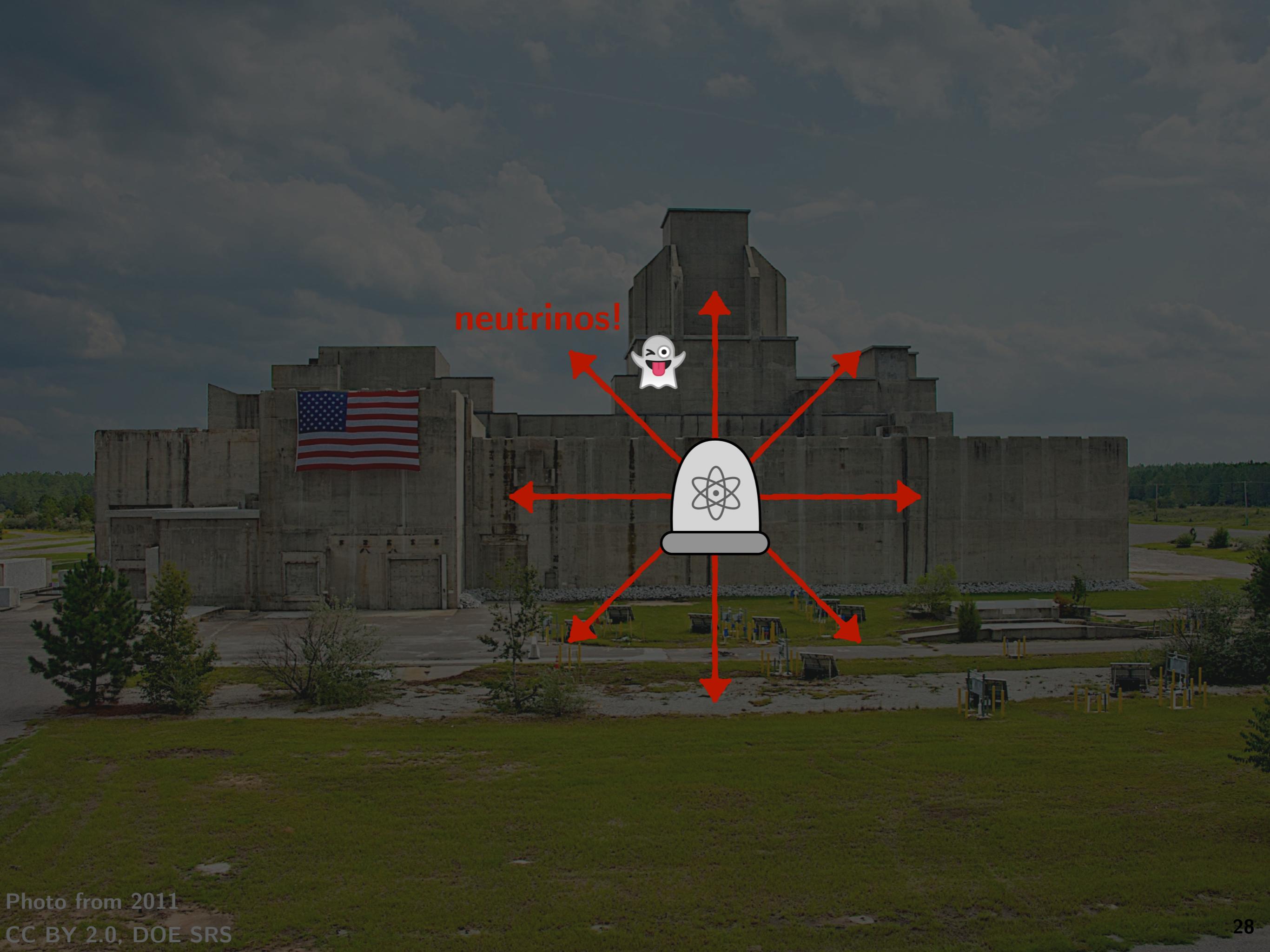


Photo from 2011

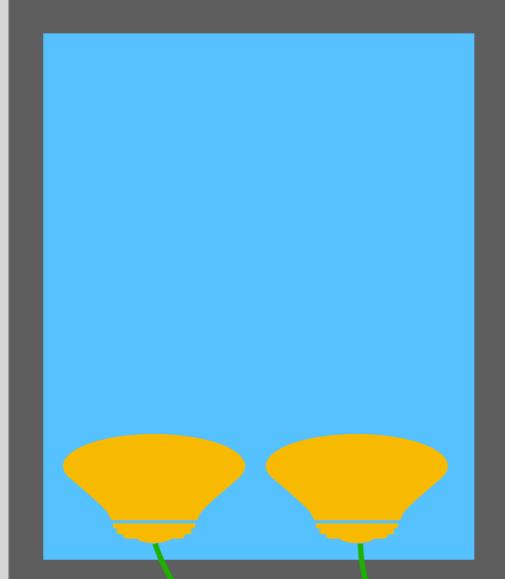
CC BY 2.0, DOE SRS

Fred Reines &
Clyde Cowan

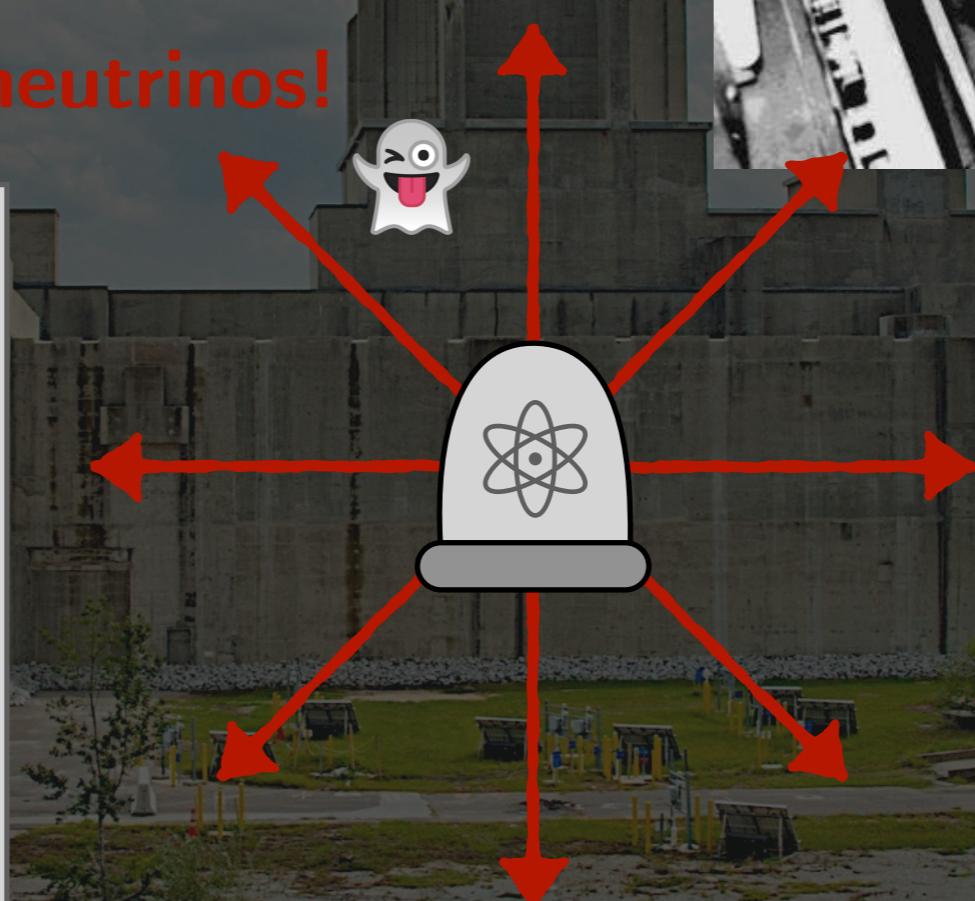


Dept. of Physics, UC Irvine

Neutrino detector



neutrinos!

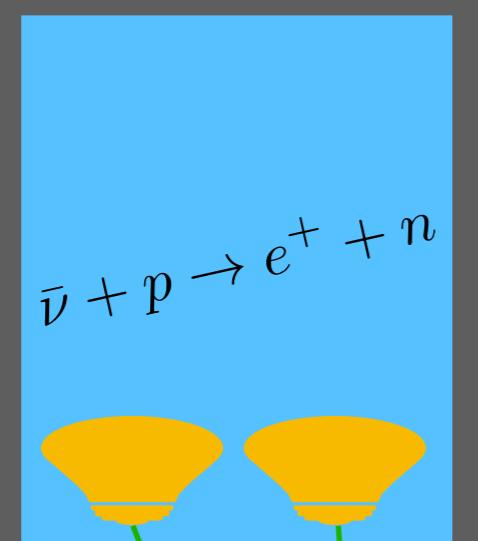


Fred Reines &
Clyde Cowan

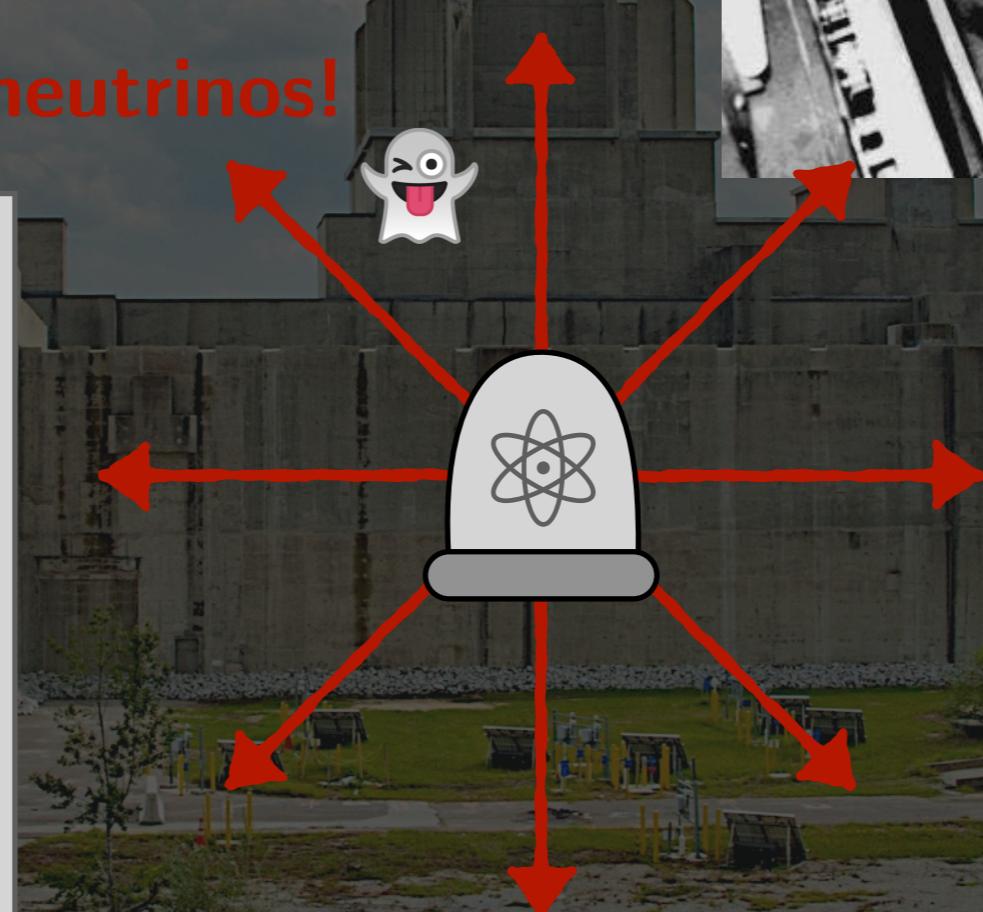


Dept. of Physics, UC Irvine

Neutrino detector



neutrinos!



OSCILLOSCOPE 3000

Neutrino Signature

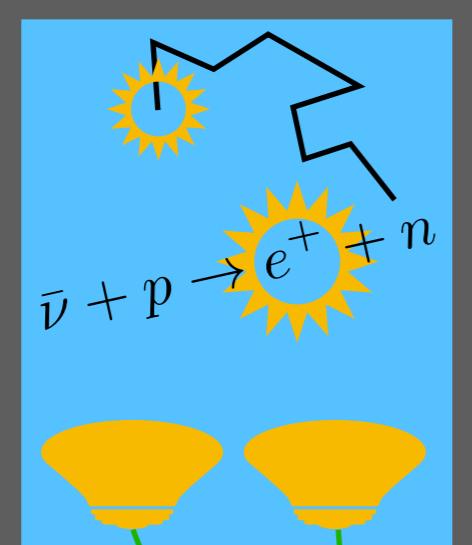
1. Flash of light from positron
2. Neutron bounces around
3. Nucleus captures neutron
4. Capturing nucleus emits gamma rays — second flash!

Fred Reines &
Clyde Cowan

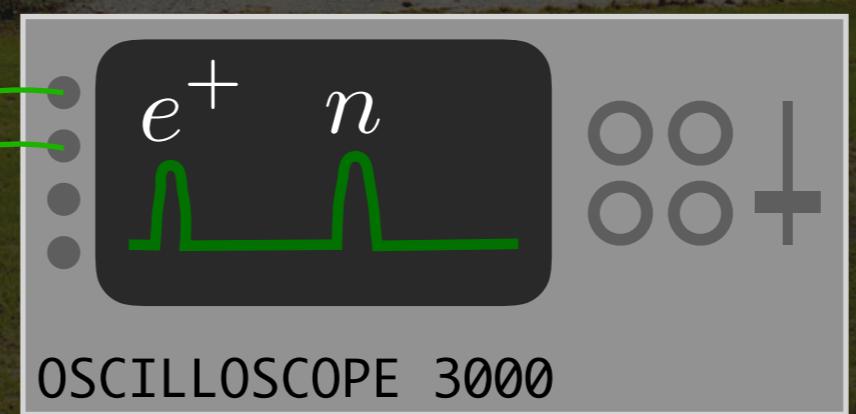
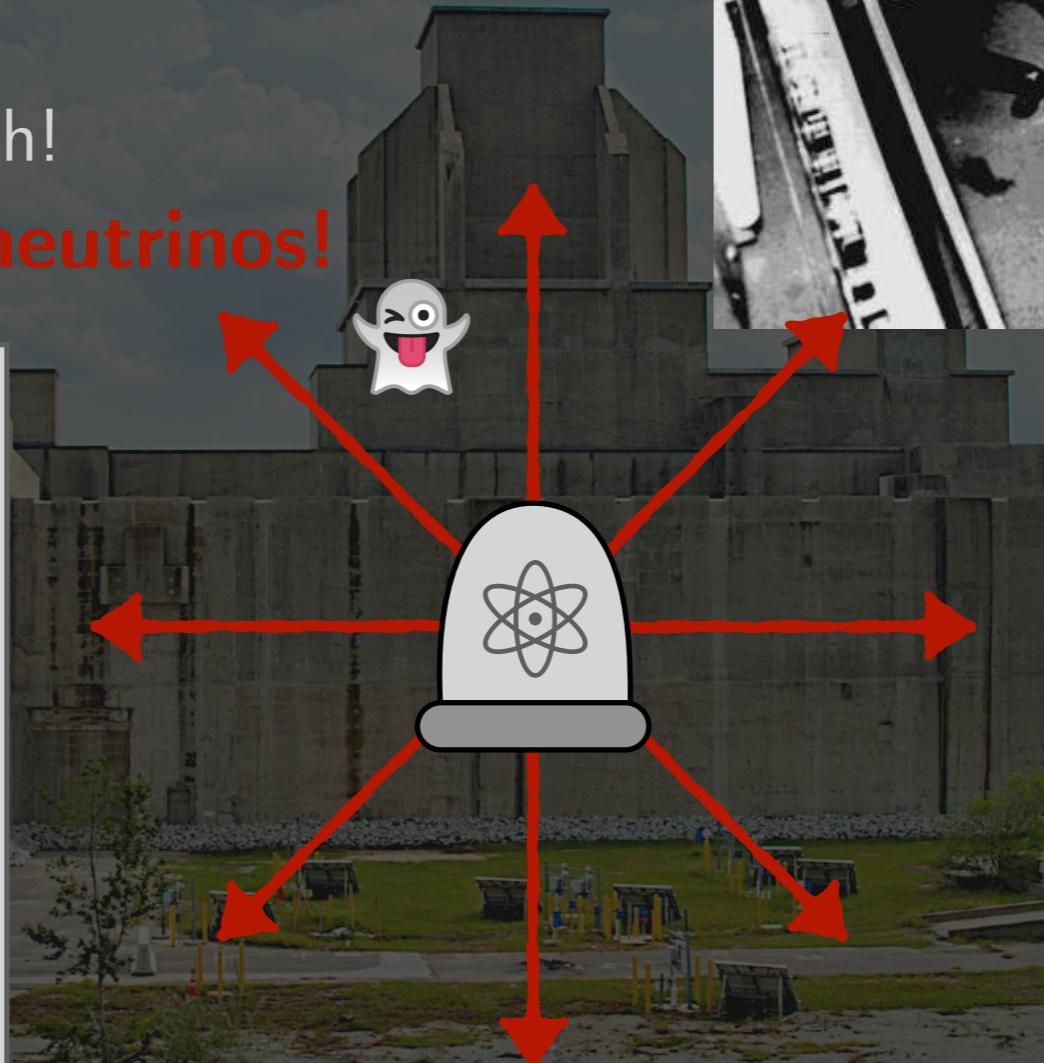


Dept. of Physics, UC Irvine

Neutrino detector



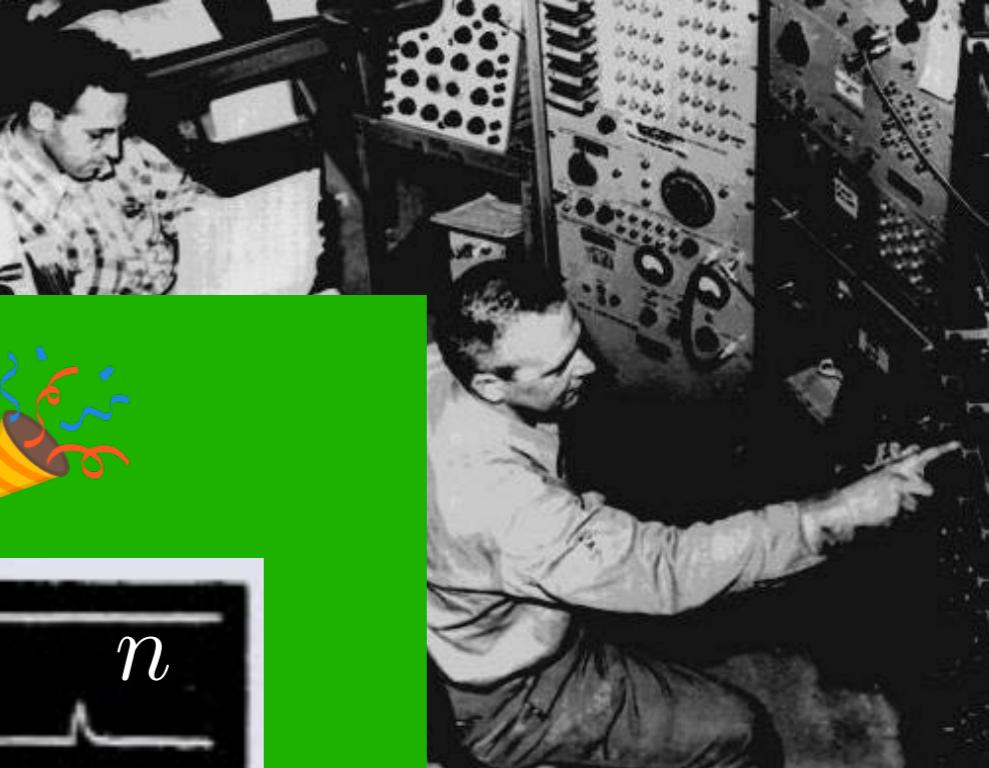
neutrinos!



Neutrino Signature

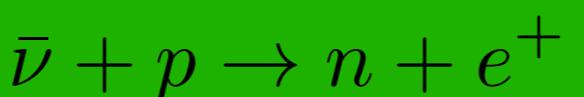
1. Flash of light from positron
2. Neutron bounces around
3. Nucleus captures neutron
4. Capturing neutron emits gamma rays

Fred Reines &
Clyde Cowan



Dept. of Physics, UC Irvine

SUCCESS!

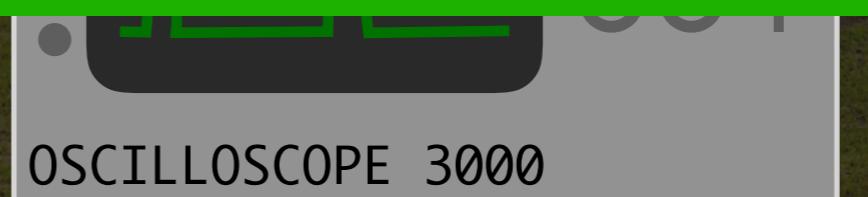


After 26 years, the "undetectable" neutrino is found!



1995 Nobel Prize in Physics

Frederick Reines, *"for the detection of the neutrino"*
(Clyde Cowan passed away in 1974)



OSCILLOSCOPE 3000

v

II. The Plot Thickens

The Plot Thickens Putting the $^-$ in $\bar{\nu}_e$: Antineutrinos

Beta Decay

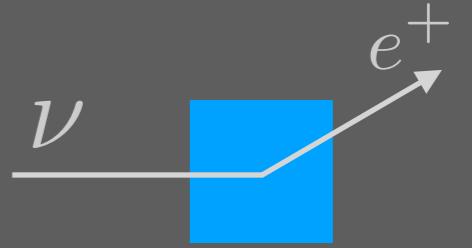


The Plot Thickens Putting the $^-$ in $\bar{\nu}_e$: Antineutrinos

Beta Decay $n \rightarrow p + e^- + \nu$



Inverse Beta Decay $\nu + p \rightarrow n + e^+$
(Cowan & Reines, 1956)



The Plot Thickens Putting the $^-$ in $\bar{\nu}_e$: Antineutrinos

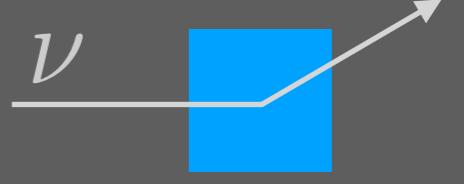
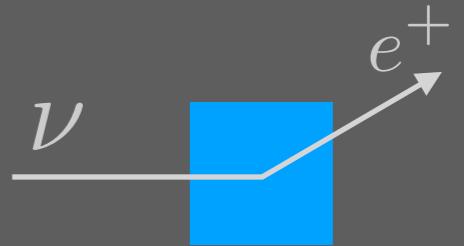
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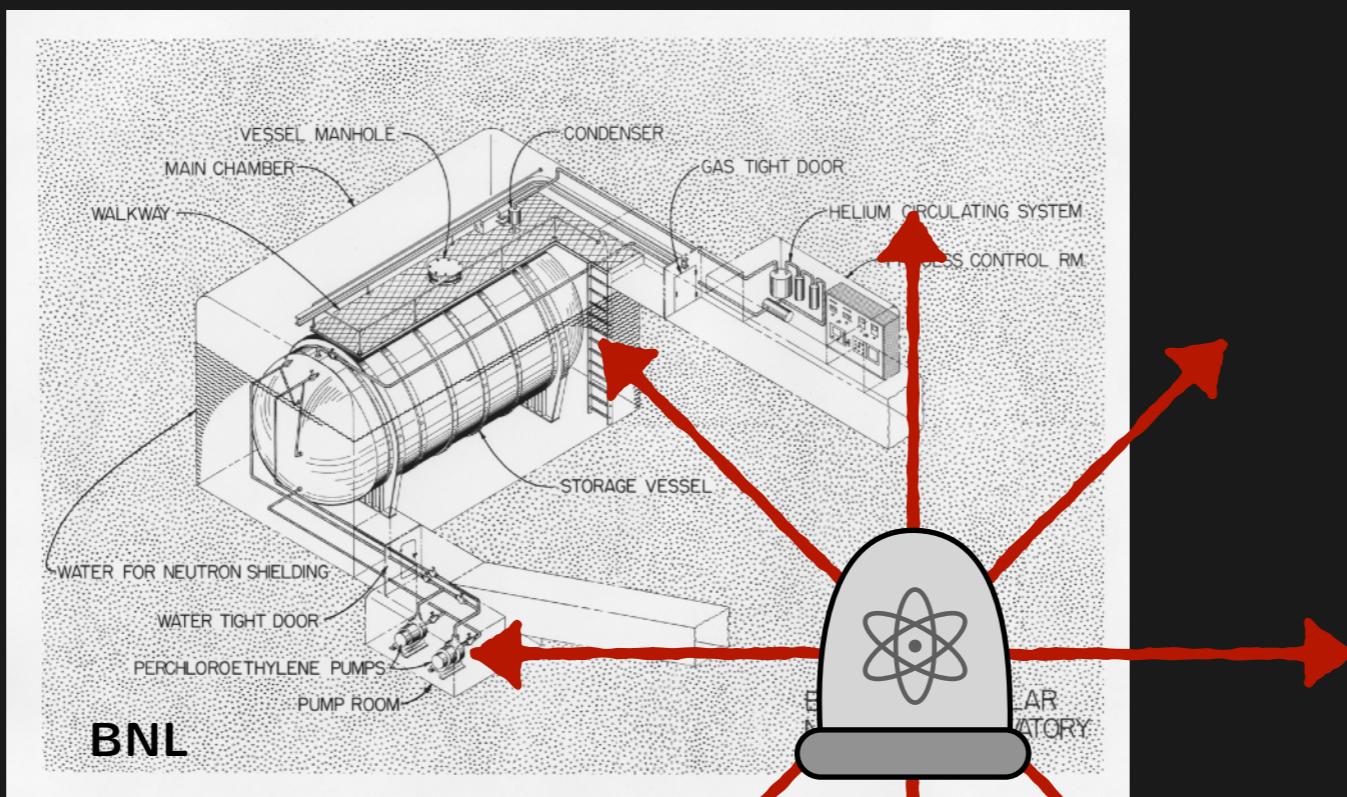
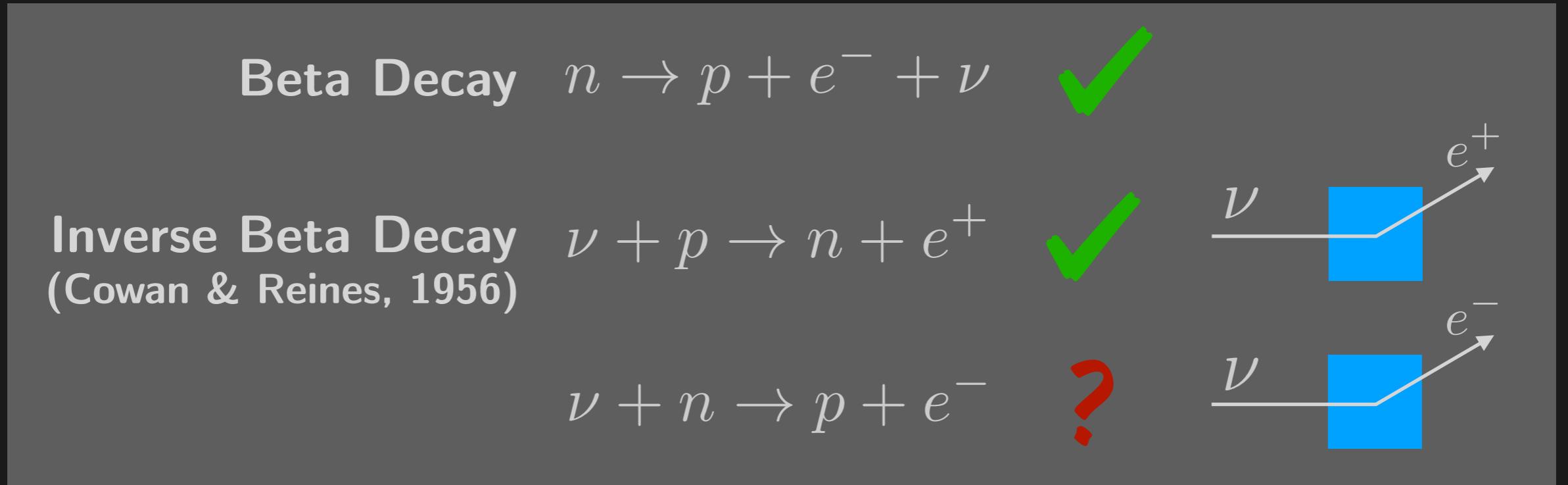
Inverse Beta Decay $\nu + p \rightarrow n + e^+$
(Cowan & Reines, 1956)



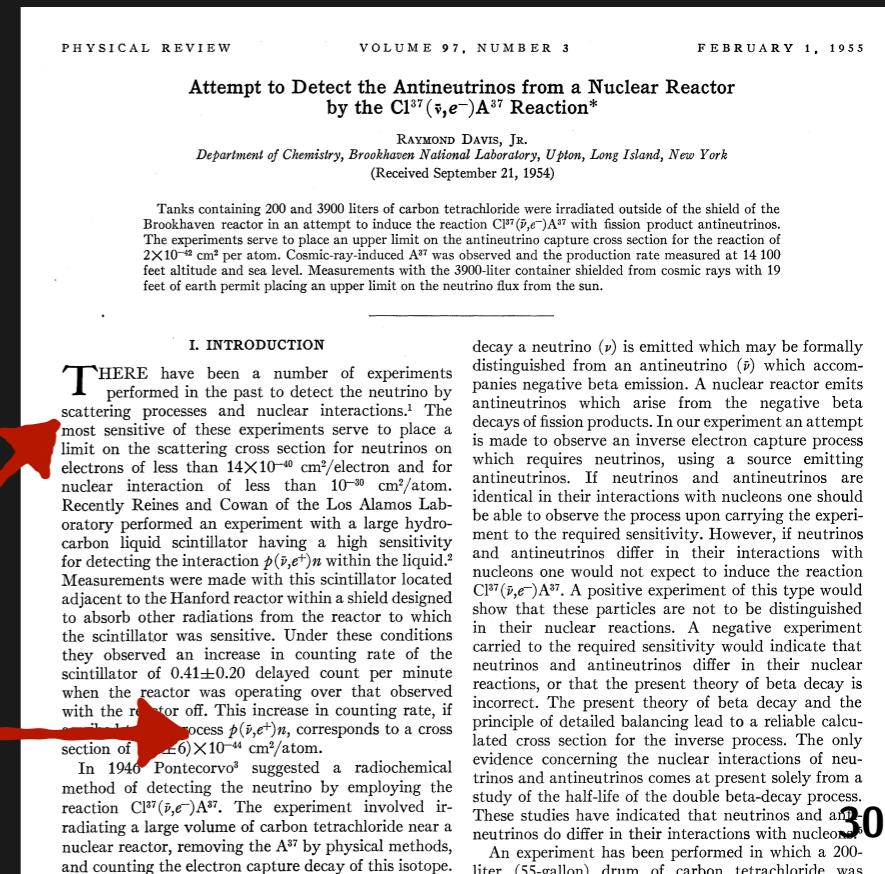
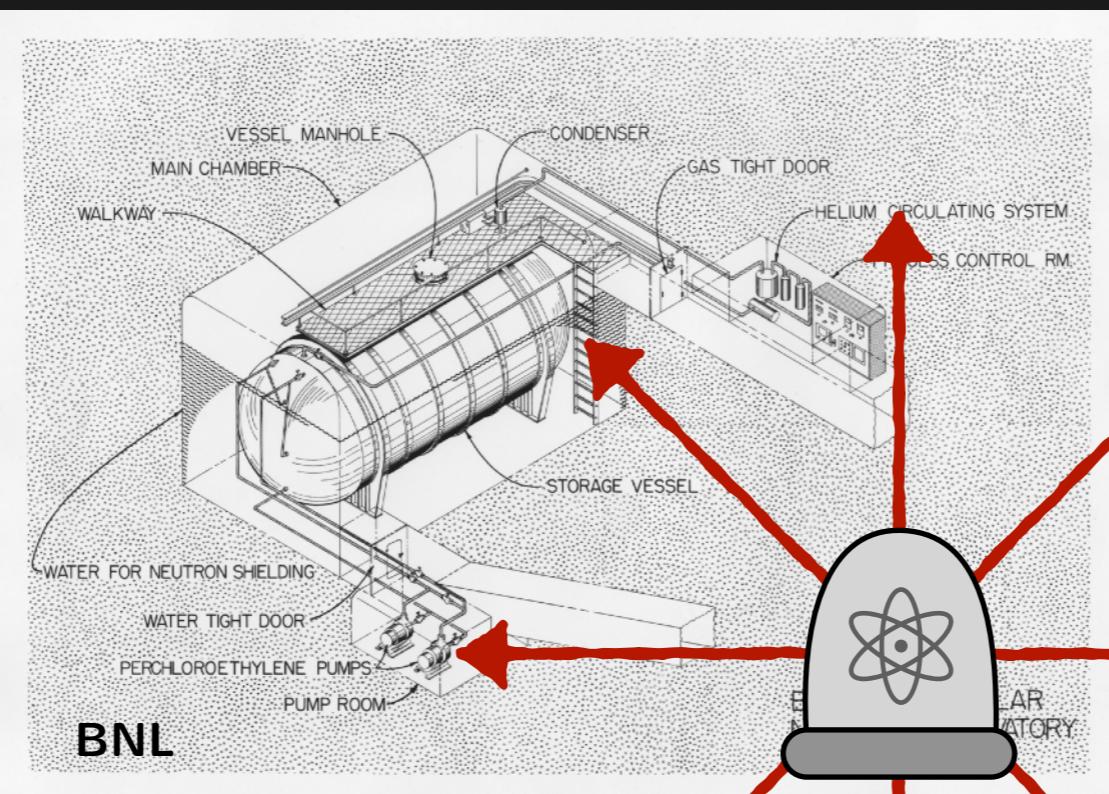
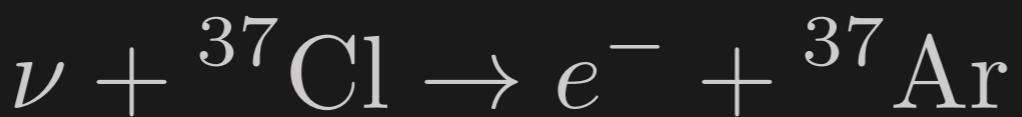
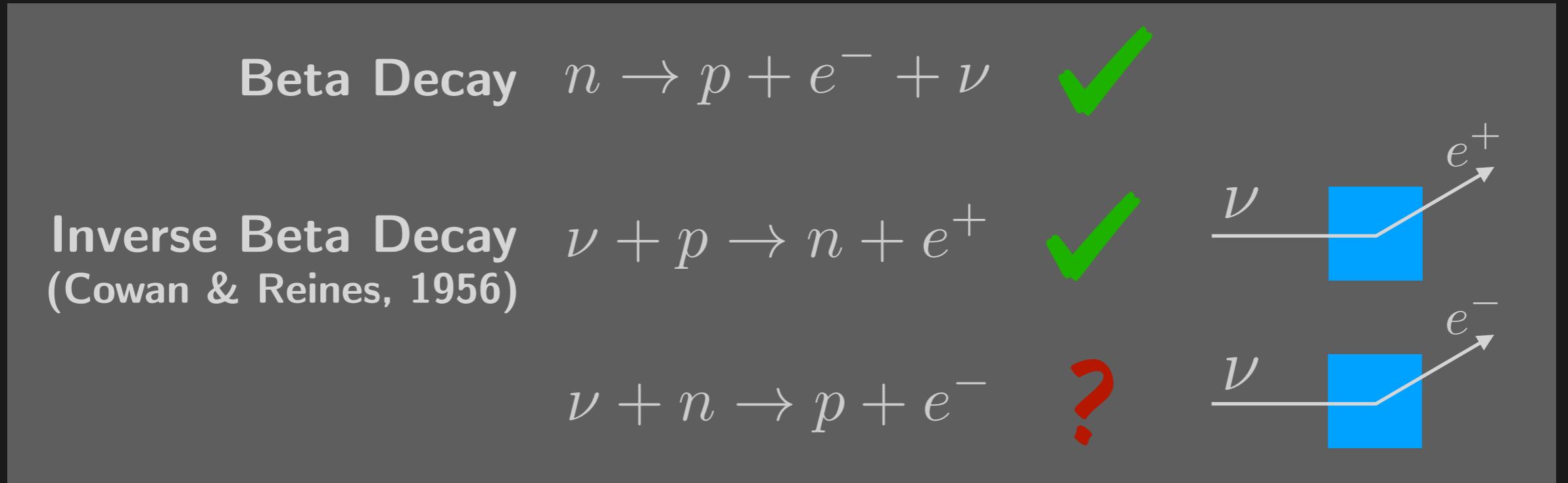
$\nu + n \rightarrow p + e^-$



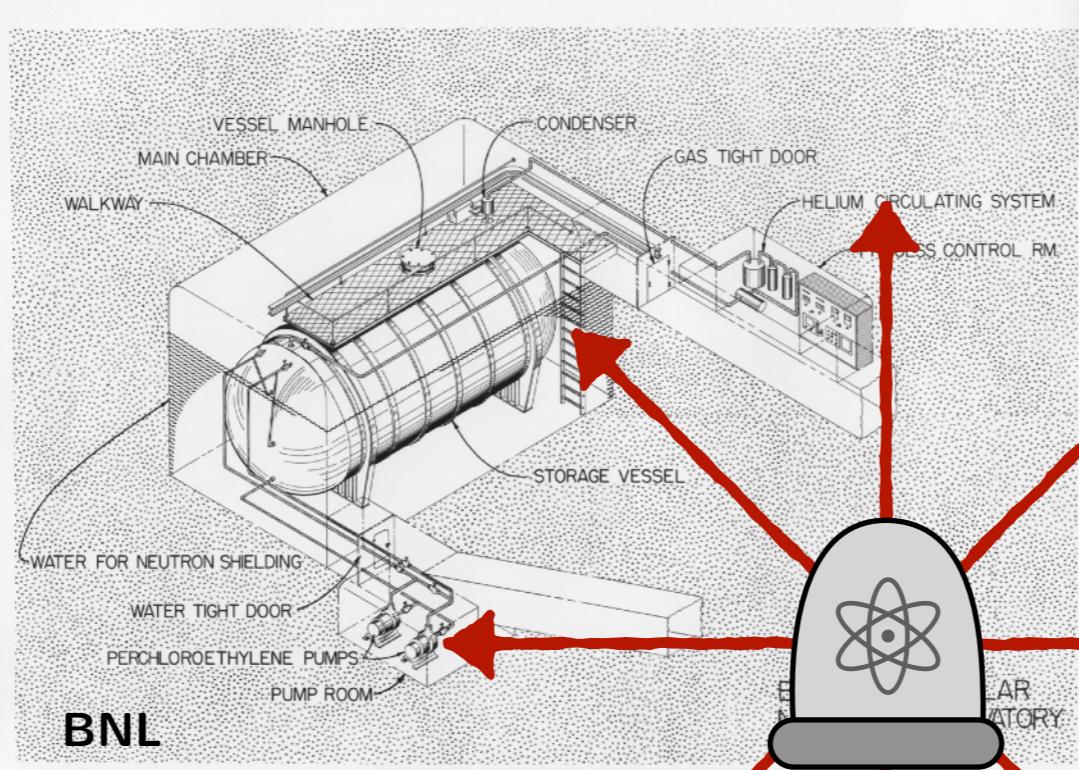
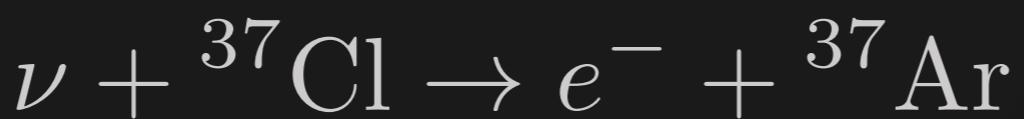
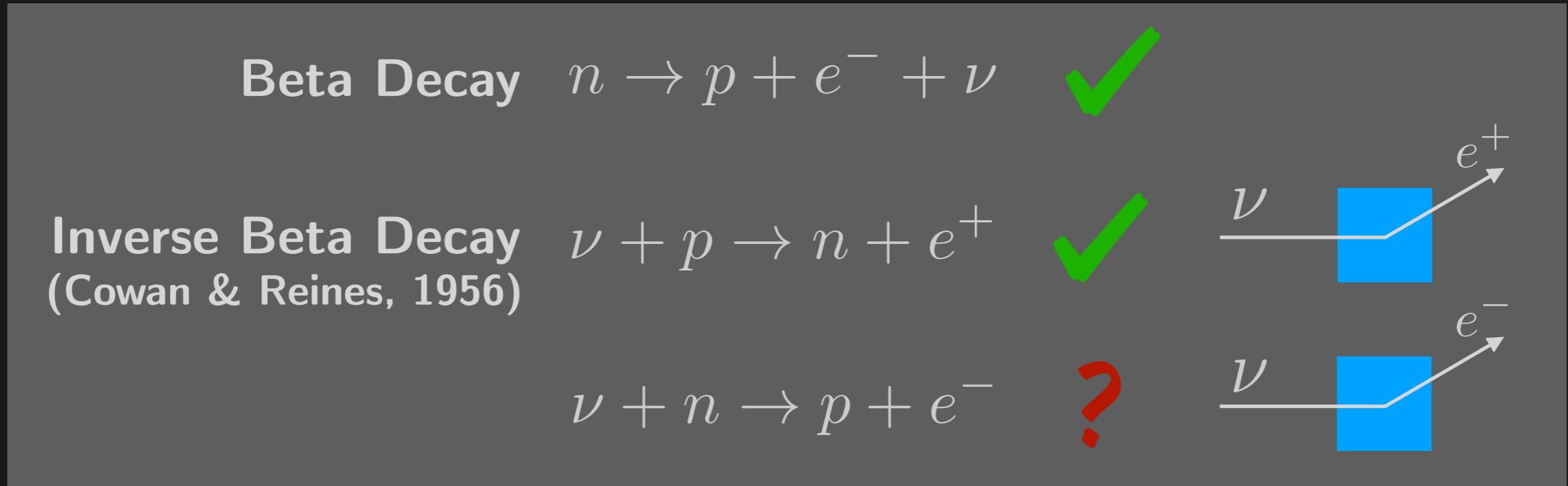
The Plot Thickens Putting the $^-$ in $\bar{\nu}_e$: Antineutrinos



The Plot Thickens Putting the $^-$ in $\bar{\nu}_e$: Antineutrinos



The Plot Thickens Putting the $^-$ in $\bar{\nu}_e$: Antineutrinos



Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $\text{Cl}^{37}(\bar{\nu}, e^-) \text{Ar}^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York
Tanks containing 200 and 3900 liters of carbon tetrachloride were irradiated outside of the shield of the Brookhaven reactor in an attempt to induce the reaction $\text{Cl}^{37}(\bar{\nu}, e^-) \text{Ar}^{37}$ with fission product antineutrinos. The experiments serve to place an upper limit on the antineutrino capture cross section for the reaction of $2 \times 10^{-42} \text{ cm}^2$ per atom. Cosmic-ray-induced Ar^{37} was observed and the production rate measured at 14 100 feet altitude and sea level. Measurements with the 3900-liter container shielded from cosmic rays with 19 feet of earth permit placing an upper limit on the neutrino flux from the sun.

I. INTRODUCTION

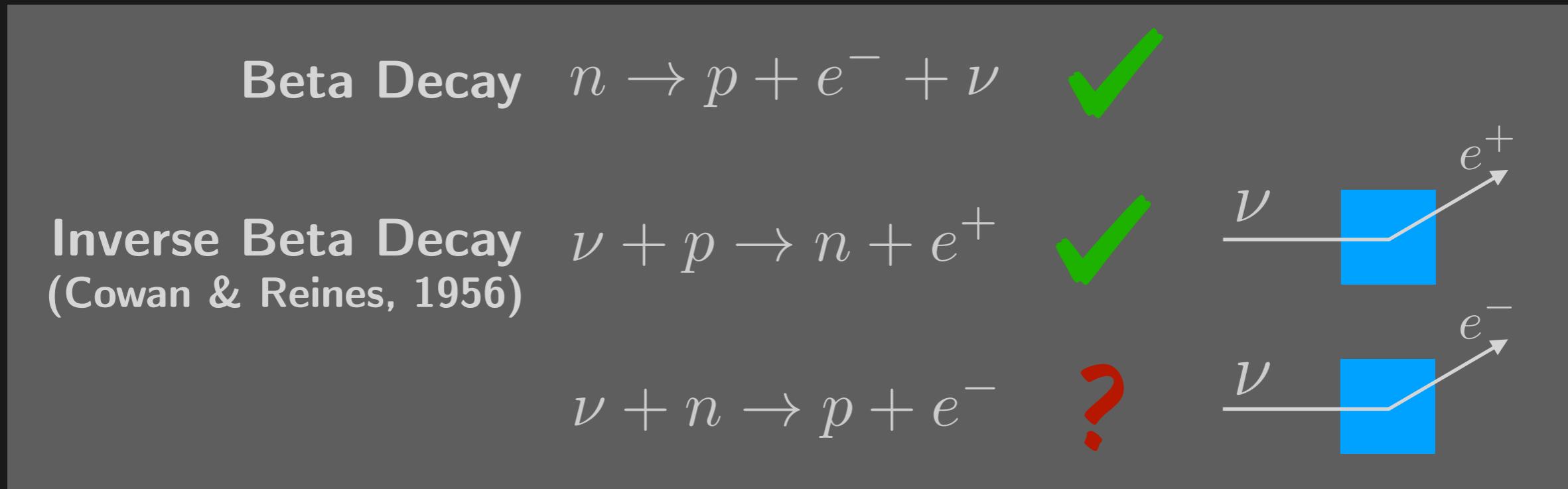
There have been a number of experiments performed in the past to detect the neutrino by scattering processes and nuclear interactions.¹ The most sensitive of these experiments serve to place a limit on the scattering cross section for neutrinos on electrons of less than $14 \times 10^{-40} \text{ cm}^2/\text{electron}$ and for nuclear interaction of less than $10^{-30} \text{ cm}^2/\text{atom}$. Recently Reines and Cowan of the Los Alamos Laboratory performed an experiment with a large hydrocarbon liquid scintillator having a high sensitivity for detecting the interaction $p(\bar{\nu}, e^-)n$ within the liquid.² Measurements were made with this scintillator located adjacent to the Hanford reactor within a shield designed to absorb other radiations from the reactor to which the scintillator was sensitive. Under these conditions they observed an increase in counting rate of the scintillator of 0.41 ± 0.20 delayed count per minute when the reactor was operating over that observed with the reactor off. This increase in counting rate, if due to the process $p(\bar{\nu}, e^+)n$, corresponds to a cross section of $(1.6 \pm 6) \times 10^{-44} \text{ cm}^2/\text{atom}$.

In 1946 Pontecorvo³ suggested a radiochemical method of detecting the neutrino by employing the reaction $\text{Cl}^{37}(\bar{\nu}, e^-) \text{Ar}^{37}$. The experiment involved irradiating a large volume of carbon tetrachloride near a nuclear reactor, removing the Ar^{37} by physical methods, and counting the electron capture decay of this isotope.

decay a neutrino (ν) is emitted which may be formally distinguished from an antineutrino ($\bar{\nu}$) which accompanies negative beta emission. A nuclear reactor emits antineutrinos which arise from the negative beta decays of fission products. In our experiment an attempt is made to observe an inverse electron capture process which requires neutrinos, using a source emitting antineutrinos. If neutrinos and antineutrinos are identical in their interactions with nucleons one should be able to observe the process upon carrying the experiment to the required sensitivity. However, if neutrinos and antineutrinos differ in their interactions with nucleons one would not expect to induce the reaction $\text{Cl}^{37}(\bar{\nu}, e^-) \text{Ar}^{37}$. A positive experiment of this type would show that these particles are not to be distinguished in their nuclear reactions. A negative experiment carried to the required sensitivity would indicate that neutrinos and antineutrinos differ in their nuclear reactions, or that the present theory of beta decay is incorrect. The present theory of beta decay and the principle of detailed balancing lead to a reliable calculated cross section for the inverse process. The only evidence concerning the nuclear interactions of neutrinos and antineutrinos comes at present solely from a study of the half-life of the double beta-decay process. These studies have indicated that neutrinos and antineutrinos do differ in their interactions with nucleons.

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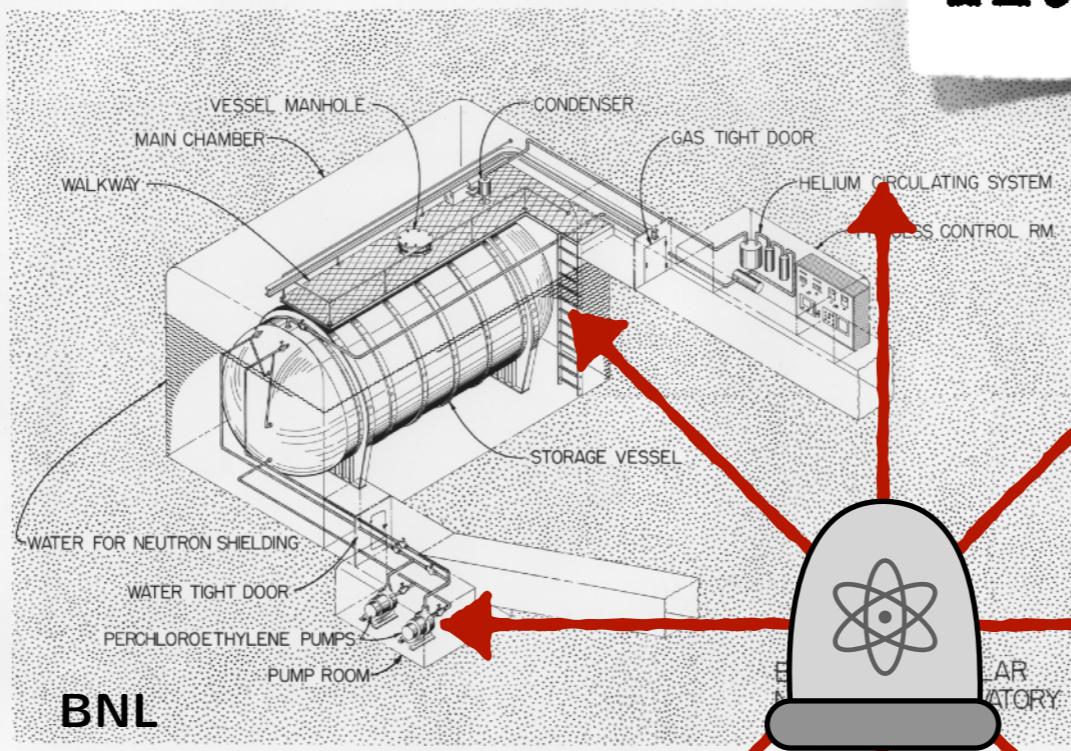


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The Plot Thickens Putting the $^-$ in $\bar{\nu}_e$: Antineutrinos

Beta Decay $n \rightarrow p + e^- + \nu$



Inver
(Cov)

No detection!

Evidence that we have "antineutrinos" that do this:

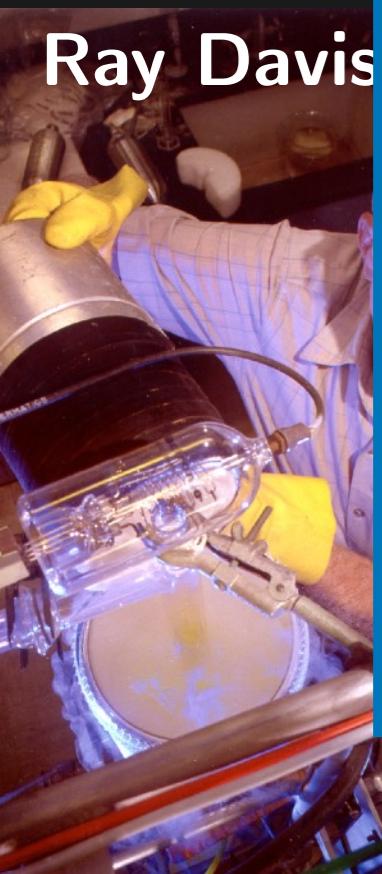


And "neutrinos" that do this:

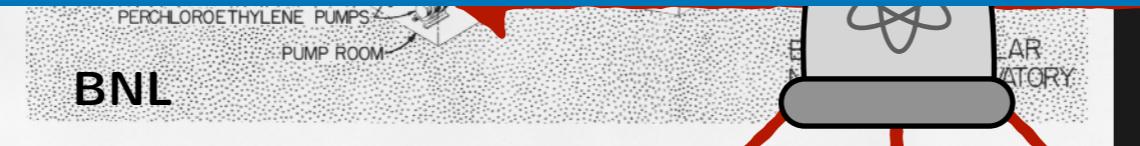


A distinct **particle** and **antiparticle**

$$\nu \neq \bar{\nu}$$



BNL



section of $1.6 \times 10^{-44} \text{ cm}^2/\text{atom}$.

In 1946 Pontecorvo³ suggested a radiochemical method of detecting the neutrino by employing the reaction $\text{Cl}^{37}(\bar{\nu}, e^-)\text{A}^{37}$. The experiment involved irradiating a large volume of carbon tetrachloride near a nuclear reactor, removing the A^{37} by physical methods, and counting the electron capture decay of this isotope.

Lated cross section for the inverse process. The evidence concerning the nuclear interactions of neutrinos and antineutrinos comes at present solely from a study of the half-life of the double beta-decay process. These studies have indicated that neutrinos and antineutrinos do differ in their interactions with nucleons.

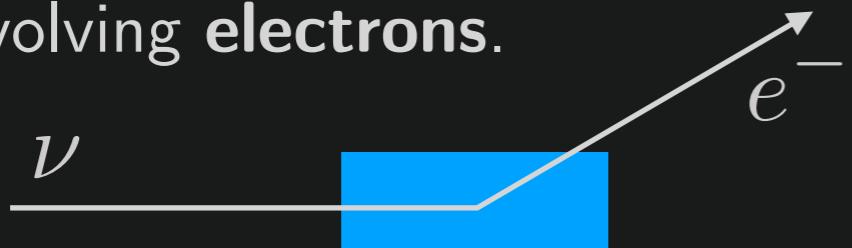
An experiment has been performed in which a 200-liter (55-gallon) drum of carbon tetrachloride was

from a Nuclear Reactor Reaction*

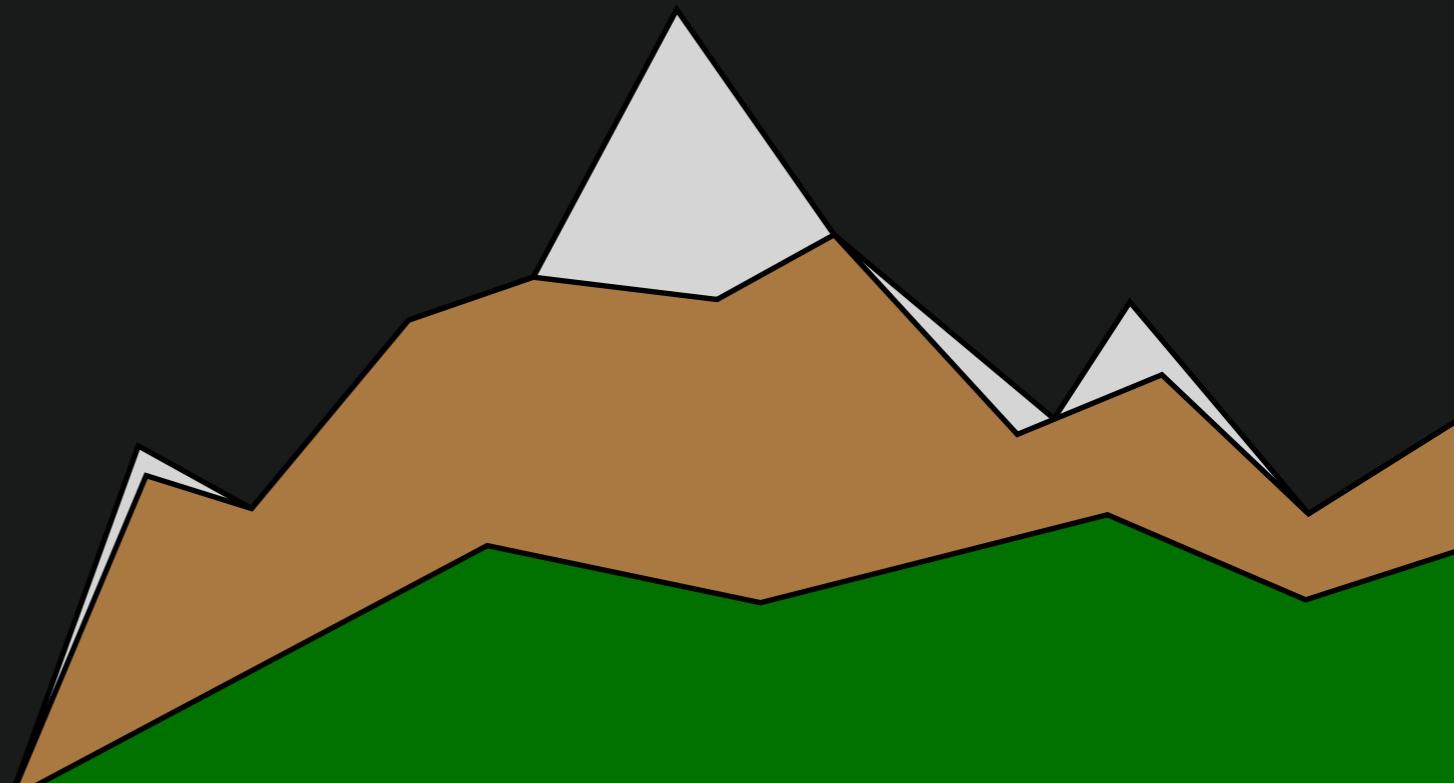
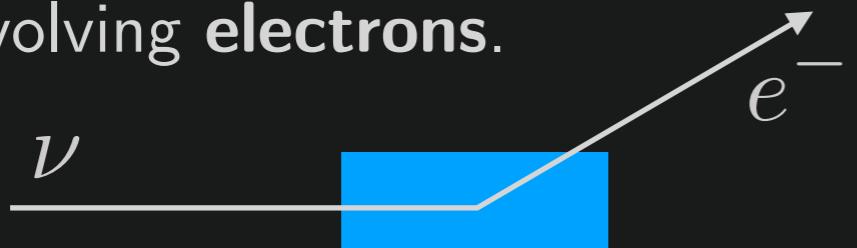
R. R. R. Upton, Long Island, New York
irradiated outside of the shield of the A³⁷ with fission product antineutrinos. capture cross section for the reaction of the production rate measured at 14 100 timer shielded from cosmic rays with 19 in the sun.

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nos which arise from the negative beta
ission products. In our experiment an attempt
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nuclear reactions. A negative experiment
the required sensitivity would indicate that
and antineutrinos differ in their nuclear
or that the present theory of beta decay is
The present theory of beta decay and the
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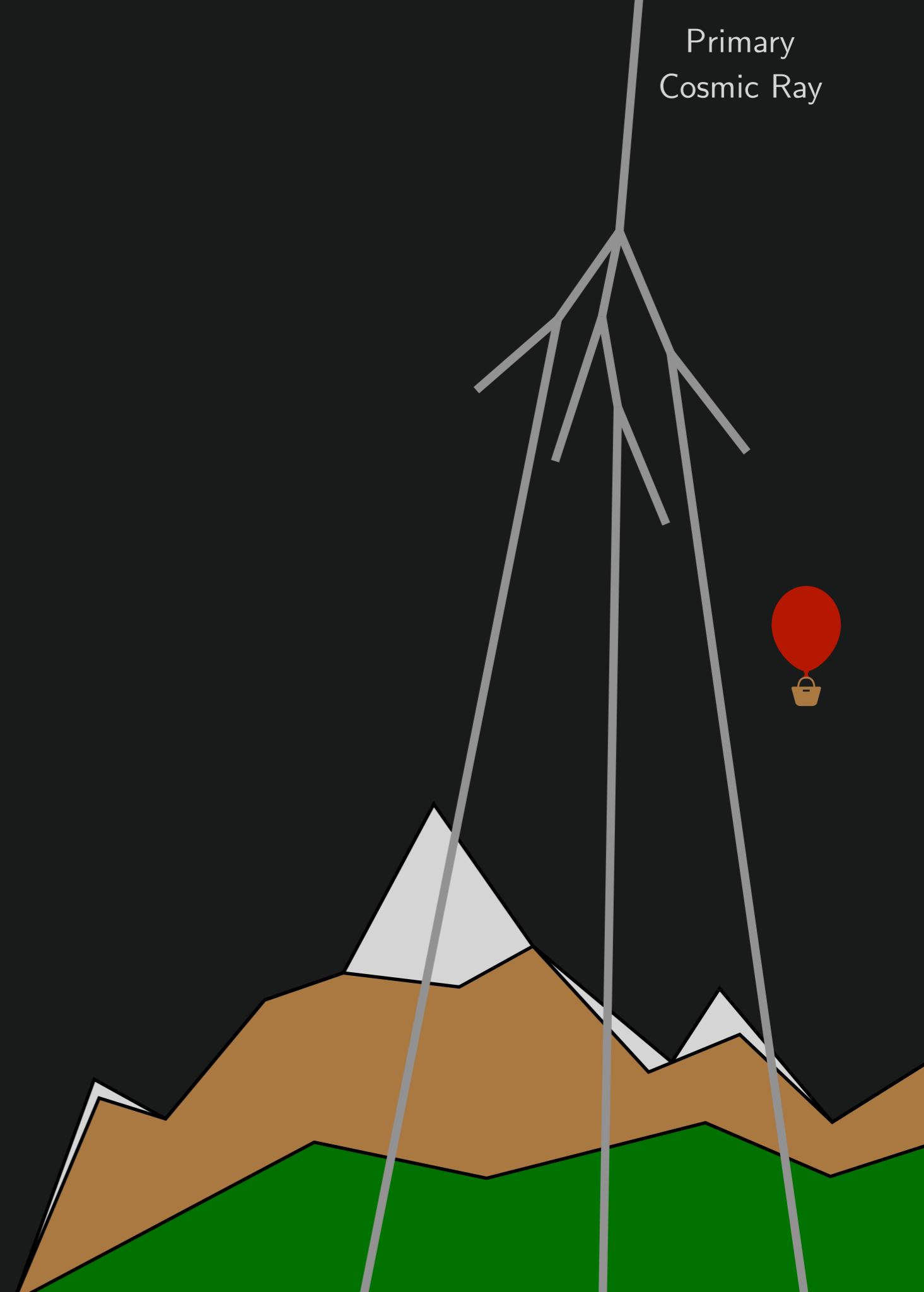
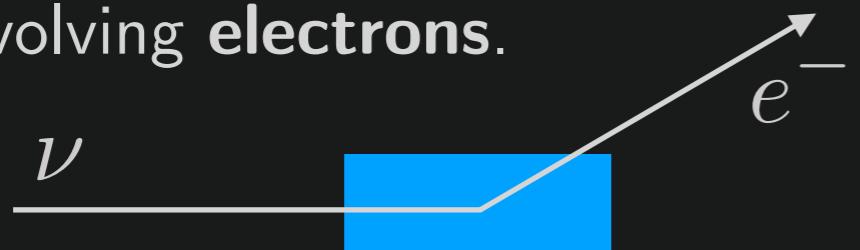
So far, we've discussed interactions involving **electrons**.



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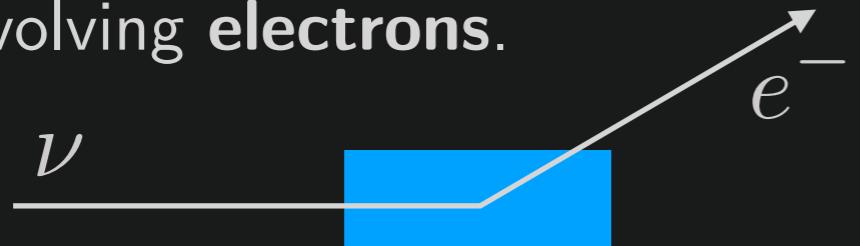


So far, we've discussed interactions involving **electrons**.



Primary
Cosmic Ray

So far, we've discussed interactions involving **electrons**.



In 1937, the **muon** is discovered.
Like a heavy electron, but it decays:

$$\mu^- \rightarrow e^- + ?$$

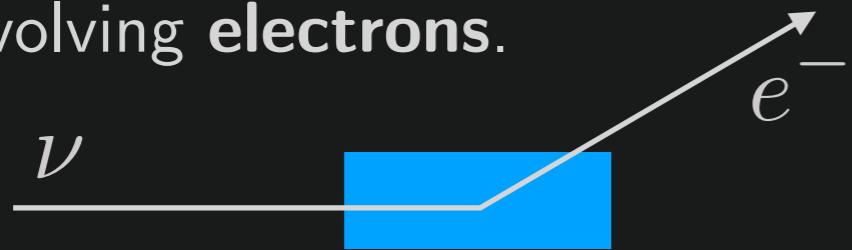


Carl Anderson

Primary
Cosmic Ray

Cloud Chamber

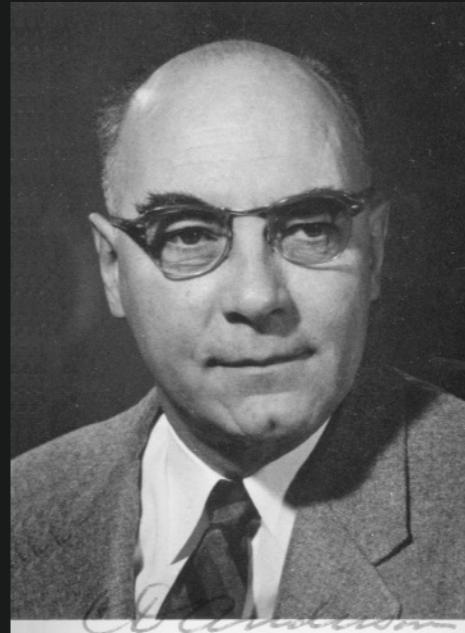
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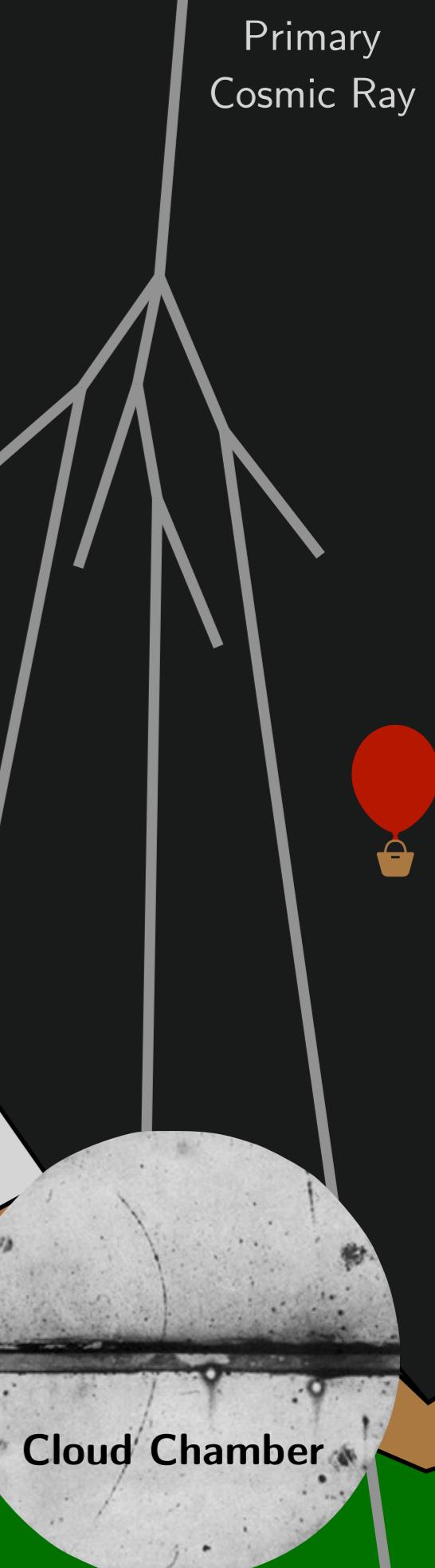


Carl Anderson

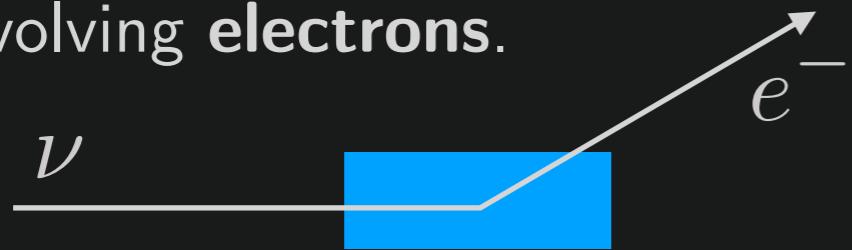
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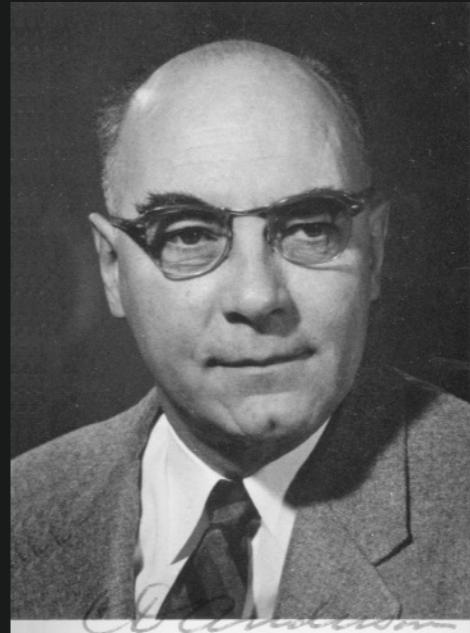
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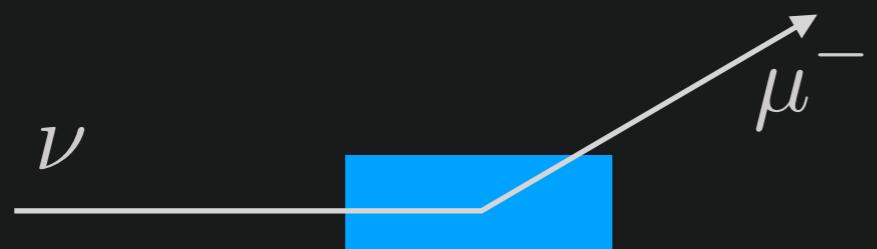
Feynman diagram illustrating the decay of a muon (μ^-) into an electron (e^-) and two neutrinos (ν). The incoming muon is represented by an orange circle, and the outgoing particles are shown as green and grey circles.



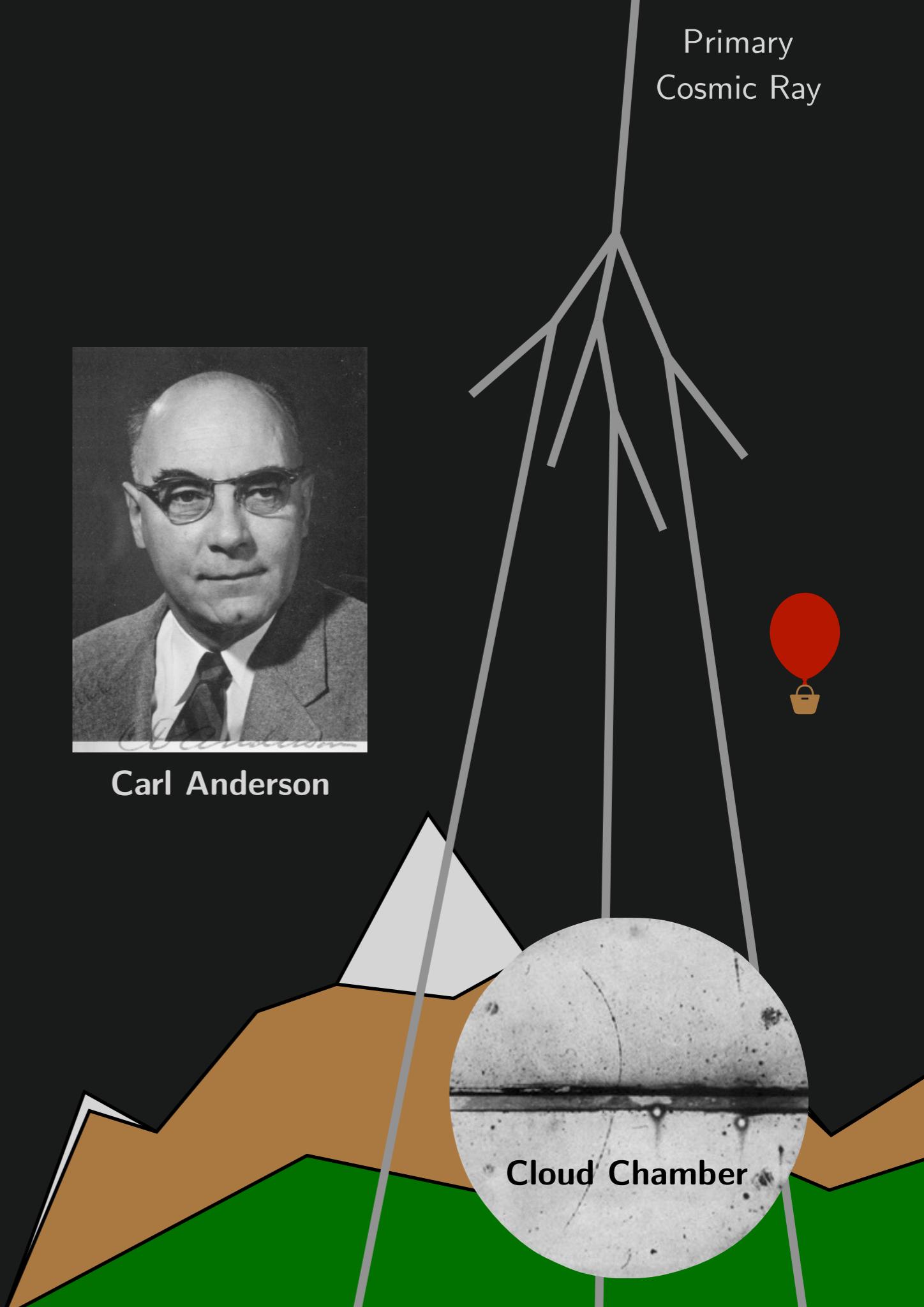
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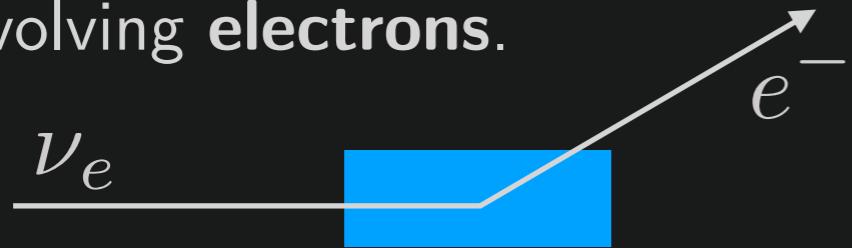
Feynman diagram illustrating the decay of a pion (π^-) into a muon (μ^-) and two neutrinos (ν). The incoming pion is represented by a magenta circle, and the outgoing particles are shown as orange and grey circles.



Primary
Cosmic Ray



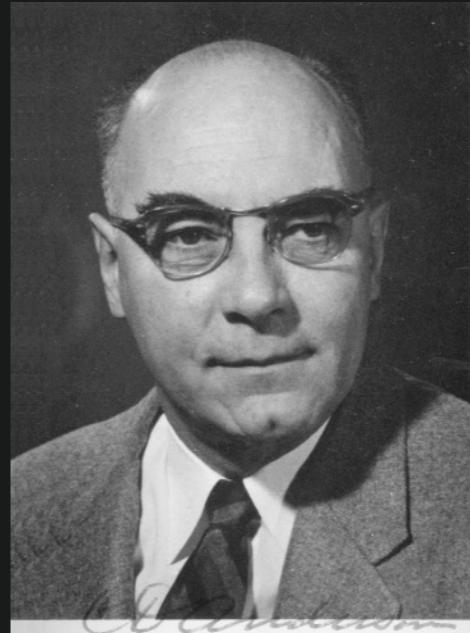
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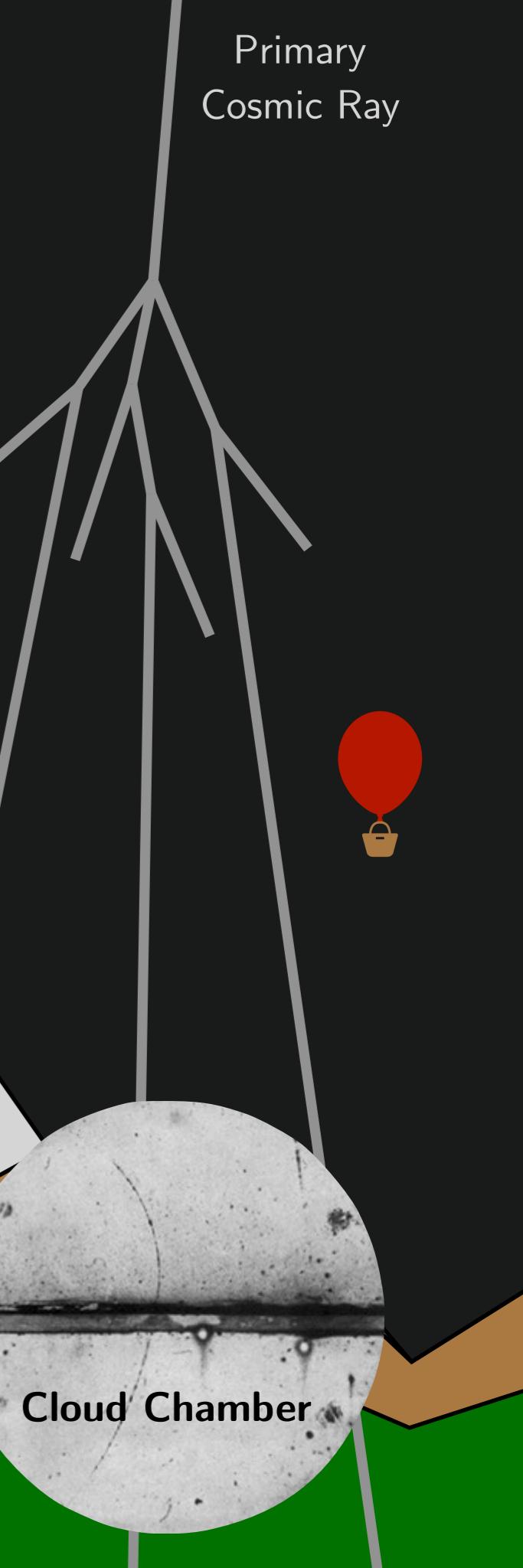
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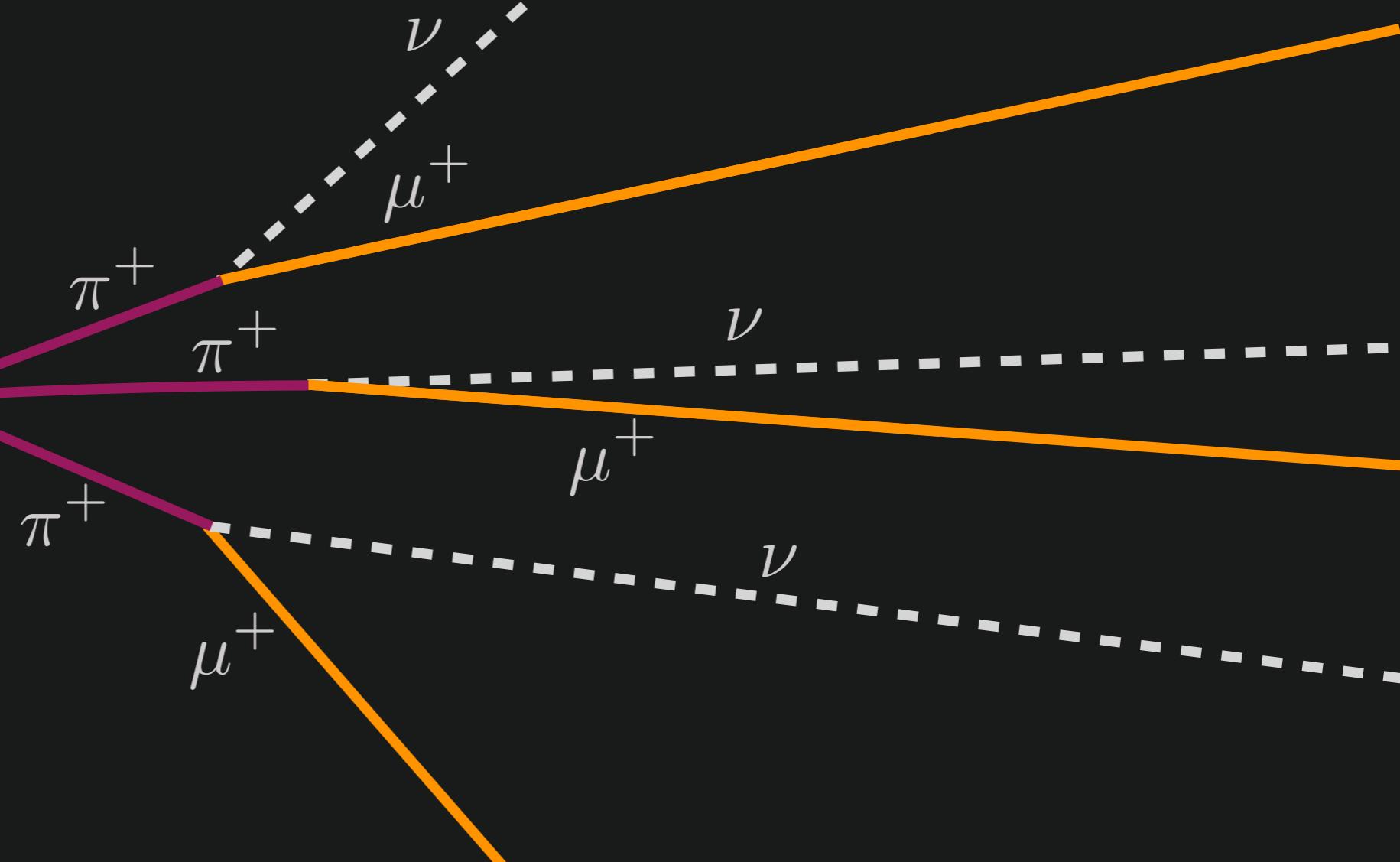
Where do we get a lot of these muon neutrinos?

Make some "cosmic rays!"



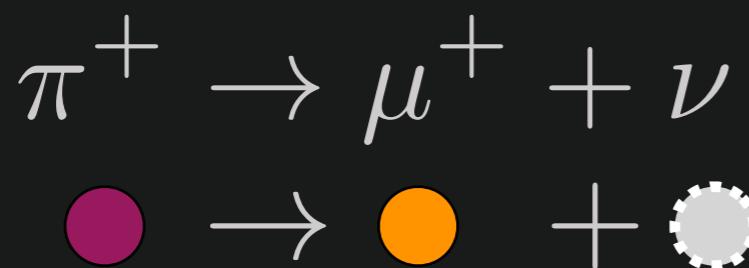
Primary
Cosmic Ray

Atmosphere
Stuff



Where do we get a lot of these muon neutrinos?

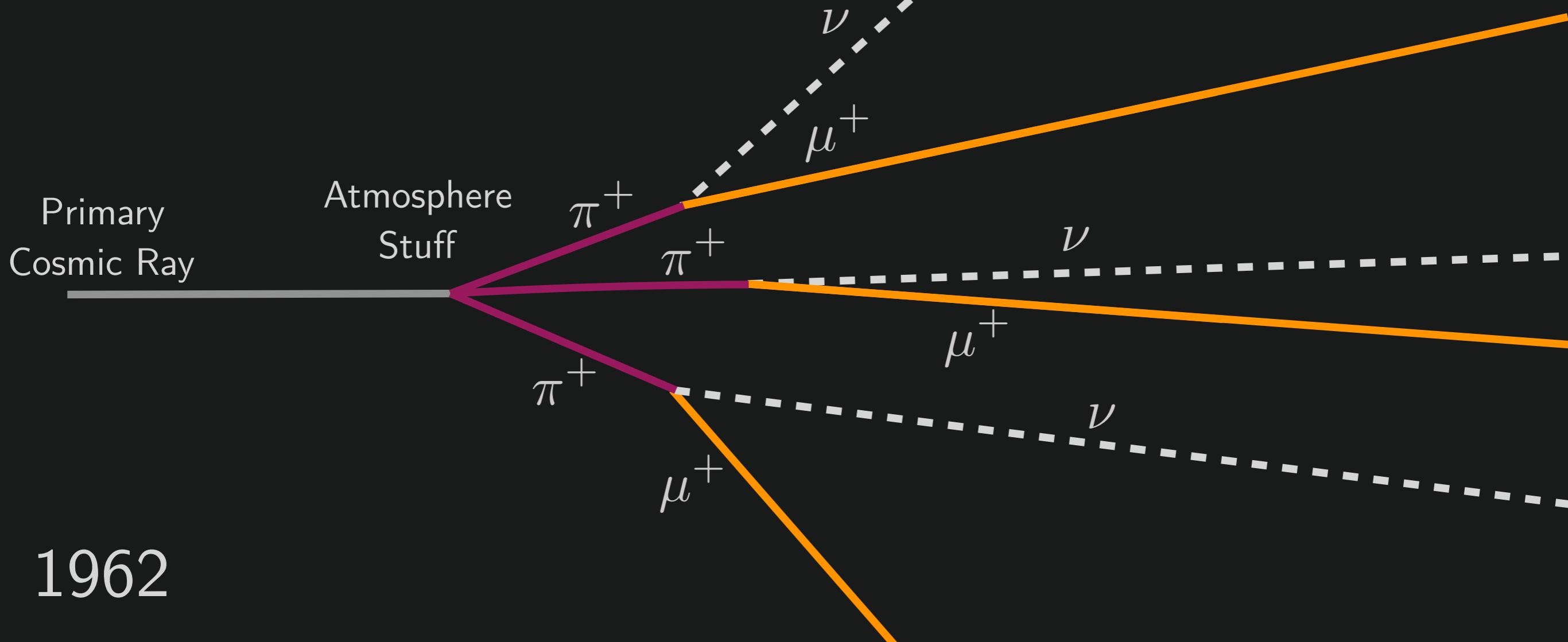
Make some "cosmic rays!"



Leon
Lederman

Melvin
Schwartz

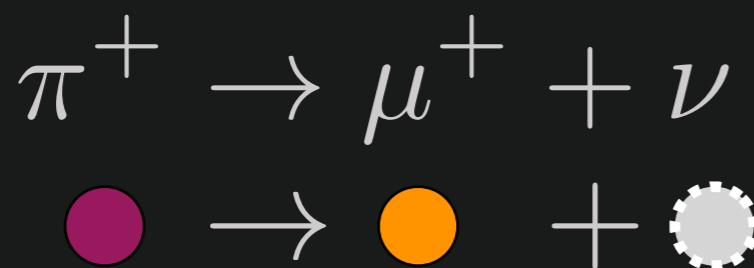
Jack
Steinberger



1962

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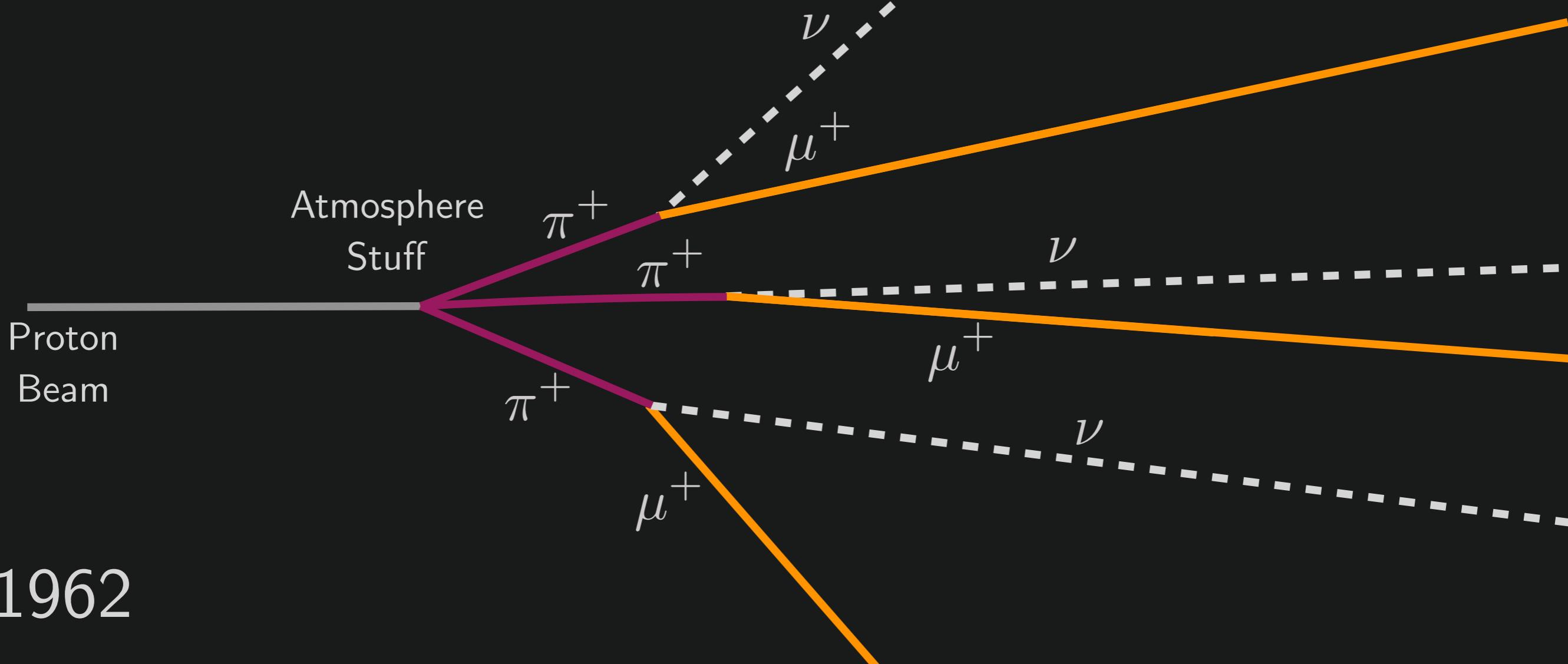
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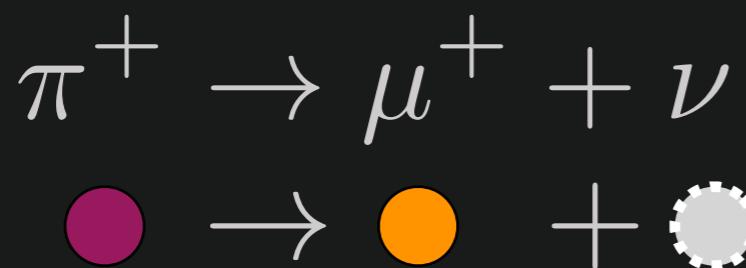
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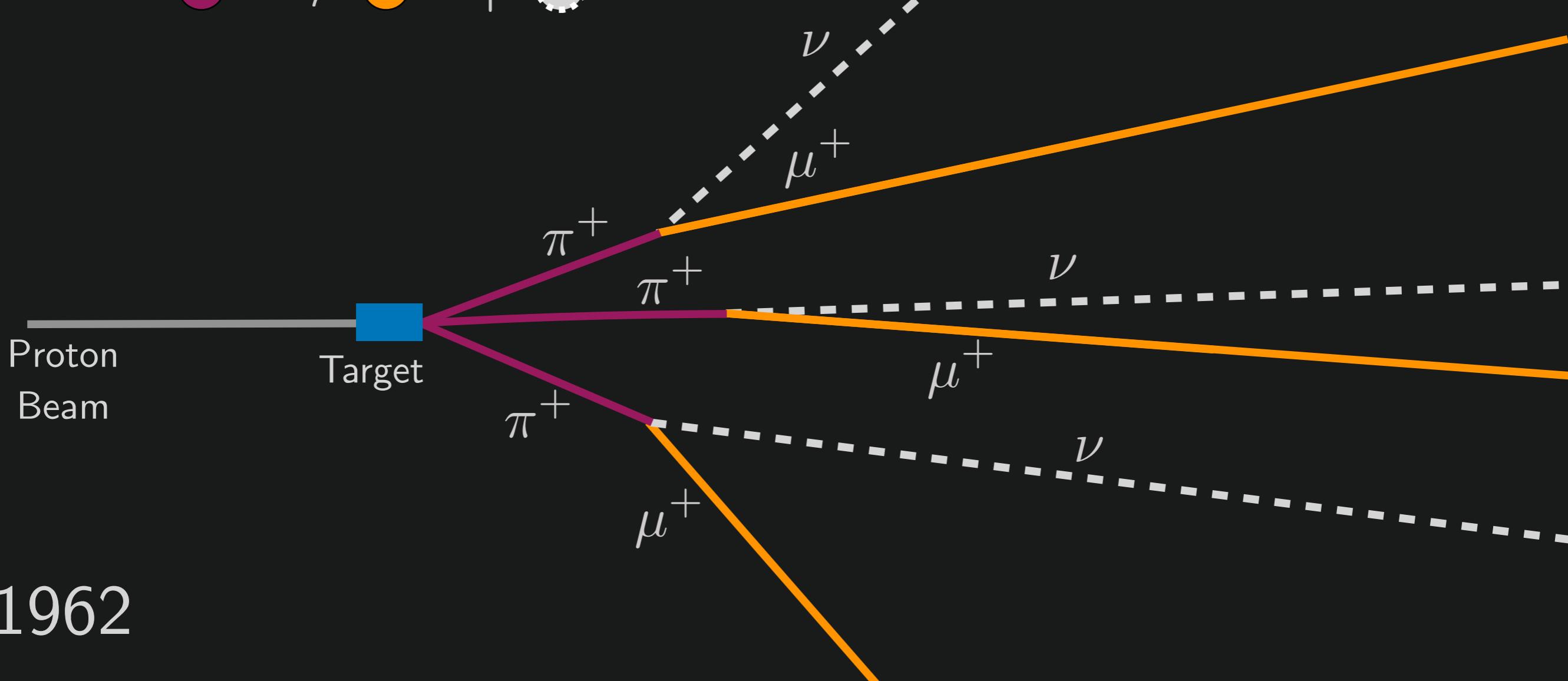
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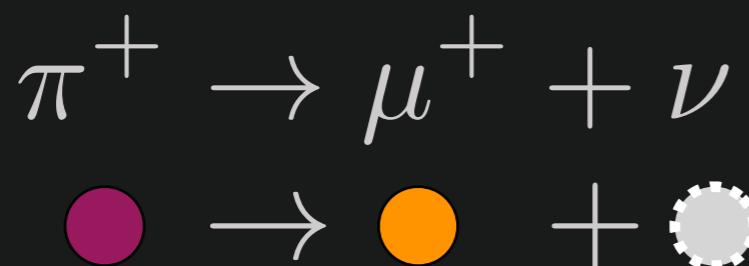
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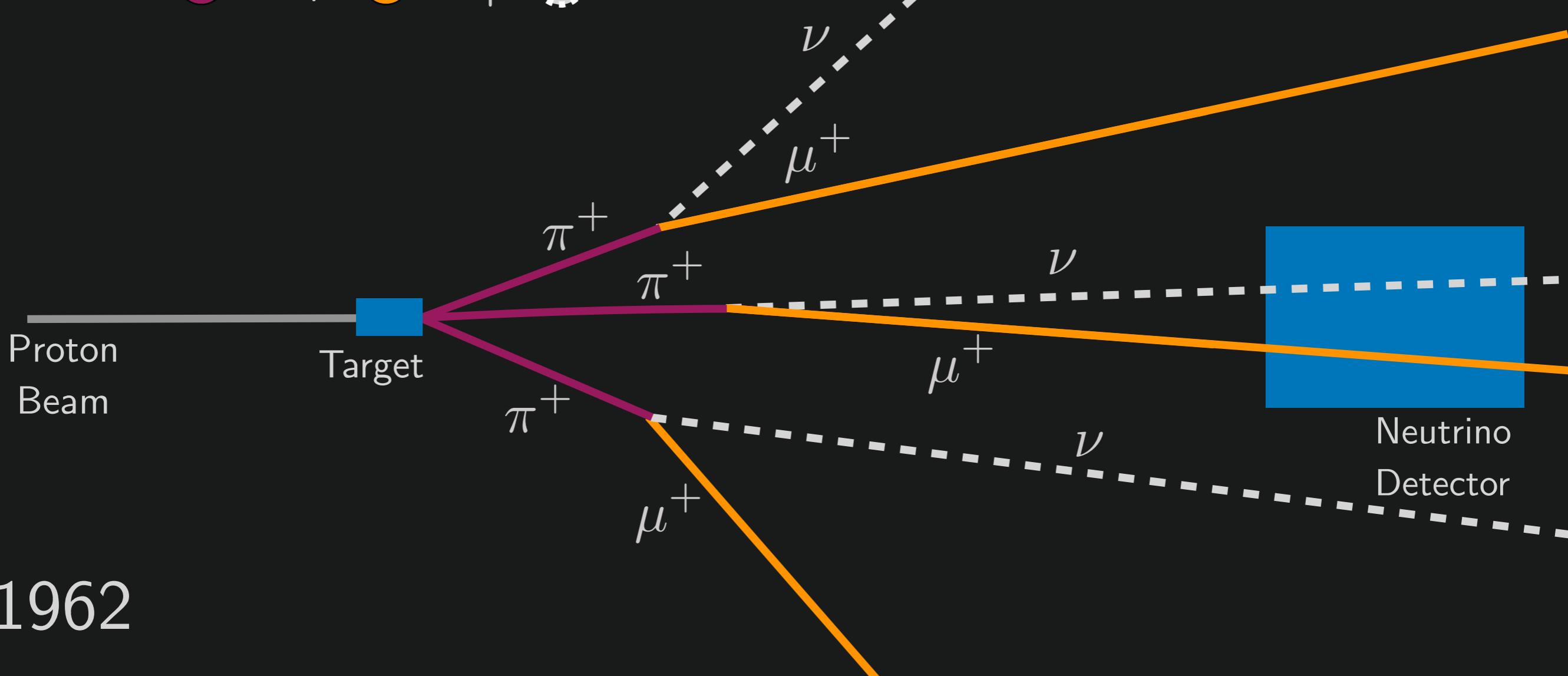
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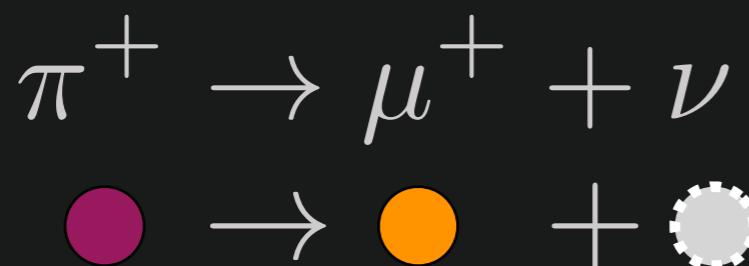
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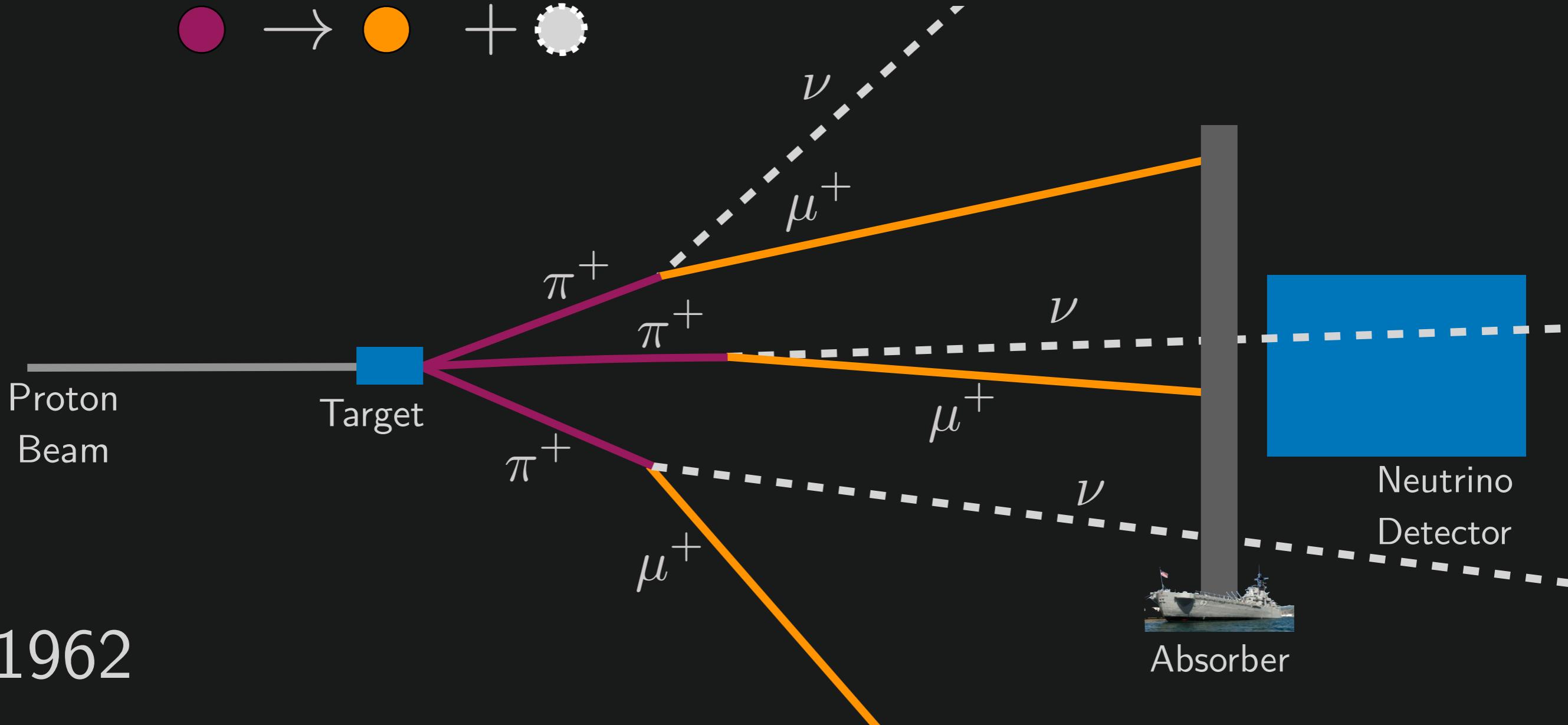
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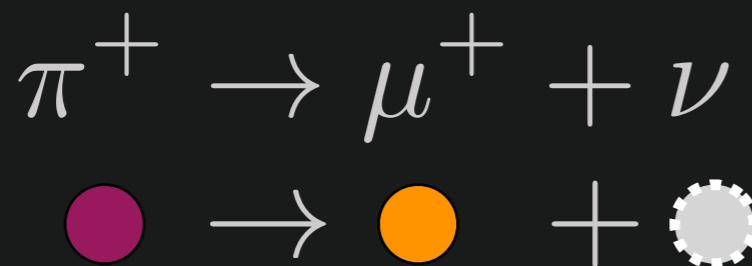
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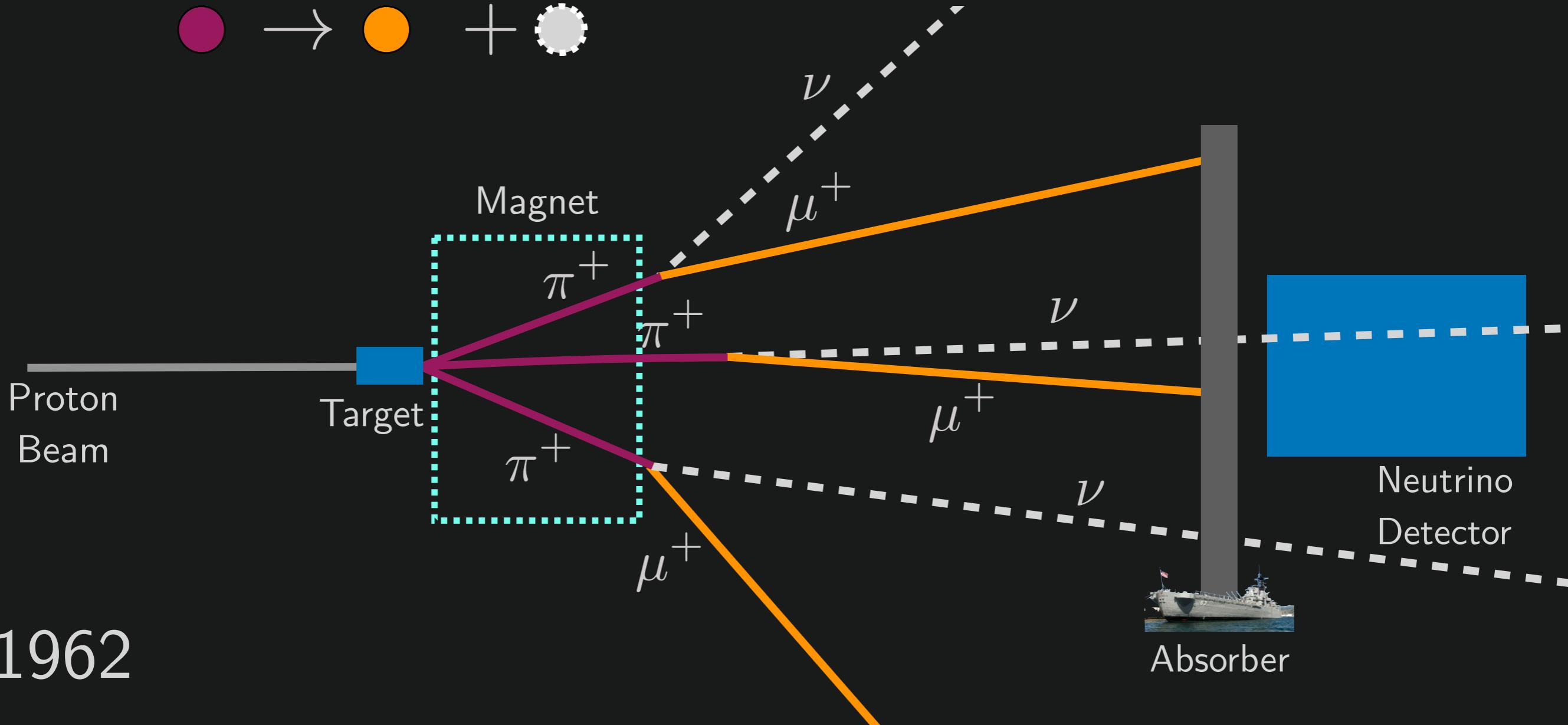
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Schwartz

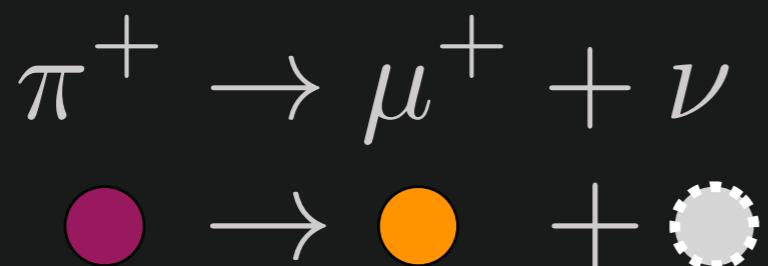
Jack
Steinberger



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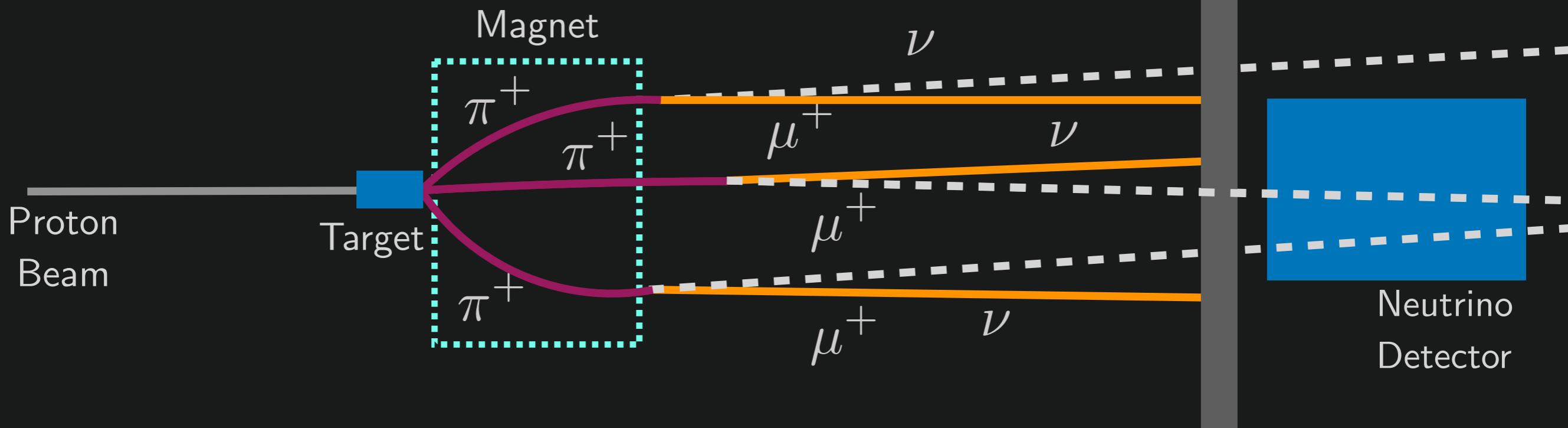
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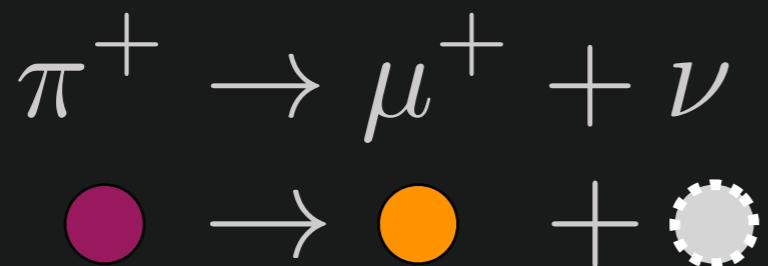


1962

Absorber

Where do we get a lot of these muon neutrinos?

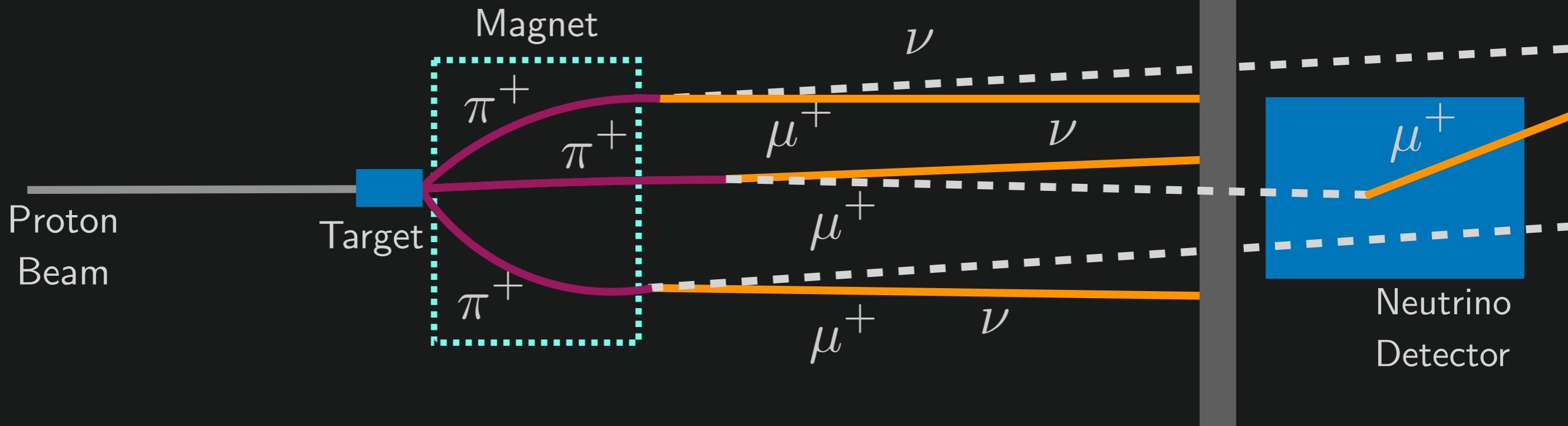
Make some "cosmic rays!"



Leon
Lederman

Melvin
Schwartz

Jack
Steinberger



1962

Absorber

Where do we get a lot of these muon neutrinos?

Make some "cos

$$\pi^+ \rightarrow \mu^+ + (\nu/\bar{\nu})$$

Proton Beam



1988 Nobel Prize in Physics

Lederman, Schwartz, and Steinberger

"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

1962

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J.-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry,
M. Schwartz,[†] and J. Steinberger[†]

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 1, 1962)

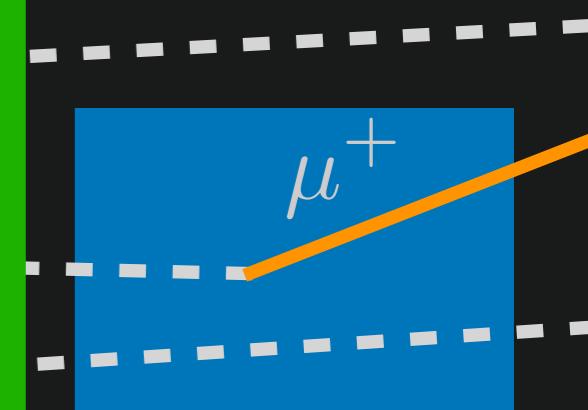
In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

$$\pi^\pm \rightarrow \mu^\pm + (\nu/\bar{\nu}). \quad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used pro-



There exist distinct muon-type and electron-type neutrinos (and antineutrinos)



Absorber

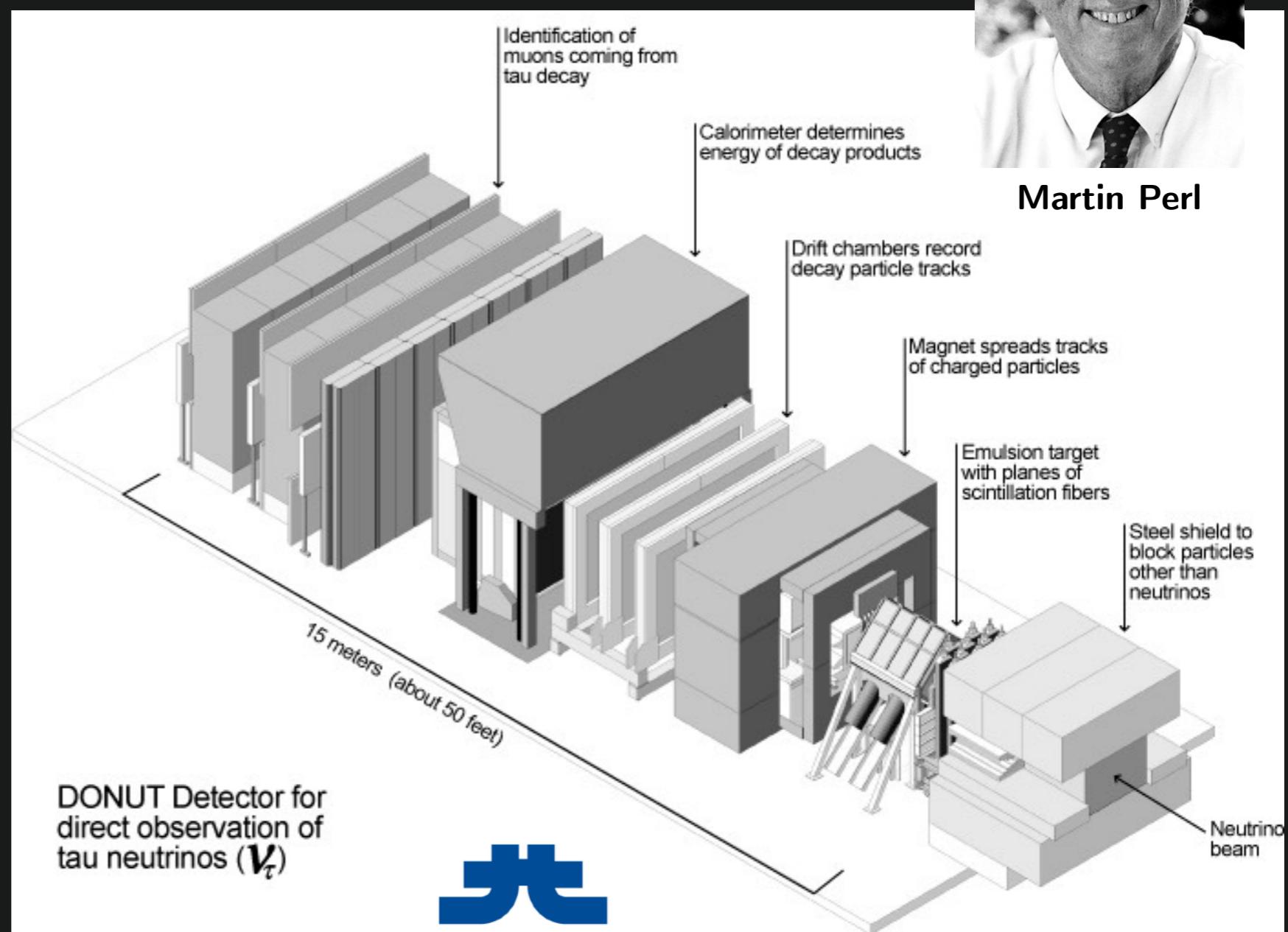
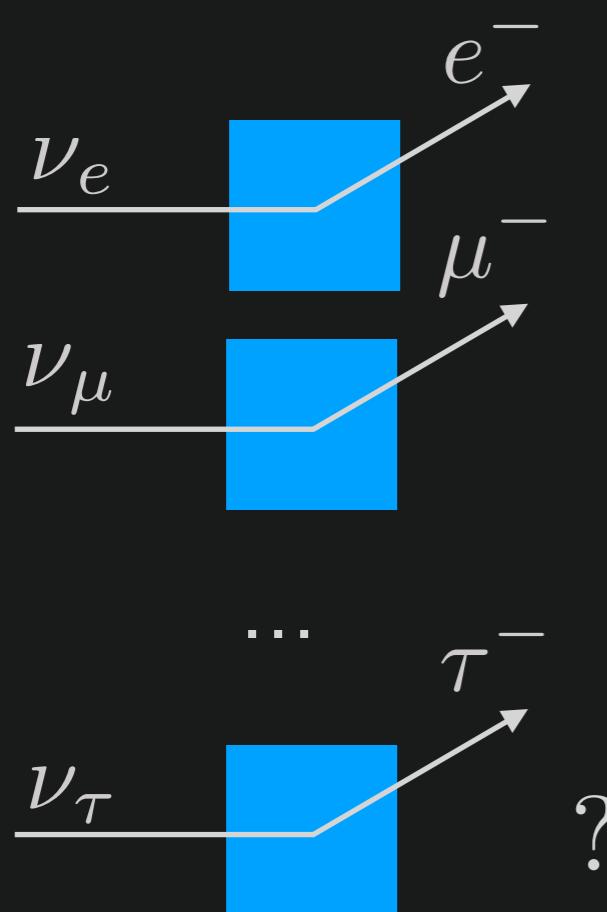
Neutrino Detector

Jack Steinberger

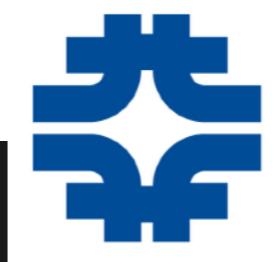
The Plot Thickens

Three!
2000: Two flavors of neutrinos

In 1975, the **tau lepton** is discovered by Perl et al. It's like a **REALLY** heavy electron.



Located at
Fermilab!

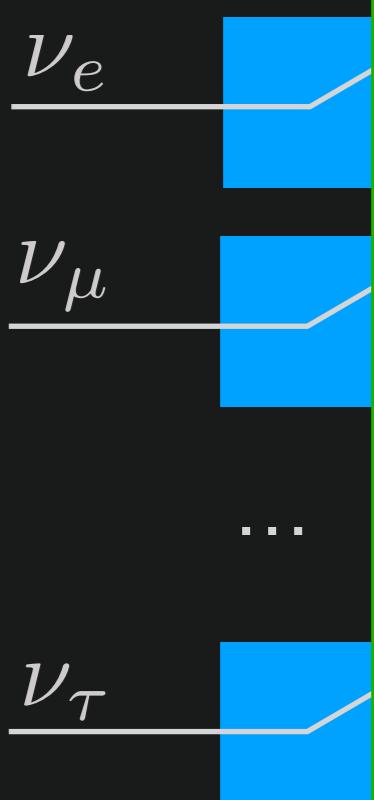


Martin Perl

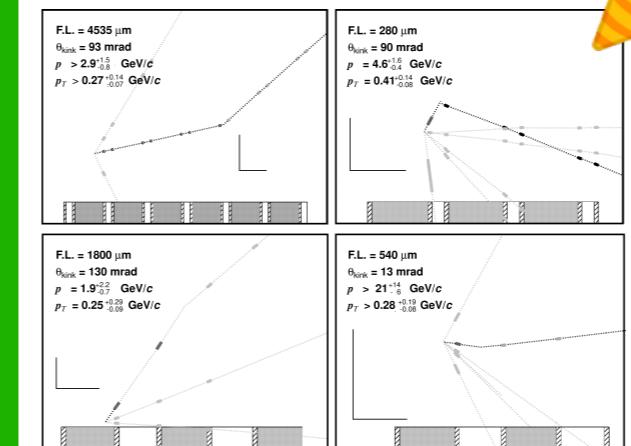
The Plot Thickens

Three!
2000: Two flavors of neutrinos

In 1975, the tau
discovered by Perl.
It's like a REALLY
electron.



Based on **four events**, the existence of a
tau-type neutrino is confirmed.

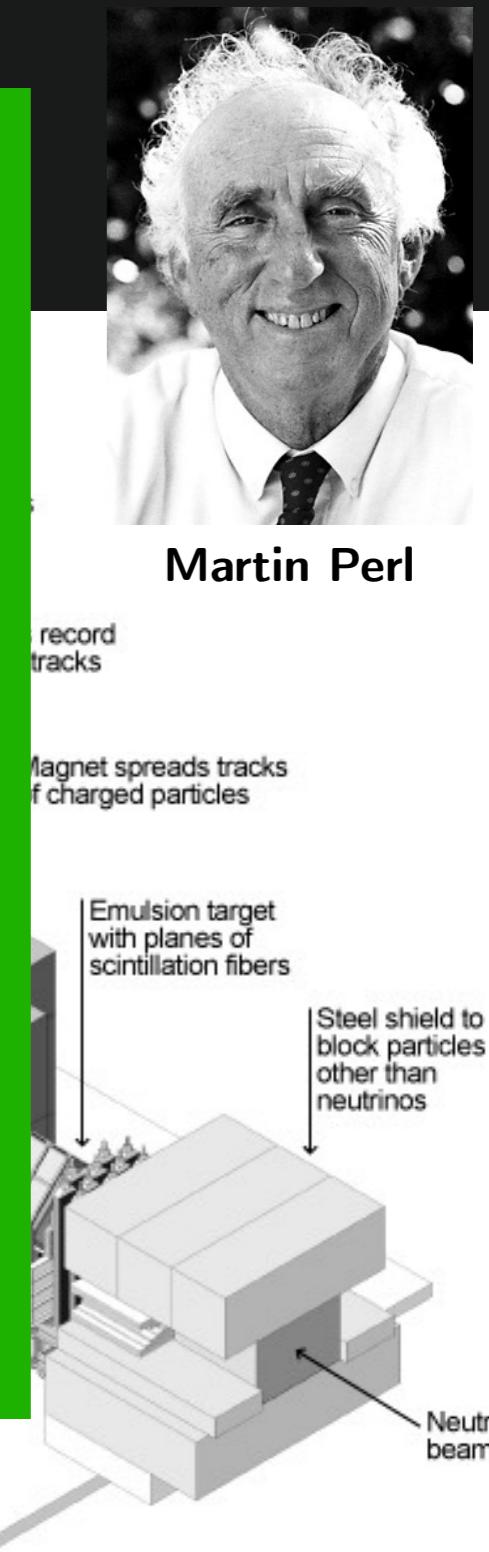


1995 Nobel Prize in Physics
Martin Perl (shared with Reines)
*"for the discovery of the **tau lepton**"*



direct observation of
tau neutrinos (ν_τ)

Located at
Fermilab!



Martin Perl

The Standard Model

Pulling it all together

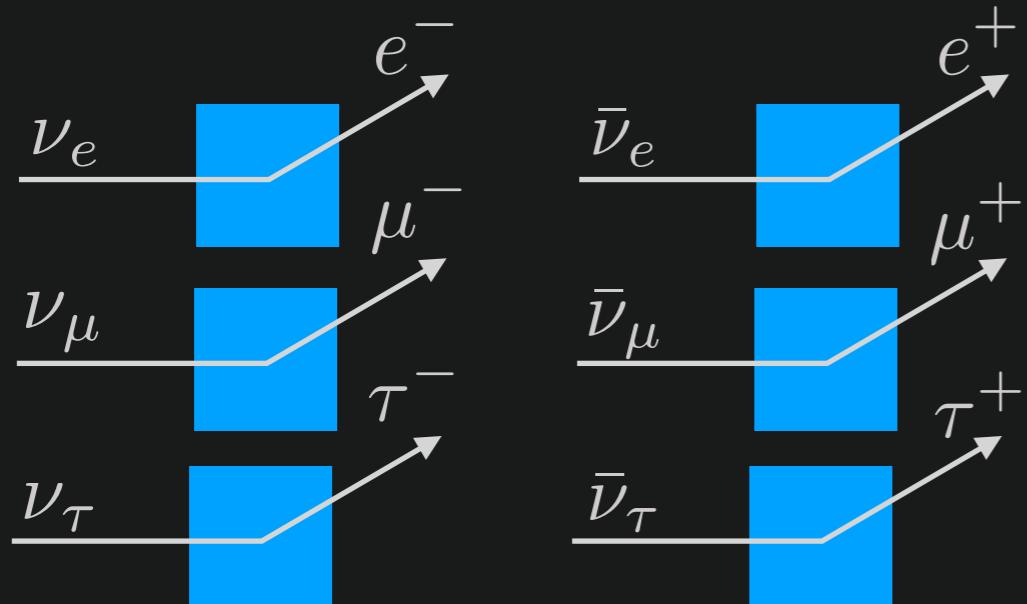
Plus all the normal matter:

So far, we've got:

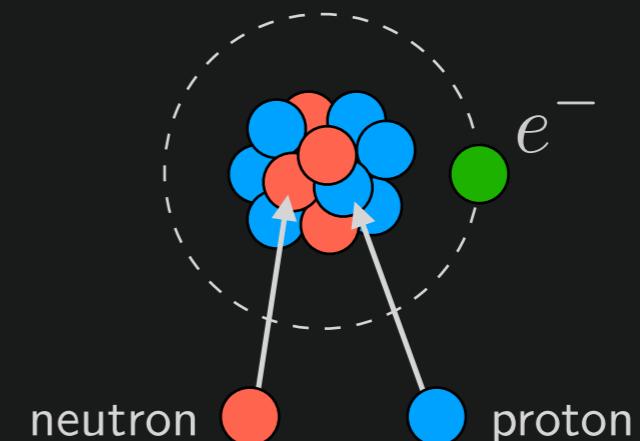
$$\nu_e, \nu_\mu, \nu_\tau$$

$$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$$

That do this:



All massless and neutral



n
 \underbrace{udd} p
 \underbrace{udu} quarks

and antimatter counterparts

And other stuff we've found:

$$\begin{array}{ll} \pi^+ = u\bar{d} & K^+ = u\bar{s} \\ \pi^- = \bar{u}d & \Delta^{++} = uuu \end{array}$$

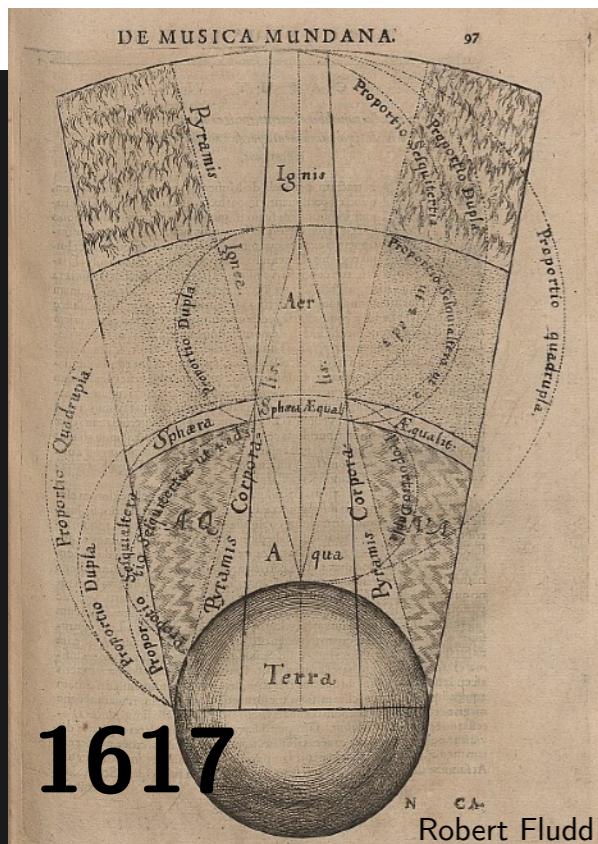
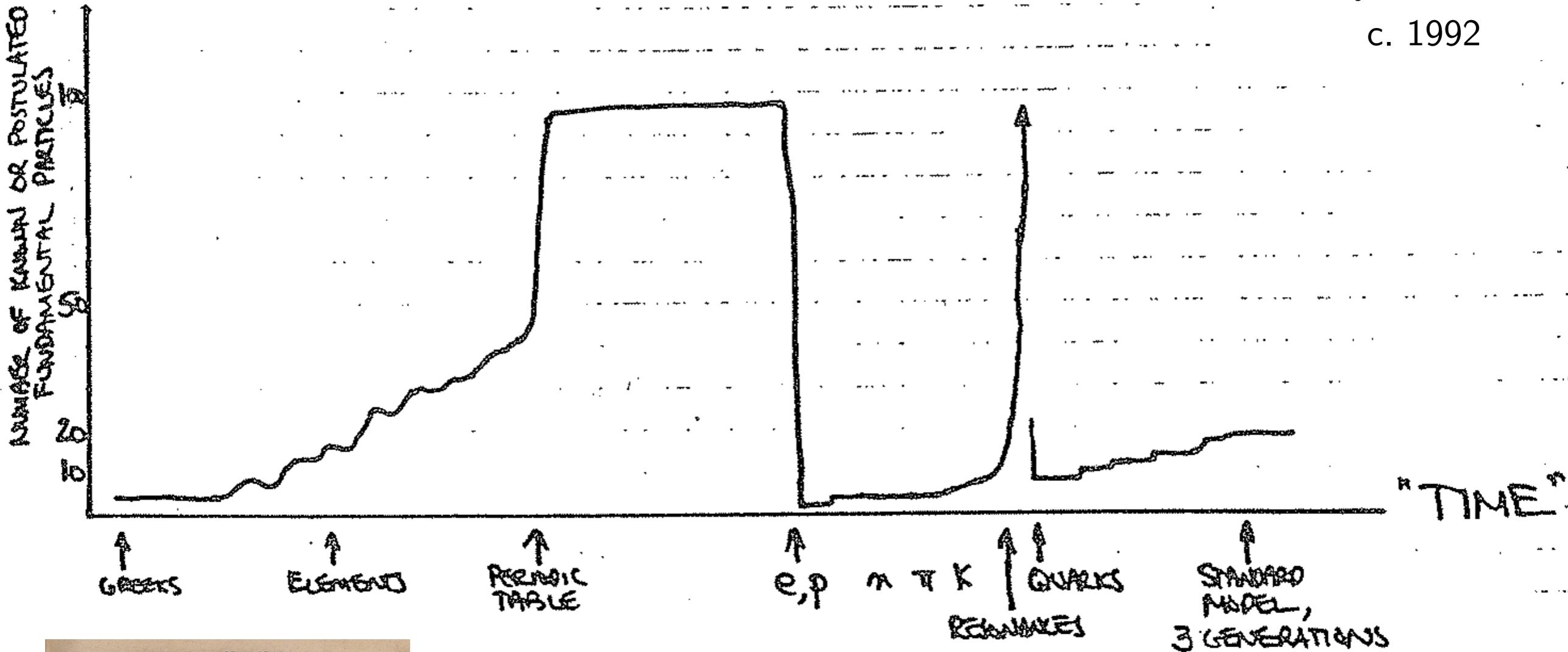
etc.

And a whole bunch of rules!

"FUNDAMENTAL" PARTICLES

P. Meyers, Princeton

c. 1992



1 H	2 He
3 Li	4 Be
11 Na	12 Mg
19 K	20 Ca
37 Rb	38 Sr
55 Cs	56 Ba
87 Fr	88 Ra
89 Ac	*
104 Rf	105 Db
106 Sg	107 Bh
108 Hs	109 Mt
110 Ds	111 Rg
112 Cn	113 Nh
114 Fl	115 Mc
116 Lv	117 Ts
118 Og	119 Ts
58 Ce	59 Pr
60 Nd	61 Pm
62 Sm	63 Eu
64 Gd	65 Tb
66 Dy	67 Ho
68 Er	69 Tm
70 Yb	71 Lu
90 Th	91 Pa
92 U	93 Np
94 Pu	95 Am
96 Cm	97 Bk
98 Cf	99 Es
100 Fm	101 Md
102 No	103 Lr

c. 1869

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Standard Model of Elementary Particles			
three generations of matter (fermions)			
mass			
charge			
spin			
I	u	c	t
II	d	s	b
III	e	μ	τ
g	γ	Z	Higgs
gluon	photon	Z boson	Higgs
SCALAR BOSONS			
LEPTONS			
QUARKS			
GAUGE BOSONS			

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1617

The Standard Model

$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
& \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \\
& \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
& \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
& W_\nu^- \partial_\nu W_\mu^+)] - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
& W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
& \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + \\
& g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-] - \\
& \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
& g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} ig [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
& W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
& ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
& ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
& \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) - \frac{1}{2} ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + \\
& m_d^\lambda) d_j^\lambda + ig s_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
& \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + \\
& (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \\
& \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \\
& \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
& i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \\
& \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \\
& \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + \\
& ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
& ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
& ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
& \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \\
& \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \\
& \bar{X}^0 X^+ \phi^-] + \frac{1}{2} ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

A Mathematical Model

The Standard Model
collects all the known
matter particles
and encodes their
interactions

Mathematically, it's a
relativistic
quantum
field theory
that's all about
groups and symmetry





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Hydrogen Wave Function

Probability density plots.

$$\psi_{nlm}(r, \vartheta, \varphi) = \sqrt{\left(\frac{2}{na_0}\right)^3 \frac{(n-l-1)!}{2n[(n+l)!]}} e^{-\rho/2} \rho^l L_{n-l-1}^{2l+1}(\rho) \cdot Y_{lm}(\vartheta, \varphi)$$

(2,0,0)

(3,0,0)

(2,1,0)

(3,1,0)

(3,1,1)

(2,1,1)

(3,2,0)

(3,2,1)

(3,2,2)

(4,0,0)

(4,1,0)

(4,1,1)

(4,2,0)

(4,2,1)

(4,2,2)

(4,3,0)

(4,3,1)

(4,3,2)

(4,3,3)



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The Standard Model

Fundamental Symmetries



Emmy Noether
(1882-1935)

Noether's Theorem (1918) relates
symmetries to conserved quantities

Time invariance \leftrightarrow Energy conservation
i.e. physics is the same at all times

Translation invariance \leftrightarrow Momentum conservation
i.e. physics is the same at all positions

Rotation invariance \leftrightarrow Angular momentum conservation
i.e. physics is the same at all angles

CP invariance \leftrightarrow Matter + antimatter conservation
i.e. (Anti-)particles are the same but opposite charge, parity

These symmetries underpin the Standard Model,
our most fundamental understanding of nature

The Standard Model

Particle Menagerie

QUARKS	I	II	III	
	$u^{+2/3}$ up $0.003 \text{ GeV}/c^2$	$c^{+2/3}$ charm $1.3 \text{ GeV}/c^2$	$t^{+2/3}$ top $175 \text{ GeV}/c^2$	
LEPTONS	$d^{-1/3}$ down $0.006 \text{ GeV}/c^2$	$s^{-1/3}$ strange $0.1 \text{ GeV}/c^2$	$b^{-1/3}$ bottom $4.3 \text{ GeV}/c^2$	
	ν_e^0 electron neutrino $<10^{-8} \text{ GeV}/c^2$	ν_μ^0 muon neutrino $<10^{-4} \text{ GeV}/c^2$	ν_τ^0 tau neutrino $<0.02 \text{ GeV}/c^2$	γ^0 photon 0
	e^-^{-1} electron $511 \text{ keV}/c^2$	μ^-^{-1} muon $0.106 \text{ GeV}/c^2$	τ^-^{-1} tau $1.78 \text{ GeV}/c^2$	g^0 gluon 0
				$W^\pm^{\pm 1}$ W boson $80.4 \text{ GeV}/c^2$
				Z^0^0 Z boson $91.2 \text{ GeV}/c^2$
				H^0 Higgs boson $125 \text{ GeV}/c^2$

The Standard Model

Particle Menagerie

QUARKS	I	II	III	Quarks organize into Hadrons	
	$u^{+2/3}$ up $0.003 \text{ GeV}/c^2$	$c^{+2/3}$ charm $1.3 \text{ GeV}/c^2$	$t^{+2/3}$ top $175 \text{ GeV}/c^2$		
LEPTONS	$d^{-1/3}$ down $0.006 \text{ GeV}/c^2$	$s^{-1/3}$ strange $0.1 \text{ GeV}/c^2$	$b^{-1/3}$ bottom $4.3 \text{ GeV}/c^2$	Mesons $q\bar{q}$ e.g. $\pi^+ = u\bar{d}$ $\pi^- = \bar{u}d$ $K^+ = u\bar{s}$	Baryons qqq e.g. $p = udu$ $n = udd$ $\Delta^{++} = uuu$
	ν_e^0 electron neutrino $<10^{-8} \text{ GeV}/c^2$	ν_μ^0 muon neutrino $<10^{-4} \text{ GeV}/c^2$	ν_τ^0 tau neutrino $<0.02 \text{ GeV}/c^2$		
	e^-^{-1} electron $511 \text{ keV}/c^2$	μ^-^{-1} muon $0.106 \text{ GeV}/c^2$	τ^-^{-1} tau $1.78 \text{ GeV}/c^2$		

$\mathbf{p} = \begin{matrix} \textcolor{blue}{u} \\ \textcolor{green}{u} \\ \textcolor{red}{d} \end{matrix}$

The Standard Model

Particle Menagerie

QUARKS	I	II	III	
	$u^{+2/3}$ up $0.003 \text{ GeV}/c^2$	$c^{+2/3}$ charm $1.3 \text{ GeV}/c^2$	$t^{+2/3}$ top $175 \text{ GeV}/c^2$	
$d^{-1/3}$ down $0.006 \text{ GeV}/c^2$	$s^{-1/3}$ strange $0.1 \text{ GeV}/c^2$	$b^{-1/3}$ bottom $4.3 \text{ GeV}/c^2$		
LEPTONS	ν_e^0 electron neutrino $<10^{-8} \text{ GeV}/c^2$	ν_μ^0 muon neutrino $<10^{-4} \text{ GeV}/c^2$	ν_τ^0 tau neutrino $<0.02 \text{ GeV}/c^2$	
	e^-^{-1} electron $511 \text{ keV}/c^2$	μ^-^{-1} muon $0.106 \text{ GeV}/c^2$	τ^-^{-1} tau $1.78 \text{ GeV}/c^2$	

γ^0 photon 0
g^0 gluon 0
$W^\pm^{\pm 1}$ W boson $80.4 \text{ GeV}/c^2$
Z^0^0 Z boson $91.2 \text{ GeV}/c^2$
H^0 Higgs boson $125 \text{ GeV}/c^2$

The Standard Model

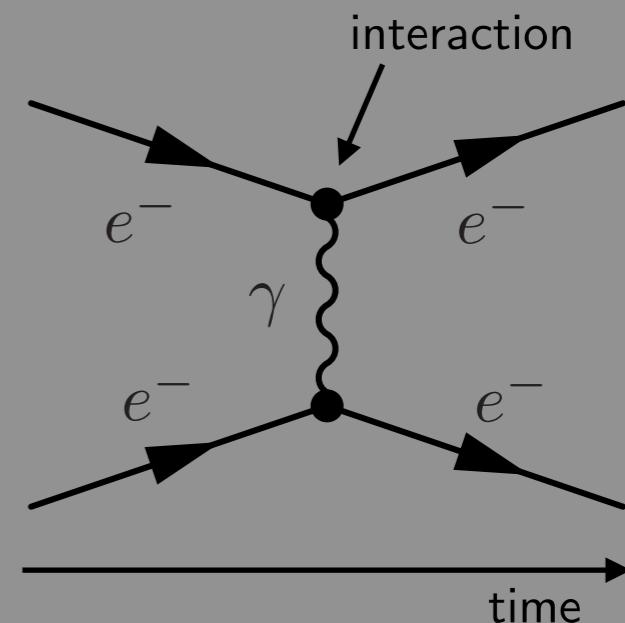
Particle Menagerie

	I	II	III
QUARKS	$u^{+2/3}$ up $0.003 \text{ GeV}/c^2$	$c^{+2/3}$ charm $1.3 \text{ GeV}/c^2$	$t^{+2/3}$ top $175 \text{ GeV}/c^2$
LEPTONS	$d^{-1/3}$ down $0.006 \text{ GeV}/c^2$	$s^{-1/3}$ strange $0.1 \text{ GeV}/c^2$	$b^{-1/3}$ bottom $4.3 \text{ GeV}/c^2$
ν_e^0 electron neutrino $<10^{-8} \text{ GeV}/c^2$	ν_μ^0 muon neutrino $<10^{-4} \text{ GeV}/c^2$	ν_τ^0 tau neutrino $<0.02 \text{ GeV}/c^2$	
e^-^{-1} electron $511 \text{ keV}/c^2$	μ^-^{-1} muon $0.106 \text{ GeV}/c^2$	τ^-^{-1} tau $1.78 \text{ GeV}/c^2$	

γ^0 photon 0
g^0 gluon 0
$W^\pm^{\pm 1}$ W boson $80.4 \text{ GeV}/c^2$
Z^0^0 Z boson $91.2 \text{ GeV}/c^2$
H^0 Higgs boson $125 \text{ GeV}/c^2$

Forces & Interactions

Matter particles (quarks & leptons) interact by exchanging messenger particles called **bosons**



Example: Electromagnetic interactions involve exchange of a **photon**

The Standard Model

Particle Menagerie

	I	II	III
QUARKS	$u^{+2/3}$ up $0.003 \text{ GeV}/c^2$	$c^{+2/3}$ charm $1.3 \text{ GeV}/c^2$	$t^{+2/3}$ top $175 \text{ GeV}/c^2$
LEPTONS	$d^{-1/3}$ down $0.006 \text{ GeV}/c^2$	$s^{-1/3}$ strange $0.1 \text{ GeV}/c^2$	$b^{-1/3}$ bottom $4.3 \text{ GeV}/c^2$
→ EM, strong, weak, Higgs			
→ EM, weak, Higgs			

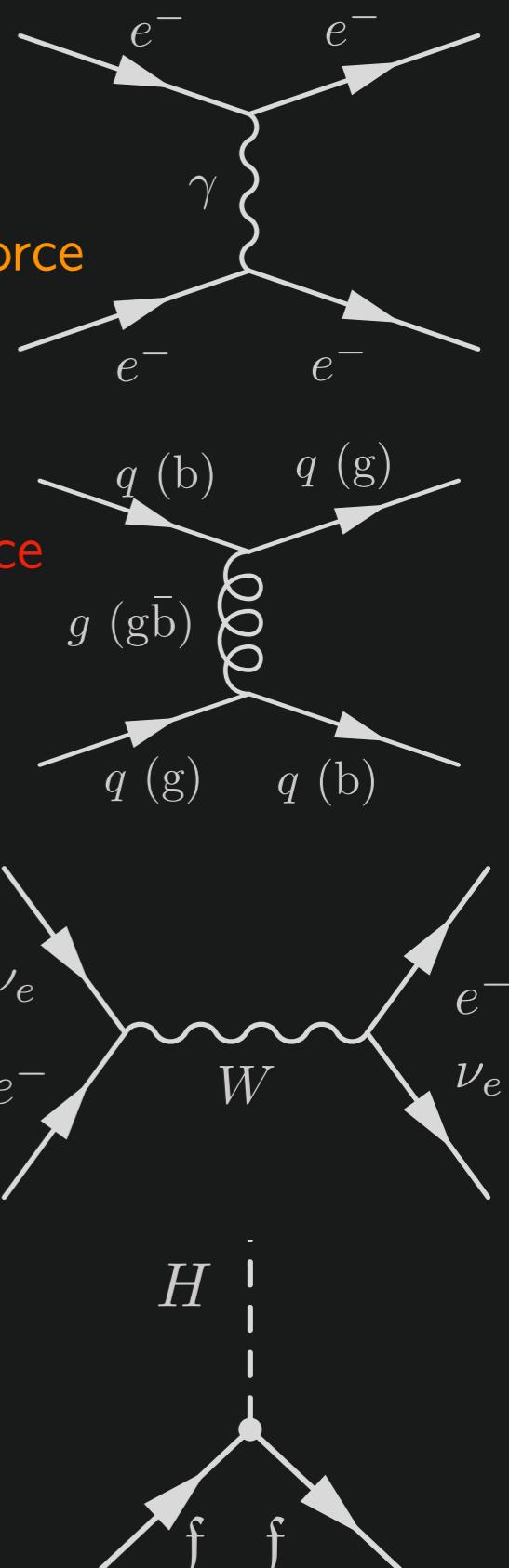
γ^0 photon
g^0 gluon
$W^{\pm\pm 1}$ W boson $80.4 \text{ GeV}/c^2$
Z^0^0 Z boson $91.2 \text{ GeV}/c^2$
H^0 Higgs boson $125 \text{ GeV}/c^2$

Electromagnetic force

Strong nuclear force

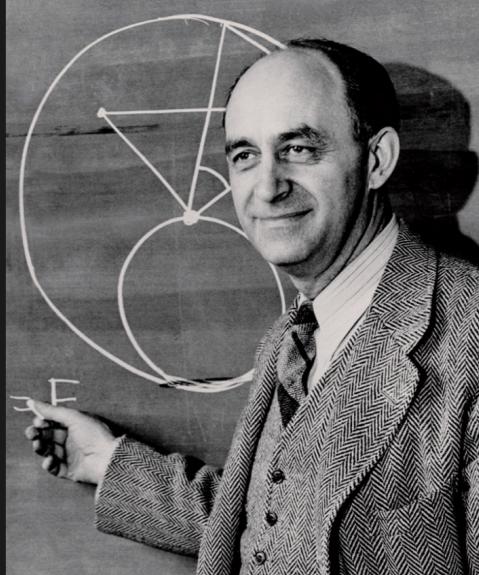
Weak nuclear force

Particle masses

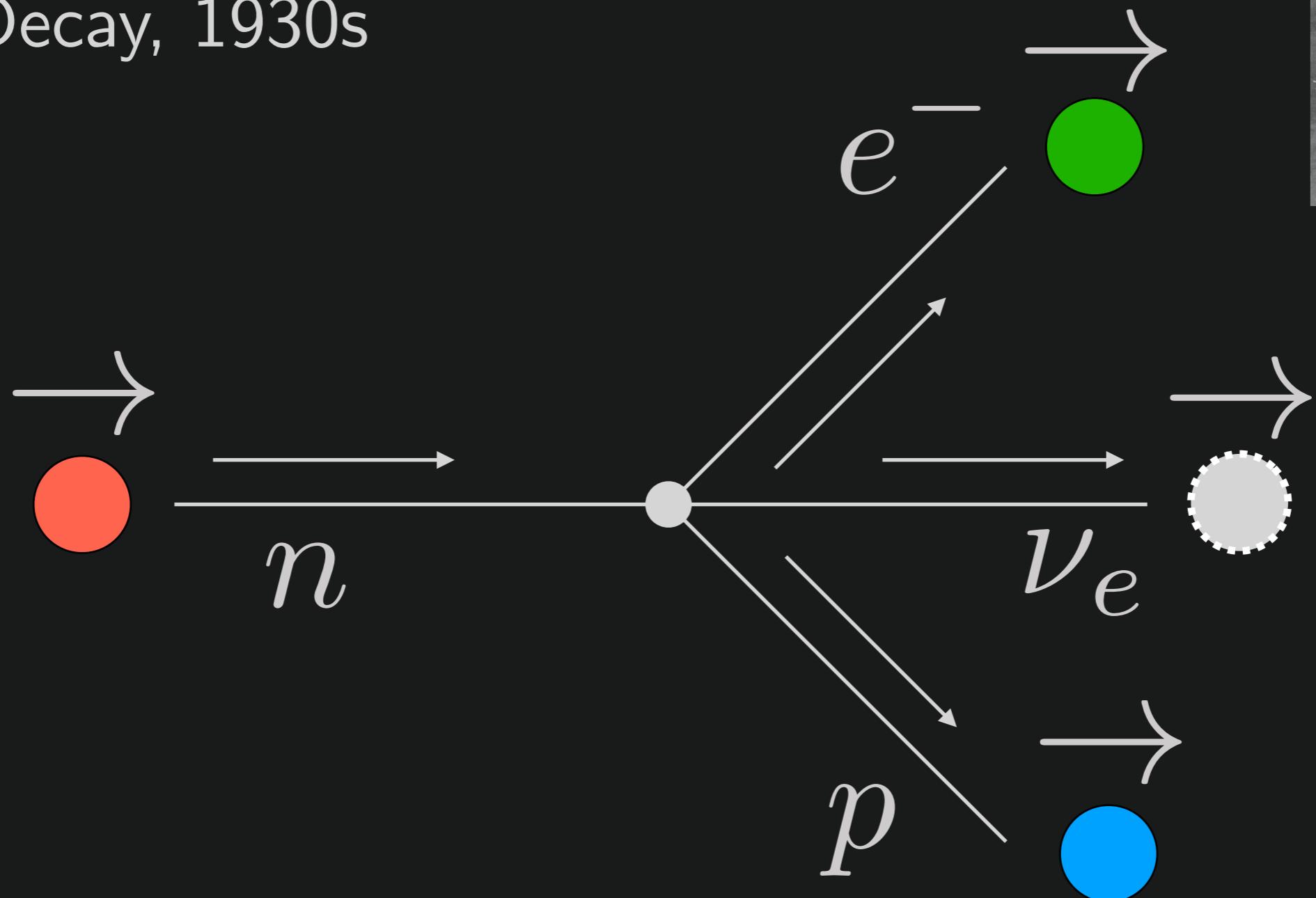


The Standard Model

Beta Decay, 1930s



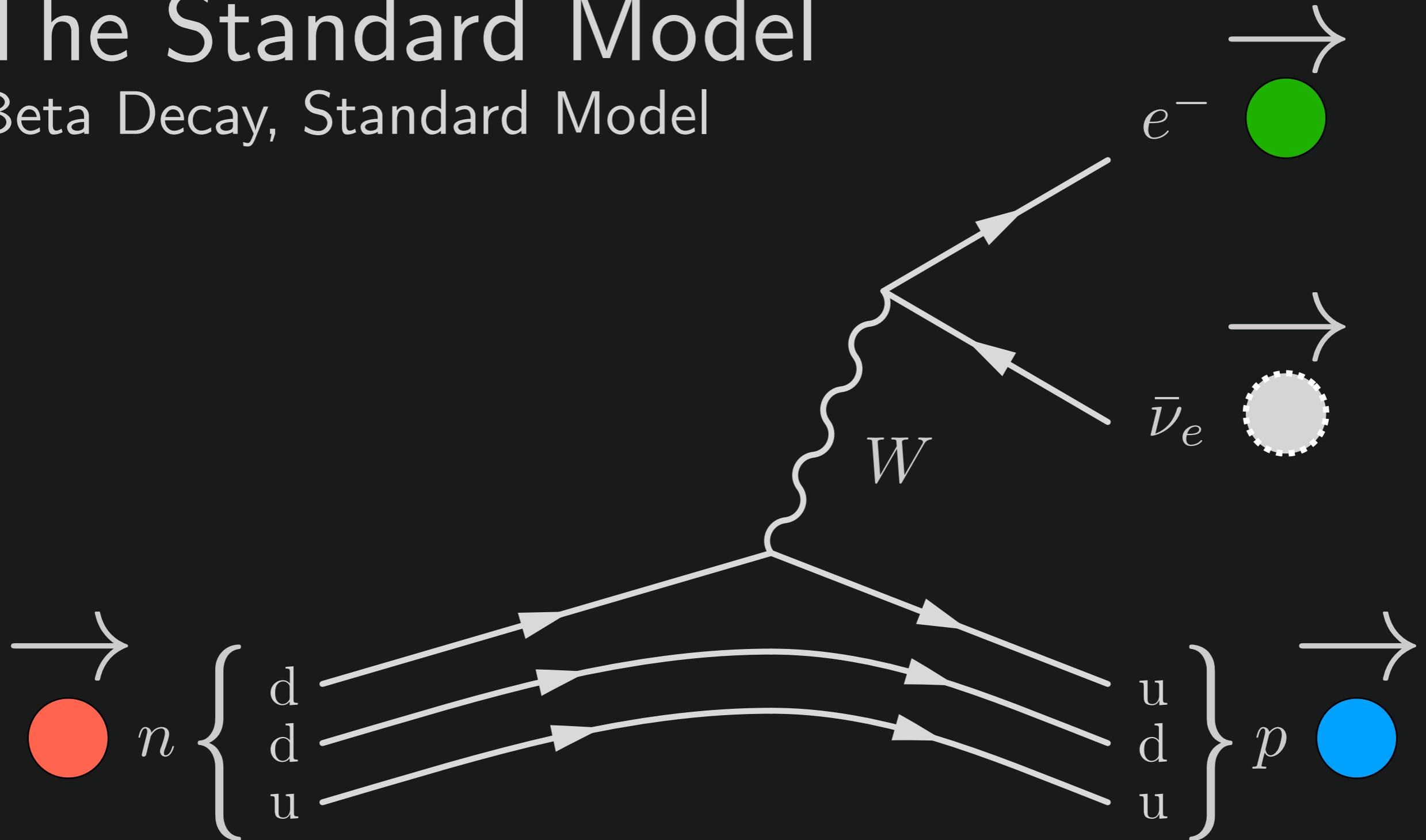
Enrico Fermi



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

The Standard Model

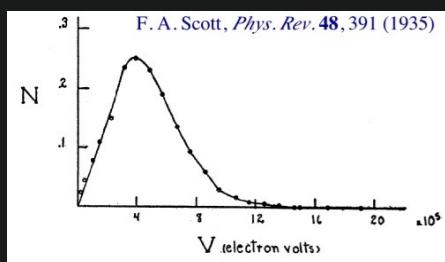
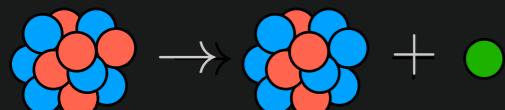
Beta Decay, Standard Model



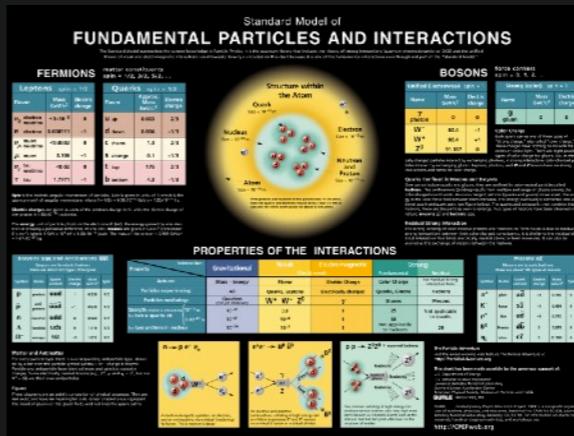
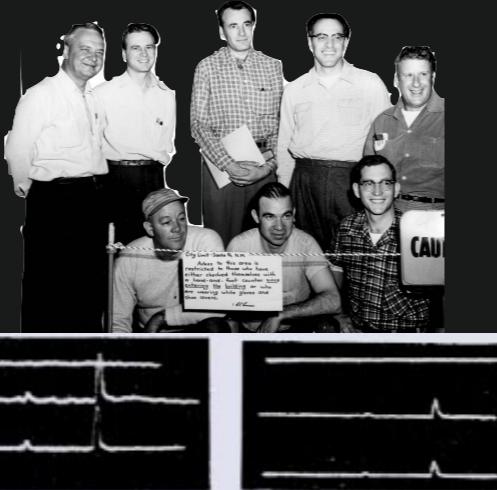
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Timeline

Chadwick



Cowan & Reines



1913:

Beta Decay Troubles

1956:

Discovery

1970s:

Standard Model

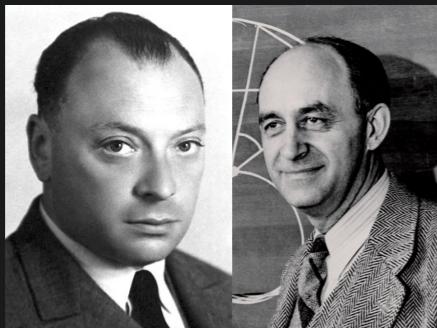
1990s - 2000s

The End of the Beginning



1930s:

Proposal & Theory



Pauli

Fermi

1962:

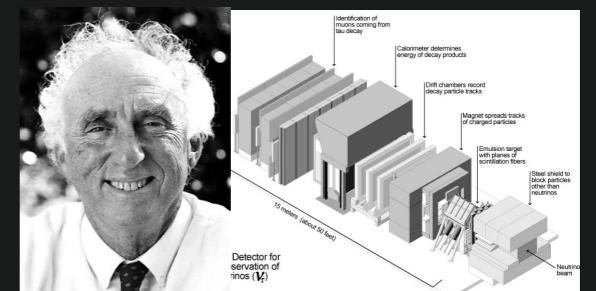
Muon Neutrinos



Lederman/Schwartz/
Steinberger

2000:

Tau Neutrinos



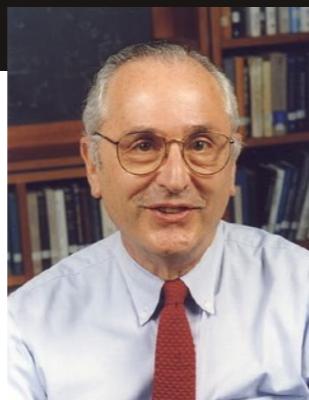
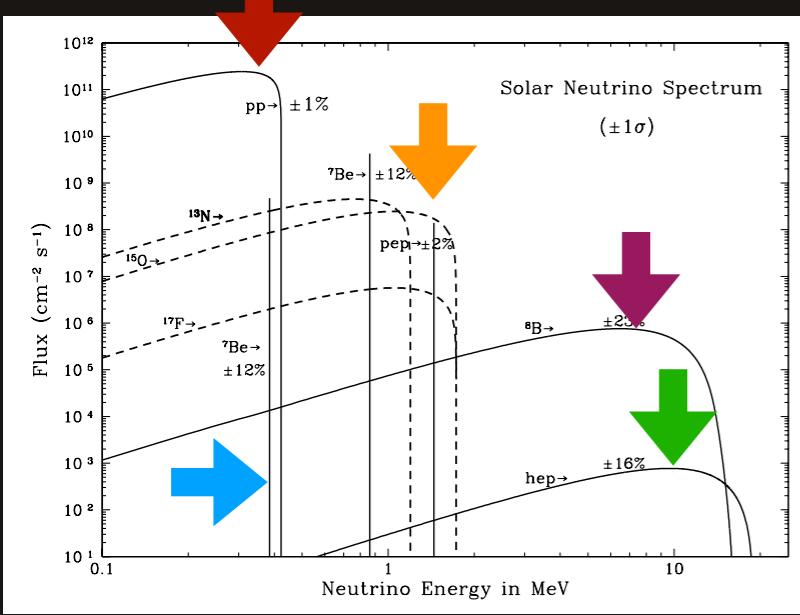
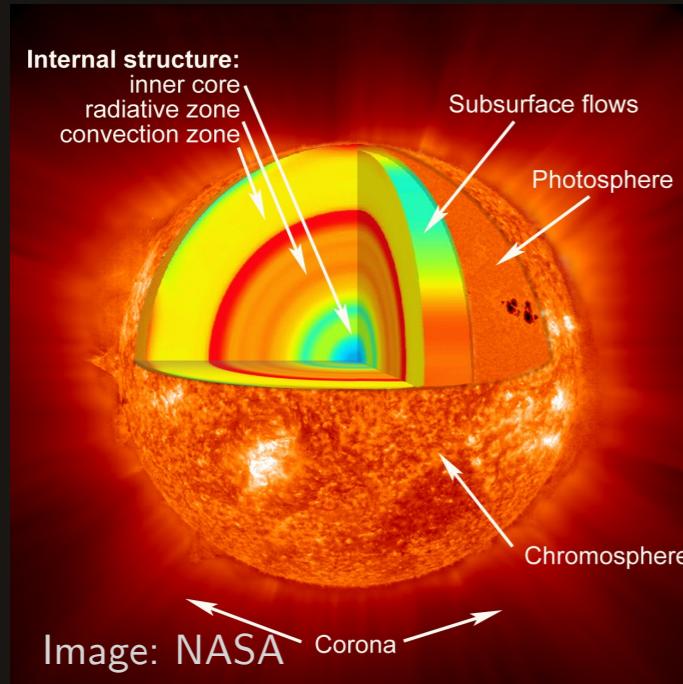
Perl, DONUT

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Next Week

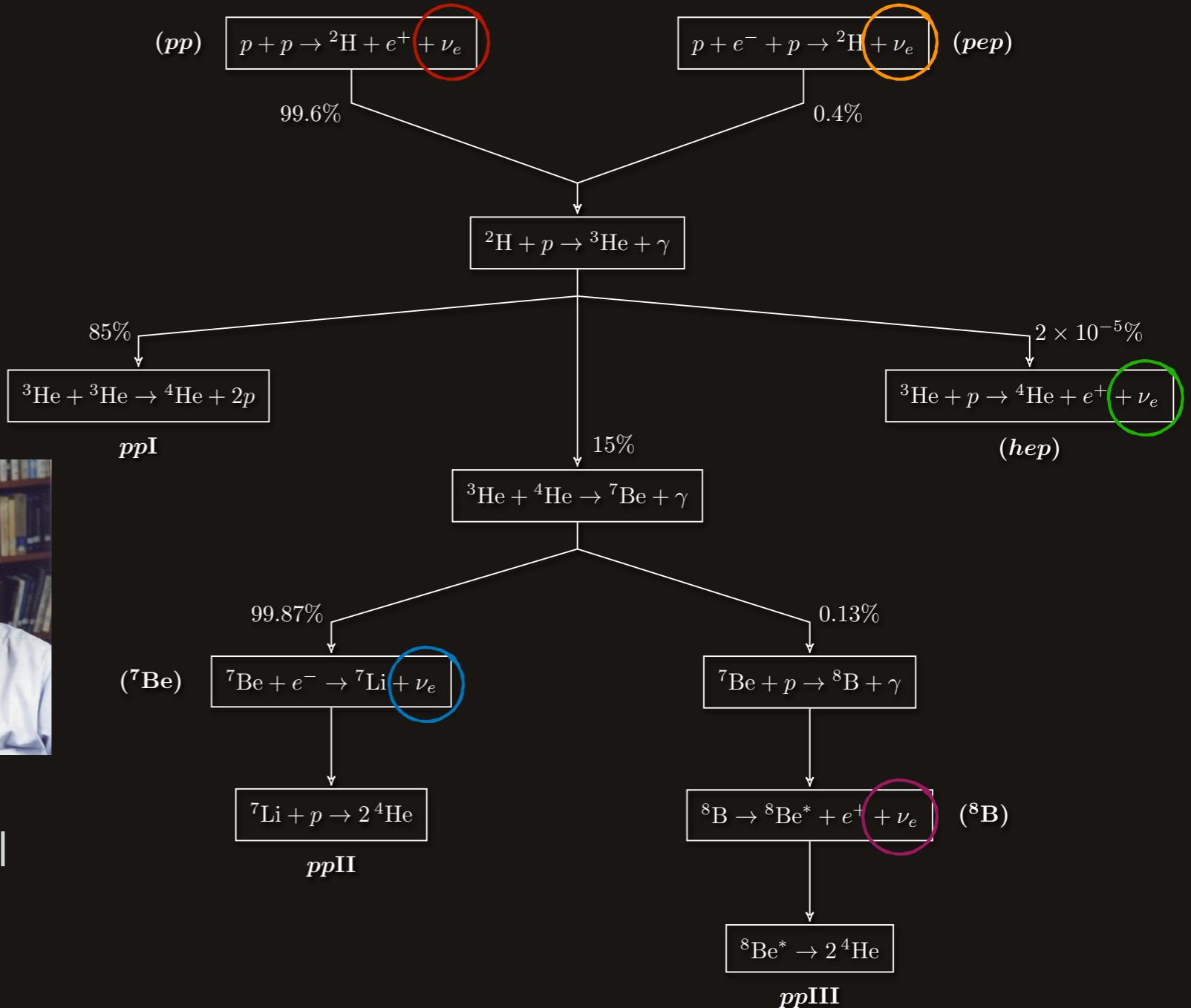
The Solar Neutrino Problem

1960s: The first neutrino anomaly



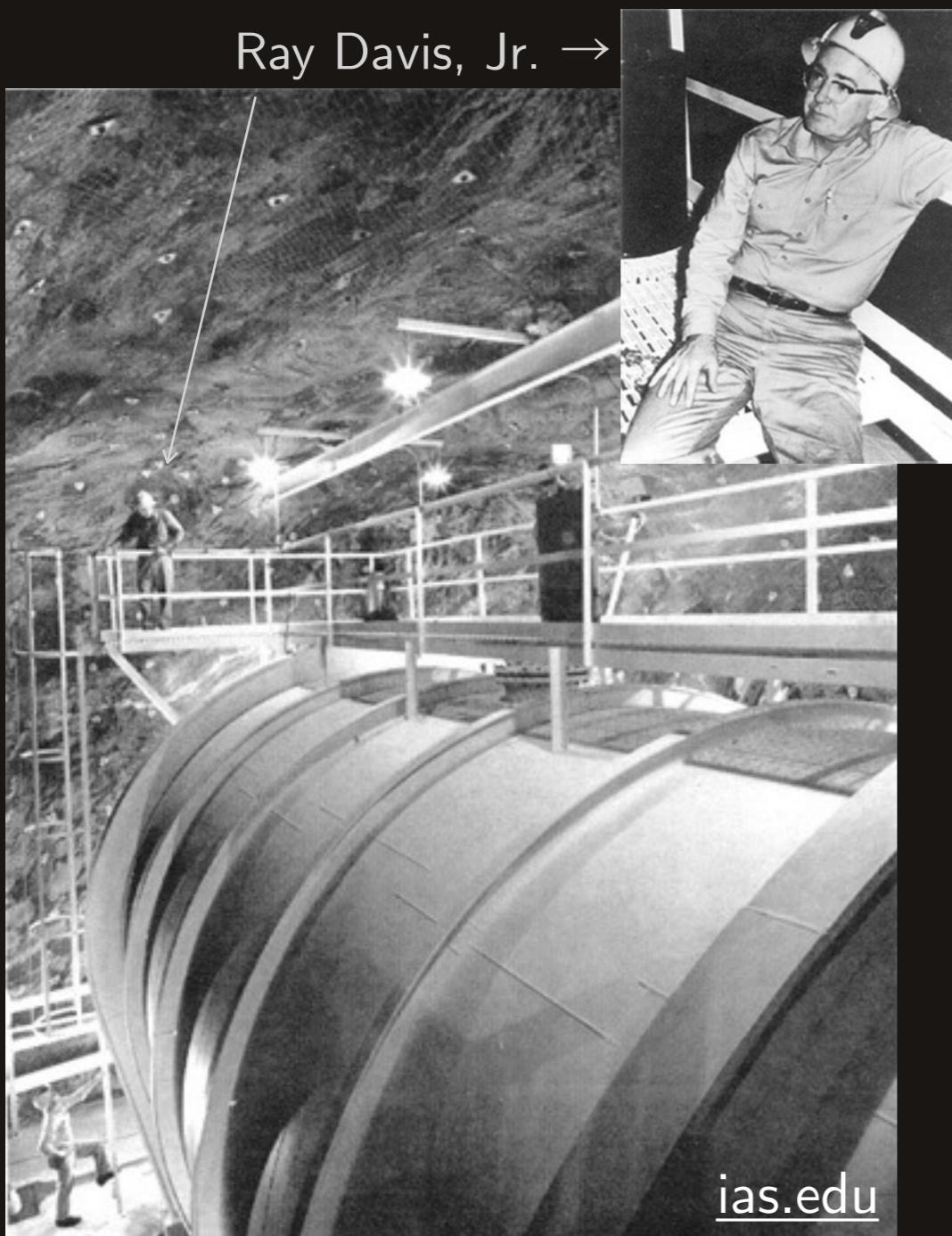
John
Bahcall

Astrophys. J. 621(1):L85-L88, 2005.



The Solar Neutrino Problem

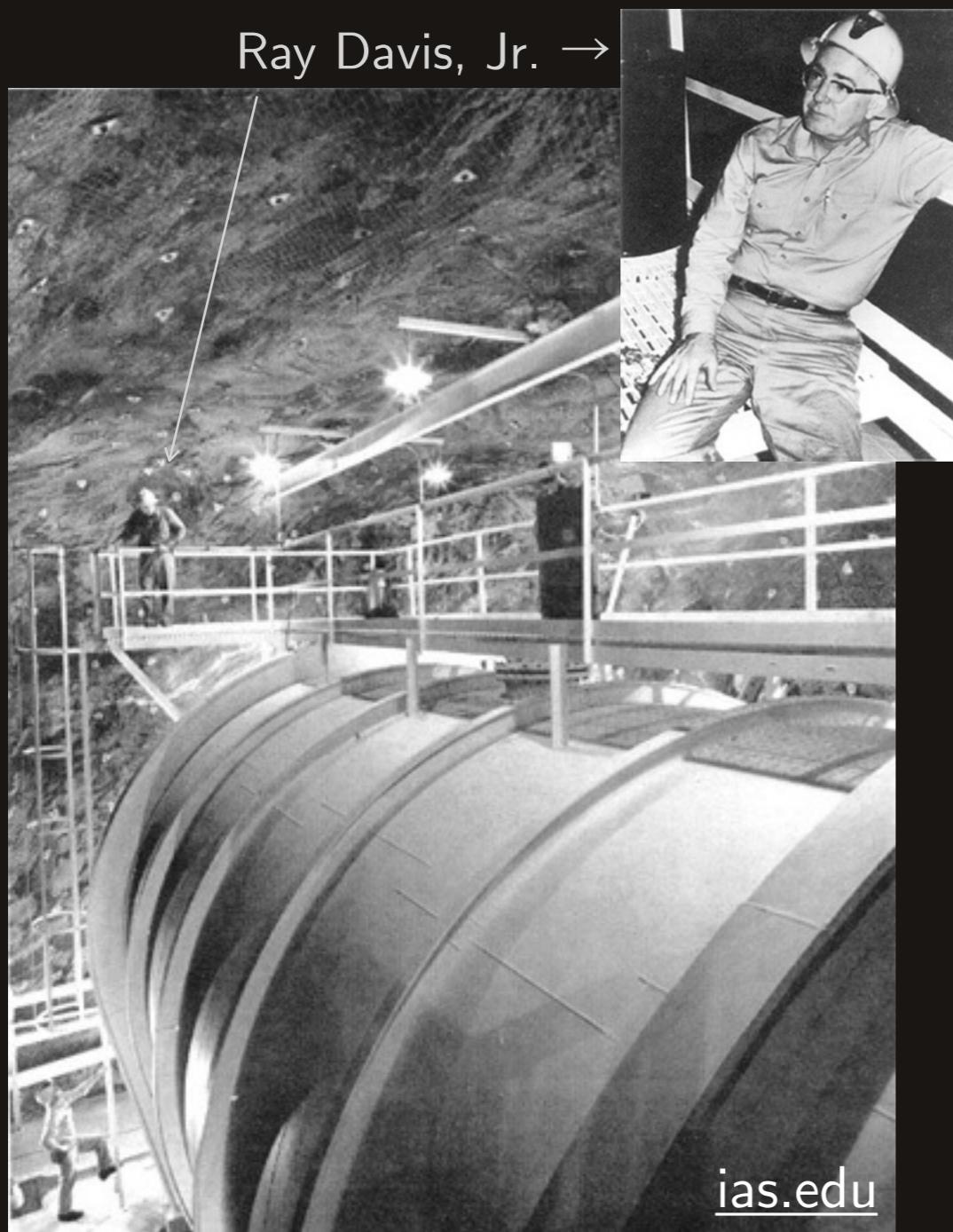
1960s: The first neutrino anomaly



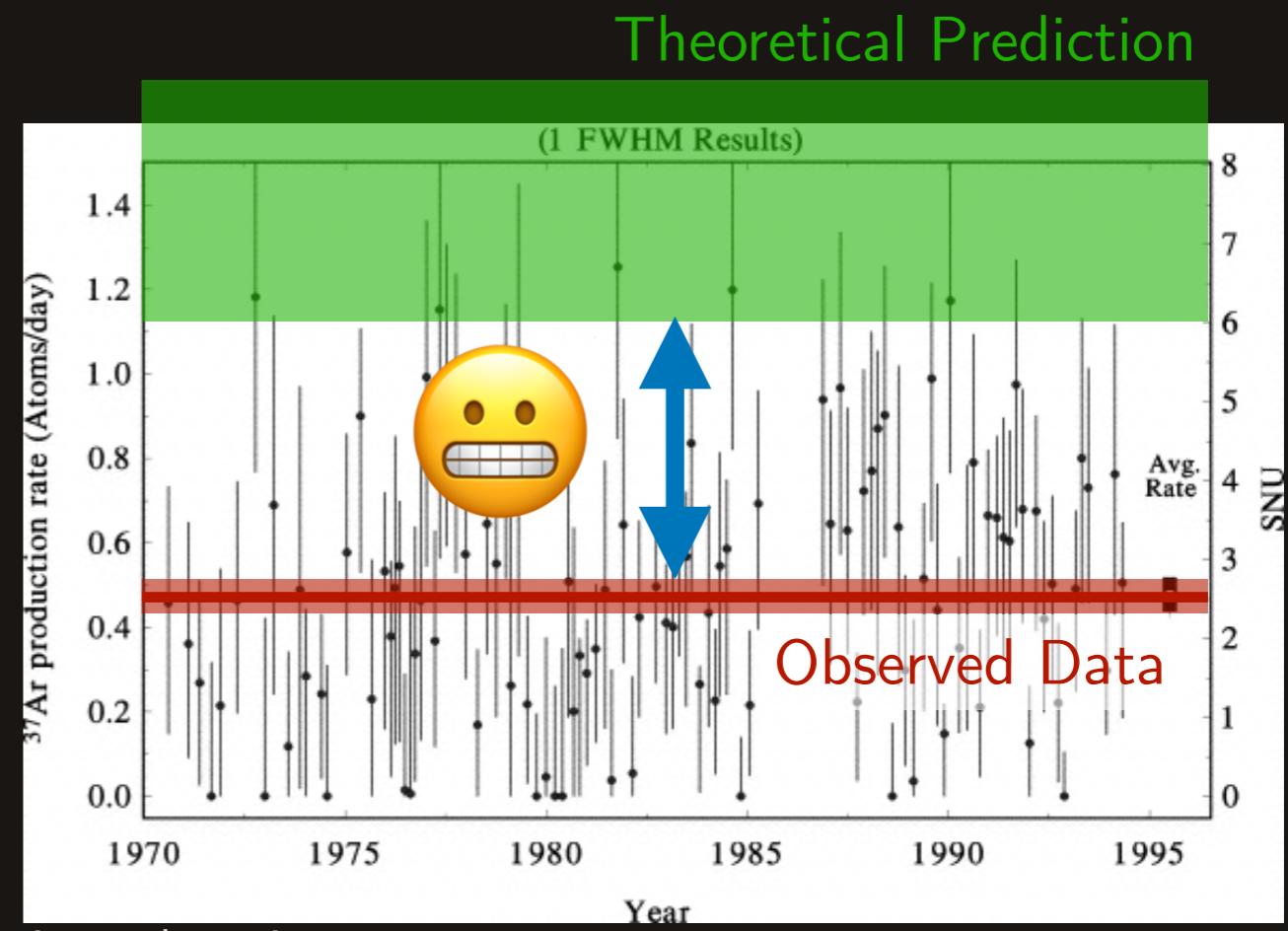
**The Homestake Solar
Neutrino Experiment**

The Solar Neutrino Problem

1960s: The first neutrino anomaly



The Homestake Solar Neutrino Experiment



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Thank You!