Neutrinos and Elementary Particles

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- **Introduction for non-experts:**
  - **Weak Interaction**
  - **Neutrinos**
    - **Oscillation**
    - **Matter Effect**
  - **What is known (very brief)**
- **A View of the J-PARC and its HEP Division from an Outsider**

Weak Interaction - 1

	Charge	1st Generation	2nd Generation	3rd Generation
Quarks	2/3	u	c	t
	-1/3	d	s	b
Leptons	-1	e	μ	τ
	0	ν_e	ν_μ	ν_τ

Quarks d, s, b and neutrinos ν_e, ν_μ, ν_τ should be stable.

Transitions between generations (flavors) do take place.

Do leptons make flavor transitions?

We do not know.

How to Interpret Transitions between Generations: Mixing

Replace d_i by d'_i

$$\begin{pmatrix} b' \\ s' \\ d' \end{pmatrix} = V \begin{pmatrix} b \\ s \\ d \end{pmatrix}$$

V : Unitary matrix called CKM Matrix

Weak Interaction - 2

	Charge	1^{st} Generation	2^{nd} Generation
Quarks	2/3	u	c
	-1/3	$d' = V_{ud}d + V_{us}s + V_{ub}b$	$s' = V_{cd}d + V_{cs}s + V_{cb}b$
Leptons	-1	e	μ
	0	ν_e	ν_μ

Neutrinos and Mixing ($m_\nu \neq 0$)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U : Unitary matrix called MNS matrix

$$V = V(\theta_{12}, \theta_{23}, \theta_{13}, \delta) =$$

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}\, e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}\, e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}\, e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}\, e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$s_{ij} = \sin(\theta_{ij})$, $c_{ij} = \cos(\theta_{ij})$

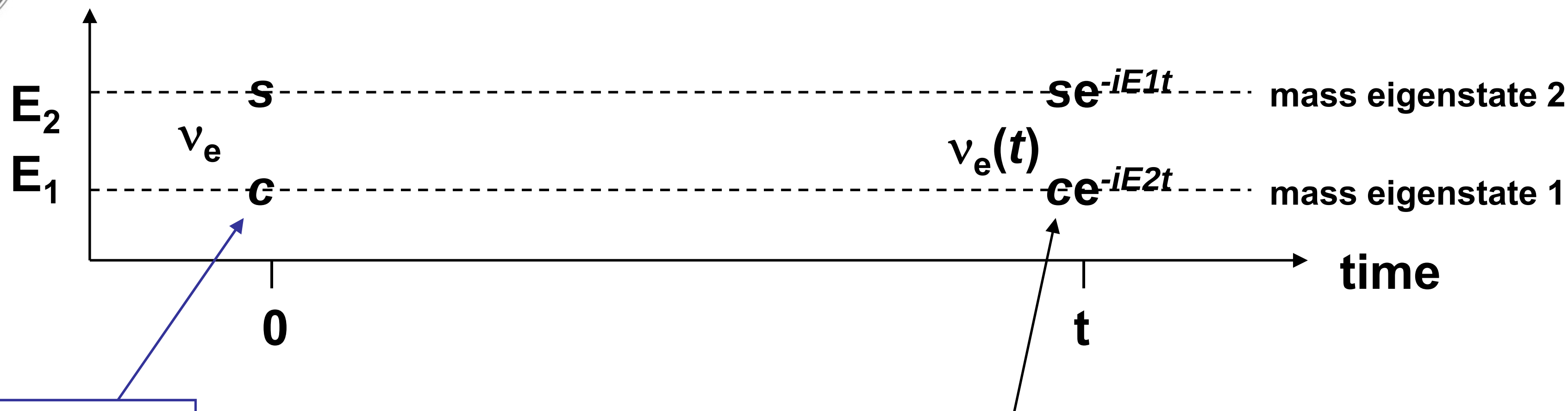
For the two-flavor case,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Weak (Flavor) eigenstates
$\alpha, \beta = e, \mu, \tau$

Mass eigenstates

Vacuum Oscillation



s = sinθ
c = cosθ

This state has a ν_μ component:

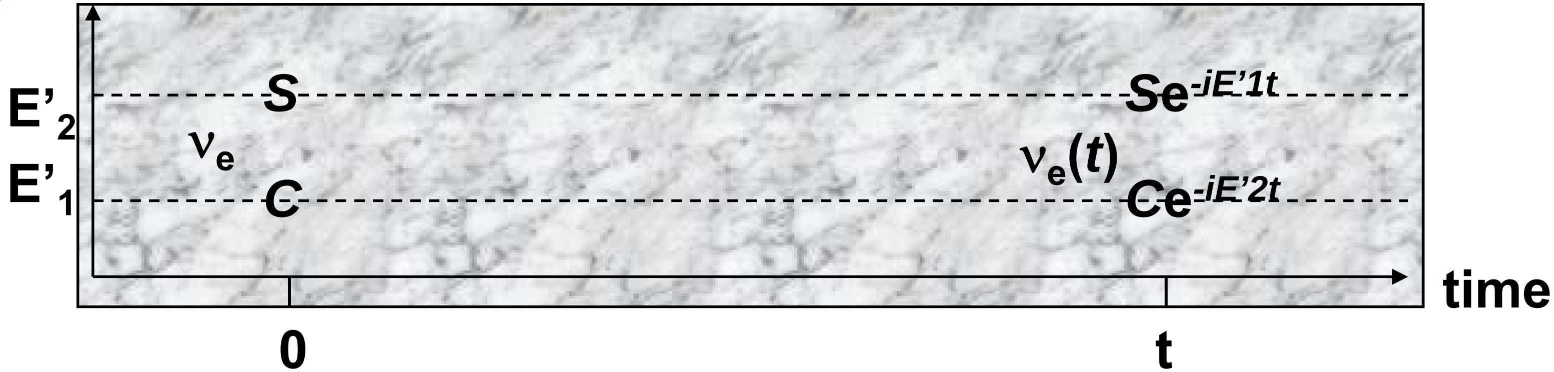
$$-cs\,\exp(-iE_1 t) + cs\,\exp(-iE_2 t)$$

The transition probability $\nu_e \rightarrow \nu_\mu$ is

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta E t}{2}\right)$$

$$\frac{\Delta E}{2} = \frac{E_2 - E_1}{2} = \frac{m^2_2 - m^2_1}{4E} = \frac{\Delta m^2}{4E}$$

Matter Oscillation



Neutrinos feel $n(\nu_\alpha)$**, the index of refraction of the matter:**

$$n = 1 + 2\pi \sum N_a \frac{f^a(0)}{p^2}$$

The neutrino runs a little slowly from v **to** $v/n(\nu_\alpha)$**.**

$f^a(0)$ **is the forward scattering amplitude,** $\nu_\alpha + a \rightarrow \nu_\alpha + a$**,**
where ν_α **is a flavor eigenstate.**
N_a **is the number density of the scatterer** a**.**

cont1

- The wave propagation is now;

  $\exp(-iEt) \rightarrow \exp(-i\frac{E}{n}t)$. [n: index of refraction]

- Write $E / n \rightarrow E - V$.

- By calculating the forward scattering amplitudes $f^a(0)$,

  $V(\nu_e) = - G_F N(3Z-A) / 2^{1/2}$, $V(\nu_{\mu,\tau}) = - G_F N(Z-A) / 2^{1/2}$.

- $V \rightarrow - V$ for anti-ν's
- Z and A are the atomic and mass numbers, resp.
- $N = \rho N_A / A$ is the number density of the atom.
- G_F is the Fermi coupling constant (1.166×10^{-5} eV^{-2}).

For Matter of Constant Density

- $P(\nu_e \rightarrow \nu_\mu) = \dfrac{\sin^2 2\theta}{B} \sin^2\left(\dfrac{\Delta E t}{2} B^{1/2}\right),$
- $B = \left(\dfrac{\Delta V}{\Delta E} - \cos 2\theta\right)^2 + \sin^2 2\theta$
- $\Delta V = V(\nu_{\mu,\tau}) - V(\nu_e) = 2^{1/2} G_F N_e$
- $\Delta E = E_2 - E_1 = \dfrac{\Delta m^2}{2E}$

When $\Delta V / \Delta E = \cos 2\theta$,
$P(\nu_e \rightarrow \nu_\mu) = \sin^2\left(\dfrac{\Delta E t}{2} B^{1/2}\right)$
$\rightarrow 1$
for $t = \pi / (\Delta E \sin 2\theta)$, and any value of $\sin 2\theta$.

- *Ne*: Electron number density of the matter

Full Expression of the Transition $\nu_\mu \rightarrow \nu_e$

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2(\Delta m_{31}^2 t/4E_\nu)(1 + 2a(1-2s_{13}^2)/\Delta m_{31}^2) \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \\
& \quad \times \cos(\Delta m_{23}^2 t/4E_\nu) \sin(\Delta m_{31}^2 t/4E_\nu) \sin(\Delta m_{21}^2 t/4E_\nu) \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \\
& \quad \times \sin(\Delta m_{23}^2 t/4E_\nu) \sin(\Delta m_{31}^2 t/4E_\nu) \sin(\Delta m_{21}^2 t/4E_\nu) \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 \\
& \quad - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2(\Delta m_{21}^2 t/4E_\nu) \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)(at/4E_\nu) \\
& \quad \times \cos(\Delta m_{23}^2 t/4E_\nu) \sin(\Delta m_{31}^2 t/4E_\nu) ,
\end{aligned}
$$

where a [eV^2] = $2^{3/2} G_F n_e E_\nu = 7.6 \times 10^{-5} \rho$ [g/cm^3] E_ν [GeV] ,

red terms change sign for anti-neutrinos

$$
A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)} \sim \frac{\Delta m_{12}^2 t}{4E_\nu} \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \sin\delta
$$

Oscillation	Measured
Vacuum	$\sin^2 2\theta_{ij}$, $\lvert\Delta m^2_{ij}\rvert$, δ
Matter	$\sin\theta_{ij}$, Δm^2_{ij}

ij = 12, 23, 31

Discoveris of Oscillations in Neutrinos from Various Sources

- **Atmospheric Neutrinos:** $\nu_\mu \rightarrow \nu_\tau$
  - Super-Kamiokande
- **Solar Neutrinos:** $\nu_e \rightarrow \nu_\mu$ (matter oscillation observed, $m_2 > m_1$)
  - Homestake, SAGE, GALLEX, Kamiokande, Super-Kamiokande, SNO
- **Reactor Neutrinos** $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$
  - KamLAND
- **Accelerator Neutrinos:** $\nu_\mu \rightarrow \nu_\tau$
  - K2K, MINOS,
- **Accelerator Neutrinos:** $\nu_\mu \rightarrow \nu_e$
  - T2K, NOvA

Masses of Particles

[numbers in () are 1σ errors]

	Masses of particles (GeV / c^2)			Remarks
Quarks	1.5-3.0 E-3	1.25 (0.09)	174.2 (3.3)	m_u/m_d=0.3-0.6,
	3.0-7.0 E-3	0.095 (0.025)	4.2 (0.07)	m_e/m_d=17-22
Leptons	0.511(4E-8) E-3	0.106 (9E-9)	1.78 (0.29/-0.26)	
	-	8.9 (0.6) E-12	44-55 E-12	sqrt(Δm_{ij}) was taken

	eV^2
Δm^2_{12}	8(0.4/-0.3)E-5
Δm^2_{23}	1.9-3.0E-3
Δm^2_{13}	[1.9-3.0E-3]

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

CKM Matrix and MNS Matrix

$|V_{ab}|$ [numbers in () are 1σ errors.]

0.97400 (0.00018)	0.22653 (0.00075)	0.00357 (0.00017) arg=67.6(2.8/-4.5) deg
0.22638 (0.00076)	0.97316 (0.00018)	0.0405 (0.0032/29)
0.00868 (0.00025/33) arg=21.7 (1.0/-0.9) deg	0.0407 (0.0009)	0.999135 (0.000037)

$|U_{ab}|$ [90% interval. No information on imaginary parts.]

0.80 – 0.84	0.53 – 0.60	0.00 – 0.17 arg ??
0.29 – 0.52	0.51 – 0.69	0.61 – 0.76
0.26 – 0.50 arg ??	0.46 – 0.66	0.64 – 0.79

U_{13} is only an upper limit and arg is not measured.

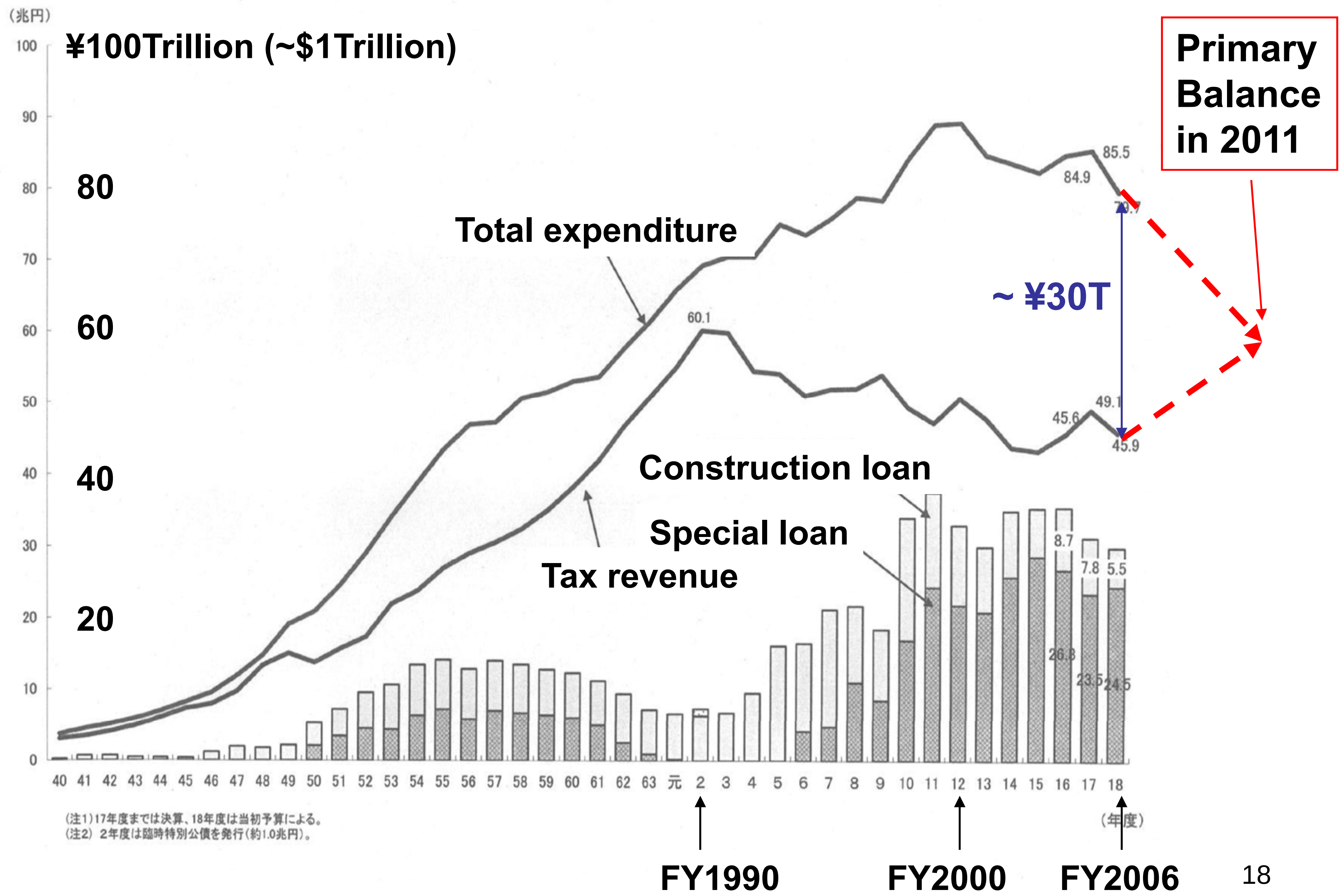
Do We Have Information Enough to Create a New Model of Particle Physics?

- Mass matrices, CKM matrices, MNS matrices
- Soon coming LHC results and MEG results

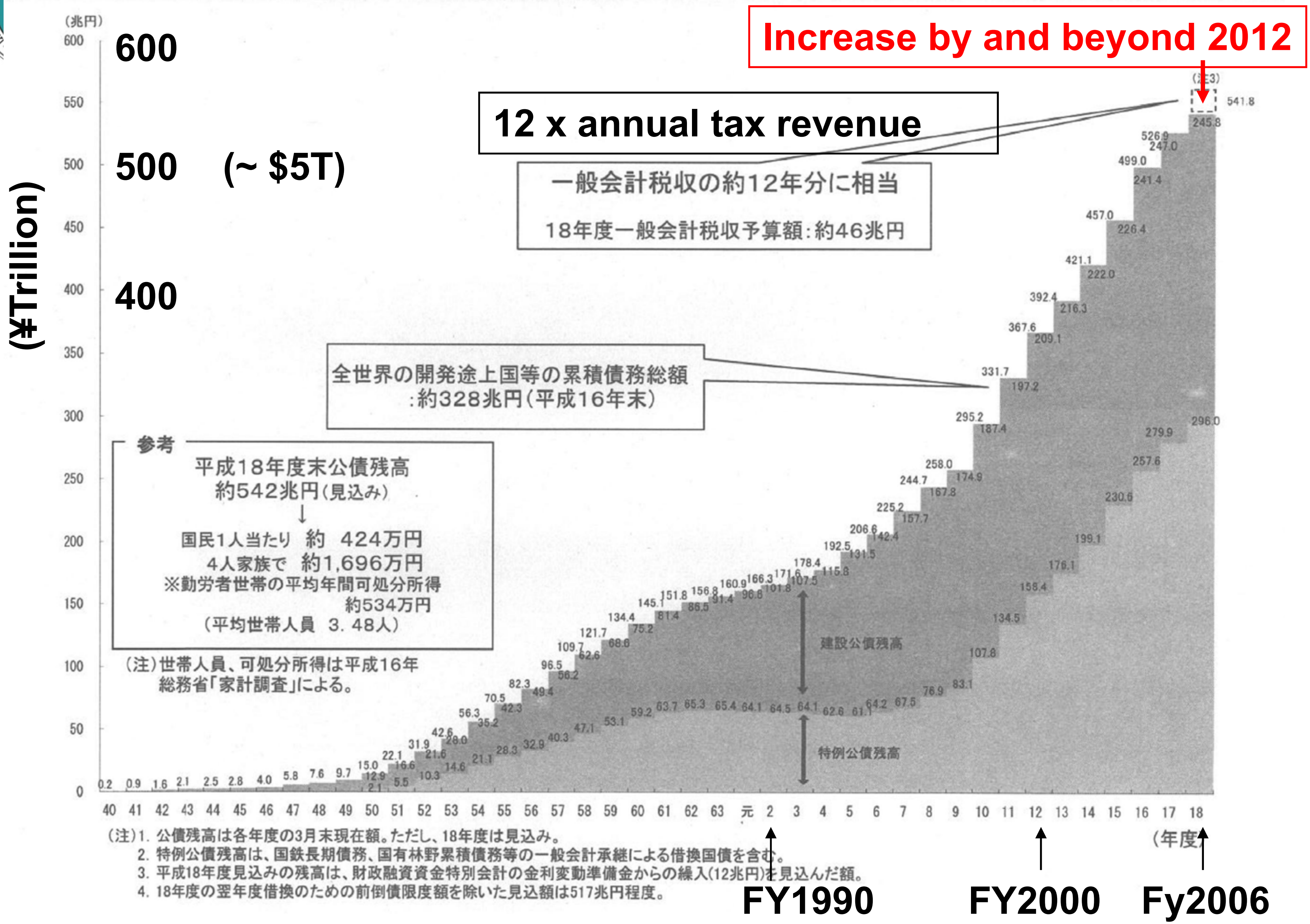
- Utmost importance is more precisely to determine neutrino masses and MNS matrix including the imaginary parts.

Viewing the J-PARC as an Outsider

Annual revenue and expenditure



Accumulated Debt



J-PARC is the biggest scientific project in Japan.

We thank the government for funding the J-PARC despite the huge budget deficit.

The government will not be generous forever.

- **The supercomputer, “Earth Simulator” costing $several 100 million to build, was shut down after only 5 year-operation due to the too much operating cost (¥5B = $50M).**

- **Get the lesson from this experience.**

The government will not be generous forever.

- The operating cost for J-PARC has to be minimized.
- It is necessary to set the priority among the proposed experiments.
- Impress people by showing the important and fascinating scientific results as quickly as possible.

The T2K experiment must be given the highest priority at J-PARC!

The next strategy (personal opinion)

- **Budget for HEP in Japan ~ $300M (For US-HEP, $690M.)**
- **KEK cannot afford to operate two accelerators for HEP simultaneously. (Calculate the operational costs.)**
- **Give the highest priority to J-PARC.**

Next neutrino experiments

- Study more in detail by combining all the available information including Mass matrices, CKM and MNS matrices, the coming LHC, and MEG results.
- Phased approach.
- Use your wisdom and make the best proposal ready by 2012.
- Think big and make cheap.

My Favorite Themes

- **Determine δ**
  - The Universe is dominated by matter and has no anti-matter.
- **Discover proton decay**
  - Origin of extremely small mass of the neutrinos.
  - The Universe was born and will die.
  - The Universe is dominated by matter and has no anti-matter.
- **What is the dark-matter?**
  - Unknown new heavy particles.
- **What is the dark energy?**
  - New paradigm beyond relativity and quantum theory?

cont

- **Make everything truly international. One country cannot afford to pay for the next generation neutrino (or whatever) experiment.**
- **Work with the ILC people and coordinate the future of HEP.**

Thanks for your attention