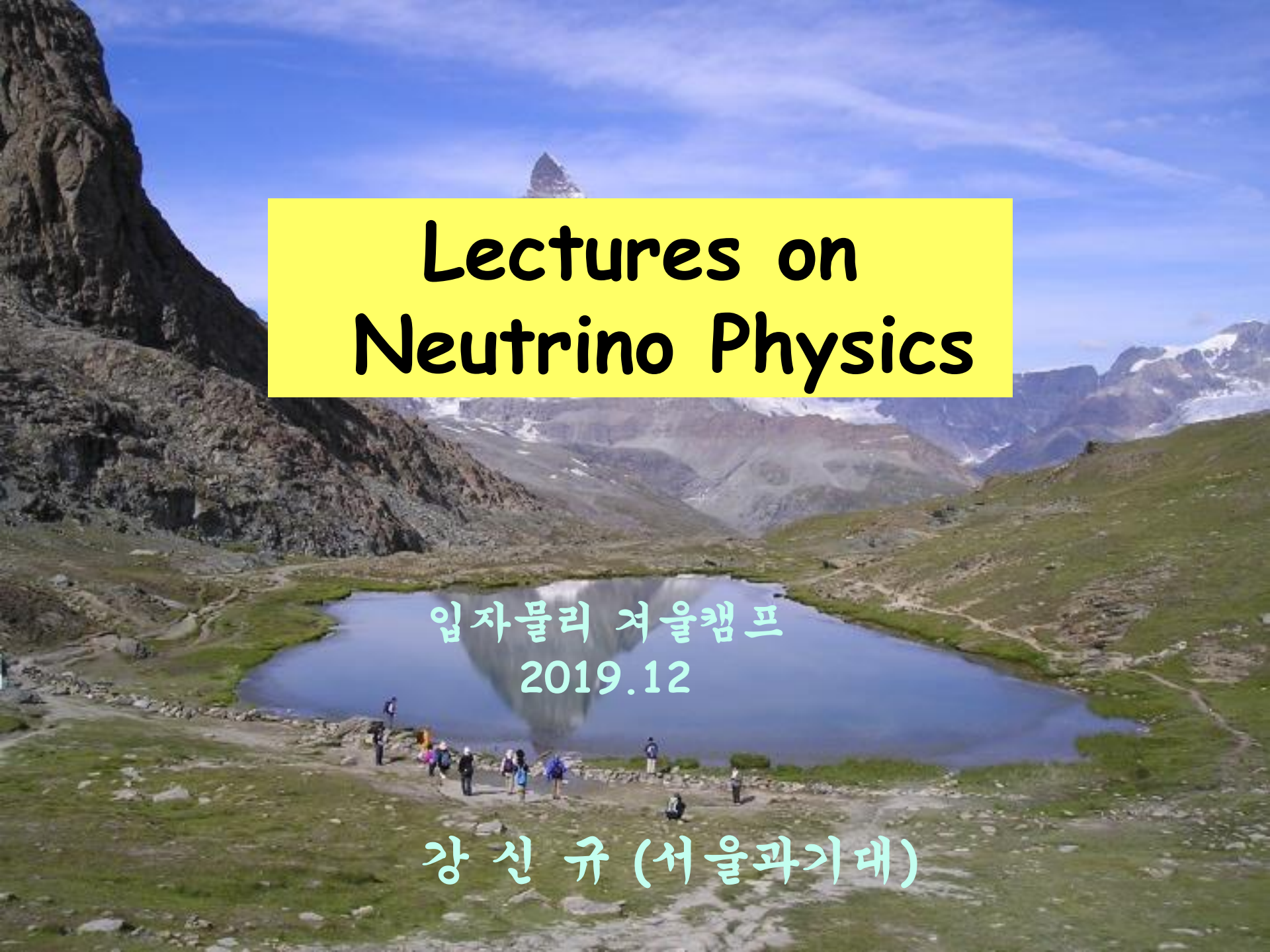

Lectures on Neutrino Physics

입자물리 겨울캠프
2019.12

강 신 규 (서울과기대)

Official Super-Kamiokande Press Release

MEDIA ADVISORY for June 5, 1998, Takayama, Japan
US EMBARGO EXPIRATION: 20:00
June 4, 1998, Pacific Daylight Time

EVIDENCE FOR MASSIVE NEUTRINOS

The Neutrino Revolution (June, 1998)

CNN interactive
CNN.com

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Scientists in Japan may have discovered secret to the universe's 'missing mass'

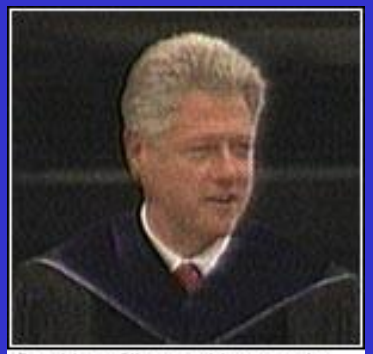
June 5, 1998
Web posted at: 5:32 a.m. EDT (0932 GMT)

TOKYO (CNN) -- An international team of scientists working from a revamped mineshaft in central Japan said Friday they may have unlocked one of the biggest mysteries of physics -- evidence that an infinitesimally small subatomic particle called the neutrino has mass.

Clinton on neutrino

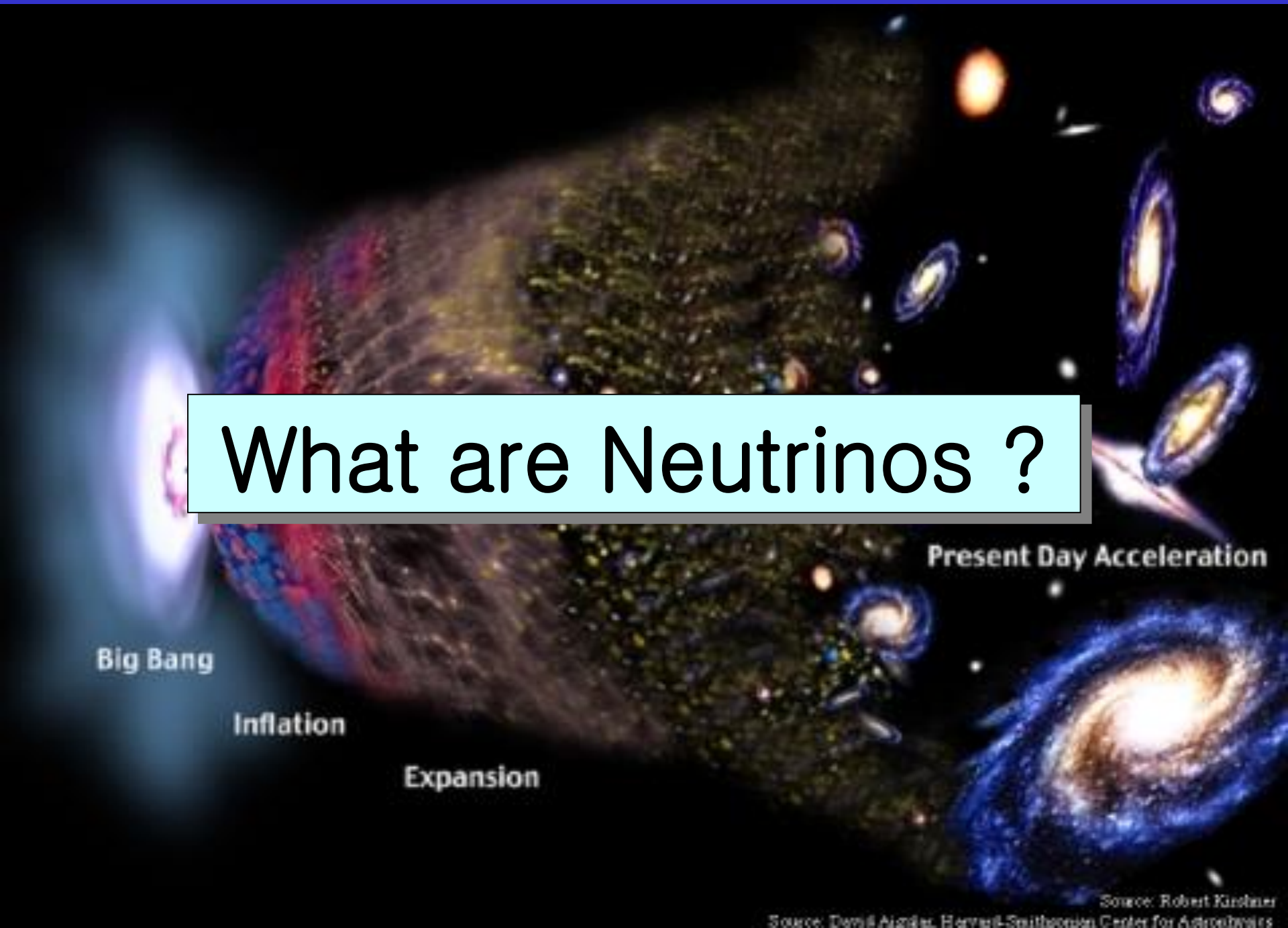
MIT 졸업식에서 Clinton연설

(excerpted from remarks at the MIT commencement, June 6, 1998)



President Clinton addresses the graduating class at MIT

[W]e must help you to ensure that America continues to lead the revolution in science and technology…….. Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. …..but it may change our most fundamental theories from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.


What are Neutrinos ?
Present Day Acceleration
Big Bang
Inflation
Expansion
Source: Robert Kirshner
Source: David Aguilar, Harvard-Smithsonian Center for Astrophysics


Elusive ghost particle
Acceleration
Big Bang
Inflation
Expansion
Source: Robert Kirshner
Source: David Aguilar, Harvard-Smithsonian Center for Astrophysics

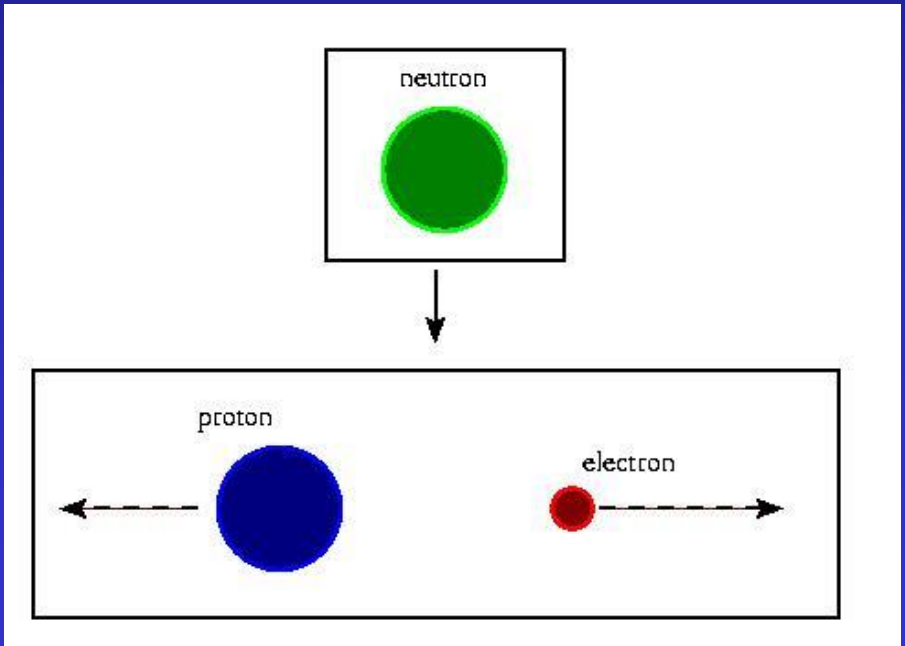
Invented to resolve a puzzle……

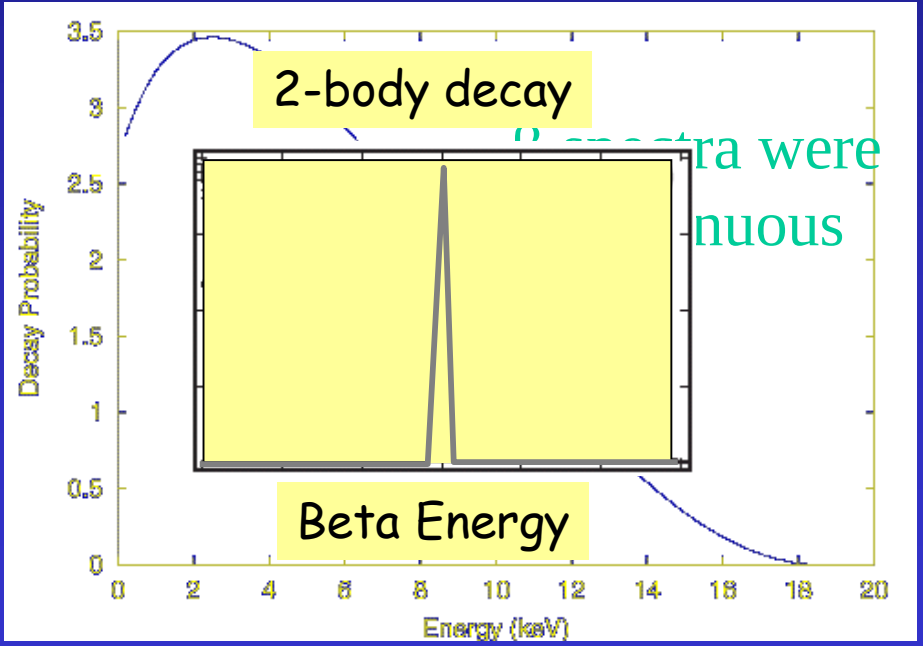
Invention of the Neutrino

Beta decay mystery (1920년대 수수께끼):

2-body decay should give mono-energetic electron

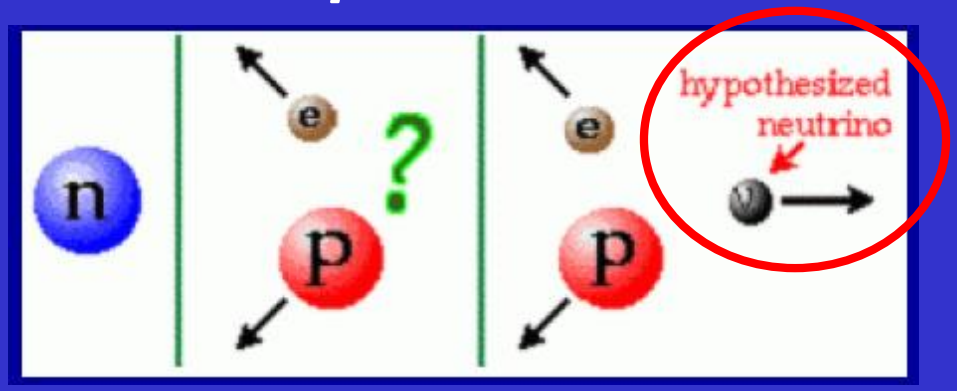
But observed spectrum is continuous





Wolfgang Pauli's solution (1930)

In β-decay



Weakly interacting massless neutral fermion
(매우 약하게 상호작용하고 질량이 없는 중성인 패르미온)

4th December 1930

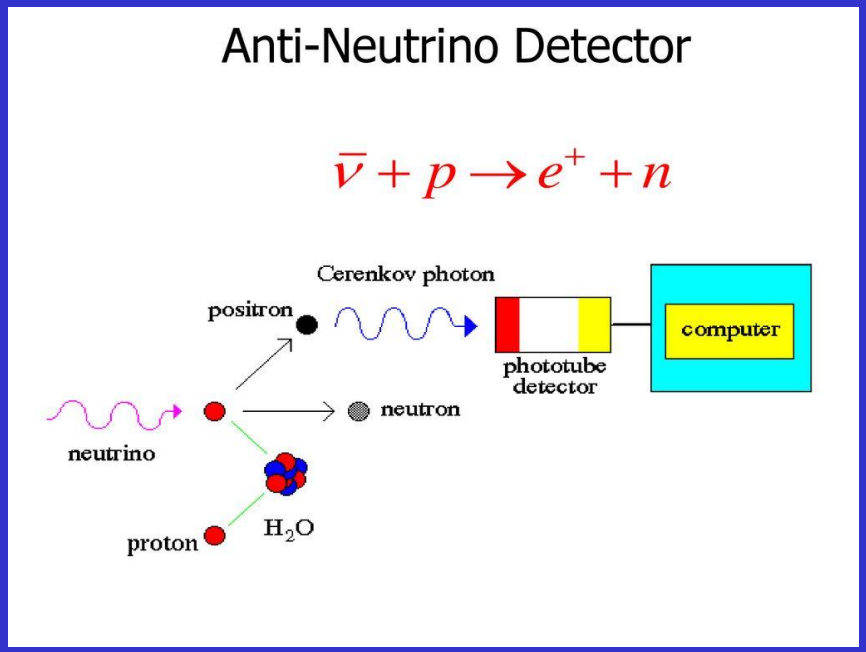
Dear Radioactive Ladies and Gentlemen,

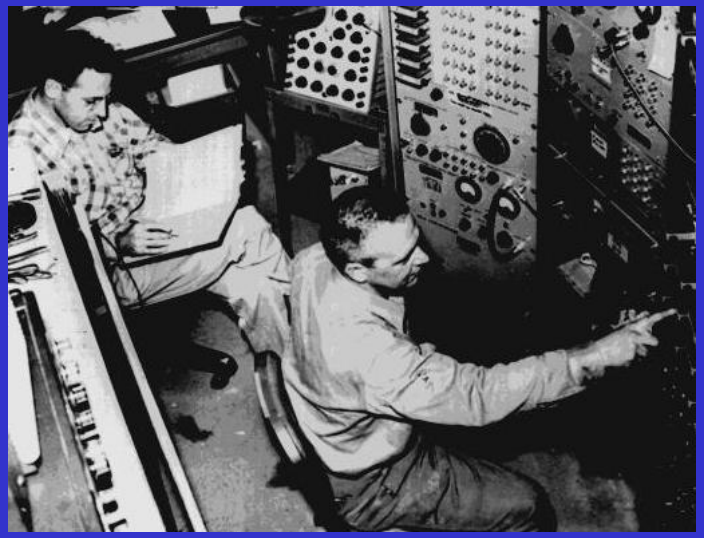
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

Discovery of Neutrino

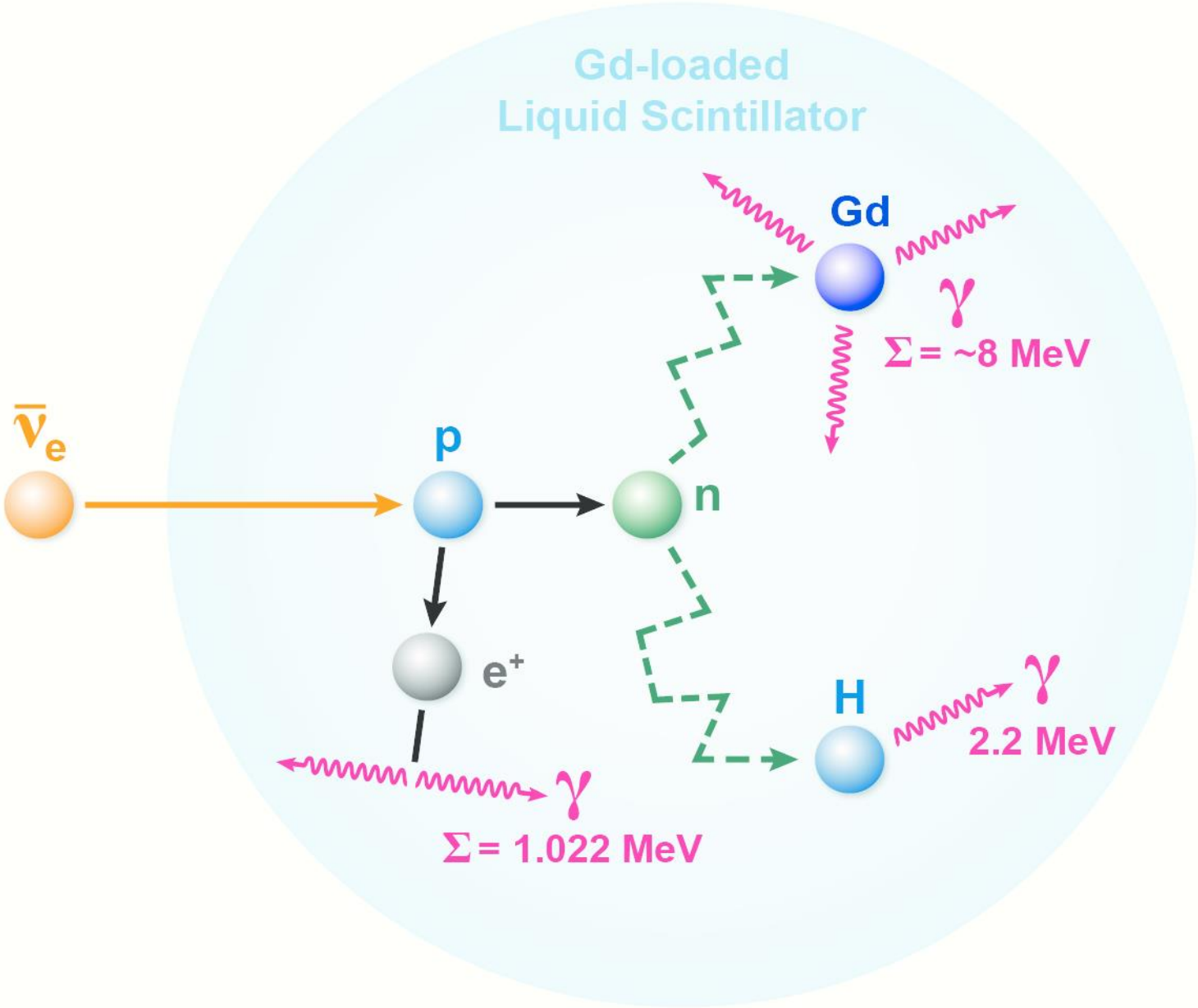
" the first detection of anti-neutrinos "

Cowan & Reines (1956)





1995년 노벨 물리학상


Gd-loaded
Liquid Scintillator
Gd
γ
Σ = ~8 MeV
$\bar{\nu}_e$
p
n
e+
H
γ
2.2 MeV
γ
Σ = 1.022 MeV

Discovery of Muon Neutrino

1950년대 수수께끼 :
당시 $\mu \to e + \nu + \bar{\nu}$ 현상은 관찰되었으나, μ→e + γ 현상은 전혀 관측할 수 없었다…

Lederman, Schwartz, Steinberger(1962)

$$\pi^- \to \mu^- + \bar{\nu}_x$$

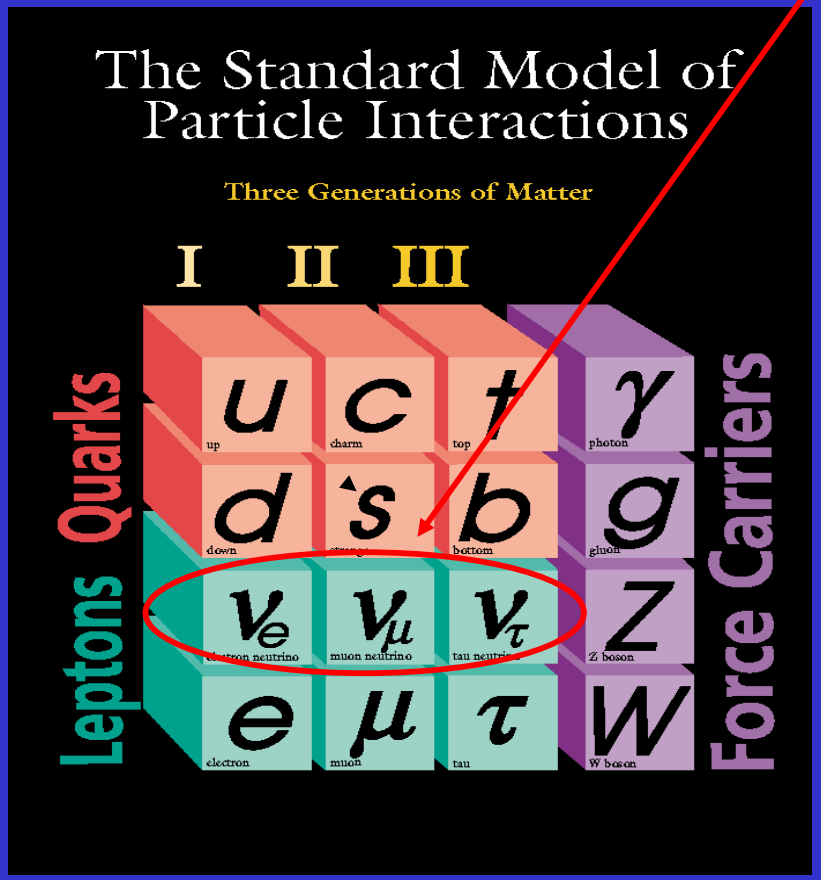
$$\bar{\nu}_x + p \to e^+ + n$$

forbidden

1988년 노벨 물리학상

Neutrinos in the standard model

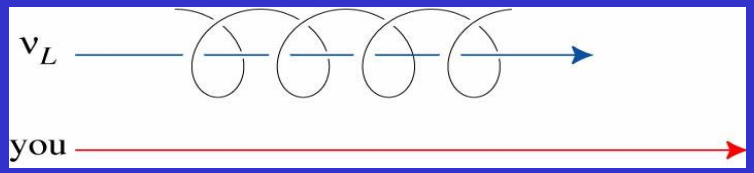
표준모형 : our best model for the microscopic universe…

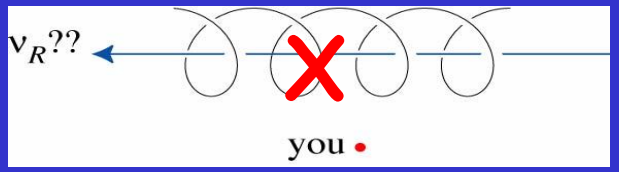


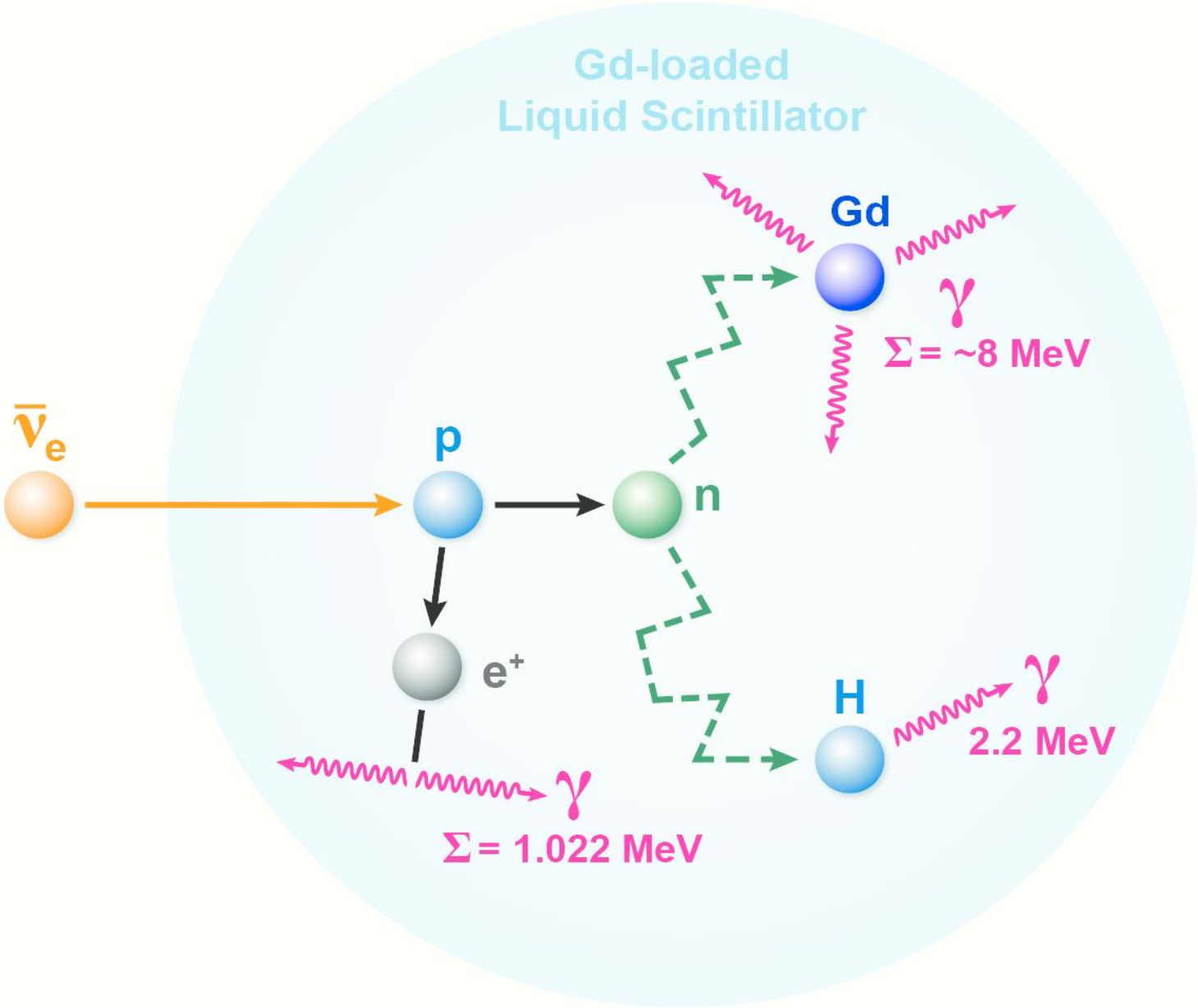
Neutrinos:

- Come in three `flavors`
- Are massless
- Interact weakly
- Cannot change flavor

All neutrinos left-handed

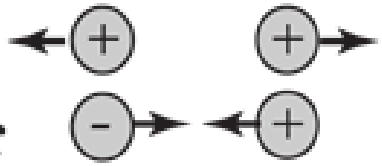





Gd-loaded
Liquid Scintillator
Gd
γ
Σ = ~8 MeV
$\bar{\nu}_e$
p
n
e+
H
γ
2.2 MeV
γ
Σ = 1.022 MeV

Neutrinos in the standard model

- *EM interaction*

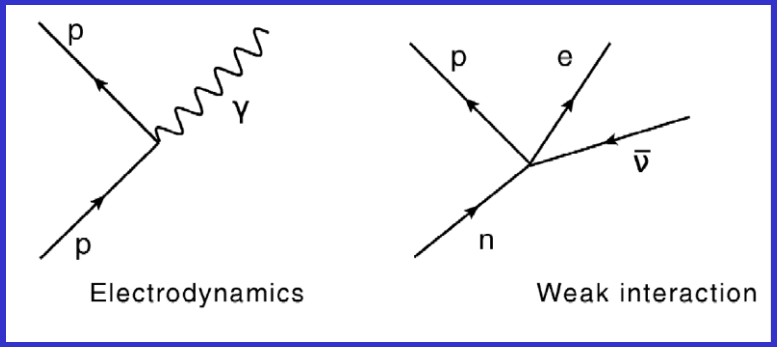
	Strength	Range (m)	Particle
Electro-magnetic 	$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1

- *Weak interaction*

	Strength	Range (m)	Particle
Weak  neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1

Neutrinos in the standard model

- *Fermi theory of weak interaction*



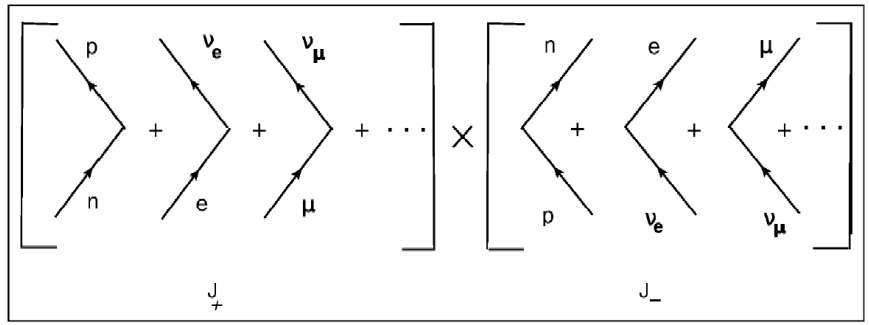
$$J^{\mu}(x) = \bar{\psi}(x)\gamma^{\mu}\psi(x)$$

namely

$$\mathcal{L}_{\gamma} = e(\bar{\psi}(x)\gamma^{\mu}\psi(x)A_{\mu}(x))$$

$$\mathcal{L}_{W} = \frac{G}{\sqrt{2}}(\bar{p}(x)\gamma^{\mu}\, n(x))(\bar{e}(x)\gamma_{\mu}\nu(x))$$

$$L_{FG} = \frac{G_F}{2\sqrt{2}}(J_+J_- + J_-J_+)$$

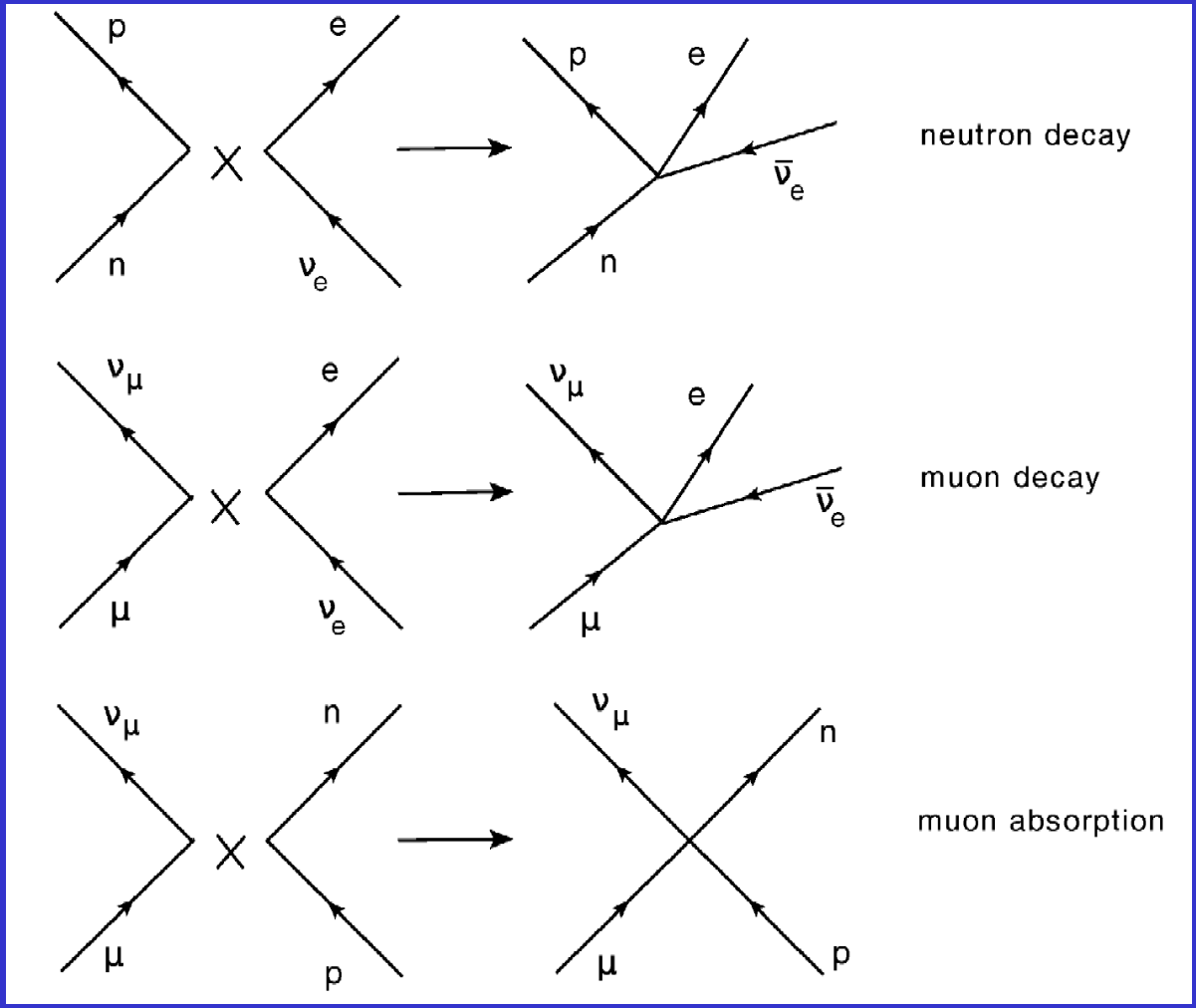


$$J_+ = \bar{p}n + \bar{\nu}_e e + \bar{\nu}_\mu \mu + \ldots,$$

$$J_- = \bar{n}p + \bar{e}\nu_e + \bar{\mu}\nu_\mu + \ldots.$$

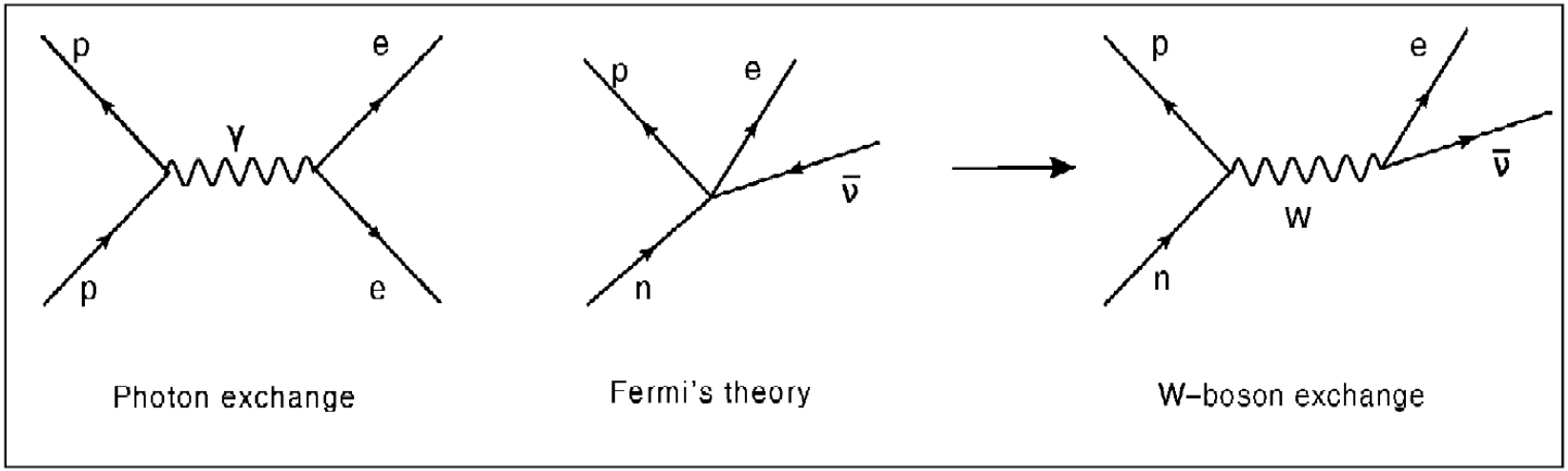
Neutrinos in the standard model

- *Fermi theory of weak interaction*



Neutrinos in the standard model

- *Fermi theory of weak interaction*



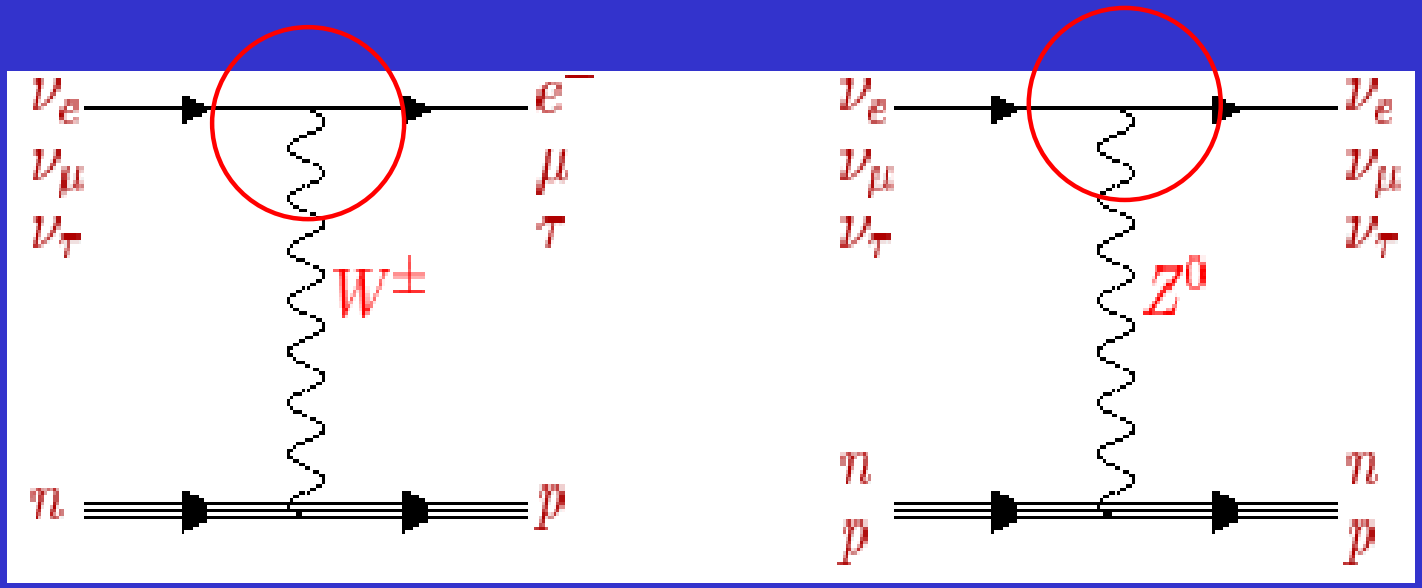
$$g(J_+W^+ + J_-W^-)$$

$$eJ_EA + g(J_+W^+ + J_-W^-) + g_NJ_NZ$$

Neutrinos in the standard model

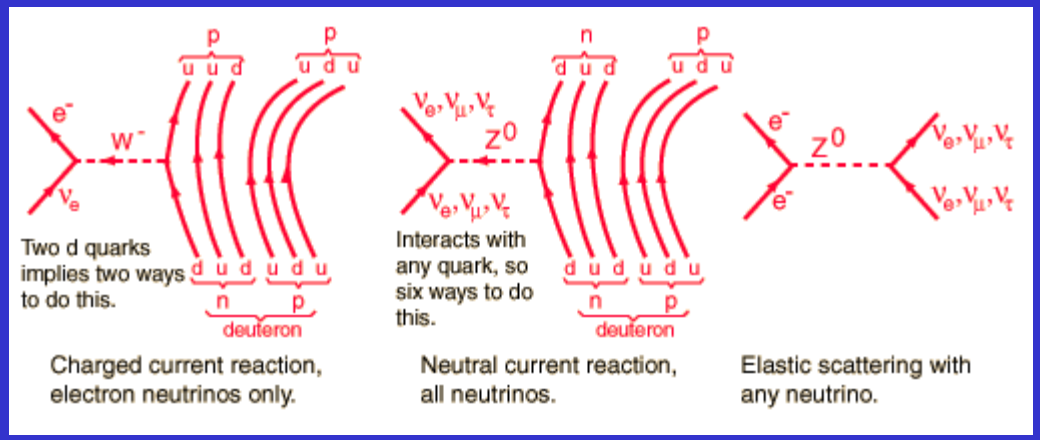
- *How neutrinos interact ?*

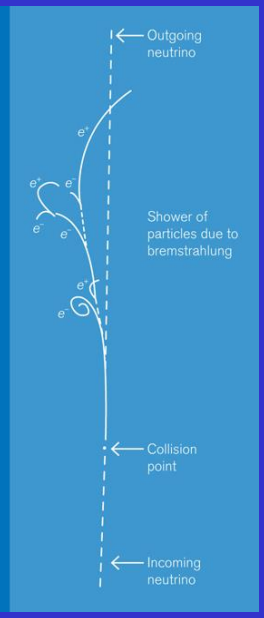
- **Weak interaction exchanging** $W^{\pm}, Z^{0}$



Neutrinos in the standard model

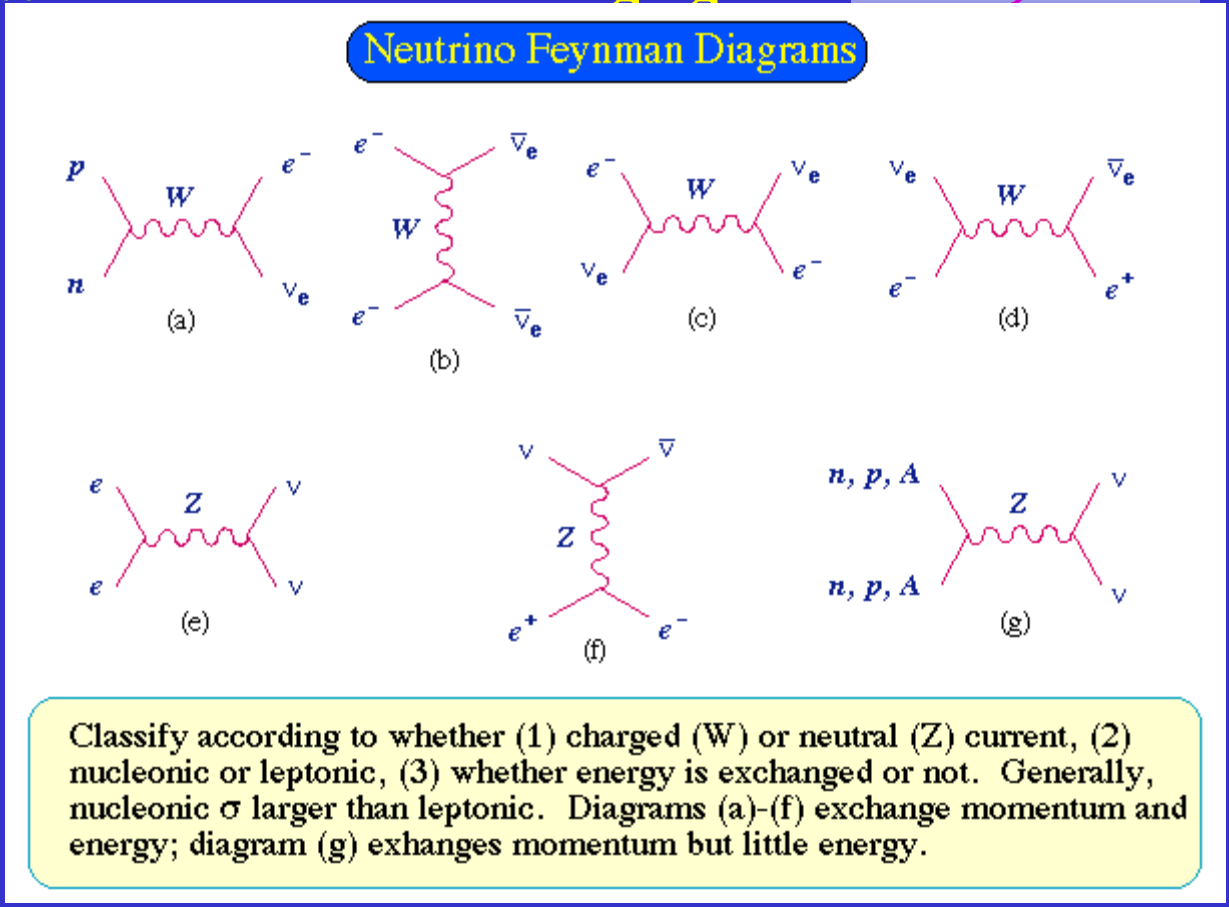
- **Weak interaction exchanging** $W^{\pm}, Z^{0}$





Neutrinos in the standard model

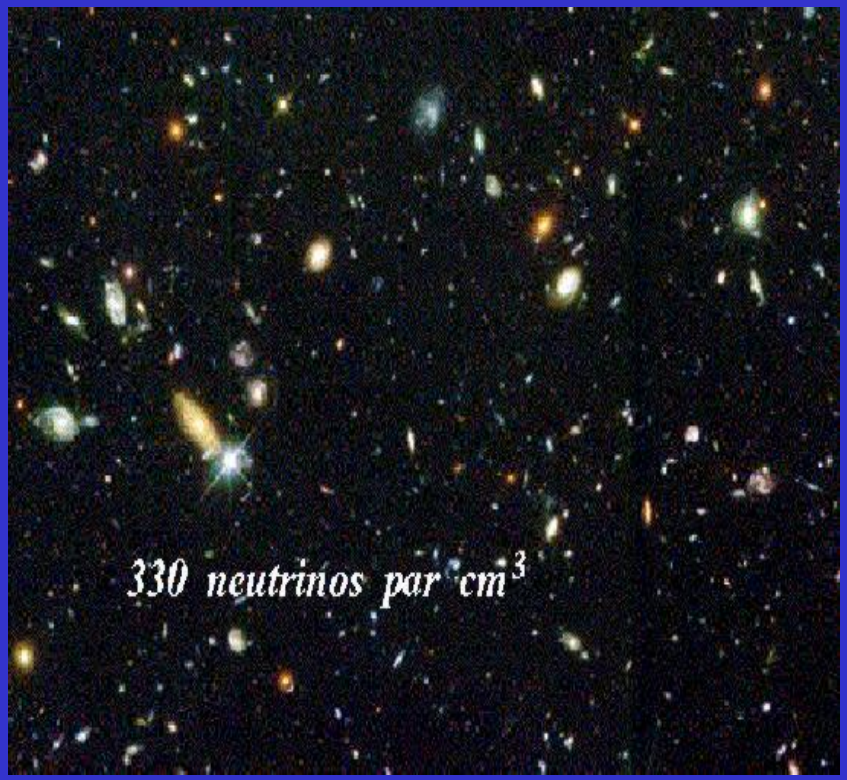
- **Weak interaction exchanging** $W^{\pm}, Z^{0}$



•Neutrinos in the Universe

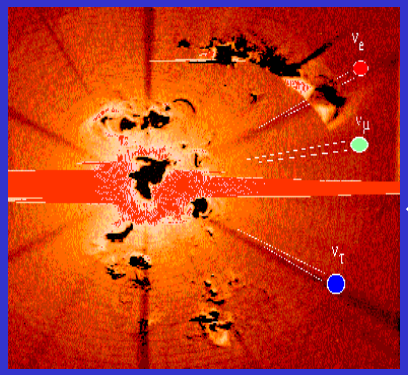
•***Birth of Neutrinos***

•***How many neutrinos in our Universe?***

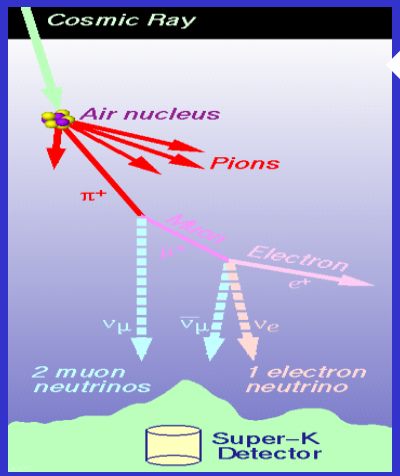


Neutrino Sources

←Sun



←Cosmology



←Atmosphere

←Earth

Astronomy: →
Supernovae
GRBs
UHE ν's

Reactors→

Accelerators→

Neutrinos are everywhere.

Every second tens of thousands of neutrinos are passing through our body.

그렇다고 넘어지지는 않는다

중성미자 물리학이 왜 중요해졌는가?

The Neutrino Revolution (1998-)

Discovery of Neutrino Oscillation

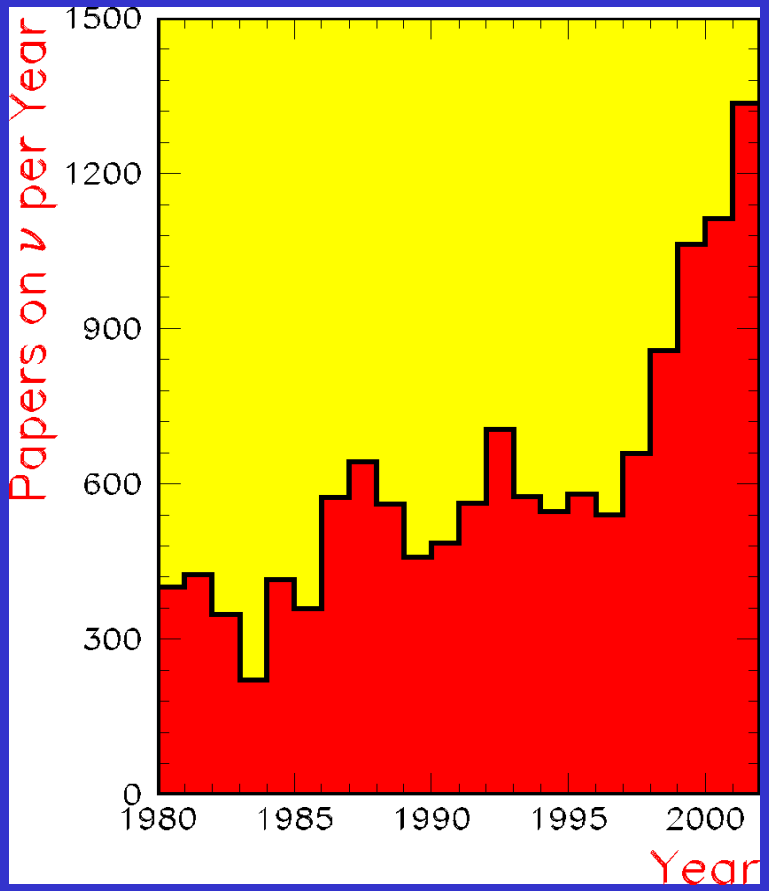
Neutrinos are massive.

Neutrinos mix.

- 새로운 물리 이론의 단서
- 우주 생성 비밀의 열쇠


고에너지 중성미자는 우주론의
여러 가지 퍼즐들을 해결하는 데
결정적 역할을 할 지도 모른다 !!!

Neutrino's are hot!



2002년 : 노벨물리학상
(Davis & Koshiba)
for detection of cosmic neutrinos

Neutrinos
from backstage to center stage

Neutrino's are still hot!

2015년 : 노벨물리학상 : *"discovery of neutrino oscillation*
Kajita & Mcdonald

Yoji Totsuka(March 6, 1942 – July 10, 2008)

"The discovery of oscillation in neutrinos was largely due to the work done by Professor Totsuka," Kajita said.