Neutrino Physics

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Lecture A:
Neutrino's history and lepton family

Lecture B:
Neutrino masses and flavor mixing

Lecture C:
Neutrino oscillation phenomenology

Lecture D:
Selected topics on cosmic neutrinos

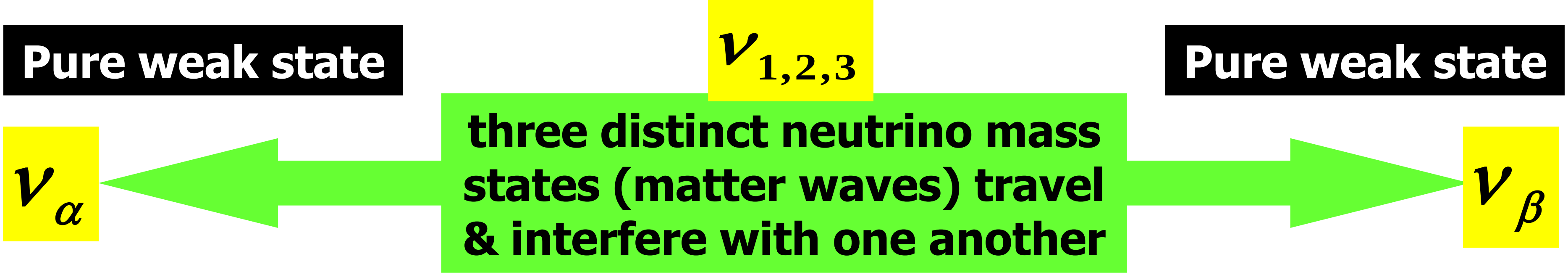
ν ν ν

@ Weihai High Energy Physics School, 2—10/8/2015

What is ν-oscillation?

Oscillation — a spontaneous periodic change from one neutrino flavor state to another, is a spectacular quantum phenomenon. It can occur as a natural consequence of neutrino mixing.

In a neutrino oscillation experiment, the neutrino beam is produced and detected via the weak **charged-current interactions**.



Pure weak state

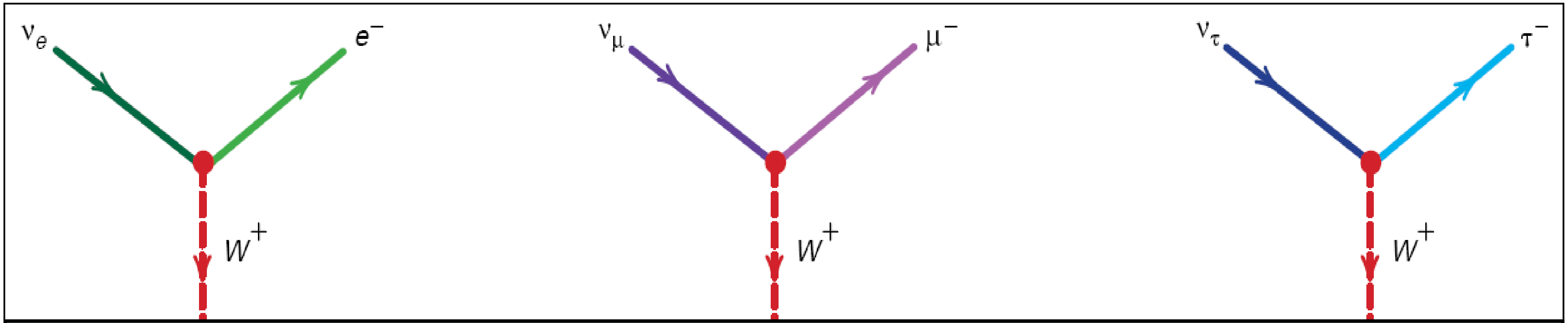
$\nu_{1,2,3}$

Pure weak state

ν_α

three distinct neutrino mass states (matter waves) travel & interfere with one another

ν_β



For example: $\overline{\nu}_e$ beam: β decay; ν_μ beam: π decay; ν_τ beam: D decay

How to calculate?

Boris Kayser (**hep-ph/0506165**): This change of neutrino flavor is a quintessentially quantum-mechanical effect. Indeed, it entails some quantum-mechanical subtleties that are still debated to this day. However, there is little debate about the "bottom line" ------- the expression for the flavor-change probability……

Typical References:

- ♣ Giunti, Kim, "Fundamentals of Neutrino Physics and Astrophysics" (2007)
- ♣ Cohen, Glashow, Ligeti: "Disentangling Neutrino Oscillations" (0810.4602)
- ♣ Akhmedov, Smirnov: "Paradoxes of Neutrino Oscillations" (0905.1903)

Our strategy: follow the simplest way (which is conceptually ill) to derive the "bottom line" of neutrino oscillations: the leading-order formula of neutrino oscillations in phenomenology.

Lecture C

- ★ Neutrino oscillation descriptions
- ★ Neutrino oscillation experiments
- ★ What are known and unknown?

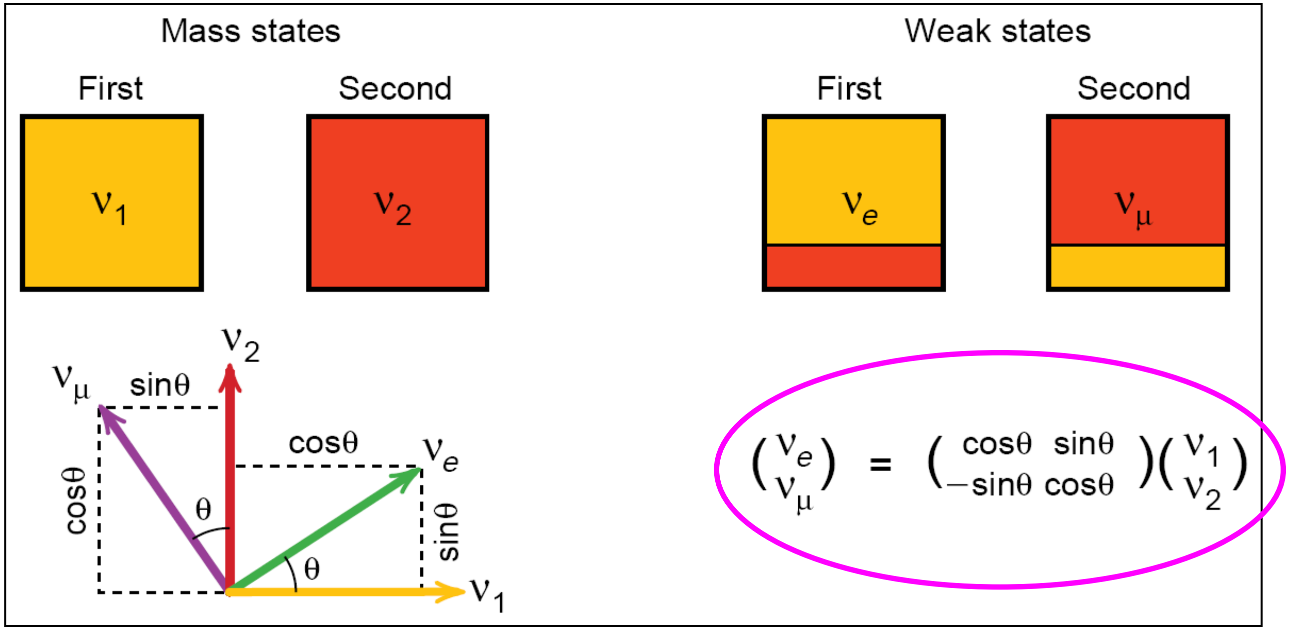
Steven Weinberg (2003):

It is to forgive yourself for wasting time. In the real world, it's very hard to know which problems are important, and you never know whether at a given moment in history a problem is solvable.

If you want to be creative, then you will have to get used to spending most of your time not being creative.

2-flavor oscillation (1)

For simplicity, we consider two-flavor neutrino mixing and oscillation:



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

Approximation:

a plane wave with a common momentum for each mass state

$$\begin{aligned} |\nu_\mu(0)\rangle &= |\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle \\ |\nu_\mu(t)\rangle &= -\sin\theta e^{-iE_1t}|\nu_1\rangle + \cos\theta e^{-iE_2t}|\nu_2\rangle \\ &= e^{-iE_1t}\left(-\sin\theta|\nu_1\rangle + \cos\theta e^{-i\Delta Et}|\nu_2\rangle\right) \end{aligned}$$

$$\begin{aligned} \Delta E &\equiv E_2 - E_1 = \sqrt{p^2+m_2^2} - \sqrt{p^2+m_1^2} \\ &\approx \left(p + \frac{m_2^2}{2p}\right) - \left(p + \frac{m_1^2}{2p}\right) \approx \frac{\Delta m^2}{2E} \end{aligned}$$

$$\Delta m^2 \equiv m_2^2 - m_1^2\ , \quad E \approx p \gg m_{1,2}\ (\text{relativistic neutrino beam})\ , \quad \hbar = c = 1\ (\text{natural units})$$

2-flavor oscillation (2)

The oscillation probability for appearance ν experiments:

$$\begin{aligned}
P\left(\nu_\mu \to \nu_e\right) &= \left|\langle \nu_e | \nu_\mu(t)\rangle\right|^2 = \left|\left(\cos\theta\langle\nu_1| + \sin\theta\langle\nu_2|\right)\left(-\sin\theta|\nu_1\rangle + \cos\theta e^{-i\Delta E t}|\nu_2\rangle\right)\right|^2 \\
&= \left|\sin\theta\cos\theta\left(1 - e^{-i\Delta E t}\right)\right|^2 = 2\left(\sin\theta\cos\theta\right)^2\left(1 - \cos\frac{\Delta m^2 t}{2E}\right) \\
&= \sin^2 2\theta \sin^2\frac{\Delta m^2 L}{4E}
\end{aligned}$$

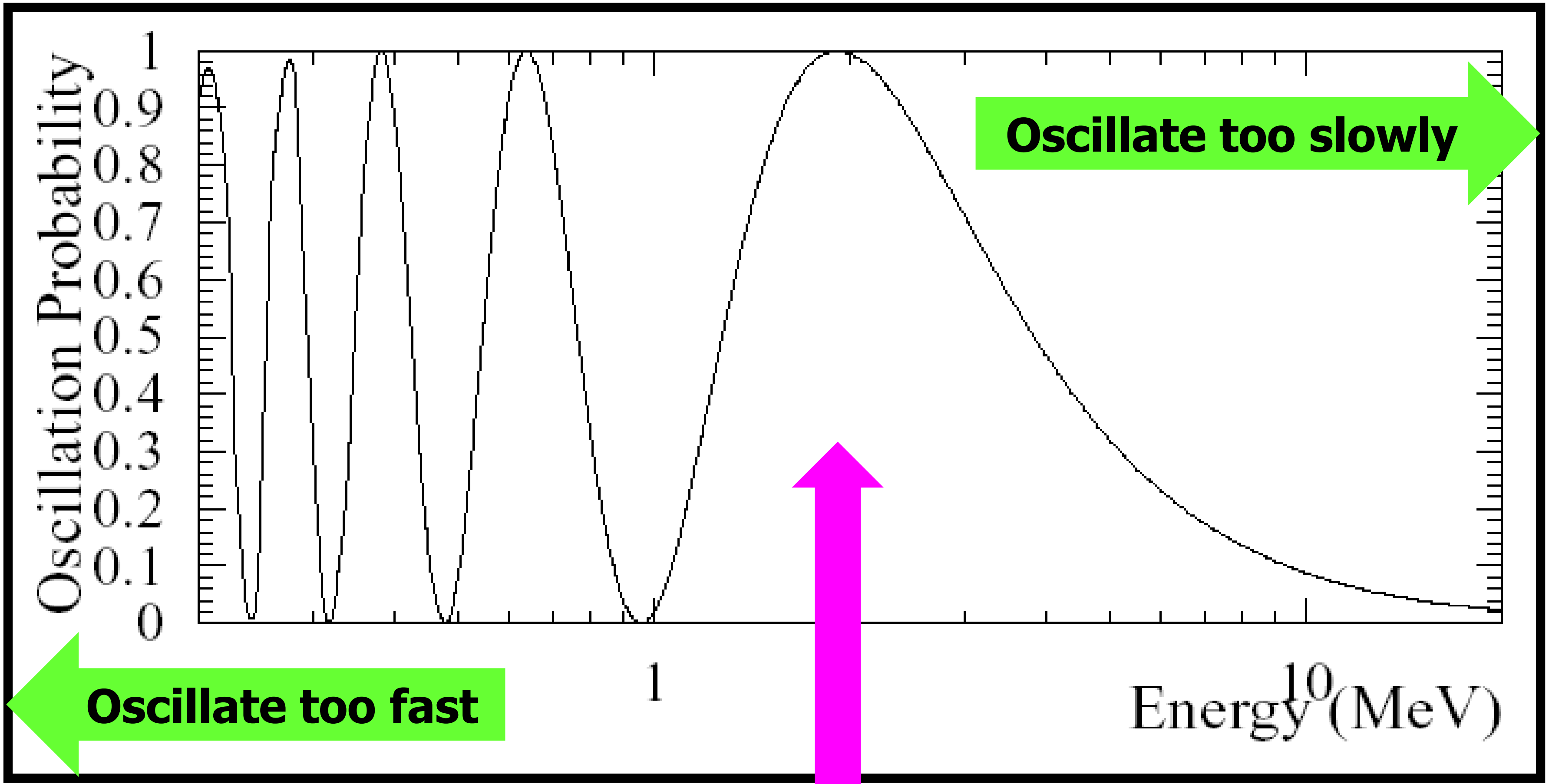
The conversion and survival probabilities in realistic units:

$$\begin{aligned}
P\left(\nu_\mu \to \nu_e\right) &= \sin^2 2\theta \sin^2\frac{1.27\Delta m^2 L}{E} \\
P\left(\nu_\mu \to \nu_\mu\right) &= 1 - \sin^2 2\theta \sin^2\frac{1.27\Delta m^2 L}{E}
\end{aligned}$$

Due to the smallness of (1,3) mixing, both solar & atmospheric neutrino oscillations are roughly the 2-flavor oscillation.

Δm^2 in unit of eV^2 , L in unit of km , E in unit of GeV

2-flavor oscillation (3)



Oscillate too slowly

Oscillate too fast

$$P(\nu_e \to \nu_\mu) = |\langle \nu_\mu | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

Exercise: why 1.27 ?

	Natural units	Realistic units
Phase factors	$\exp\left(-iE_{1,2}t\right)$	$\exp\left(-i\frac{E_{1,2}}{\hbar}t\right)$
Energies and momentum	$E_{1,2}=\sqrt{p^2+m_{1,2}^2}$	$E_{1,2}=\sqrt{p^2c^2+m_{1,2}^2c^4}$
Energy difference	$\Delta E=\frac{\Delta m^2}{2E}$	$\Delta E=\frac{\Delta m^2c^3}{2p}=\frac{\Delta m^2c^4}{2E}$
Time and distance	$t=L$	$t=\frac{L}{c}$
Oscillation argument	$\frac{1}{2}\Delta Et=\frac{\Delta m^2L}{4E}$	$\frac{1}{2}\frac{\Delta E}{\hbar}t=\frac{c^3}{\hbar}\cdot\frac{\Delta m^2L}{4E}$

$$c=2.998\times10^{5}\ \text{km}\,\text{s}^{-1}$$

$$\hbar=6.582\times10^{-25}\ \text{GeV s}$$

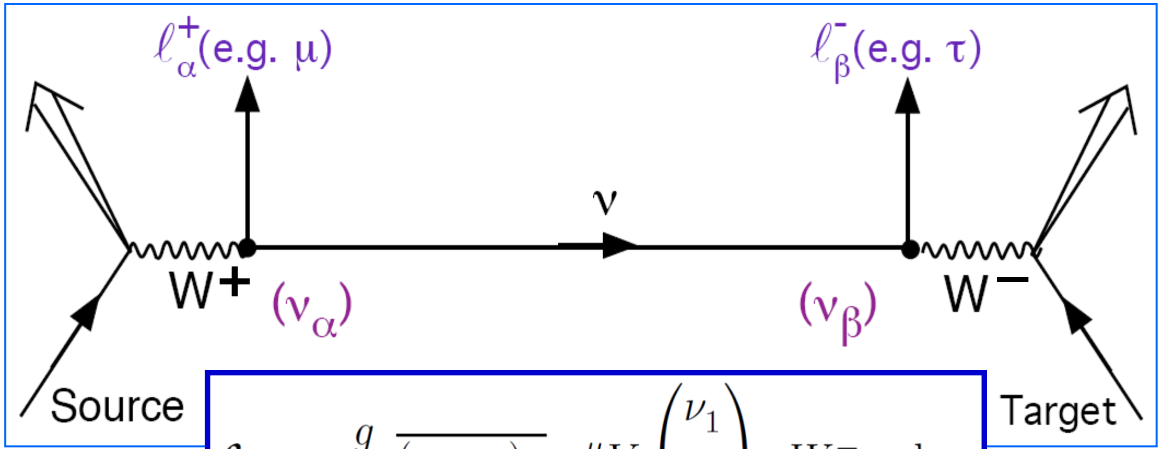
$$\frac{c^3}{4\hbar}\Rightarrow\frac{1}{4\times0.1973}=1.267\approx1.27$$

$$c=1\quad\Rightarrow\quad\hbar=6.582\times10^{-25}\ \text{GeV}\times2.998\times10^{5}\ \text{km}$$

$$=1.973\times10^{-19}\ \text{GeV km}=0.1973\,\text{eV}^2\,\text{GeV}^{-1}\,\text{km}$$

3-flavor oscillation (1)

Production and detection of a neutrino beam by CC weak interactions:



$$\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \overline{(e\ \mu\ \tau)_{\rm L}}\, \gamma^\mu \underset{\Uparrow}{V} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}_{\rm L} \underset{\Uparrow}{W^-_\mu} + \text{h.c.}$$

$$|\nu_\alpha(0)\rangle = |\nu_\alpha\rangle = \sum_{i=1}^{3} \underline{V^*_{\alpha i}} |\nu_i\rangle$$

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{3} \underline{V^*_{\alpha i}} e^{-iE_i t} |\nu_i\rangle$$

$$\alpha, \beta, \gamma = e, \mu, \tau$$

$$i, j, k = 1,2,3$$

$$A\left(\nu_\alpha \to \nu_\beta\right) = \langle \nu_\beta | \nu_\alpha(t)\rangle = \left(\sum_{j=1}^{3} V_{\beta j} \langle \nu_j|\right)\left(\sum_{i=1}^{3} V^*_{\alpha i} e^{-iE_i t} |\nu_i\rangle\right) = \sum_{i=1}^{3} V^*_{\alpha i} V_{\beta i} e^{-iE_i t}$$

$$P\left(\nu_\alpha \to \nu_\beta\right) = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2 = \left|\sum_{i=1}^{3} V^*_{\alpha i} V_{\beta i} e^{-iE_i t}\right|^2$$

$$= \sum_{i=1}^{3} \left|V^*_{\alpha i} V_{\beta i}\right|^2 + 2 \sum_{i<j}^{3} \mathrm{Re}\left[V^*_{\alpha i} V_{\beta i} V_{\alpha j} V^*_{\beta j} e^{i\left(E_j - E_i\right)t}\right]$$

3-flavor oscillation (2)

The formula of three-flavor oscillation probability with CP/T violation:

$$
\begin{aligned}
P\left(\nu_\alpha \to \nu_\beta\right) &= \sum_{i=1}^{3} \left| V_{\alpha i}^{*} V_{\beta i} \right|^2 + 2 \sum_{i<j}^{3} \mathrm{Re}\left(V_{\alpha i}^{*} V_{\beta i} V_{\alpha j} V_{\beta j}^{*} \right) \cos \frac{\Delta m_{ji}^2 L}{2E} \\
&\qquad - 2 \sum_{i<j}^{3} \mathrm{Im}\left(V_{\alpha i}^{*} V_{\beta i} V_{\alpha j} V_{\beta j}^{*} \right) \sin \frac{\Delta m_{ji}^2 L}{2E} \\
&= \sum_{i=1}^{3} \left| V_{\alpha i}^{*} V_{\beta i} \right|^2 + 2 \sum_{i<j}^{3} \mathrm{Re}\left(V_{\alpha i}^{*} V_{\beta i} V_{\alpha j} V_{\beta j}^{*} \right) \\
&\quad -4 \sum_{i<j}^{3} \mathrm{Re}\left(V_{\alpha i}^{*} V_{\beta i} V_{\alpha j} V_{\beta j}^{*} \right) \sin^2 \frac{\Delta m_{ji}^2 L}{4E} - 2 \sum_{i<j}^{3} \mathrm{Im}\left(V_{\alpha i}^{*} V_{\beta i} V_{\alpha j} V_{\beta j}^{*} \right) \sin \frac{\Delta m_{ji}^2 L}{2E} \\
&= \left| \sum_{i=1}^{3} V_{\alpha i}^{*} V_{\beta i} \right|^2 - 4 \sum_{i<j}^{3} \mathrm{Re}\left(V_{\alpha i} V_{\beta j} V_{\alpha j}^{*} V_{\beta i}^{*} \right) \sin^2 \frac{\Delta m_{ji}^2 L}{4E} \\
&\qquad + 2 \sum_{i<j}^{3} \mathrm{Im}\left(V_{\alpha i} V_{\beta j} V_{\alpha j}^{*} V_{\beta i}^{*} \right) \sin \frac{\Delta m_{ji}^2 L}{2E}
\end{aligned}
$$

Jarlskog

$$\left| \sum_{i=1}^{3} V_{\alpha i}^{*} V_{\beta i} \right|^2 = \delta_{\alpha\beta}$$

$$\mathrm{Im}\left(V_{\alpha i} V_{\beta j} V_{\alpha j}^{*} V_{\beta i}^{*} \right) = \mathcal{J} \sum_{\gamma, k} \left(\epsilon_{\alpha\beta\gamma} \epsilon_{ijk} \right)$$

3-flavor oscillation (3)

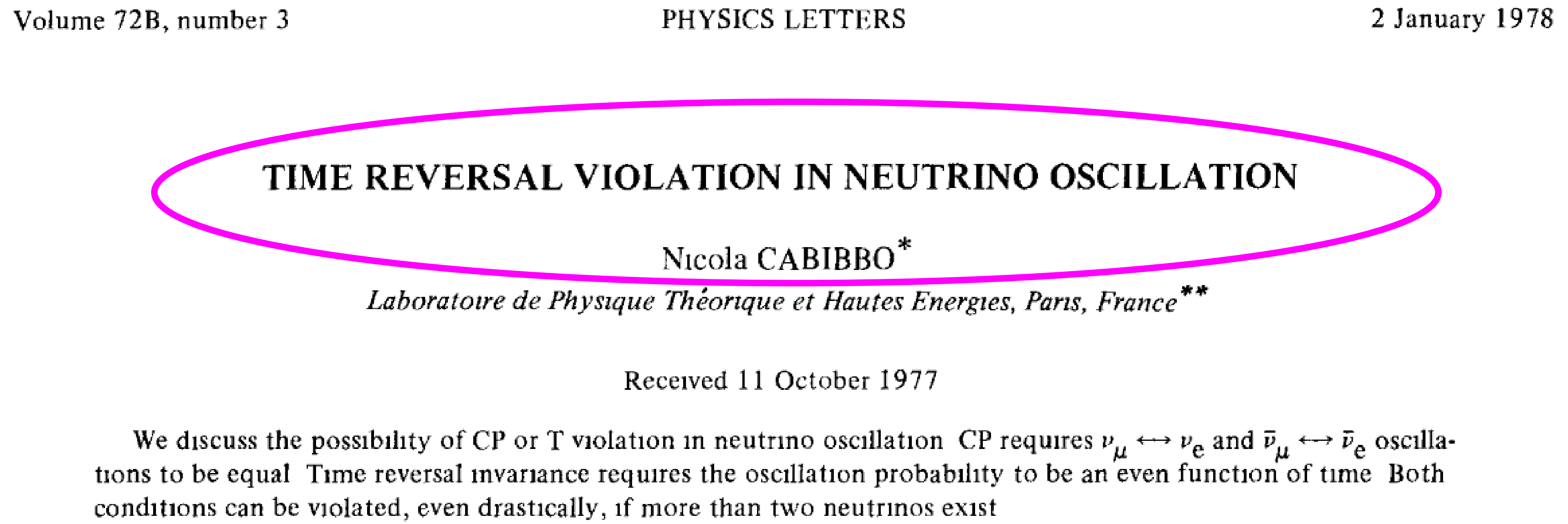
The final formula of 3-flavor oscillation probabilities with CP violation:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \delta_{\alpha\beta} - 4\sum_{i<j}^{3} \mathrm{Re}\left(V_{\alpha i}V_{\beta j}V_{\alpha j}^{*}V_{\beta i}^{*}\right)\sin^2\frac{\Delta m_{ji}^2 L}{4E} + 8\mathcal{J}\sum_{\gamma}\epsilon_{\alpha\beta\gamma}\sin\frac{\Delta m_{21}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}\sin\frac{\Delta m_{32}^2 L}{4E}$$

$$\begin{aligned}
& 2\sum_{i<j}^{3}\mathrm{Im}\left(V_{\alpha i}V_{\beta j}V_{\alpha j}^{*}V_{\beta i}^{*}\right)\sin\frac{\Delta m_{ji}^2 L}{2E} \\
= \; & +2\mathcal{J}\sum_{\gamma}\epsilon_{\alpha\beta\gamma}\left(\sin\frac{\Delta m_{21}^2 L}{2E} - \sin\frac{\Delta m_{31}^2 L}{2E} + \sin\frac{\Delta m_{32}^2 L}{2E}\right) \\
= \; & -2\mathcal{J}\sum_{\gamma}\epsilon_{\alpha\beta\gamma}\left(\sin\frac{\Delta m_{12}^2 L}{2E} + \sin\frac{\Delta m_{23}^2 L}{2E} + \sin\frac{\Delta m_{31}^2 L}{2E}\right) \\
= \; & +8\mathcal{J}\sum_{\gamma}\epsilon_{\alpha\beta\gamma}\sin\frac{\Delta m_{12}^2 L}{4E}\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{31}^2 L}{4E}
\end{aligned}$$

NOTE: If you have seen a different sign in front of the CP-violating part in a lot of literature, it most likely means that a complex conjugation of *V* in the production point of neutrino beam was not properly taken into account.

The 1st paper on ν-CPV



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TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

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We discuss the possibility of CP or T violation in neutrino oscillation. CP requires $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations to be equal. Time reversal invariance requires the oscillation probability to be an even function of time. Both conditions can be violated, even drastically, if more than two neutrinos exist.

Tri-maximal neutrino mixing + maximal CP violation:

$$\boxed{J = 1/6\sqrt{3}}$$

$$A = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^* \\ 1 & a^* & a \end{pmatrix}, \qquad a = \exp[2\pi i/3]$$

CP and T violation

Under CPT invariance, CP- and T-violating asymmetries are identical:

$$\begin{aligned} P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\overline{\nu}_\alpha \to \overline{\nu}_\beta\right) &= P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\nu_\beta \to \nu_\alpha\right) \\ &= 16\mathcal{J} \sum_\gamma \epsilon_{\alpha\beta\gamma} \sin\frac{\Delta m^2_{21} L}{4E} \sin\frac{\Delta m^2_{31} L}{4E} \sin\frac{\Delta m^2_{32} L}{4E} \end{aligned}$$

Comments:

★ **CP / T violation cannot show up in the disappearance neutrino oscillation experiments ($\alpha = \beta$);**

★ **CP / T violation is a small three-family flavor effect;**

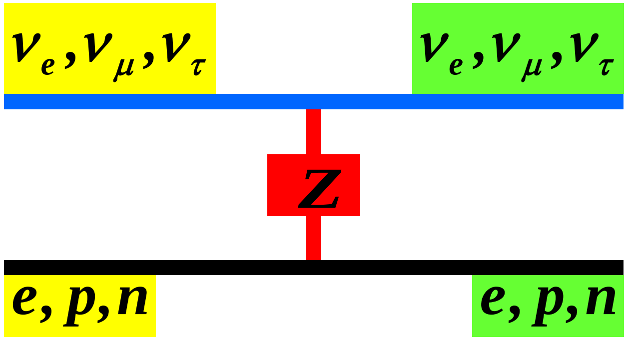
★ **CP / T violation in normal lepton-number-conserving neutrino oscillations depends only upon the Dirac phase of *V*; hence such oscillation experiments cannot tell us whether neutrinos are Dirac or Majorana particles.**

$$J = \sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\theta_{13}\cos^2\theta_{13}\sin\delta \le 1/6\sqrt{3} \approx 9.6\%$$

What’s matter effect?

When light travels through a medium, it sees a refractive index due to coherent forward scattering from the constituents of the medium.

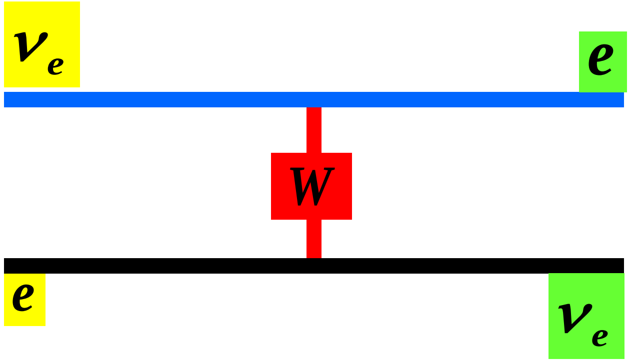
A similar phenomenon applies to neutrino flavor states as they travel through matter. All flavor states see a common refractive index from NC forward scattering, and the electron (anti) neutrino sees an extra refractive index due to CC forward scattering in matter.

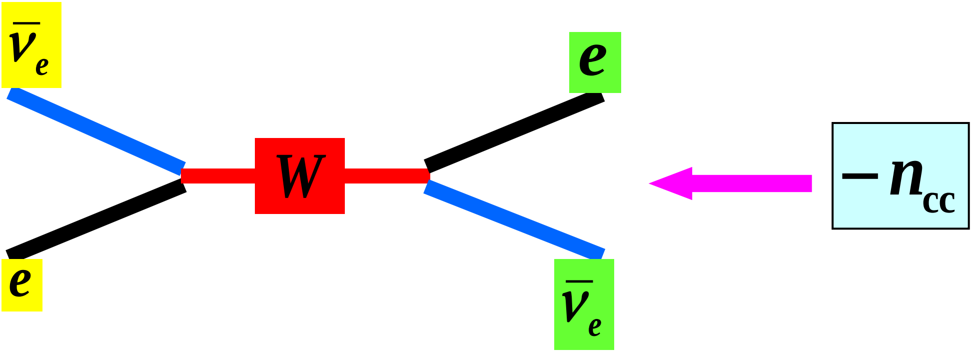


Refractive index

$$n_{\rm nc} = 1 + \frac{2\pi N_e}{p^2} f_{\rm nc}$$

$$n_{\rm cc} = \frac{2\pi N_e}{p^2} f_{\rm cc} \Longrightarrow n_{\rm cc} = \frac{\sqrt{2} G_{\rm F} N_e}{p}$$

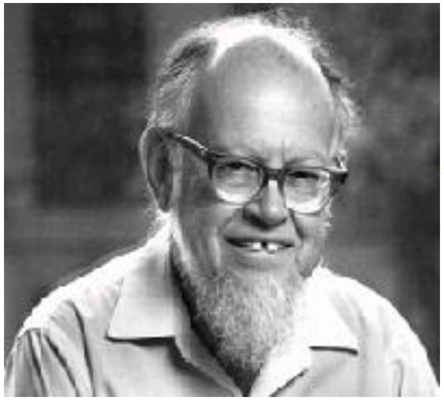




Matter matters

In travelling a distance, each neutrino flavor state develops a "matter" phase due to the refractive index. The overall NC-induced phase is trivial, while the relative CC-induced phase may change the behaviors of neutrino oscillations: matter effects — L. Wolfenstein (1978)

$$\nu_e : \exp[ipx(n_{\rm nc} + n_{\rm cc} - 1)]$$
$$\nu_\mu : \exp[ipx(n_{\rm nc} - 1)]$$
$$\nu_\tau : \exp[ipx(n_{\rm nc} - 1)]$$



MSW

Matter effect inside the Sun can enhance the solar neutrino oscillation (S.P. Mikheyev and A.Yu. Smirnov 1985 — MSW effect); matter effect inside the Earth may cause a day-night effect. Note that matter effect in long-baseline experiments might result in fake CP-violating effects.

MSW resonance

Neutrino oscillation in matter:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}-\frac{\Delta m^2}{4E}\cos 2\theta+\sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$P(\nu_e\to\nu_\mu)_{\mathrm{v}}=\sin^2 2\theta\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$$P(\nu_e\to\nu_\mu)_{\mathrm{m}}=\sin^2 2\tilde{\theta}\sin^2\left(\frac{1.27\Delta\tilde{m}^2 L}{E}\right)$$

The matter density changes for solar neutrinos to travel from the core to the surface

$$\begin{pmatrix}|\nu_e\rangle\\ |\nu_\mu\rangle\end{pmatrix}=\begin{pmatrix}\cos\tilde{\theta} & \sin\tilde{\theta}\\ -\sin\tilde{\theta} & \cos\tilde{\theta}\end{pmatrix}\begin{pmatrix}|\tilde{\nu}_1\rangle\\ |\tilde{\nu}_2\rangle\end{pmatrix}$$

$$\Delta\tilde{m}^2=\sqrt{\left(\Delta m^2\cos 2\theta-2\sqrt{2}\,G_{\mathrm{F}}N_e E\right)^2+\left(\Delta m^2\sin 2\theta\right)^2}$$

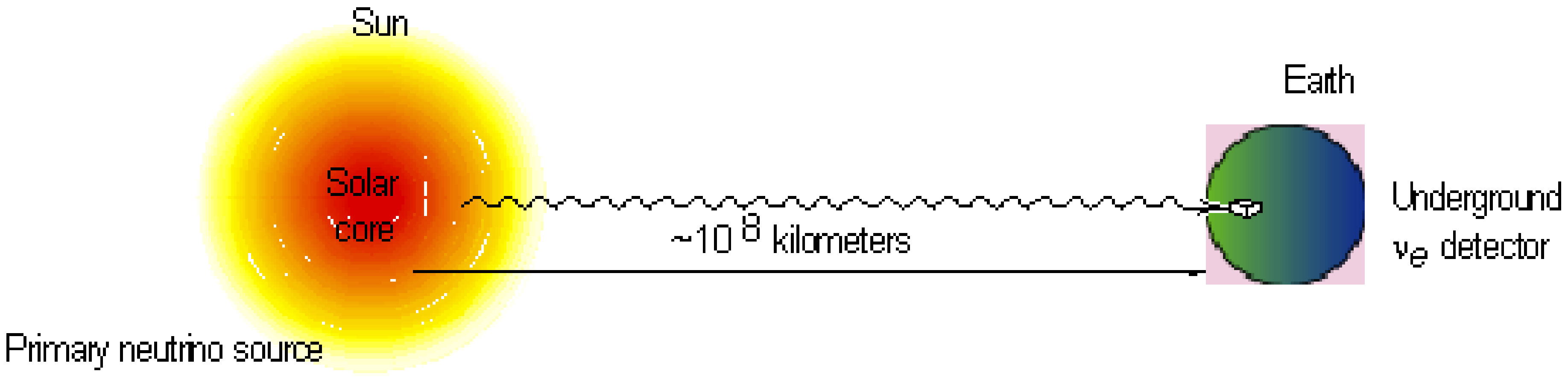
$$\tan 2\tilde{\theta}=\frac{\Delta m^2\sin 2\theta}{\Delta m^2\cos 2\theta-2\sqrt{2}\,G_{\mathrm{F}}N_e E}$$

resonance →

MSW

$$\tilde{\theta}=45^\circ$$

1968: solar neutrinos

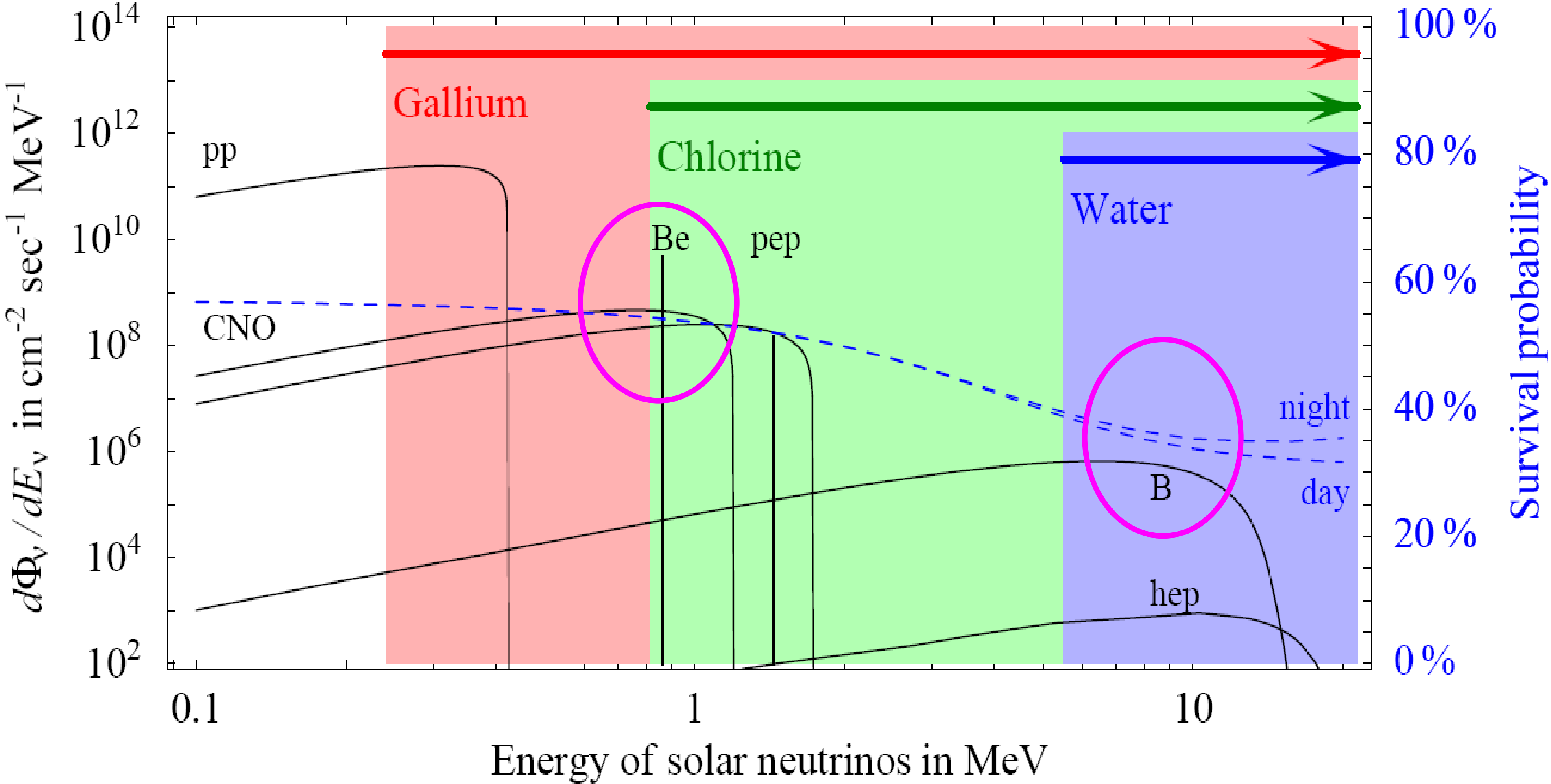


$$4p \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 26.73\ \mathrm{MeV}$$

Ray Davis **made the first observation of a solar neutrino shortfall (compared to** **John Bahcall’s prediction for the ν-flux) at the Homestake Mine in 1968.**

The simplest solution to this problem is **neutrino oscillation!**

Energy spectrum



DATA

Strumia and Vissani, hep-ph/0606054

Examples: Boron (硼) ν's ~ 32%, Beryllium (铍) ν's ~ 56%

MSW solution

In the two-flavor approximation:

$$N_e(0) \approx 6 \times 10^{25}\ \mathrm{cm}^{-3}$$

$$\mathcal{H}_{\mathrm{eff}} = \frac{\Delta m^2_{21}}{4E}\begin{bmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{bmatrix} + \begin{bmatrix} \sqrt{2} G_{\mathrm{F}} N_e(r) & 0 \\ 0 & 0 \end{bmatrix}$$

$7.6\times10^{-5}\ \mathrm{eV}^2$

$0.75\times10^{-5}\ \mathrm{eV}^2/\mathrm{MeV}$ (at $r = 0$)

Be-7 ν's: *E* ~ 0.862 MeV. The vacuum term is dominant. The survival probability on the earth is (for theta_12 ~ 34°):

$$P(\nu_e \to \nu_e) \approx 1 - \frac{1}{2}\sin^2 2\theta_{12} \sim 0.56$$

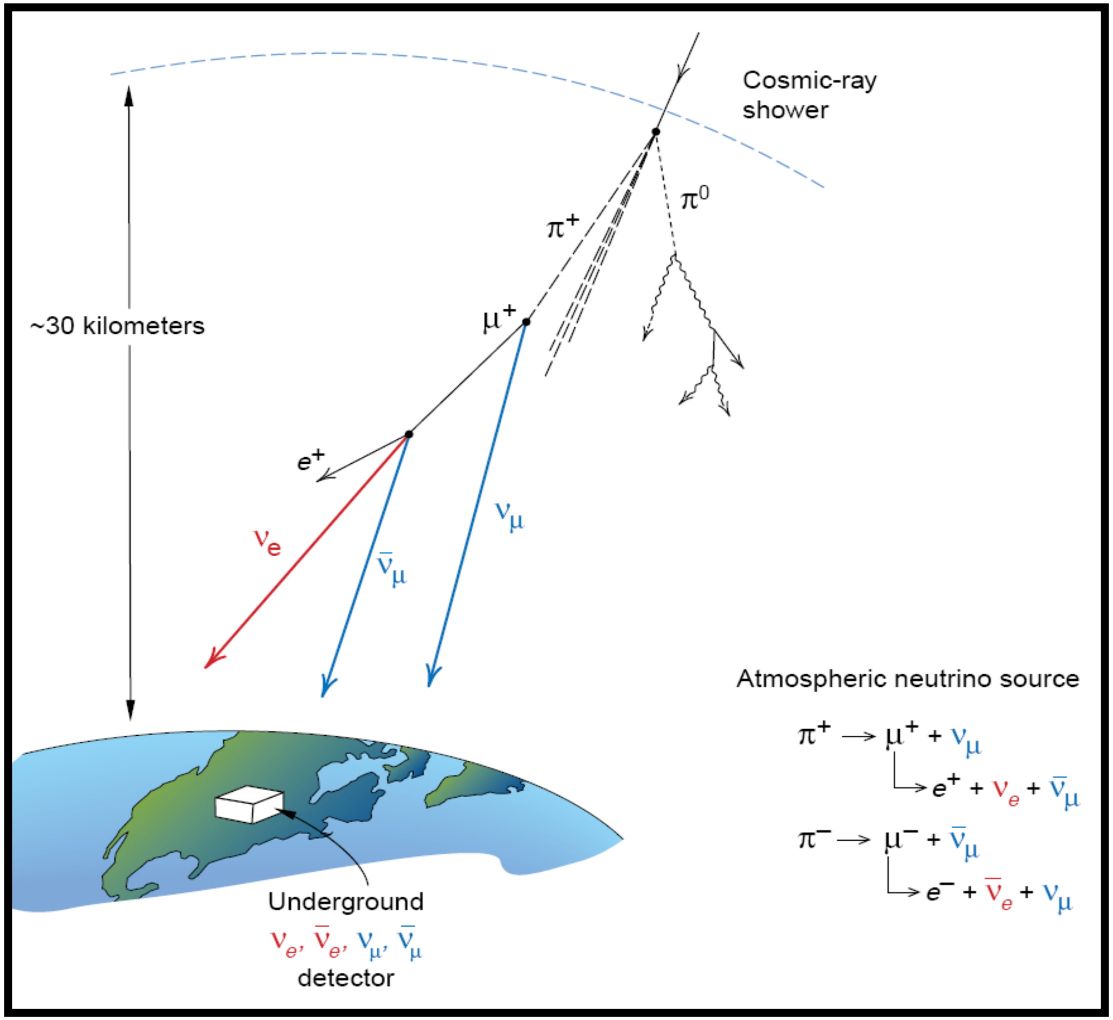
B-8 ν's: *E* ~ 6 to 7 MeV. The matter term is dominant. The produced ν is roughly ν_e ~ ν_2 (for *V* >0). The ν-propagation from the center to the outer edge of the Sun is approximately adiabatic. That is why it keeps to be ν_2 on the way to the surface (for theta_12 ~ 34°):

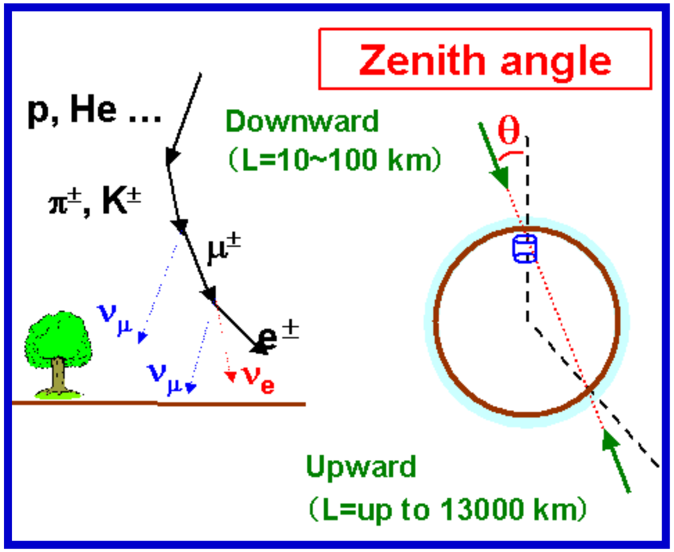
$$|\nu_2\rangle \approx \sin\theta_{12}|\nu_e\rangle + \cos\theta_{12}|\nu_\mu\rangle$$

$$P(\nu_e \to \nu_e) = |\langle \nu_e|\nu_2\rangle|^2 = \sin^2\theta_{12} \approx 0.32$$

1998: atmospheric ν's

Atmospheric muon neutrino deficit was firmly established at Super-Kamiokande (Y. Totsuka & T. Kajita 1998).





Zenith angle distributions

C. Sagi/ICHEP04

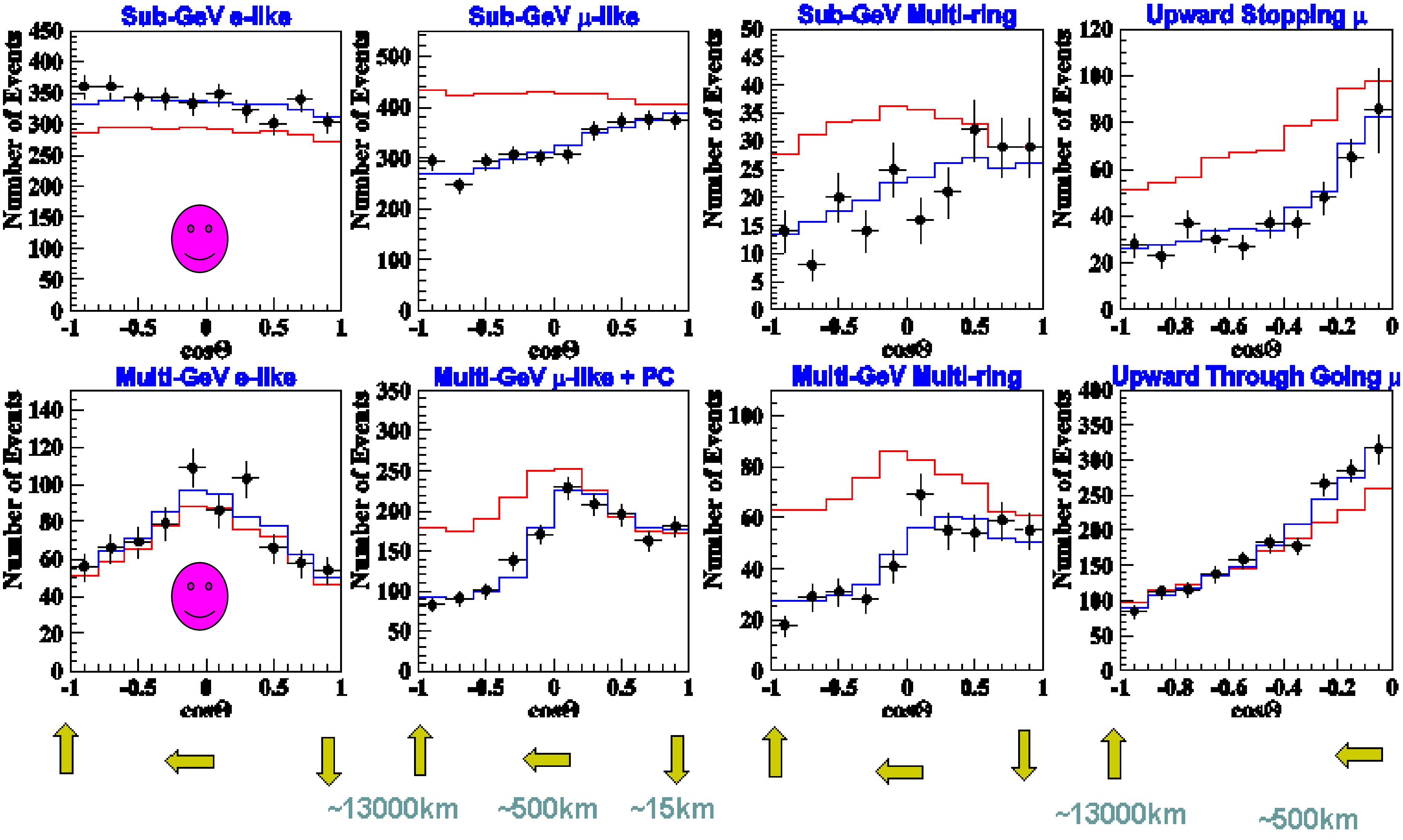
$\nu_\mu \leftrightarrow \nu_\tau$

2-flavor oscillations

Best fit

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.1\times10^{-3}$ eV^2

Null oscillation



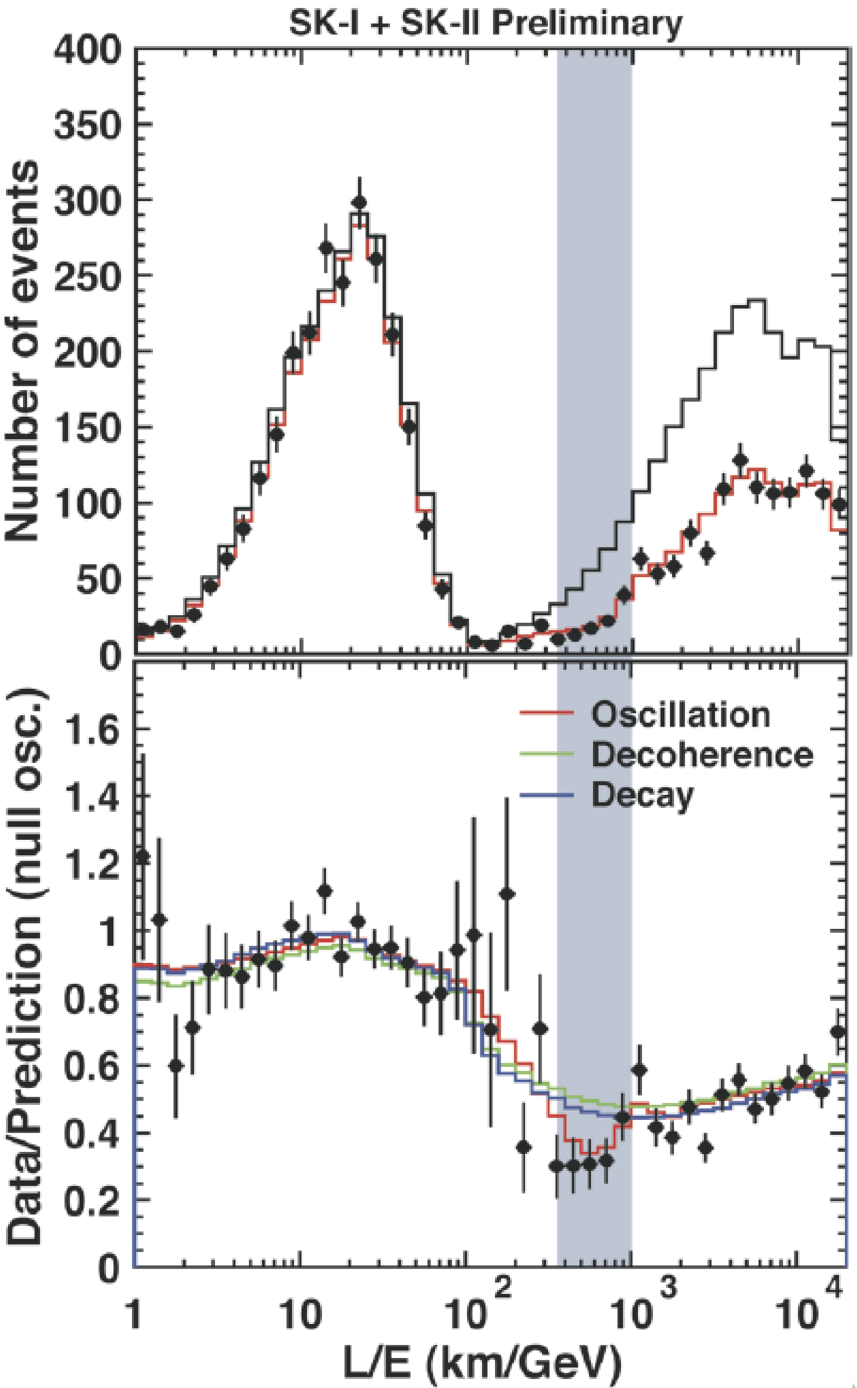
L/E Analysis: SK-I + SK-II

J. Raaf/Neutrino08

Datasets

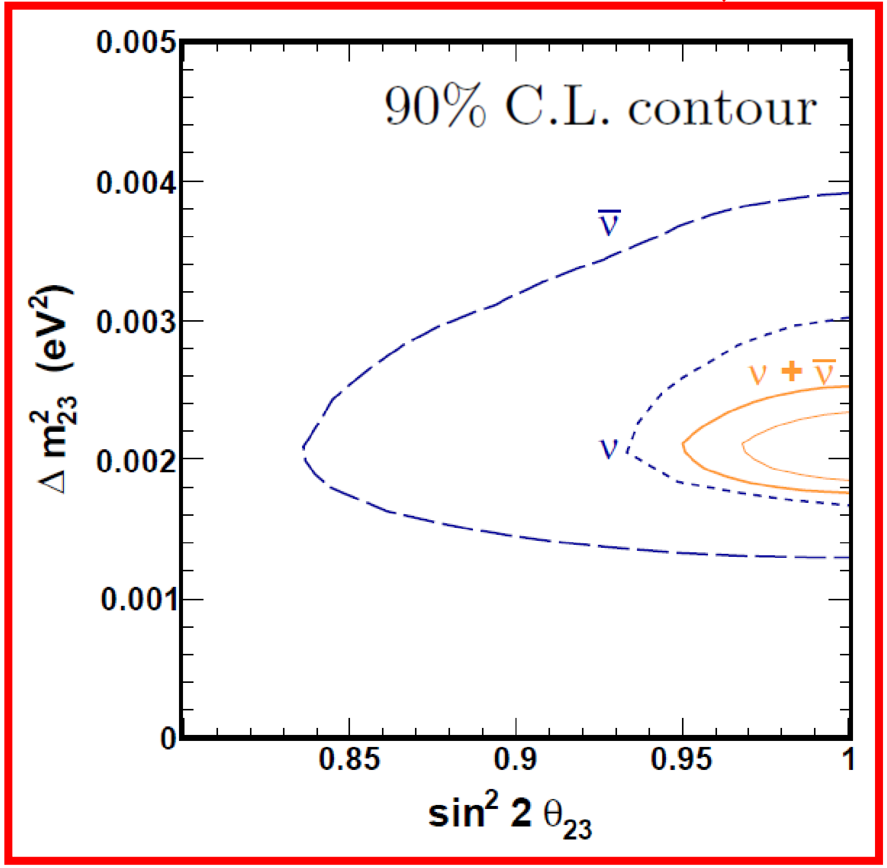
SK-I FC/PC μ-like: 1489 days

SK-II FC/PC μ-like: 799 days



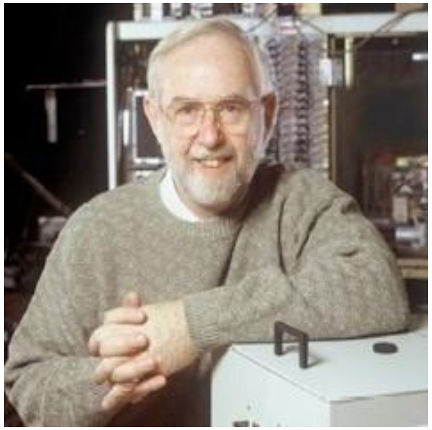
Phys. Rev. Lett. 107, 241801 (2011)

SK-I+II+III data set



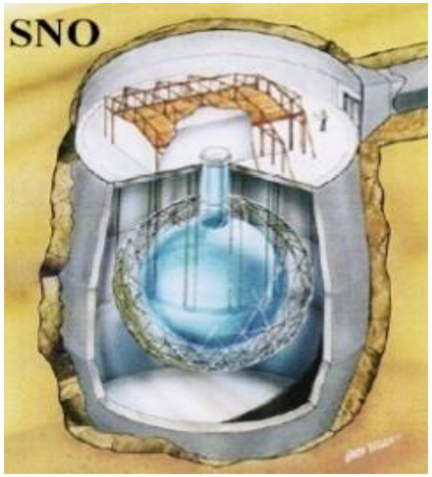
2001: solar neutrinos

The **heavy water** Cherenkov detector at SNO confirmed the solar neutrino flavor conversion (A.B. McDonald 2001)

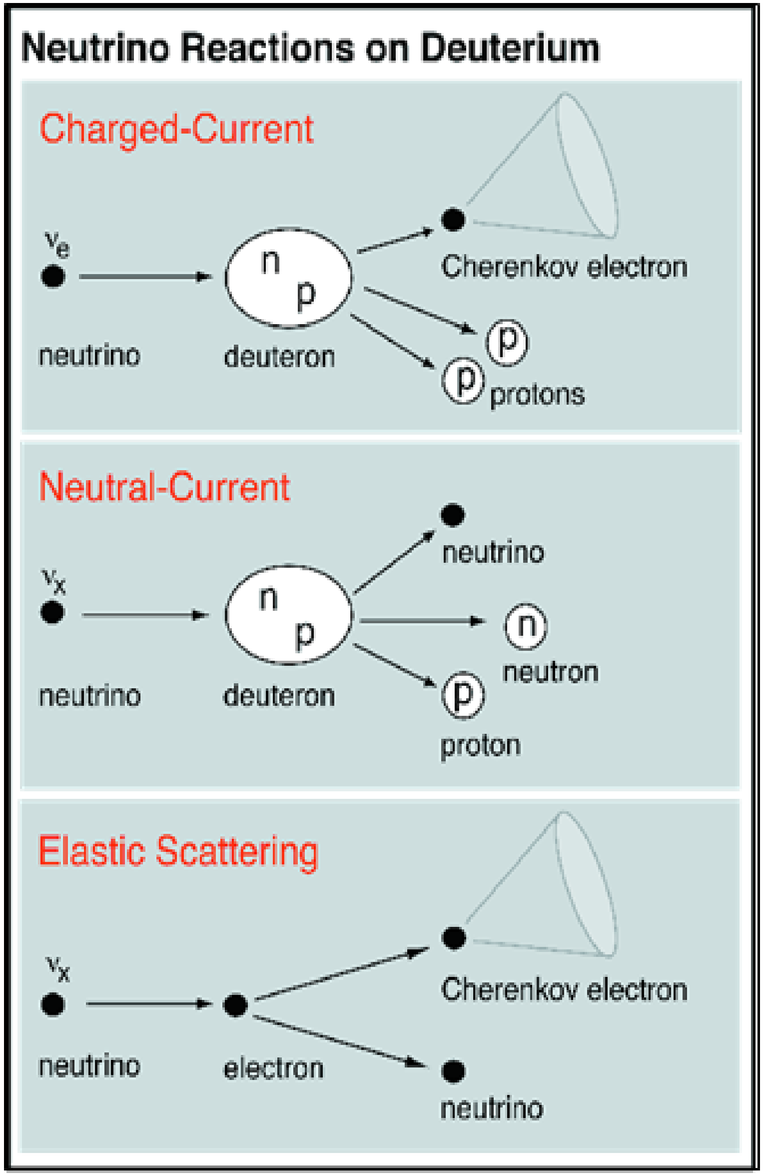


The Salient features:

- Boron-8 *e*-neutrinos
- Flux and spectrum
- Deuteron as target
- 3 types of processes
- Model-independent



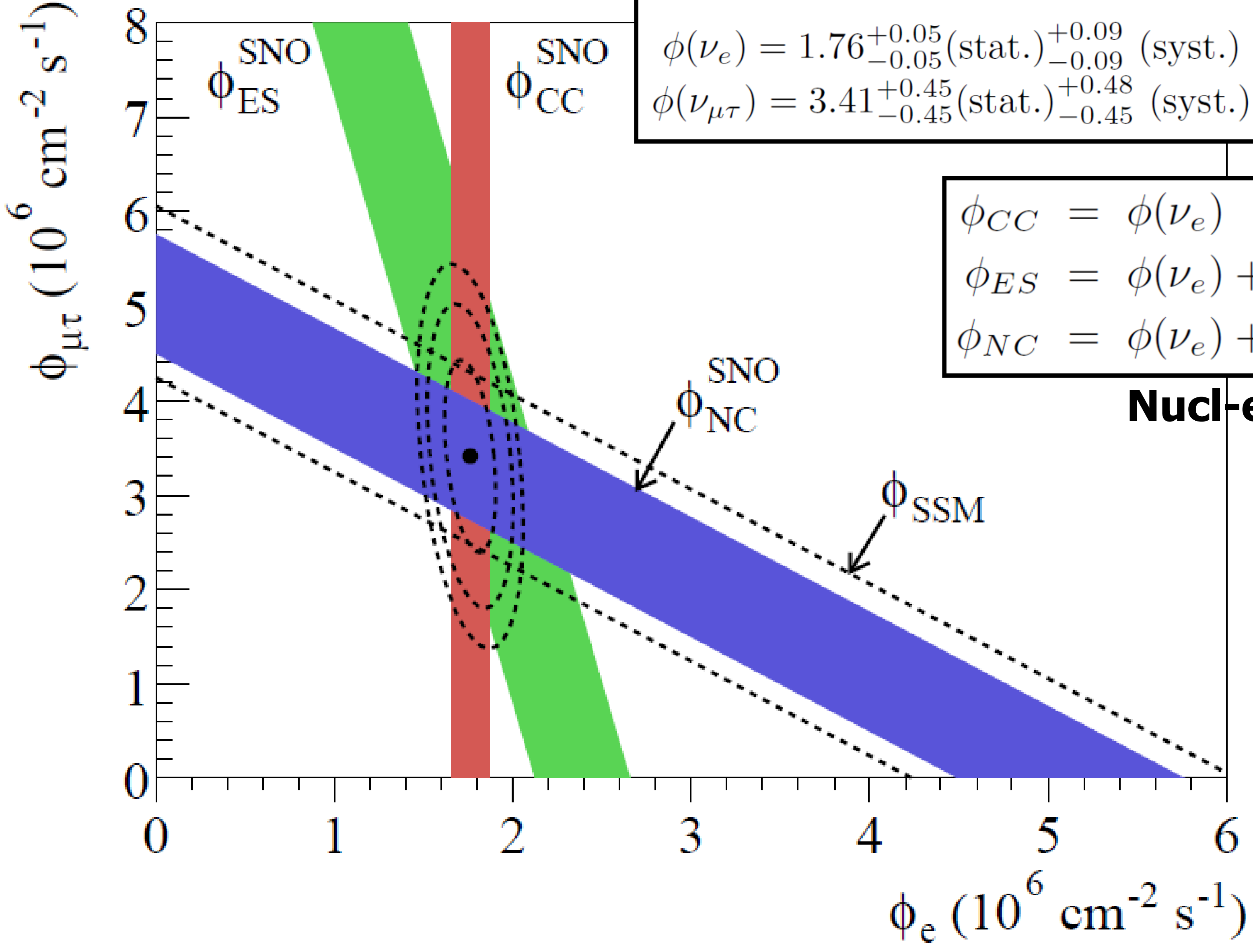
At Super-Kamiokande only elastic scattering can happen between solar neutrinos & the ordinary water.



SNO result

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$
$$\phi_{ES} = 2.39^{+0.24}_{-0.23}(\text{stat.})^{+0.12}_{-0.12}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$
$$\phi_{NC} = 5.09^{+0.44}_{-0.43}(\text{stat.})^{+0.46}_{-0.43}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

$$\phi(\nu_e) = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$
$$\phi(\nu_{\mu\tau}) = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$



$$\begin{aligned} \phi_{CC} &= \phi(\nu_e) \\ \phi_{ES} &= \phi(\nu_e) + 0.1559\phi(\nu_{\mu\tau}) \\ \phi_{NC} &= \phi(\nu_e) + \phi(\nu_{\mu\tau}) \end{aligned}$$

Nucl-ex/0610020

John Bahcall

Nobel Prize in 2002

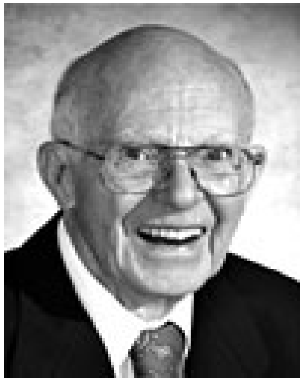
The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

55-88-92

A lesson?



Raymond Davis Jr.

◔ 1/4 of the prize

USA

Masatoshi Koshiba

◔ 1/4 of the prize

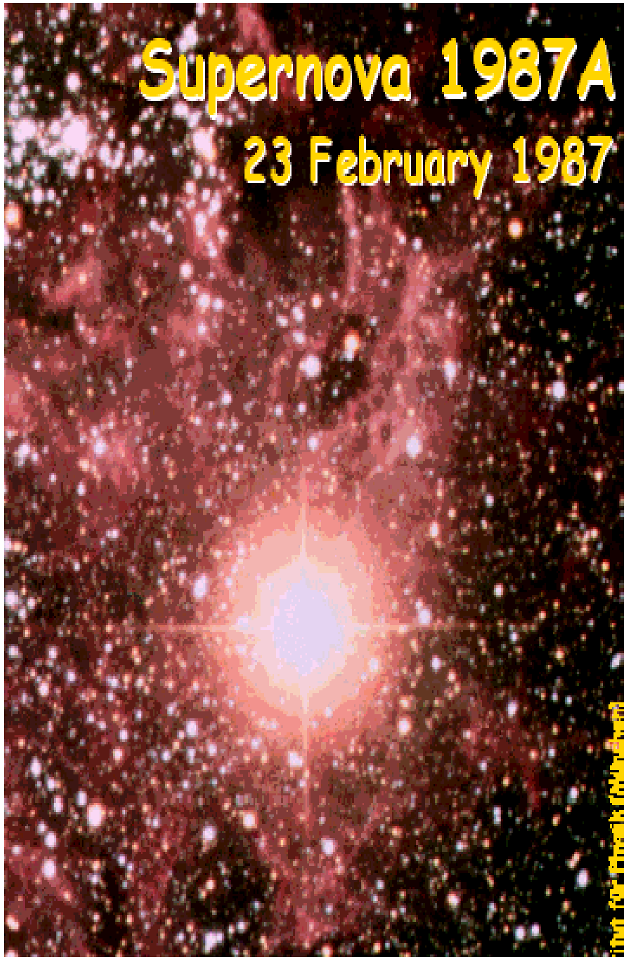
Japan

Riccardo Giacconi

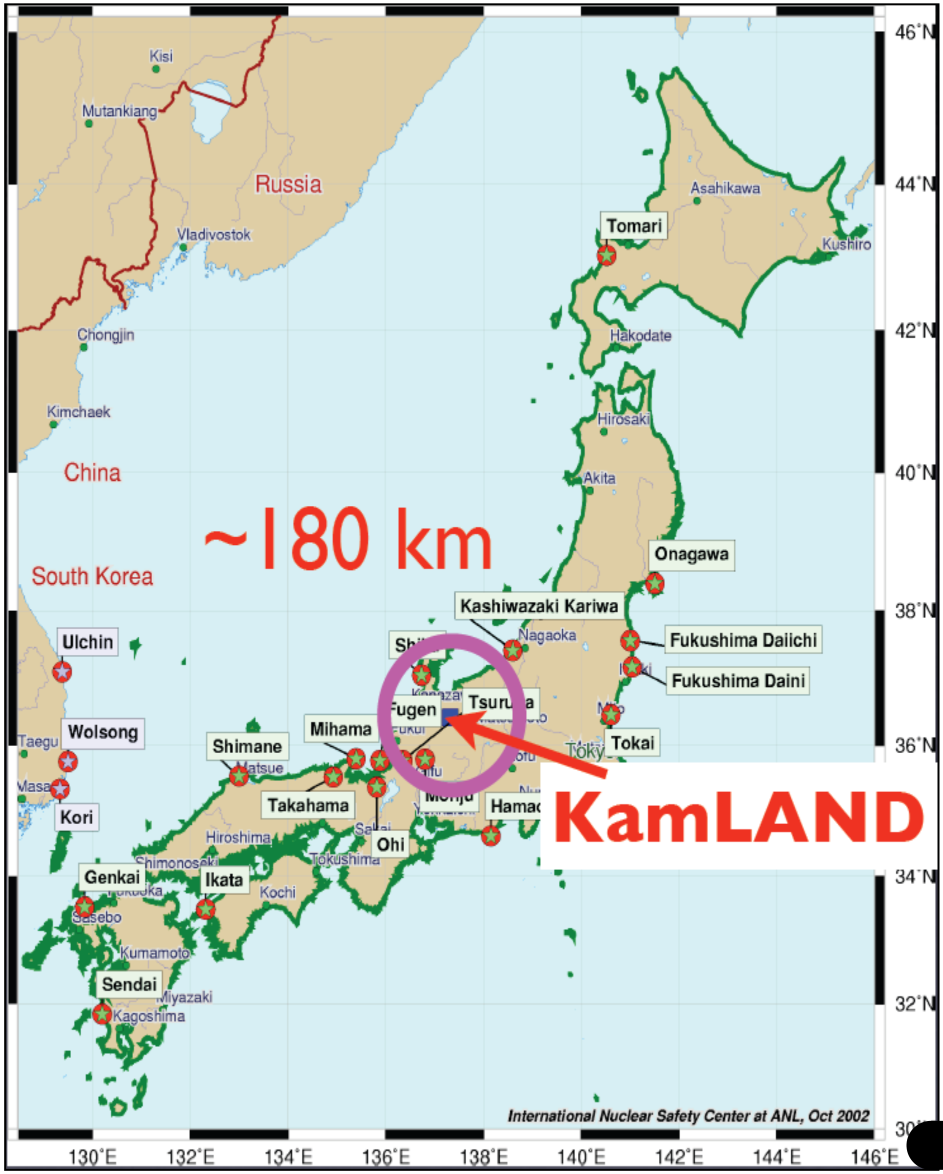
◑ 1/2 of the prize

USA

M. Koshiba: **the first detection of Supernova neutrinos in 1987.**



2002: KamLAND



International Nuclear Safety Center at ANL, Oct 2002

Verify the large angle MSW solution to the solar neutrino Problem

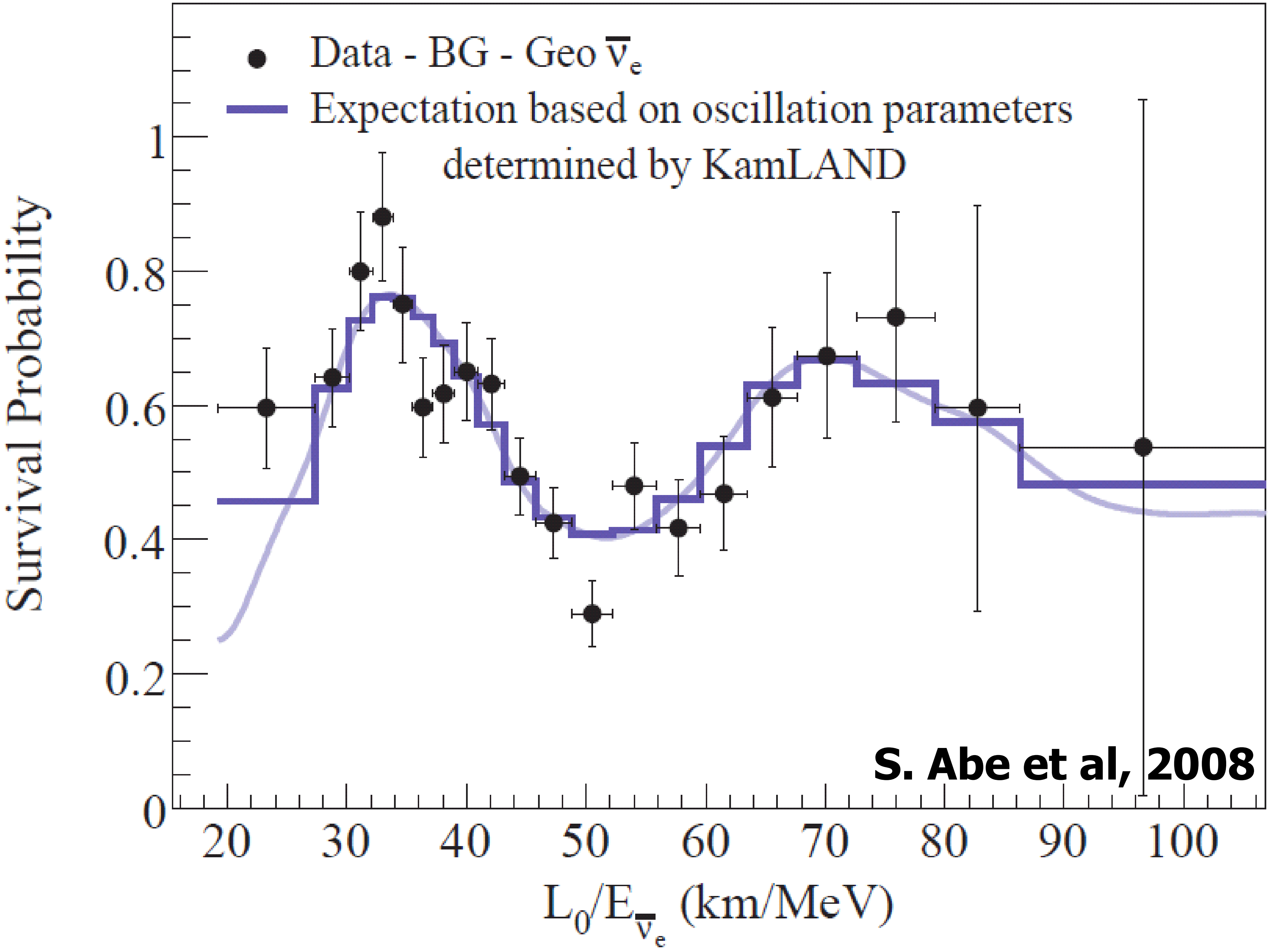
大学共同利用機関法人

KEK

高エネルギー加速器研究機構

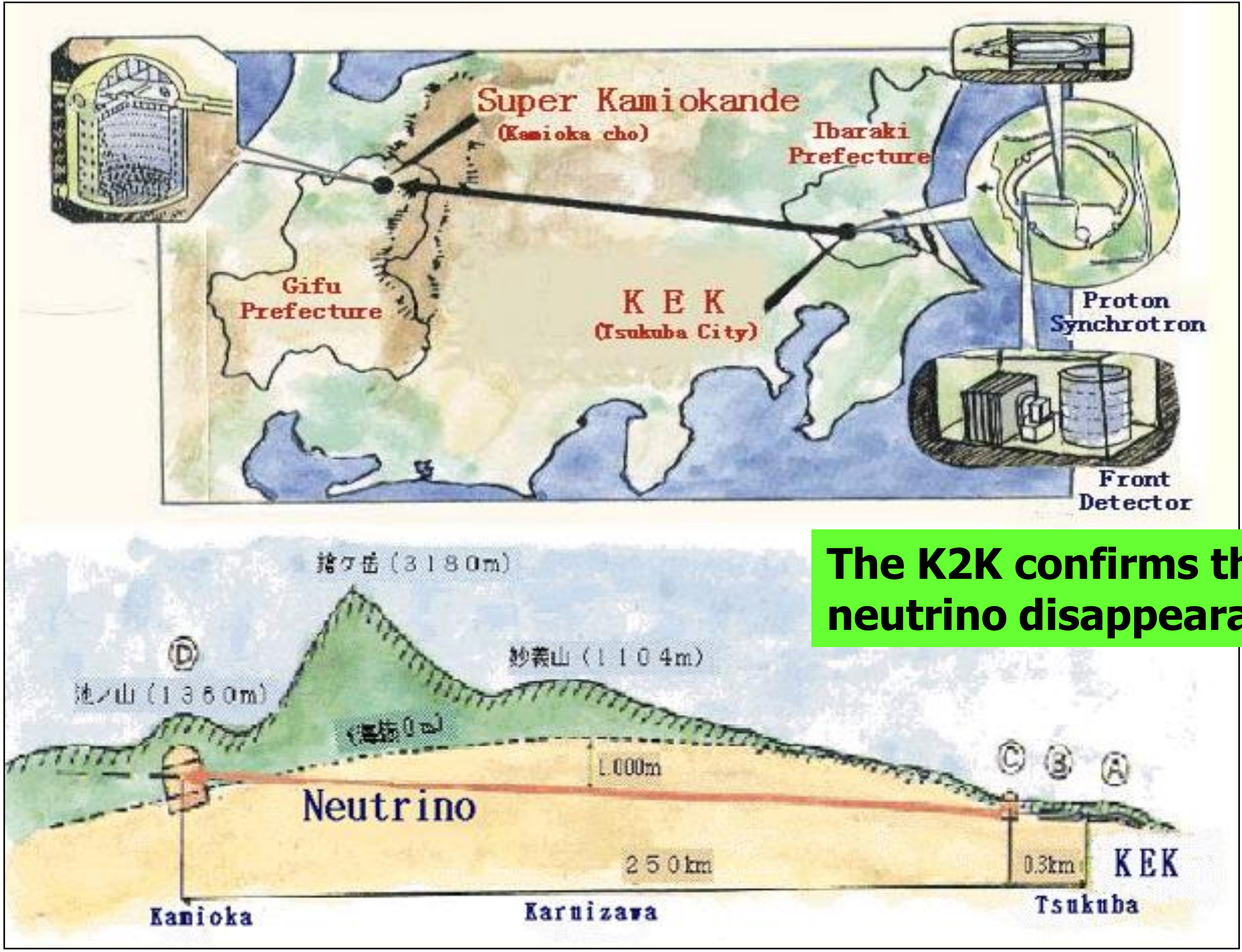
last update: 06/04/1

Atsuto Suzuki
Director General



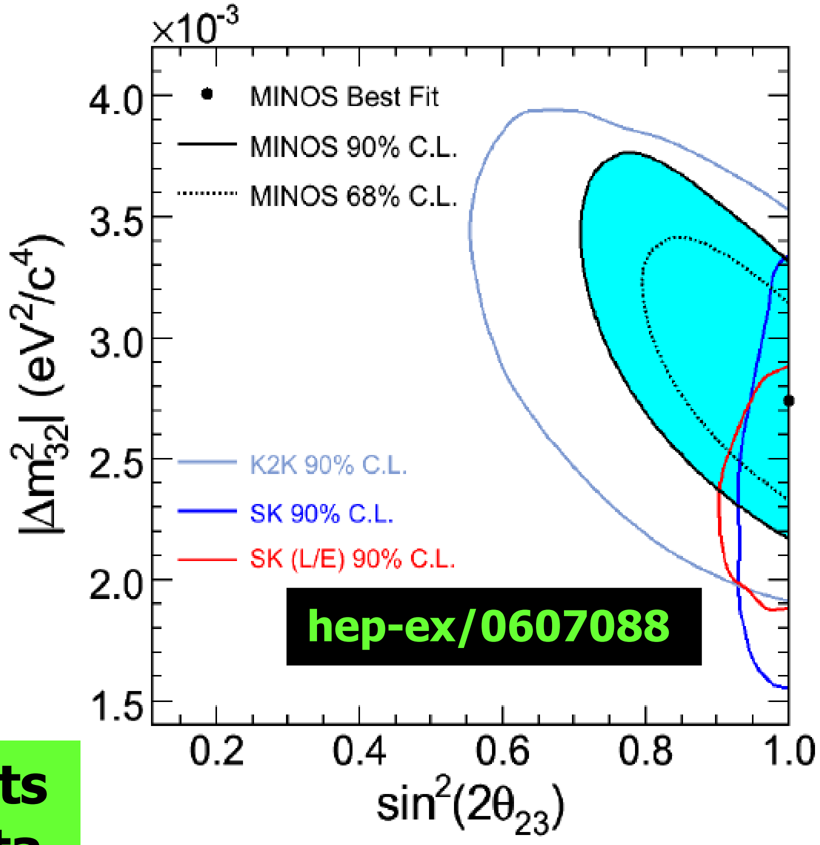
S. Abe et al, 2008

2003: K2K



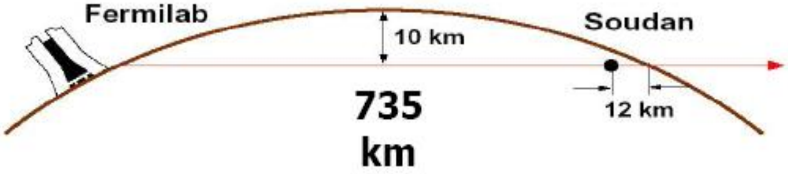
The K2K confirms the μ-neutrino disappearance

2006: MINOS



hep-ex/0607088

The MINOS supports Super-K & K2K data



$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}\,(\text{stat}+\text{syst})\times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00\,_{-0.13}\,(\text{stat}+\text{syst})$$

Constrained to $\sin^2(2\theta_{23}) \le 1$

2011: T2K

T2K (Tokai-to-Kamioka) experiment

arXiv:1106.2822 [hep-ex] 14 June 2011

Hint for unsuppressed theta(13) !

T2K Main Goals:

★ Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)

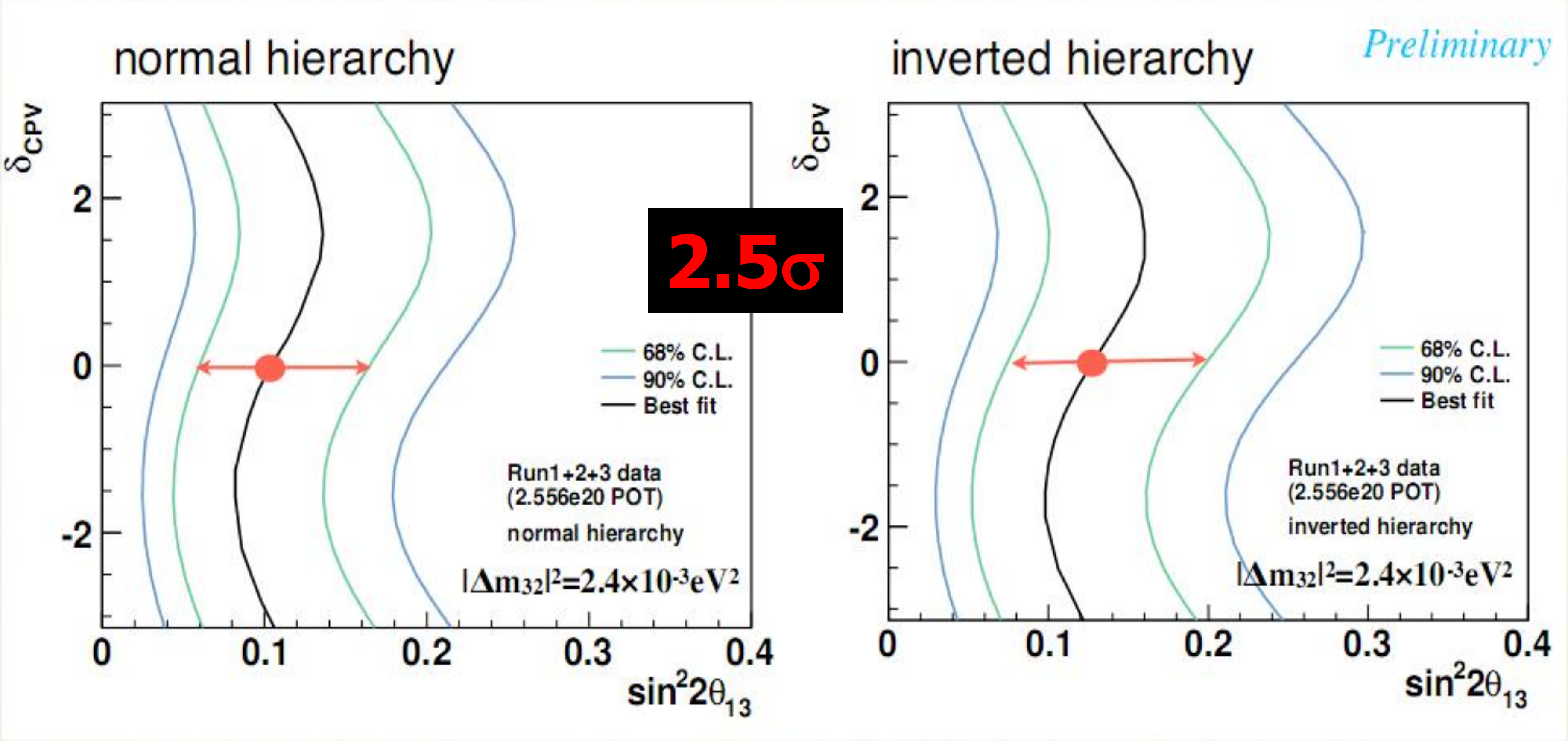
★ Precision measurement of ν_μ disappearance

2.5σ

T. Nakaya (Neutrino 2012)

Allowed Region (constant χ^2 method)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m_{32}^2 L/E) + CPV + \text{matter effect.} + \ldots$$

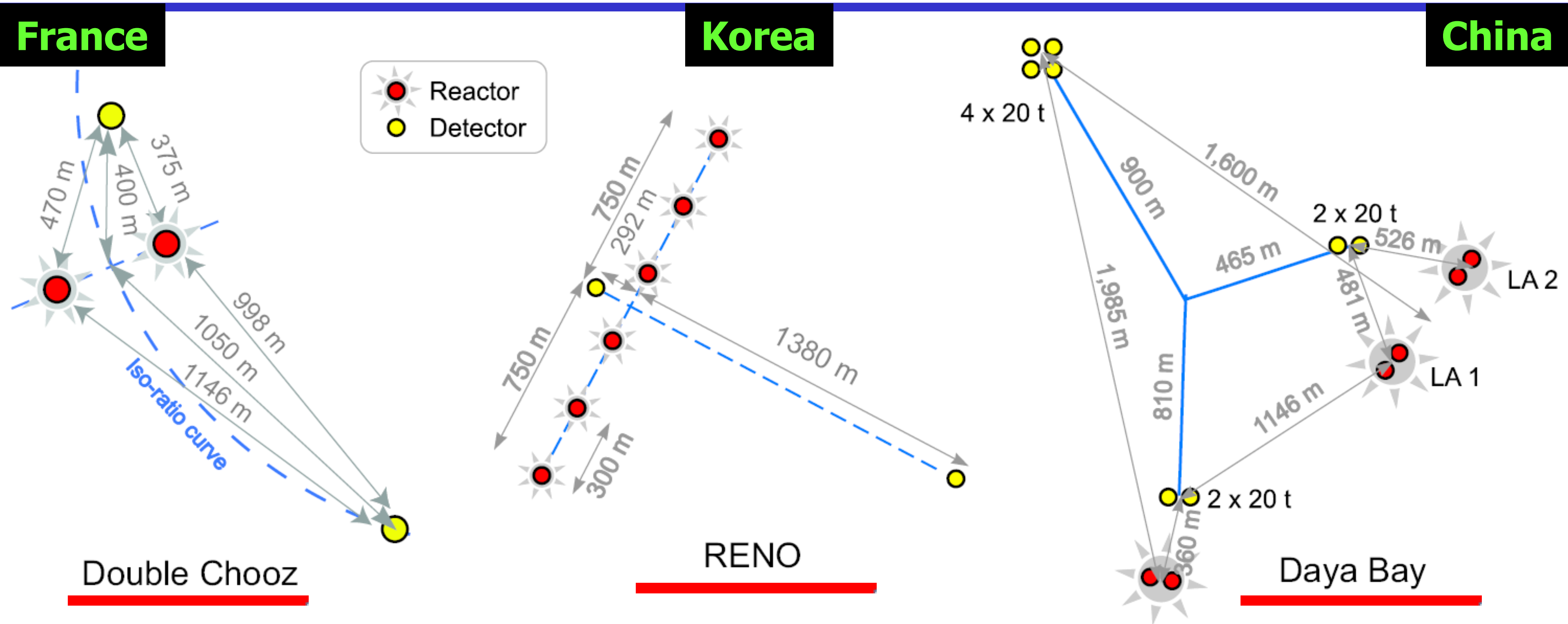


2.5σ

$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$ @ $\delta_{CP} = 0$

$\sin^2 2\theta_{13} = 0.128^{+0.070}_{-0.055}$ @ $\delta_{CP} = 0$

3 Reactor Experiments



Double Chooz

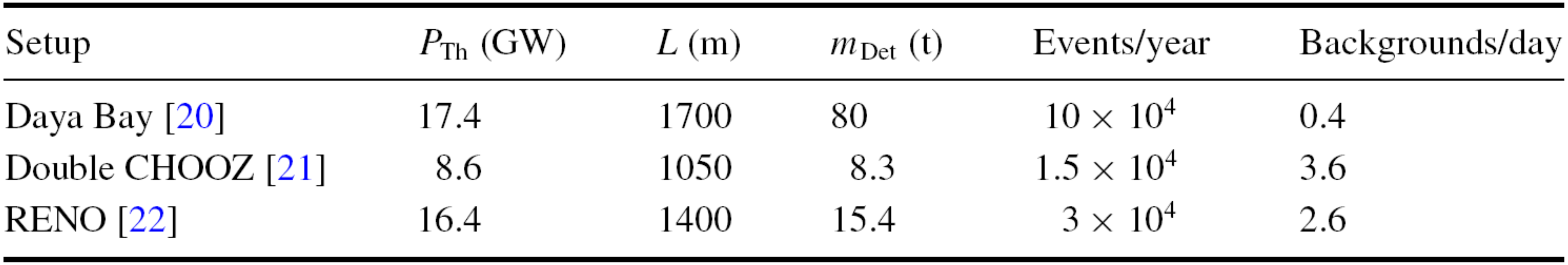
RENO

Daya Bay

Thermal power

Baseline

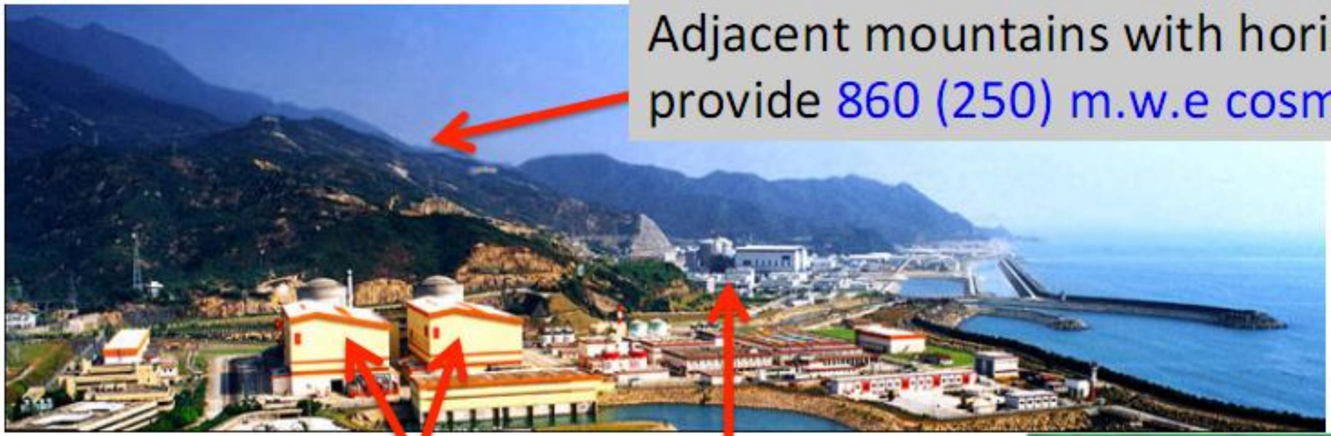
Detector mass



Setup	P_{Th} (GW)	L (m)	m_{Det} (t)	Events/year	Backgrounds/day
Daya Bay [20]	17.4	1700	80	10×10^4	0.4
Double CHOOZ [21]	8.6	1050	8.3	1.5×10^4	3.6
RENO [22]	16.4	1400	15.4	3×10^4	2.6

2012: Daya Bay

The Daya Bay Experiment

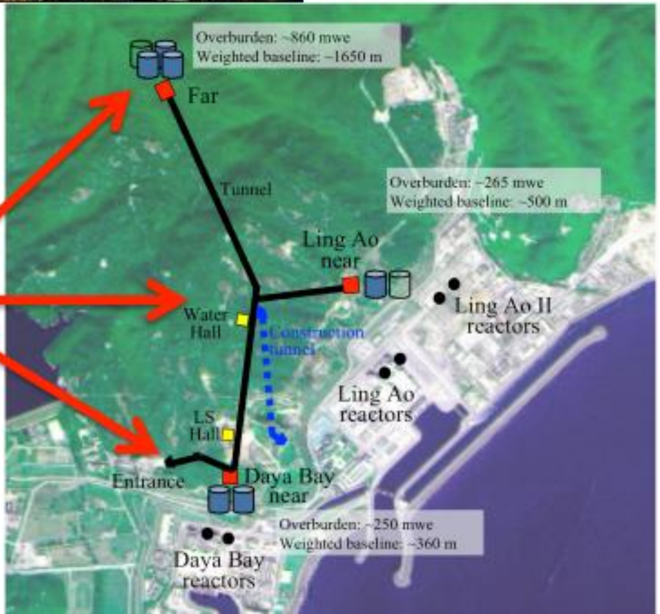


Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

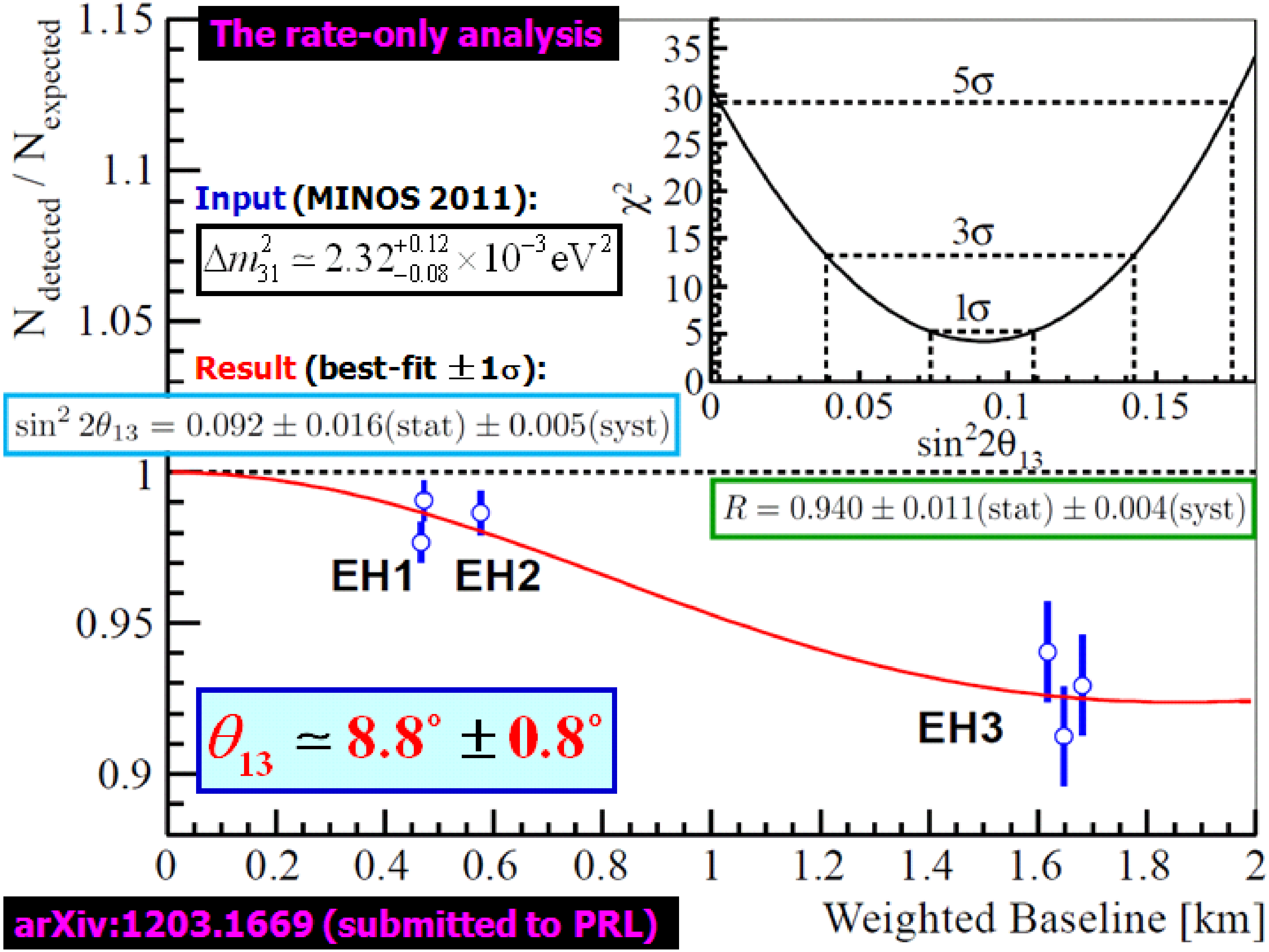
6 commercial reactor cores with 17.4 GW_{th} total power.

6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.



DYB: 2012.3.8



The rate-only analysis

Input (MINOS 2011):

$\Delta m^2_{31} \simeq 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$

Result (best-fit ±1σ):

$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$

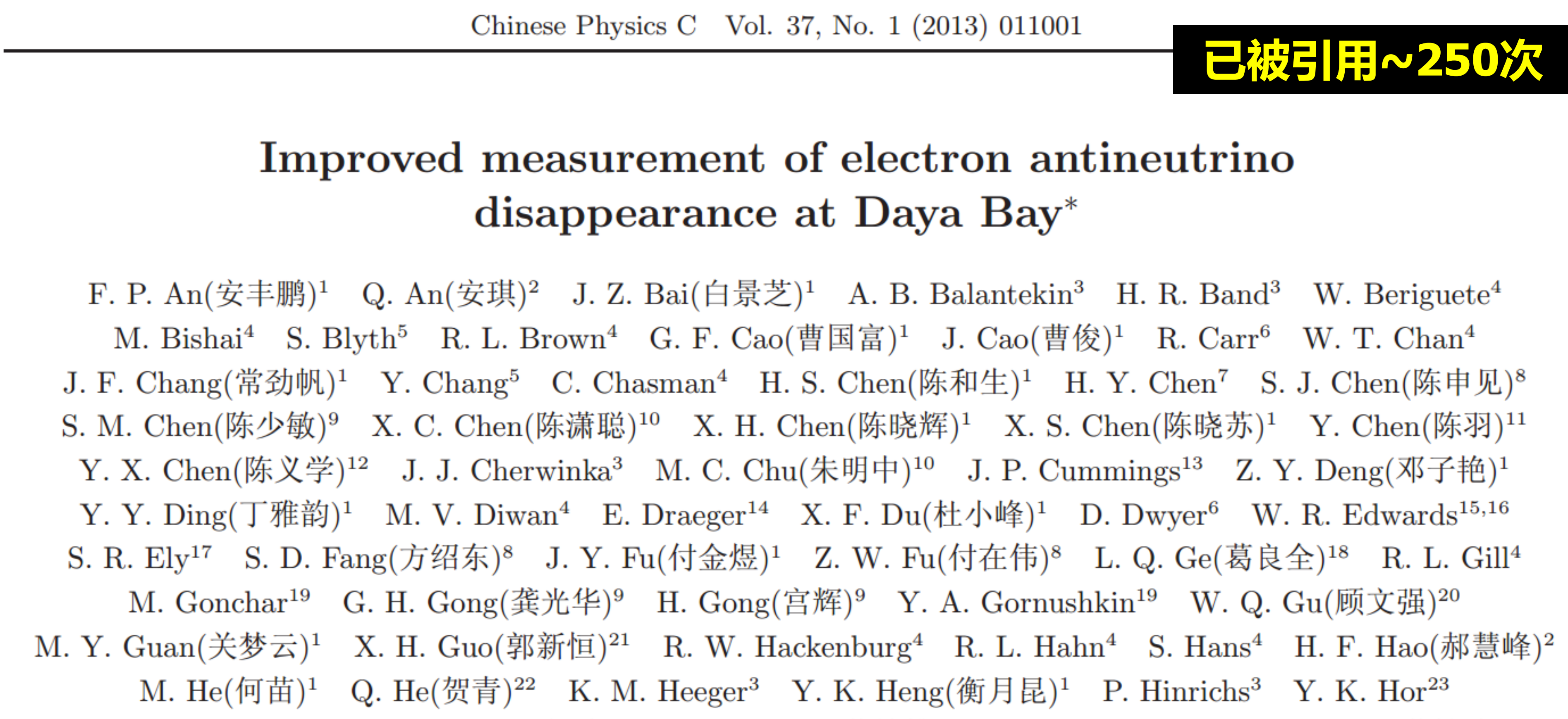
$R = 0.940 \pm 0.011(\mathrm{stat}) \pm 0.004(\mathrm{syst})$

$\theta_{13} \simeq 8.8^\circ \pm 0.8^\circ$

arXiv:1203.1669 (submitted to PRL)

发表在PRL上，已被引用~1200次

DYB: 2012.10.23



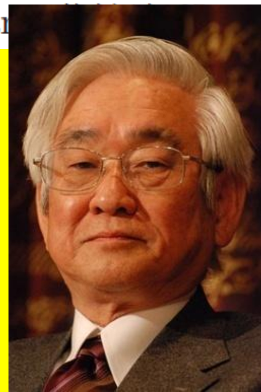
Chinese Physics C Vol. 37, No. 1 (2013) 011001

Improved measurement of electron antineutrino disappearance at Daya Bay*

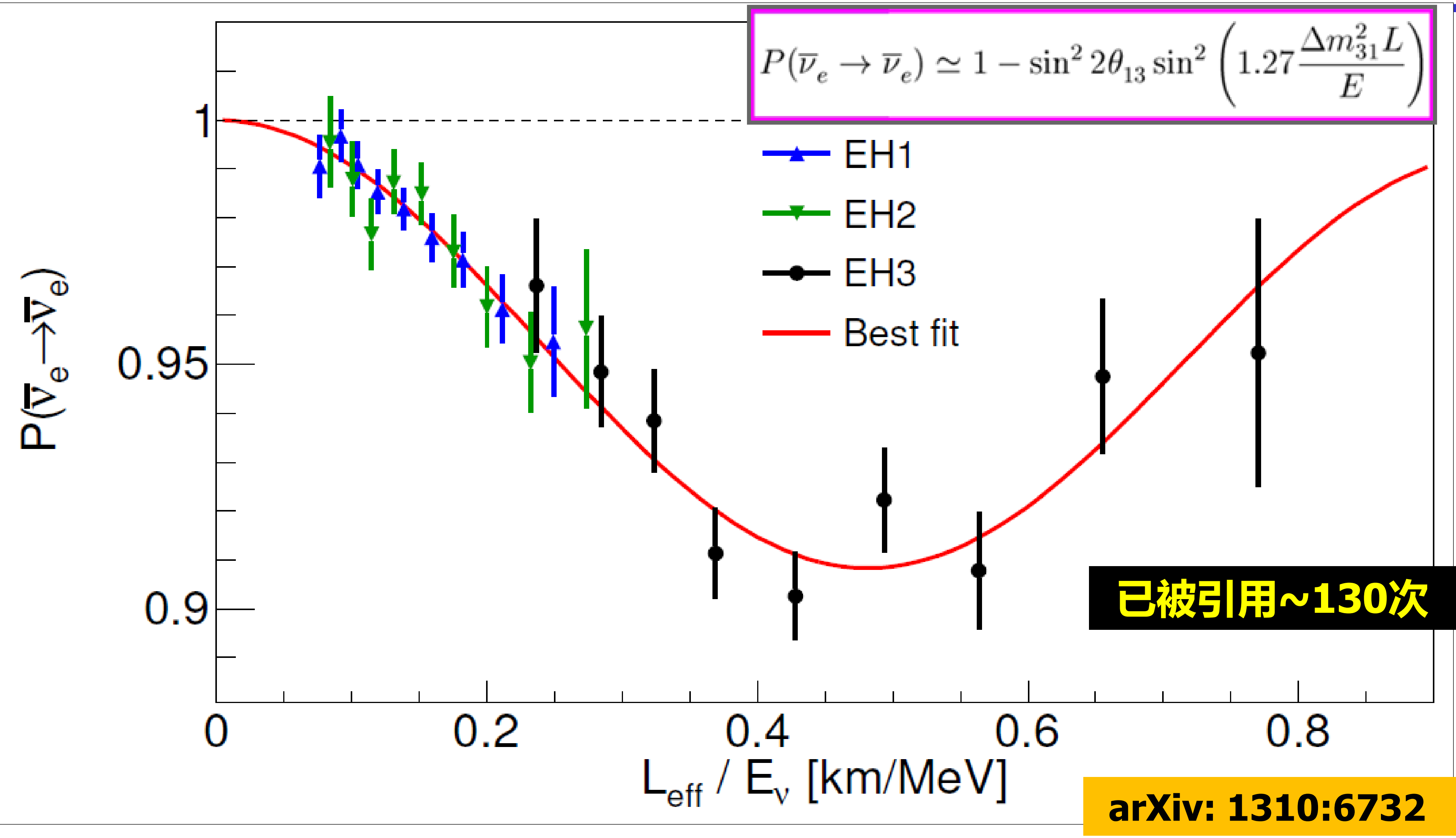
F. P. An(安丰鹏)[1] Q. An(安琪)[2] J. Z. Bai(白景芝)[1] A. B. Balantekin[3] H. R. Band[3] W. Beriguete[4] M. Bishai[4] S. Blyth[5] R. L. Brown[4] G. F. Cao(曹国富)[1] J. Cao(曹俊)[1] R. Carr[6] W. T. Chan[4] J. F. Chang(常劲帆)[1] Y. Chang[5] C. Chasman[4] H. S. Chen(陈和生)[1] H. Y. Chen[7] S. J. Chen(陈申见)[8] S. M. Chen(陈少敏)[9] X. C. Chen(陈潇聪)[10] X. H. Chen(陈晓辉)[1] X. S. Chen(陈晓苏)[1] Y. Chen(陈羽)[11] Y. X. Chen(陈义学)[12] J. J. Cherwinka[3] M. C. Chu(朱明中)[10] J. P. Cummings[13] Z. Y. Deng(邓子艳)[1] Y. Y. Ding(丁雅韵)[1] M. V. Diwan[4] E. Draeger[14] X. F. Du(杜小峰)[1] D. Dwyer[6] W. R. Edwards[15,16] S. R. Ely[17] S. D. Fang(方绍东)[8] J. Y. Fu(付金煜)[1] Z. W. Fu(付在伟)[8] L. Q. Ge(葛良全)[18] R. L. Gill[4] M. Gonchar[19] G. H. Gong(龚光华)[9] H. Gong(宫辉)[9] Y. A. Gornushkin[19] W. Q. Gu(顾文强)[20] M. Y. Guan(关梦云)[1] X. H. Guo(郭新恒)[21] R. W. Hackenburg[4] R. L. Hahn[4] S. Hans[4] H. F. Hao(郝慧峰)[2] M. He(何苗)[1] Q. He(贺青)[22] K. M. Heeger[3] Y. K. Heng(衡月昆)[1] P. Hinrichs[3] Y. K. Hor[23] Y. B. Hsiung[24] B. Z. Hu[7] T. Hu(胡涛)[1] H. X. Huang(黄翰雄)[25] H. Z. Huang[26] X. T. Hua

已被引用~250次

益川敏英教授本人在得知自己获得了诺贝尔奖之后强调，“**拥有一份主要由日本人经营的世界级的学术期刊，对于来自日本以外的关于日本本土的学术研究的客观评价来说是极其重要的。**” 这句话对于盲目追求论文发表率和 SCI 期刊影响因子的中国学术界而言，无疑是值得深思的真知灼见。



Daya Bay: ν oscillation



$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m^2_{31} L}{E}\right)$$

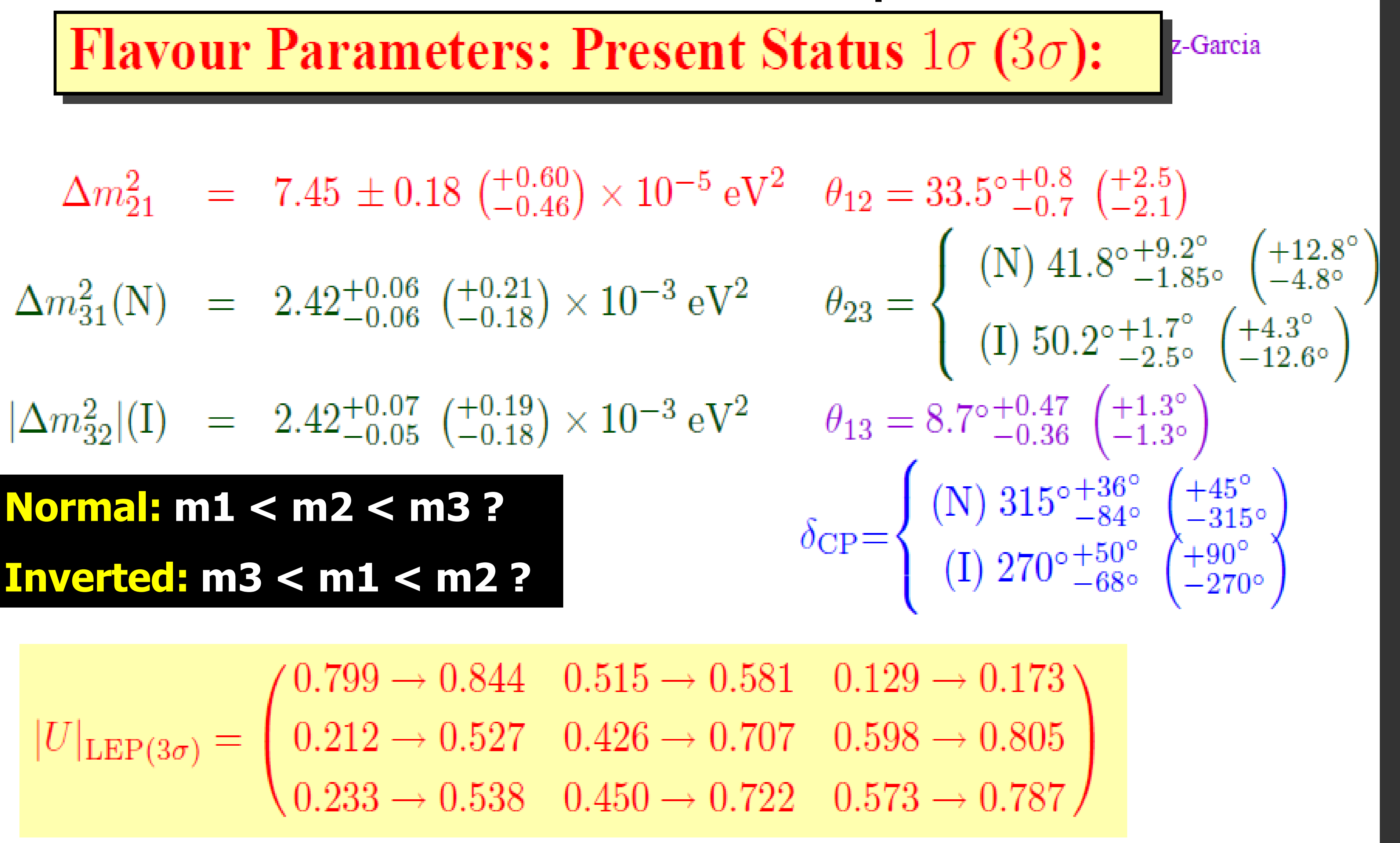
已被引用~130次

arXiv: 1310:6732

Where to go: half to anti-μ flavor, half to anti-τ flavor.

3-flavor global fit

M.C. Gonzalez-Garcia (Talk at TAUP 2013, September 2013).



Flavour Parameters: Present Status 1σ (3σ):

z-Garcia

$$\Delta m^2_{21} = 7.45 \pm 0.18 \left({}^{+0.60}_{-0.46}\right) \times 10^{-5}\ \text{eV}^2 \qquad \theta_{12} = 33.5^{\circ}{}^{+0.8}_{-0.7} \left({}^{+2.5}_{-2.1}\right)$$

$$\Delta m^2_{31}(\text{N}) = 2.42^{+0.06}_{-0.06} \left({}^{+0.21}_{-0.18}\right) \times 10^{-3}\ \text{eV}^2 \qquad \theta_{23} = \begin{cases} (\text{N})\ 41.8^{\circ}{}^{+9.2^{\circ}}_{-1.85^{\circ}} \left({}^{+12.8^{\circ}}_{-4.8^{\circ}}\right) \\ (\text{I})\ 50.2^{\circ}{}^{+1.7^{\circ}}_{-2.5^{\circ}} \left({}^{+4.3^{\circ}}_{-12.6^{\circ}}\right) \end{cases}$$

$$|\Delta m^2_{32}|(\text{I}) = 2.42^{+0.07}_{-0.05} \left({}^{+0.19}_{-0.18}\right) \times 10^{-3}\ \text{eV}^2 \qquad \theta_{13} = 8.7^{\circ}{}^{+0.47}_{-0.36} \left({}^{+1.3^{\circ}}_{-1.3^{\circ}}\right)$$

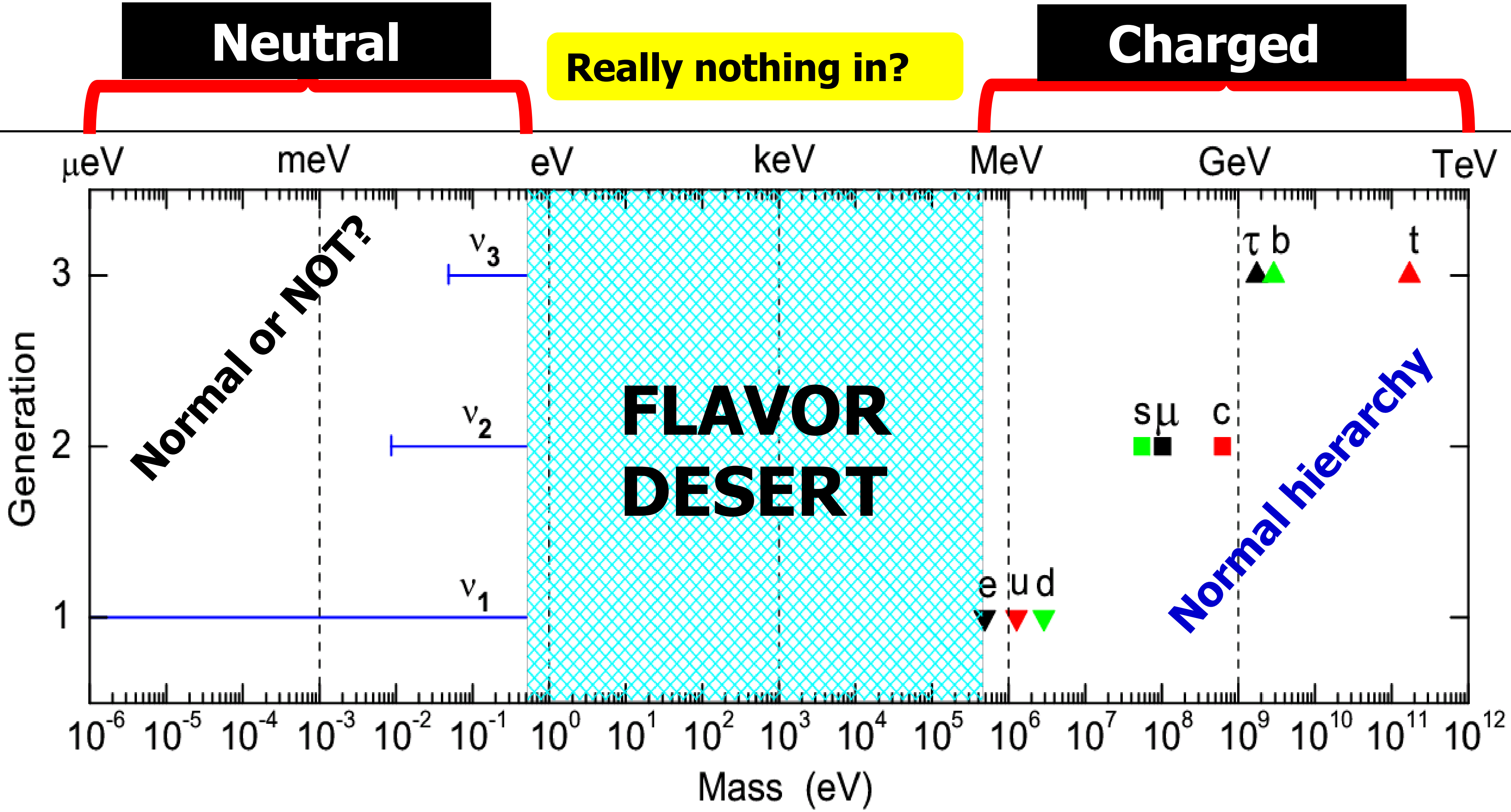
Normal: **m1 < m2 < m3 ?**

Inverted: **m3 < m1 < m2 ?**

$$\delta_{\text{CP}} = \begin{cases} (\text{N})\ 315^{\circ}{}^{+36^{\circ}}_{-84^{\circ}} \left({}^{+45^{\circ}}_{-315^{\circ}}\right) \\ (\text{I})\ 270^{\circ}{}^{+50^{\circ}}_{-68^{\circ}} \left({}^{+90^{\circ}}_{-270^{\circ}}\right) \end{cases}$$

$$|U|_{\text{LEP}(3\sigma)} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.129 \to 0.173 \\ 0.212 \to 0.527 & 0.426 \to 0.707 & 0.598 \to 0.805 \\ 0.233 \to 0.538 & 0.450 \to 0.722 & 0.573 \to 0.787 \end{pmatrix}$$

Fermion mass spectrum



Flavor hierarchy + Flavor desert puzzles: 12 free (mass) parameters.

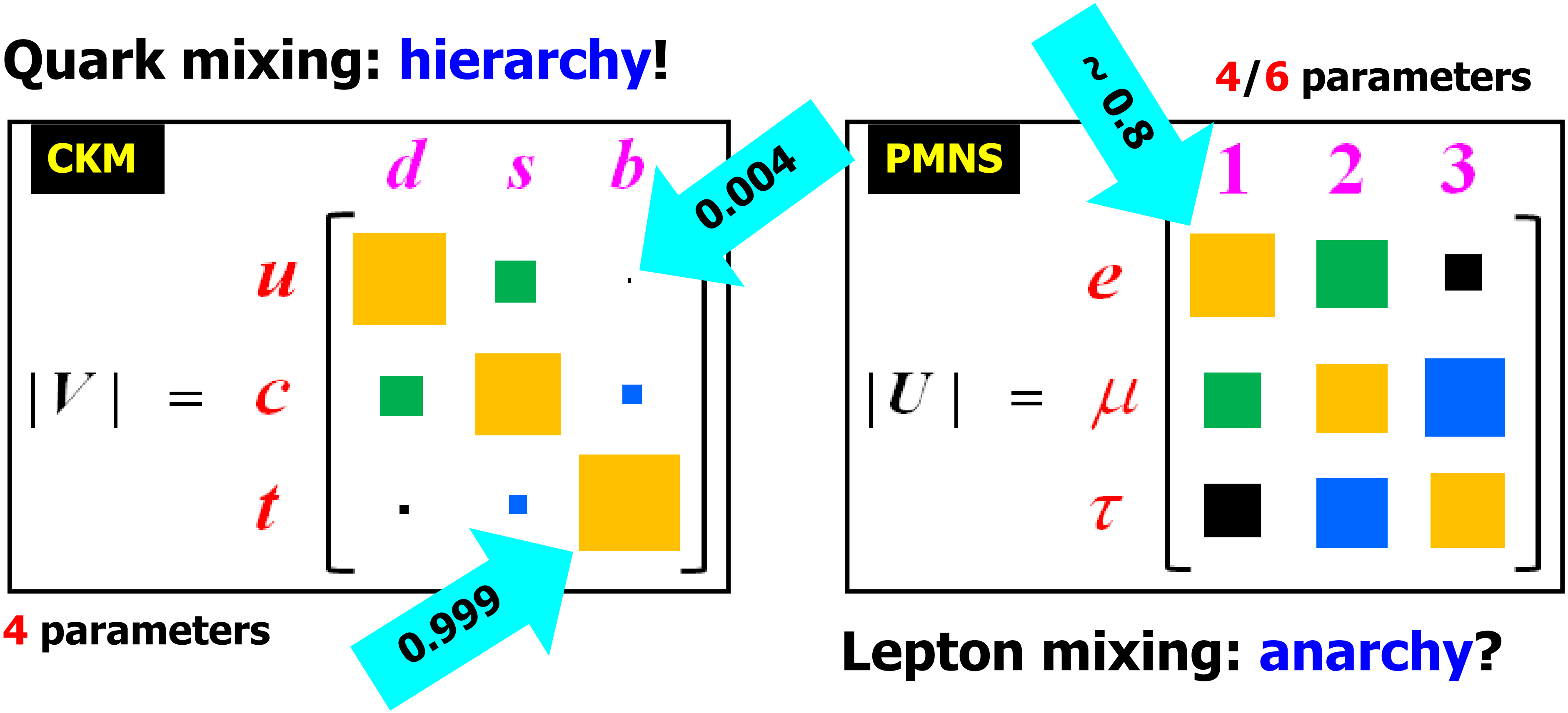
In the quark sector, why is the up quark lighter than the down quark?

Flavor puzzles

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\left[\overline{(u\ \ c\ \ t)}_{\mathrm{L}}\,\gamma^\mu\, V \begin{pmatrix} d\\ s\\ b\end{pmatrix}_{\mathrm{L}} W^+_\mu + \overline{(e\ \ \mu\ \ \tau)}_{\mathrm{L}}\,\gamma^\mu\, U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}_{\mathrm{L}} W^-_\mu\right] + \mathrm{h.c.}$$

CKM **PMNS**

Quark mixing: hierarchy!



4 parameters

4/6 parameters

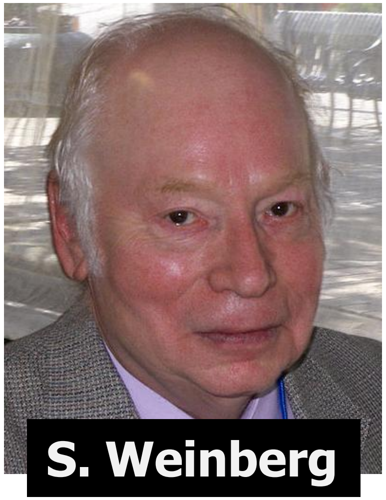
Lepton mixing: anarchy?

Two strategies

Strategy (A): flavor mixing angles depend on mass ratios.

$$\theta_{ij} = f\left(\frac{m_\alpha}{m_\beta}, \frac{m_k}{m_l}, \cdots\right)$$

$$M_{l,\nu} = \begin{pmatrix} 0 & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix}$$



S. Weinberg

1977

2×2 3×3

Texture zeros

1978

H. Fritzsch

Strategy (B): constant leading term + perturbation matrix.

Flavor symmetries

$$U = \left(U_0 + \Delta U\right) P_\nu$$

1996

$$M_\nu = \begin{pmatrix} b+c & -b & -c \\ -b & a+b & -a \\ -c & -a & a+c \end{pmatrix}$$

Some linear correlations or equalities

Texture zeros

Example: **15 two-zero textures of the Majorana neutrino mass matrix.**

Pattern	Texture of M_ν	The scales of neutrino masses
A_1	$\begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}$	$m_3 \approx \sqrt{\Delta m^2}\,, \quad \langle m \rangle_{ee} = 0$
A_2	$\begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$	$m_3 \approx \sqrt{\Delta m^2}\,, \quad \langle m \rangle_{ee} = 0$
B_1	$\begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix}$	$m_3 \approx \sqrt{\frac{\Delta m^2}{1 - \tan^4\theta_{23}}}\,, \quad \langle m \rangle_{ee} \approx m_3 \tan^2\theta_{23}$
B_2	$\begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$	
B_3	$\begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$	
B_4	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$	
C	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}$	

笑星

Frampton

Frampton, **Glashow**, **Marfatia**:

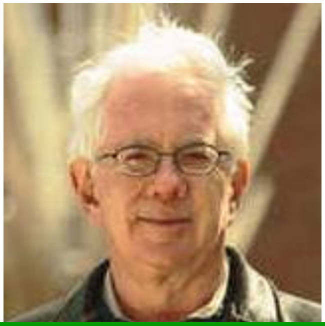
hep-ph/0201008

(02 Jan 2002)

Phys. Lett. B 536

(2002) 79

30 May 2002



~250 citations

doing research is a fun

Xing:

hep-ph/0201151

(17 Jan 2002)

Phys. Lett. B 530

(2002) 159

28 March 2002

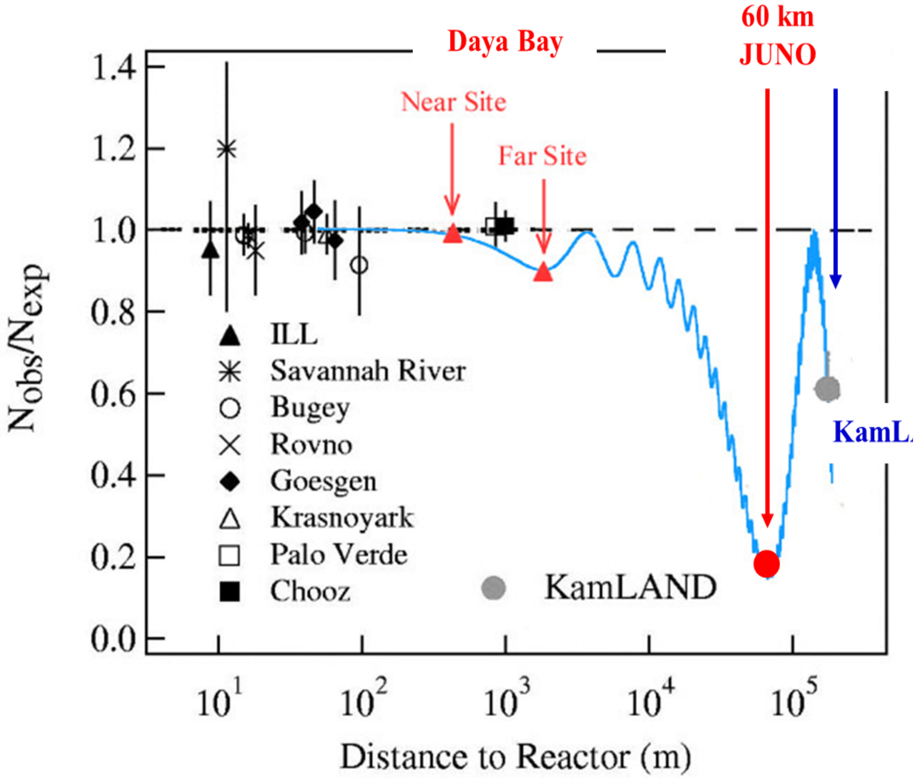
~150 citations

ν mass ordering

Accelerator/atmospheric: matter effects

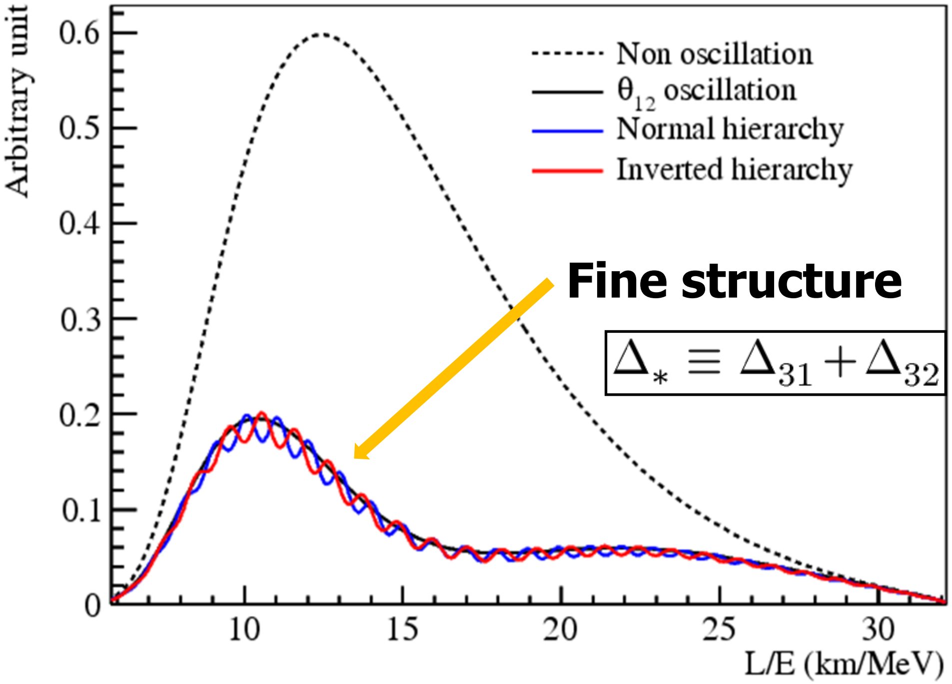
$$\boxed{\Delta m^2_{31} - 2\sqrt{2}G_F N_e E} \qquad \boxed{\theta_{23}}$$

Reactor (JUNO): Optimum baseline at the valley of Δm^2_{21} oscillations, corrected by the fine structure of Δm^2_{31} oscillations.



江门实验原理

$$\boxed{\Delta_{ji} \equiv \Delta m^2_{ji} L/(4E)}$$

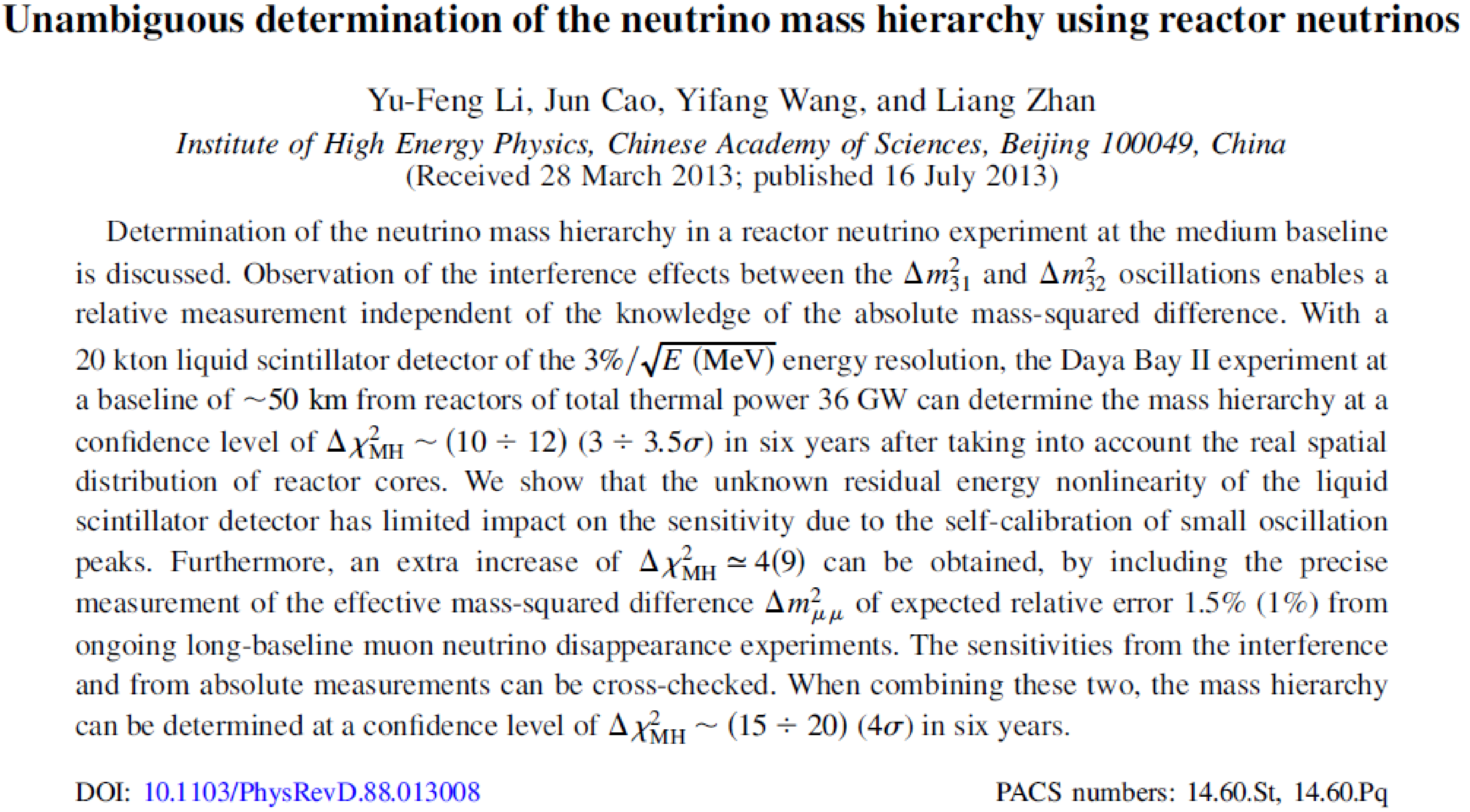


$$\boxed{\Delta_* \equiv \Delta_{31} + \Delta_{32}}$$

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21} - \frac{1}{2} \sin^2 2\theta_{13} [1 - \cos \Delta_* \cos \Delta_{21} + \cos 2\theta_{12} \sin \Delta_* \sin \Delta_{21}]$$

An official paper

PHYSICAL REVIEW D **88,** 013008 (2013)



Unambiguous determination of the neutrino mass hierarchy using reactor neutrinos

Yu-Feng Li, Jun Cao, Yifang Wang, and Liang Zhan
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

(Received 28 March 2013; published 16 July 2013)

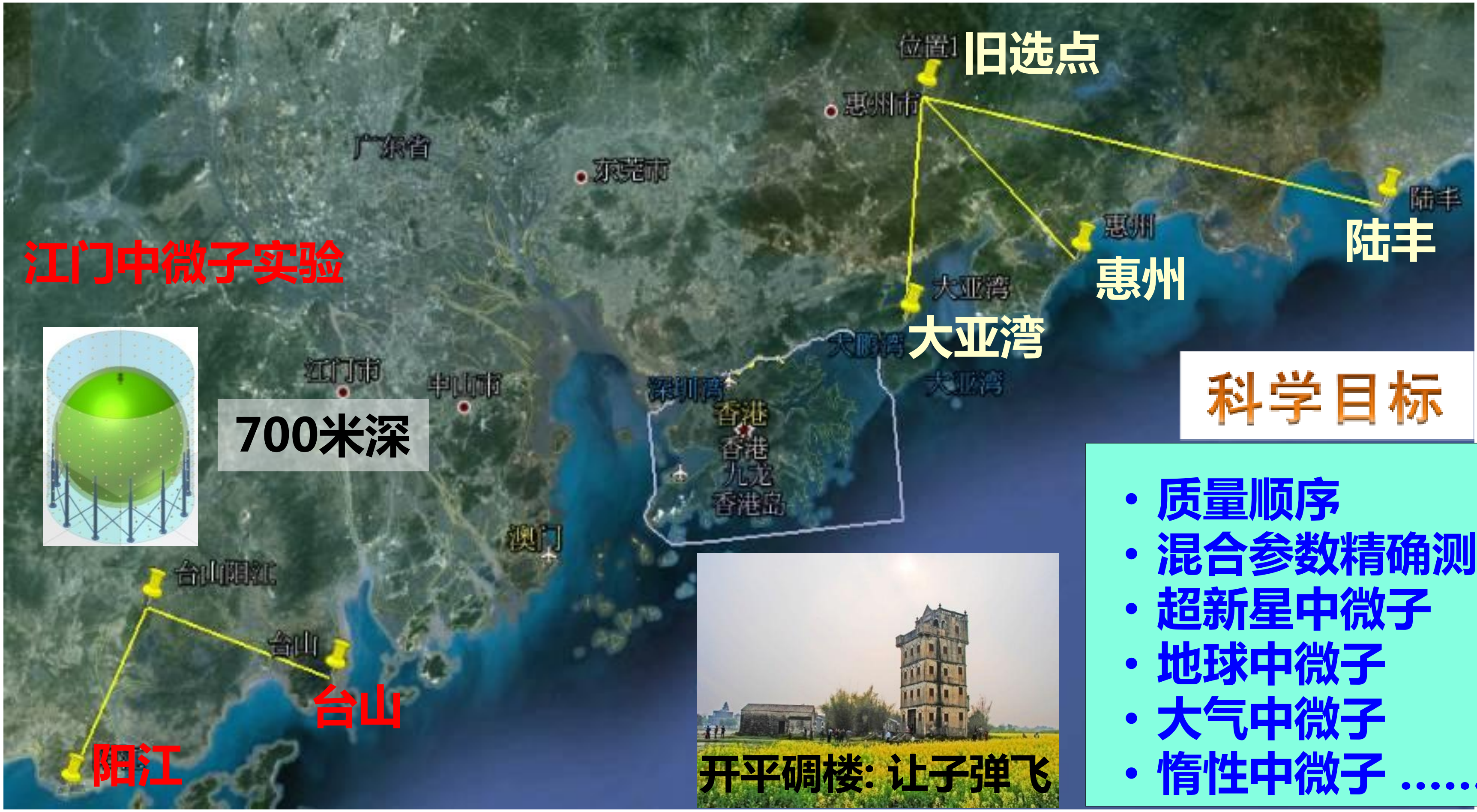
Determination of the neutrino mass hierarchy in a reactor neutrino experiment at the medium baseline is discussed. Observation of the interference effects between the Δm^2_{31} and Δm^2_{32} oscillations enables a relative measurement independent of the knowledge of the absolute mass-squared difference. With a 20 kton liquid scintillator detector of the $3\%/\sqrt{E\text{ (MeV)}}$ energy resolution, the Daya Bay II experiment at a baseline of ~50 km from reactors of total thermal power 36 GW can determine the mass hierarchy at a confidence level of $\Delta\chi^2_{\mathrm{MH}} \sim (10 \div 12)$ $(3 \div 3.5\sigma)$ in six years after taking into account the real spatial distribution of reactor cores. We show that the unknown residual energy nonlinearity of the liquid scintillator detector has limited impact on the sensitivity due to the self-calibration of small oscillation peaks. Furthermore, an extra increase of $\Delta\chi^2_{\mathrm{MH}} \simeq 4(9)$ can be obtained, by including the precise measurement of the effective mass-squared difference $\Delta m^2_{\mu\mu}$ of expected relative error 1.5% (1%) from ongoing long-baseline muon neutrino disappearance experiments. The sensitivities from the interference and from absolute measurements can be cross-checked. When combining these two, the mass hierarchy can be determined at a confidence level of $\Delta\chi^2_{\mathrm{MH}} \sim (15 \div 20)$ (4σ) in six years.

DOI: 10.1103/PhysRevD.88.013008 PACS numbers: 14.60.St, 14.60.Pq

JUNO: 让中微子飞一会儿

	大亚湾	惠州	陆丰	阳江	台山
状态	运行	计划	计划	建设中	建设中
功率/GW	17.4	17.4	17.4	17.4	18.4

江门中微子实验



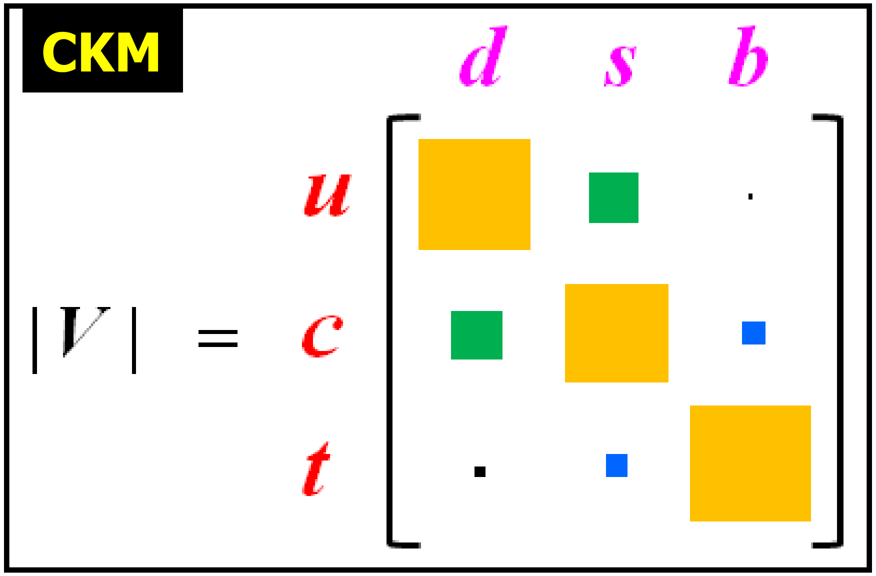
开平碉楼: 让子弹飞

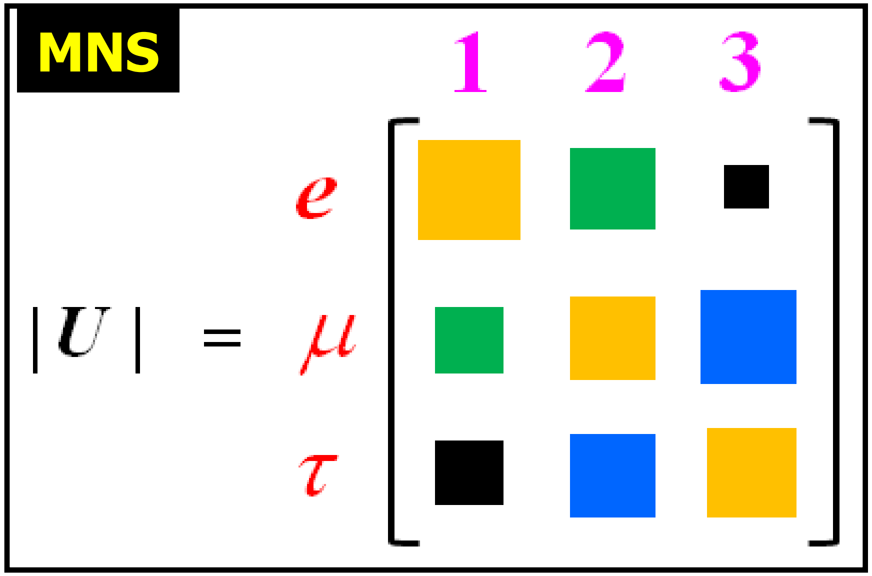
科学目标

- 质量顺序
- 混合参数精确测量
- 超新星中微子
- 地球中微子
- 大气中微子
- 惰性中微子 ……

Mixing + CP violation

Lepton flavor mixing pattern: Approximate μ-τ symmetry?





To determine the deviation of theta(23) from π/4, and to measure the Dirac phase.

μ-τ: $\left|U_{\mu i}\right| = \left|U_{\tau i}\right|$

$$\begin{cases} \theta_{13} = 0 \\ \theta_{23} = \pi/4 \end{cases}$$

or

$$\begin{cases} \delta = \pm\pi/2 \\ \theta_{23} = \pi/4 \end{cases}$$

✖

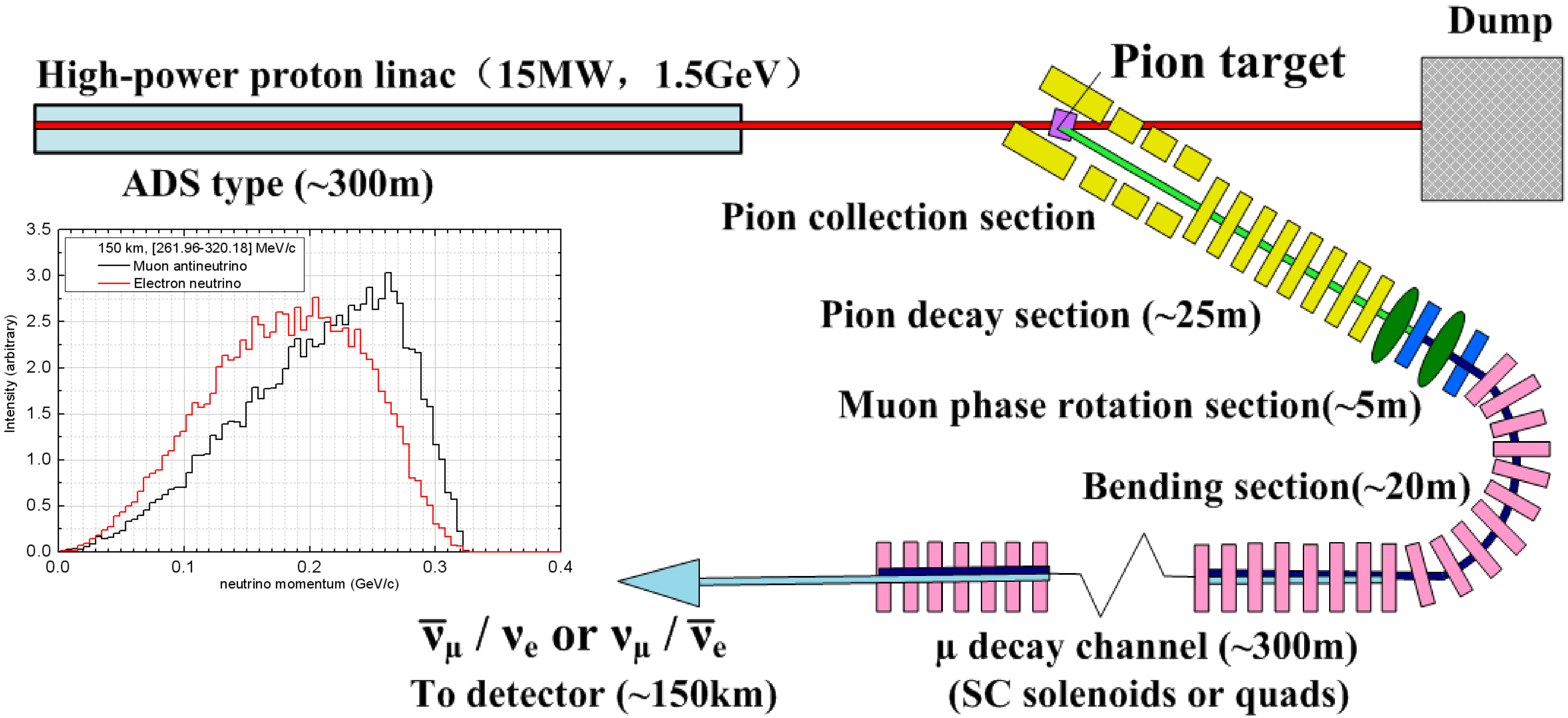
✖

CP violation

$$\begin{aligned} P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\overline{\nu}_\alpha \to \overline{\nu}_\beta\right) &= P\left(\nu_\alpha \to \nu_\beta\right) - P\left(\nu_\beta \to \nu_\alpha\right) \\ &= 16\mathcal{J}\sum_\gamma \epsilon_{\alpha\beta\gamma} \sin\frac{\Delta m^2_{21}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{32}L}{4E} \end{aligned}$$

$$J = \sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\theta_{13}\cos^2\theta_{13}\sin\delta \simeq 3.6\sin\delta\times 10^{-2}$$

MOMENT: a new idea


High-power proton linac（15MW，1.5GeV）

ADS type (~300m)

Pion target

Dump

Pion collection section

Pion decay section (~25m)

Muon phase rotation section(~5m)

Bending section(~20m)

$\overline{\nu}_\mu$ / ν_e or ν_μ / $\overline{\nu}_e$

To detector (~150km)

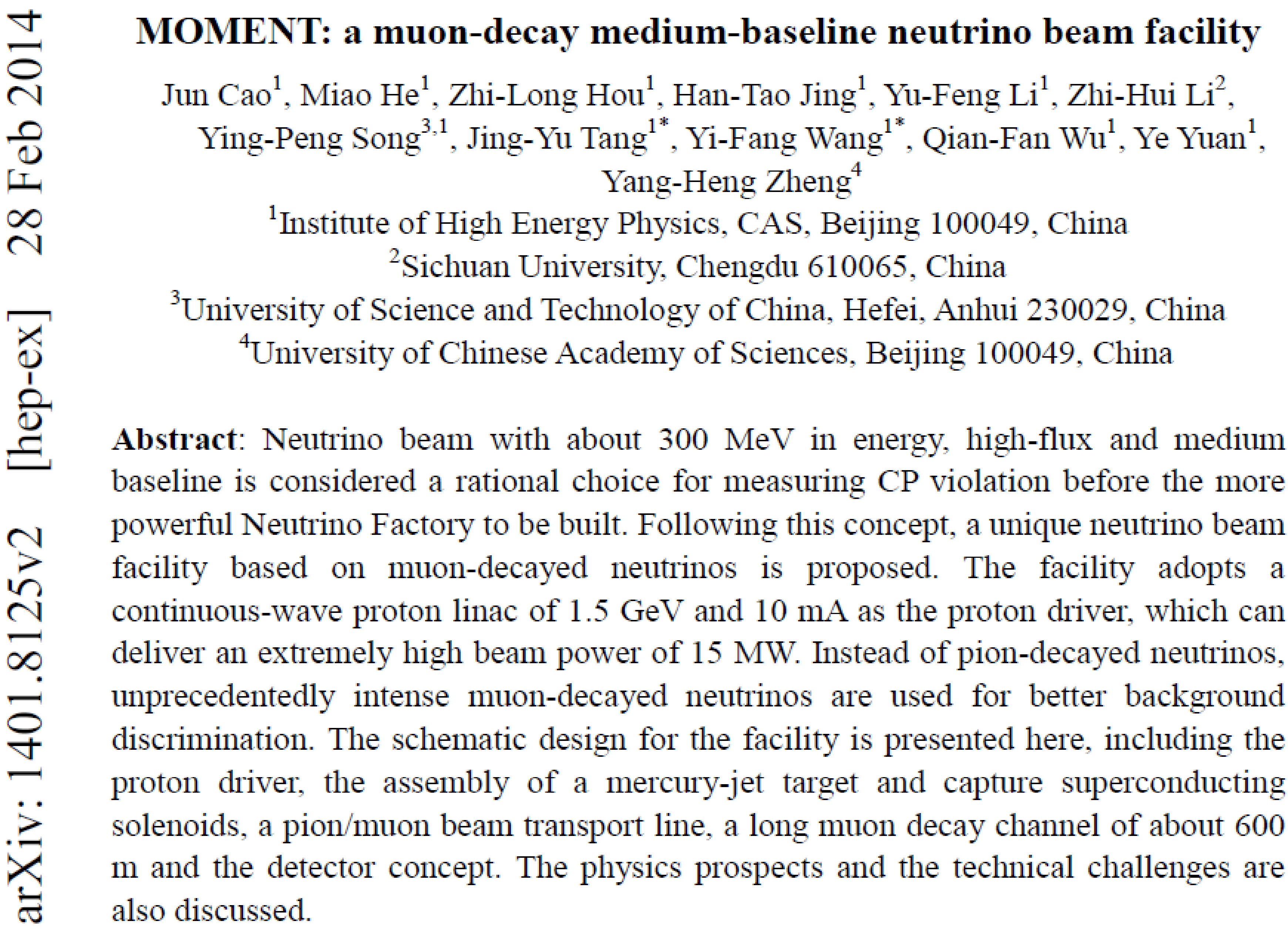
μ decay channel (~300m)

(SC solenoids or quads)

- **Neutrinos from muon decay**
- **Proton LINAC for ADS ~15 MW**
- **To JUNO detector (150 km)**

Neutrinos after the target/collection/decay: ~ 10^{21} n/year

MOMENT: beam study



MOMENT: a muon-decay medium-baseline neutrino beam facility

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Abstract: Neutrino beam with about 300 MeV in energy, high-flux and medium baseline is considered a rational choice for measuring CP violation before the more powerful Neutrino Factory to be built. Following this concept, a unique neutrino beam facility based on muon-decayed neutrinos is proposed. The facility adopts a continuous-wave proton linac of 1.5 GeV and 10 mA as the proton driver, which can deliver an extremely high beam power of 15 MW. Instead of pion-decayed neutrinos, unprecedentedly intense muon-decayed neutrinos are used for better background discrimination. The schematic design for the facility is presented here, including the proton driver, the assembly of a mercury-jet target and capture superconducting solenoids, a pion/muon beam transport line, a long muon decay channel of about 600 m and the detector concept. The physics prospects and the technical challenges are also discussed.

中国 Neutrino Trilogy 广东

★ from **Daya Bay** to **JUNO** and **MOMENT**. ν ν ν

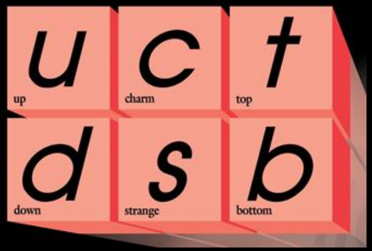
★ Martinus Veltman: We go on until we go wrong!


Angela Merkel

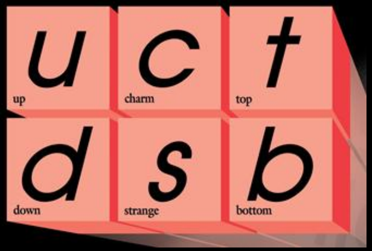

关于选题、竞争和结果的思考

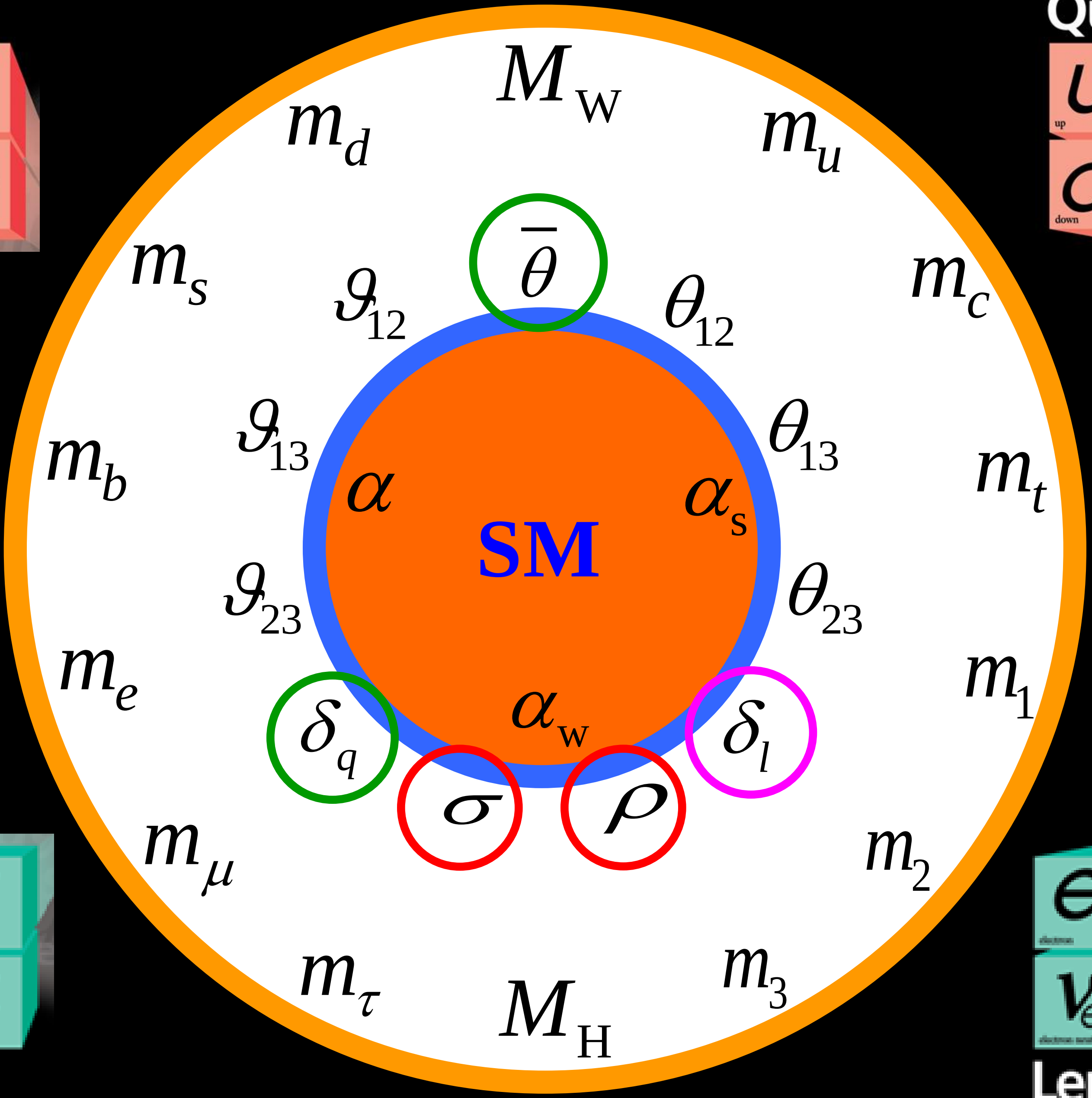
SM + neutrinos are left with **CP-violating phases**

Quarks



Quarks





1/5

OK!

4/5

NO!

Leptons

Leptons