中微子实验前沿

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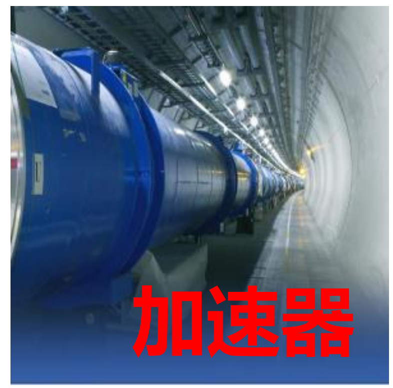
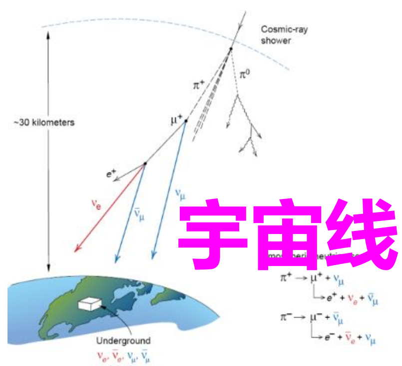
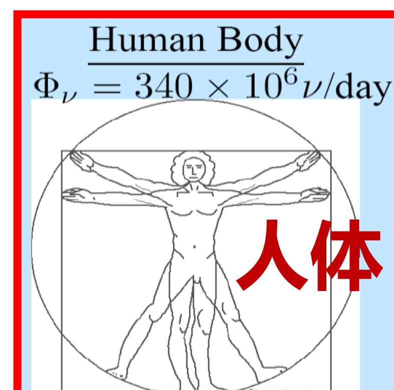
中微子无处不在

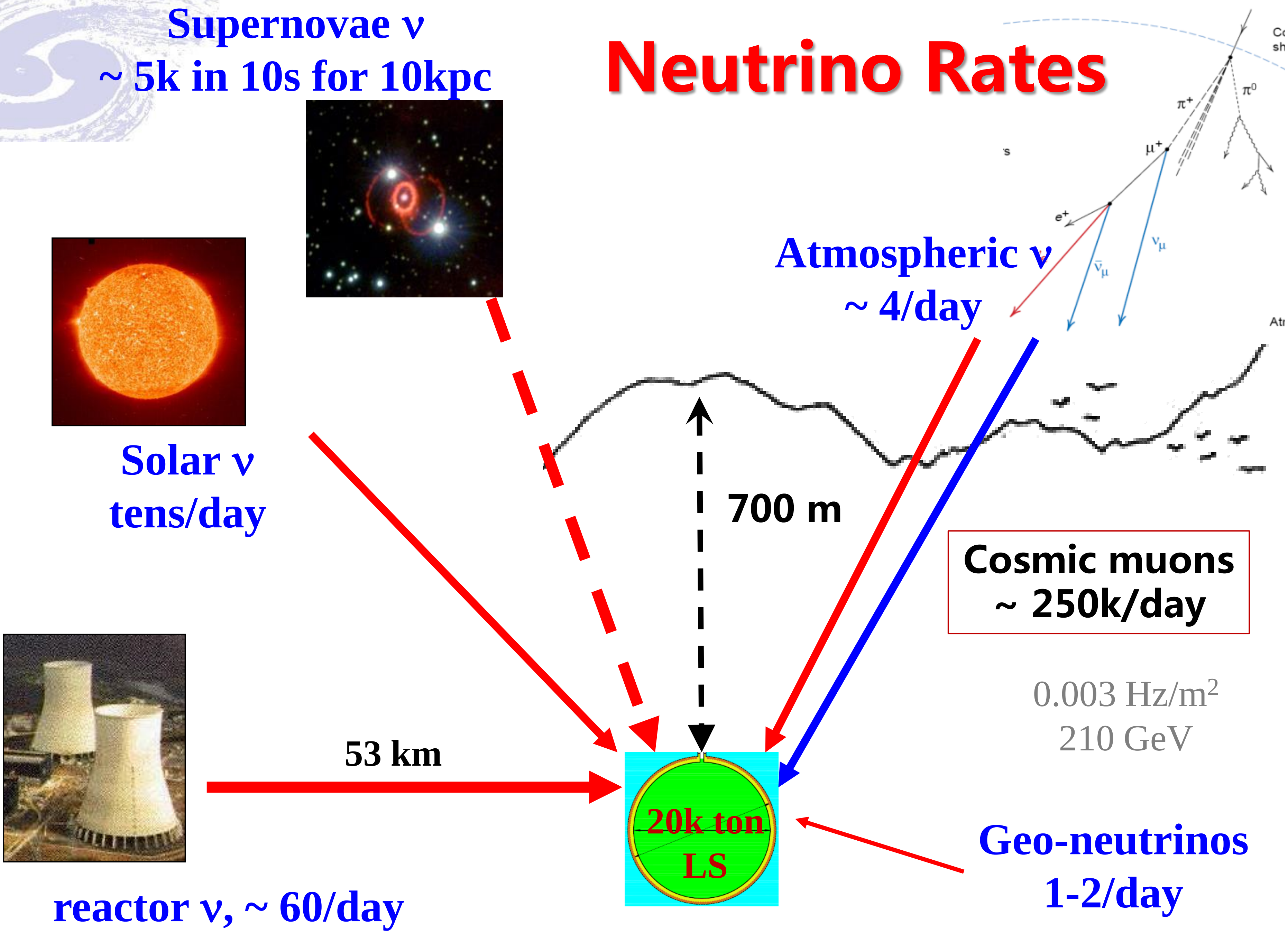
- 一种无处不在的基本粒子，组成世界的基本单元之一
- 不带电，极轻，几乎不与物质反应（**极难探测**）
- 它们都能产生中微子：







Neutrino Rates



中微子实验

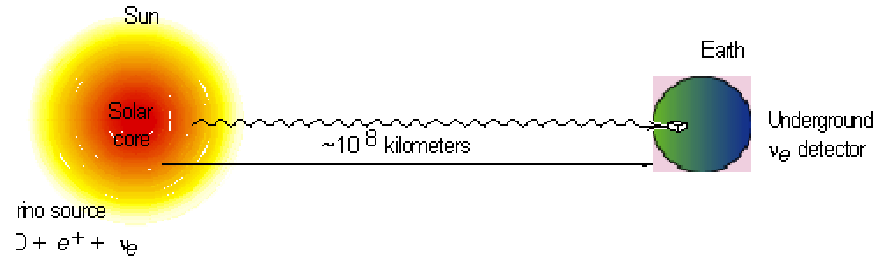
- 中微子振荡实验
  - 太阳中微子振荡实验
  - 大气中微子振荡实验
  - 长基线加速器中微子振荡实验
  - 反应堆中微子振荡实验
  - 寻找惰性中微子
- 非振荡实验
  - 中微子质量的测量
  - 无中微子双beta衰变实验
  - 中微子相互作用截面
  - 中微子磁矩的测量
- 中微子天文学

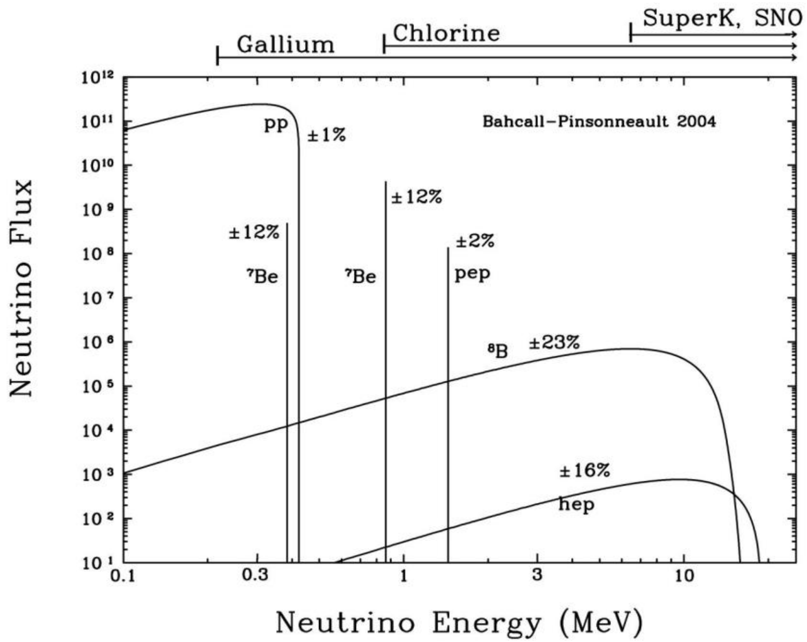
Covered

Not covered

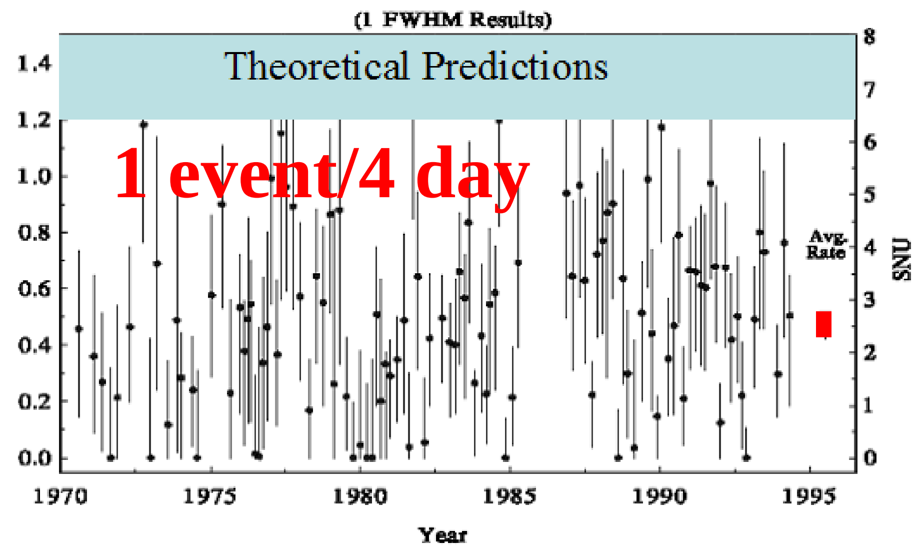
太阳中微子失踪之谜

- 1968年，Homestake实验发现观测到的太阳中微子只有预期的1/3。
- 中微子振荡？太阳模型可信吗？不同实验结果之间不一致。真空振荡解释条件太苛刻。



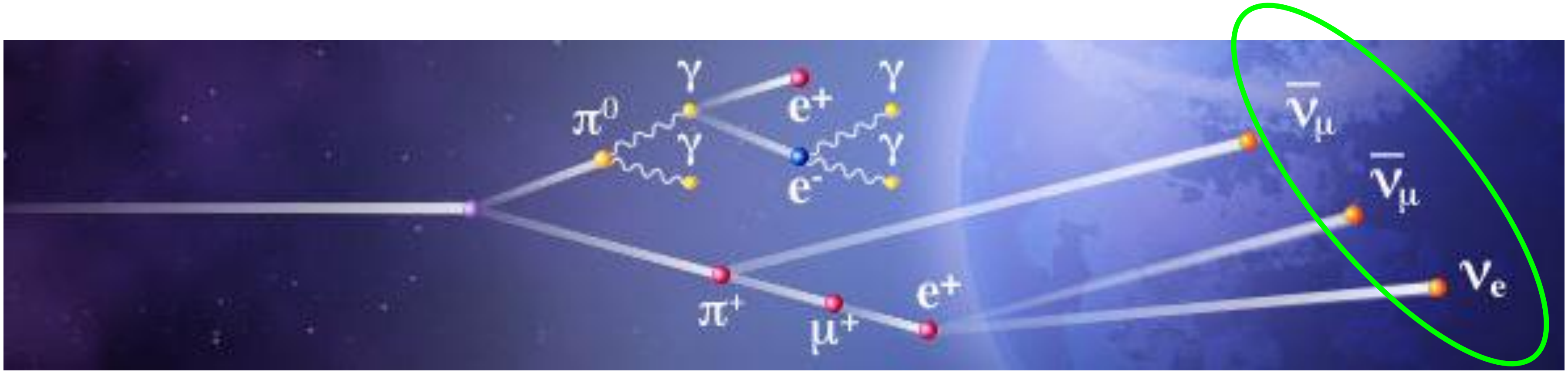


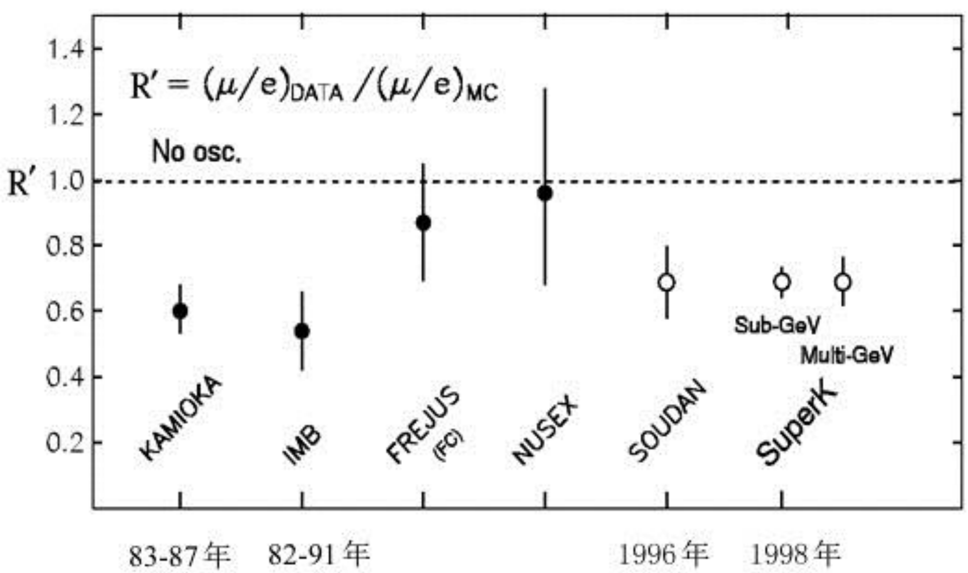
$$\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e$$



大气中微子反常

80年代，美国IMB和日本神岗实验发现大气中微子反常



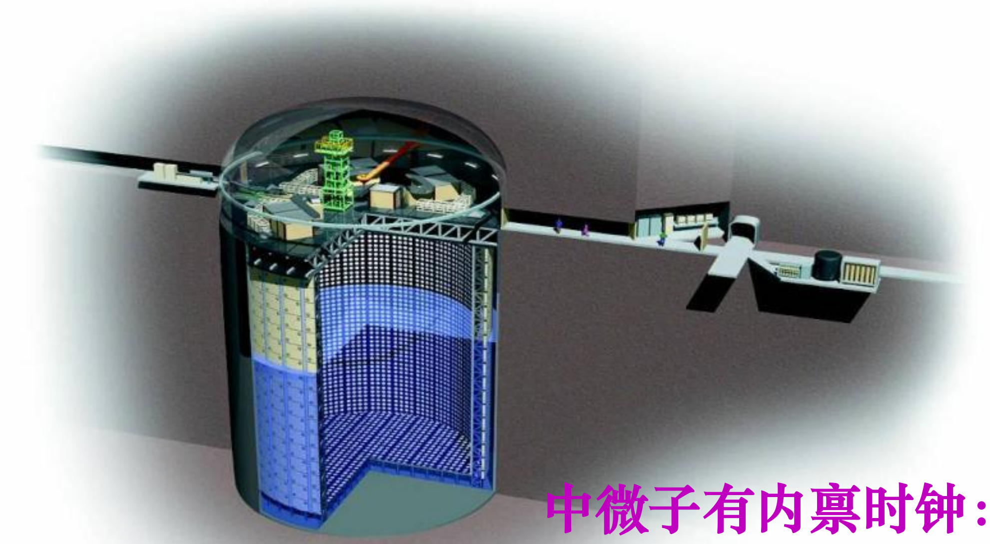


寻找质子衰变，
意外发现大气中微子反常

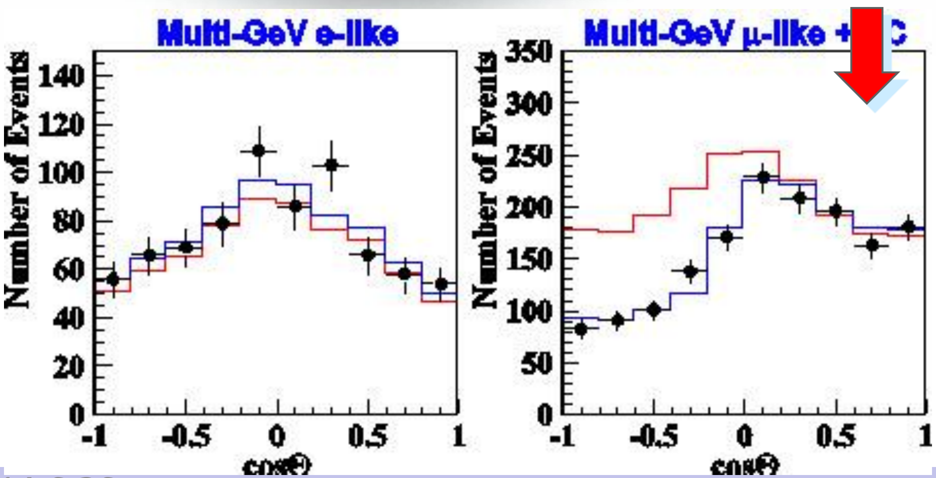
中微子振荡?
- 大气中微子能谱不准确
- 理论家不相信大混合角

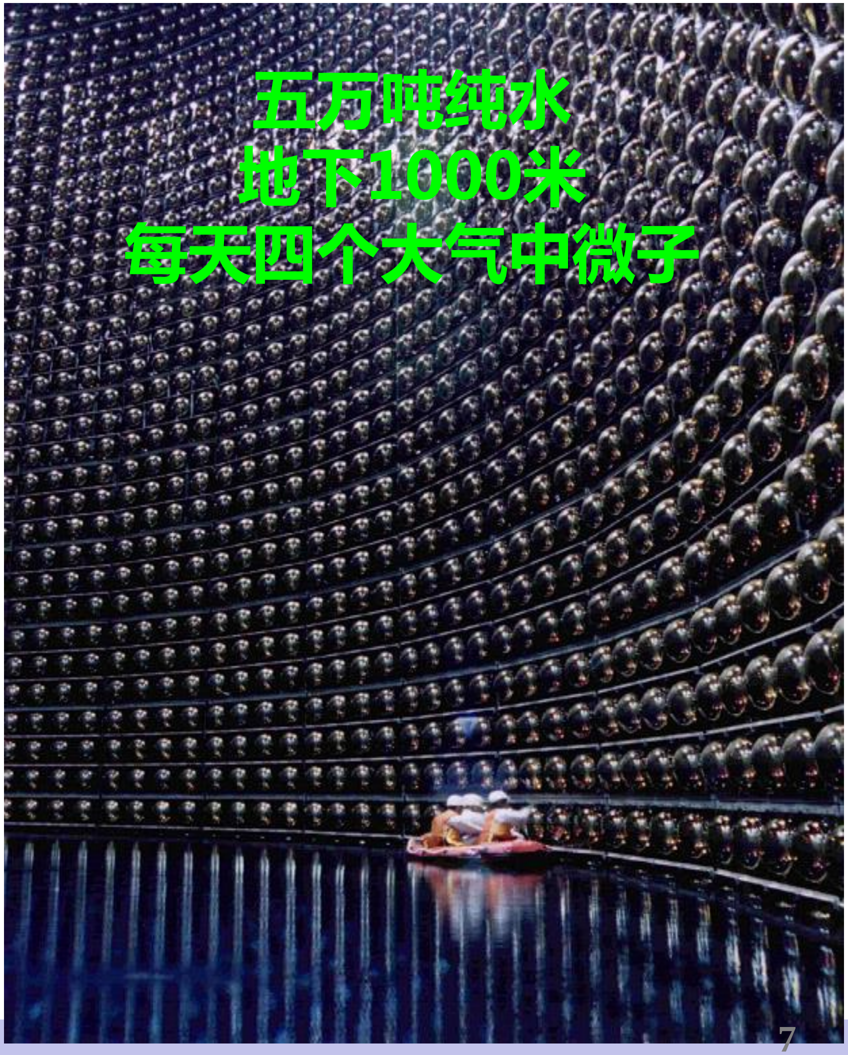
发现中微子振荡

1998年日本超级神岗实验发现大气中微子振荡

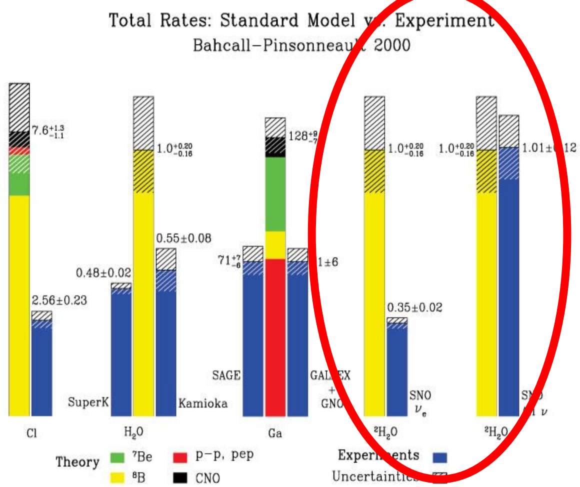


中微子有内禀时钟：
中微子有质量

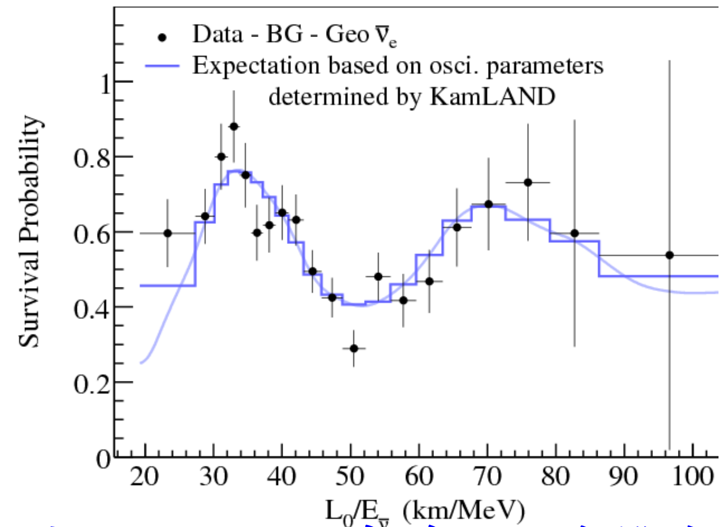




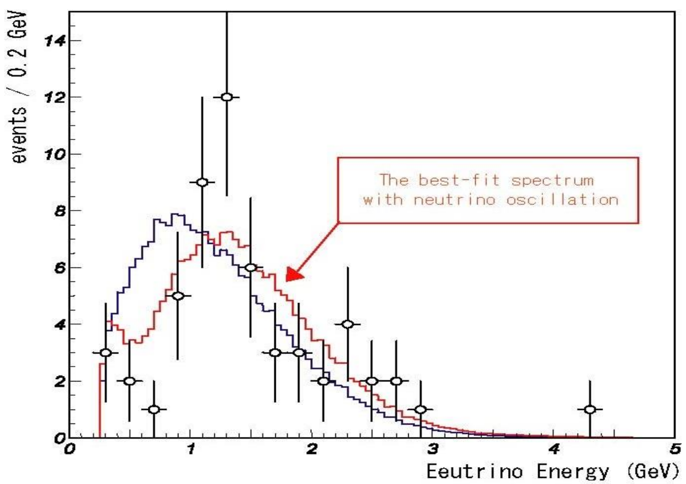
不同实验、不同方法确立中微子振荡现象



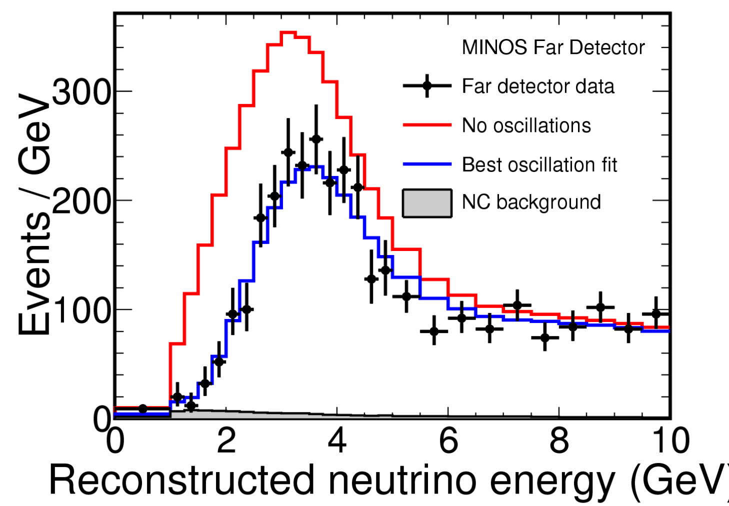
加拿大SNO实验，太阳中微子



日本KamLAND实验，反应堆中微子



日本K2K实验，加速器中微子



美国MINOS实验，加速器中微子

中微子振荡

- 中微子在传播中将从一种中微子变成另外一种，如果
  - ⇨中微子有非零质量，且
  - ⇨弱作用本征态不等于质量本征态（混合）

Pontecorvo 1968

弱作用本征态

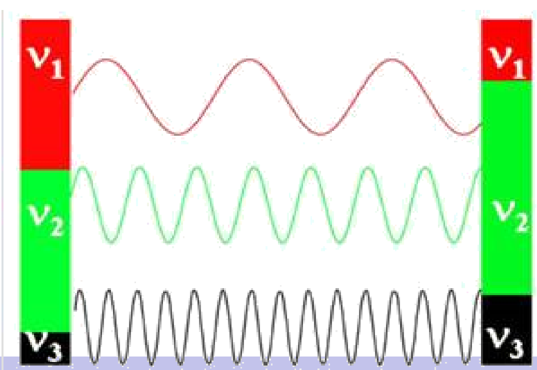
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

质量本征态

产生时为弱作用本征态→质量态的混合，传播按质量本征态频率

微观量子干涉现象的宏观表现

$$|\nu_e\rangle =$$

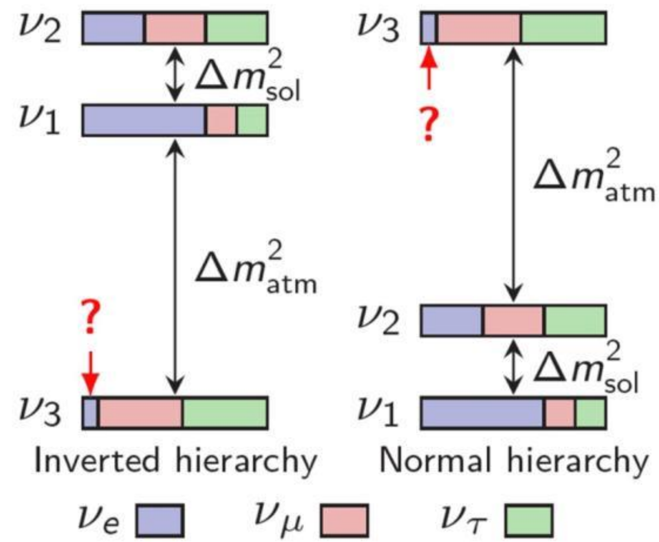


$$= c_1|\nu_e\rangle + c_2|\nu_\mu\rangle + c_3|\nu_\tau\rangle$$

中微子混合规律

In a 3-ν framework

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



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

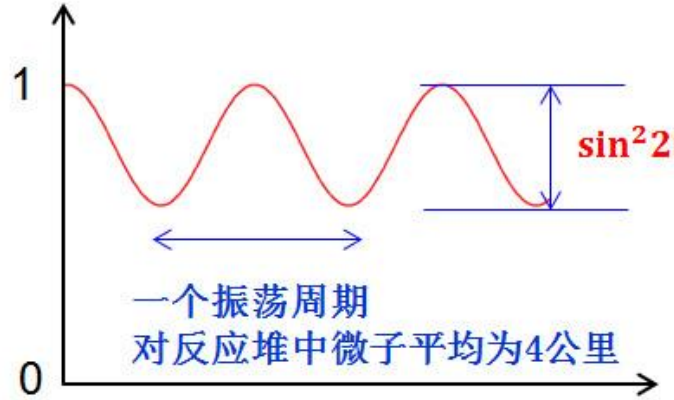
$\theta_{23} \sim 45°$	$\theta_{13} \sim 9°$	$\theta_{12} \sim 34°$	
Atmospheric	**Reactor**	**Solar**	**0νββ**
Accelerator	**Accelerator**	**Reactor**	

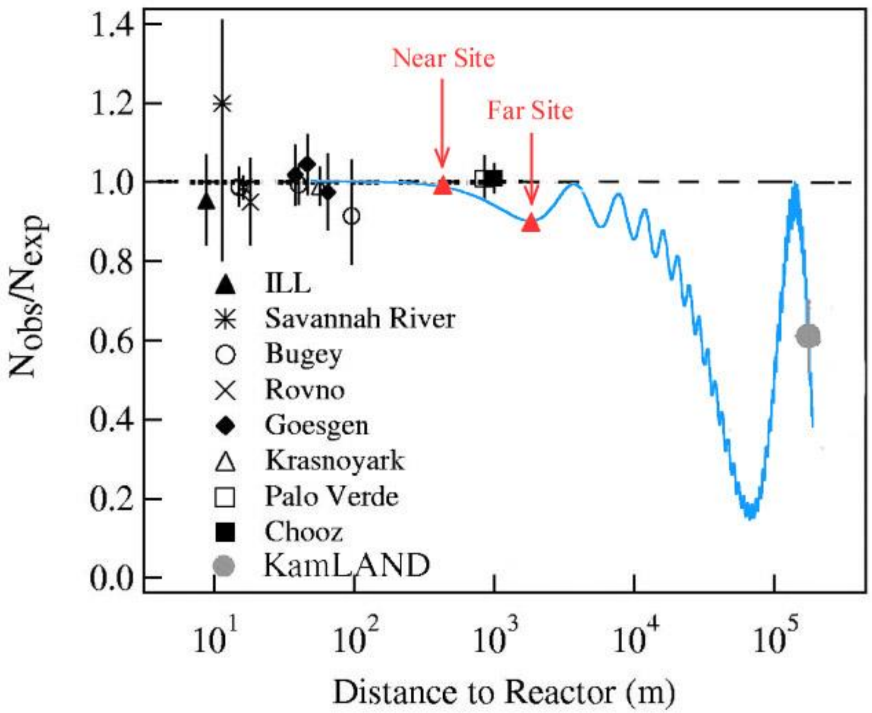
中微子振荡几率（反应堆）

飞行距离/中微子能量

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27 \cdot \Delta m^2_{31} \cdot \frac{L}{E}\right)$$

振幅大小　振荡频率





$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$P_{21} = 0.81\ \sin^2\Delta_{21}$$
$$P_{31} = 0.7 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{31}$$
$$P_{32} = 0.3 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{32}$$

中微子振荡研究前沿

- Global Fit

主要：太阳中微子实验、长基线反应堆

$$\Delta m^2_{21} = 7.54(1.00^{+0.034}_{-0.029}) \times 10^{-5}\,\mathbf{eV}^2, \qquad \sin^2\theta_{12} = 0.308(1 \pm 0.055)$$

主要：大气中微子实验、长基线加速器

$$|\Delta m^2_{32}| = 2.39(1 \pm 0.025) \times 10^{-3}\,\mathbf{eV}^2, \qquad \sin^2\theta_{23} = 0.437\left(1.00^{+0.076}_{-0.053}\right)$$

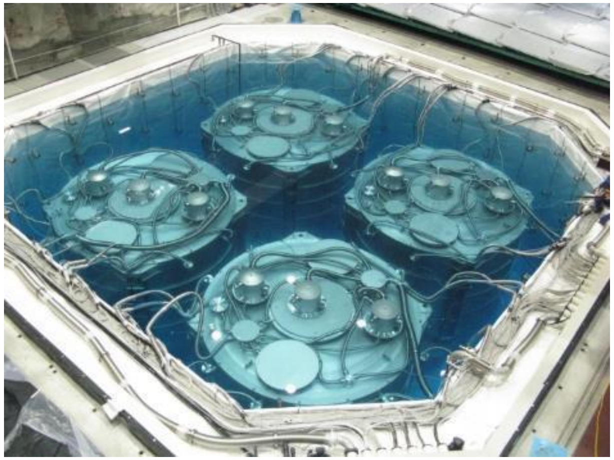
主要：反应堆

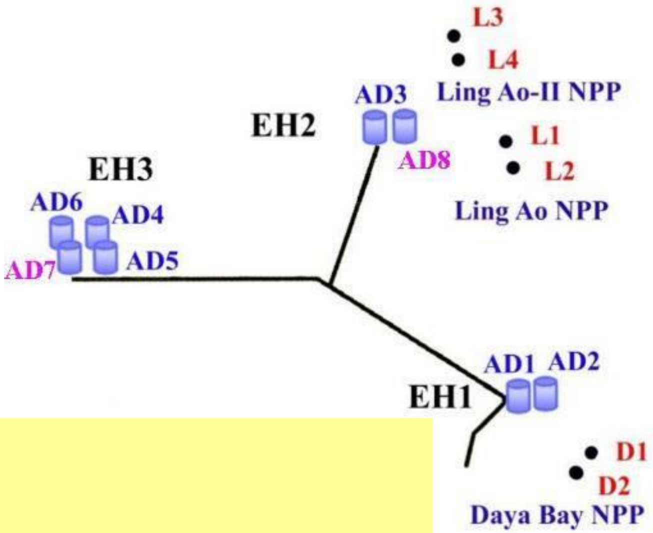
$$\sin^2\theta_{13} = 0.0234\left(1.00^{+0.085}_{-0.091}\right)$$

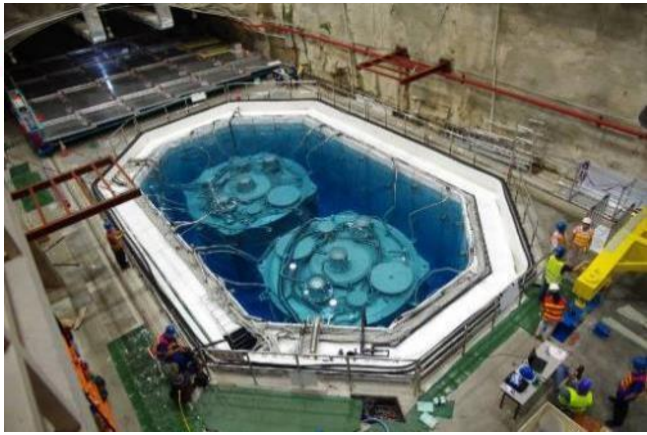
- 精确测量混合参数
- 中微子质量顺序（Mass Hierarchy）
- 中微子CP破坏相角
- θ_{23} Octant
- 寻找惰性中微子

大亚湾实验装置

- 国际领先的实验装置，探测器相对精度0.2%，为大型中微子探测器**国际最高精度**







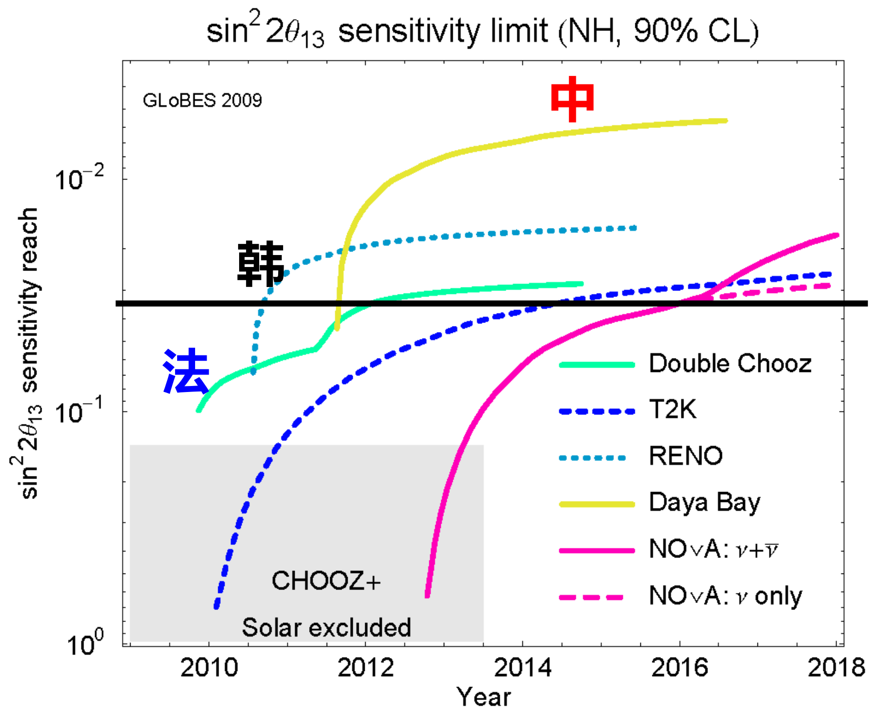
- 3000 米隧道
- 5 个地下实验厅
- 8 个 110 吨重的中微子探测器
- 3 个水切伦科夫探测器(4400 吨纯净水）
- 3200 m^2 阻性板探测器
- 8000 道电子学读出。

与国际同类装置比较

实验	亮度 (吨 • GW)	探测器设计误差	岩石覆盖(近/远) (m.w.e.)	3年灵敏度 (90%CL)
中国 大亚湾	1400	0.38%	250 / 860	~ 0.008
法国 Double Chooz	70	0.6%	120 / 300	~ 0.03
韩国 RENO	260	0.5%	120 / 450	~ 0.02

2003年前后，国际上7个国家共提出8个方案，最终三个得以实施。与主要国际竞争对手相比：

- 亮度高5-20倍 (地理优势+设计优化)
  → 积累数据更快
- 探测器误差小 (设计创新, 实达0.2%)
  → 精度更高
- 岩石覆盖厚 (地理优势)
  → 本底更小，精度更高

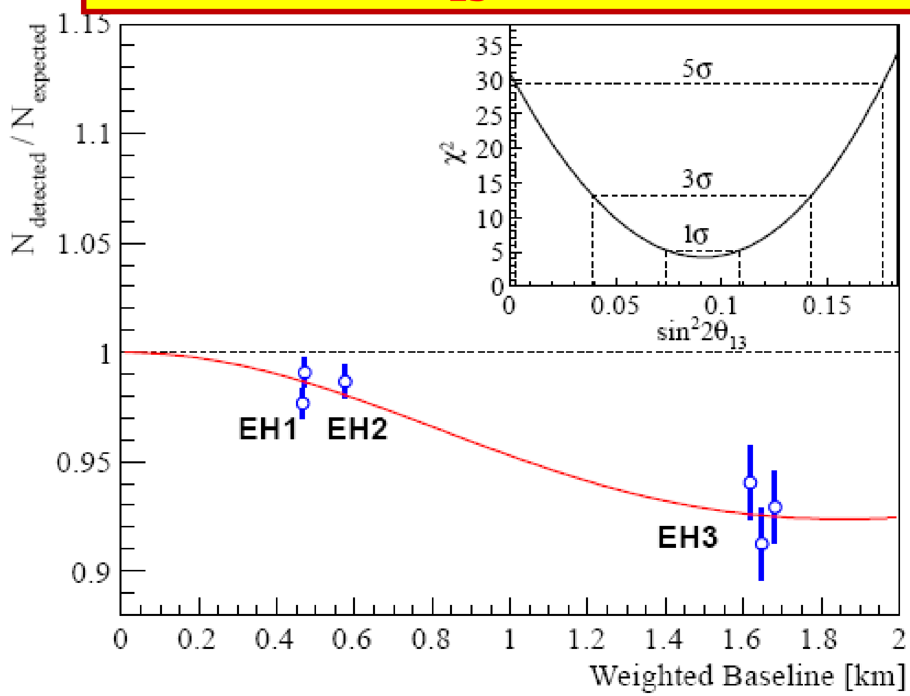


大亚湾发现新的中微子振荡

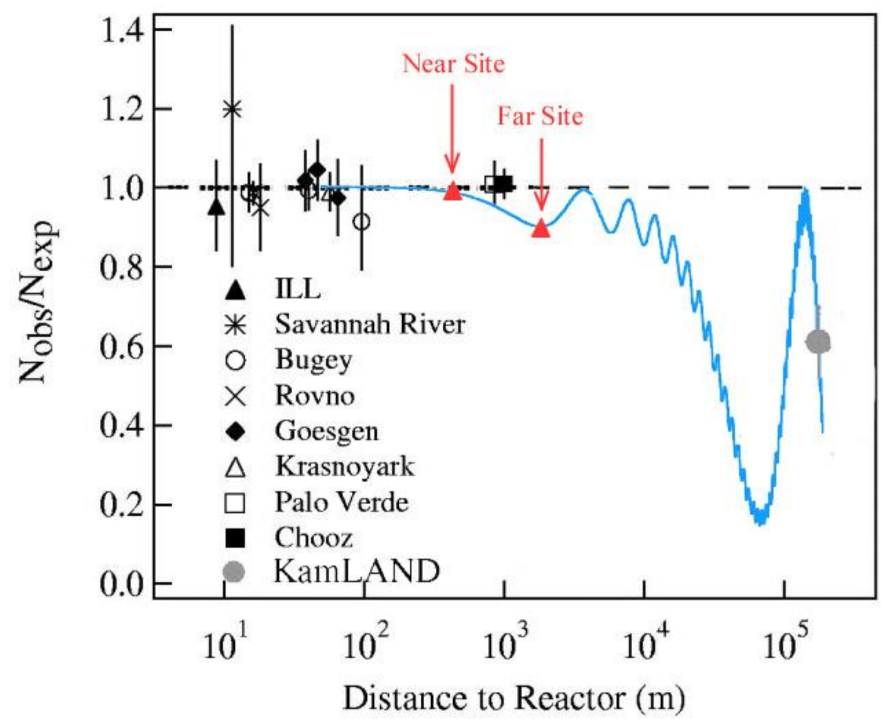
- 2012年3月8日，凭借仅55天的数据量，抢在竞争对手之前，发现了新的中微子振荡，测得混合角 θ_{13}

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

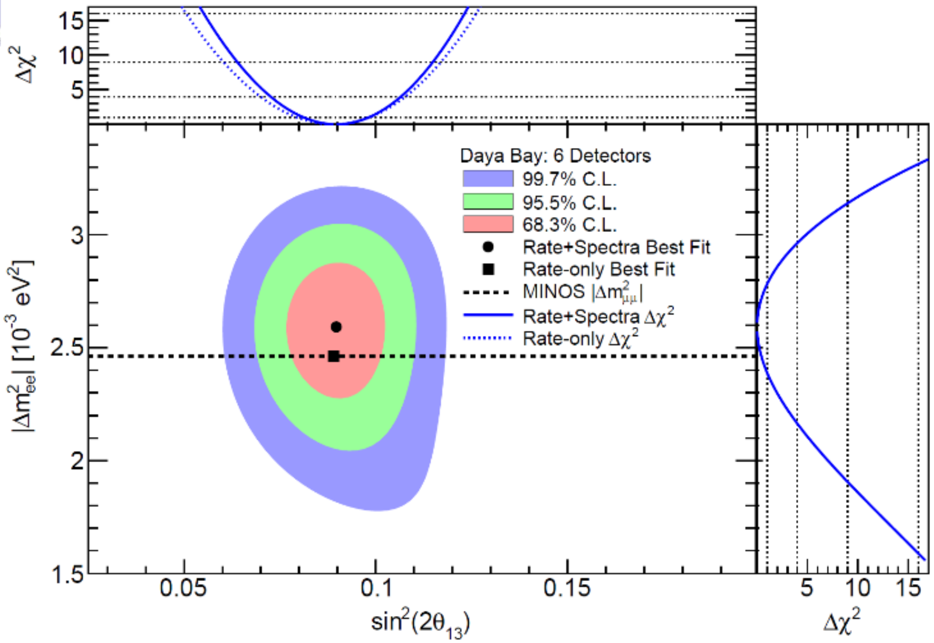
θ_{13}不为零：5.2 倍标准偏差的置信度



Phys. Rev. Lett. 108, 171803 (2012)



First Measurement of $|\Delta m^2_{ee}|$



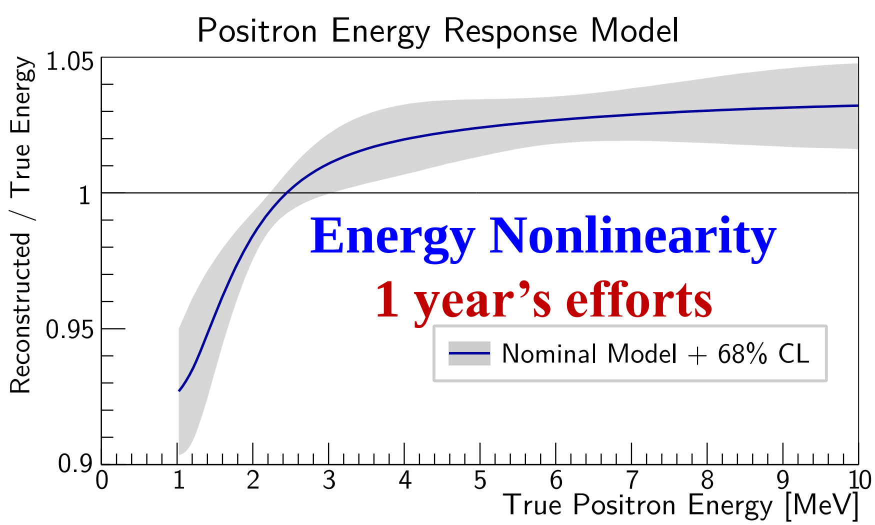
Announced on Aug.22 at Nufact2013
Submitted to PRL, arXiv: 1310.6732

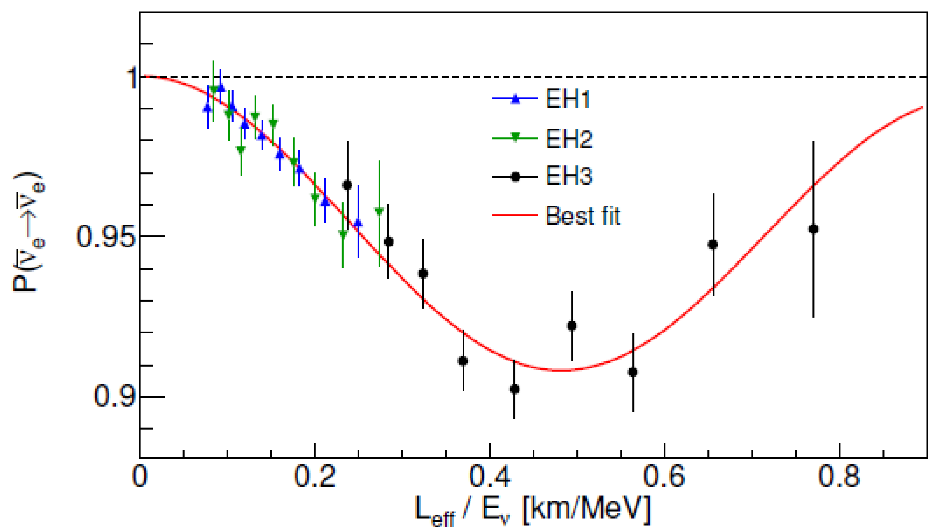
$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$

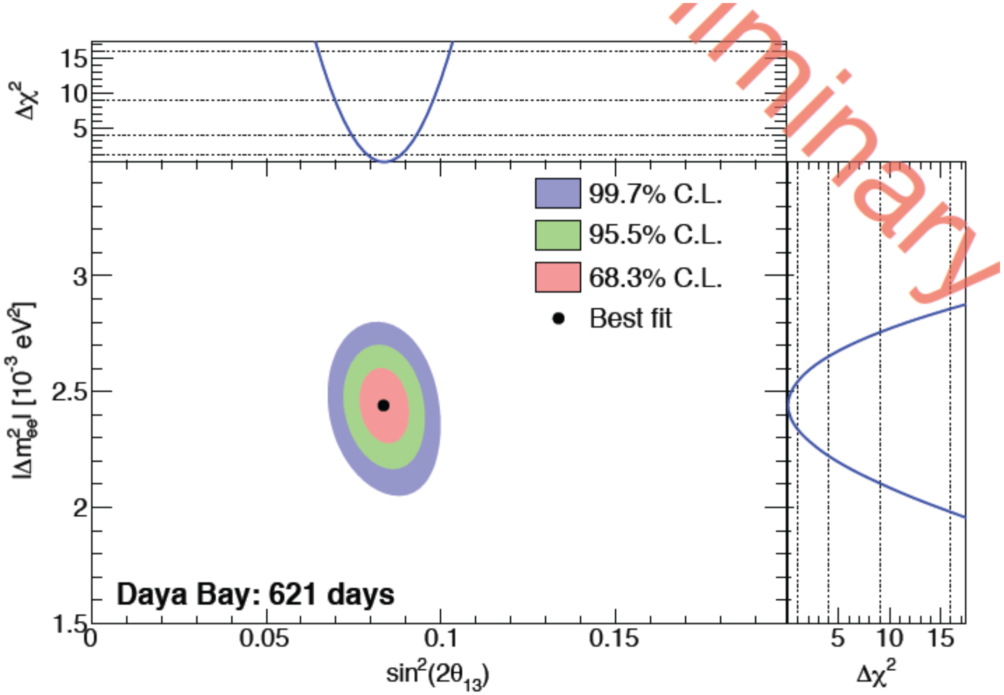
$$\Delta m^2_{ee} \sim 0.7\Delta m^2_{31} + 0.3\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} \sim 0.3\Delta m^2_{31} + 0.7\Delta m^2_{32} + CP$$





Latest Results from Daya Bay



217 days data (2013)

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$

621 days data (Neutrino 2014)

$$\boldsymbol{\sin^2 2\theta_{13} = 0.084 \pm 0.005}$$

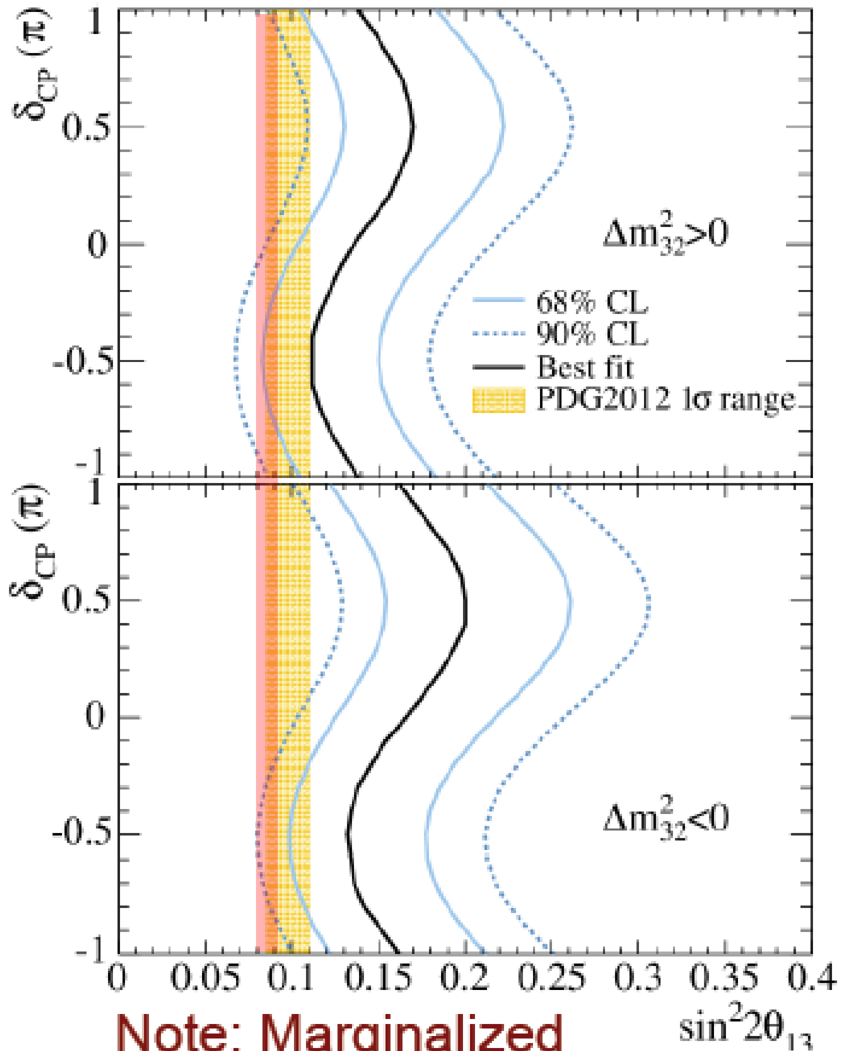
$$\boldsymbol{|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2}$$

$$\Delta m^2_{ee} \sim 0.7\Delta m^2_{31} + 0.3\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} \sim 0.3\Delta m^2_{31} + 0.7\Delta m^2_{32} + CP$$

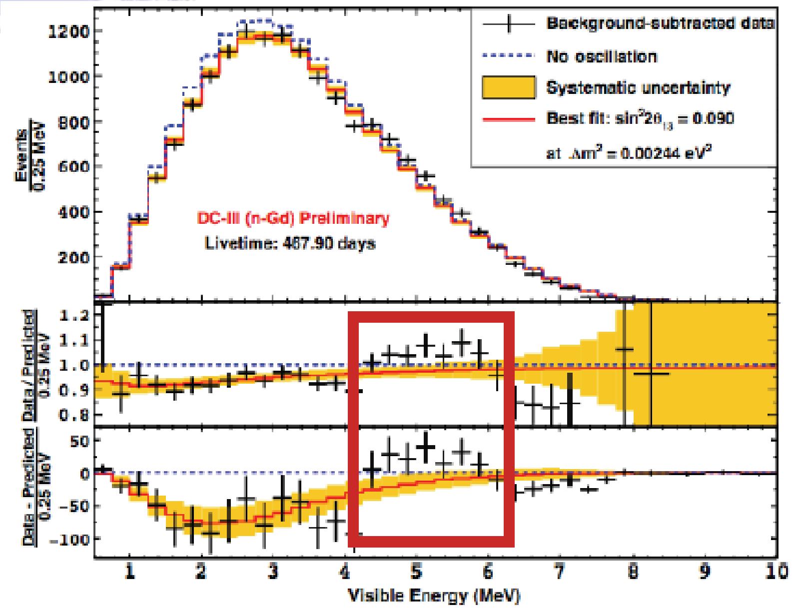
Let's think about these regions!

- Comparing with the external reactor constraint the best overlap is for the normal hierarchy with $\delta_{cp}=-\pi/2$.
- This is a **lucky point**!
- You also need to increase the θ_{23} mixing angle to account for the number of observed events.



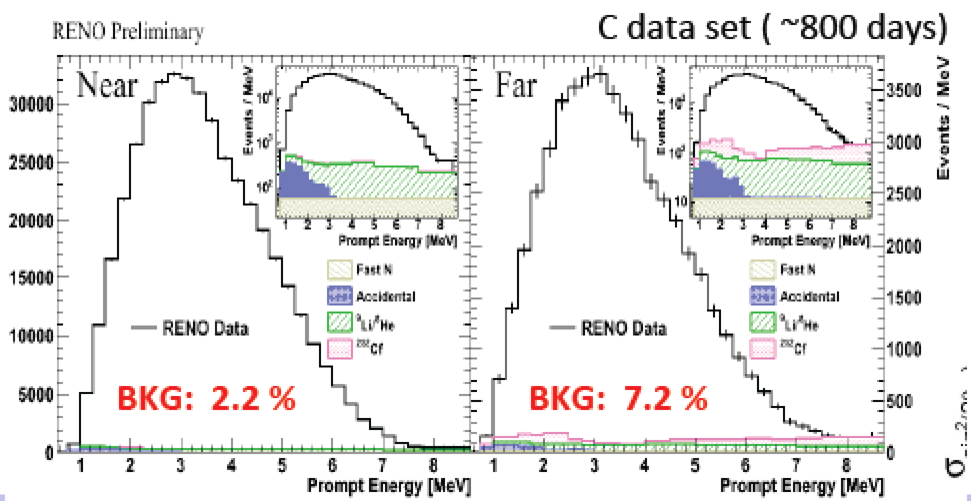
Note: Marginalized over θ_{23} and Δm^2_{32}

Double Chooz and RENO



- $\sin^2(2\theta_{13}) = 0.09 \pm 0.03$ ($\chi 2$/n.d.f.) = 51.4/40
- Observed excess at [4,6] MeV not yet understood
- Correlation with reactor power is found
- Consistent with unaccounted reactor neutrino flux @ 1.5σ
- Near detector coming by end of summer 2014

5

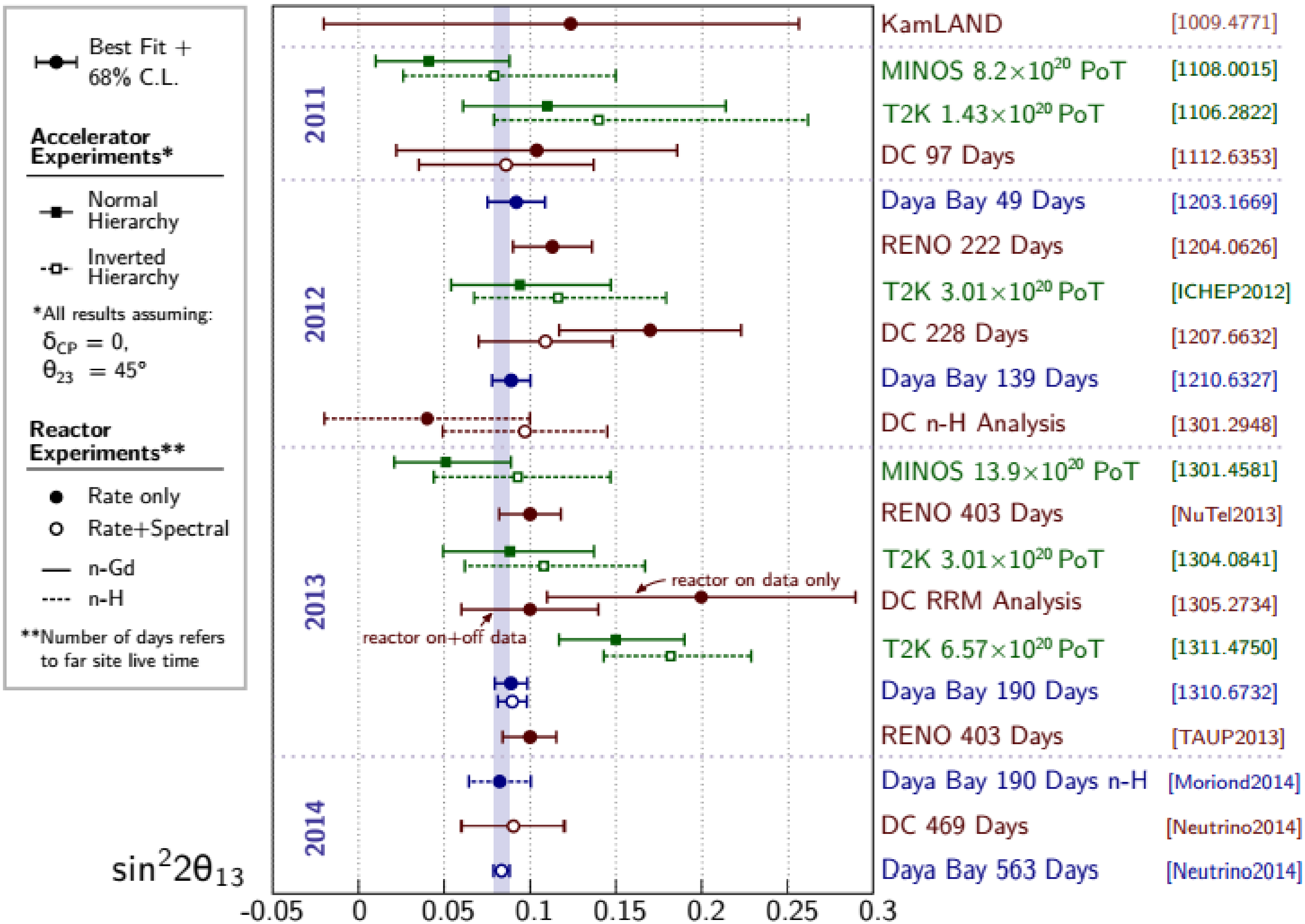


Preliminary result

C data set (~800 days)

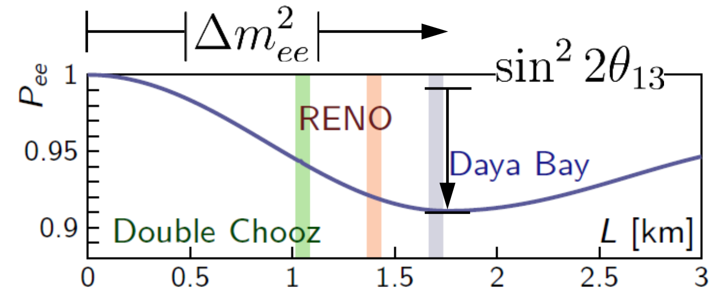
$\sin^2(2\theta_{13}) = 0.101 \pm 0.008$ (stat.) ± 0.010 (sys.)

- Data before ^{252}Cf contamination: previous **0.012 (sys.)** → **0.007 (sys.)**
- Data after ^{252}Cf contamination: → **0.018 (sys.)**

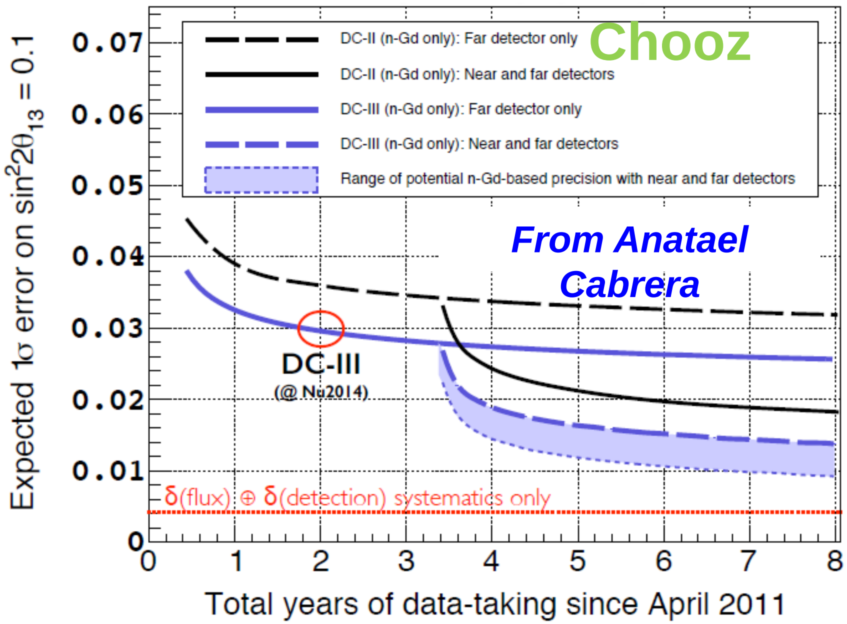


Best Fit + 68% C.L.
Accelerator Experiments*
Normal Hierarchy
Inverted Hierarchy
*All results assuming:
$\delta_{CP} = 0$,
$\theta_{23} = 45°$
Reactor Experiments**
Rate only
Rate+Spectral
n-Gd
n-H
**Number of days refers to far site live time
2011
2012
2013
2014
reactor on data only
reactor on+off data
$\sin^2 2\theta_{13}$
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
KamLAND [1009.4771]
MINOS 8.2×10^{20} PoT [1108.0015]
T2K 1.43×10^{20} PoT [1106.2822]
DC 97 Days [1112.6353]
Daya Bay 49 Days [1203.1669]
RENO 222 Days [1204.0626]
T2K 3.01×10^{20} PoT [ICHEP2012]
DC 228 Days [1207.6632]
Daya Bay 139 Days [1210.6327]
DC n-H Analysis [1301.2948]
MINOS 13.9×10^{20} PoT [1301.4581]
RENO 403 Days [NuTel2013]
T2K 3.01×10^{20} PoT [1304.0841]
DC RRM Analysis [1305.2734]
T2K 6.57×10^{20} PoT [1311.4750]
Daya Bay 190 Days [1310.6732]
RENO 403 Days [TAUP2013]
Daya Bay 190 Days n-H [Moriond2014]
DC 469 Days [Neutrino2014]
Daya Bay 563 Days [Neutrino2014]

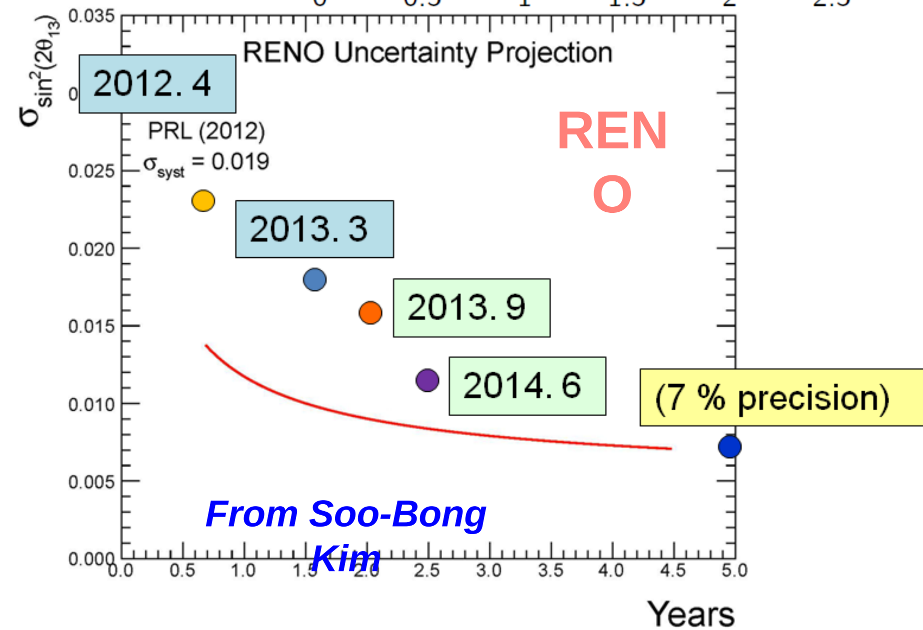
Projections of θ_{13} companies

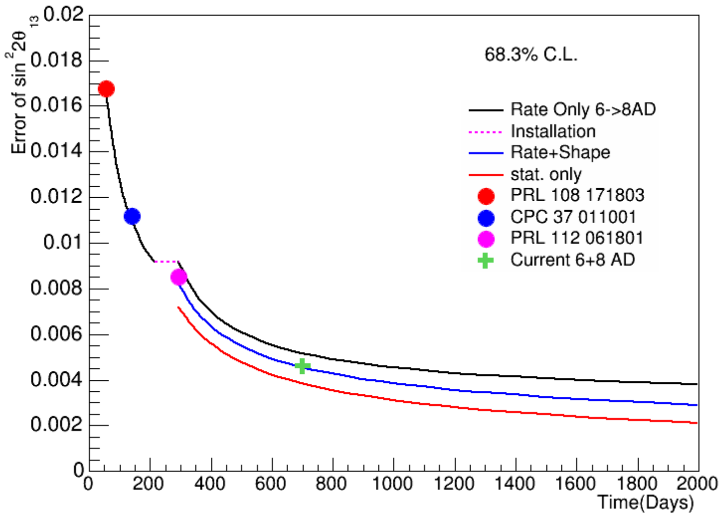


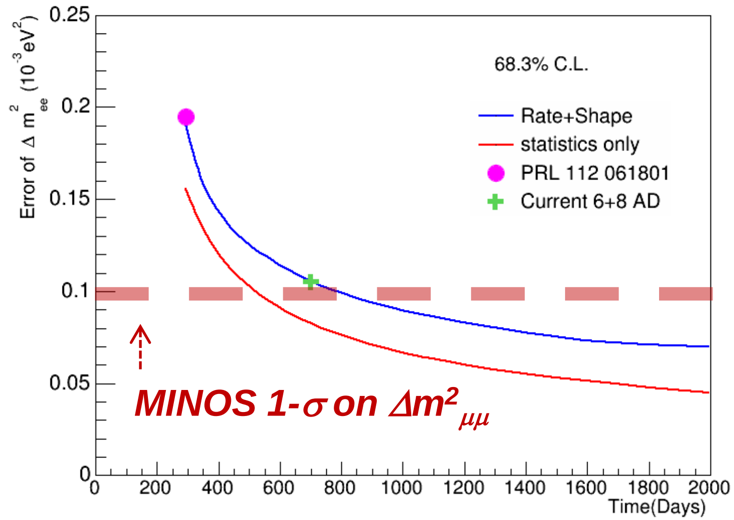
Double Chooz



RENO

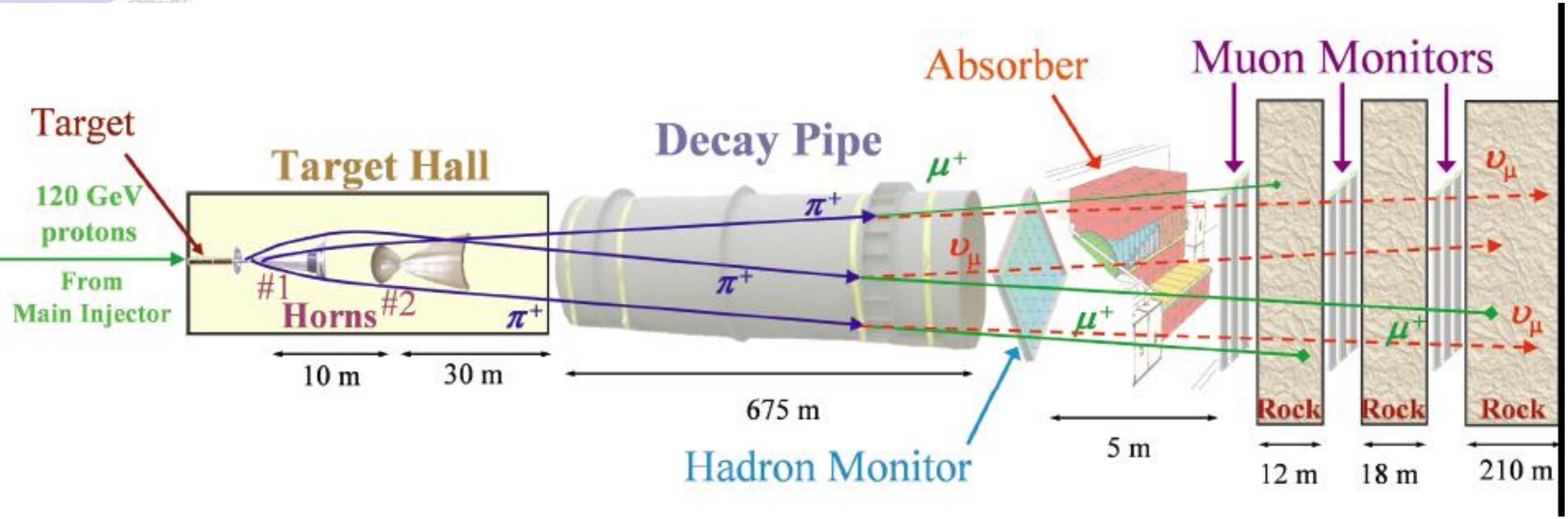






Daya Bay

加速器中微子

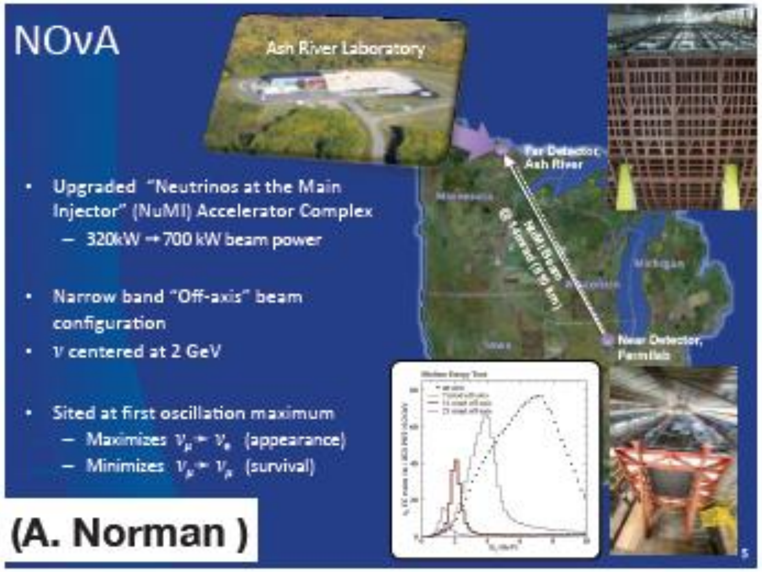


- Neutrinos at the Main Injector(NUMI)
  - 120 GeV proton beam from the main Injector on graphite target, power ~ 310 kW
  - Produced hadrons, mainly pi and K, will decay to neutrinos

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

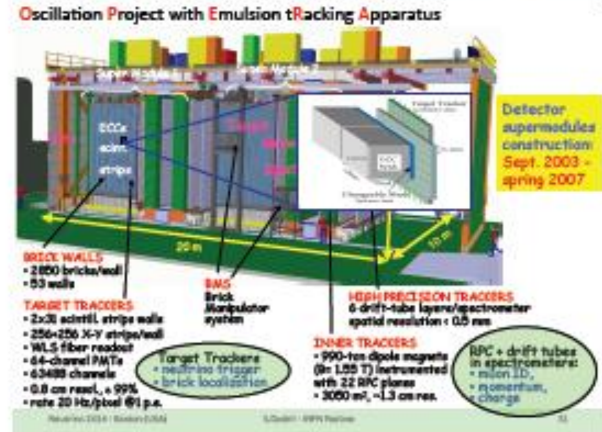
$$\pi^+ \to \mu^+ + \nu_\mu \qquad \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

Accelerator neutrinos



(A. Norman)

(S. Dusini)



(C. Farnese)

(A. Sousa)

(C. Walter)

2011 : Indication from T2K

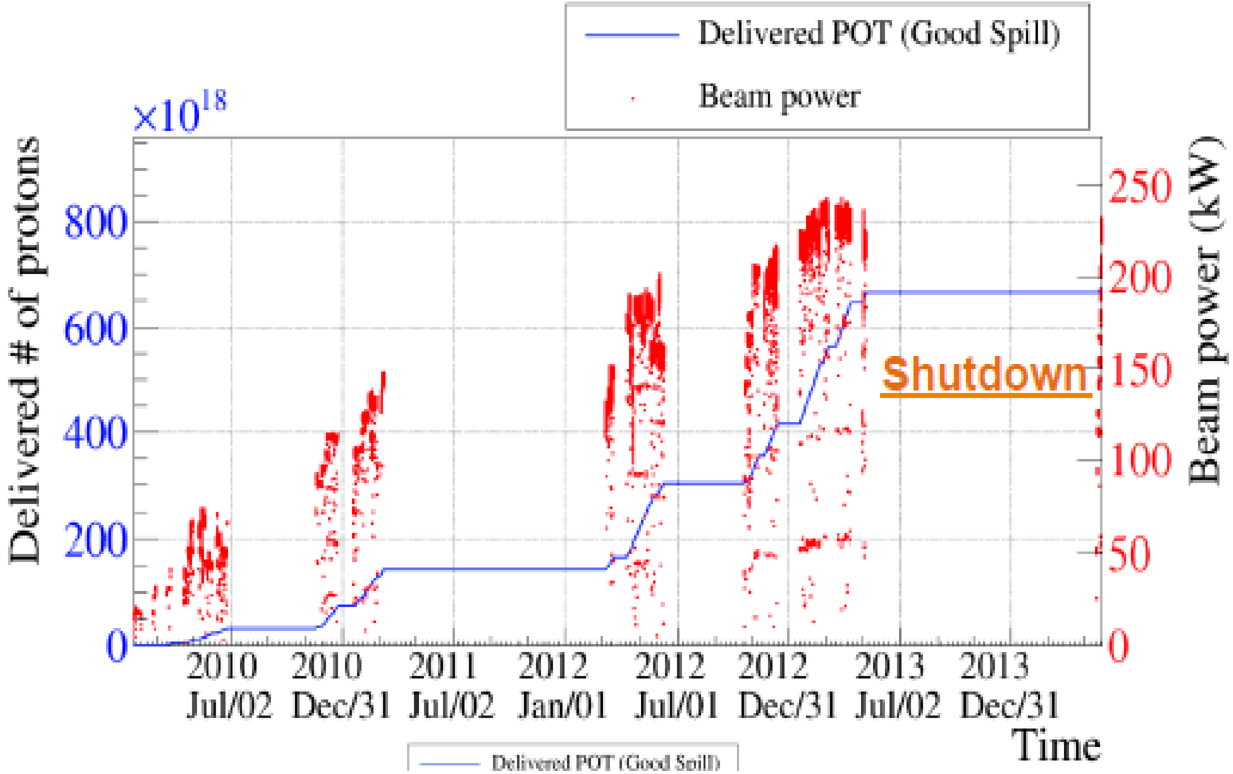
- We reported new results on $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 1.43×10^{20} p.o.t. (2% exposure of T2K's goal)
  - The expected number of events is 1.5 ± 0.3 ($\sin^2 2\theta_{13} = 0$)
  - 6 candidate events are observed
  - Under $\theta_{13}=0$ hypothesis, the probability to observe 6 or more candidate events is 0.007 (equivalent to 2.5σ significance)
  - $0.03\ (0.04) < \sin^2 2\theta_{13} < 0.28\ (0.34)$ at 90% C.L. for normal (inverted) hierarchy (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

Indication of ν_e appearance

submitted to PRL

- Resume experiment as soon as possible and improve analysis method to conclude ν_e appearance phenomenon
- ν_μ disappearance result with 1.43×10^{20} p.o.t. data will be reported this summer

T2K Data



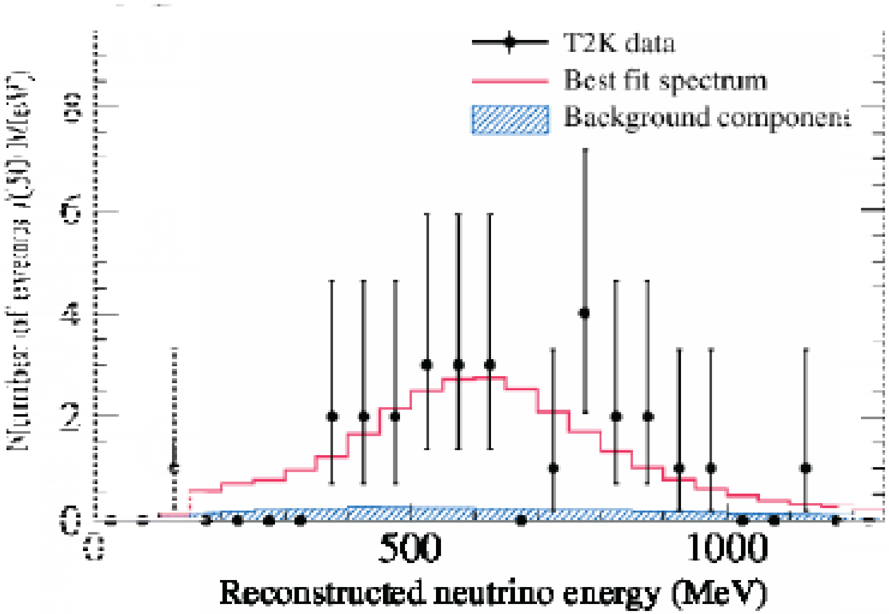
In this shutdown period:
- Linac upgraded to 400 MeV
- 3 horns replaced
- New beam monitors

- Data sets contain 6.57 x 10^{20} POT
- Run 1 instantaneous power reached 50 kW
- ➔ Increased # bunches/pulse, protons/bunch, repetition rate
- Run 4 stable power reached **235 kW**

POT ~8% of final design goal

Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of ν_e Appearance

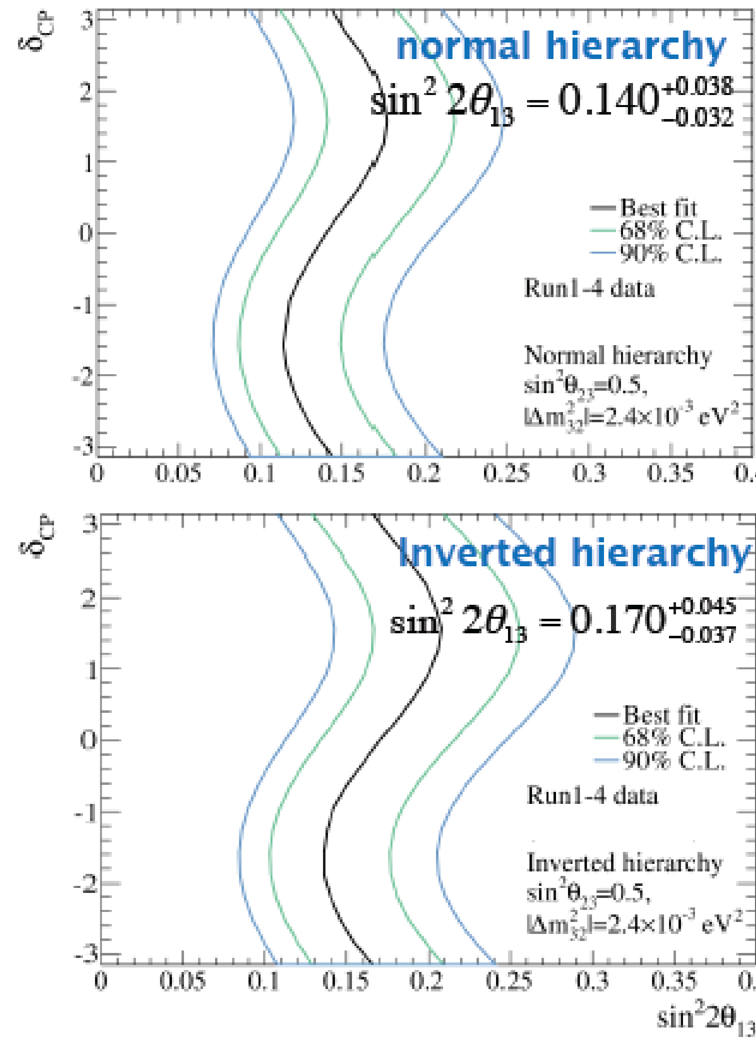


4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13}$= 0.1

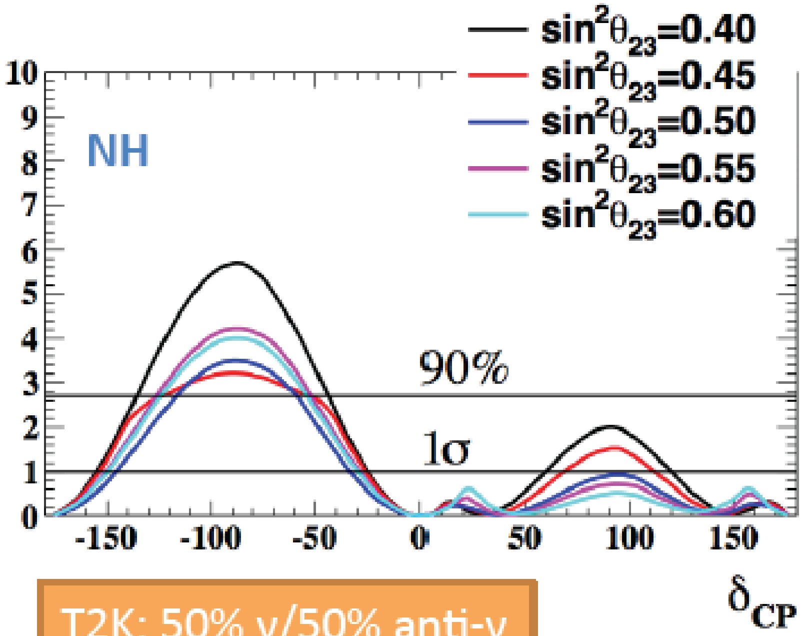
δ_{CP}= 0, $\sin^2\theta_{23}$= 0.5



7.3 σ significance for non-zero θ_{13}

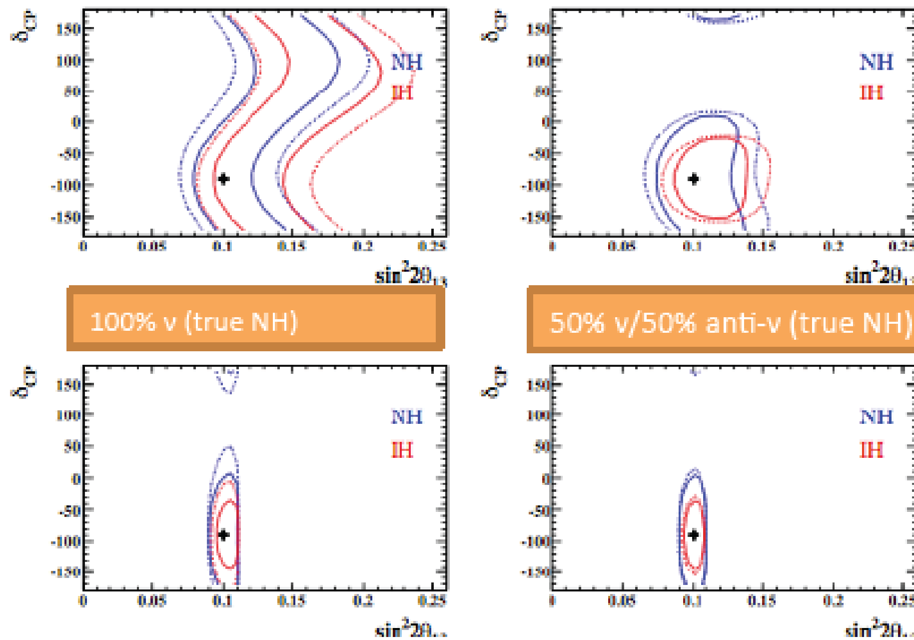
First ever observation (>5σ) of an explicit ν appearance channel

Future Sensitivity to CPV using T2K



T2K: 50% ν/50% anti-ν

"Lucky! (+: $Sin^2 2\theta$=0.1, δCP=-90)"



100% ν (true NH)

50% ν/50% anti-ν (true NH)

100% ν (true NH)
w/ Reactor constraint

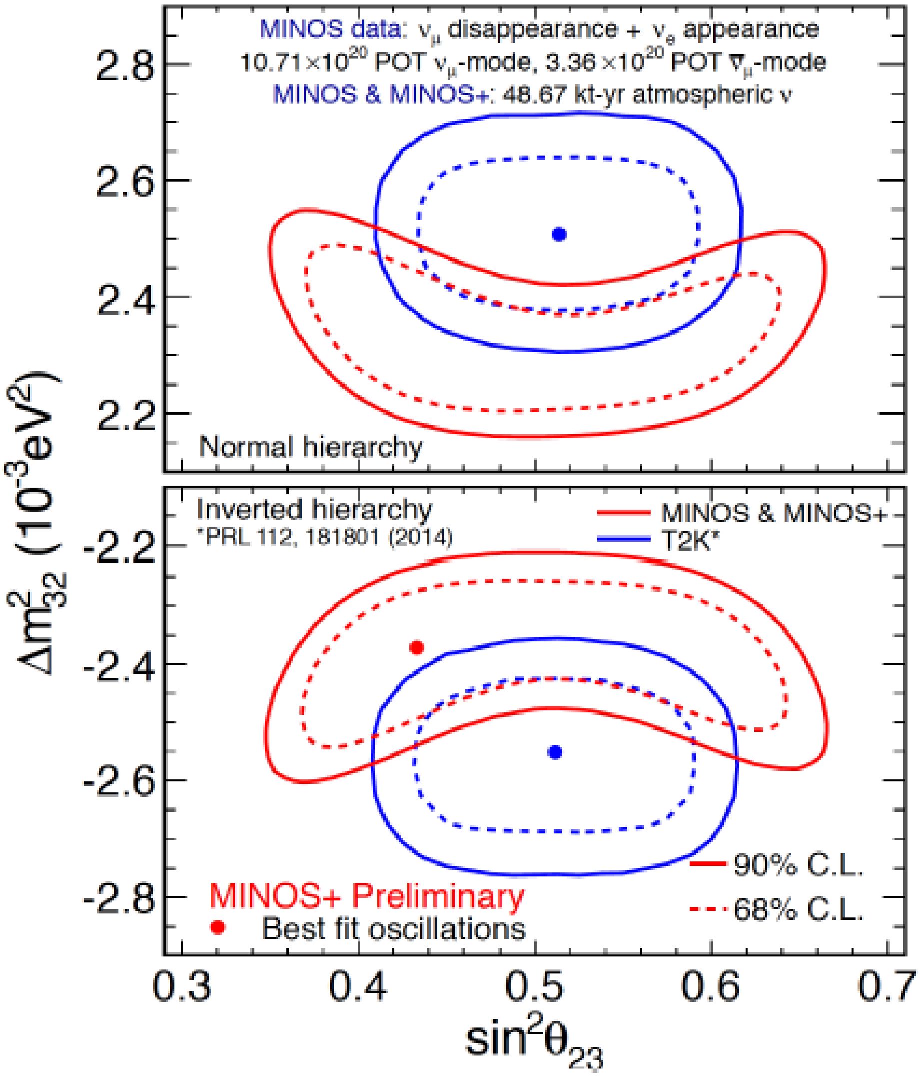
50% ν/50% anti-ν (true NH)
w/ Reactor constraint

No systematics

5% error on signal, 10% on background

T2K studies indicate our best sensitivity will be for 50% ν/50% anti-ν running. Anti-nu running also opens a large new physics program.

MINOS and MINOS+



Three-Flavor Oscillations Best Fit

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

Normal Hierarchy

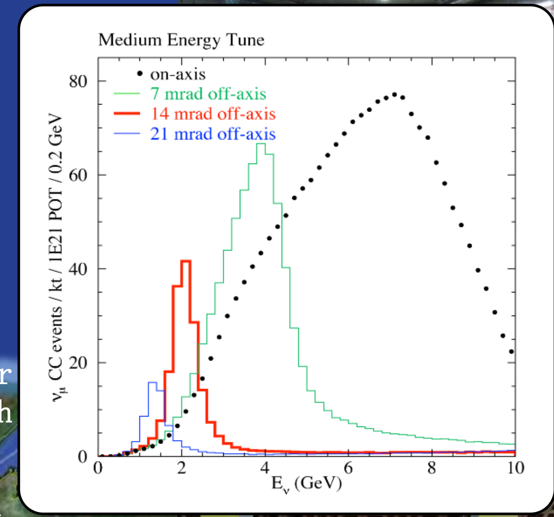
$|\Delta m^2_{32}| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2$

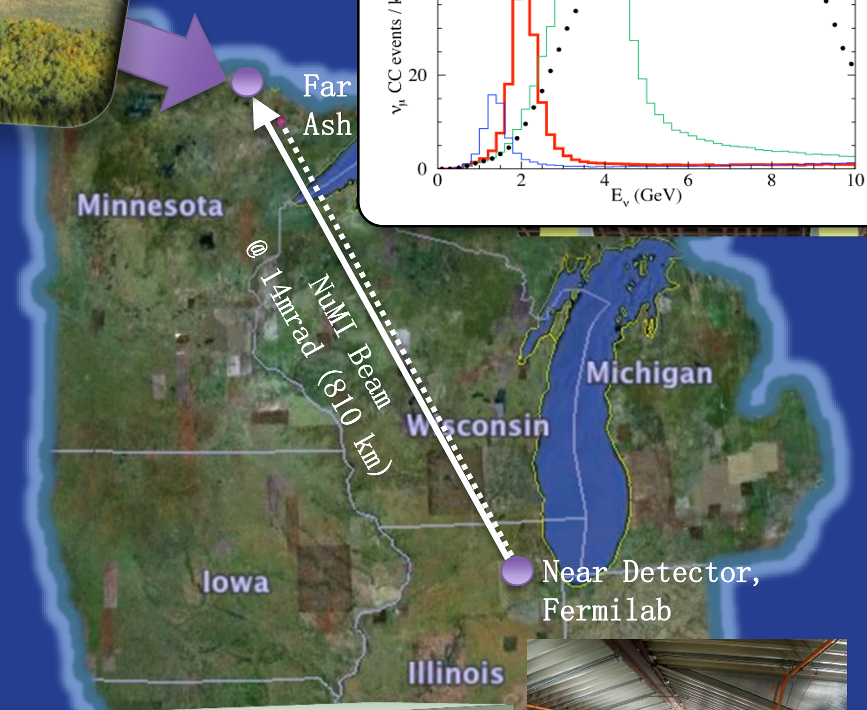
$\sin^2\theta_{23} = 0.43^{+0.16}_{-0.04}$

$0.37 < \sin^2\theta_{23} < 0.64$ (90% C.L.)

- **Most precise measurement of $|\Delta m^2_{32}|$**
- Consistent with maximal mixing

NOvA

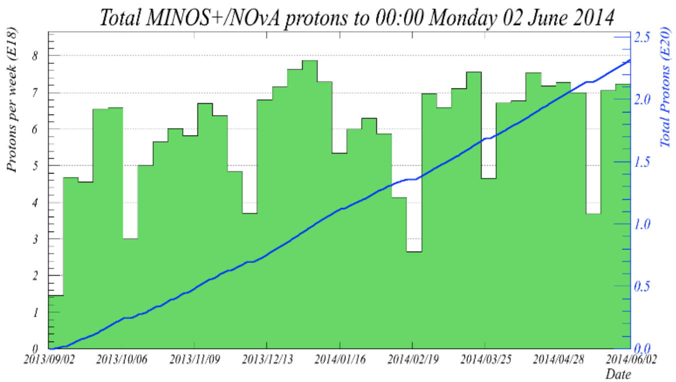


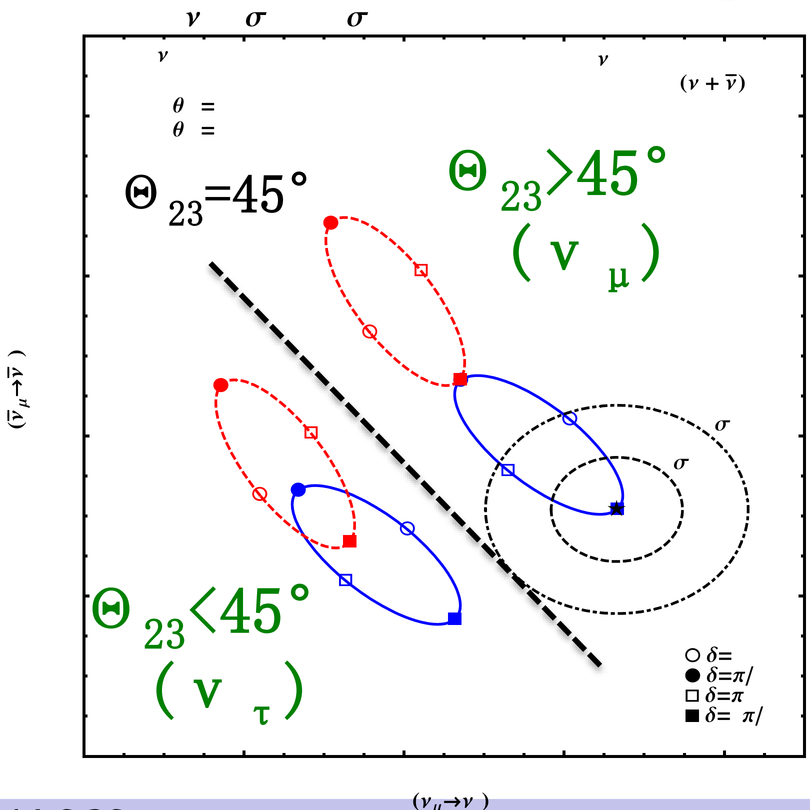


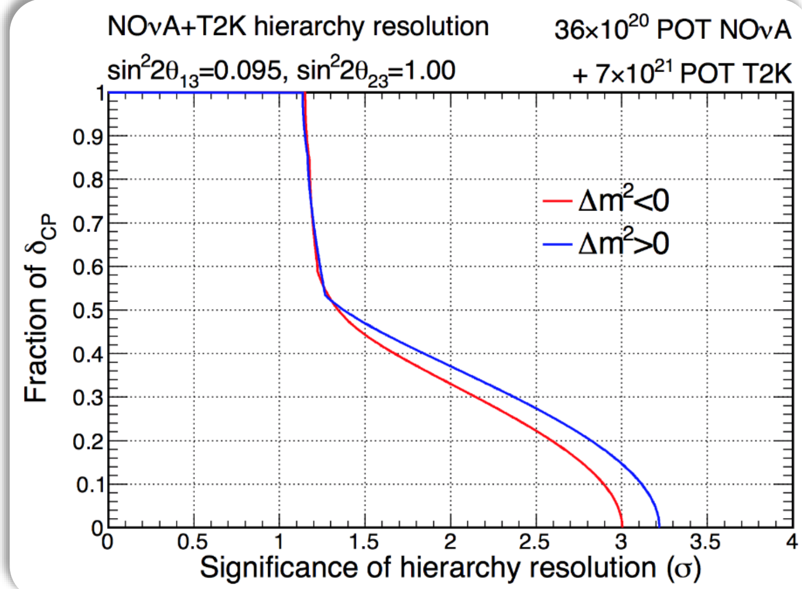
- Designed to make precision measurements of the $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ for both ν and $\bar{\nu}$

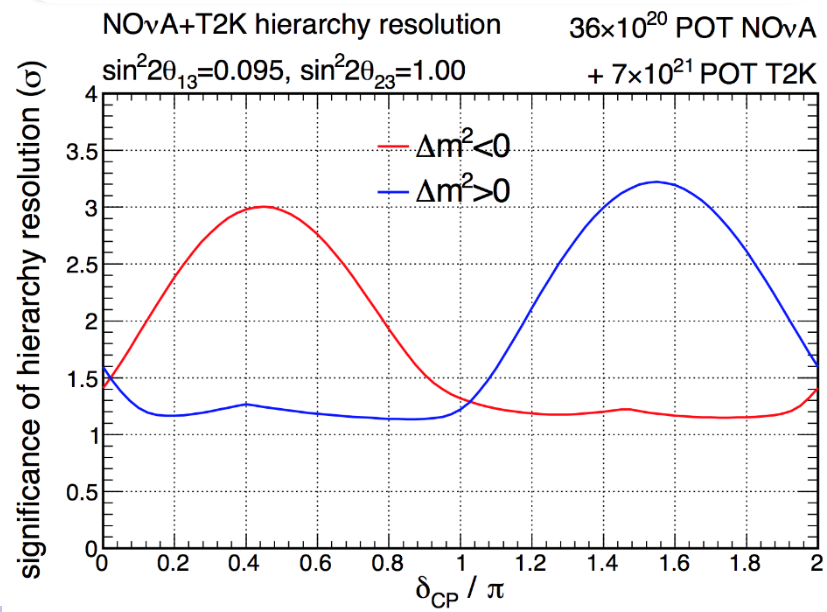
- 14 kt *totally active*, liquid scintillator , surface detector
- Optimized as a highly segmented low Z calorimeter/range stack
- Tuned to:
  - Reconstruct EM showers
  - Measure μ track momenta
  - Identify interaction vertices and nuclear recoils

NOvA- Mass Hierarchy



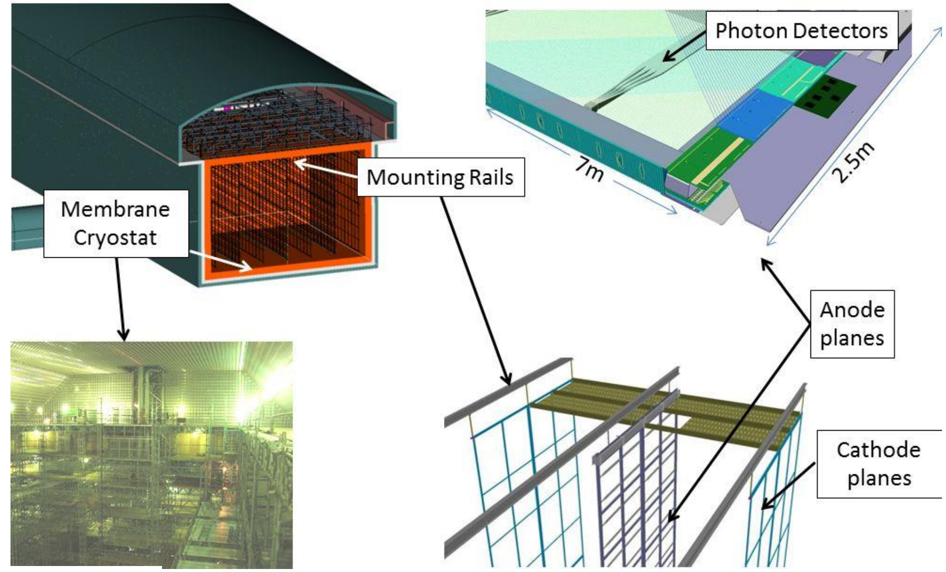


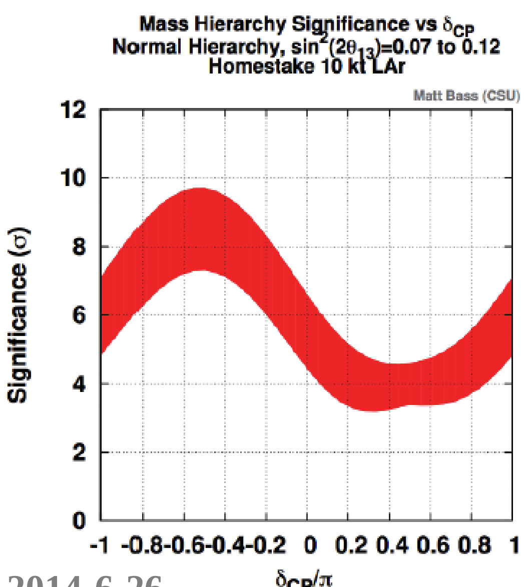


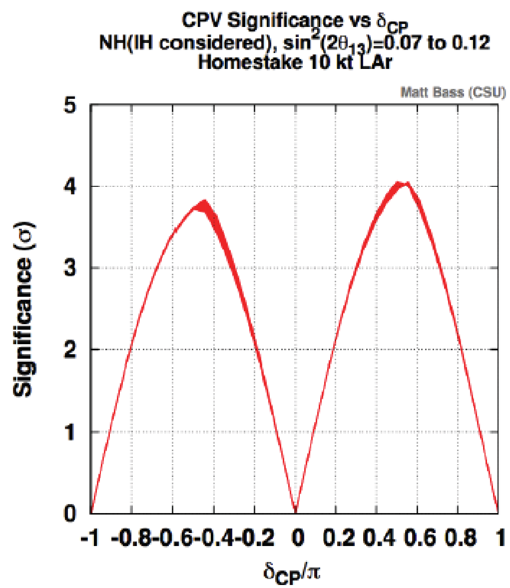


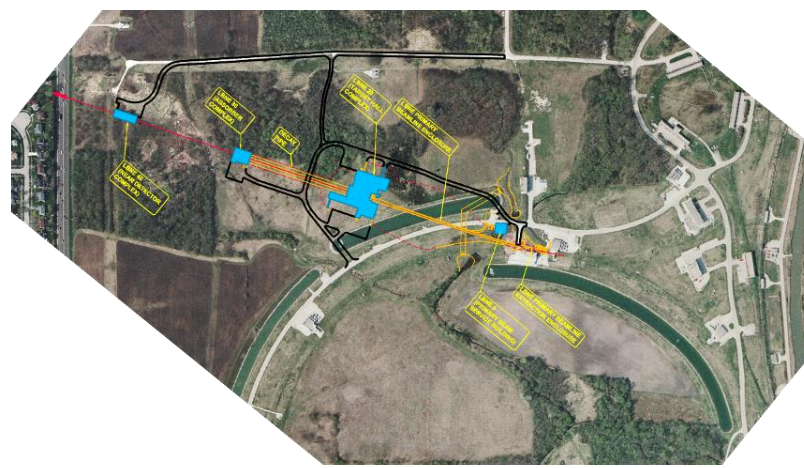
美国：LBNE

- 10kt LAr on surface
- Fermilab NUMI beam: 0.7 MW
- Detector Construction：2014
- Operation：2022
- Cost：0.8 B$



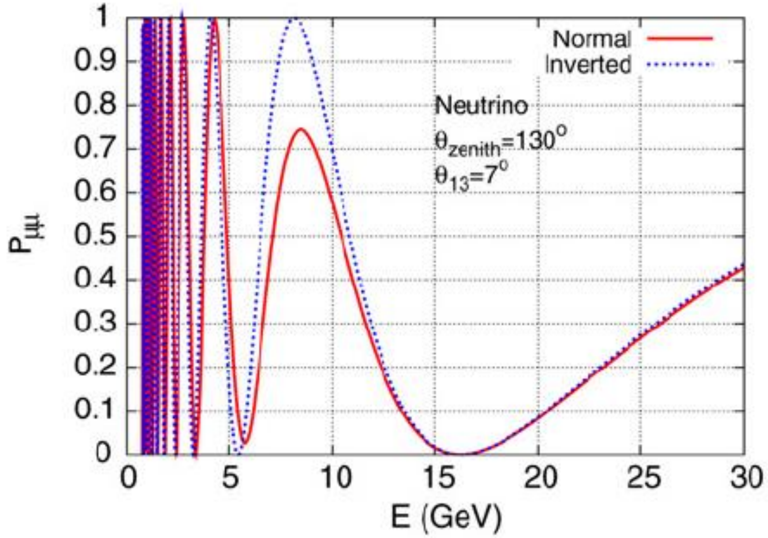


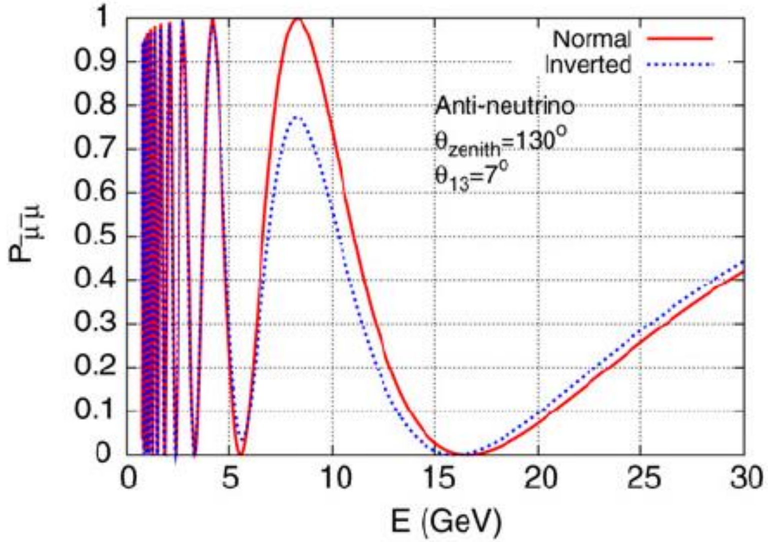




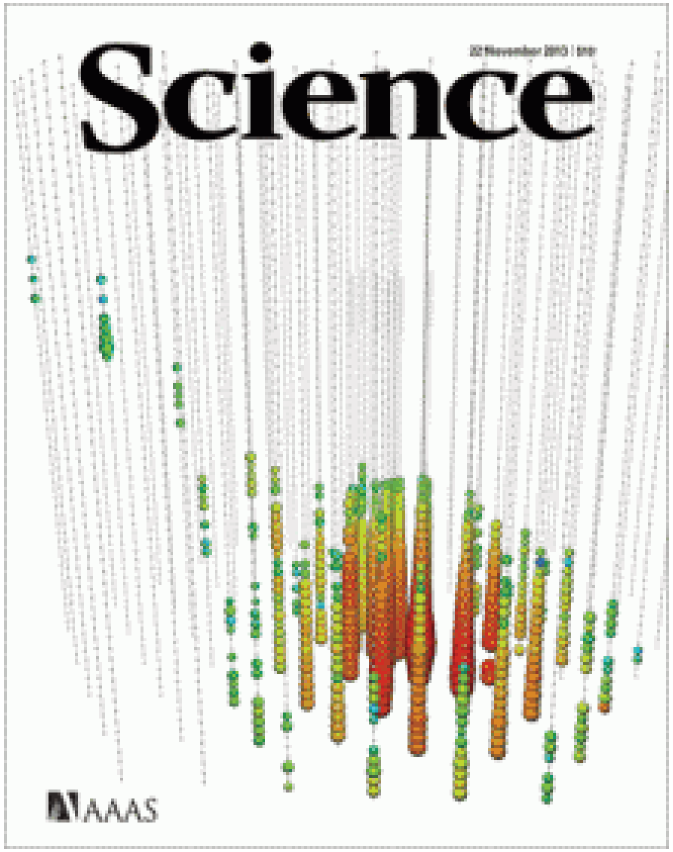
大气中微子确定质量等级

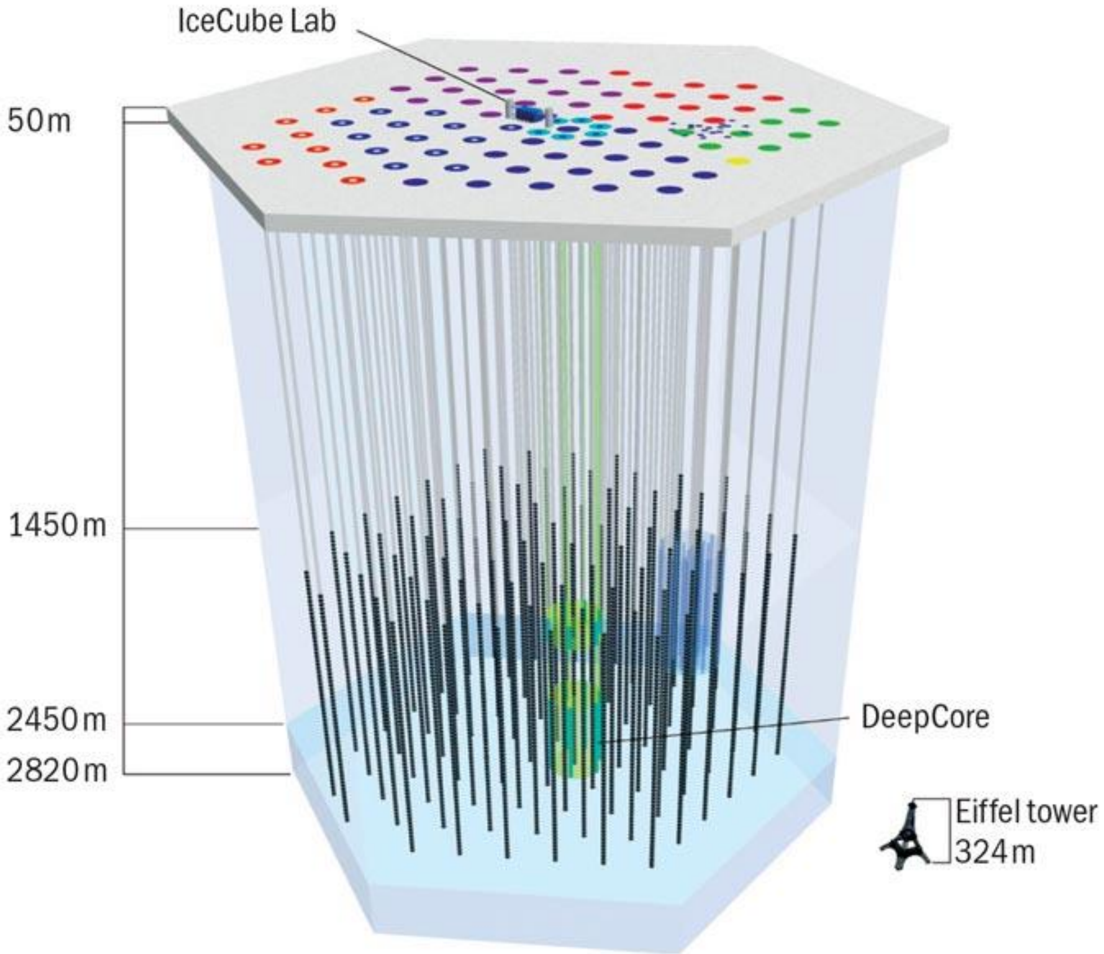
- 由于物质效应，大气中微子穿过地球时的振荡几率与正反质量等级相关。
- 如果能区分正反中微子，效应比较明显。
- 如不能区分，正反中微子的效应抵消，还残余一部分效应。





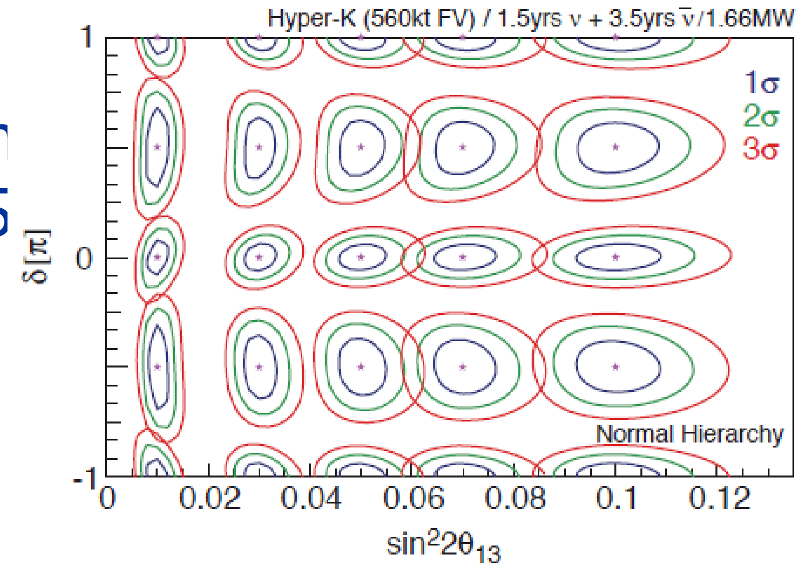
PINGU

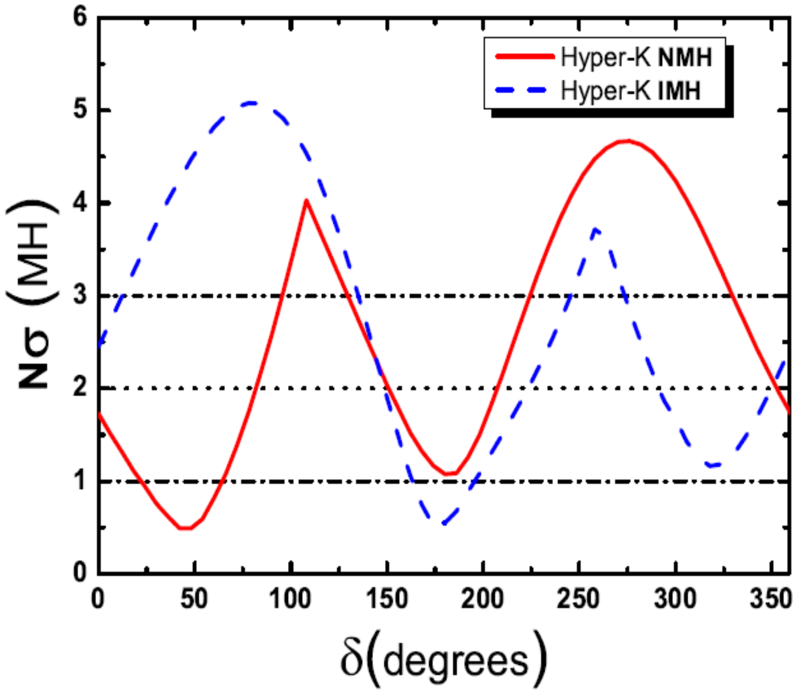

Science
AAAS

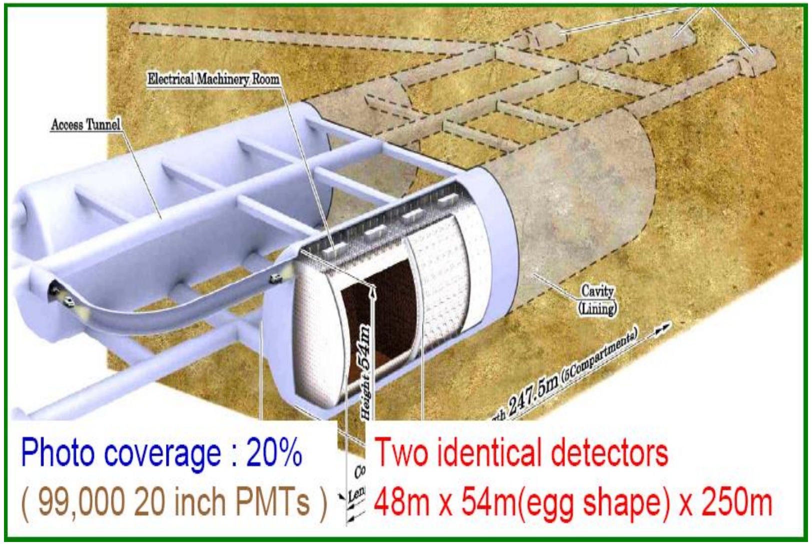

IceCube Lab
50m
1450m
2450m
2820m
DeepCore
Eiffel tower
324m

日本：HyperK

- 560 kt water Cherenkov
- Atmospheric & J-PARC beam
- Detector Construction：2015
- Operation: 2022
- Cost：1B $

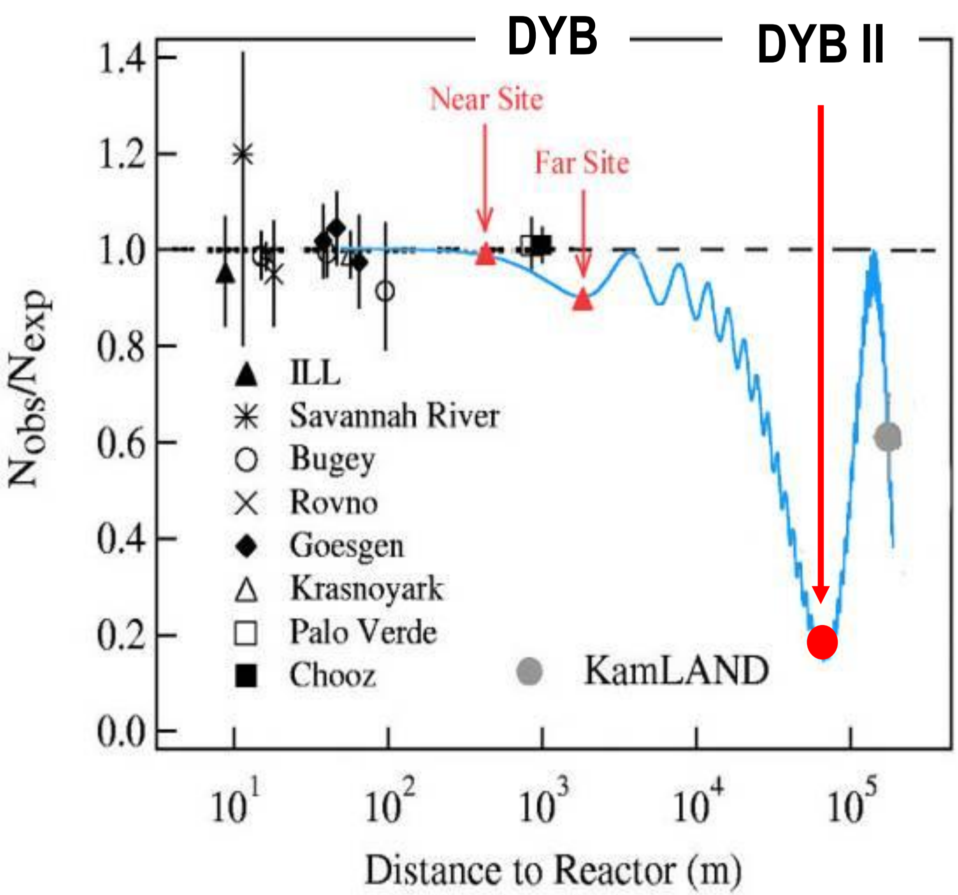






江门中微子实验

- 2万吨液体闪烁体探测器，3%能量精度



科学目标

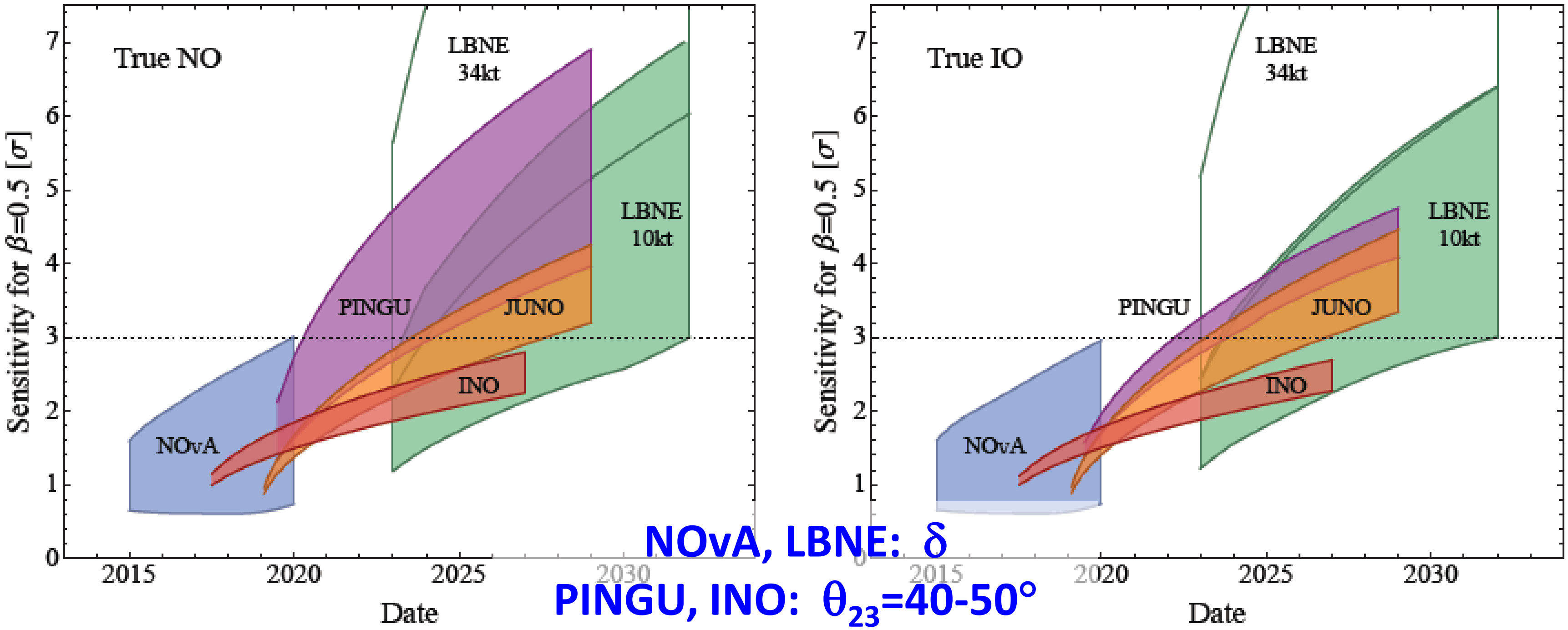
- 质量顺序
- 混合参数精确测量
- 超新星中微子
- 地球中微子
- 太阳中微子
- 大气中微子
- 不活跃中微子
- ……

2008年提出初步实验方案，
开始关键技术的预研

Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007, 2009
Talk by Y.F. Wang at ICFA seminar 2008...NuFact 2012; by J. Cao at Nutel 2009...NPB 2012 (ShenZhen)

Experiments/Proposals for MH

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, LBNE: δ
PINGU, INO: θ_{23}=40-50°
JUNO: 3%-3.5%

JUNO: Competitive in schedule and Complementary in physics

- Have chance to be the first to determine MH
- Independent of the CP phase and θ_{23} (Acc. and Atm. do)
- Combining with other experiments can significantly improve the sensitivity
- Well established liquid scintillator detector technology

Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

原名大亚湾二期实验

2013年2月批准（先导专项A）

预期20202取数

预期人员规模 ~500人

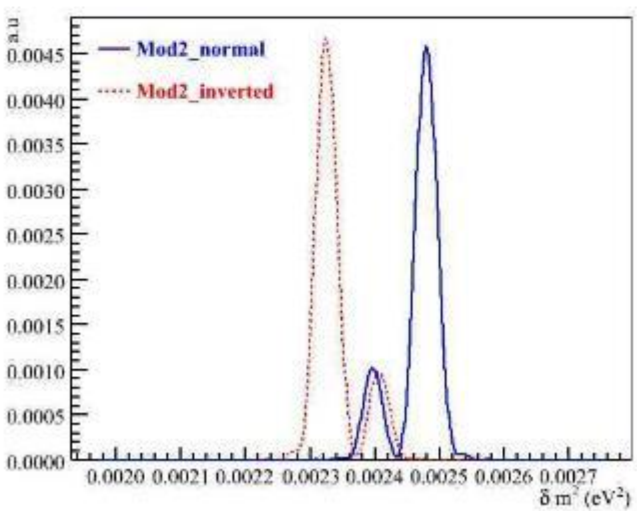
Interference: Relative Measurement

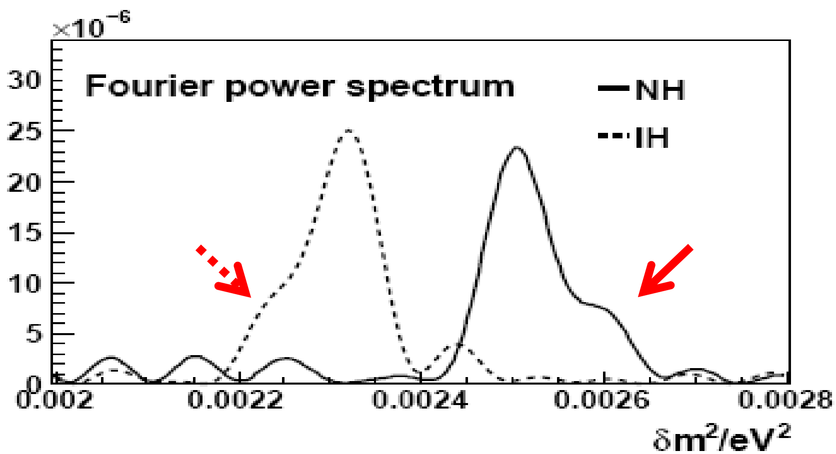
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

$$P_{21} = 0.81\ \sin^2\Delta_{21}$$
$$P_{31} = 0.7 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{31}$$
$$P_{32} = 0.3 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{32}$$

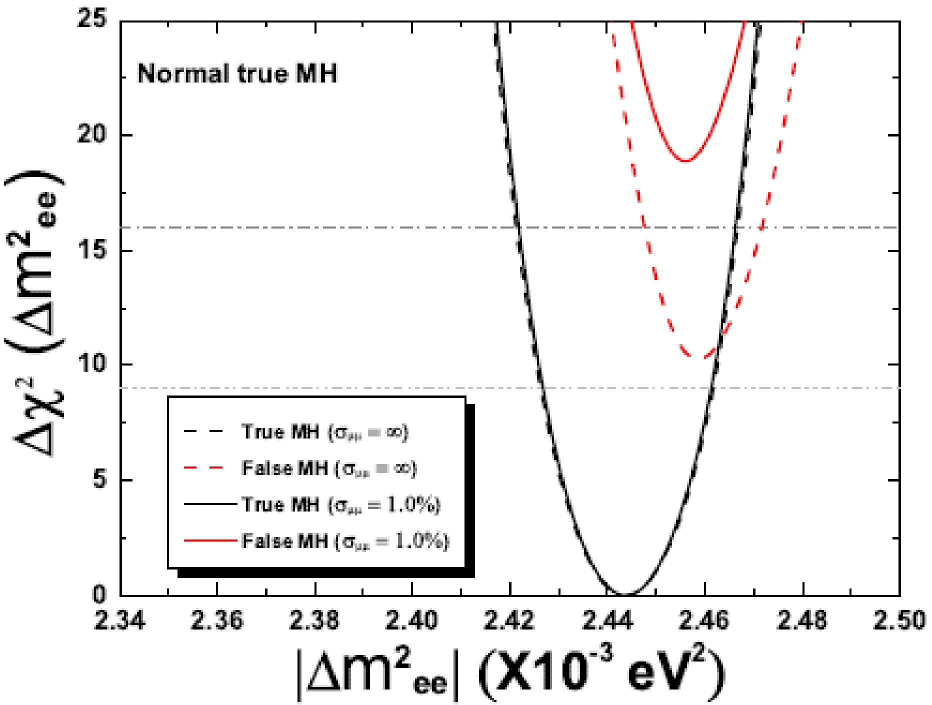
- The relative larger (0.7) oscillation and smaller (0.3) oscillation, which one is slightly (1/30) faster?
- Take Δm^2_{32} as reference, after a Fourier transformation
  - NH: $\Delta m^2_{31} > \Delta m^2_{32}$, Δm^2_{31} peak at the right of Δm^2_{32}

Δm





物理灵敏度



	Current	DYB II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	14%➔ 4%	~ 15%

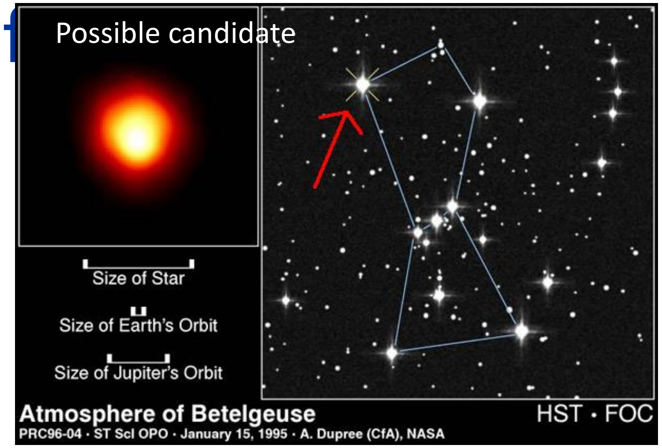
寻找新物理：
检验混合矩阵幺正性 ~1%

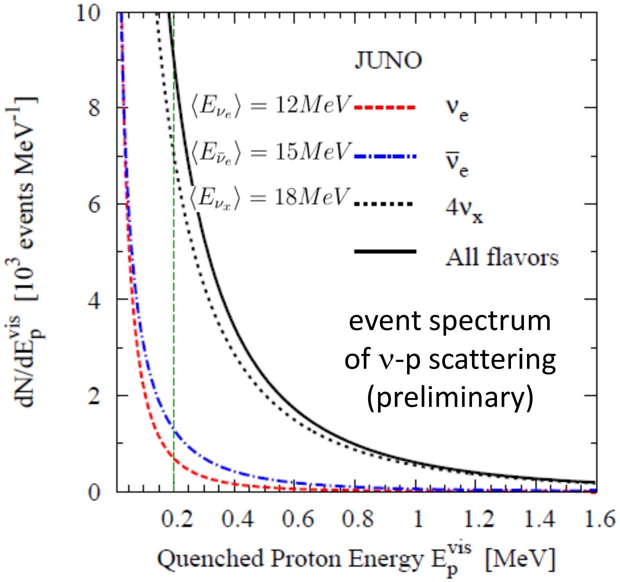
江门实验6年数据，对质量顺序 (arXiv:1303.6733)：

- 理想情况下，相对测量 4σ，加上Δm^2绝对 测量5σ
- 考虑到实际反应堆分布、能量非线性等因素，相对测量3σ，加上Δm^2绝对 测量4σ

Supernova Neutrinos

- Less than 20 events observed so f
- Assumptions:
  - Distance: 10 kpc (our Galaxy center)
  - Energy: 3×10^{53} erg
  - L_ν the same for all types





Estimated numbers of neutrino events in JUNO (preliminary)

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	6.0×10^1	1.1×10^2	1.6×10^2

LS detector vs. Water Cerenkov detectors: much better detection to these correlated events

→ Measure energy spectra & fluxes of almost all types of neutrinos

Other Physics

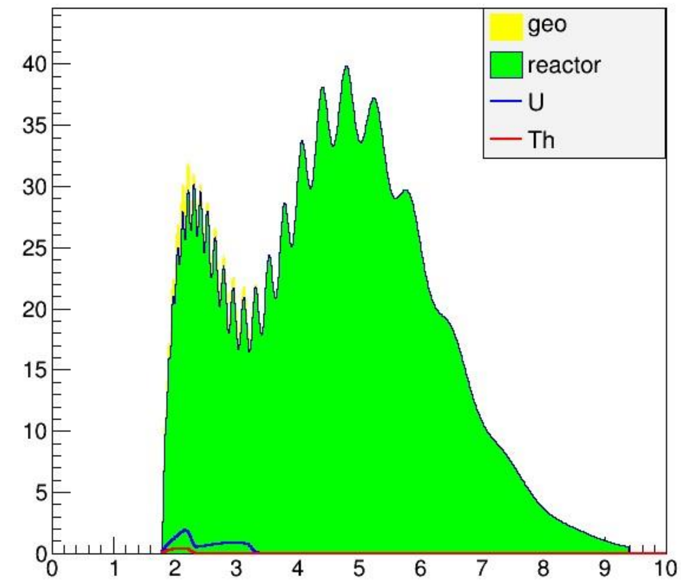
Geo-neutrinos

- Current results

  KamLAND: 30±7 TNU *(PRD 88 (2013) 033001)*

  Borexino: 38.8±12.2 TNU *(PLB 722 (2013) 295)*

  Statistics dominant
- Desire to reach an error of 3 TNU
- JUNO: ×10 statistics
  - Huge reactor neutrino backgrounds
  - Expectation: ? ±10%±10%



Solar neutrino

- ⇨ Metallicity? Vacuum oscillation to MSW?
- ⇨ need LS purification, low threshold
- ⇨ background handling (radioactivity, cosmogenic)

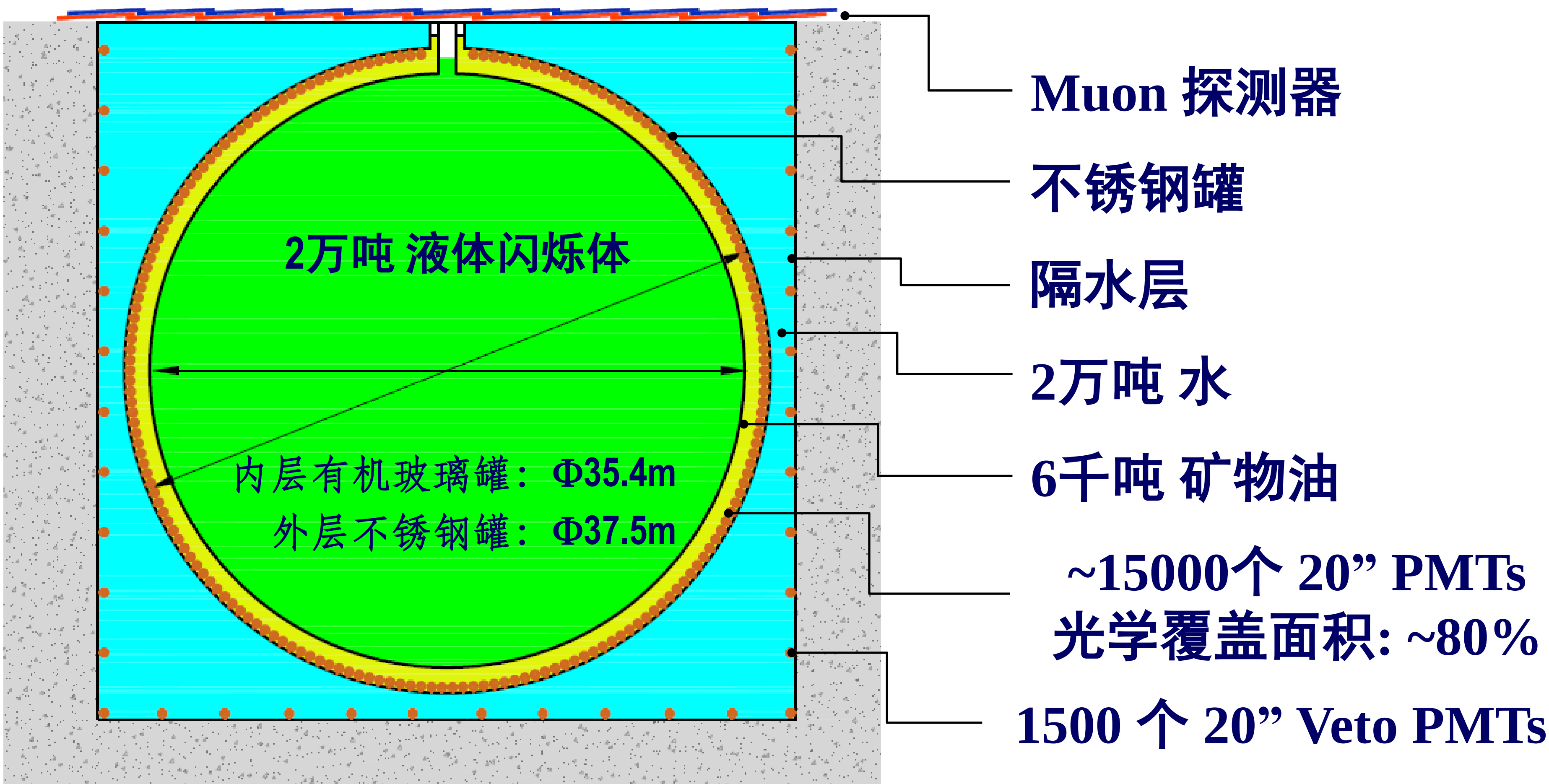
Atmospheric neutrino

- ⇨ measure ν energy instead of leptons' in LS. ~ 2σ for MH in 10 years

Diffuse supernovae ν, Sterile ν, Indirect dark matter, Nucleon decay

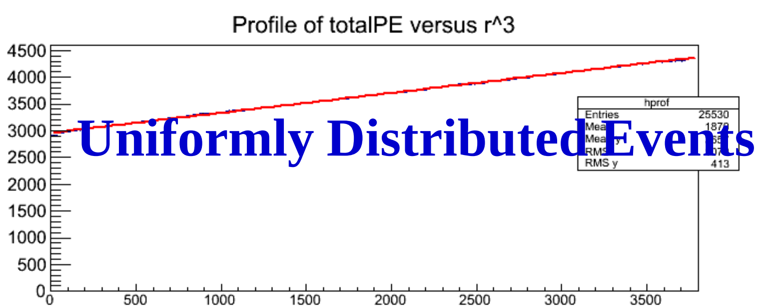
实验方案：大型液体探测器

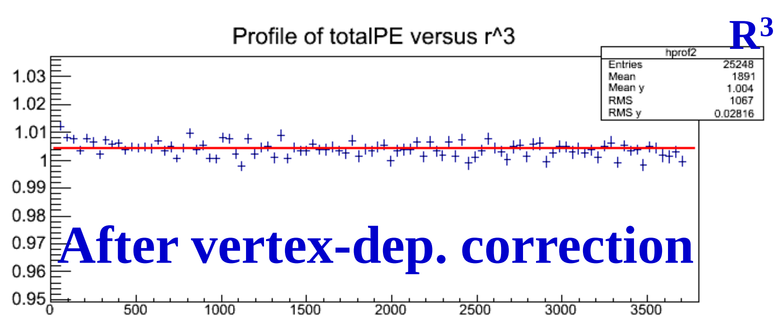
- 较目前国际最好水平：
  - 液闪体积↥ 20 倍➔增加靶质量（难点：探测器尺寸，液闪透明度）
  - 光产额↥3 倍➔提高能量分辨率　（难点：光电倍增管，液闪）

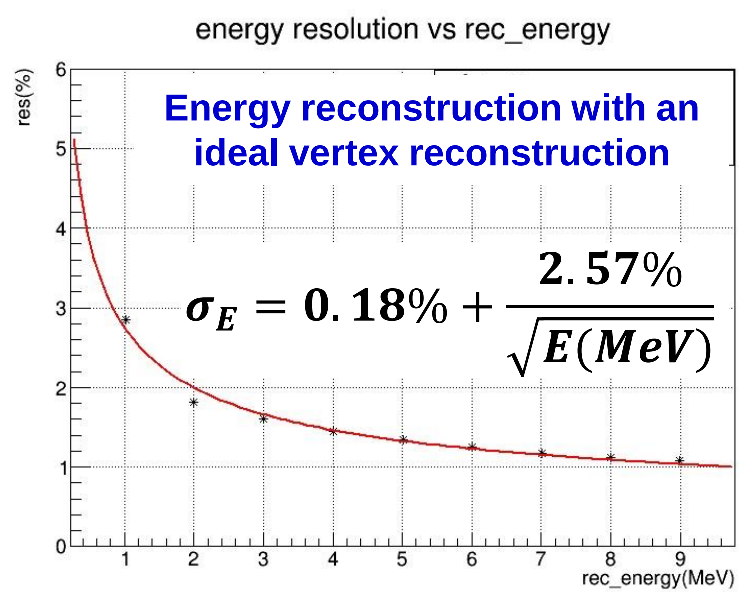


Energy Resolution

- JUNO MC, based on DYB MC (p.e. tuned to data), except
  - JUNO Geometry and 77% photocathode coverage
  - High QE PMT: maxQE from 25% -> 35%
  - LS attenuation length (1 m-tube measurement@430 nm)
    - from 15 m = absoption 30 m + Rayleigh scattering 30 m
    - to 20 m = absorption 60 m + Rayleigh scattering 30 m

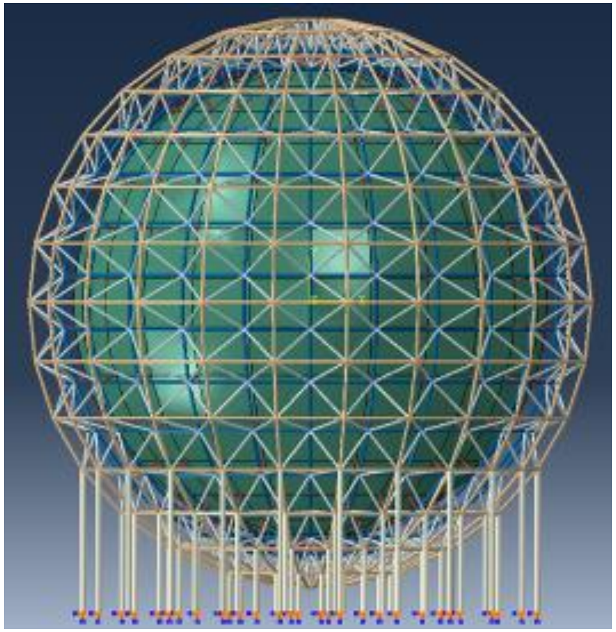


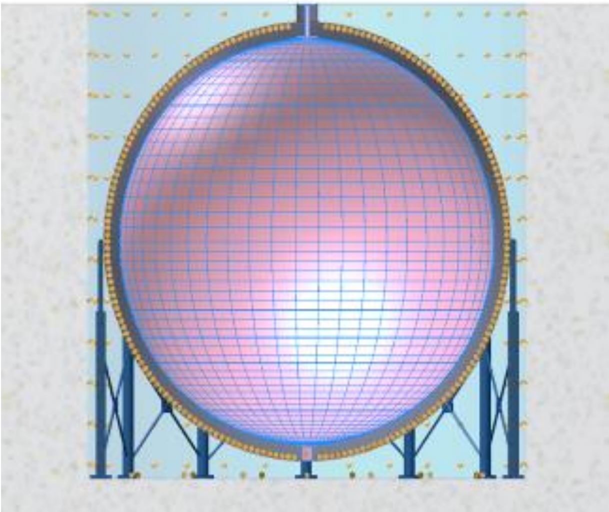




JUNO Central Detector

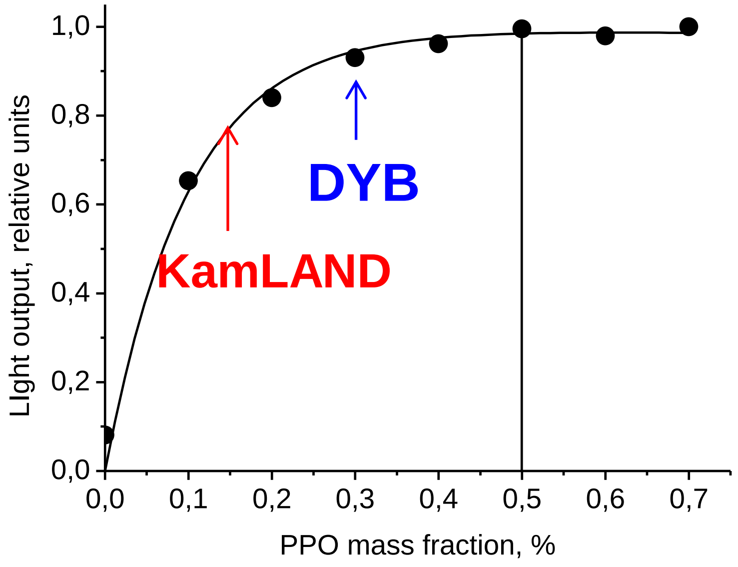
- Some basic numbers:
  - Target: 20 kt LS
  - Backgrounds/reactor signal with 700 m overburden: Accidentals (~10%), $^{9}Li/^{8}He$ (<1%), fast neutrons (<1%)
- A huge detector in a water pool:
  - Default option: acrylic tank (D~35m) + SS truss
  - Alternative option: SS tank (D~39m) + acrylic structure + balloon
- Challenges:
  - Engineering: mechanics, safety, lifetime, …
  - LS: high transparency, low background
  - PMT: high QE, high coverage
- Design & prototyping underway





Liquid Scintillator in JUNO

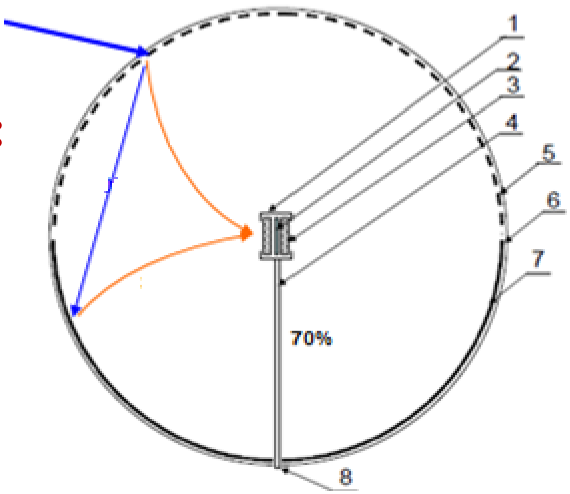
- Recipe
  LAB+PPO+bisMSB (no Gd-loading)
- Increase light yield
  - Optimization of fluors concentration
- Increase transparency
  - Good raw solvent LAB
    - Improve production processes: cutting of components, using Dodecane instead of MO, improving catalyst, etc
  - Online handling/purification
    - Distillation, Filtration, Water extraction, Nitrogen stripping, …
- Reduce radioactivity
  - Less risk, since no Gd
  - Instrinsic singles < 3Hz (above 0.7MeV), if $^{40}K/U/Th < 10^{-15}$ g/g

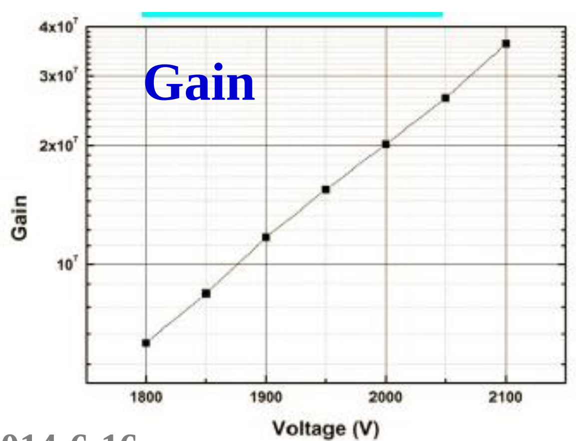


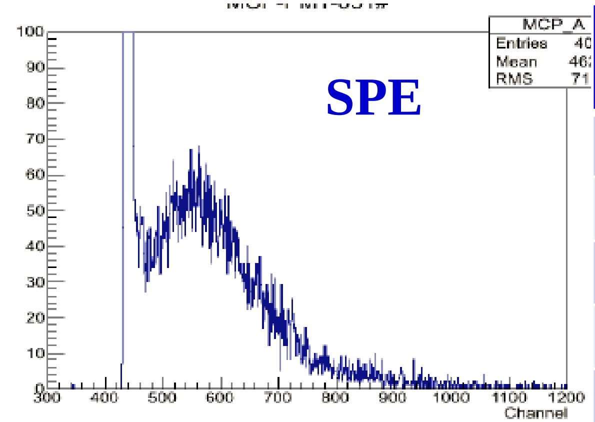
Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	22.3 m
LAB from Nanjing, Raw	20 m
Al_2O_3 coloum	25 m

High QE PMT Effort in JUNO

- High QE 20" PMTs under development:
  - **A new design using MCP: 4p collection**
- MCP-PMT development:
  - **Technical issues mostly resolved**
  - **Successful 8" prototypes**
  - **A few 20" prototypes**
- **Alternative options:** Hamamatsu or Photonics



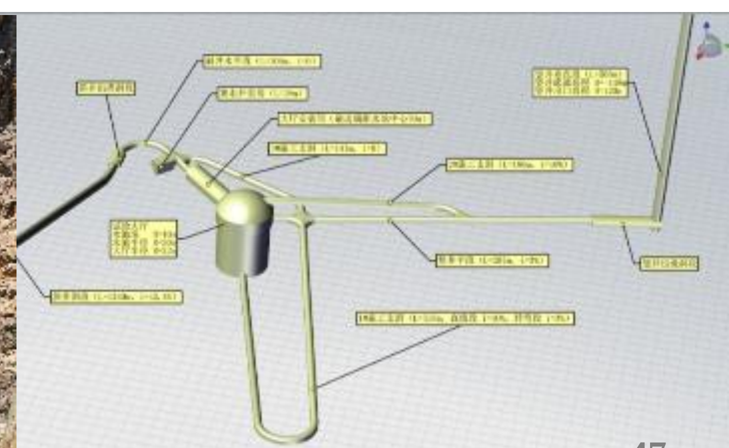




	R5912	R5912-100	MCP-PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
SPE Amp.	17mV	18mV	17mV
P/V of SPE	>2.5	>2.5	~2
TTS	5.5ns	1.5 ns	3.5 ns

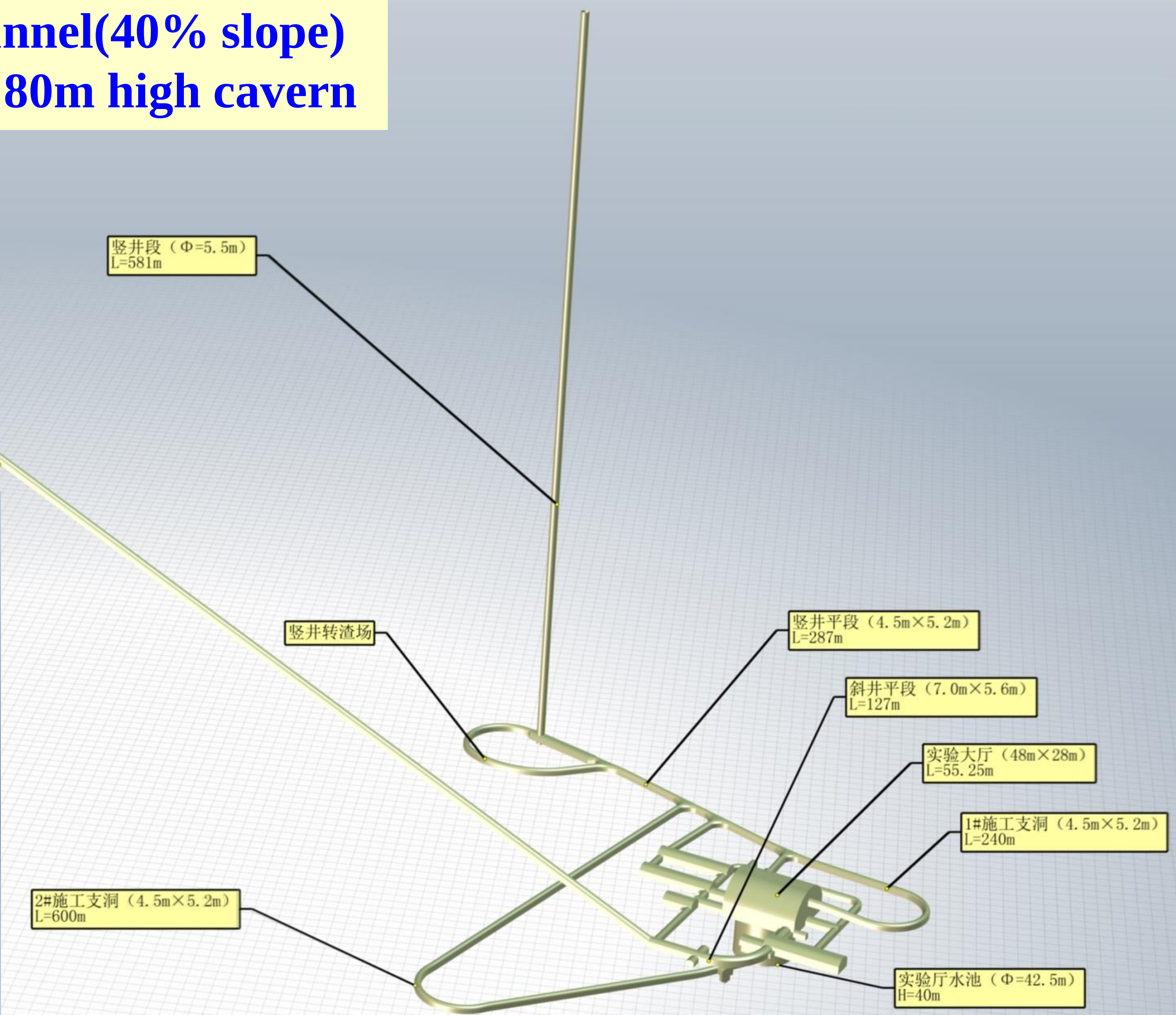
JUNO: Brief schedule

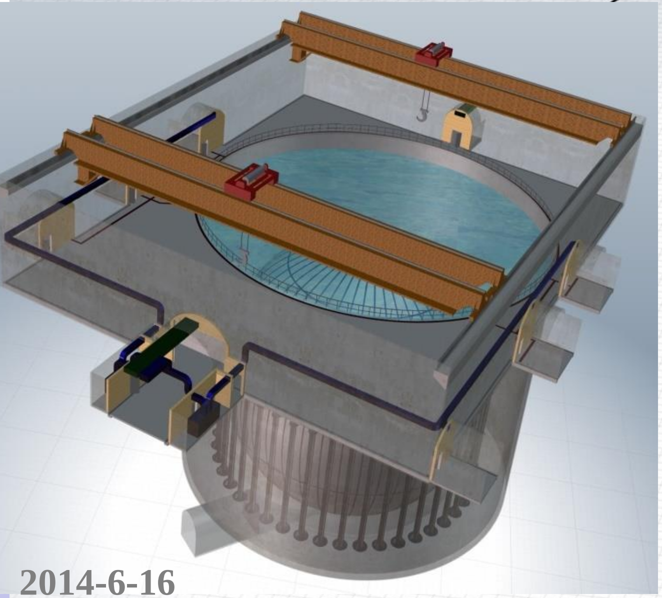
- Civil preparation：2013-2014
  - Current status: site survey completed. Civil design on-going.
- Civil construction：2014-2017
- Detector R&D：2013-2016
- Detector component production：2016-2017
- PMT production：2016-2019
- Detector assembly & installation：2018-2019
- Filling & data taking：2020



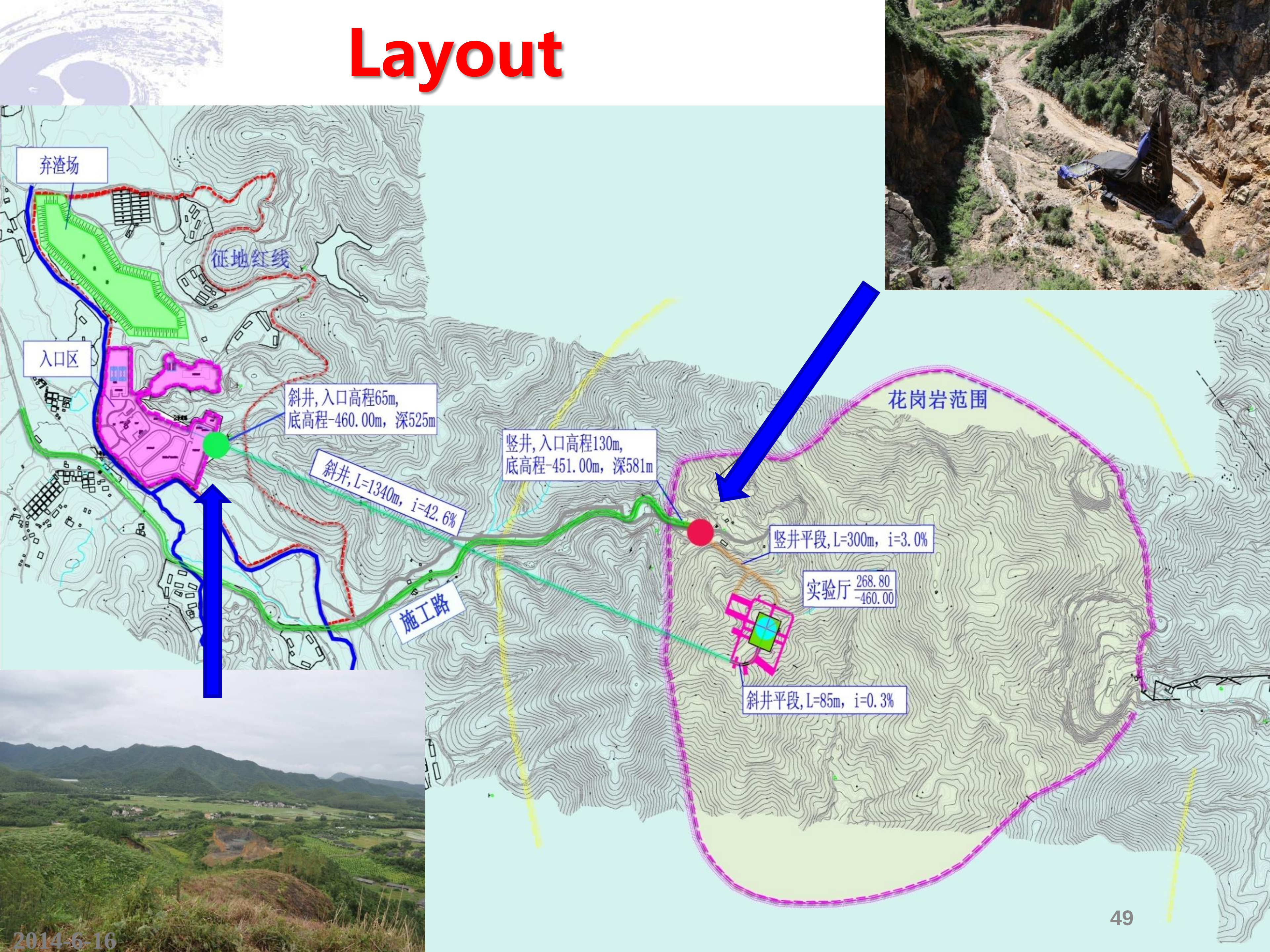
Civil Construction

A 600m vertical shaft
A 1300m long tunnel(40% slope)
A 50m diameter, 80m high cavern





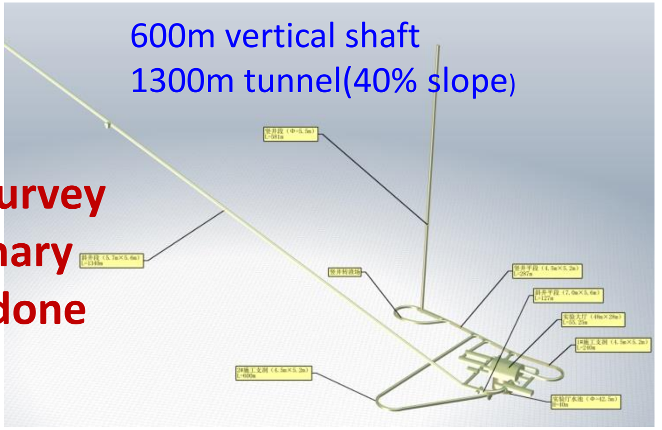
Layout



弃渣场
征地红线
入口区
斜井，入口高程65m，
底高程-460.00m，深525m
斜井，L=1340m，i=42.6%
竖井，入口高程130m，
底高程-451.00m，深581m
施工路
花岗岩范围
竖井平段，L=300m，i=3.0%
实验厅 268.80/-460.00
斜井平段，L=85m，i=0.3%

Project Progresses

- Progresses since 2013



First get-together meeting

Funding(2013-2014) review approved by CAS

Geological survey and preliminary civil design done

2013

2014

Now

Kaiping Neutrino Research Center established

Civil/infrastructure construction bidding

Great support from CAS: "Strategic Leading Science & Technology Programme", CD1 approved

Yangjiang NPP started to build the last two cores

Expected in 2014

- **Ground-breaking (civil construction takes 3 years)**
- **Publish a physics book and CDR**
- **Form international collaboration**

International collaboration

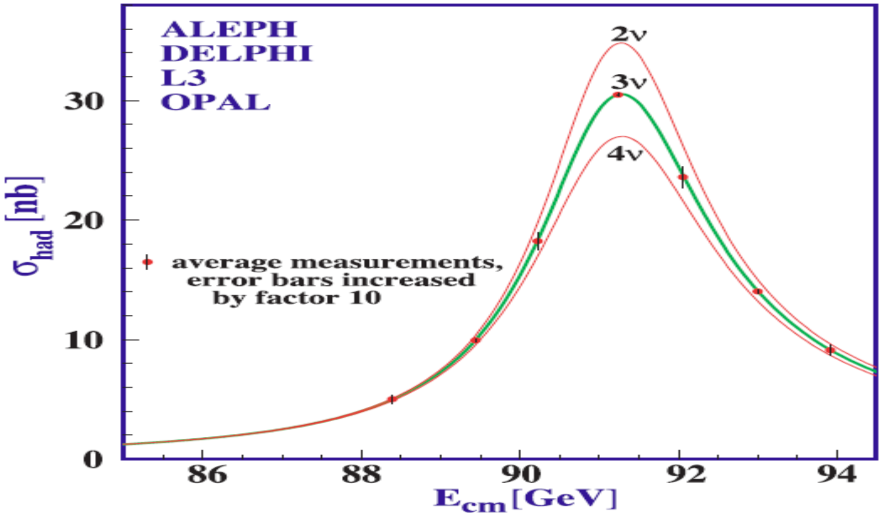
- Strong interests from Czech, France, Germany, Italy, Russia, U.S …
- The proto-collaboration welcome new collaborators
- Establish the international collaboration this year

发现第二、三种中微子

- 1962年，莱德曼、施瓦茨和斯坦博格用加速器发现第二种中微子：μ 中微子（1988年诺贝尔奖）

- 1989年，欧洲核子研究中心（CERN）的实验证明只存在3种中微子（参与弱作用，质量小于几十GeV）

- 2000年，费米实验室DONUT实验发现 第三种中微子：τ 中微子



(Joachim Kopp)

Sterile neutrinos

Few oscillation anomalies could be explained through a forth sterile neutrino

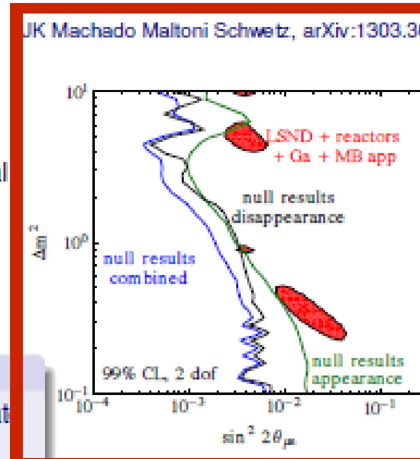
Appearance & disappearance evidence are expected to be consistent among them

Some global fit says they are not!

Some other fit say they are…

The global oscillation fit

3 + 1 Severe tension between appearance and disappearance and between exp's with and without a signal



Parameter goodness of fit (PG) test:

Compares χ^2_{min} from global and separat fits to test compatibility of 2 data sets

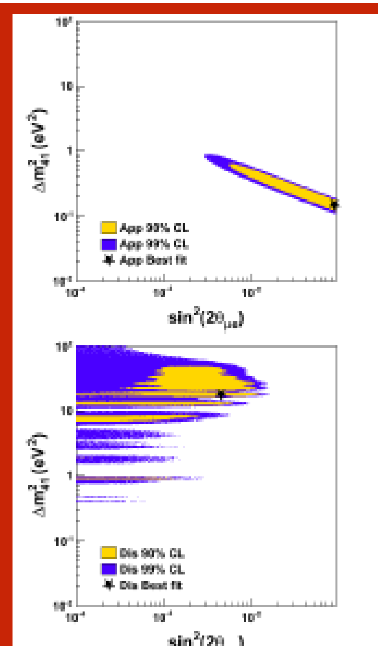
	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 – 9)	19%	18.0/2	1.2×10^{-4}

The MIT/Columbia fit

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - KARMEN
  - NOMAD
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - MiniBooNE
  - Minos CC ν_μ
  - CDHS
  - CCFR
  - Atmospheric neutrinos
- $\overset{(-)}{\nu}_e$ disappearance data:
  - Short baseline reactor experiments
  - Gallium experiments
  - ν_e–[12]C CC scattering in KARMEN, LSND

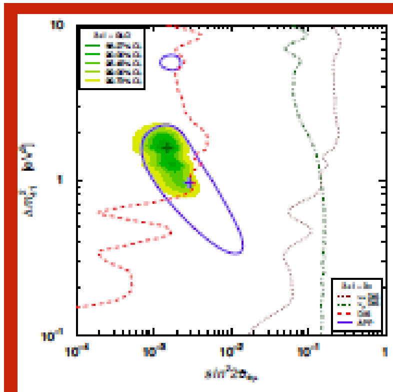
Conrad Ignarra Karagiorgi Shaevitz Spitz, arXiv:1207.4765
Poster by Gabriel Collin

χ^2/dof and PG test results in qualitative agreement with ours → tension confirmed



The GL[4] fit

- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance data:
  - LSND
  - MiniBooNE
  - E776
  - KARMEN
  - NOMAD
  - ICARUS
  - OPERA
- $\overset{(-)}{\nu}_\mu$ disappearance data:
  - MiniBooNE/SciBooNE
  - Minos NC+CC ν_μ
  - CDHS
  - CCFR
  - Atmospheric neutrinos
- $\overset{(-)}{\nu}_e$ disappearance data:
  - Reactor experiments
  - Gallium experiments
  - Solar neutrinos
  - ν_e–[12]C scattering in KARMEN, LSND



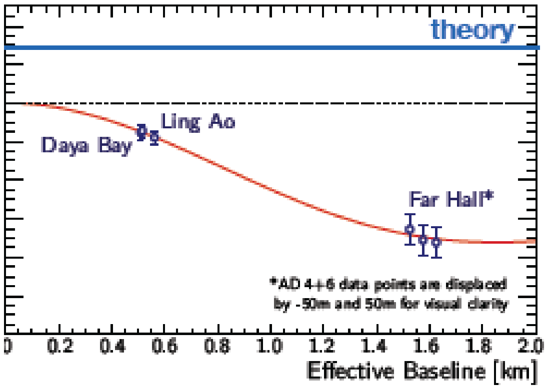
Giunti Laveder Li Long arXiv:1308.528
Giunti Laveder Li Liu Long arXiv:1210.571
Giunti Laveder arXiv:1111.106

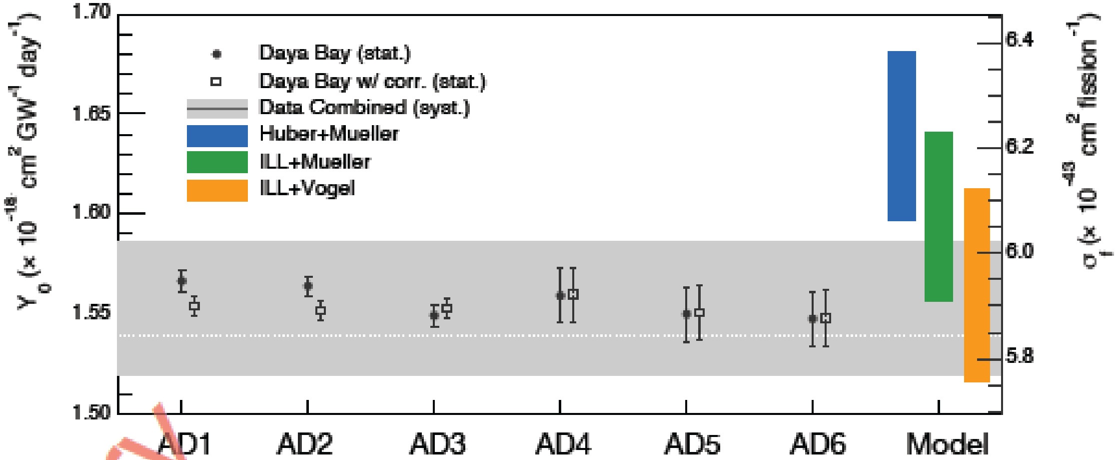
Conclusion

NO tension found

反应堆中微子反常

Absolute Reactor Antineutrino Flux





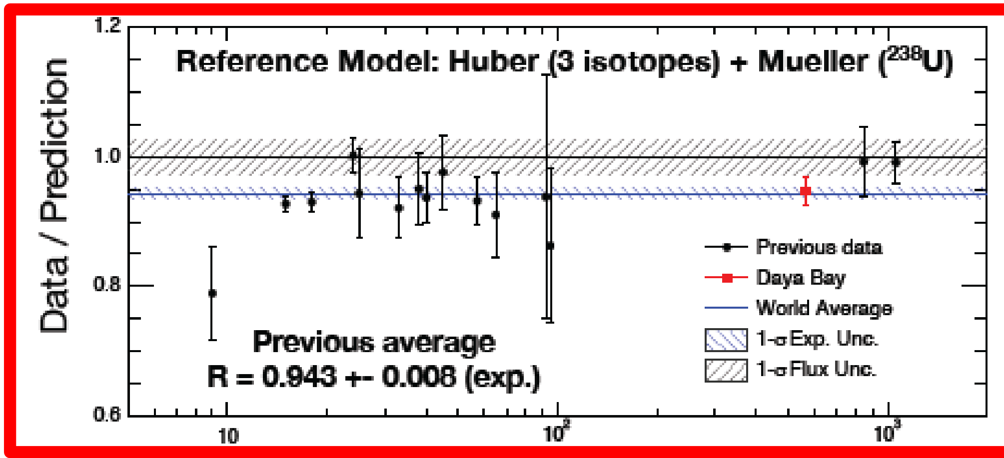
Flux Measurement Uncertainty

	Uncertainty
statistics	0.2%
θ_{13}	0.2%
reactor	0.9%
detector efficiency	2.1%
Total	2.3%

^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu	0.586 : 0.076 : 0.288 : 0.050
Y_0 (cm^2 GW^{-1} day^{-1})	1.553×10^{-18}
σ_f (cm^2 fission^{-1})	5.934×10^{-43}
Data / Prediction (Huber+Mueller)	0.947 ± 0.022
Data / Prediction (ILL+Vogel)	0.992 ± 0.023

preliminary

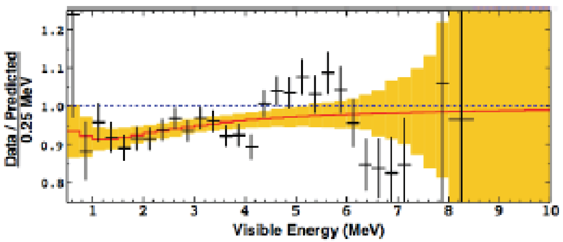
Daya Bay's reactor flux measurement is consistent with previous short baseline experiments



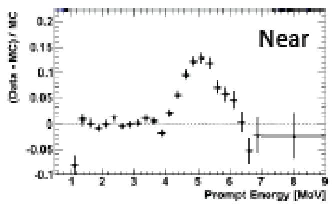
Excess at 5 MeV

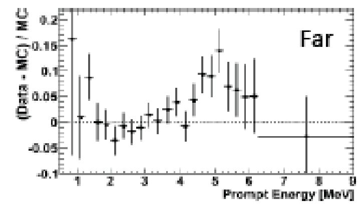
Hint of the bump reported by Double Chooz and RENO already present in CHOOZ, Bugey and Rovno: easy to say with hindsight!

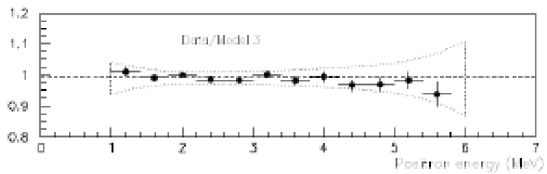
Double Chooz, this conference



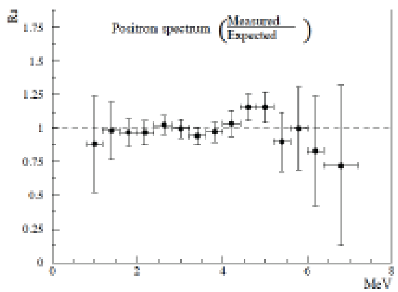
RENO, this conference



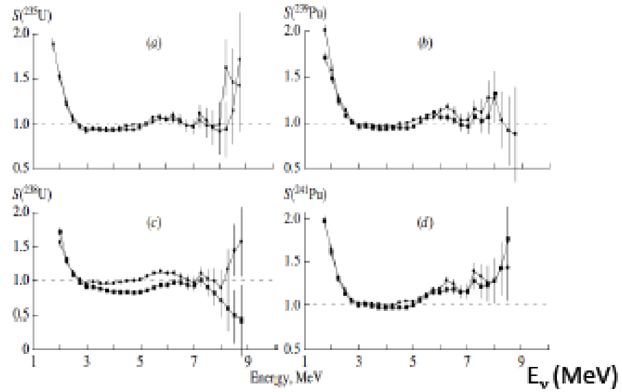




Bugey, Phys.Lett. B374 (1996) 243-248



CHOOZ, Phys.Lett. B466 (1999) 415-430



Rovno, V. Sinev, arXiv:1207.6956

5

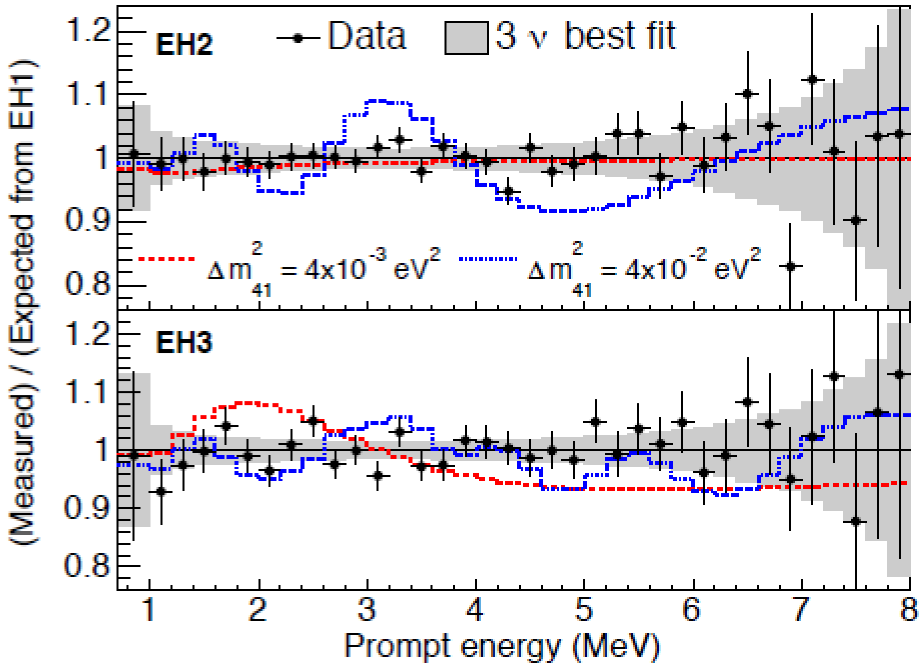
David Lhuillier

- **Origin of the excess to be understood:**
  - Bias in the conversion procedure? Difficult to induce a localized excess with distortion of (forbidden) beta-decay branches.
  - Bias in the reference electron-ILL data? Well beyond the currently known systematics.
  - New neutrino interaction?

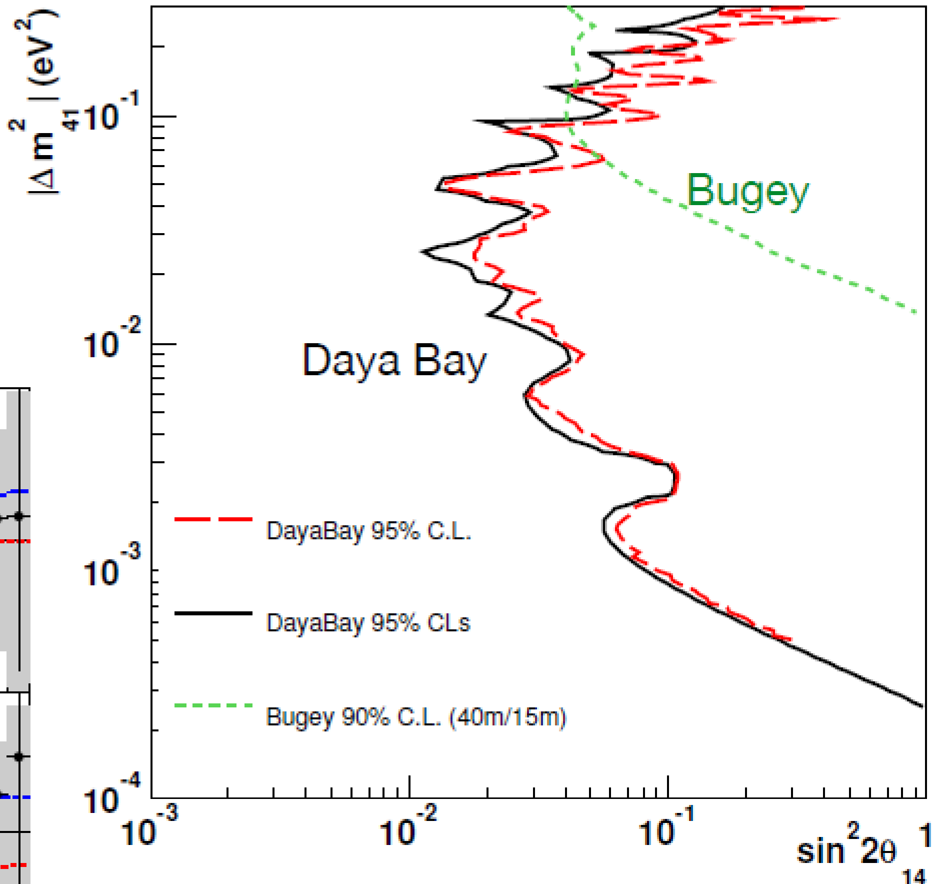
Alberto Remoto

Daya Bay

- All 217 days of 6-AD period
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2



dashed curves assumes $\sin^2 2\theta_{14} = 0.1$



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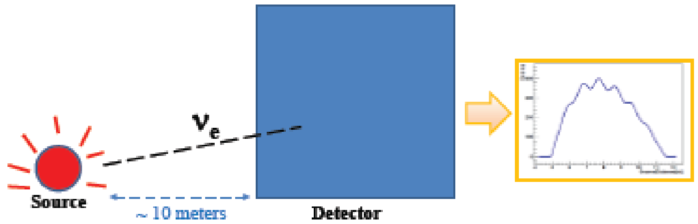
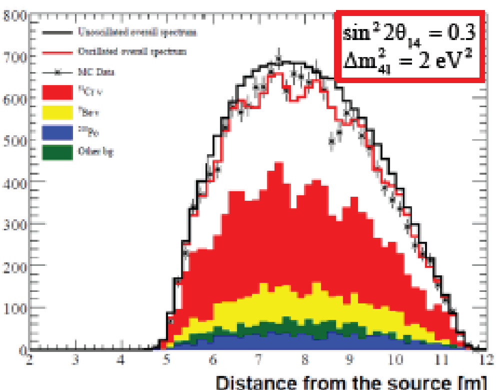
(Barbara Caccianiga)

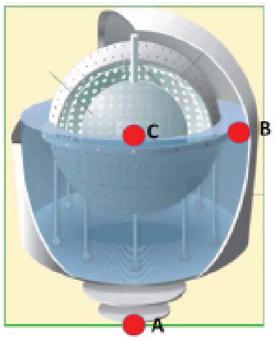
With nuclear decay

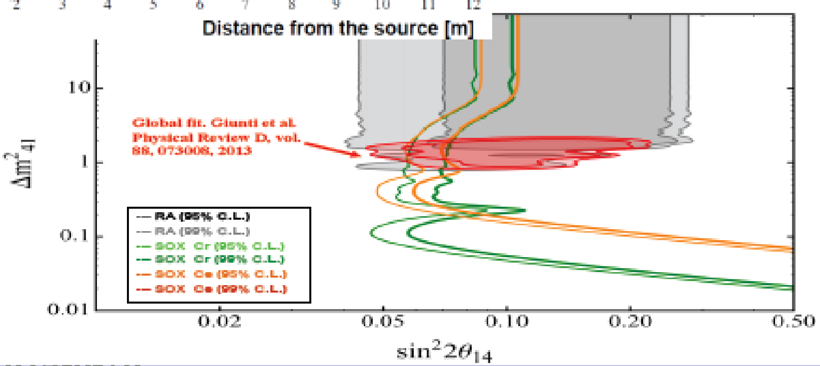
Short baseline oscillometry with MCi ν_e source close to a big LS detector



Cr or Cr anti-ν_e source in different position close to borexino







Many proposal on the market…only cover SOX (in detail)

Technique	Detector	Sources	Reaction	Activity	Reference
Large Liquid scintillator detectors	SOX (Borexino)	^{51}Cr,	ν+e → ν+e	10MCi	JHEP08(2013)038,
		^{144}Ce-^{144}Pr	$\bar{\nu}$+p → e$^+$+n	100kCi	Phys. Rev. Lett. 107, 201801 (2011)
	KamLAND	^{8}Li (ISODAR)	$\bar{\nu}$+p → e$^+$+n	8.2 x 10 ^{14} ν/sec	arXiv:1205.4419, arXiv:1310.3857
		^{144}Ce(CeLAND)	$\bar{\nu}$+p → e$^+$+n	100kCi	arXiv:1312.0896
	Daya-Bay	^{144}Ce-^{144}Pr	$\bar{\nu}$+p → e$^+$+n	500kCi	arXiv:1109.6036
	LENS	^{51}Cr	ν+^{115}In → ^{115}Sn*+e	10MCi	Phys.Rev.D75 093006(2007)
	JUNO	^{8}Li (ISODAR)	$\bar{\nu}$+p → e$^+$+n	8.2 x 10 ^{14} ν/sec	arXiv:1310.3857
Radiochemical	BEST	^{51}Cr	ν+^{70}Ga → ^{71}Ge+e	3MCi	arXiv:1204.5379
Bolometers	Richochet	^{37}Ar	ν+N → ν+N	5MCi	Phys. Rev. D85, 013009, (2012)

Quite challenging logistics for source production and transportation

- Spent nuclear fuel will be shipped from Kola reactor to Mayak ~ end of 2014;
- ^{144}Ce source ready for shipment to Gran Sasso by Fall 2015;
- Transportation to Gran sasso in November 2015;

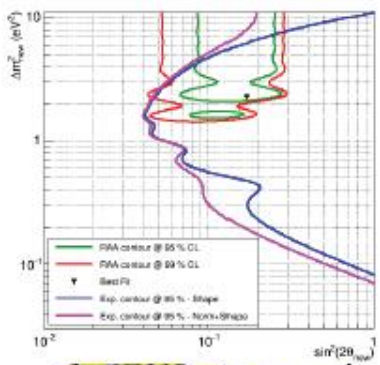
With short baseline with reactors

	Gd	^{6}Li	Highly Segmented	Moving detector	2 det.
Nucifer (FRA)	■				
Poseidon (RU)	■				
Stéréo (FRA)	■			■	
Neutrino 4 (RU)	■			■	
Hanaro (KO)	◣	◥	■	■	
DANSS (RU)	■		■		
Prospect (USA)	◣	◥	■		■
SoLid (UK)		■	■		

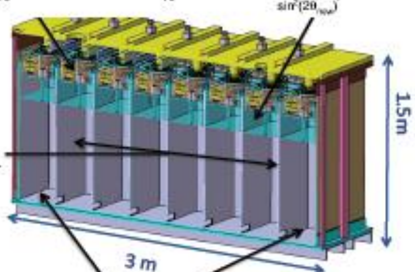
STEREO @

ILL site:

- 57 MW, compact core < 1m
- [8.9–11.1] m from core, possible extension to 12.3 m.
- 15 mwe overburden
- High level of reactor background



- 300 days, L_0 = 10 m
- E_{prompt}>2 MeV, $E_{delayed}$>5 MeV
- ~410ν_e/day
- δE_{scale} = 2%
- All syst. of predicted spectra
- S/B = 1.5, 1/E+flat model
- Norm 4%
- Start data taking in 2015



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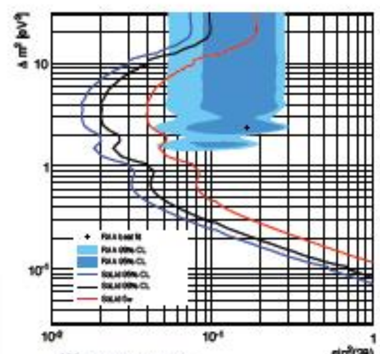
SoLid

BR2 REACTOR, Mol, Belgium

- Core: 45-80 MW, HEU fuel
- Favorable reactor background level

DETECTOR

- Novel type of composite solid scintillator detector (PVT + ^{6}LiF:ZnS)
- 2.88t fiducial volume, highly segmented.



X^2 fit Rate + Shape
- IBD efficiency 41% (416nu/day/tonne)
- 300 days running at 6.8m baseline
- S/B ~ 6
- include flux normalisation (4.1%), detector efficiency (2%) systematics and backgrounds
- large bins to account for energy smearing effects

33

(Joshua Spitz)

With accelerators

Mainly focusing on the LAr effort @ FNAL ==> toward LBNE

LAr1-ND MicroBooNE ICARUS (T150+T600)

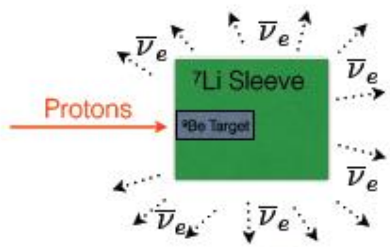
Combining forces!

A coherent, collaborative, international program at FNAL's BNB (and NuMI off-axis) likely featuring three detectors by 2018: near, MicroBooNE at mid-distance, and far.

(a CDR is to be presented at the FNAL July 2014 PAC)

	Primary Channel	Other osc channels	Definitive sterile?	Other physics	Tech R&D?	Cost	Why worry?	Comment
MicroBooNE (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	$20M	tech, cosmics	Exists!
LAr1-ND (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	$13M	tech, cosmics	
ICARUS@FNAL (π DIF)	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$		GeV-scale xsec	Yes	Under study	tech, cosmics	
TripleLAr@FNAL (π DIF)	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$	Probably	GeV-scale xsec	Yes	Under study	tech, cosmics	Work in progres Anti-nu
OscSNS (π,μ DAR)	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_e \to \nu_e$	Yes	Supernova xsec	No	$20M	intrinsic $\bar{\nu}_e$	
JPARC MLF (π,μ,K DAR)	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_e \to \nu_e$ $\nu_\mu \to \nu_e$	Not in phase 1	Supernova and 235 MeV ν_μ xsec	No	$5M	intrinsic $\bar{\nu}_e$	Phase 1
IsoDAR-KamLAND (Isotope DAR)	$\bar{\nu}_e \to \bar{\nu}_e$	-	Yes	$\nu_e e^-$ (electroweak)	Yes	$30M	timeline, tech	
nuSTORM (μ DIF)	$\nu_e \to \nu_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$ $\nu_e \to \nu_e$	Yes	GeV-scale xsec	Yes	$300M	timeline, tech, cost	P5 says no

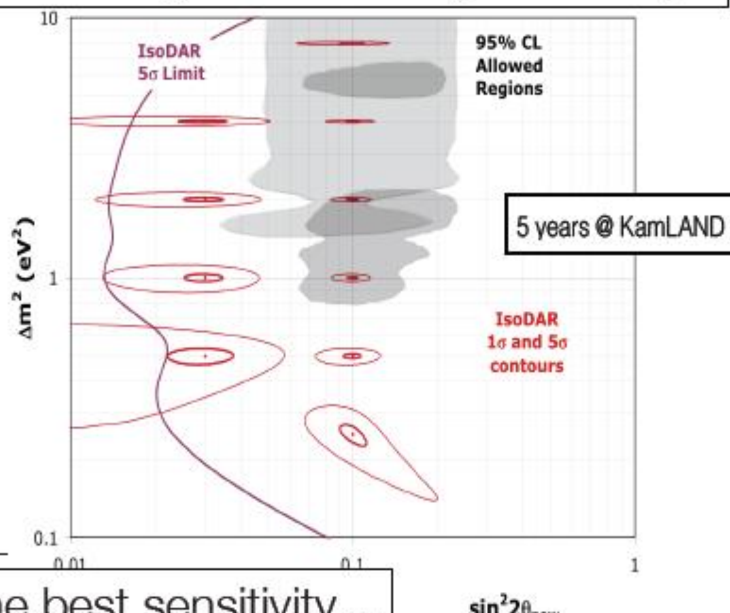
IsoDAR: ^{7}Li anti-ν_e spallation source to install close a big LS detector (Kamland?)



$$p + {}^9\mathrm{Be} \to {}^8\mathrm{Li} + 2p$$

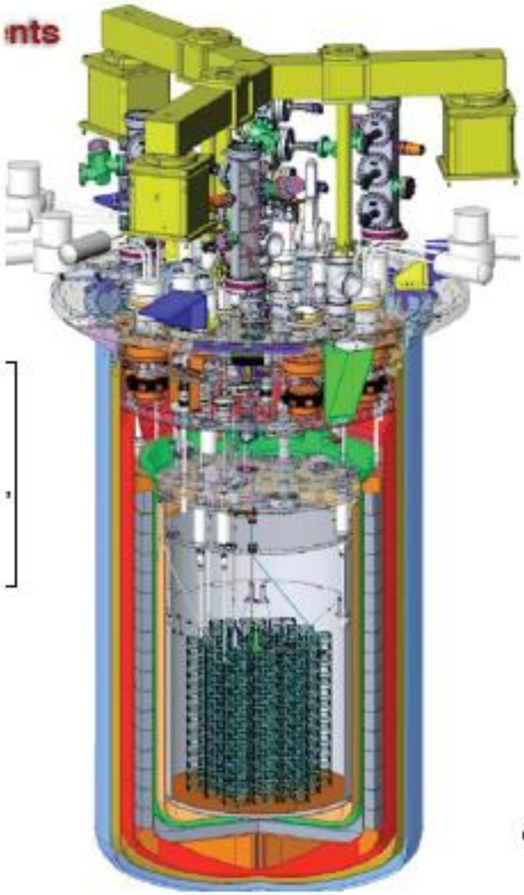
$$p + {}^9\mathrm{Be} \to {}^9\mathrm{B} + n$$
$$n + {}^7\mathrm{Li} \to {}^8\mathrm{Li} + \gamma$$

$$^8\mathrm{Li} \to {}^8\mathrm{Be} + e^- + \bar{\nu}_e$$



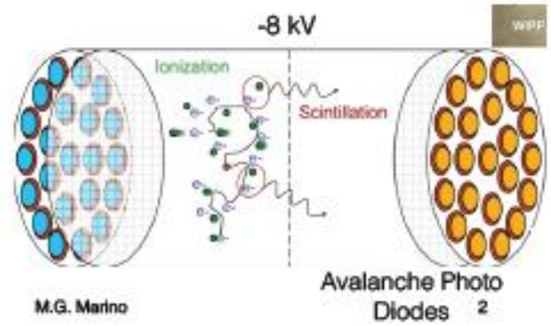
Could provide one of the best sensitivity…

Neutrino-less double beta decay

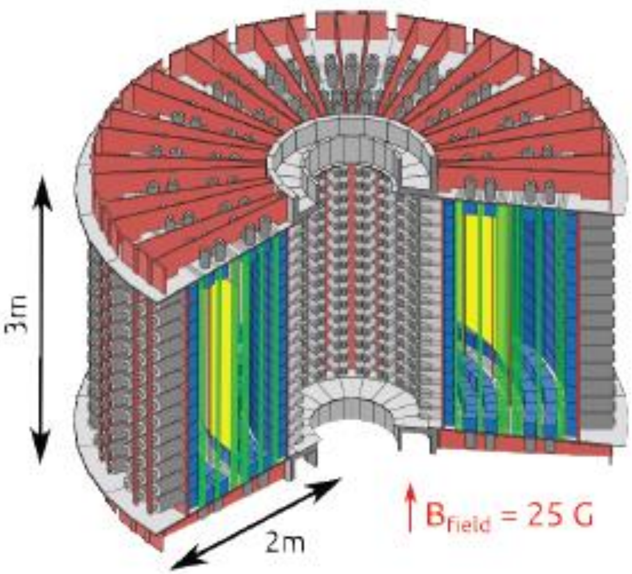


CUORE0 (O. Cremonesi)

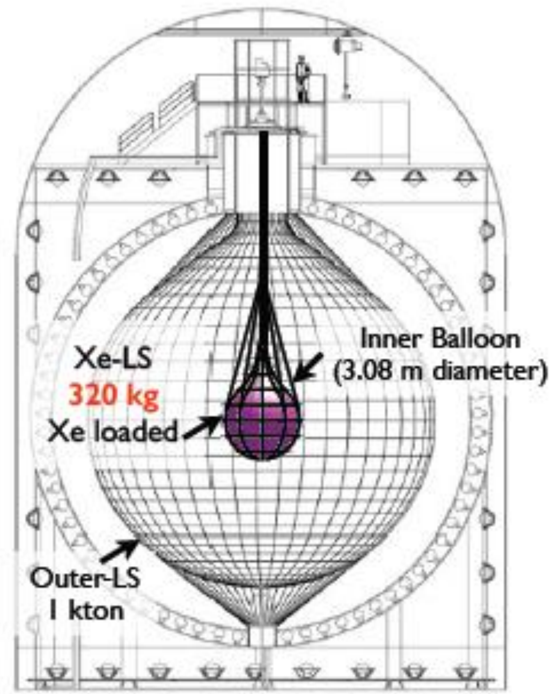
EXO-200 (M. Marino)



NEMO3 (M. Bongrand)



KamlandZEN (I. Shimizu)

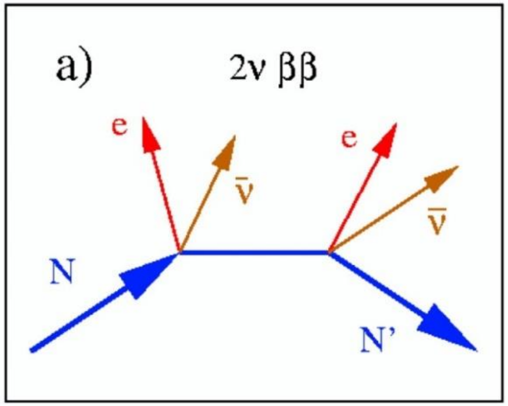


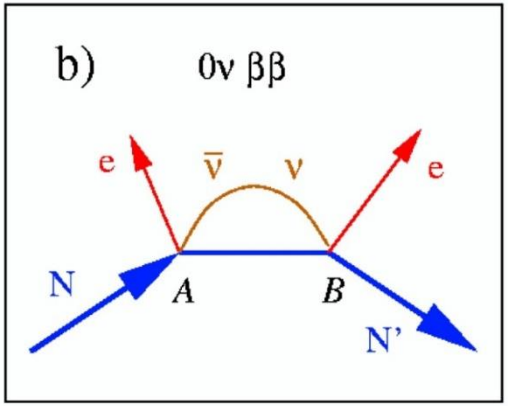
ββ-decays: two modes

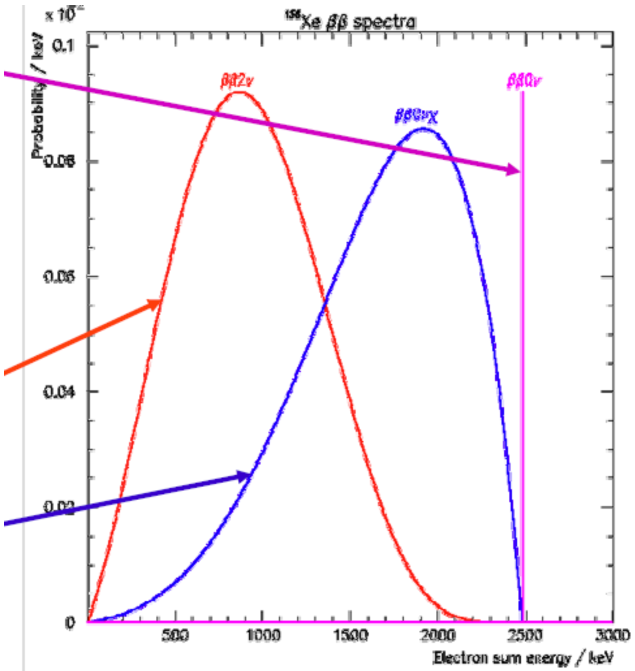
2ν mode: a conventional 2nd order process in nuclear physics

0ν mode: a hypothetical process can happen only if: • $M_\nu \neq 0$ • $\overline{\nu} = \nu$

Since helicity has to "flip"



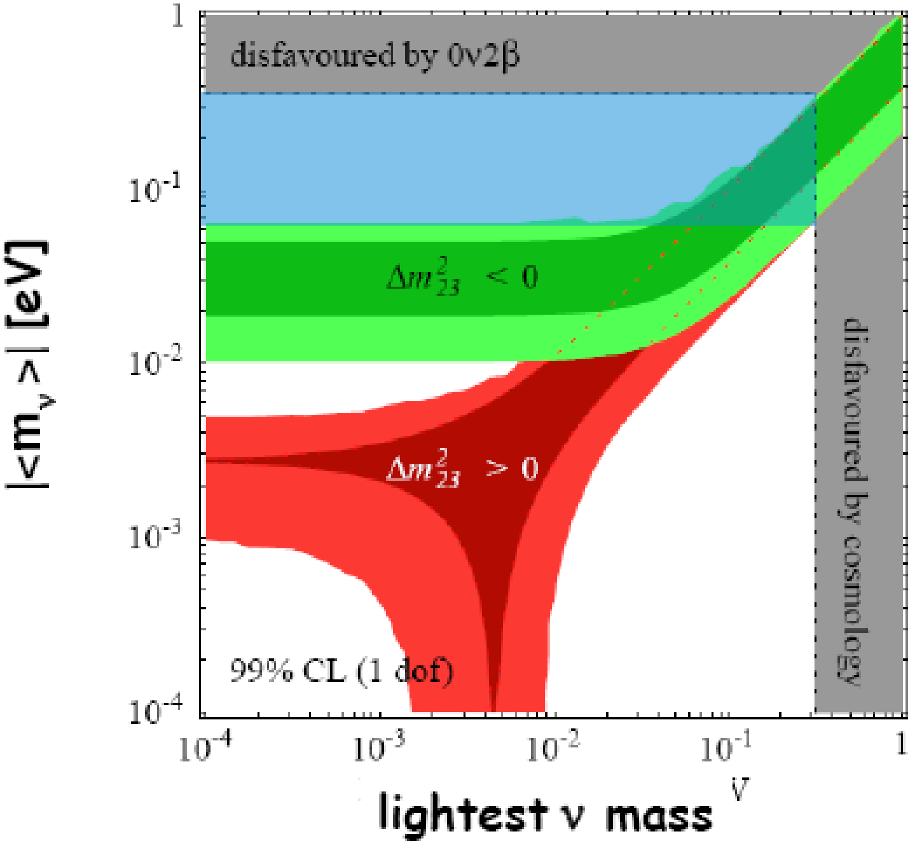


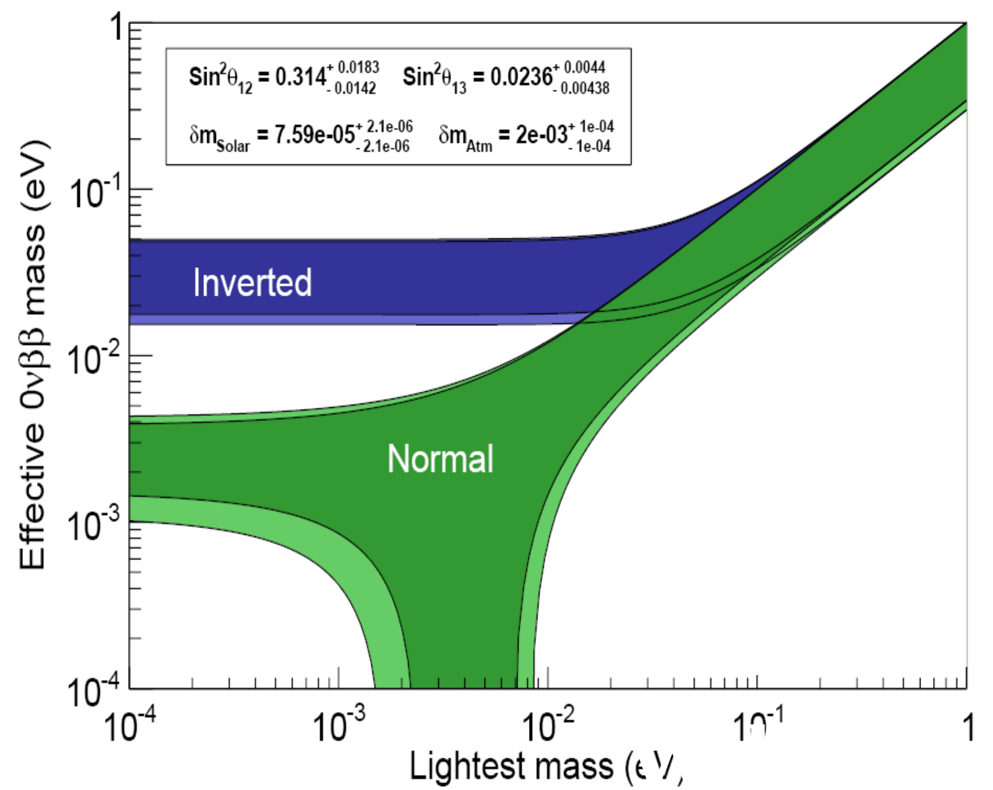


- 2ν mode ββ decays would have a half lives in excess of 10^{20} years M. Goeppert-Mayer, Physics. Rev. 48 (1935) 512
- A second order process, Only if the first order beta decay is forbidden
- Experimental observation of 2ν ββ–decays in 1980'

Current sensitivity

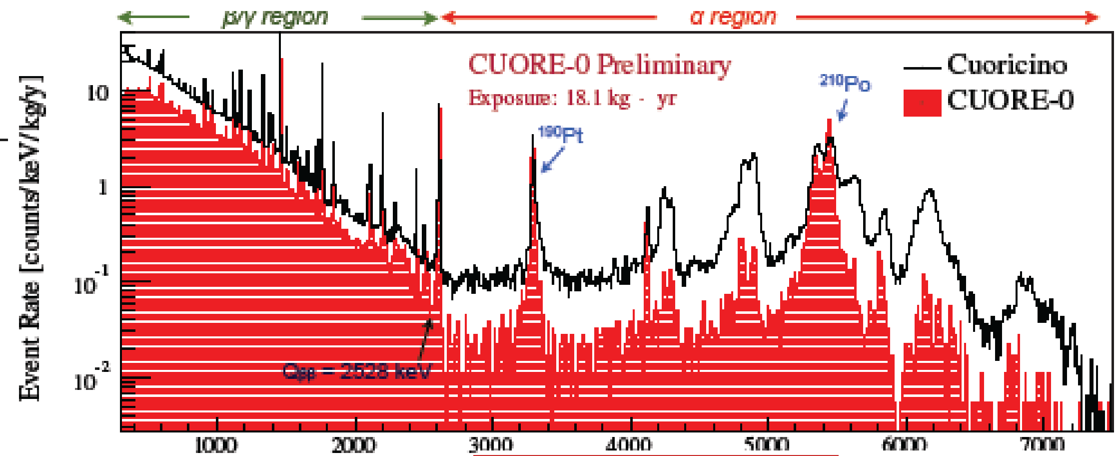
Double Beta Decay $|\langle m_\nu \rangle| = |\sum U_{ei}^2 m_i|$ ≤ 0.05 eV



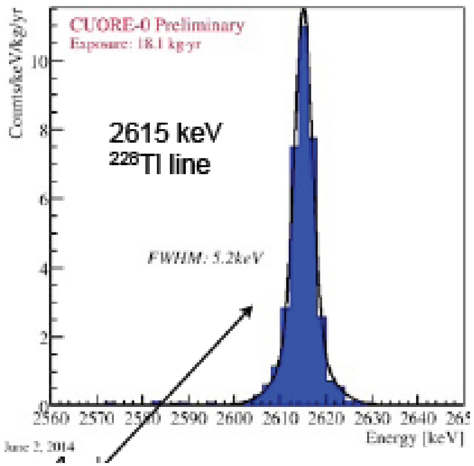


CUORE0/CUORE

Confirm Cuoricino bkg. model



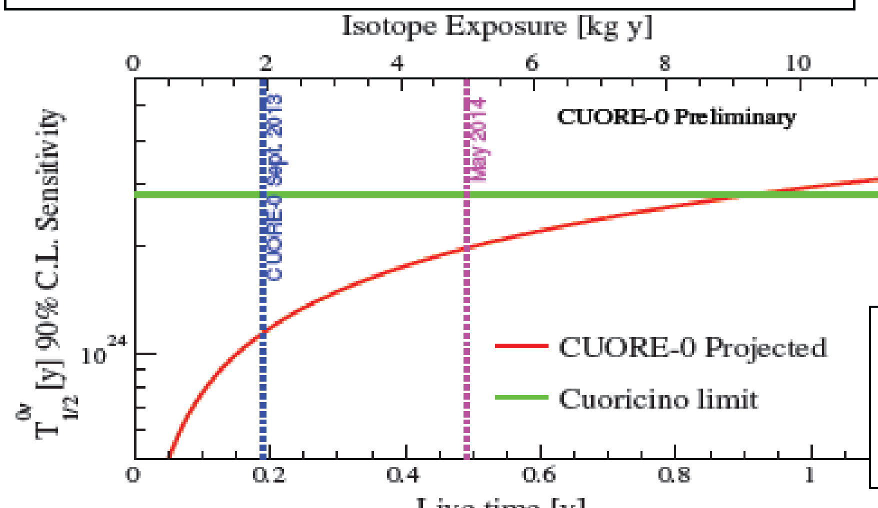
Reach design resolution ~0.2 %

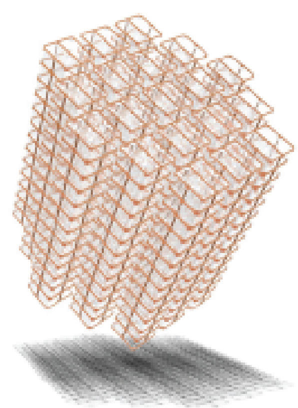


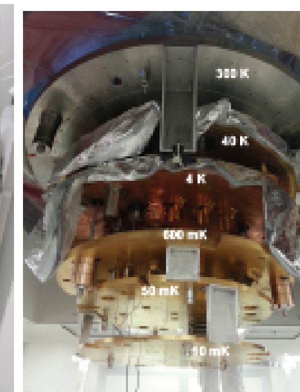
Bkg reduction x2.5 in ROI
Not yet at required value
0.01 cts/(keV kg y)

	0νββ region cnts/(keV kg y)	2700-3900 keV	ε(%)
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	0.063 ± 0.006	0.020 ± 0.001	78

CUORE-0 expected to surpass Cuoricino sensitivity with ~1 year of livetime





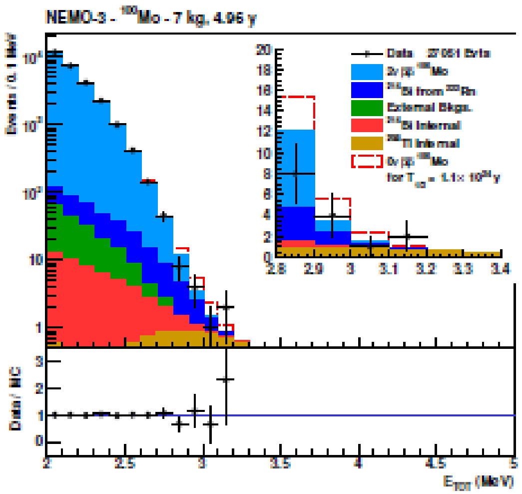


CUORE tower assembly completed
Cryostat commissioning ongoing (background?)
Data taking expected in 2015, first results in 2016

NEMO3/SuperNEMO

NEMO-3 $0\nu2\beta$ Search with ^{100}Mo

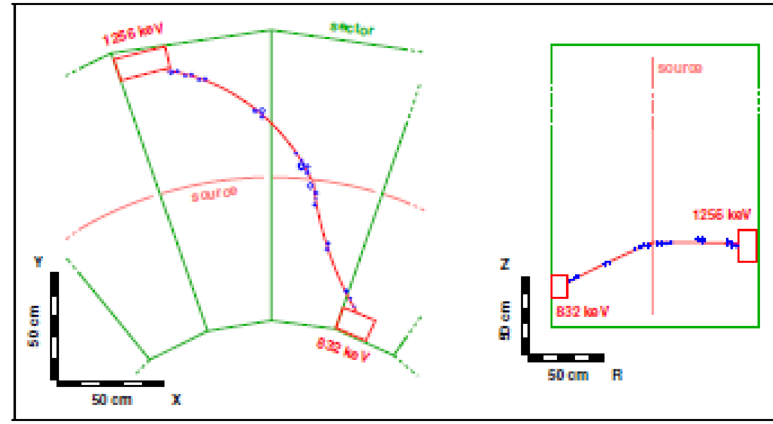
- Detection efficiency $\mathcal{E}_{0\nu} = 4.7$ % in the [2.8 – 3.2] MeV region
- No event excess observed in ^{100}Mo after 34.3 kg·y exposure:
  $T^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y (90 % CL) $\langle m_\nu \rangle < 0.33 - 0.87$ eV



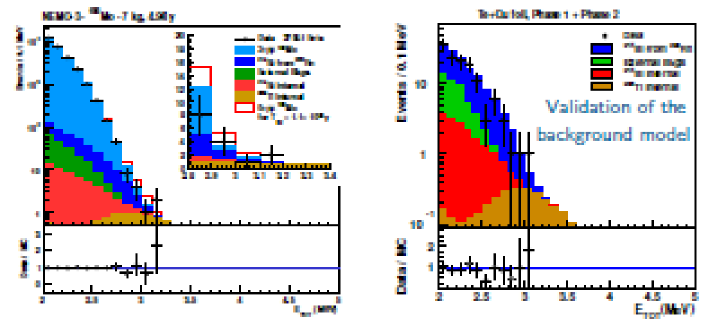
Expected background in [2.8 – 3.2] MeV	
$2\nu2\beta$	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	**18.0 ± 0.6**
Data	**15**

Total background
1.3×10^{-3} cts·keV^{-1}·kg^{-1}·y^{-1}

[To appear in Phys. Rev. D - arXiv:1311.5695]



NEMO-3 High Energy Background



[To appear in Phys. Rev. D - arXiv:1311.5695]

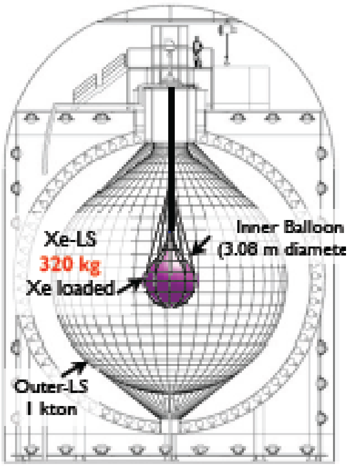
- No events in ^{100}Mo after 34.3 kg·y exposure above 3.2 MeV
- No events in copper and natural tellurium samples after 13.5 kg·y exposure above 3.1 MeV
- Background-free technique for high energy $Q_{\beta\beta}$ isotopes: ^{48}Ca: 4.272 MeV, ^{150}Nd: 3.368 MeV or ^{96}Zr: 3.350 MeV

SuperNEMO demonstrator with 7 kg of ^{82}Se under construction:

- Commissioning and physics data by Summer 2015
- No background in the $0\nu2\beta$ region in 2.5 years for 7 kg of ^{82}Se:
  $T^{0\nu}_{1/2} > 6.5 \times 10^{24}$ y → $\langle m_\nu \rangle < 0.20 - 0.40$ eV (90 % CL)

KamlandZEN

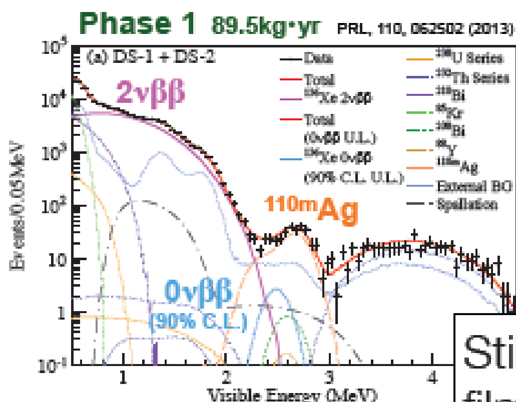
KamLAND-Zen
Phase I



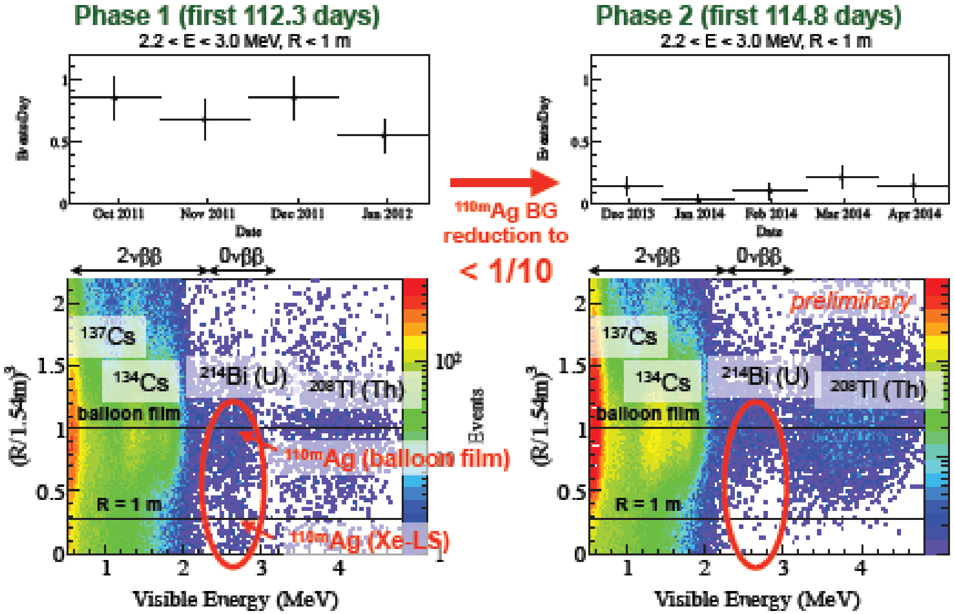
Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

σ_E(2.5MeV) = 4%

Unlucky phase one due to ^{110m}Ag contamination from Fukushima fall-out

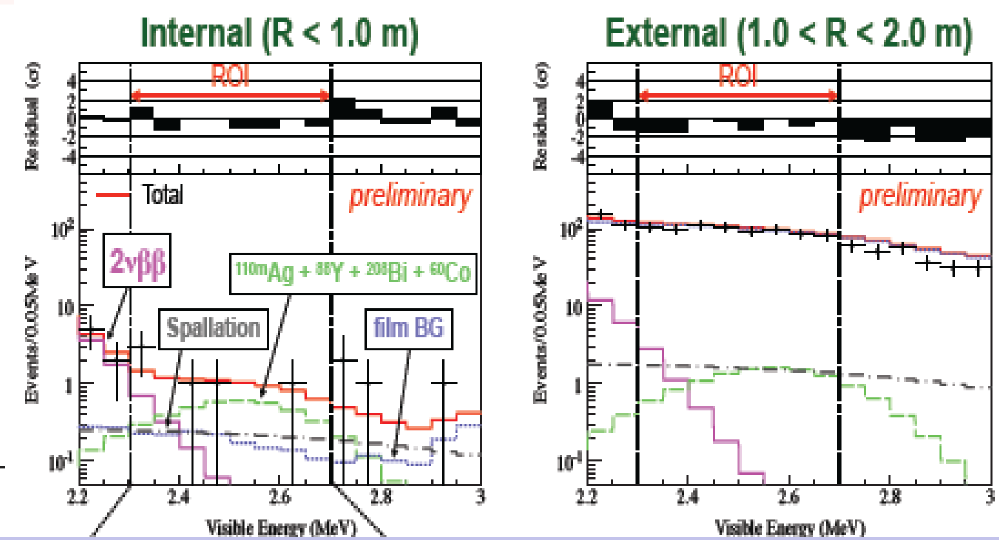


$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% C.L.)



LS purification (1.5y) reduce ^{110m}Ag by 1/10!!

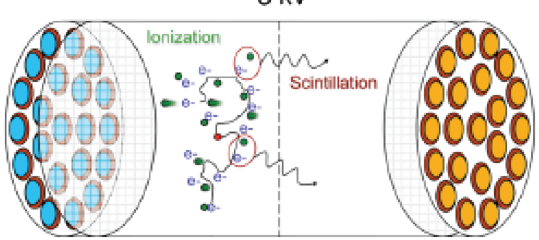
Still large contamination from ^{214}Bi from balloon film but drastically reduced with fiducial volume cut



- ^{136}Xe 90.77% enriched (348 kg ^{136}Xe)
- Live time 114 d
- 6 events in the ROI [2.3; 2.7] MeV
- Combined(phase 1&2)
  - $T_{0\nu 1/2} > 2.6 \times 10^{25}$ yr
  - ⟨mββ⟩ < 0.14-0.28 eV

EXO200

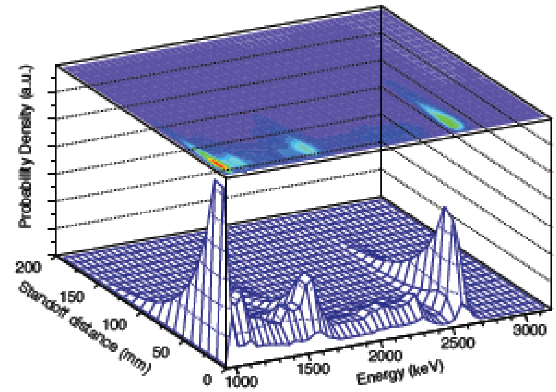
- Liquid Xe Time Projection Chamber (TPC)
- Enriched ^{136}Xe to 80.6%
- Q-value 2458 keV



- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- 1585 meters water equivalent

M.G. Marino 2 6 June 2014, Nu 2014

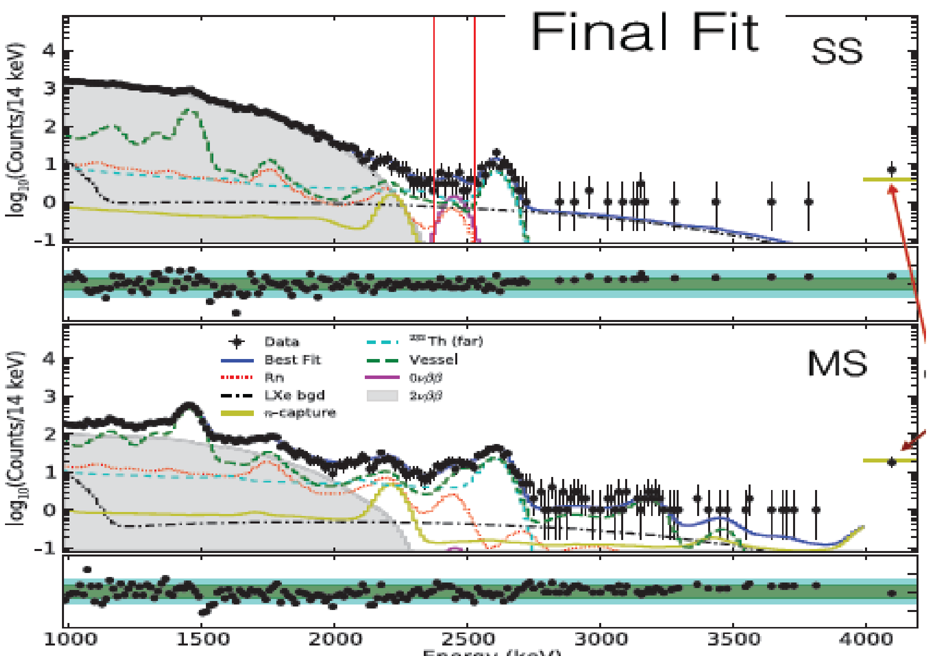
Only experiment performing full multivariate analysis so far



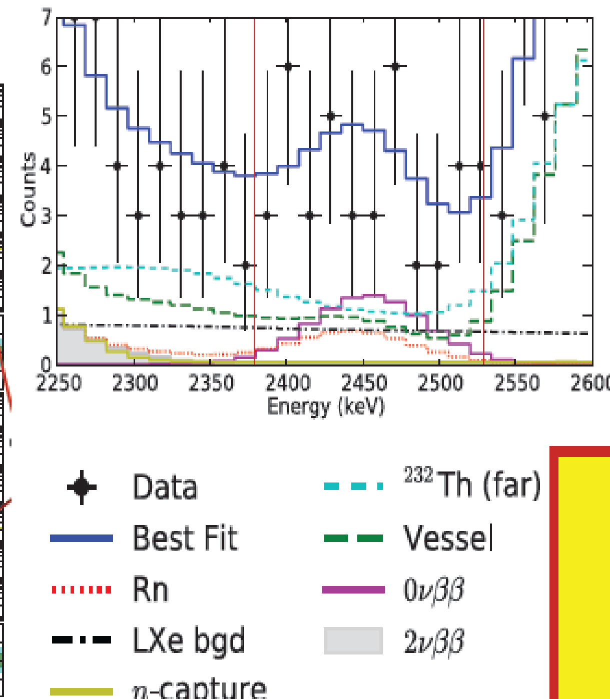
- Variables
  - Energy
  - Position (standoff distance)
- Multiplicity
  - SS
  - MS

Two sample depending from event topology

90% bb evt. are SS.



New results



Backgrounds In ± 2σ ROI	
Th-228 chain	16.0
U-232 chain	8.1
Xe-137	7.0
Total	**31.1 ± 3.8**

From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 190 - 450$ meV

(90% C.L.)

***Nature* (2014)**

doi:10.1038/nature13432

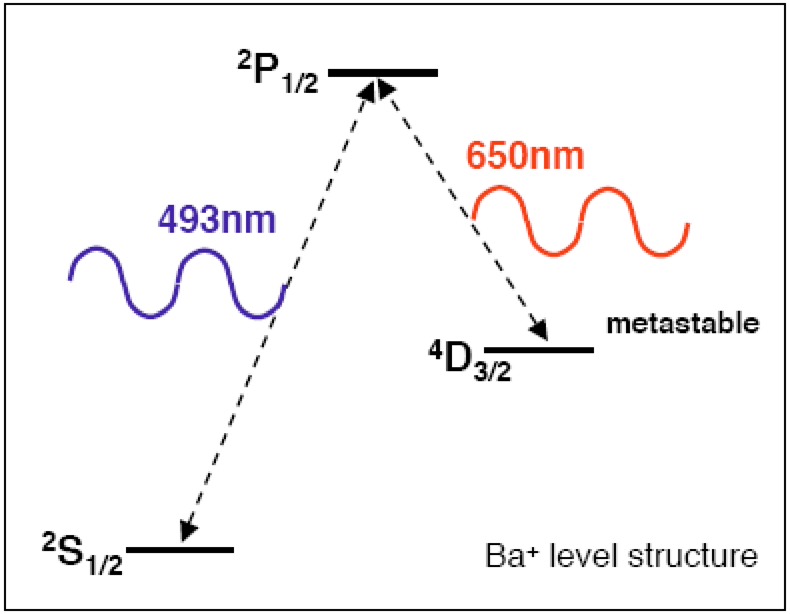
Ba^{++} tagging — a novel technology

- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$

Allow to remove all bkg but $2\nu\beta\beta$

⬇

identified using optical spectroscopy



Technical challenge

- locate the ion
- Extract the ion and release it to a low pressure region
- Trap the ion and identify it
- Understand the efficiency

2 years EXO-200 without Ba++ tagging: ~100 meV

nEXO:

Ultimate goal with Ba++ tagging: 20-5 meV

总结

- 中微子振荡共6个参数，δ_{CP}未知，MH、θ_{23} Octant未知
- 未来15年可确定MH， δ_{CP} 和θ_{23} Octant很可能确定
- 混合参数的精确测量可检验混合矩阵的幺正性到1%以内，刺探新物理。
- 大量惰性中微子寻找实验正在进行。
- 直接质量测量可到0.2 eV，新技术有可能到0.1 eV，难以提高。
- 磁矩$5.8\times10^{-11}\sigma_B$，难以大幅提高。
- 如果看到了$0\nu\beta\beta$ 衰变，中微子极可能是Majorana中微子，一定存在新物理。如果未看到，计划中的实验未来10年内可排除反质量顺序，如果质量顺序为正，则无法排除。