- From 1967-1973 (~5 years) we have 5 works which received the Nobel Prizes in particle physics

- I thought it was **too late** for me to join the GUT paradigm
- I started to consider some different direction from the GUT, which motivated me to the idea of *the seesaw mechanism*

GUT Paradigm **form 1974**

- The GUT breaks down to the standard model at very high energies M ~10^{15} GeV

SU(5) → SU(3)xSU(2)xU(1)

We strongly believed unifications of interactions and matters at very high energies !!!

I started to consider a unification of matters

Unification of Families

Maehara, Yanagida （1977）
Wilzeck, Zee （1978）

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad \begin{matrix} u_R^i \\ d_R^i \end{matrix} \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad e_R^i \qquad (i = 1 - 3)$$

←SU(3)→ ←SU(3)→

Horizontal Gauge Symmetry

M~10^{15} GeV

- But we had **a serious problem**

There is a gauge anomaly and we can not quantize the SU(3) gauge symmetry

We need to introduce **three right-handed neutrinos** to cancel the gauge anomaly

Yanagida (1979)

ν_R^i

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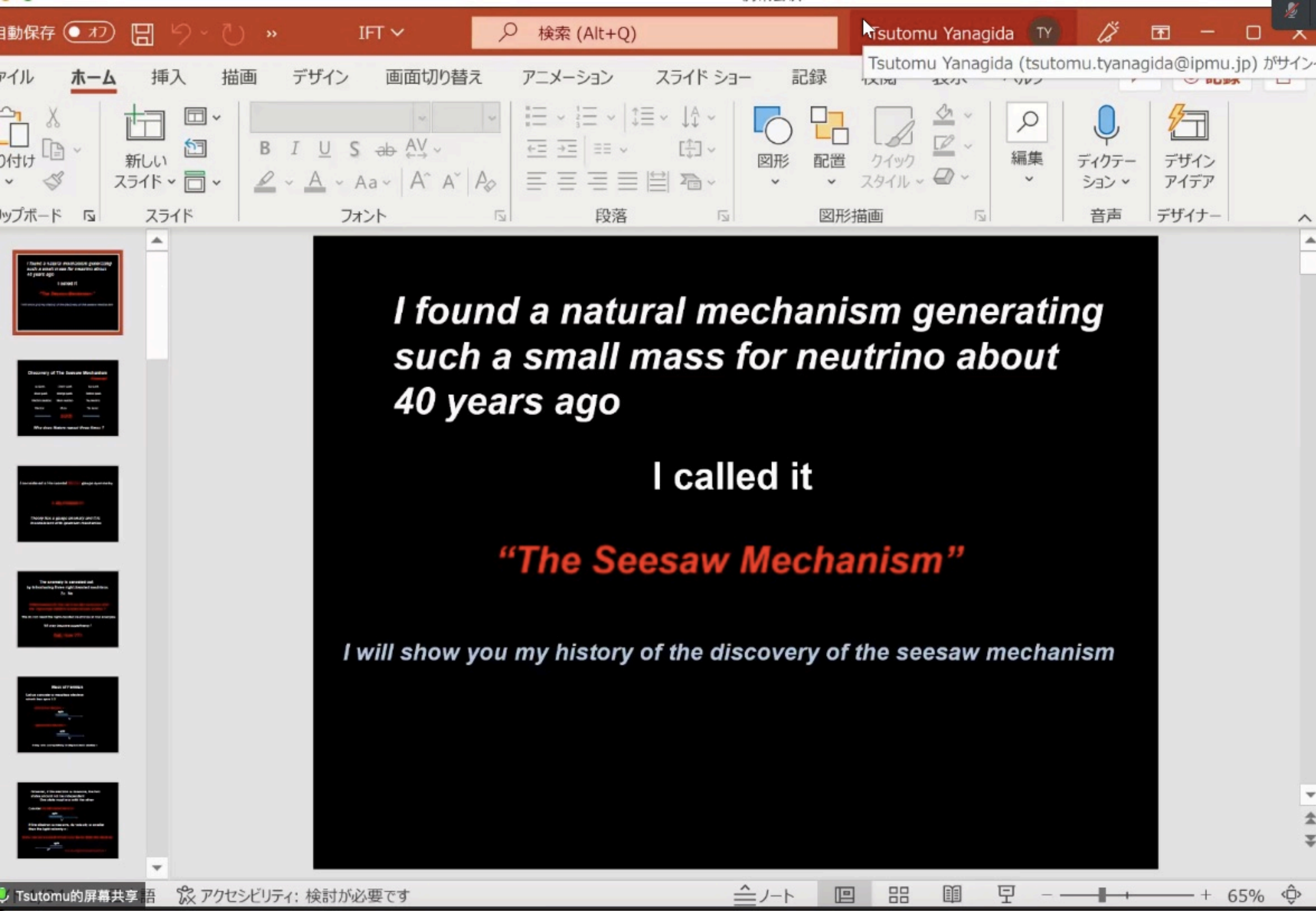

I found a natural mechanism generating such a small mass for neutrino about 40 years ago
I called it
“The Seesaw Mechanism”
I will show you my history of the discovery of the seesaw mechanism

Mass of Fermion

Let us consider a massless electron which has spin 1/2

| left-handed electron > :

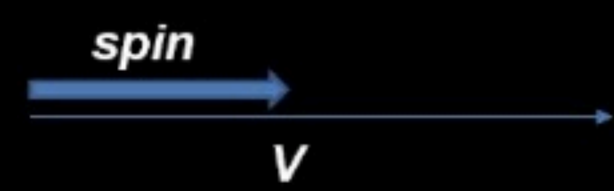
| right-handed electron > :

They are completely independent states !

However, if the electron is massive, the two states should not be independent

One state must mix with the other

Consider the left handed electron



If the electron is massive, its velocity is smaller than the light velocity c !

Now, ride on a rocket which runs faster than the electron

It is the right-handed electron !

I searched for Pauli's papers and found a paper published in 1957

The anti-particle of a chiral fermion has its opposite chirality

The anti-particle of N_R is left-handed !

They are neutral and mix with each other

M_R becomes superheavy !!!

Seesaw mechanism

T. Yanagida (1979)
Gell-Mann, Ramond, Slansky (1979)
P. Minkowski (1977)

ν_R is singlet and has no charge. Thus it may have a large Majorana mass

$$\frac{1}{2} M \bar{\nu}_R^C \nu_R$$

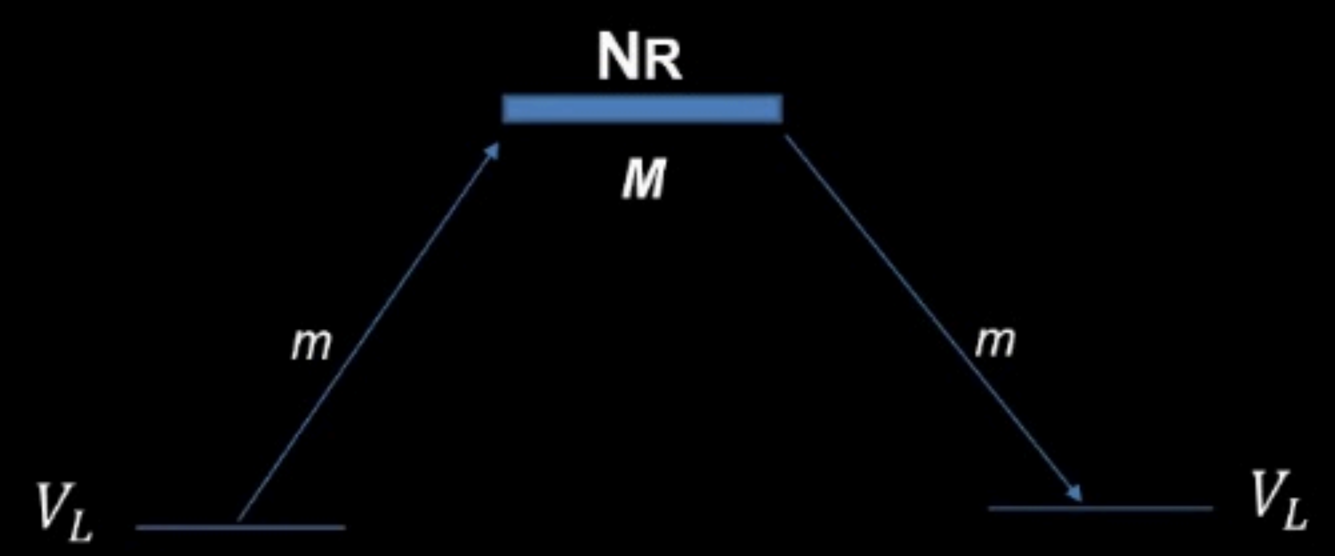
Pauli-Gursey transformation: Weyl fermion → Majorana fermion

$$\nu = \nu_L + \nu_L^C \quad ; \quad N = \nu_R + \nu_R^C$$

neutrino mass matrix :

$$(\bar{\nu} \ \bar{N}) \begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \qquad m = y_\nu \langle H \rangle$$

What happens for the <u>left handed</u> neutrinos ?



Heisenberg Uncertainty Principle

dt x <u>dE</u> ~1 :   (<u>dE</u>=M)

The left-handed neutrino transfers to NR for a very short time dt~1/M and gets a mass m (1/M) m

Two mass eighen values :

$$m_\nu \simeq \frac{m^2}{M} \quad ; \quad M_N \simeq M$$

$$m_\nu \simeq 0.05\text{eV} \longrightarrow M \simeq 10^{15}\text{GeV} \;\; \text{for } m \simeq m_t \simeq 173\text{GeV}$$

The small neutrino masses strongly suggest the presence of super heavy Majorana neutrinos N

Out-of-thermal equilibrium processes may be easily realized around the threshold of the super heavy neutrinos N

The Yukawa coupling constants y_ν can be a new source of CP violation

....

....

- Come back from the Madrid File

I found the seesaw mechanism

m(neutrino) = m^2/M

predictes very small masses O(1) eV in 1979

The neutrino masses were discovered in the super-Kamiokande experiments in 1998,

m(v)=0.05 eV...

Nobel prize in 2015

New paradigm in high energy physics (1974-1986)

- It produced many new ideas
- 1974; Grand Unification Georgi, Glashow
- 1977; Axion Peccei, Quinn; Weinberg, Wilczek
- 1979; Seesaw Yanagida, Gell-Man …
- 1980; Supersymmetry Maiani, Veltman
- 1981; Inflation Guth
- 1983; Dark Matter .....
- 1986; Leptogenesis Fukugita, Yanagida

1990 ~ present

- Deep understanding on quantum field theories
- Details about the new ideas created in the GUT paradigm
- String theories
- Detection of CMB temperature fluctuations (1992)
- Confirmation of the neutrino oscillation (1998)

General Relativity Einstein (1935)

- Quantum Gravity has unremovable divergences General Relativity is **inconsistent** with Quantum Mechanics
- Construction of String Theories began from 1980th However they are not completed
- But we have a hope that a string theory will open the next stage of fundamental physics,

General Relativity Einstein (1935)

- Quantum Gravity has unremovable divergences General Relativity is **inconsistent** with Quantum Mechanics
- Construction of String Theories began from 1980th However they are not completed
- But we have a hope that a string theory will open the next stage of fundamental physics, unifying the General Relativity and Quantum Mechanics

String theories predict

1. Ten (9+1) dimension space time

2. Supersymmetry

3. Multiverse

   $10^{500-1000}$ universes

I will talk about my new idea on SUSY

in the morning of Aug. 1 (Monday)

at

TDLI-PKU BSM workshop 2022: Electroweak lights the way (1-3 A...

https://indicotdli.sjtu.edu.cn/event/1040/timetable/#all.detailed

welcome !