# Поиск осцилляций нейтрино в реакторных экспериментах

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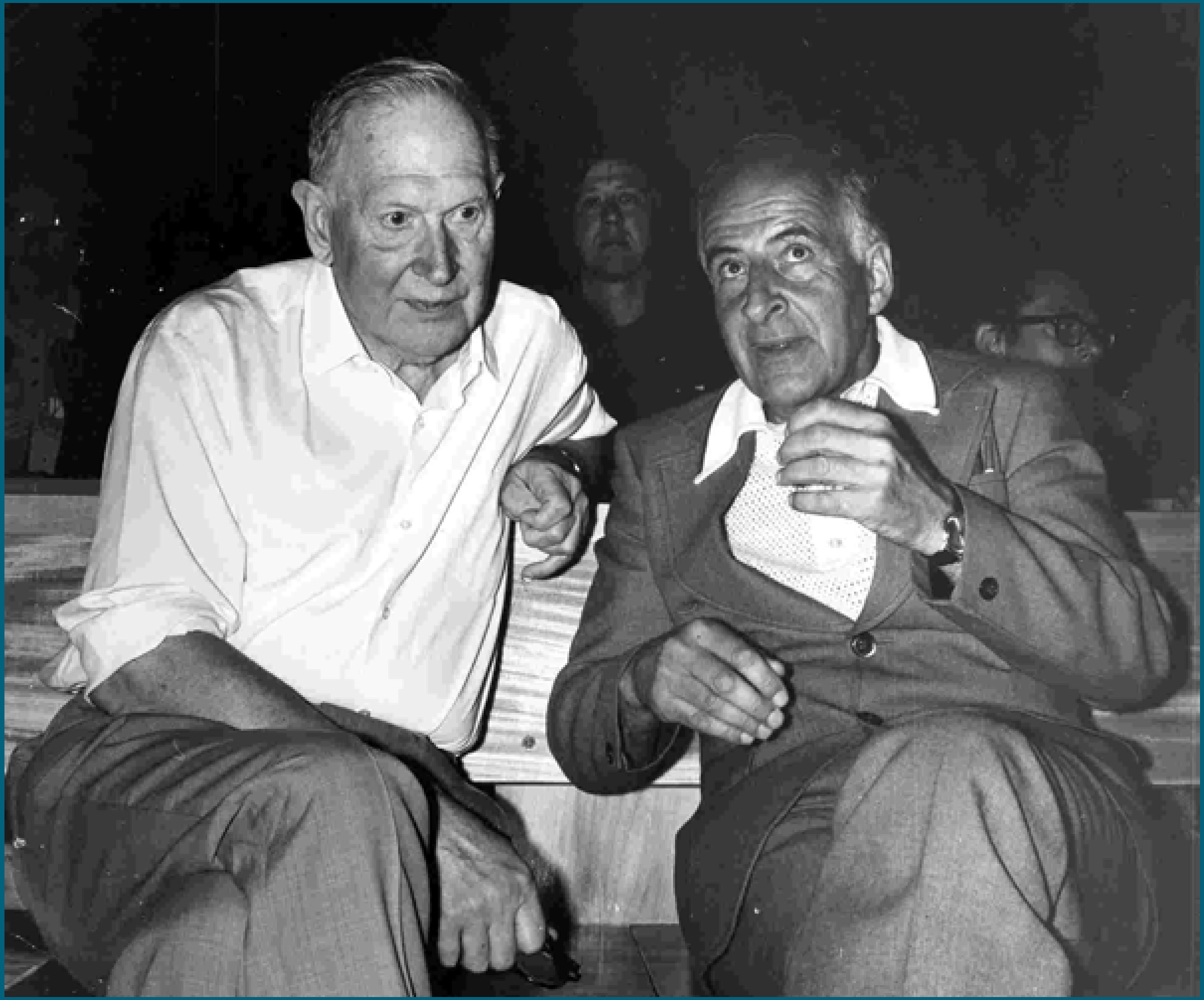
Марковские чтения

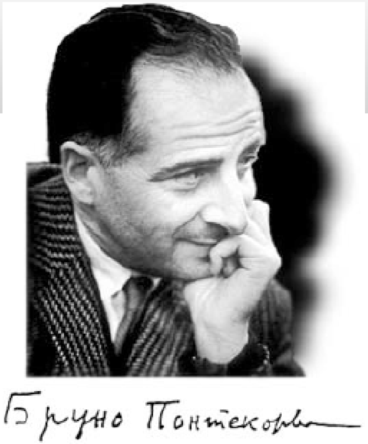
14 Мая 2013



М.А.Марков и Б.М.Понтекорво на Международной конференции по физике нейтрино и нейтринной астрофизике. Баксанское ущелье, Чегет, 1977 г.

# Introduction

## Nuclear Reactors as a Neutrino Source



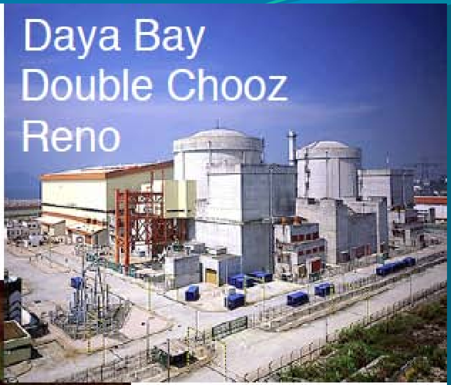
Reactors are intense and pure sources of $\bar{\nu}_e$

*B. Pontecorvo Natl.Res.Council Canada Rep. (1946) 205*
*Helv.Phys.Acta.Suppl. 3 (1950) 97*

Good for systematic studies of neutrinos.

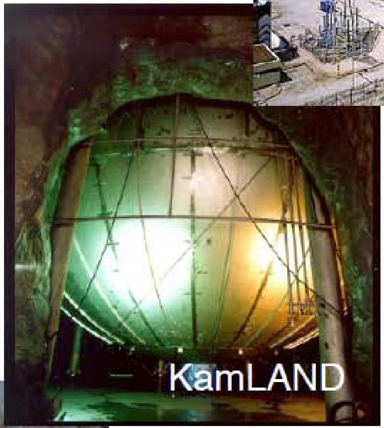
# 60 years of reactor neutrino physics

**2011/2012** - The year of $\theta_{13}$



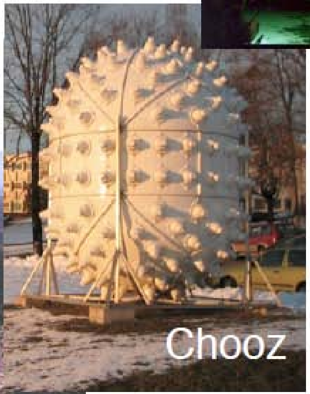

**2008** - Precision measurement of $\Delta m_{12}^2$. Evidence for oscillation

**2003** - First observation of reactor antineutrino disappearance

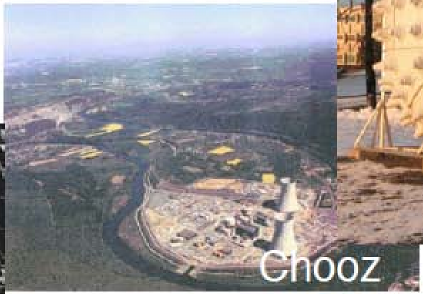



**1995** - Nobel Prize to Fred Reines at UC Irvine

**1980s & 1990s** - Reactor neutrino flux measurements in U.S. and Europe




**1956** - First observation of (anti)neutrinos





**Past Reactor Experiments**

- Hanford
- Savannah River
- ILL, France
- Bugey, France
- Rovno, Russia
- Goesgen, Switzerland
- Krasnoyark, Russia
- Palo Verde
- Chooz, France

1953 – first experiment at Hanford

# Матрица PMNS сегодня

## Neutrinos and mixing

Motoyasu Ikeda

Flavor $(e,\mu,\tau)$ Eigenstate $\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS} \times \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$ Mass $(m_1,m_2,m_3)$ Eigenstate

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

$$c_{ij} \equiv \cos\theta_{ij} \qquad s_{ij} \equiv \sin\theta_{ij}$$

### Current status

Solar and reactor (KamLAND)

$$\theta_{12} = 33.6° \pm 1.0°$$

Atmospheric, accelerator

$$\theta_{23} = 45° \pm 6° \quad (90\%\mathrm{CL})$$

Accelerator, reactor (DayaBay,DoubleChooz,RENO)

$$\theta_{13} = 9.1° \pm 0.6°!$$

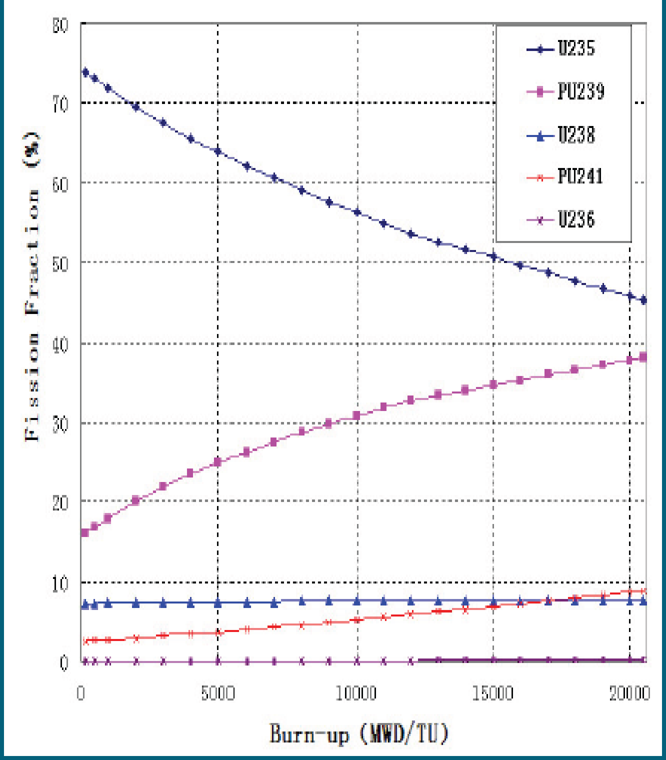
### Remaining questions:

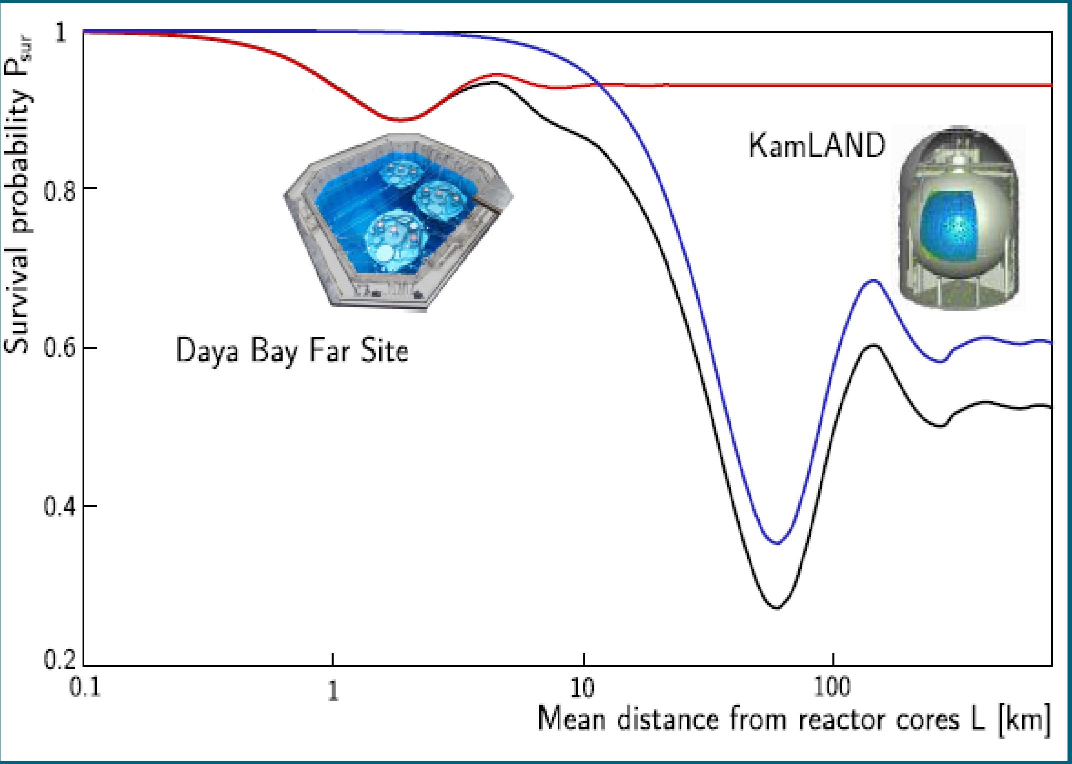
- Is $\theta_{23} = \pi/4$ ?
- CP phase $(\delta)$ ?
- Mass hierarchy
  $m_1<m_2<m_3$? $m_3<m_1<m_2$?

# Reactor Antineutrino Experiments with 1-2 km baselines are sensitive to $\theta_{13}$ ,

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

Isotope fission rates vs. reactor burn-up



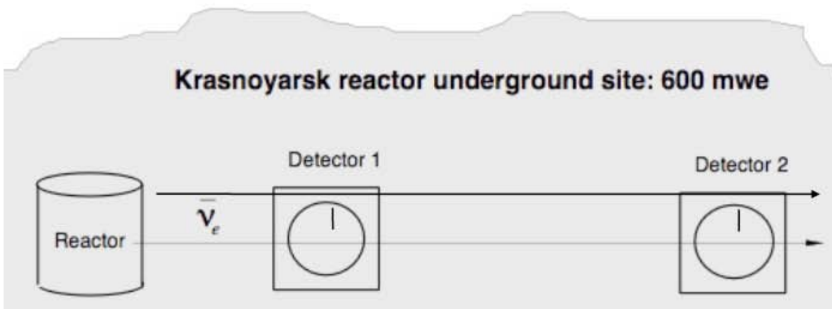

## but have significant neutrino flux normalization uncertainty

**Absolute Reactor Flux**: Largest uncertainty in previous measurements

**Relative Measurement**: Multiple detectors removes absolute uncertainty

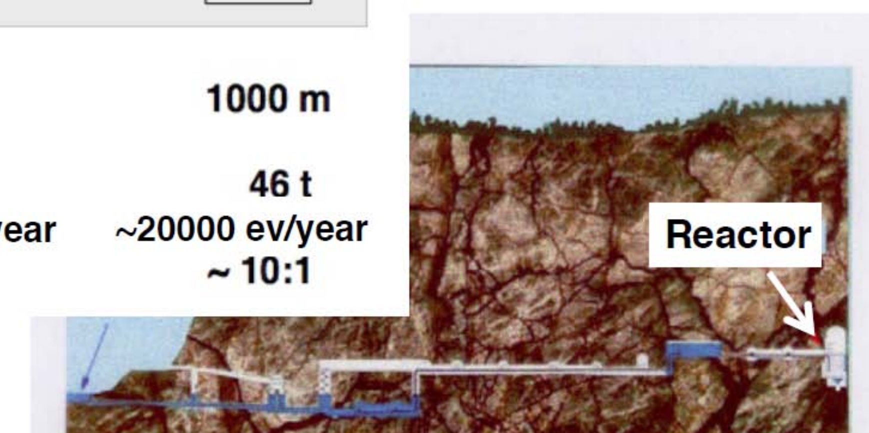
## Relative Measurement: A 2-Detector Experiment

Krasnoyarsk, Russia
first proposed at Neutrino2000




Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure

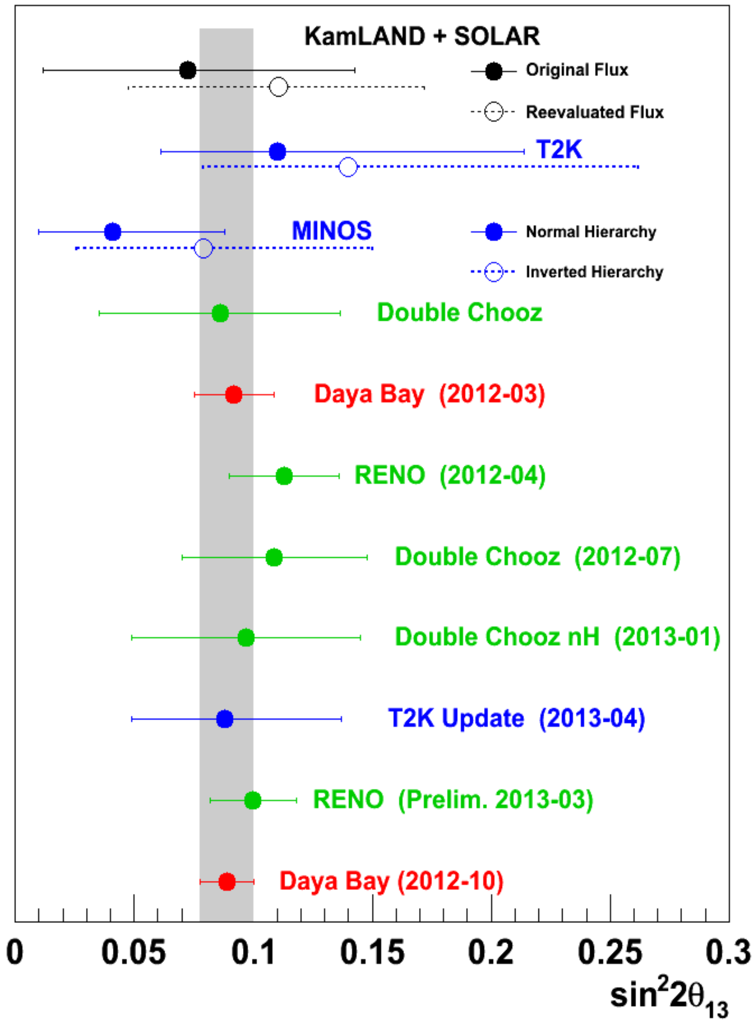
| | 115 m | 1000 m |
|---|---|---|
| Target: | 46 t | 46 t |
| Rate: | ~1.5 x $10^6$ ev/year | ~20000 ev/year |
| S:B | >>1 | ~ 10:1 |




Ref: Marteyamov et al, hep-ex/0211070

**First proposed** by L. A. Mikaelyan et al., Phys. Atomic Nucl. 63 1002 (2000)

# 2011/2012 – The year of $\theta_{13}$



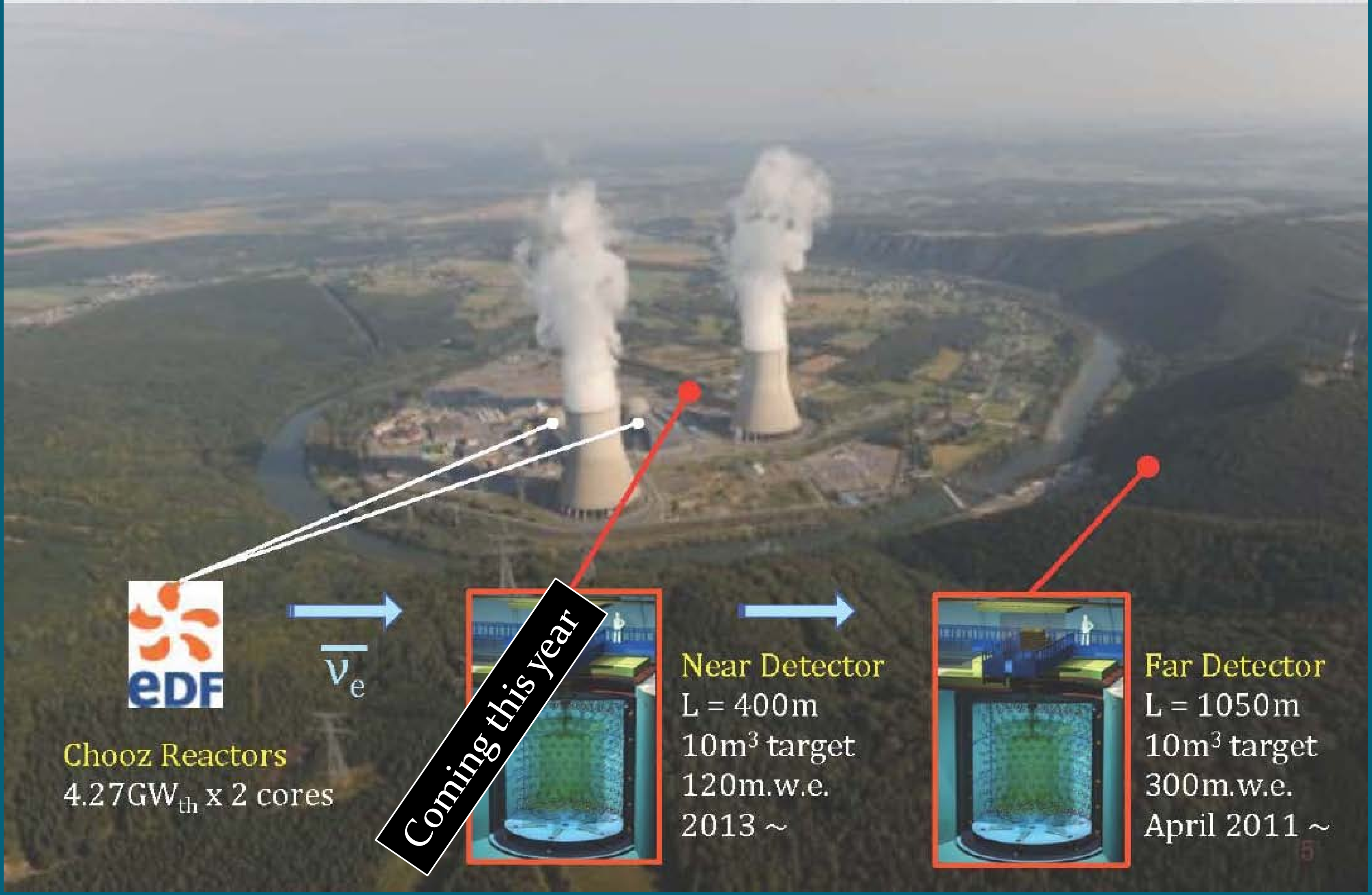

2011 – Early indications

2012 Mar – Daya Bay observes non-zero $\theta_{13}$ with 5.2σ

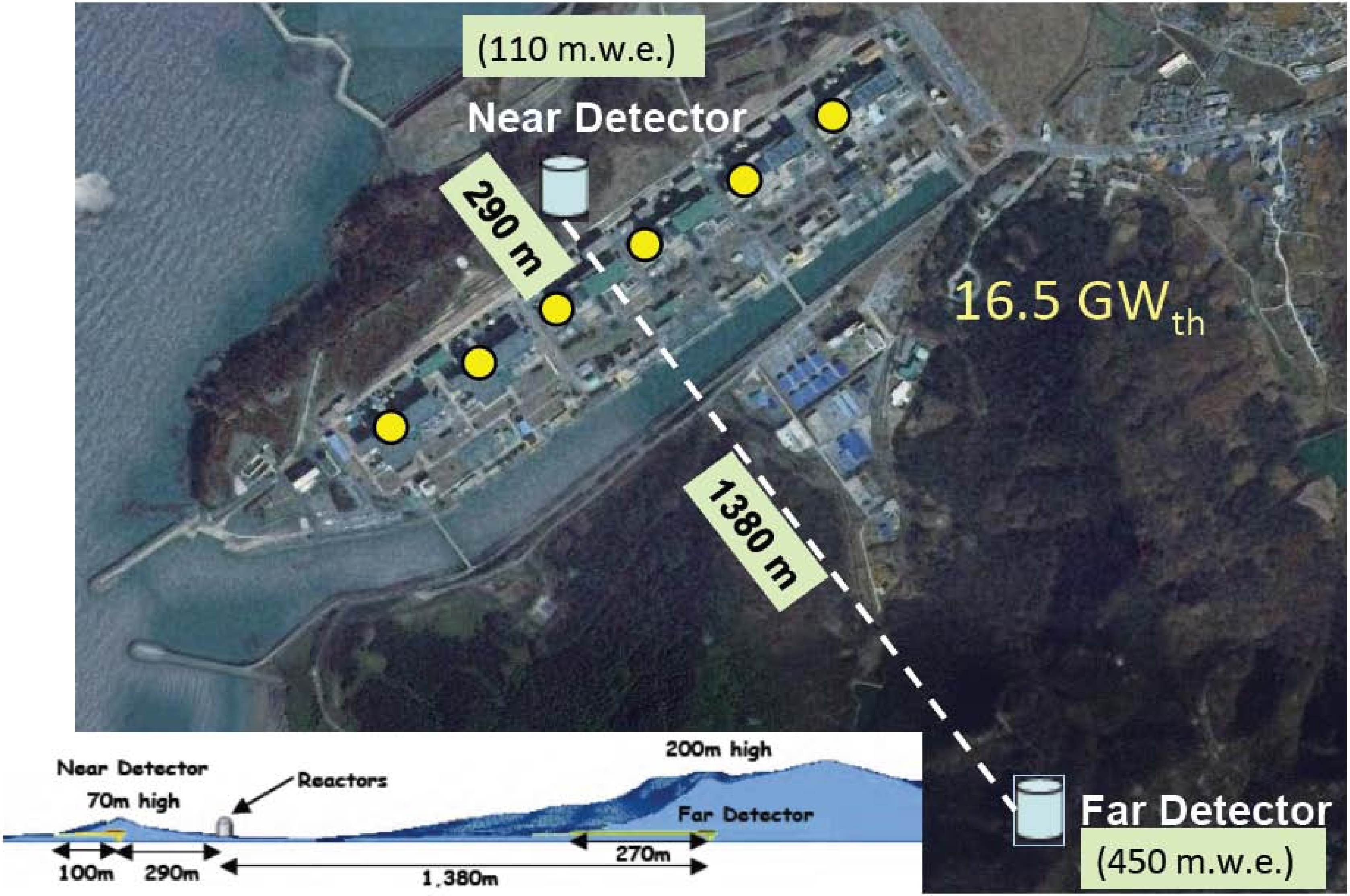
2012 Apr – RENO confirms

2012/2013 – Improved by T2K, DC, DB, RENO

# Double Chooz experiment



# RENO Experimental Setup



# Daya Bay Experiment Site

Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

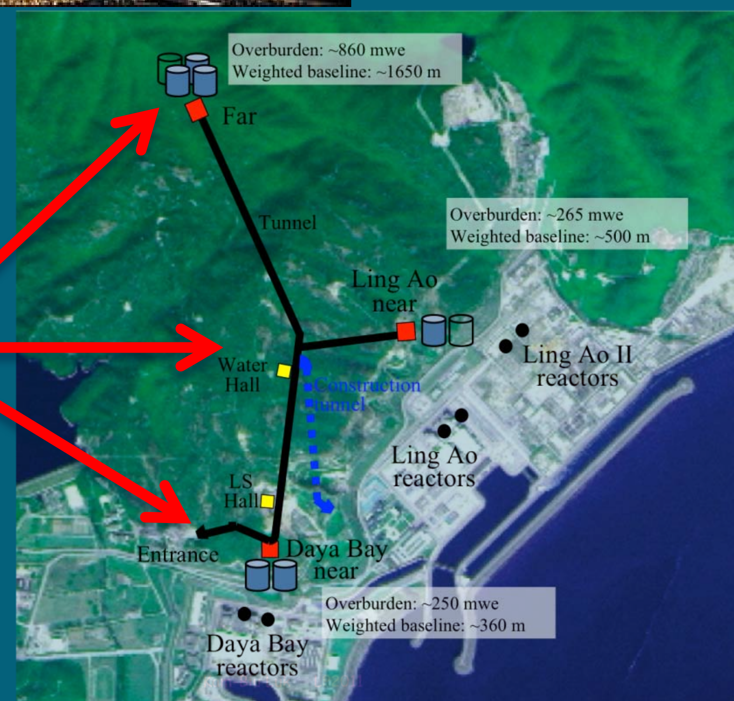
Daya Bay

Ling Ao I + II

6 commercial reactor cores with 17.4 $GW_{th}$ total power.

6(8) Antineutrino Detectors (ADs) give 120(160) tons total target mass.

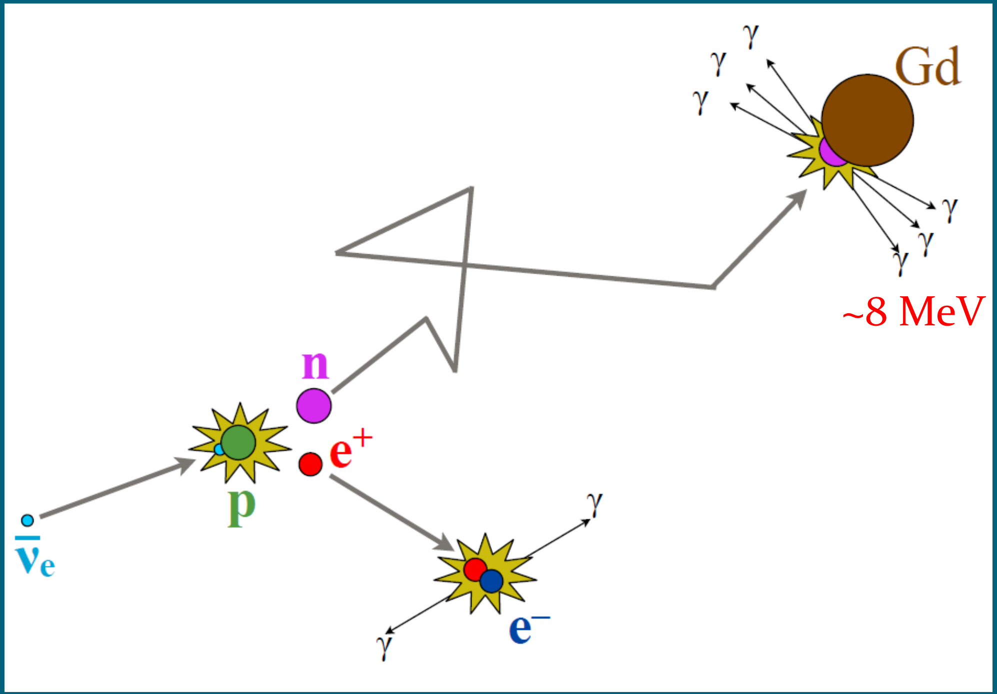
Via GPS and modern theodolites, relative detector-core positions known to 3 cm.



# Inverse beta decay has a distinctive signature

**Inverse β-decay (IBD):**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$




**Prompt positron:**
**Carries antineutrino energy**
$E_{e+} \approx E_\nu - 0.8$ **MeV**

**Delayed neutron capture:**
**Efficiently tags antineutrino signal**

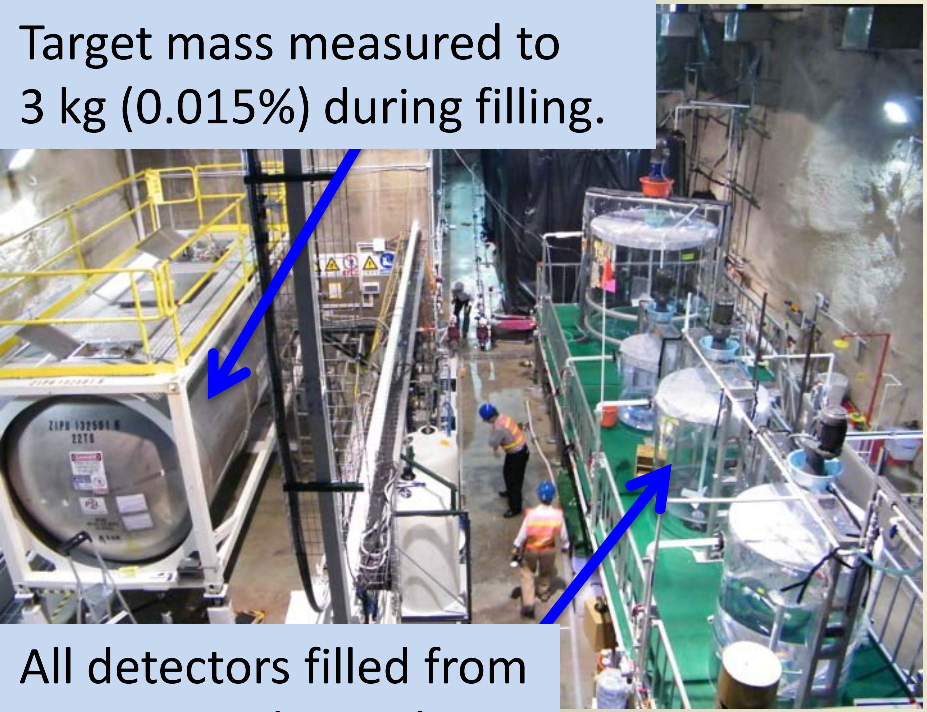
**Prompt + Delayed coincidence provides distinctive signature**

# Antineutrino Detectors

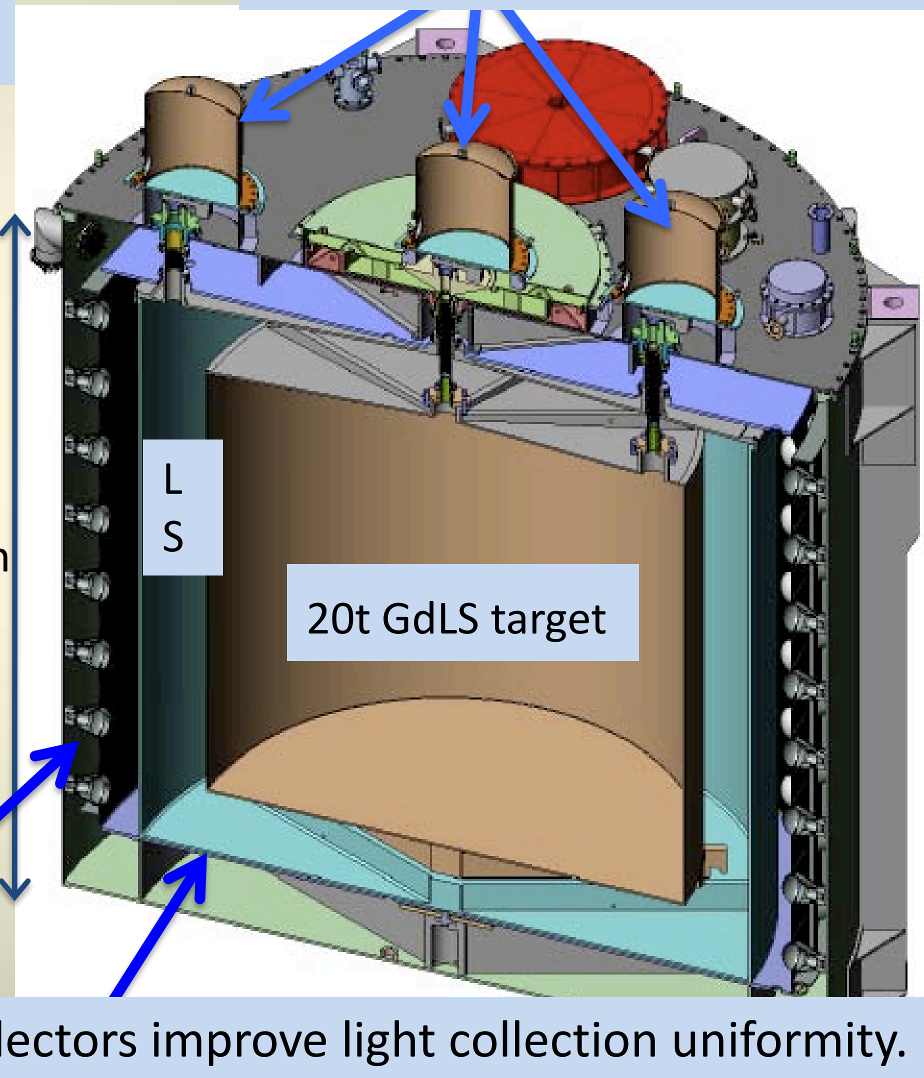
**'Functionally identical' detectors:**
Reduce systematic uncertainties

Calibration robots insert radioactive sources and LEDs.

Target mass measured to 3 kg (0.015%) during filling.



All detectors filled from common GdLS tanks.




192 8" PMTs detect light in target, ~163 p.e./MeV.

Reflectors improve light collection uniformity.

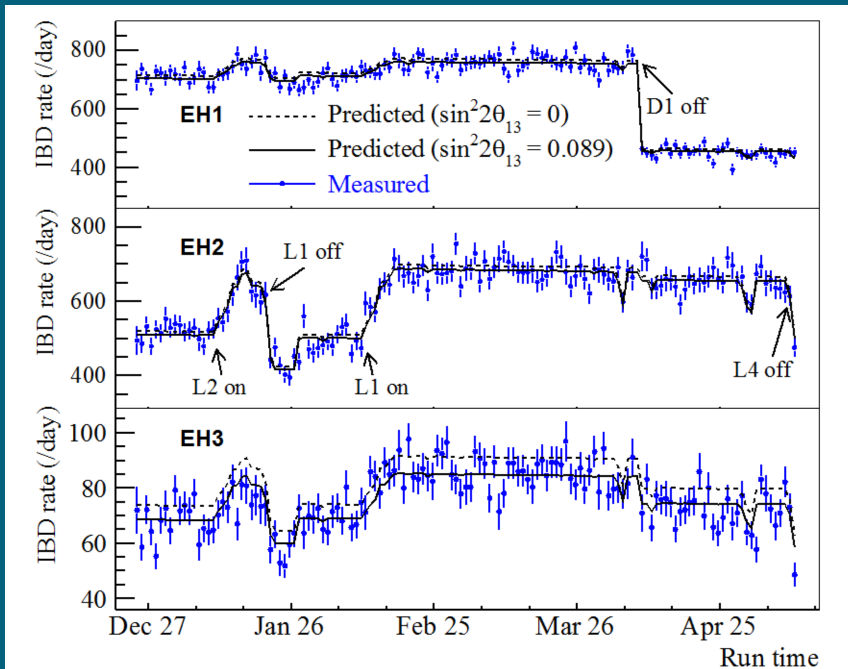
# JINR contribution to Daya Bay

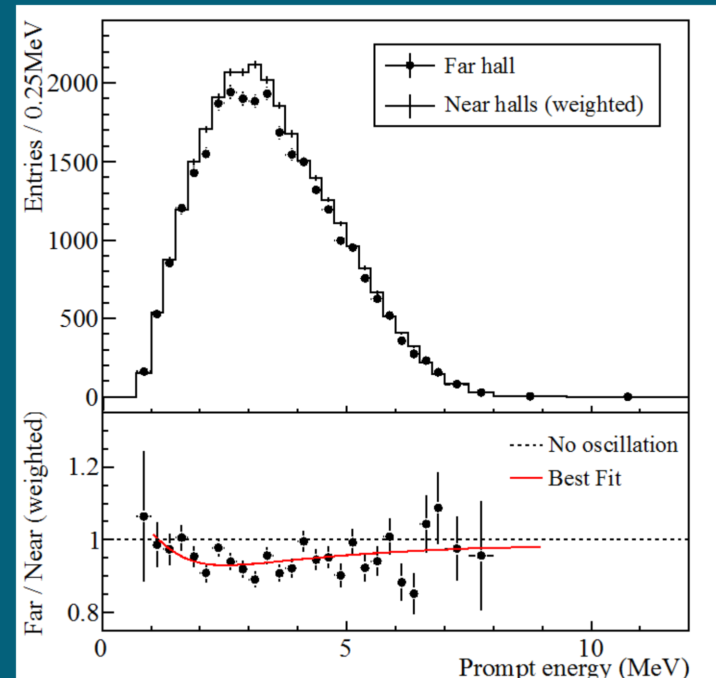
- **Liquid Scintillator measurements and optimization:**
  - Light Yield
  - Transparency
  - Energy Resolution
  - Neutron capture for Gd loaded LS

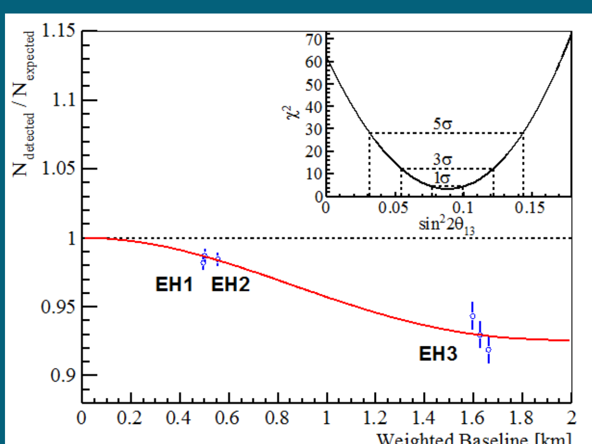
| Scintillator layer height, cm | Total detection efficiency of < 0,4 eV thermal neutrons, % | |
|---|---|---|
| | Gd-LS | LS |
| 1 | 12 ± 2 | – |
| 2 | 19 ± 3 | – |
| 3,5 | 29 ± 4 | – |
| 4,5 | 35 ± 5 | 17 ± 3 |

- **Technology of PPO production** was restored in the JINR Member State Ukraine and **1.5t of PPO were produced and delivered to Daya Bay**
- **Data analysis:**
  - Background simulation
  - Oscillation Analysis

# Измерение угла смешивания $\theta_{13}$ в эксперименте Daya Bay



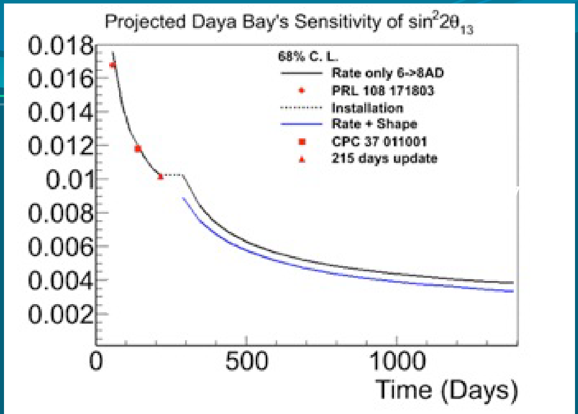



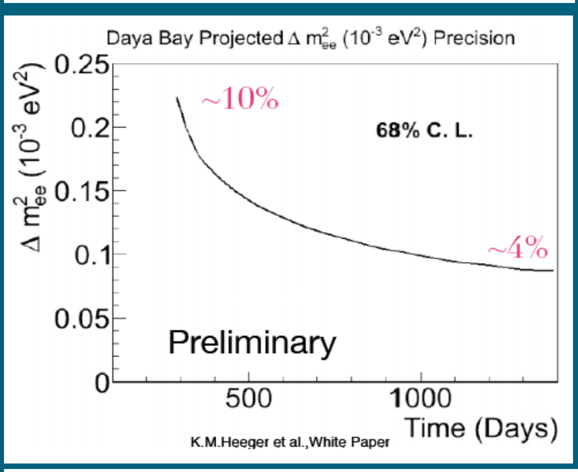

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\,(\text{stat}) \pm 0.005\,(\text{syst})$$

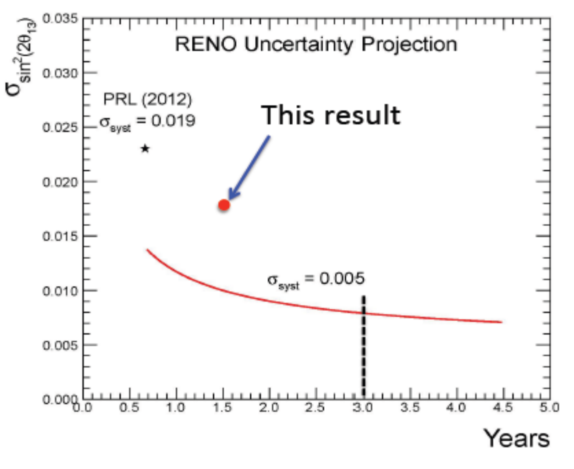
**Breakthrough of the Year, 2012, by Science Magazine**

# Ongoing work

- Daya Bay
  - Running with 8 detectors since October 2012
  - Rate + Shape analysis for $\theta_{13}$
  - Independent determination of $\Delta m^2$ (~10%→~4%)
  - Absolute neutrino flux measurement
  - Neutrino flux spectral shape
- Double Chooz
  - Near detector (systematics 2.2% → 0.6%)
  - Improving all analyses
  - Expected precision on $\sin^2 2\theta_{13}$ of 0.01
- RENO
  - Rate + Shape analysis
  - Reduce systematic uncertainty on $\sin^2 2\theta_{13}$ to < 0.01
  - Goal: total uncertainty <0.011 after 3 years



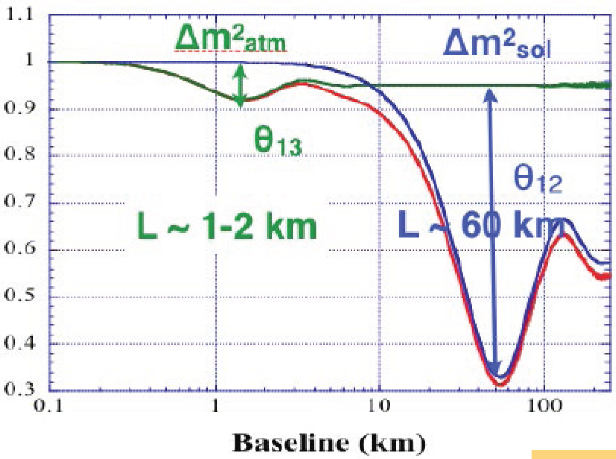



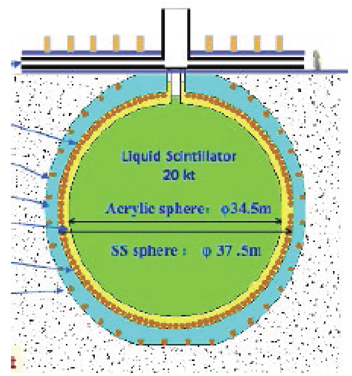



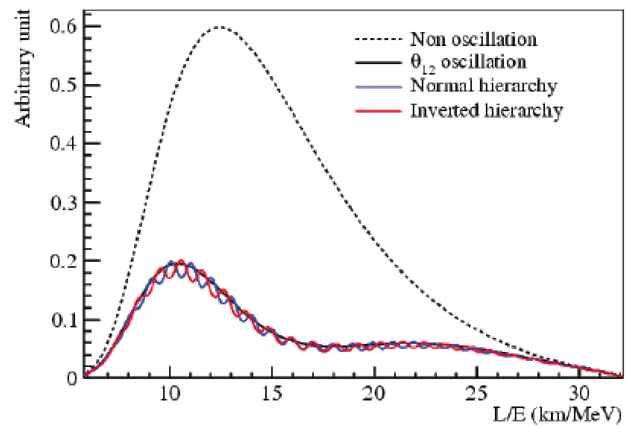
# Future (proposed experiments and R&D)

## Determining Mass Hierarchy with Reactor Antineutrinos

Daya Bay II (and RENO 50km)

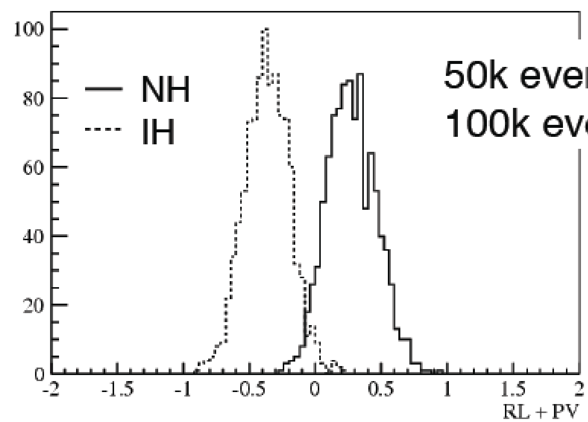


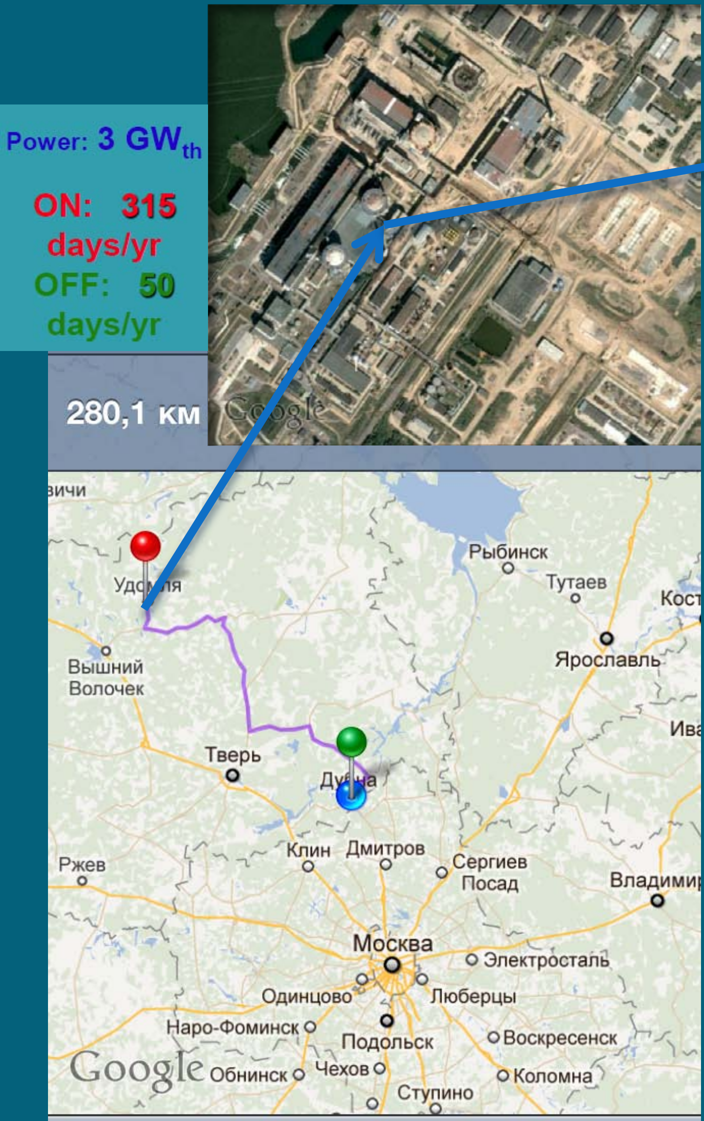

Daya Bay II
*proposed*

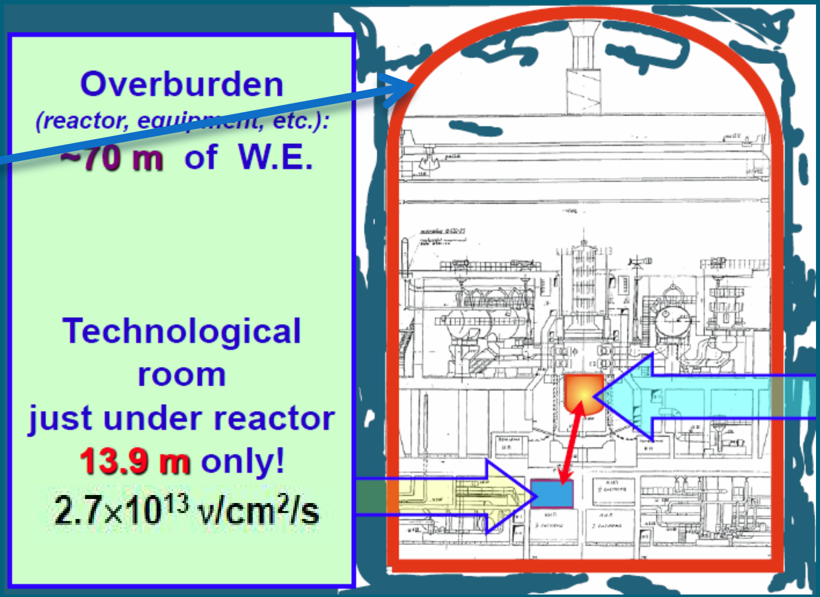

Daya Bay II R&D from 2012-2015
Construction start ~ 2015/16?




50k events, 3 years→ 96%
100k events → 3σ

# Эксперименты ОИЯИ/ИТЭФ на Калининской Атомной Электростанции




Задачи фундаментальной и прикладной физики нейтрино:

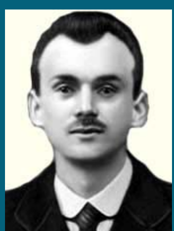
- ✓ Поиск магнитного момента нейтрино
- ✓ Поиск стерильных нейтрино
- ✓ Измерение потоков и спектров нейтрино от реактора

# Neutrino Magnetic Moment

In the (extended) Standard Model
Magnetic moment of neutrino is connected to the neutrino mass
and is very small.

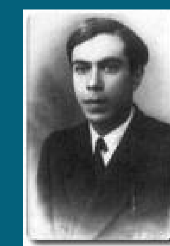
$\mu_\nu \sim 10^{-19}\,\mu_B \times (m_\nu / 1\mathrm{eV})$

$\mu_\nu \equiv 0$



if neutrino
Dirac

if neutrino
Majorana



But some models predict:

$\mu_\nu \leq 10^{-14}\,\mu_B \times (m_\nu / 1\mathrm{eV})$

$\mu_\nu \sim 10^{-10} - 10^{-11}\,\mu_B$

And this is already in the present sensitivity region

Detection of the Neutrino Magnetic Moment could be an argument in support of Majorana neutrino nature

# Измерение магнитного момента

## GEMMA: Результаты и Перспективы

**HpGe detector**
**1.5 kg, 14m**

**Phase-1: $\mu_\nu \leq 5.8\times10^{-11}\ \mu_B$**

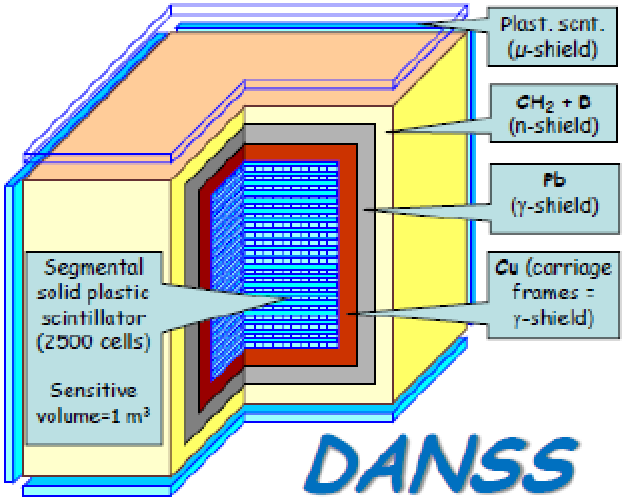
**Phases 1+2: $\mu_\nu \leq 3.2\times10^{-11}\ \mu_B$**

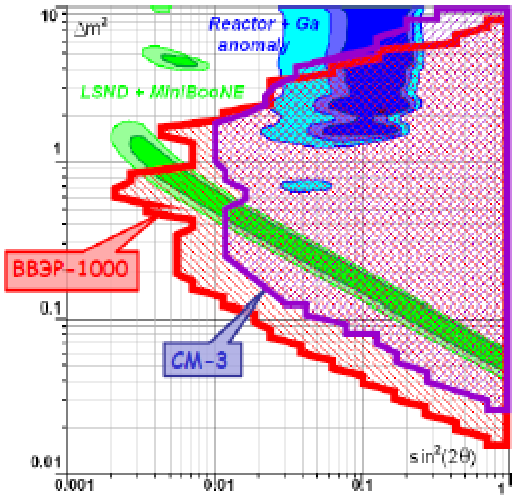
**Phases 1+2+3: $\mu_\nu \leq 2.9\times10^{-11}\ \mu_B$**

**New Phase (6kg, 10m): $\mu_\nu \leq 1.0\times10^{-11}\ \mu_B$**

# Детектор DANSS

## Измерение потоков и спектров реакторных антинейтрино


**Goal of the project:**

To build relatively small (1-2 $m^3$) detector which

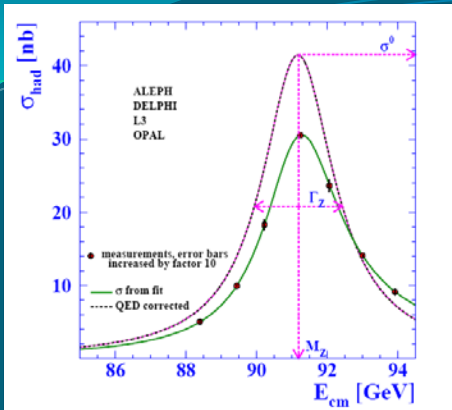
- would not contain any aggressive, cryogenic or other dangerous liquids in big amount
- could be installed close to the industrial power reactor (ВВЭР-1000)
- and detect about $10^4$ neutrino/day with good S/B ratio.

**Direct detection of the reactor antineutrino allows**

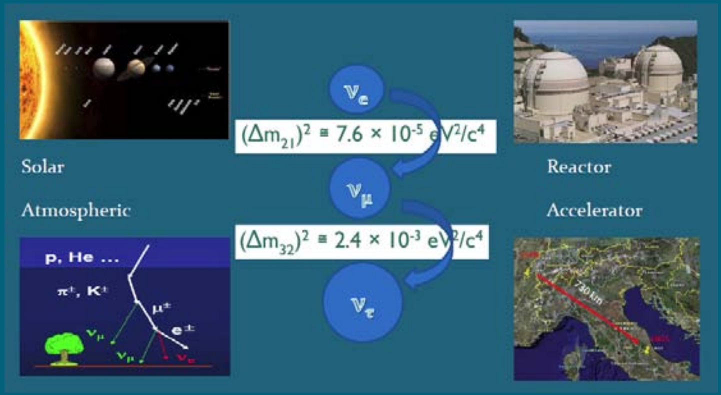
Measure the actual reactor power (Nν)
Deduce the actual fuel composition(Eν)
On-line reactor monitoring (tomography?) .
Especially important in view of the future Non-proliferation (prevent unauthorized extraction of 239-Pu)

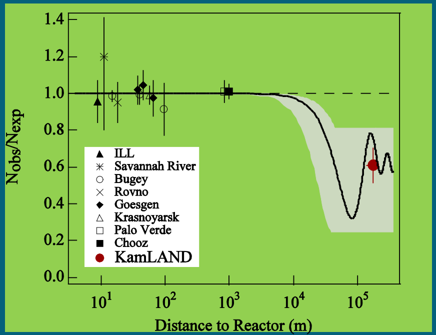
Weak (ν-e) cross-section (more precise)
Neutrino oscillations (to a sterile state?)

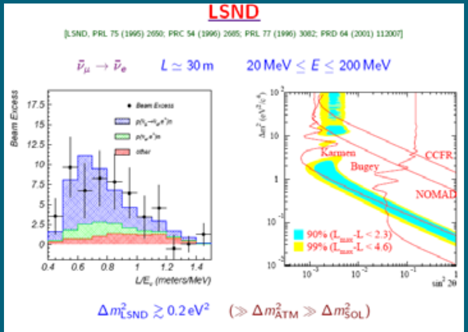
# Что нам известно о числе типов нейтрино?

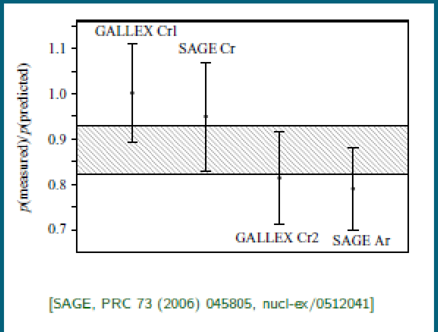



LEP: $N_\nu$ = 2.9840±0.0082

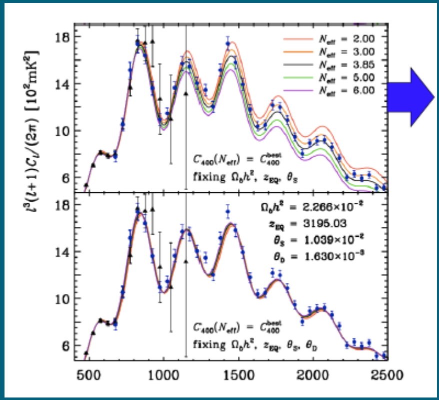



Another
$\Delta m^2 \sim 1 eV^2$ ??




Cosmology:

**Num of Nus:**

$N_{eff}$ = 3.62 ± 0.48 (SPT+WMAP7)

$N_{eff}$ = 3.71 ± 0.35 (SPT+WMAP7+$H_0$+BAO)

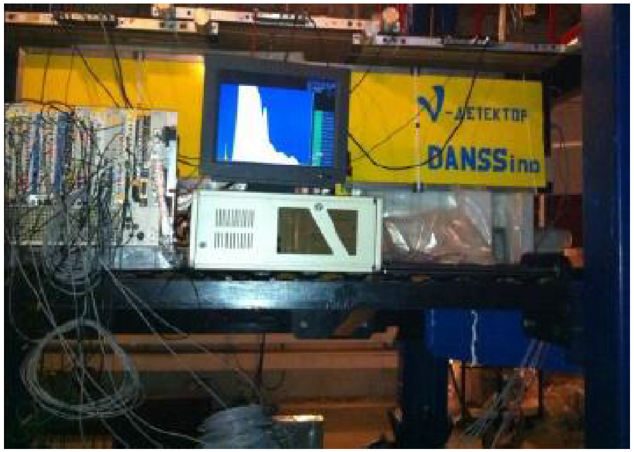
$N_{eff}$ = 2.97 ± 0.56 (ACT+WMAP7)

$N_{eff}$ = 3.50 ± 0.42 (ACT+WMAP7+$H_0$+BAO)

**Необходим поиск осцилляционных переходов нейтрино в стерильные состояния на (сверх) малых расстояниях**

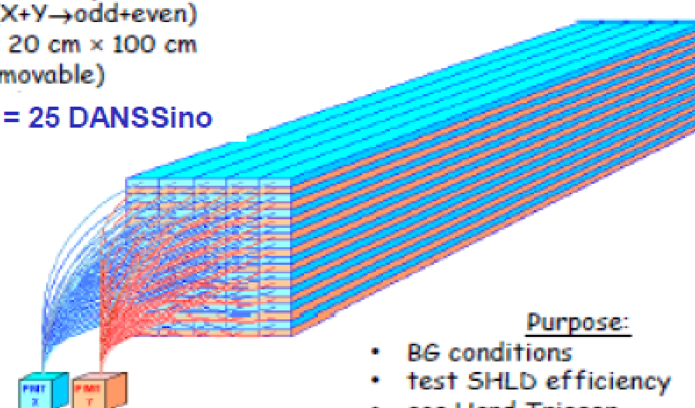
# There is already a well working prototype:

## DANSSino



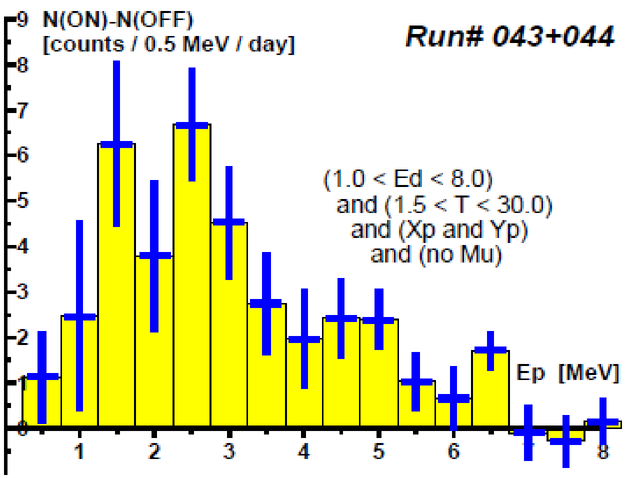

50+50=100 strips
2 PMT (X+Y→odd+even)
20 cm × 20 cm × 100 cm
40 kg (movable)

**DANSS = 25 DANSSino**

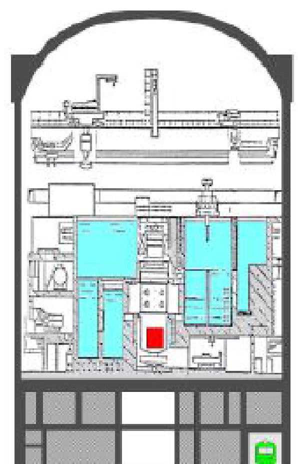


Purpose:

- BG conditions
- test SHLD efficiency
- acq Hard Trigger
- btw IBD count rate ~400/day



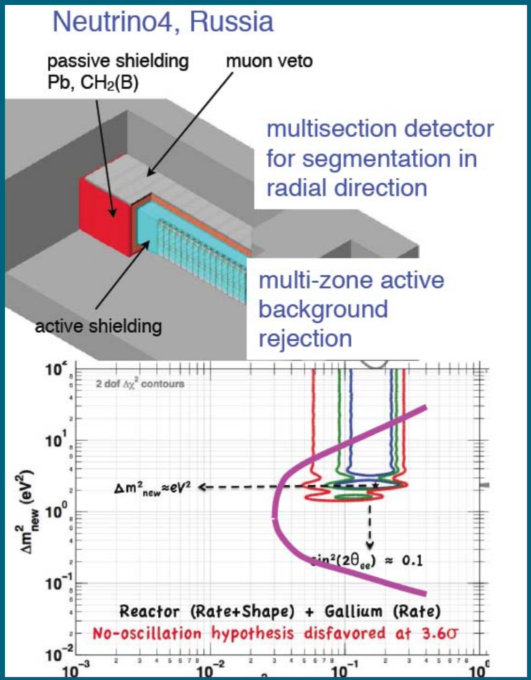

**This is already measured reactor (anti)neutrino spectrum!**

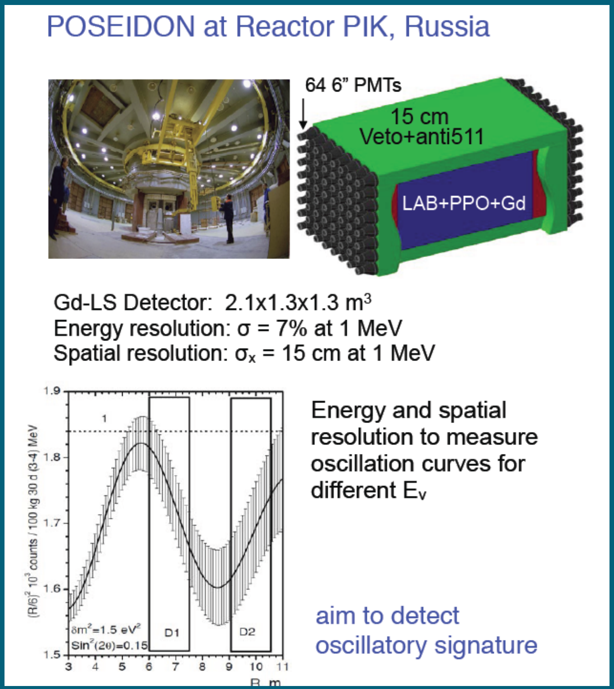


Conclusions :

- It works!!! ☺ *(even without flash ADCs and MPPC)*
- In spite of huge edge-effects, we see ν ☺
- 10 cm of (Pb+Cu) is enough to shield against γ
  The main (important) BG = fast *n*
- Impossible to operate on-ground ☹
- ВВЭР-1000 shields well against cosmic *n* ☺
- μ-produced (secondary) fast neutrons = ☹
- Improve eff. of μ-veto ( 4π + "sandwich")
- Avoid heavy materials inside. *Change the shield composition (and mechanical construction?)*

# Измерения на исследовательских реакторах




100 MW thermal power

Small zone: h=**50** cm, d=**39** cm

Start of experimental program 2014-15

- Benchmark measurements of reactor neutrino spectra and beta-particles spectra from irradiated targets
- Neutrino sources production: $^{51}Cr$, $^{8}Li$ etc (thermal neutron flux $4.5\times10^{15}$ $cm^{-2}s^{-1}$)
- Search for short base line oscillations
- Coherent scattering neutrino by nuclei
- Neutrino-electron elastic scattering
- BSM processes search at low energies

# Заключение

- На протяжении многих лет реакторные эксперименты были и остаются мощным инструментом для изучении свойств нейтрино

- Недавнее открытие (относительно) большого угла смешивания $\theta_{13}$ открывает новые перспективы для дальнейших исследований в физике нейтрино

- Проведение нейтринных экспериментов на своей базе, а также участие в ведущих международных проектах, является приоритетной задачей для Российских институтов и ОИЯИ