Neutrinos: Yesterday and Tomorrow

——解读2015年度诺贝尔物理学奖——

ν

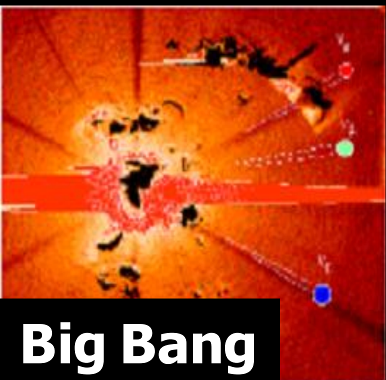
邢志忠

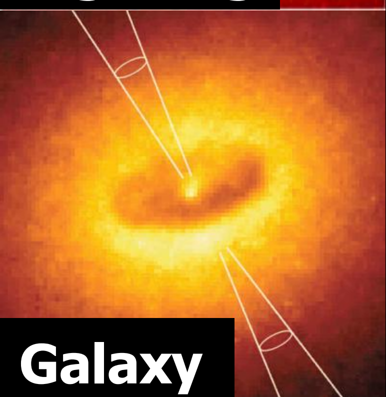
中科院高能所、国科大近物系

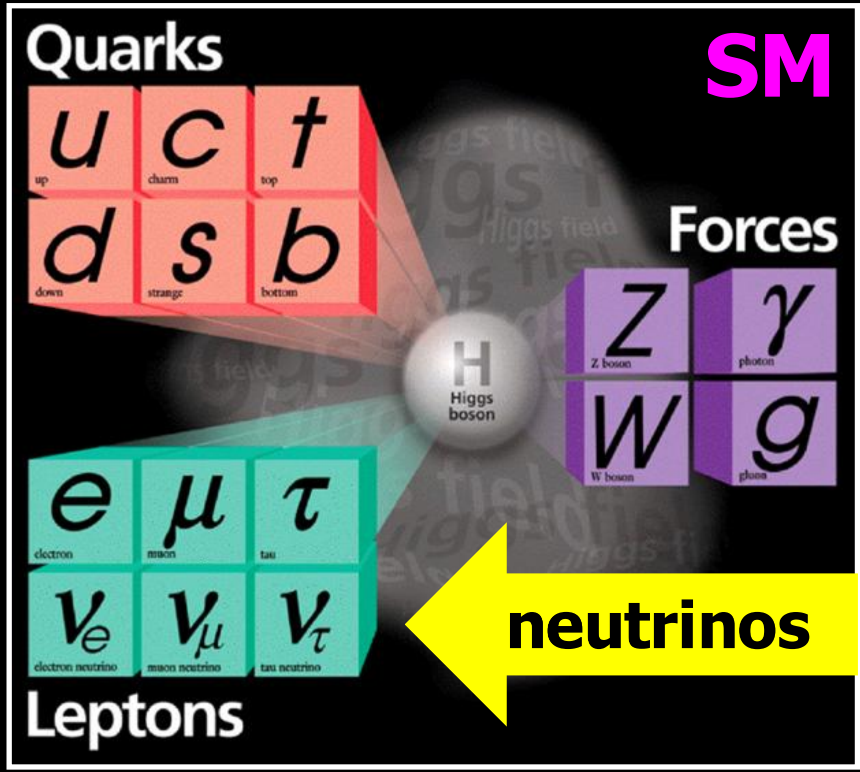
- ★ 引言：历史是需要被见证的
- ★ 发现大气中微子振荡：两个好学生
- ★ 破解太阳中微子失踪之谜：前后人都乘凉
- ★ 展望：中微子还有多少火烧眉毛的问题亟待解决

——北京大学物理学院，2015年10月28日下午3点——

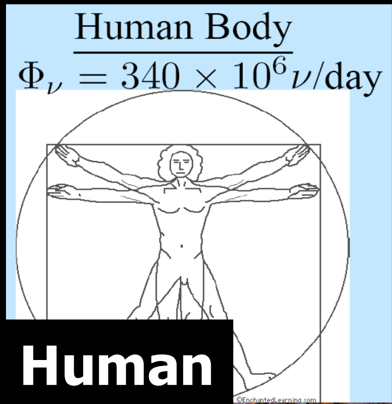
中微子：宇宙空间无所不在的幽灵粒子!

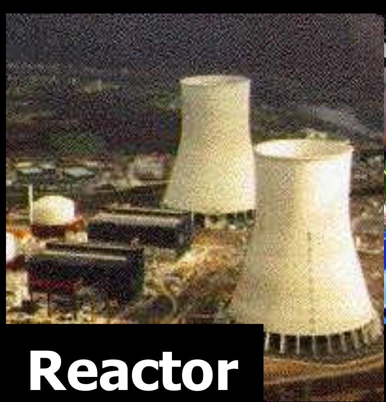




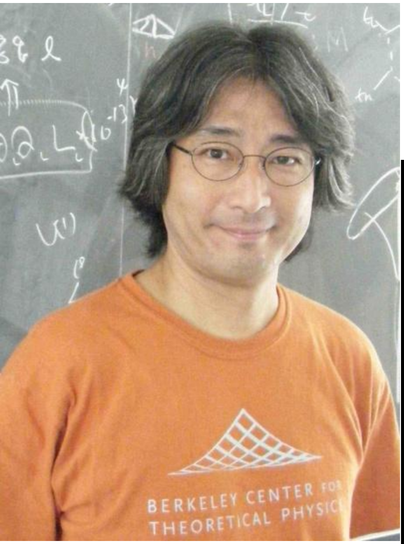


charge = 0
spin = ½
mass = 0
speed = c





上世纪90年代初



Hitoshi Murayama: Director of the Kavli Institute for the Physics and Mathematics of the Universe

Typical Theorists' View 1990

- Solar neutrino solution *must* be small angle MSW solution because it's cute — Most likely wrong!
- Natural scale for $\Delta m^2_{23} \sim 10\text{–}100\ \mathrm{eV}^2$ because it is cosmologically interesting — *Wrong!*
- Angle θ_{23} must be of the order of V_{cb} — *Wrong!*
- Atmospheric neutrino anomaly must go away because it needs a large angle — *Wrong!*

LP01 Hitoshi Murayama 6

Hitoshi's typical arguments

1995年9月

Motivated by an idea about quark flavor mixing, Harald Fritzsch and I invented an unprecedentedly untypical pattern of lepton flavor mixing

H. Fritzsch, Z.Z. Xing, hep-ph/9509389, Phys. Lett. B 372 (1996) 265

$$M_l = \frac{c_l}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \Delta M_l$$

$$M_\nu = c_\nu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \Delta M_\nu$$

symmetry breaking

$$\Delta M_l = \frac{c_l}{3}\begin{pmatrix} -i\delta_l & 0 & 0 \\ 0 & i\delta_l & 0 \\ 0 & 0 & \varepsilon_l \end{pmatrix}$$

$$\Delta M_\nu = c_\nu \begin{pmatrix} -\delta_\nu & 0 & 0 \\ 0 & \delta_\nu & 0 \\ 0 & 0 & \varepsilon_\nu \end{pmatrix}$$

For the first time, lepton flavor mixing with 2 large + 1 small angles:

$$U \approx \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & \frac{-2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} + i\sqrt{\frac{m_e}{m_\mu}} \begin{pmatrix} \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & \frac{-2}{\sqrt{6}} \\ \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 \end{pmatrix} + \frac{m_\mu}{m_\tau} \begin{pmatrix} 0 & 0 & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} \\ \frac{-1}{\sqrt{12}} & \frac{-1}{\sqrt{12}} & \frac{1}{\sqrt{3}} \end{pmatrix}$$

Our predictions:

$$\theta_{12} \simeq 42^\circ \,, \quad \theta_{23} \simeq 52^\circ \,, \quad \theta_{13} \simeq 4^\circ \,, \quad \delta \simeq \pm 90^\circ$$

1998年6月

Y. Suzuki
June 4

Solar ν's

Atmospheric ν's

T. Kajita
June 5

"Modest" Conclusions

(1) Flux: $\phi^{8B} = 2.44 \pm 0.05 (stat.) ^{+0.09}_{-0.07} (syst.) \times 10^6 / cm^2/s$
(0.368 for BP95, 0.474 for BP98)

(2) No seasonal variations.

(3) $(D-N)/(D+N) = -0.023 \pm 0.020 (stat) \pm 0.014 (syst)$
no difference:
excluded regions
extended into "small angle sol
No core enhancement found.

(4) Day-Night + E-shape analysis.
(a) "No oscillation" is disfavoured @ 1~5% C.L.
(b) L.A. solution is disfavoured @ 1~5% C.L.
(c) V.O. regions are favoured (than MSW regions) @ 95% C.L.
(MSW is ok for 99% C.L.)

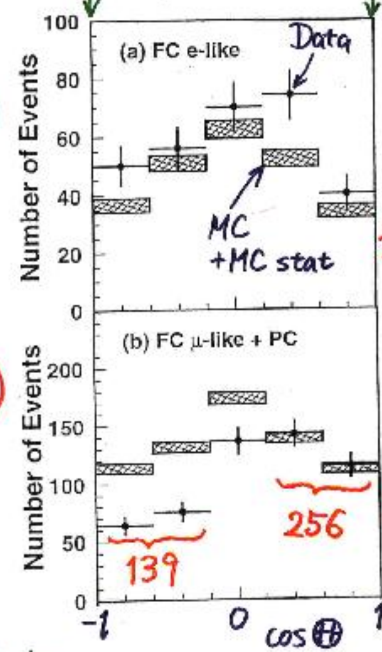
Super-K

Neutrino98
TAKAYAMA

Yes,
2 large
angles!

于是得以见
证这段历史

Zenith angle dependence
(Multi-GeV)



e: χ^2(shape) = 2.8/4 dof
Up/Down = $0.93^{+0.13}_{-0.12}$

μ: χ^2(shape) = 30/4 dof
Up/Down = $0.54^{+0.06}_{-0.05}$
(6.2σ!!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background …. < 2%) 2.1%

克林顿的感慨

REMARKS BY THE PRESIDENT
AT MIT 1998 COMMENCEMENT
June 5, 1998

Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.

This discovery was made, in Japan, yes, but it had the support of the investment of the U.S. Department of Energy. This discovery calls into question the decision made in Washington a couple of years ago to disband the super-conducting supercollider, and it reaffirms the importance of the work now being done at the Fermi National Acceleration Facility in Illinois.

The larger issue is that these kinds of findings have implications that are not limited to the laboratory. They affect the whole of society --- not only our economy, but our very view of life, our understanding of our relations with others, and our place in time....

追溯1962年6月

日本粒子物理研究的传承能力令人惊叹，值得学习

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

(Received June 25, 1962)

A particle mixture theory of neutrino is proposed assuming the existence of two kinds of neutrinos. Based on the neutrino-mixture theory, a possible unified model of elementary

$$\nu_1 = \nu_e \cos\delta + \nu_\mu \sin\delta,$$

$$\nu_2 = -\nu_e \sin\delta + \nu_\mu \cos\delta.$$

Bruno Pontecorvo conjectured $\nu \leftrightarrow$ anti-ν transition in 1957.

梶田隆章在北京 INSS2013 暑期学校上授课解惑

照片版权人：陈丽

2015年10月6日，诺贝尔物理学奖授予梶田隆章和亚瑟·麦克唐纳

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我的祝贺邮件

Congratulations from China

发件人：XING Zhizhong <xingzz@ihep.ac.cn>
时　间：2015年10月06日 20:11:07 (星期二)
收件人：kajita@icrr.u-tokyo.ac.jp

状态: 发送成功 [查看详情]

Dear Kajita san,

Congratulations to you! You deserve the Nobel Prize!
This is the greatest news i have received this year.

i have just written a blog paper in Chinese to introduce you and your work. Another formal paper for a popular science journal is under preparation.

All the best,
Zhi-zhong

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博文

科学网

解读诺贝尔物理学奖：少了一个人？ 精选

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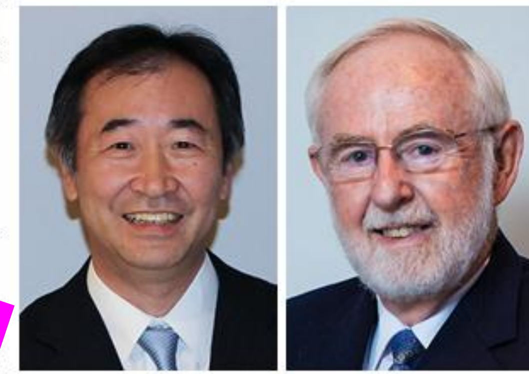
• 学术会议的主席台：是闹着玩
• 已知的未知：美国防长与物理
• 研究生与本科生（一）：智商
• 阿兰说："You got me!"

作者的其他最新博文 全部
• 屠呦呦教授在诺贝尔颁奖典礼
• 诺贝尔颁奖晚宴上的精彩致词

解读今年的诺贝尔物理学奖

2015 年的诺贝尔物理学奖授予了在超级神冈（简记为 SK）实验中发现了大气中微子振荡现象的日本物理学家梶田隆章（Takaaki Kajita）和在萨德伯里中微子观测站（简记为 SNO）破解了太阳中微子失踪之谜的加拿大物理学家亚瑟·麦克唐纳（Arthur B. McDonald）。这一结果既在情理之中，又在意料之外。一方面，这两个实验开启了中微子物理学的黄金时代，以令人信服的方式表明中微子具有极小的质量和较大的混合效应，相应的主要贡献者理应获奖；另[illegible]，几位相关的候选[illegible]落选、[illegible]态归于[illegible]内的期盼声也[illegible]时梶田和麦克唐纳教授却[illegible]获了名至实归的惊喜。



科学世界

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梶田的回复

Re: Congratulations from China

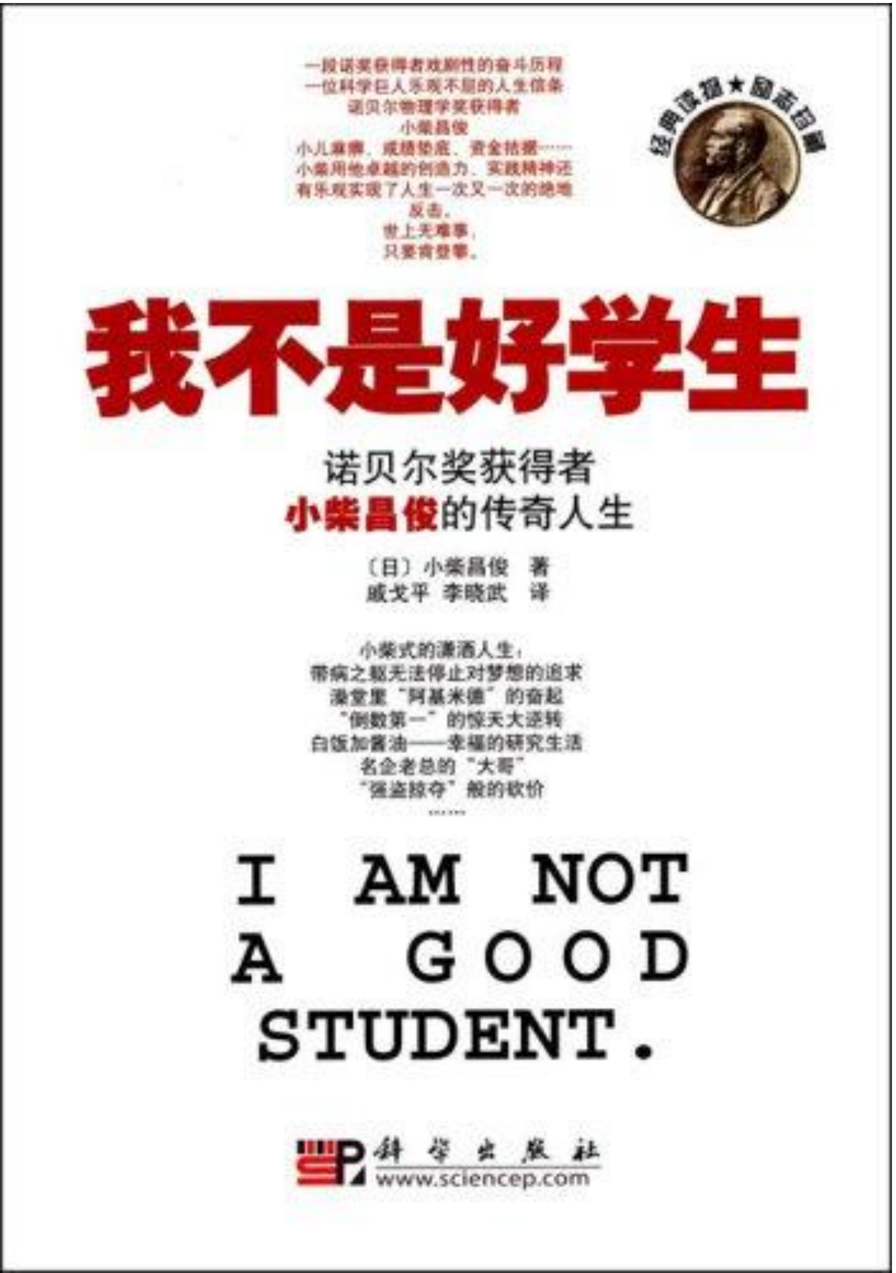
发件人：kajita@icrr.u-tokyo.ac.jp
时　间：2015年10月08日 22:13:37 (星期四)
收件人：XING Zhizhong <xingzz@ihep.ac.cn>

Dear Zhi-zhong,

Thank you very, very much for the warm message!

Best regards,
Takaaki Kajita

可你是好老师呀



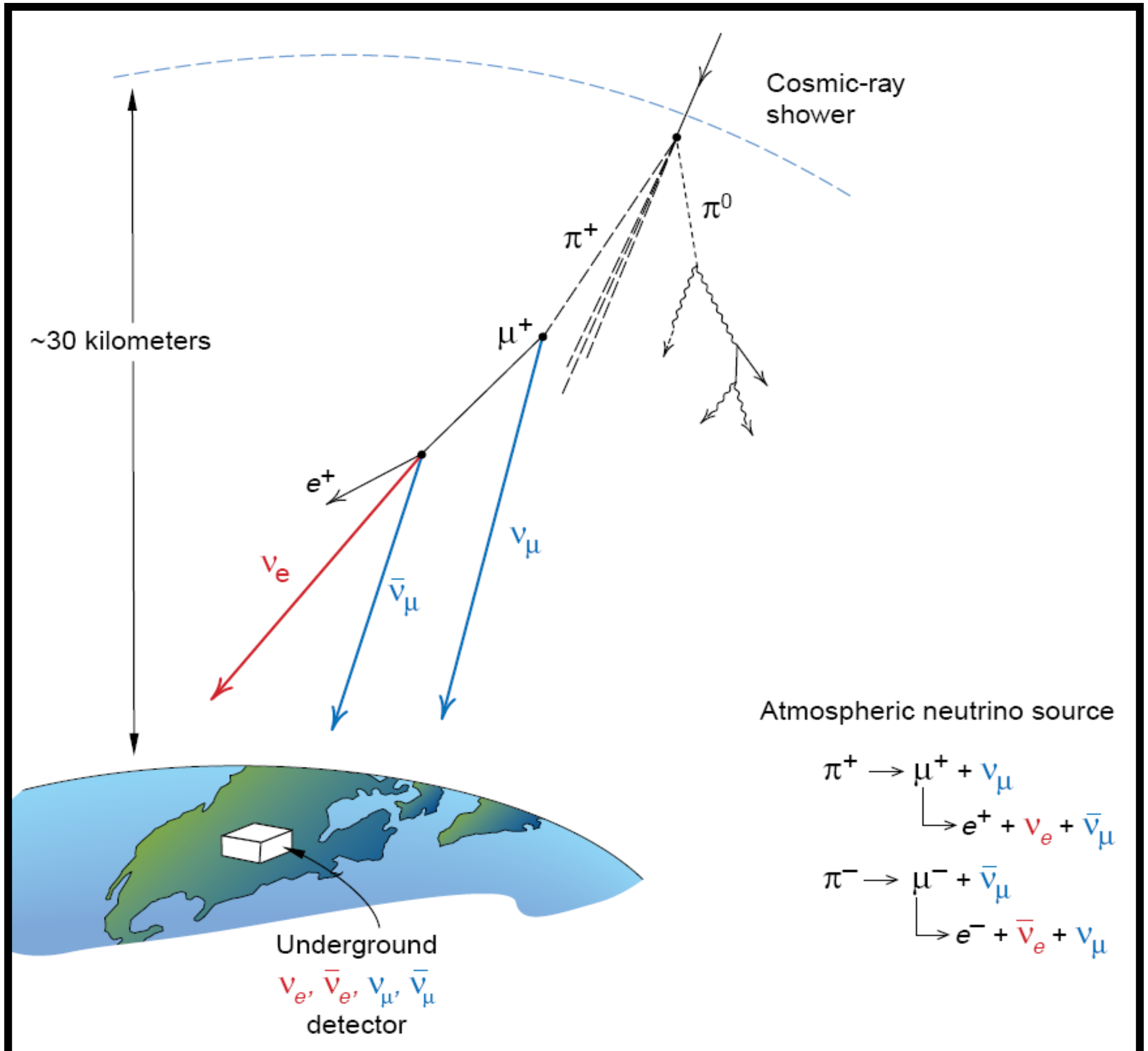
小柴昌俊

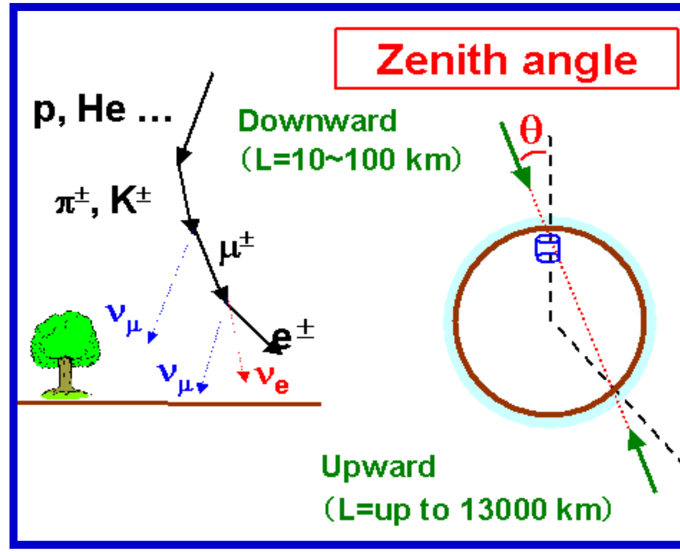
Yoji Totsuka
（户塚洋二）
1942/03/06
2008/07/10

Takaaki Kajita
（梶田隆章）
1959/03/09

1998年：大气中微子

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

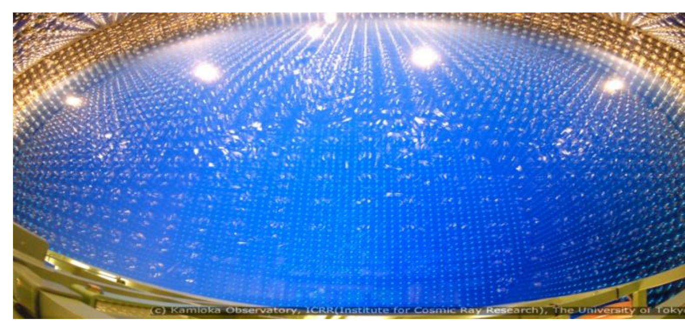




$$\nu_\alpha + N \to l_\alpha^- + X$$

$$\overline{\nu}_\alpha + N \to l_\alpha^+ + X$$

SK水契仑柯夫探测器



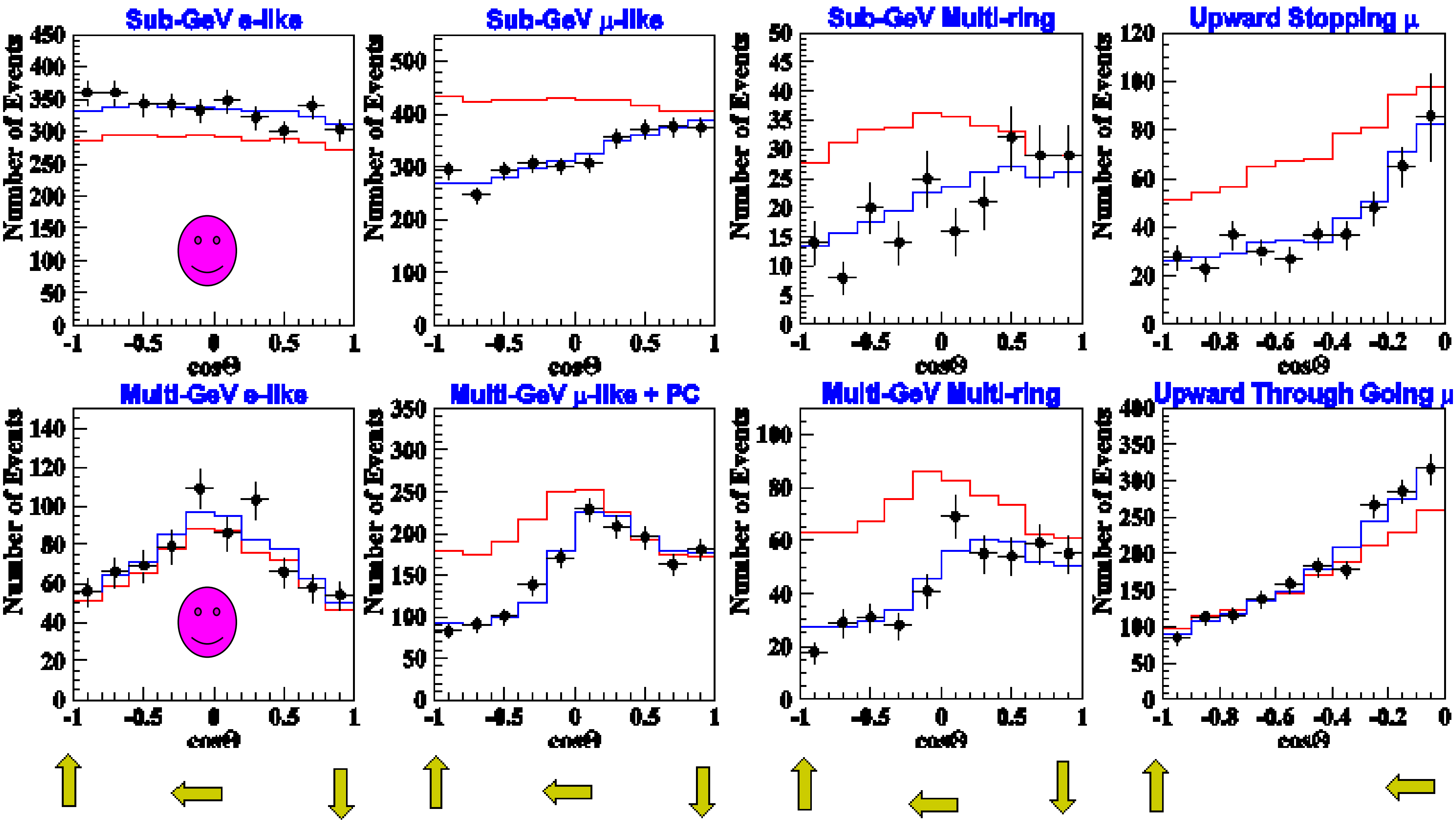
Zenith angle distributions

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

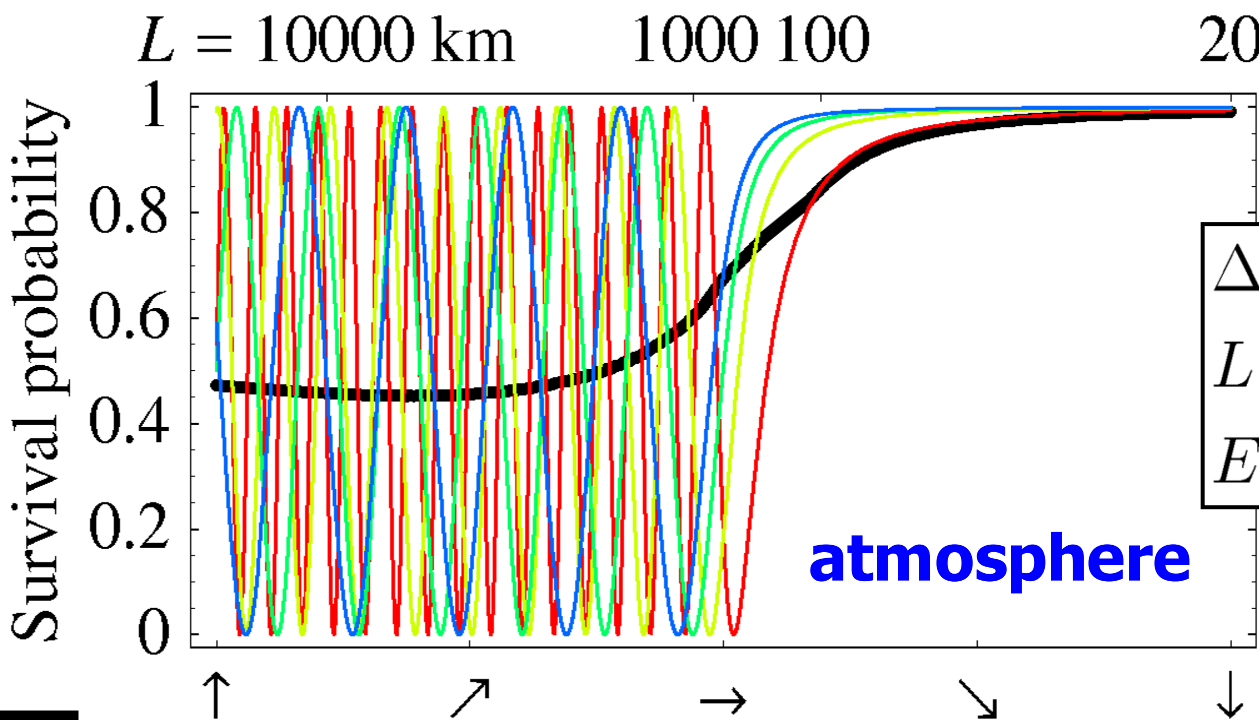


~13000km ~500km ~15km

~13000km ~500km

最简单的解：中微子振荡

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\frac{\Delta m^2_{32} L}{E}\right)$$



$\Delta m^2_{32} \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$

L in unit of km

$E \sim \mathcal{O}(1)$ GeV

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

中微子混合

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

曹则贤的比喻：妇联、工会、团委纠缠态

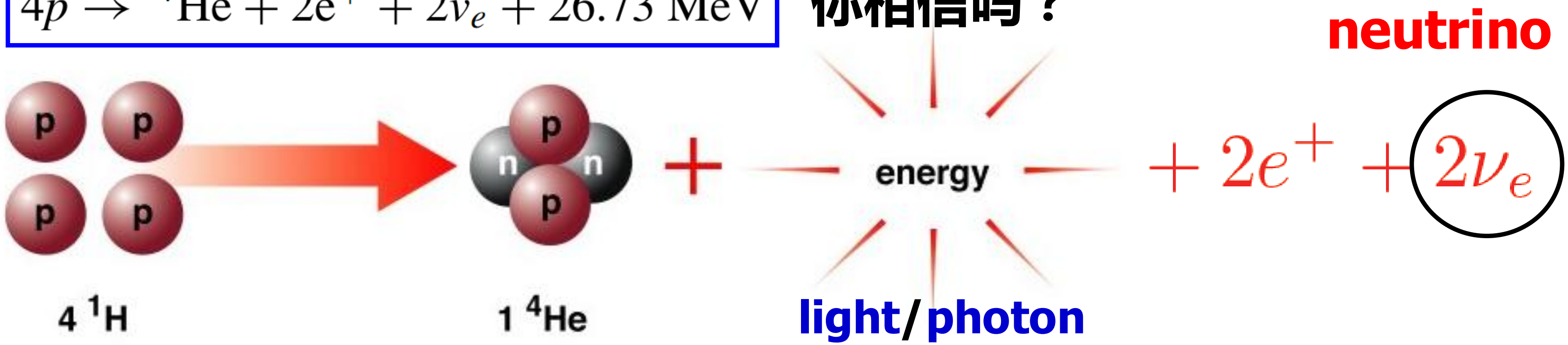
中微子振荡

一种中微子在空间传播一定距离后转化为另外一种类型。前提是中微子有质量且及味混合效应。

1968年：太阳中微子失踪之谜

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

你相信吗？



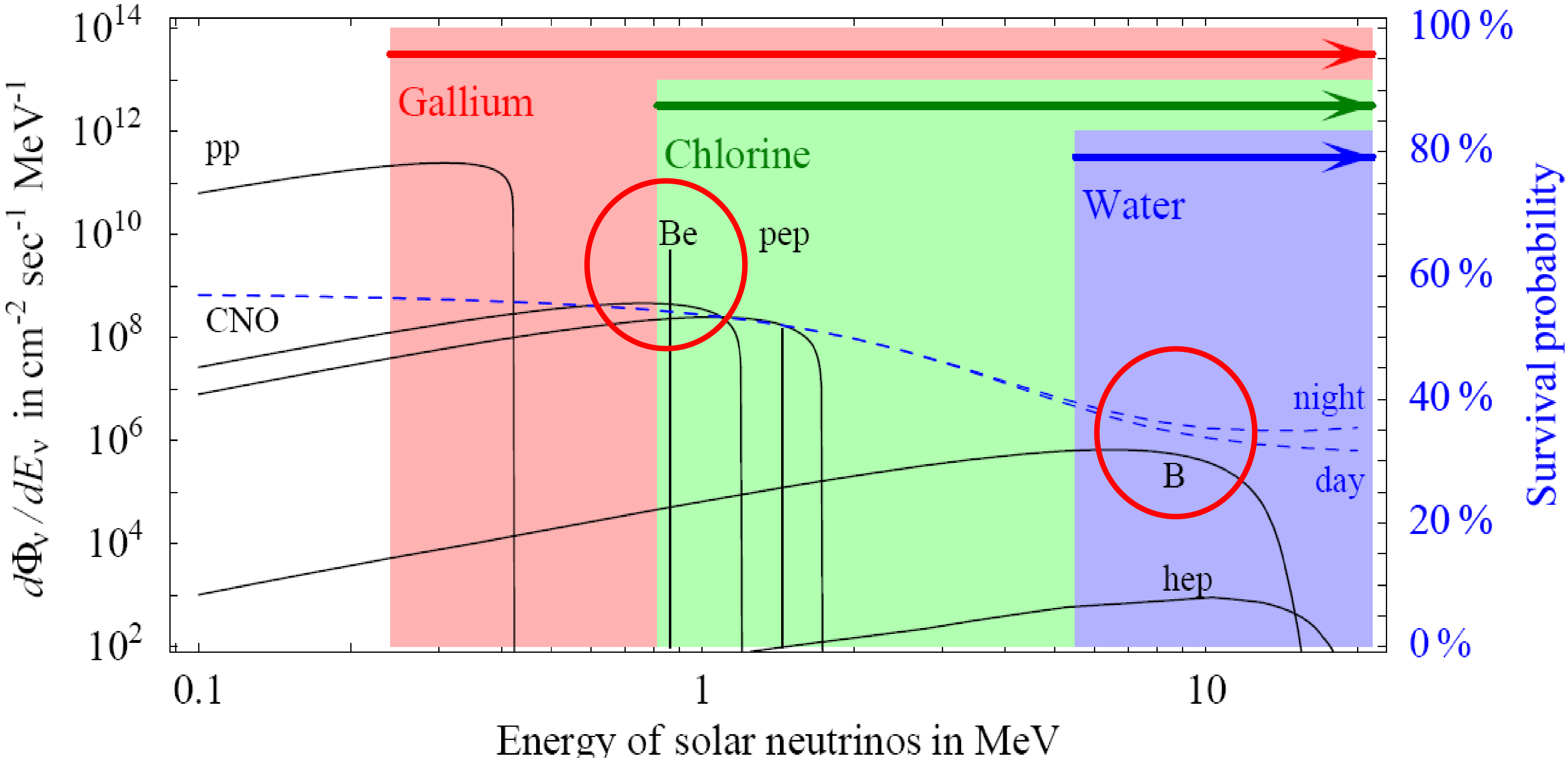
Hans Bethe (1939), George Gamow & Mario Schoenberg (1940, 1941)

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!

太阳中微子能谱

R. Davis observed a solar neutrino deficit, compared with J. Bahcall's prediction for the ν-flux, at the Homestake Mine in 1968.



Strumia & Vissani, hep-ph/0606054.

DATA

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

物质效应

In the 2-flavor approximation, solar neutrinos are governed by

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

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

$7.6 \times 10^{-5}\ \mathrm{eV}^2$

$0.75 \times 10^{-5}\ \mathrm{eV}^2$ / MeV (at $r = 0$)

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

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

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

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

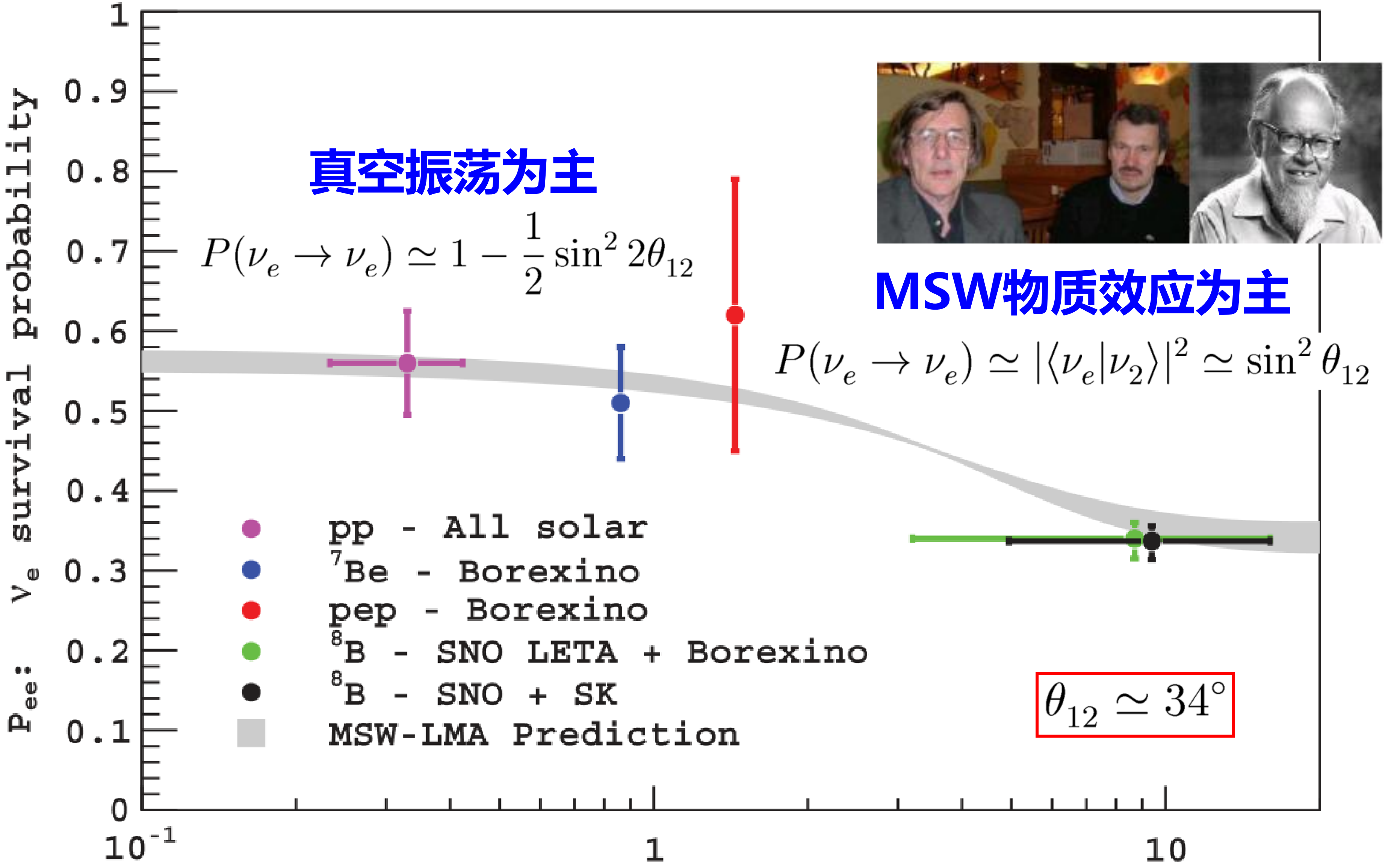
$$\Delta \tilde{m}^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - 2\sqrt{2}\, G_{\mathrm{F}} N_e E\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

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

MSW

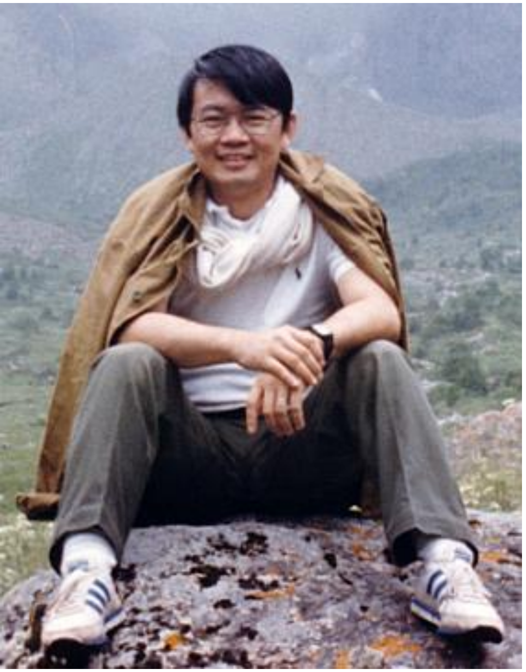
resonance → $\tilde{\theta} = 45^\circ$

太阳中微子振荡



Beryllium ν's ~ 56% **Boron ν's ~ 32%**

测量太阳中微子的新想法



陈华森：1942年3月16日出生于重庆，1987年11月7日因白血病去世。1984年SNO合作组成立之初，陈担任美方发言人……

1964年
加州理工学士

1968年
普林斯顿博士

$$\text{CC:}\quad \nu_e + d \to p + p + e^-$$

$$\text{NC:}\quad \nu_\alpha + d \to p + n + \nu_\alpha$$

$$\text{ES:}\quad \nu_\alpha + e^- \to \nu_\alpha + e^-$$

以重水作为探测媒介，一石三鸟

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

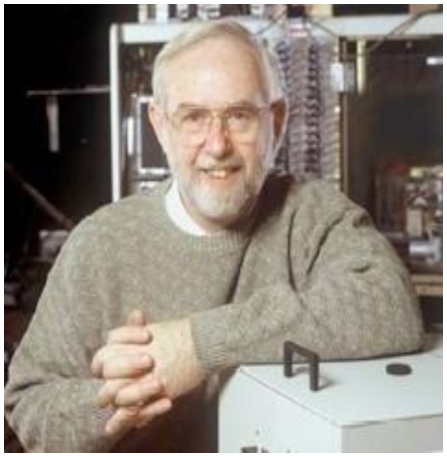
Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \to \nu + p + n$ and the charged-current reaction $\nu_e + d \to e^- + p + p$, is suggested for this purpose.

2001年：SNO实验

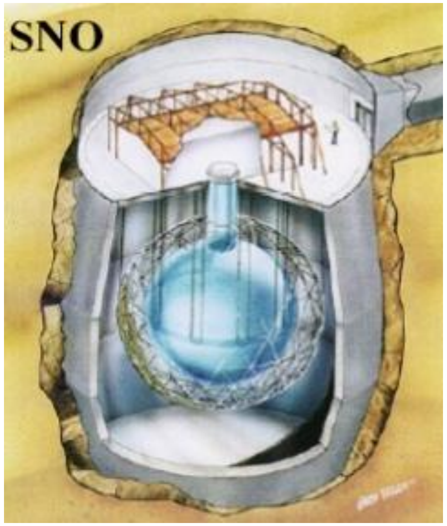
The heavy water Cherenkov detector at SNO confirmed the solar neutrino flavor conversion (A.B. McDonald 2001)



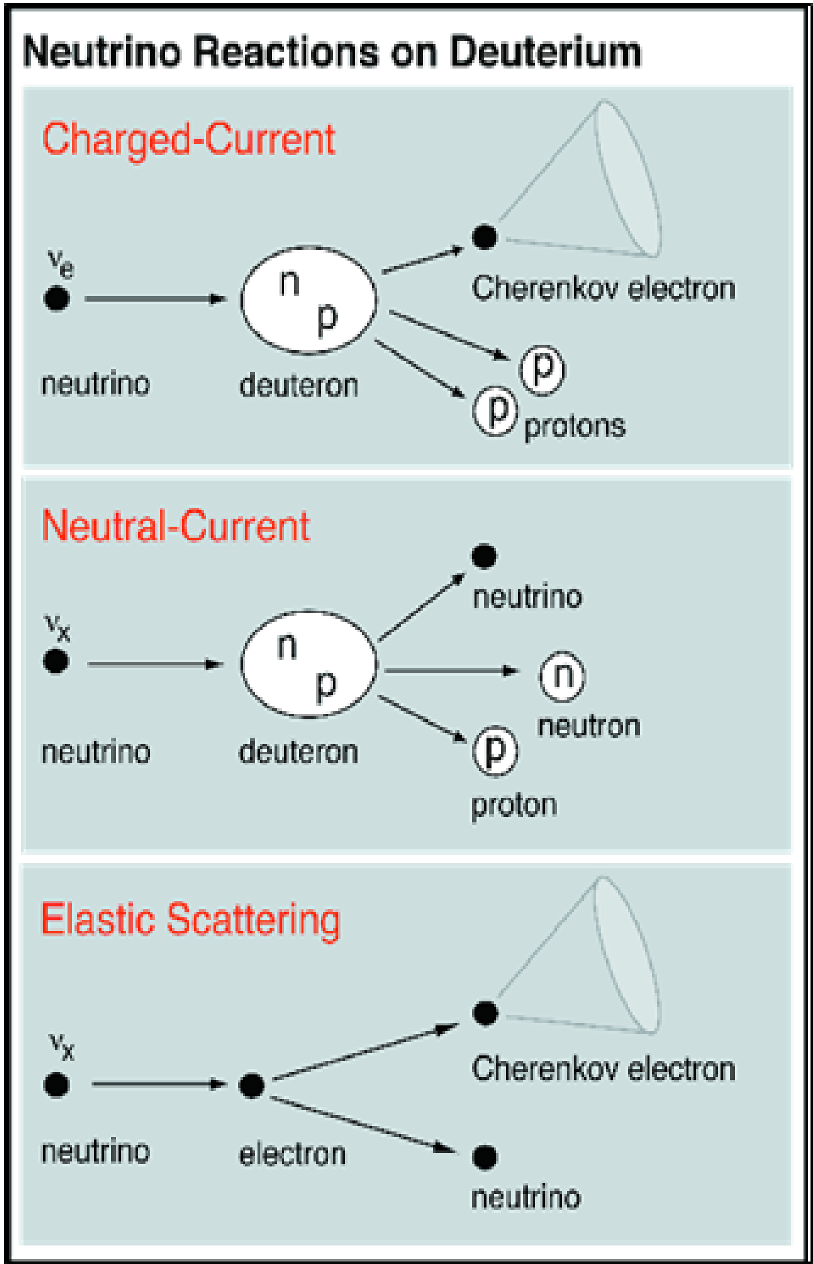
The Salient features:

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.

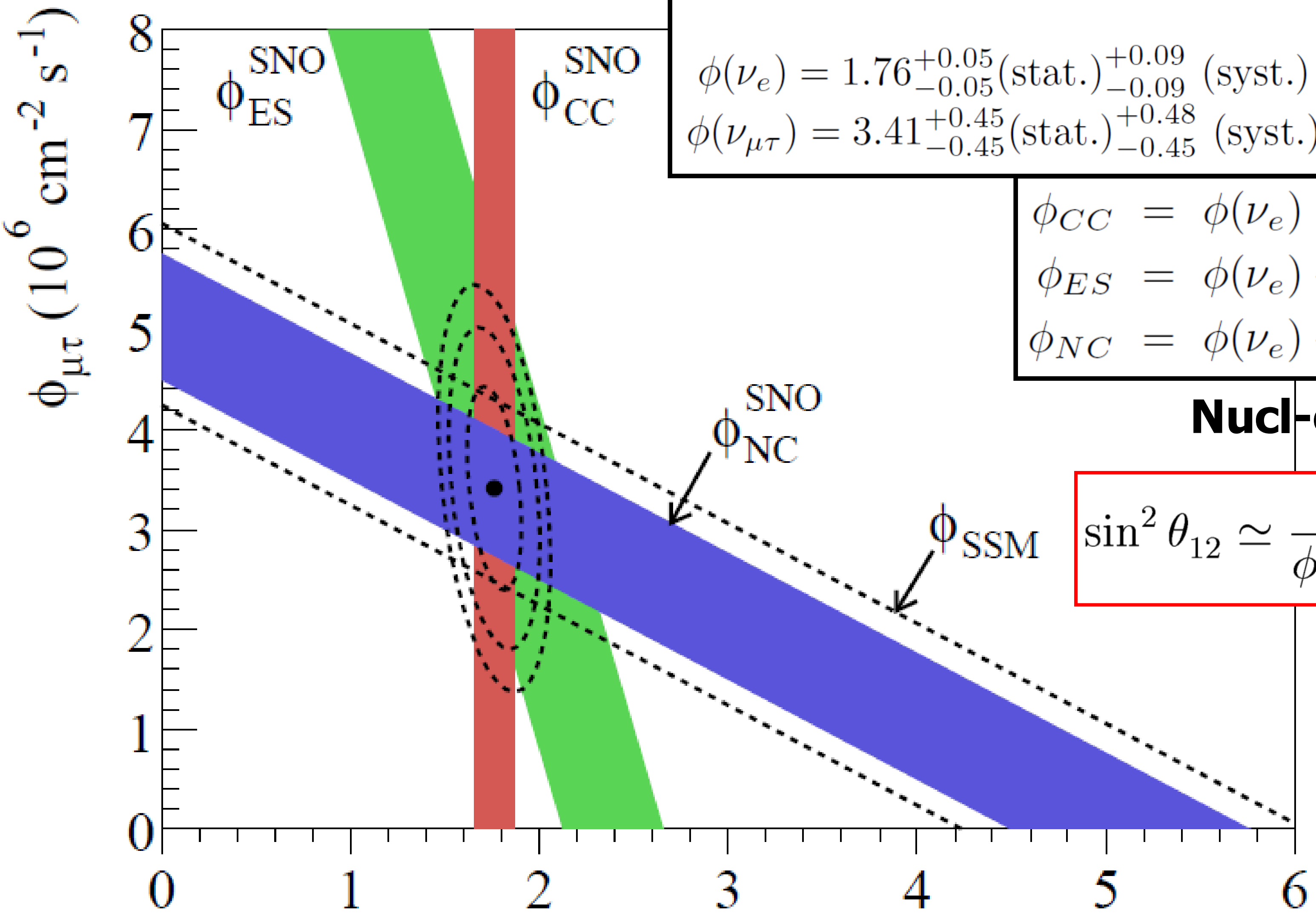


SNO实验结果

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

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

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



Nucl-ex/0610020

$$\sin^2\theta_{12} \simeq \frac{\phi_e}{\phi_e + \phi_{\mu\tau}} \simeq 34\%$$

J. Bahcall

Solar electron neutrinos convert to muon and tau neutrinos!

2002年：SNO的后果

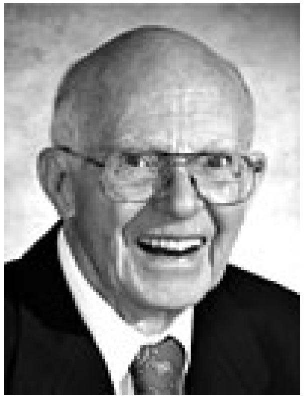
The Nobel Prize in Physics 2002

"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"

54-88-92

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.**

幸运之星

反应堆实验后来居上

2002年12月：铃木厚人带领KamLAND合作组成功发现了长基线反应堆反中微子振荡，挑选了太阳中微子振荡的MSW大角解。

2012年03月：王贻芳和陆锦标带领大亚湾合作组成功发现了较短基线反应堆反中微子振荡，首次测定了最小中微子混合角。

这期间，加速器实验以及其他若干实验也对确认中微子振荡功不可没

契柯夫的枪

户塚洋二不幸于2008年7月因病去世，有人在2009年修改了Murayama模型的自由参数，做了新预测:

没有他？

2015：已知与未知

We've learnt a lot from ν oscillations:

$$\Delta m^2_{21}\ ,\ \left|\Delta m^2_{31}\right|\ ,\ \theta_{12}\ ,\ \theta_{13}\ ,\ \theta_{23}$$

It's more exciting that the SM is incomplete, although the Higgs has been discovered.

But a number of burning questions:

- ♣ **the Majorana nature?**
- ♣ **the absolute ν mass scale?**
- ♣ **the ν mass hierarchy?**
- ♣ **the octant of θ_{23}?**
- ♣ **the Dirac phase δ?**
- ♣ **the Majorana phases?**
- ♣ **the sterile neutrino species?**

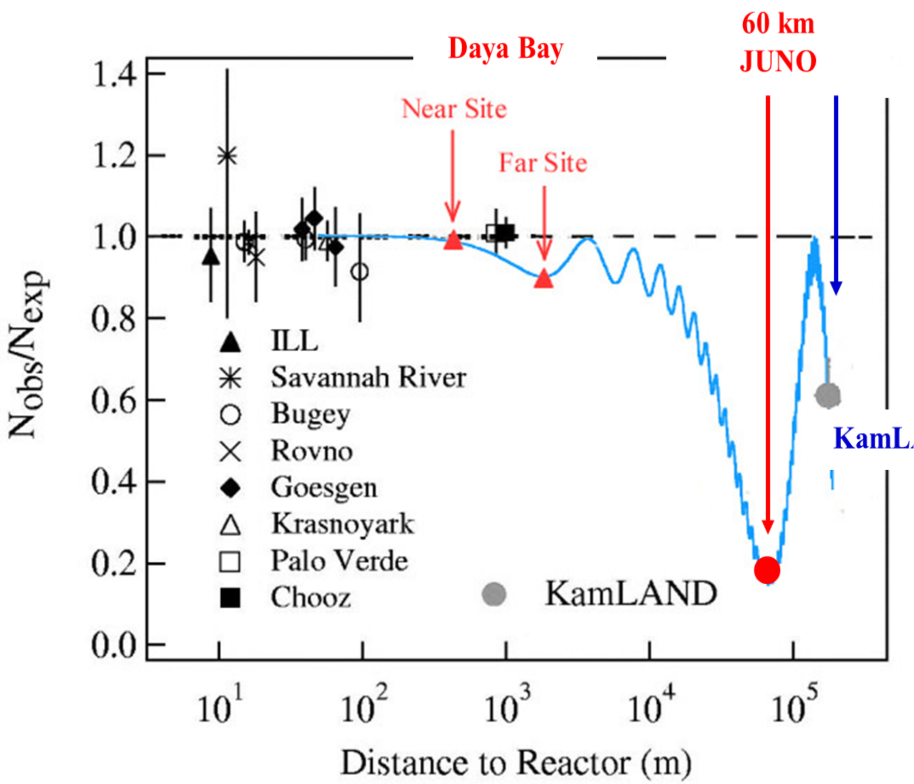
举例：江门实验原理

Accelerator/atmospheric: terrestrial matter effects play crucial roles.

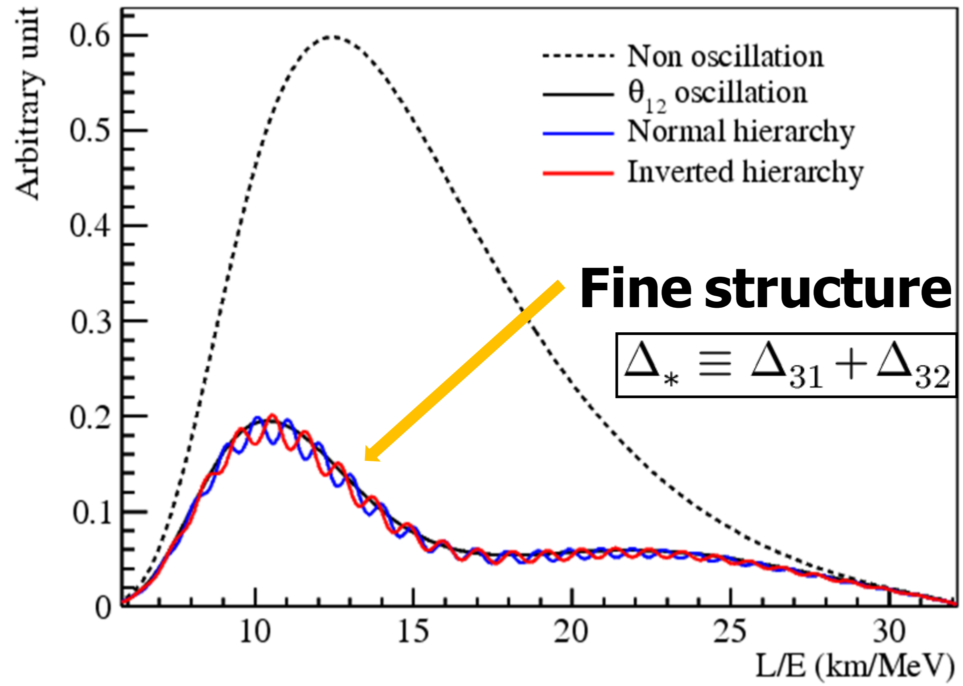
$$\Delta m^2_{31} \mp 2\sqrt{2} G_F N_e E$$

θ_{23} **its octant matters a lot**

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



JUNO's idea $\Delta_{ji} \equiv \Delta m^2_{ji} L/(4E)$



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

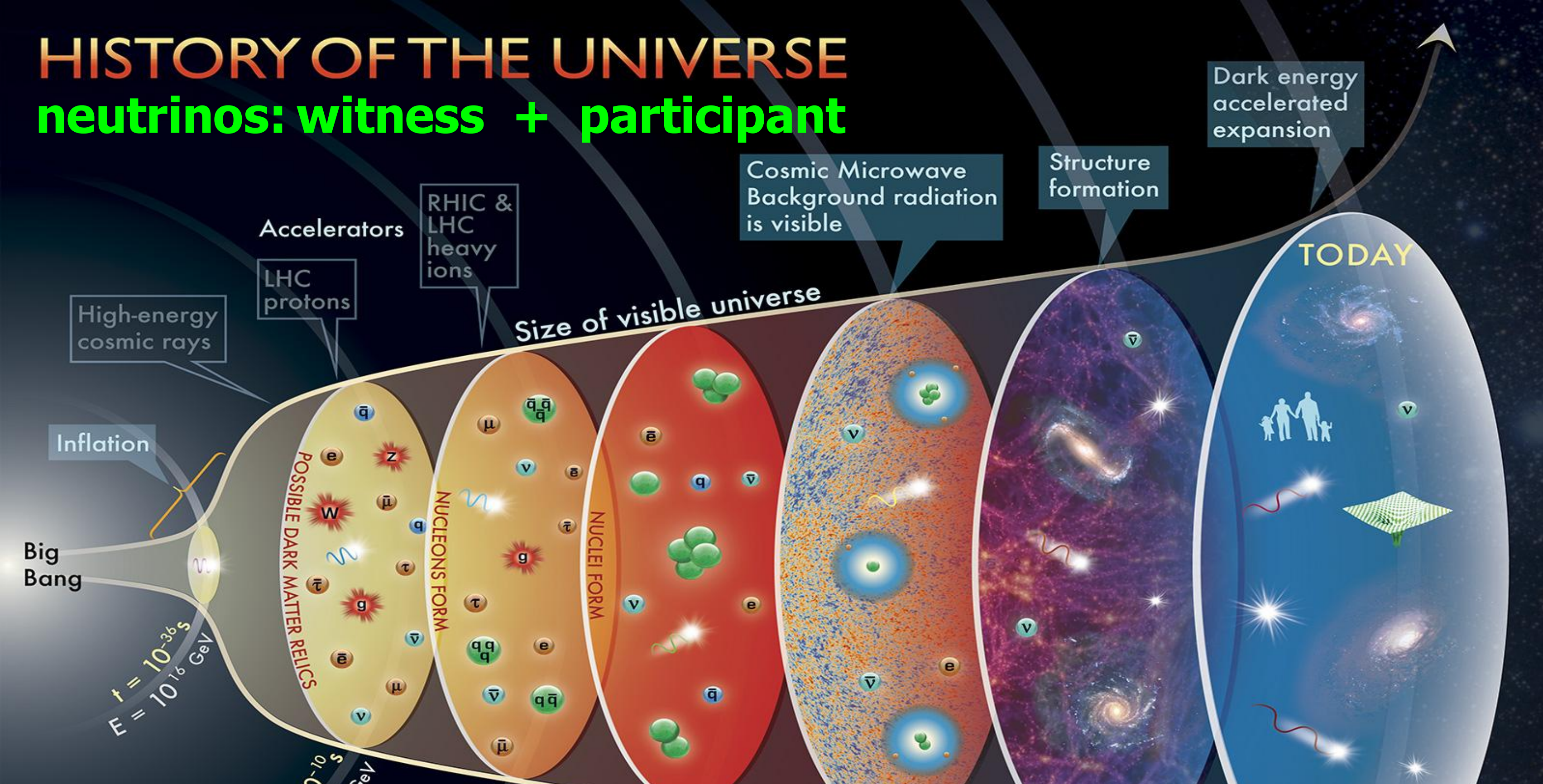
举例：江门实验现场

	Daya Bay	Yangjiang	Taishan
Status	running	construction	construction
Power/GW	17.4	17.4	18.4

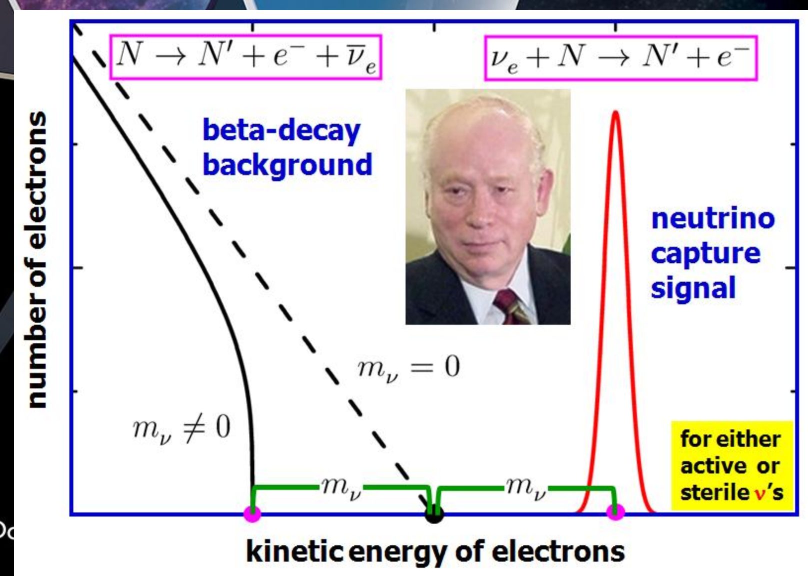
- Idea 2008
- 20 kton LS detector
  3% E-resolution
- Approved 2/2013
- Groundbreaking 1/2015

neutrinos: witness + participant

宇宙背景中微子



ν decoupling



还有，这盘是谁的菜？

理 ν ν ν 论

THANK YOU FOR YOUR ATTENTION