Reactor Neutrino Experiment

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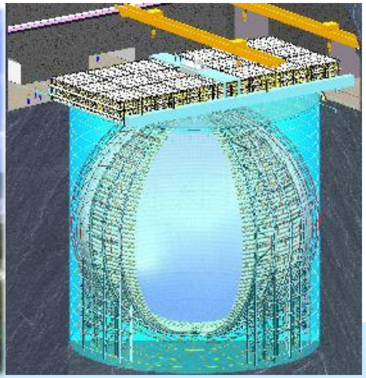
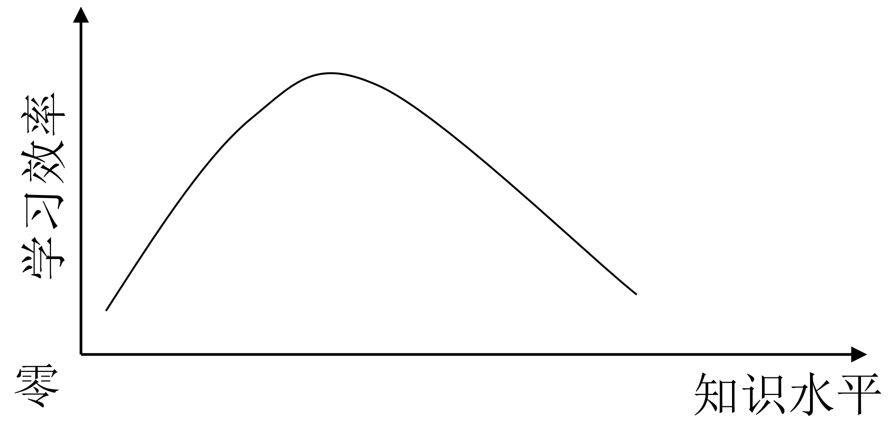
CCEPP Summer School, Aug. 20-28, 2021

Many slides taken from CCEPP 2017 talk given by Jun Cao



学、问、讲

- 积极学
  - ⇨ 学习效率个体差异



- 多问
  - ⇨ 针对自己的知识缺口

- 除了学和问，也要善于分享（讲）
  - ⇨ 费曼学习法：讲给别人听
  - ⇨ 积极参加学员学术交流和展示环节
  - ⇨ 知识是最独特的财富：不会因为分享而减少，只会因为分享而更加强大。

Reactor neutrino experiments

- **A global but not complete picture in a matrix**

	IBD (scintillator，water)	Electron scattering （crystal、Ge、TPC）	Coherent scattering （noble gas, crystal)	Future technology
Oscillation parameters	Many(KamLAND ,Daya Bay, JUNO)	?	?	
Mass ordering	JUNO	?	?	
Flux and spectrum	Many	Yes	Yes	
Sterile neutrino	Many	?	?	
Magnetic moment	?	Yes	Yes	
New physics	Yes	Yes	Yes	
Unknown science				

Outline

重点讲大亚湾实验

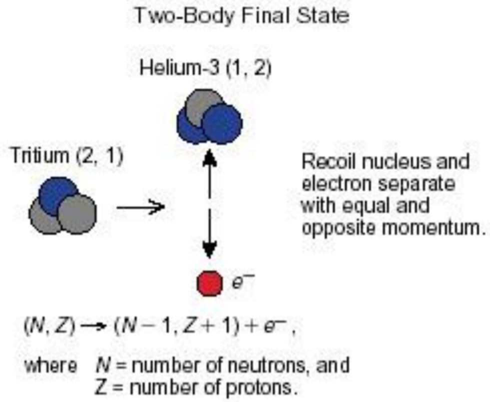
① 反应堆中微子实验（总体）
② 反应堆产生中微子,流强和能谱
③ 天然放射性（为什么要泡在水里，要3层探测器）
④ 宇宙线（为什么要到地下，要有反符合）
⑤ 探测器响应与刻度（看到的数字信号与物理量）
⑥ 事例的构成与挑选（从物理量到中微子事例）
⑦ 本底（真的是中微子吗？）
⑧ 效率与误差（不能多挑也不能少挑）
⑨ 振荡参数结果

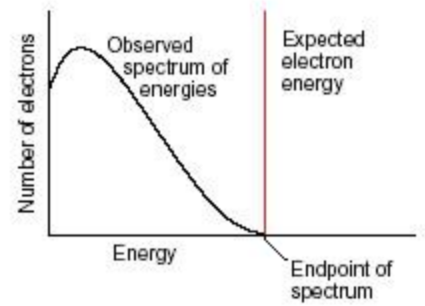
1 – Reactor Neutrino Experiments

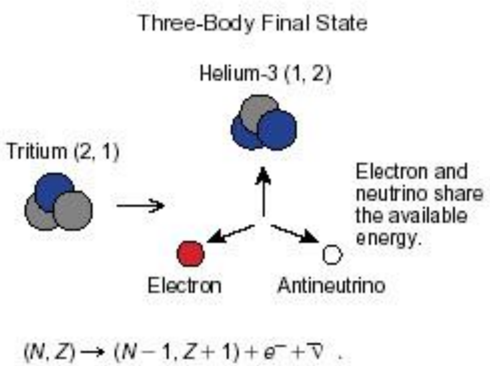
预言中微子的存在

- β 衰变的能谱是连续的
  - ⇨ 能量不守恒？
- 1930年，泡利提出中微子假设来挽救能量守恒定律
- 自旋1/2
  质量很小或没有
  不带电荷
  几乎不与物质反应

- **"I have done a terrible thing. I have postulated a particle that cannot be detected." -- Puali**

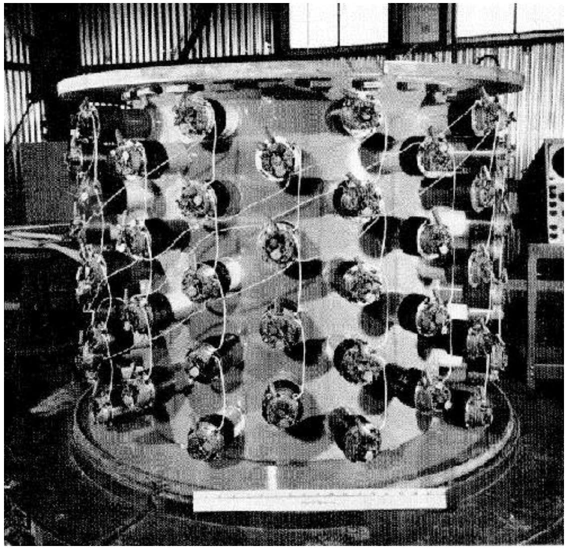






Hanford experiment

- Hanford reactor
- 0.3m^3 liquid scintillator
- 90 2” PMTs
- Paraffin to shield neutrons
- Lead to shield gammas
- Expected events: 0.1~0.3 /min
- Observed: 5/min（bkg >>signals）

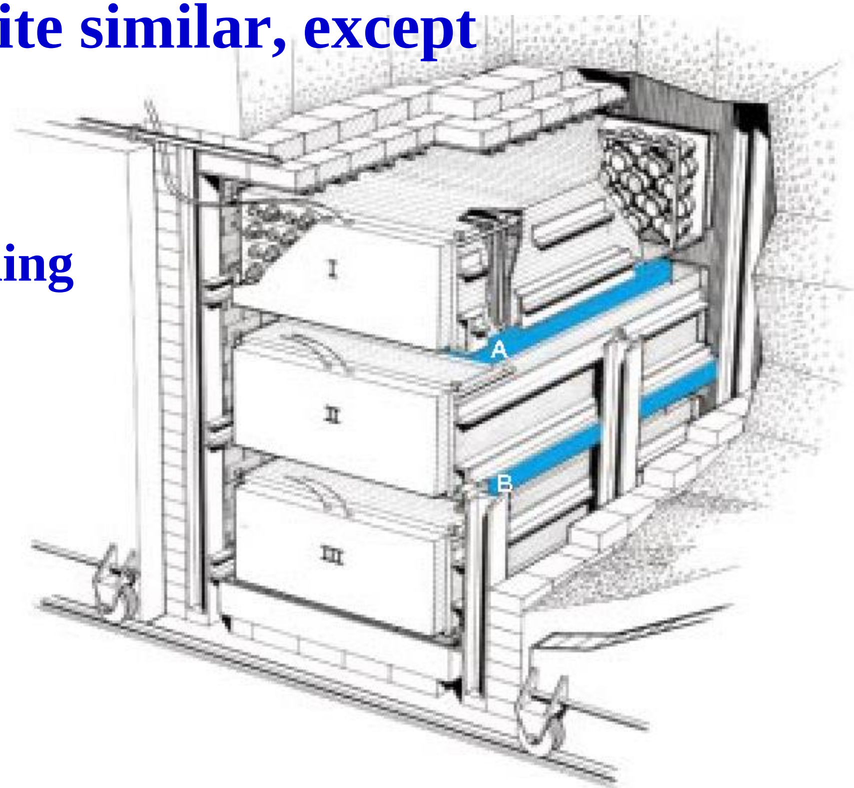


Cowan: The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos.

Savannah River experiment：12 m rock overburden + veto → Discovery of Neutrino

Savannah River experiment

- **The first observation of neutrinos in 1956 by Reines & Cowan.**
  - **Inverse beta decay in $CdCl_3$ water solution → coincidence of prompt and delayed signal**
  - **Liquid scintillator + PMTs**
  - **Underground**
- **Modern experiments are still quite similar, except**
  - **Loading Gd into liquid scintillator**
  - **Larger, better detector**
  - **Deeper underground, better shielding**



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

1995 Nobel Prize 

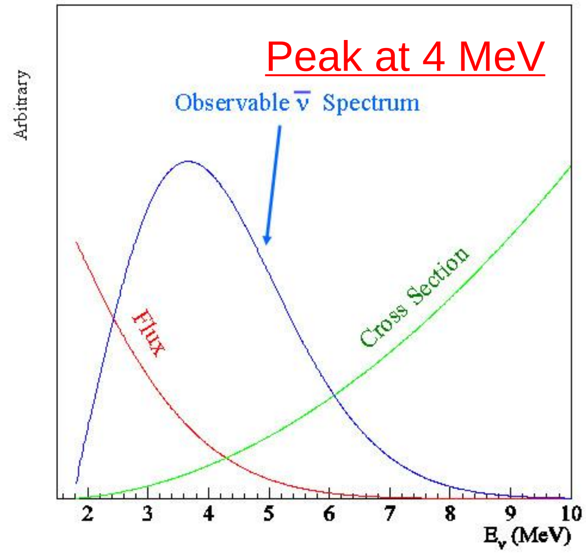
Neutrino Signal (IBD)

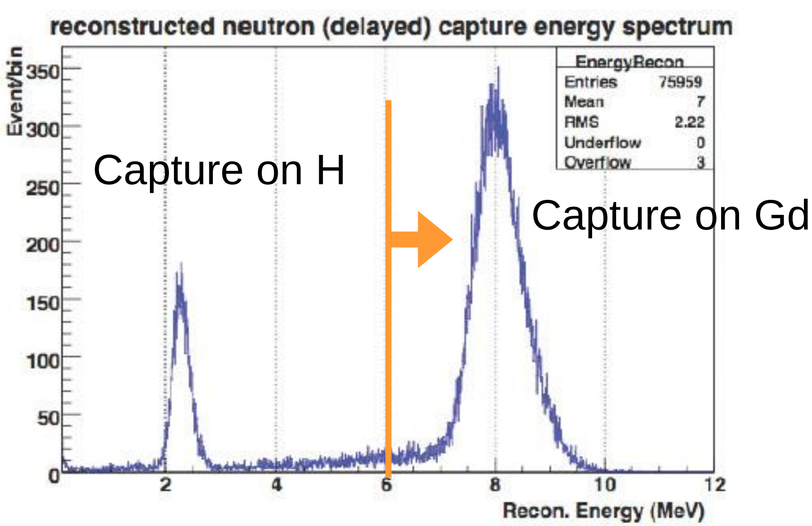
Prompt signal

$$e^{+} + e^{-} \rightarrow 2\gamma$$

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

Capture on H or Gd,
Delayed signal, 2.2, 8 MeV





Neutron capture after thermalization

Time constant ~30 us（0.1% Gd）

- **Inverse beta decay reaction,** proposed by Pontecorvo, called Cowan-Reines reaction
- **Coincidence of**
  - ⇨ Prompt: positron, energy correlated to neutrino energy
  - ⇨ Delayed: neutron capture
- **10^4 times bkg reduction**

CHOOZ

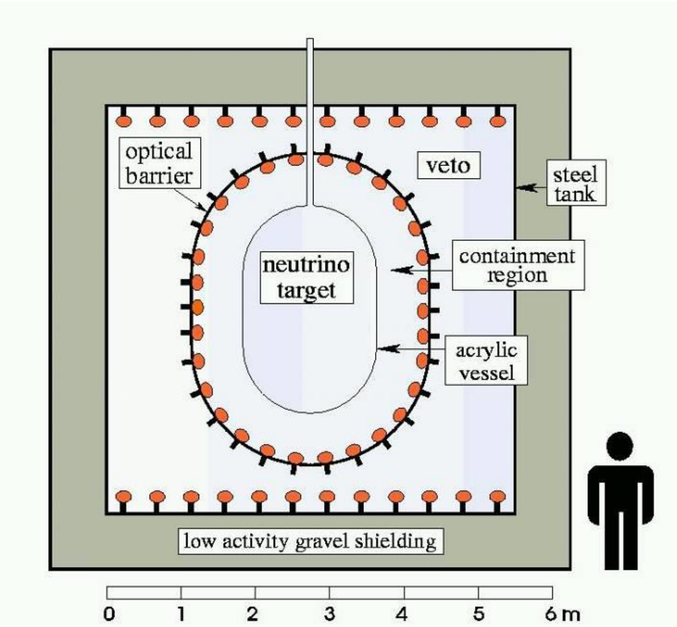
1997-1998, France

8.5 GWth

300 mwe

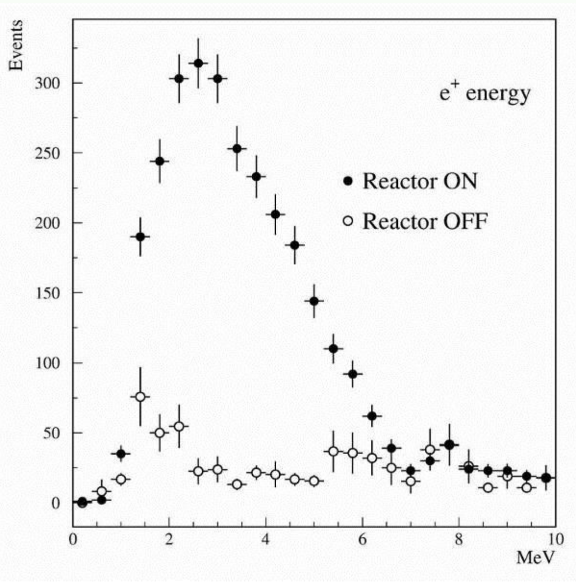
5 ton 0.1% Gd-LS

Bad Gd-LS



$R=1.01\pm2.8\%(stat)\pm2.7\%(syst)$, $\sin^2 2\theta_{13}<0.17$

Parameter	Relative error
Reaction cross section	1.9 %
Number of protons	0.8 %
Detection efficiency	1.5 %
Reactor power	0.7 %
Energy released per fission	0.6 %
Combined	**2.7 %**



Eur. Phys. J. C27, 331 (2003)

Palo Verde

1998-1999, US

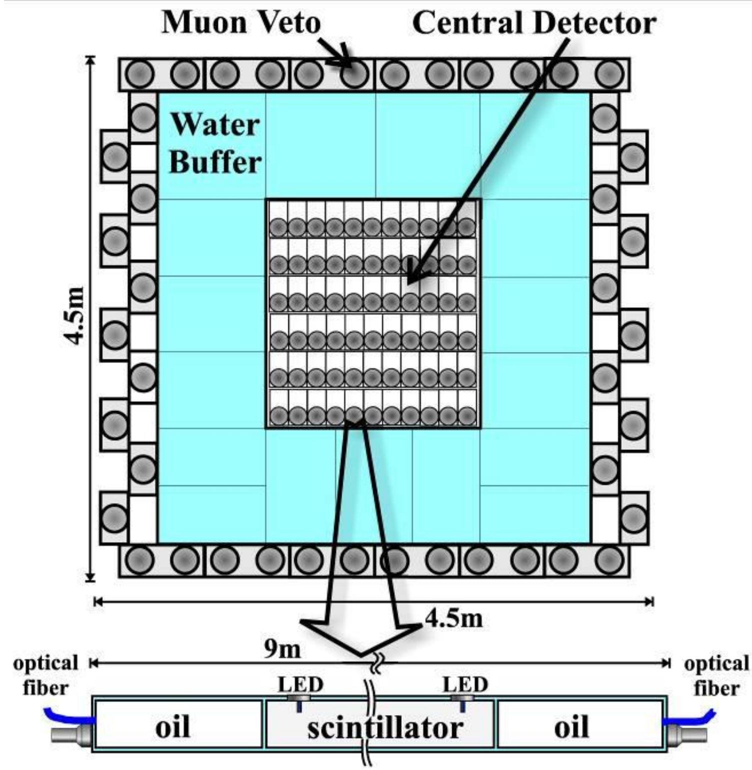
11.6 GWth

Segmented detector

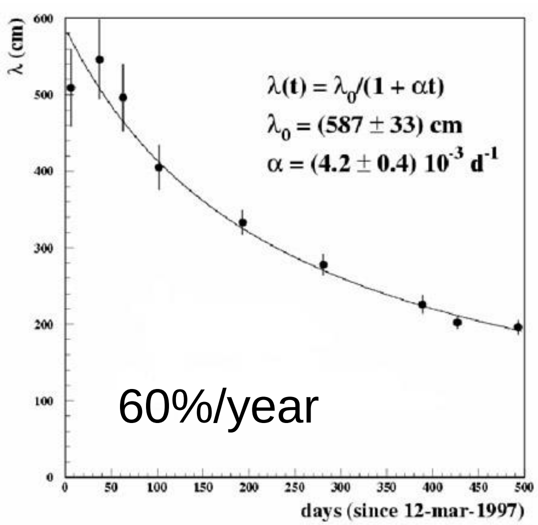
12 ton 0.1% Gd-LS

Shallow overburden

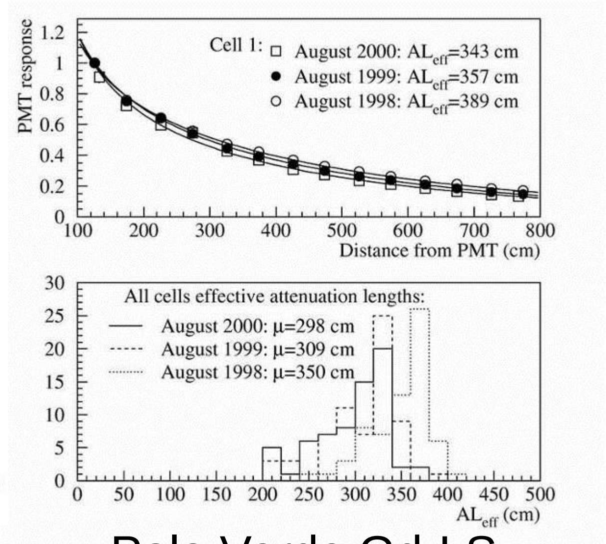
32 mwe



R=1.01±2.4%(stat) ±5.3%(syst)

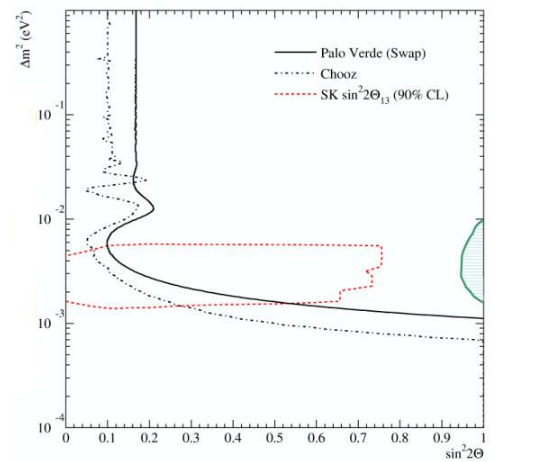


Chooz Gd-LS



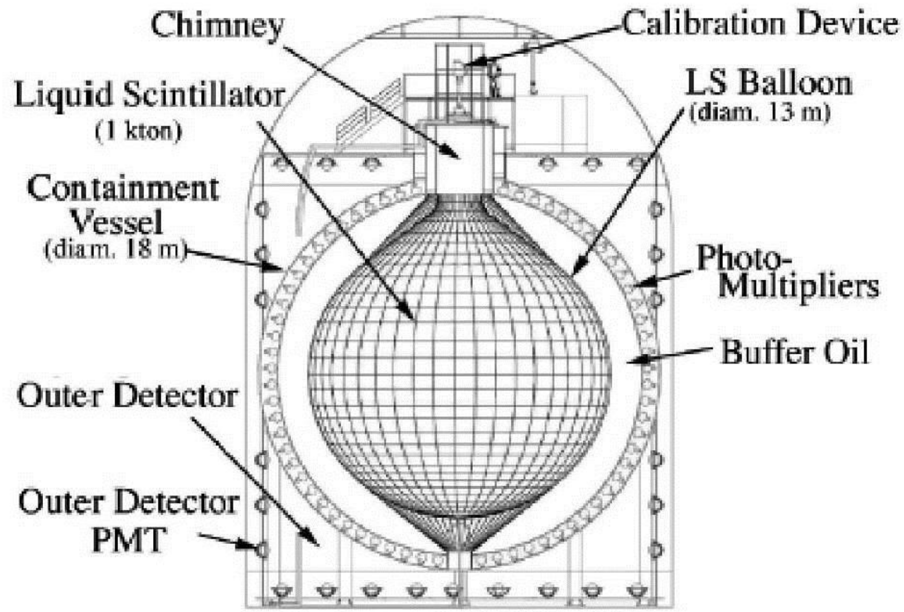
Palo Verde Gd-LS

1st year 12%, 2nd year 3%



Phys.Rev.D64, 112001(2001)

KamLAND



2002-, Japan

53 reactors, 80 GWth

1000 ton LS

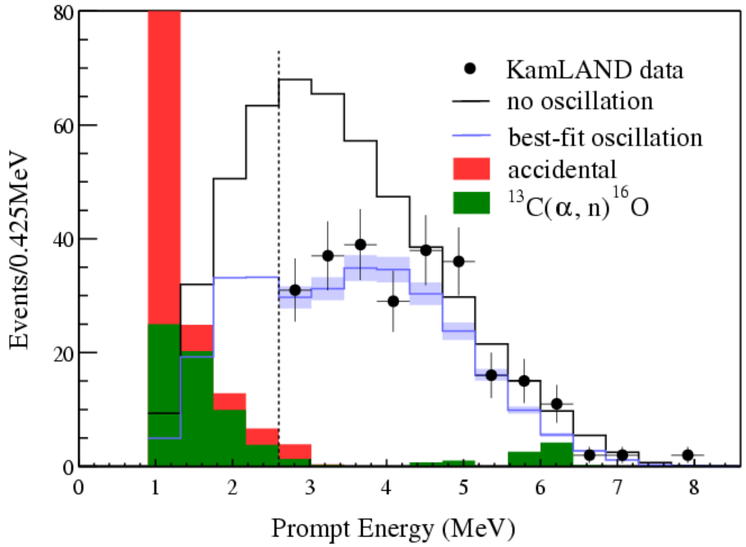
2700 mwe

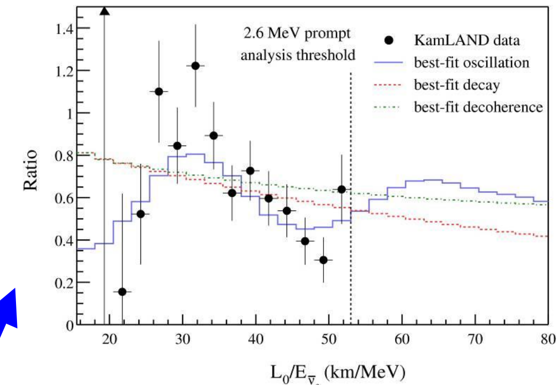
Radioactivity → fiducial cut,
Energy threshold

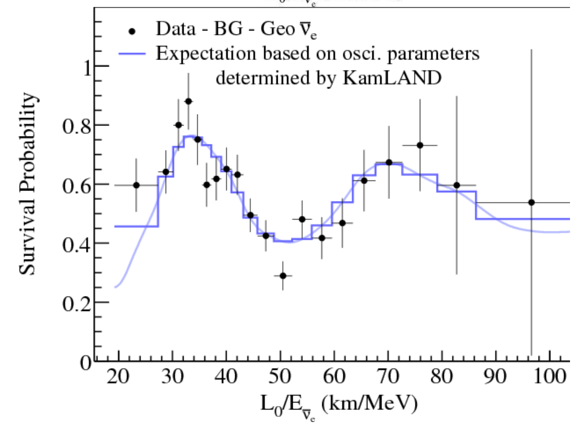
TABLE I: Estimated systematic uncertainties (%).

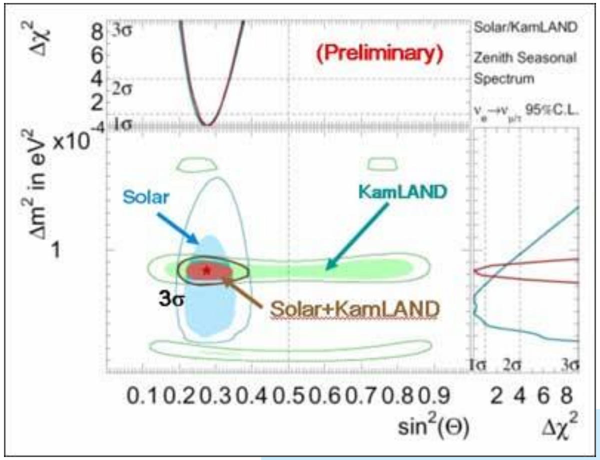
Fiducial Volume	4.7	Reactor power	2.1
Energy threshold	2.3	Fuel composition	1.0
Efficiency of cuts	1.6	$\overline{\nu}_e$ spectra [3]	2.5
Livetime	0.06	Cross section [5]	0.2
Total systematic uncertainty			6.5

KamLAND









R=0.658±0.044(stat) ±0.047(syst)

The first observation of reactor anti-neutrino disappearance

Confirmed antineutrino disappearance at 99.998% CL

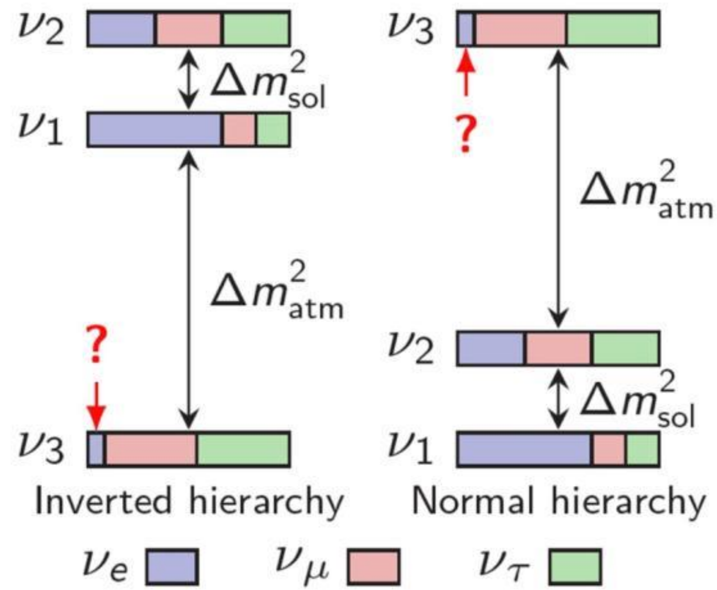
Excluded neutrino decay at 99.7% CL

Excluded decoherence at 94% CL

Neutrino Mixing @ 2003

In a 3-ν framework

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



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

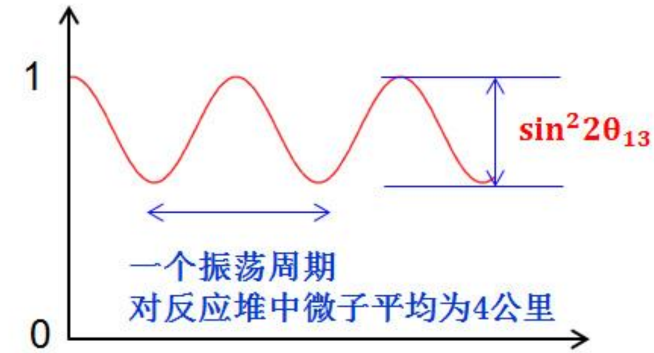
$\theta_{23} \sim 45°$	**$\theta_{13} = ?$**	**$\theta_{12} \sim 34°$**	
Atmospheric	**Reactor**	**Solar**	**0νββ**
Accelerator	**Accelerator**	**Reactor**	

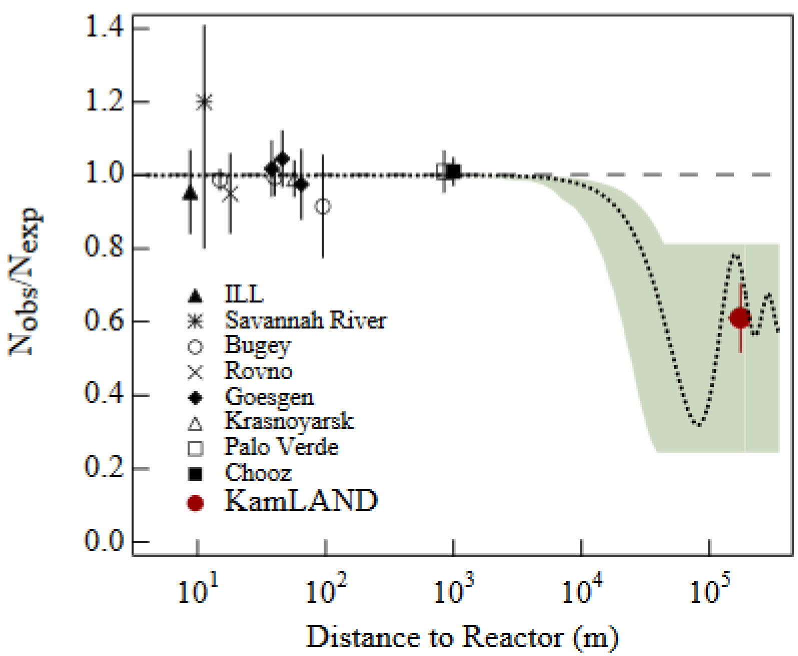
Reactor Neutrion Oscillation

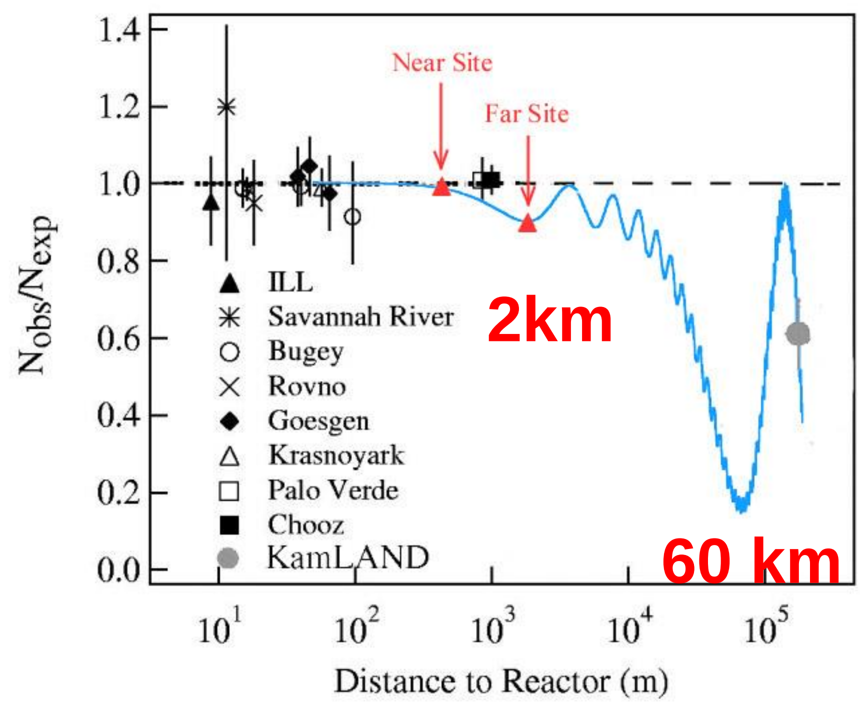
飞行距离/中微子能量

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

振幅大小　振荡频率

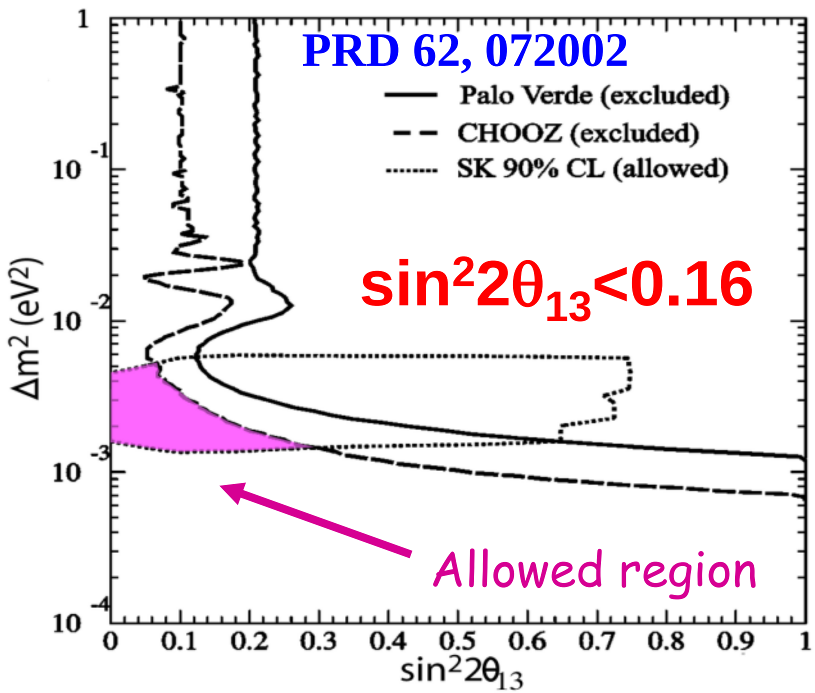




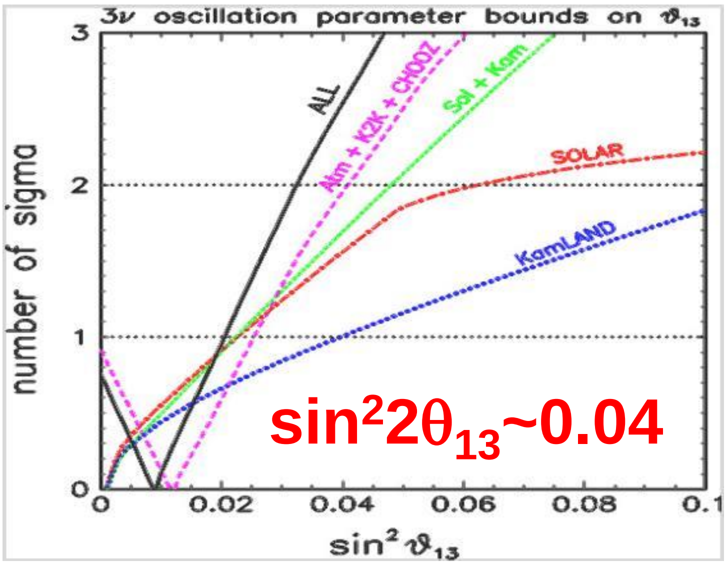


Question: what is the difference between two figures?

How large is θ_{13}?



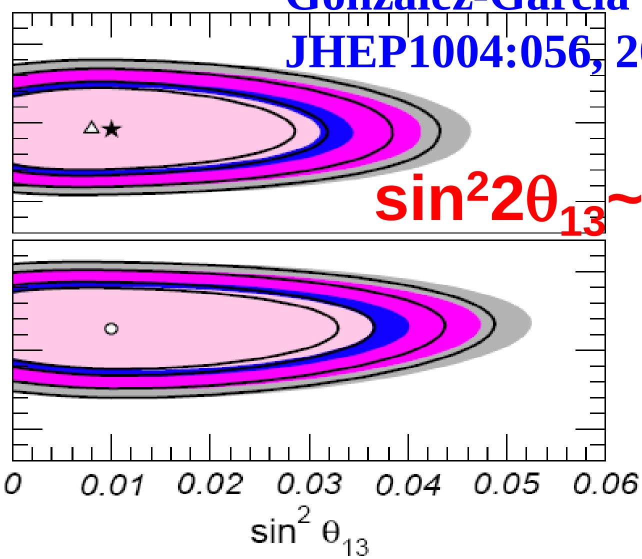
$\sin^2 2\theta_{13} < 0.16$



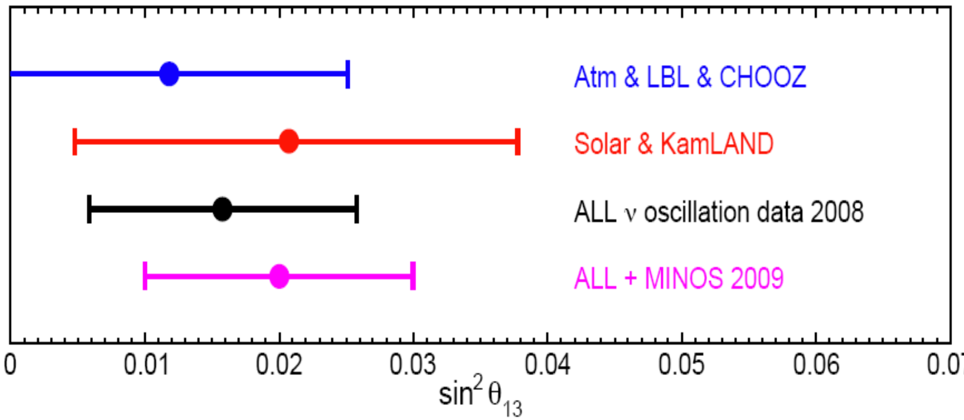
$\sin^2 2\theta_{13} \sim 0.04$

Fogli et al., hep-ph/0506307

Gonzalez-Garcia et al., JHEP1004:056, 2010



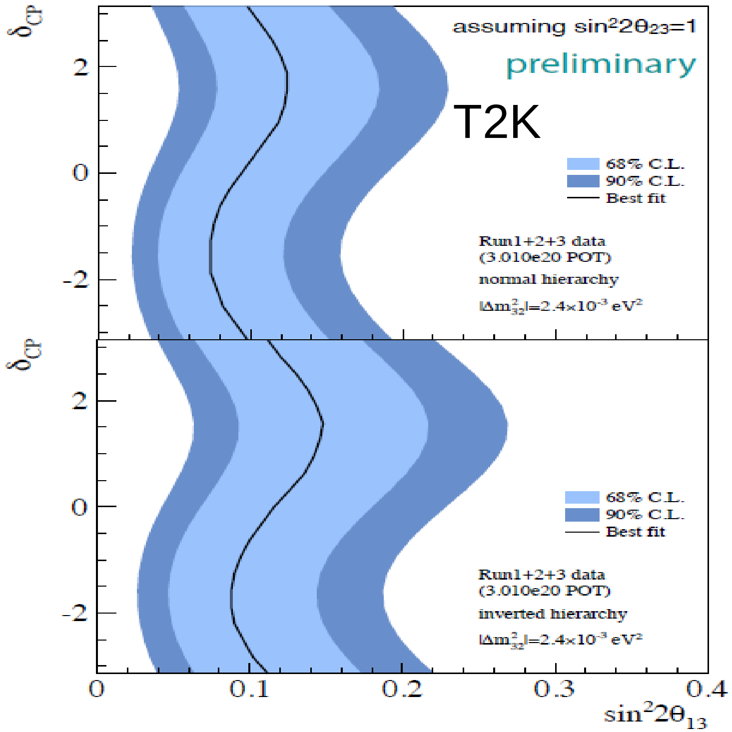
$\sin^2 2\theta_{13} \sim 0.04$



$\sin^2 2\theta_{13} \sim 0.08$, non-zero 2σ

Fogli et al., J.Phys.Conf.Ser.203:012103 (2010)

How to measure θ_{13}



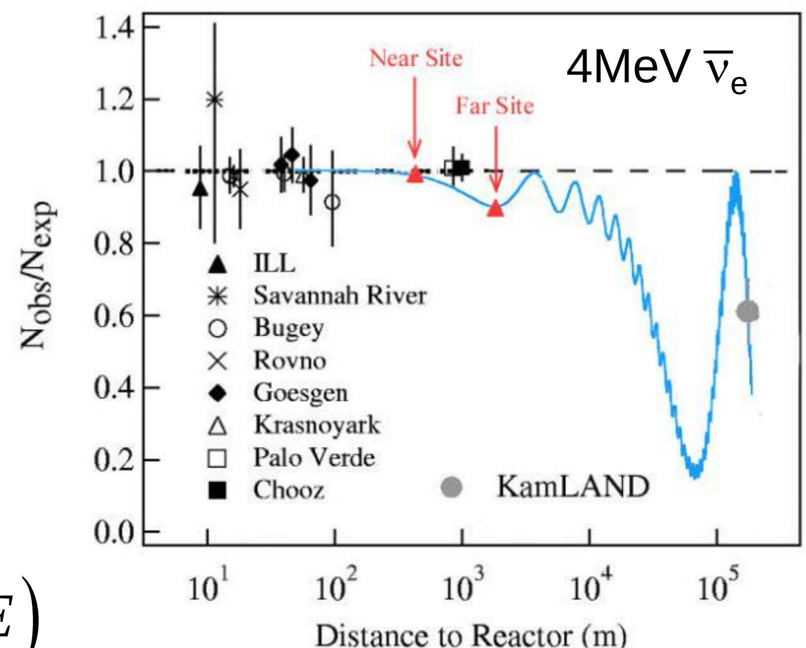
Accelerator (appearance)

Related with CPV and matter effect

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\Delta m_{31}^2 L / 4E\right)$$

$$+ (\text{CPV term}) + (\text{matter term})$$

$$+ \cdots\cdots$$



Reactor (disappearance)

Clean in physics, only related to θ_{13}

Precision measurement

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m_{31}^2 L / 4E\right)$$

$$- \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m_{21}^2 L / 4E\right)$$

Precision Measurement at Reactors

Major sources of uncertainties:

- **Reactor related ~2%**
- **Detector related ~2%**
- **Background 1~3%**

Lessons from past experience:

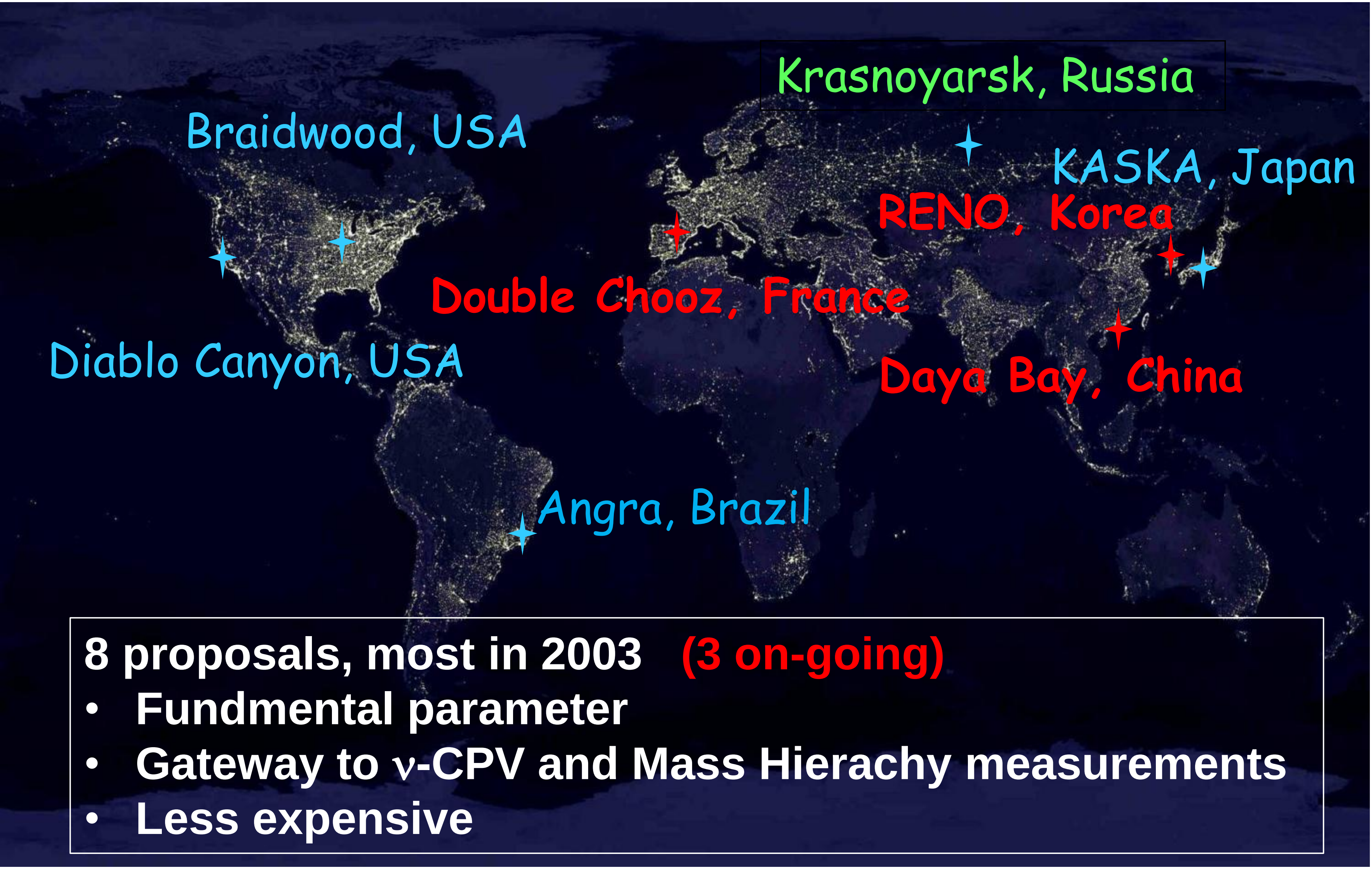
- **CHOOZ: Good Gd-LS**
- **Palo Verde: Better shielding**
- **KamLAND: No fiducial cut**

Near-far relative measurement

Mikaelyan and Sinev, hep-ex/9908047

Parameter	Error	Near-far
Reaction cross section	1.9 %	0
Energy released per fission	0.6 %	0
Reactor power	0.7 %	~0.1%
Number of protons	0.8 %	< 0.3%
Detection efficiency	1.5 %	0.2~0.6%
CHOOZ Combined	2.7 %	< 0.6%

Proposed Reactor Experiments

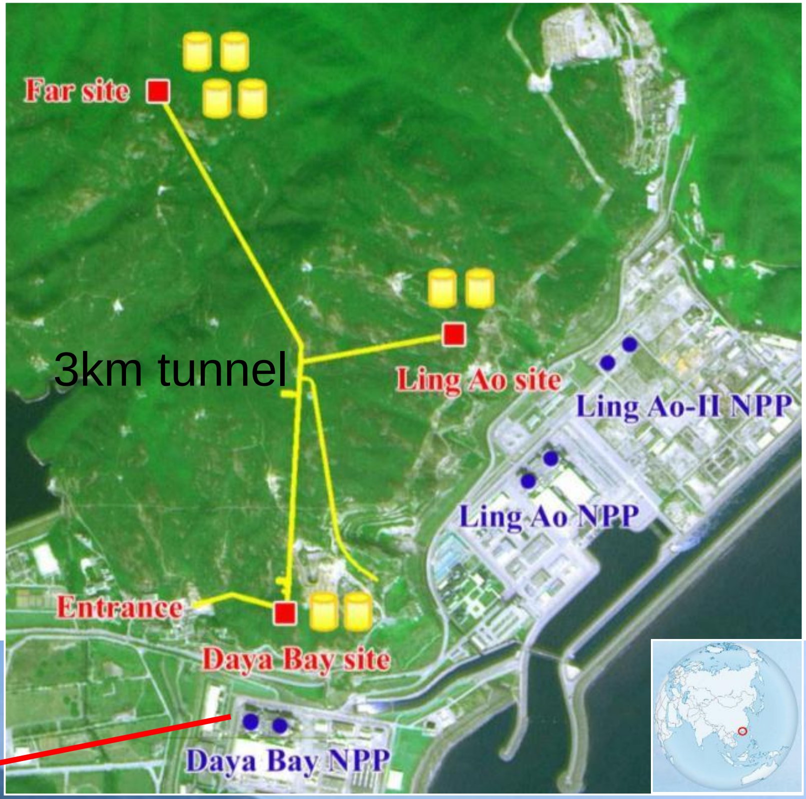


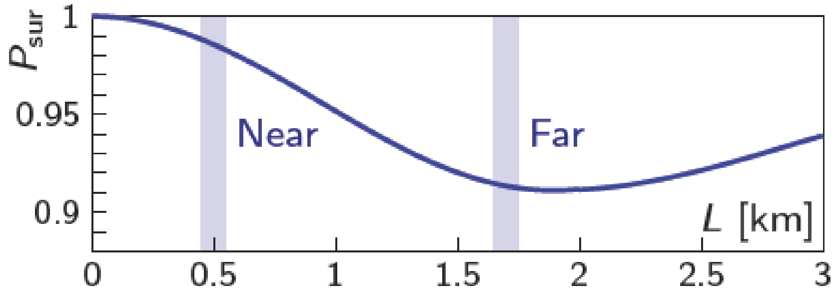
8 proposals, most in 2003 (3 on-going)

- **Fundmental parameter**
- **Gateway to ν-CPV and Mass Hierachy measurements**
- **Less expensive**

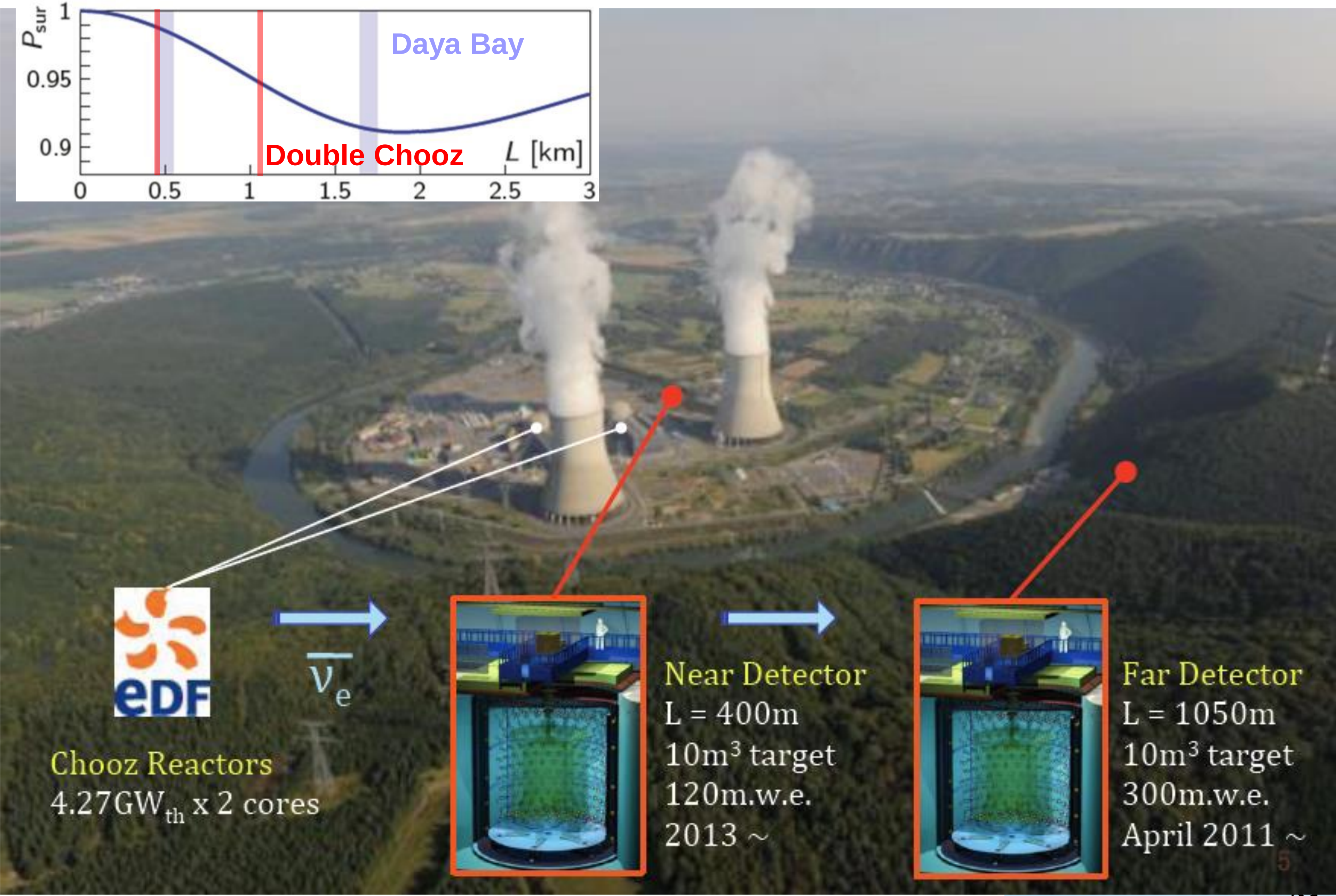
The Daya Bay Experiment

- 6 reactor cores, 17.4 GW_{th}
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic shielding
  - 250 m.w.e @ near sites
  - 860 m.w.e @ far site
- Redundancy

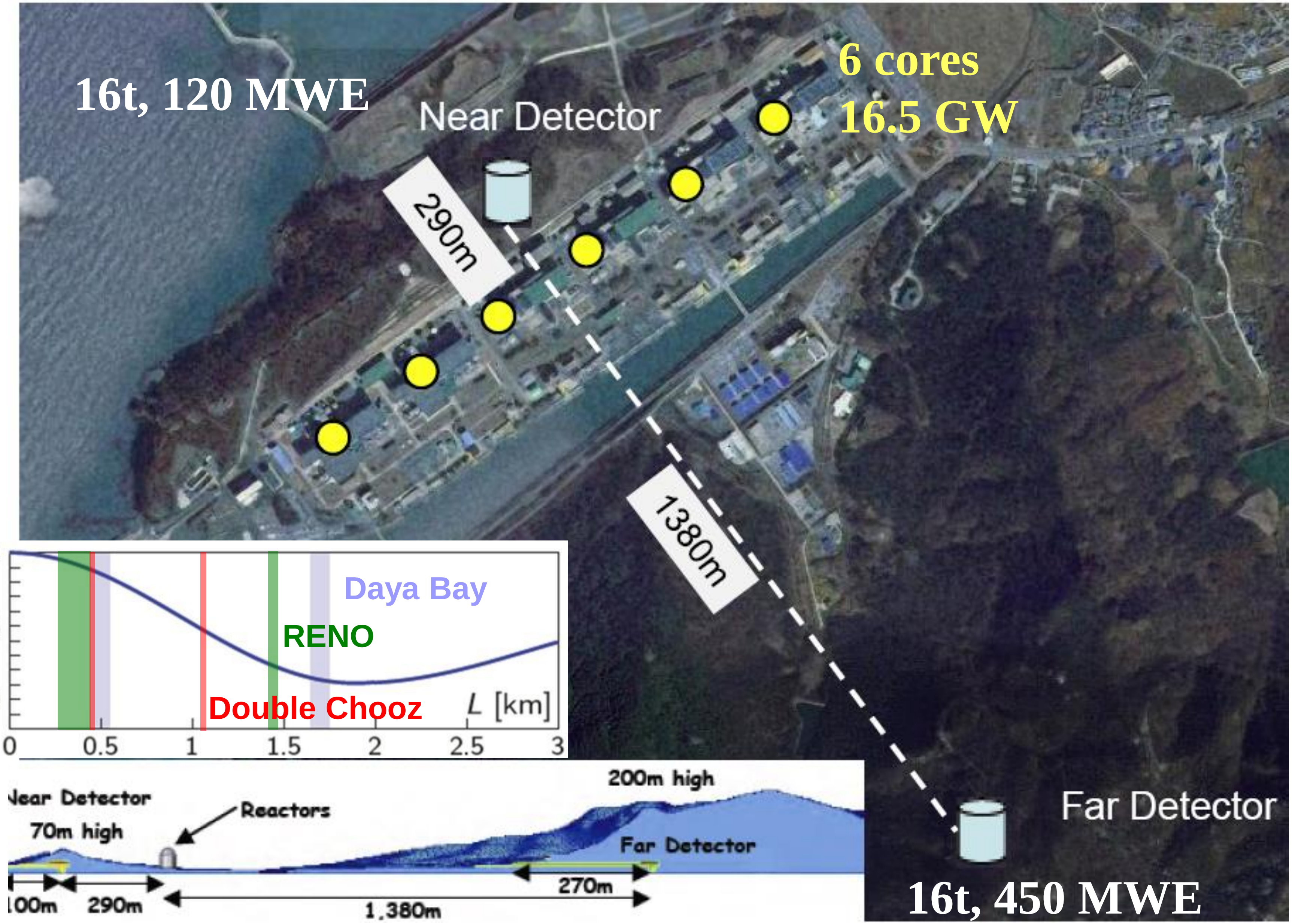




Double Chooz



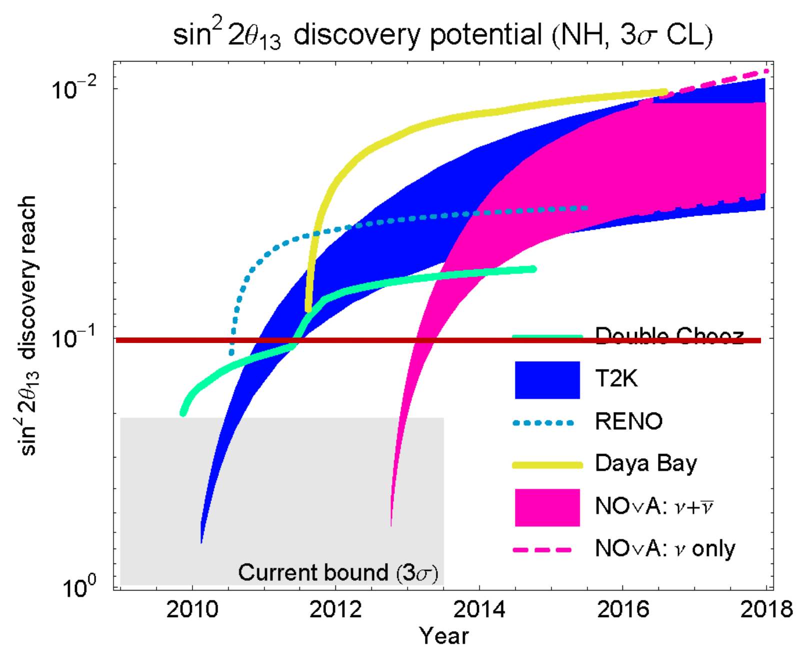
RENO

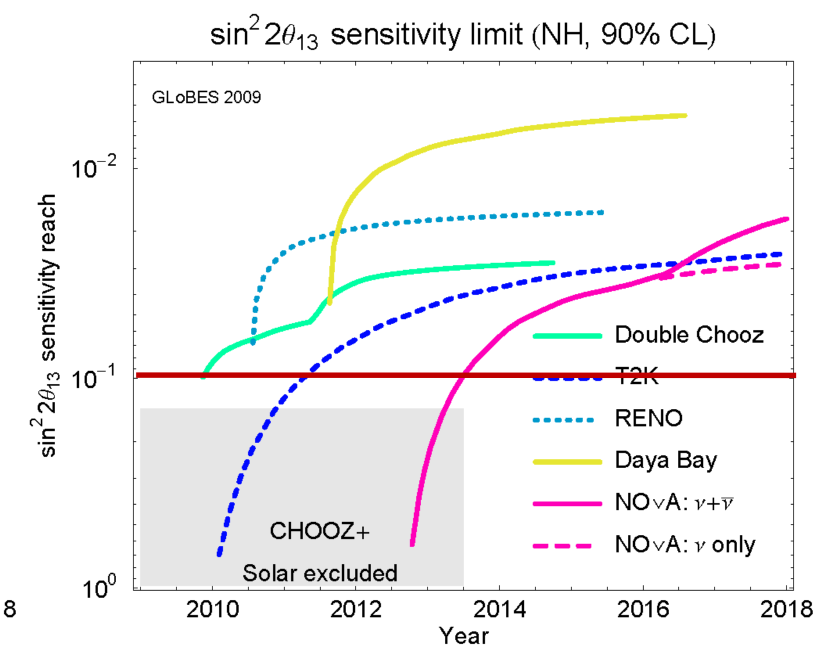


16t, 120 MWE
Near Detector
6 cores
16.5 GW
290m
1380m
Far Detector
16t, 450 MWE
P_{sur}
1
0.95
0.9
0
0.5
1
1.5
2
2.5
3
Daya Bay
RENO
Double Chooz
L [km]
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
270m
1,380m

Three on-going experiments

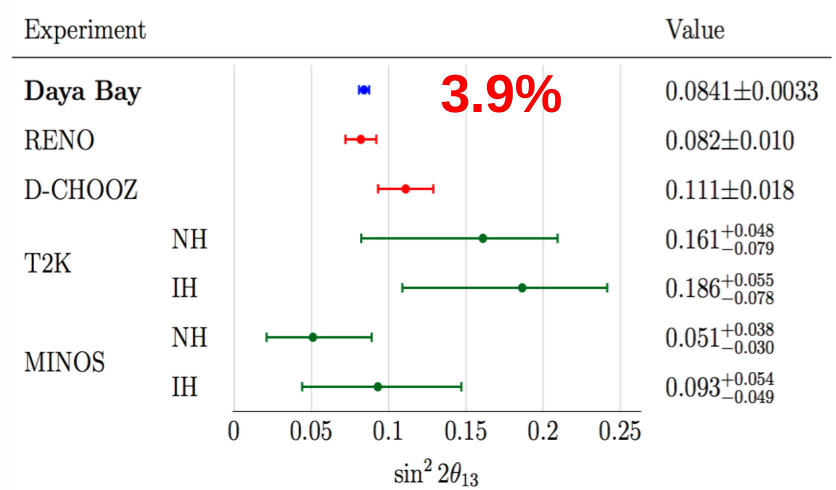
Experiment	Power (GW)	Detector(t) Near/Far	Overburden (m.w.e.) Near/Far	Sensitivity (3y,90%CL)
Daya Bay	17.4	40 / 80	250 / 860	~ 0.008
Double Chooz	8.5	8 / 8	120 / 300	~ 0.03
RENO	16.5	16 / 16	120 / 450	~ 0.02

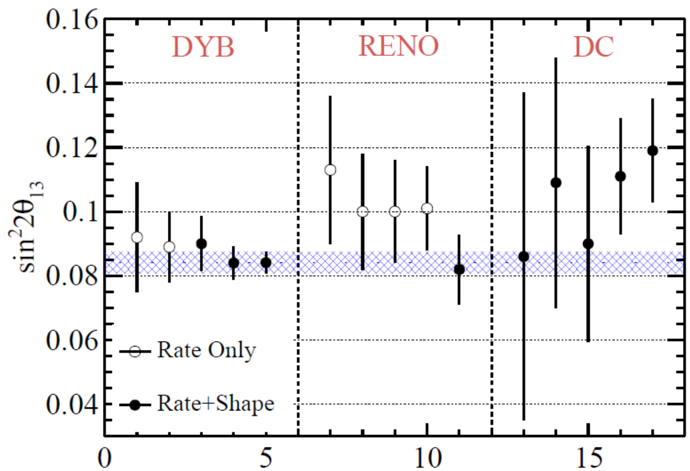


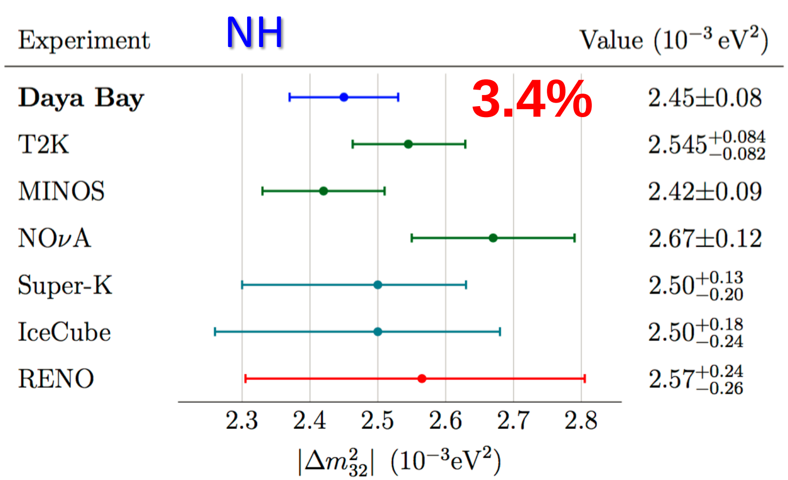


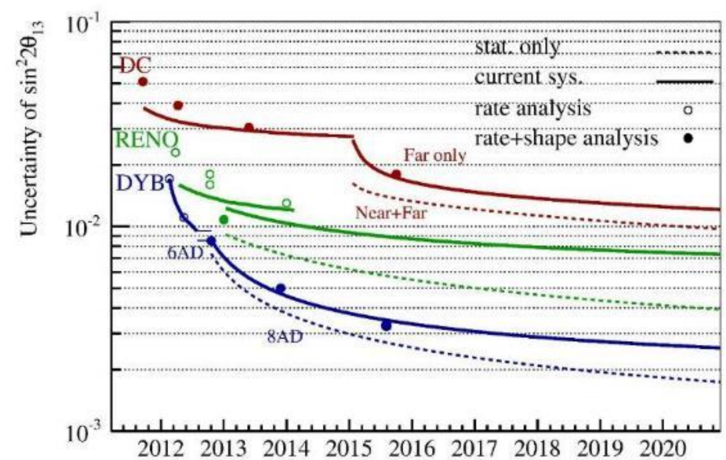
Huber et al. JHEP 0911:044, 2009

Theta13 and Dmee





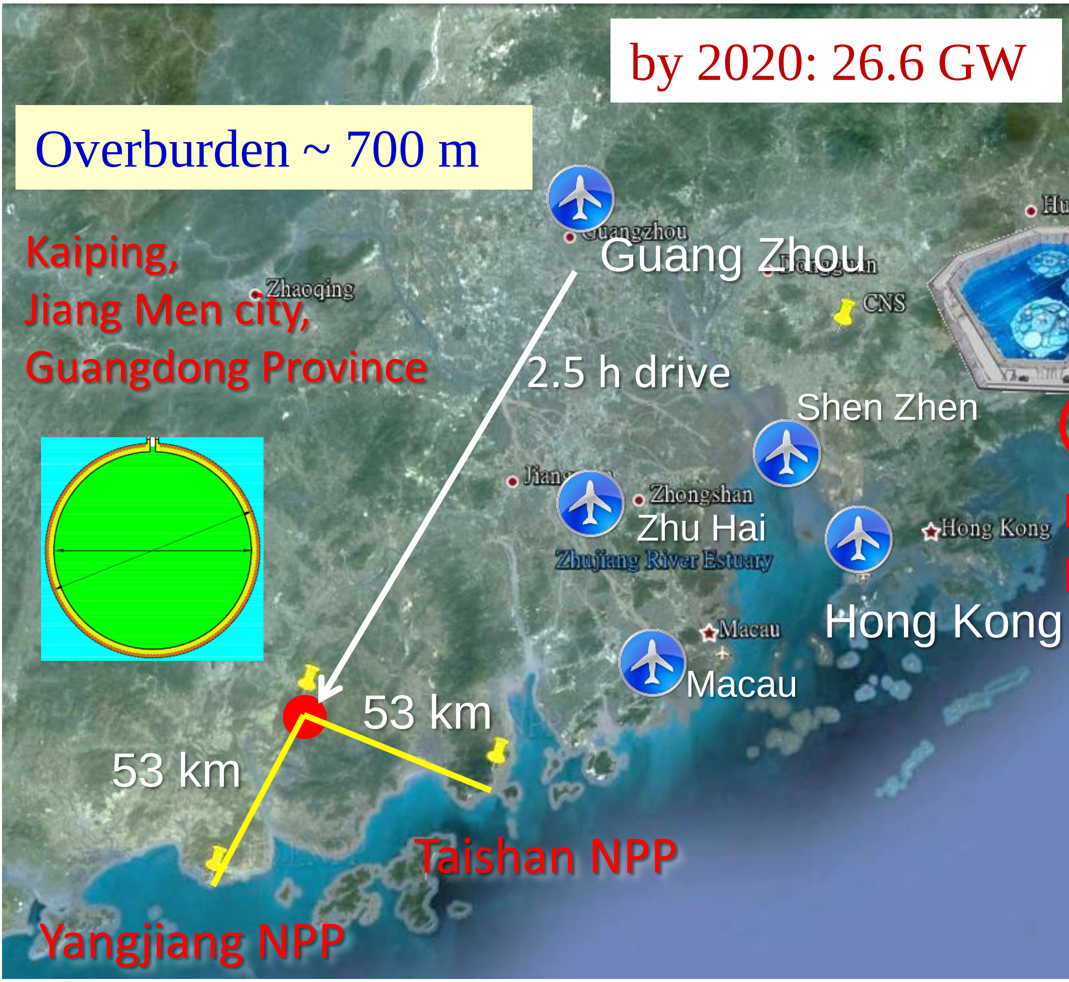


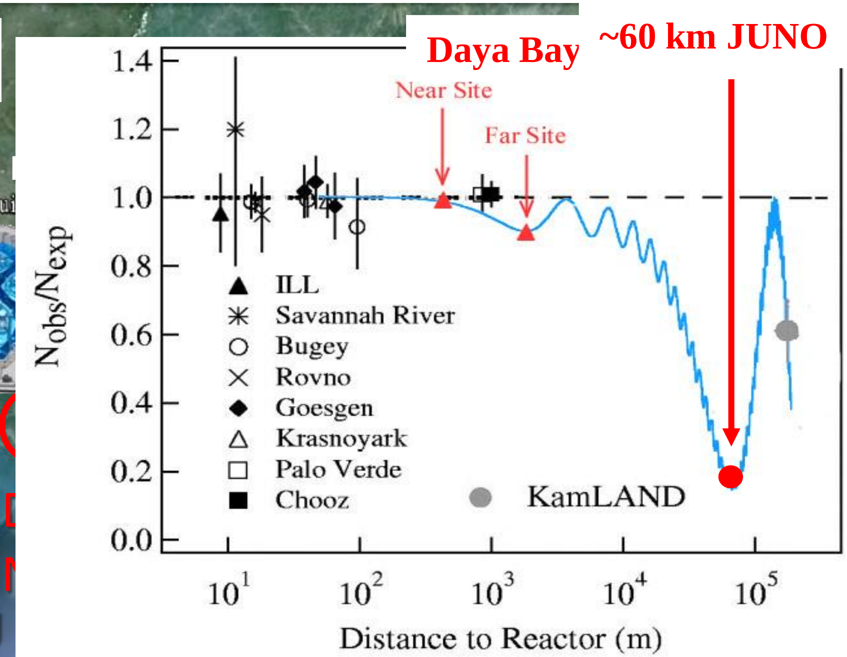


- DYB: running to 2020, 3% precision (1.5x stat. in 2018 summer)
- RENO: running to 2021
- Double Chooz: Dec. 2017

Mass Hierarchy

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

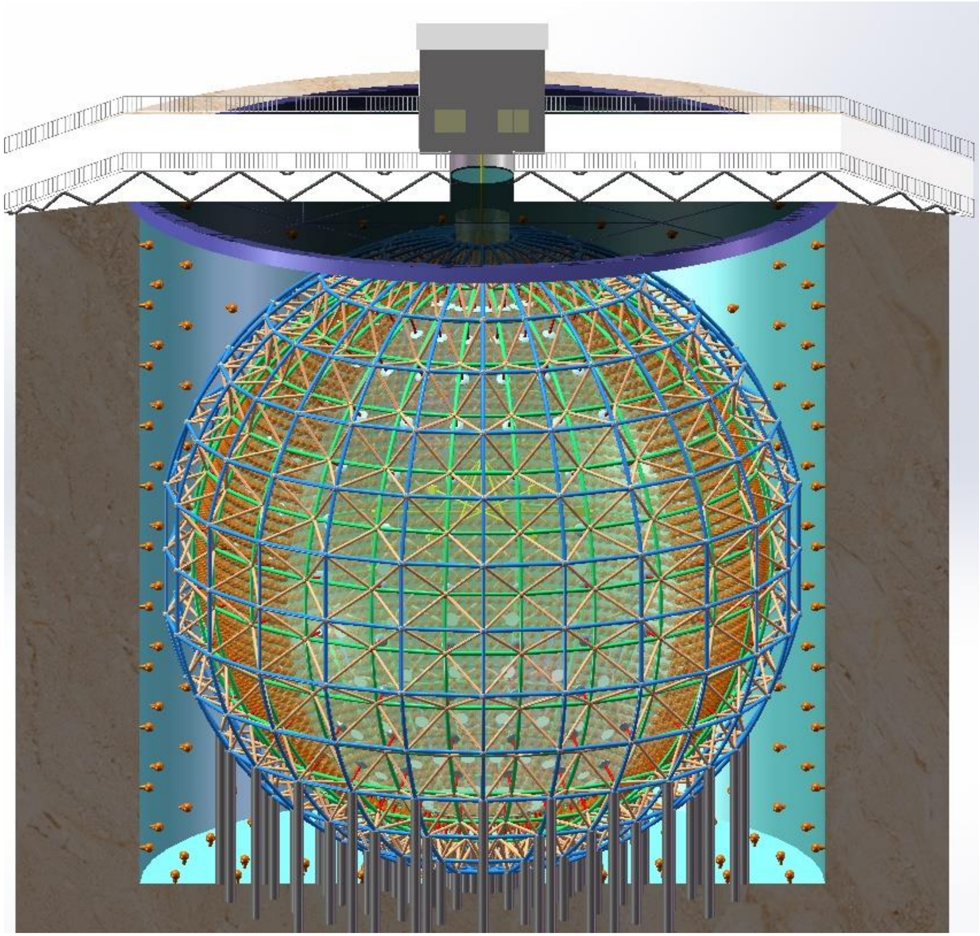




Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

The JUNO Experiment

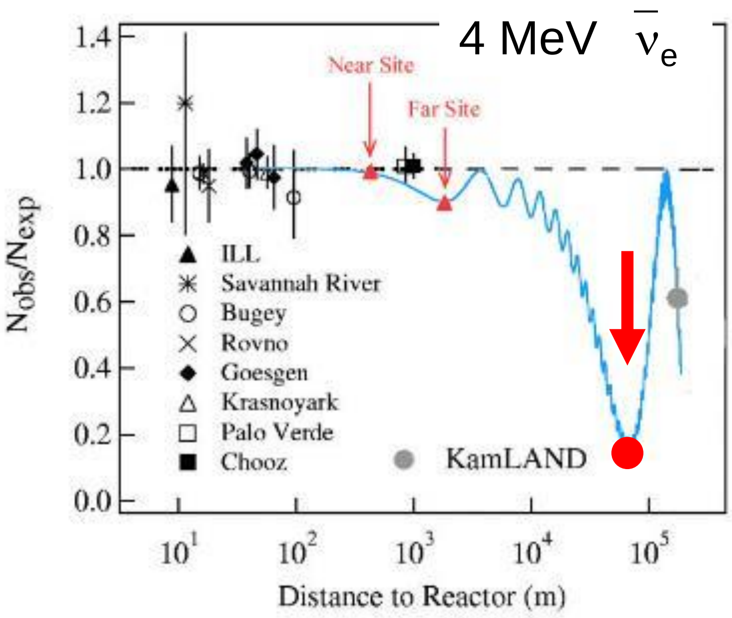
- Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.



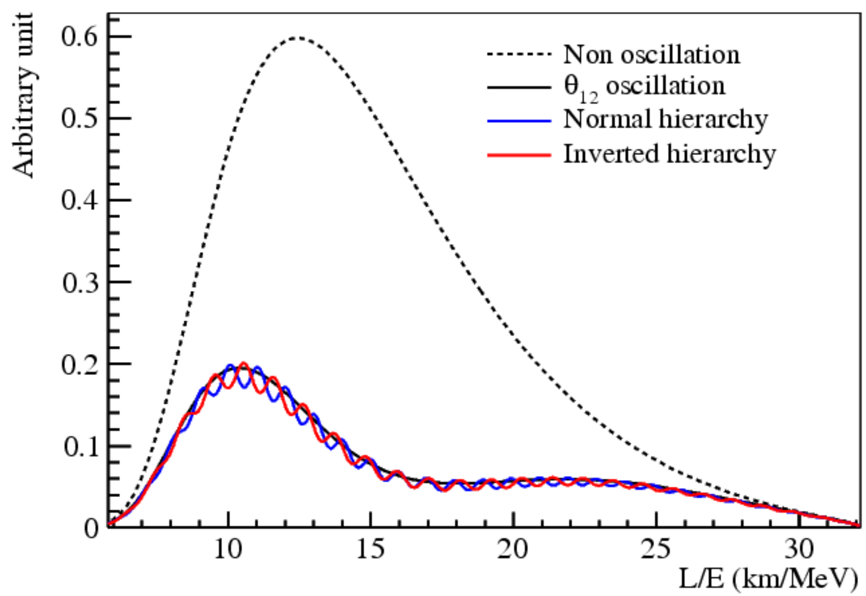
- 20 kton LS detector
- 3% energy resolution
- 700 m underground
- Rich physics possibilities
  - ⇨ Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
  - ⇨ Supernovae neutrino
  - ⇨ Geoneutrino
  - ⇨ Solar neutrino
  - ⇨ Atmospheric neutrino
  - ⇨ Proton decay
  - ⇨ Exotic searches

L. Zhan, Y.F. Wang, J. Cao, L.J. Wen,
PRD78:111103, 2008; PRD79:073007,2009

Determine MH with Reactors



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

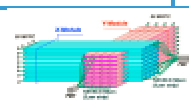
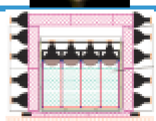
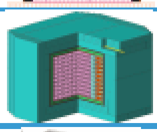
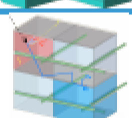
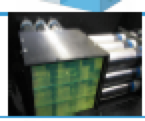


Precision energy spectrum measurement interference between P_{31} and P_{32}
→ **ϕ: Relative measurement**

Further improvement with $\Delta m^2_{\mu\mu}$ measurement from accelerator exp.
→ Δm^2_{ee}: **Absolute measurement**

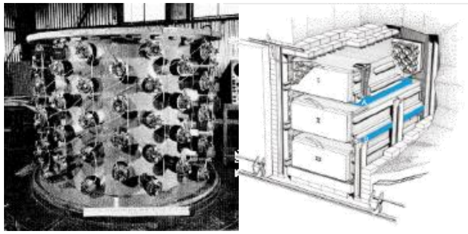
Very Short Baseline Exps.

- Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)
- Most have sensitivity 0.02~0.03 @Δm~1eV^2 @90%CL

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Reactor Neutrino Experiments

Discovery of ν

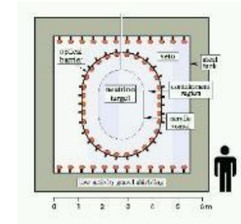


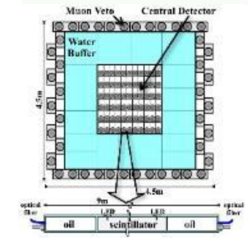
1953, Hanford, 0.3 ton
1956, Savannah River, 4.2 ton

Early searches for oscillation

1980 Savannah,
1980 ILL,
1984 Bugey,
1986 Gosgen,
1995 Bugey-3,

Reactor ν spectra ~2%

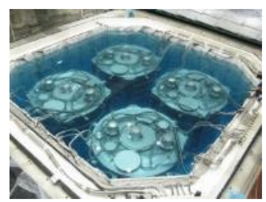


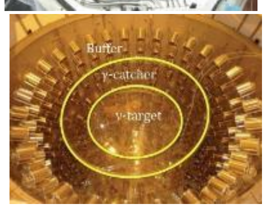


1997, CHOOZ, 8 ton
2000, Palo Verde, 12 ton

$\sin^2 2\theta_{13} < 0.15$

2012,
Daya Bay, 160 ton
Double Chooz, 16 ton
RENO, 32 ton

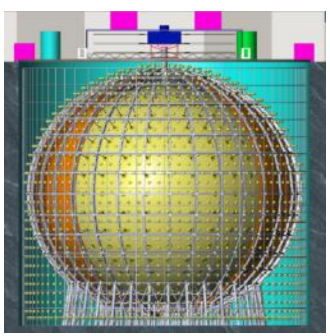




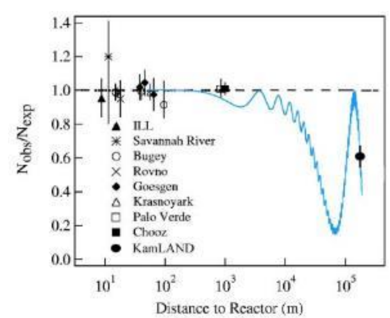
Non-zero θ_{13}

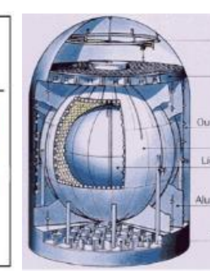
Mass Hierarchy,
Precision meas.

2020, JUNO, **20 000 ton**



Reactor ν oscillation (θ_{12})





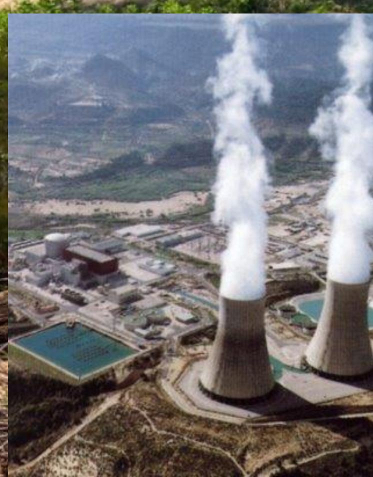
2002, KamLAND, **1000 ton**

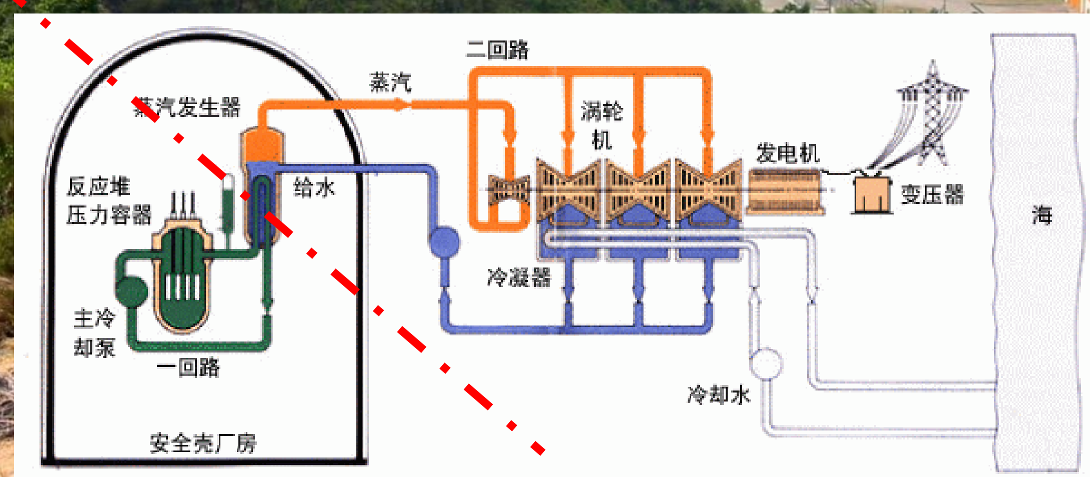
Very short baseline exp. for sterile ν

2 - Neutrino from Reactor

大亚湾核电站

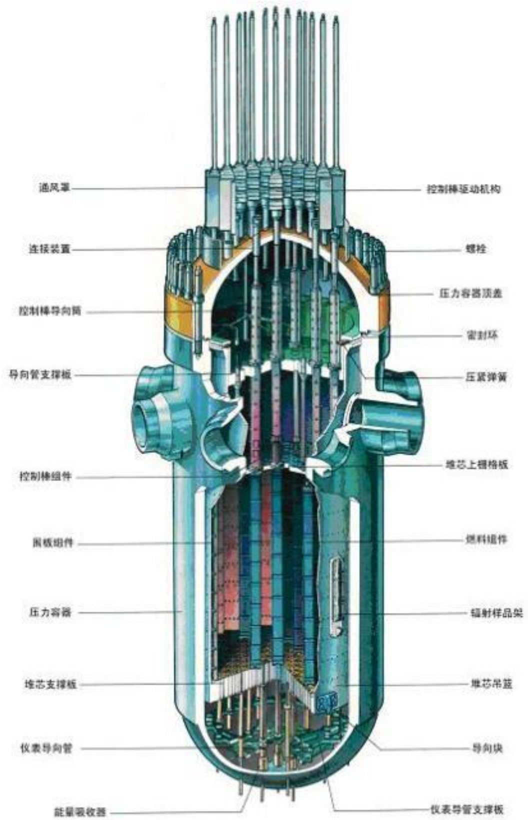
绝大部分商用反应堆为压水堆或沸水堆，两者原理相同
电功率约为热功率的1/3。大亚湾：2.9 GW_{th}，千兆瓦反应堆。



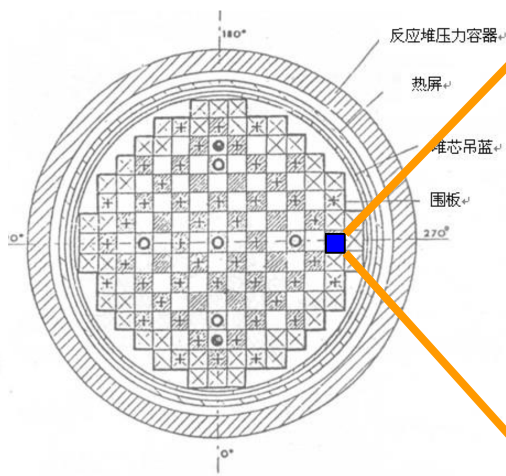


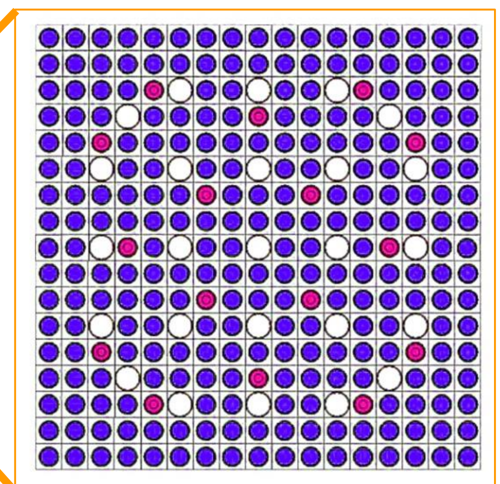
Structure of a Reactor Core

- 压力容器、活性区、组件、燃料棒、元件
- 157个组件（assembly），3.7m高，3m直径
- 每组件17×17根棒（其中264根燃料棒，25根导管）
- 每燃料棒271个燃料元件。燃料元件二氧化铀烧结成1厘米大小的陶瓷状圆柱体，U-235 4.45%（1.8-4.45%)

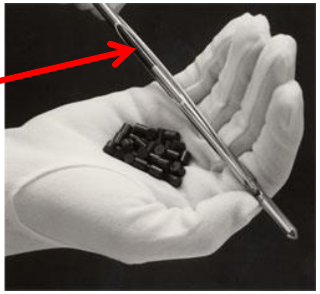


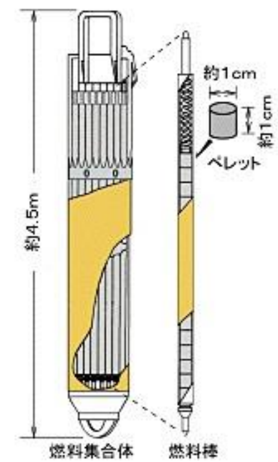
72吨核燃料
每天消耗3kg U235





锆合金管

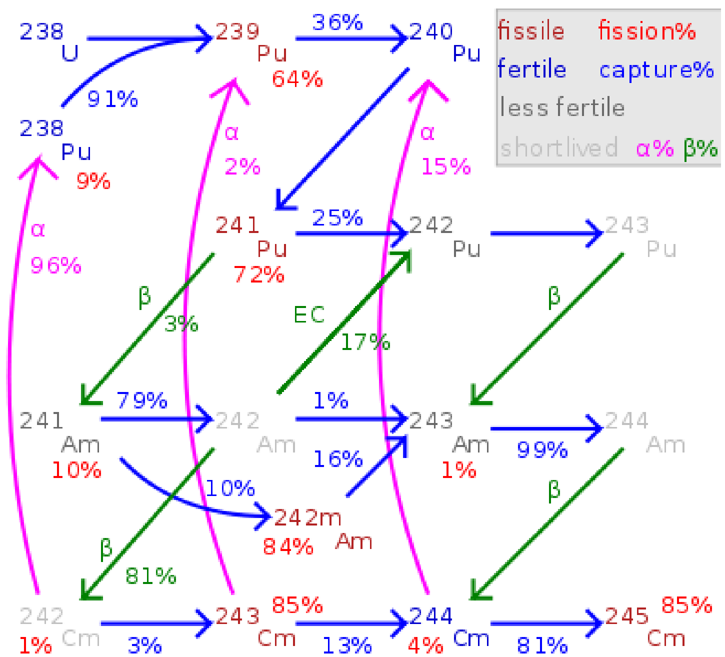


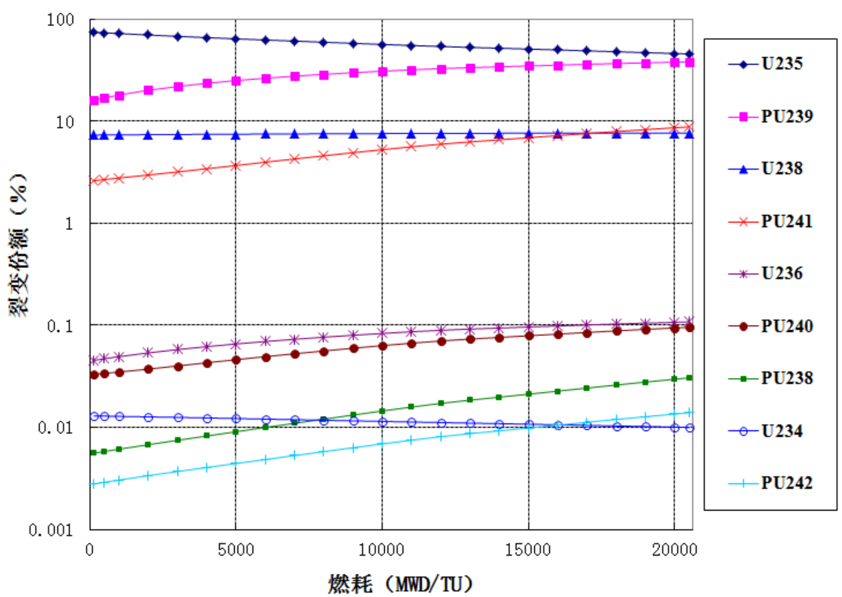


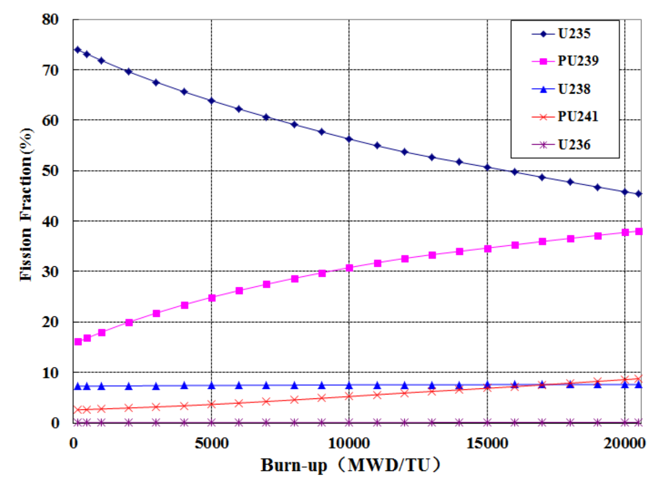
红色：可燃毒物棒 8% Gd

Fuel Evolution

- **Initial 4.45% U235, Others:U238 and O**
- **U238 → n capture → Pu239 →2x n capture → Pu241**
- **Four major fission isotopes**
  - ⇨ **U235, Pu239, Pu241**
  - ⇨ **U238 fission w/ fast n**
- **燃耗(Burnup)： MW·day/ton U**







每裂变释放能量

- 每裂变释放能量是指核燃料裂变时放出的能量中，在反应堆内被吸收转化为热能的部分。
- 核燃料释放的能量
  - ⇨ 一部分作为裂变产物的动能转化为热能；
  - ⇨ 一部分被中微子带走；
  - ⇨ 一部分来自子核的衰变能，长寿命子核能量释放延后（时间变化）
  - ⇨ 还有一部分来自富余中子的俘获（时间变化）
- 采用整个寿期内的平均值做为近似，误差 **(0.30-0.47)%.**

Isotope	E_{fi}, MeV/fission
^{235}U	201.92 ± 0.46
^{238}U	205.52 ± 0.96
^{239}Pu	209.99 ± 0.60
^{241}Pu	213.60 ± 0.65

Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)

Isotopes	Energy (MeV)
U-235	201.7±0.6
U-238	205.0±0.9
Pu-239	210.0±0.9
Pu-241	212.4±1.0

M.F. James, J. Nucl. Energy 23, 517 (1969)

反应堆产生中微子

- **Neutrinos from subsequent β-decays of fission fragments.**
- 两裂变为主。钱三强、何泽慧发现存在三裂变
- 裂变产物是富中子核，平均每裂变释放6个中微子

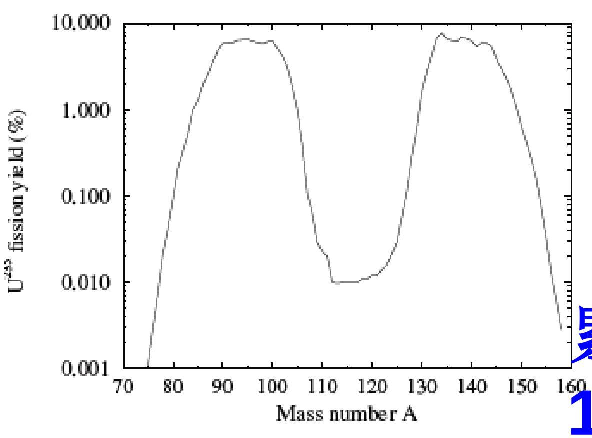
β衰变: $^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e$ 忽略反冲核能量: $E_0 = E_e + E_\nu$

中微子能谱:

$$S_f(E) = \sum_b \left(K_f^b \cdot F(Z_f, A_f, E) \cdot pE(E - E_{0f}^b)^2 \cdot C_f^b(E) \cdot (1 + \delta_f^b(Z_f, A_f, E)) \right)$$

核素裂变的碎片有固定的质量分布

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



核素裂变有固定的中微子能谱

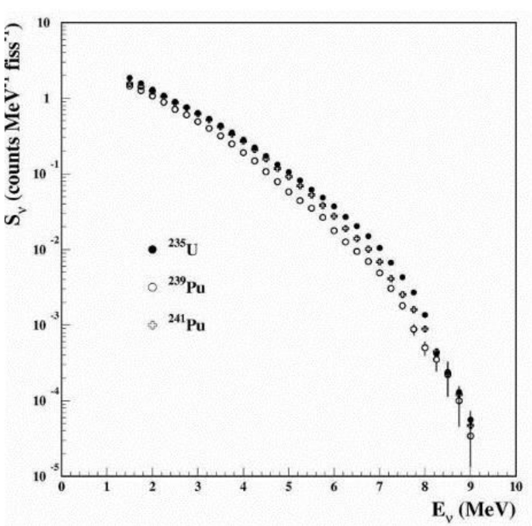
$$S_k = \sum_f A_f \cdot S_f$$

累加各核素得到的能谱误差较大:

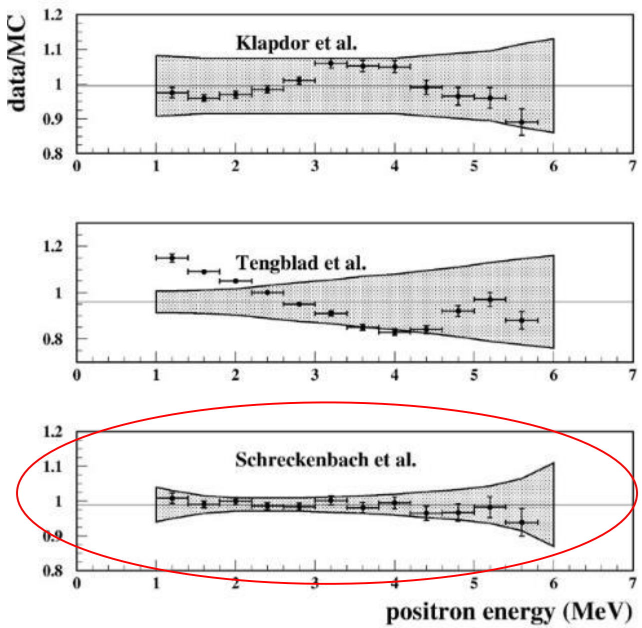
1000多种核素，6000道，10%误差

Spectra of Isotopes

- **Ab initio: Nuclear database, Σ fragments, Σ chains, Σ branches → 10% uncertainty** (e.g. Vogel et al., PRC24, 1543 (1981)).
- **Conversion: ILL measured the β-spectra → convert to neutrino spectra**
  - ⇨ **ILL spectra: Use spectra of 30 virtual (allowed) decays, fit amplitude and endpoints (ILL-Vogel spectra)**
  - ⇨ **Mueller: 90% ab initio + 10% fit → rate anomaly**
  - ⇨ **Huber: fit w/ improved nuclear effects (Huber-Mueller spectra)**
  - ⇨ **1.34% at 3 MeV to 9.2% at 8 MeV.**



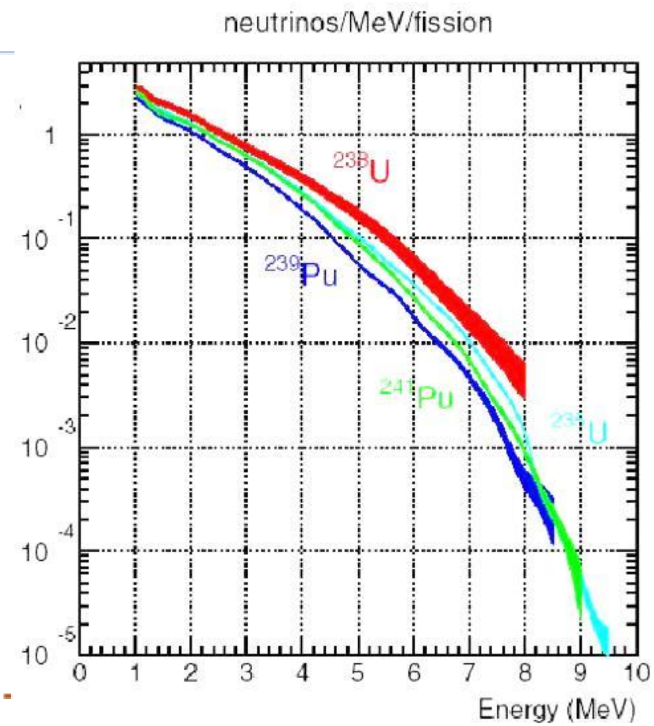
K. Schreckenbach et al. PLB118, 162 (1985)
A.A. Hahn et al. PLB160, 325 (1985)



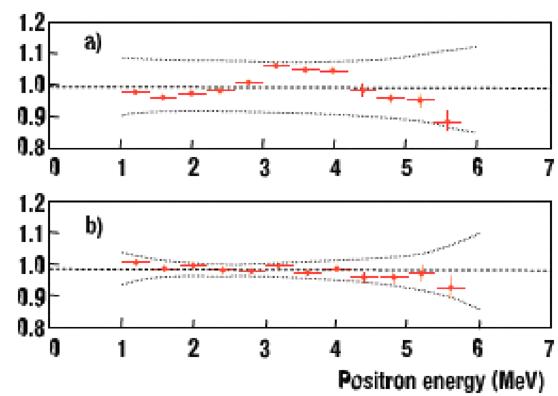
Shape verified by Bugey-3 data
Normalization by Bugey-4, 1.6%

ILL实验（劳厄-朗之万研究所）

- 测量原理:
  - 将核素的薄片样品置入反应堆中接受中子照射(1~2天), 样品裂变发射的电子被高精度谱仪记录.
  - 采用拟合的办法将测量的电子能谱转换成中微子能谱.(假设了20条虚拟的β分支)
- ^{238}U采用Vogel的理论计算.
  - ^{238}U主要由快中子诱发裂变, 堆芯中快中子很少.
  - ^{238}U在堆芯中裂变贡献较少(~10%), 误差影响有限.



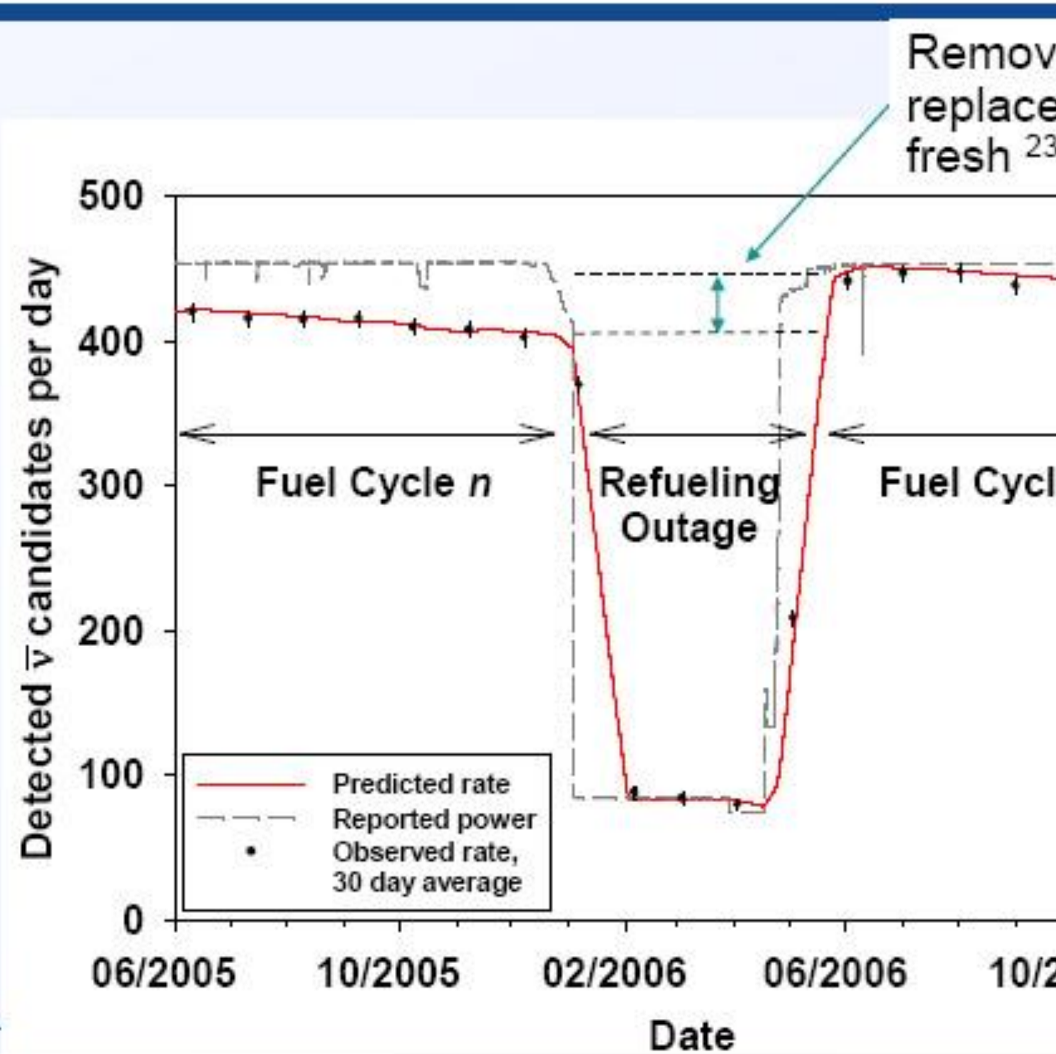
Bugey实验在距离反应堆15米和40米的地方近距离测量反应堆中微子能谱, 利用ILL模型和Vogel计算的^{238}U能谱计算的总中微子能谱和实验结果符合的很好.

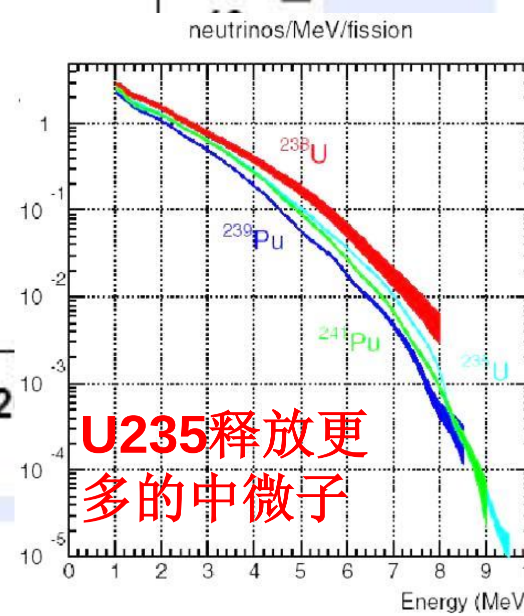


ILL的模型和Bugey实验测量符合最好

反应堆非增殖监测

Long Term Monitoring – Fuel composition





Bowden, LLNL, 2008

Flux Calculation

Neutrino Flux $S(E_\nu) = \sum_i^{isotopes} f_i S_i(E_\nu)$

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

$$W_{th} = \sum_i f_i e_i \; , \qquad F = \sum_i f_i$$

E_ν : Neutrino energy

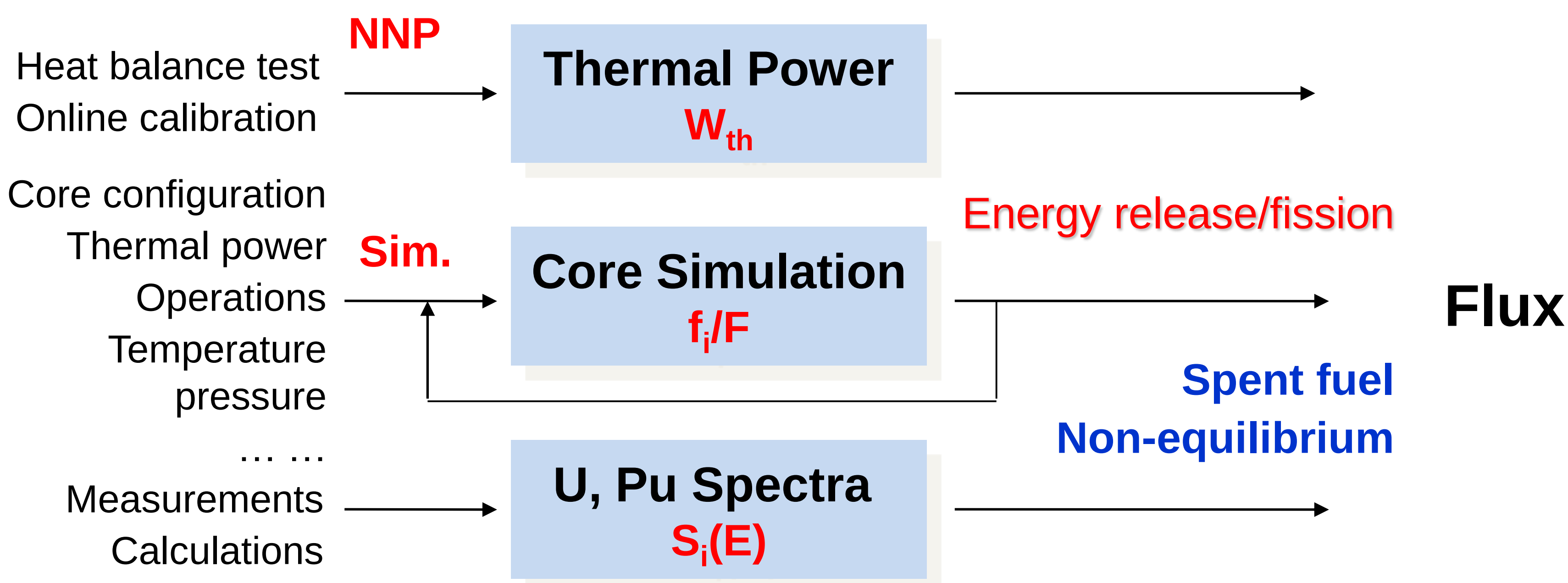
f_i : Fission rate of isotope i

$S_i(E_\nu)$: Neutrino energy spectra/f

(f_i/F): Fission fraction

W_{th} : Reactor thermal power

e_i : Energy release per fission

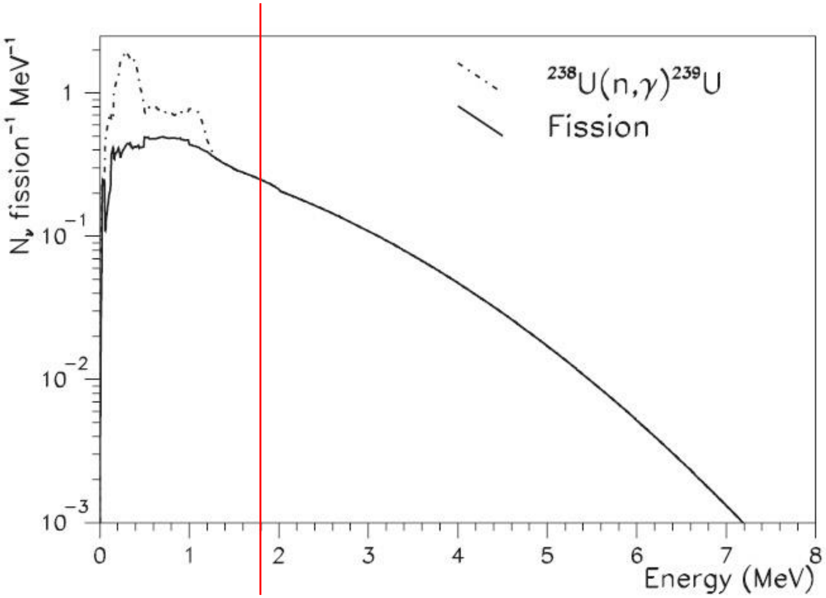


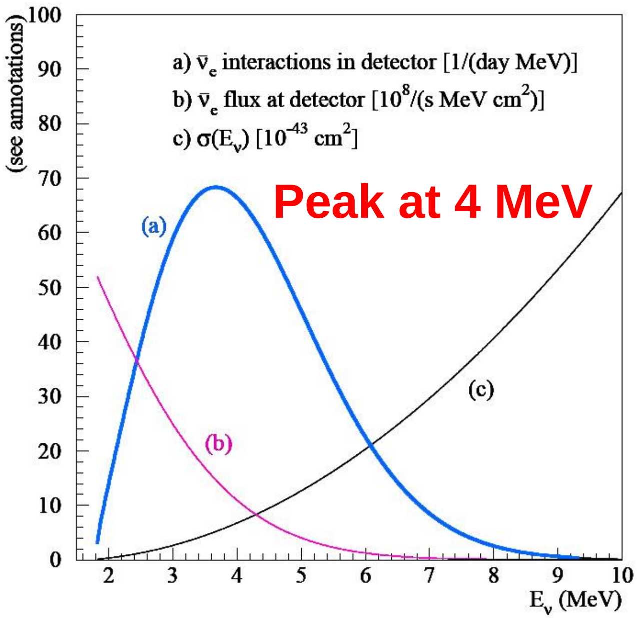
Event Rate

- Back-on-the-envelope: 2.9GW$_{th}$, 200 MeV/fission, 6 ν/fission
  - ⇨ 5.4×10^{20} $\overline{\nu}_e$/s (only 1/3 higher than 1.8 MeV threshold

$$S(E_\nu) = \frac{W_{th}}{\sum_i \left(\frac{f_i}{F}\right) \cdot e_i} \sum_i \left(\frac{f_i}{F}\right) \cdot S_i\,(E_\nu)$$

- IBD event rate at 1 km from reactor
  ~ 1 IBD/(day·ton·GW) → 20 ton × 2.9GW×2/(0.36×0.36km)

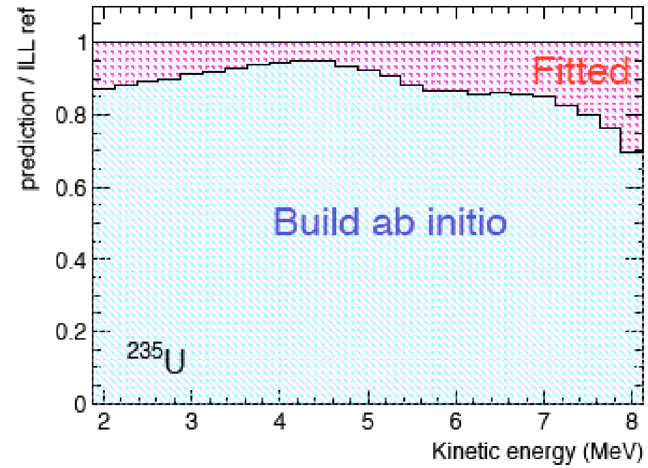




新的中微子能谱

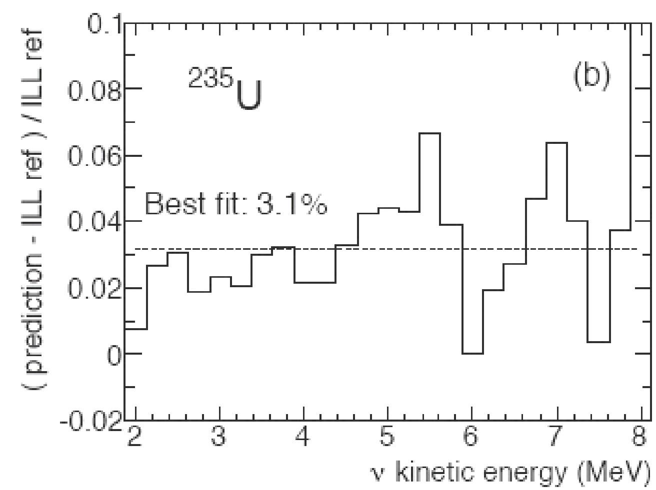
T. Mueller *et al.*, *Phys. Rev. C83, 054615 (2011).*

- 2011年Mueller等人对ILL测量的电子能谱重新进行了先转换.
  - 利用了真实的核数据库计算出绝大部分能谱
  - 剩余的部分按照ILL的办法假设5条虚拟的β分支拟合.
  - 与 P.Huber 的独立计算相符合
- 影响: 所得到的核素裂变中微子能谱比原来ILL的能谱整体抬高~3%, 引起惰性中微子的讨论.



新方法的能谱同ILL能谱的比较

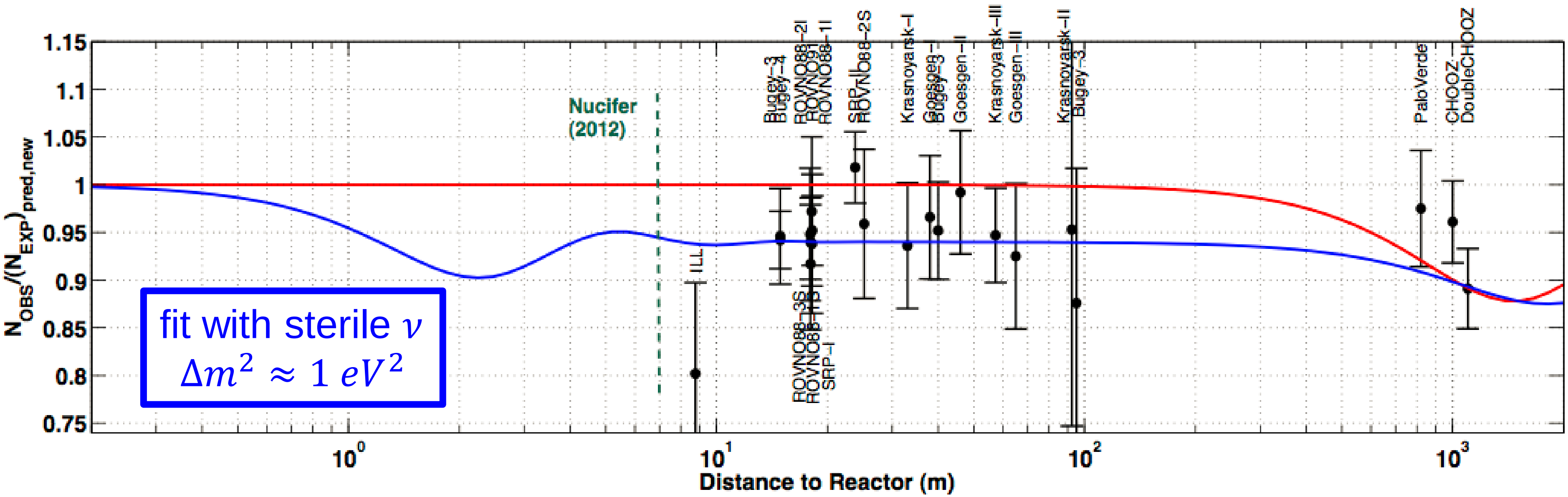
- 对大亚湾实验的影响
  - Rate Analysis: 同时用新能谱和ILL能谱进行能谱预测，不对灵敏度分析产生影响
  - Shape Analysis: 可能会产生影响, 将同时使用两种能谱进行比较.



新的能谱比ILL能谱整体抬高

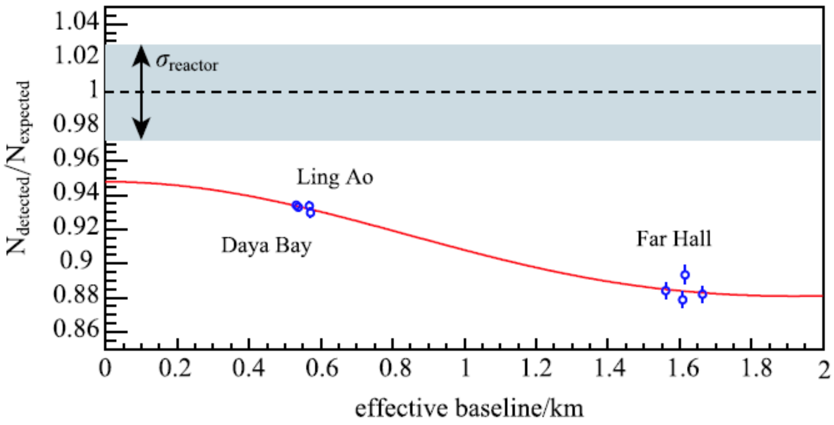
Reactor Anomaly (Rate)

- ILL spectra agree w/ data
- 2011, Huber-Mueller spectra higher than data by 6%
- Sterile neutrino?

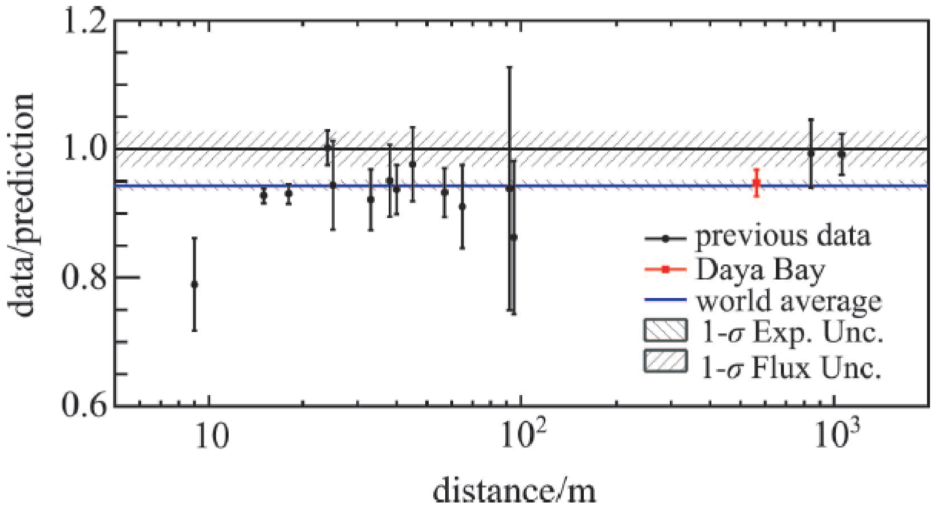


G. Mention et al.
Phys.Rev. D83 (2011) 073006

Daya Bay Absolute Rate Measurement



Chin. Phys. C41, 013002 (2017)



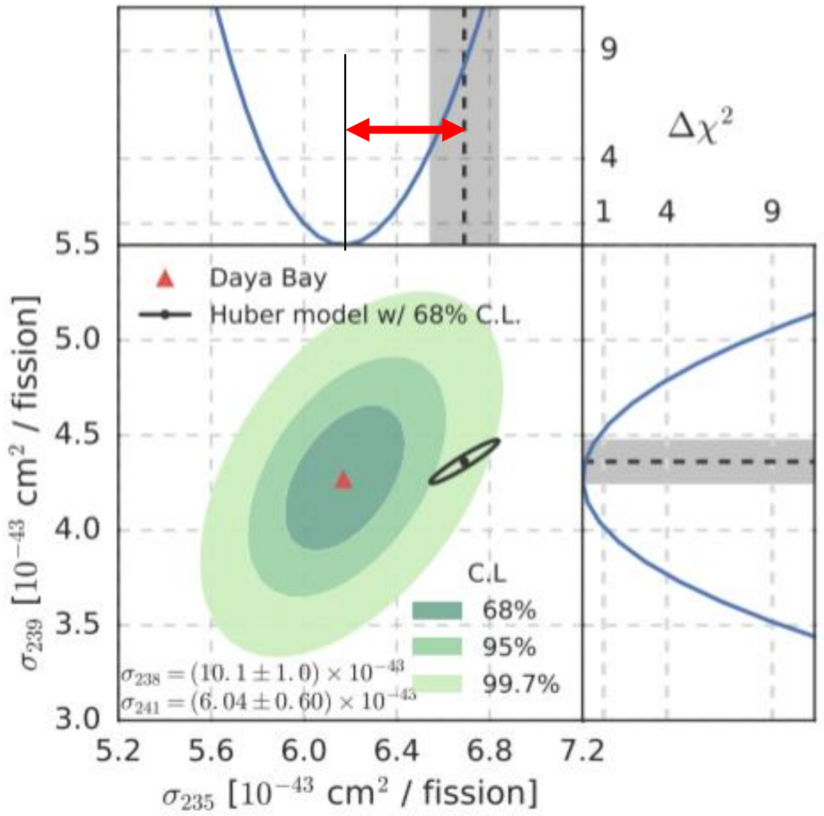
- ⇨ **Data/(Huber+Mueller): 0.946±0.020**
- ⇨ **Past global average: 0.942±0.009**
- ⇨ **Data/(ILL+Vogel): 0.992±0.021**

contribution	uncertainty
statistics	0.1%
oscillation	0.1%
reactor	0.9%
detection efficiency	1.93%
total	2.1%

Special calibration in Jan. 2017

Daya Bay Fuel Evolution

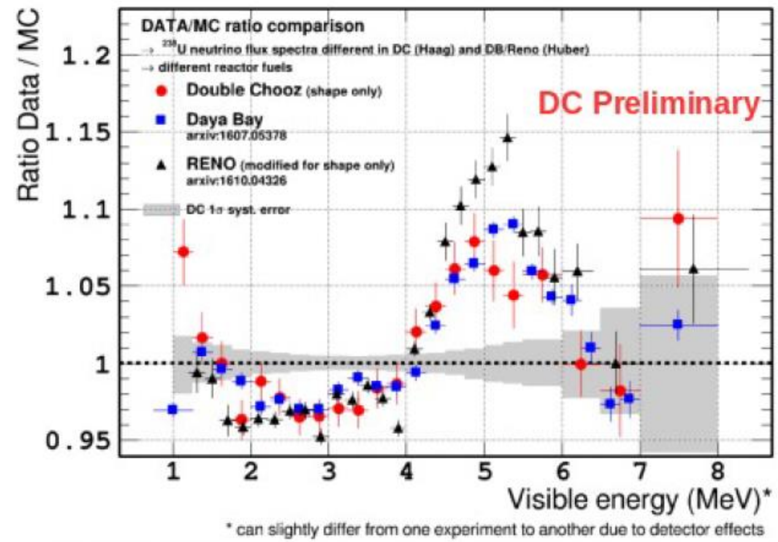
- Combined fit for major fission isotopes ^{235}U and ^{239}Pu
- σ235 is 7.8% lower than Huber-Mueller model (2.7% meas. uncertainty)
- σ239 is consistent with the prediction (6% meas. uncertainty)
- 2.8σ disfavor equal deficit (H-M model & sterile hypothesis)

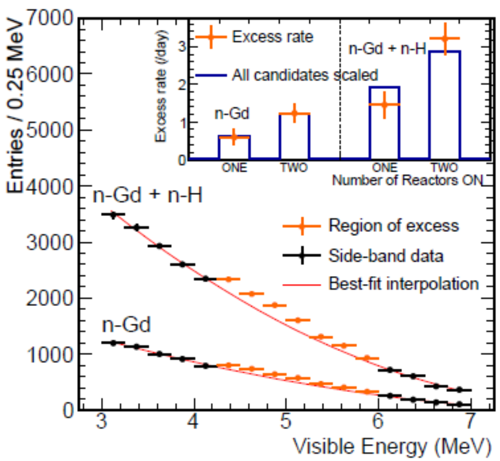


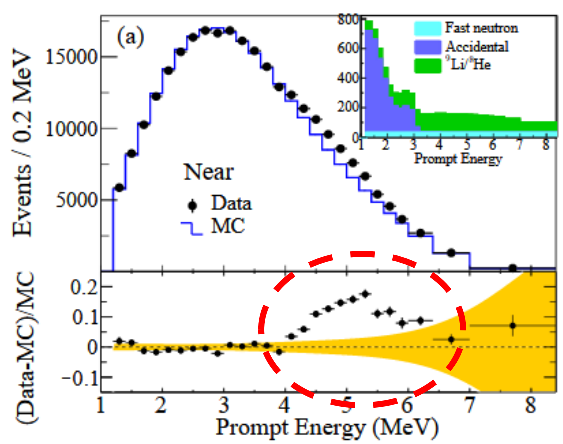
PRL118, 251801 (2017)

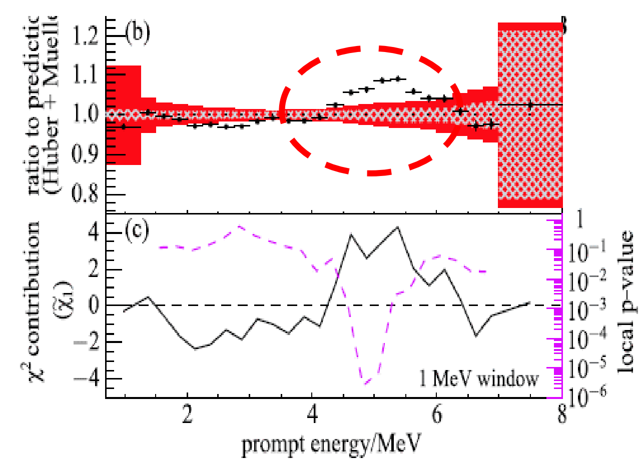
Reactor Anomaly (Spectrum)

- 5 MeV Bump
- Not due to energy non-linearity
- Not due to sterile ν
- Possibly due to forbidden decays (PRL112: 2021501; PRL114:012502)





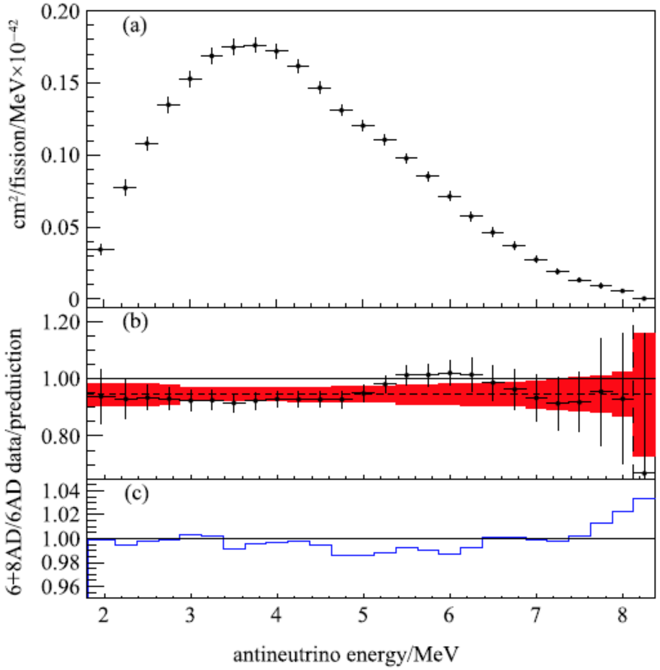


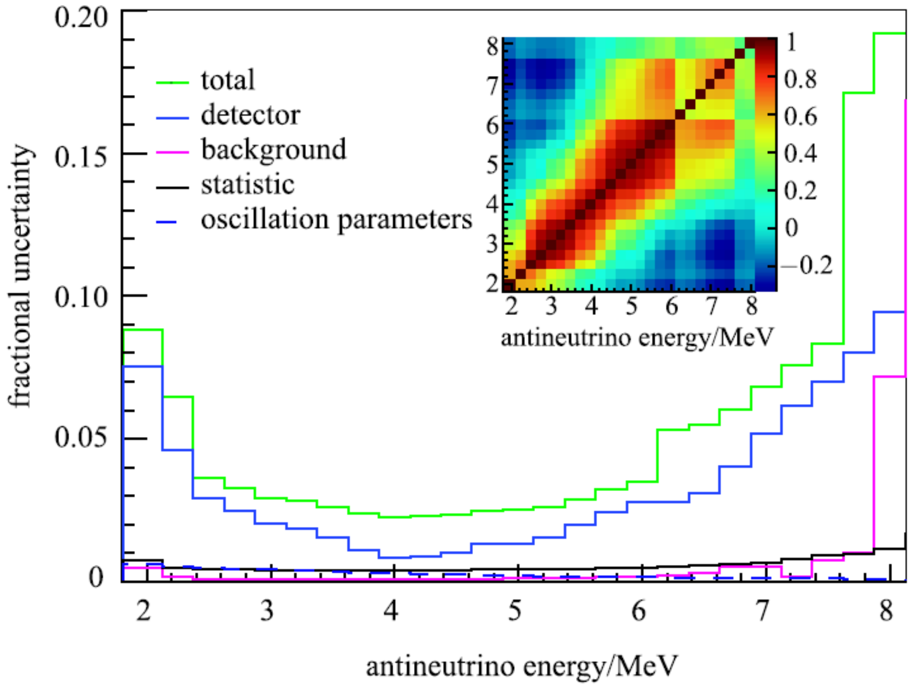


DC, JHEP 1410 (2014) 086 **RENO:arXiv:1610.04326** **Chin. Phys. C41, 013002 (2017)**

Measuring the spectrum

- **Unfolding the reactor neutrino spectrum**
  - ⇨ Between 1.5 and 7MeV: 1.0% at 3.5 MeV, 6.7% at 7 MeV
  - ⇨ Above 7 MeV it is larger than 10%.

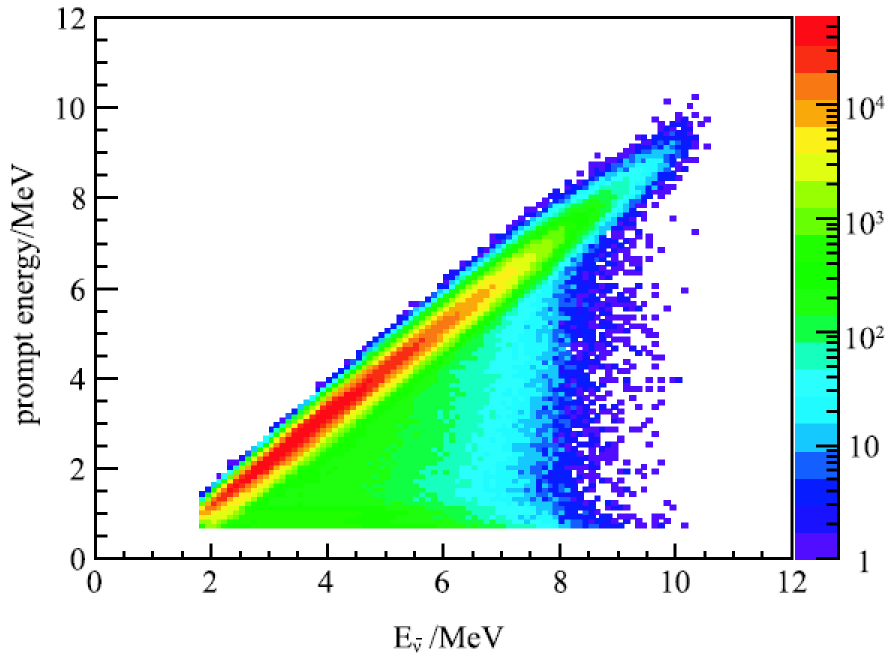




- **New prediction besides *ab initio* method and conversion method**
- **W/ the direct measurement, spectra uncertainty comes mainly from energy non-linearity uncertainty: 1% energy scale → 10% uncertainty in spectrum.**

Unfolding

$$S(E_\mathrm{p}) = \int S(E_{\bar{\nu}_\mathrm{e}}) R(E_{\bar{\nu}_\mathrm{e}}, E_\mathrm{p}) \mathrm{d}E_{\bar{\nu}_\mathrm{e}}$$



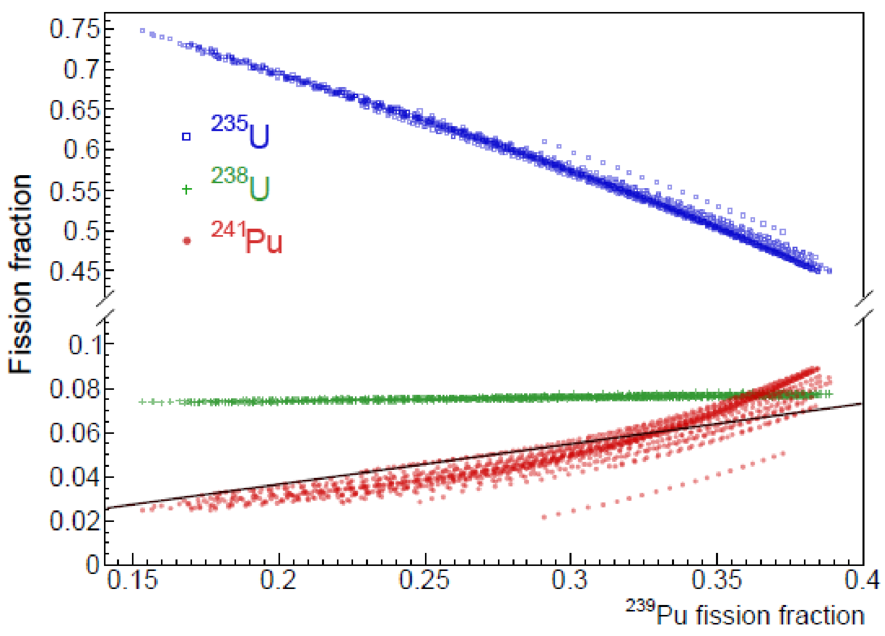
- **SVD方法（矩阵方法）**
- 贝叶斯迭代法

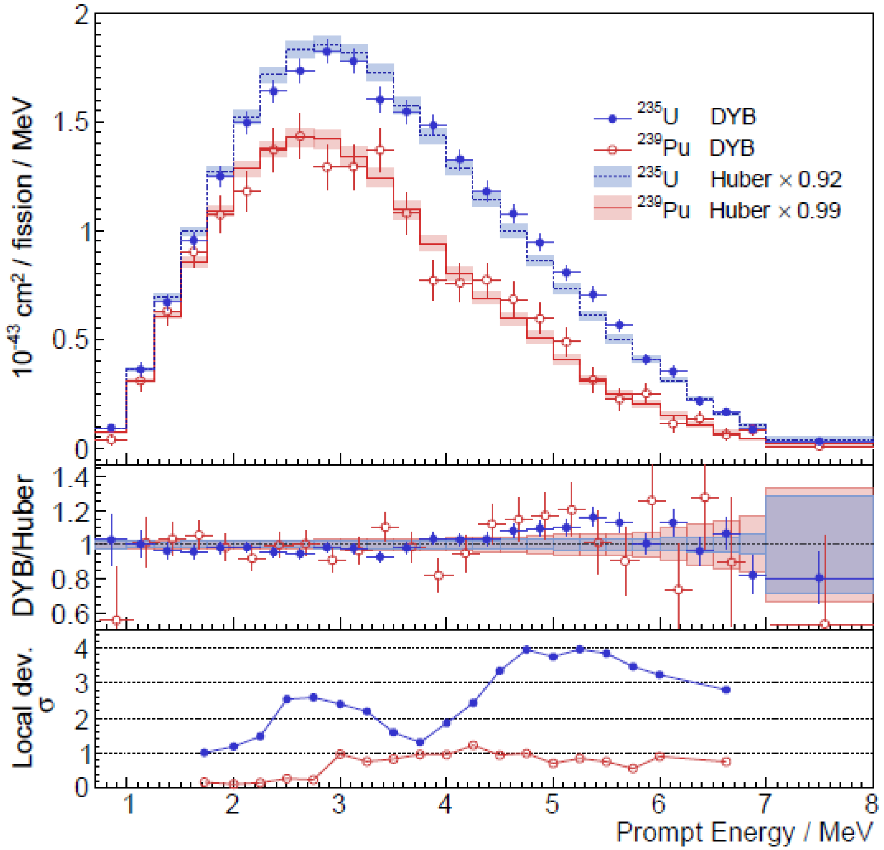
$$\chi^2(x) = (Ax - y)^\mathrm{T} V_y^{-1} (Ax - y) + \tau (Cx)^\mathrm{T} Cx.$$

U235 and Pu239 spectra

$$\chi^2(\eta^5,\eta^9)=2\sum_{djk}(S_{djk}-M_{djk}+M_{djk}\ln\frac{M_{djk}}{S_{djk}})+f(\epsilon,\Sigma),$$

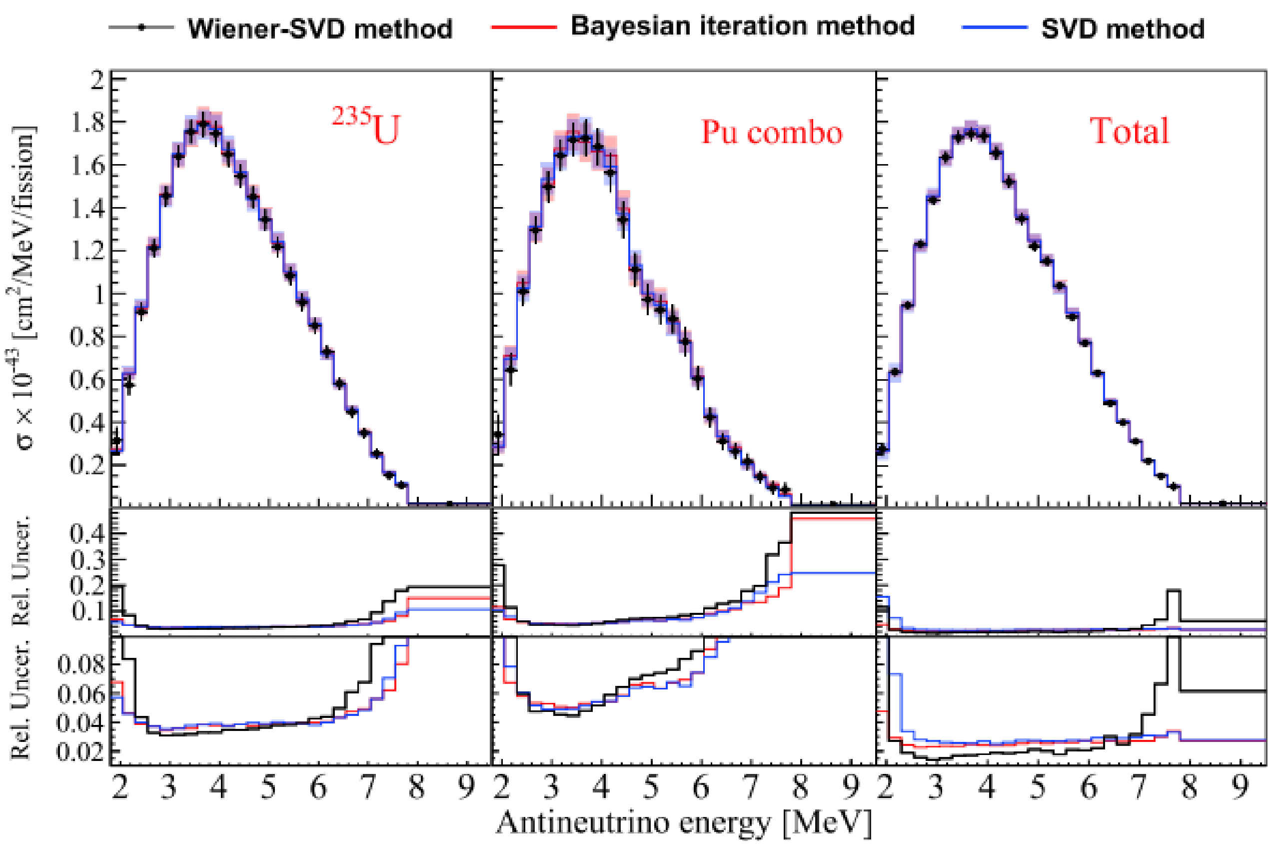
$$S_{djk}=\alpha_k(\epsilon)s_k^5(\eta_k^5)+\beta_k(\epsilon)s_k^9(\eta_k^9)+s_k^{238+241}(\epsilon)+c_k(\epsilon)$$





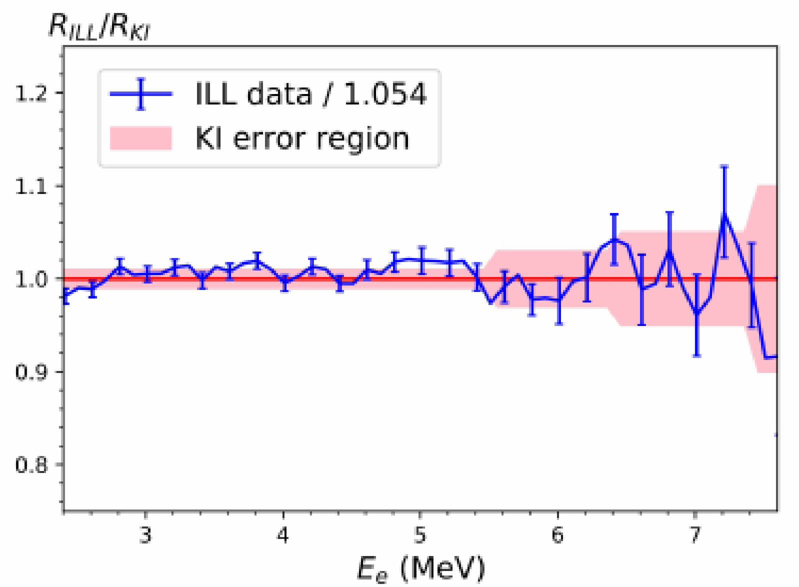
Neutrino spectra

- Antineutrino energy spectrum unfolding based on the Daya Bay measurement and its applications, F. P. An *et al* 2021 *Chinese Phys. C* **45** 073001.



中微子反常问题

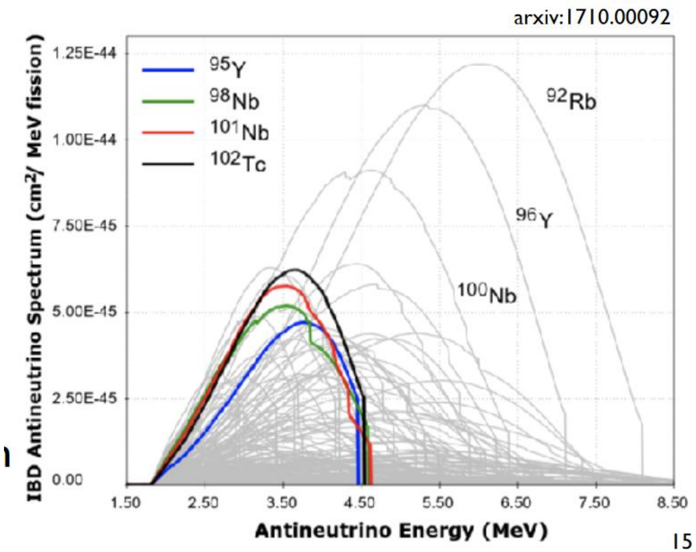
- 事例率反常的可能原因
  - Sterile中微子？基本被排除
  - 流强模型有问题：Kurchatov Institute重新测量U235/Pu239电子谱，解释了U235事例率反常，arXiv:2103.01684

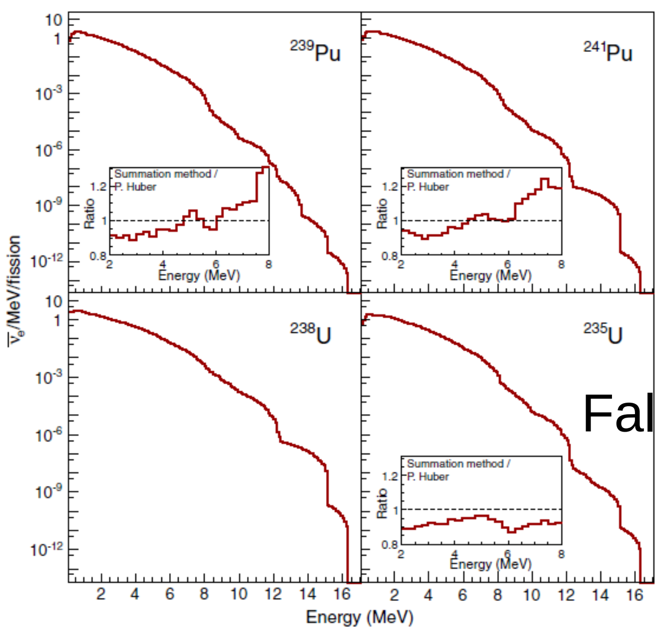


- 能谱反常现象
  - 能谱模型有问题，误差低估，中心值不对。
  - 5 MeV bump还没有解释。

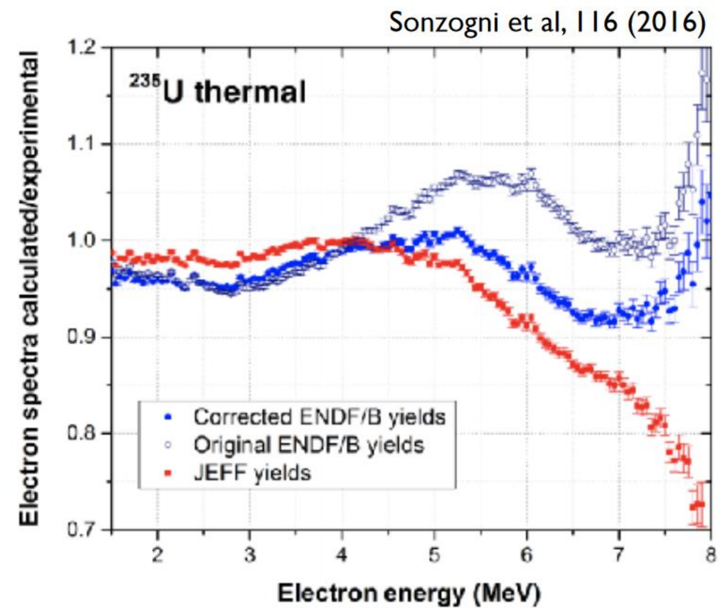
Ab-initio method

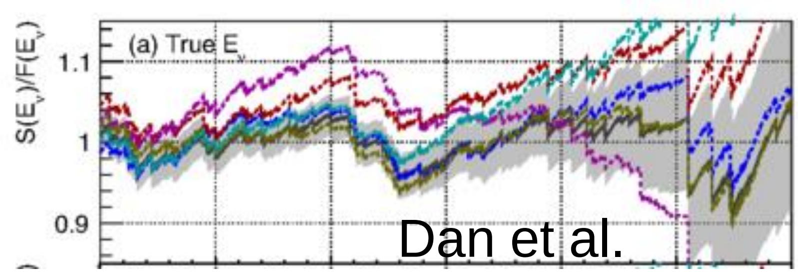
- 有希望发现反常的原因，哪些核素贡献？
- 全吸收谱仪重新测量beta谱=>更新数据库
- 但是不同组算的结果得不出一致的结果。





Fallot et al.



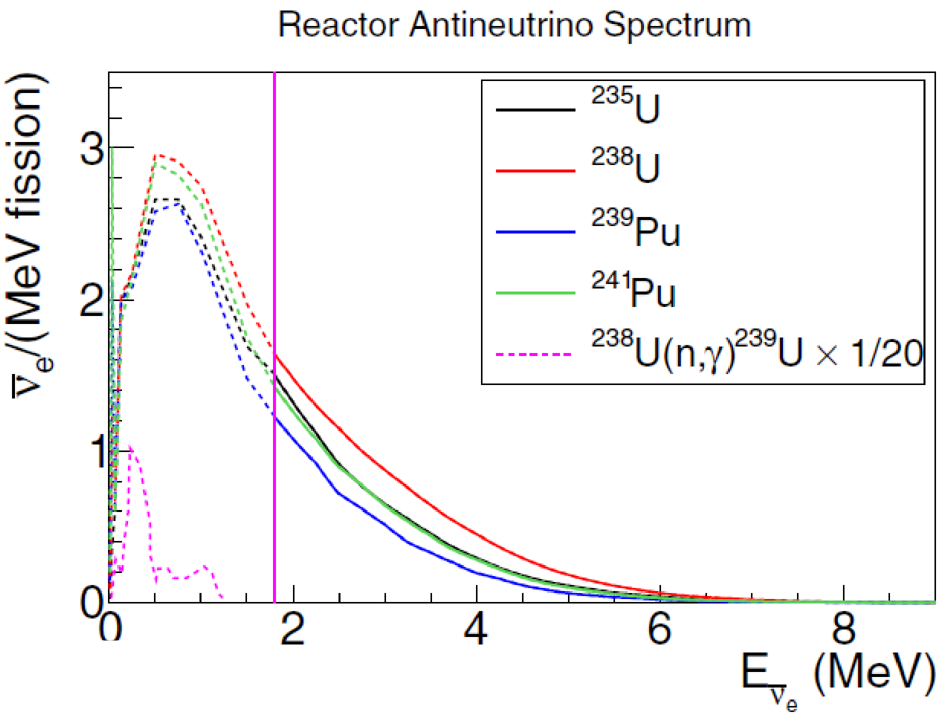


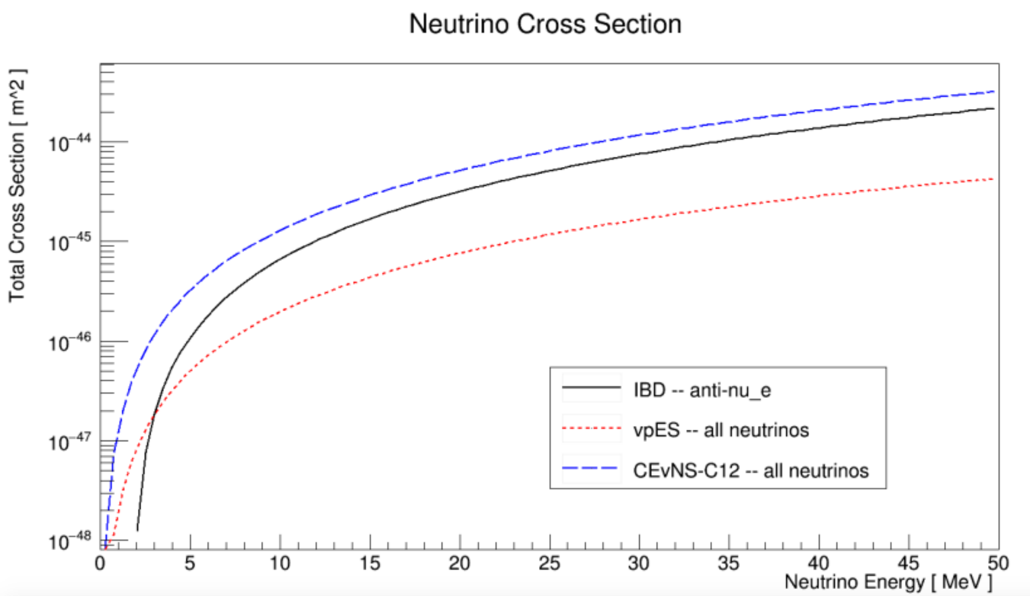
Dan et al.

其他方法测量能谱

◆ 中微子散射

- IBD ， $\bar{\nu}_e + p \longrightarrow e^+ + n$
- νpES ， $\nu + p \longrightarrow \nu + p$
- νeES ， $\nu + e^- \longrightarrow \nu + e^-$

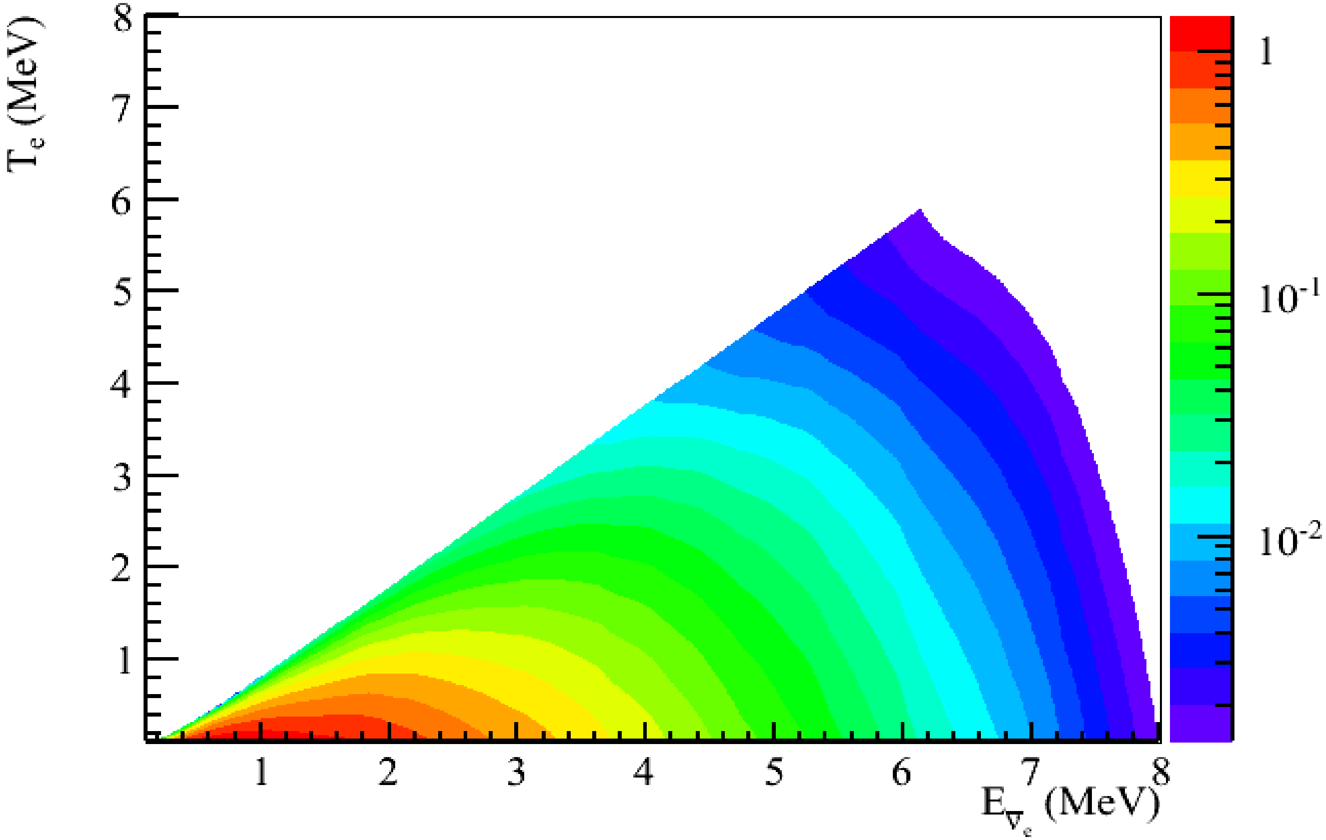




- 可以低于1.8 MeV IBD阈值
- 反应截面大

电子散射

- 确定中微子能量需要：散射角，电子动能
- 只有一部分能量传递给电子动能
- 本底鉴别比IBD事例更难



Precision Spectrum with Gas TPC

- **How to reach 1% spectrum uncertainty?**
- **Improving Daya Bay**
  - **Electronics non-linearity**
    - 192 channels Flash ADC for AD1. Data taking completed.
  - **Liquid scintillator non-linearity**
    - Replaced LS in AD1 for JUNO R&D

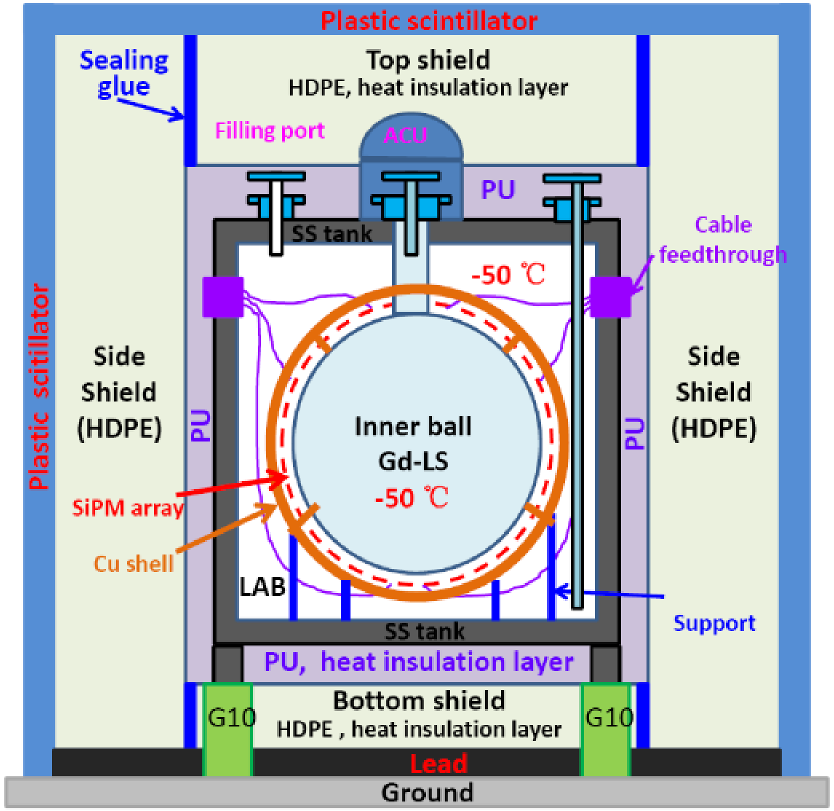
      → Consequence: Daya Bay from 8 AD to 7 AD since Dec. 2016
    - Testing detector responses with 13 different LS configurations (PPO from 0.5g/L to 4g/L, bis-MSB from 0.1-15 mg/L)

      → Building precision Monte Carlo
  - **Relative meas. to cancel non-linearity btwn Daya Bay and JUNO**
- **Gas TPC detector at ~20 m from a reactor (Prototyping at IHEP)**
  - **ν-e scattering**
  - **High energy resolution (1%/sqrt(E), Daya Bay 8%, JUNO 3%)**
  - **Other motivations: θw, abnormal magnetic moment (to 10^{-12})**

台山中微子实验

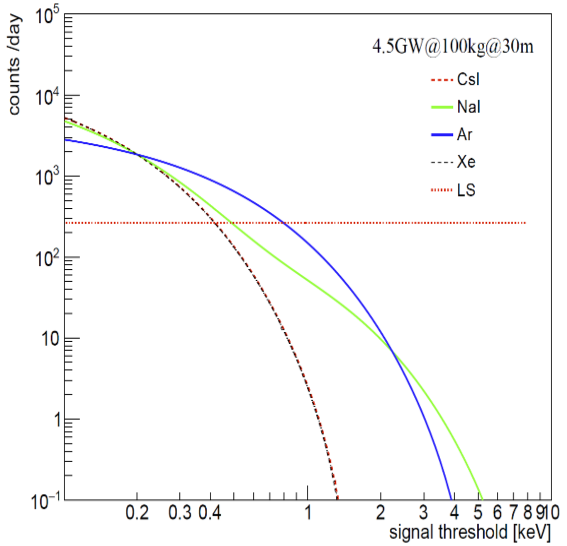
- **JUNO-TAO：液闪实验**
  - 追求液闪实验最高能量分辨率，为JUNO提供参照能谱输入。
  - SiPM高量子效率，低温探测器

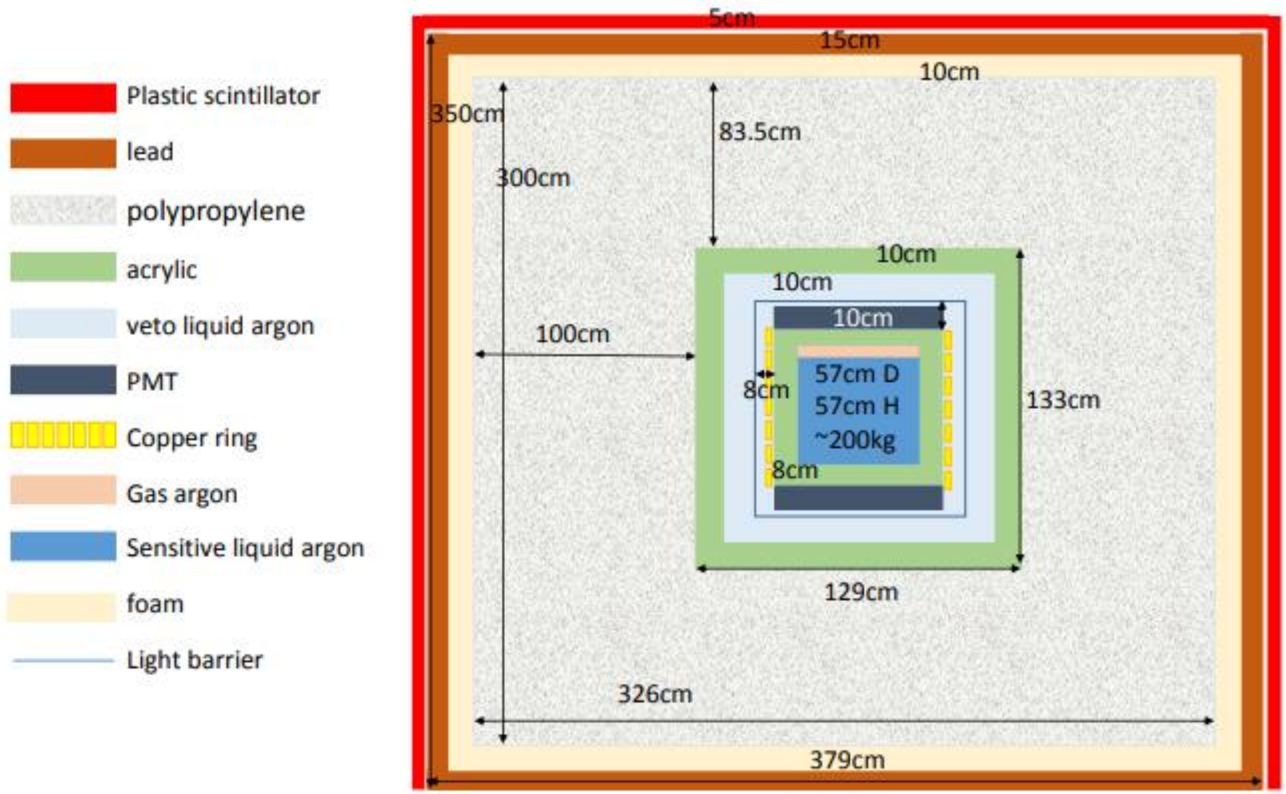
Compare w/ JUNO	1200pe/MeV
Cov. 75%→100%	X 1.33
PDE 27% → 50%	X 1.85
LS temp. at -50℃	X 1.25
Less absorption	X 1.4
1.4% photo-statistics	X4.3



JUNO-TAO CDR arXiv:2005.08745

◆ 两相氩相干散射实验


4.5GW@100kg@30m
CsI
NaI
Ar
Xe
LS
counts /day
signal threshold [keV]


Plastic scintillator
lead
polypropylene
acrylic
veto liquid argon
PMT
Copper ring
Gas argon
Sensitive liquid argon
foam
Light barrier
5cm
15cm
10cm
350cm
83.5cm
300cm
10cm
10cm
10cm
100cm
8cm
57cm D
57cm H
~200kg
8cm
133cm
129cm
326cm
379cm

3 – Natural Radioactivity

天然放射性

- 天然放射性无处不在，例如：
  - ⇨ ^{238}U (^{222}Rn，^{210}Pb来历) 岩石、土壤、空气
  - ⇨ ^{232}Th

  有灰尘的地方就会有以上两种放射性
  - ⇨ ^{40}K （玻璃、人体～5000Bq）
- 宇生放射性 ^{14}C测定年代
- 人工放射性，例如：
  - ⇨ ^{60}Co （不锈钢、育种、刻度源）
  - ⇨ ^{137}Cs （水、刻度源）

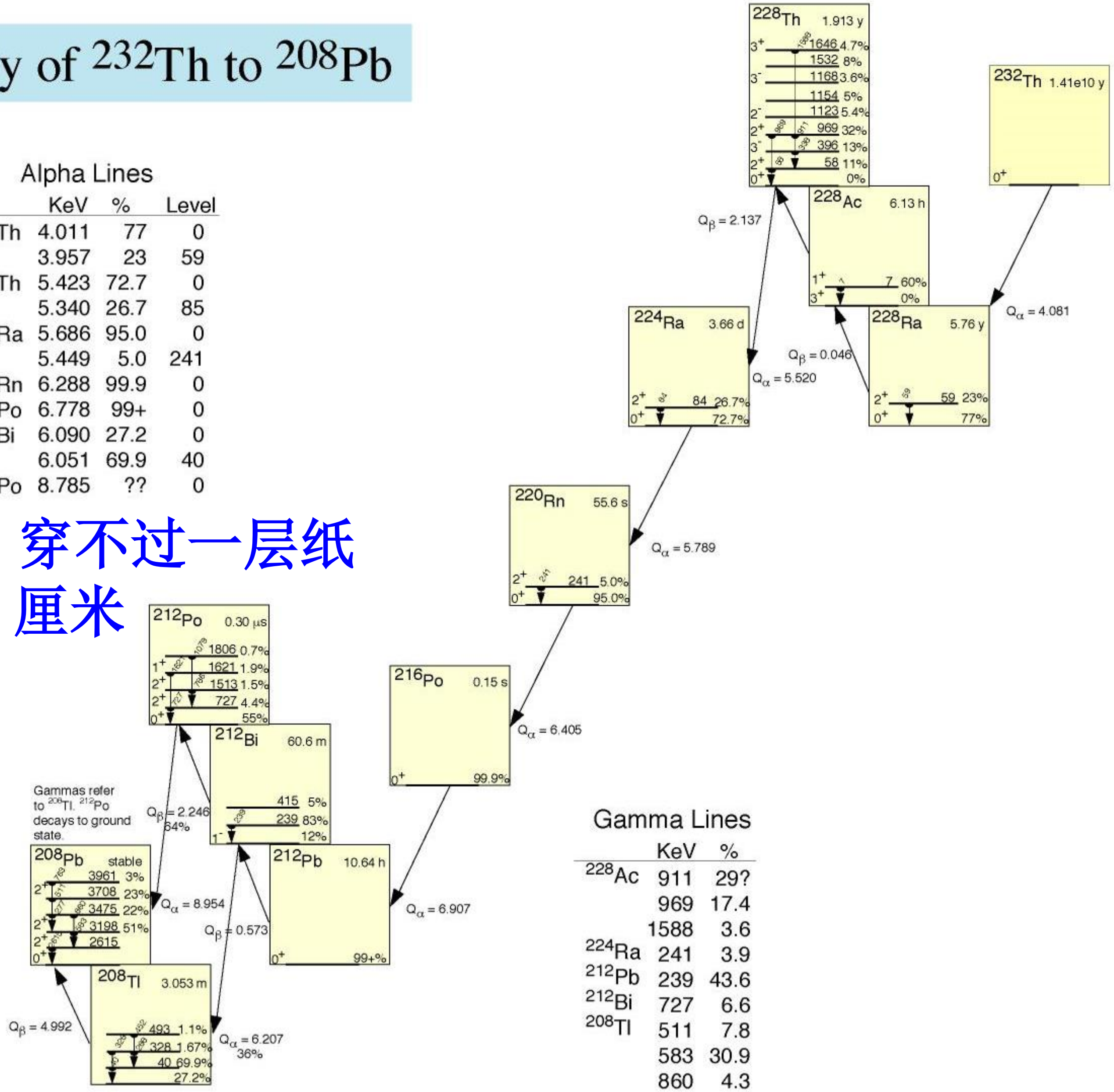
Decay of ^{232}Th to ^{208}Pb

Alpha Lines

	KeV	%	Level
^{232}Th	4.011	77	0
	3.957	23	59
^{228}Th	5.423	72.7	0
	5.340	26.7	85
^{224}Ra	5.686	95.0	0
	5.449	5.0	241
^{220}Rn	6.288	99.9	0
^{216}Po	6.778	99+	0
^{212}Bi	6.090	27.2	0
	6.051	69.9	40
^{212}Po	8.785	??	0

α粒子：穿不过一层纸

β射线：厘米



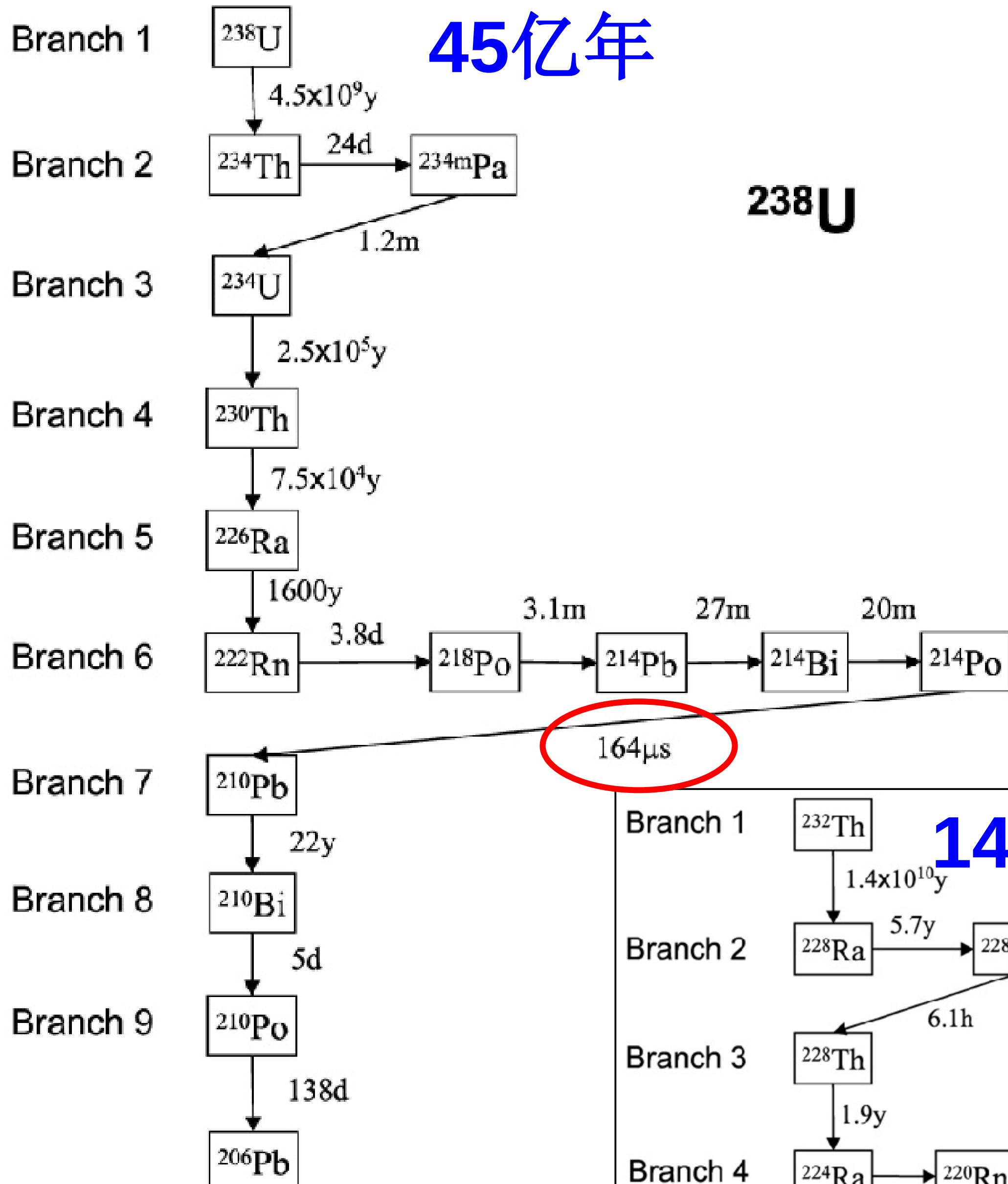
Gamma Lines

	KeV	%
^{228}Ac	911	29?
	969	17.4
	1588	3.6
^{224}Ra	241	3.9
^{212}Pb	239	43.6
^{212}Bi	727	6.6
^{208}Tl	511	7.8
	583	30.9
	860	4.3
	2615	35.9

γ射线：衰减长度20 cm水

U、Th衰变链

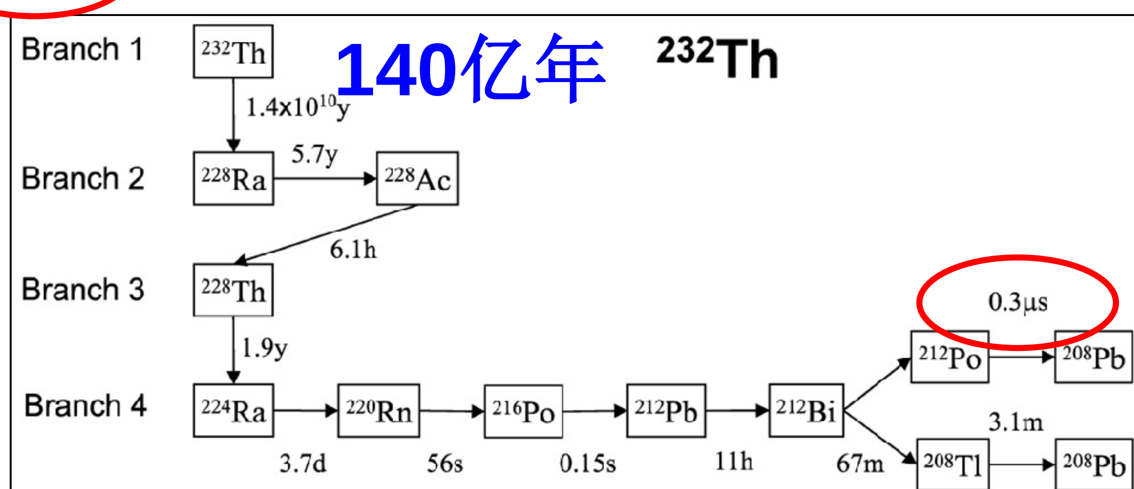
45亿年



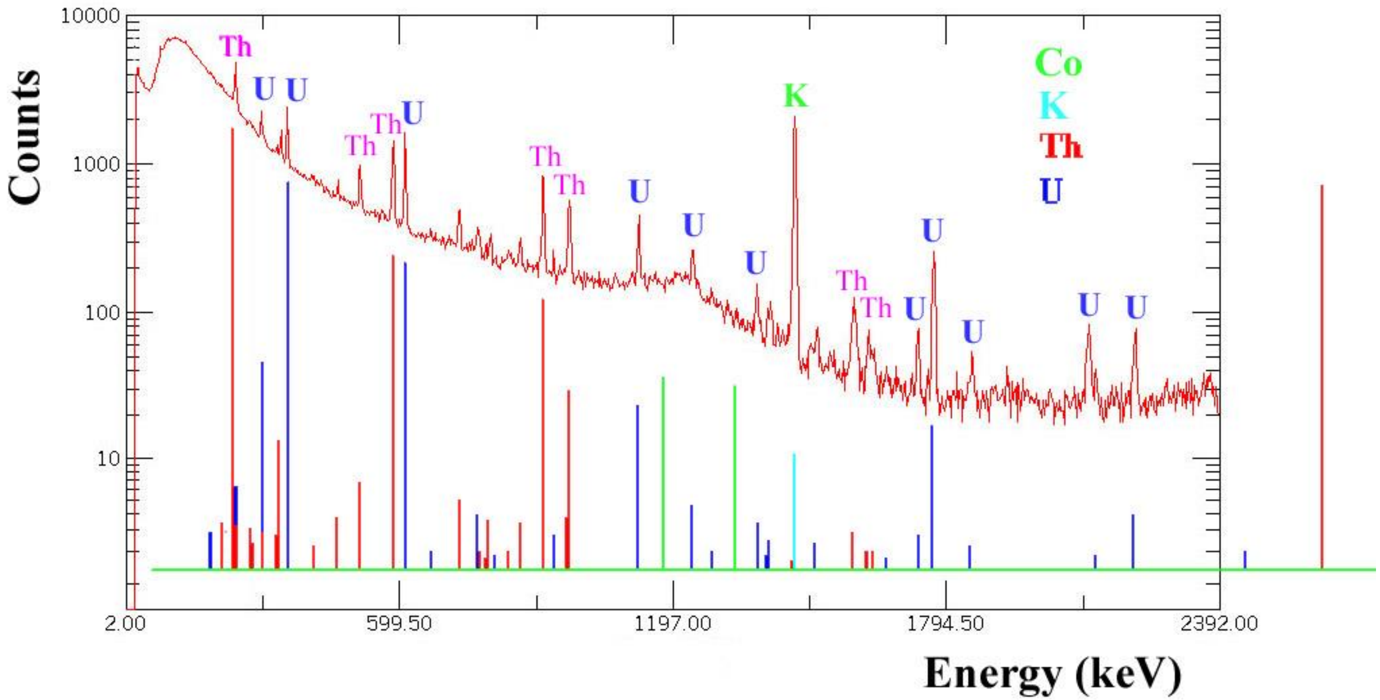
^{238}U

- 平衡态
- 非平衡态
  - ⇨ 纯化光除U、Th不够，还需要除掉Ra
  - ⇨ Pb-210（老铅）
- 级联衰变 (Cascade)
- 模拟的产生子

140亿年 ^{232}Th



大亚湾花岗石伽马谱



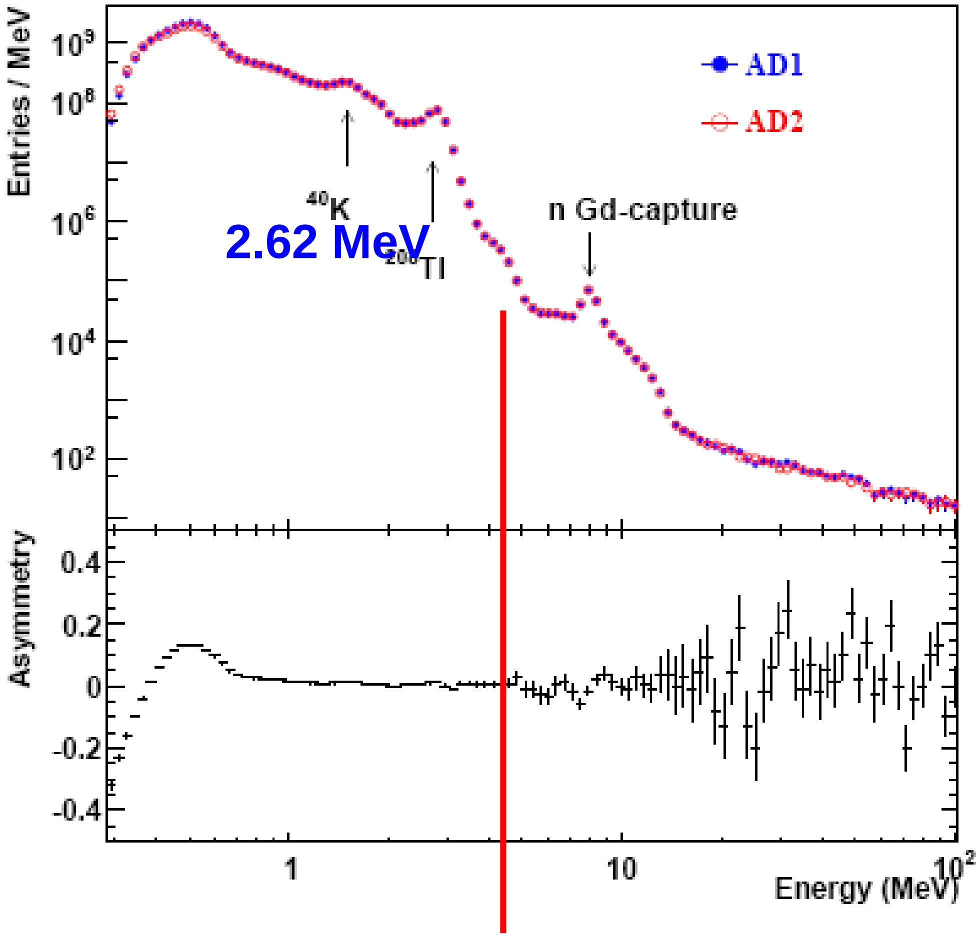
- 贝克（Bq）：每秒一次衰变
- 居里（Ci）：3.7×10^{10} Bq，微居=安全，毫居=小心，居里=致命
- ppm, ppb：
  - ⇨ 1 ppb 40K = 258.4 mBq/kg
  - ⇨ 1 ppb 238U = 12.4 mBq/kg
  - ⇨ 1 ppb 232Th = 4.0 mBq/kg

- 花岗石（火成岩）是放射性比较高的岩石；大亚湾花岗石是世界平均值的3倍：
- 10 ppm U
- 30 ppm Th
- 5 ppm K40

Where the radioactivities come from?

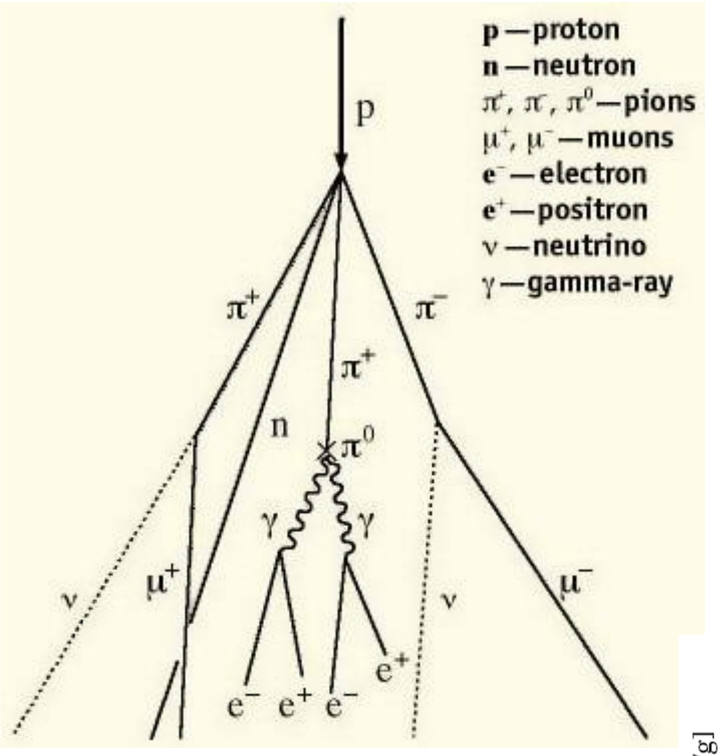
- 大亚湾花岗石放射性较高
  - **8.8ppm U, 28.7ppm Th, 4.5ppm K**
  - **~ 20 Hz 单事例率（2米水，0.45米油）**
- 氡气（铀的衰变产物，从石缝逸出）
  - 液闪存储、探测器运行时需要流氮
- **PMT**玻璃，不能与液闪接触，找低本底玻璃
- 钢罐材料，需选低本底钢材
- 不能用铝（摄像头）、玻璃（全反射镜）等
- 所有探测器材料，特别是与液闪接触的，必须进行低本底测量。
- 探测器安装在清洁间中进行（万级）防灰尘

- Why Daya Bay dope Gadolinium into LS?
- Why JUNO will not dope Gadolinium into LS?



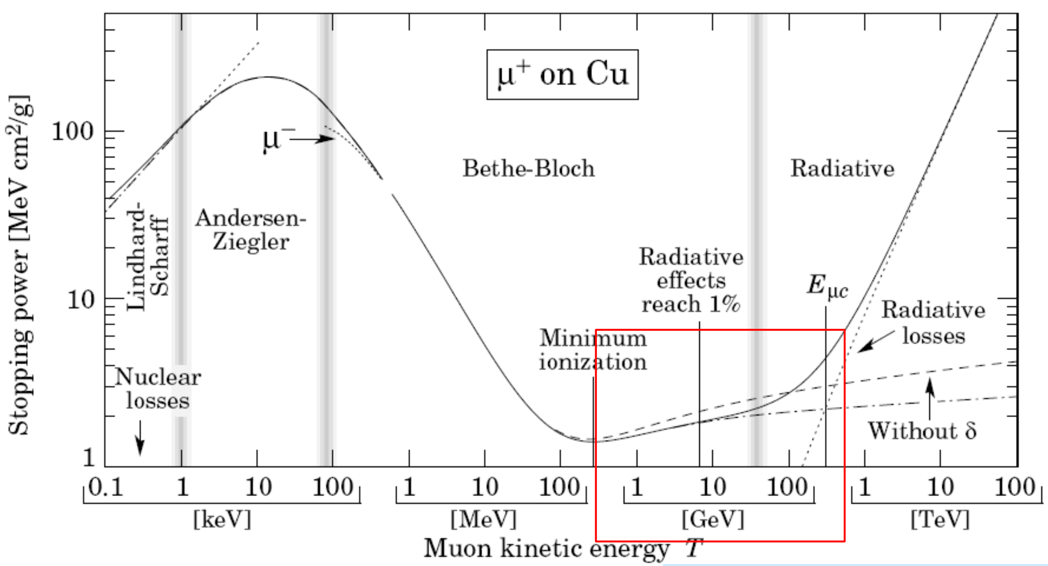
4 – Cosmic Muon

Cosmic Muon



μ Flux on surface ~ 200Hz/m^2

Minimum ionization muon: ~200MeV/m.w.e.

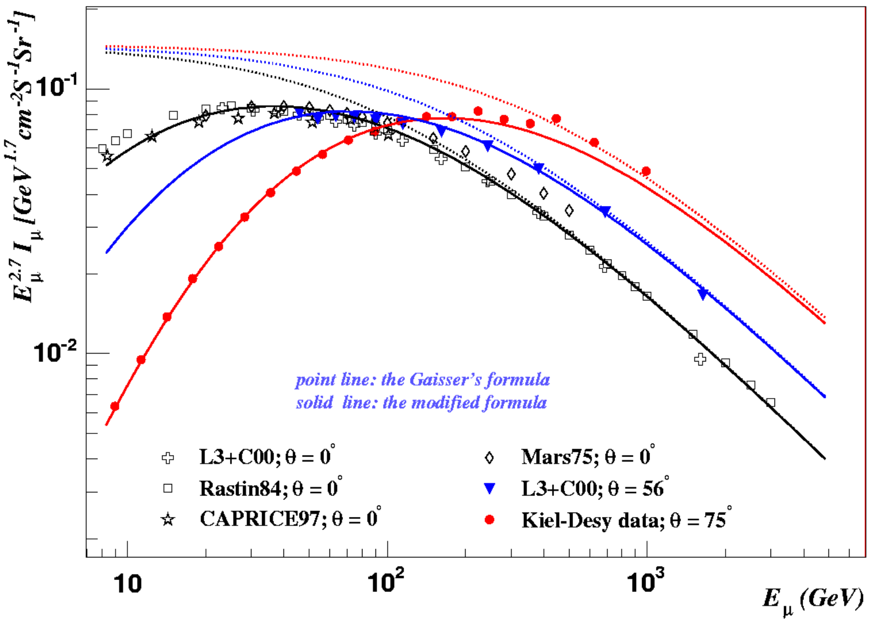


Muon Flux

- **Muon on surface: Gaisser formula**

$$\frac{dI_\mu}{dE_\mu d\cos(\theta)} = 0.14\left(\frac{E_\mu}{GeV}\right)^{-2.7}\left[\frac{1}{1+\frac{1.1E_\mu\cos(\theta)}{115GeV}} + \frac{0.054}{1+\frac{1.1E_\mu\cos(\theta)}{850GeV}}\right]$$

$$\frac{dI_\mu}{dE_\mu d\cos(\theta)} = 0.14\left(\frac{E_\mu}{GeV}(1+\frac{3.64GeV}{E_\mu[\cos(\theta^*)]^{1.29}})\right)^{-2.7}\left[\frac{1}{1+\frac{1.1E_\mu\cos(\theta^*)}{115GeV}} + \frac{0.054}{1+\frac{1.1E_\mu\cos(\theta^*)}{850GeV}}\right]$$



Modified Gaisser formula

More precise flux need simulation (Earth Magnetic field)

Muon Energy Loss

- **Continuous process —— Ionization energy loss**

$$\frac{dE}{dx} \approx -[1.9 + 0.08ln(\frac{E_\mu}{m_\mu})]$$

- **Discrete process ——Bremsstrahlung, pair production, hadron process, important for high energy muon**

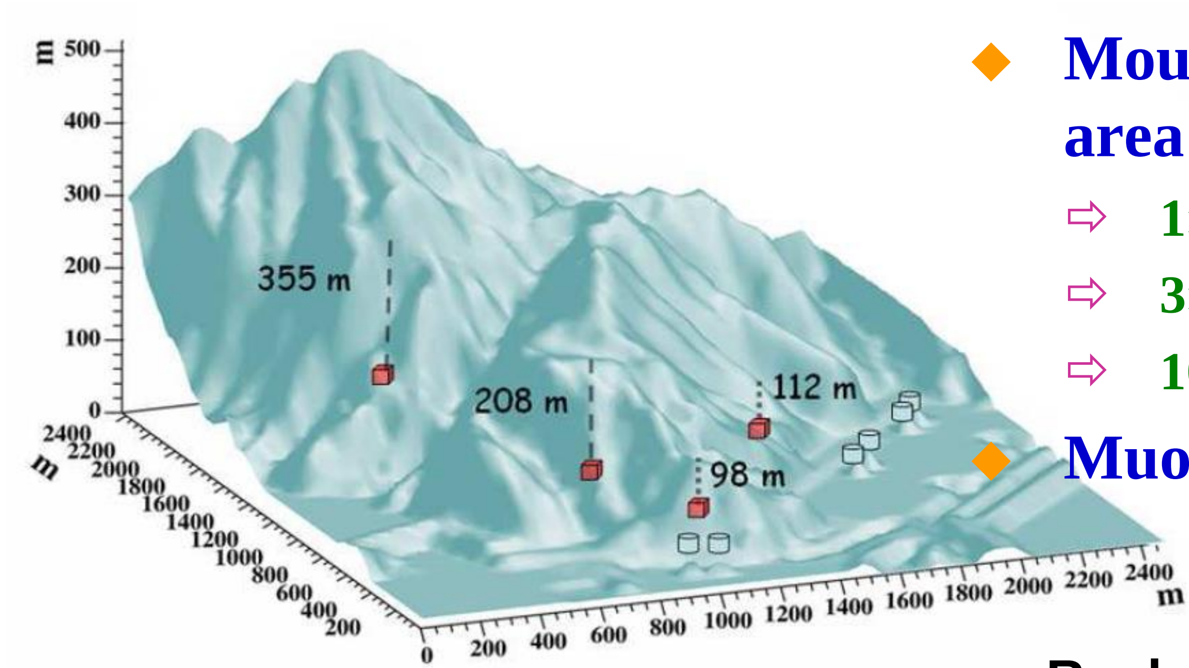
$$\frac{dE}{dx} = -\frac{E_\mu}{\xi}$$ 在岩石中，$\xi \approx 2.5 \times 10^5 g \cdot cm^{-2}$,

- **Minimum muon energy to pass x_{min} thick rock**

$$E_0^{min} = \epsilon \left(e^{\frac{x_{min}}{\xi}} - 1 \right)$$

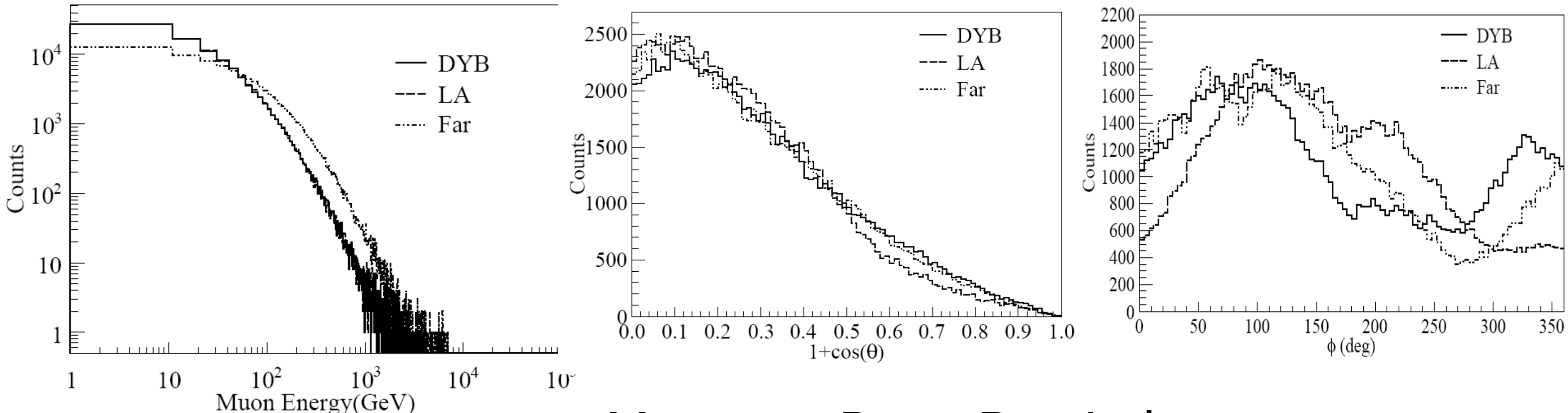
ε=500GeV, the energy at which the continuous process has equal contribution to discrete process

Propagate Muon to Underground Lab



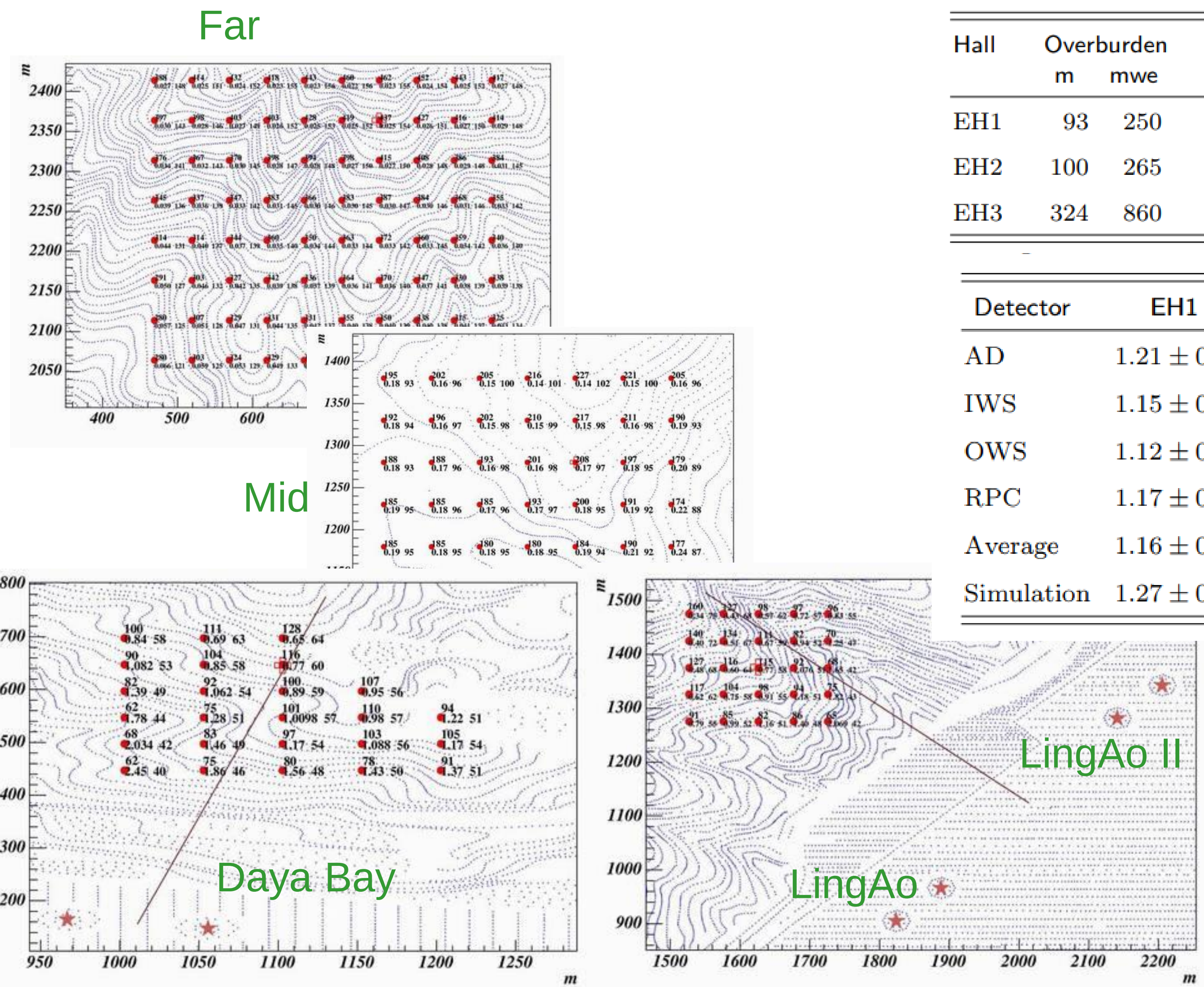
- **Mount map of Daya Bay area**
  - 1×2 km high precision (1m)
  - 3×4 km 1:5000 map (5m)
  - 10×10 km SRTM map
- **Muon propagation software:**
  MUSIC, FLUKA

Rock density: ~2.6 g/cm^3



Muons at Daya Bay Lab

Muon Simulation



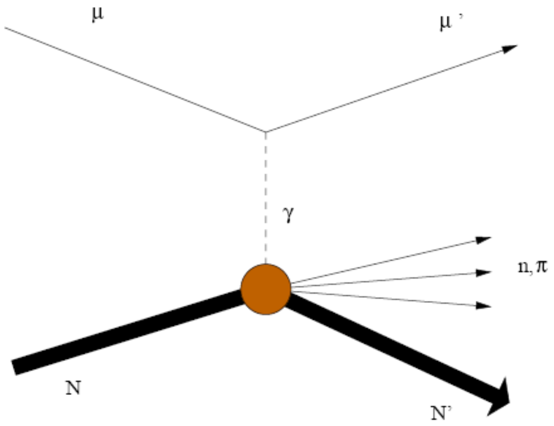
Hall	Overburden m	Overburden mwe	Muon flux Hz/m^2	Average Energy GeV
EH1	93	250	1.27	57
EH2	100	265	0.95	58
EH3	324	860	0.056	137

Detector	EH1	EH2	EH3
AD	1.21 ± 0.12	0.87 ± 0.09	0.056 ± 0.006
IWS	1.15 ± 0.12	0.86 ± 0.09	0.055 ± 0.005
OWS	1.12 ± 0.11	0.84 ± 0.08	0.053 ± 0.005
RPC	1.17 ± 0.09	0.87 ± 0.11	0.053 ± 0.006
Average	1.16 ± 0.11	0.86 ± 0.09	0.054 ± 0.006
Simulation	1.27 ± 0.13	0.95 ± 0.10	0.056 ± 0.006

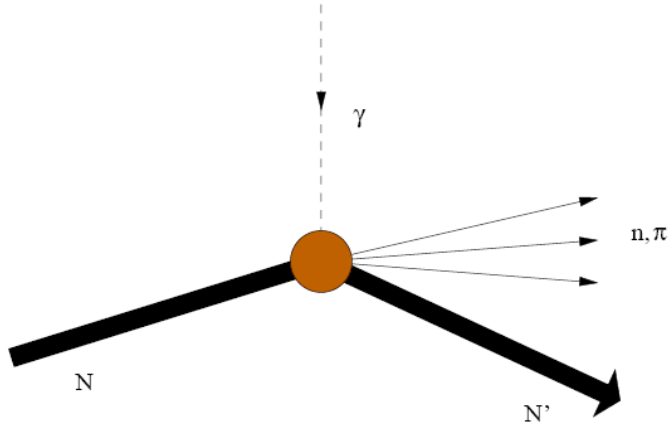
NIMA 773 (2015) 8-20

Spallation Neutron

muon Spallation



Gamma-N



- 中子可打出次级中子
- muon在核上俘获产生中子（低能）

◆ **Cosmogenic neutron is one of the most important bkg**

◆ **Neutron yield**

$$N_n = 4.14 E_\mu^{0.74} \times 10^{-6}\ neutron/(muon \bullet g/cm^2)$$

Y.F. Wang et al

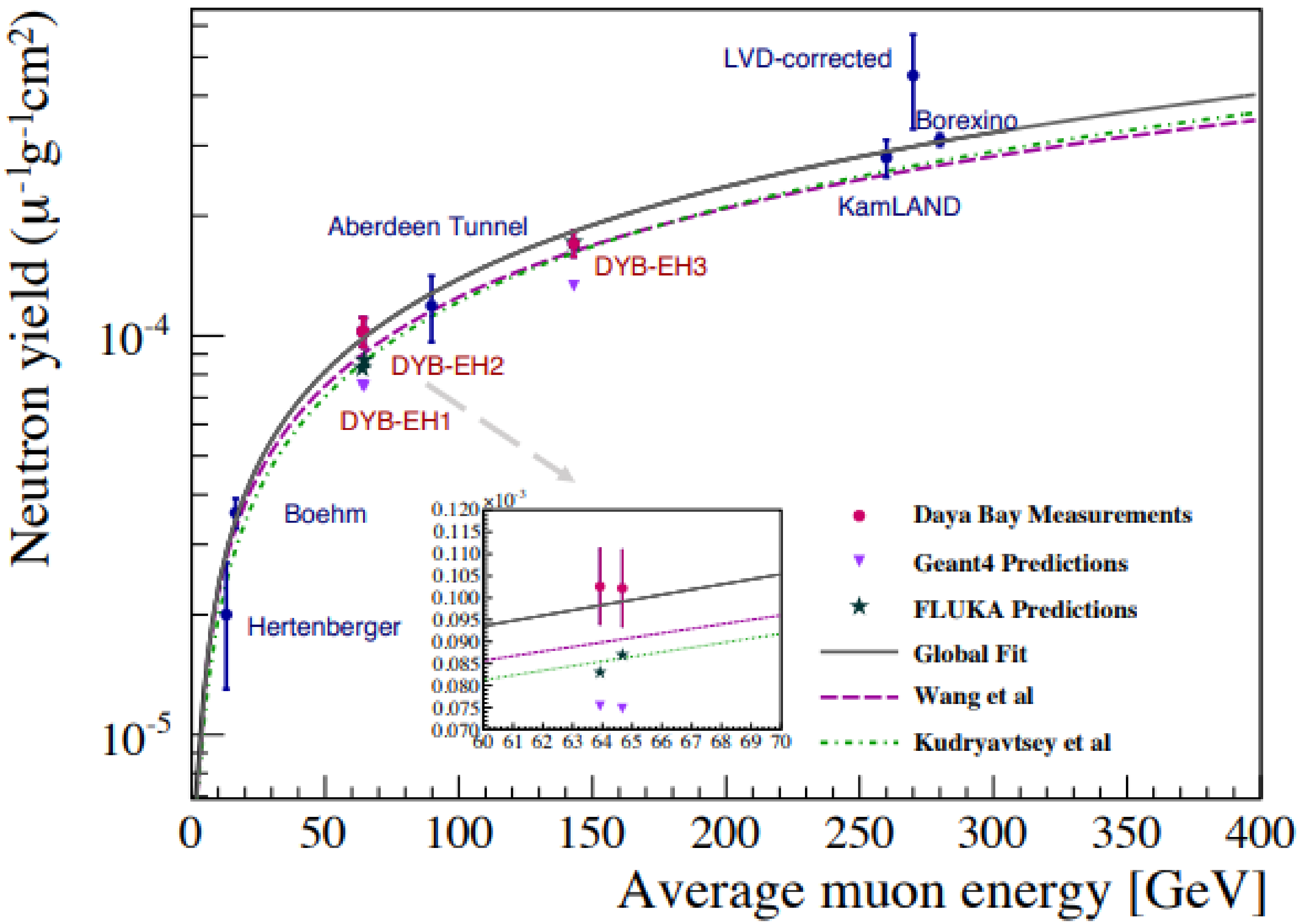
（当物质密度为1 g/cm^{3}时）每个muon经过1cm产生的中子数（中子的海洋）

◆ **Neutron density at Daya Bay near (far) site**

0.03（0.001） neutron/m^3/sec

Neutron yield

- Cosmogenic neutron production at Daya Bay, *Phys.Rev.D* 97 (2018) 5, 052009



Muon capture on nuclei

- **Stopping muon: $\mu \to e + \nu$, Michel e, lifetime 2.19703 μs**
- **Form a μ^- molecule, then decay $\mu^- \to e^- + \bar{\nu}$, or capture on nuclei.**

$$\mu^- + p \rightarrow \nu_\mu + n$$

$$\mu^- + ^{12}C \rightarrow \nu_\mu + ^{12}B^*$$

元素	μ^- 寿命 (ns)	核俘获率 (s^{-1})	核俘获过程几率 (%)	平均中子个数 (/反应)
C	2026.3	0.388×10^5	7.85	1
H	2194.9	0.420×10^3	0.11	1
O	1795.4	1.026×10^5	18.43	0.98
Fe	201	45.30×10^5	91.08	1.12

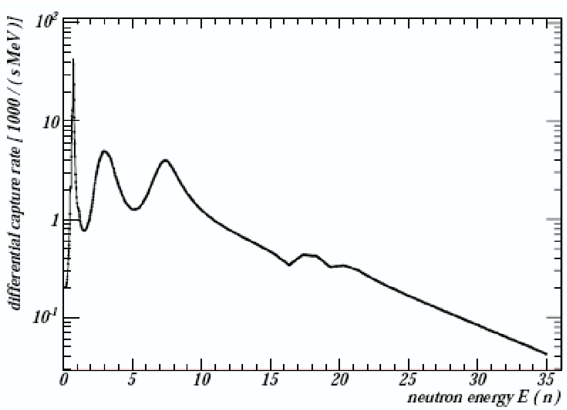


图 1.33: 碳核俘获带负电荷的 μ 子后放出的中子能谱 [64]

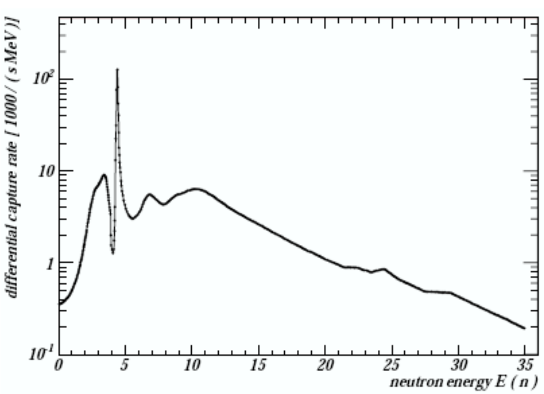


图 1.35: 氧核俘获带负电荷的 μ 子后放出的中子能谱 [64]

Cosmogenic Longlived Isotopes

- **Hard to remove by muon veto**
- **The most important bkg in DYB: He8/Li9 with a delayed neutron**

$$\sigma_{tot}(E_\mu) \propto E_\mu^{0.73}$$

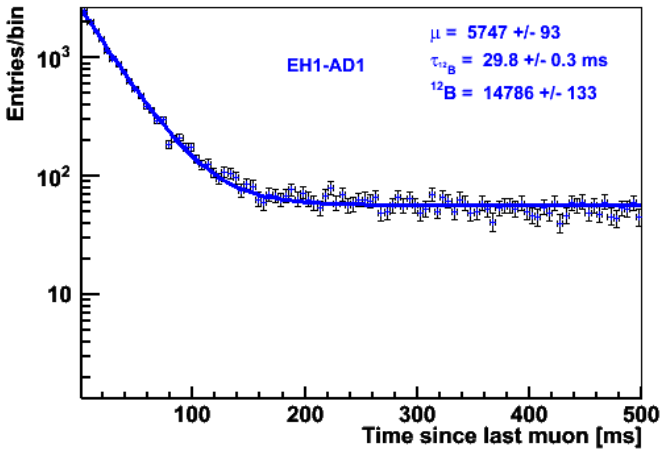
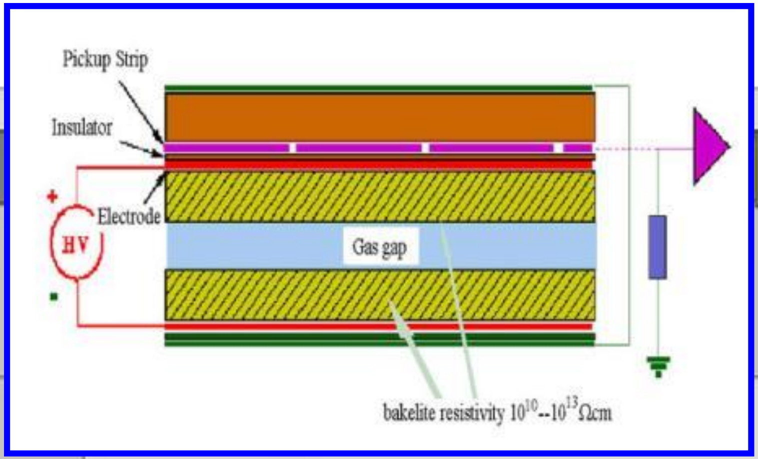
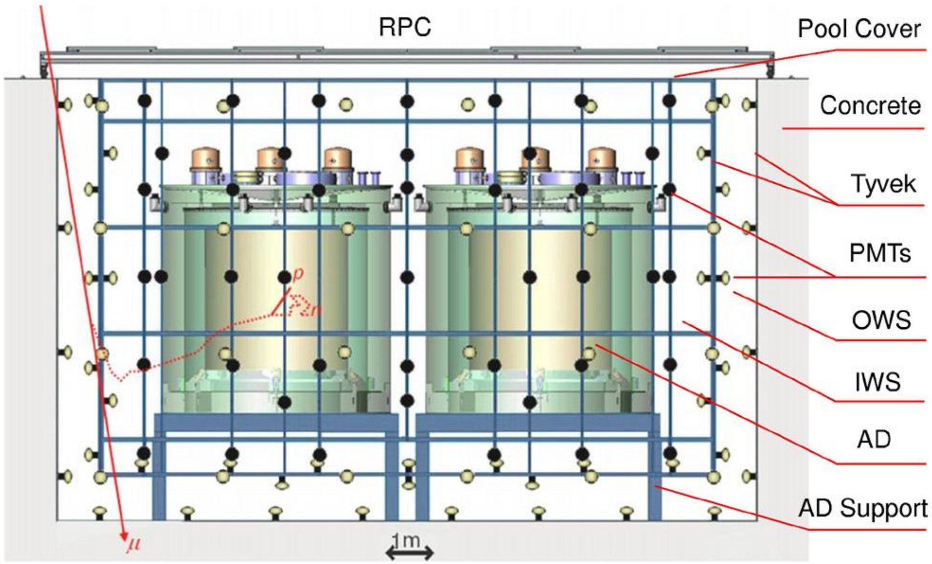


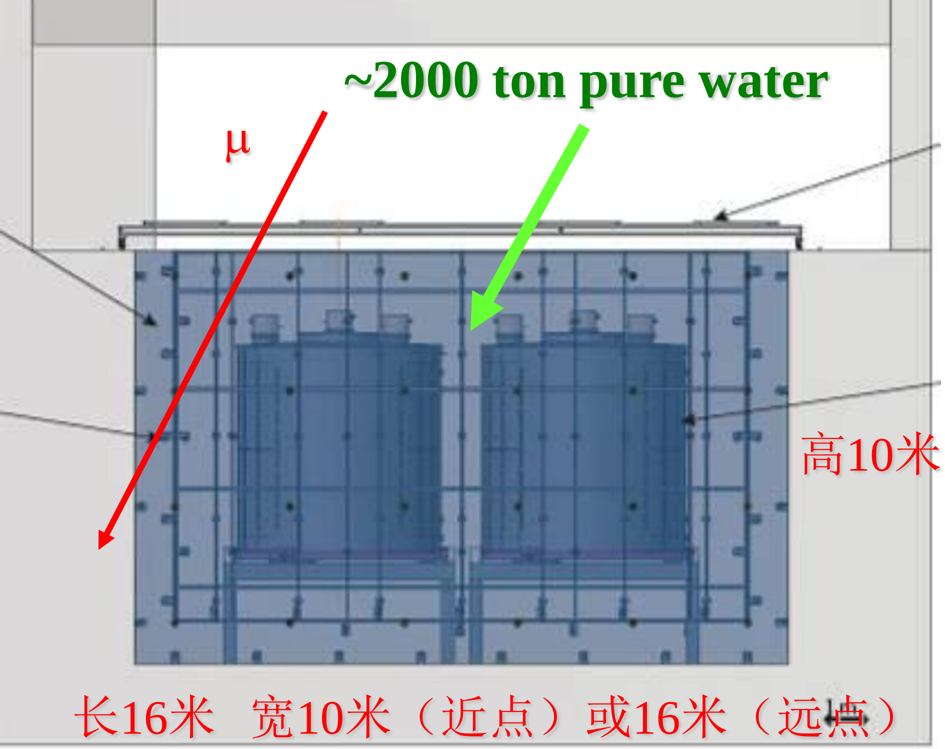
TABLE V: Summary of the neutron and isotope production yields from muon-initiated spallation in KamLAND. The results of the FLUKA calculation shown in this table include corrections for the muon spectrum and the μ^+/μ^- composition of the cosmic-ray muon flux.

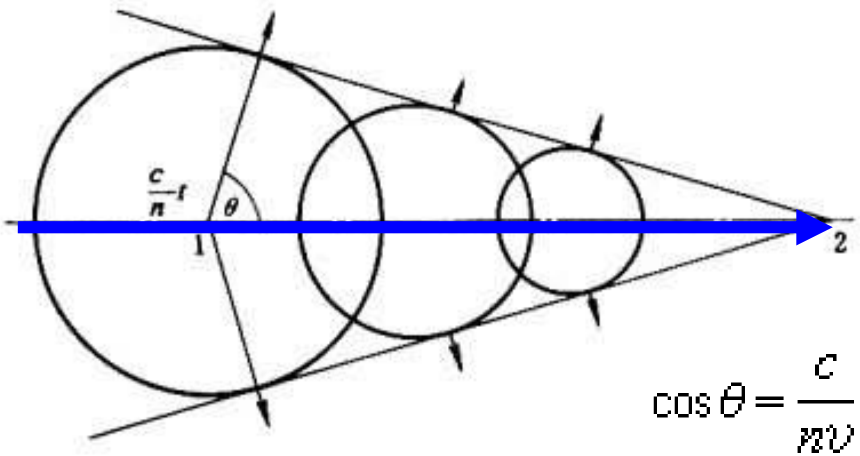
	Lifetime in KamLAND LS	Radiation Energy	Spallation Production Yield $(\times 10^{-7}\ (\mu \cdot (\mathrm{g/cm^2}))^{-1})$ Hagner, *et al.* [10]	FLUKA calc.	this measurement	Fraction from showering μ this measurement
n	207.5 μs	2.225 MeV (capt. γ)	—	2097 ± 13	2787 ± 311	$64 \pm 5\%$
^{12}B	29.1 ms	13.4 MeV (β^-)	—	27.8 ± 1.9	42.9 ± 3.3	$68 \pm 2\%$
^{12}N	15.9 ms	17.3 MeV (β^+)	—	0.77 ± 0.08	1.8 ± 0.4	$77 \pm 14\%$
^{8}Li	1.21 s	16.0 MeV ($\beta^-\alpha$)	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6	$65 \pm 17\%$
^{8}B	1.11 s	18.0 MeV ($\beta^+\alpha$)	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4	$78 \pm 23\%$
^{9}C	182.5 ms	16.5 MeV (β^+)	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2	$91 \pm 32\%$
^{8}He	171.7 ms	10.7 MeV ($\beta^-\gamma n$)	1.0 ± 0.3 (He+Li)	0.32 ± 0.05	0.7 ± 0.4	$76 \pm 45\%$
^{9}Li	257.2 ms	13.6 MeV ($\beta^-\gamma n$)		3.16 ± 0.25	2.2 ± 0.2	$77 \pm 6\%$
^{11}C	29.4 min	1.98 MeV (β^+)	421 ± 68	416 ± 27	866 ± 153	$62 \pm 10\%$
^{10}C	27.8 s	3.65 MeV ($\beta^+\gamma$)	54 ± 12	19.1 ± 1.3	16.5 ± 1.9	$76 \pm 6\%$
^{11}Be	19.9 s	11.5 MeV (β^-)	< 1.1	0.84 ± 0.09	1.1 ± 0.2	$74 \pm 12\%$
^{6}He	1.16 s	3.51 MeV (β^-)	7.5 ± 1.5	12.08 ± 0.83	—	—
^{7}Be	76.9 day	0.478 MeV (ECγ)	107 ± 21	105.3 ± 6.9	—	—

RPC + Water Cherenkov Detector









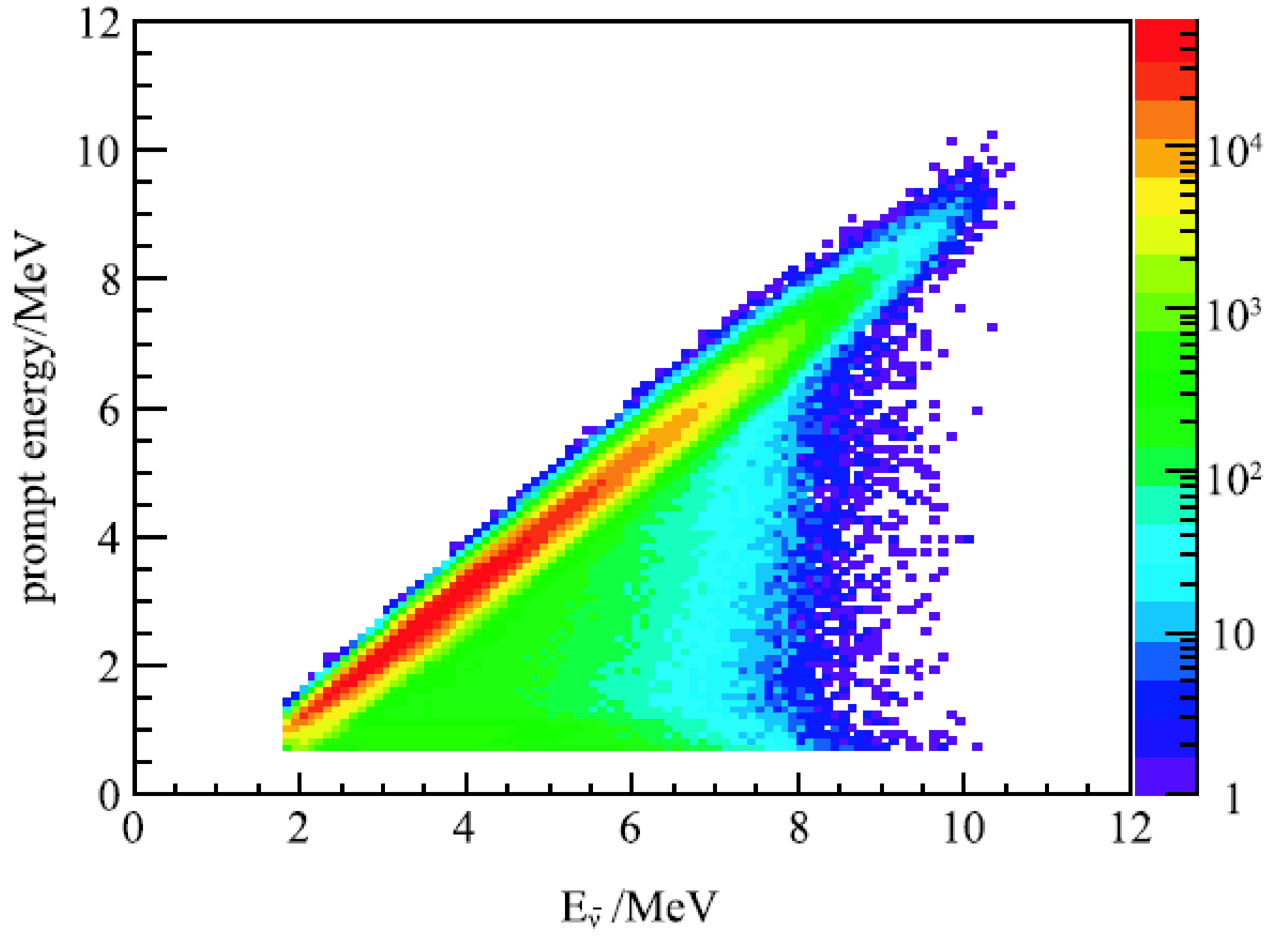
$$\cos\theta = \frac{c}{nv},$$

运动带电粒子所激发的电磁场

5 – Detector Response and Calibration

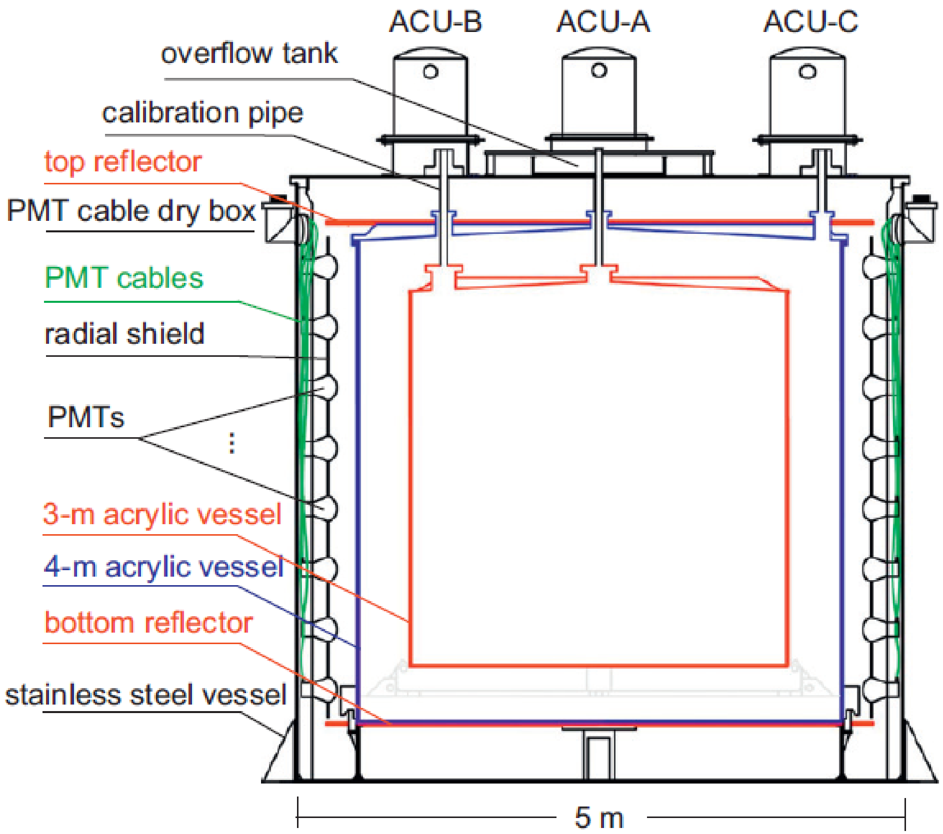
Response matrix

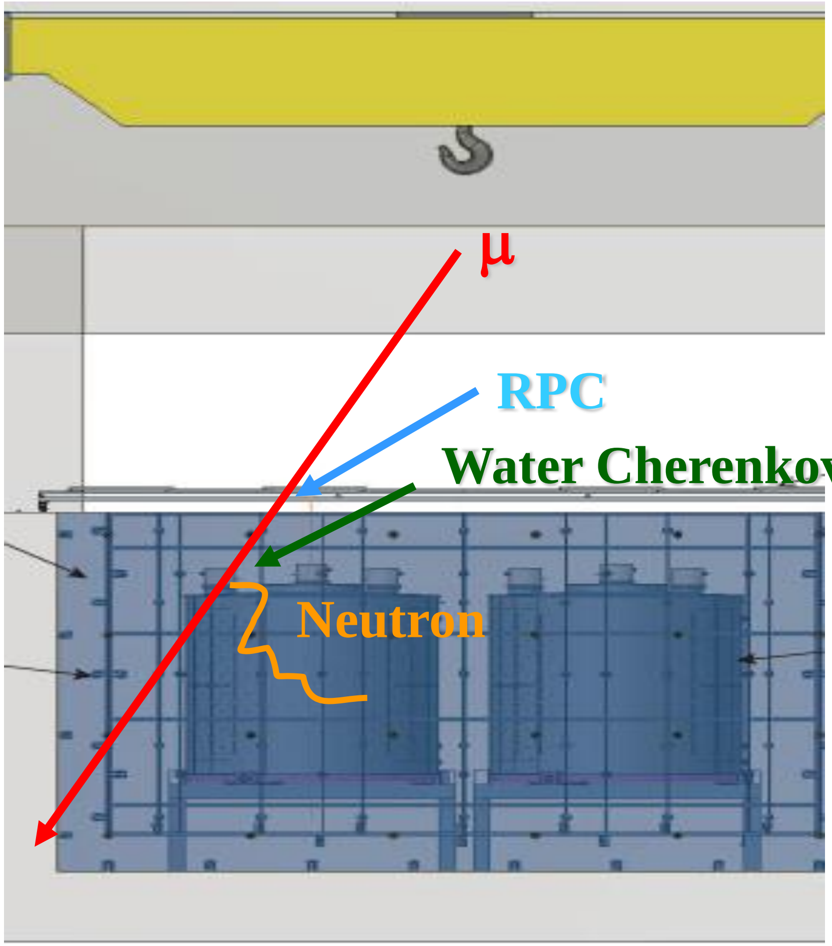
$$S(E_{\rm p}) = \int S(E_{\bar{\nu}_{\rm e}}) R(E_{\bar{\nu}_{\rm e}}, E_{\rm p}) {\rm d}E_{\bar{\nu}_{\rm e}}$$



Detectors

3 layers separated by Acrylic Vessels



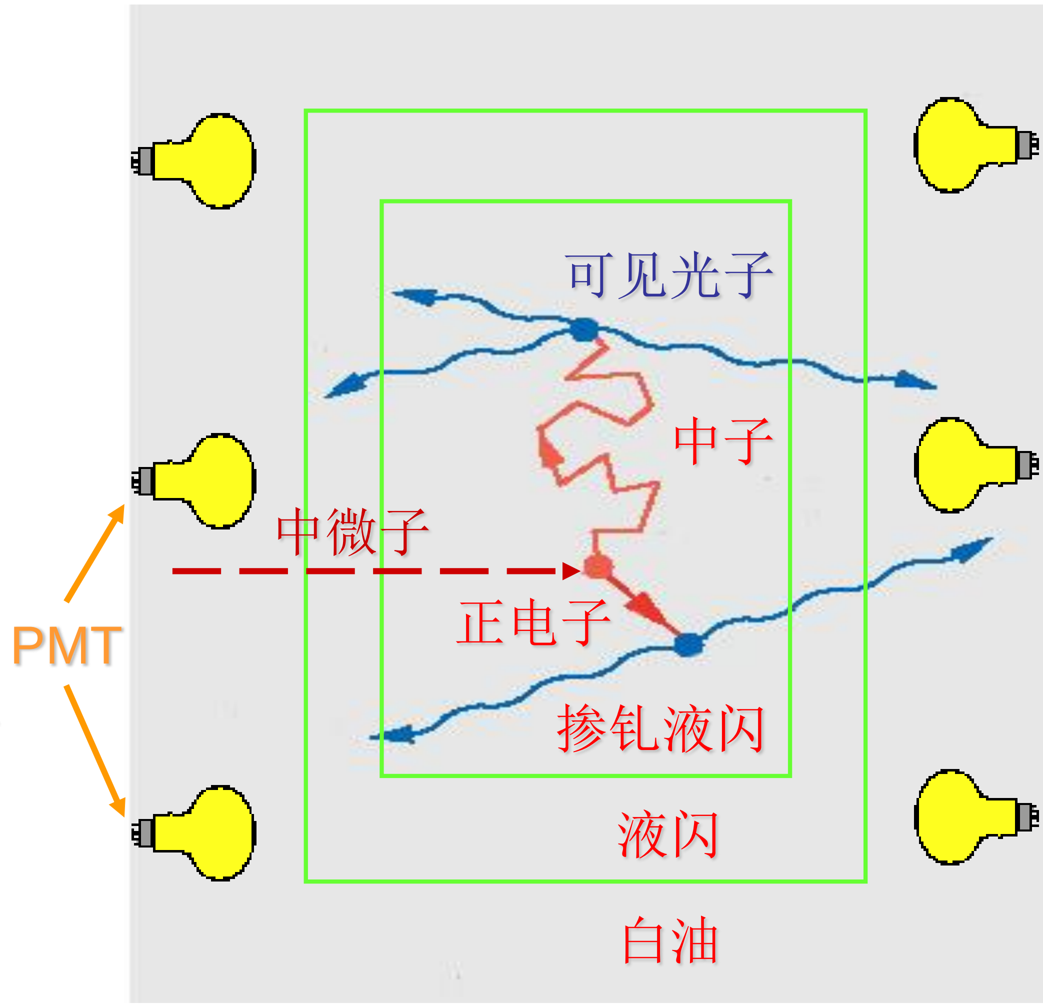


Water shields radioactivity and neutron

- **Two layer water Cherenkov detector**
- **RPC**
- **Combined eff. 99.5%+-0.25%**

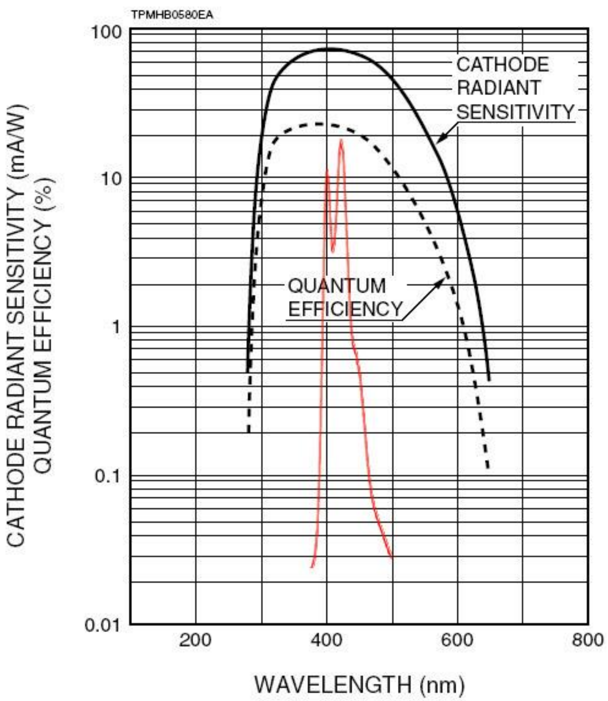
探测反应堆中微子

- 中微子与氢核反应，生成正电子与中子
- 正电子直接电离激发液闪发光；然后与电子湮灭生成一对伽马；伽马与电子发生康普顿散射，将能量传递给电子，电子再电离激发液闪发光。
- 中子在液闪中慢化（平均~30微秒），在钆和氢上俘获，释放总能量为8MeV或2.2MeV的伽马光子，同上，激发液闪发光。
- 液闪发的光由PMT探测。



Photoelectrons

- LS ~ 10k photons/MeV, isotropic, point-like
- Photocathode coverage (with reflector): 12%
- Light attenuation ~exp(-3/20)=0.86
- PMT quantum eff. ~20%, PMT collection eff. 0.8
- 10k*0.12*0.86*20%*0.8 ~ 165 p.e./MeV



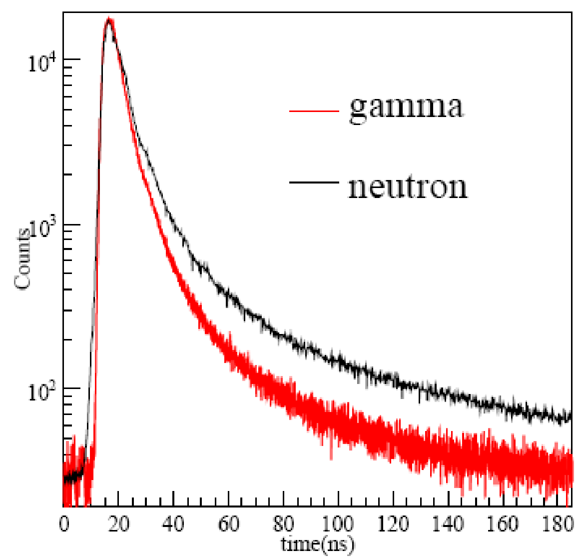
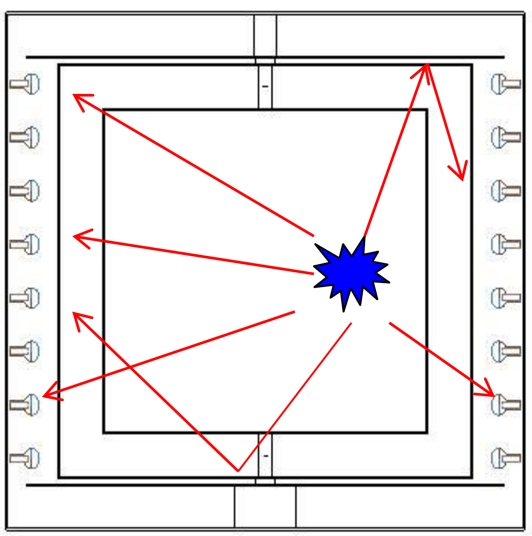
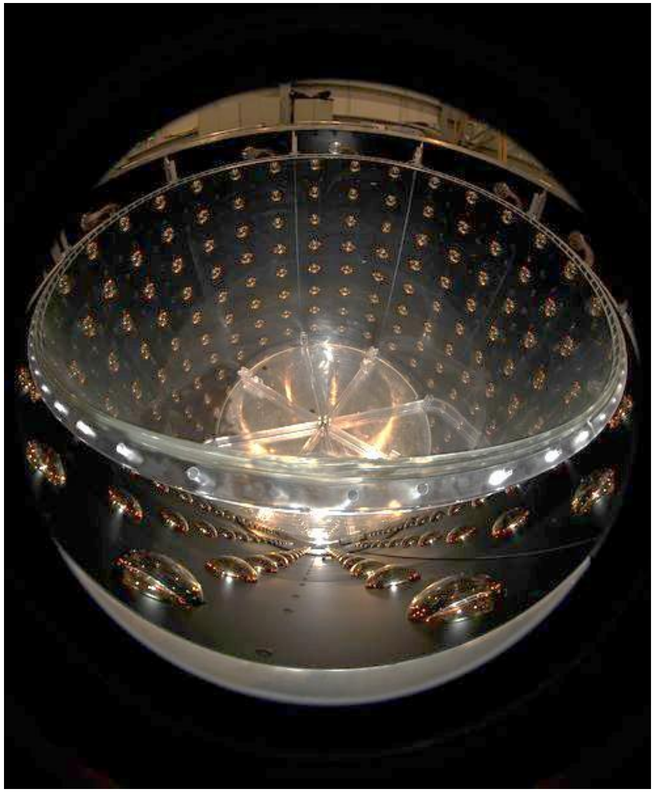


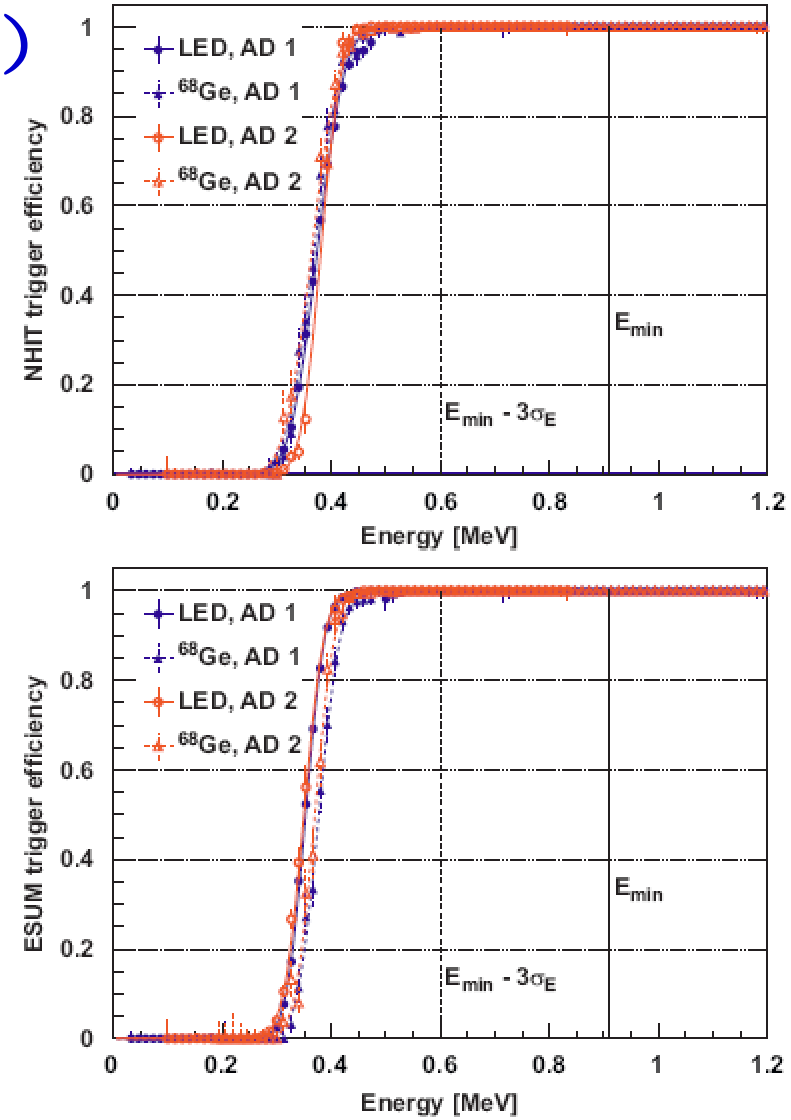
Fig. 15. Experimental light pulse measured for LAB+3 g/L PPO +15 mg/L bis-MSB under γ and fast neutron radiation



触发

- 去掉噪声和低能本底事例
- NHIT（100ns内PMT击中数）
- ESUM（总光电子数）



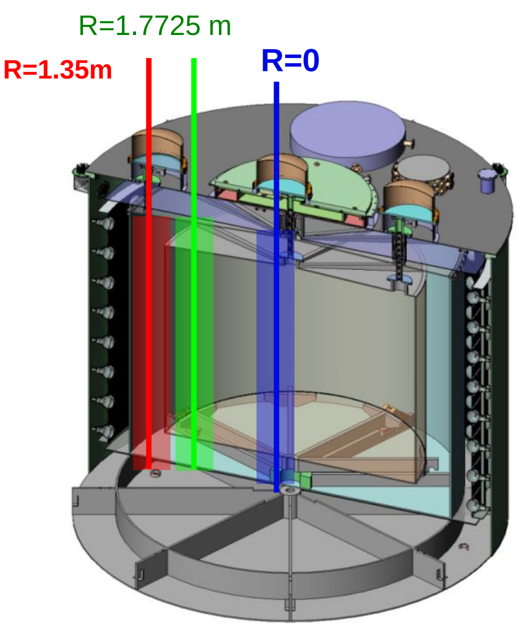


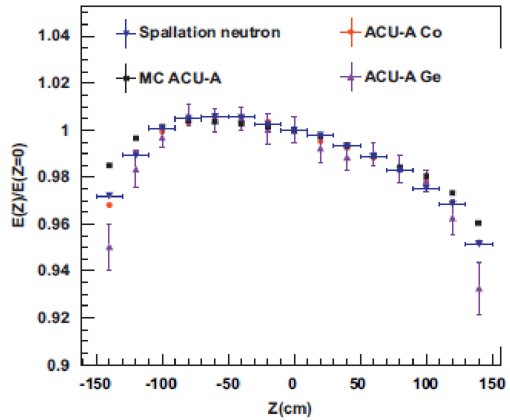
PMT暗噪声，常温下 kHz – 10 kHz

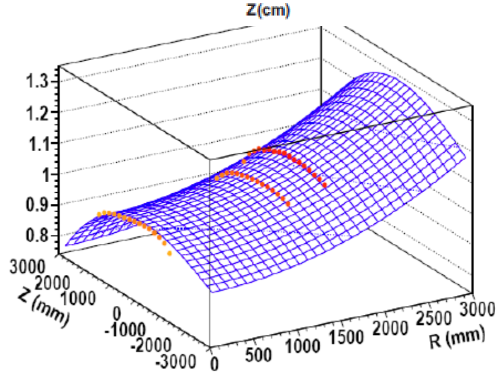
Energy Calibration

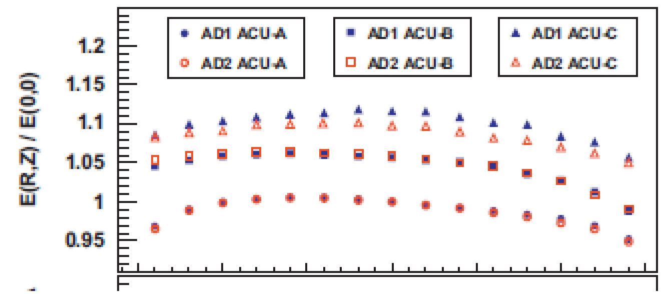
- LED (PMT gain， timing)
- Ge68 (positron threshold 1.022 MeV)
- Co60 (2.506 MeV) + Am-C (neutron)

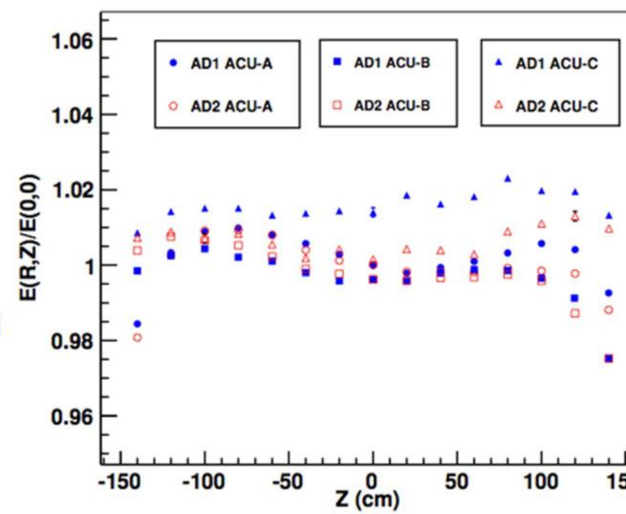
$$r_{\rm rec} = c_1 \times r_{\rm COC} - c_2 \times r_{\rm COC}^2,$$
$$z_{\rm rec} = (z_{\rm COC} - c_3 \times z_{\rm COC}^3) \times (c_4 - c_5 \times r_{\rm COC}),$$
$$\phi_{\rm rec} = \phi_{\rm COC}.$$











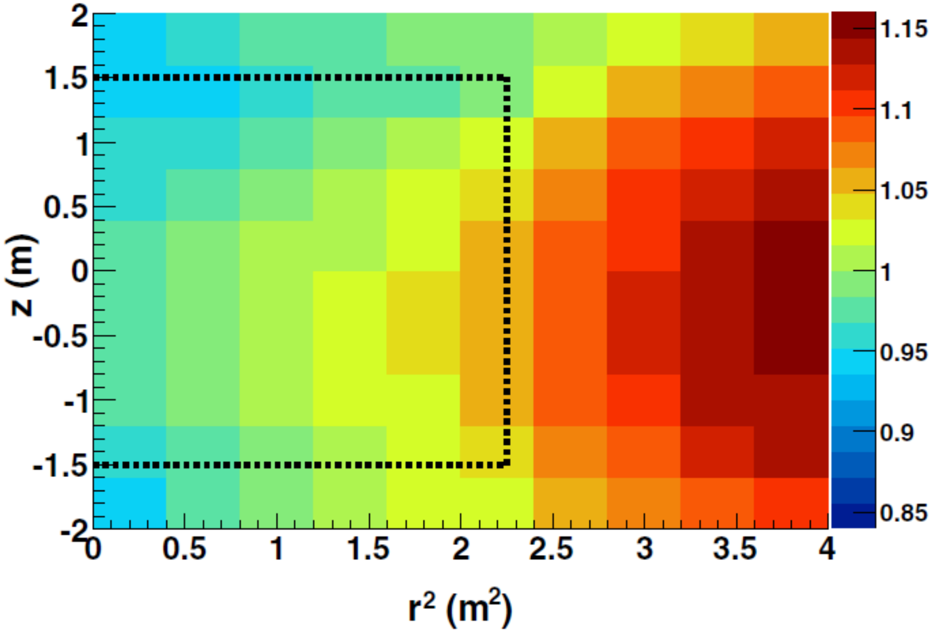
Ge68: 15 Hz
0.511x2 MeV

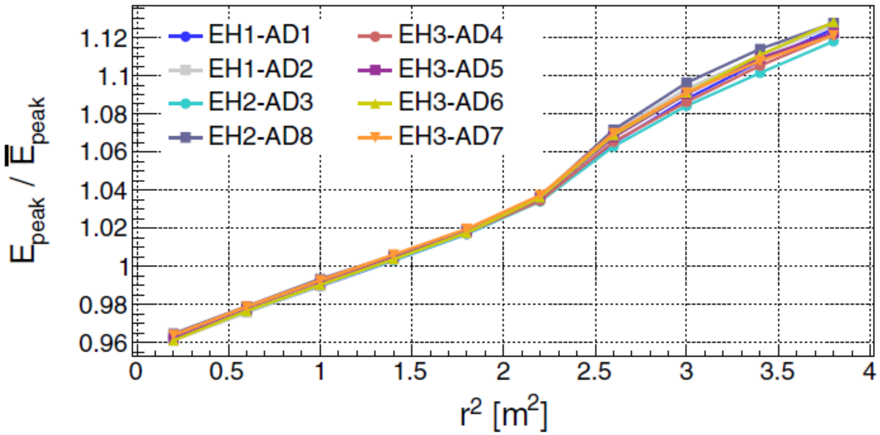
Am-C:
0.5 Hz

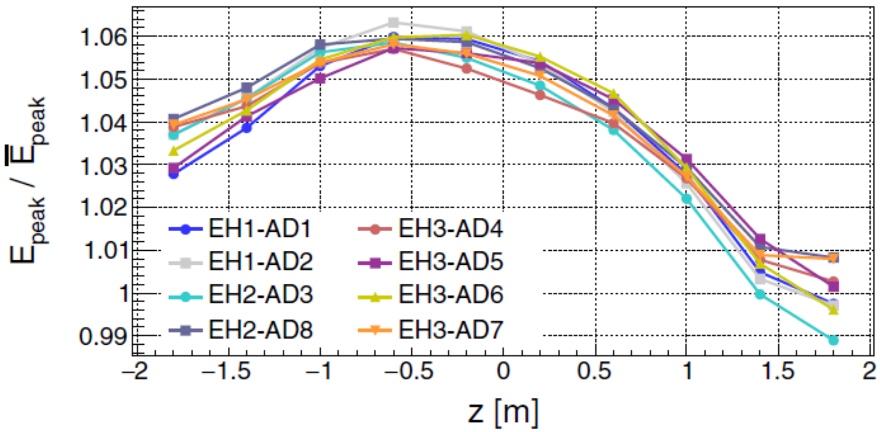
Co60: 100 Hz
1.173 + 1.332 MeV

Alternative method

- **Spallation neutron**

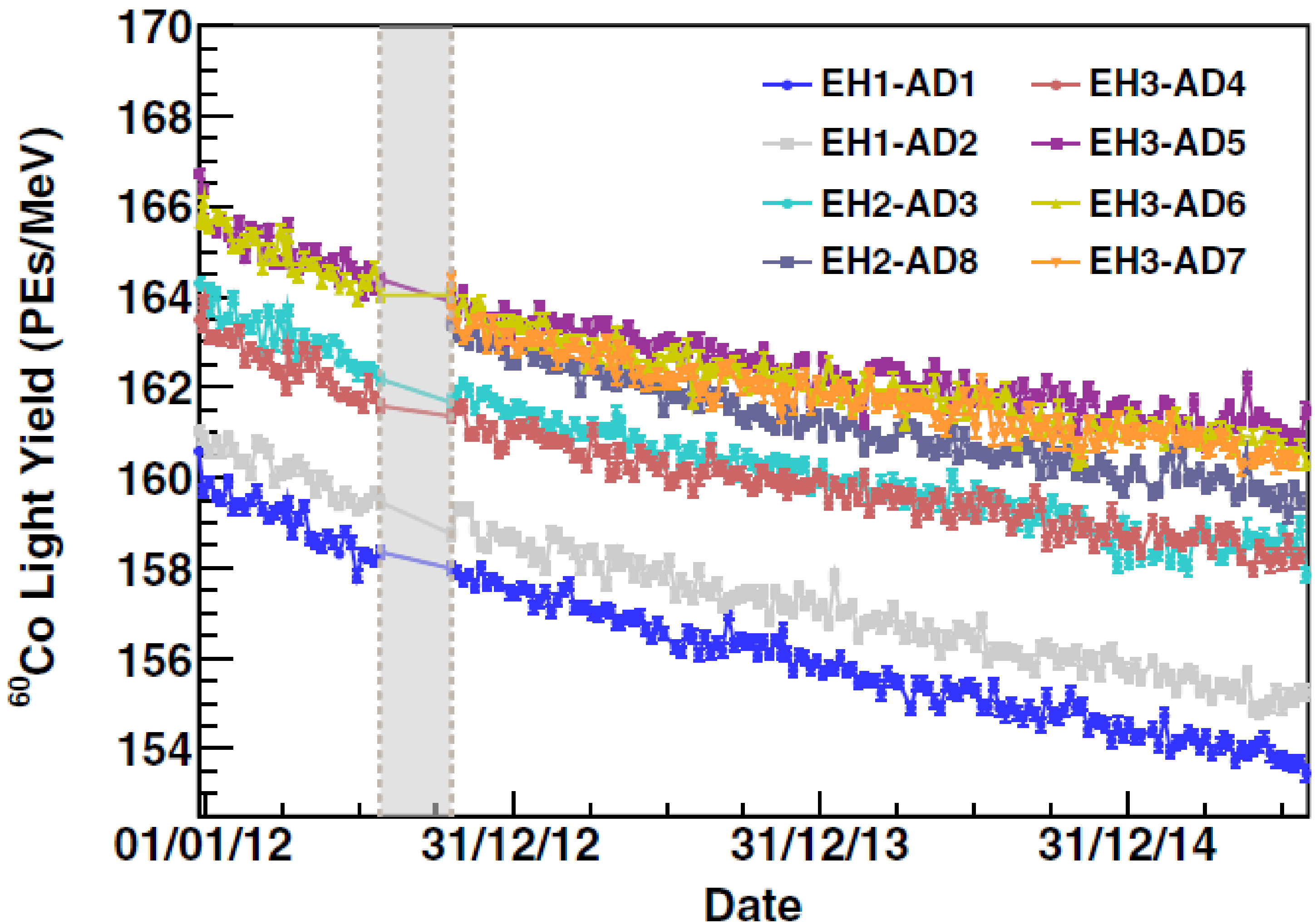




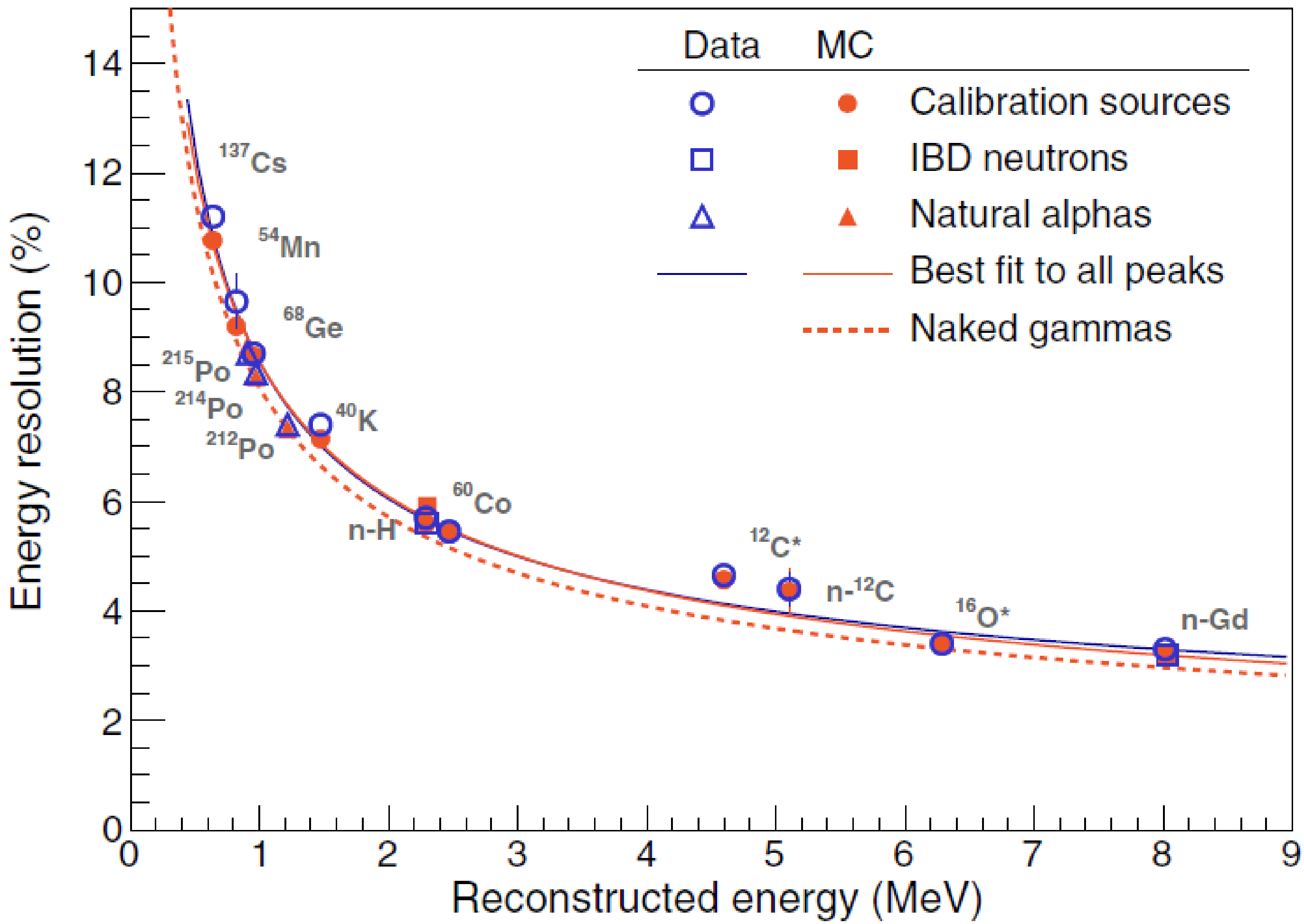


Energy scale stability

- Good scintillator



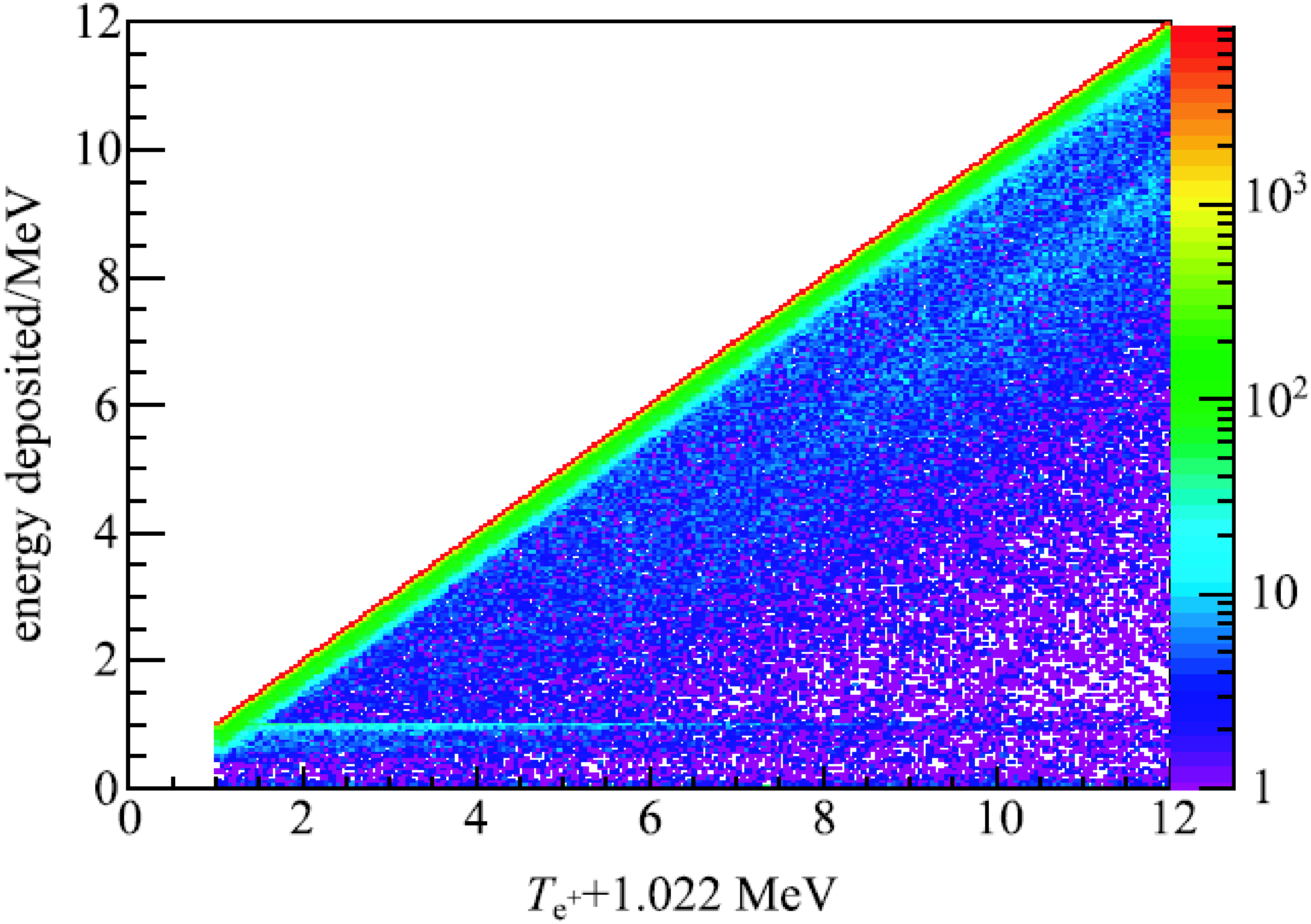
Energy resolution



- **Question: Why energy resolution is not important for Daya Bay and very important for JUNO?**

IAV effect

- **Energy leakage**



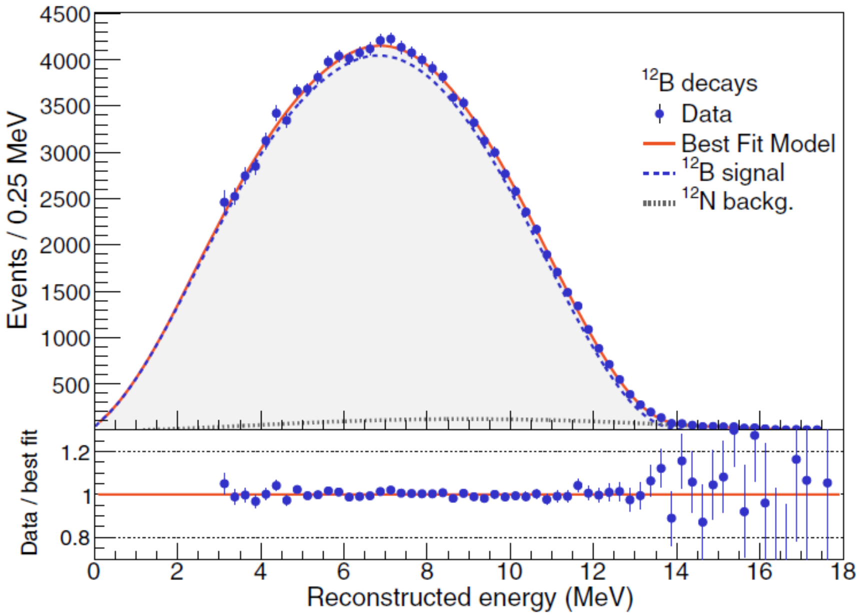
Non-linearity

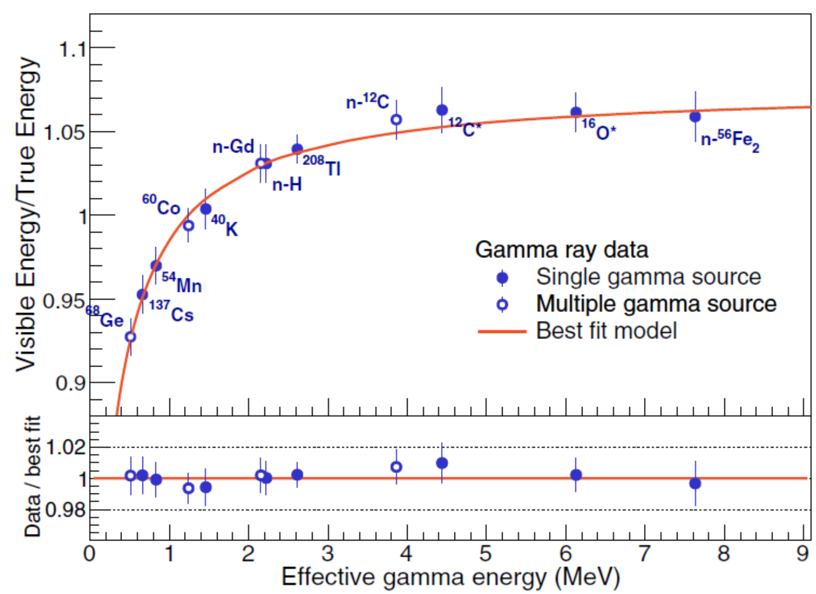
- **LS nonlinearity**

$$\frac{E_{\rm vis}}{E_{\rm true}} = \beta_{\rm vis}[f_q(E_{\rm true}, k_B) + k_c f_c(E_{\rm true})],$$

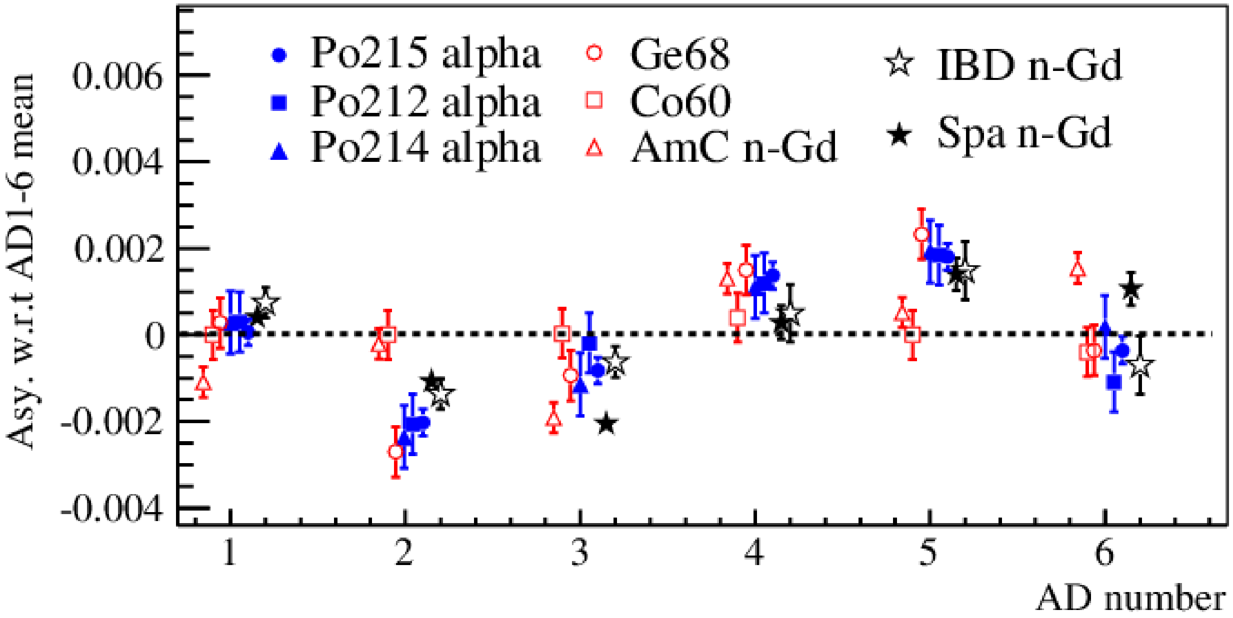
- **Electronics nonlinearity**

$$\frac{E_{\rm rec}}{E_{\rm vis}} = \beta_{\rm rec}\left[1 + \alpha \exp\left(-\frac{E_{\rm vis}}{\tau}\right)\right],$$



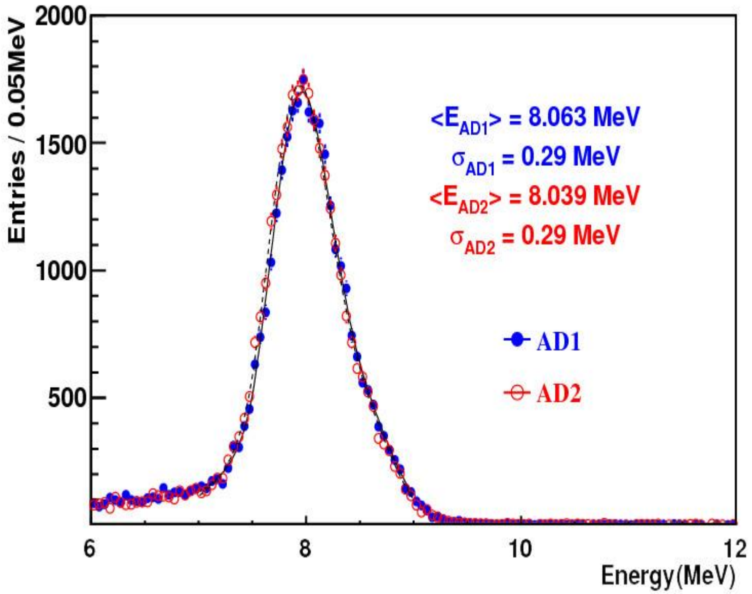


Energy Scale Uncertainty



能标误差 0.2%

通过Monte Carlo方法传递能标误差到效率误差→不同AD有 0.12% 的相对效率差别



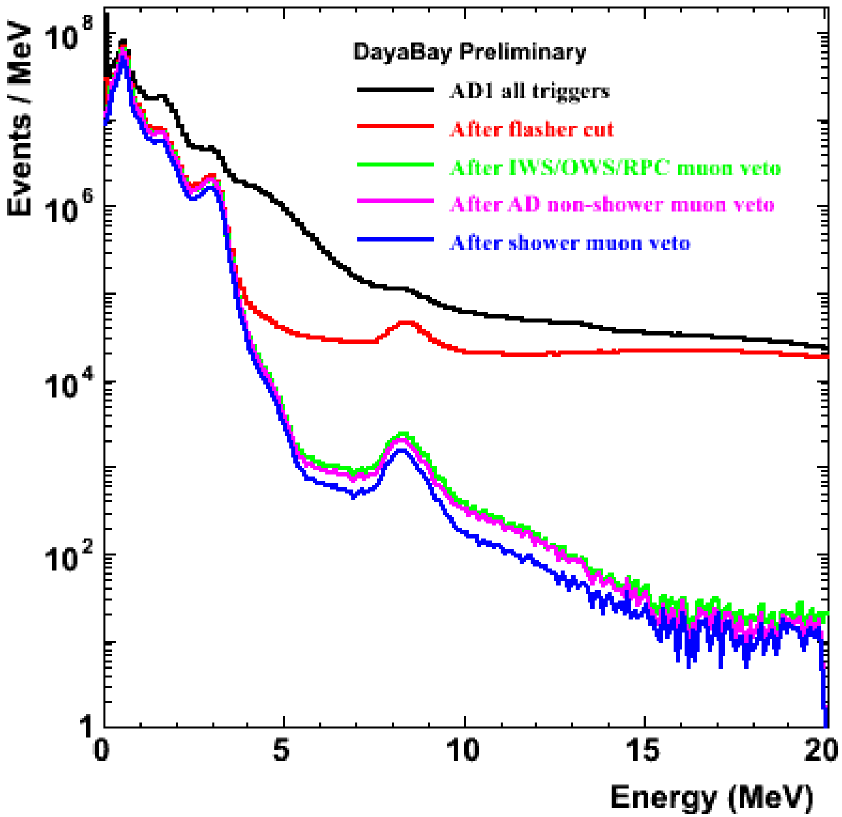
远近AD全同性的设计和数据验证

6- Event in Detector and Event Selection

数据的构成

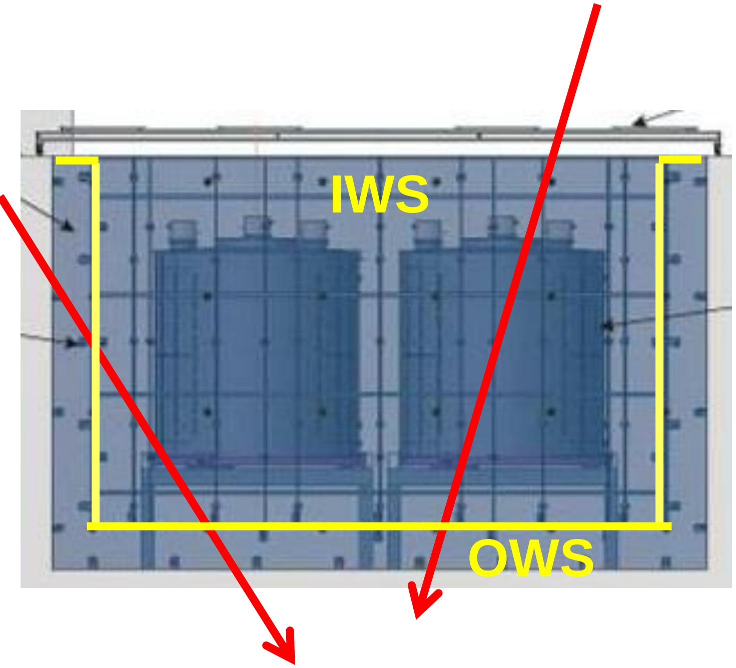
- Neutrino event rate（0.01 Hz@near site)
- Trigger ~ 0.4 MeV
- AD event rate 280 Hz
  - ⇨ PMT dark noise
  - ⇨ PMT flasher
  - ⇨ Radioactivity (low E）
  - ⇨ Muon(high E)
  - ⇨ Cosmogenic n, isotope
  - ⇨ Neutron source bkg
  - ⇨ Neutrino

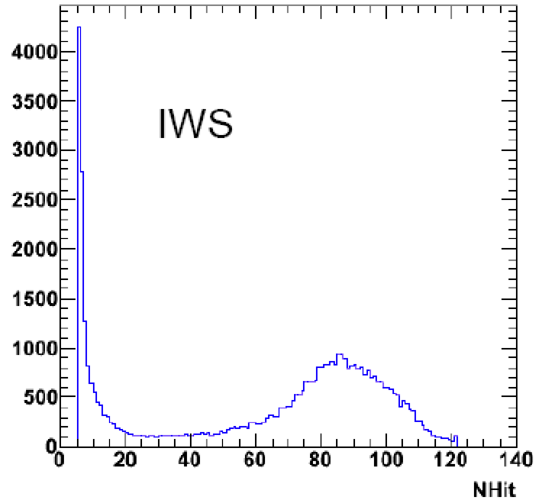
Data reduction

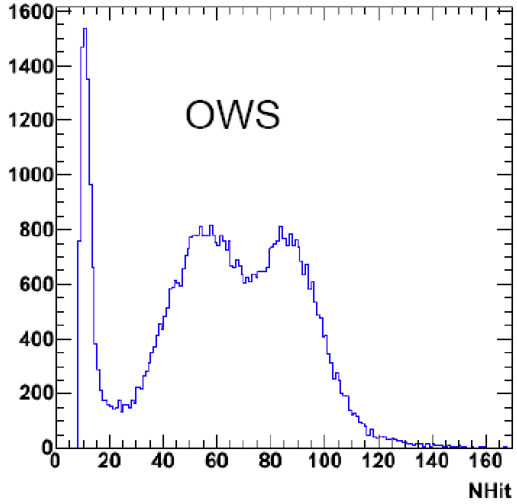


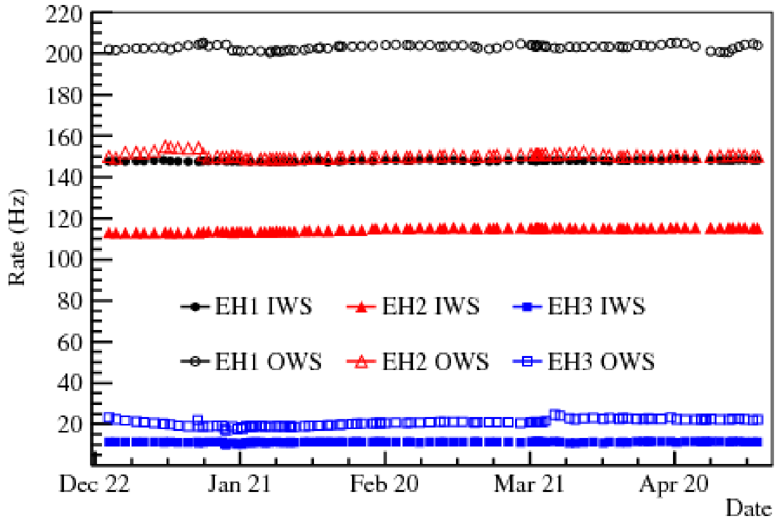
- Muons in Inner Water Pool (IWS), outer (OWS)
- RPC、FADC readout

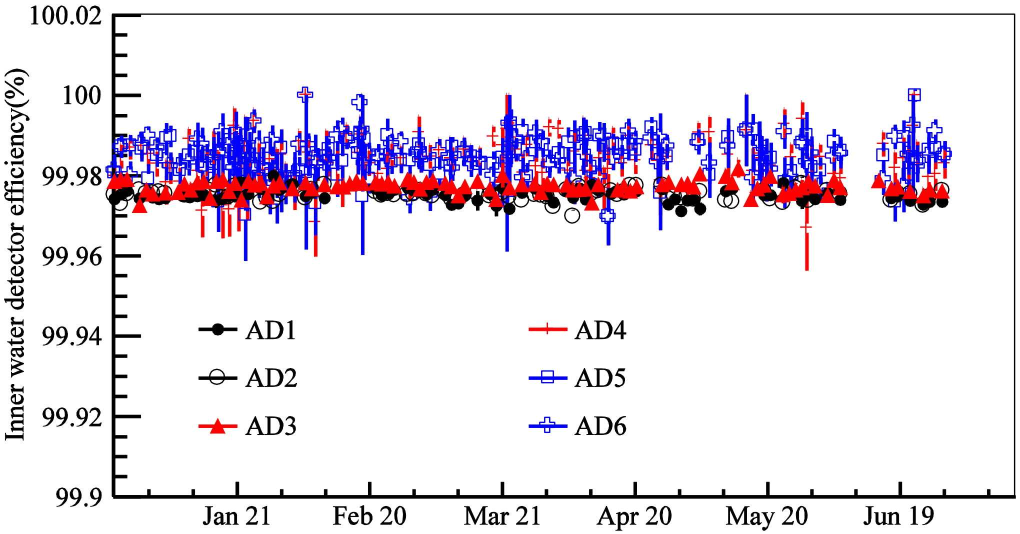
水池宇宙线事例





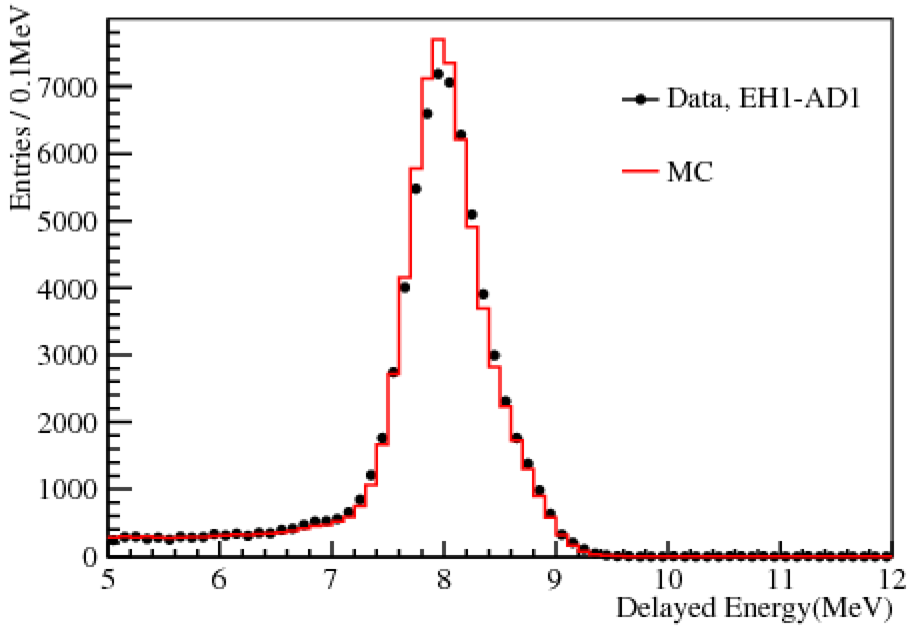


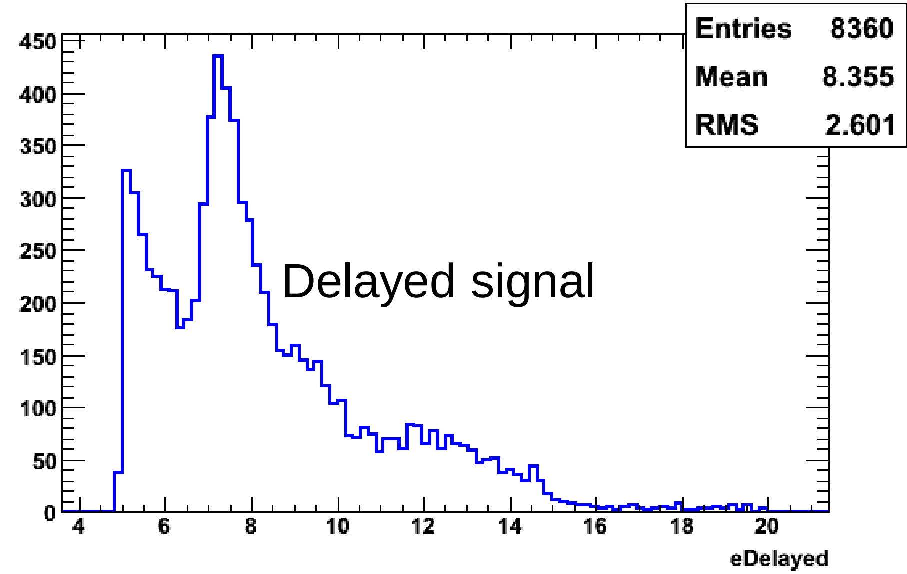


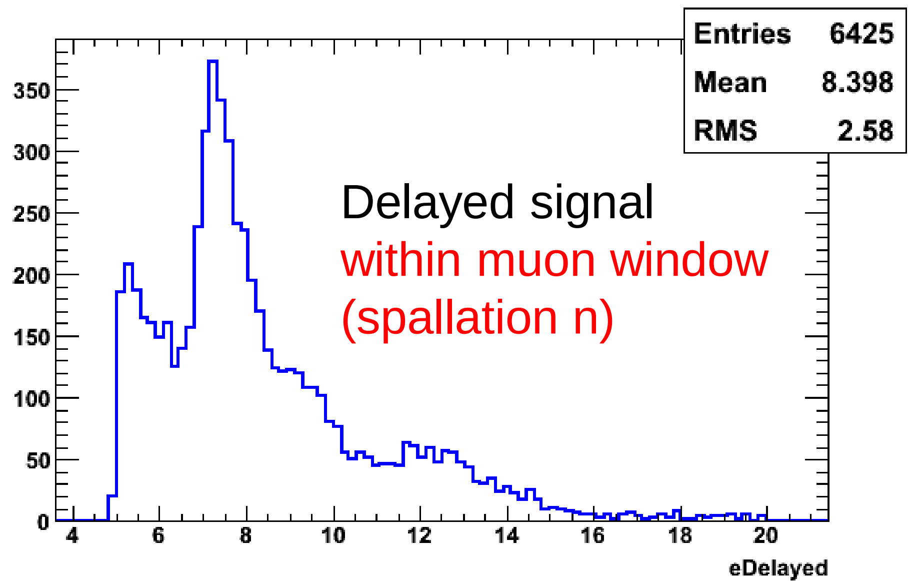


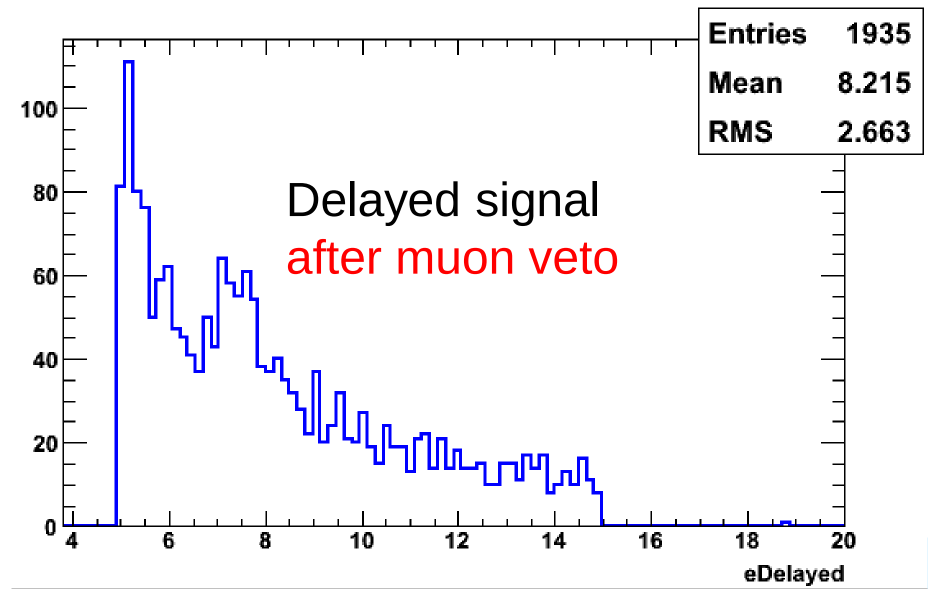
Nhit > 12

First look at the delayed (n) signal

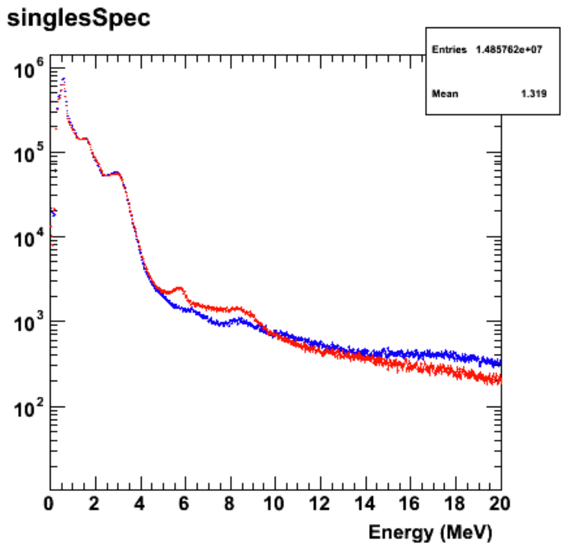




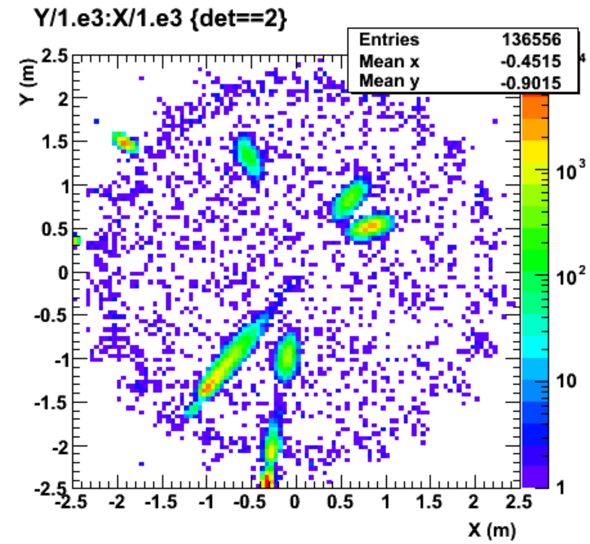




PMT Flasher

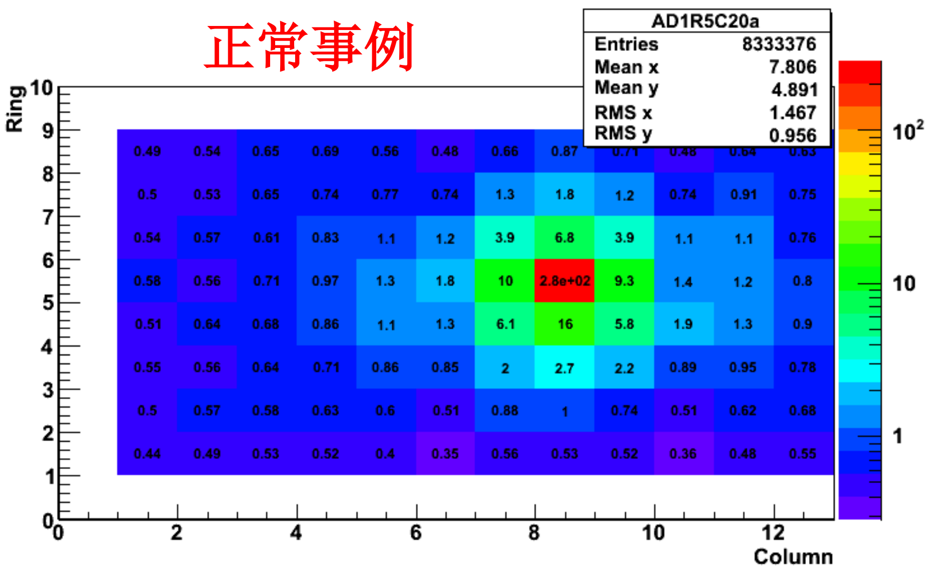


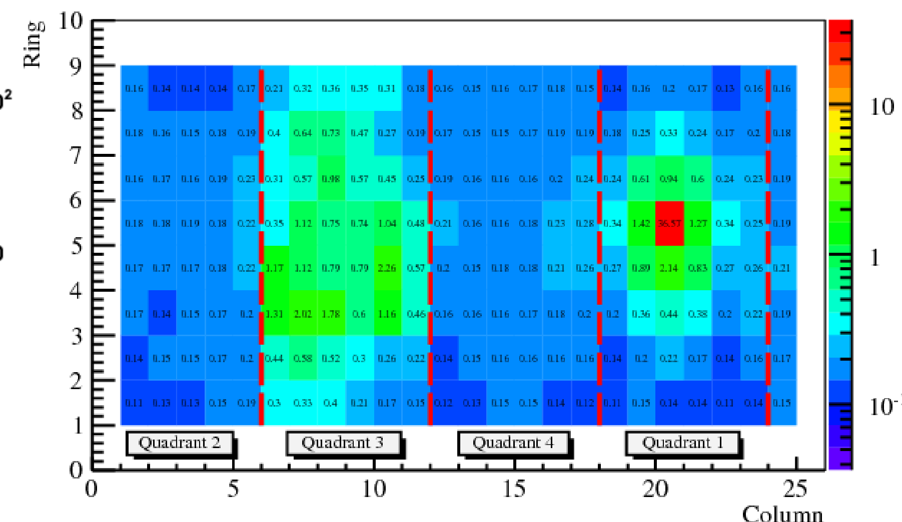
AD1/2的能谱应该相同



顶点分布，说明存在未知本底，本底有固定hit pattern

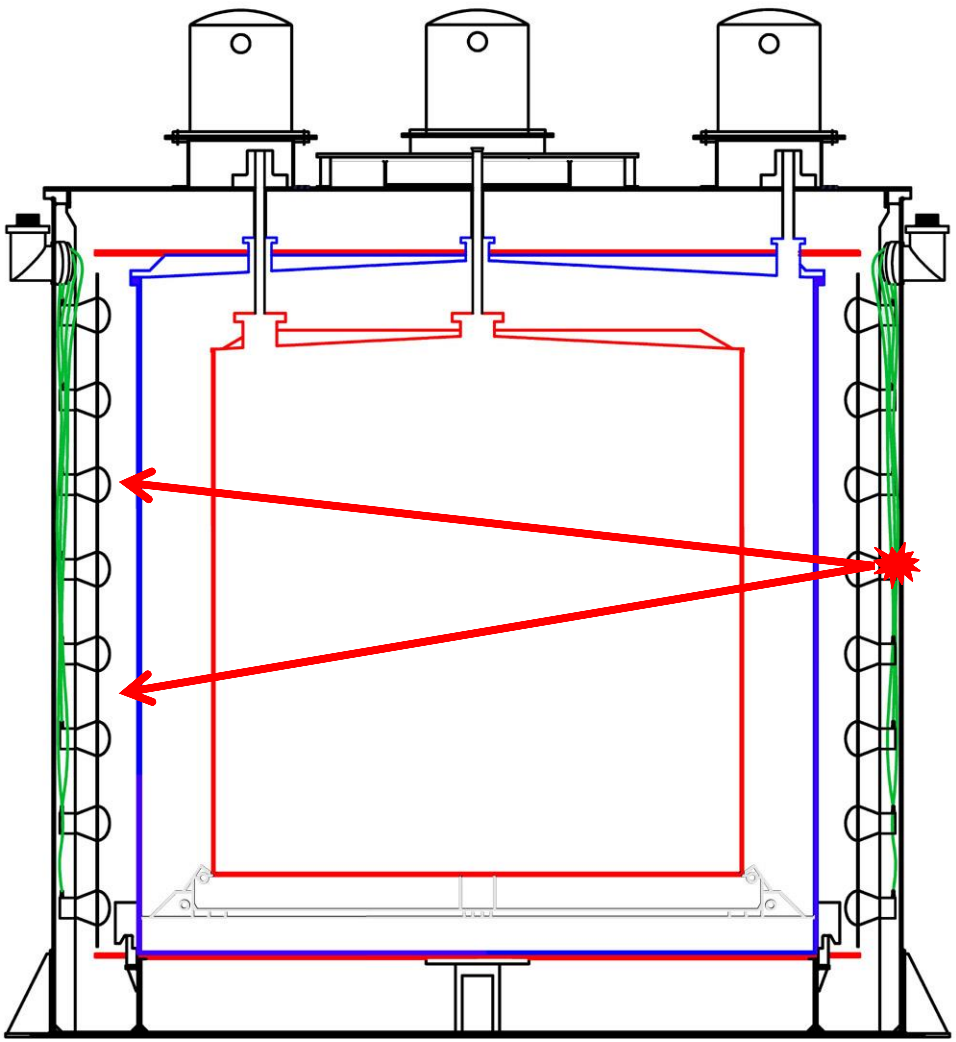
正常事例



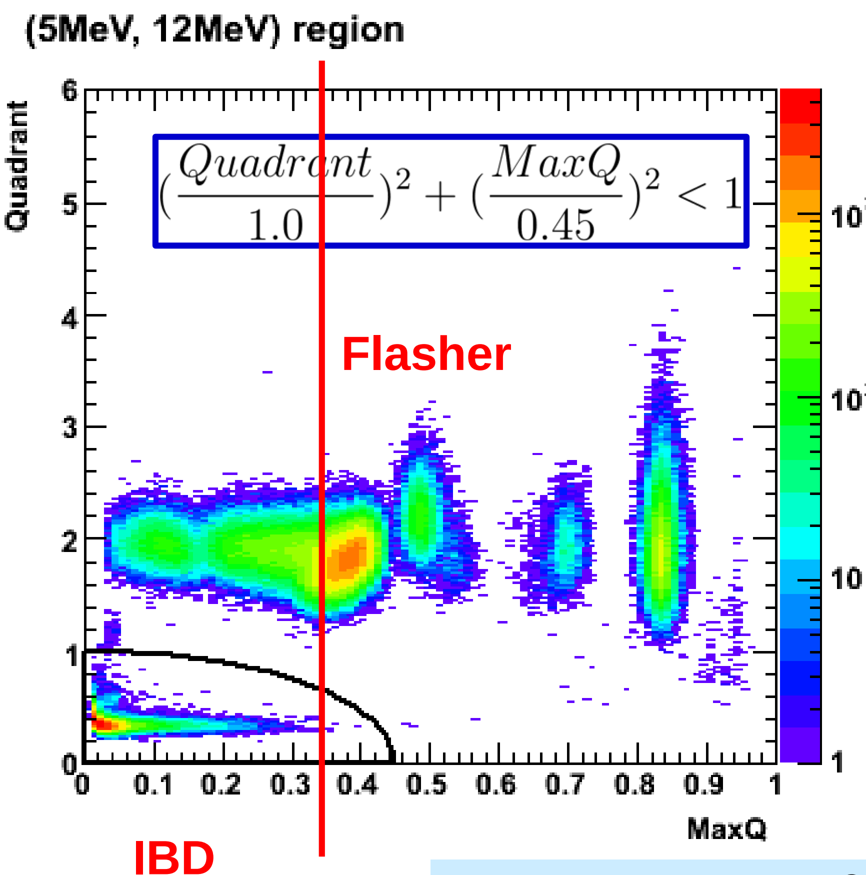


Flasher本底

PMT Flasher

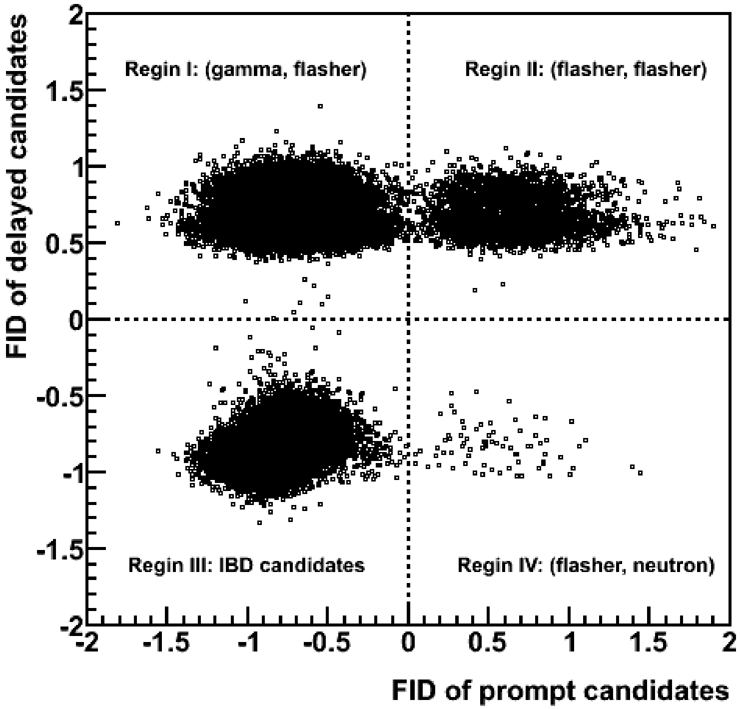


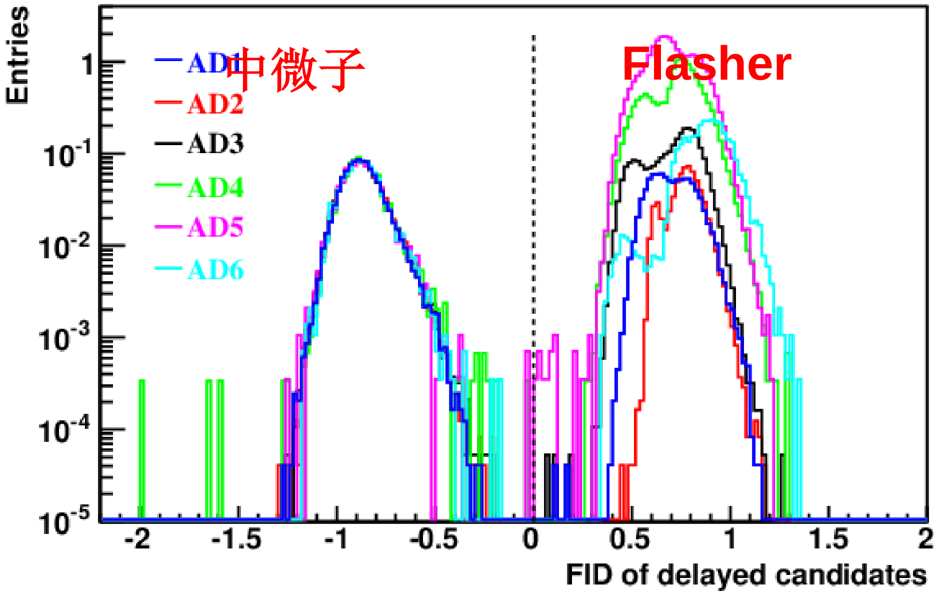
- 光电倍增管底座打火。
- 打火PMT电荷最大
- 对面一些PMT也被照亮



Reject PMT Flasher

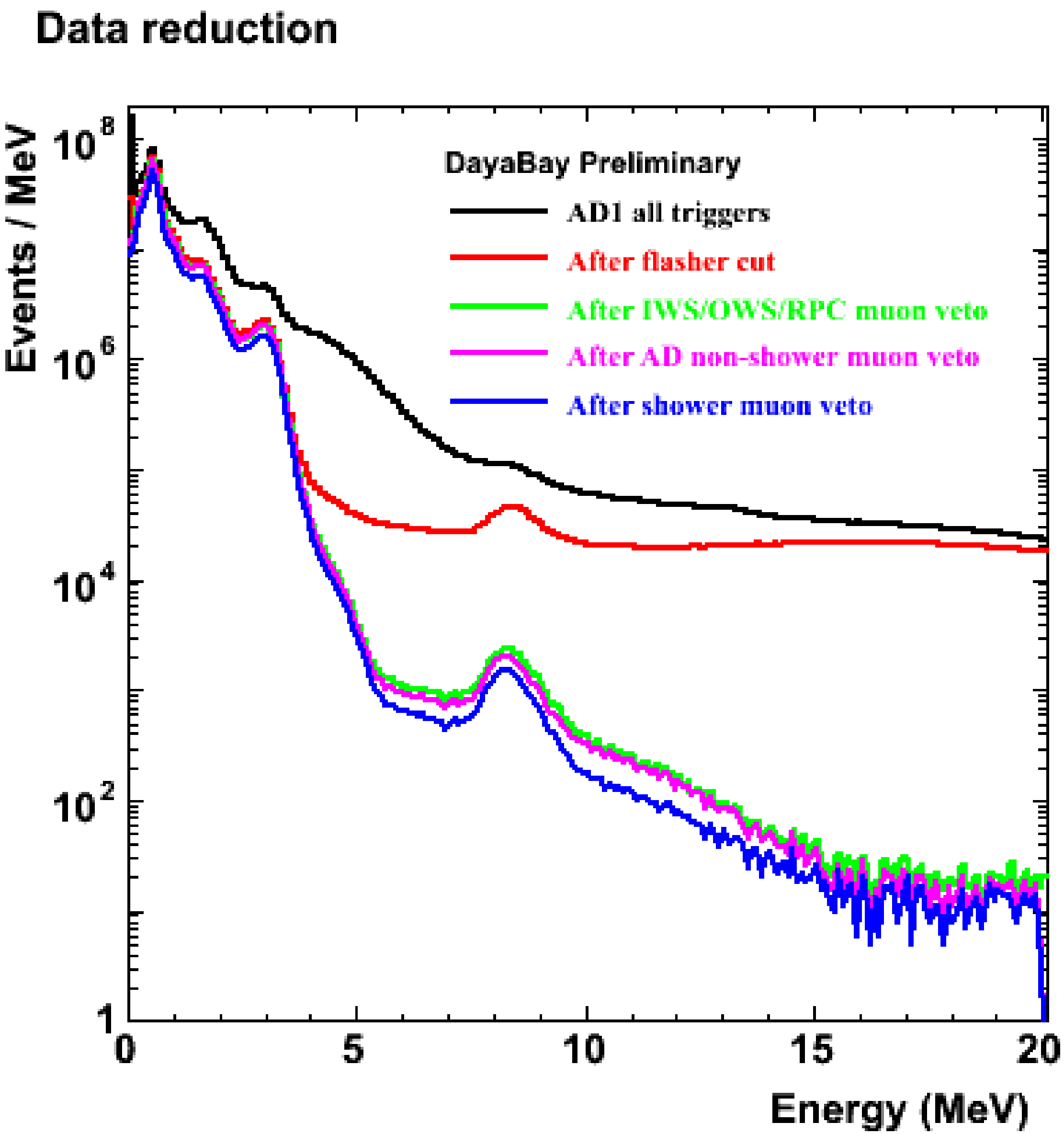
- 5%的PMT会打火，形成的本底事例占总事例5%





会带来0.01%的相对误差 →

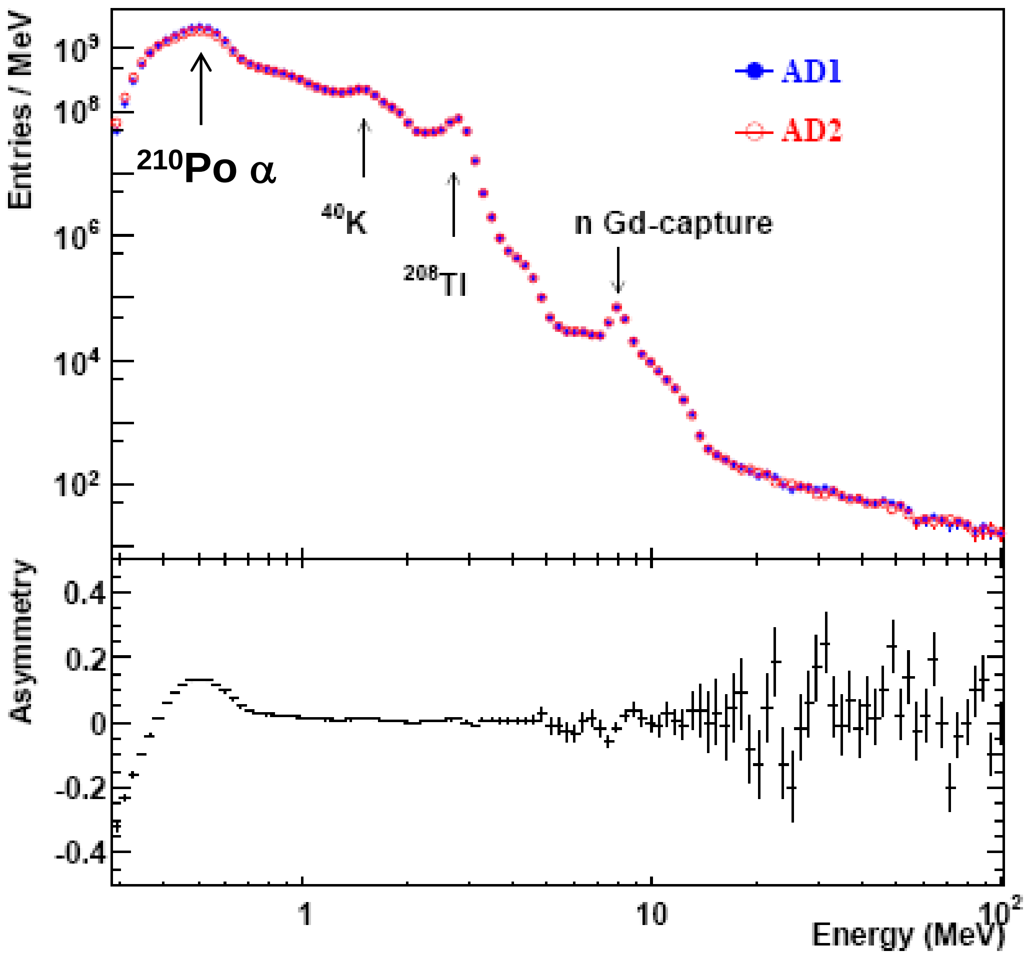
Data Reduction



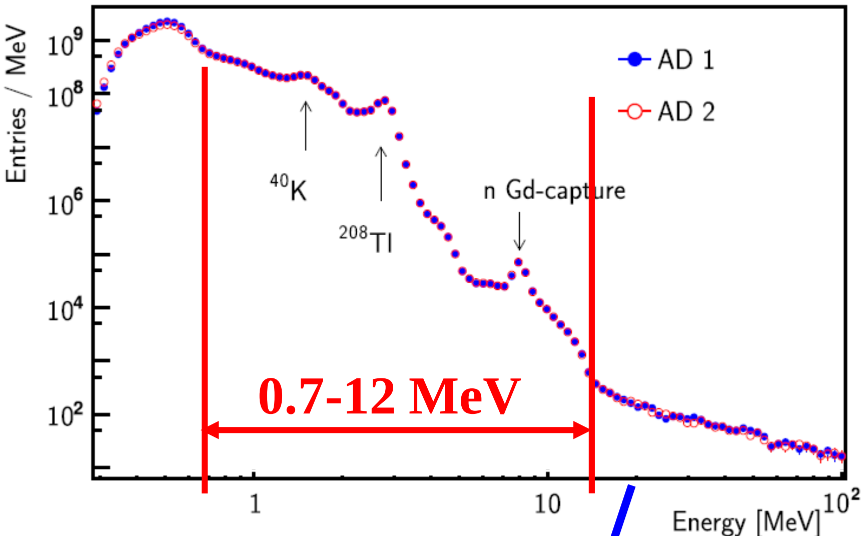
- 首先去掉非物理事例——**Flasher**
- 再去掉宇宙线、以及宇宙线引起的本底
  - 大信号后**PMT**过冲形成的电子学噪声
  - 米歇尔电子
  - **spallation**中子
  - 其它长寿命同位素

全能谱

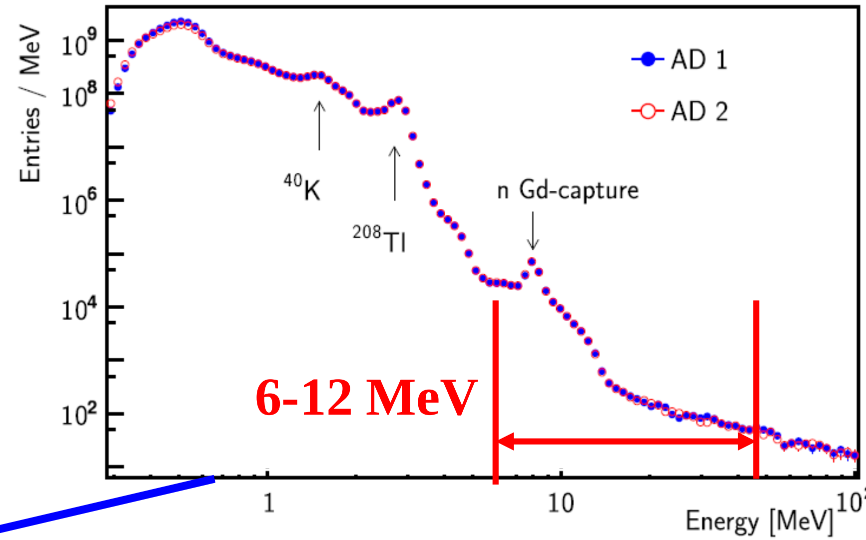
- 去掉Flasher，排除宇宙muon及其后200微秒的事例后，得到的能谱



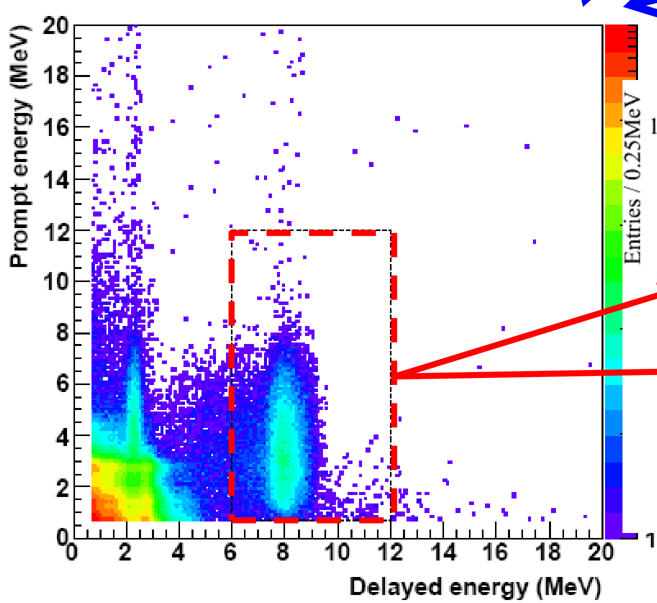
Neutrino Selections



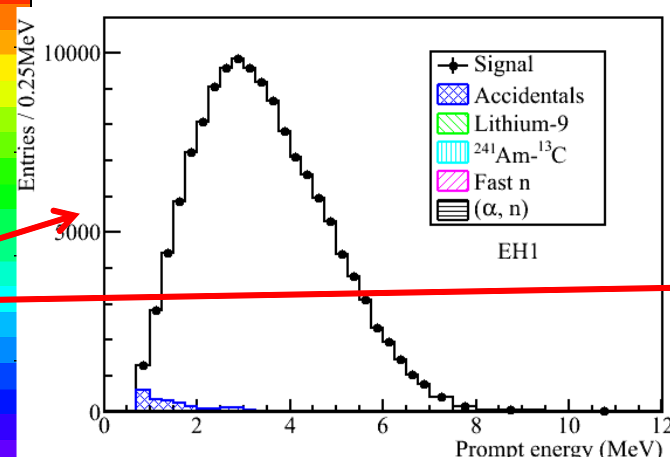
Prompt candidate



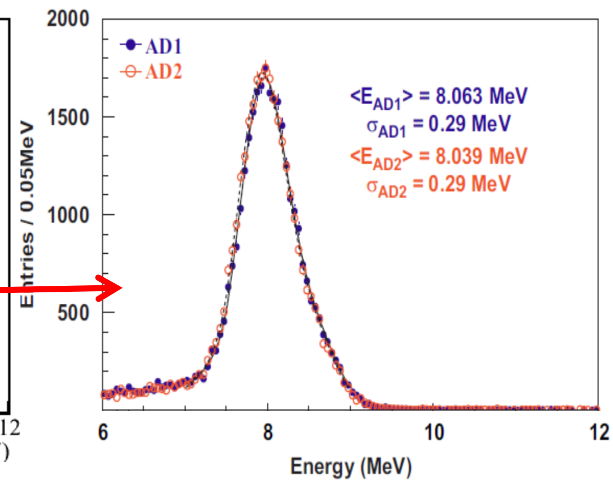
Delayed candidate



Correlated Events in 1-200 μs



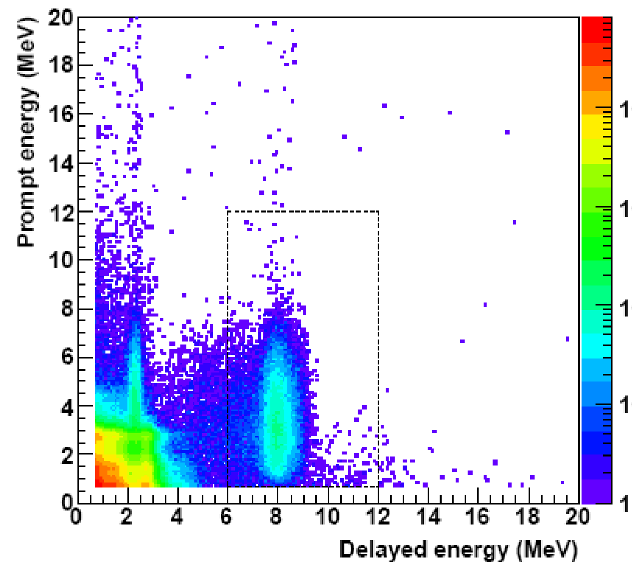
Reactor Neutrinos (Prompt)



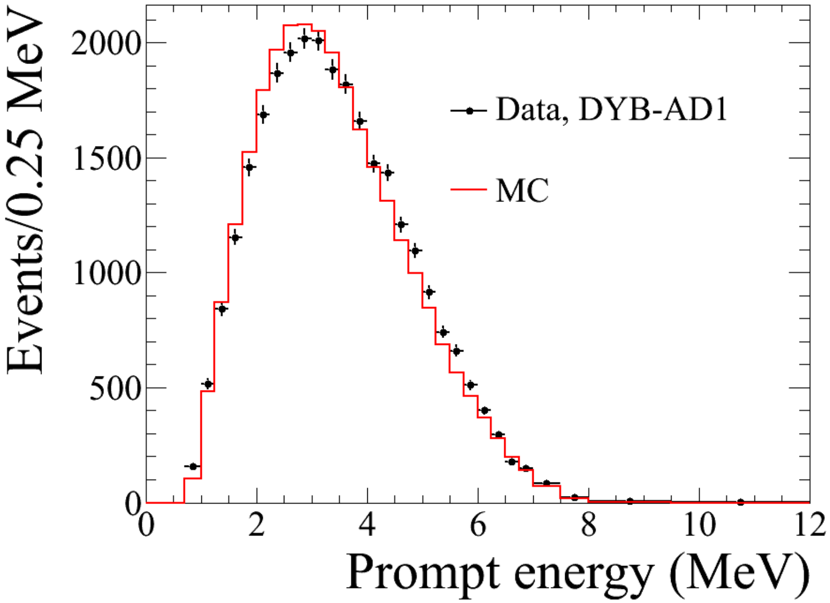
Neutrons (Delayed)

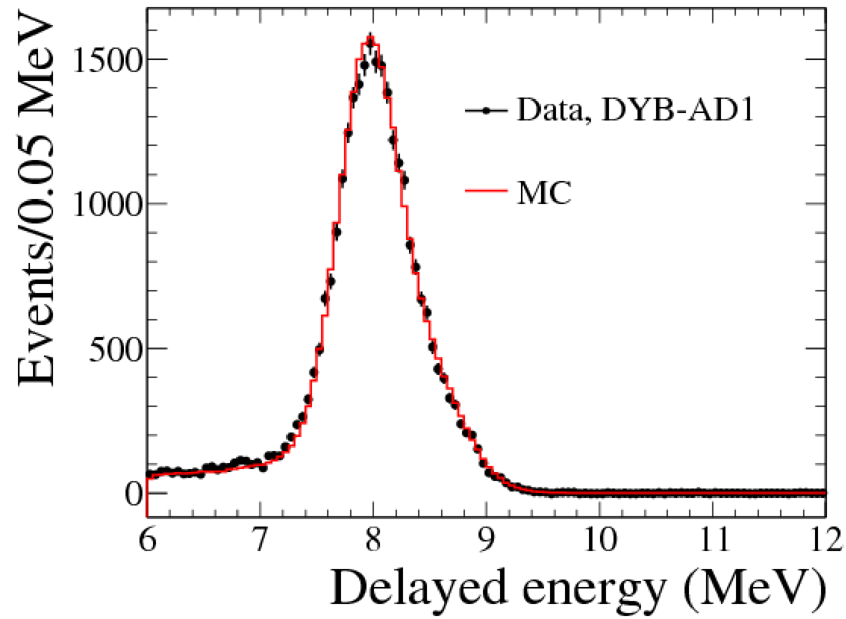
Neutrino Event Selection

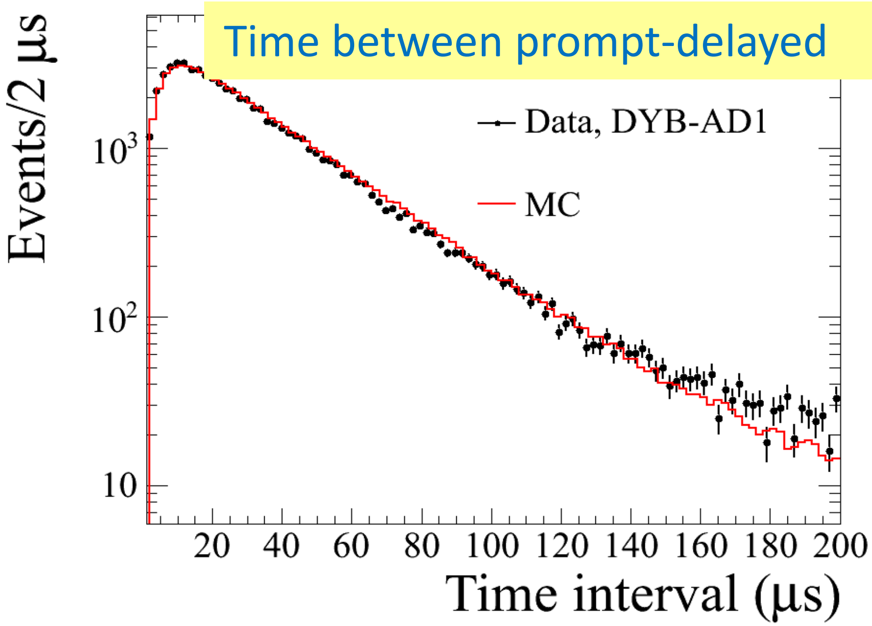
- **Pre-selection**
  - **Reject Flashers**
  - **Reject Triggers within (-2 μs, 200 μs) to a tagged water pool muon**
- **Neutrino event selection**
  - **Multiplicity cut**
    - Prompt-delayed pairs within a time interval of 200 μs
    - No triggers(E > 0.7MeV) before the prompt signal and after the delayed signal by 200 μs
  - **Muon veto**
    - *1s* after an AD shower muon (He8/Li9)
    - *1ms* after an AD muon (double n)
    - *0.6ms* after an WP muon
  - **$0.7MeV < E_{prompt} < 12.0MeV$**
  - **$6.0MeV < E_{delayed} < 12.0MeV$**
  - **$1\mu s < \Delta t_{e^+\text{-}n} < 200\mu s$**

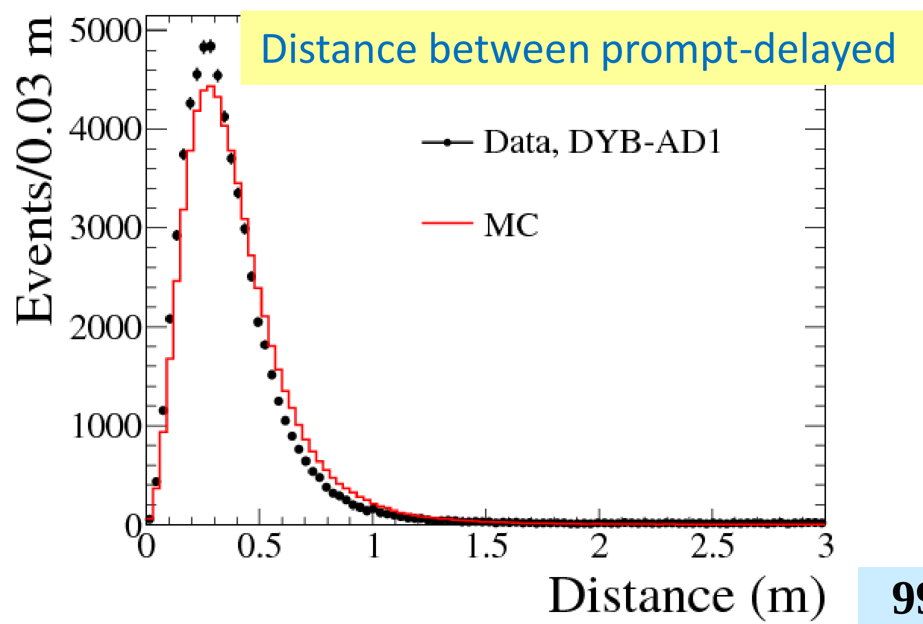


Selected Signal Events









Efficiency and Uncertainty

每做一次挑选（cut条件）就会带来一个误差！

- 不同探测器之间的差别当成误差（非关联）

	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Total	78.8%	1.9%	0.2%

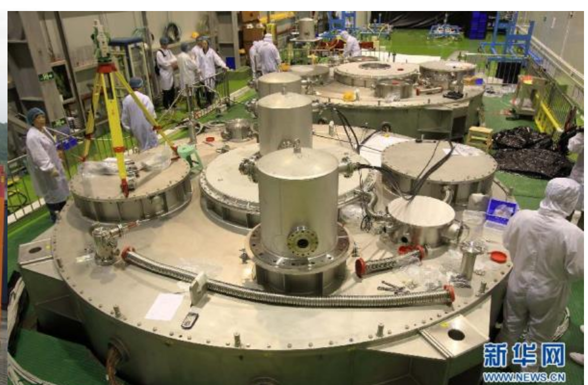
Functional Identical Detectors

- **Why systematics is so small?** c.f. An et al. NIM. A 685 (2012) 78
  - **Idea of "identical detectors" throughout the procedures of design / fabrication / assembly / filling.**
  - **For example: Inner Acrylic Vessel, designed D=3120±5 mm**
    - Variation of D by geometry survey=**1.7mm**, Var. of volume: 0.17%
    - Target mass var. by load cell measurement during filling: 0.19%

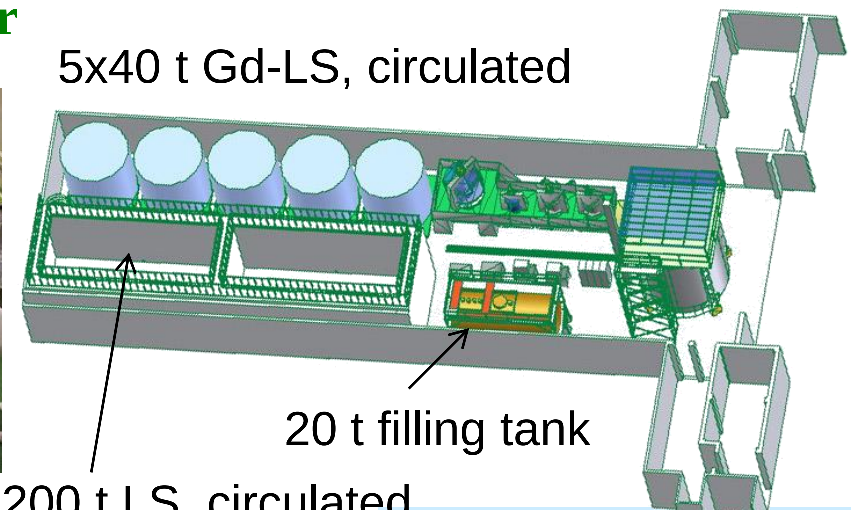
Diameter	IAV1	IAV2	IAV3	IAV4	IAV5	IAV6
Surveyed(mm)	3123.12	3121.71	3121.77	3119.65	3125.11	3121.56
Variation (mm)	1.3	2.0	2.3	1.8	1.5	2.3

  - **"Same batch" of liquid scintillator**

4-m AV in pairs

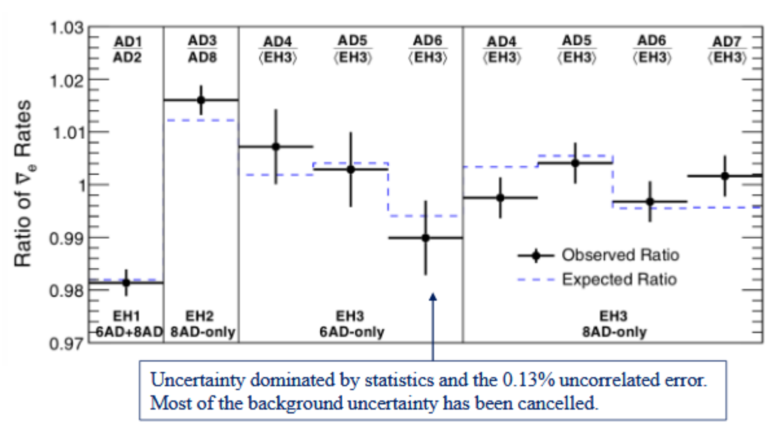


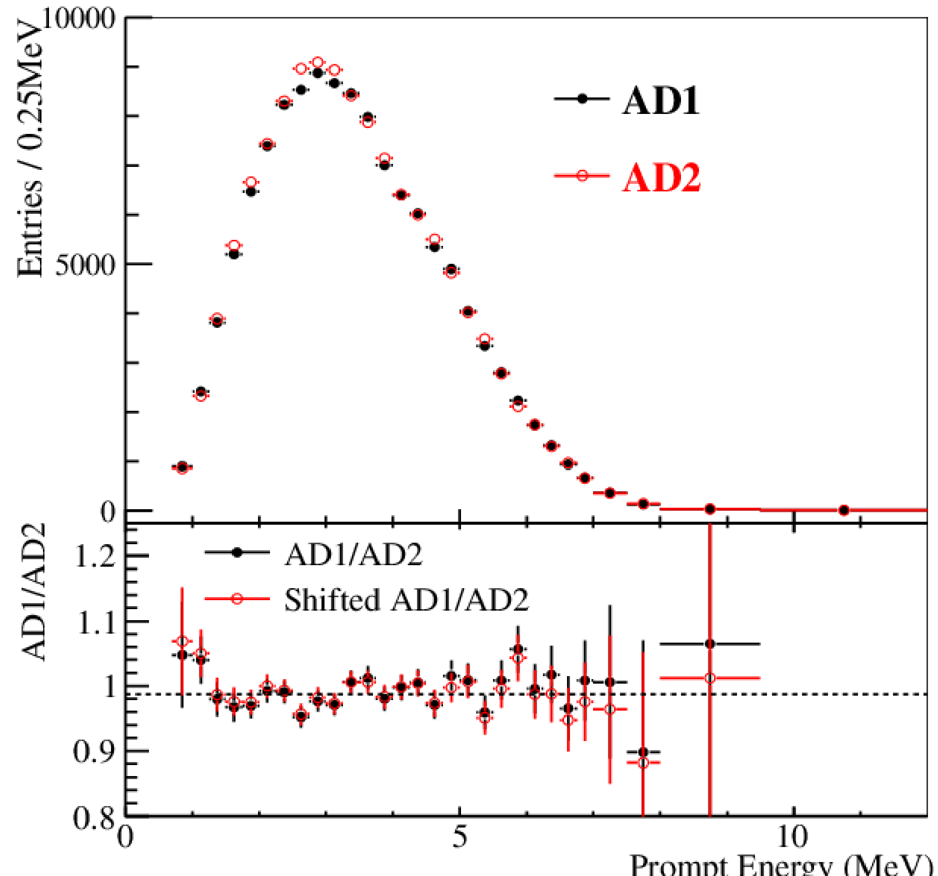
Assembly in pairs



Side-by-side Comparison

- **Expected ratio of neutrino events: R(AD1/AD2) = 0.982**
- **Measured ratio: 0.987 ± 0.004(stat) ± 0.003(syst)**

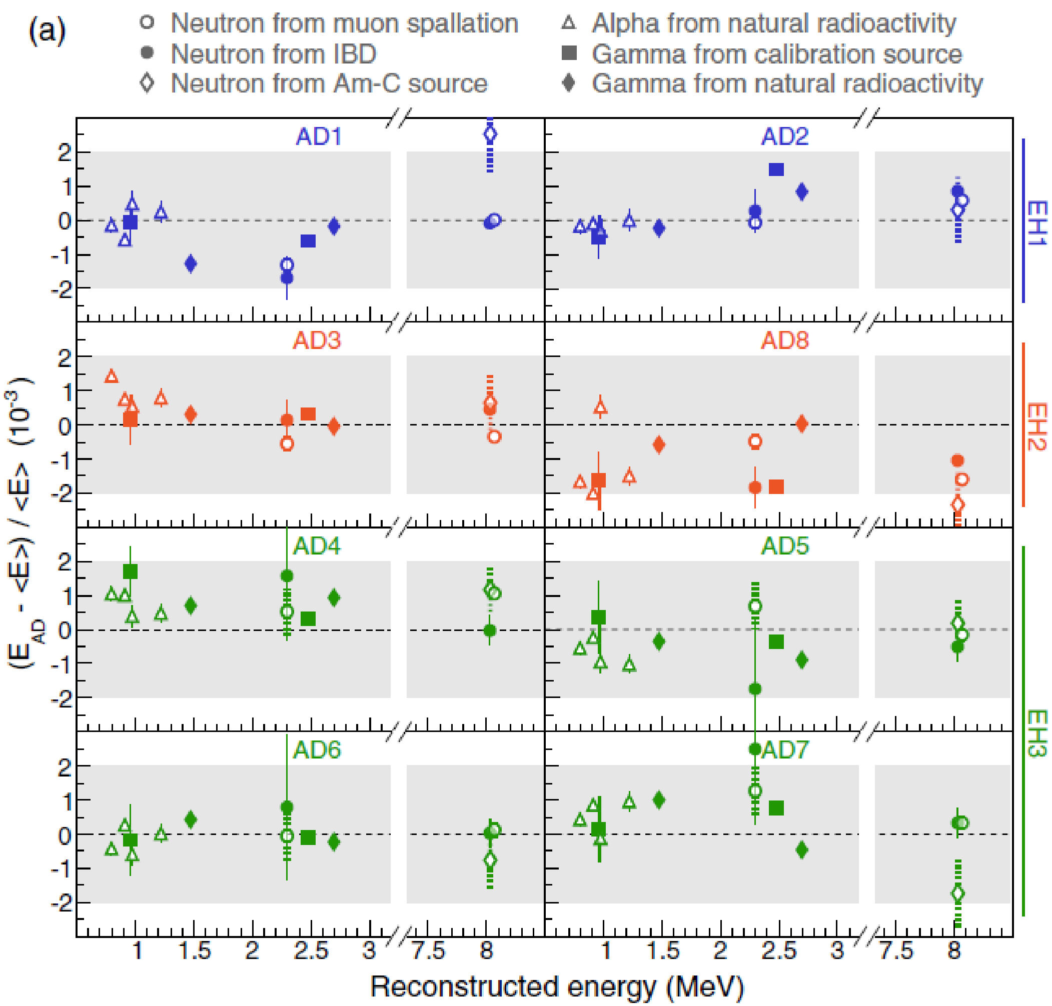


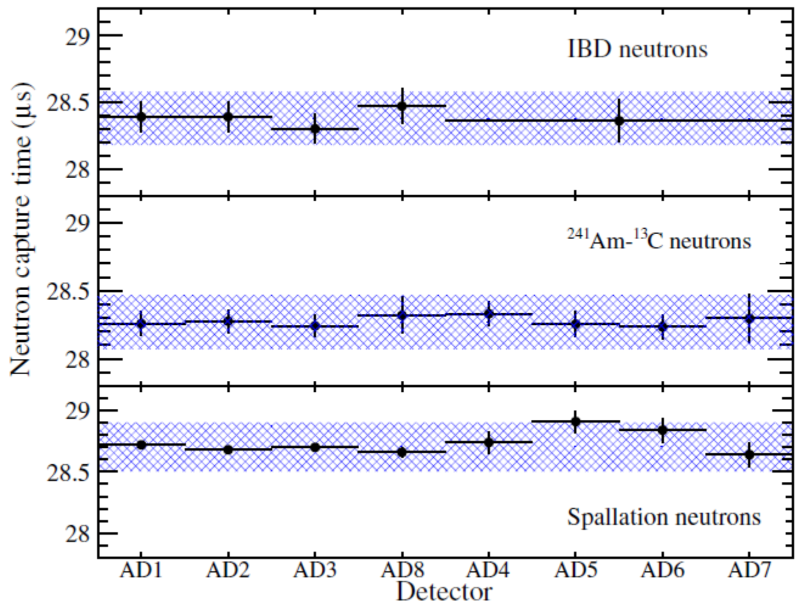


This check shows that systematic errors are under control, and will verify the final systematic error

Data set: Dec 24 to May 11

Side-by-side comparison





7 - Background

本底（设计值）

来源：宇宙线，天然放射性，从以前实验的经验：

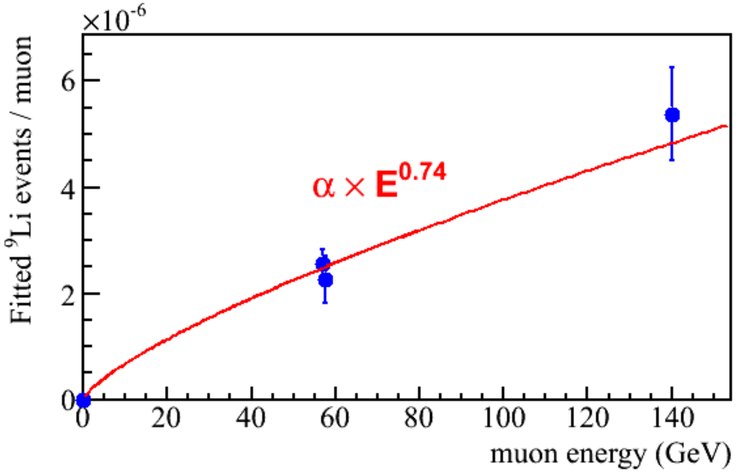
- $^{9}Li/^{8}He$ （关联本底）（估计B/S 0.3%）
  - ⇨ 宇宙线产生的长寿命同位素，β-n级联衰变，与中微子信号类似。
- “快中子” 本底 （关联本底）（估计B/S 0.1-0.2%)
  - ⇨ 宇宙线产生的高能中子，中子与质子碰撞形成快信号，慢化中子形成慢信号。
  - ⇨ 中子在碳、氧核中俘获，发射高能中子。
- 偶然符合本底（估计B/S ~1%，减除误差 ~0.1%）
  - ⇨ 类正电子信号 (单事例率 <100 Hz)
    - 天然放射性 (PMT, 岩石, 钢罐, 液闪, … <50 Hz)
    - 宇宙线、宇宙线产生的同位素，等等
  - ⇨ 类中子信号 (<200/day)
    - 单中子：宇宙线产生的、未留下质子反冲信号的中子。
    - 宇宙线产生的长寿命同位素 (例如 $^{12}B/^{12}N$)
    - 其它在 6-10 MeV 范围内的事例 (例如 Michel’s electron, 宇宙线等)

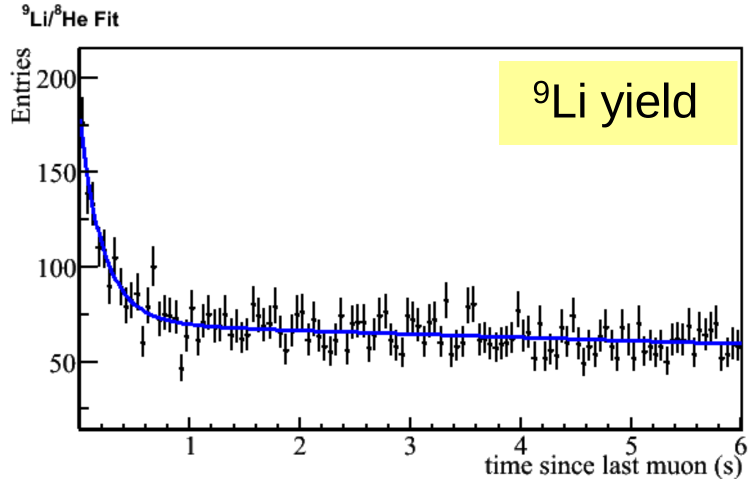
1 – $^{8}He/^{9}Li$

- **Cosmic μ produced $^{9}Li/^{8}He$ in LS**
  - **β-decay + neutron emitter**
  - **$\tau(^{8}He/^{9}Li) = 171.7ms/257.2ms$**
  - **$^{8}He/^{9}Li$, Br(n) = 12%/48%, ^{9}Li dominant**
  - **Production rate follow $E_{\mu}^{0.74}$ power law**
- **Measurement:**
  - **Time-since-last-muon fit**

$$f(t) = B/\lambda \cdot e^{-t/\lambda} + S/T \cdot e^{-t/T}$$

  - **Improve the precision by reducing the muon rate:**
    - **Select only muons with an energy deposit >1.8MeV within a [10us, 200us] window**
    - **Issue: possible inefficiency of ^{9}Li**
  - **Results w/ and w/o the reduction is studied**





Error follows

$$\sigma_b = \frac{1}{N} \cdot \sqrt{(1+\tau R_\mu)^2 - 1}$$

NIM A564 (2006)471

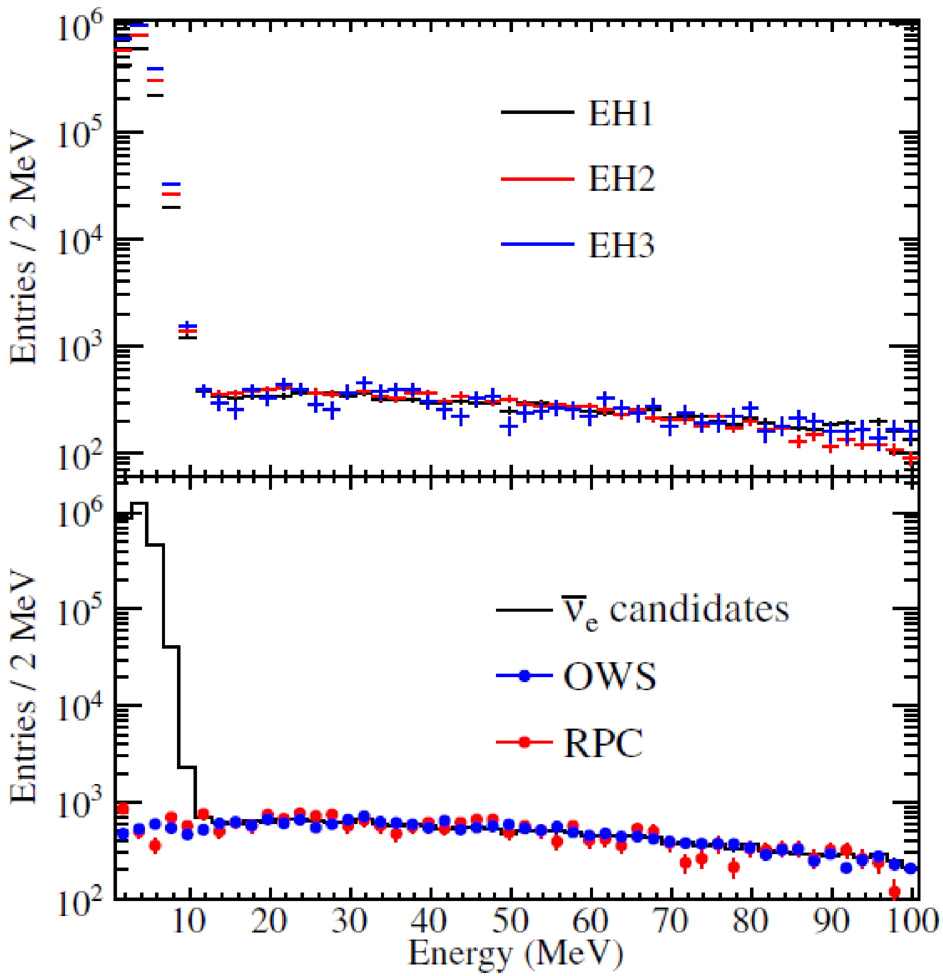
2 - Fast Neutron

宇宙线muon产生高能中子

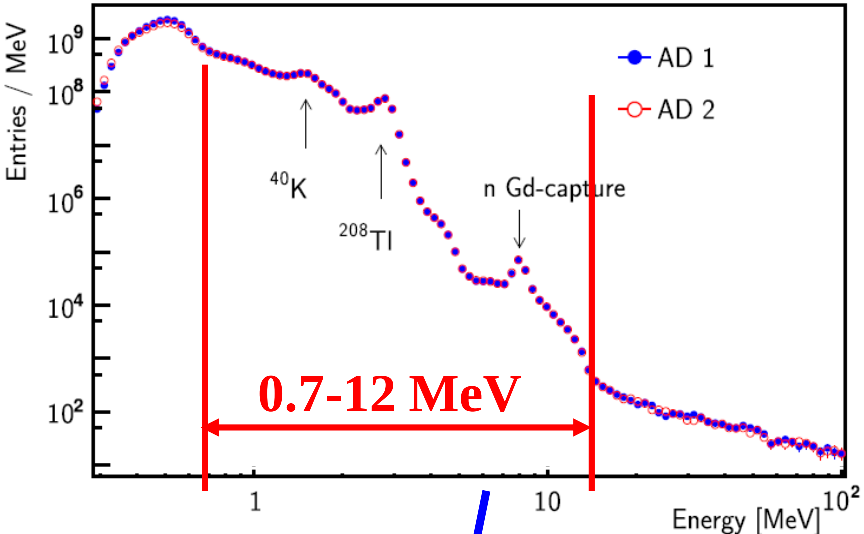
- 质子反冲（快信号）
- 慢化中子俘获（慢信号）

方法1 ：外推

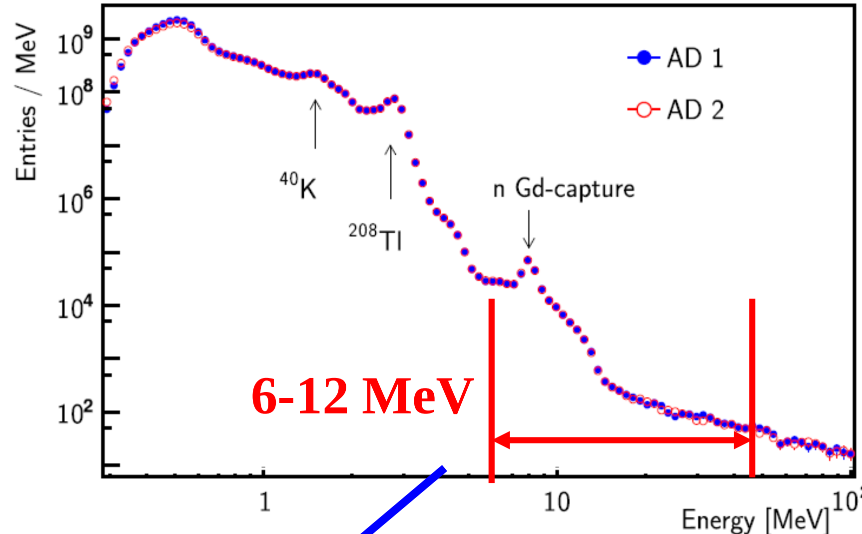
方法2： 本底样本



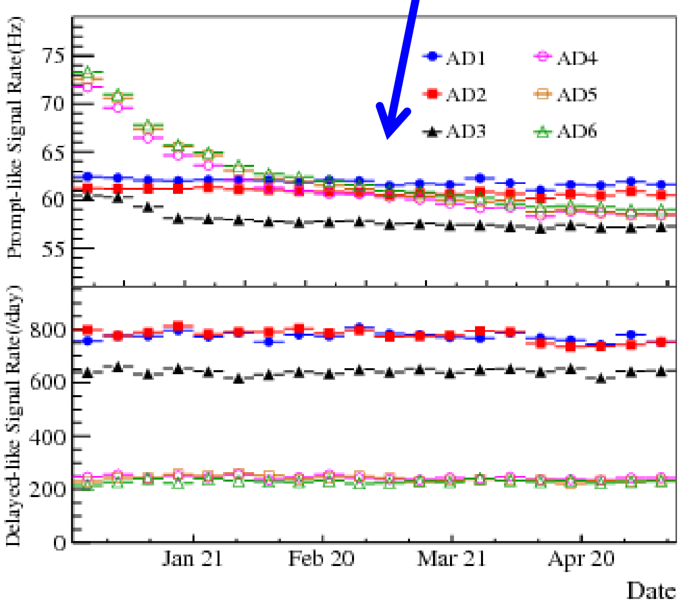
3 - Accidental

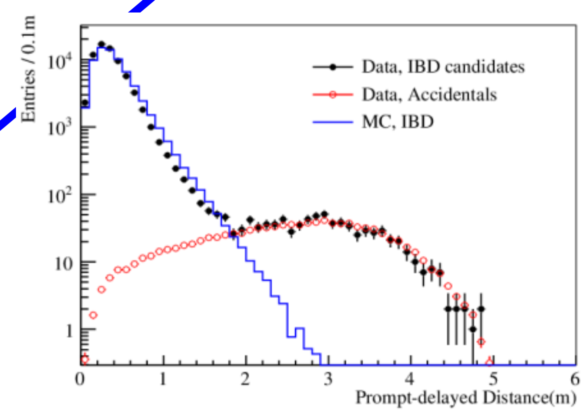


Prompt candidate



Delayed candidate





方法1：Evaluated by coincidence probability

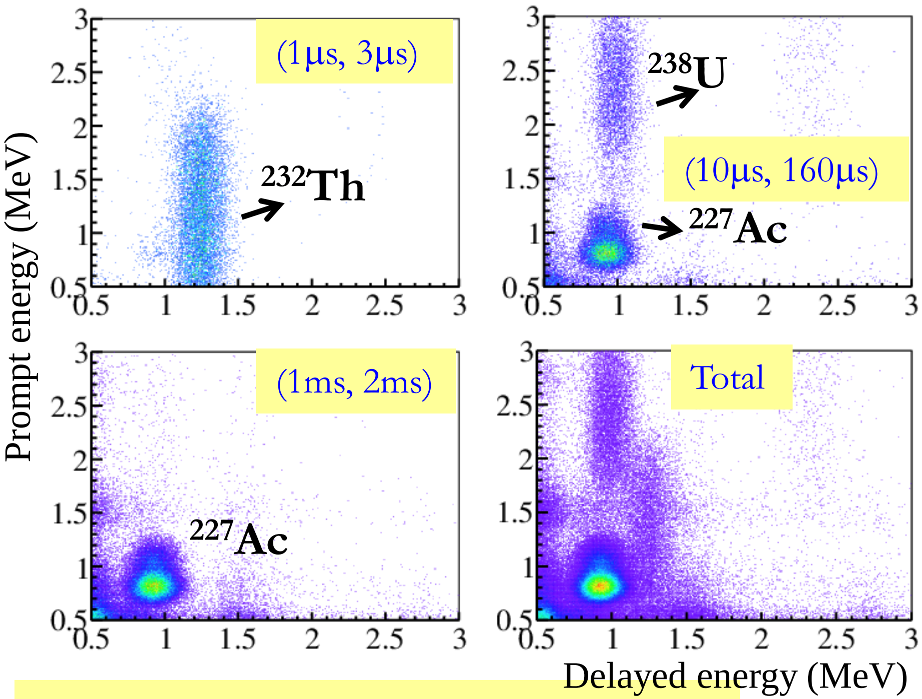
方法2：off-windows coincidence

方法3： vertex distance distribution

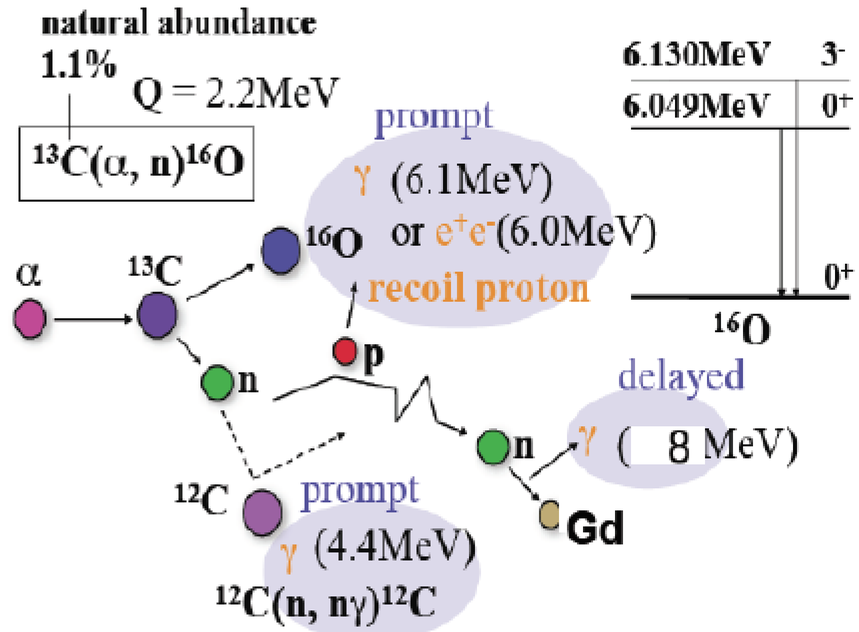
4,5 – neutron souce and $^{13}C(\alpha,n)^{16}O$

- 中子源本底：大亚湾独有
- Alpha-n本底，KamLAND实验

B/S @ EH1/2 ~ 0.01%, B/S @ EH3 ~ 0.05%， ΔB/B ~ 50%

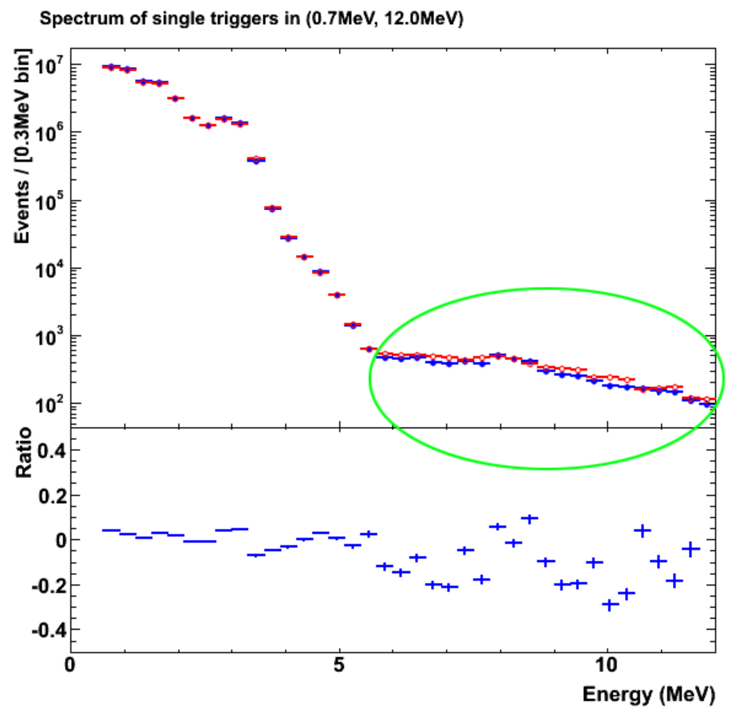


Time correlations of the cascade decays



排它性分析

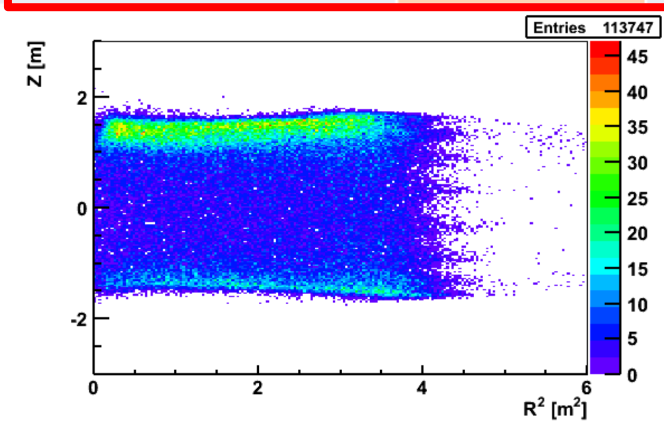
- 为什么中子能区有这么多事例？(6.0~12.0MeV)?
- **Possible sources**

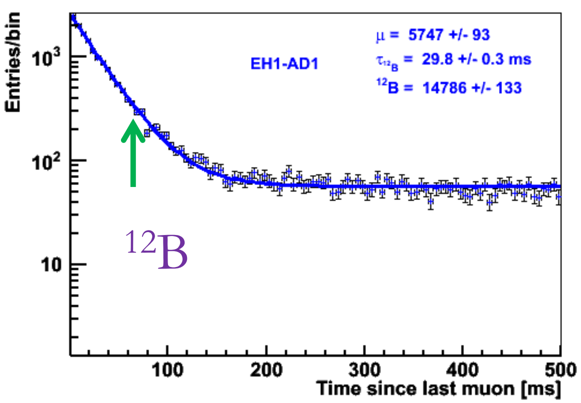


- 排它性分析（Exclusive）：假如我们找到了全部事例的来源，就不存在未知本底

中子能区事例

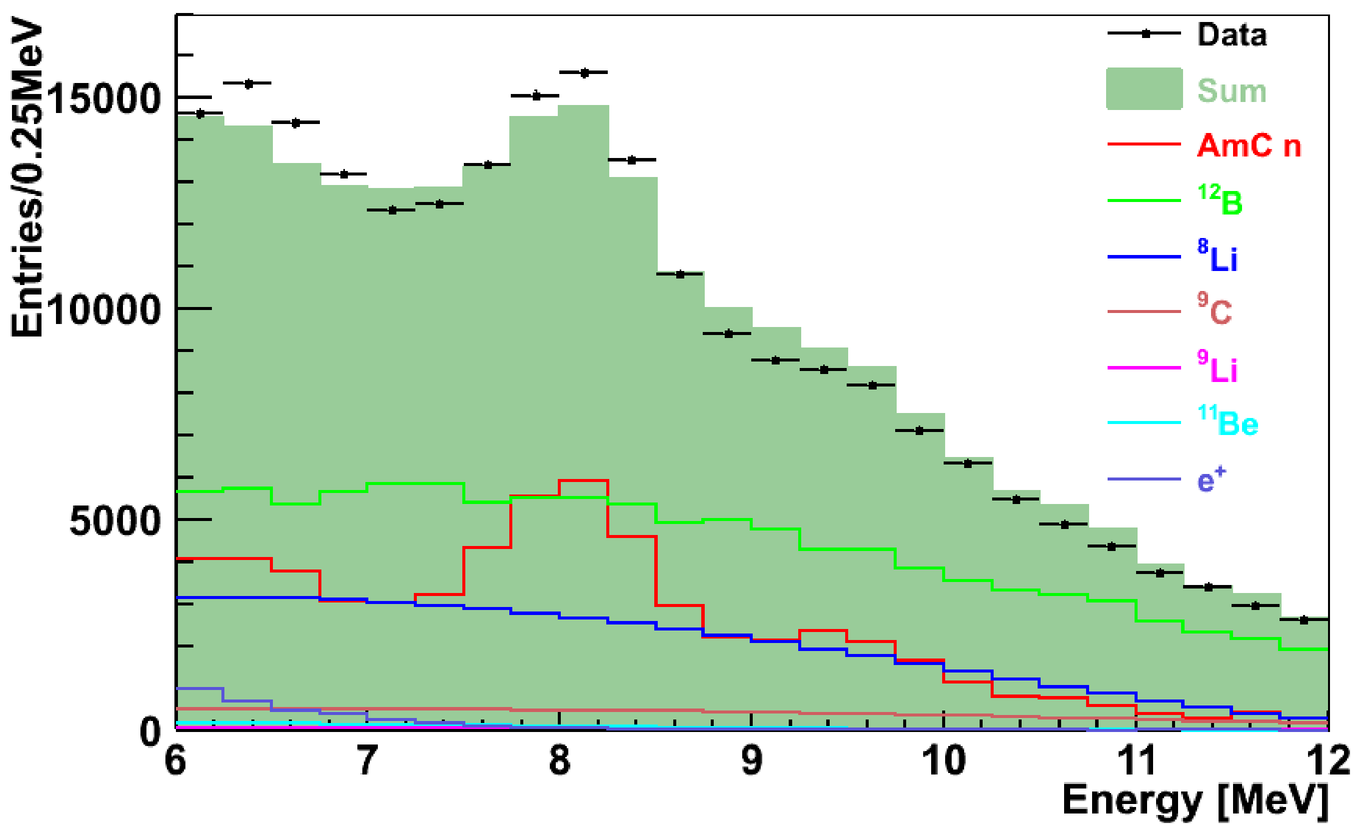
Sources	EH1		EH2		EH3	
	Rate (/day/AD)	Fraction	Rate (/day/AD)	Fraction	Rate (/day/AD)	Fraction
AmC neutron	271+-10	26.3+-1.0	277+-7	33.0+-0.8	205+-11	74.3+-5.5%
$^{12}B/^{12}N$	478+-13	46.4+-1.3%	354+-4	42.1+-0.5%	35+-2	12.7+-1.0%
$^{8}Li/^{8}B$	216+-18	21.0+-1.8%	155+-16	18.5+-1.9%	16+-5	5.8+-1.8%
^{9}C	40+-16	3.8+-1.6%	24+-9	2.9+-1.1%	4+-4	1.4+-1.4%
$^{9}Li/^{8}He$	4+-2	0.4+-0.2%	3+-2	0.4+-0.2%	<1	<0.4%
^{11}Be	7+-4	0.7+-0.4%	5+-3	0.6+-0.4%	<1	<0.4%
IBD e^+ (n captured on H)	14+-1	1.4+-0.1%	12+-1	1.4+-0.1%	2+-1	0.7+-0.4%
Sum	1030+-29	100.0+-2.9%	830+-20	98.8+-2.4%	262+-13	94.9+-6.7%
All singles	1030+-7	-----	840+-3	-----	276+-14	-----



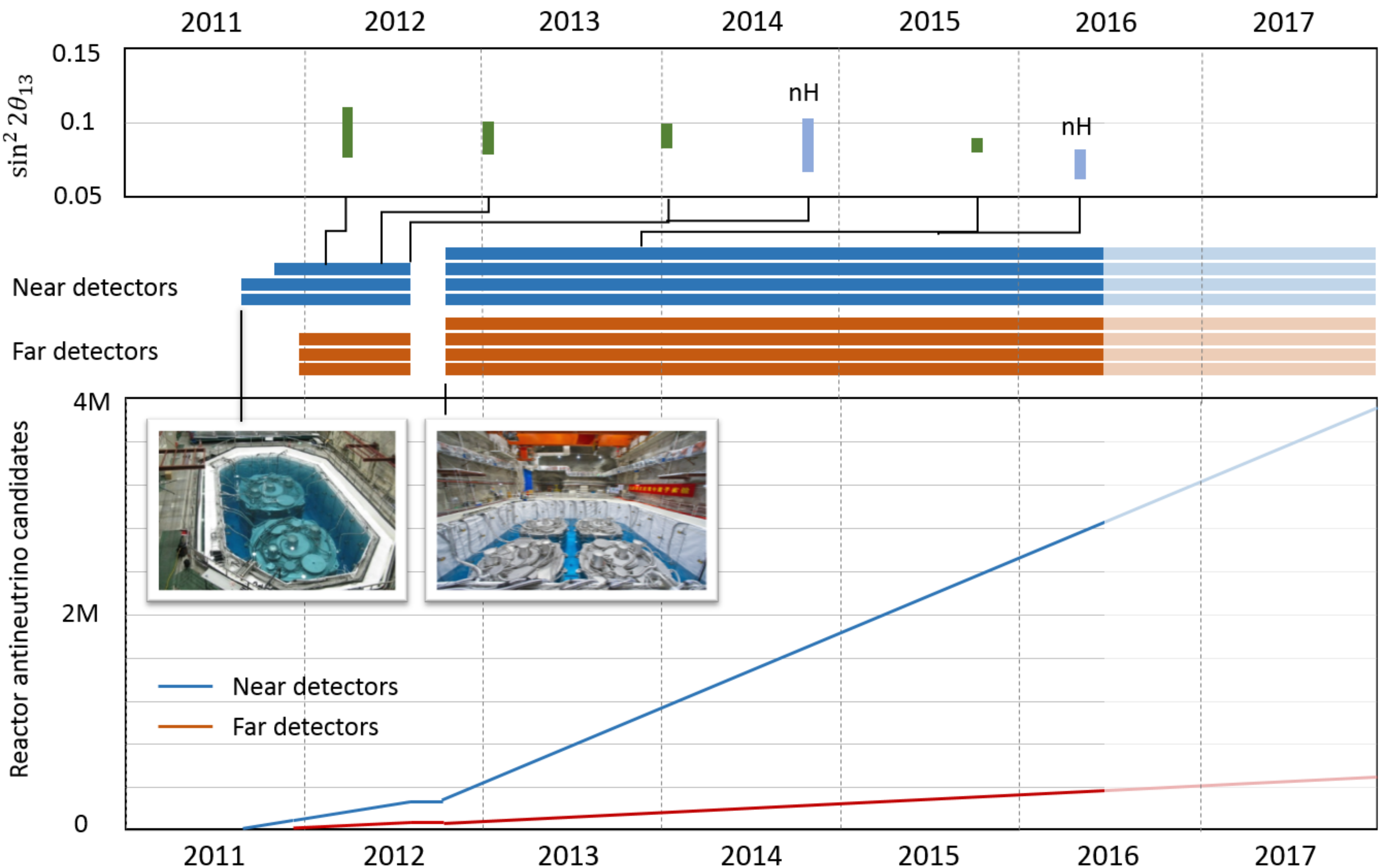


中子能区事例能谱的比较

- 各分量求和得到的能谱与总能谱比较
- 理解了探测器事例，没有大的未知本底（排它性）



大亚湾运行历史



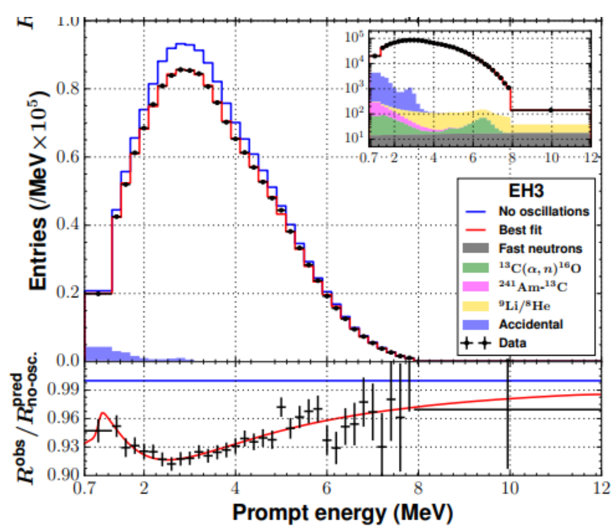
2011
2012
2013
2014
2015
2016
2017
0.15
0.1
0.05
$\sin^2 2\theta_{13}$
nH
nH
Near detectors
Far detectors
4M
2M
0
Reactor antineutrino candidates
Near detectors
Far detectors
2011
2012
2013
2014
2015
2016
2017

课后练习

◆ 本底闯三关

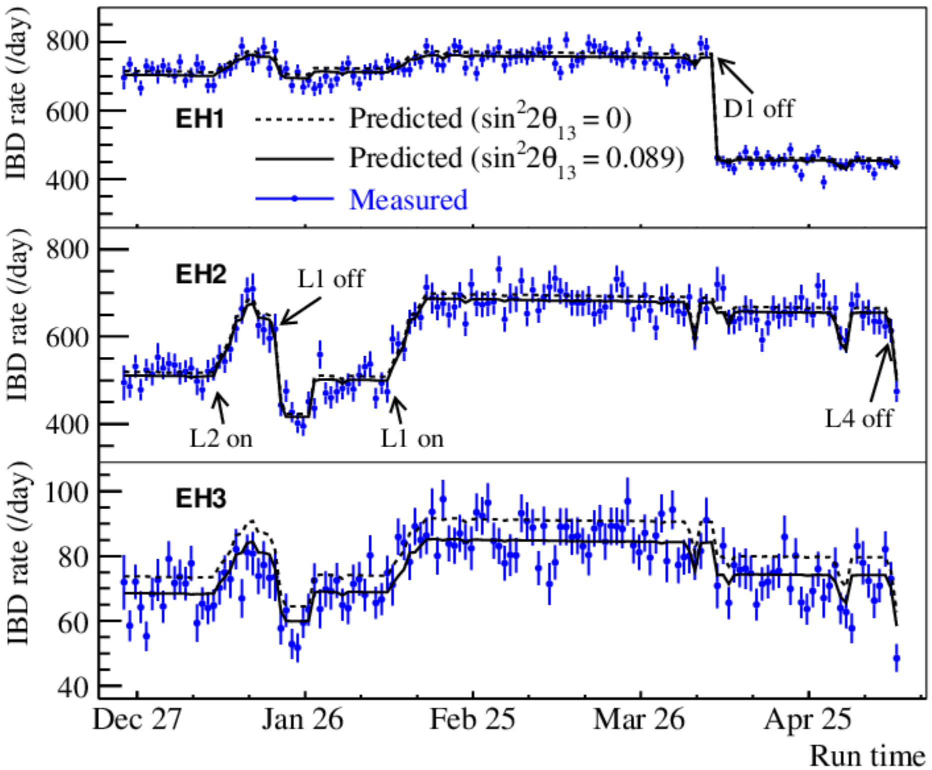
	Shielding	Selection cut	Subtraction (estimation)
Accidental			
He8/Li9			
Fast neutron			

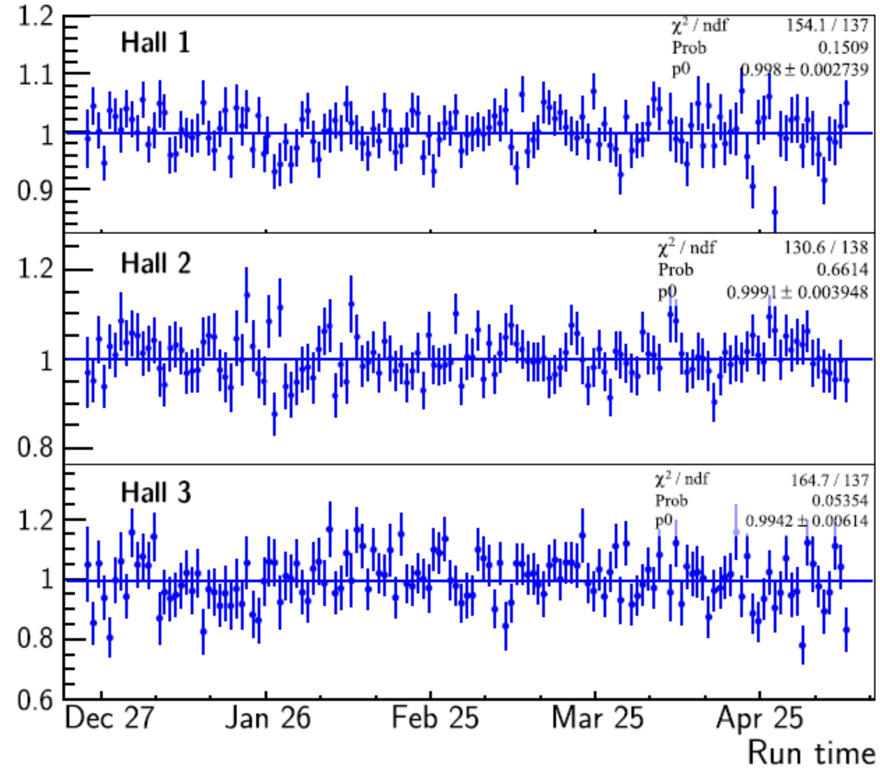
◆ 问题：如果本底能够通过估计，减除掉，还需要花钱做shielding吗？



8 – 振荡参数结果

Observed Neutrino Rate





$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d\right) + \eta_d\right]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$

6个数据点（探测器），三大误差来源：反应堆、探测器、本底

远近比值

$$R=\frac{M_f}{\overline{N}_f}=\frac{M_f}{\alpha M_a+\beta M_b}$$

- **归一化条件：无振荡时R＝1**

$$\sum_i f_i\overline{\nu}_i=\alpha\sum_i a_i\overline{\nu}_i+\beta\sum_i b_i\overline{\nu}_i\,.$$

denote $F=\sum_i f_i\overline{\nu}_i$, $A=\sum_i a_i\overline{\nu}_i$, and $B=\sum_i b_i\overline{\nu}_i$.

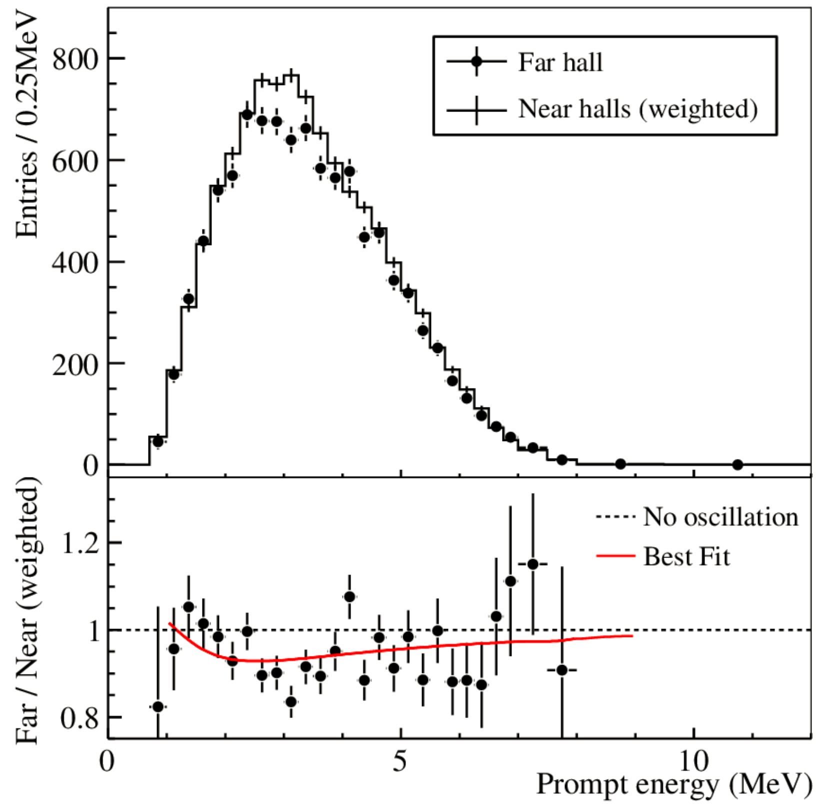
$$\beta=(F-\alpha A)/B\,.$$

- **误差最小化条件**

$$\Delta N_f=N_f-\overline{N}_f=\sum_i f_i\nu_i-(\alpha M_a+\beta M_b)$$

$$\sigma^2_{\Delta N}=\sum_i(f_i-\alpha a_i-\beta b_i)^2\sigma^2\,.$$

$$\frac{\partial\sigma^2_{\Delta N}}{\partial\alpha}=0\,,$$

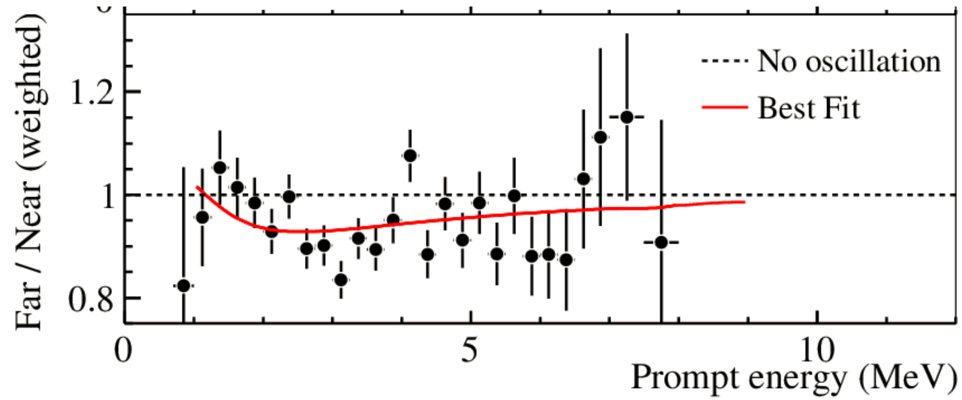


$$R=0.944\pm0.007(\mathrm{stat})\pm0.003(\mathrm{syst})$$

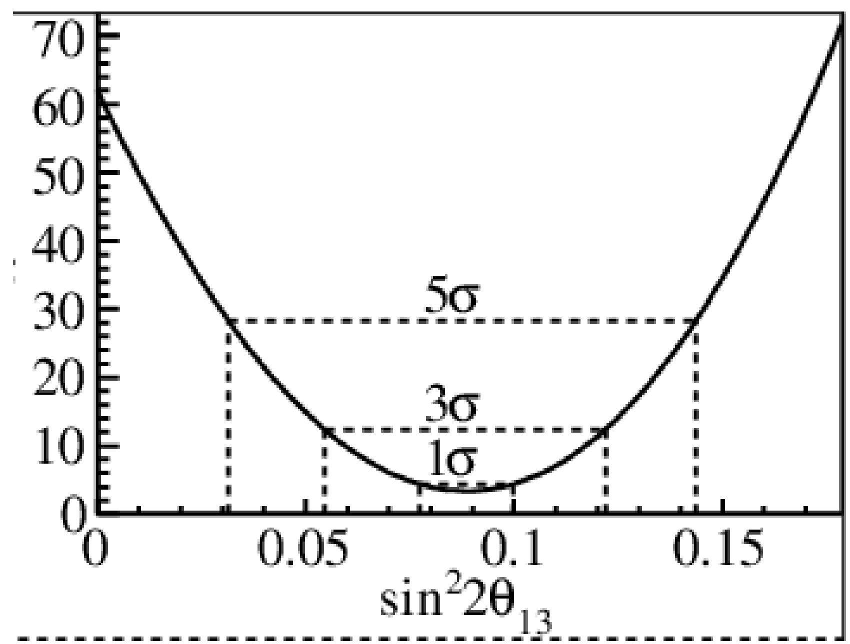
假如无振荡，则远点中微子丢失5.6%。总误差为0.0076。由统计涨落造成缺失的概率为7.4 sigma

χ^2 与$\Delta\chi^2$

- 假设检验与参数拟合
- 假设检验：理论与数据符合得好不好，χ^2/ndf（拟合的优度）
- 参数拟合：假定理论是对的，确定参数。
- χ^2，χ^2_{min}，与$\Delta\chi^2$



$$\chi_1^2 = \frac{(T-O)^2}{T+T^2\sigma_{sys}^2} = \min_{\alpha}\left\{\frac{[T(1+\alpha)-O]^2}{T} + \frac{\alpha^2}{\sigma_{sys}^2}\right\}$$



Rate-only analysis

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1+\varepsilon+\sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$

大亚湾分析中ndf应该等于几？

M_d：第d个AD的测量中微子数

T_d：第d个AD的预测中微子数

B_d：第d个AD的本底数

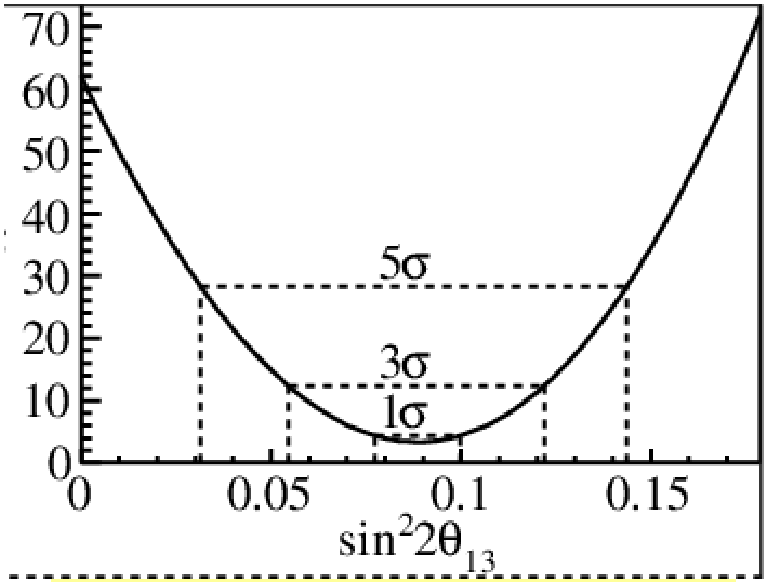
ε：整体归一化系数，对应反应关联误差与探测器关联误差3.6%。分析时未加约束，即完全相对测量

ω^d_r：第r个反应堆对第d个探测器的中微子贡献比例

α_r：反应非关联误差，对应σ_r＝0.8%

ε_d：探测器非关联误差，对应σ_d＝0.2%

η_d：本底误差，对应σ_d=0.2-0.37%（对应的信号与本底表）



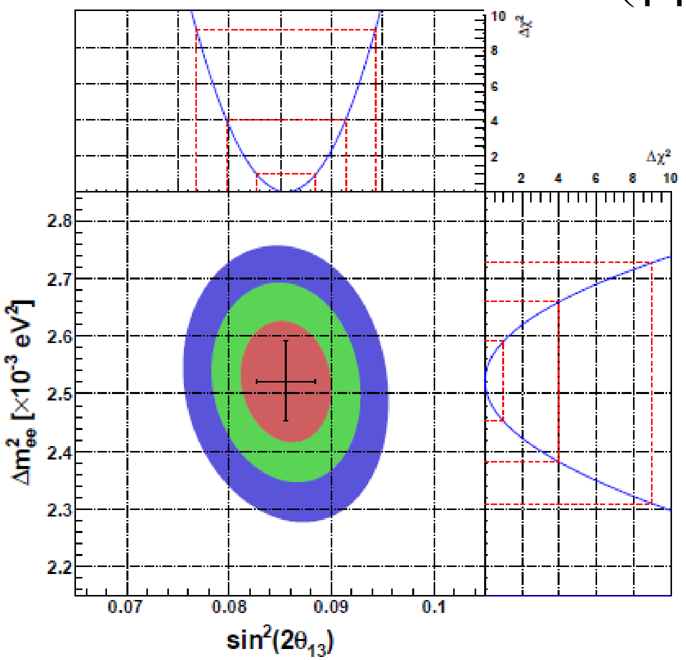
$\sin^2 2\theta_{13}$=0.089±0.010(stat)±0.005(syst)

精确的θ_{13}测量

Release time	Data	Config	$\sin^2 2\theta_{13}$	Δm^2_{ee}
2012/3/8 [17]	55 days	6 ADs	$0.092 \pm 0.016 \pm 0.005$	-
2012/10/23 [18]	139 days	6 ADs	$0.089 \pm 0.010 \pm 0.005$	-
2013/10/24 [20]	217 days	6 ADs	$0.090^{+0.008}_{-0.009}$	$2.59^{+0.19}_{-0.20}$
2014/6/24 [19]	217 days	6 ADs (nH)	0.083 ± 0.018	-
2015/5/13 [21]	621 days	6+8 ADs	0.084 ± 0.005	2.42 ± 0.11
2016/3/14 [22]	621 days	6+8 ADs (nH)	0.071 ± 0.011	-
2016/7/5 [23]	1230 days	6+8 ADs	0.0841 ± 0.0033	2.50 ± 0.08

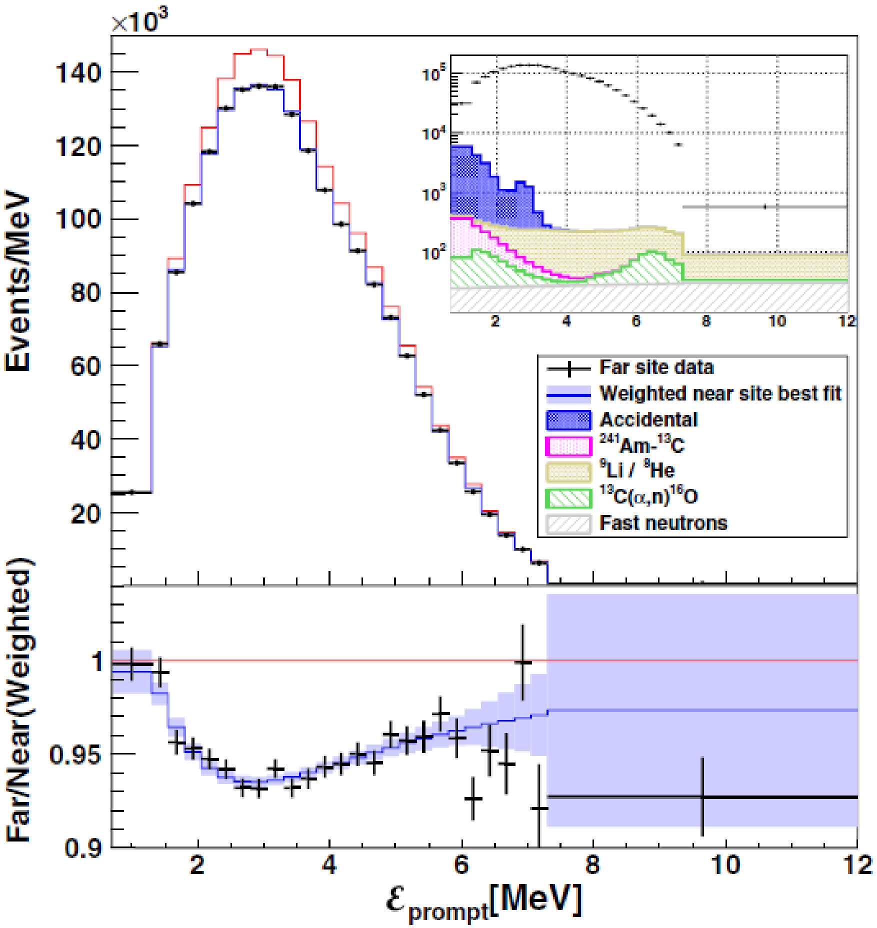
2018年基于1958天数据最新结果：$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

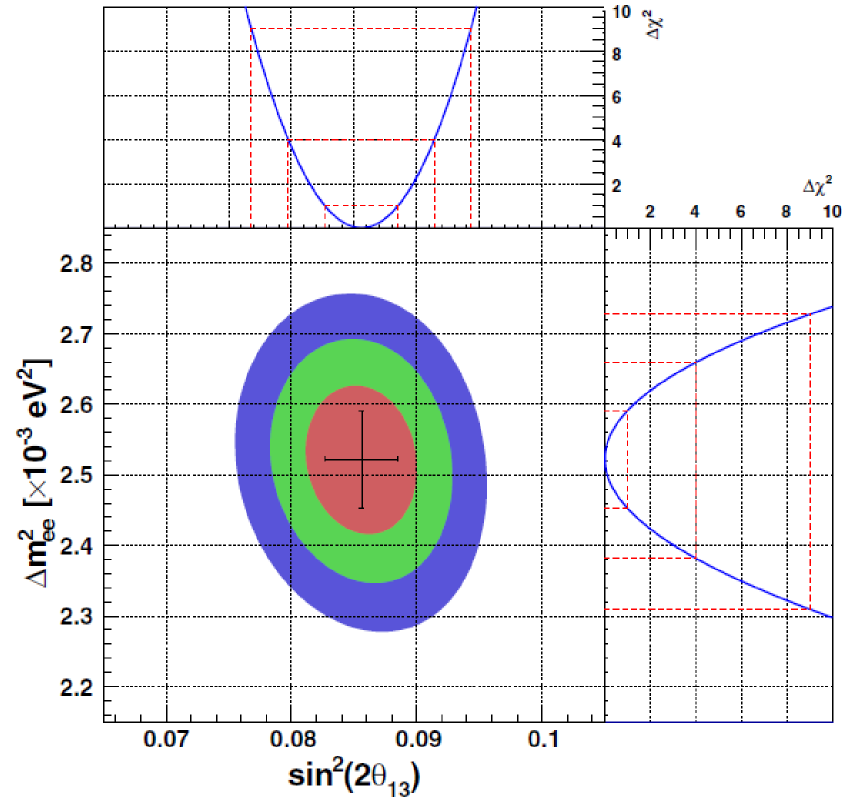
（PRL接收）



- 6次发表 θ_{13}测量结果，（另有两次nH独立测量），误差从20%降低到3.4%。
- 首篇论文引用在粒子物理领域2011年后发表的论文中排名第4。
- 4篇在当年的约5万篇论文中排名第77，92，219，180/3万。

Precision Measurement at Daya Bay





Using this method, values of $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ and $\Delta m^2_{ee} = (2.522^{+0.068}_{-0.070}) \times 10^{-3}$ eV^2 are obtained, with $\chi^2/\mathrm{NDF} = 148.0/154$. Consistent results are obtained

1958天数据

TABLE I. Summary of signal and backgrounds. Rates are corrected for the muon veto and multiplicity selection efficiencies $\varepsilon_\mu \cdot \varepsilon_m$. The procedure for estimating accidental, fast neutron, Am-C, and (α, n) backgrounds is unchanged from Ref. [7].

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\bar{\nu}_e$ candidates	830 036	964 381	889 171	784 736	127 107	127 726	126 666	113 922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
$\varepsilon_\mu \times \varepsilon_m$	0.8050	0.8013	0.8369	0.8360	0.9596	0.9595	0.9592	0.9595
Accidentals (day^{-1})	8.27±0.08	8.12±0.08	6.00±0.06	5.86±0.06	1.06±0.01	1.00±0.01	1.03±0.01	0.86±0.01
Fast neutron (AD^{-1} day^{-1})	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^{9}Li/^{8}He (AD^{-1} day^{-1})	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated (day^{-1})	0.17±0.07	0.15±0.07	0.14±0.06	0.13±0.06	0.06±0.03	0.05±0.02	0.05±0.02	0.04±0.02
^{13}C (α, n) ^{16}O (day^{-1})	0.08±0.04	0.06±0.03	0.04±0.02	0.06±0.03	0.04±0.02	0.04±0.02	0.04±0.02	0.04±0.02
$\bar{\nu}_e$ rate (day^{-1})	659.36±1.00	681.09±0.98	601.83±0.82	595.82±0.85	74.75±0.23	75.19±0.23	74.56±0.23	75.33±0.24

- **思考题**
  - ⇨ 统计误差？
  - ⇨ 系统误差？
  - ⇨ 为什么$\sin^2 2\theta_{13}$误差为3%？

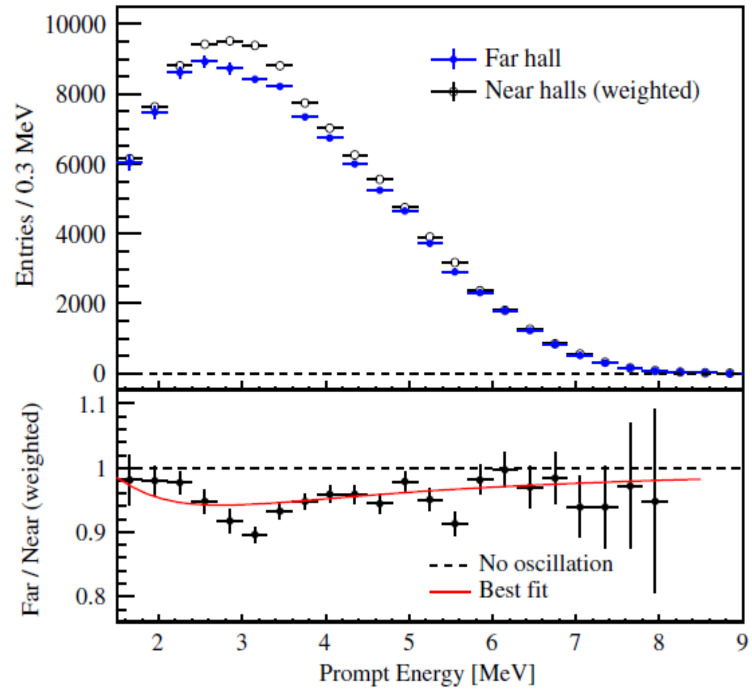
	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill in	104.9%	1.00%	0.02%
Live time	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

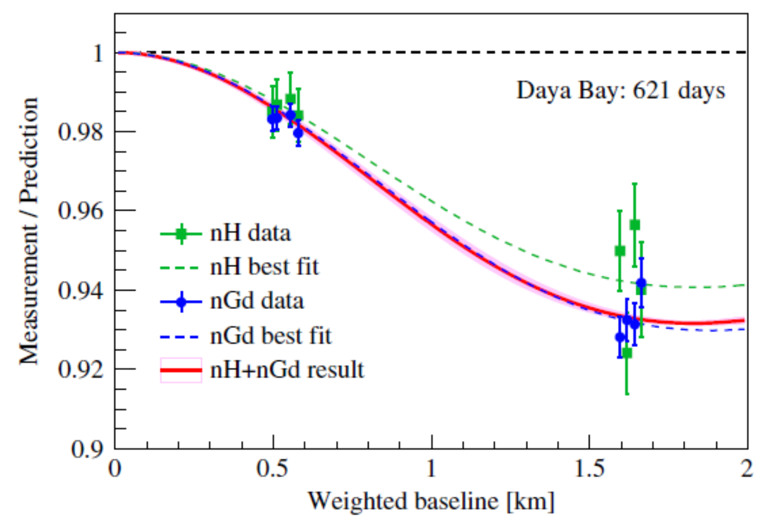
利用n-H中微子事例独立测量θ_{13}

- **主要特点**：独立的数据量，不同的系统误差
- **挑战**：较高的偶然符合本底（远厅12%，近厅54%）
- **策略**：提高快信号能量阈值（>1.5MeV）和要求快慢信号距离（<0.5m）
- 利用**事例率亏损**做振荡分析：与n-Gd分析结果一致

数据（天）	$\sin^2 2\theta_{13}$	*参考文献*
217	0.083±0.018	**PRD 90, 071101(R) (2014)**
621	0.071±0.011	**PRD 93, 072011 (2016)**

- 能谱分析正在进行中





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Experimental Neutrino Physics

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Deadline on Jul 1, 2022

Job description:
The Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences in Beijing invites applications for **two** postdoctoral fellowship positions in Experimental Neutrino Physics.

IHEP carries out a comprehensive program in neutrino researches, including leading the Daya Bay (http://dayabay.ihep.ac.cn/) and JUNO (http://juno.ihep.ac.cn/) experiments, participating in EXO/nEXO, and actively carrying out R&D of detection technologies. The postdoc fellows are expected to play important roles in one or more aspects in the areas of data analysis with the Daya Bay experiment, design and construction of the JUNO experiment (including physics, software, detector, data acquisition, etc.), R&Ds of nEXO (including charge readout tiles, cold electronics, SiPMs readout, software, ICP-MS technologies, etc.), R&D of new technology, as well as neutrino phenomenology.

The positions are open to candidate of all nationalities. Candidates should have a PhD degree in related fields awarded in 6 years, or to be awarded when the term starts. The successful applicants will be based in Beijing, China. Knowledge of Chinese language is not required.

The position comes with an international competitive salary. Initial appointment will be made for two years, with possible renewal. The successful candidates could also compete for "Chung-Yao Chao Fellowship" hosted by CAS Center for Excellence in Particle Physics, and the "CAS President's International Fellowship Initiative" program (PIFI, http://international-talent.cas.cn/front/index.html#/bicsite/pifiIntroduce/pifi). The outstanding postdocs could also apply for research grants hosted by the China Postdoctoral Science Foundation.

The neutrino group in the Experimental Physics Division of IHEP has 14 employees including several professors: Yifang Wang, Jun Cao, Miao He, Liangjian Wen, Liang Zhan and Wuming Luo.

Interested candidates should submit applications including a curriculum vitae, a statement of research interest and plan, a list of publications, and three letters of recommendation to Miao He (hem@ihep.ac.cn) and Liang Zhan (zhanl@ihep.ac.cn).

Contact: He, Miao (hem@ihep.ac.cn); Zhan, Liang (zhanl@ihep.ac.cn)

- 待遇不错
- 机会难得 （JUNO实验2023年取数）

谢谢