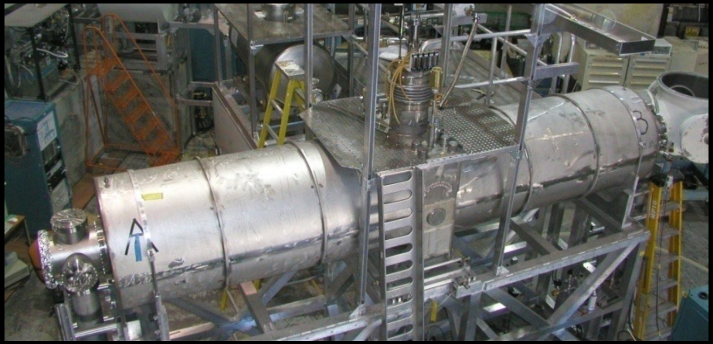
中微子和暗物质实验

刘江来
上海交通大学

G0 experiment at Jefferon Lab

UCNA spectrometer at Los Alamos



PandaX Dark Matter Experiment

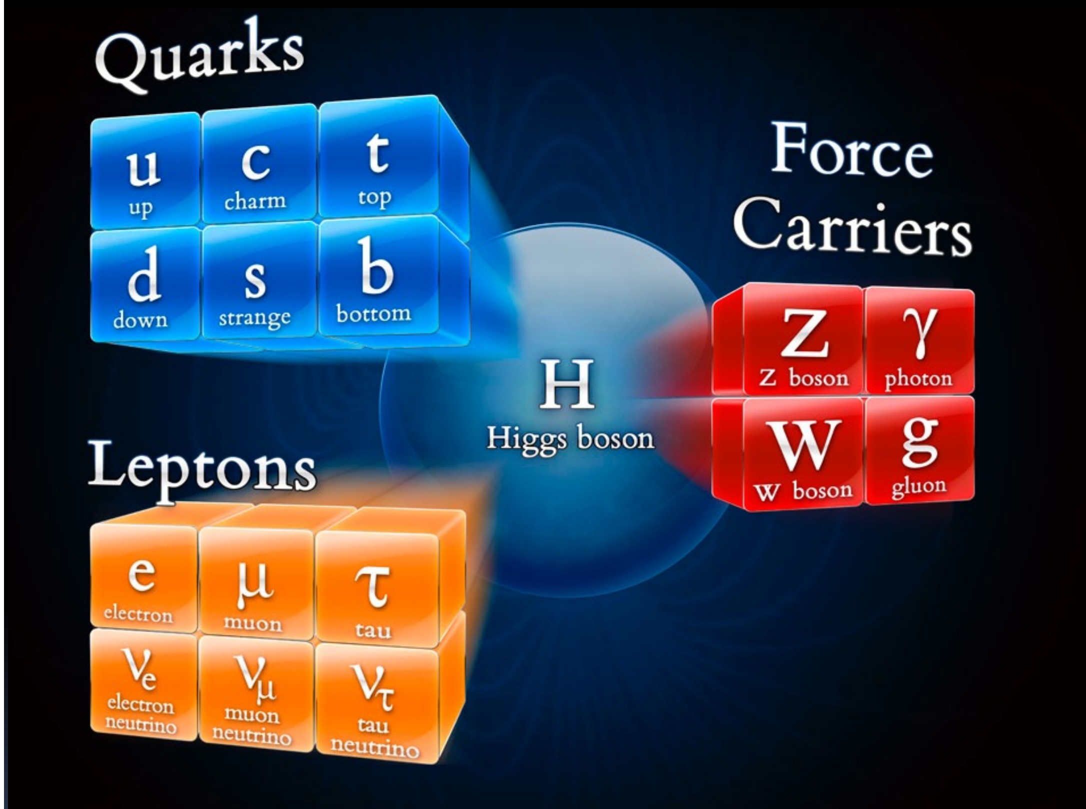
Daya Bay
Reactor
Neutrino
Experiment

报告提纲

- 中微子及弱相互作用
- 中微子振荡
- 从中微子相干散射到暗物质探测
- 最不像中微子实验的中微子实验

1. 中微子以及弱相互作用

粒子物理的元素周期表



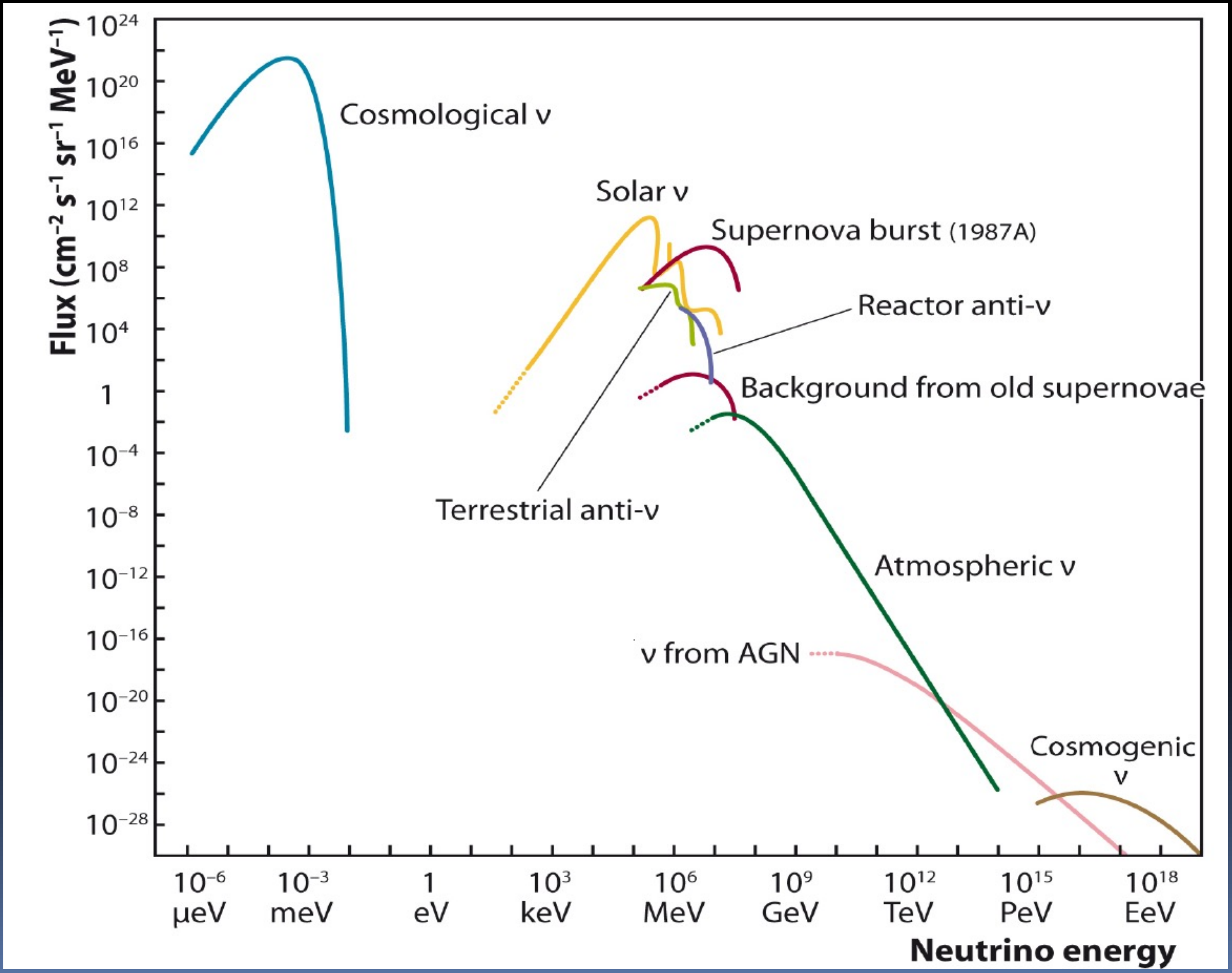
$\nu_e, \bar{\nu}_e; \quad \nu_\mu, \bar{\nu}_\mu; \quad \nu_\tau, \bar{\nu}_\tau$

三种不同种类的中微子

只参与弱相互作用!

"无"质量

无所不在的“幽灵”



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

“幽灵”粒子

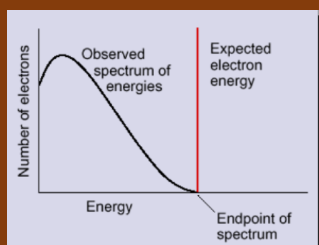
- 宇宙大爆炸的残骸（330个/毫升）
- 弱相互作用：在铅块里的平均作用长度=1光年!
- 比电子轻1百万倍!

宇宙中的信使：

- 早期宇宙的信息（大爆炸中微子）
- 天体中微子（超新星爆发、极高能量中微子、太阳中微子、地球中微子）
- 基本粒子的一种，链接宇宙中正-反物质不对成性

中微子：诺奖宠儿

1930, Pauli postulated light neutral particle to save energy conservation in beta decay



1953-59 Reines and Cowan discovered anti-electron neutrino, Nobel Prize 1995

1960-90 Davis, 小柴昌俊 discovered cosmic neutrino, Nobel Prize 2002

1930 — 1933 — 1953-59 — 1962 — 1960-90 — 1998-2001

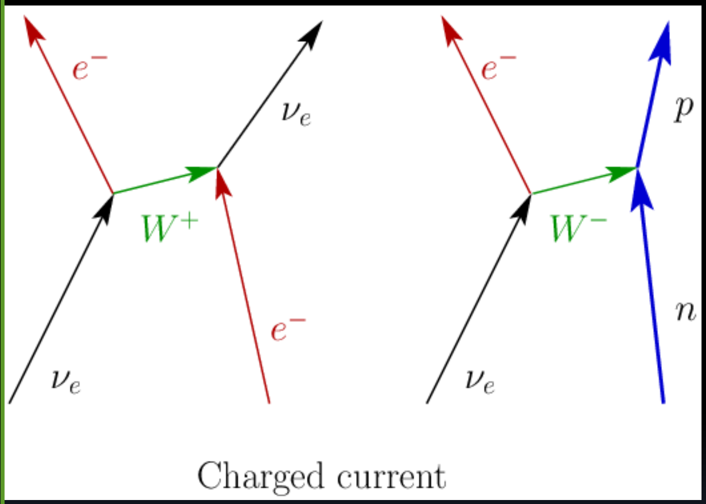
1933, Fermi developed theory of beta decay. Christened light neutral

1962, Lederman, Steinberger, Schwatz discovered muon neutrino, 1988 Nobel Prize

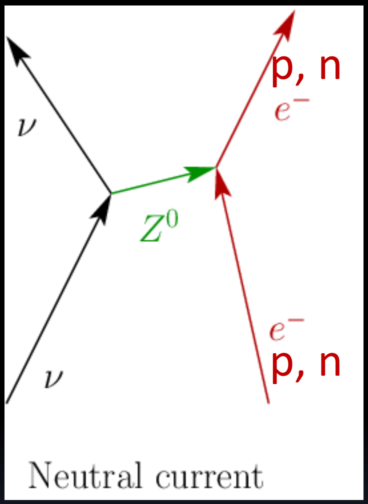
1998-2001,梶田隆章, McDonald discovered neutrino oscillation, 2015 Nobel Prize

中微子的“发明”。泡利和费米因为别的工作获得诺奖。

中微子和物质的相互作用



“电荷流”



“中性流”

第一个测量中微子的方案

间接测量 （王淦昌，1941）

Physical Review 61 (1–2): 97

A Suggestion on the Detection of the Neutrino

KAN CHANG WANG
Department of Physics, National University of Chekiang Tsunyi, Kweichow, China

October 13, 1941

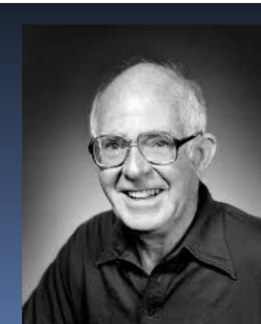
$$Be^7+e_K\rightarrow Li^7+\eta+(1\ \text{Mev})$$

and

$$Be^7+e_K\rightarrow (Li^7)^*+\eta+(0.55\ \text{Mev}),$$
$$(Li^7)^*\rightarrow Li^7+h\nu+0.45\ \text{Mev}.$$

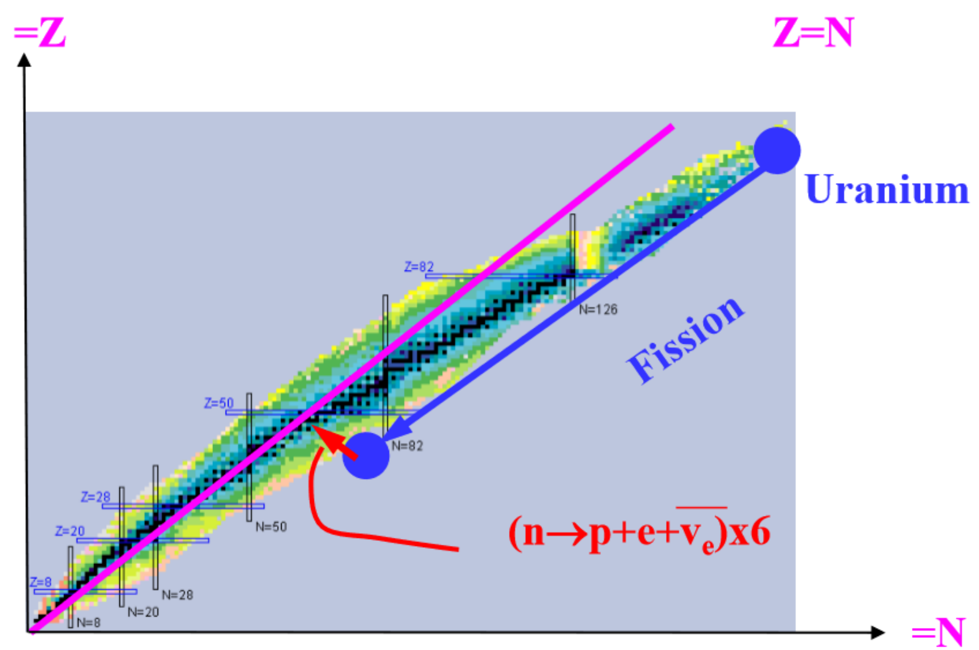
My first successful experiment was a study of the recoil energy of a ^{7}Li nucleus resulting from the electron-capture decay of ^{7}Be. In ^{7}Be decay, a single monoenergetic neutrino is emitted with an energy of 0.862 MeV, and the resulting ^{7}Li nucleus should recoil with a characteristic energy of 57 eV. A measurement of this process provides evidence for the existence of the neutrino. In my experiment, the energy spectrum of a recoiling ^{7}Li ion from a surface deposit of ^{7}Be was measured and found to agree with that expected from the emission of a single neutrino (Davis, 1952). This was a very nice result, but I was scooped by a group from the University of Illinois (Smith and Allen, 1951).

Ray Davis, Nobel lecture



1. 人造中微子源：核裂变

Nuclear Reactors： Source of $\overline{\nu}_e$



1 Fission ⇔ 200 MeV ⇔ 6 $\overline{\nu}_e$

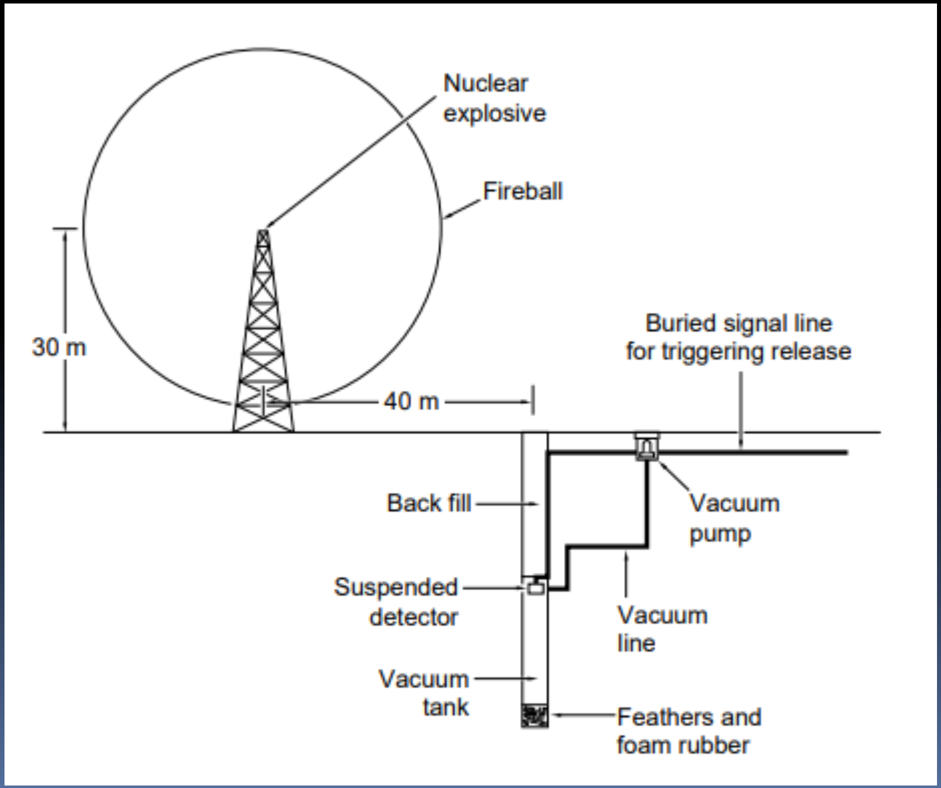
So 1 GWth (typical power reactor) ⇒ 2×10^{20} $\overline{\nu}_e$ /s

测量中微子的方案

2. 直接测量

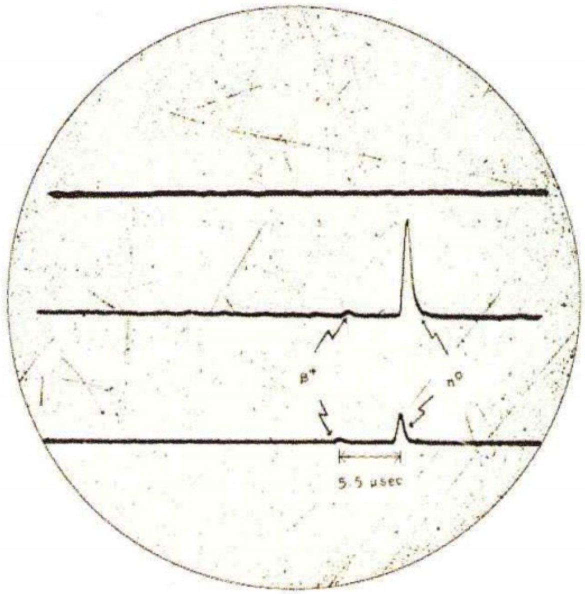
Fred Reines, Cowan

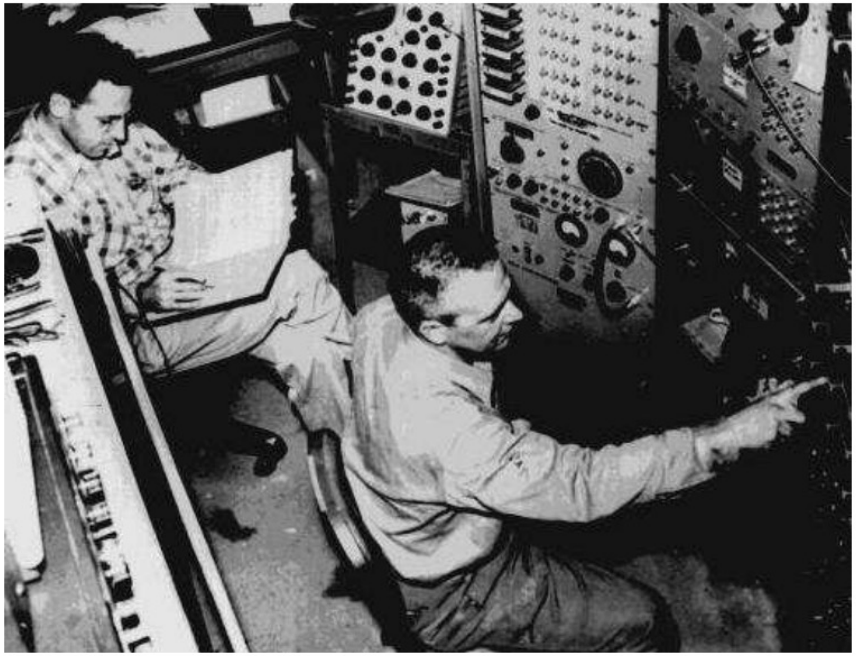
$$\bar{\nu} + p \rightarrow n + e^{+}$$



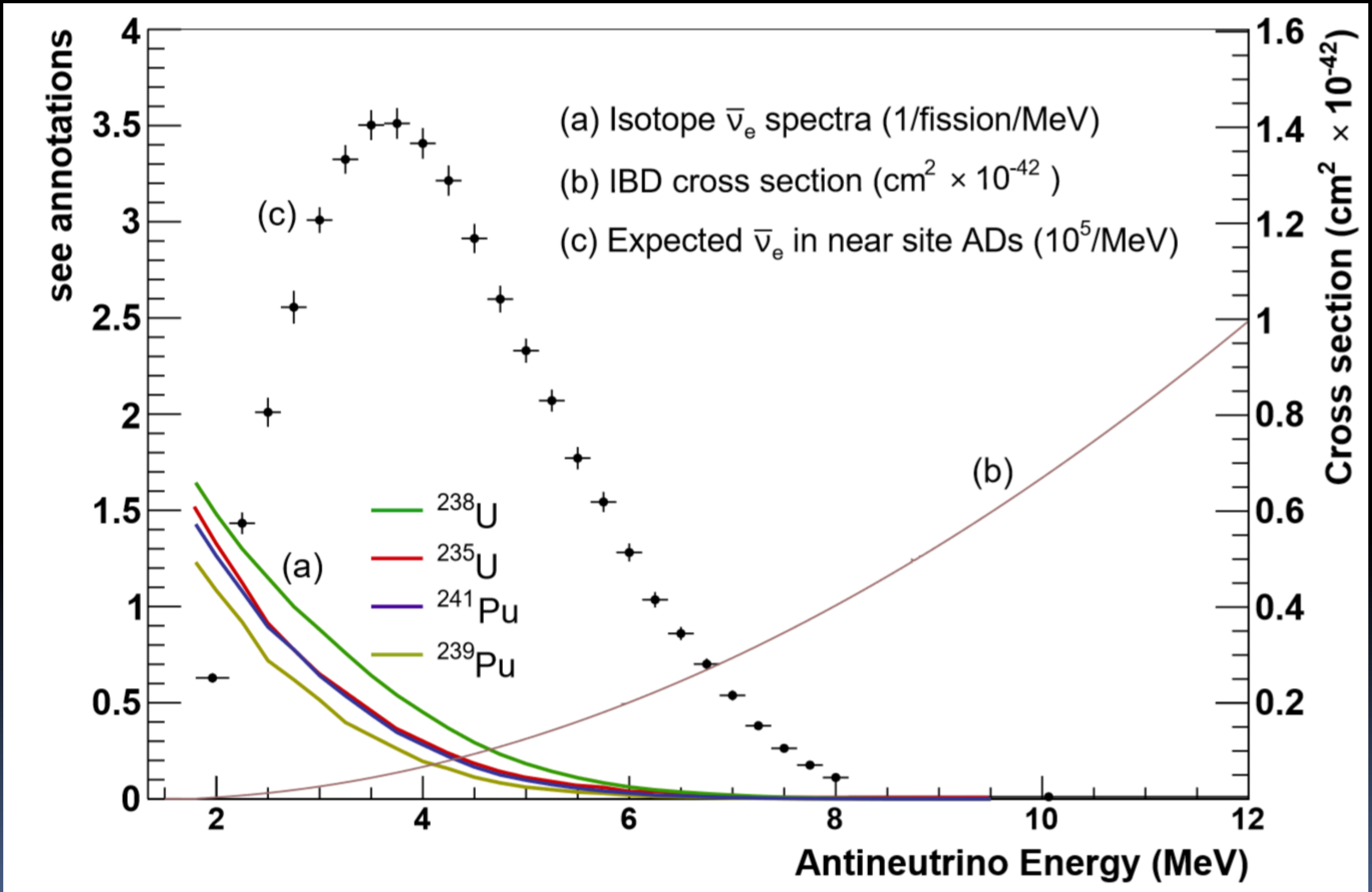
第一个测量核弹爆破产生中微子的proposal!

核反应堆上的发现





逆贝塔衰变散射截面

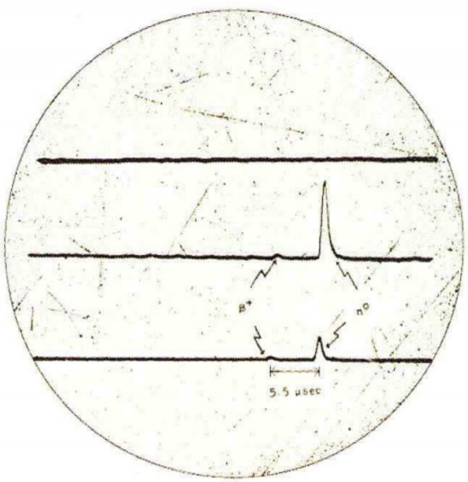


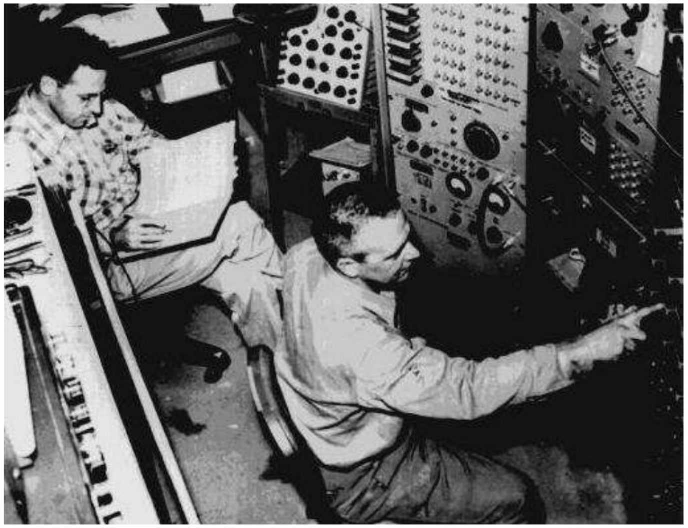
see annotations
Cross section (cm^2 × 10^{-42})
Antineutrino Energy (MeV)
(a) Isotope $\bar{\nu}_e$ spectra (1/fission/MeV)
(b) IBD cross section (cm^2 × 10^{-42})
(c) Expected $\bar{\nu}_e$ in near site ADs (10^5/MeV)
(a)
(b)
(c)
^{238}U
^{235}U
^{241}Pu
^{239}Pu
0
0.5
1
1.5
2
2.5
3
3.5
4
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
2
4
6
8
10
12

1953-1955：中微子的发现

$$\bar{\nu} + p \rightarrow n + e^{+}$$

逆贝塔衰变



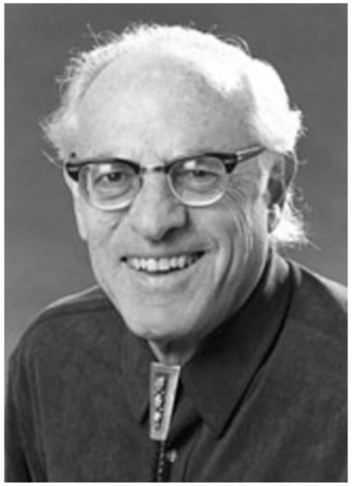


Detection of the Free Neutrino*

F. REINES AND C. L. COWAN, JR.

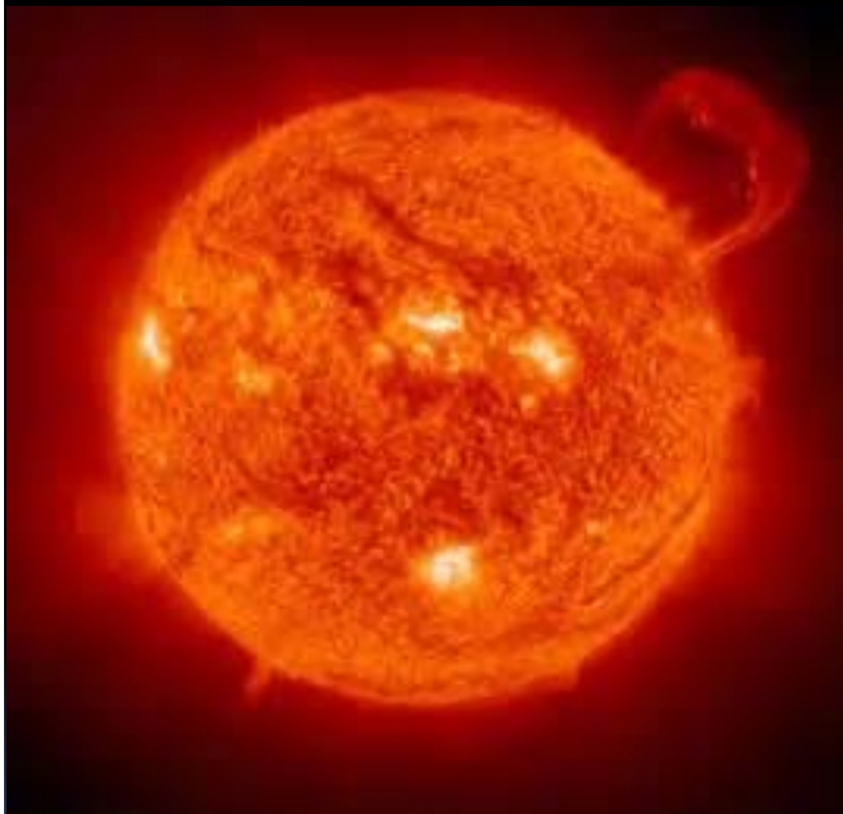
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

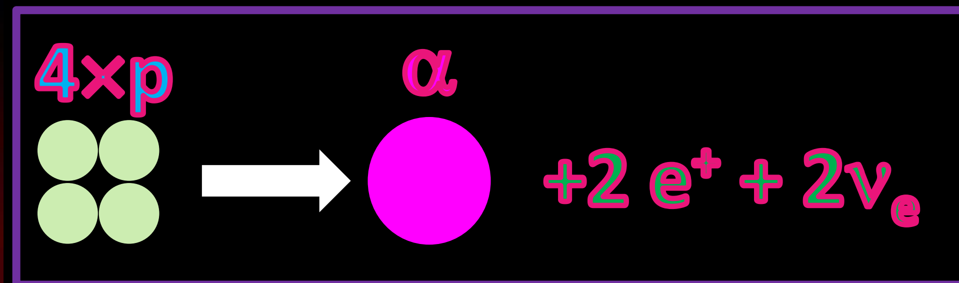
(Received July 9, 1953; revised manuscript received September 14, 1953)

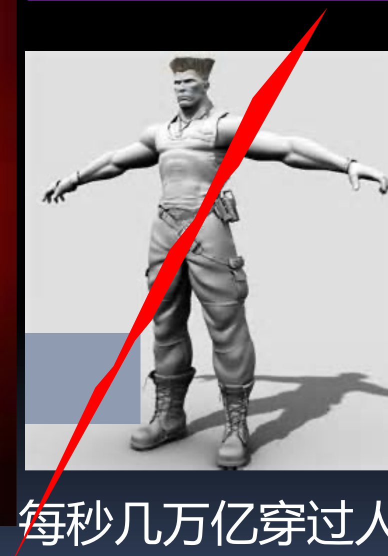


Fred Reines
1995 年诺奖

2. 太阳中微子

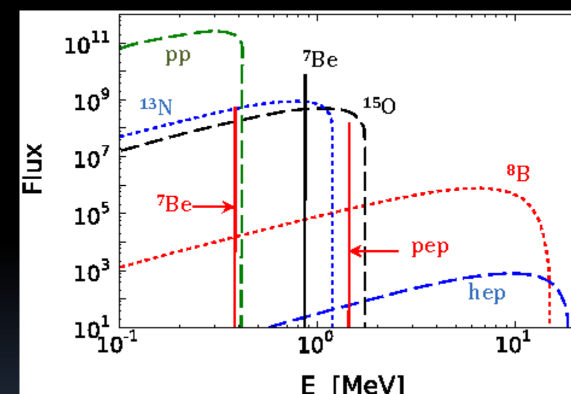






每秒几万亿穿过人体

John Bahcall标准太阳模型



无电荷、“无”质量，仅仅参与“弱”相互作用

捕捉他们需要很大的探测器、很“安静”的实验室

Homestake实验

- 1968-1995, Ray Davis在 Homestake 矿井里探测到了太阳中微子!
- 仅仅是Bahcall理论预言1/3的^{8}B中微子!

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

Homestake实验的implication

到底是理论错了？实验错了？还是都有问题？

30年后我们知道电子中微子变身（“振荡”）了，Davis 2002年获诺奖，他也是深地物理实验的“奠基人”

Herbert Chen’s proposal

陈华森， 加州大学欧文分校
1942-1987

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

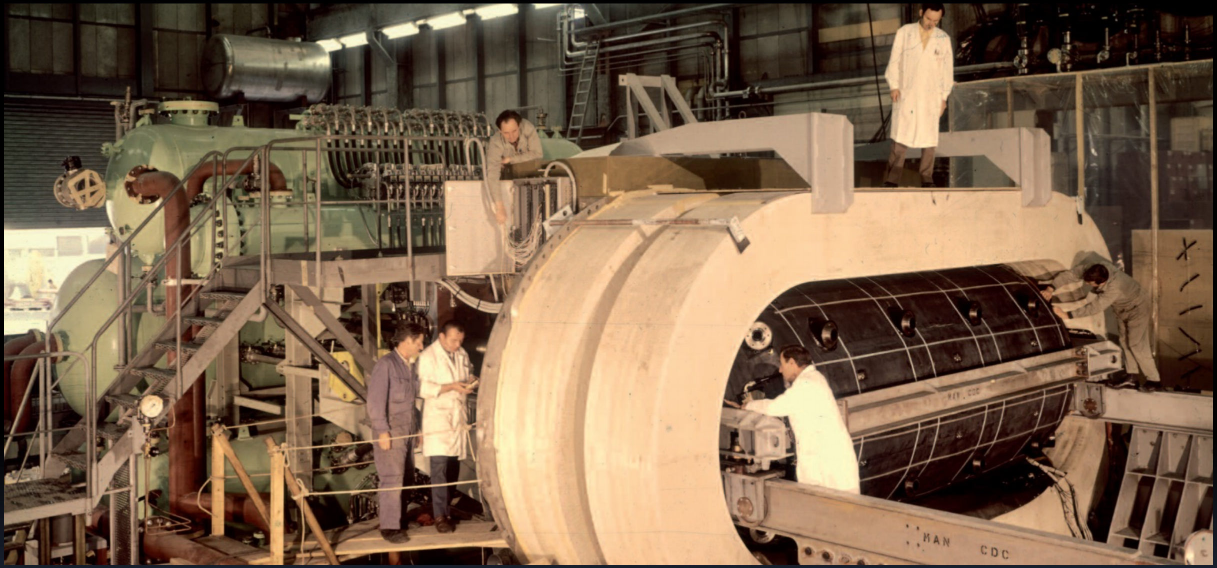
Direct Approach to Resolve the Solar-Neutrino Problem

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 $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

扯闲篇：中性流的发现 Gargamelle @ CERN (late 60’s to 70’s)



12 m^3 heavy-liquid Freon bubble chamber CF_3Br.

Bubble chamber

- The bubble chamber, invented by Donald Glaser in 1952, consists of a tank of unstable (superheated) transparent liquid
- Sensitive to the passage of charged particles $\Rightarrow$ boiling as a result of the energy they deposit by ionizing the atoms along the track

First leptonic NC events

360000 pictures scanned
Isolated forward e observed
at Aachen Dec 1972.
Interpretation:

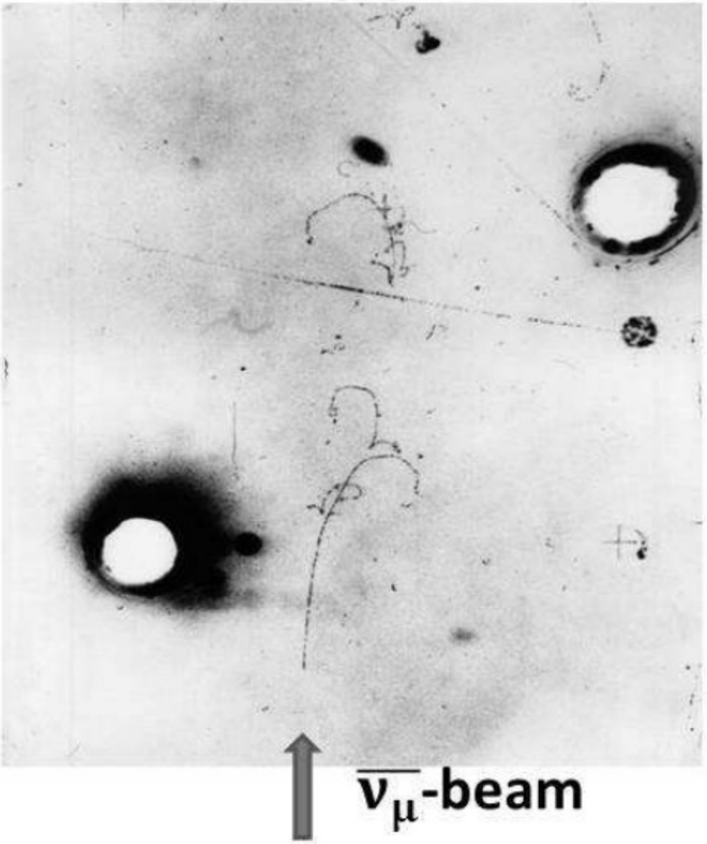
$$\overline{\nu_\mu} e \rightarrow \overline{\nu_\mu} e$$

Properties of electron :

- **Identification** : unique by bremsstrahlung and curling
- **Energy** 385 ± 100 MeV
- **Angle** 1.4 ± 1.4 degree

Background : 0.03 ± 0.02

$$\nu_e\, n \rightarrow e + p$$
$(proton\ invisible)$



$\overline{\nu_\mu}$-beam

First hadronic NC events

How do we tell a hadronic vertex from a leptonic vertex?

Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

F.J. HASERT, S. KABE, W. KRENZ, J. Von KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G.H. BERTRAND-COREMANS, J. SACTON, W. Van DONINCK and P. VILAIN*[1]
Interuniversity Institute for High Energies, U.L.B., V.U.B. Brussels, Belgium

U. CAMERINI*[2], D.C. CUNDY, R. BALDI, I. DANILCHENKO*[3], W.F. FRY*[2], D. HAIDT, S. NATALI*[4], P. MUSSET, B. OSCULATI, R. PALMER*[4], J.B.M. PATTISON, D.H. PERKINS*[6], A. PULLIA, A. ROUSSET, W. VENUS*[7] and H. WACHSMUTH
CERN, Geneva, Switzerland

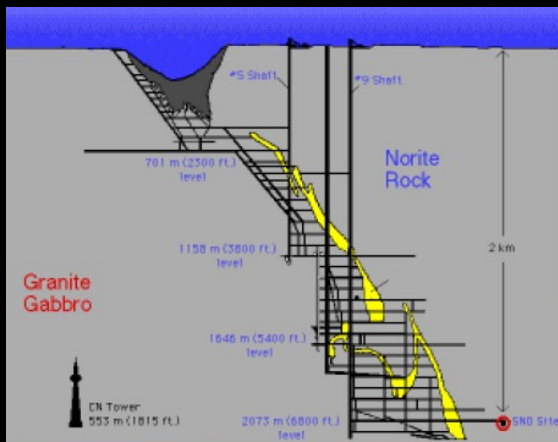
V. BRISSON, B. DEGRANGE, M. HAGUENAUER, L. KLUBERG, U. NGUYEN-KHAC and P. PETIAU
Laboratoire de Physique Nucléaire des Hautes Energies, Ecole Polytechnique, Paris, France

E. BELOTTI, S. BONETTI, D. CAVALLI, C. CONTA*[8]. E. FIORINI and M. ROLLIER
Istituto di Fisica dell'Università, Milano and I.N.F.N. Milano, Italy

B. AUBERT, D. BLUM, L.M. CHOUNET, P. HEUSSE, A. LAGARRIGUE, A.M. LUTZ, A. ORKIN-LECOURTOIS and J.P. VIALLE
Laboratoire de l'Accélérateur Linéaire, Orsay, France

F.W. BULLOCK, M.J. ESTEN, T.W. JONES, J. McKENZIE, A.G. MICHETTE*[9] G. MYATT* and W.G. SCOTT*[6],*[9]
University College, London, England

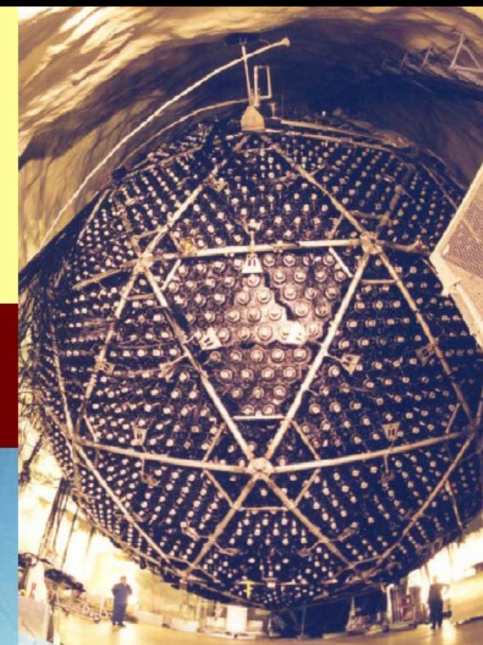
斯诺太阳中微子实验

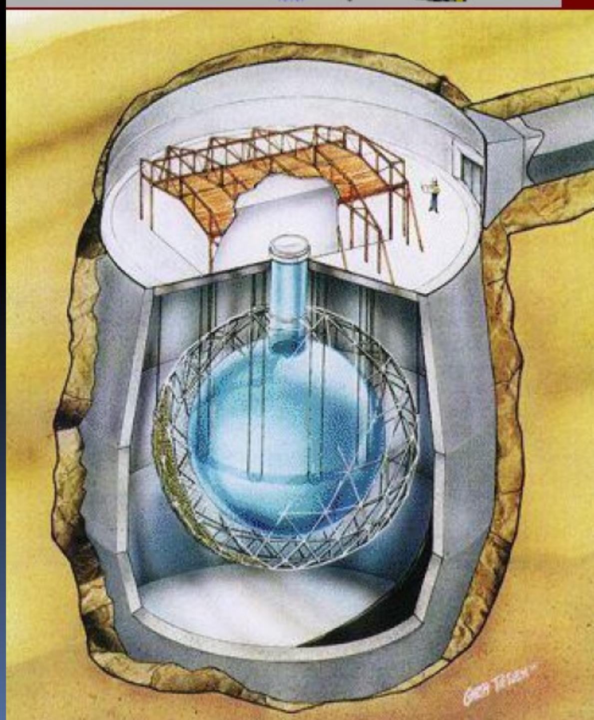


SNO

Sudbury Neutrino Observatory

In Sudbury, Ontario





- Cerenkov detector
- Heavy water (can do solar model independent measurements)
- 6800 feet underground
- 9600 PMTs

45

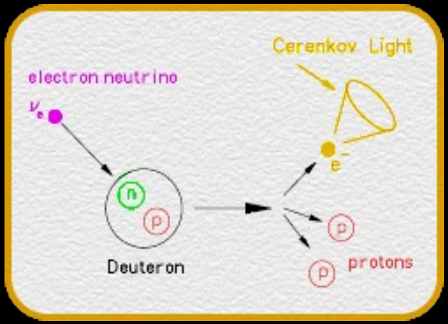
斯诺太阳中微子实验

令电子中微子流量 e, 其他中微子流量 x

$$\nu_e + {}^2H \rightarrow e^- + p + p \quad (\mathrm{CC})$$

Charge current： 电荷流

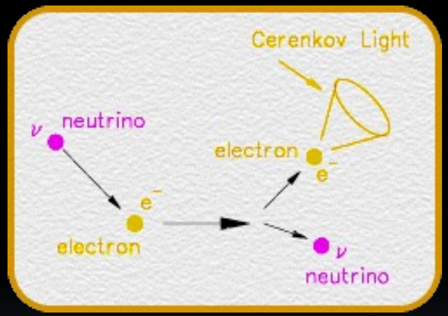
CC = e



$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (\mathrm{ES})$$

Elastic scattering: 弹性散射

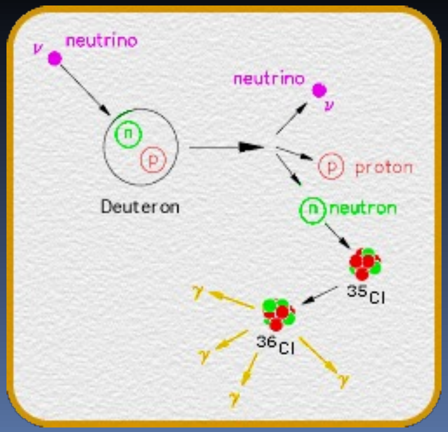
ES = 1 e + 1/7 x



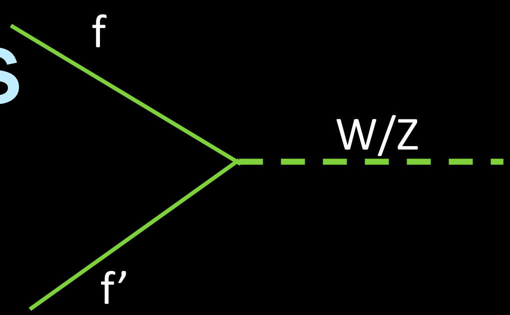
$$\nu_x + {}^2H \rightarrow \nu_x + p + n \quad (\mathrm{NC})$$

Neutral current: 中性流

NC = 1 e + 1 x



Feynman rules for electroweak interactions



W vertices

$$\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$

Z vertices

$$\frac{-ig_Z}{2}\gamma^\mu(c_V^f - c_A^f\gamma^5)$$

$\sin^2\theta_W = 0.2312$

$$g_Z = \frac{g_W}{\cos\theta_W}$$

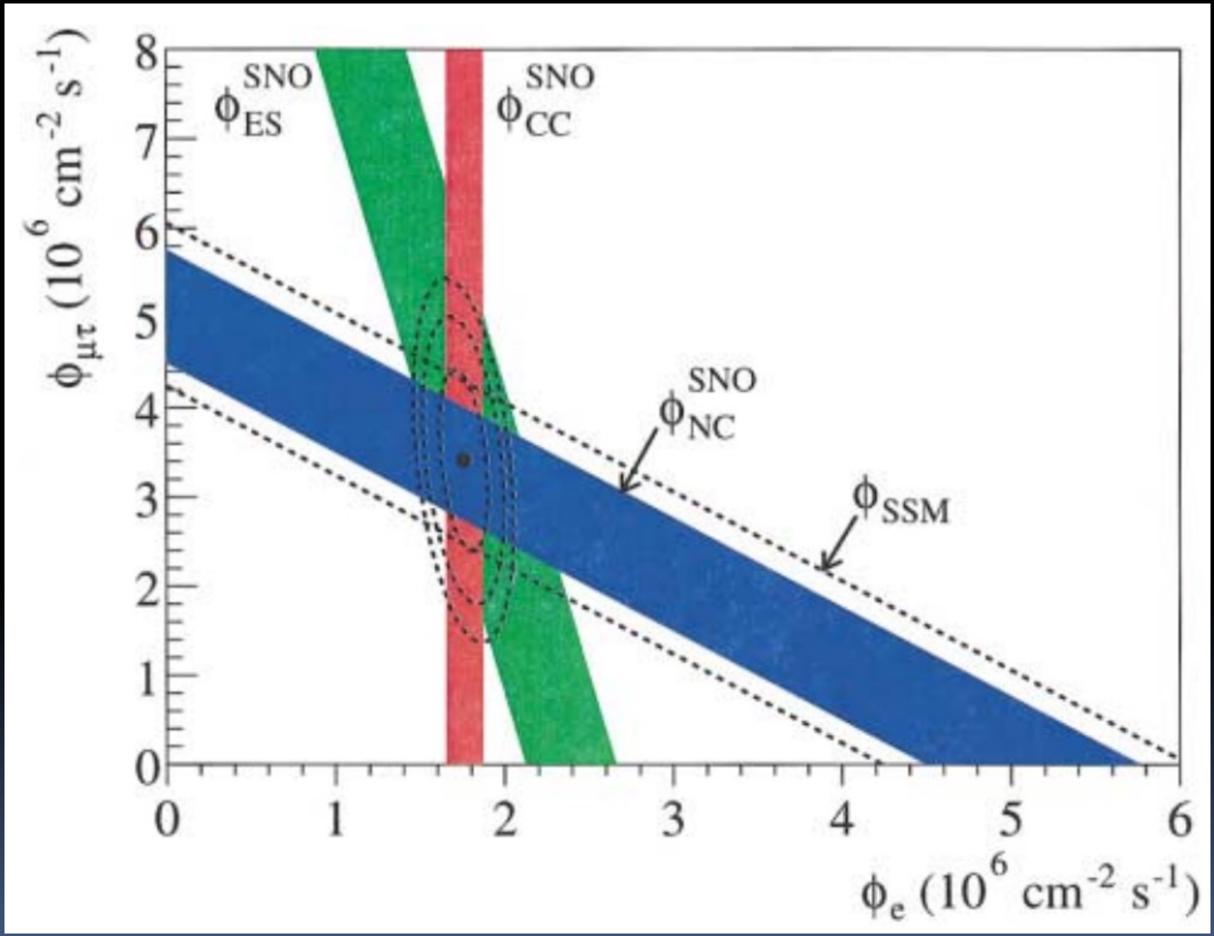
$$M_Z = \frac{M_W}{\cos\theta_W}$$

	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e, μ, τ	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2}-\frac{4}{3}\sin^2\theta_W$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}$

Exercise

- Calculate C_v of the electron
- Express proton in quarks
- Express neutron in quarks
- Calculate C_v of the proton, and the neutron
- Conclusion: $C_v(p) = -C_v(e) = -1/12\ C_v(n)$!!! Neutrons see more weak force than proton and electrons!

SNO solving solar neutrino mystery



Art McDonald

2015年诺奖

CC = e

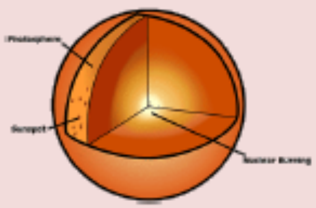
ES = 1 e + 1/7 x

NC = 1 e + 1 x

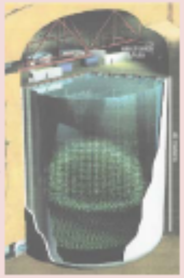
2. 中微子振荡

Neutrino Oscillation

Source	Fly In Space	Detection



ν_A → L →



$$|\nu(x_0)\rangle = |\nu_A\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu(\vec{x},t)\rangle = \cos\theta|\nu_1\rangle e^{i(Et-\vec{k}_1\cdot\vec{x})} + \sin\theta|\nu_2\rangle e^{i(Et-\vec{k}_2\cdot\vec{x})}$$

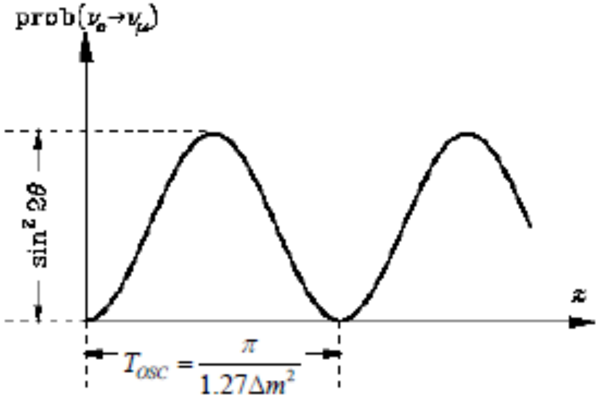
$$P(\nu_A \to \nu_A) = |\langle \nu_A | \nu(t)\rangle|^2$$

Linear Light → **Birefringent Crystal** → Analyzer

Two-flavor Neutrino Oscillation in Vacuum

$$P(A \rightarrow B, \text{appearance}) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$
$$P(A \rightarrow A, \text{survival}) = 1 - \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

$\Delta m^2 = m_1^2 - m_2^2$ in eV^2
L in m, E in MeV



$$\begin{pmatrix} \nu_A \\ \nu_B \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Given L/E sensitive to a range of Δm^2: MeV neutrino & 1000 m $\Rightarrow$ $\Delta m^2 \sim 10^{-3} eV^2$

Neutrino mixing

Transformation from mass to weak eigenstates

$\Delta m^2_{atm} = 2.4\times10^{-3}$ eV^2

$\Delta m^2_{sol} \sim 7.6\times10^{-5}$ eV^2

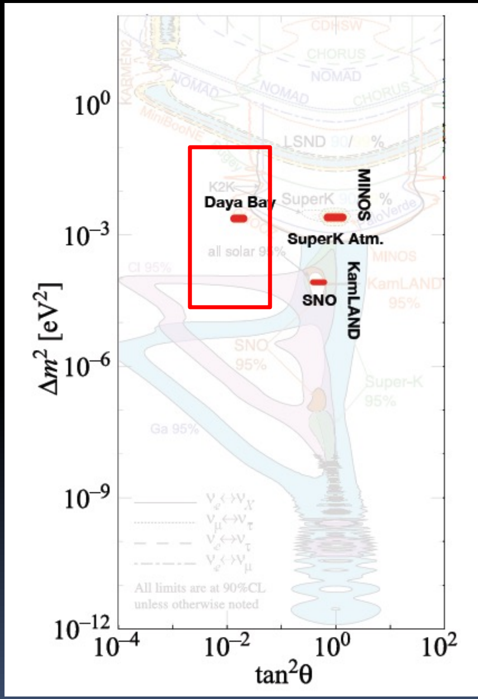
Solar: θ_{12}~32^o Atmospheric: θ_{23}~45^o

$$U_{PMNS} \square \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

θ_{13}~9^o

δ: CP Violation Phase

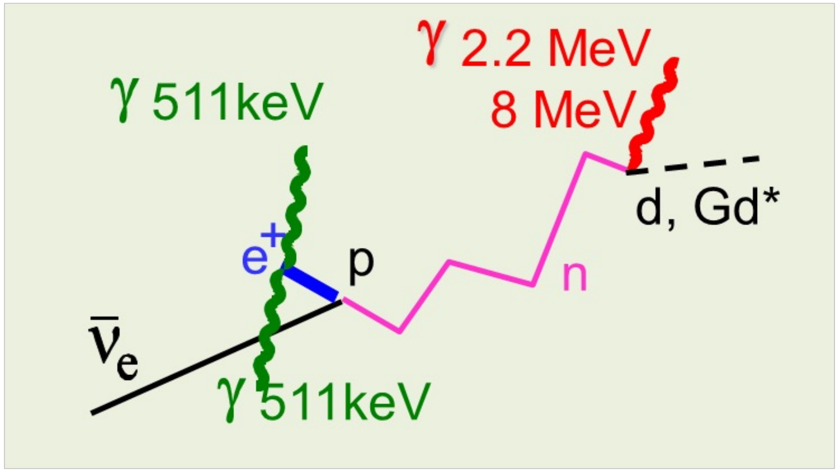


大亚湾中微子实验

Inverse Beta Decay

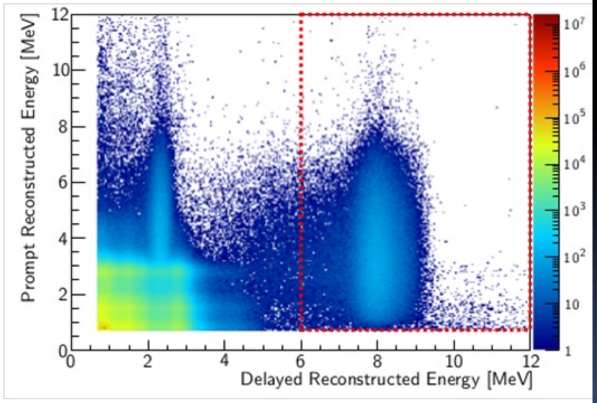
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Use liquid scintillator doped with Gd



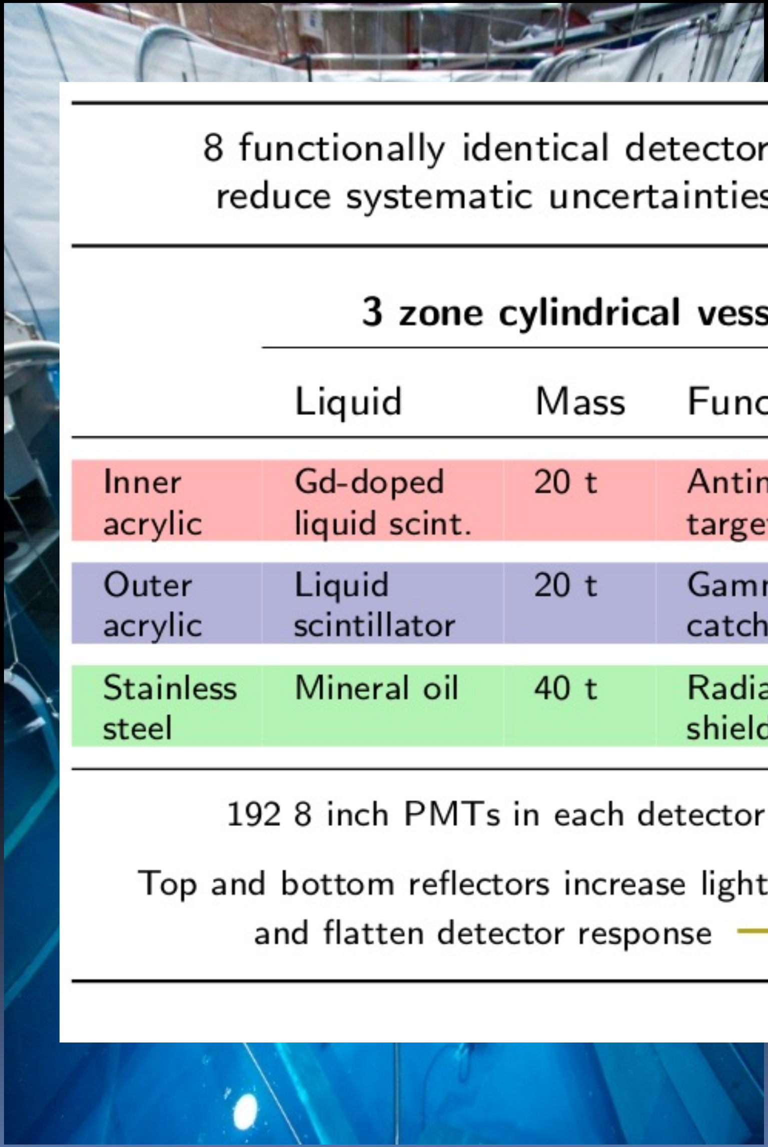
Coincidence signal: detect

- **Prompt**: e^+ annihilation $E_\nu = KE_{e+} + 1.8$ MeV
- **Delayed**: **n** capture on proton (2.2 MeV) or Gd (8 MeV)
- Δt (delayed-prompt) ~ 28 usec for 0.1% Gd-doped LS



- 要求中微子能量大于1.8 MeV
- 一旦发生反应，探测效率大约是80%

大亚湾中微子探测器



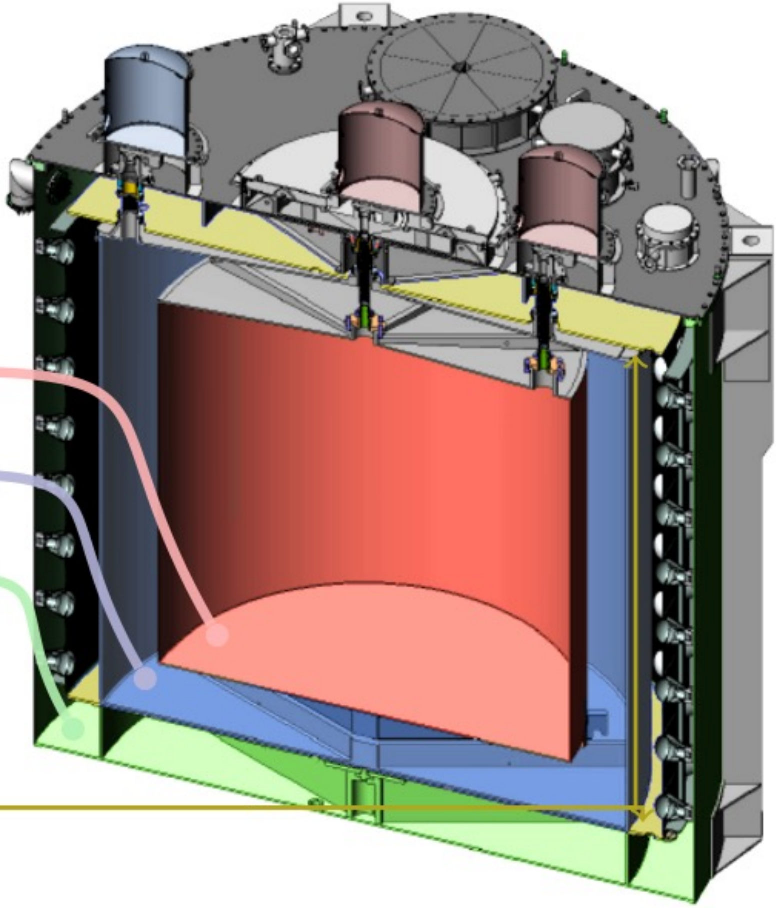
8 functionally identical detectors reduce systematic uncertainties

3 zone cylindrical vessels

	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

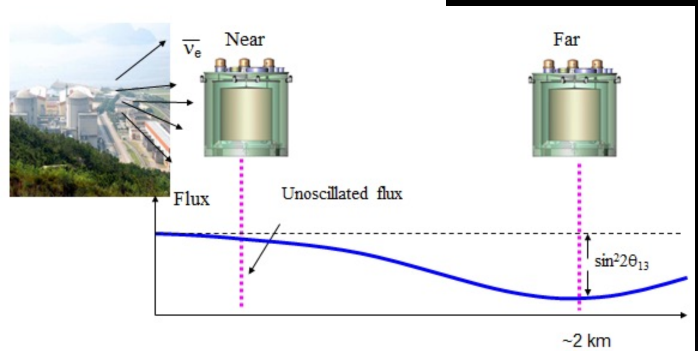
Top and bottom reflectors increase light yield and flatten detector response

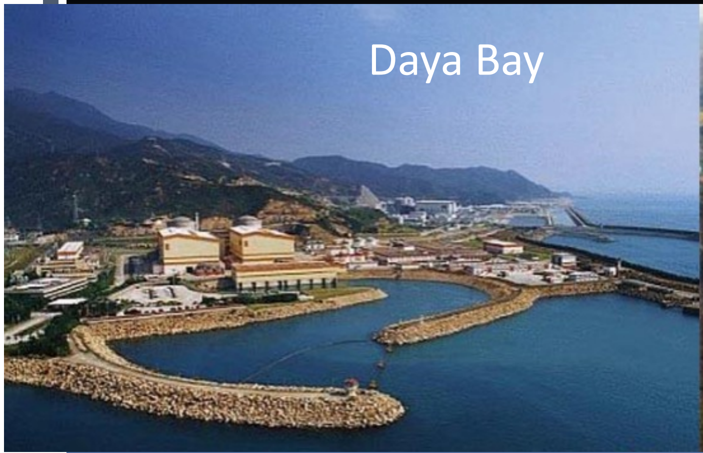


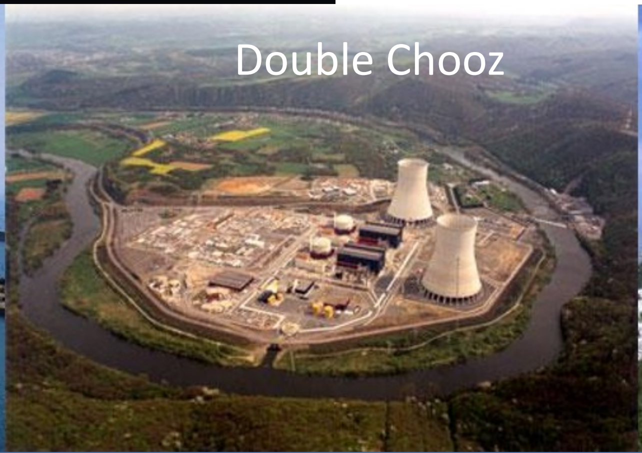
The last mixing angles θ_{13}

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{12}$$

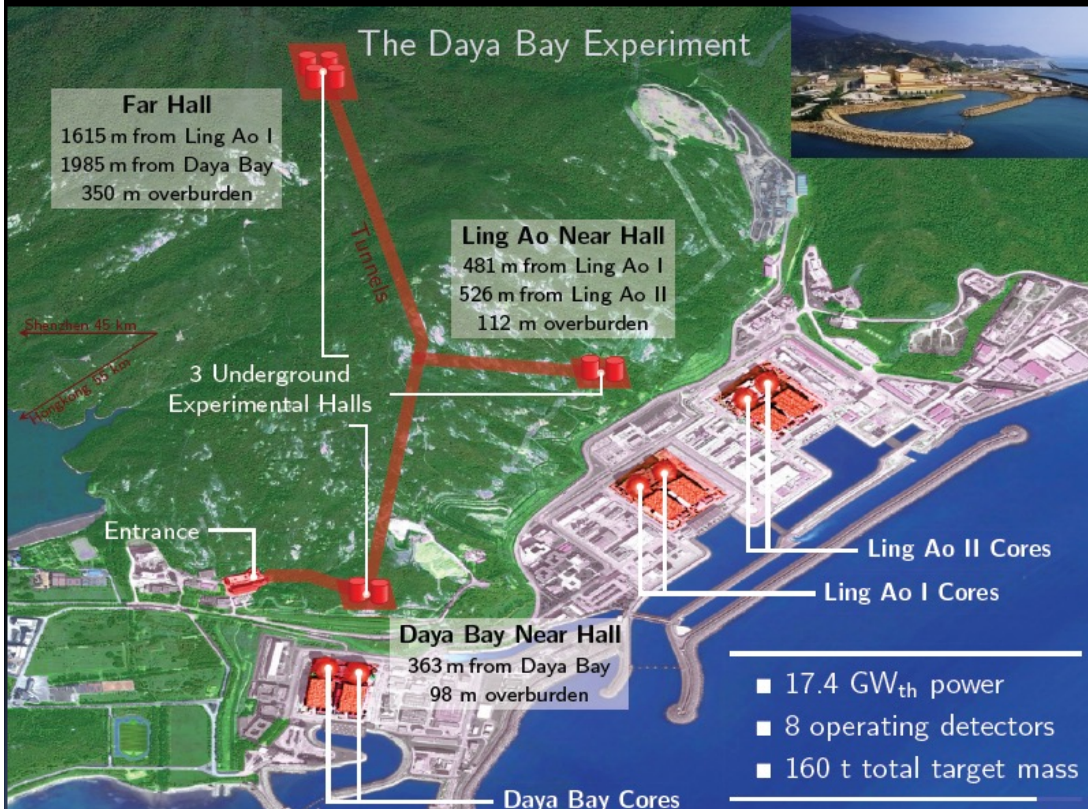
$\Delta m_{31}^2 = 2.4 \times 10^{-3}\ eV^2$, reactor neutrino $E\nu \sim 4$ MeV, L = 2 km



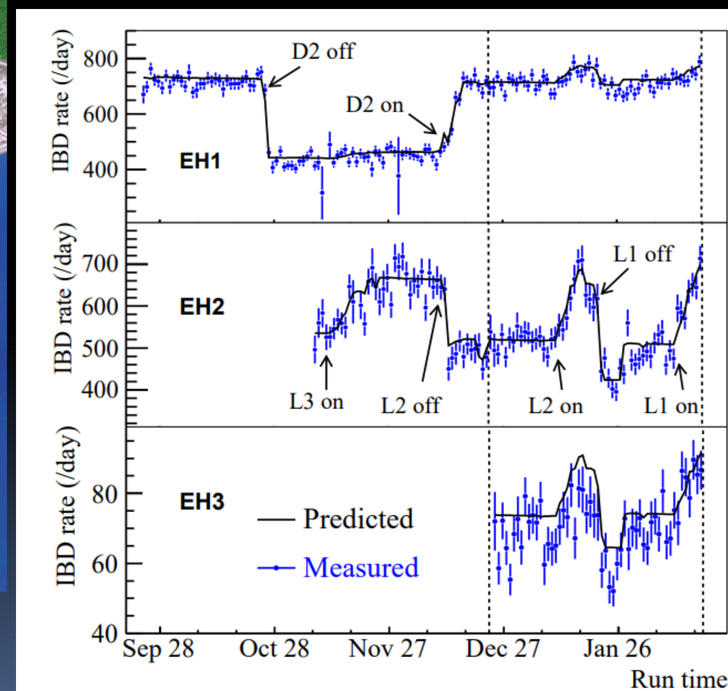




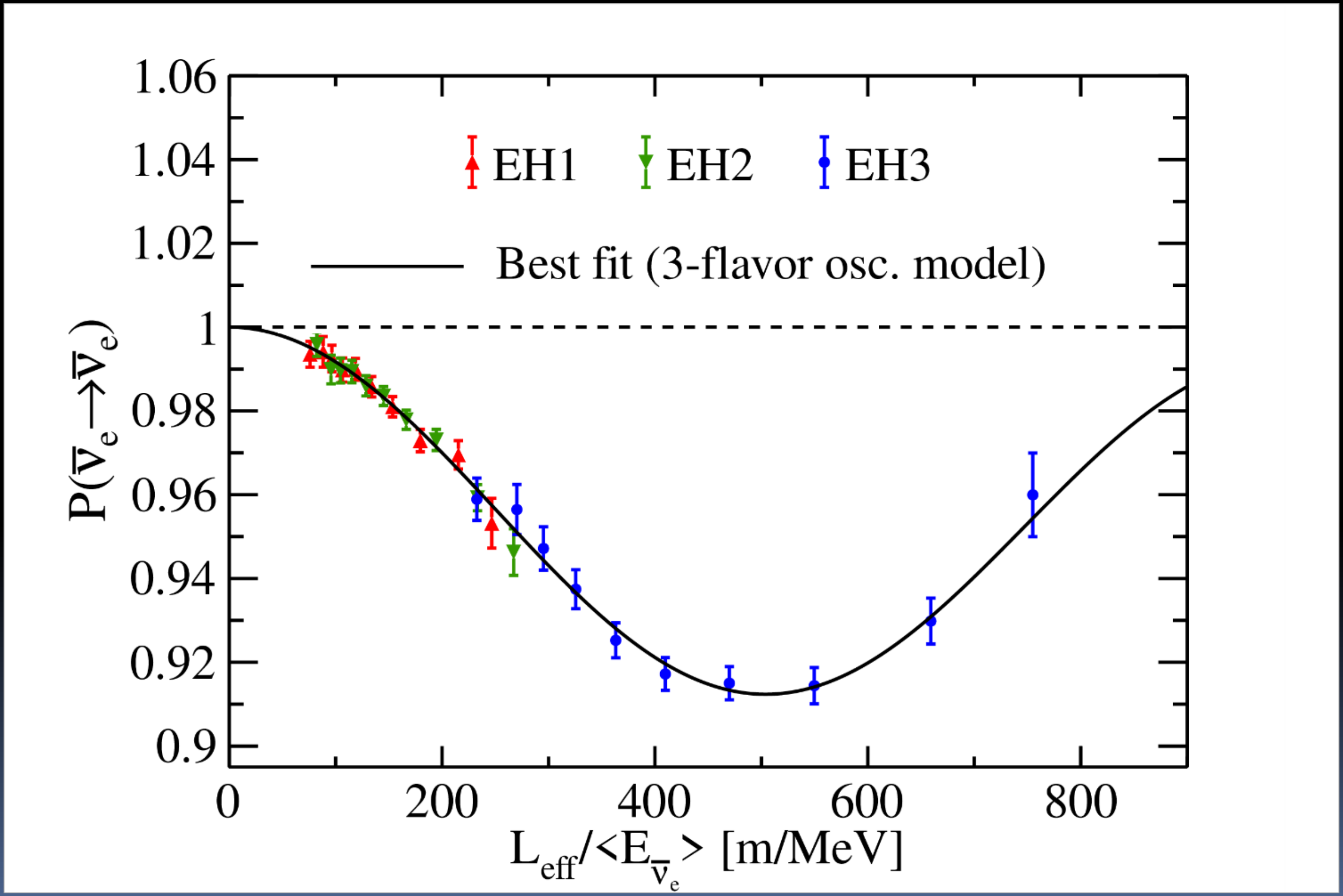
大亚湾实验：2017自然科学一等奖



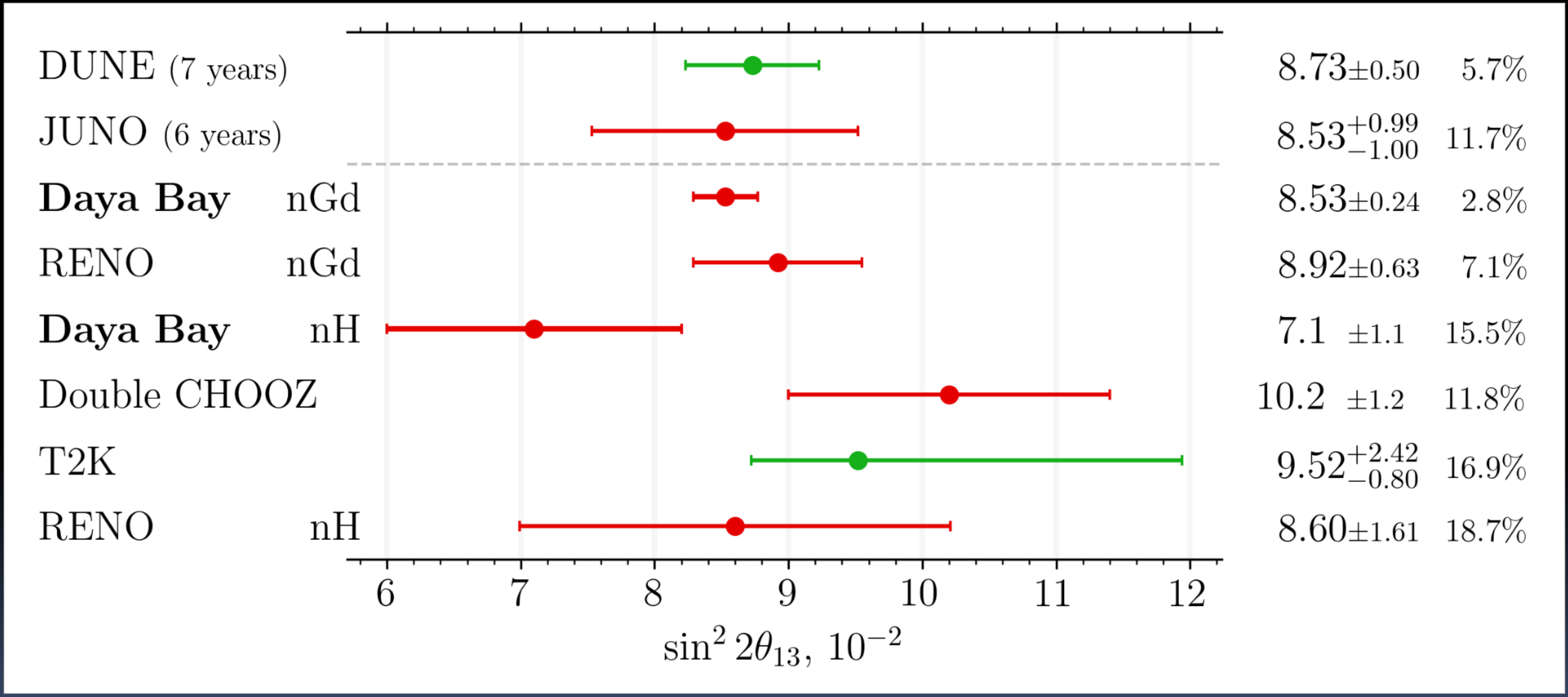
比如：大亚湾“远点”探测器，距离6个2.9 GWth的商用核反应堆1.6公里，每个20吨探测器每天约可以测量到70个事例



L/E final data set



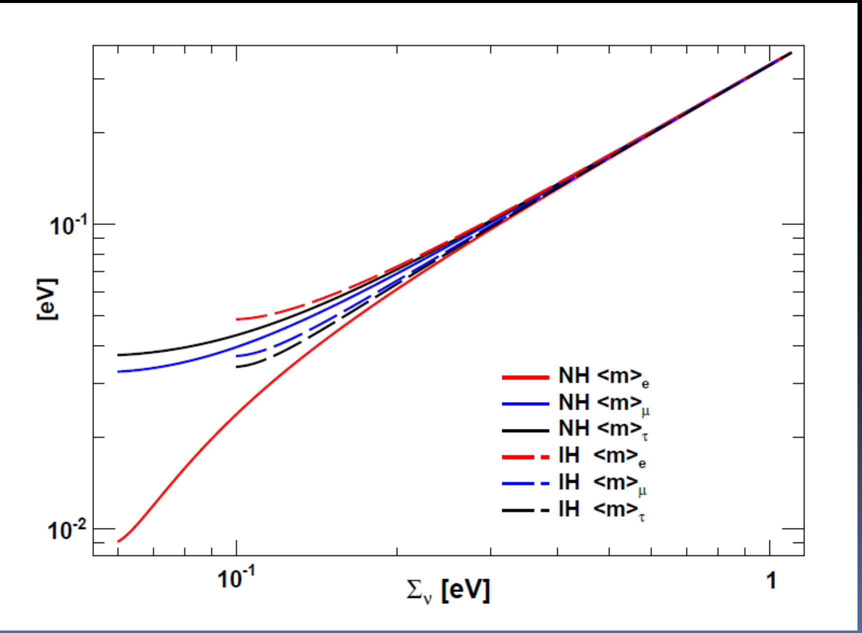
Impressive world data on θ_{13}

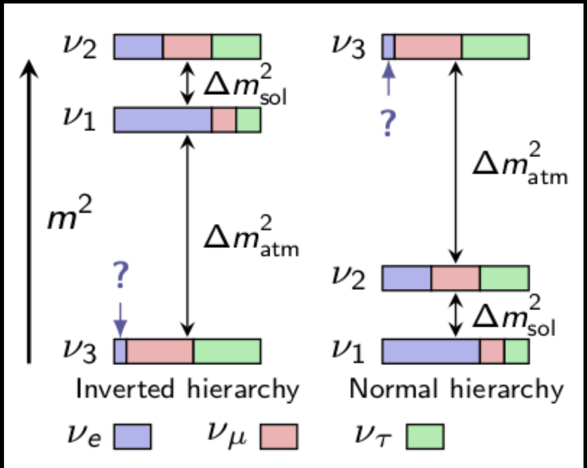


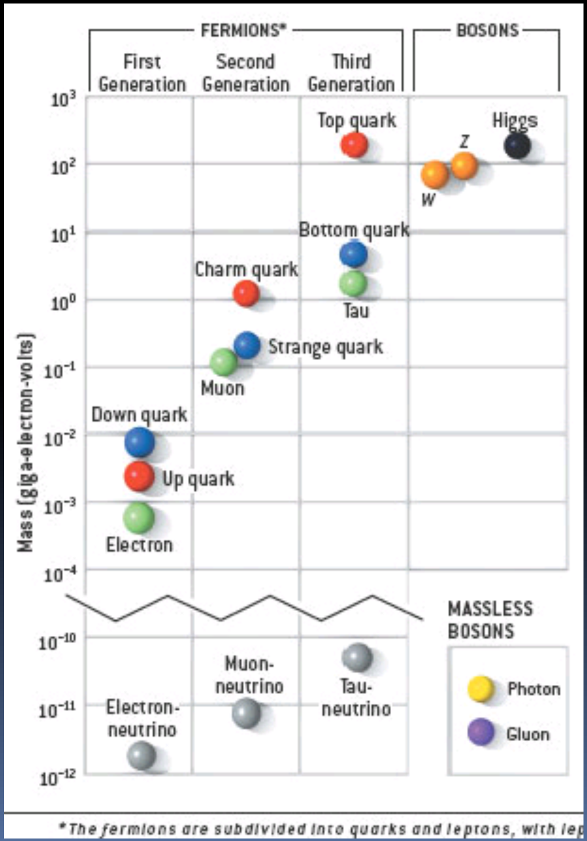
Mass hierarchy?

- $|\Delta m_{31}^2| = 2.4\times10^{-3}$ eV^2, $\Delta m_{21}^2 = 7.5\times10^{-5}$ eV^2
- Mass hierarchy:

  Is m_1 the lightest (normal) or m_3 the lightest (inverted)?







通过反应堆中微子测量质量顺序

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

$$\approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

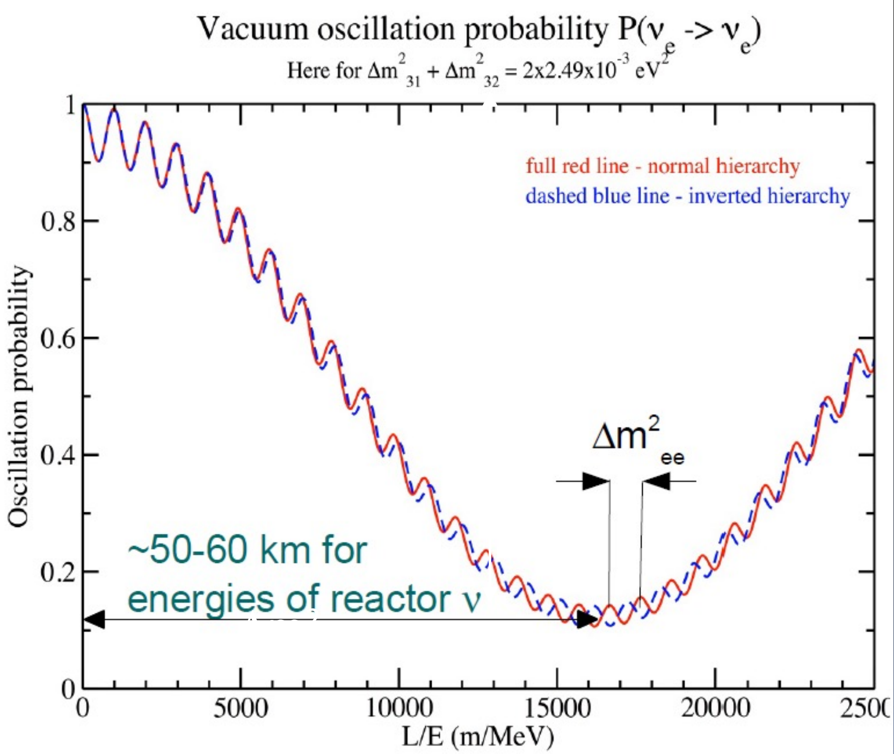
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

Δm^2_{ee} = effective neutrino mass-squared difference (beat frequency)

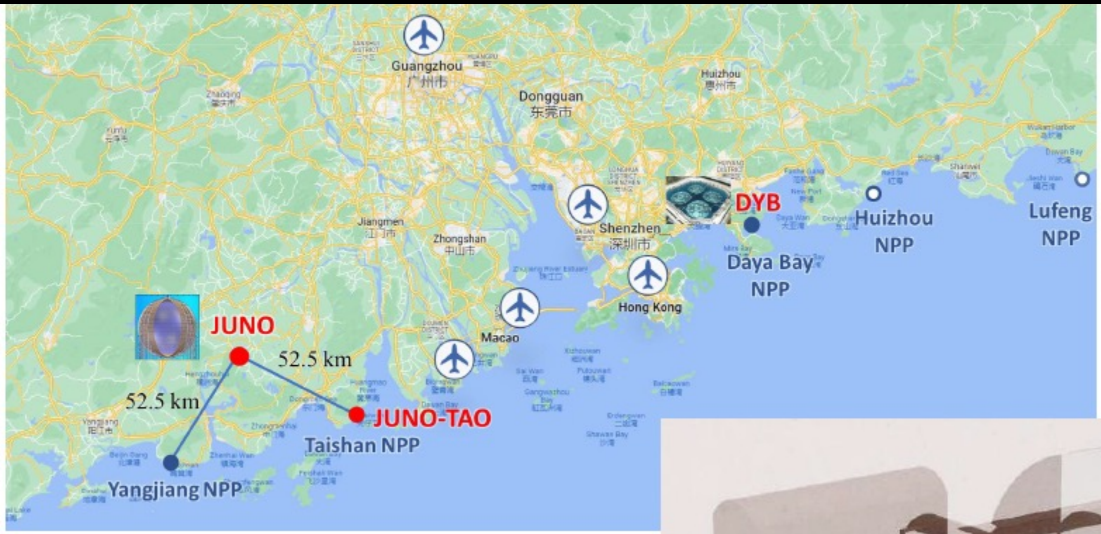
$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \text{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \text{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

with $\Delta m^2_{12} \ll \Delta m^2_{32}$

→ different beat frequency (Δm^2_{ee}) for both hierarchies

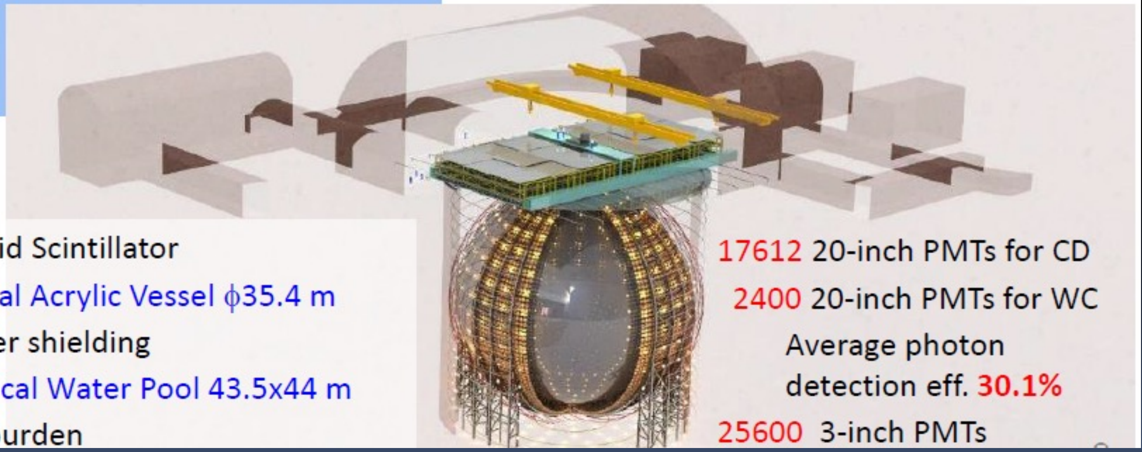


江门中微子实验



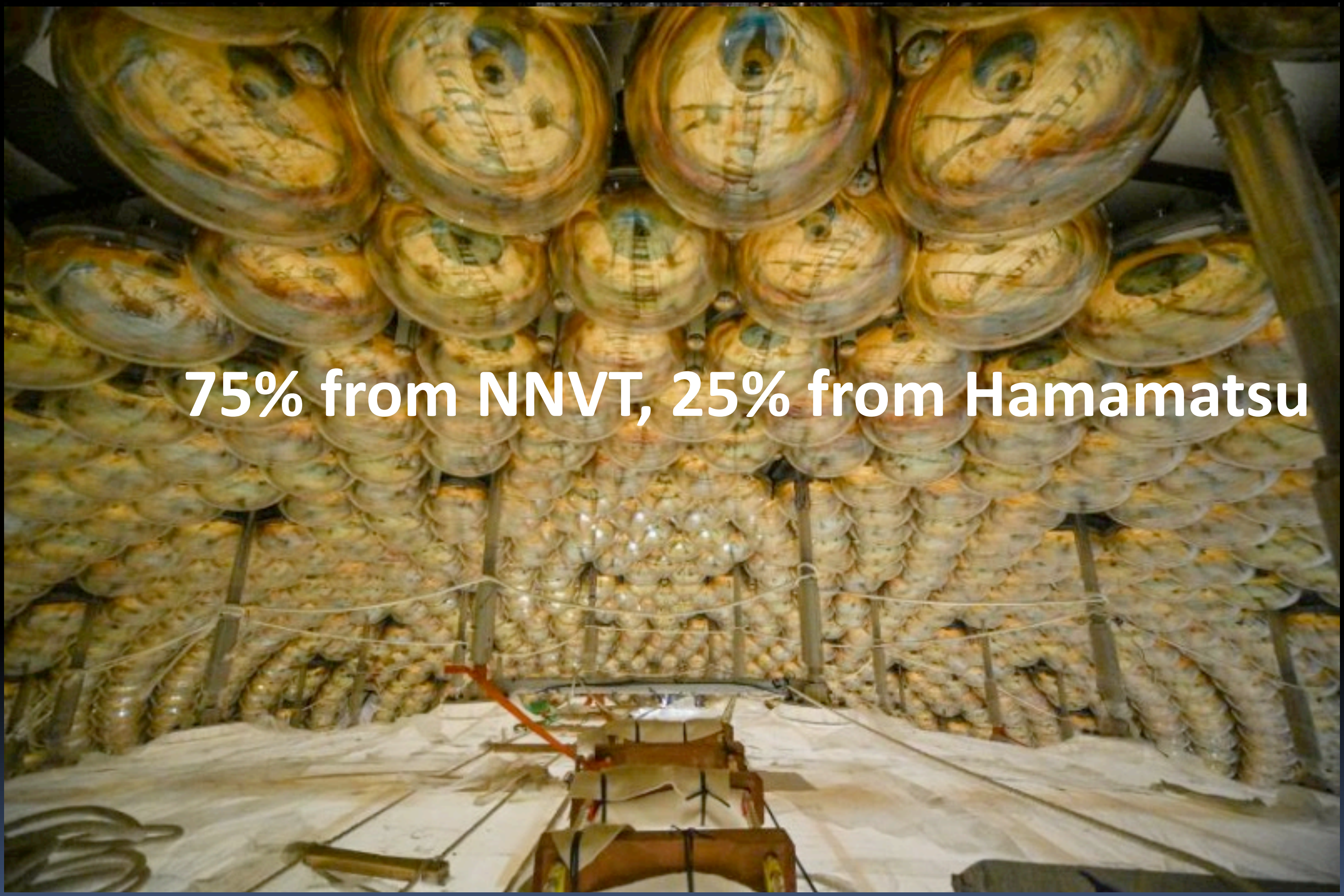
Yangjiang NPP: 2.9 GW x 6
Taishan NPP: 4.6 GW x 2
Equal baseline: 52.5 km

JUNO collaboration: >700 collaborators,
74 institutions, 17 countries/regions



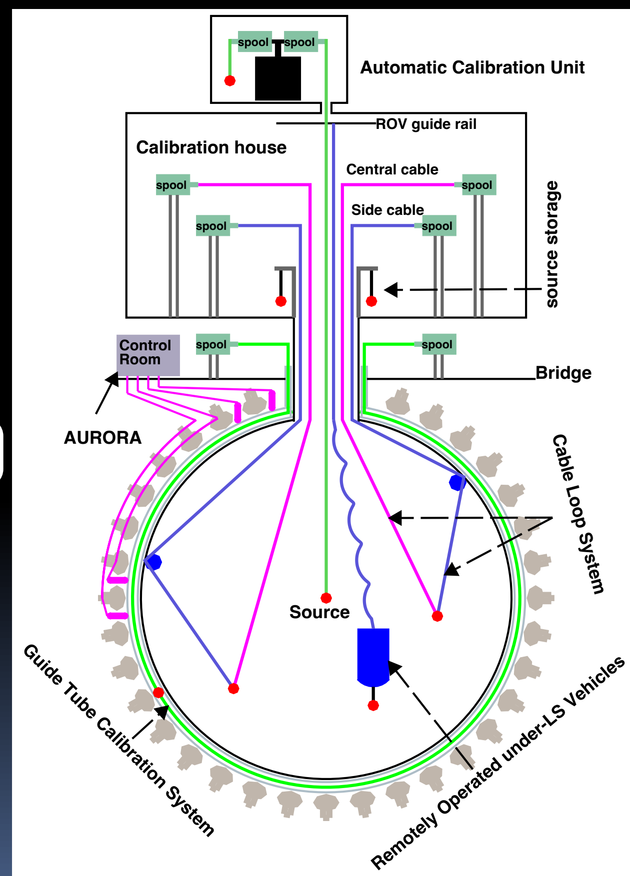
20 kton Liquid Scintillator
Spherical Acrylic Vessel ϕ35.4 m
35 kton water shielding
Cylindrical Water Pool 43.5x44 m
700 m overburden

17612 20-inch PMTs for CD
2400 20-inch PMTs for WC
Average photon detection eff. 30.1%
25600 3-inch PMTs


75% from NNVT, 25% from Hamamatsu

高精度刻度装置

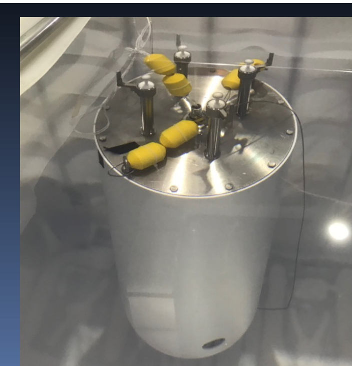
1D Automatic Calibration



Calibration house with all control systems

2D Cable Loop System

3D Remotely operated vehicles



3.从中微子相干散射到暗物质探测

中微子散射截面

- http://cupp.oulu.fi/neutrino/nd-cross.html

Antineutrino-nucleon

$$\sigma_{\bar{\nu}_e p \to e^+ n} = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2)\left(1 - \frac{Q}{E_\nu}\right)\sqrt{1 - 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}\,\theta(E - Q)$$

$$\frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2) = 9.3 \cdot 10^{-48}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2$$

Elastic scattering

$$\sigma_{\nu_e e^- \to \nu_e e^-} = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2} + \xi\right)^2 + \frac{1}{3}\xi^2\right] \approx 9.5 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

$$\sigma_{\bar{\nu}_e e^- \to \bar{\nu}_e e^-} = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2} + \xi\right)^2 + \xi^2\right] \approx 4.0 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

Neutrino-nucleon elastic c.s.

$$\sigma_{\nu n \to \nu n}(E) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(1 + 3g_A^2) \approx 9.3 \cdot 10^{-48}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2.$$

$$\sigma_{\nu p \to \nu p}(E) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{4\pi}\left((16\xi^2 - 8\xi + 1)(1 + 3g_A^2)\right) \approx 6.0 \cdot 10^{-50}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2.$$

- 对于氢元素，逆贝塔衰变截面最大，也最容易测！
- 中微子-中子弹性截面也很大，但是反冲能非常底，非常难测！

中微子-原子核相干散射

Quantum mechanics: 200 MeV ~ 1 fm
So MeV neutrino cannot resolve atomic nucleus

Coherent effects of a weak neutral current

Daniel Z. Freedman
Phys. Rev. D **9**, 1389 – Published 1 March 1974

Article | References | Citing Articles (412) | PDF | Export Citation

ABSTRACT

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about $10^{-38}\ \mathrm{cm}^2$ on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

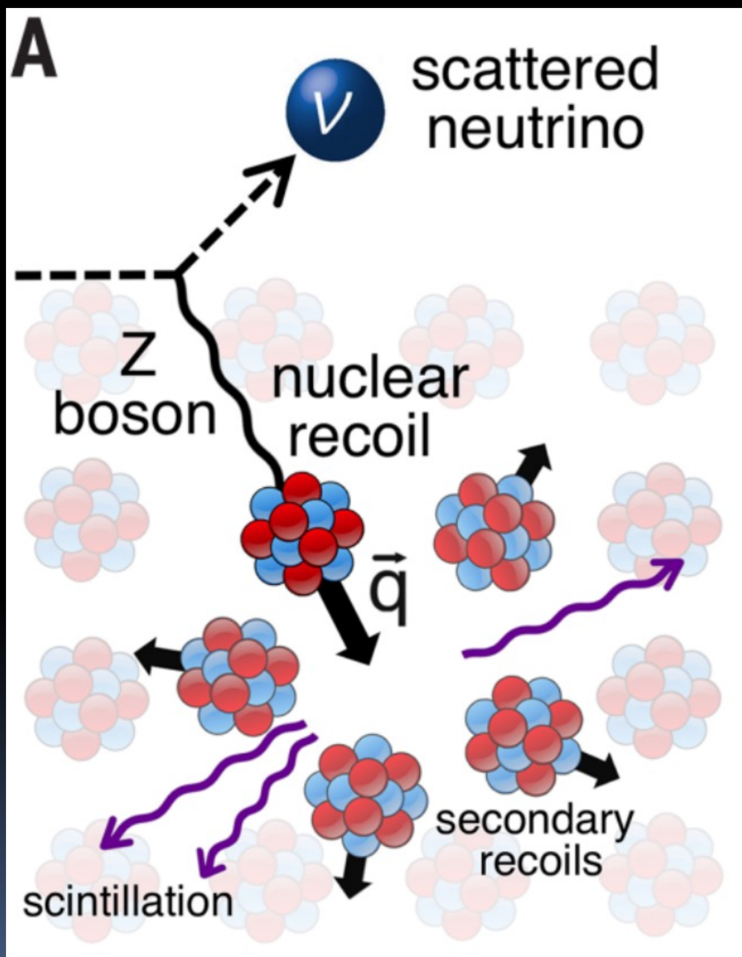
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10—10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

中微子-原子核相干散射



近似公式，N：中子数

$$\sigma = \frac{G^2}{16\pi} N^2 \Delta_{max}{}^2 = \frac{G^2 N^2}{4\pi} E^2 \,.$$

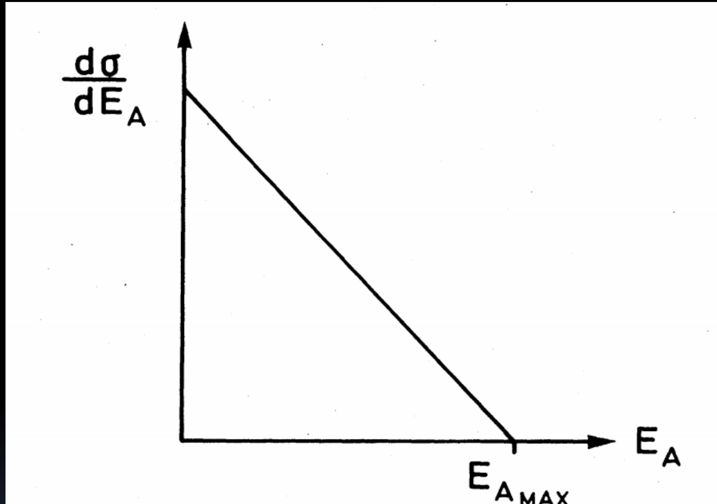


FIG. 1. Recoil-energy spectrum of the struck nucleus A in elastic neutrino scattering.

$$\bar{E}_A = \frac{2}{3A} (E/1\ \mathrm{MeV})^2\ \mathrm{keV}$$

COHERENT实验

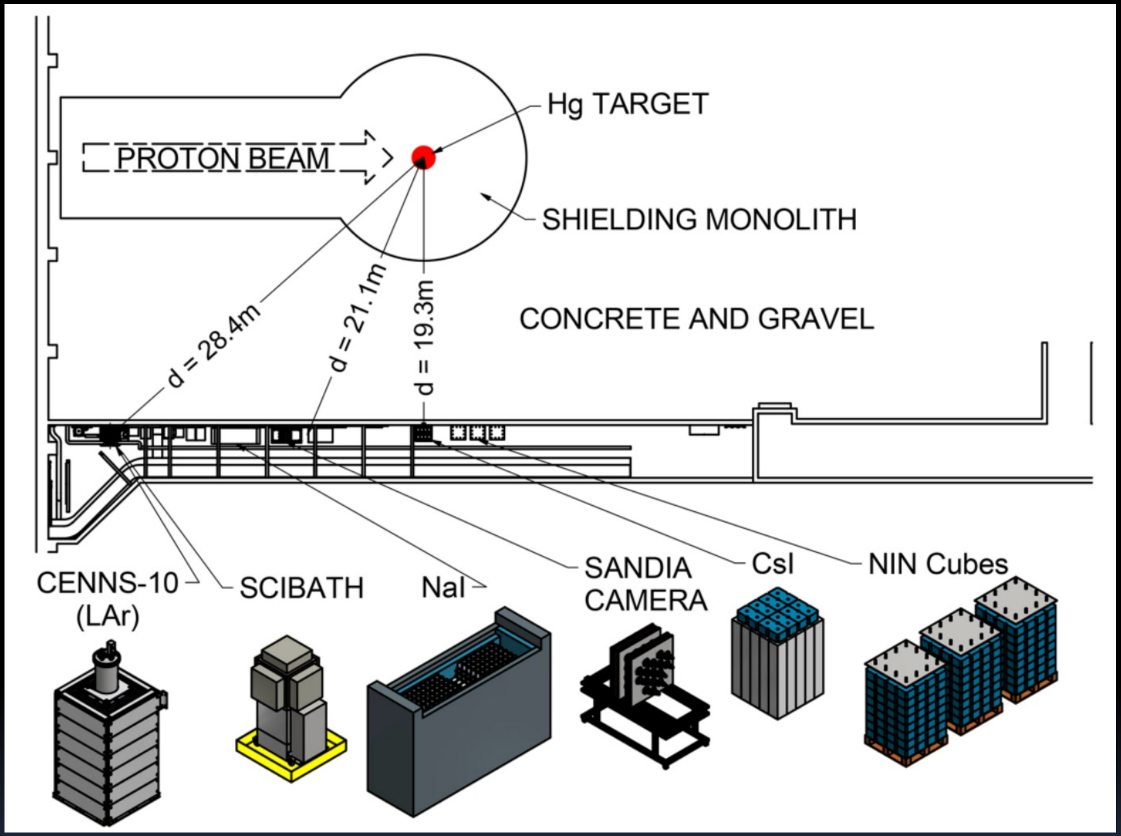
Science REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

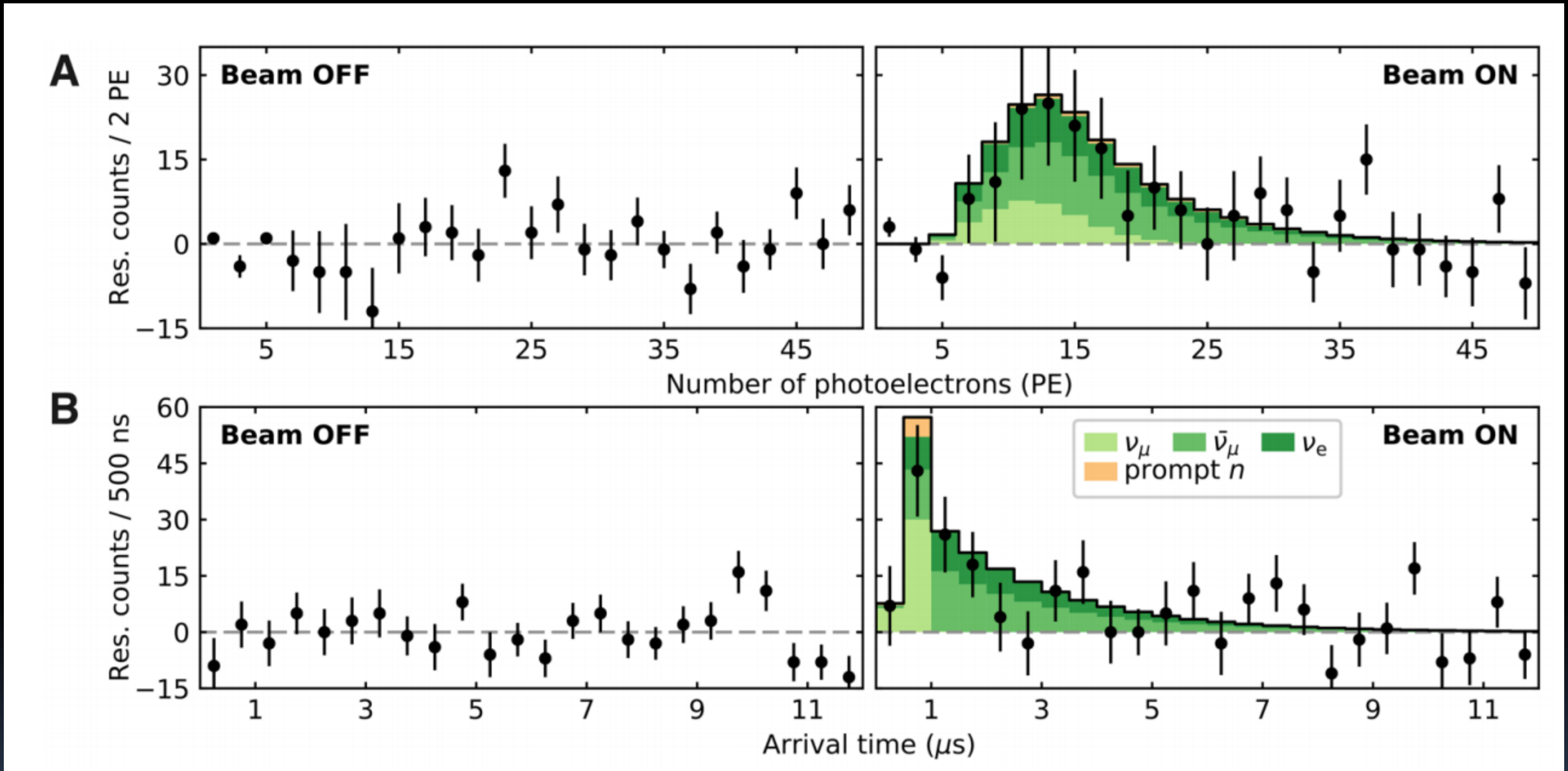
COHERENT实验



美国Oak Ridge国家实验室
质子束能量：1 GeV，脉冲式
中微子能量：16-53 MeV （数据选择条件）
活时间：154天

测量结果

光产额~1.17 PE/keV_{nr}



Drukier想法在“新”领域的应用

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

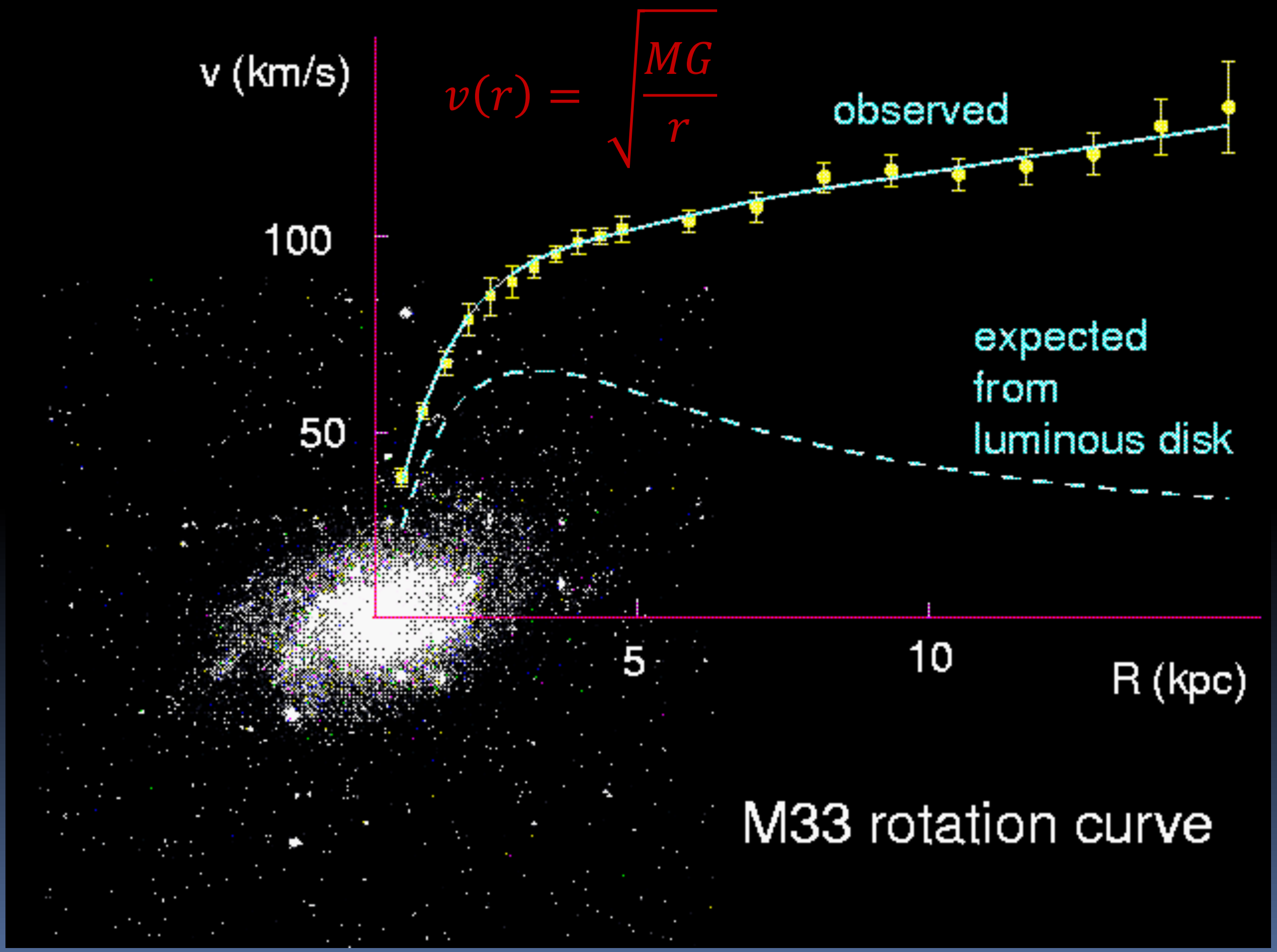
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Recently, Drukier and Stodolsky proposed[5] a new way of detecting solar and reactor neutrinos. The idea is to ex-

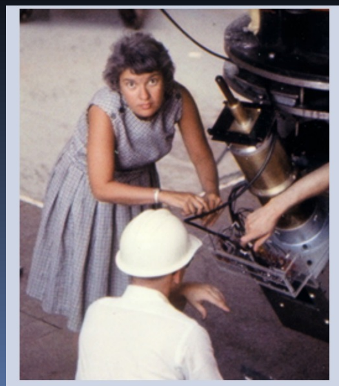
In this paper, we will calculate the sensitivity of the detector considered in Ref. 5 to various dark-matter candidates. Although this detector is not very sensitive to

天文学家的发现



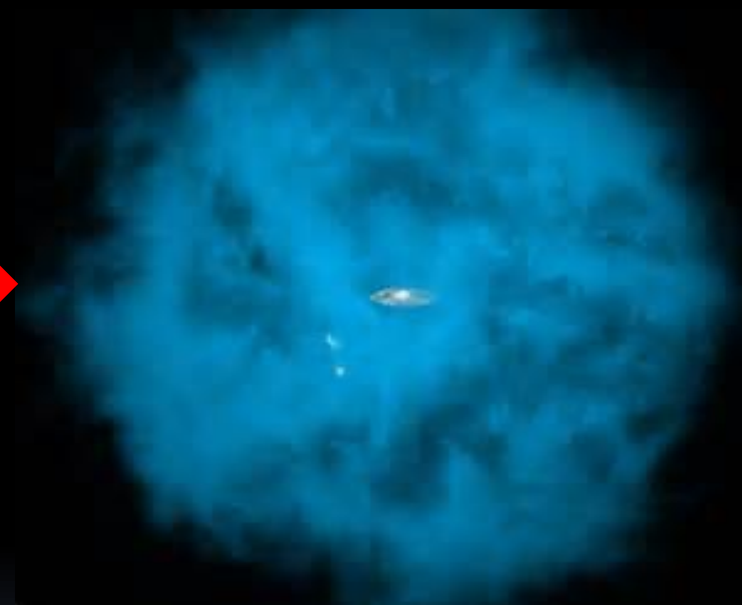
Fritz Zwicky

Vera Rubin



Vera Cooper Rubin at the Lowell Observatory. Kent Ford has his back to us.

暗物质：星系中的幽灵“雾霾”

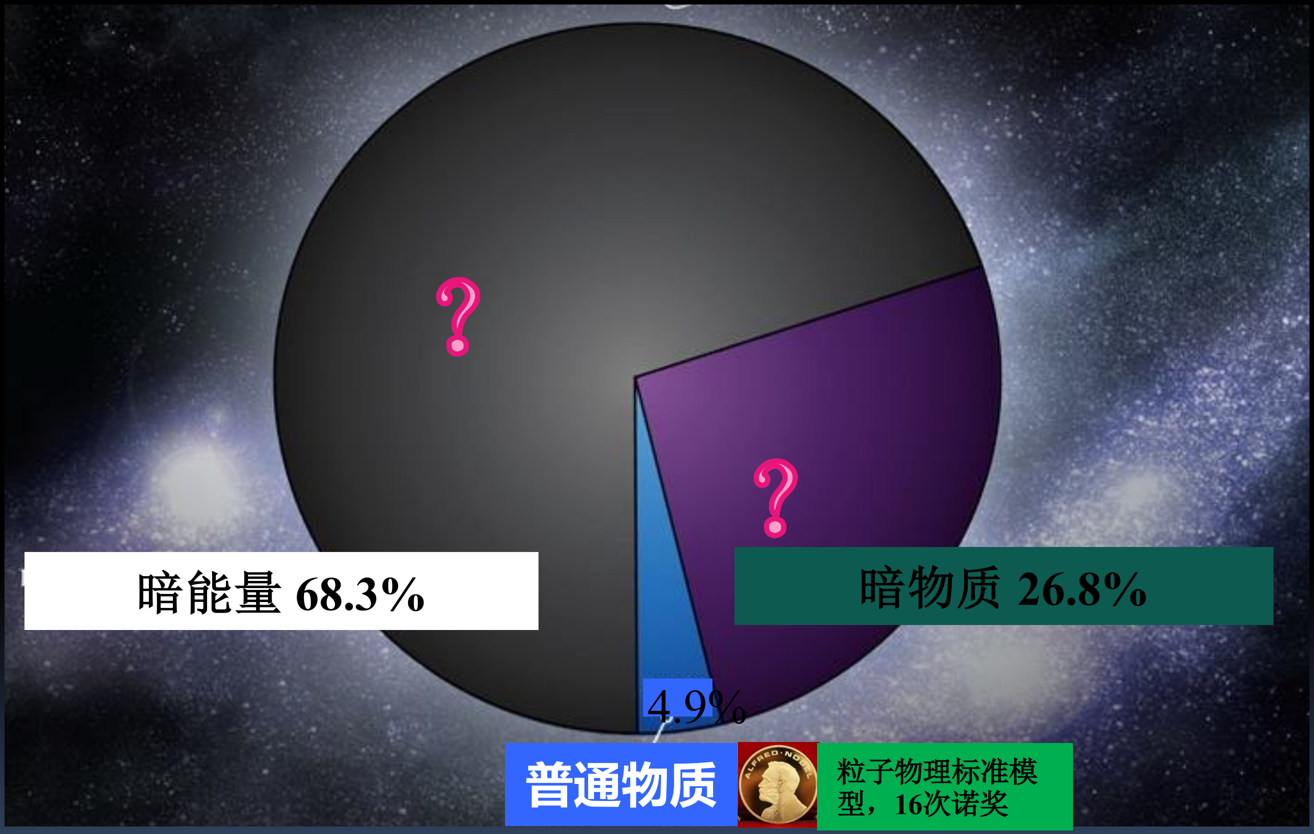


太阳轨道附近，每毫升中暗物质的重量约为1/3个质子
空气的密度比暗物质的密度高了
2000000000000000000000 （是的，21个零）

Quiz

- 无处不在的暗物质为何不会影响地球绕太阳的旋转？？？

宇宙中的“三国演义”

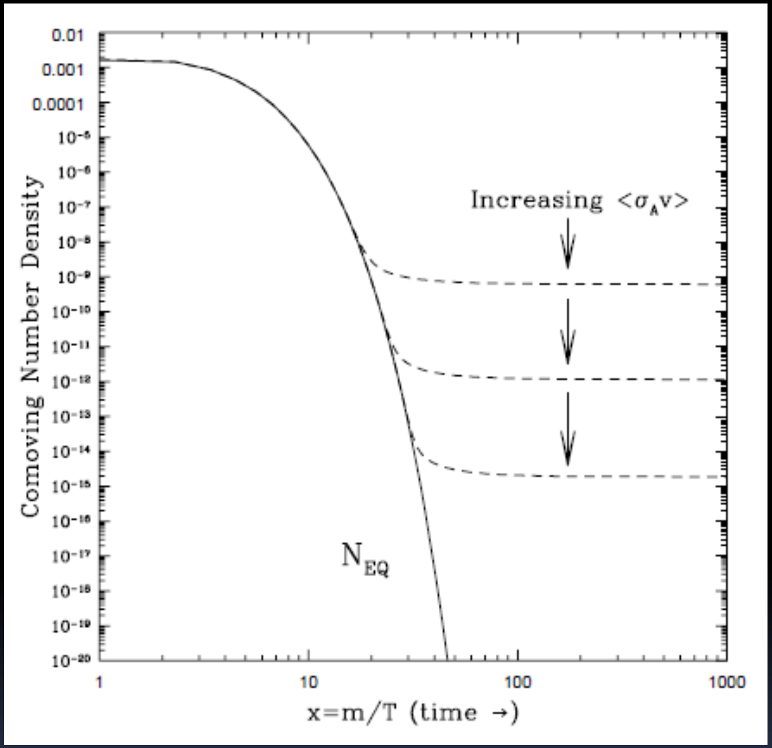


暗物质：宇宙的化石

- 暗物质“最可能的”质量： 100 GeV-10TeV (已知最重的基本粒子，顶夸克180GeV)
- 估算产生100GeV的暗物质粒子对的宇宙温度

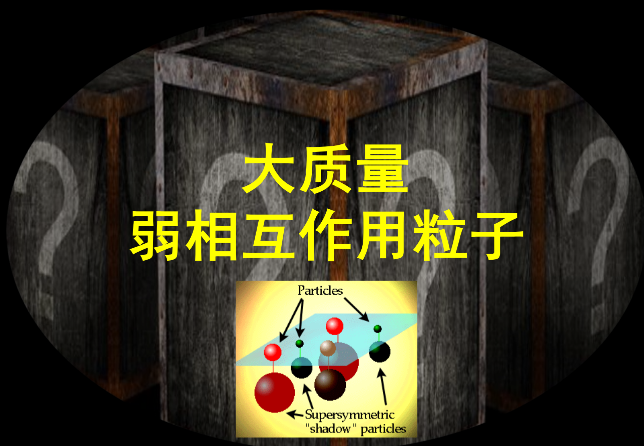
$$X\bar{X} \leftrightarrow Y\bar{Y}$$

暗物质“冻结”



- 宇宙冷却，暗物质不再产生，只能湮灭
- 宇宙在不断膨胀！
- 当暗物质找不到自己的反物质去湮灭，暗物质在宇宙中就永生了

Comoving: a volume which increases as the universe expands



大质量
弱相互作用粒子

→

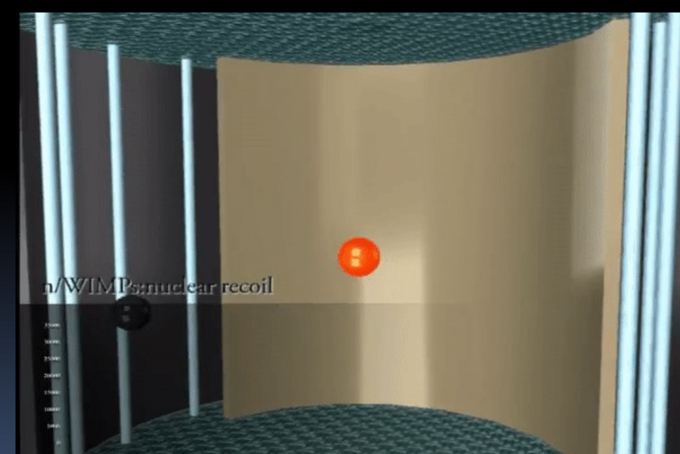
宇宙物质密度

WIMP奇迹！！！

WIMP“直接探测”

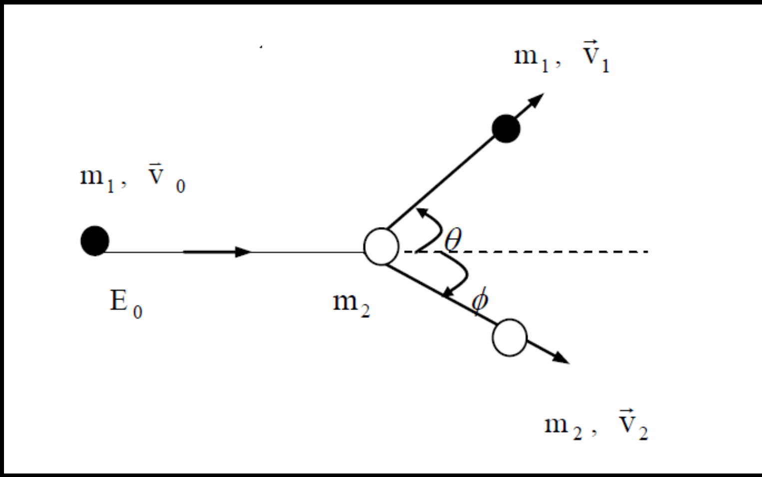
- The solar system is cycling the center of galaxy with 220 km/s speed

- DM direct detection: wait for DM interacting atomic nucleus in the detector, and detect its recoil (Goodman & Witten, 1985)



守株待兔：测量暗物质和靶原子碰撞后原子核反冲的信号

如何探测?



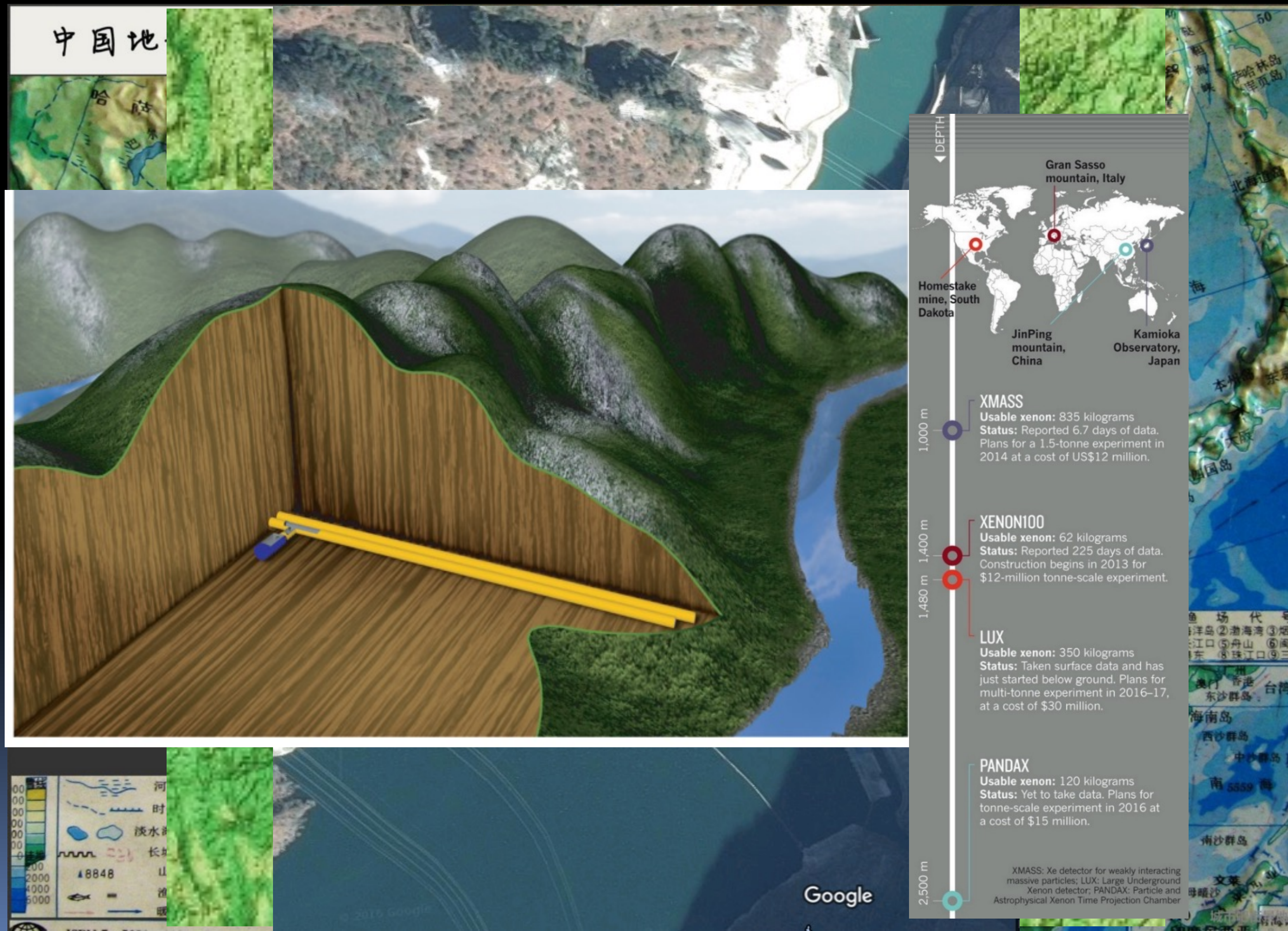
反冲后的原子核携带能量

暗物质直接探测就是可以将反冲转化为可观测信号，从而推断暗物质粒子的质量（反冲能）和同普通物质的相互作用强度（数率）

餐巾纸估算

- 估算100GeV重的暗物质的动能
- 考虑弹性散射，希望碰撞后能量传递最有效，你应当采用何种靶？

中国锦屏地下实验室



DEPTH
Gran Sasso mountain, Italy
Homestake mine, South Dakota
JinPing mountain, China
Kamioka Observatory, Japan
1,000 m
XMASS
Usable xenon: 835 kilograms
Status: Reported 6.7 days of data. Plans for a 1.5-tonne experiment in 2014 at a cost of US$12 million.
1,400 m
1,480 m
XENON100
Usable xenon: 62 kilograms
Status: Reported 225 days of data. Construction begins in 2013 for $12-million tonne-scale experiment.
LUX
Usable xenon: 350 kilograms
Status: Taken surface data and has just started below ground. Plans for multi-tonne experiment in 2016–17, at a cost of $30 million.
PANDAX
Usable xenon: 120 kilograms
Status: Yet to take data. Plans for tonne-scale experiment in 2016 at a cost of $15 million.
2,500 m
XMASS: Xe detector for weakly interacting massive particles; LUX: Large Underground Xenon detector; PANDAX: Particle and Astrophysical Xenon Time Projection Chamber
Google
中国地

氙：Xenon

无色无味

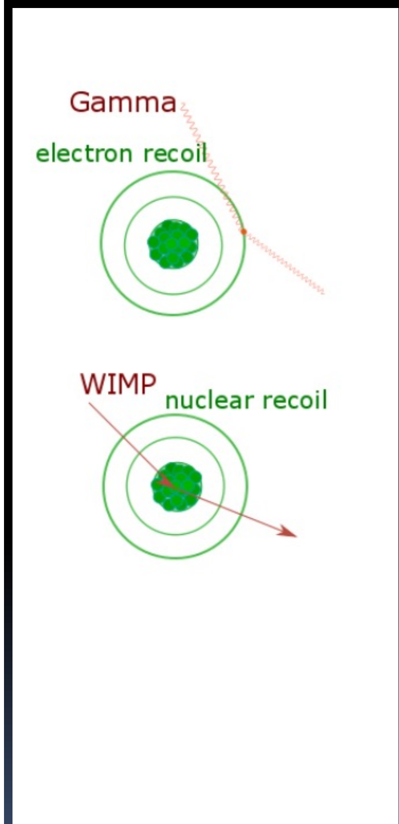
密度（液）：3 g/cc

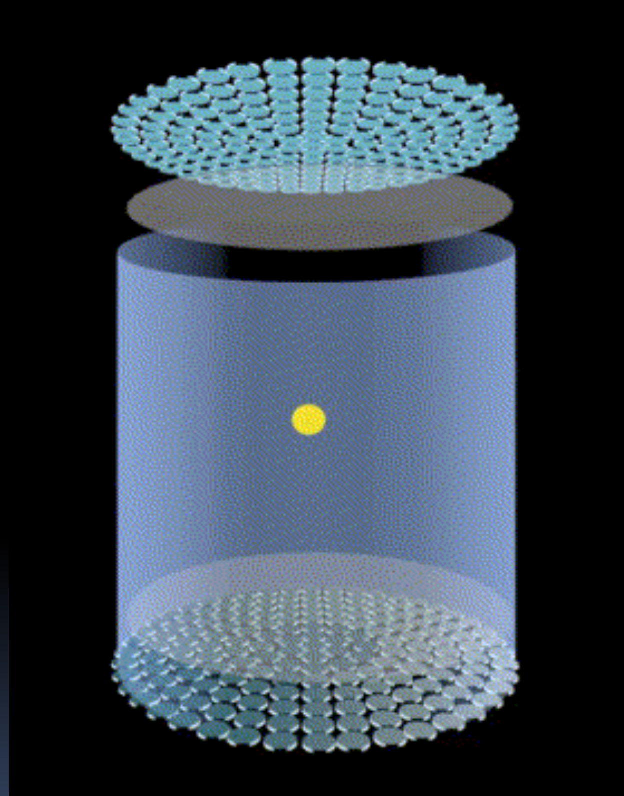
沸点：-100C

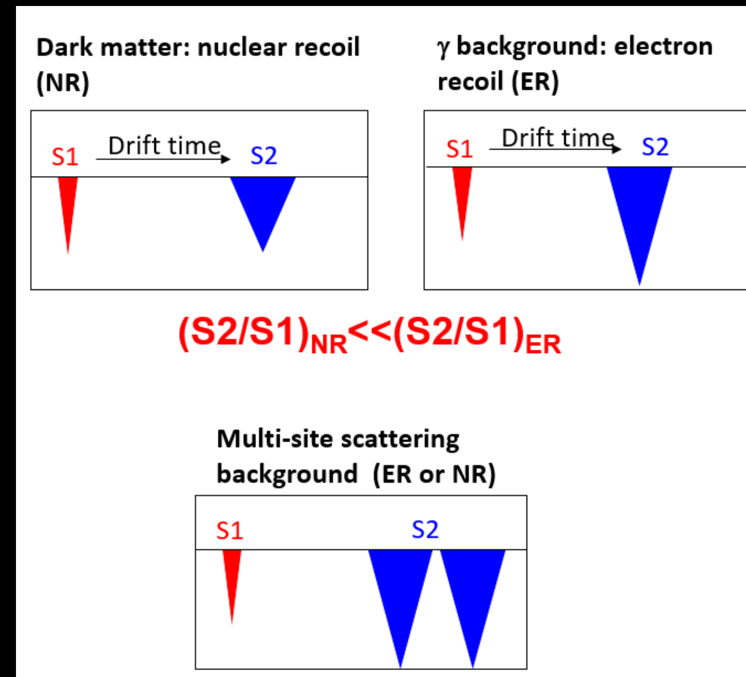
价格：10000元/公斤

全世界年产量：60吨

“两相型”液氙探测器





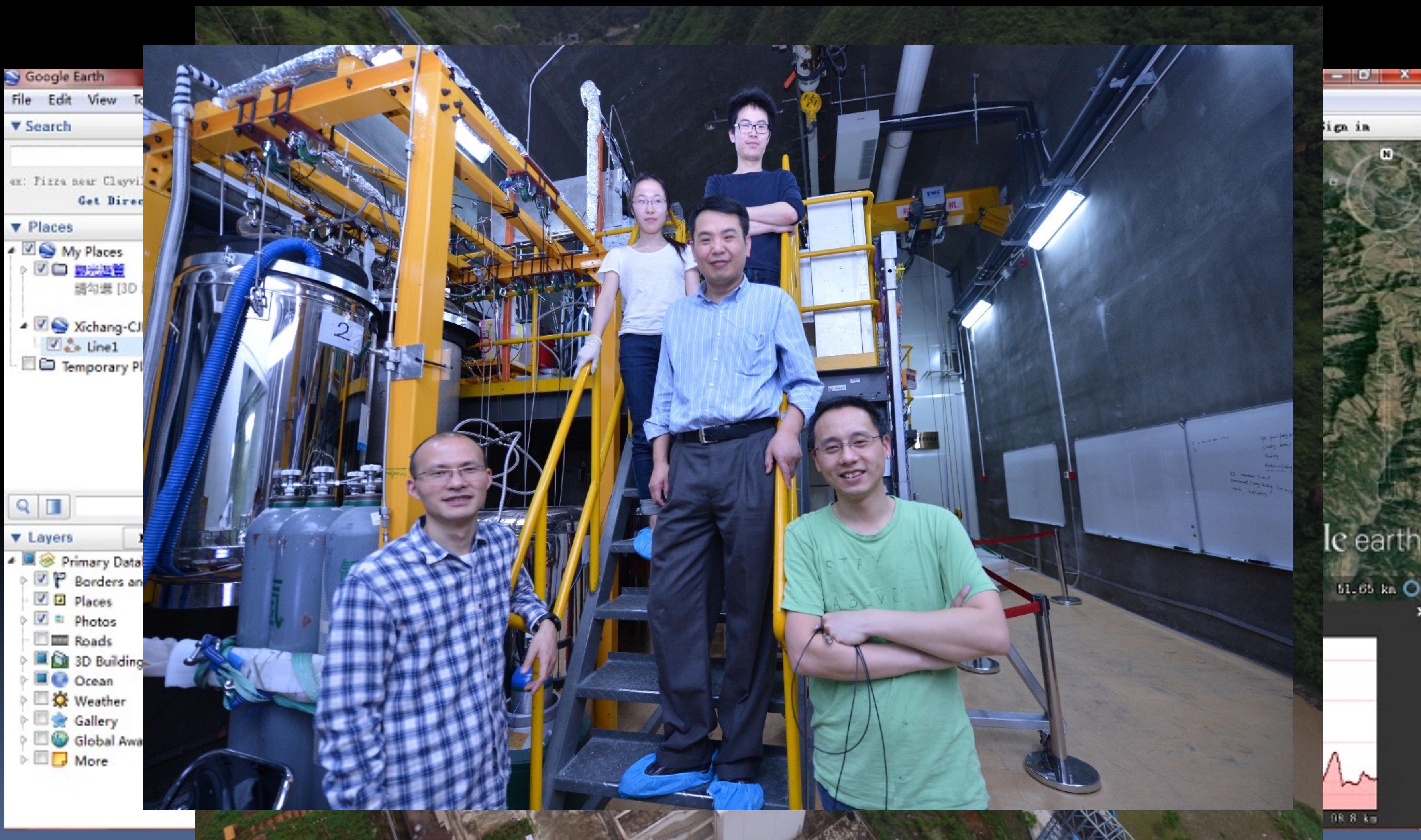


Detector capability:

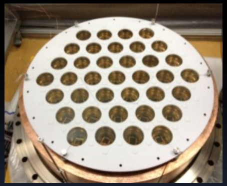
- Large monolithic target
- 3D reconstruction and fiducialization
- Good ER/NR rejection
- Calorimeter capable of seeing a couple of photons/electrons

PandaX初创团队

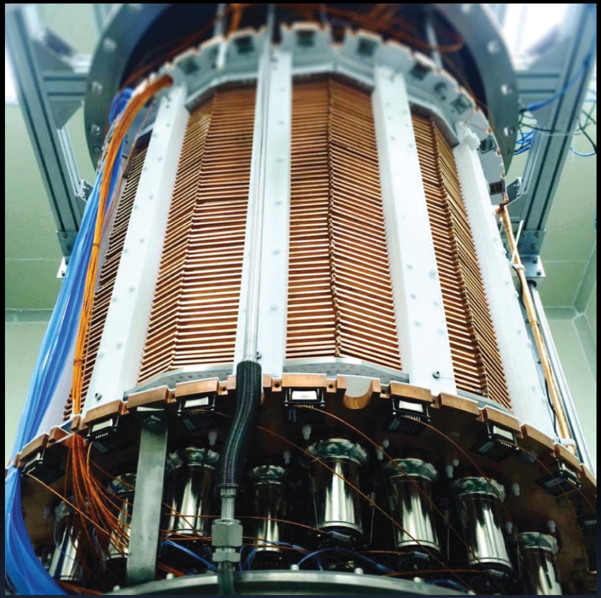
锦屏实验室里的PandaXer

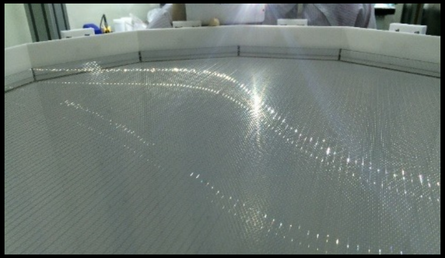


PandaX-I实验



PandaX-II实验



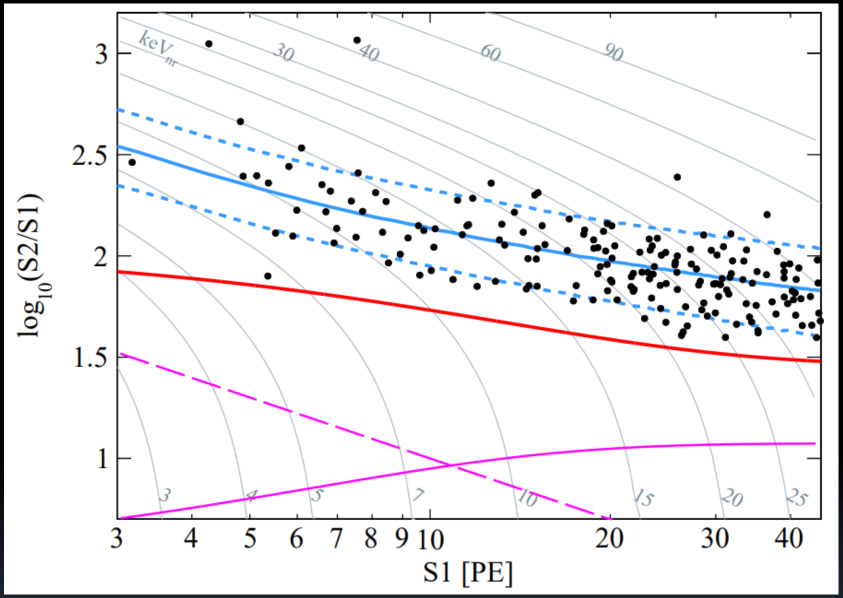


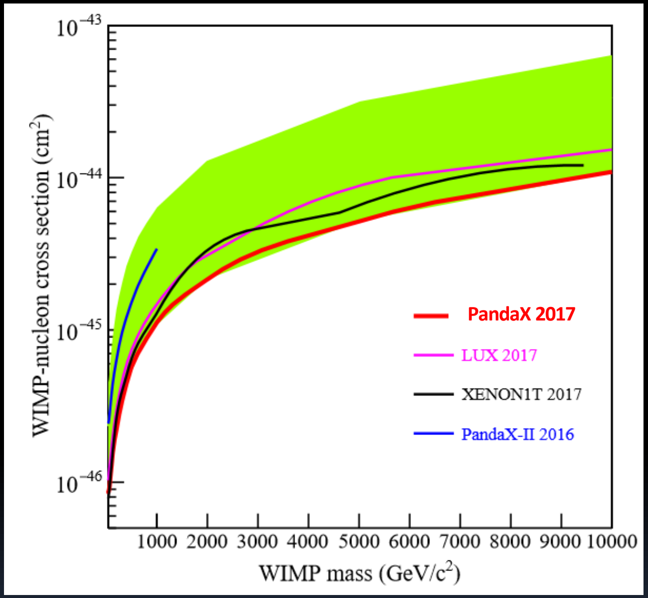
580kg

↑

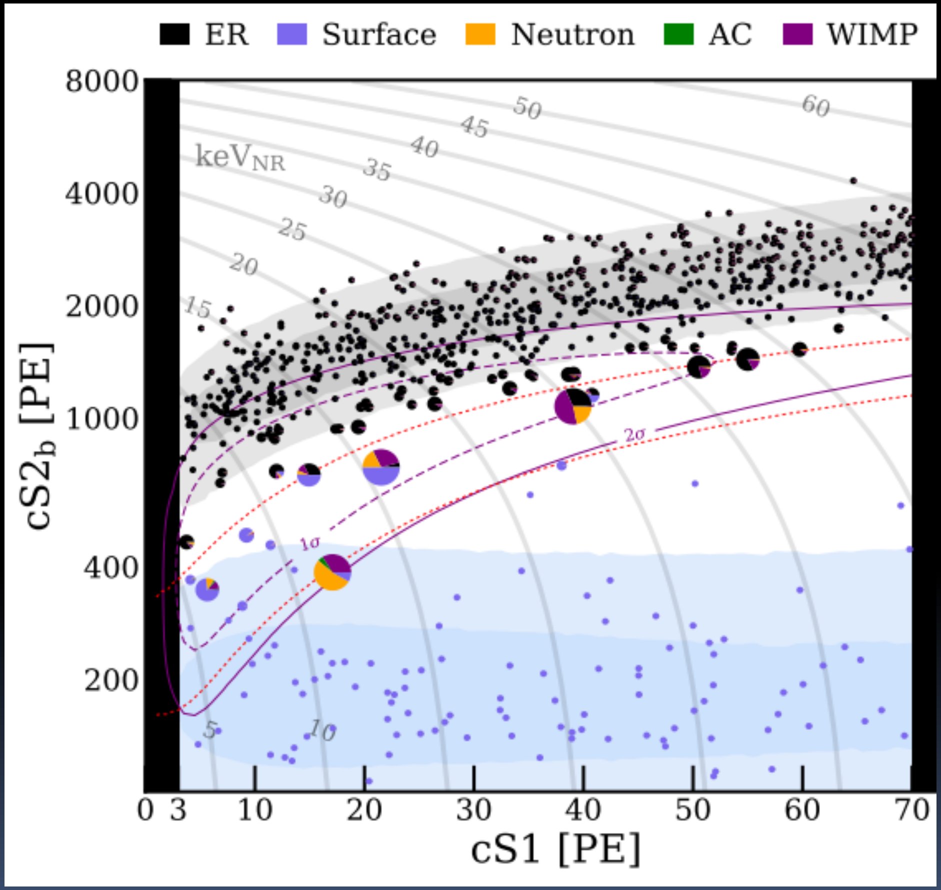
120kg

“你追我赶”


keV$_{nr}$
30
40
60
90
3
4
5
7
10
15
20
25
log$_{10}$(S2/S1)
3
2.5
2
1.5
1
3 4 5 6 7 8 9 10 20 30 40
S1 [PE]

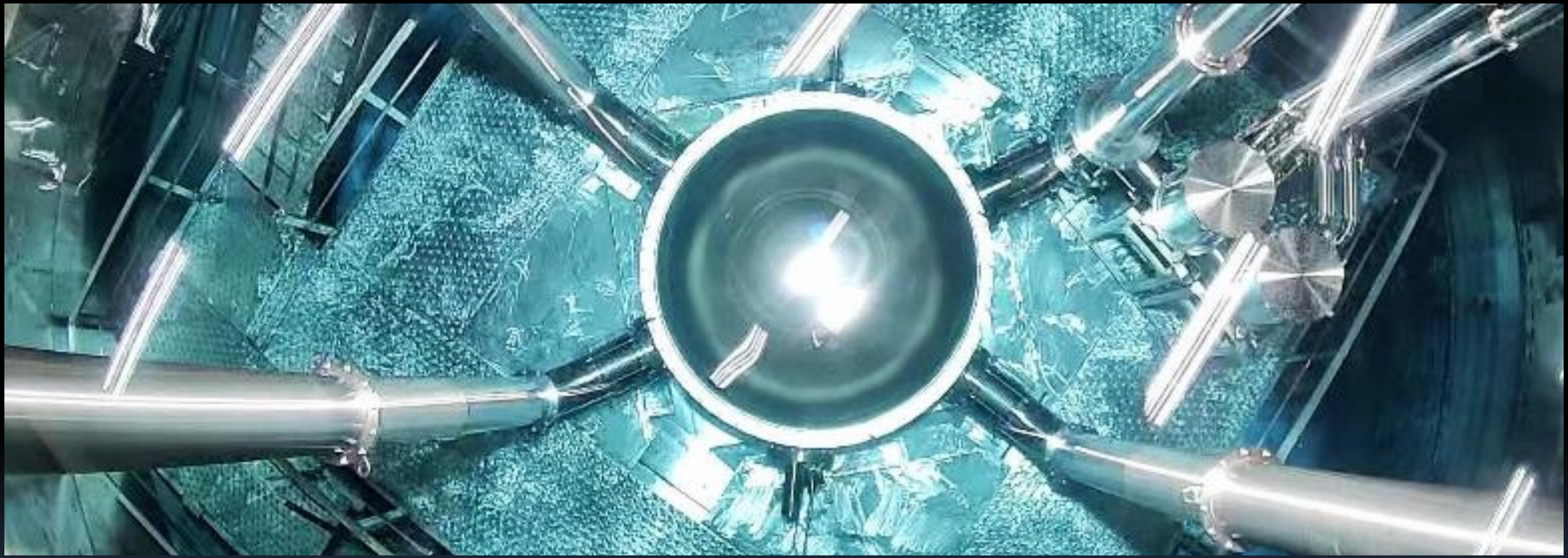

PandaX 2017
LUX 2017
XENON1T 2017
PandaX-II 2016
WIMP-nucleon cross section (cm^2)
10^{-43}
10^{-44}
10^{-45}
10^{-46}
1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
WIMP mass (GeV/c^2)

意大利人带来的“惊喜”

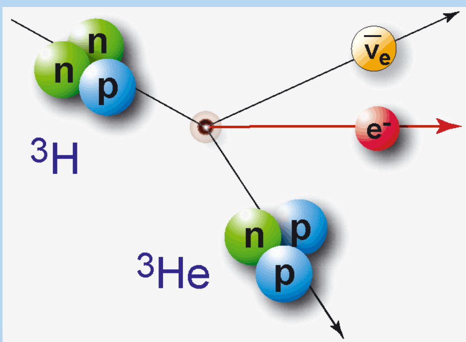


ER Surface Neutron AC WIMP
keV$_{NR}$
5 10 15 20 25 30 35 40 45 50 60
1σ 2σ
8000 4000 2000 1000 400 200
cS2$_b$ [PE]
0 3 10 20 30 40 50 60 70
cS1 [PE]

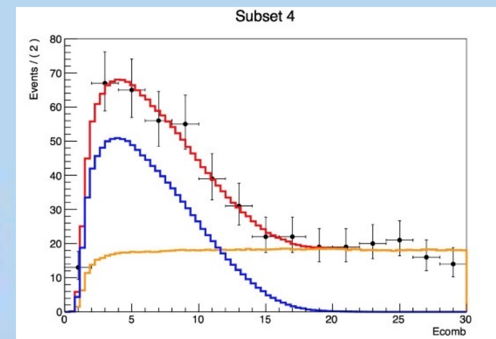
PandaX-4T:新一代探测器



氚:PandaX探测器内的“病毒”

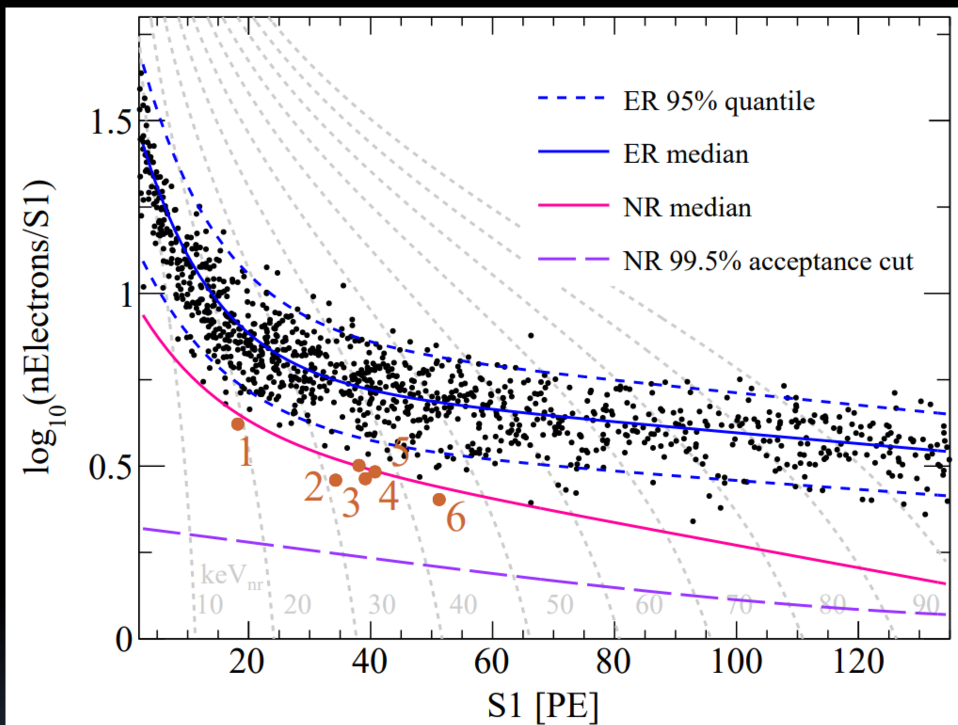


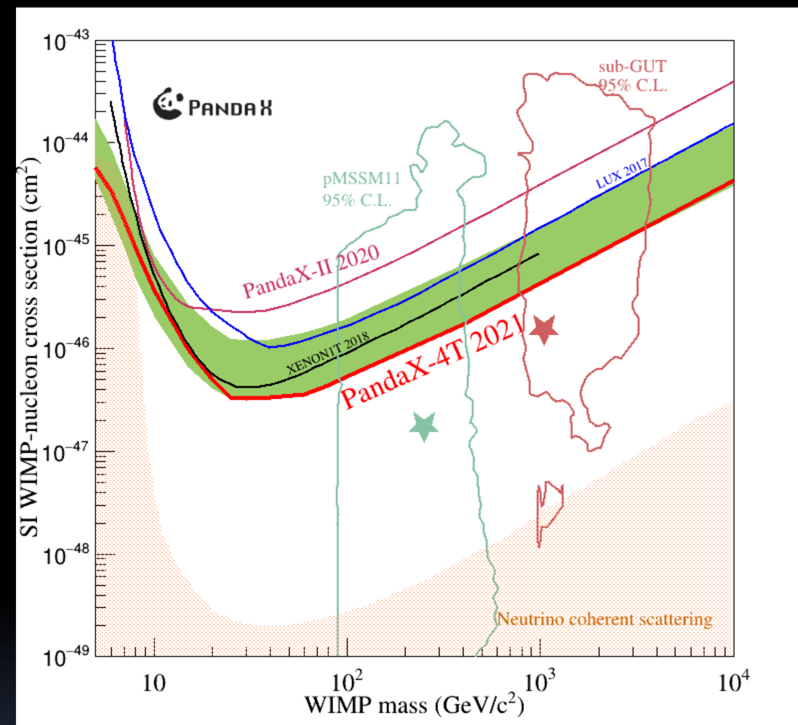
氚：^3H



每公斤氙中20个！

氚的平均寿命为18年， 3 吨氙中的氚的平均衰变率为多少？


ER 95% quantile
ER median
NR median
NR 99.5% acceptance cut
log10(nElectrons/S1)
S1 [PE]
keVnr
1
2
3
4
5
6


PANDA X
SI WIMP-nucleon cross section (cm2)
WIMP mass (GeV/c2)
pMSSM11
95% C.L.
sub-GUT
95% C.L.
LUX 2017
PandaX-II 2020
XENON1T 2018
PandaX-4T 2021
Neutrino coherent scattering

nature

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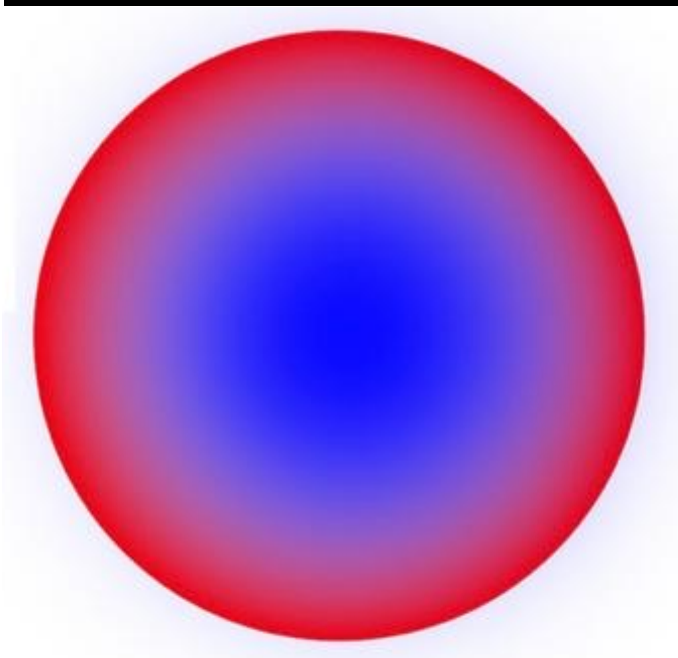
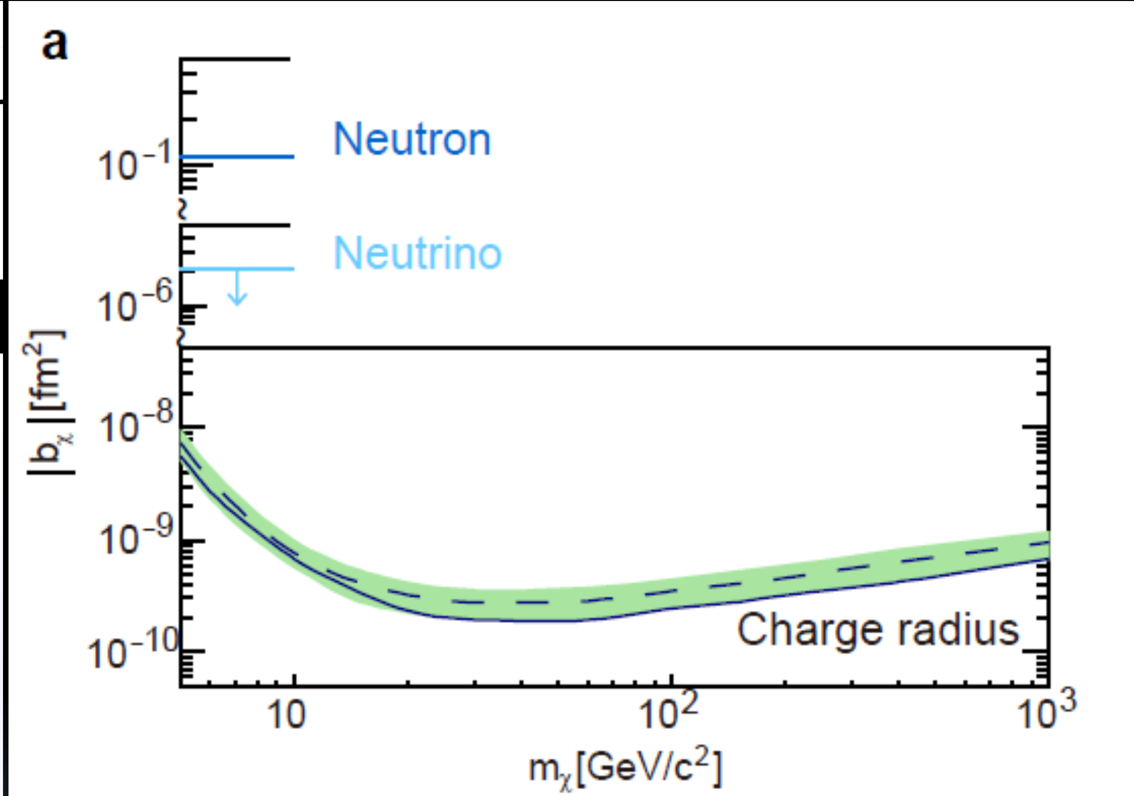
Article | Published: 17 May 2023

Limits on the luminance of dark matter from xenon recoil data

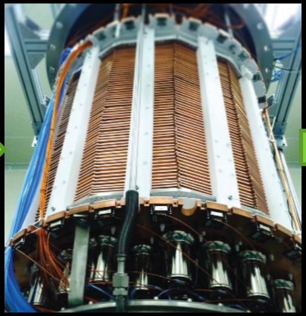




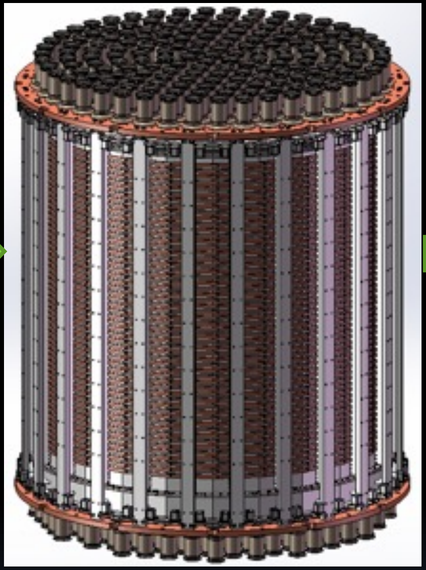
暗物质的电荷半径比质子小10万倍以上

步步升级

PandaX一期
120公斤



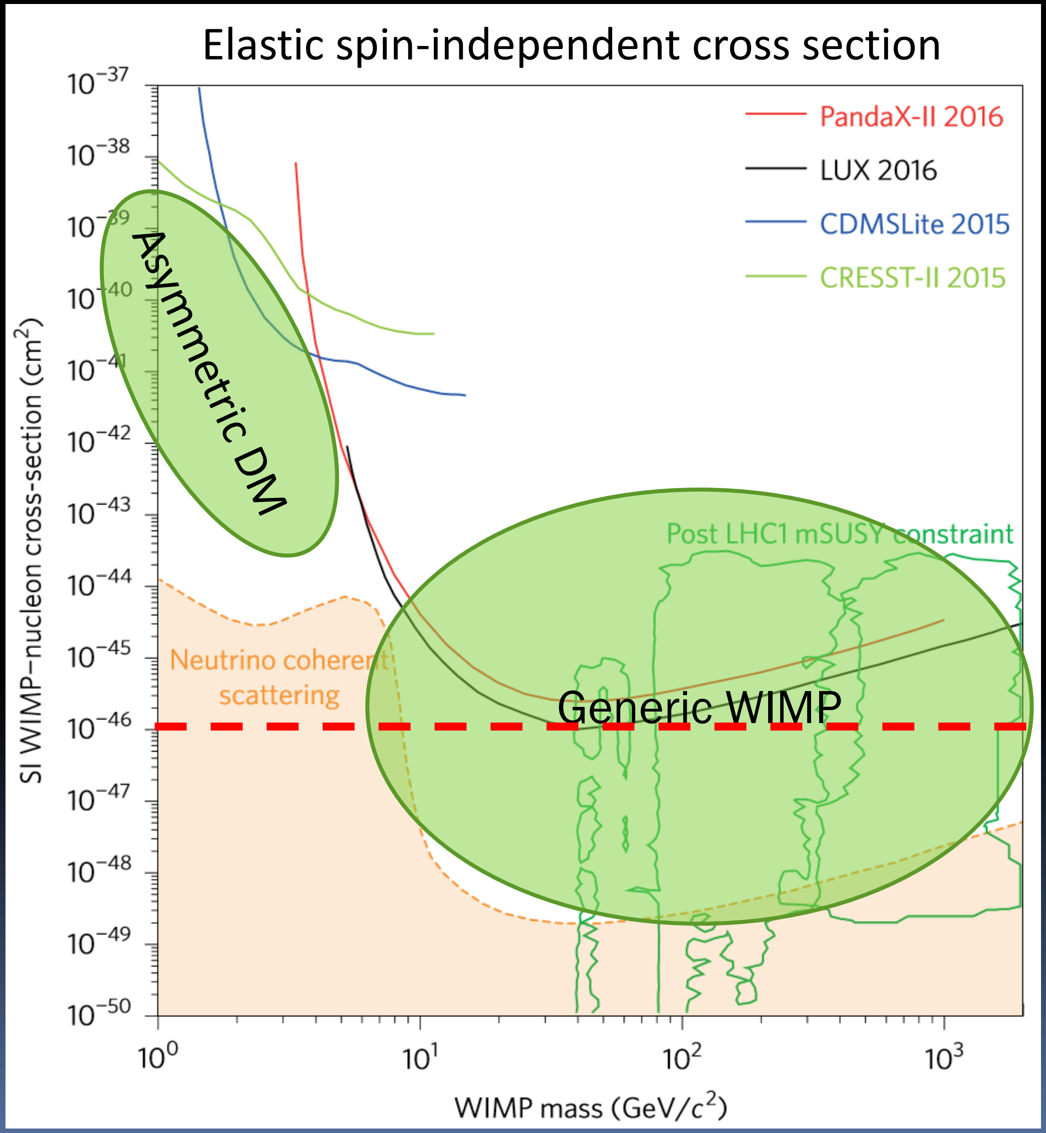
PandaX二期
580公斤



PandaX-4T

PandaX-xT

“轮回”：中微子本底！！

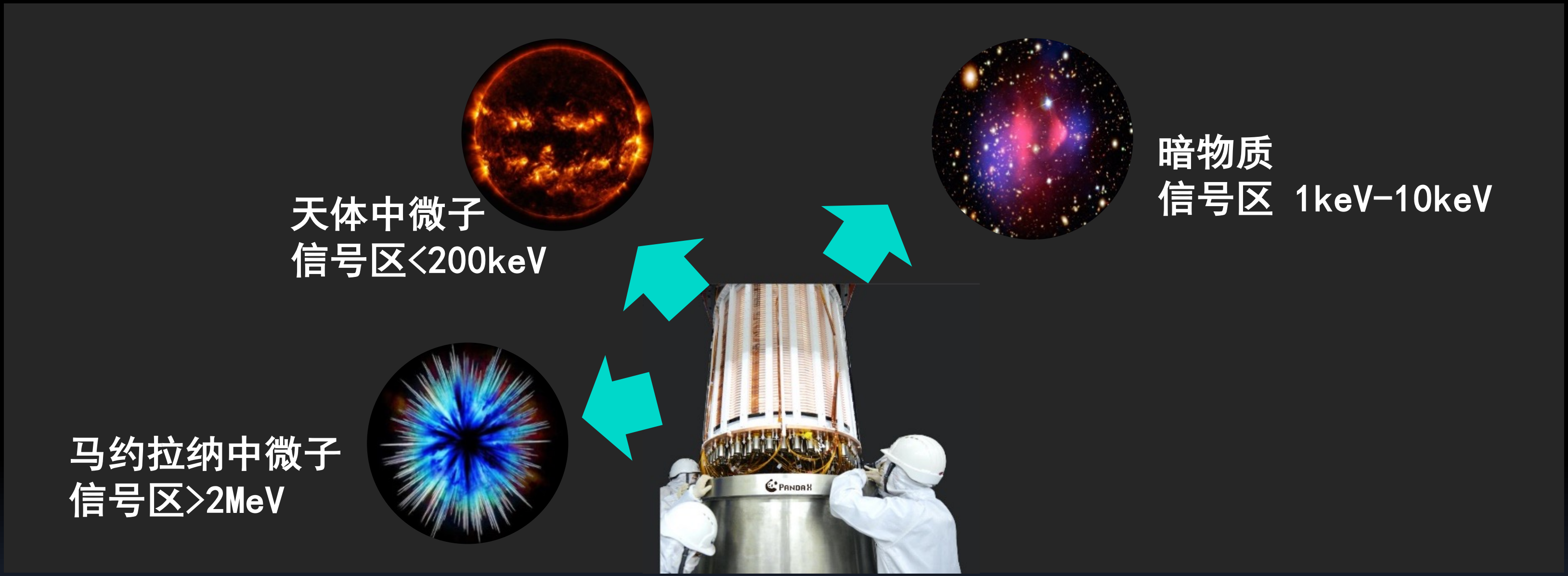


a few events/100kg/year

Nature Physics 13, 212–216 (2017)

4.最不像中微子实验的中微子实验

PandaX：其他科学目标



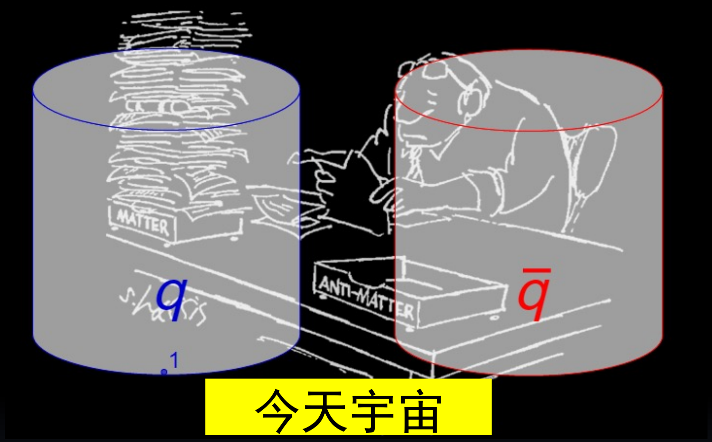
Majorana particles

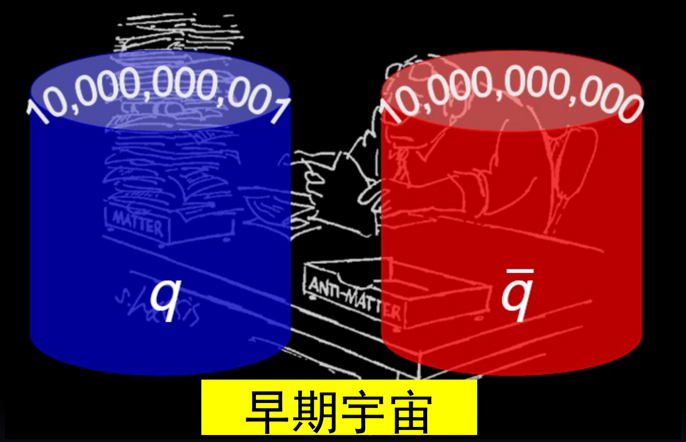
Majorana mass term:

$$m_R \overline{\nu_R^{\,C}} \nu_R$$

- Majorana, 1937
- Can be tested via neutrinoless double β decay, W. Furry, 1939

宇宙中的反物质是如何消失的？

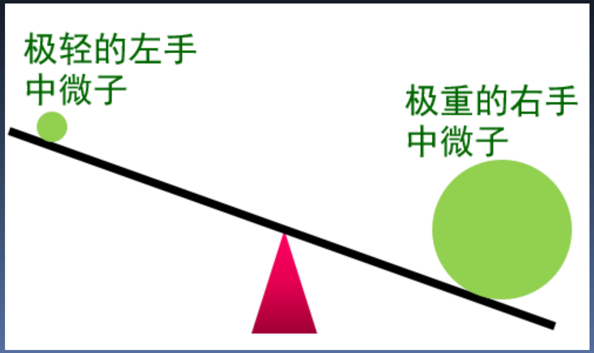




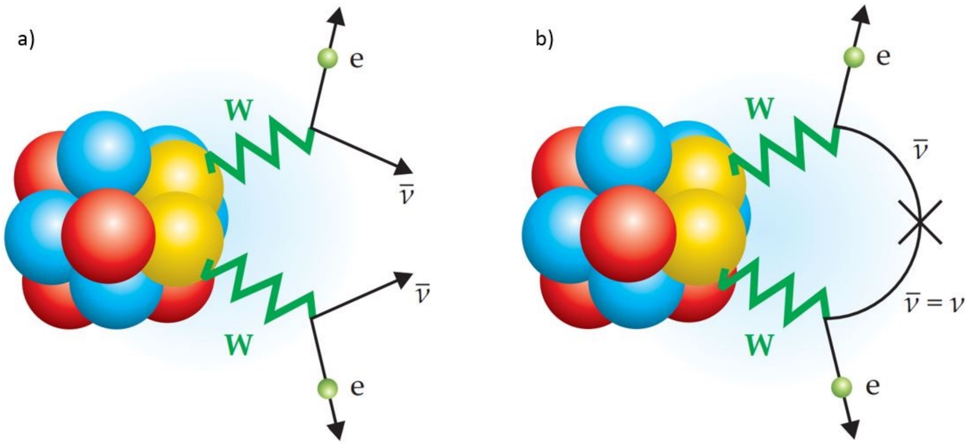
宇宙进化中的“基因突变” —十亿分之一的不对称，究竟从何而来？

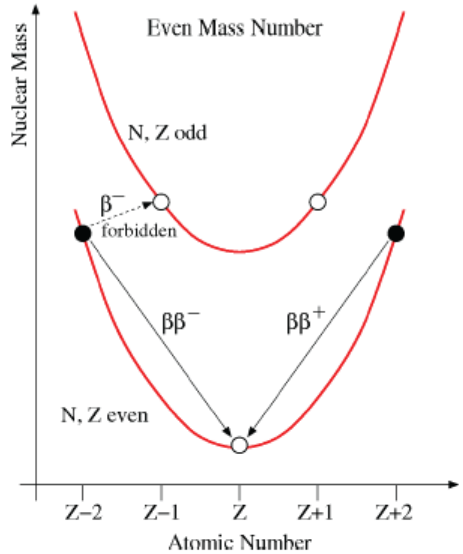
“轻子创世纪”

- 柳田勉等（1987），马约拉纳中微子是早期宇宙中物质-反物质不对称性的来源（Leptongenesis)
  - 中微子是马约拉纳粒子
  - 中微子“跷跷板”质量来源
  - 中微子有CP破缺



无中微子双贝塔衰变

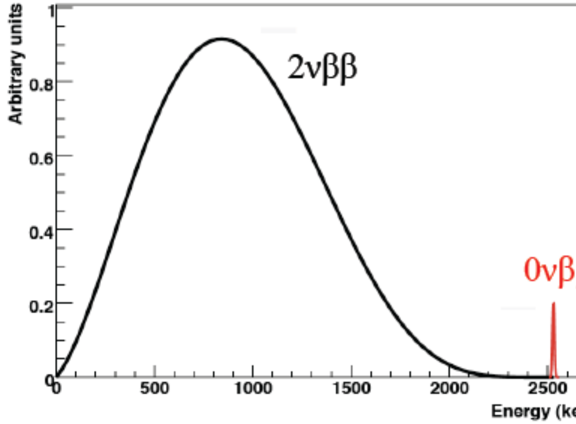




- Neutrinoless double beta decay
  - The nature of neutrinos, Dirac or Majorana
  - lepton number violation
- Extremely rare events T > 10^{24} year.

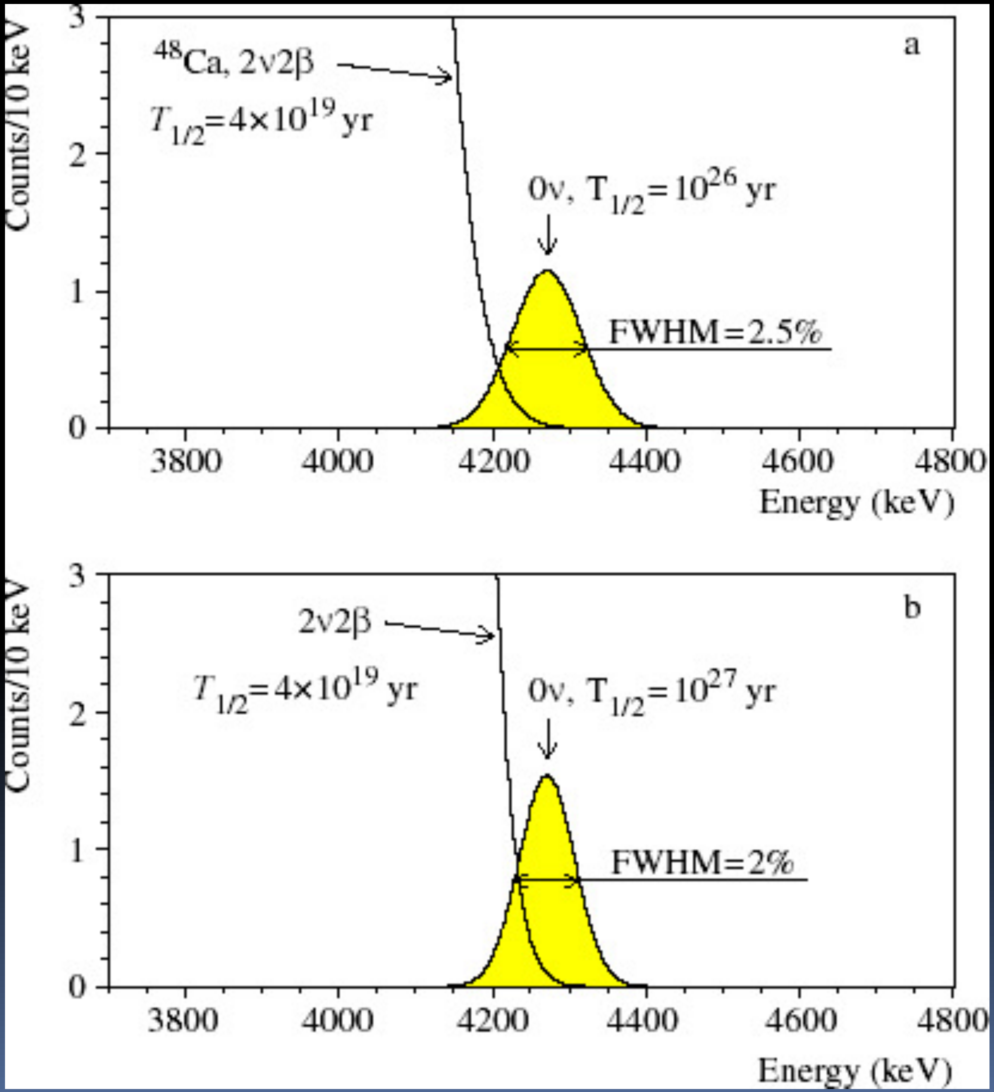
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

$$m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2\, m_i\right|.$$



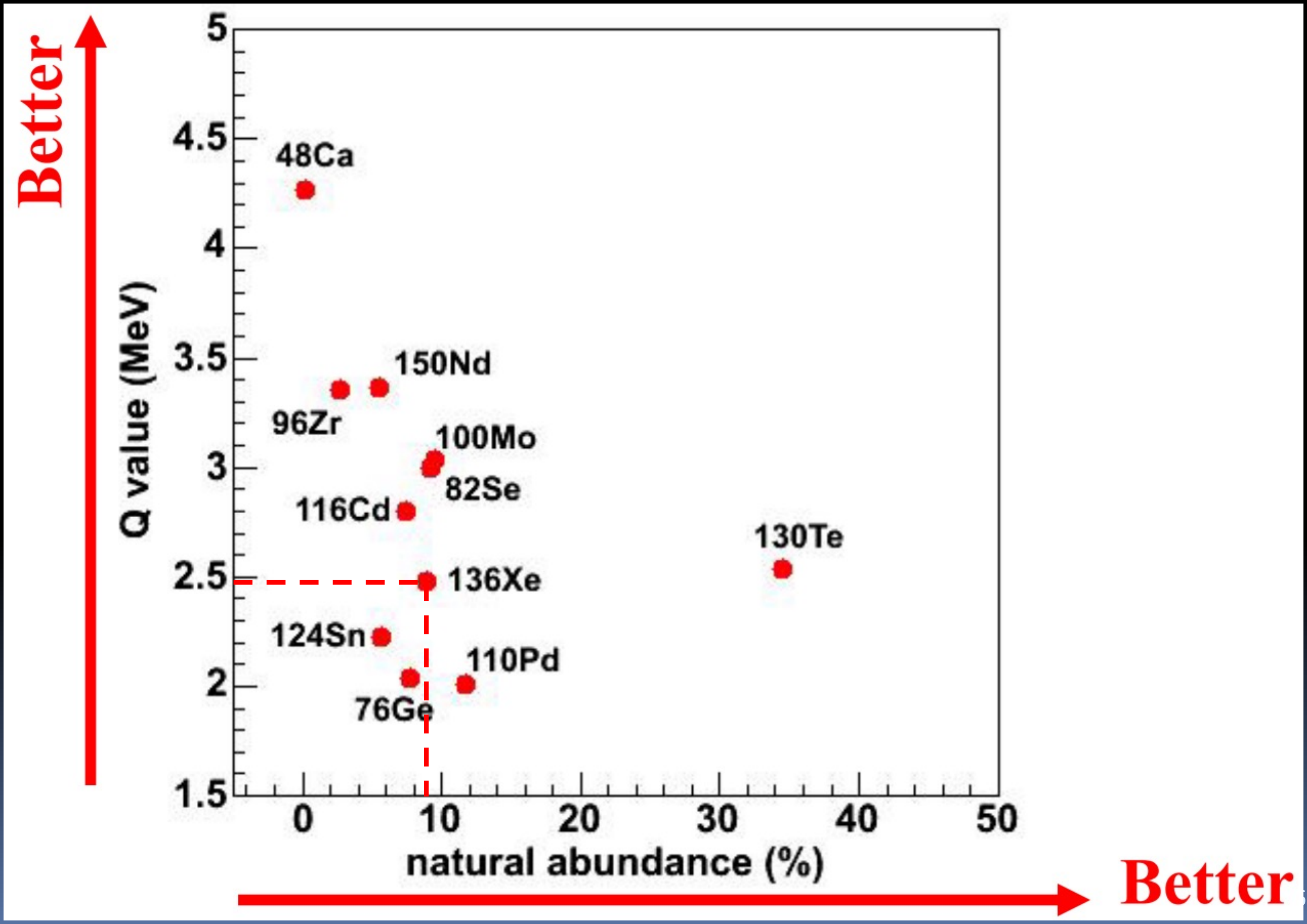
Sum of electrons energy

无中微子双贝塔衰变



^{48}Ca, 2ν2β
$T_{1/2}$=4×10^{19} yr
0ν, $T_{1/2}$=10^{26} yr
FWHM=2.5%
a
Counts/10 keV
Energy (keV)
3800 4000 4200 4400 4600 4800
2ν2β
$T_{1/2}$=4×10^{19} yr
0ν, $T_{1/2}$=10^{27} yr
FWHM=2%
b
Counts/10 keV
Energy (keV)

Naturally occurring double-beta-



Front runners

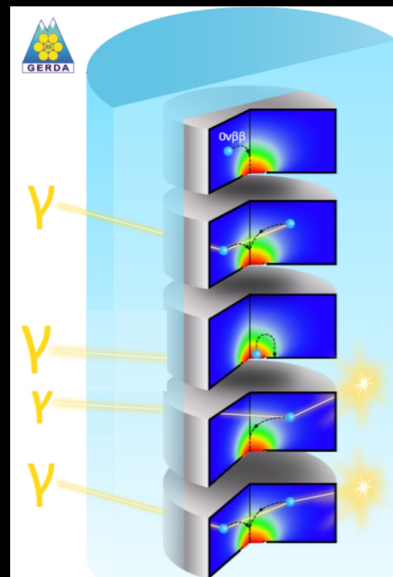
Experiment	Isotope	Resolution (keV)	Efficiency	Phase	Mass (kg)	Exposure (kg·year)	Background rate (counts/(keV · kg · y))	Sensitivity (meV)
CUORE	^{130}Te	5	0.8	2015–2017 (I) 2018–2020 (II)	200 200	600 600	10^{-1} 4×10^{-2}	140 85
EXO	^{136}Xe	100	0.7	2012–2014 (I) (II) 2016–2020	160 160	480 800	7×10^{-3} 5×10^{-3}	185 150
GERDA	^{76}Ge	5	0.8	2012–2014 (I) 2016–2020 (II)	18 35	54 175	10^{-2} 10^{-3}	214 112
KamLAND-Zen	^{136}Xe	250	0.8	2013–2015 (I) 2017–2020 (II)	360 35	1440 2700	10^{-3} 5×10^{-4}	97 60

Table 1.1: Proposals considered in the $m_{\beta\beta}$ sensitivity comparison. For each proposal, the isotope that will be used, together with estimates for detector performance parameters — FWHM energy resolution, detection efficiency and background rate per unit of energy, time and $\beta\beta$ isotope mass — are given. Two possible operation phases, with estimates for the detector mass and the background rate achieved, are given for each experiment.

^{130}Te/^{100}Mo

CUORE/CUPID

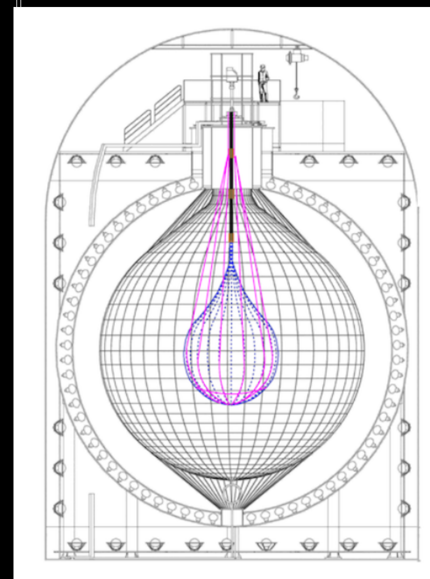
微量热器

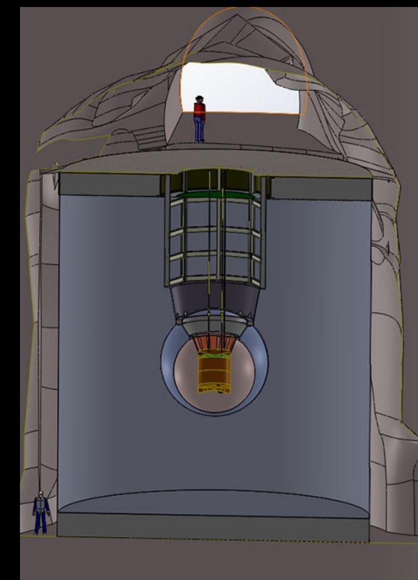


^{76}Ge

LEGEND family

高纯锗





^{136}Xe (8.9% natural abd.)

KamLAND-ZEN

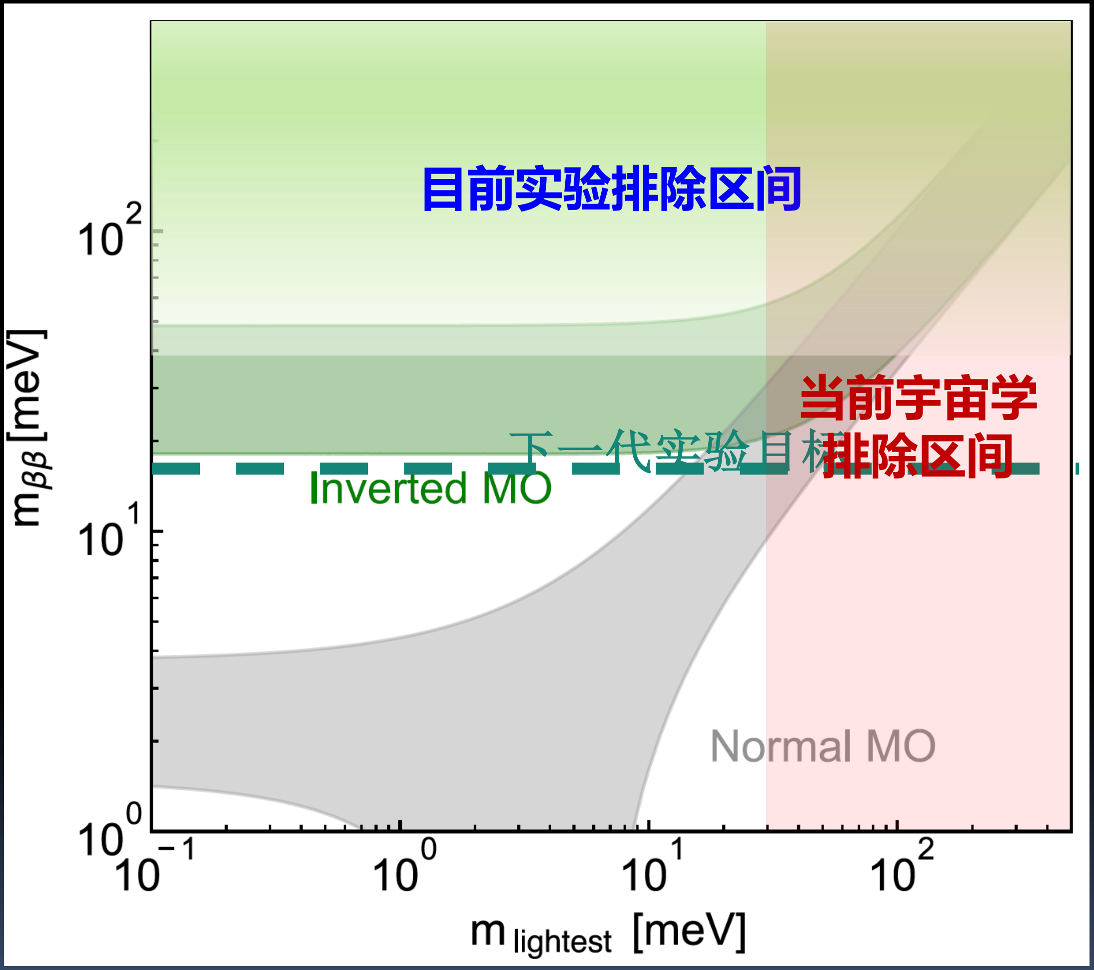
液体闪烁体

88

EXO/nEXO

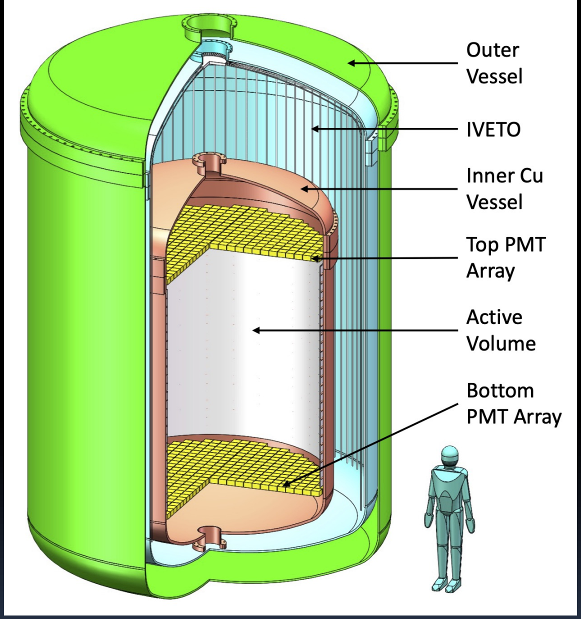
液氙时间投影室

信号在哪里?

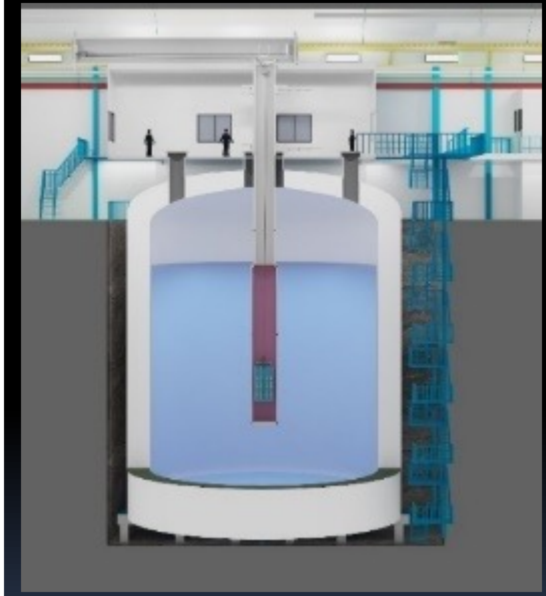

目前实验排除区间
当前宇宙学
排除区间
下一代实验目标
Inverted MO
Normal MO
$m_{\beta\beta}$ [meV]
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
$m_{lightest}$ [meV]

我国下一代的实验

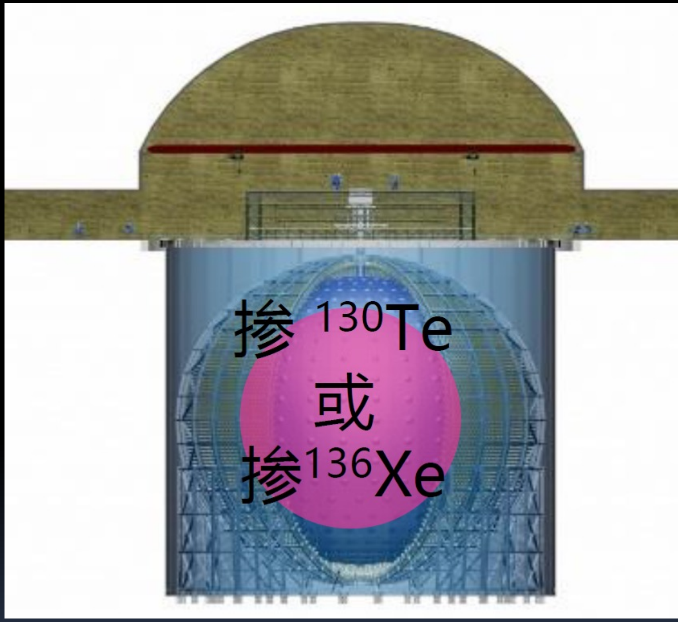
PandaX-xT



CDEX-1T



JUNO-DBD



总结

- 暗物质和中微子实验：Really Cool！

- 宇宙本原问题！揭秘时刻的时间表我们还不清楚

- 过去的近20年里，我国在这个方面已经开展了大量前沿研究

- 需要坚持！希望突破！