大气中微子

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内容提要：

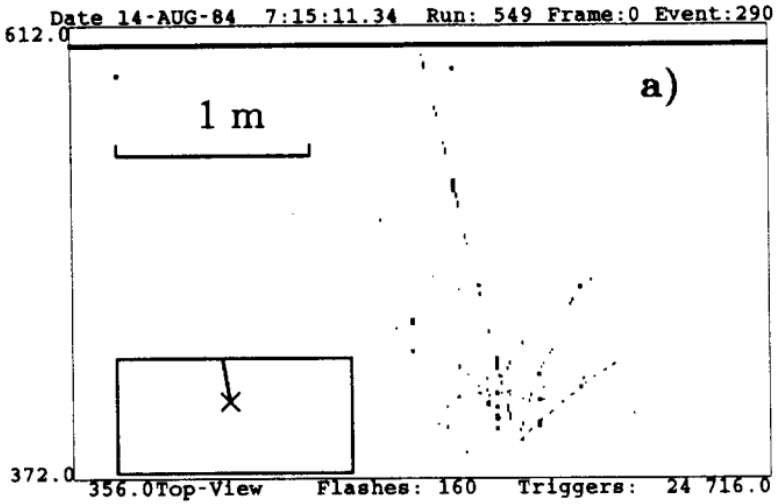
1. 大气中微子研究的历史和方向
2. 大气中微子的产生
3. 大气中微子传播
4. 大气中微子的探测方法
5. 实验进展

1. 研究历史与方向

早期实验

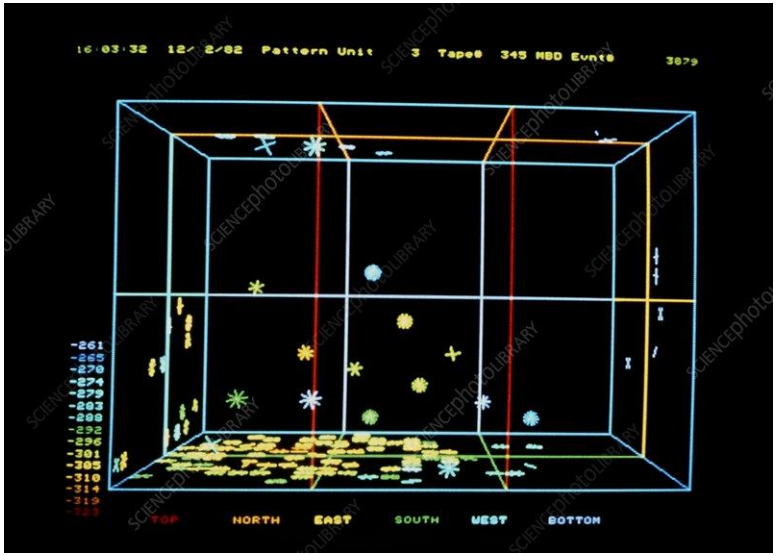
- Frejus: iron calorimeter with a total mass of 900 tons measuring 6m*6m*12.3m

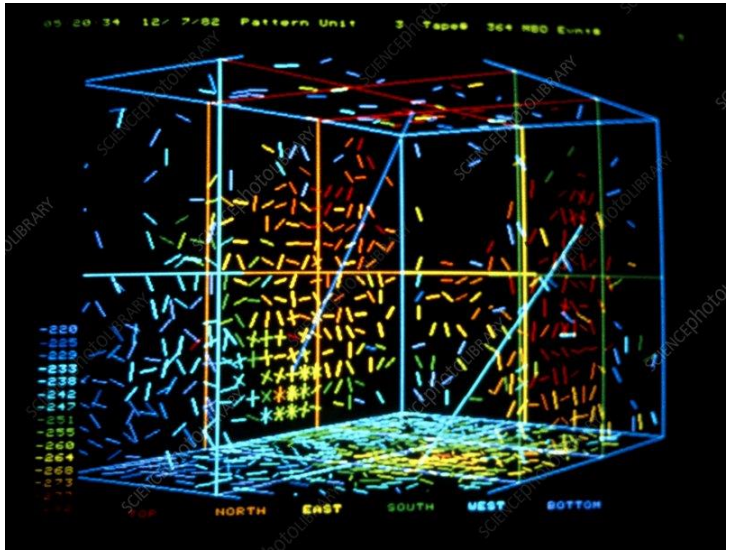
- NUSEX: a cube 3.5 m3 size made by 134 horizontal iron plates I em thick, interleaved with planes of limited streamer tubes I cm2 section.



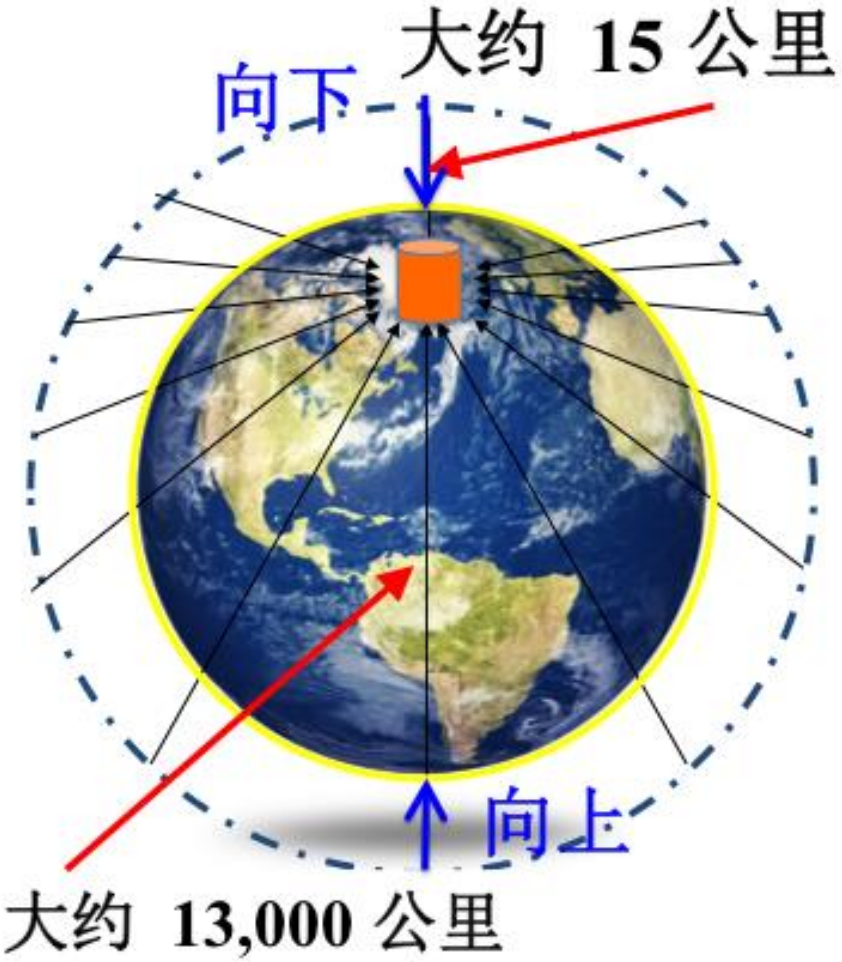
IMB detector

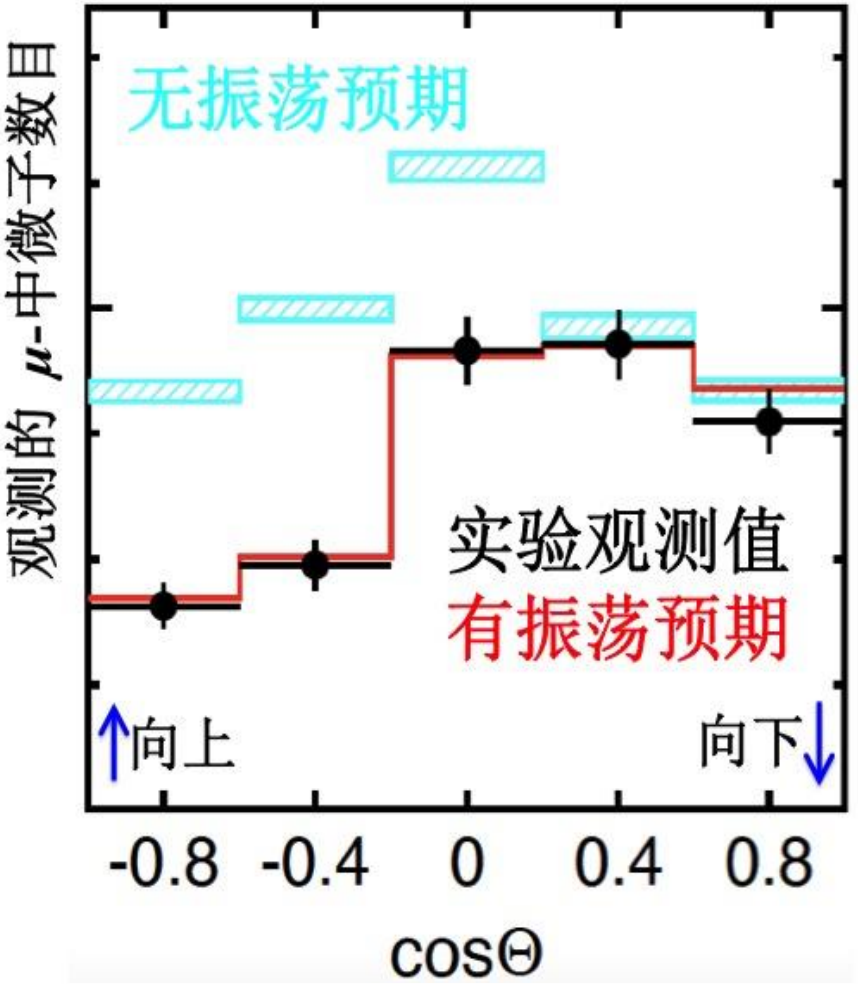
- Water Cherenkov Detector, like Kamiokande



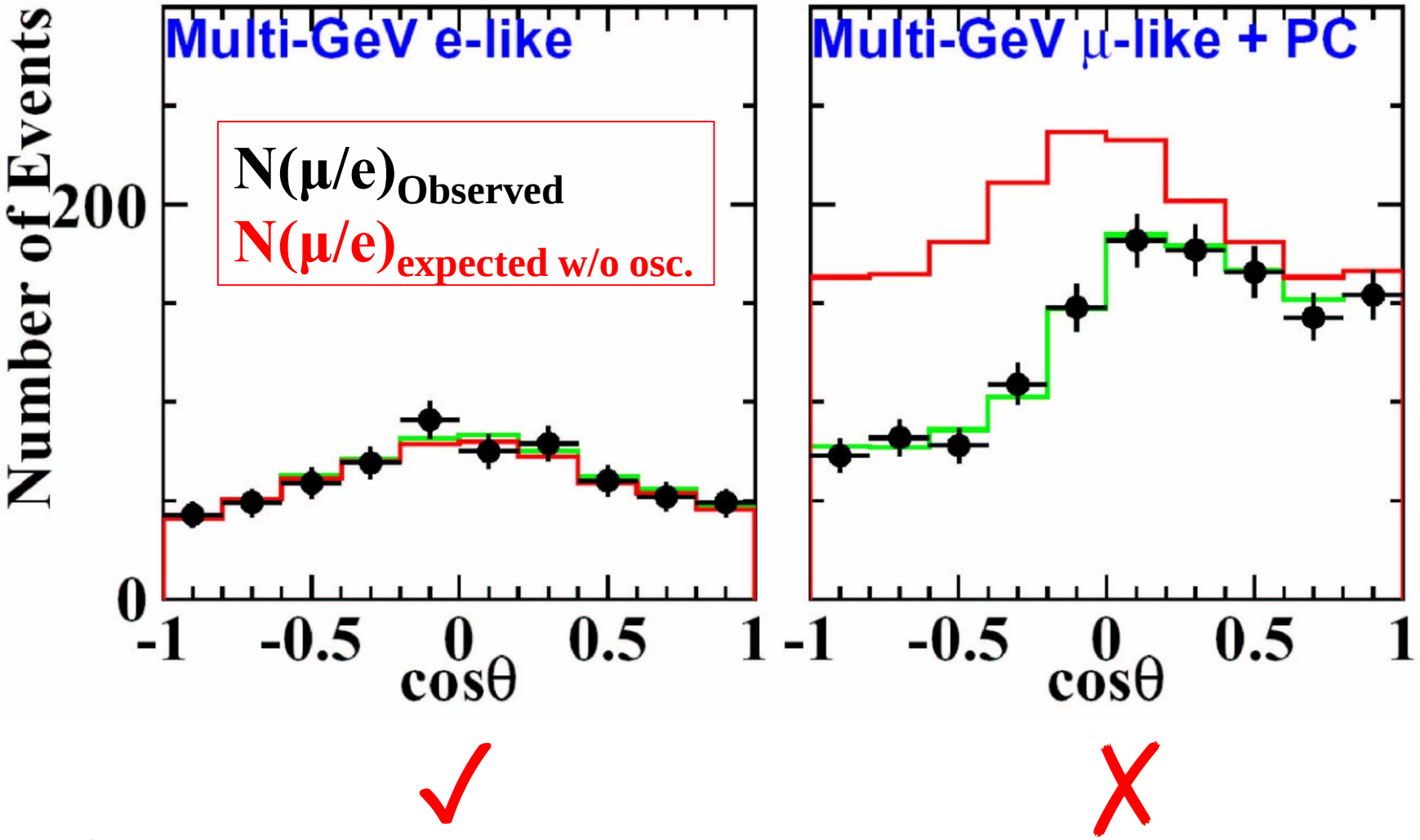


大气中微子的上下不对称性

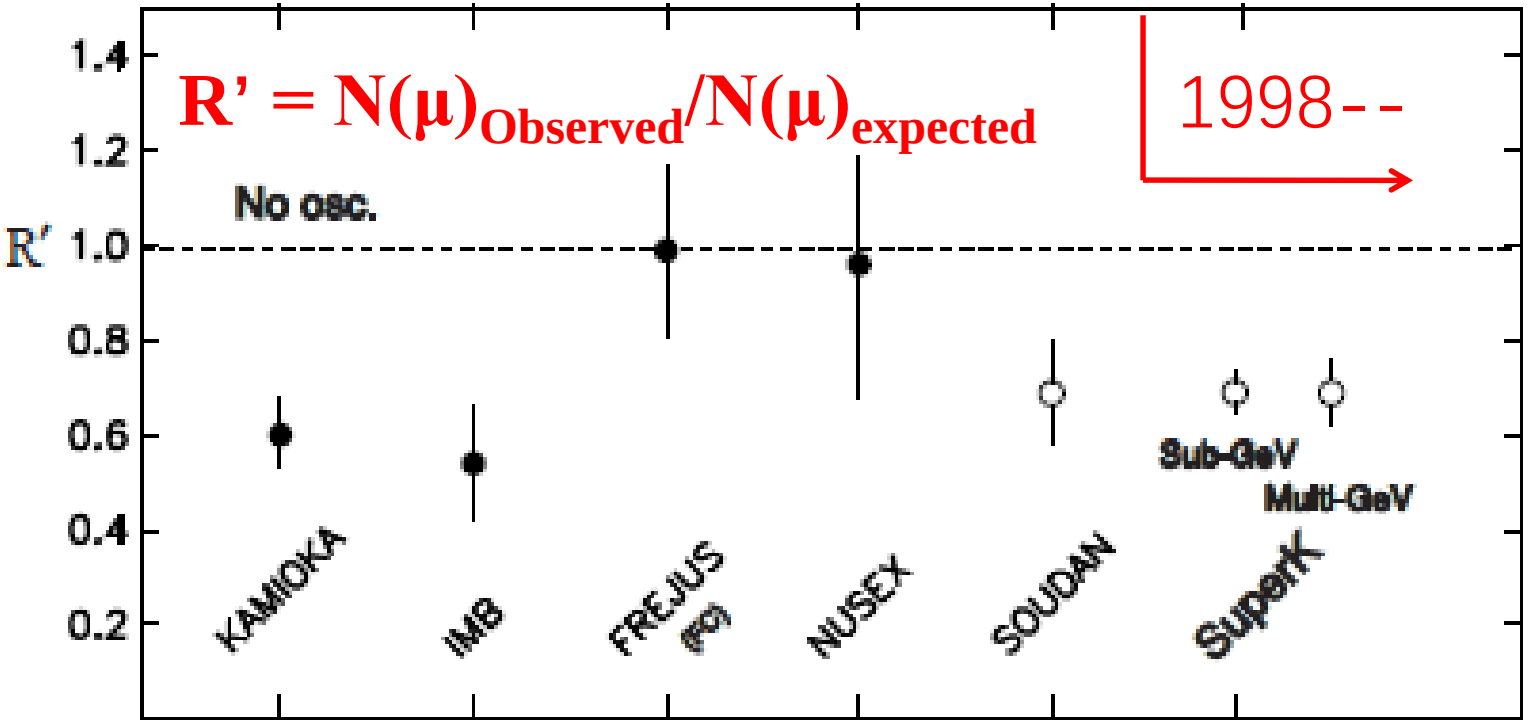




Super-Kamiokande的实验结果



大气中微子通量测量的总结

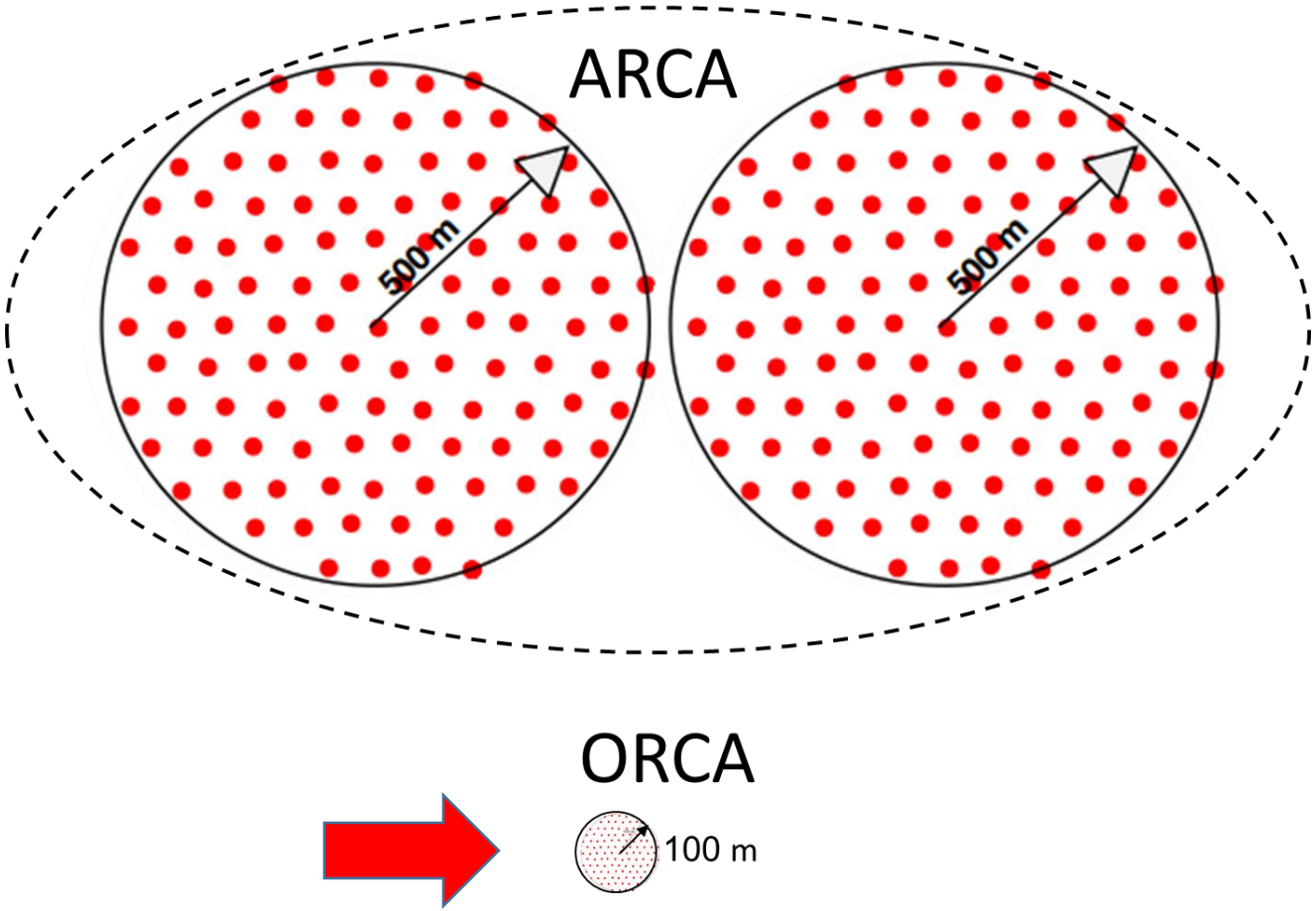


In early 1998, there are three observed hints of neutrino oscillation, and thus of neutrino mass. These hints are the behavior of solar neutrinos, the behavior of atmospheric neutrinos, and the results of the LSND experiment.

PDG1998

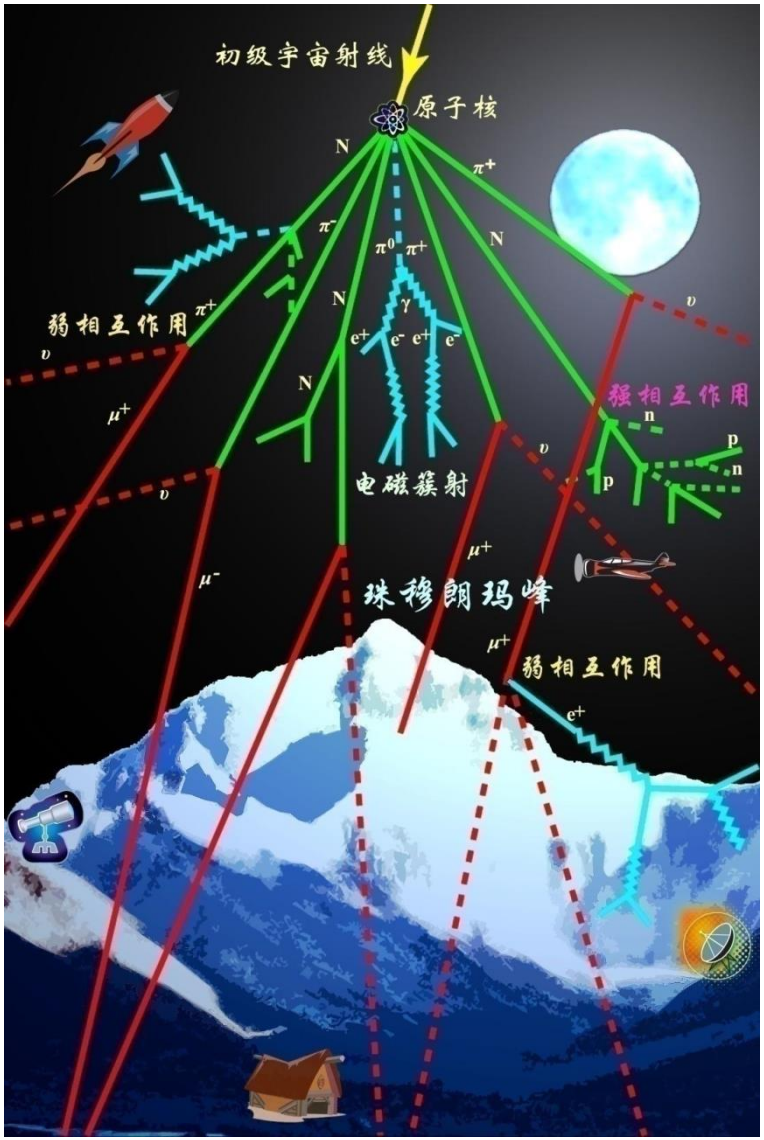
大气中微子研究正在朝质量谱顺序测量发展

- KM3NET (ORCA, ARCA); IceCube (DeepCore)



2. 大气中微子产生

大气中微子



大量的宇宙线粒子和大气分子相互作用，末态粒子多为K，π，μ，e

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

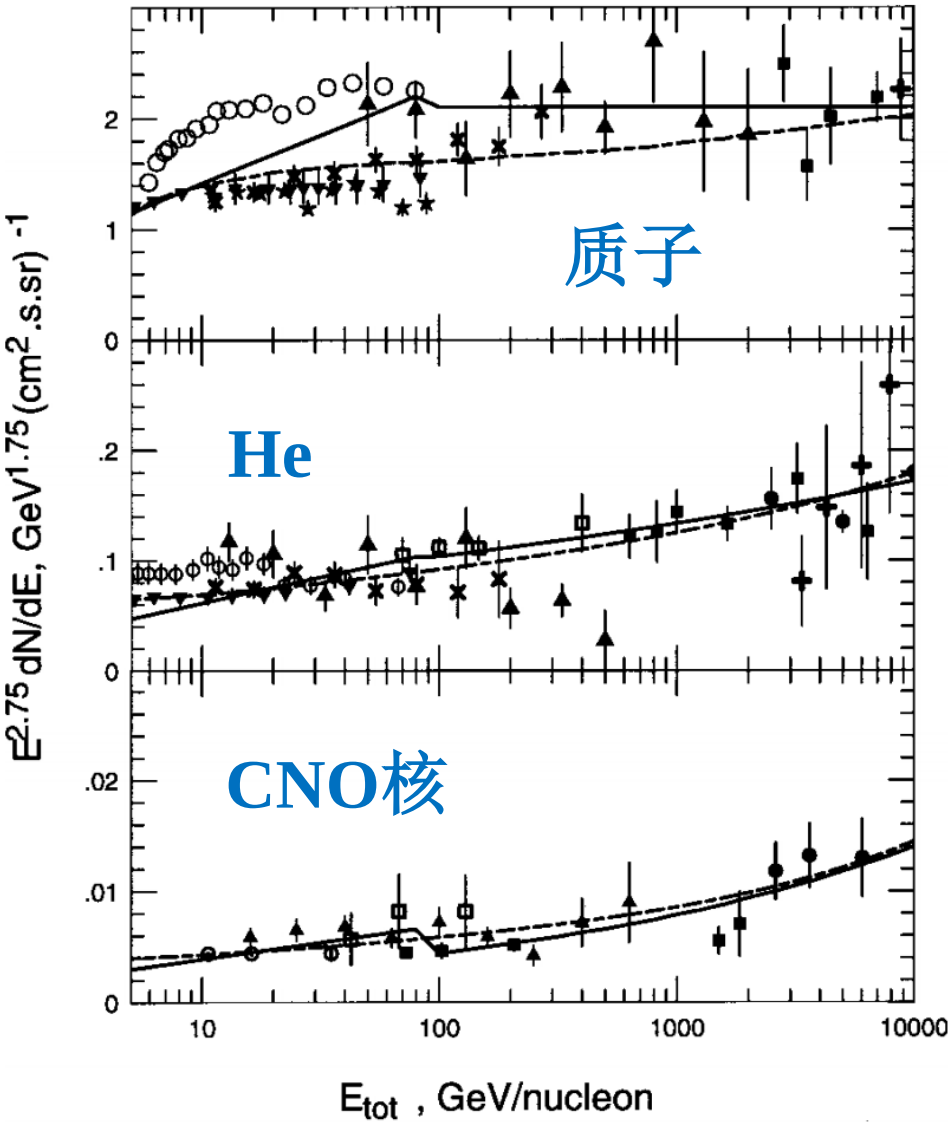
$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu$$

假定原初宇宙线能量为：E

中微子能量大约为：0.1 E

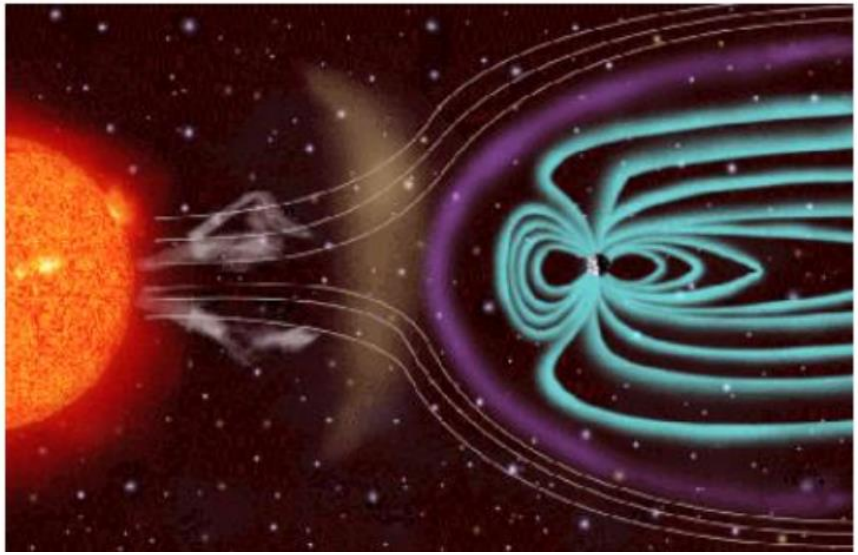
太空中的初级粒子成分

- 原处粒子（地球外空的粒子）：
  质子（95%），He（4.5%），CNO核等（0.3%）
- 通量基本上符合$E^{-2.7}$的规律
- <100 GeV 磁谱仪
- 1000-10^5 GeV 量能器等



太阳风的影响

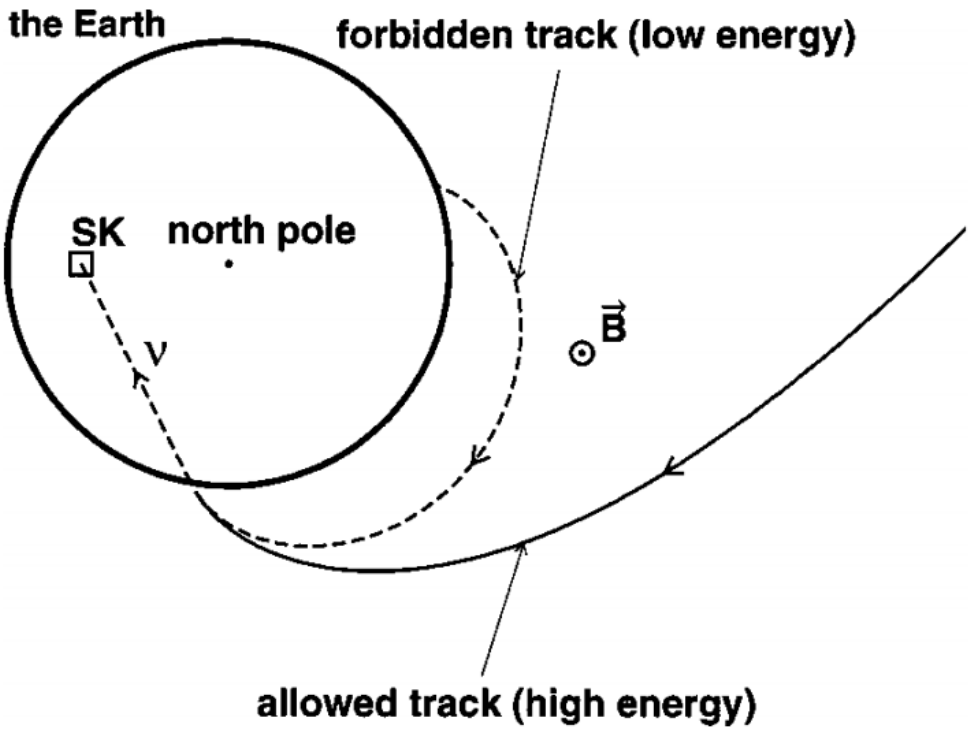
- 太阳风：往外抛射大量的物质，周期11年，影响磁场
- 对原初质子通量影响
  1 GeV，变化一倍
  10 GeV，10-20%

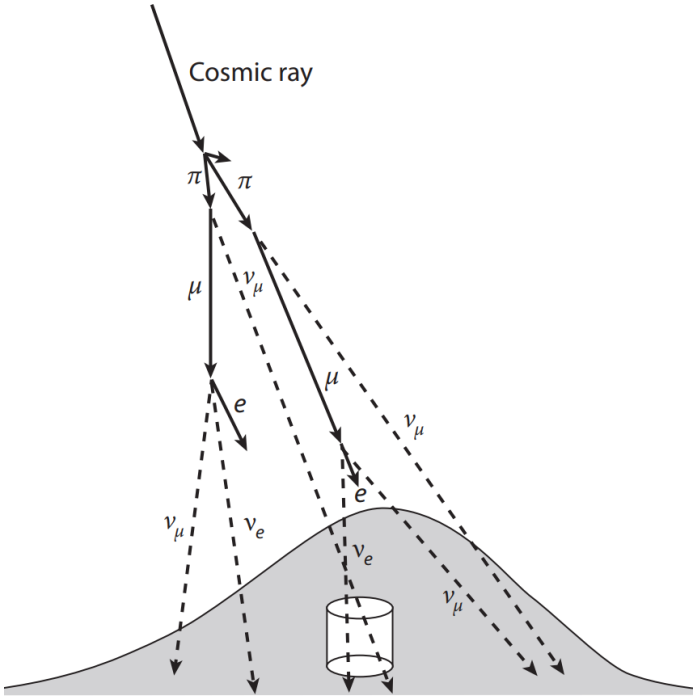


The white lines represent the solar wind; the purple line is the bow shock line; and the blue lines surrounding Earth represent its protective magnetosphere.

地磁场和刚度，地形

- 刚度（Rigidity）=momentum/charge
  小刚度的粒子无法到达探测器
- 地形也有重要影响



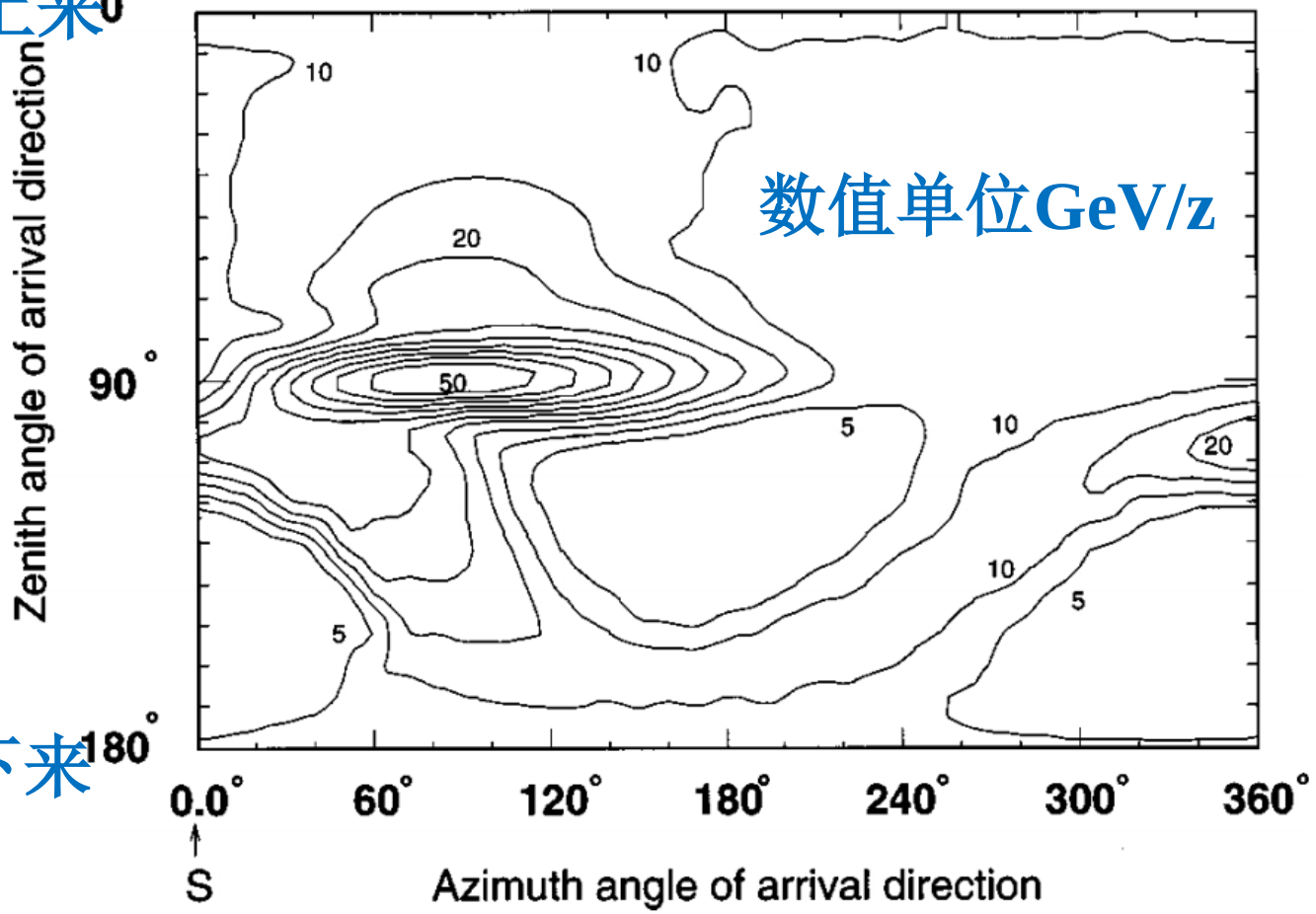


刚度阈值（例：神冈实验点）

从天上来

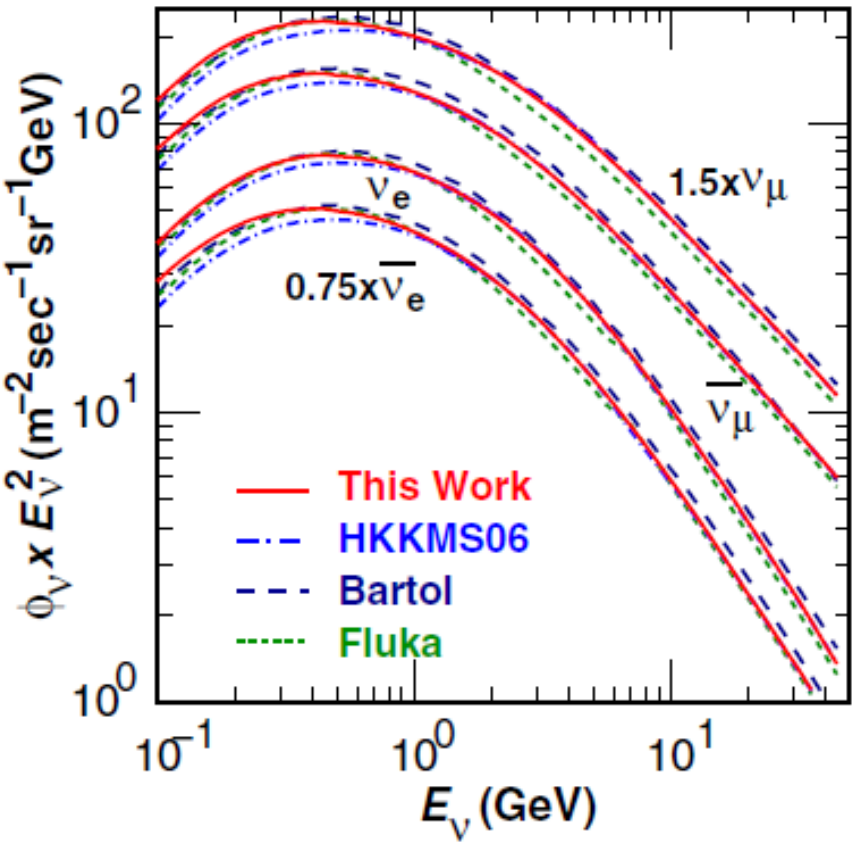
水平

从地下来

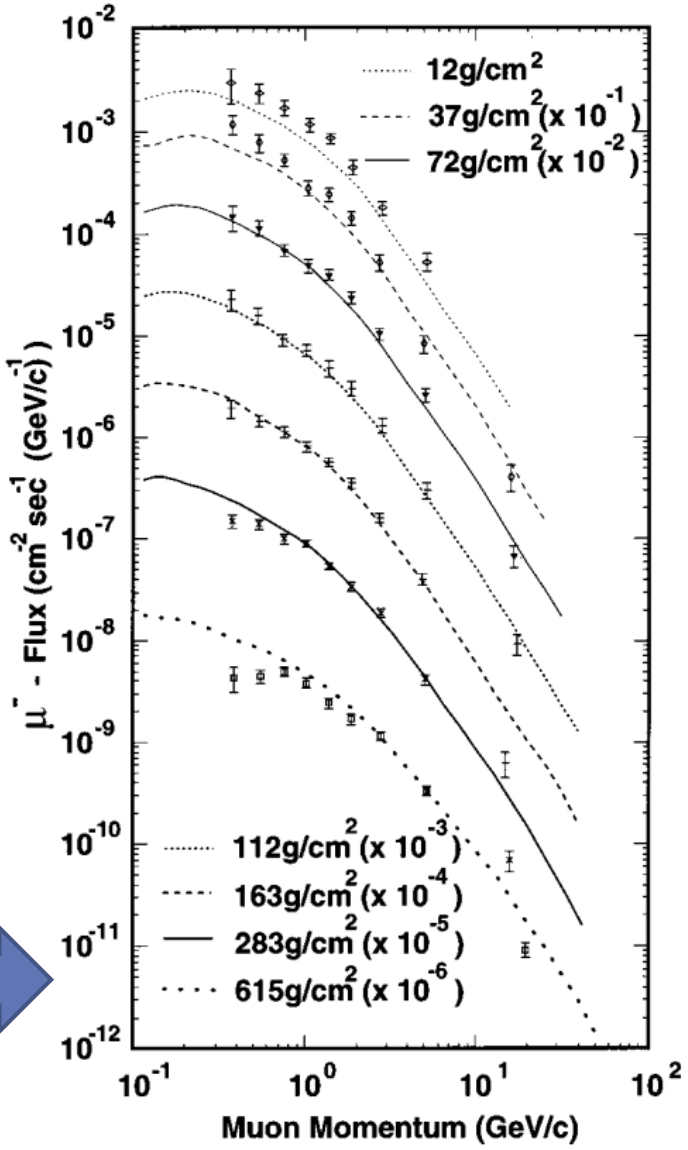


南　　东　　北　　西

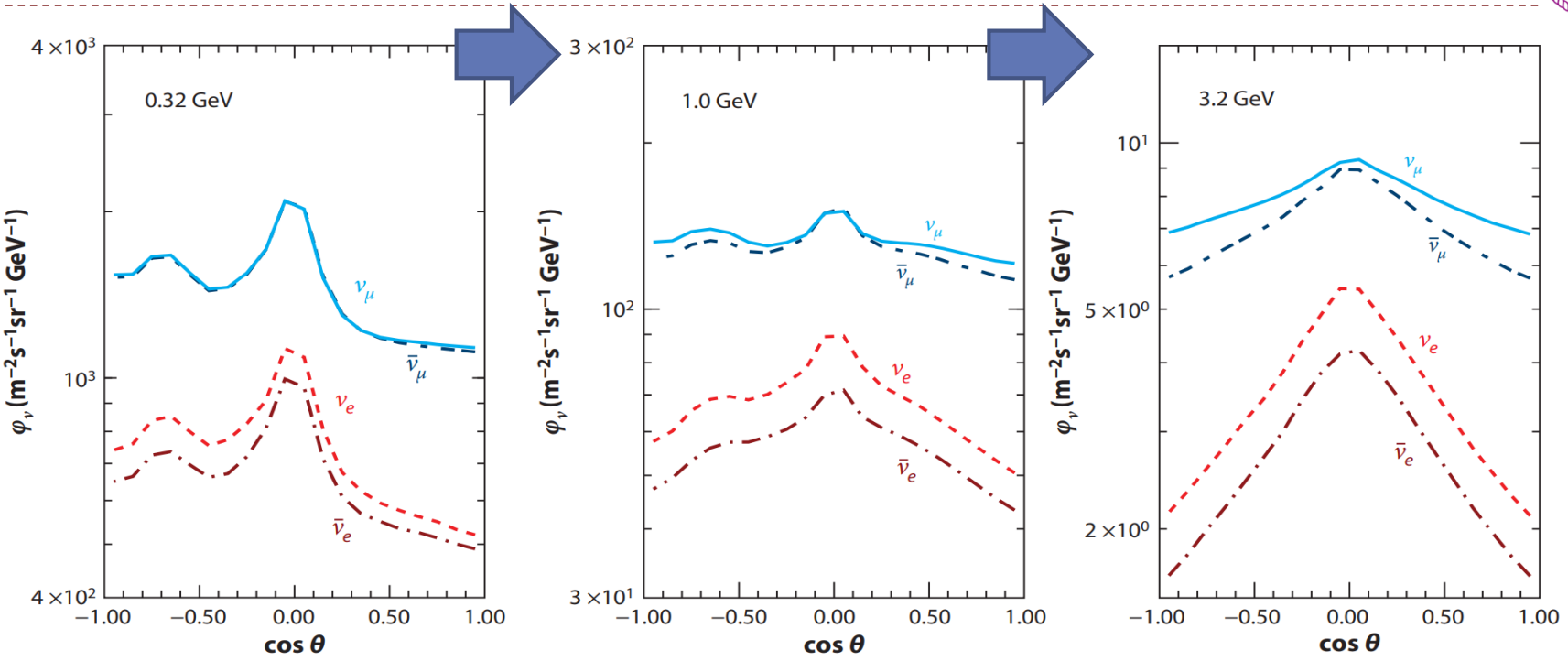
大气中微子能谱与验证



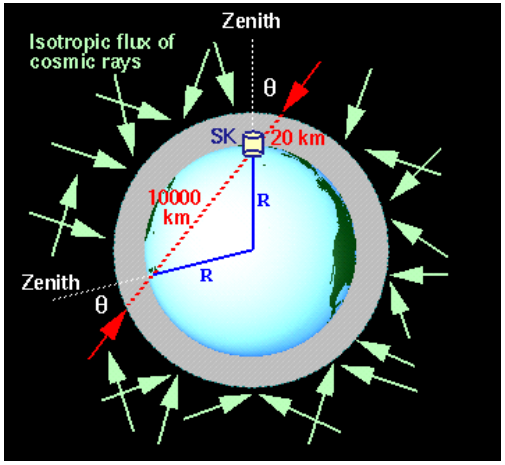
- 中微子通量的误差~10%
- 可以利用缪子通量和能谱验证



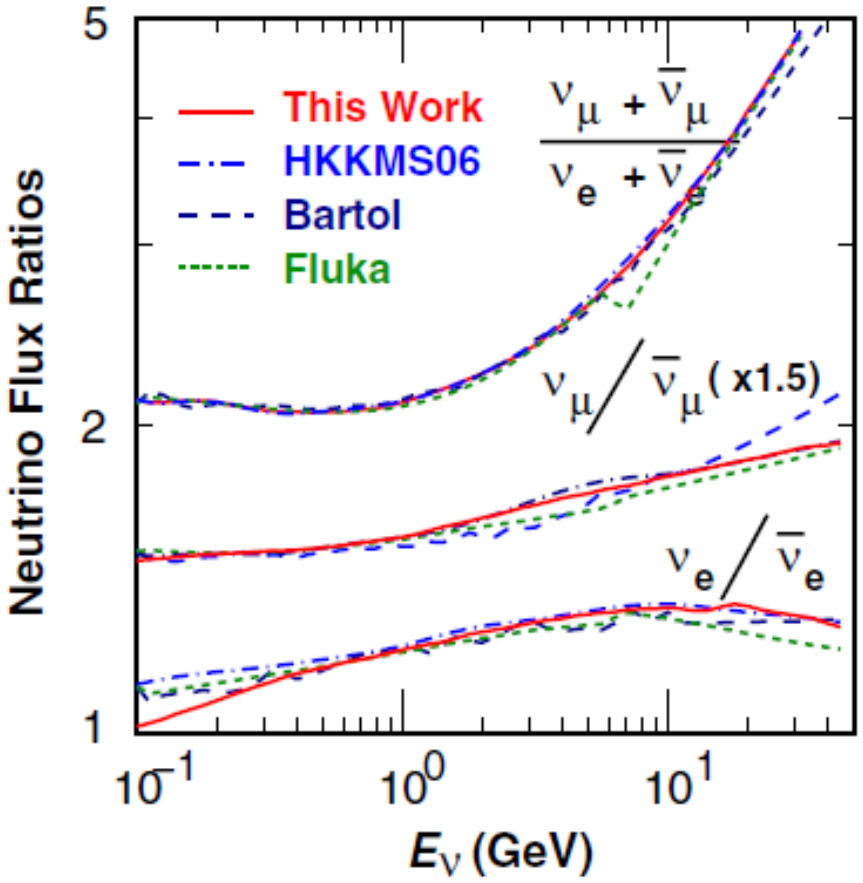
高能中微子角分布的上下对称性



- 上下对称性，实验系统误差小，用于研究大气中微子振荡



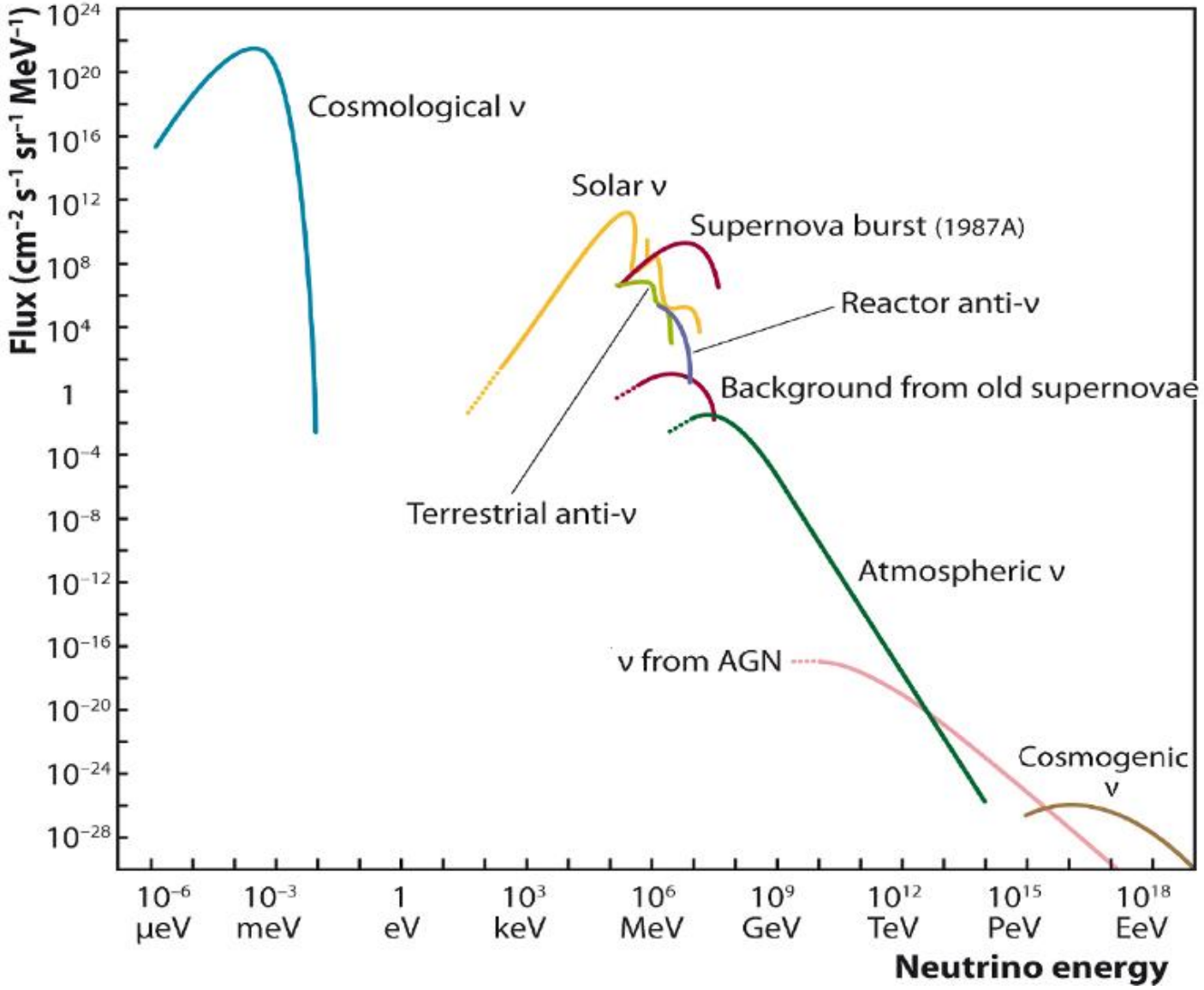
几种大气中微子通量的比值



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

- R(mu/e)=2
- R受外部的影响小
- 预期R的误差只有5%正好适用于研究中微子振荡

大气中微子的通量和能谱的位置



3. 大气中微子传播

中微子混合矩阵

Neutrino mixing at the 3-neutrino framework

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

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

大气和加速器中微子的振荡公式

Disappearance:

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}$$

Appearance:

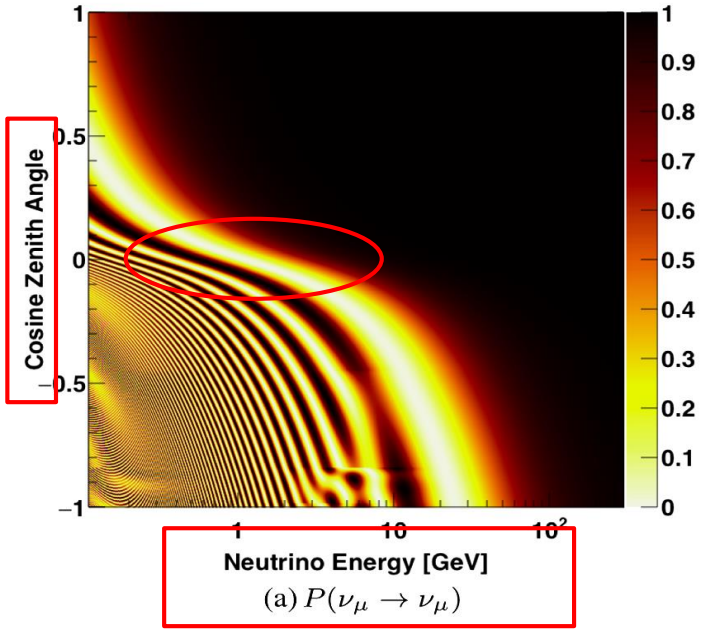
$$\begin{aligned} P_{\nu_\mu \to \nu_e} = & \frac{1}{(A-1)^2}\sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2[(A-1)\Delta] \\ & -(+)\frac{\alpha}{A(1-A)}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13} \\ & \times \sin\delta_{CP}\sin\Delta\sin A\Delta\sin[(1-A)\Delta] + \frac{\alpha}{A(1-A)} \\ & \times \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13} \\ & \times \cos\delta_{CP}\cos\Delta\sin A\Delta\sin[(1-A)\Delta] \\ & + \frac{\alpha^2}{A^2}\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2 A\Delta. \end{aligned}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} \ll 1$$

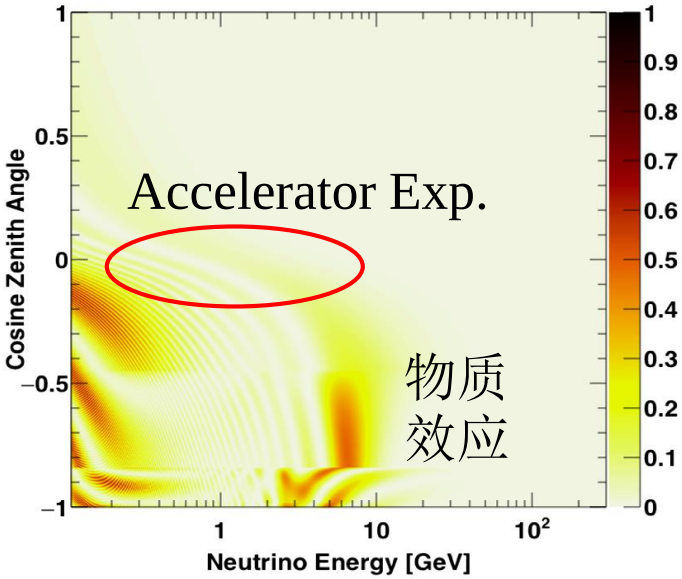
$$\Delta = \frac{\Delta m^2_{32}L}{4E}$$

$$A = 2\sqrt{2}G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$$

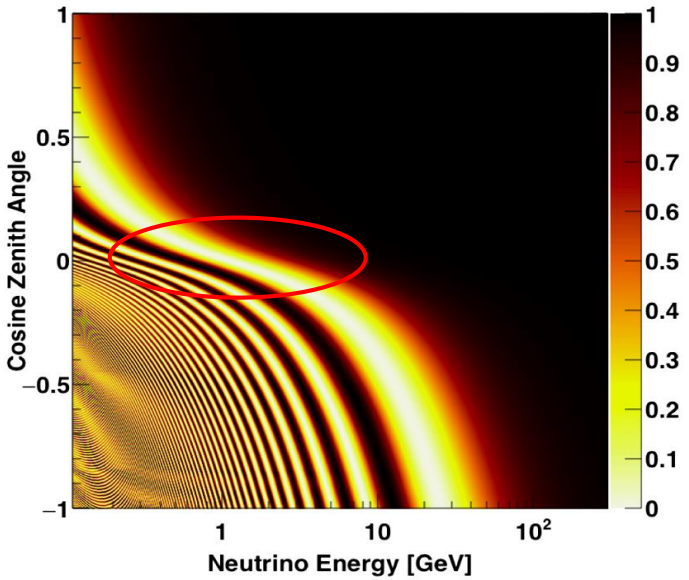
大气和加速器中微子的振荡模式：



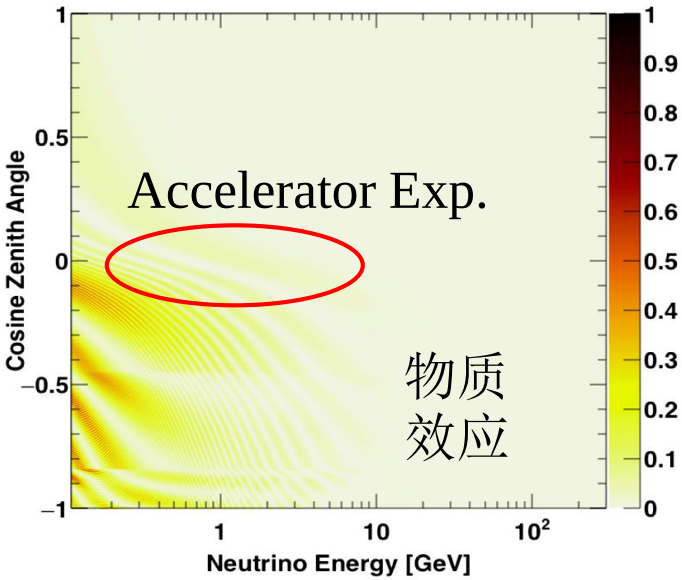
(a) $P(\nu_\mu \to \nu_\mu)$



(b) $P(\nu_\mu \to \nu_e)$



(c) $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$



(d) $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

4. 大气中微子的探测方法

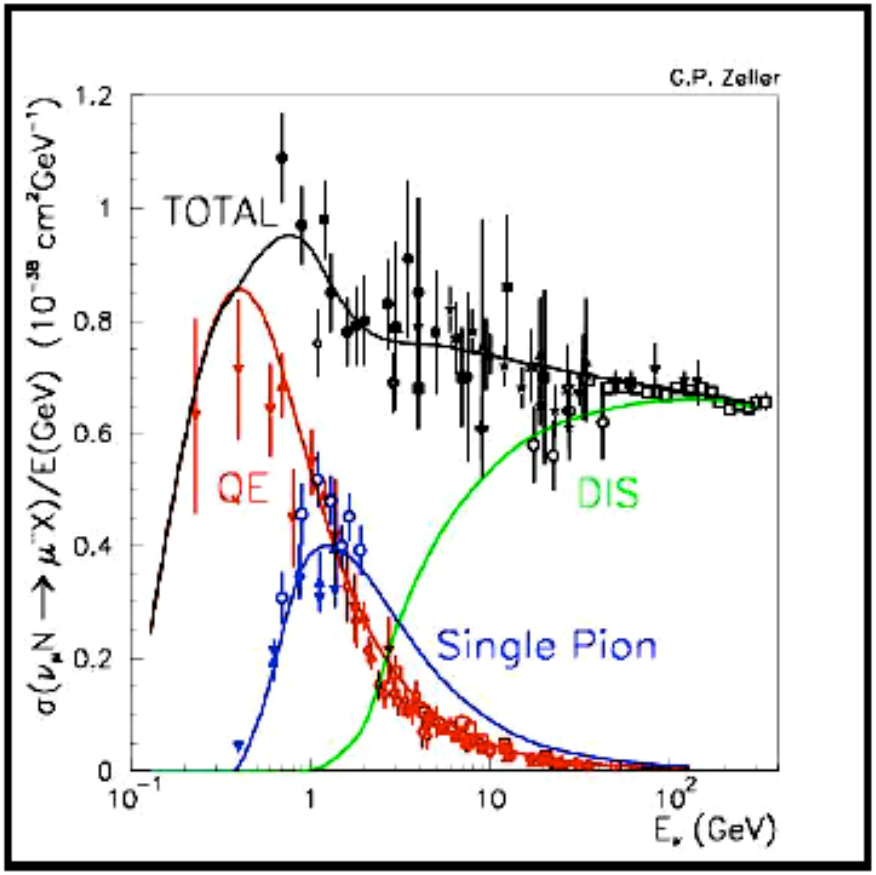
中微子电子散射截面

- $\nu_e\,(\bar{\nu}_e) + e^- \rightarrow \nu_e\,(\nu_e) + e^-$　　CC和NC
  - $\sigma(\nu_e e^-) \approx 0.9\times10^{-43}\ (E_\nu/10\ \mathrm{MeV})\ \mathrm{cm}^2$
  - $\sigma(\bar{\nu}_e e^-) \approx 0.4\times10^{-43}\ (E_\nu/10\ \mathrm{MeV})\ \mathrm{cm}^2$

- $\nu_{\mu,\tau}\,(\bar{\nu}_{\mu,\tau}) + e^- \rightarrow \nu_{\mu,\tau}\,(\nu_{\mu,\tau}) + e^-$　　NC过程
  - $\sigma(\nu_{\mu,\tau} e^-) \approx 0.15\times10^{-43}\ (E_\nu/10\ \mathrm{MeV})\ \mathrm{cm}^2$
  - $\sigma(\bar{\nu}_{\mu,\tau} e^-) \approx 0.14\times10^{-43}\ (E_\nu/10\ \mathrm{MeV})\ \mathrm{cm}^2$

GeV能量区间与核子反应过程及截面

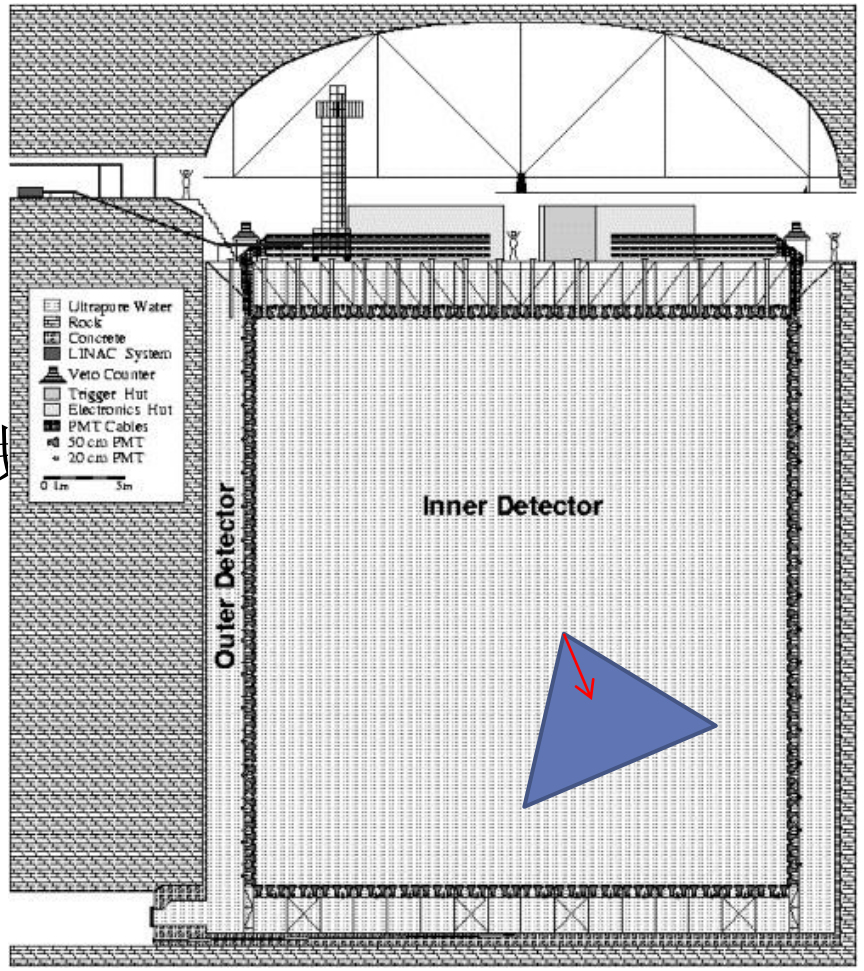
- quasi-elastic scattering
  $\nu_\mu n \rightarrow \mu p$
- single π production
  $\nu_\mu N \rightarrow \mu N' \pi$
- deep inelastic scattering (DIS)
  $\nu_\mu N \rightarrow \mu X$
- elastic ν-electron scattering
  $\nu_\mu e^- \rightarrow \nu_\mu e^-$ (not shown)



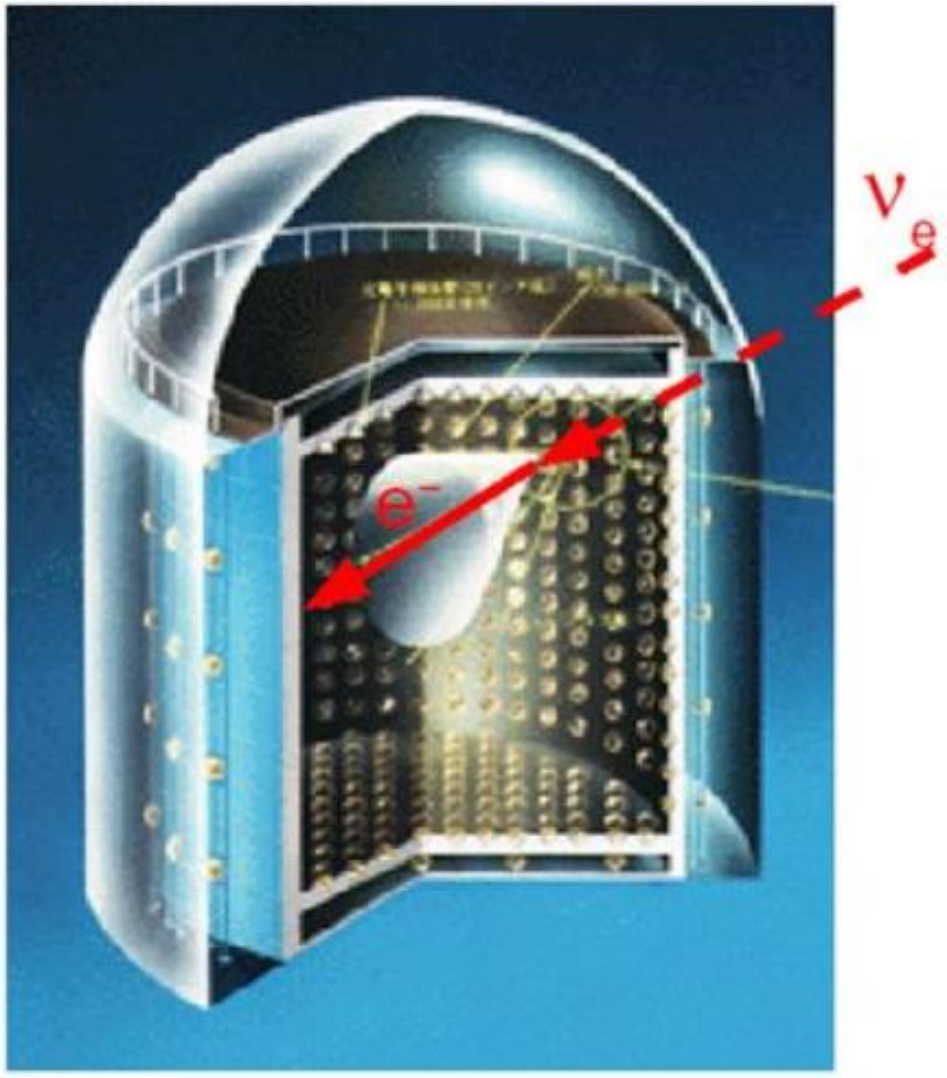
Sam Zeller

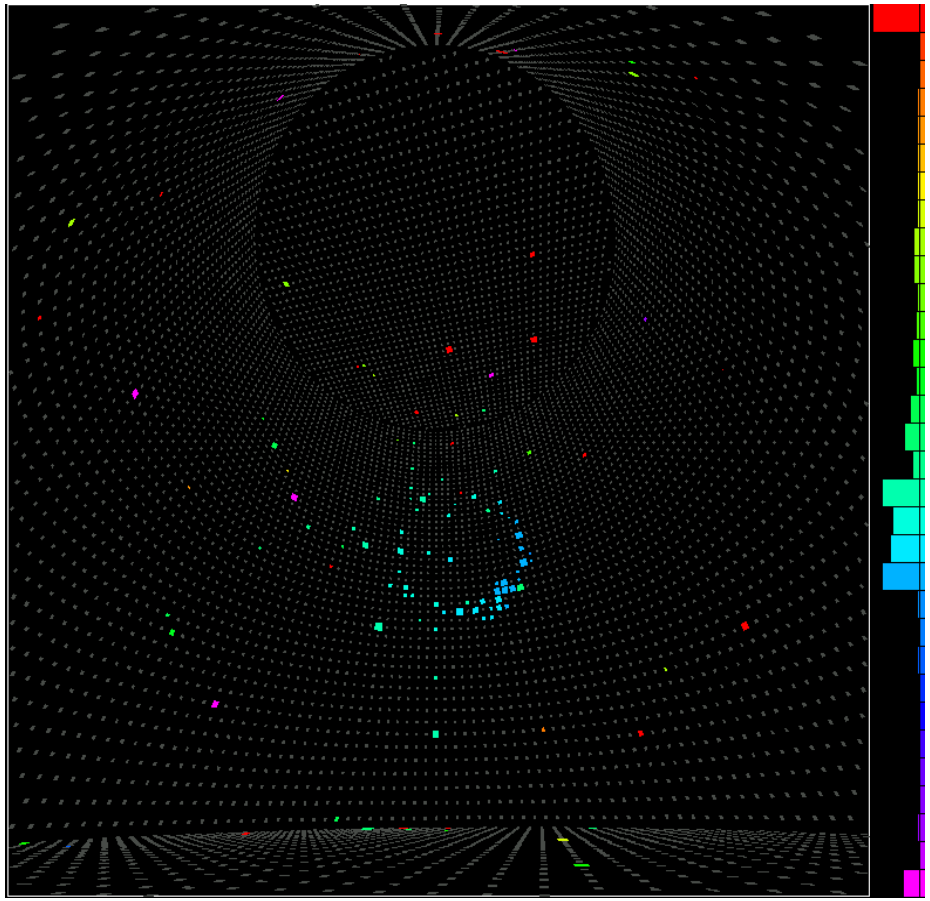
判选探测到中微子的一般标准

- 第一种：
  - ✓ 外探测器与内探测器
  - ✓ 事例顶点必须在内探测器内
  - ✓ 外探测器必须没有明显信号，以此排除宇宙线的本底过程
- 或者是从地下来的缪子或电子



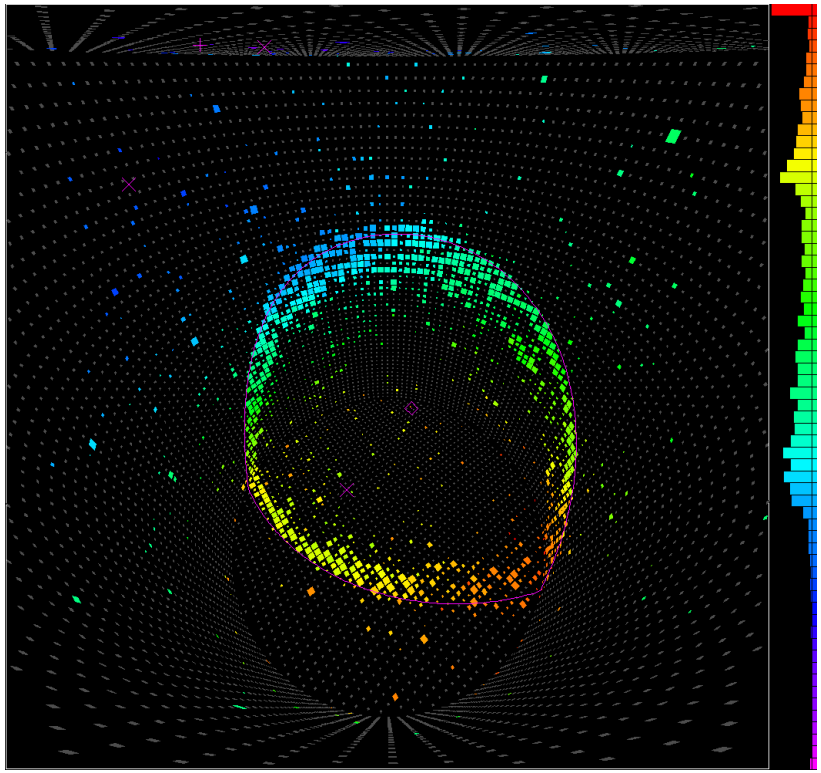
纯水探测器，切伦科夫光



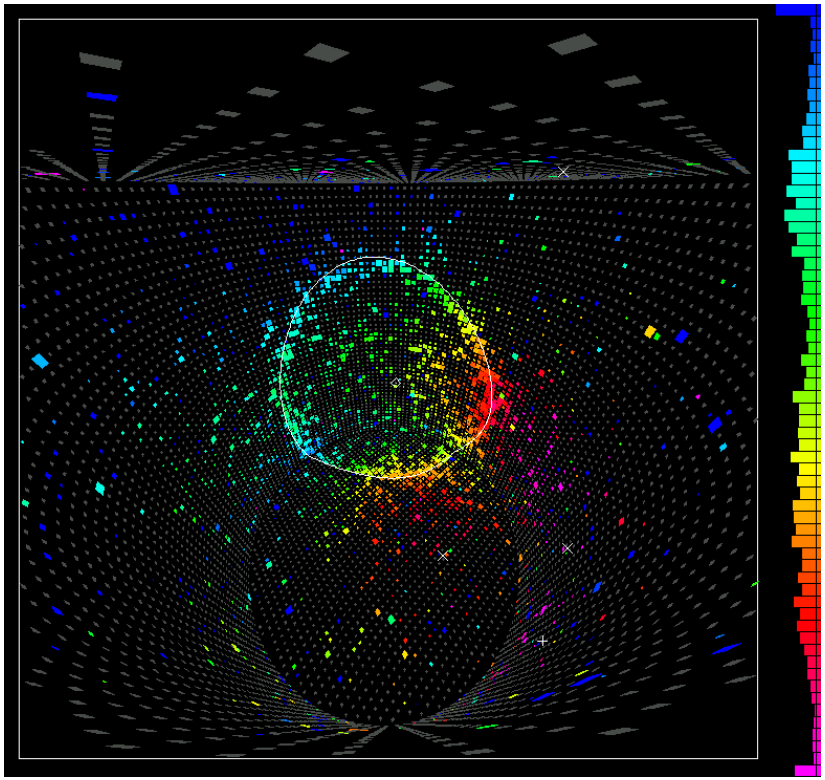


太阳中微子信号，几MeV

大气中微子信号，几十MeV到几个GeV



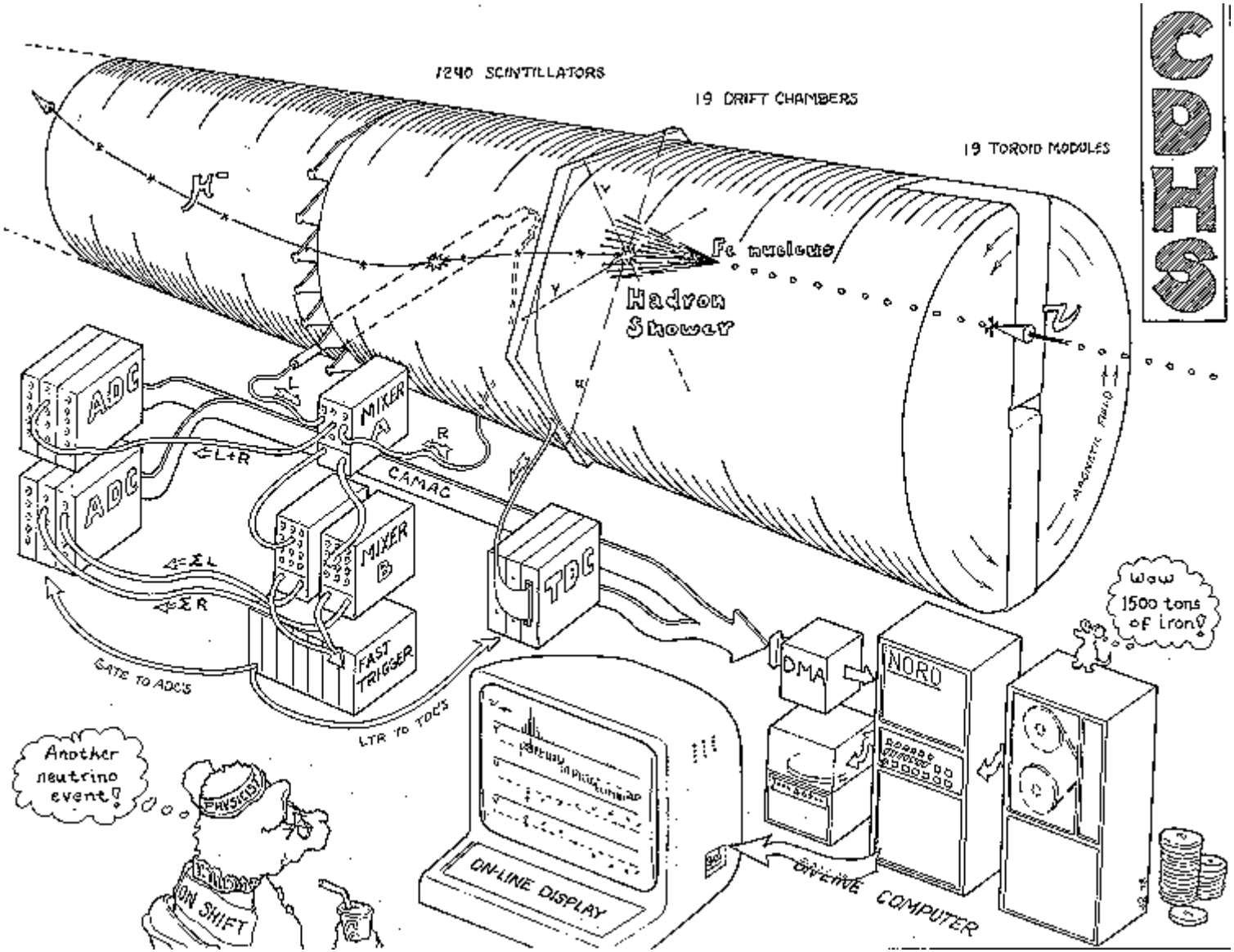
高能缪中微子事例
光滑边界



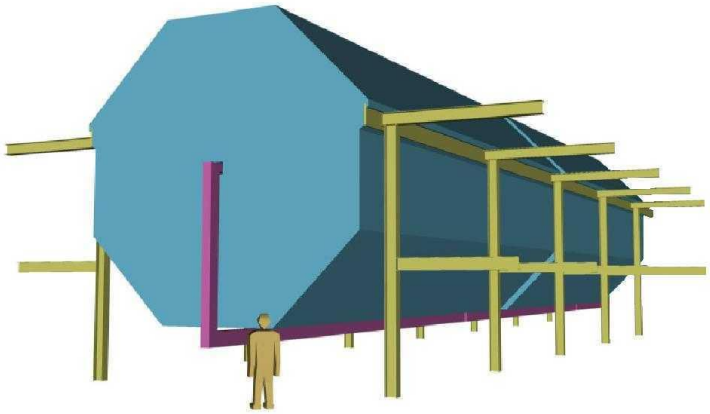
高能电子中微子事例
粗糙边界

三明治型的缪子探测器

- 主要用于探测$\nu_\mu + N \rightarrow \mu + M$中的高能缪子
- 加速器中微子，μ能量的GeV量级
- 添加磁场，缪子的正负电荷可以区分
- 电子的径迹短，也可以和缪子区分
- Minos，Nova实验

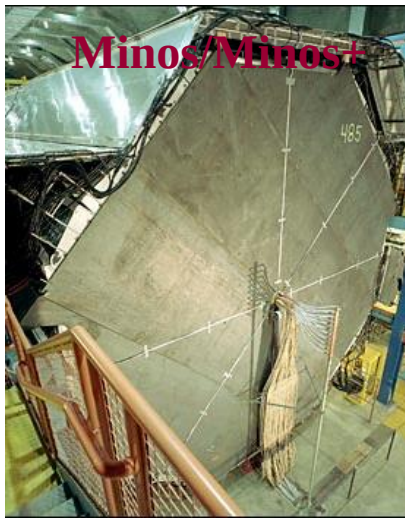

1240 SCINTILLATORS
19 DRIFT CHAMBERS
19 TOROID MODULES
CDHS
Fe nucleus
Hadron Shower
ADC
ADC
MIXER A
MIXER B
FAST TRIGGER
TDC
CAMAC
GATE TO ADCs
LTR TO TDCs
DMA
NORD
Wow 1500 tons of iron!
Another neutrino event!
ON SHIFT
ON-LINE DISPLAY
ON-LINE COMPUTER

MINOS探测器

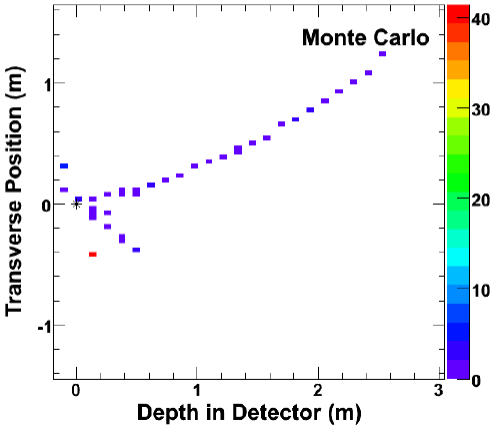


粉色为磁场导线走向，提供非均匀磁场

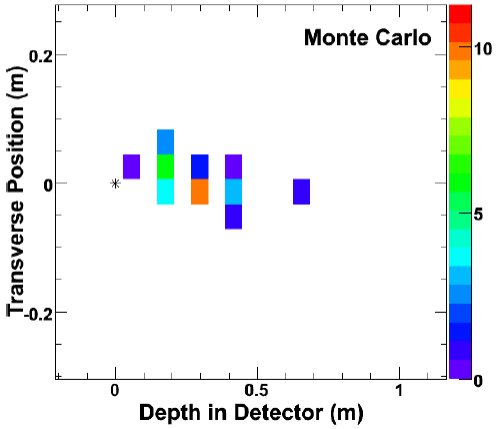
大气中微子事例的特征



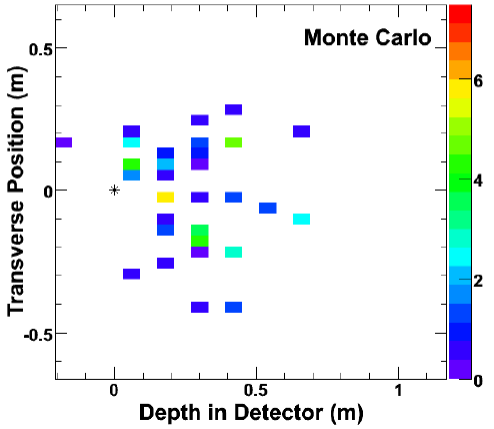
ν_μ-CC event

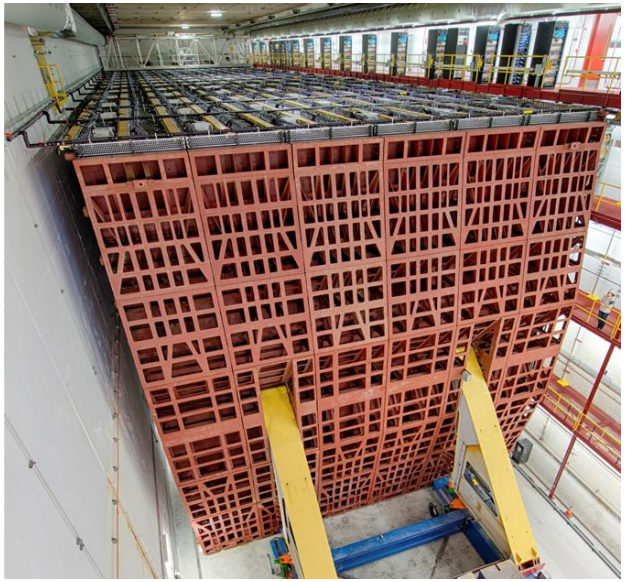


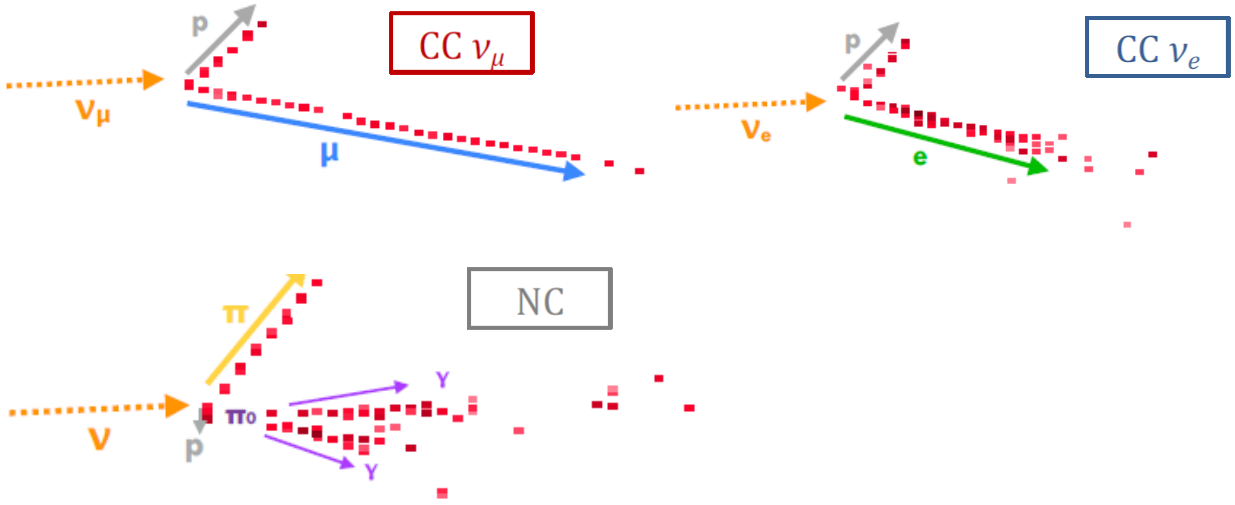
ν_e-CC event



NC event



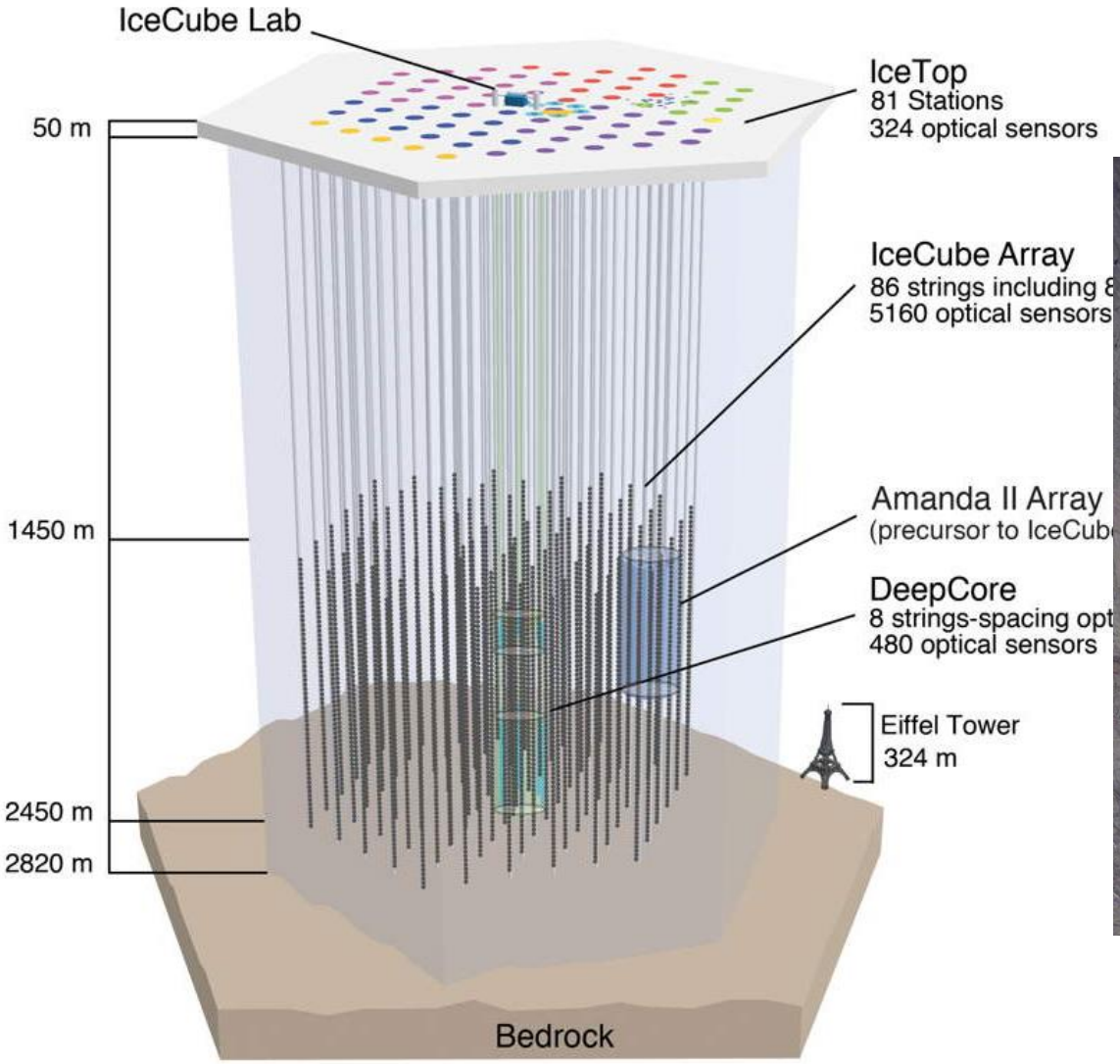


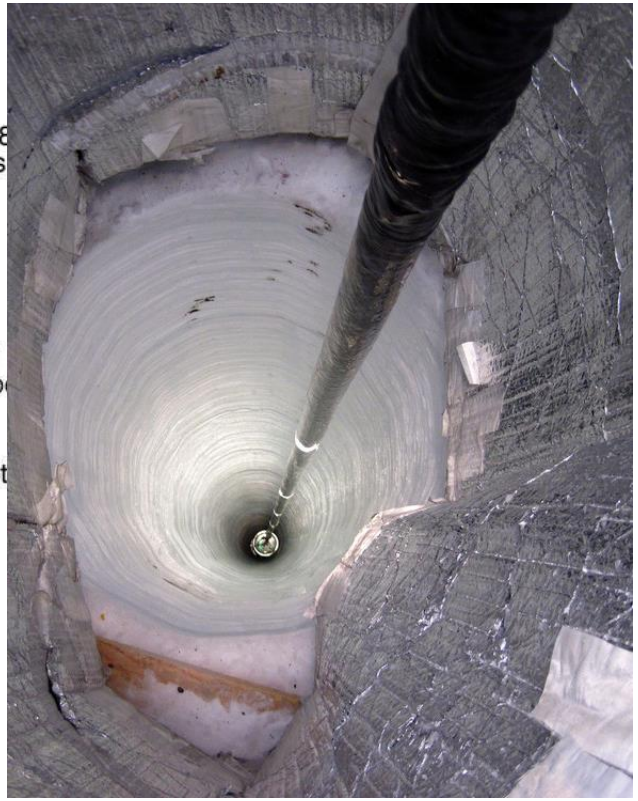


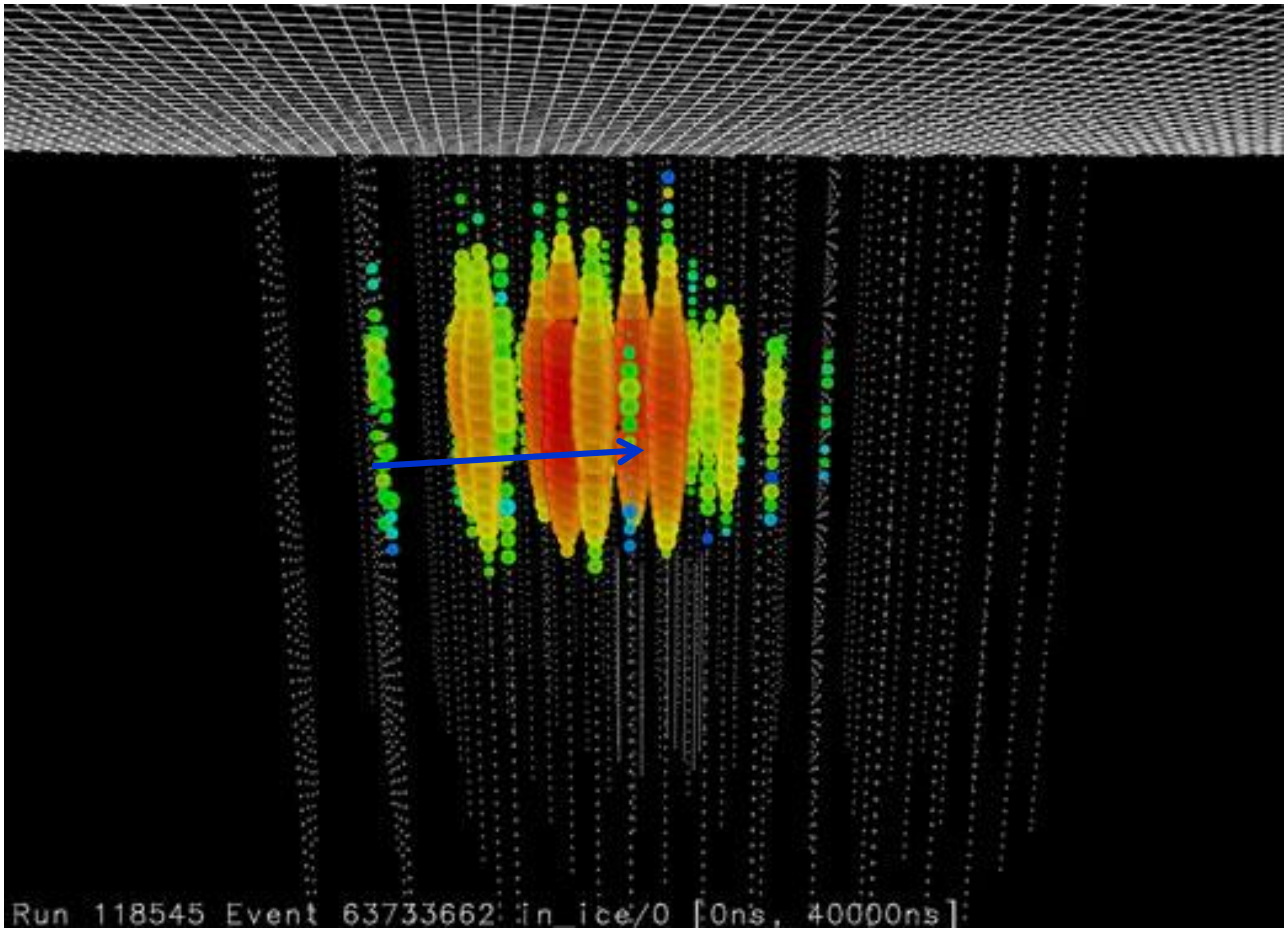
巨大水体或冰体

- 利用天然水体或冰体，提高探测器体积
- $\nu_\mu + N \rightarrow \mu + M$
- $\nu_e + N \rightarrow e + M$
- PMT的排布也变平均话，拟补衰减长度的不足
- 目标是可以探测高能，甚至超高能的中微子
- 实验：IceCube，ORCA等

IceCube，KM3Net等



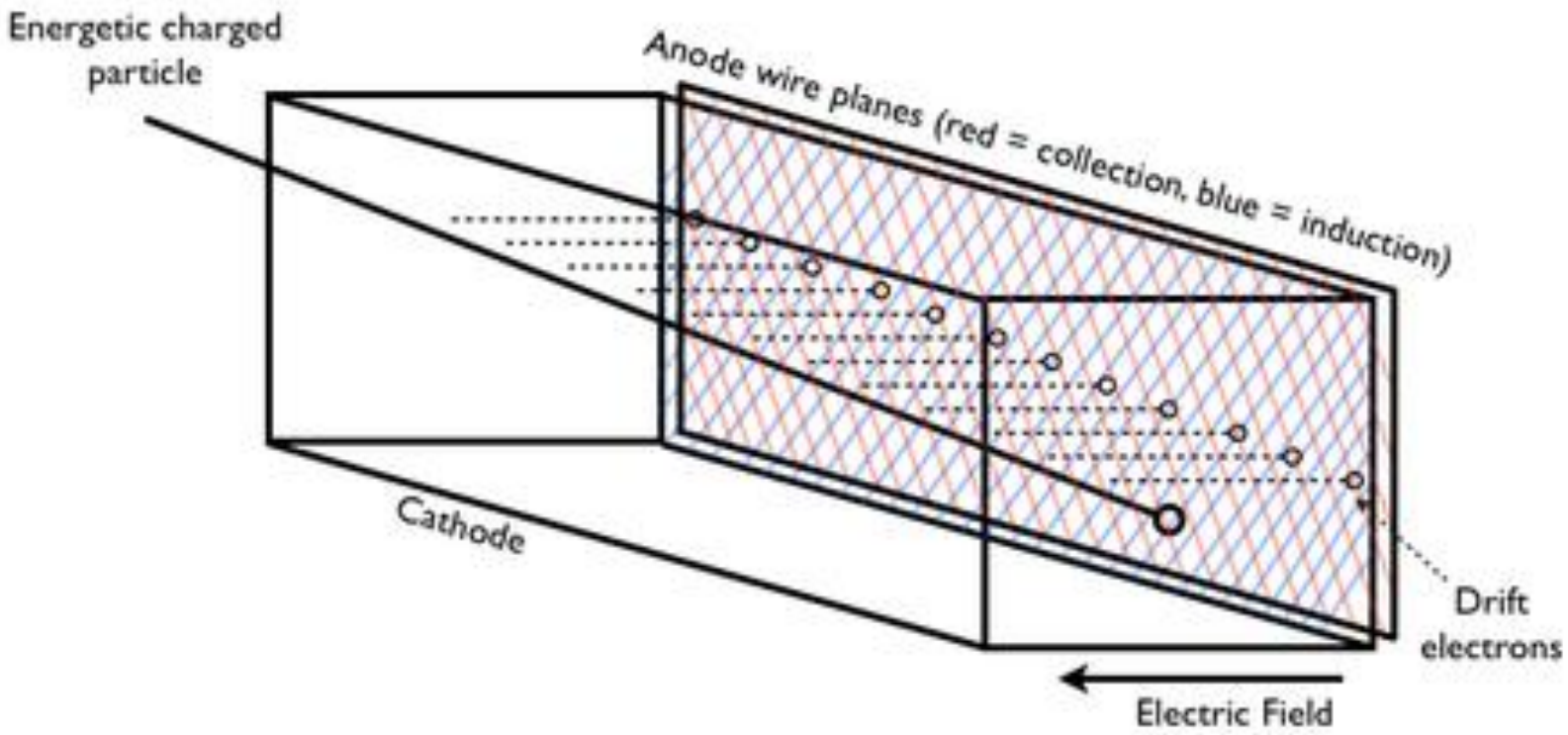




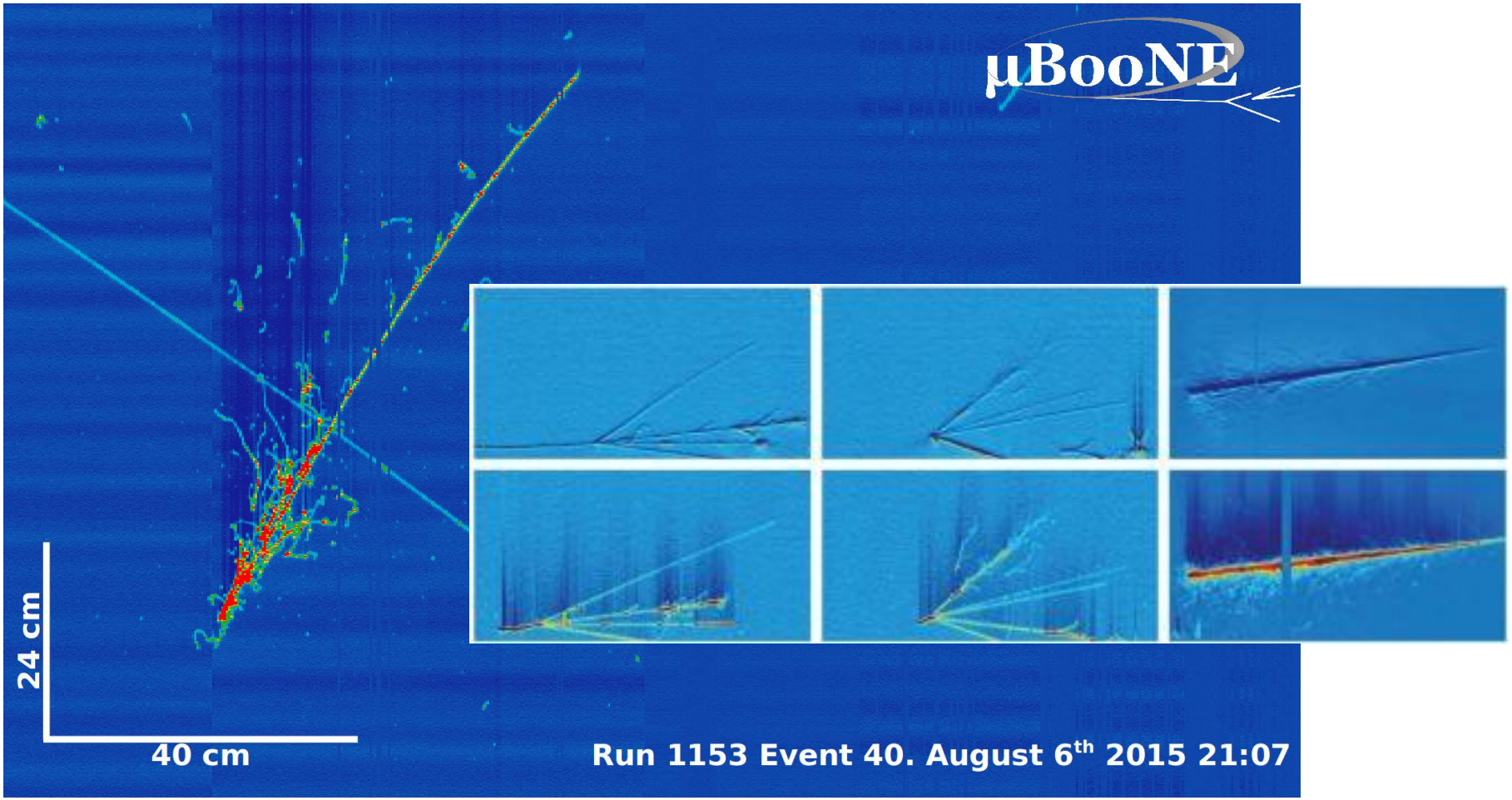
- 中心的多串PMT看到了强的Cherenkov光，也必须不能出现在外部的反符合层

液氩时间投影室

- 原理
  - X，Y，由阳极平面的击中位置决定
  - Z，由阳极平面上的击中时间及漂移速度决定



- 小模型的测试结果：



- 能够区分各种粒子，p，e，μ，等等
- 未来的DUNE实验的目标方案
- 目前在低能段有些限制，但主要是来自于读出装置的空间分辨

5. 实验进展

大气中微子的振荡结果

Super Kaminokande

Linyan@Neutrino2022

930 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK NO	1000.42	4.71	0.49	2.4×10^{-3} eV^2
SK IO	1006.19	4.71	0.49	2.4×10^{-3} eV^2

Preliminary

Maximal mixing； $\delta_{CP}\approx-\pi/2$； NO（$\Delta\chi^2=5.8$）

IceCube/DeepCore

PRD 99, 032007 (2019)

$\Delta m^2_{32} = 2.55^{+0.12}_{-0.11}$ x10^{-3} eV^2 $\sin^2\theta_{23} = 0.58^{+0.04}_{-0.13}$

Norm ν_τ(CC+NC) $= 0.73^{+0.34}_{-0.24}$ Reject no-ν_τ with 3.2σ (CC+NC)

Minos/Minos+

Atmospheric Best Fit
Normal Hierarchy
$\Delta m^2_{32} = 2.11\times10^{-3}$ eV^2
$\sin^2\theta_{23} = 0.52$

arXiv:2006.15208v2 (2020)

感谢大家的关注
能力有限，错误纰漏之处还请多原谅