大亚湾实验结果的唯象学后果

邢志忠

A: A brief introduction
(忐忑)

B: The Daya Bay result
(春天的故事)

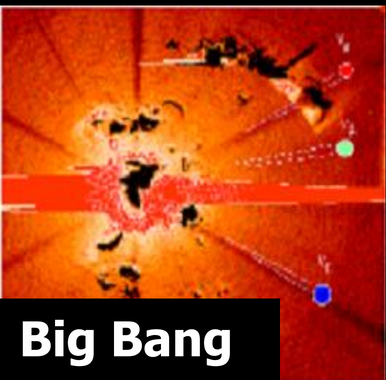
C: The phenomenology
(敢问路在何方)

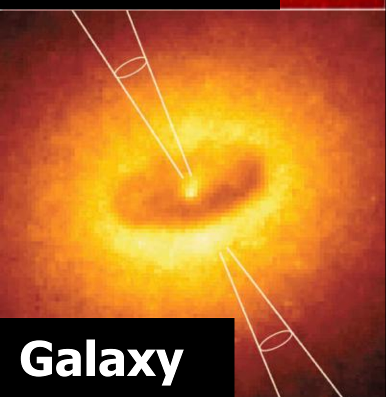
D: Concluding remarks
(传奇)

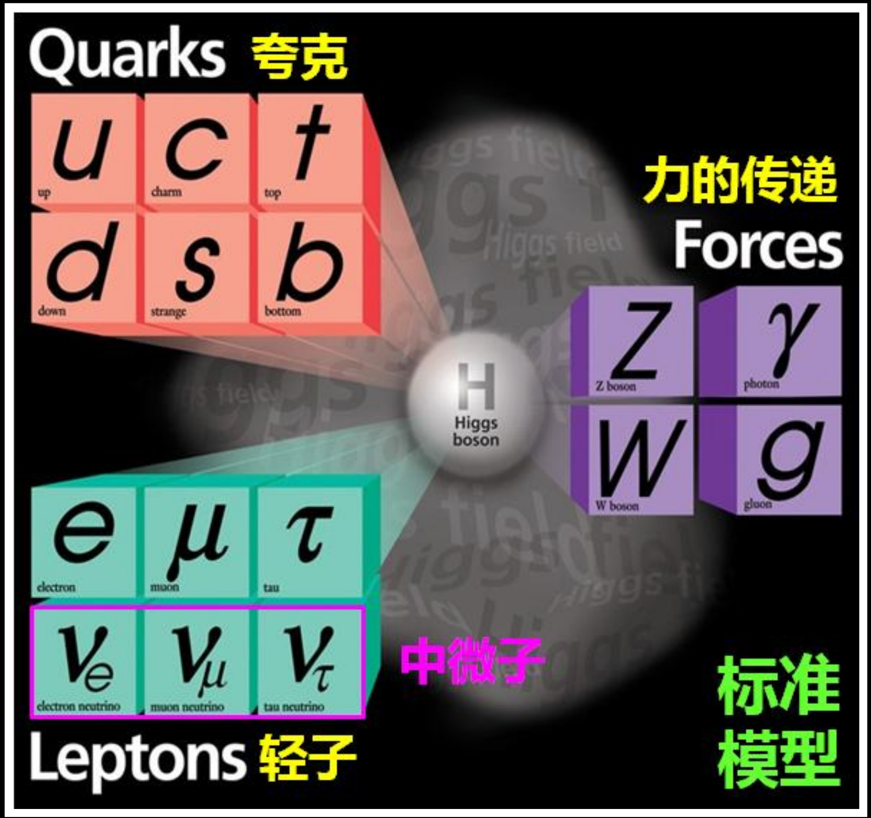
Disclaimer: 报告人的观点只代表其个人的学术见解

@ 中科大交叉学科理论研究中心, 2012年3月22日

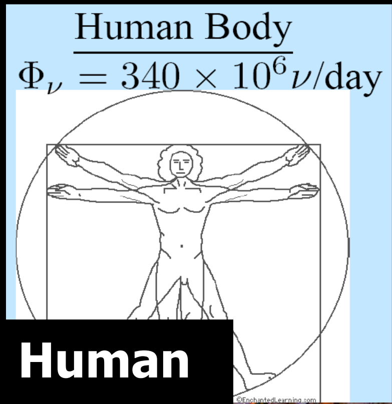
Neutrino: the most elusive particle


Big Bang

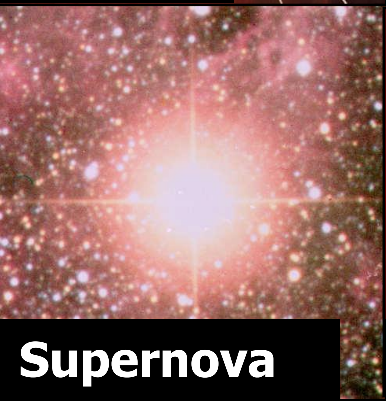

Galaxy

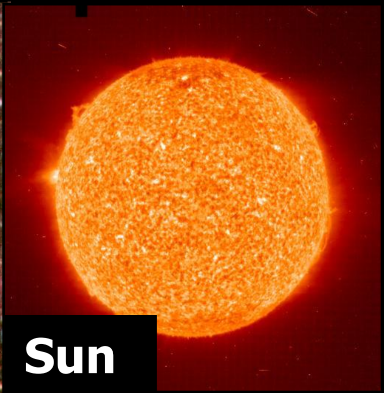


charge = 0
spin = ½
mass = 0
speed = c



Human


Supernova

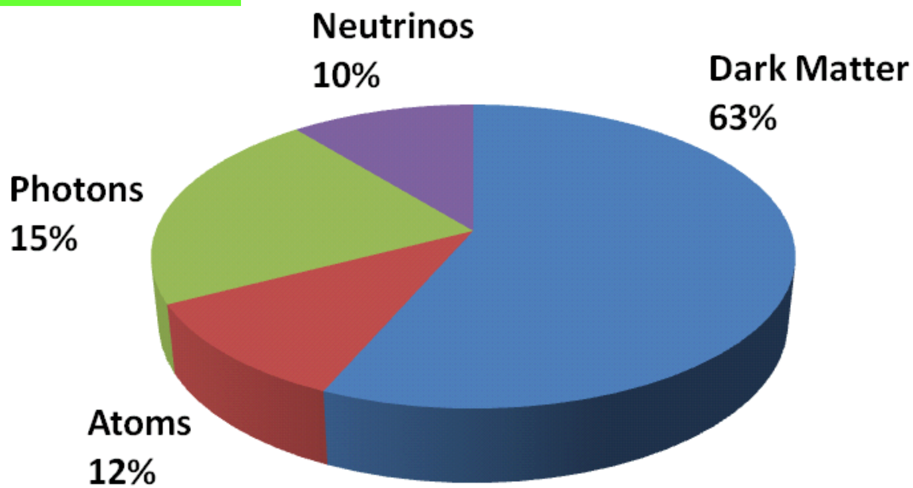

Sun


Earth

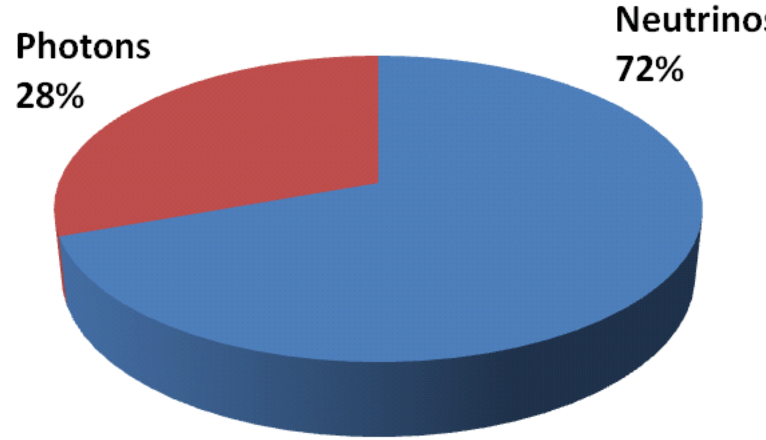

Reactor


Accelerator

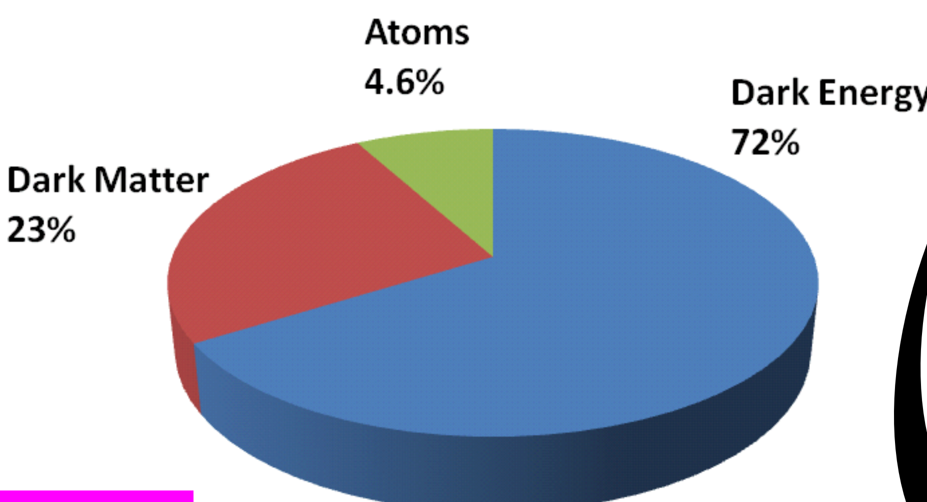
Universe



photon decoupling
t = 380 000 years



neutrino decoupling
t = 1 second



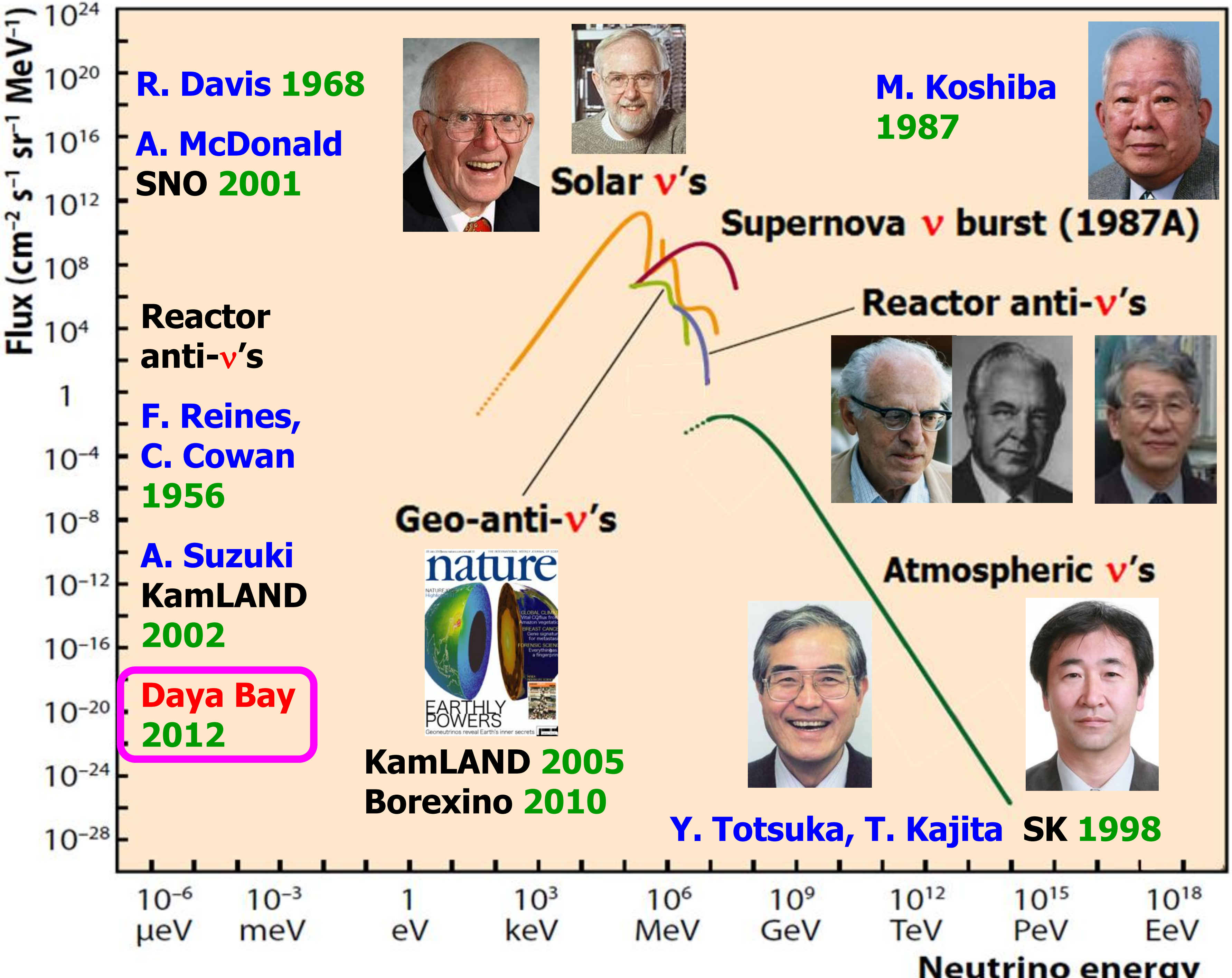
< 1%

Today
t = 13.7 billion years

曾经沧海难为水

A very important role in the evolution of the Universe

ν ν ν



Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
R. Davis 1968
A. McDonald
SNO 2001
Reactor anti-ν's
F. Reines, C. Cowan 1956
A. Suzuki KamLAND 2002
Daya Bay 2012
Solar ν's
Supernova ν burst (1987A)
M. Koshiba 1987
Reactor anti-ν's
Geo-anti-ν's
nature
EARTHLY POWERS
KamLAND 2005
Borexino 2010
Atmospheric ν's
Y. Totsuka, T. Kajita
SK 1998
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

Part A

As a Witness

第一次会议: Studying neutrino oscillation by using Daya Bay Nuclear Power Plant as the neutrino source **November 28-29, 2003**, UHK

第二次会议: Workshop on the feasibility study of the Daya Bay reactor neutrino experiment **January 17-18, 2004**, IHEP

香山科学会议: 中微子振荡与反应堆中微子实验 **2005年4月5日**, 香山

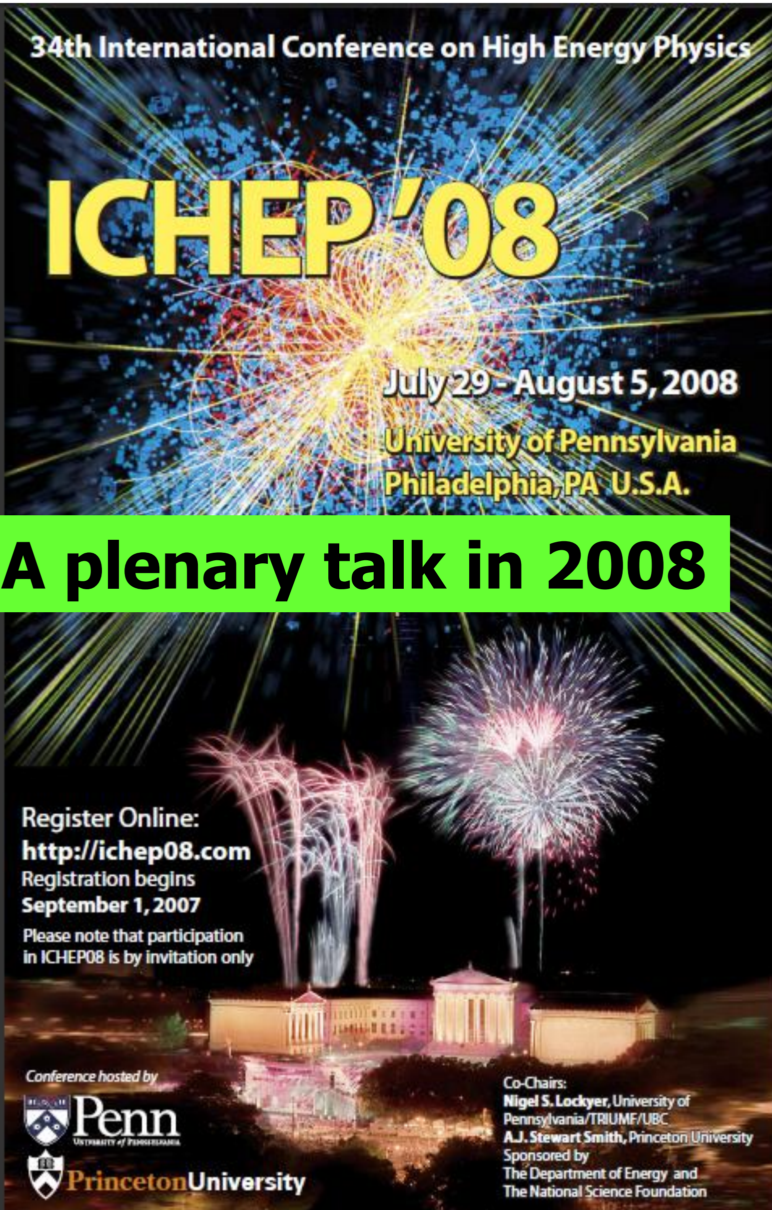
中美合作会议: Workshop on future PRC-US cooperation in high energy physics **June 12, 2006**, IHEP

My last show:

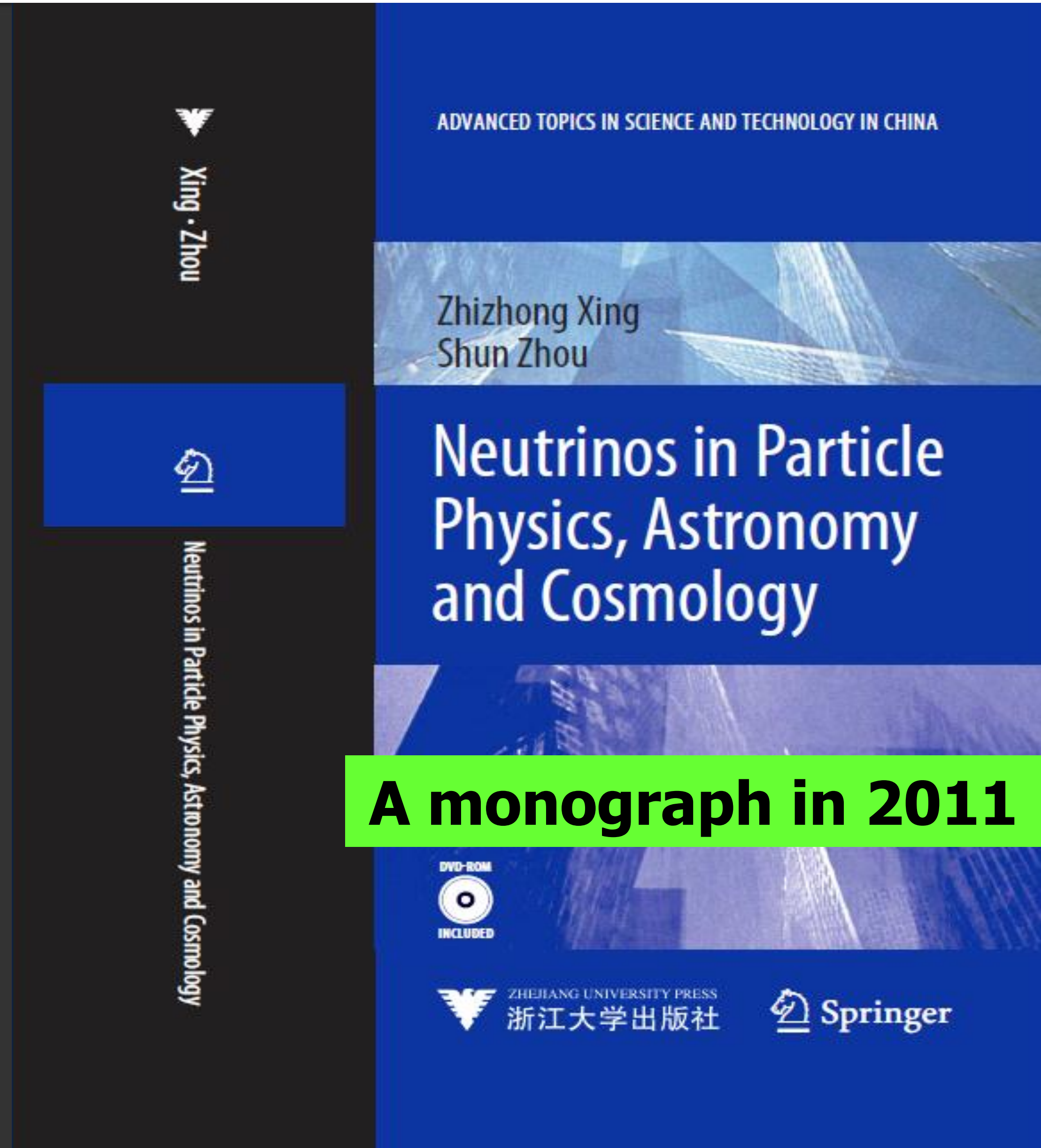
一项新事业，十个人当中有一两个人赞成就可以开始；有五个人赞成时已经迟了一步；如果有七八个人赞成，那就太晚了（稻盛和夫）。

Part A

As a Background



A plenary talk in 2008



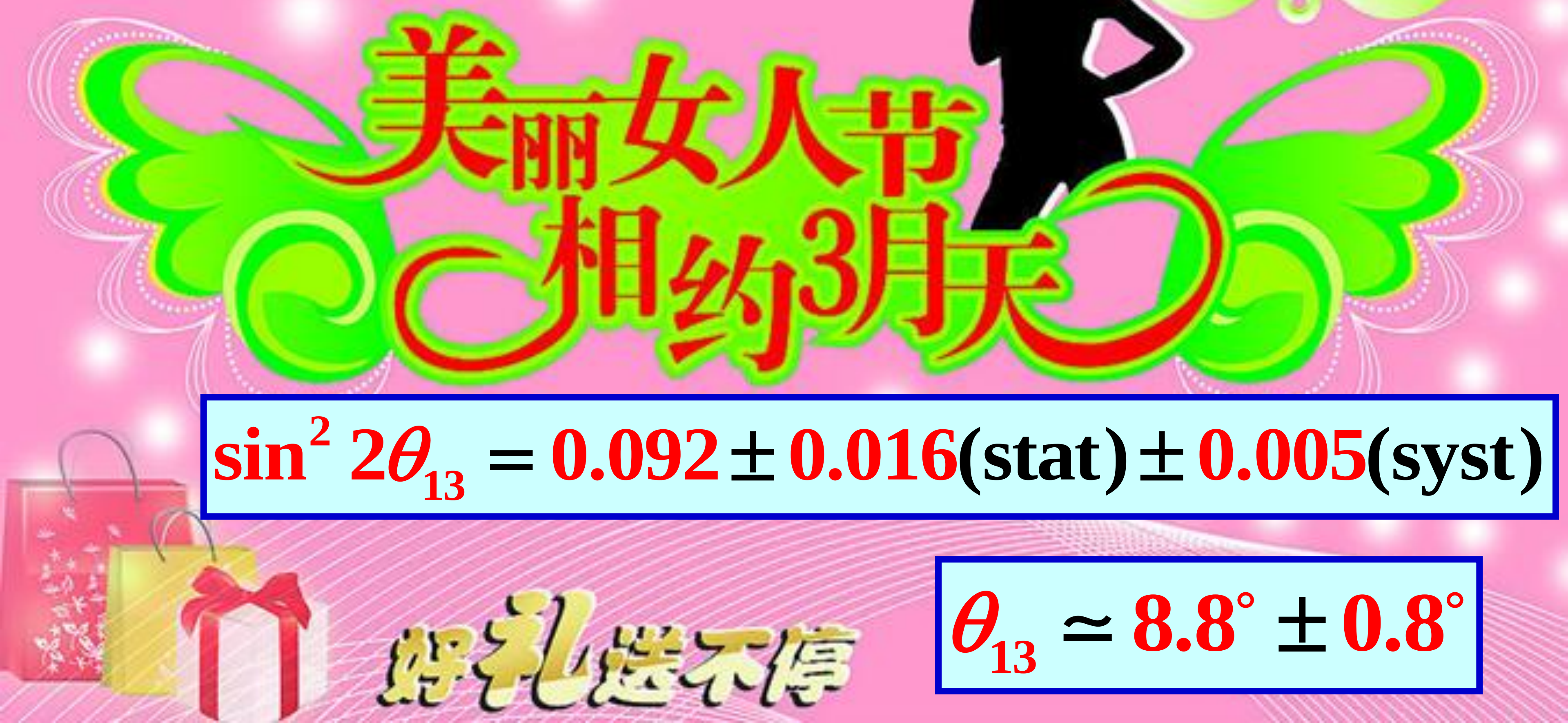
A monograph in 2011

Part B

March 8: Why Today?

News Release +

Special Seminar

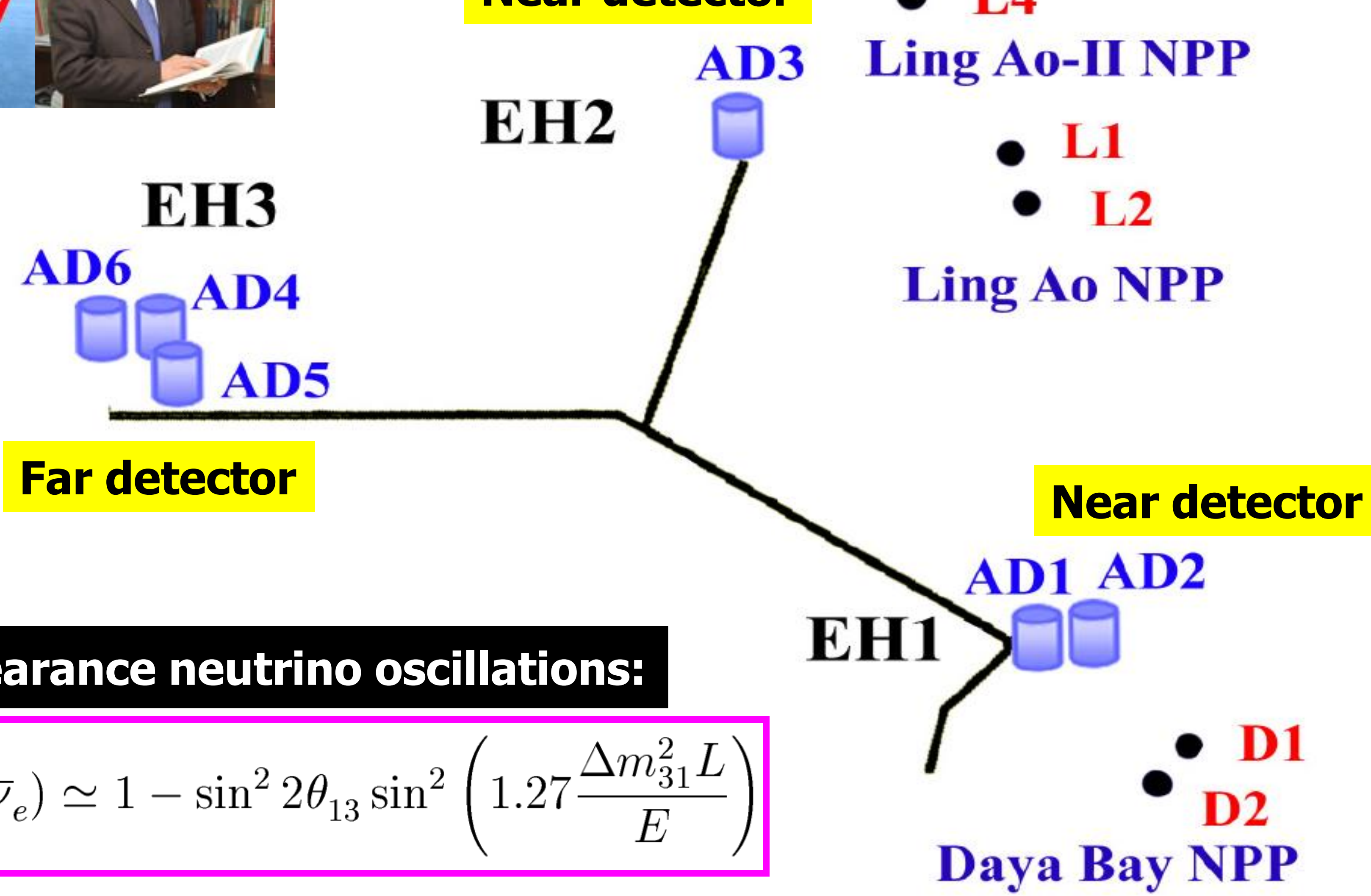


$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

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

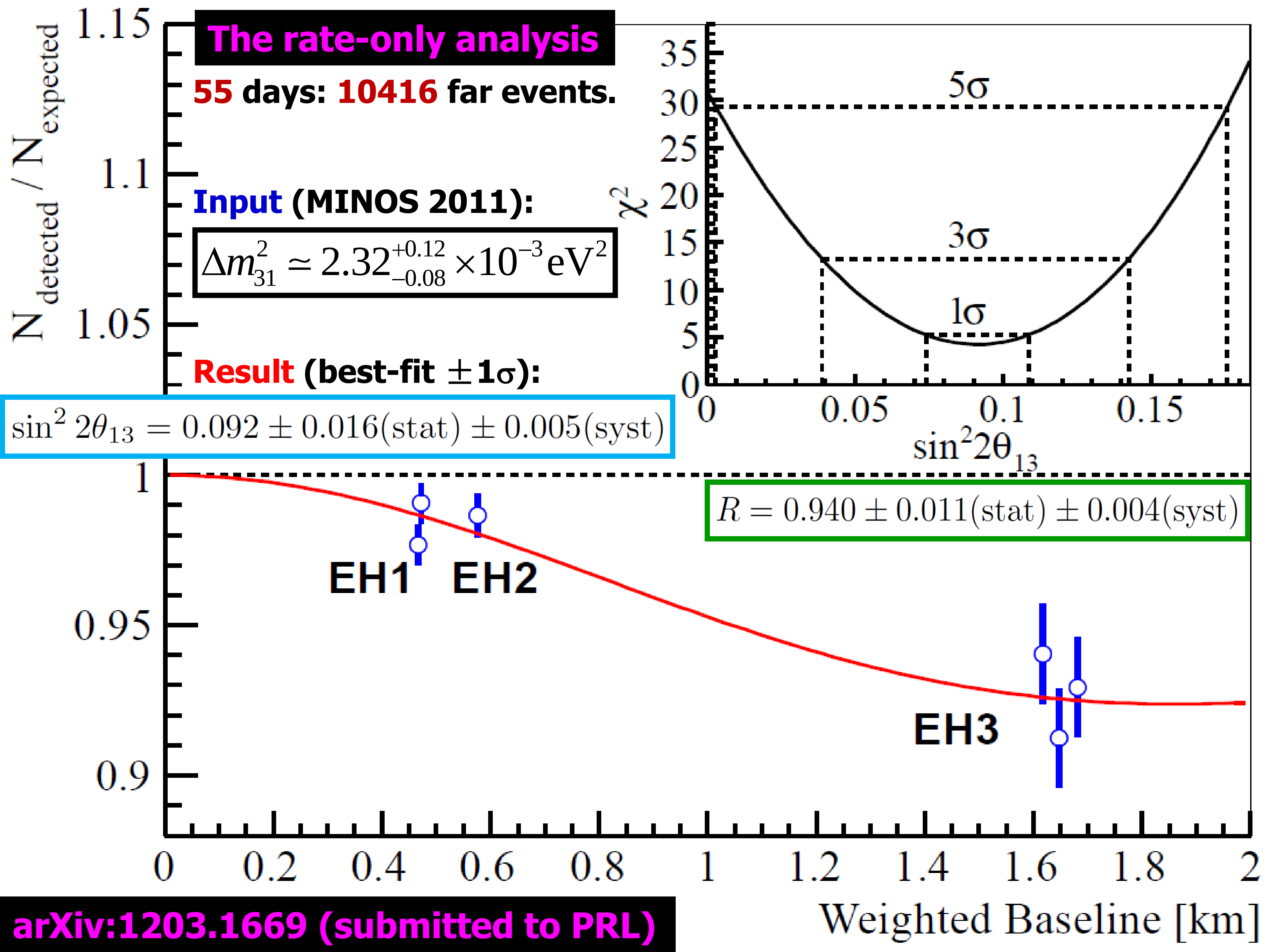
Part B

The Experiment

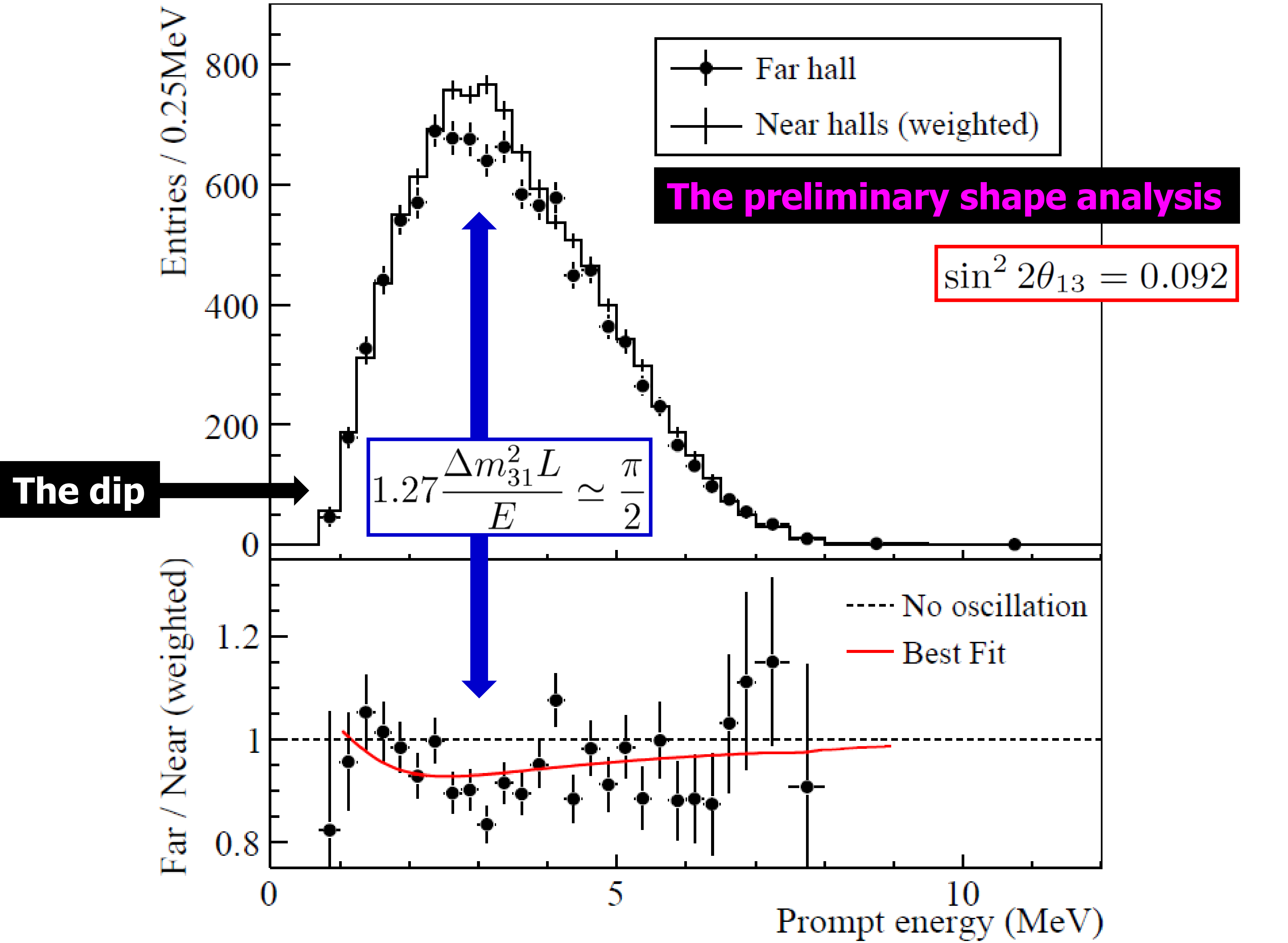


Disappearance neutrino oscillations:

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



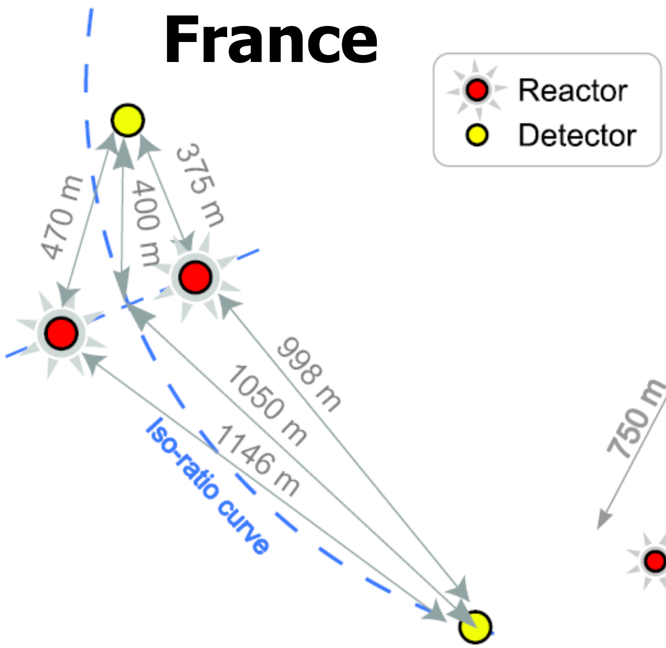
The rate-only analysis
55 days: 10416 far events.
Input (MINOS 2011):
$\Delta m^2_{31} \simeq 2.32^{+0.12}_{-0.08} \times 10^{-3} \mathrm{eV}^2$
Result (best-fit ±1σ):
$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$
$R = 0.940 \pm 0.011(\mathrm{stat}) \pm 0.004(\mathrm{syst})$
$N_{detected} / N_{expected}$
Weighted Baseline [km]
EH1
EH2
EH3
χ^2
$\sin^2 2\theta_{13}$
5σ
3σ
1σ
arXiv:1203.1669 (submitted to PRL)



The preliminary shape analysis
$\sin^2 2\theta_{13} = 0.092$
The dip
$1.27\frac{\Delta m^2_{31} L}{E} \simeq \frac{\pi}{2}$
Far hall
Near halls (weighted)
No oscillation
Best Fit
Entries / 0.25MeV
Far / Near (weighted)
Prompt energy (MeV)
0
200
400
600
800
0.8
1
1.2
5
10

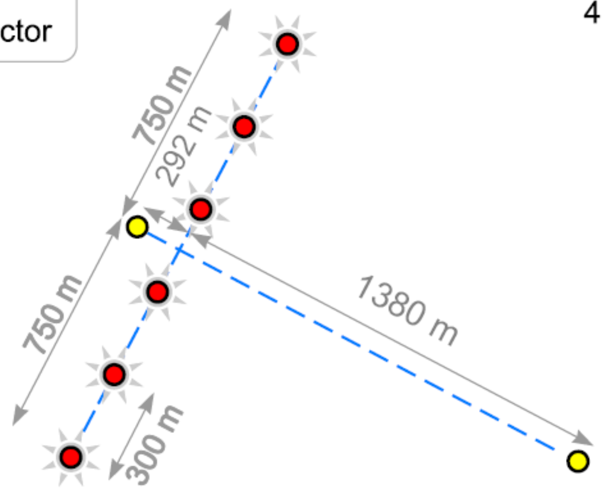
A Milestone

France



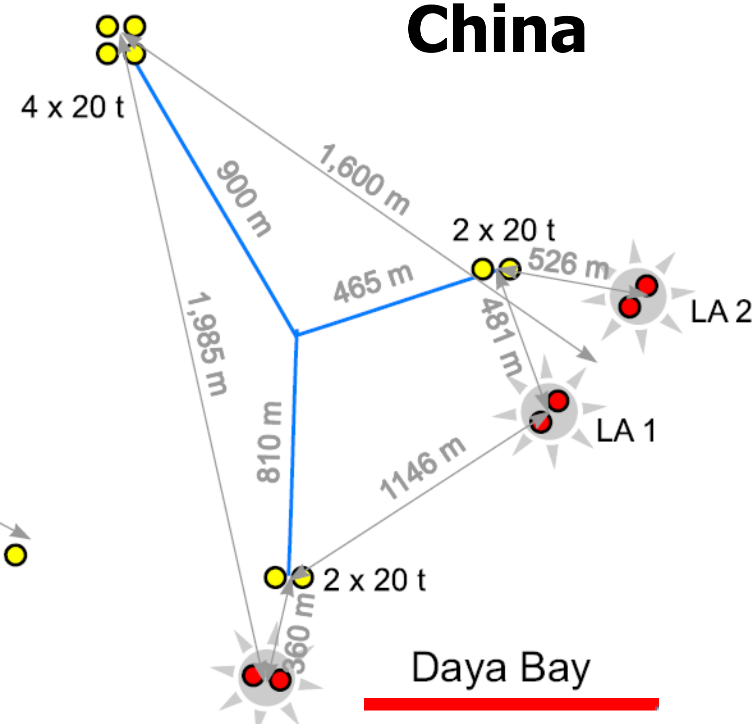
Double Chooz

Korea



RENO

China



Daya Bay

The preliminary hints in 2011

T2K (Japan): 2.5σ

$\theta_{13} \sim 8^{\circ}$

MINOS (USA): 1.7σ

Double Chooz (France): 1.7σ

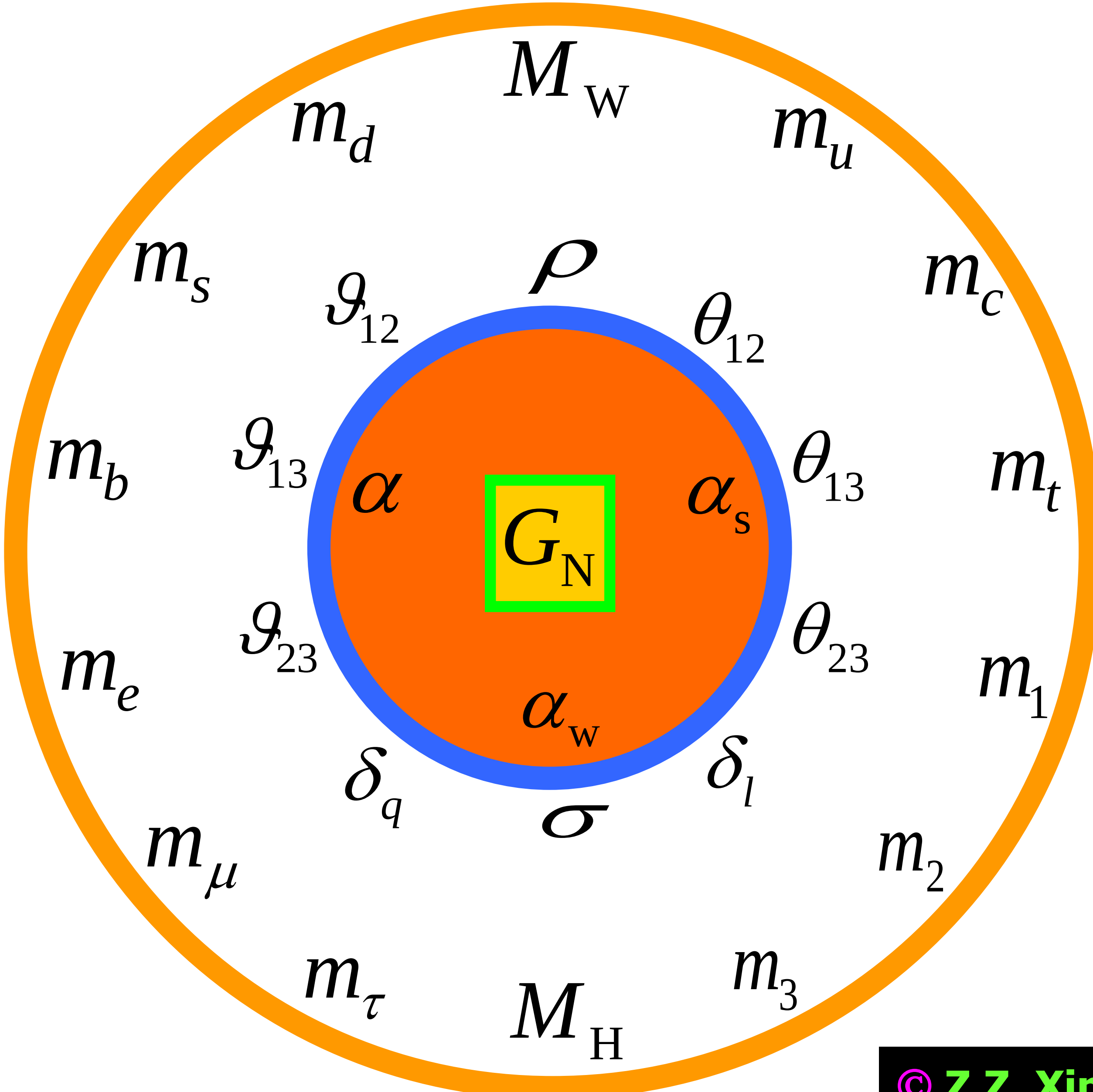
Signature in HEP

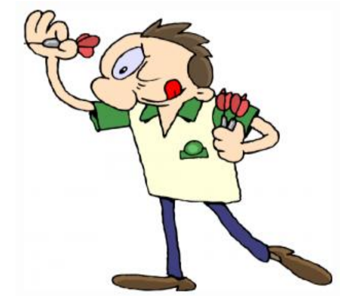
< 3σ (hint)

3~5σ (evidence)

> 5σ (discovery)

Fritzsch-Xing Plot (28 fundamental parameters in Nature)





Part B

Flavor Mixing

Quarks (63 — 73):

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

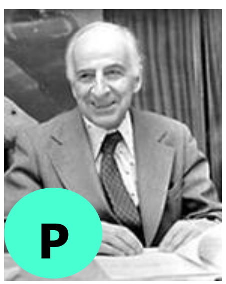
Experiments:

θ_{12} ➡ θ_{23} ➡ θ_{13} ➡ δ new physics ?

~13° ~2° ~0.2° ~65° unitarity ?

turning point

Leptons (1962): (we assume three Majorana neutrinos + unitarity)



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

θ_{23} ➡ θ_{12} ➡ θ_{13} ➡ $\delta/\rho/\sigma$ new physics ?

~45° ~34° ~9° ~? ? ? unitarity ?

Origin of Flavor Mixing

Weak interaction (flavor) state:

$$-\mathcal{L}_{\rm mass} = \overline{(\, e' \quad \mu' \quad \tau' \,)_{\rm L}} \, M_l \begin{pmatrix} e' \\ \mu' \\ \tau' \end{pmatrix}_{\rm R} + \frac{1}{2} \overline{(\, \nu_e \quad \nu_\mu \quad \nu_\tau \,)_{\rm L}} \, M_\nu \begin{pmatrix} \nu_e^c \\ \nu_\mu^c \\ \nu_\tau^c \end{pmatrix}_{\rm R} + {\rm h.c.}$$

Mass state:

$$-\mathcal{L}'_{\rm mass} = \overline{(\, e \quad \mu \quad \tau \,)_{\rm L}} \, \widehat{M}_l \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}_{\rm R} + \frac{1}{2} \overline{(\, \nu_1 \quad \nu_2 \quad \nu_3 \,)_{\rm L}} \, \widehat{M}_\nu \begin{pmatrix} \nu_1^c \\ \nu_2^c \\ \nu_3^c \end{pmatrix}_{\rm R} + {\rm h.c.}$$

Weak charged-current interactions:

$$-\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \overline{(\, e \quad \mu \quad \tau \,)_{\rm L}} \, \gamma^\mu \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} W^-_\mu + {\rm h.c.}$$

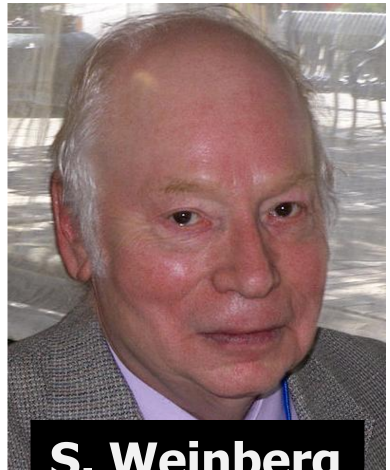
The MNSP matrix: $U = O_l^\dagger O_\nu$ ← **mass matrices**

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

Flavor Symmetries

Guiding Principle

The **Flavor** or **Family Symmetry** might be the promising way towards deeper understanding of **fermion mass generation** and **flavor mixing** (Harari et al 78; Froggatt, Nielsen 79; ......).

Flavor Symmetry

S_3 , S_4 , A_4 , Z_2 , $U(1)_F$, $SU(2)_F$, ...

Quantum Corrections

Symmetry Breaking

李政道-Friedberg

Observed patterns of fermion masses and flavor mixing

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	$\begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix}$	$m_3 \approx \sqrt{\dfrac{\Delta m^2}{1 - \tan^4\theta_{23}}}\,, \quad \langle m \rangle_{ee} \approx m_3 \tan^2\theta_{23}$
B_2	$\begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$	$m_3 \approx \sqrt{\dfrac{\Delta m^2}{1 - \cot^4\theta_{23}}}\,, \quad \langle m \rangle_{ee} \approx m_3 \cot^2\theta_{23}$
B_3	$\begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$	$m_3 \approx \sqrt{\dfrac{\Delta m^2}{1 - \tan^4\theta_{23}}}\,, \quad \langle m \rangle_{ee} \approx m_3 \tan^2\theta_{23}$
B_4	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$	$m_3 \approx \sqrt{\dfrac{\Delta m^2}{1 - \cot^4\theta_{23}}}\,, \quad \langle m \rangle_{ee} \approx m_3 \cot^2\theta_{23}$
C	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix}$	$m_3 \approx \sqrt{\dfrac{\tan^2 2\theta_{23} \cot^2\theta_{12} \sin^2\theta_{13} \Delta m^2}{1 + 2\cot\theta_{12} \tan 2\theta_{23} \sin\theta_{13} \cos\delta}}$ $\langle m \rangle_{ee} \approx m_3 \sqrt{1 - \dfrac{4\cot 2\theta_{12} \cos\delta}{\tan 2\theta_{23} \sin\theta_{13}} + \dfrac{4\cot^2 2\theta_{12}}{\tan^2 2\theta_{23} \sin^2\theta_{13}}}$

Frampton, Glashow, Marfatia:

hep-ph/0201008

(02 Jan 2002)

Phys. Lett. B 536

(2002) 79

30 May 2002

180 citations

doing research is a fun

Xing:

hep-ph/0201151

(17 Jan 2002)

Phys. Lett. B 530

(2002) 159

28 March 2002

100 citations

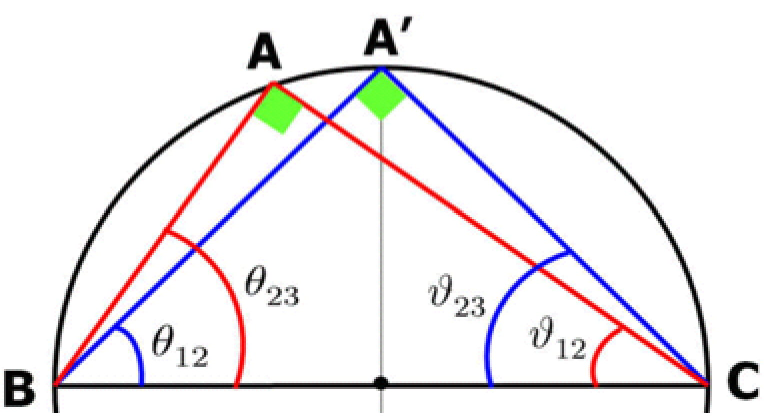
Constant Patterns

Example (A): Democratic FlavorMixing Pattern (Fritzsch, Xing 1996).

$$U = \begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{6}}{6} & \frac{\sqrt{6}}{3} \\ \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} \end{pmatrix}$$

$$U = \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

Example (B): Tri-bimaximal Flavor Mixing Pattern (Harrison, Perkins, Scott 2002; Xing 2002; He, Zee, 2003)



$$\theta_{12} = \pi/4 \qquad \vartheta_{12} = \pi/4 - \theta_*$$
$$\theta_{23} = \pi/4 + \theta_* \qquad \vartheta_{23} = \pi/4$$

Democratic | **Tri-bimaximal**

$$\theta_* = \arctan(\sqrt{2}) - \pi/4 = \pi/4 - \arctan(1/\sqrt{2}) \approx 9.7^\circ$$

Part C

Perturbations

To illustrate, we typically take $\theta_{12} \simeq 34^\circ,\ \theta_{13} \simeq 9^\circ \text{ and } \theta_{23} \simeq 45^\circ$

$$U = \begin{pmatrix} 0.819 & 0.552 & 0.156e^{-i\delta} \\ -0.395 - 0.092e^{i\delta} & 0.586 - 0.062e^{i\delta} & 0.698 \\ 0.395 - 0.092e^{i\delta} & -0.586 - 0.062e^{i\delta} & 0.698 \end{pmatrix} P_\nu$$

Democratic

$$\Delta U = \begin{pmatrix} 0.112 & -0.155 & 0.156e^{-i\delta} \\ 0.013 - 0.092e^{i\delta} & 0.178 - 0.062e^{i\delta} & -0.118 \\ -0.182 - 0.092e^{i\delta} & -0.009 - 0.062e^{i\delta} & 0.121 \end{pmatrix}$$

The nine matrix elements are all O(0.1) ---- natural?

Tri-bimaximal

$$\Delta U = \begin{pmatrix} 0.003 & -0.025 & 0.156e^{-i\delta} \\ 0.013 - 0.092e^{i\delta} & 0.009 - 0.062e^{i\delta} & -0.009 \\ -0.013 - 0.092e^{i\delta} & -0.009 - 0.062e^{i\delta} & -0.009 \end{pmatrix}$$

The smallest (largest) angle receives the maximum (minimum) correction ---- unnatural?

Part C

Quantum Corrections

New Physics Scale

A mechanism of neutrino mass generation most likely works at a super-high energy scale. After integrating out heavy degrees of freedom, one is left with the unique Weinberg operator:

$$\frac{\mathcal{L}_{\rm d=5}}{\Lambda} = \frac{1}{2}\kappa_{\alpha\beta}\overline{\ell_{\alpha \rm L}}\tilde{H}\tilde{H}^T\ell^c_{\beta \rm L} + {\rm h.c.}$$

Impossible unless ……

arXiv:1203.3118

RGEs = Cable Car

To compare a theory with experiments, one must run the RGEs of the effective ν-mass matrix down to low energies:

RGE = renormalization-group equation

Electroweak Scale

Part C

Initially $\theta_{13} \neq 0^\circ$?

Example (A): **Tetra-maximal mixing (Xing, 2008)**

$$U_0 = \begin{pmatrix} \frac{2+\sqrt{2}}{4} & \frac{1}{2} & \frac{2-\sqrt{2}}{4} \\ -\frac{\sqrt{2}}{4} + \frac{i\left(\sqrt{2}-1\right)}{4} & \frac{1}{2} - \frac{i\sqrt{2}}{4} & \frac{\sqrt{2}}{4} + \frac{i\left(\sqrt{2}+1\right)}{4} \\ -\frac{\sqrt{2}}{4} - \frac{i\left(\sqrt{2}-1\right)}{4} & \frac{1}{2} + \frac{i\sqrt{2}}{4} & \frac{\sqrt{2}}{4} - \frac{i\left(\sqrt{2}+1\right)}{4} \end{pmatrix}$$

$\theta_{12}^{(0)} \simeq 30.4^\circ$

$\theta_{13}^{(0)} \simeq 8.4^\circ$

$\theta_{23}^{(0)} = 45^\circ$

$\delta^{(0)} = 90^\circ$

Example (B): **Correlative mixing (Xing, Jan 2011)**

$$U_0 = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} c_* & \frac{1}{\sqrt{3}} c_* & s_* e^{-i\delta} \\ -\frac{1}{\sqrt{6}} - \frac{1}{\sqrt{3}} s_* e^{i\delta} & \frac{1}{\sqrt{3}} - \frac{1}{\sqrt{6}} s_* e^{i\delta} & \frac{1}{\sqrt{2}} c_* \\ \frac{1}{\sqrt{6}} - \frac{1}{\sqrt{3}} s_* e^{i\delta} & -\frac{1}{\sqrt{3}} - \frac{1}{\sqrt{6}} s_* e^{i\delta} & \frac{1}{\sqrt{2}} c_* \end{pmatrix}$$

$\theta_{12}^{(0)} \simeq 35.3^\circ$

$\theta_{13}^{(0)} \simeq 9.7^\circ$

$\theta_{23}^{(0)} = 45^\circ$

Comment (1): it is easier to get perturbations or quantum corrections

Comment (2): it is not easy to get such a pattern from group theories

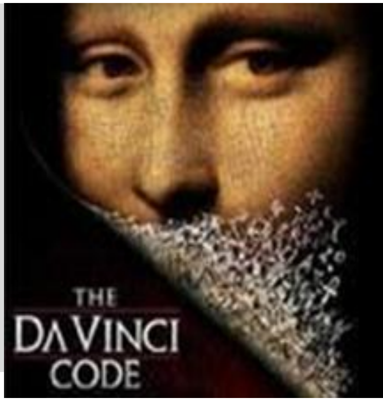
Part C

How to Play?

What distinguishes different families of fermions?

----- they have the same gauge quantum numbers,

yet they are quite different from one another.



- ★ **Radiative Mechanism** (S. Weinberg 1972; A. Zee 1980)
- ★ **Texture Zeros** (S. Weinberg; H. Fritzsch 1977; H. Fritzsch 1978)
- ★ **Family Symmetries** (H. Harari et al 1978; C. Froggatt, H. Nielsen 1979)
- ★ **Seesaw Mechanism** (P. Minkowski 1977; T. Yanagida 1979; ......)
- ★ **Extra Dimensions** (K. Dienes et al; G. Dvali, A. Smirnov 1999)

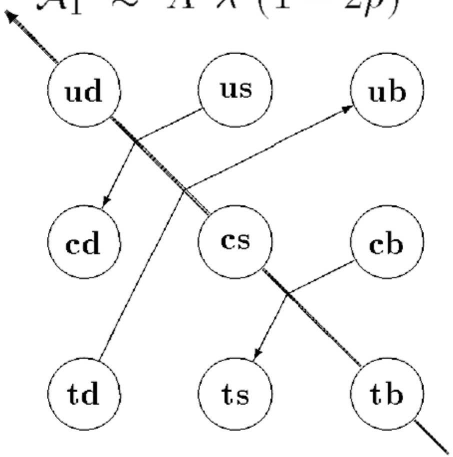
Our Philosophy

Although nature commences with reason and ends in experience, it is necessary for us to do the opposite, that is, to commence with experience and from this to proceed to investigate the reason

The Structure

Off-diagonal asymmetries of the CKM matrix: Almost symmetric!

$$\mathcal{A}_1 \approx A^2\lambda^6(1-2\rho)$$



BESIII Experiment

$$\mathcal{A}_1 = |V_{us}|^2 - |V_{cd}|^2 = |V_{cb}|^2 - |V_{ts}|^2 = |V_{td}|^2 - |V_{ub}|^2$$

$$\mathcal{A}_2 = |V_{us}|^2 - |V_{cb}|^2 = |V_{cd}|^2 - |V_{ts}|^2 = |V_{tb}|^2 - |V_{ud}|^2$$

$$M_\nu = \begin{pmatrix} a & b & -b \\ b & c & d \\ -b & d & c \end{pmatrix} \qquad \theta_{23} = 45^\circ , \quad \theta_{13} = 0^\circ$$

$$M_\nu = \begin{pmatrix} a & b & -b^* \\ b & c & d \\ -b^* & d & c^* \end{pmatrix} \qquad \theta_{23} = 45^\circ , \quad \delta = \pm 90^\circ$$

The MNSP matrix exhibits an approximate μ–τ symmetry in modulus:

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

$$\theta_{13} \simeq 9^\circ$$

Conditions: $\theta_{23} = 45^\circ , \quad \theta_{13} = 0^\circ$ **or** $\theta_{23} = 45^\circ , \quad \delta = \pm 90^\circ$

What to do next ?

The 1st Paper on CPV

Volume 72B, number 3 PHYSICS LETTERS 2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

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Received 11 October 1977

Quarks: $\mathcal{J}_q \simeq 3 \times 10^{-5}$

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

The Cabibbo Texture: the tri-maximal mixing + maximal CP violation:

$$V_{\rm C} = \begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & \frac{\omega}{\sqrt{3}} & \frac{\omega^2}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & \frac{\omega^2}{\sqrt{3}} & \frac{\omega}{\sqrt{3}} \end{pmatrix} \Rightarrow V'_{\rm C} = \begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{-i}{\sqrt{3}} \\ -\frac{1}{2}\left(1+\frac{i}{\sqrt{3}}\right) & \frac{1}{2}\left(1-\frac{i}{\sqrt{3}}\right) & \frac{1}{\sqrt{3}} \\ \frac{1}{2}\left(1-\frac{i}{\sqrt{3}}\right) & -\frac{1}{2}\left(1+\frac{i}{\sqrt{3}}\right) & \frac{1}{\sqrt{3}} \end{pmatrix}$$

The Jarlskog invariant:

$$\mathcal{J}_{\rm max} = c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23} \sin\delta = 1/(6\sqrt{3}) \simeq 9.6 \times 10^{-2}$$

Part C

CP & T Violation

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

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

Comments:

$\theta_{12} \simeq 34^\circ$

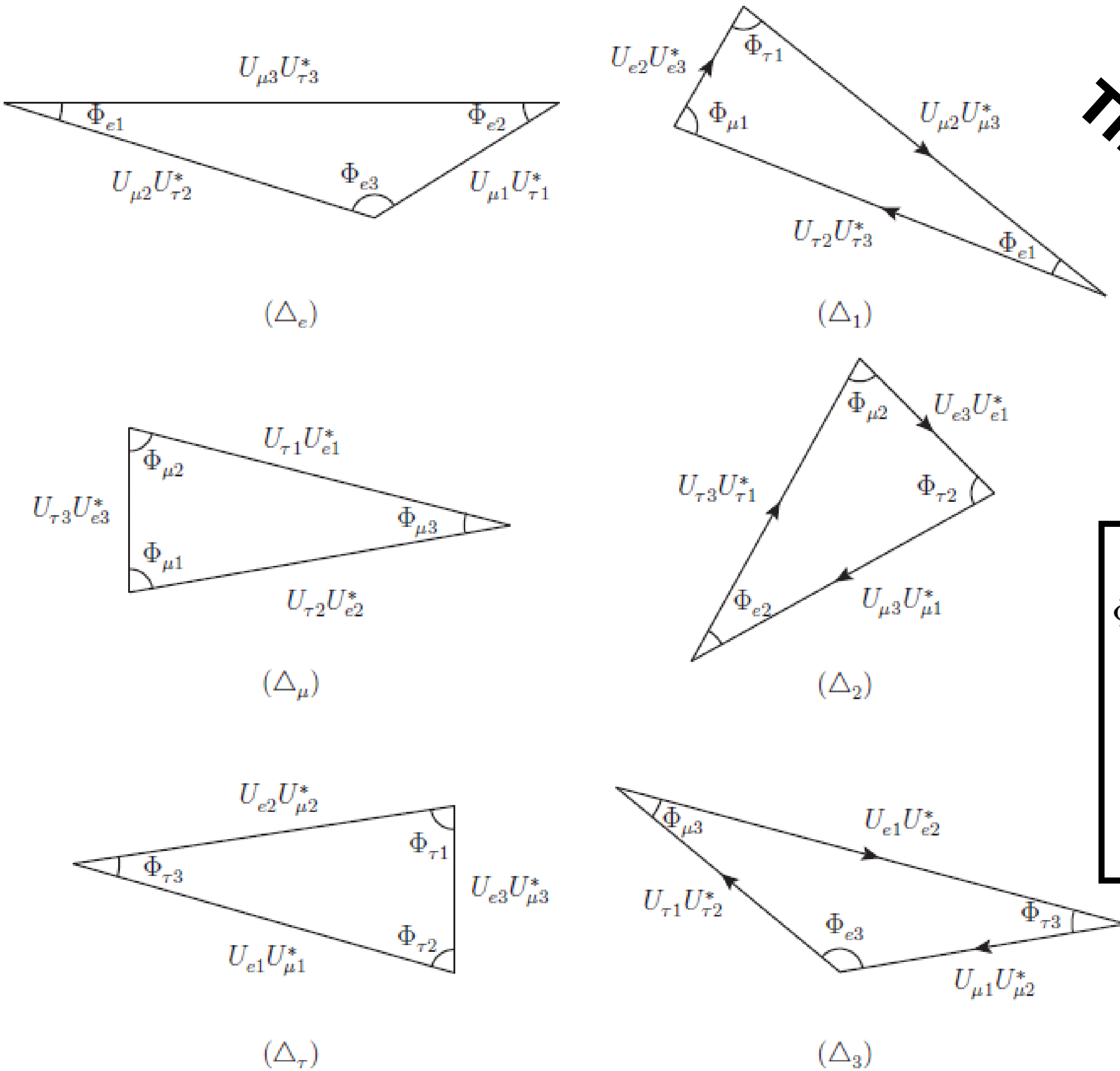
$\theta_{13} \simeq 9^\circ$

$\theta_{23} \simeq 45^\circ$

- ★ **CP / T violation cannot show up in the disappearance neutrino oscillation experiments (α = β);**
- ★ **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 *U*; hence such oscillation experiments cannot tell us whether neutrinos are Dirac or Majorana particles.**

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

Unitarity Triangles



The same area

$\theta_{12} \simeq 34^\circ$

$\theta_{13} \simeq 9^\circ$

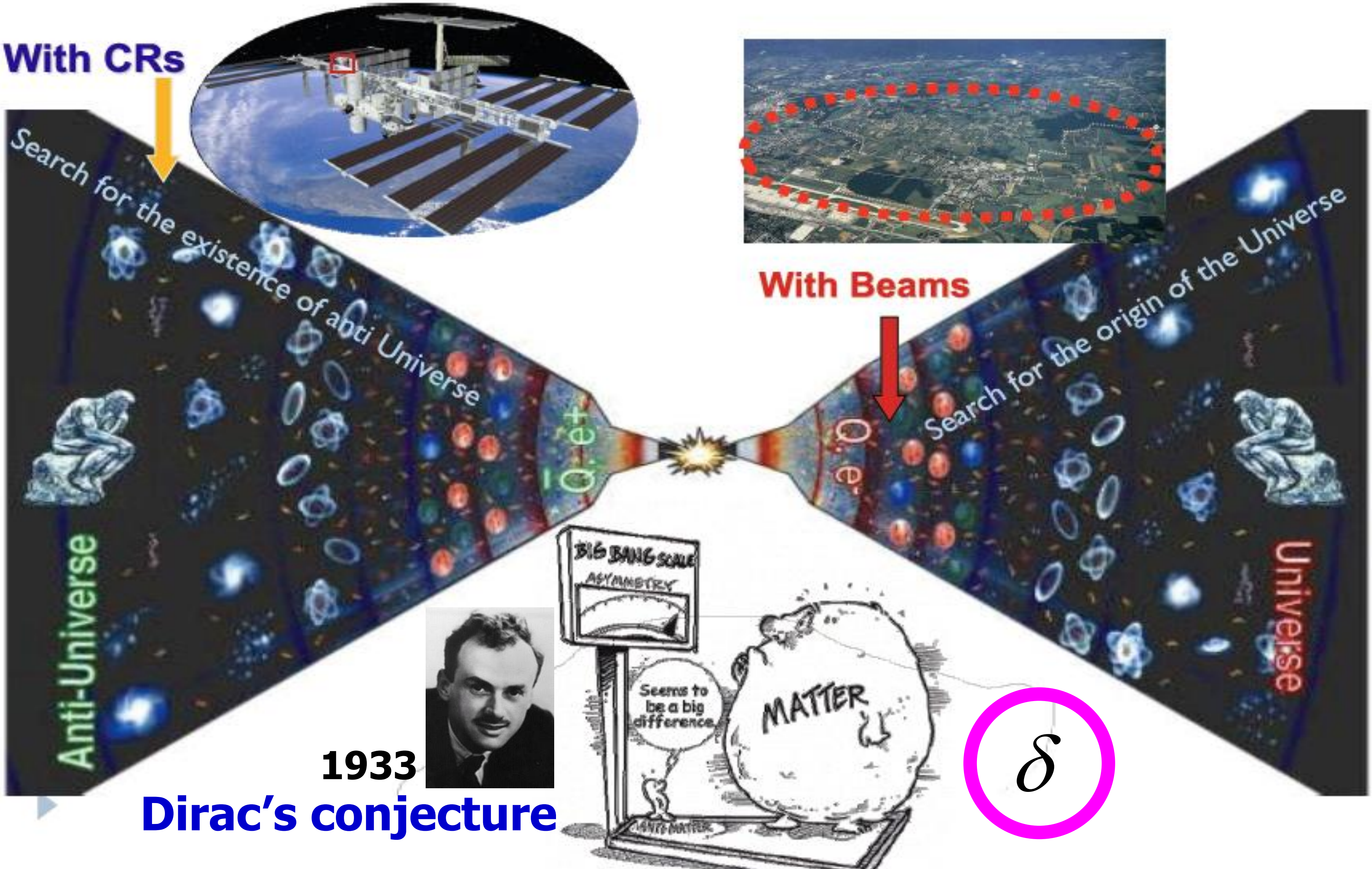
$\theta_{23} \simeq 45^\circ$

$\delta \simeq 90^\circ$

$$\Phi \equiv \begin{pmatrix} \Phi_{e1} & \Phi_{e2} & \Phi_{e3} \\ \Phi_{\mu 1} & \Phi_{\mu 2} & \Phi_{\mu 3} \\ \Phi_{\tau 1} & \Phi_{\tau 2} & \Phi_{\tau 3} \end{pmatrix} \simeq \begin{pmatrix} 12.05^\circ & 26.11^\circ & 141.8^\circ \\ 83.98^\circ & 76.94^\circ & 19.08^\circ \\ 83.98^\circ & 76.94^\circ & 19.08^\circ \end{pmatrix}$$

$$\sum_\alpha \Phi_{\alpha i} = \sum_i \Phi_{\alpha i} = 180^\circ$$

Matter-Antimatter



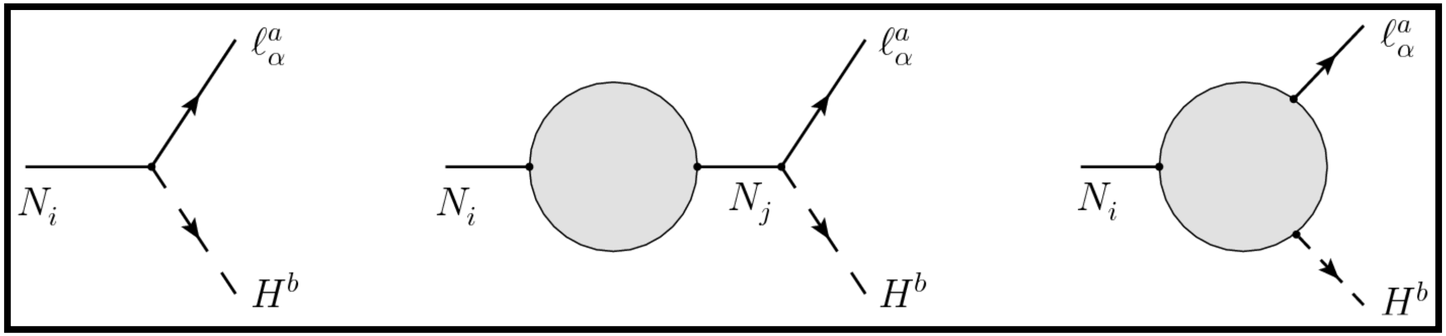
Leptogenesis

◆ add 3 heavy right-handed Majorana neutrinos into SM & keep its SU(2)×U(1) gauge symmetry:

$$-\mathcal{L}_{\rm lepton} = \overline{\ell_{\rm L}} Y_l H E_{\rm R} + \overline{\ell_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^{\rm c}_{\rm R}} M_{\rm R} N_{\rm R} + {\rm h.c.}$$

Fukugita, Yanagida 86

◆ lepton-number-violating & CP-violating decays of heavy neutrinos:

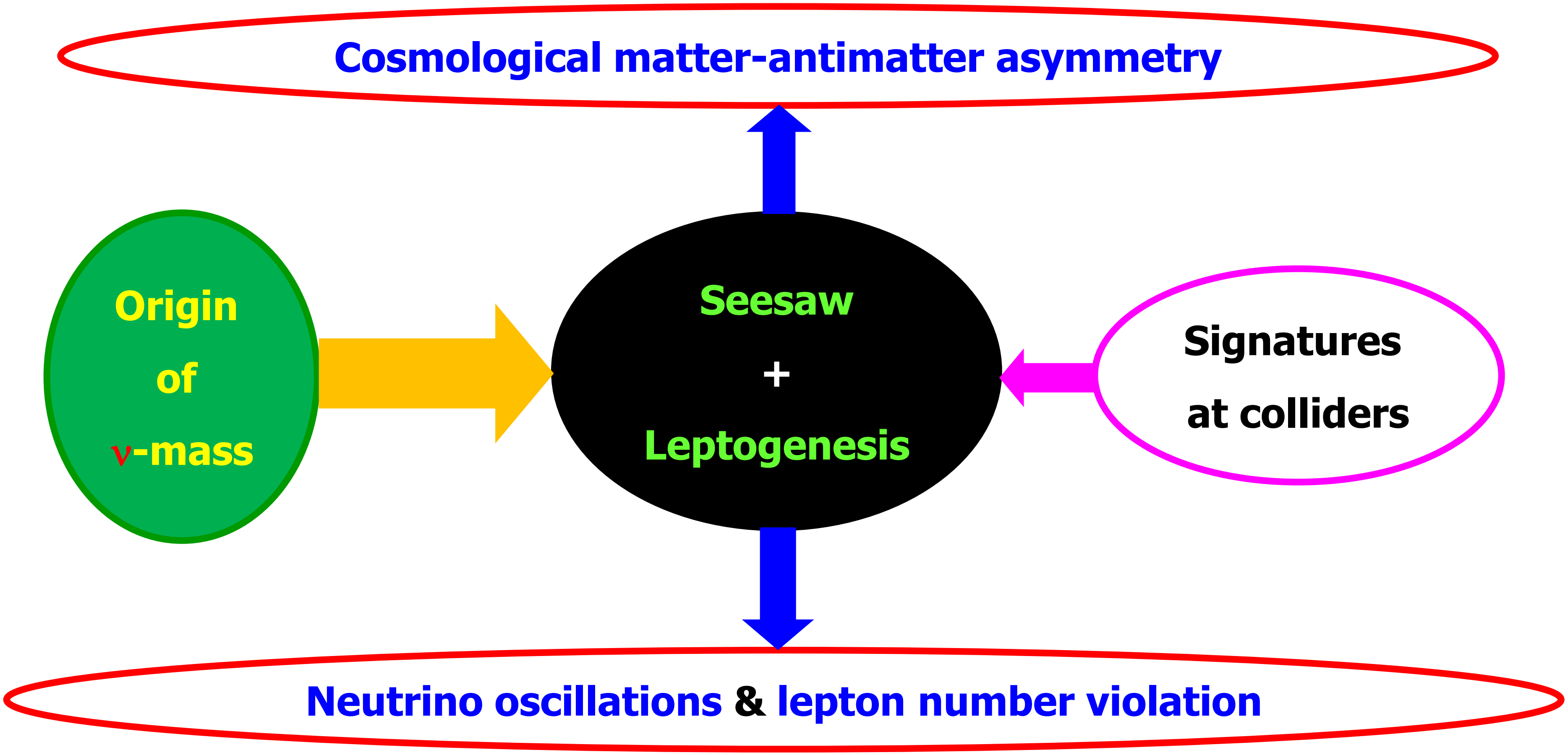


◆ non-perturbative (B-L)-conserving weak sphaleron reactions work:

CP violation → L-number asymmetry → B-number asymmetry

◆ a link to low-energy CP violation? The phase counting: 9 phases at high scales, 3 phases at low scales ----- related indirectly via SEESAW.

It's a Dream!



Cosmic messenger: neutrino astronomy and neutrino cosmology.

Surprise maker: history of neutrino physics was full of surprises.

Sterile Neutrinos?

active flavor

sterile flavor

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_x\\ \nu_y\\ \nu_z\end{pmatrix} = \mathcal{U}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\\ \nu_5\\ \nu_6\end{pmatrix}$$

mass state

Seesaw

LSND

MiniBooNE

RANA

Warm DM

....

Part C

Parametrization

$$\mathcal{U} = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & U_0 \end{pmatrix} \begin{pmatrix} A & R \\ S & B \end{pmatrix} \begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}$$

sterile part **interplay** **active part**

$$\begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix} = O_{23} O_{13} O_{12} \; ,$$

$$\begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & U_0 \end{pmatrix} = O_{56} O_{46} O_{45} \; ,$$

$$\begin{pmatrix} A & R \\ S & B \end{pmatrix} = O_{36} O_{26} O_{16} O_{35} O_{25} O_{15} O_{34} O_{24} O_{14}$$

Full parametrization:

15 rotation angles

15 phase phases

Xing, arXiv:1110.0083

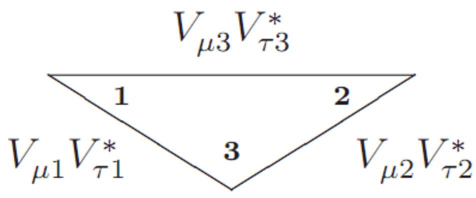
Part C

Unitarity Polygons

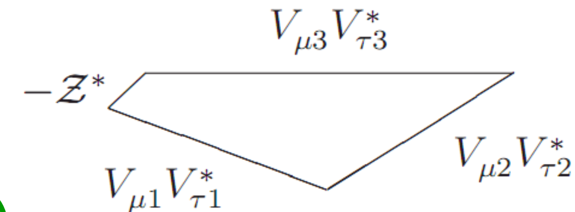
$$\begin{aligned}\triangle_e &: \quad V_{\mu 1}V^*_{\tau 1} + V_{\mu 2}V^*_{\tau 2} + V_{\mu 3}V^*_{\tau 3} = 0\\ \triangle_\mu &: \quad V_{\tau 1}V^*_{e 1} + V_{\tau 2}V^*_{e 2} + V_{\tau 3}V^*_{e 3} = 0\\ \triangle_\tau &: \quad V_{e 1}V^*_{\mu 1} + V_{e 2}V^*_{\mu 2} + V_{e 3}V^*_{\mu 3} = 0\end{aligned}$$

Deformed unitarity triangles

$$\begin{aligned}\triangle'_e &: \quad V_{\mu 1}V^*_{\tau 1} + V_{\mu 2}V^*_{\tau 2} + V_{\mu 3}V^*_{\tau 3} \simeq -\mathcal{Z}^*\\ \triangle'_\mu &: \quad V_{\tau 1}V^*_{e 1} + V_{\tau 2}V^*_{e 2} + V_{\tau 3}V^*_{e 3} \simeq -\mathcal{Y}\\ \triangle'_\tau &: \quad V_{e 1}V^*_{\mu 1} + V_{e 2}V^*_{\mu 2} + V_{e 3}V^*_{\mu 3} \simeq -\mathcal{X}^*\end{aligned}$$

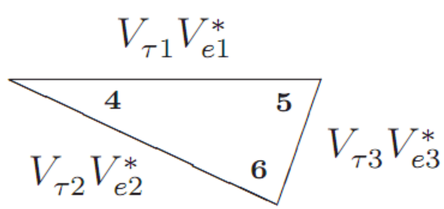


$(\triangle_e)$

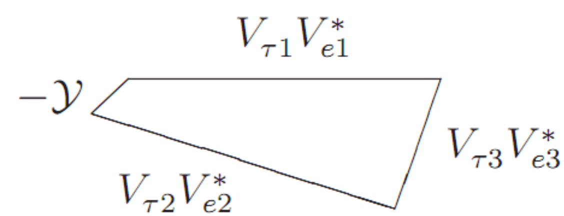


$(\triangle'_e)$

$$\begin{aligned}\mathcal{X} &\equiv \hat{s}_{14}\hat{s}^*_{24} + \hat{s}_{15}\hat{s}^*_{25} + \hat{s}_{16}\hat{s}^*_{26}\\ \mathcal{Y} &\equiv \hat{s}_{14}\hat{s}^*_{34} + \hat{s}_{15}\hat{s}^*_{35} + \hat{s}_{16}\hat{s}^*_{36}\\ \mathcal{Z} &\equiv \hat{s}_{24}\hat{s}^*_{34} + \hat{s}_{25}\hat{s}^*_{35} + \hat{s}_{26}\hat{s}^*_{36}\end{aligned}$$



$(\triangle_\mu)$



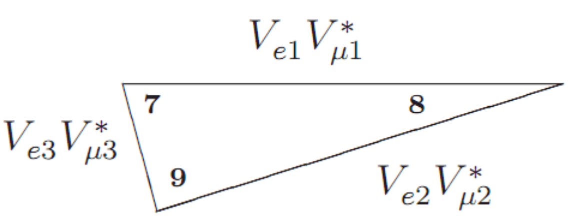
$(\triangle'_\mu)$

New effects

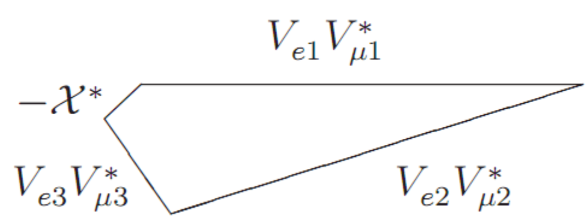
of

CP violation

≤ 1% level



$(\triangle_\tau)$



$(\triangle'_\tau)$

Open Questions

the absolute mass scale?

the mass hierarchy problem?

the flavor desert problem?

how small is θ_{13}? ← answered

leptonic CP violation?

the Majorana nature?

how many species? ...

cosmic ν background?

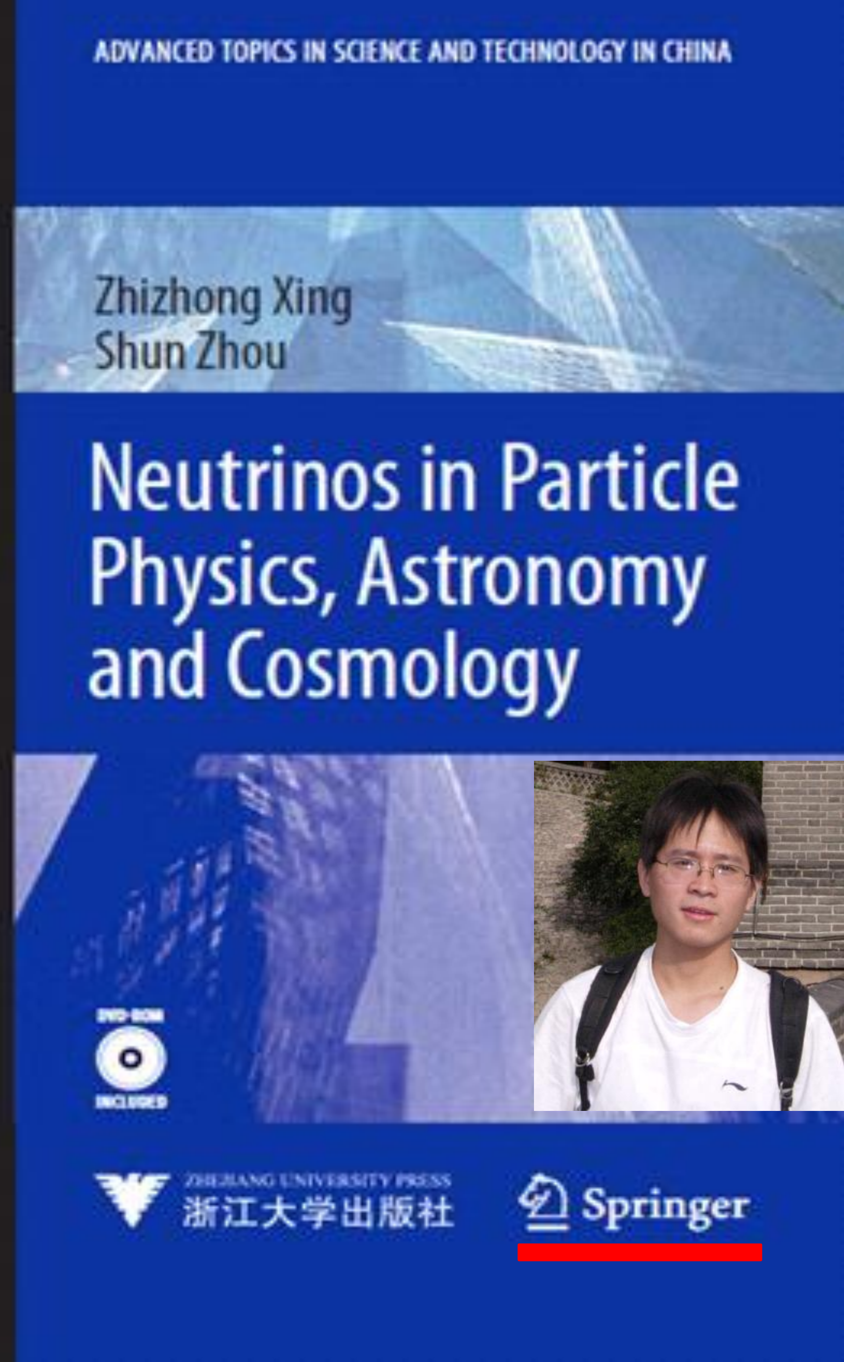
supernova & stellar ν's?

UHE cosmic ν's?

warm dark matter?

matter-antimatter asymmetry

2011 (440 pages)



Cosmic Flavor Physics

CνB
Hot DM

keV ν's
Warm DM

Baryogenesis
Leptogenesis

Energetic ν's
from cold DM

UHE
Cosmic ν's

Supernova ν's
(relic background)

……

A New Road Ahead?

Reference

CPC(HEP & NP), 2012, **36**(4): 281–297 Chinese Physics C Vol. 36, No. 4, Apr., 2012

arXiv:1203.1672

Implications of the Daya Bay observation of θ_{13} on the leptonic flavor mixing structure and CP violation *

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Abstract: The Daya Bay collaboration has recently reported its first $\overline{\nu}_e \rightarrow \overline{\nu}_e$ oscillation result which points to $\theta_{13} \simeq 8.8^\circ \pm 0.8^\circ$ (best-fit $\pm 1\sigma$ range) or $\theta_{13} \neq 0^\circ$ at the 5.2σ level. The fact that this smallest neutrino mixing angle is not strongly suppressed motivates us to look into the underlying structure of lepton flavor mixing and CP violation. Two phenomenological strategies are outlined: (1) the lepton flavor mixing matrix U consists of a constant leading term U_0 and a small perturbation term ΔU; and (2) the mixing angles of U are associated with the lepton mass ratios. Some typical patterns of U_0 are reexamined by constraining their respective perturbations with current experimental data. We illustrate a few possible ways to minimally correct U_0 in order to fit the observed values of three mixing angles. We point out that the structure of U may exhibit an approximate μ-τ permutation symmetry in modulus, and reiterate the geometrical description of CP violation in terms of the leptonic unitarity triangles. The salient features of nine distinct parametrizations of U are summarized, and its Wolfenstein-like expansion is presented by taking U_0 to be the democratic mixing pattern.

I Wish You Another Fairy Tale

VVV 传奇

只是因为在人群中多看了你一眼
再也没能忘掉你的容颜
梦想着偶然能有一天再相见
从此我开始孤单地思念
想你时你在天边
想你时你在眼前
想你时你在脑海
想你时你在心田
宁愿相信我们前世有约
今生的爱情故事不会再改变
宁愿用这一生等你发现
我一直在你身旁
从未走远……