Phenomenology of neutrino oscillation

Osamu Yasuda
Tokyo Metropolitan University

Oct. 8, 2020 @ International Physics Webinar,

Pabna University of Science and Technology

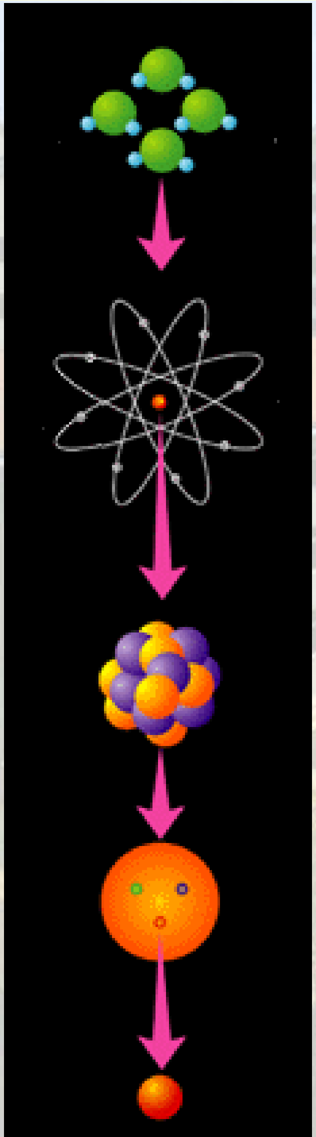
Contents

Part I. The Standard Model

(1) Elementary particles (the Standard Model)

Elementary particles: what cannot be divided further

At present, electrons and quarks are regarded as elementary particles.



10^{-7}cm — Molecule of water (hydrogen + oxygen)

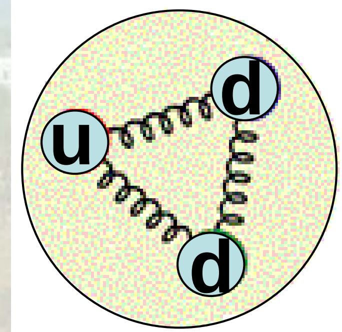
10^{-8}cm — Oxygen atom (nucleus + electrons)

10^{-12}cm — nucleus (proton(p) + neutron(n))

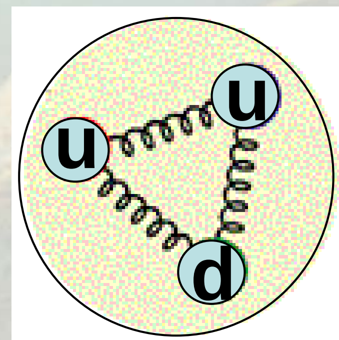
Nucleons (N)

10^{-13}cm — nucleon (u quark + d quark)

<10^{-16}cm — quark



neutron



proton

Neutrino (ν)

Elementary particles predicted in 1933

nobelprize.org

Pauli

neutron → proton + electron

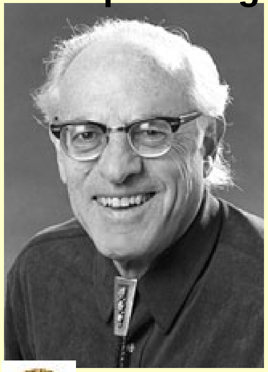
This process does not satisfy energy + momentum conservation

➡ Neutral particle called **neutrino** was introduced:

neutron → proton + electron + (anti-)neutrino

ν was first discovered in 1955

nobelprize.org



Reines

www.aps.org

Cowan

Discovery of neutrinos in 1955 (neutrinos from a reactor)

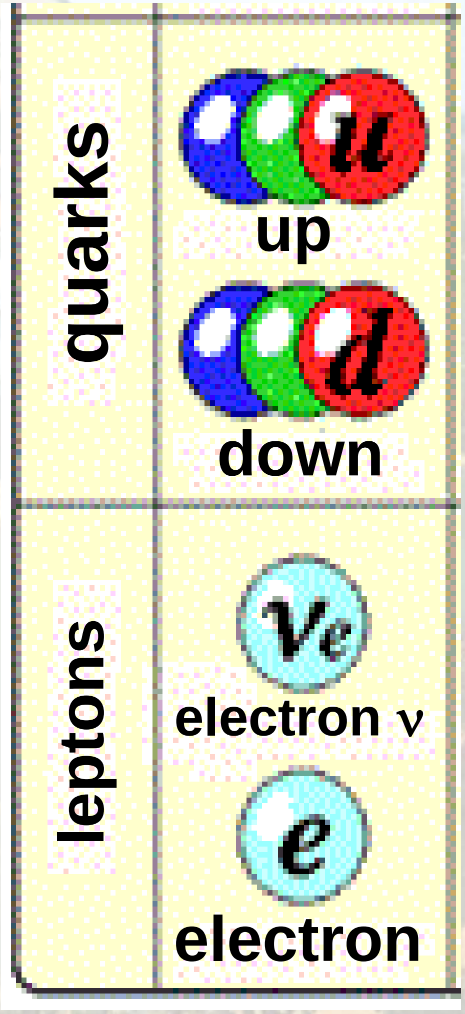
Until 1998 neutrino was regarded as **massless**.

Summary (1): elementary particles

Matter consists of quarks & leptons

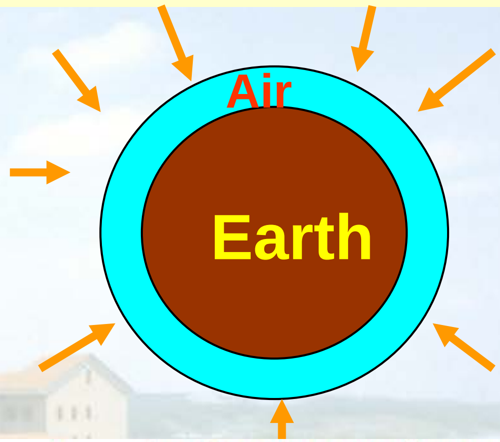
Quarks constitute composite particles (e.g., protons, neutrons) by attractive force between quarks

Leptons have properties different from quarks, and do not constitute composite particles



Cosmic rays

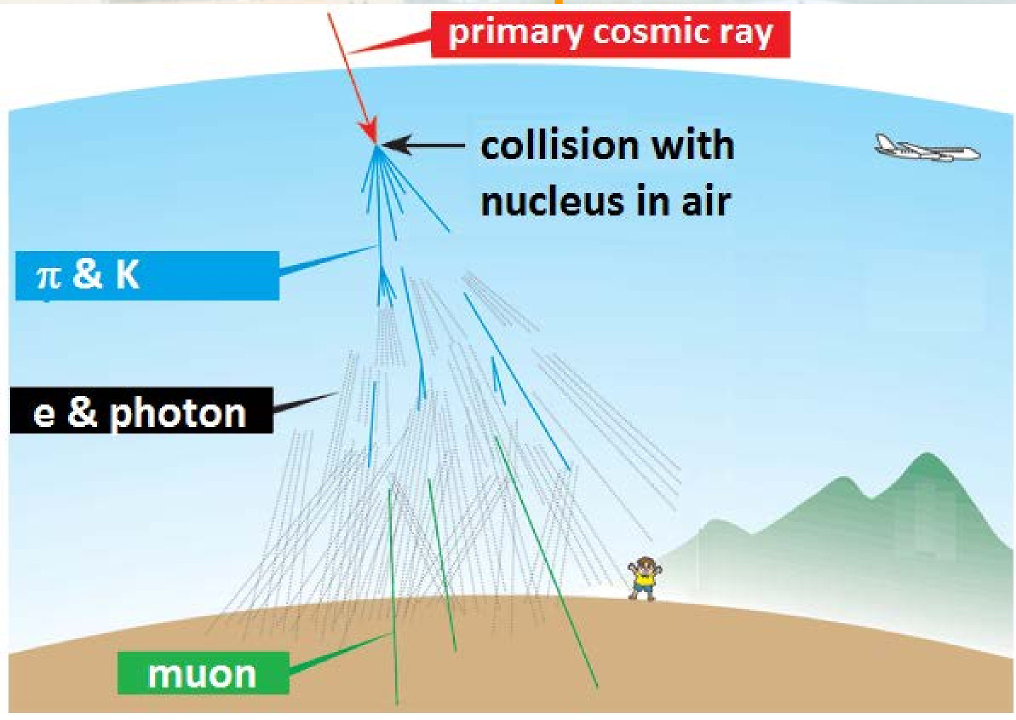
Primary cosmic rays (p, He)



It is known that so-called cosmic rays are falling down on Earth.

- Primary cosmic rays collide with nuclei in the air to produce particles which are called secondary cosmic rays.

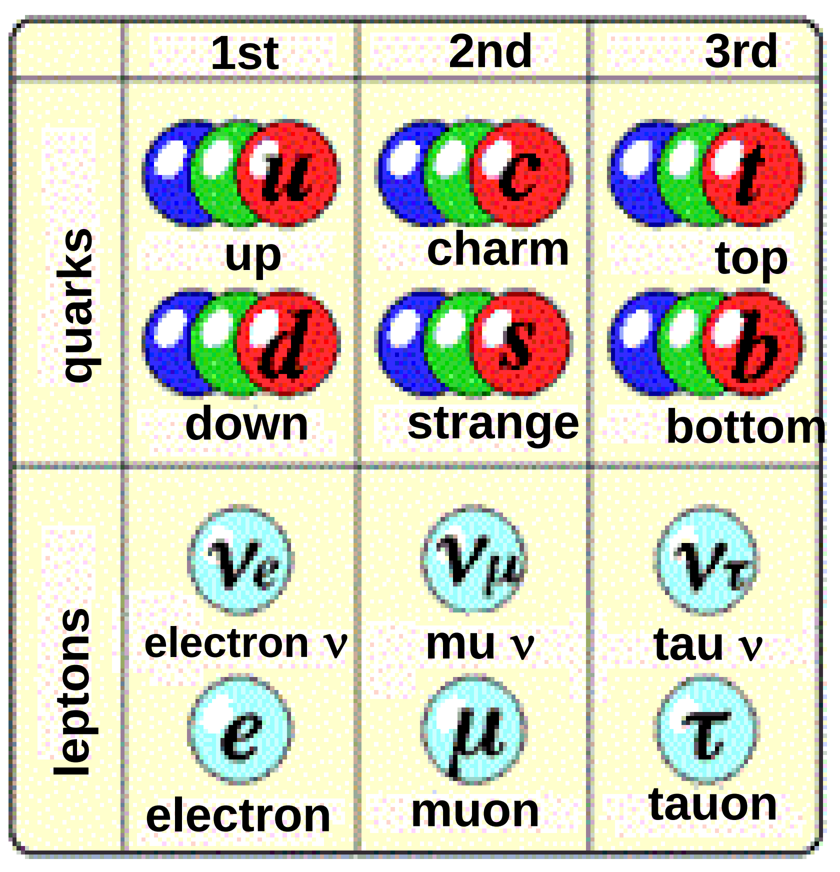
- The major components of 2ndary cosmic rays are muons which have almost the same properties as electrons except their mass ($m_{\mu}=200m_e$)



muons ：elementary particle of 2nd generation

Summary (2): elementary particles

- There are 3 generations of elementary particles.
- Neutrinos are **massless** in the Standard Model of Elementary particles.



	1st	mass[MeV]
quarks	u	3
	d	6
leptons	e	0.5
	ν_e	0

	2nd	mass[MeV]
quarks	c	1,200
	s	120
leptons	μ	106
	ν_μ	0

	3rd	mass[MeV]
quarks	t	174,300
	b	4,000
leptons	τ	1777
	ν_τ	0

Higher mass for higher **generation**

$E=mc^2$ tells us we need much energy to produce heavy particles

→

We need special device to produce particle of 2nd or 3rd generation

Anti-particle: Particle with the same mass and opposite electric charge

1930: Dirac equation (Relativity+Quantum mechanics)

Dirac

Positron(=anti-particle of electron) was theoretically predicted.

	Mass	Electric charge
electron	0.5MeV	-e
positron	0.5MeV	+e

1932：Discovery of positron

nobelprize.org

Anderson

In general, particles (3 generation of quarks & leptons) have their own anti-particles.

Actually 3 generation of quarks were theoretically predicted!

1972 Kobayashi-Maskawa

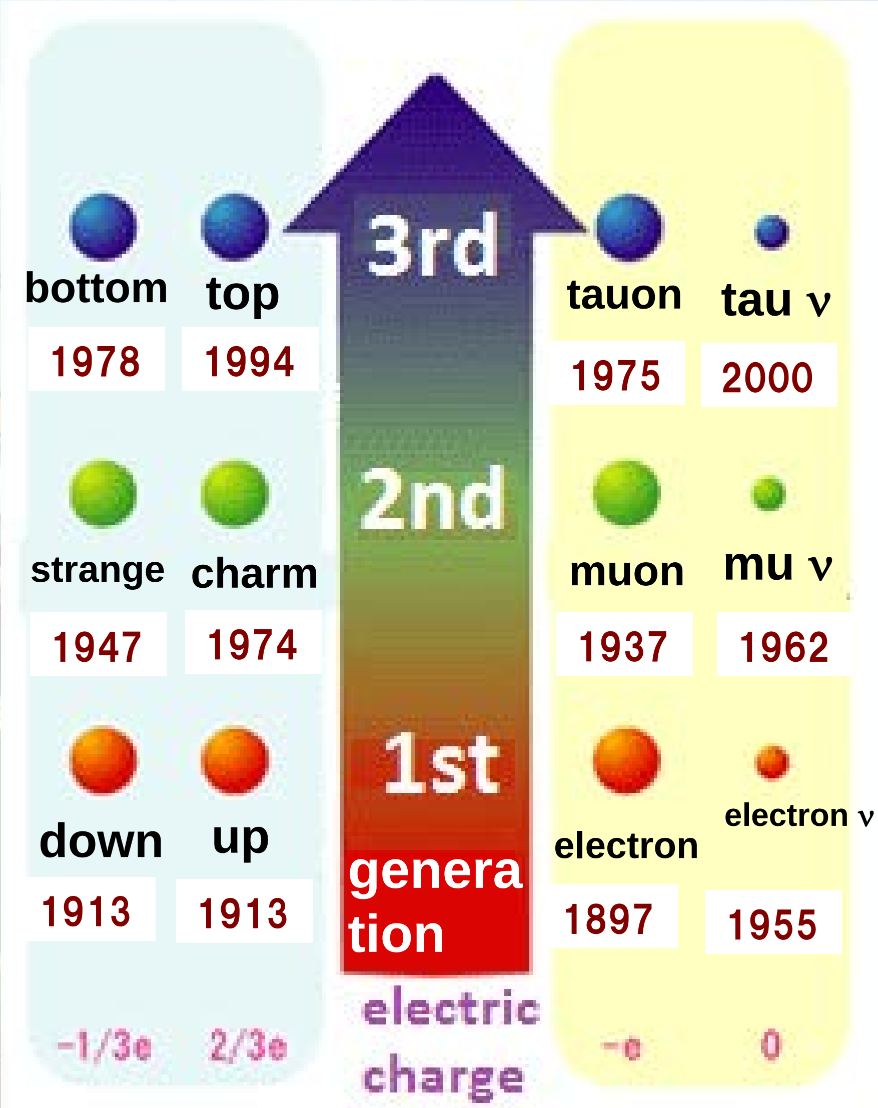
From motivation for so-called CP violation, 3 generation of quarks were theoretically predicted.

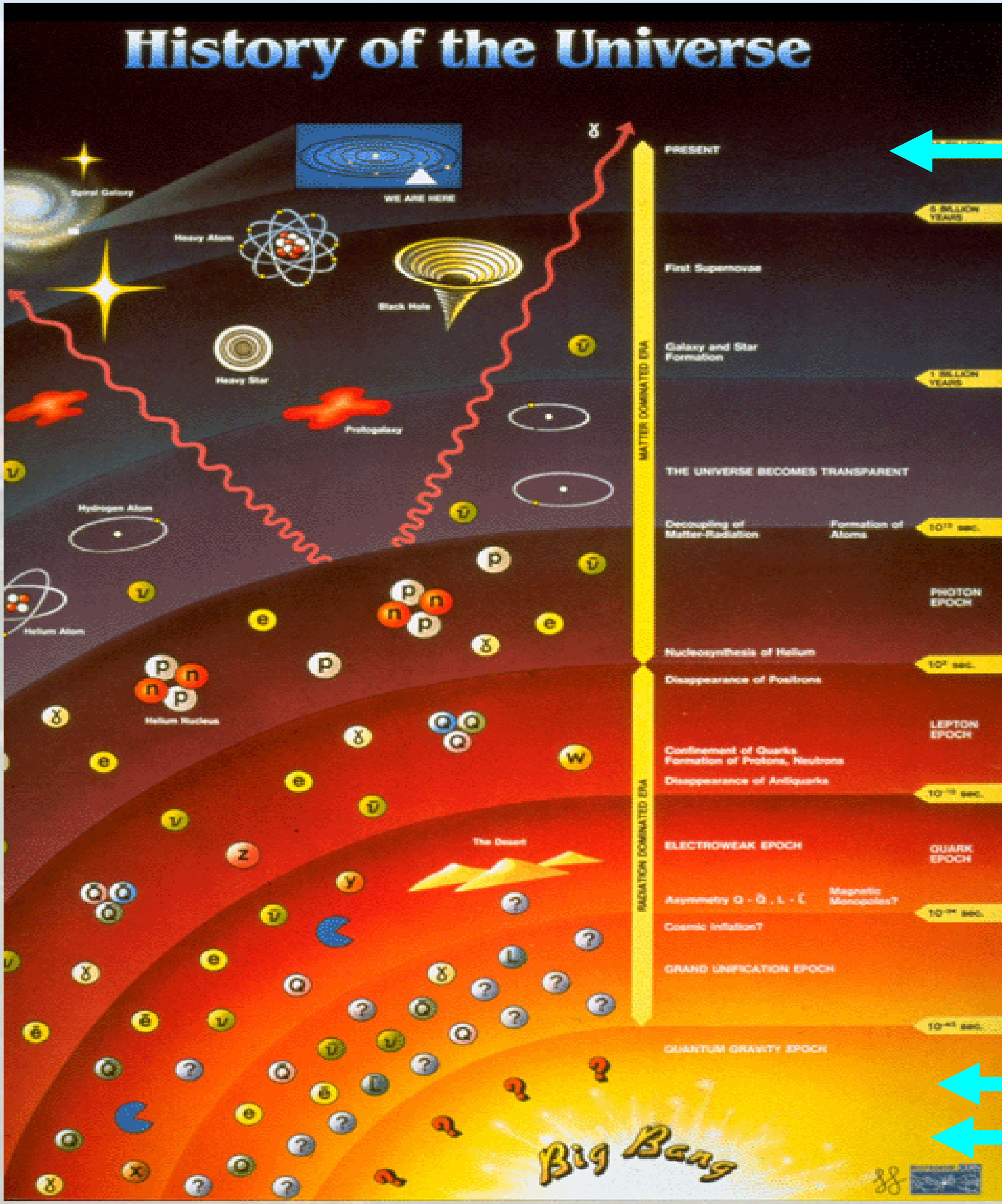
nobelprize.org

Kobayashi

nobelprize.org

Maskawa





T=3 deg (=-270^{o}C)
Present Universe is dominated by matter (w/o anti-matter)

Universe expanded &T decreased

There must have been asymmetry between particles & anti-particles at some stage

Temperature T=10^{32}deg
At the beginning of universe, #(particle) = #(anti-particles)
→ There must be equal amount of matter & anti-matter

Universe was born by Big Bang

CP symmetry (Invariance under CP transformation)

CP = C x P

C: Charge conjugation

P: Parity transformation

If CP symmetry is broken, then there can be difference between the speeds of the following reactions:

Heavy particle → Light particle ＋・・・

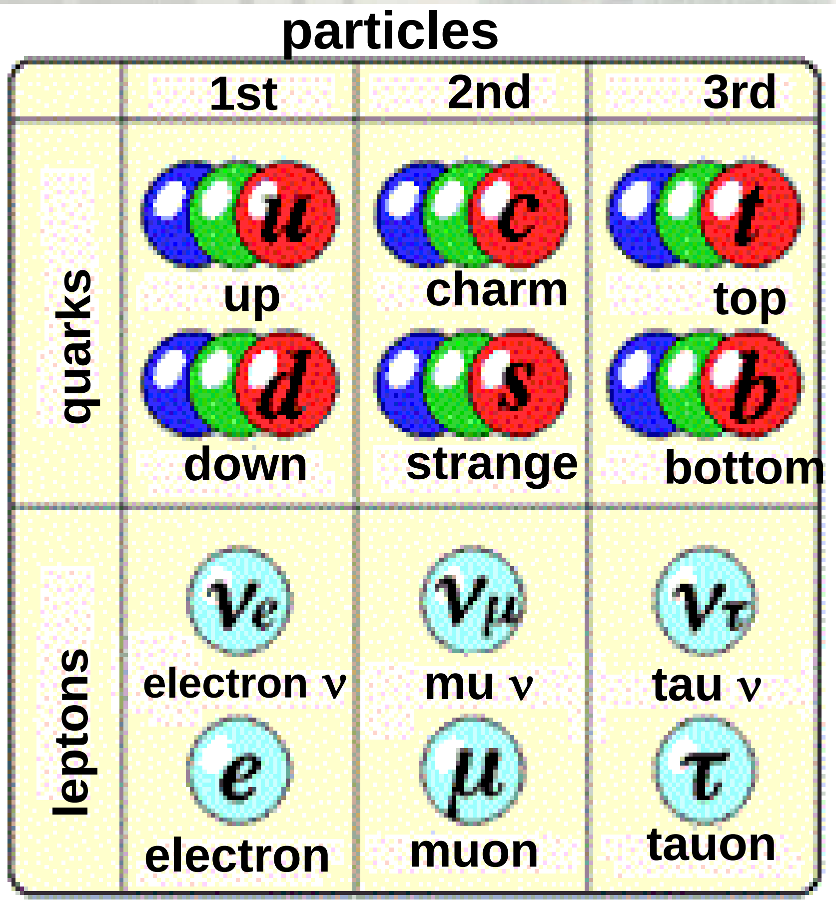
Heavy anti-particle → Light anti-particle ＋・・・

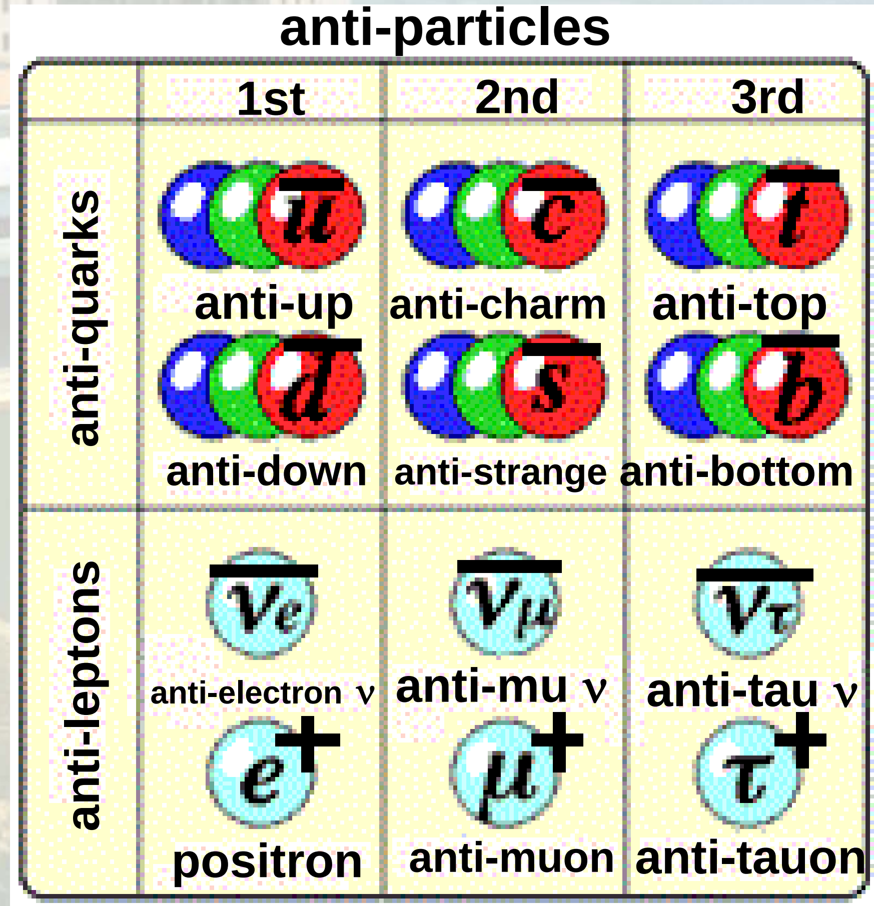
⇨ **If CP symmetry is broken, then we may be able to explain matter-anti-matter asymmetry of the Universe by cosmology + particle theory!**

Summary (3): elementary particles

- There are 3 generation of particles & anti-particles
- In our Universe, we have only matter (made of particles) but have no anti-matter (made of anti-particles)

→ Matter-anti-matter asymmetry is a mystery at present



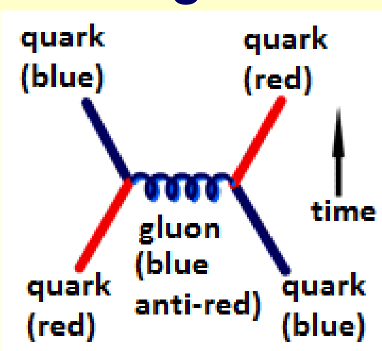


(2) Interactions of elementary particles (the Standard Model)

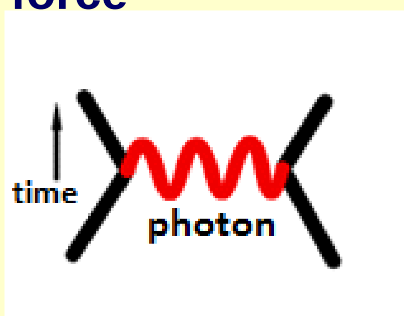
Interactions of Elementary particles

Interactions (force)	Strong force	Electromagnetic force	Weak force	Gravity
Force mediating particles	Gluon	Photon	W,Z boson	Graviton
Strength of force	1	10^{-2}	10^{-5}	10^{-40}

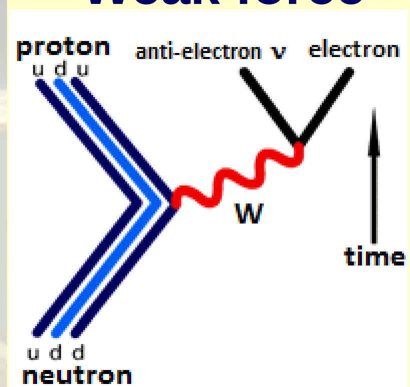
Strong force



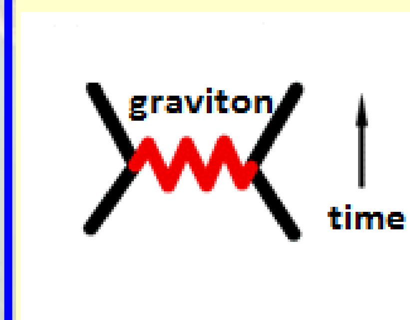
Electromagnetic force



Weak force



Gravity



So-called **Standard Model** describes 3 interactions (Strong, Electromagnetic, Weak forces)

Gravity among particle is so weak that it is **ignored**

(NB) Neutrinos feel only weak force → It is extremely difficult to observe them.

particles		Strong force	Electro magnetic force	Weak force	Gravity
quark	u	✓	✓	✓	✓
	d	✓	✓	✓	✓
leptons	e	×	✓	✓	✓
	ν_e	×	×	✓	✓

Flavor of neutrino is inferred by observing the charged lepton.

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

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\nu_\tau + n \rightarrow \tau^- + p$$

Part II. Physics beyond the Standard Model

(3) Neutrino oscillation (Physics beyond the Standard Model)

ν oscillation: quantum mechanical interference

- Neutrinos are **massless** in the Standard Model, while they are massive in the theory beyond the Standard Model.

Theory	Neutrino mass	Flavor vs Mass eigenstate
Standard Model	0	the same
Beyond Standard Model	≠0	different

Mass eigenstate

Flavor eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν oscillation in vacuum

If ν of two different flavor eigenstates ν_μ, ν_τ are related to two ν mass eigenstates ν_1, ν_2 (mass m_1, m_2) by a 2x2 matrix

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

θ: mixing angle

then probability of transforming from ν_μ to ν_τ while propagating for distance L is given by

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(1.27 \frac{(\Delta m^2 c^4/eV^2)(L/km)}{(E/GeV)}\right)$$

$\Delta m^2 \equiv m_2^2 - m_1^2$

: mass squared difference

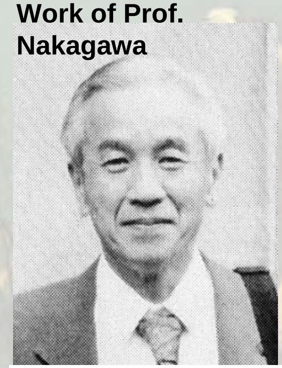
Probability in natural units ($\hbar$=c=1)

1962 Maki-Nakagawa-Sakata

www2.yukawa.kyoto-u.ac.jp/~sg/

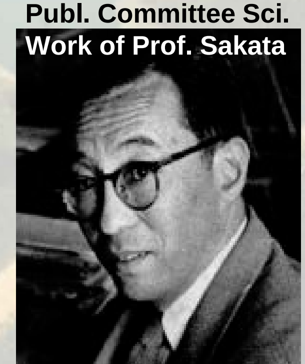
Maki

Publ. Committee Sci. Work of Prof. Nakagawa



Nakagawa

Publ. Committee Sci. Work of Prof. Sakata



Sakata

Probability has an oscillatory behavior with respect to L

$$\sin^2 2\theta \sin^2\left(1.27\frac{(\Delta m^2/\mathrm{eV}^2)(L/\mathrm{km})}{E/\mathrm{GeV}}\right)$$

P=maximum
→ Argument=$\pi/2$

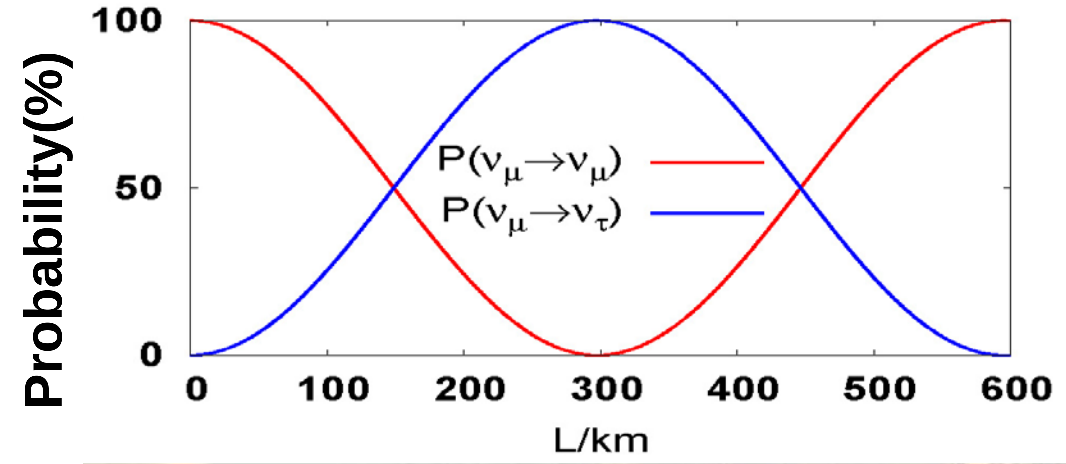
$\Delta m^2 = 3\times10^{-3}\mathrm{eV}^2$ → E=0.6GeV, L=300km (accelerator)

$\Delta m^2 = 3\times10^{-3}\mathrm{eV}^2$ → E=4MeV, L=2km (short L reactor)

$\Delta m^2 = 8\times10^{-5}\mathrm{eV}^2$ → E=4MeV, L=60km (long L reactor)

$\Delta m^2 \equiv m_2^2 - m_1^2$ is mass squared difference and not mass itself

Experiments give us info on θ and Δm^2



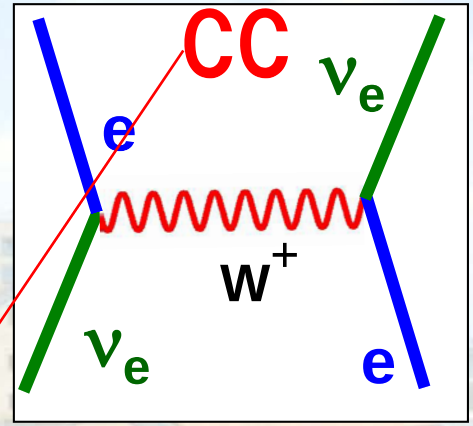
- In the presence of ν mass & mixing, flavor transition occurs.
- Macroscopic distance is required to see flavor transitions.

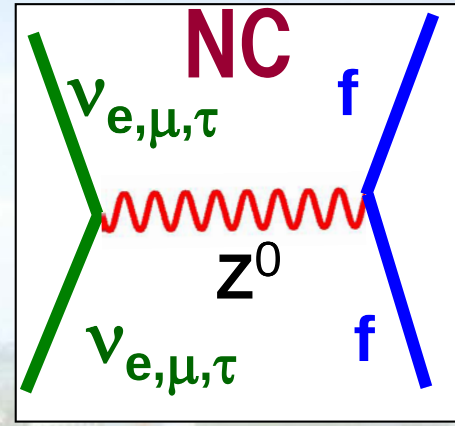
ν oscillation in vacuum (MSW effect)

f = e, u, d

$$L_{eff} = \sqrt{2} G_F \overline{\nu_e} \nu_e \bar{e} e$$

$$\rightarrow \sqrt{2} G_F \overline{\nu_e} \nu_e n_e(x)$$





$$i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \left[U \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} U^{-1} + \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$$E_j = \sqrt{\vec{p}^2 + m_j^2}$$

$$A \equiv \sqrt{2} G_F n_e(x)$$

If the density N_e is constant, we have a similar formula:

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

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A}$$

$$\Delta \tilde{E} \equiv \left[(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2 \right]^{1/2}$$

$$\Delta E \equiv \Delta m^2 / 2E$$

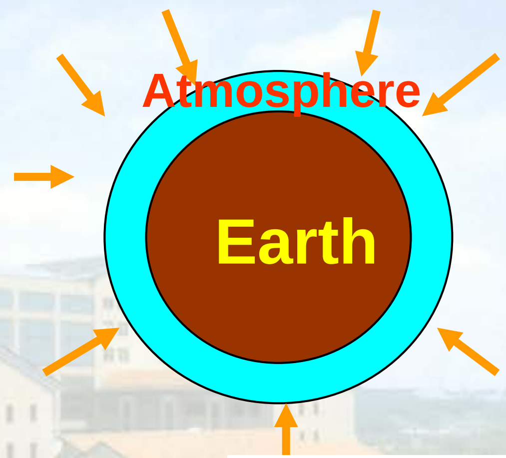
(4) Atmospheric ν + Accelerator ν

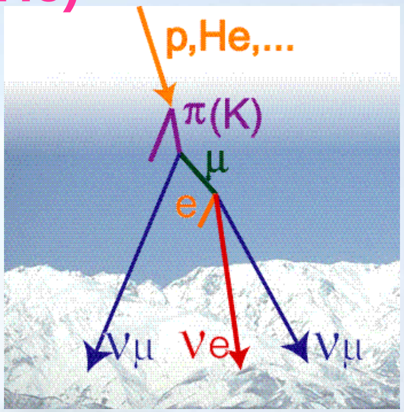
Atmospheric ν

- So-called primary cosmic rays are falling onto ground, and they collide w/ nucleons in the atmosphere, and produce 2ndary cosmic rays.
- Almost all the particles become $\pi^{\pm}$ mesons, which decay into $\mu^{\pm}$ and then $\mu^{\pm}$ decay into electrons and positrons.
- If we ignore the difference between ν and $\bar{\nu}$, then

$$(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) = 2:1$$

Is predicted.





$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

However, the observation was

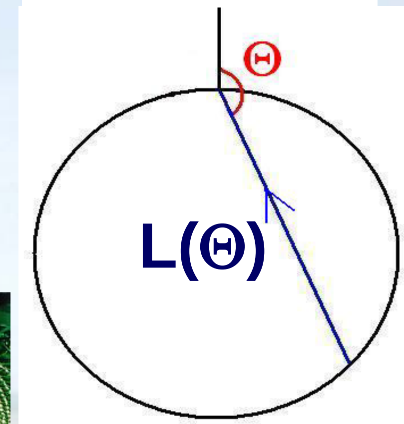
$$(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) = 1.3:1$$

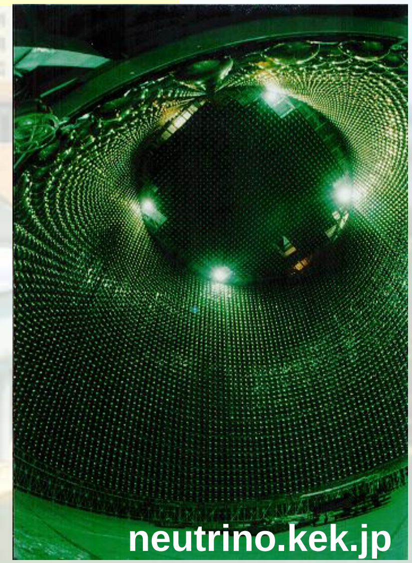
which disagrees w/ prediction.

Cause of Atmospheric ν anomaly:

Because of $\nu_\mu \Leftrightarrow \nu_\tau$ oscillation,

ν_μ decreases (SK cannot observe ν_τ)





Experimental value of

$$(\nu_\mu + \overline{\nu_\mu}) : (\nu_e + \overline{\nu_e})$$

depends on L & E and

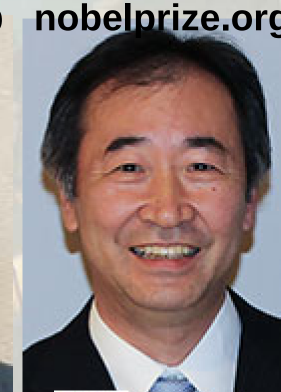
Superkamiokande proved that it is consistent with the formula

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

www2.kek.jp

Totsuka

nobelprize.org



Kajita

Accelerator ν

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Experiments in the past

- K2K (JP, KEKgSK, 1999-2004)
  L=250km, E∼1.3GeV
  $\nu_\mu \to \nu_\mu$
- MINOS (US, FNALgSoudan, MN, 2005-2012)
  L=735km, E∼4GeV
  $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \nu_\mu \to \nu_e$
- OPERA (CH, CERNgGransasso, IT, 2010-2018)
  L=730km, E∼17GeV
  $\nu_\mu \to \nu_\tau$

Experiments in operation

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

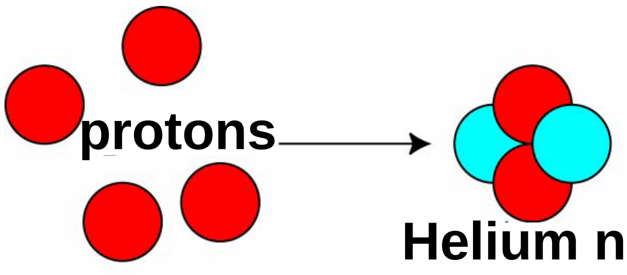
- T2K(JP, JPARC → SK, 2009-) L=295km, E∼0.6GeV
- MINOS+(US, FNAL → Soudan, MN, 2013-)L=735km, E∼4GeV
- Nova(US, FNAL → Ash River, MN, 2014-), L=810km, E∼2GeV

All the results are consistent with the atmospheric ν experiments

(5) Solar ν + Long baseline reactor ν

Solar ν deficit

The fusion reaction



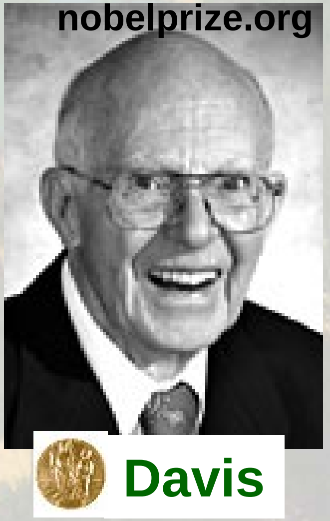
$+ 2e^{+} + 2\nu_e$

solar ν

produces electron neutrinos: They are called solar ν

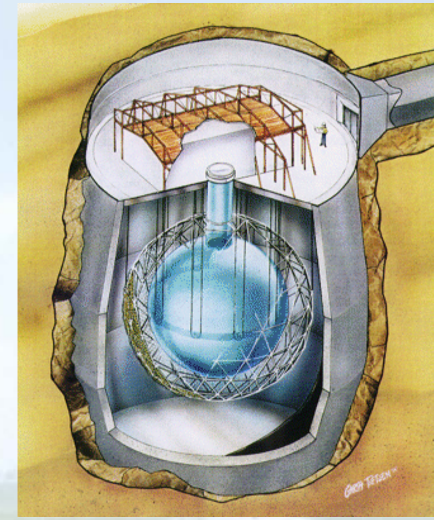
- **Solar ν were detected since 1960's by Davis at Homesteak, SD. Observed flux was less than ½ of theoretical prediction: Solar ν problem**

It turned out that flux of ν is reduced due to conversions $\nu_e \to \nu_\mu$、$\nu_e \to \nu_\tau$



Davis

SNO (Sudbury Neutrino Observatory, 1999-2006)



- Detector w/ heavy water(1kt)

D_2O, d=(pn), deutron

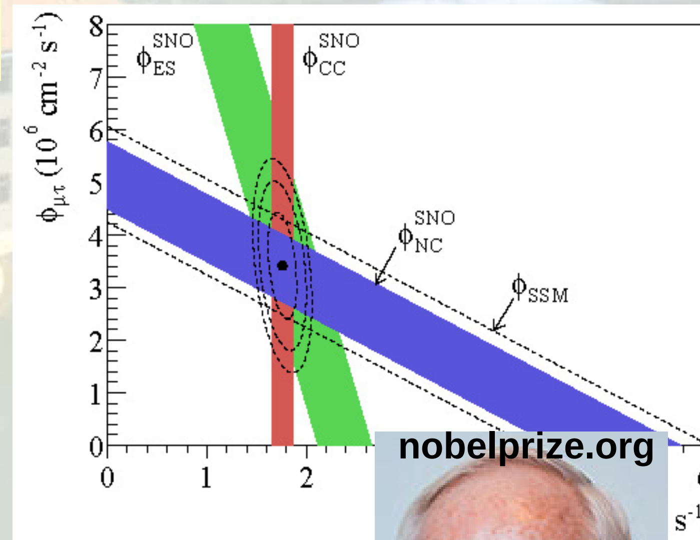
- Underground laboratory (∼2km) (To reduce BackGround)
- Direct proof for solar ν deficit

SNO can detect the both reactions:

$$\nu_e + d \rightarrow p + p + e^-$$ → only for ν_e

$$\nu_x + d \rightarrow p + n + \nu_x$$ → for all ν_x

$x = e, \mu, \tau$



nobelprize.org

McDonald

From the data of these 2 reactions, it was concluded that $\nu_e + \nu_\mu + \nu_\tau$ agrees w/ theory, but ν_e is less than theory

KamLAND (JP, 2002-, long baseline reactor ν)

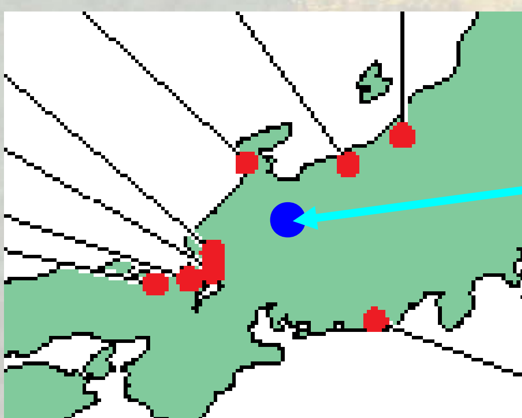
$\overline{\nu}_e \rightarrow \overline{\nu}_e$

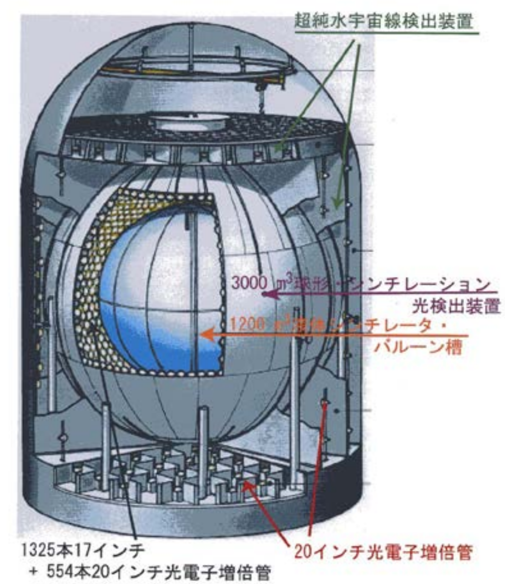
L～200km, E～4MeV

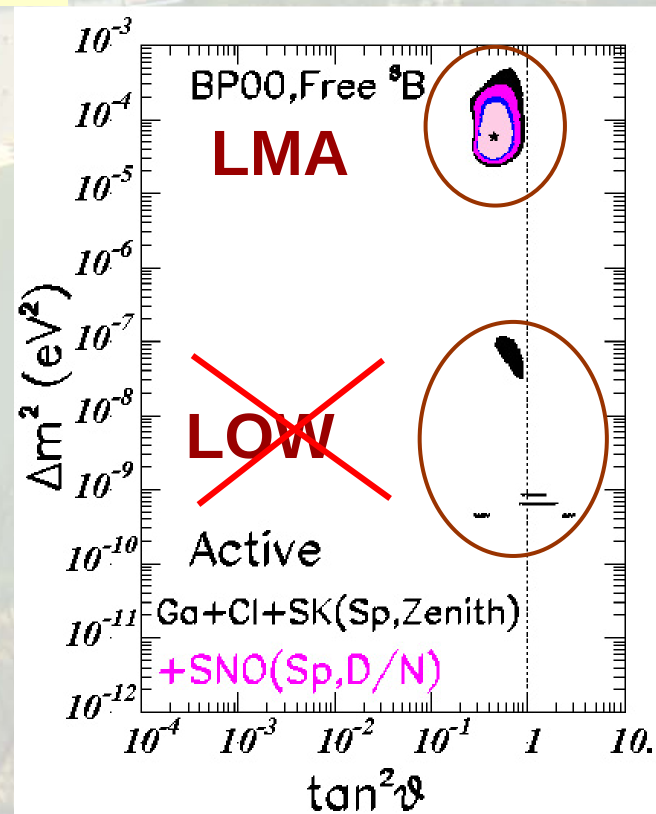
Atsuto Suzuki

- **Detector w/ liquid scintillator**
- **Detected $\overline{\nu}_e$ from various nuclear power plants (average distance 200km)**
- **Observed deficit of reactor neutrinos for the 1st time**

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$







(6) Short baseline reactor ν

Reactor ν (short baseline)

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ L～2km, E～4MeV

Double CHOOZ (Fr) (2016/3)	$\sin^2 2\theta = 0.111 \pm 0.018$
Daya Bay (Cn) (2015/5)	$\sin^2 2\theta = 0.084 \pm 0.005$
Reno (Kr) (2015/12)	$\sin^2 2\theta = 0.082 \pm 0.011$

$\theta=0$ is excluded at 168σ

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

(7) 3 flavor neutrino oscillation

3 flavor mixing framework (in the real world)

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

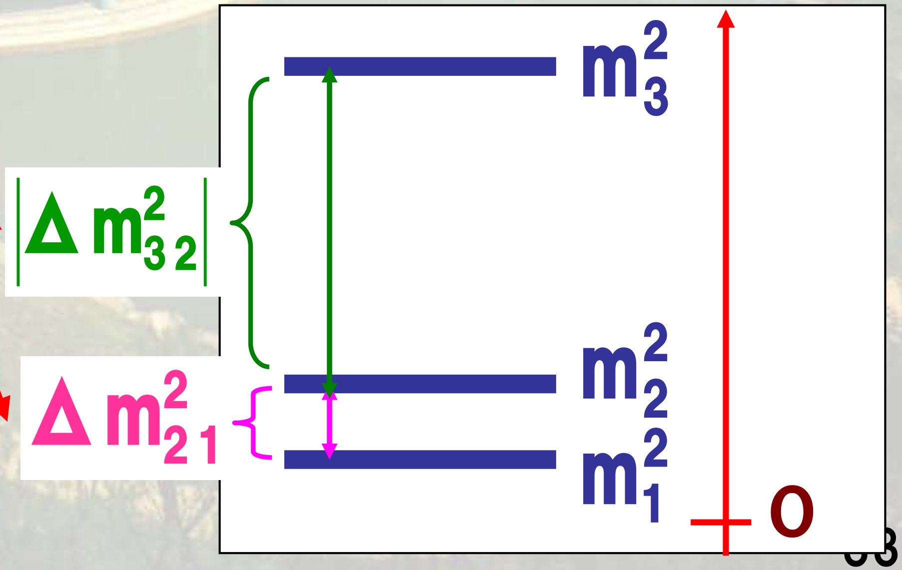
Mixing matrix is 3x3

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

There are 2 independent mass squared differences

θ_{12}, θ_{23}, θ_{13}: mixing angle

δ: CP violating phase



Features of 3 flavor mixing framework

(1) Mass hierarchy

$$\Delta m^2_{21} << \left|\Delta m^2_{32}\right| \cong \left|\Delta m^2_{32}\right|$$

→Oscillation probabilities are simplified

(2) Small θ_{13}

$$\sin^2 2\theta_{13}=0.08$$

→In the 0-th approximation, we can work with $\theta_{13}=0$

→ We have further simplification.

Determination of 3 ν oscillation parameters

(i) Solar ν deficit + Long baseline reactor ν deficit (KamLAND)

→ $\Delta m^2_{21} \sim 8\times 10^{-5} eV^2$ $\sin^2 2\theta_{12} \sim 0.8$

(ii) Atmospheric ν anomaly + Accelerator ν oscillation (K2K, MINOS, OPERA,T2K, Nova)

→ $|\Delta m^2_{32}| \sim 3\times 10^{-3} eV^2$ $\sin^2 2\theta_{23} \sim 1$

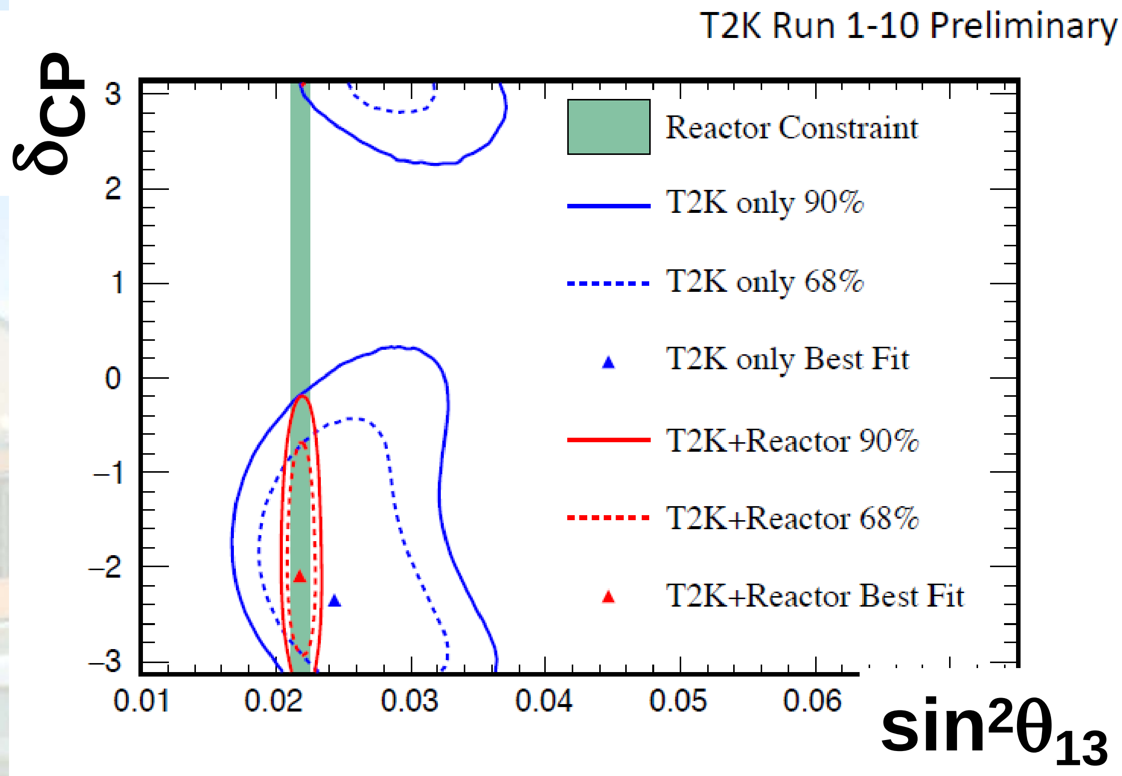
(iii) Short baseline reactor ν deficit (Double CHOOZ, Daya Bay, RENO) + Accelerator ν appearance (T2K, MINOS , Nova)

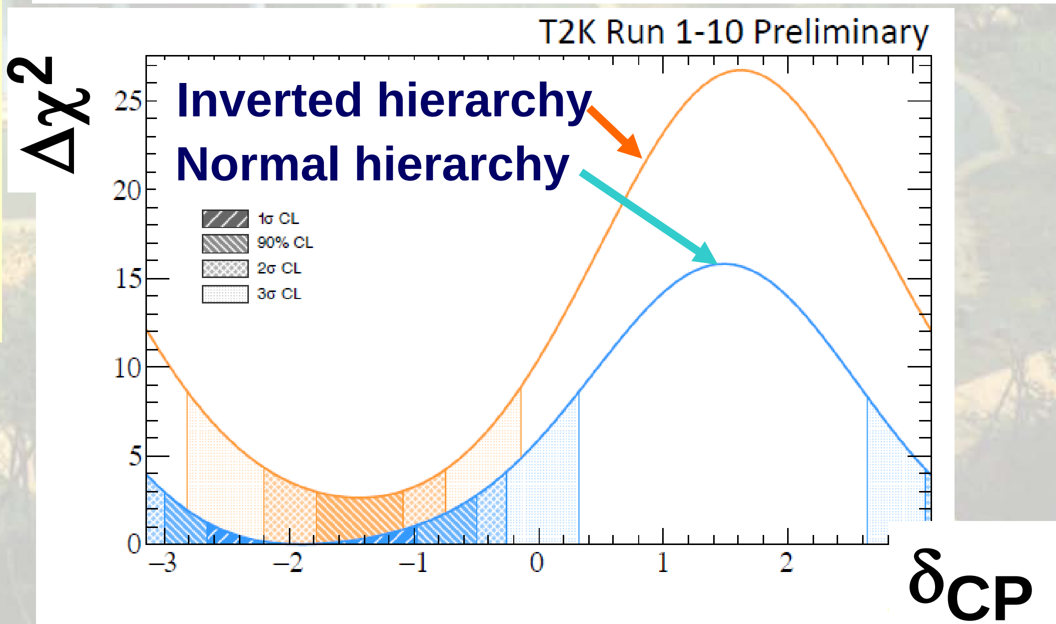
→ $\sin^2 2\theta_{13}=0.08$

Recent T2K results

Dunne@Neutrino2020

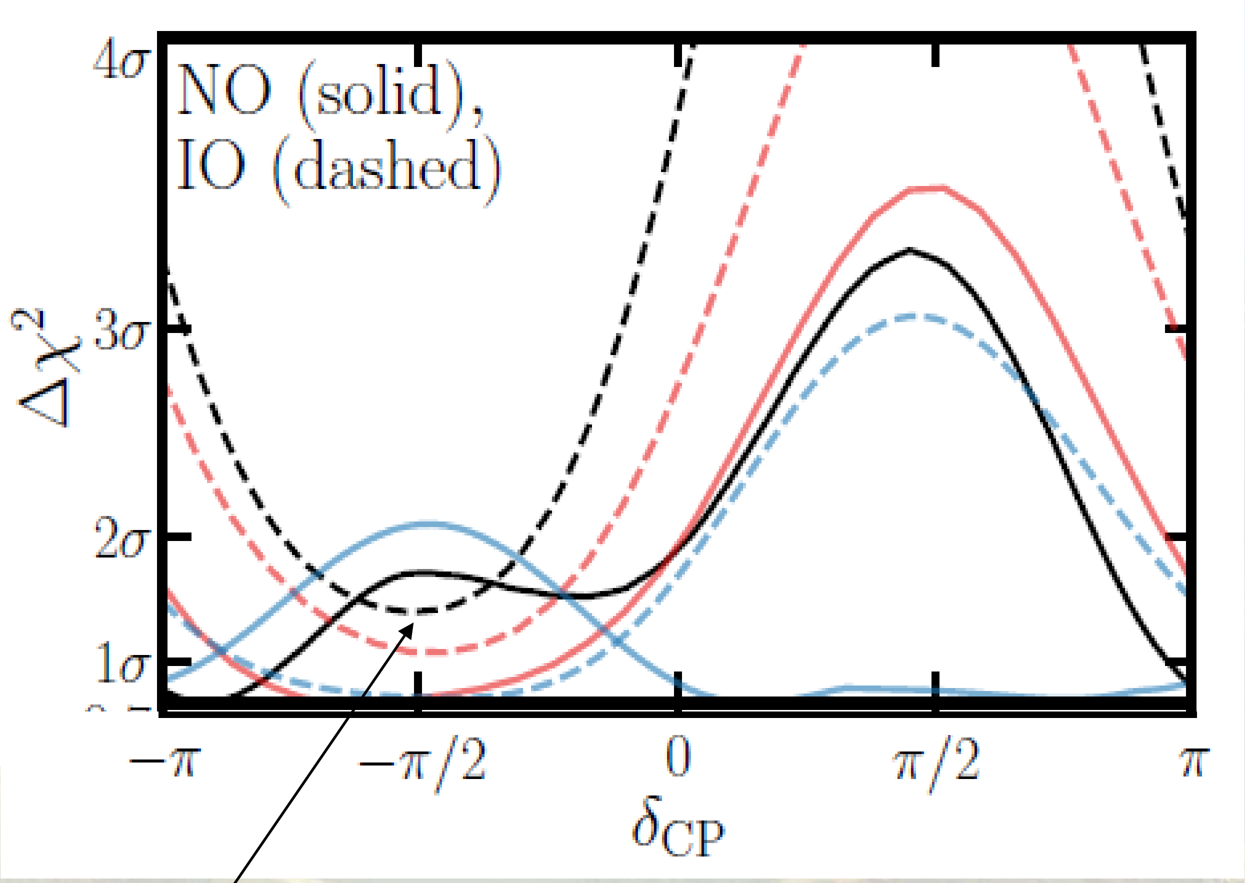
Normal hierarchy & δ_{CP}~$-\pi/2$ seems to be favored, but we need more data to conclude





Recent status: Tension between T2K and Nova?

Kelly et al, arXiv:2007.08526v1 [hep-ph]



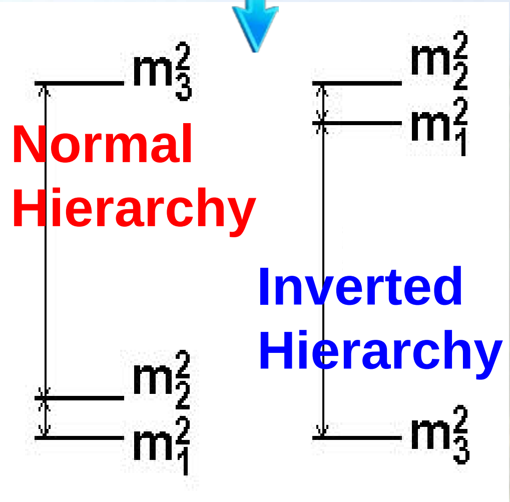
Black lines: a joint fit of T2K/NOvA/SK18
Blue: NOvA alone
Red: T2K alone

Joint fit may indicate preference for Inverted Hierarchy

Present status of 3 flavor mixing framework

$N_\nu=3$: $\nu_{atm}+\nu_{solar}+\nu_{reactor}+\nu_{accelerator}$

Both hierarchy patterns are allowed



$\Delta m^2_{32} > 0$ $\Delta m^2_{32} < 0$

Mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \varepsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Mixing angles & mass squared differences

$\theta_{12} \cong \pi/6, \quad \theta_{23} \cong \pi/4$

$\theta_{13} \cong \pi/20$

$\Delta m^2_{21} \cong 8 \times 10^{-5} eV^2$

$|\Delta m^2_{32}| \cong 2.5 \times 10^{-3} eV^2$

- Less known parameters : δ_{CP} , sign(Δm^2_{31})

(8) Future plans

Future plans

Next task is to measure sign(Δm^2_{31}) and δ_{CP} precisely

Proposed experiments

$$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$$

- **T2HK(JP, JPARC-->HK) L=295km, E~0.6GeV**
- **DUNE (US, FNAL-->Homestake, SD), E~2GeV, L=1300km**

These experiments are expected to measure sign(Δm^2_{31}) and δ_{CP}

Future plan: T2HK

- **Phase 2**

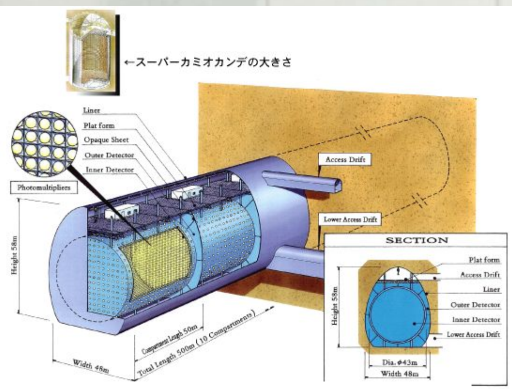
1.66MW ν beam ⇒ Hyperkamiokande
(300 times K2K) (20 times SK)

- **Extension of T2K**
- **Measurement of CP phase δ_{CP}**

Kobayashi

www-he.scphys.kyoto-u.ac.jp

Nakaya

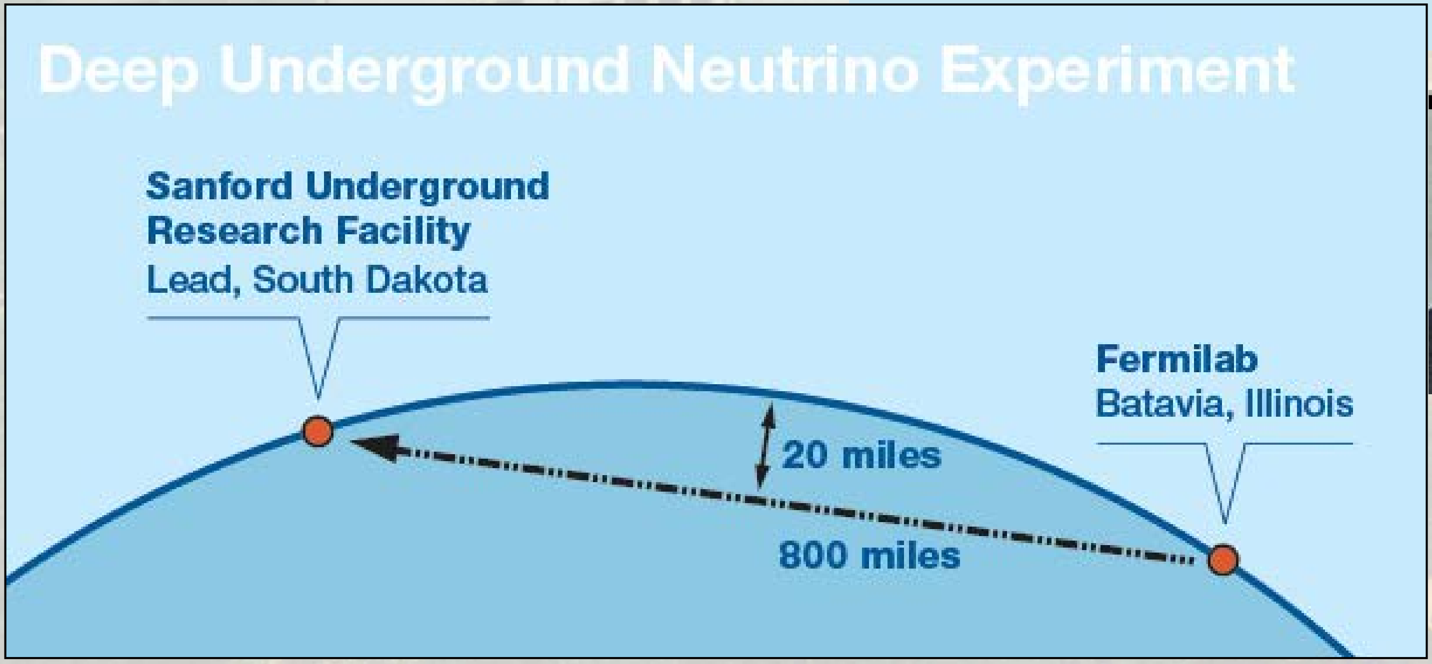


Hyper-kamiokande

Future plan: DUNE

2.3MW ν beam@Fermilab ⇒ 40-kt Liquid Argon detector @ Sanford Underground RF

E ∼ 2GeV, L ∼ 1300km



naturalsciences.ch

A.Rubbia

www.hep.phy.cam.ac.uk

Thomson

(9) Beyond the standard scenario

Nonstandard scenarios

High precision measurements of ν oscillation in future experiments can be used also to probe **physics beyond SM** by looking at deviation from SM+massive ν

T2HK, DUNE, ν_{atm}@Hyperkamiokande

New Physics discussed in this talk

Scenario beyond SM+m_ν	Experimental indication ?	Phenomenological constraints on the magnitude of the effects
(1) Light sterile ν	Maybe	O(10%)
(2) Non Standard Interaction	Maybe	e-τ: O(100%) Others: O(1%)

Neither sterile ν nor Non Standard Interaction is required from theory.
$\rightarrow$ They are introduced phenomenologically.

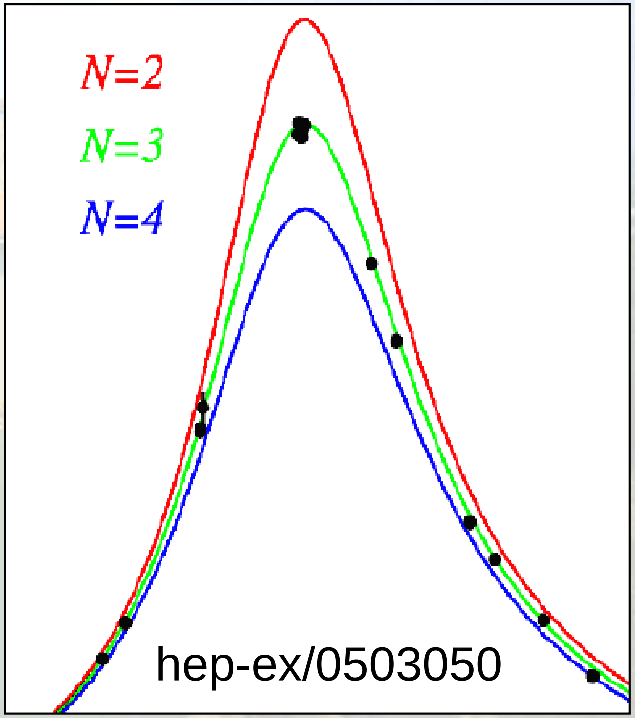
(1) Light sterile neutrinos (ν_s)

● Motivation for ν_s

A) 4th neutrino mass eigenstate has been phenomenologically motivated by the following affirmative results:

- LSND anomaly (E～50MeV, L～30m)
- Reactor anomaly (E～4MeV, L<10m)
- Galium anomaly (E<1MeV, L<5m)

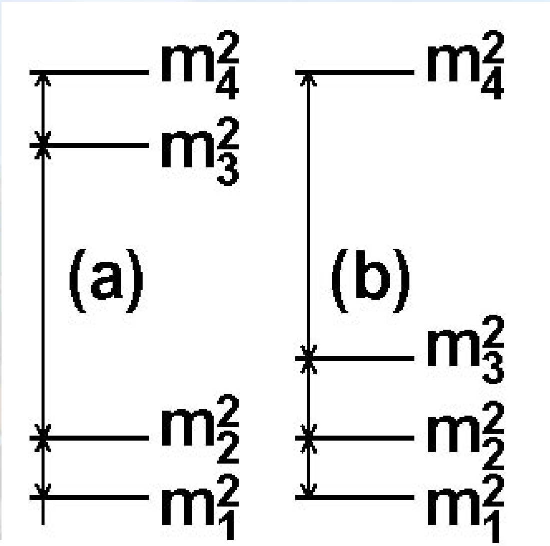
B) From LEP result, #(ν coupled to Z)=3



A) ➡ $\Delta m^2 \sim O(1) eV^2 >> \Delta m^2(atm) >> \Delta m^2(solar)$

B) ➡ 4th ν flavor eigenstate has to be sterile (i.e., it has no weak interaction)

Mass pattern for sterile neutrinos (ν_s)



(2+2)-scheme (3+1)-scheme

$$\Delta m_{41}^2 = \Delta m_{LSND}^2 \simeq 1\,eV^2$$

$$\Delta m_{21}^2 = \Delta m_{sol}^2, \Delta m_{32}^2 = \Delta m_{atm}^2$$

(a): (2+2)-scheme is completely excluded by ν_{solar} & ν_{atm}

(b): (3+1)-scheme has tension between $\nu_\mu \to \nu_\mu + \nu_e \to \nu_e$ & $\nu_\mu \to \nu_e$

(2+2)-scheme

$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \rightarrow 0$$

$$\nu_{atm} : \nu_\mu \rightarrow \nu_s (100\,\%)$$

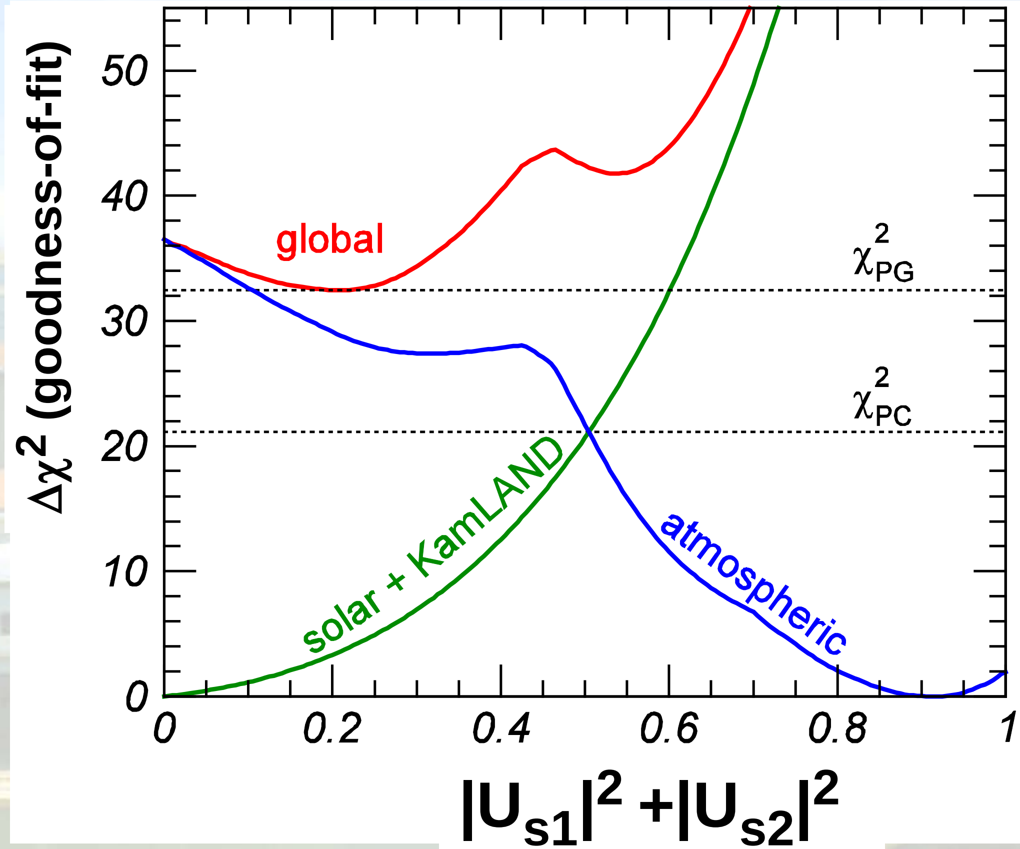
Strongly disfavored by SK ν_{atm} data

$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \rightarrow 1$$

$$\nu_{sol} : \nu_e \rightarrow \nu_s (100\,\%)$$

Strongly disfavored by SNO ν_{sol} data

Maltoni et al., hep-ph/0405172



PC: parameter consistency test
PG: parameter goodness-of-fit test

For any value of $|U_{s1}|^2 + |U_{s2}|^2$, fit to sol+atm data is bad.

(3+1)-scheme

Bugey (reactor): negative

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2(\Delta m_{41}^2 L/4E)$$

$$\sin^2 2\theta_{\mathrm{Bugey}} > 4|U_{e4}|^2(1-|U_{e4}|^2) \cong 4|U_{e4}|^2$$

CDHSW (accelerator): negative

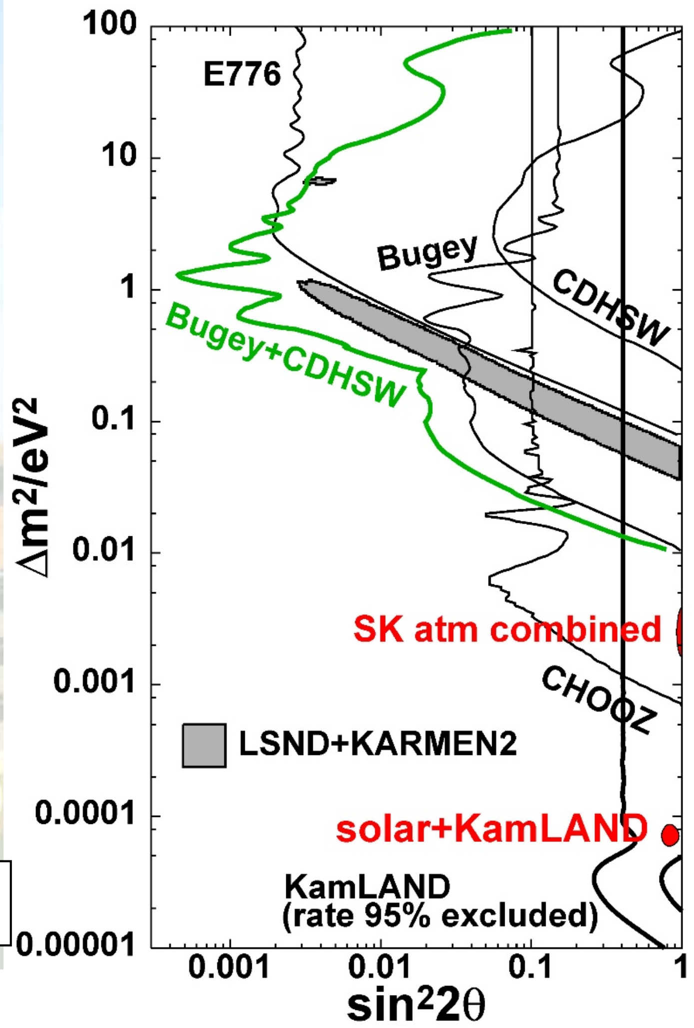
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2(\Delta m_{41}^2 L/4E)$$

$$\sin^2 2\theta_{\mathrm{CDHSW}} > 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) \cong 4|U_{\mu 4}|^2$$

LSND (accelerator): affirmaive

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu 4}|^2\sin^2(\Delta m_{41}^2 L/4E)$$

$$\sin^2 2\theta_{\mathrm{LSND}} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

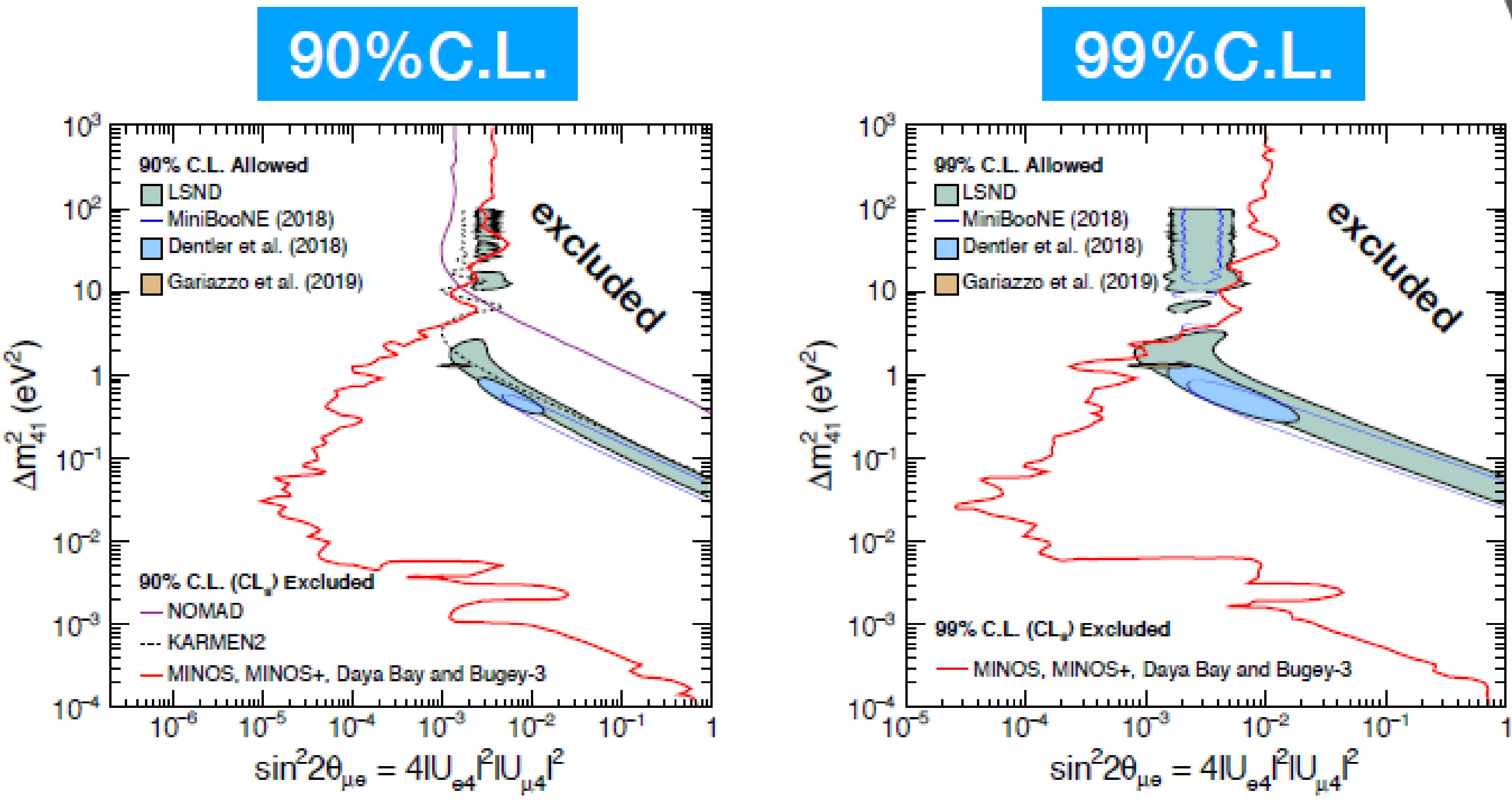


$$\Rightarrow \quad \sin^2 2\theta_{\mathrm{LSND}}(\Delta m^2) < \frac{1}{4}\sin^2 2\theta_{\mathrm{Bugey}}(\Delta m^2)\sin^2 2\theta_{\mathrm{CDHSW}}(\Delta m^2)$$

must be satisfied but there is no overlap between the left side of Bugey+CDHSW and the inside of LSND (Okada-OY Int.J.Mod.Phys.A12:3669,1997)

Carroll@
Neutrino2020

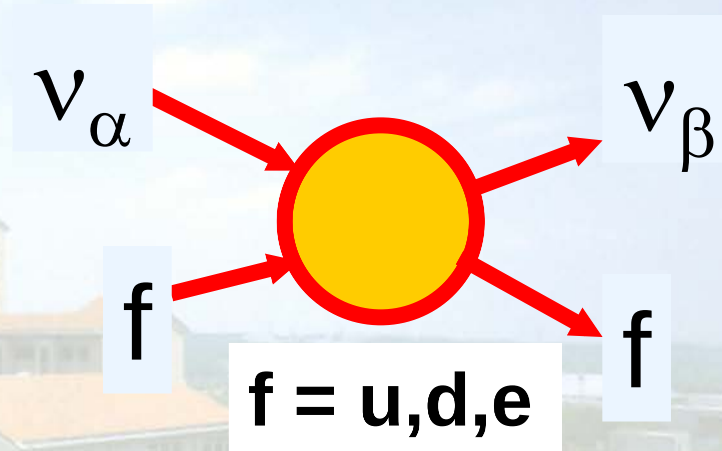
MINOS+/Daya Bay/Bugey-3 Exclusion



arXiv:2002.00301 (accepted by PRL)

(2) Nonstandard Interactions

$$\mathcal{L}_{eff} \;=\; G_{NP}^{\alpha\beta}\,\bar{\nu}_\alpha\gamma^\mu\nu_\beta\,\bar{f}\gamma_\mu f'$$



Matter potential is modified by Physics Beyond the Standard Model

→

ν experiments can give constraints or hints on Physics BSM

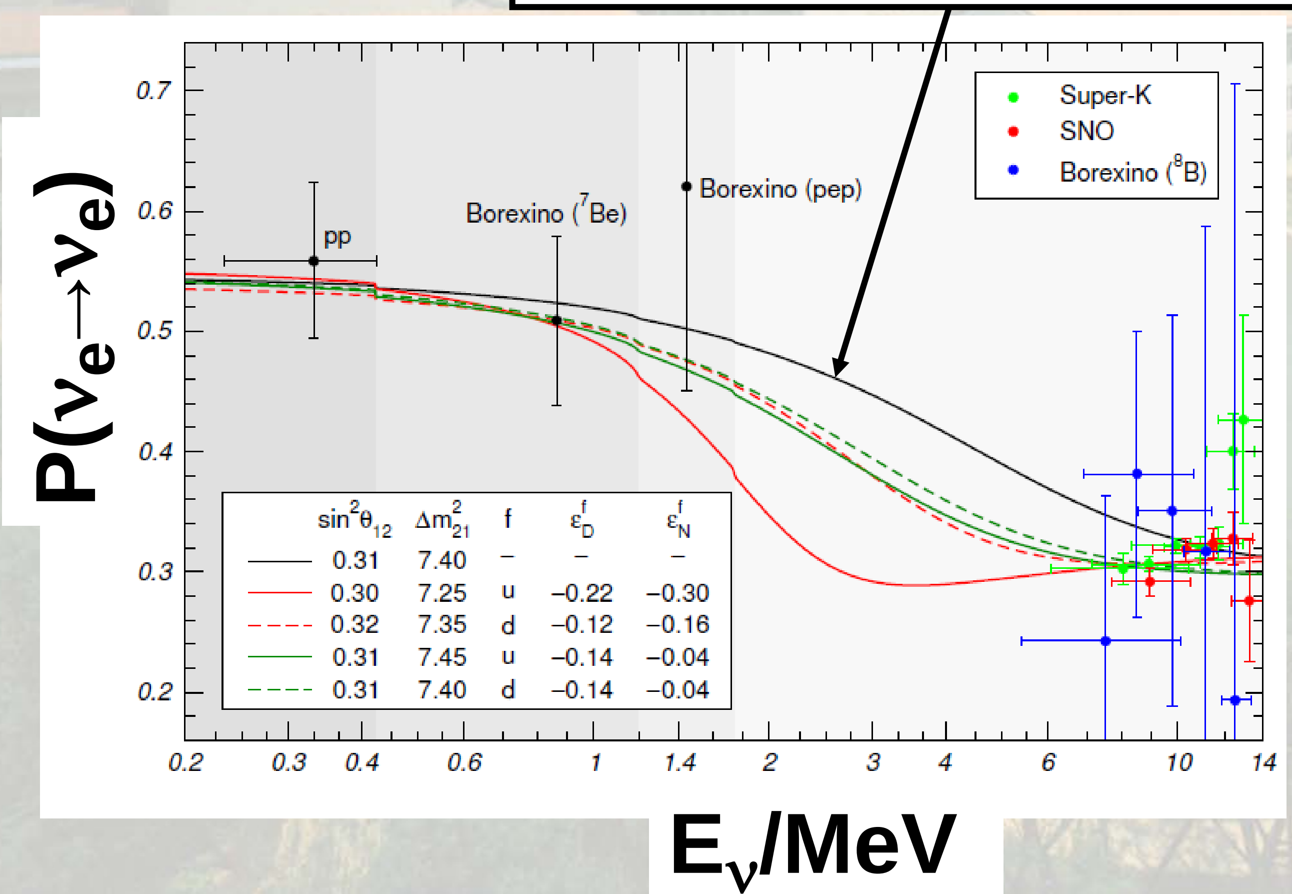
SM $\quad$ **NP**

$$\mathcal{A}_0 \equiv A\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad\rightarrow\quad \mathcal{A} \equiv A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$A \equiv \sqrt{2}G_F N_e$ $\quad$ $N_e \equiv$ electron density

●Motivation for Non Standard Interactions

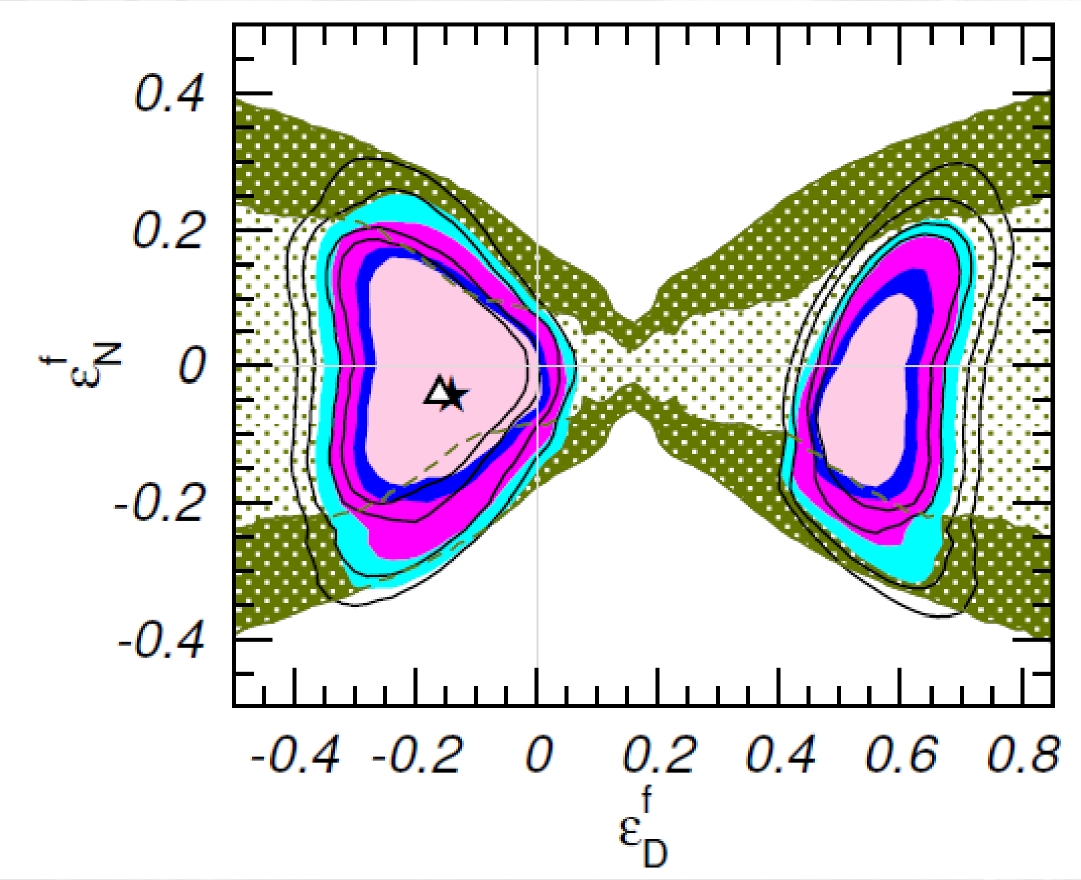
Tension between solar ν & KamLAND data comes from little observation of upturn by SK & SNO



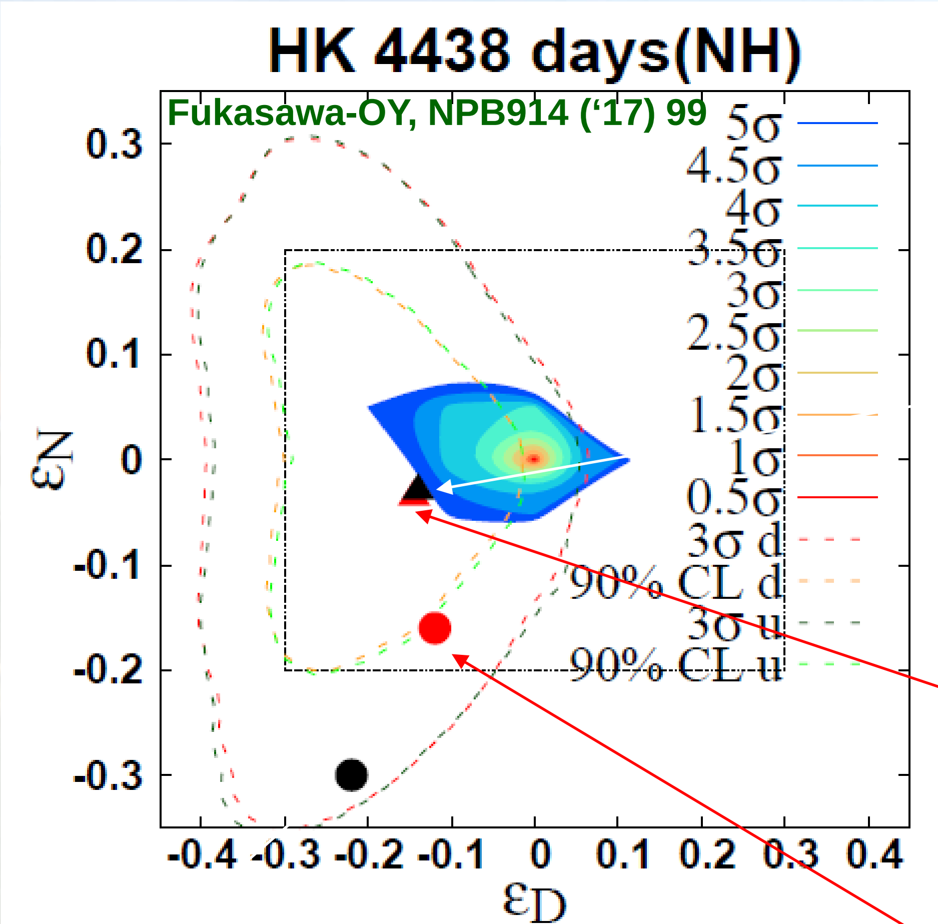
Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

The tension between solar ν & KamLAND data may be resolved by Non Standard Interaction.

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



Sensitivity of future experiment HK ν_{atm} to NSI



HK ν_{atm} has sensitivity to some region of the ν_{solar} anomaly

$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=u: significance:5σ

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

Best fit point of glolal analysis for f=d: significance:5σ

$$(\epsilon_D^d, \epsilon_N^d) = (-0.12, -0.16)$$

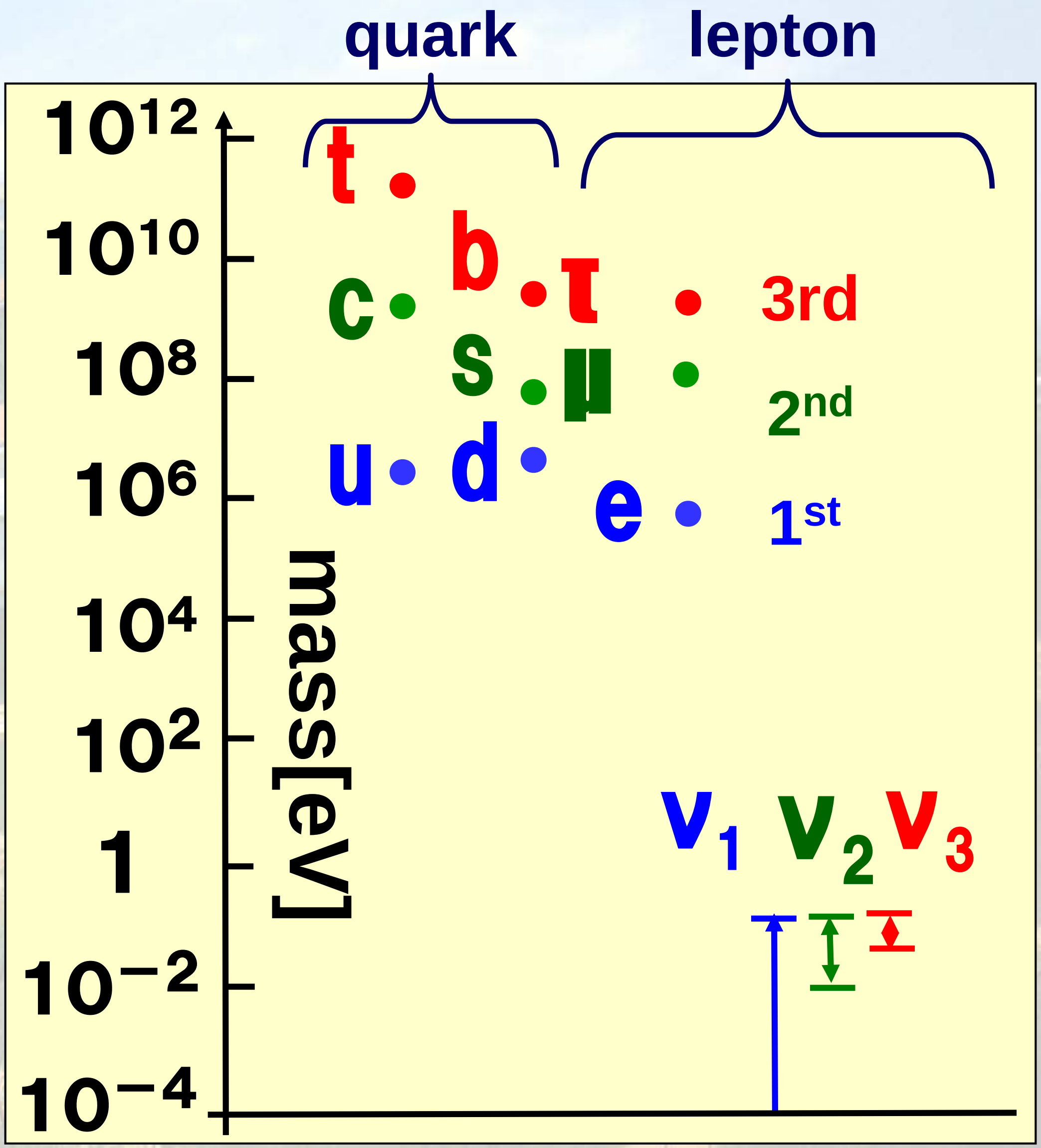
Best fit point of solar & KamLAND for f=d: significance:11σ

$$(\epsilon_D^u, \epsilon_N^u) = (-0.22, -0.30)$$

Best fit point of solar & KamLAND for f=u: significance:38σ

Implication of discovery of ν mass

- ν mass is evidence of physics **B**eyond the **S**tandard **M**odel→ It gives us a clue for BSM
- ν mass is much smaller than that of other quarks & leptons→ New mystery for hierarchy
- δ_{CP} stands for difference between ν & $\bar{\nu}$ → It is expected to give us a clue on matter-anti-matter asymmetry of our Universe



Physics beyond the Standard Model & ν

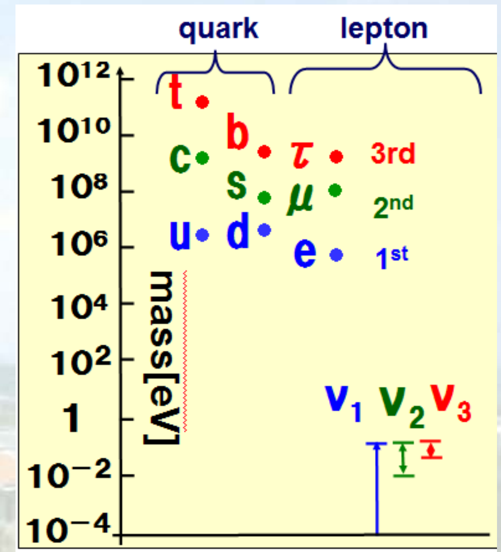
● **Small ν mass --> Hint for physics at high energy scale?**

Seesaw mechanism

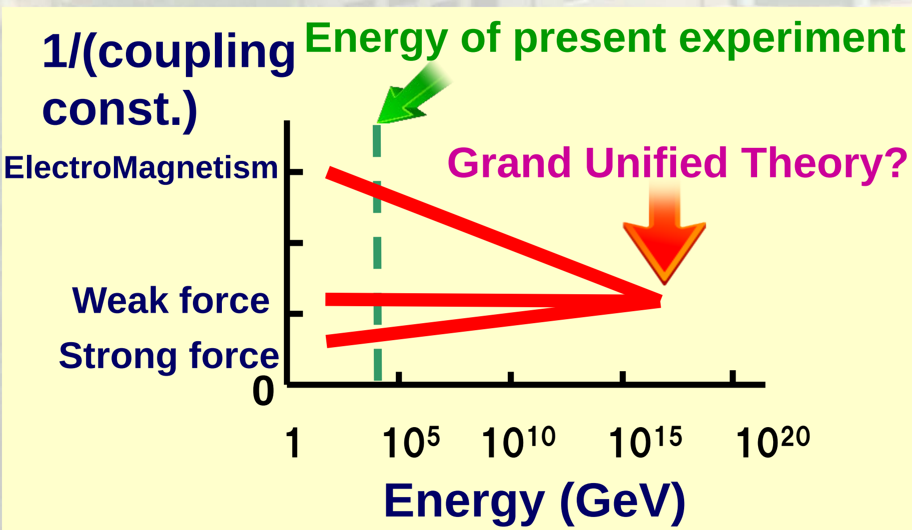
If 1GeV∼m<<M

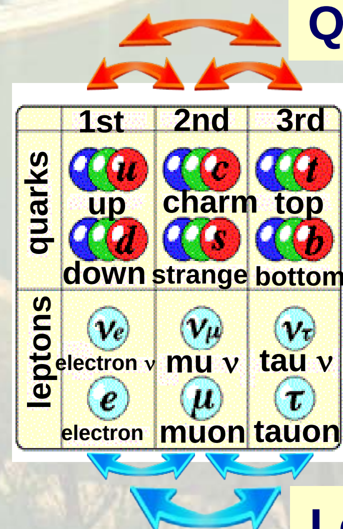
$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \rightarrow \begin{pmatrix} -m^2/M & 0 \\ 0 & M \end{pmatrix}$$

$$m_\nu = m^2/M < 1\ \text{eV} \quad \rightarrow \quad M > 10^9\,\text{GeV}$$



● **Relation between quark & lepton mixings-->Symmetry at high energy?**





If **Grand Unified Theory** is chosen by Nature, the mixings must coincide

Summary

- From various ν oscillation experiments, 3 mixing angles and 2 mass squared difference have been determined. Undetermined parameters are δ & sign(Δm^2_{31}).
- Future experiments are planned to determine δ & sign(Δm^2_{31}) .
- New physics can be investigated at ν oscillation experiments by looking for deviation from the standard scenario.

Backup slides

In natural units

$$\hbar = c = 1 \quad (1)$$

In the units (1), every quntity can be expressed in terms of power of mass or power of length. In the units (1), we have

$$\begin{aligned} 1 = \hbar c &= 0.197 \text{ GeV} \cdot \text{fm} \\ &= 0.197 \times 10^{9-15} \text{ eV} \cdot \text{m} = 0.197 \times 10^{-6} \text{ eV} \cdot \text{m} \\ &= 0.197 \times 10^{9-18} \text{ eV} \cdot \text{km} = 0.197 \times 10^{-9} \text{ eV} \cdot \text{km} \end{aligned}$$

Thus the argument of sine factor can be calculated as

$$\begin{aligned} \frac{\Delta m^2 L}{4E} &= \frac{\Delta m^2 L}{4E\hbar c} \\ &= \frac{(\Delta m^2/\text{eV}^2)\,\text{eV}^2 (L/\text{km})\,\text{km}}{4 \times (E/\text{GeV})\,\text{GeV} \times 0.197 \times 10^{-9} \text{ eV} \cdot \text{km}} \\ &= \frac{(\Delta m^2/\text{eV}^2)\,(L/\text{km})}{4 \times 0.197\,(E/\text{GeV})} \\ &= 1.269 \frac{(\Delta m^2/\text{eV}^2)\,(L/\text{km})}{(E/\text{GeV})} \end{aligned}$$

ν oscillation

2 flavor case in vacuum

1 component of Dirac eq. for mass eigenstate (w/ common $\vec{p}$)

$$\begin{cases} i\dfrac{d}{dx}\nu_1(x) = E_1\nu_1(x) \\ i\dfrac{d}{dx}\nu_2(x) = E_2\nu_2(x) \end{cases}$$

$$E_j = \sqrt{\vec{p}^2 + m_j^2}$$

Mixing angle

Flavor eigenstates

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

$$U \equiv \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

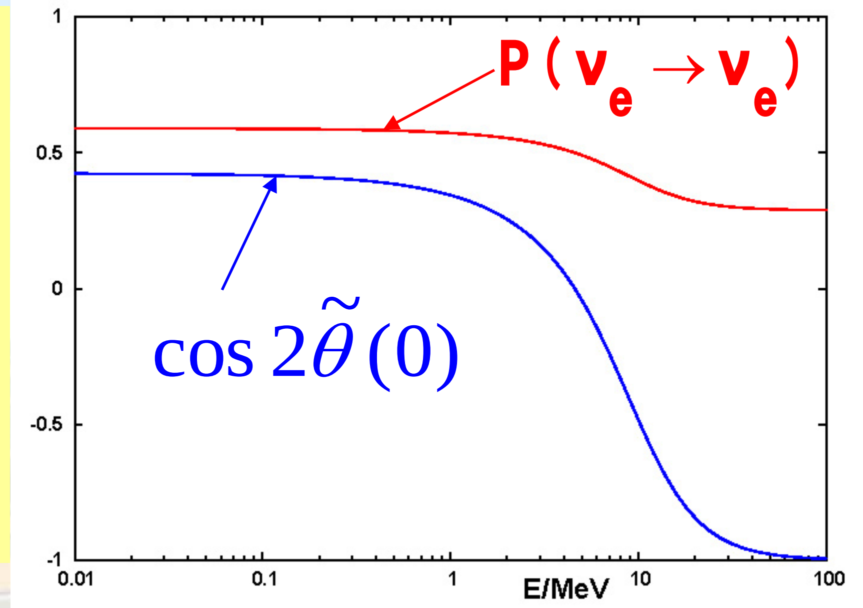
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Delta E = E_2 - E_1 \cong \frac{m_2^2 - m_1^2}{2E} = \frac{\Delta m^2}{2E}$$

- In the presence of ν mass & mixing, flavor transition occurs.

- The probability of flavor transition has an **oscillatory** behavior with respect to L

Probability for solar ν can be obtained by an adiabatic approximation and the limit L →∞. It is expressed in terms of the initial and final mixing angles, and depends on E_ν through the initial mixing angle.



$$A \equiv \sqrt{2} G_F n_e(x)$$

$$P(\nu_e \to \nu_e; \theta_\odot; A)_{N_\nu=2} \simeq c_\odot^2 \tilde{c}^2(t_1) + s_\odot^2 \tilde{s}^2(t_1)$$
$$= \frac{1}{2}\left[1 + \cos 2\theta_\odot \cos 2\tilde{\theta}(t_1)\right]$$
$$= \frac{1}{2}\left(1 + \cos 2\theta_\odot \frac{\Delta E \cos 2\theta_\odot - A}{\Delta \tilde{E}(t_1)}\right)$$

Final mixing angle (in vacuum)

Initial mixing angle (in matter)

Expression in the case of adiabatically varying N_e

$$\Delta E \equiv E_2 - E_1 \simeq \Delta m^2/2E$$
$$\tan 2\tilde{\theta}(t_1) \equiv \frac{\Delta E \sin 2\theta_\odot}{\Delta E \cos 2\theta_\odot - A(t_1)}$$
$$\Delta \tilde{E}(t_1) \equiv \left\{[\Delta E \cos 2\theta_\odot - A(t_1)]^2 + (\Delta E \sin 2\theta_\odot)^2\right\}^{1/2}$$

solar ν experiments

Ga: Gallex-GNO, SAGE

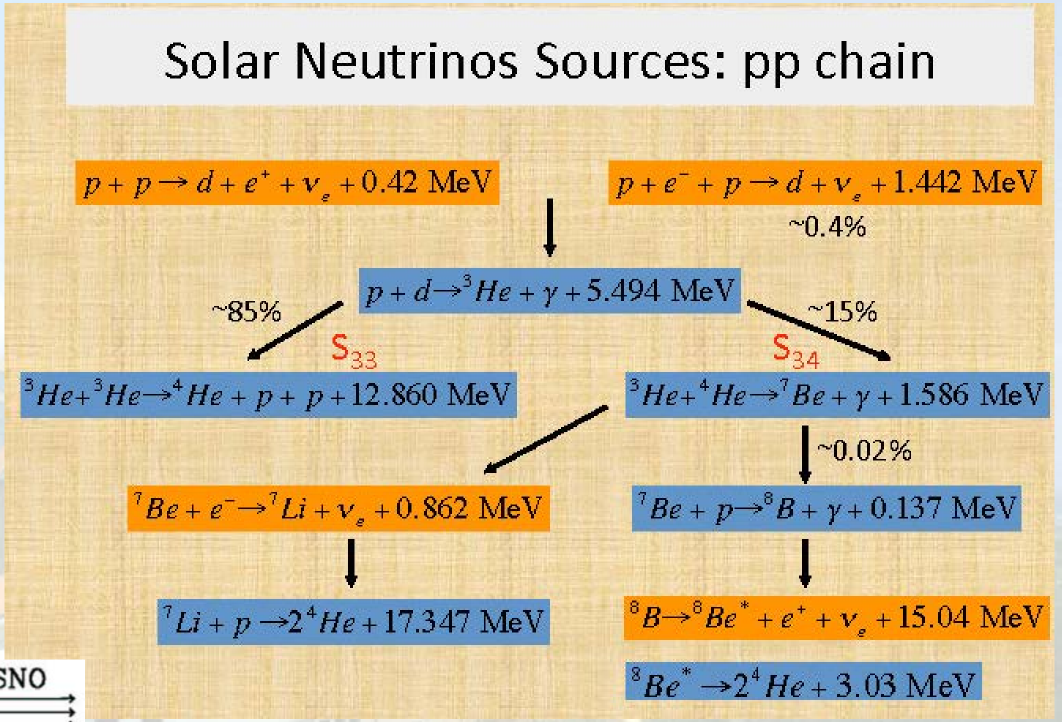
Cl: Homestake

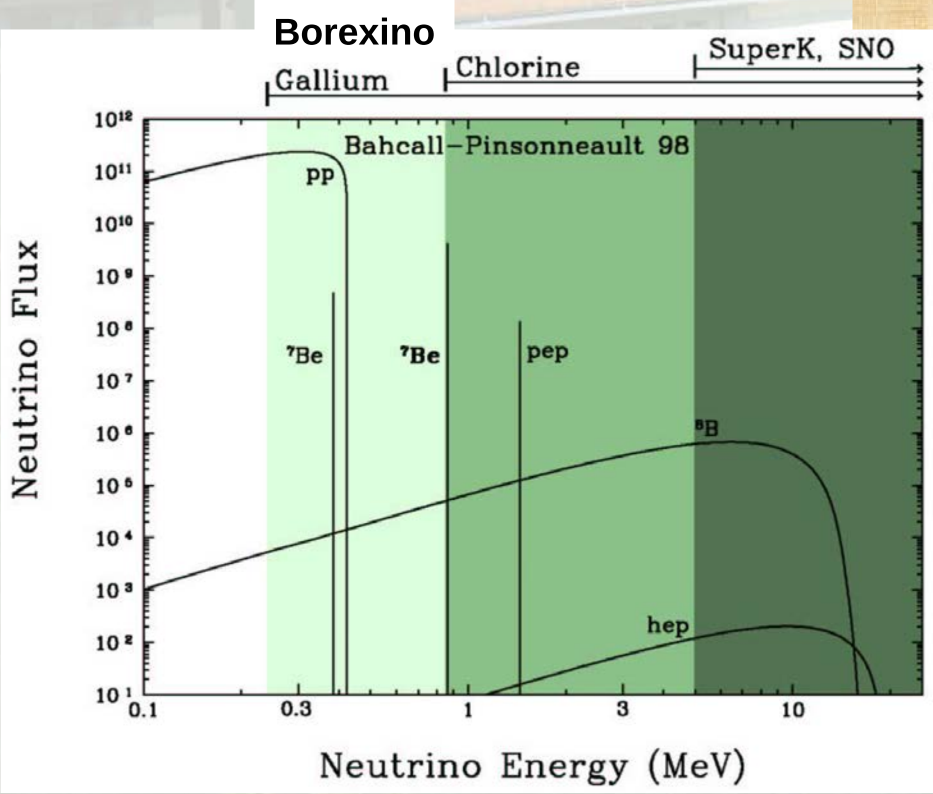
H_2O: Kam, SK

D_2O: SNO

$(CH_2)_n$: Borexino

in operation



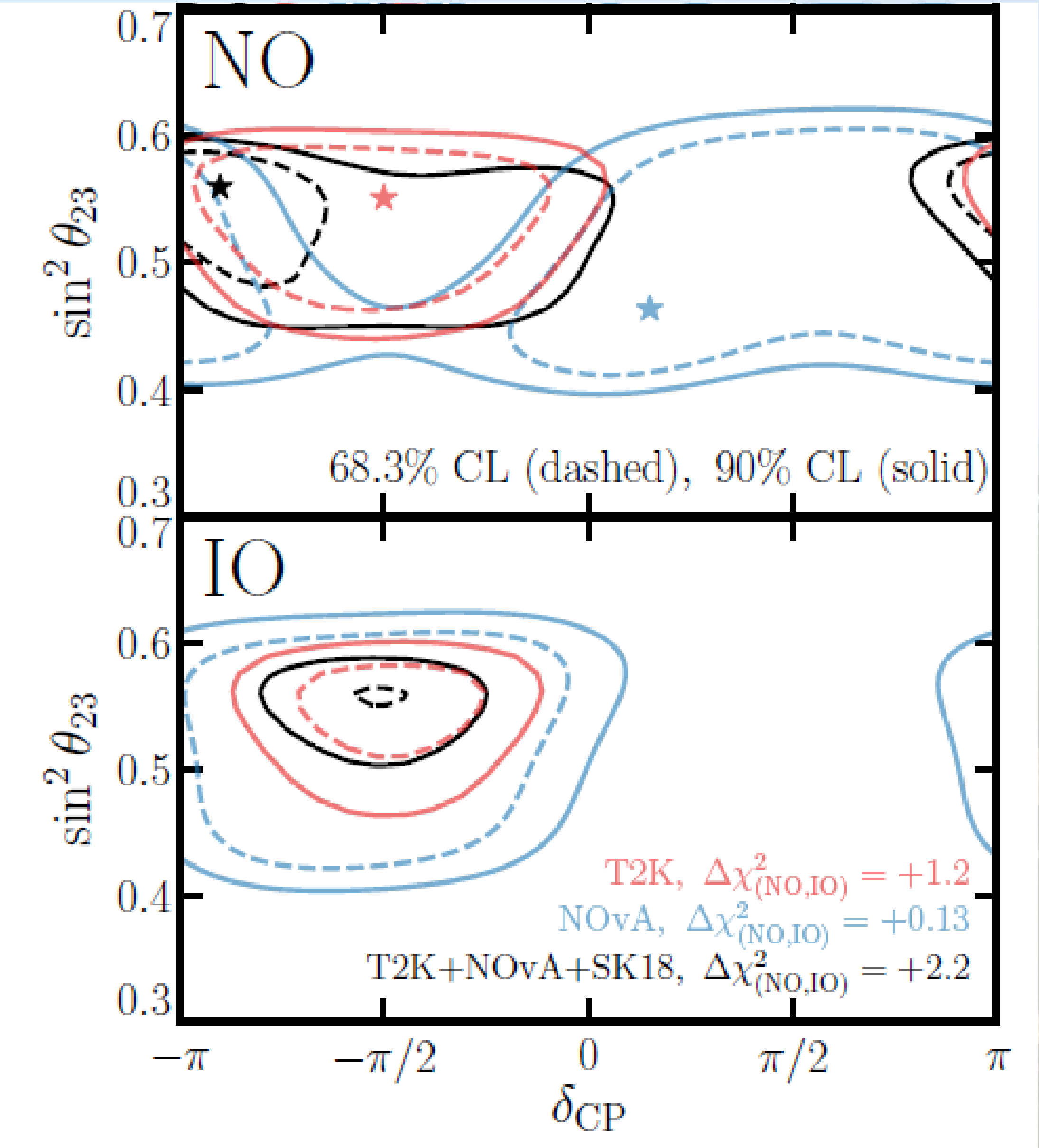


From various solar ν experiments with different threshold energies, info on Δm^2 and $\sin^2 2\theta$ can be obtained

Recent status: Tension between T2K and Nova?

Kelly et al, arXiv:2007.08526v1 [hep-ph]

Black lines: a joint fit of T2K/NOvA/SK18
Blue: NOvA alone
Red: T2K alone



Joint fit may indicate preference for Inverted Hierarchy