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Université Libre de Bruxelles
Campus Plaine - Solvay Room

Brussels
27 - 29 May, 2015

Solvay-Francqui Workshop on

Neutrinos:
from Reactors to the Cosmos

Recent results from reactor experiments and prospects for the future

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Outline

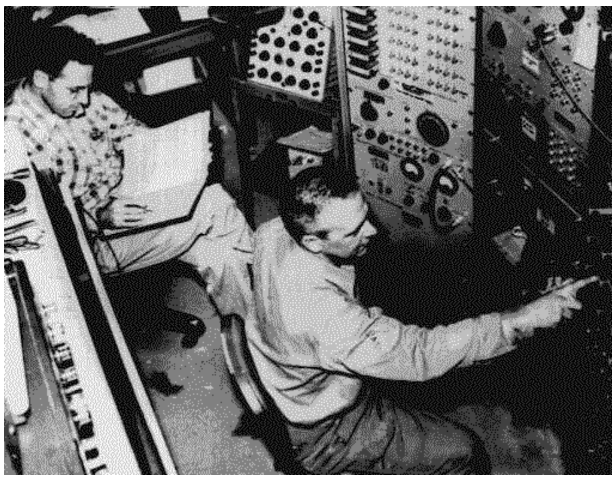
ν

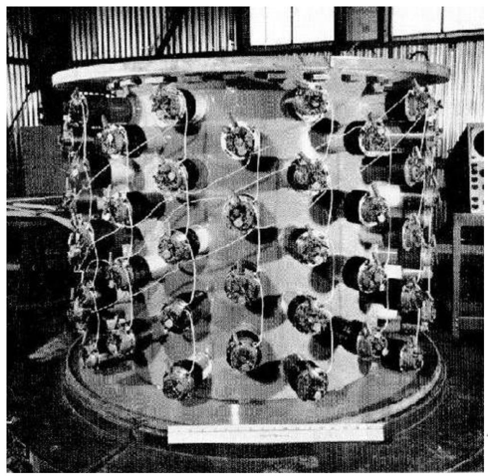
- Neutrino Oscillations
- Past Oscillation Experiments for θ_{13} measurement
- θ_{13} hunting
- Present neutrino oscillation reactor experiments
- Future projects and neutrino mass hierarchy

First neutrino detection…

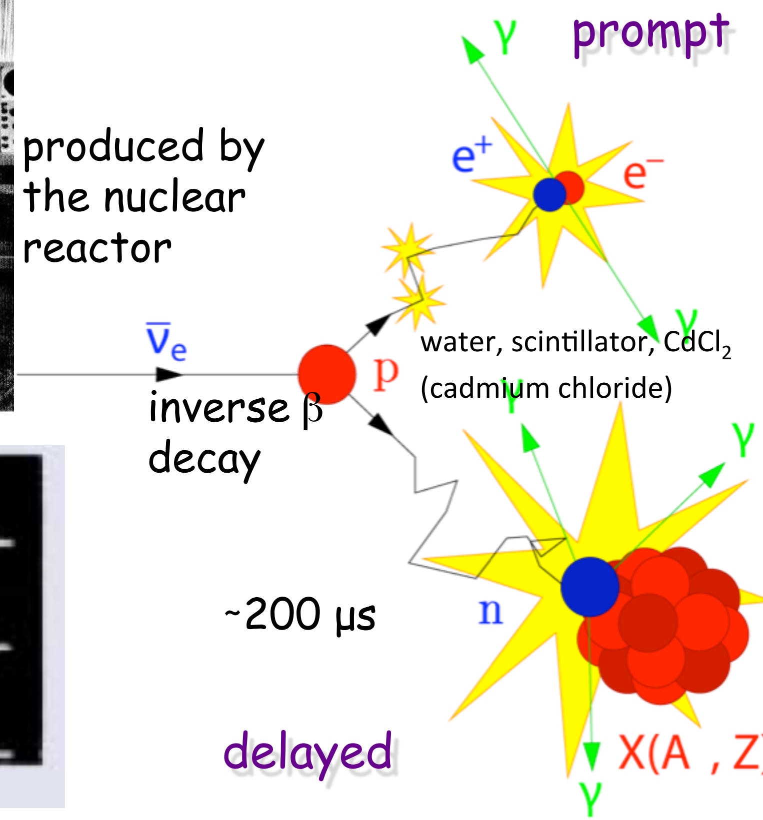
1956: Fred Reines and Clyde Cowan detect the first neutrino interactions near the nuclear reactor of Savannah River at the USA (11 m from the reactor and 12 m underground).

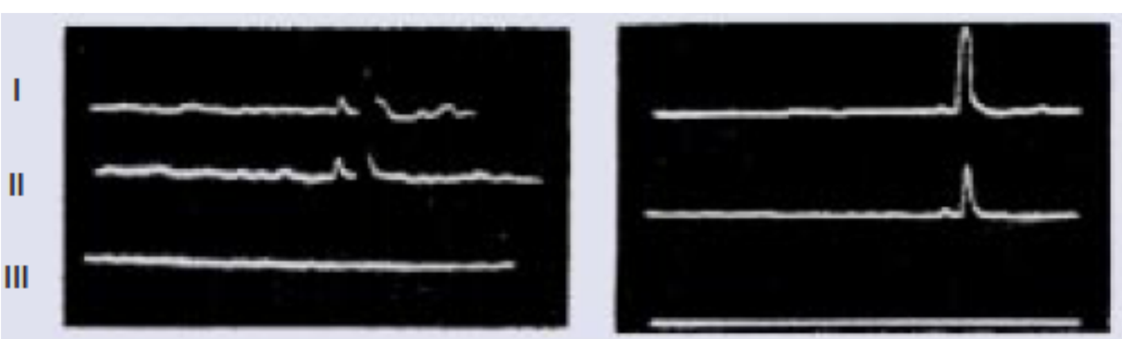
Nobel prize in 1995





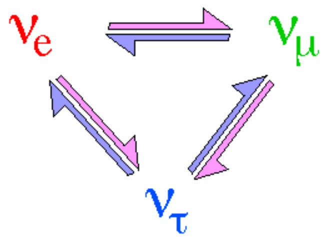
about three neutrinos per hour

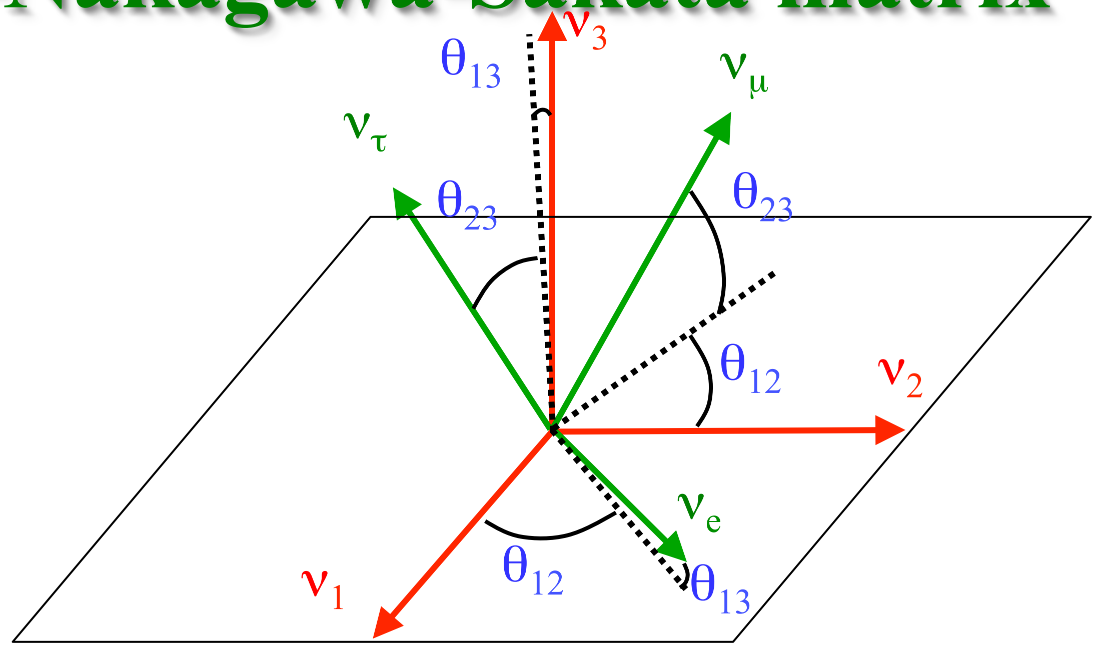




(a) Positron scope
Neutron scope

Pontecorvo-Maki-Nakagawa-Sakata matrix





Usual parametrization

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \qquad \text{with } c_{ij} = \cos\theta_{ij} \textit{ and } s_{ij} = \sin\theta_{ij}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{rotation around } x-axis \text{ with angle } \theta_{23}} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{rotation around } y-axis \text{ with angle } \theta_{13}} \cdot \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{rotation around } z-axis \text{ with angle } \theta_{12}}$$

atmospheric,
accelerators

reactors,
accelerators
CP violation

solar,
reactors

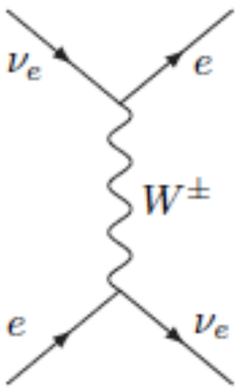
- δ_{CP} for neutrinos
- $-\delta_{CP}$ for anti-neutrinos

How neutrinos propagate through matter?
(Mikheyev-Smirnov-Wolfenstein effect)

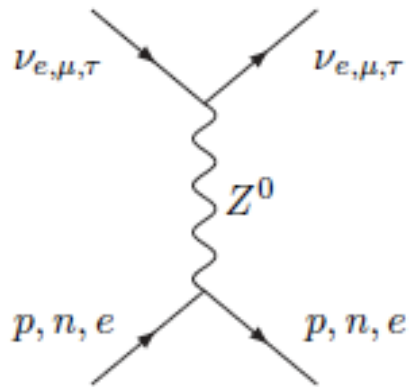
$$\left|\nu_j(t)\right\rangle = e^{-iHt/\hbar}\left|\nu_j(0)\right\rangle$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H_f\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

only for electron neutrinos



CC



NC

in "ordinary" matter

$$H_f = UHU^\dagger = \frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger \rightarrow \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + \begin{pmatrix}A_{CC} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]$$

with: $A_{CC} = 2EV_{CC} = 2\sqrt{2}EG_F N_e \approx 7.56\times10^{-5}\,eV^2\left(\frac{\rho}{g/cm^3}\right)\left(\frac{E}{GeV}\right)$

(ρ~3 g/cm^3 for earth crust)

How neutrinos propagate through matter?
(Mikheyev-Smirnov-Wolfenstein effect)

LBL experiments

$$P_{\nu_\mu\to\nu_e(\overline{\nu_\mu}\to\overline{\nu_e})} \simeq s_{23}^2 \sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{\widetilde{B}_\mp}\right)^2 \sin^2\left(\frac{\widetilde{B}_\mp L}{2}\right)$$ "atmospheric"

$$+c_{23}^2 \sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$ "solar"

$$+\widetilde{J}\,\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\widetilde{B}_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\widetilde{B}_\mp L}{2}\right)\cos\left(\pm\delta_{CP}-\frac{\Delta_{13}L}{2}\right)$$ "interference"

$$\widetilde{J}\equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13},\ \Delta_{ij}\equiv\frac{\Delta m_{ij}^2}{2E_\nu},\ \widetilde{B}_\mp\equiv\left|A\mp\Delta_{13}\right|,\ A=\sqrt{2}G_F N_e$$

matter effect

reactor experiments

$$P\left(\overline{\nu_e}\to\overline{\nu_e}\right)\simeq 1-\sin^2 2\theta_{12}c_{13}^4\sin^2\frac{\Delta m_{21}^2 L}{4E}$$

no δ_{CP} dependence

matter effect negligible

$$-\sin^2 2\theta_{13}\left[c_{12}^2\sin^2\frac{\Delta m_{31}^2 L}{4E}+s_{12}^2\sin^2\frac{\Delta m_{32}^2 L}{4E}\right]$$

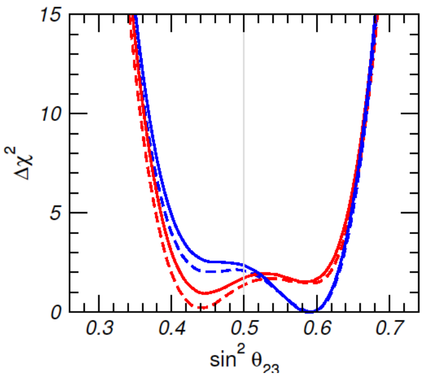
Present measurements

$$\theta_{23} = 42.3^{+3.0}_{-1.6} \text{ or } 49.5^{+1.5}_{-2.2} \text{ deg}.$$

$$\left|\Delta m^2_{31}\right| = (2.46 \pm^{+0.05}_{-0.05}) \times 10^{-3} \text{ eV}^2$$

$$\theta_{12} = 33.5 \pm 0.8°$$

$$\Delta m^2_{21} = (7.50 \pm 0.19) \times 10^{-5} \text{ eV}^2$$



$\theta_{13} < 12.4°$, 90% CL

up to recently

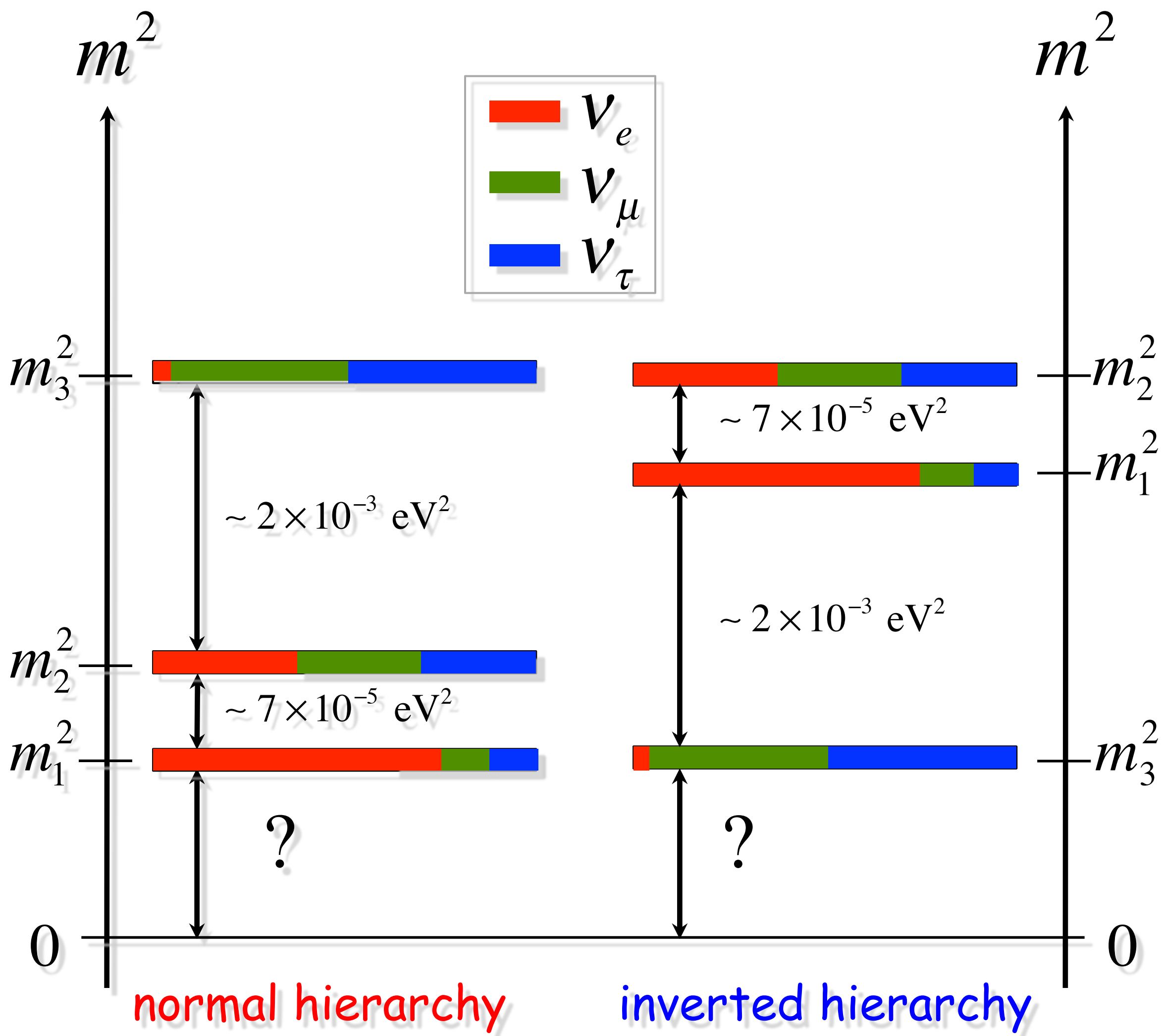
~no information about δ_{CP}

We can then write:

$$\Delta m_{13} \approx \Delta m_{23} \equiv \Delta m$$

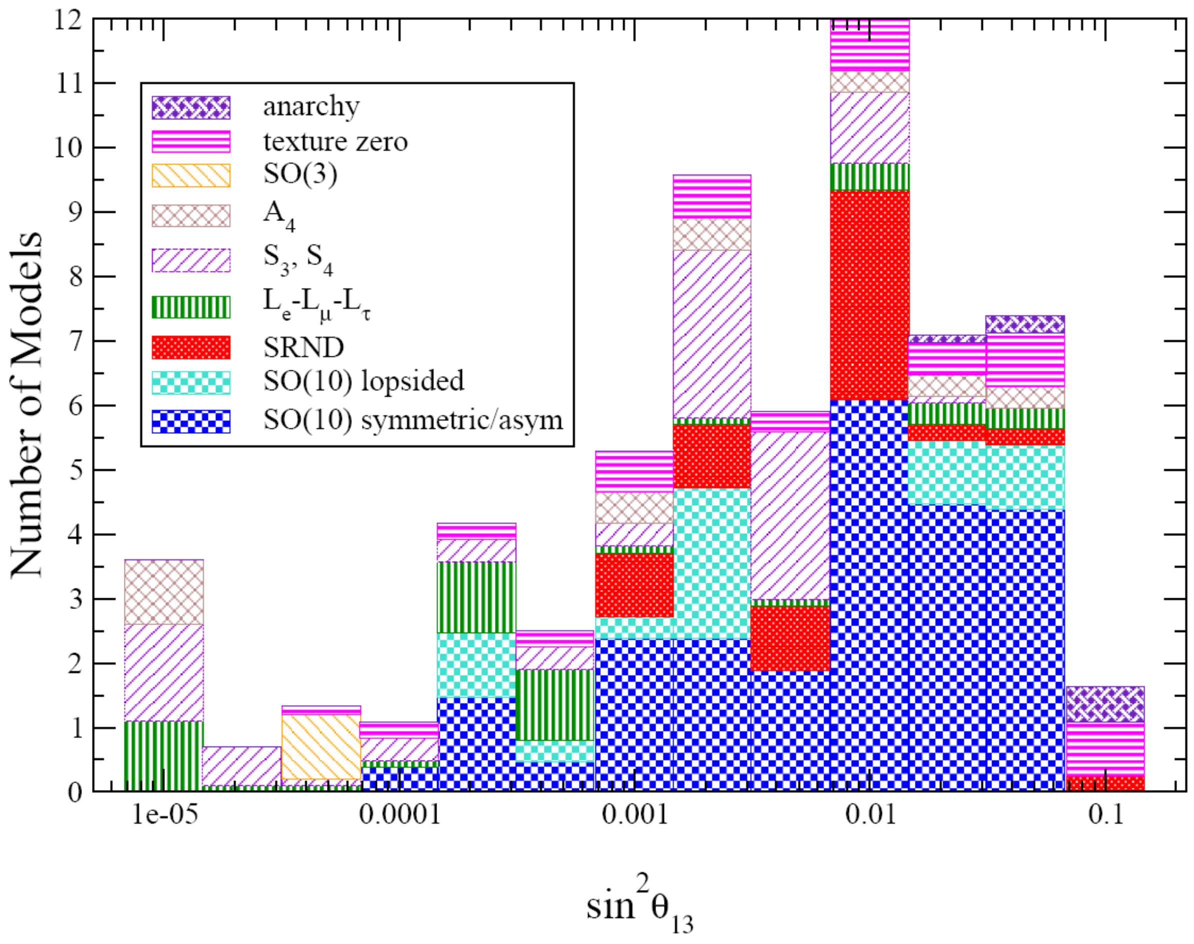
$$\Delta m_{12} \equiv \delta m$$

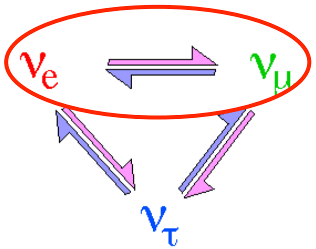
$$\Delta m \gg \delta m$$



The θ_{13} hunting

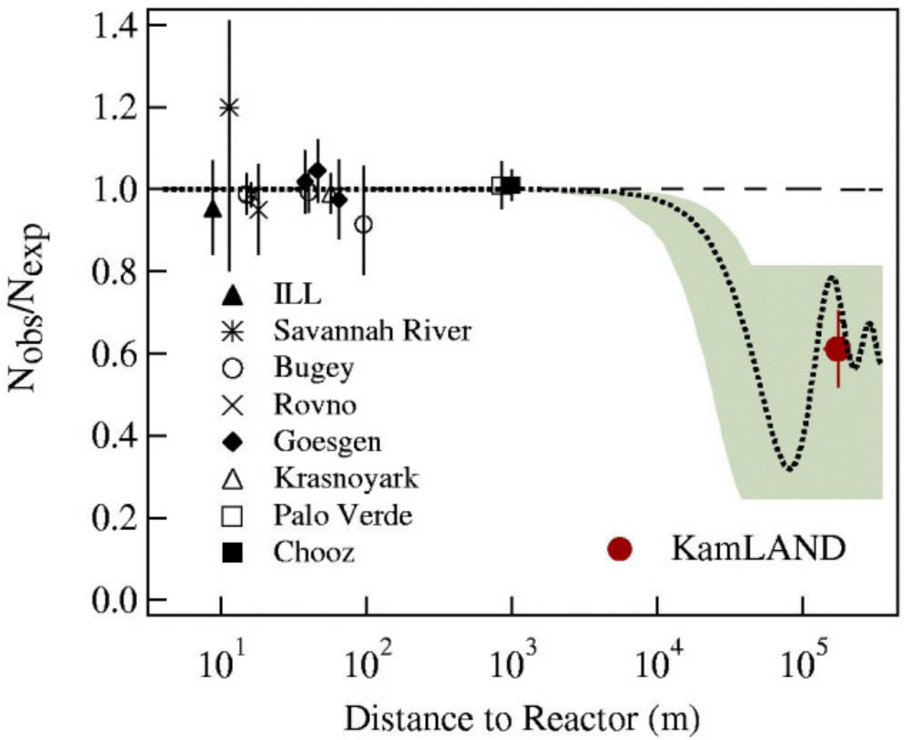
predictions of 63 models

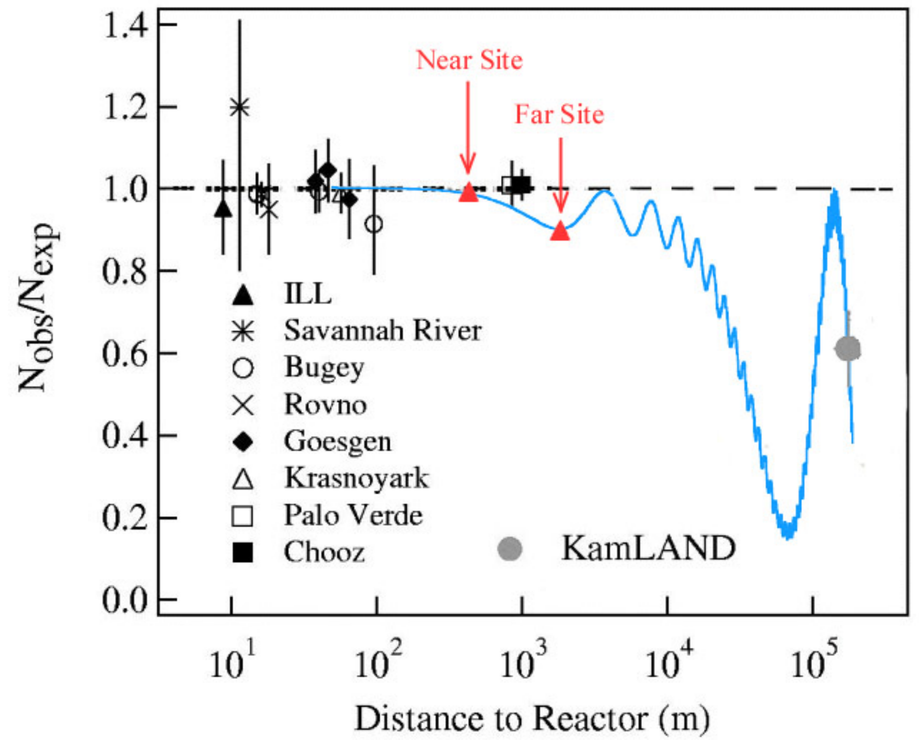




The θ_{13} hunting

disappearance of electron neutrinos

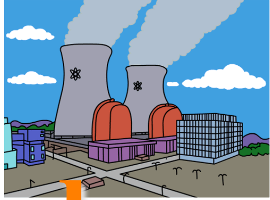


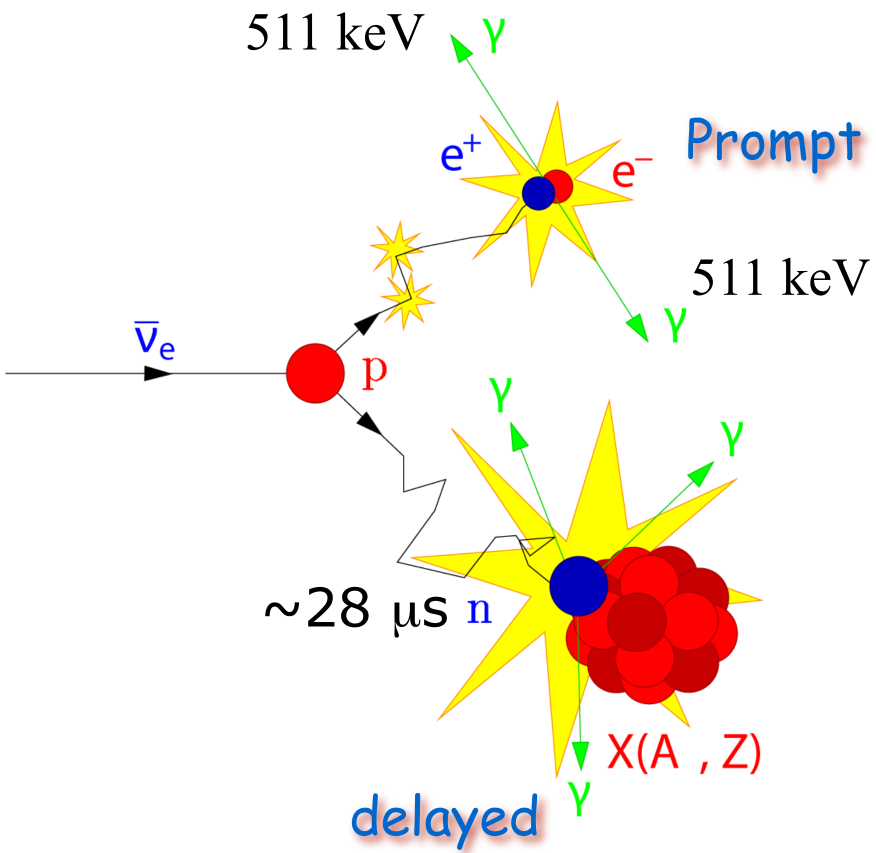


Actually, we have almost neglected θ_{13} on this figure

For $\theta_{13} \sim 10°$

Inverse β decay and reactor neutrino detection mode



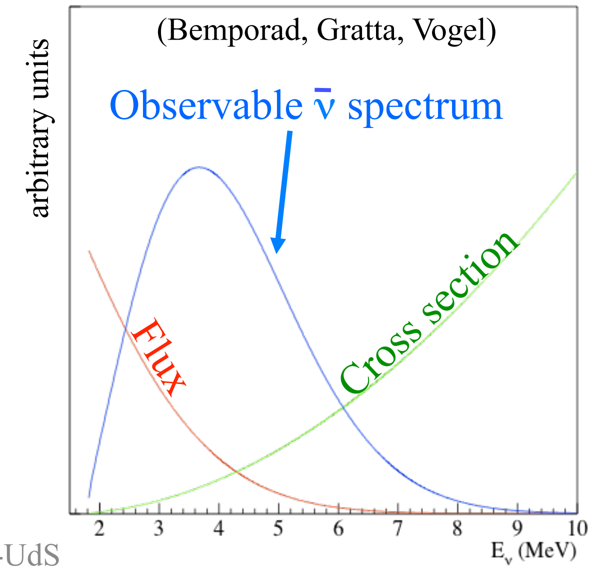


In a pure scintillator the neutron will be captured by hydrogen:

n H ⟶ D γ (2.2 MeV)

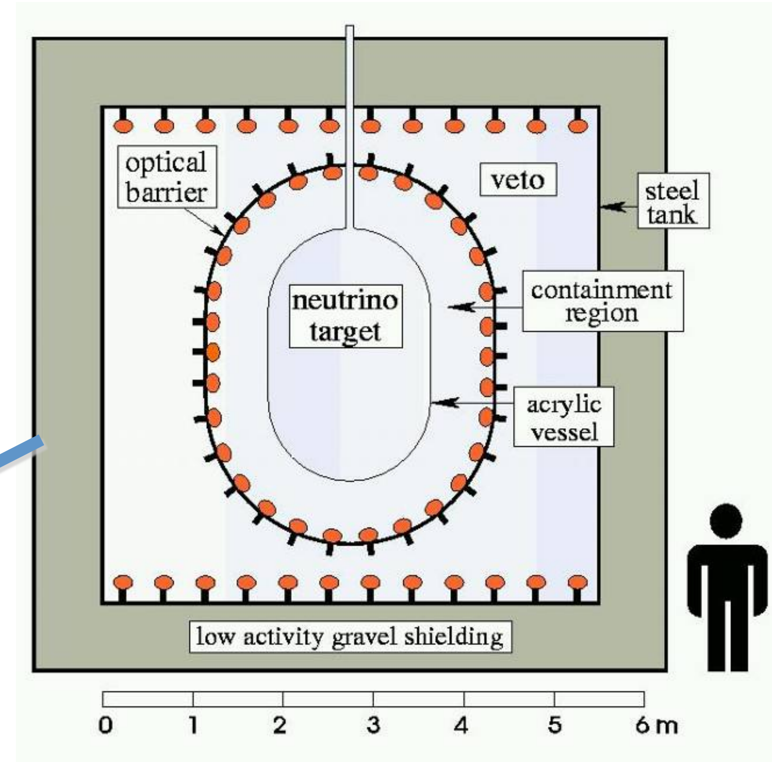
Very often the scintillator is doped with gadolinium that increase the capture probability and liberates more γ's:

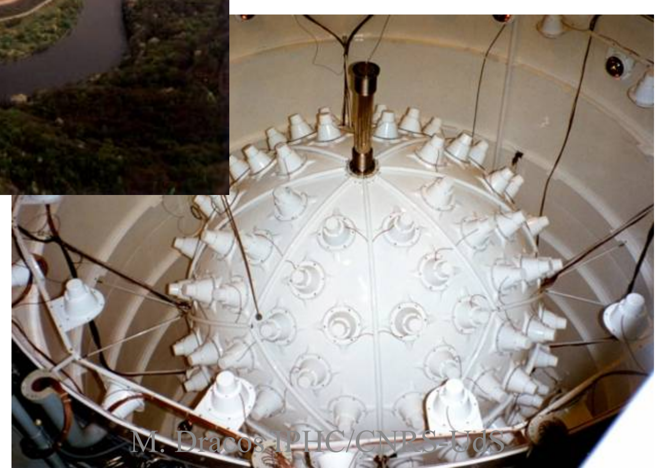
n ^{m}Gd ⟶ $^{m+1}$Gd γ' s (8 MeV)



The CHOOZ detector

- Site: nuclear plant of CHOOZ, Ardennes (France)
- 2 reactors: 2x4200 MW
- deep: 300 mwe
- 5 tons liquid scintillator (doped with gadolinium)
- <L> ~ 1 km



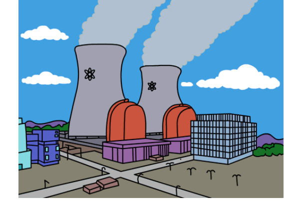


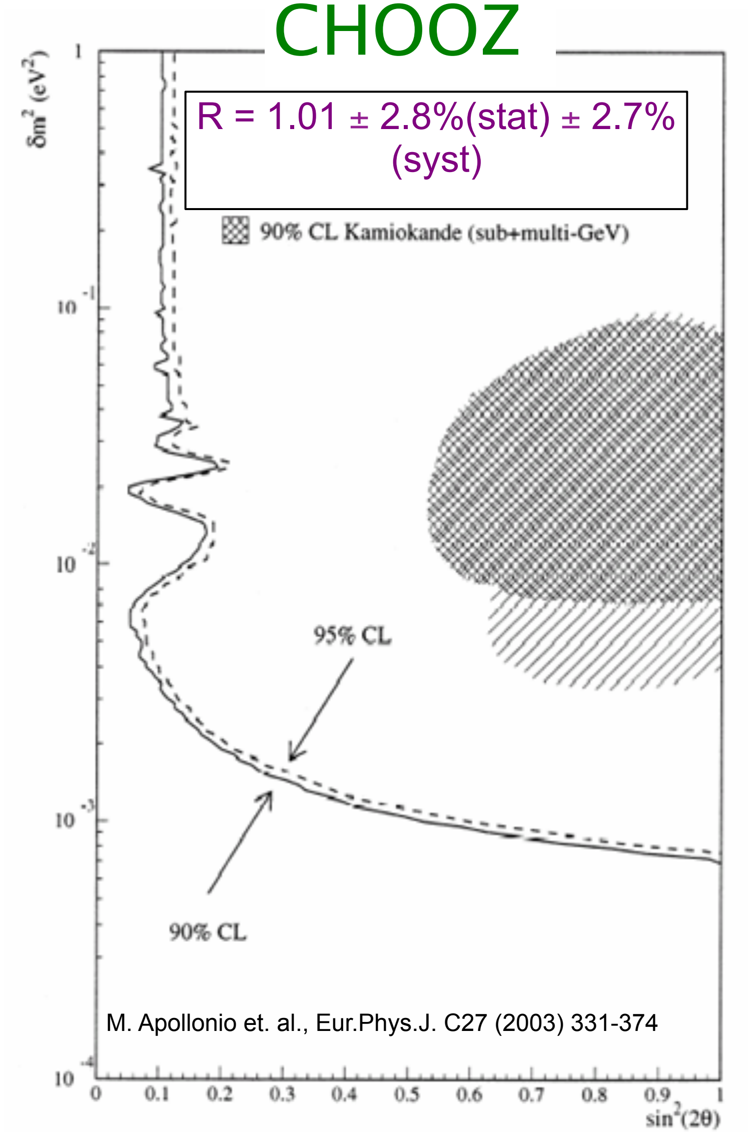
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$n + Gd \rightarrow 8 \text{ MeV } \gamma$$

5-tons target

Chooz results



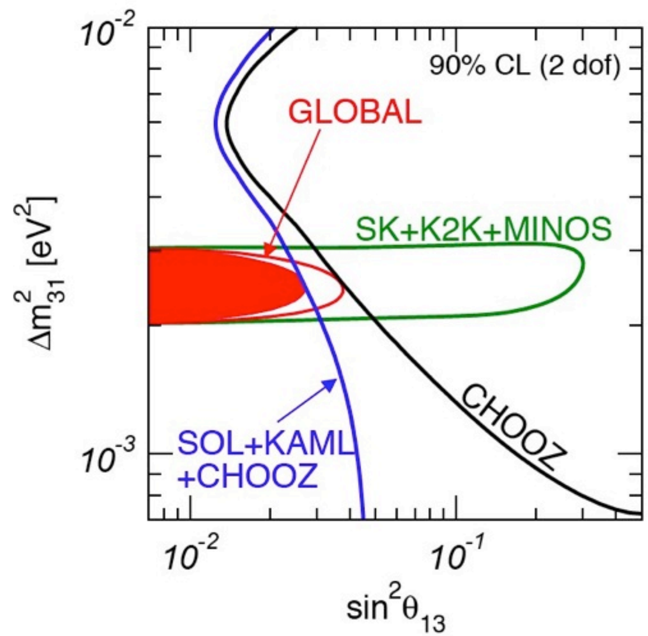


- Best limit up to 2011: CHOOZ nuclear reactor experiment

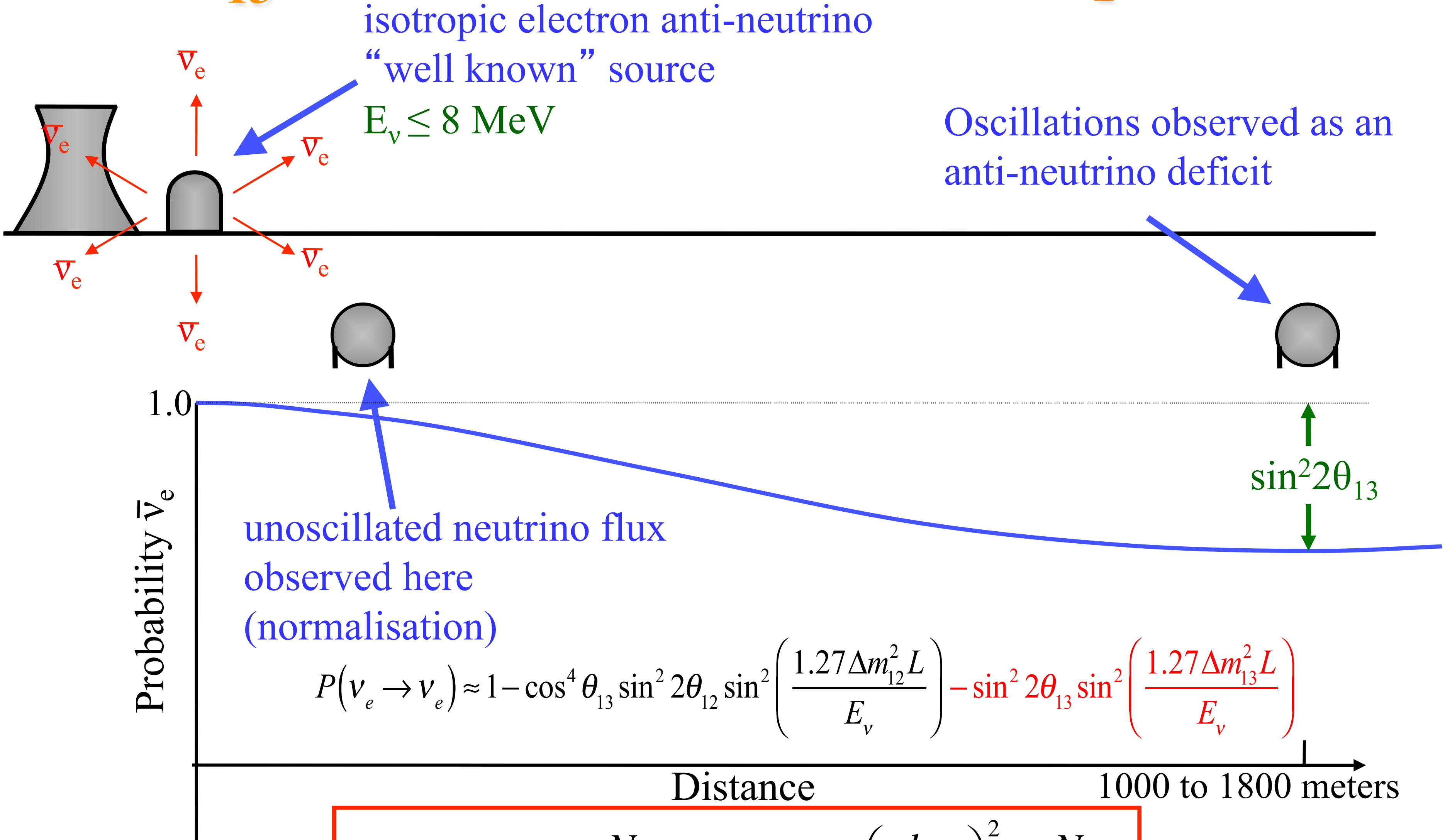
$\bar{\nu}_e \rightarrow \bar{\nu}_x$ disappearance experiment

$\sin^2(2\theta_{13}) < 0.12 - 0.2$

(90% C.L)



$\sin^2 2\theta_{13}$ and the "new" reactor experiments

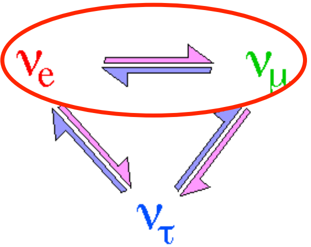


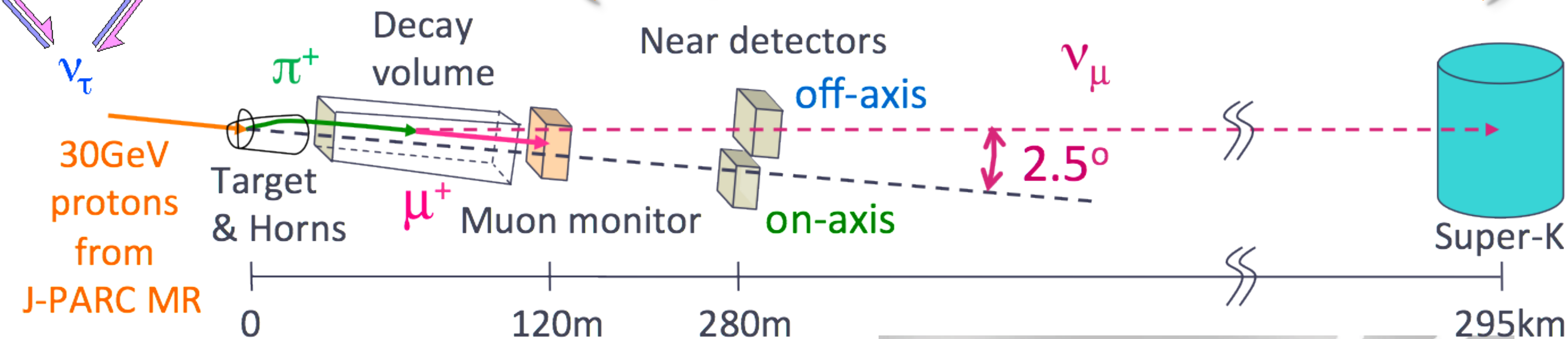
$$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m^2_{12}L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{13}L}{E_\nu}\right)$$

$$P_{surv.}(E_\nu, d_{far}) = \frac{N_{p,near}}{N_{p,far}} \times \frac{\varepsilon_{near}}{\varepsilon_{far}} \times \left(\frac{d_{far}}{d_{near}}\right)^2 \times \frac{N_{far}}{N_{near}}$$

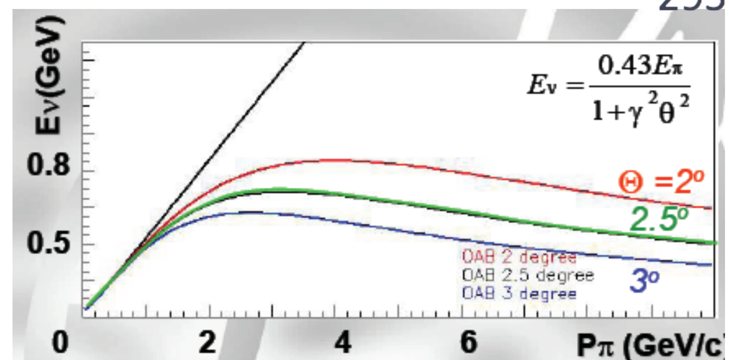
=1! =1!

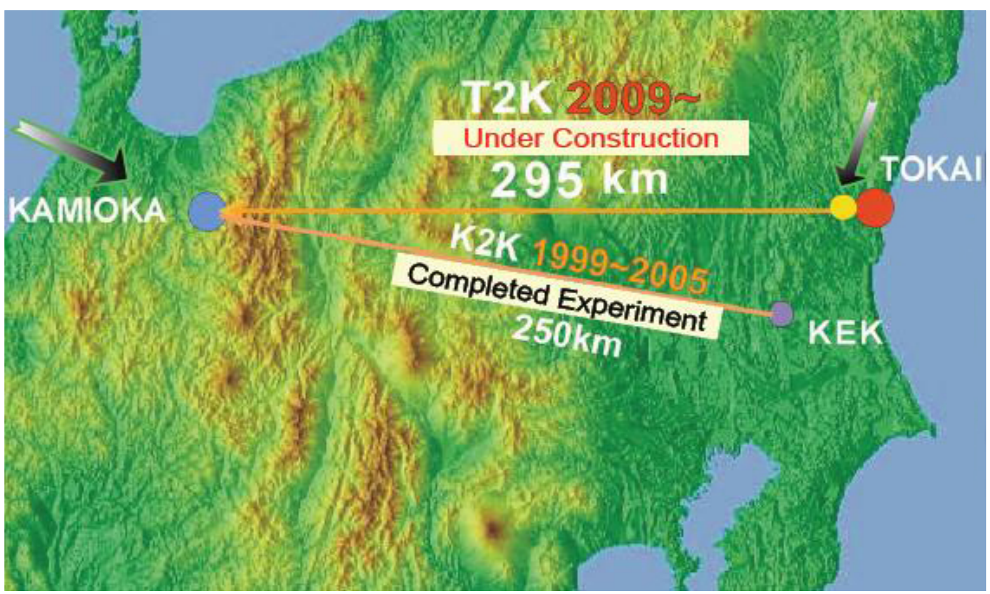
T2K (θ_{13} on accelerators)

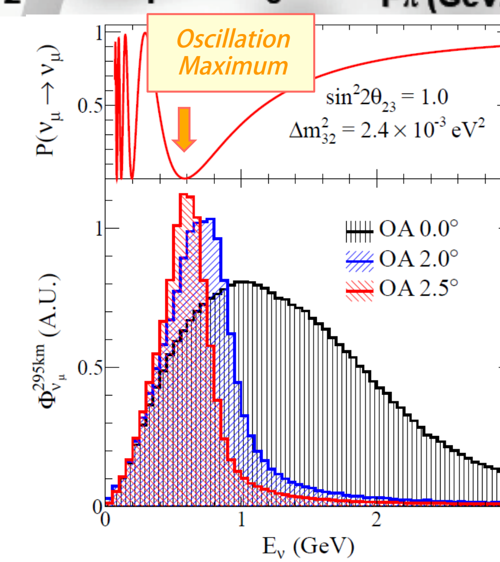




Very intense proton beam
(0.75 MW nominal power, 30 GeV)
Off-axis (2.5 deg.)
< E > 0.7 GeV

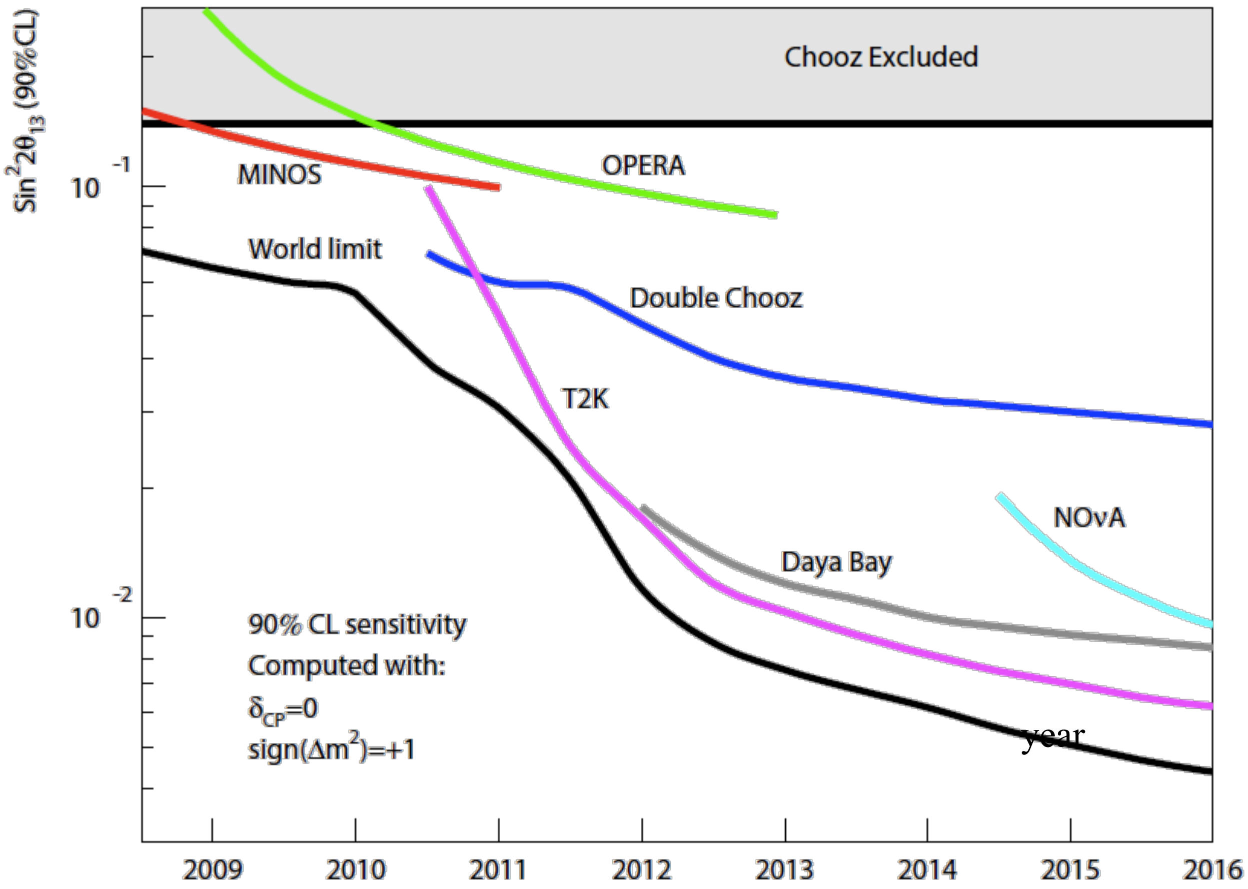






θ_{13} hunting…
(<2012)

~short term expectations

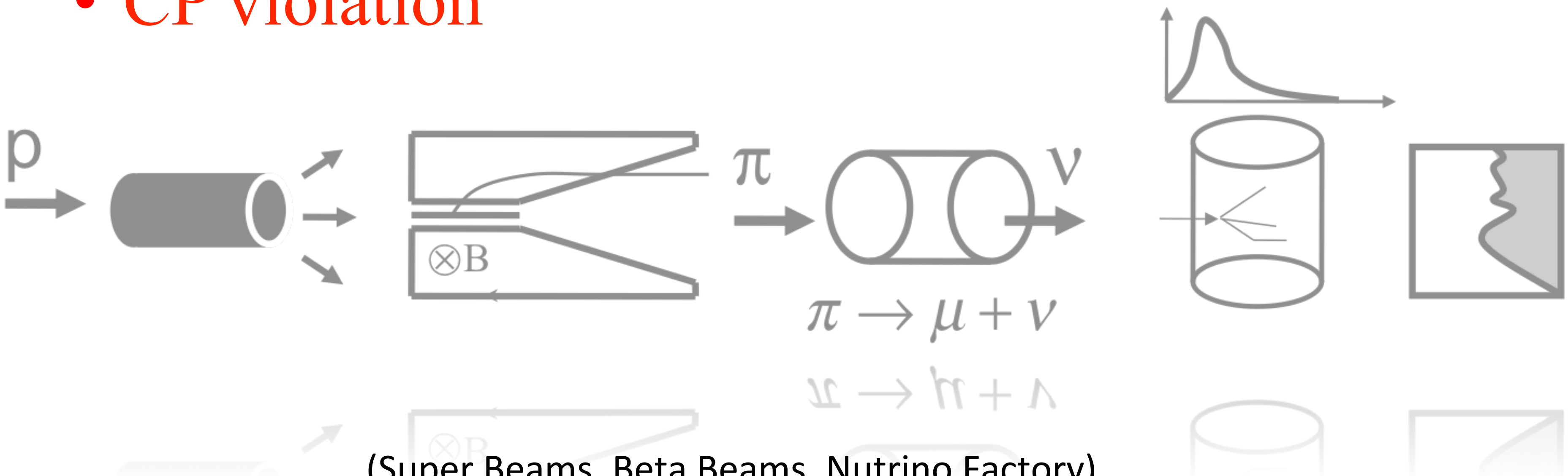


optimization in order to go as low as possible in θ_{13}

Meanwhile…

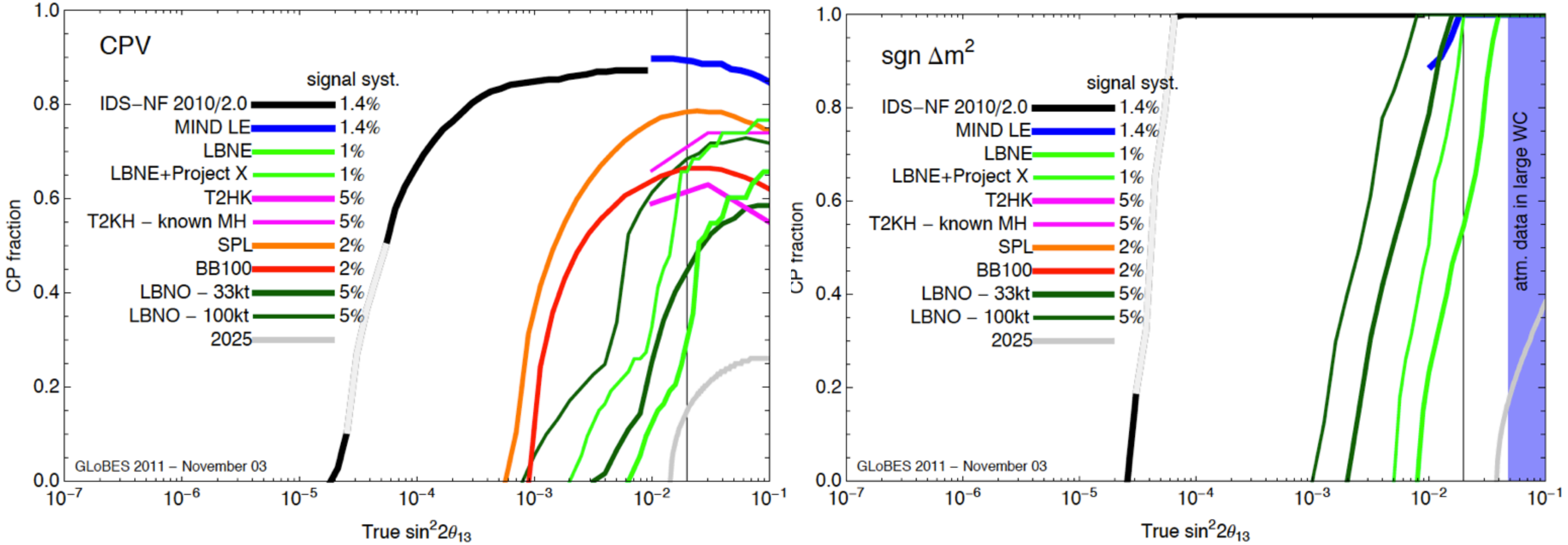
New proposals for neutrino beams to measure:

- θ_{13} as low as possible
- neutrino mass hierarchy (sign of Δm_{13})
- CP violation



(Super Beams, Beta Beams, Nutrino Factory)

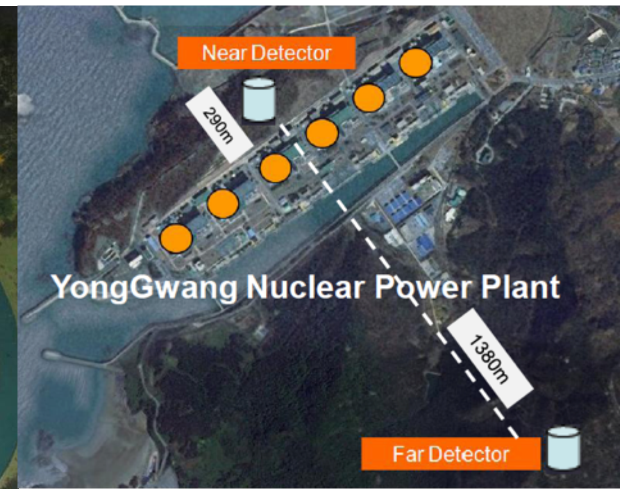
Project Comparison (unknown θ_{13})



name	baseline	type	mass	power	sec. in year	years	sig. syst.
LBNE	1300	WC/LAr	200/33	0.7MW	2×10^7	5+5	1%
LBNE+ Pro. X	1300	WC/LAr	200/33	2.3MW	2×10^7	5+5	1%
LBNO 33kt	2300	LAr	33	1.7MW	1.7×10^7	5+5	5%
LBNO 100kt	2300	LAr	100	1.7MW	1.7×10^7	5+5	5%
T2HK	295	WC	560	1.66MW	1×10^7	2.1+2.9	5%
SPL	130	WC	440	4MW	1×10^7	2+8	2%
BB100	130	WC	440	1.1×10^{18} Ne 2.9×10^{18} He	1×10^7	5+5	2%
IDS-NF 2.0	4000+7500	MIND	100+50	4MW	1×10^7	5+5	1.4%
MIND LE	2000	MIND	100	4MW	1×10^7	5+5	1.4%

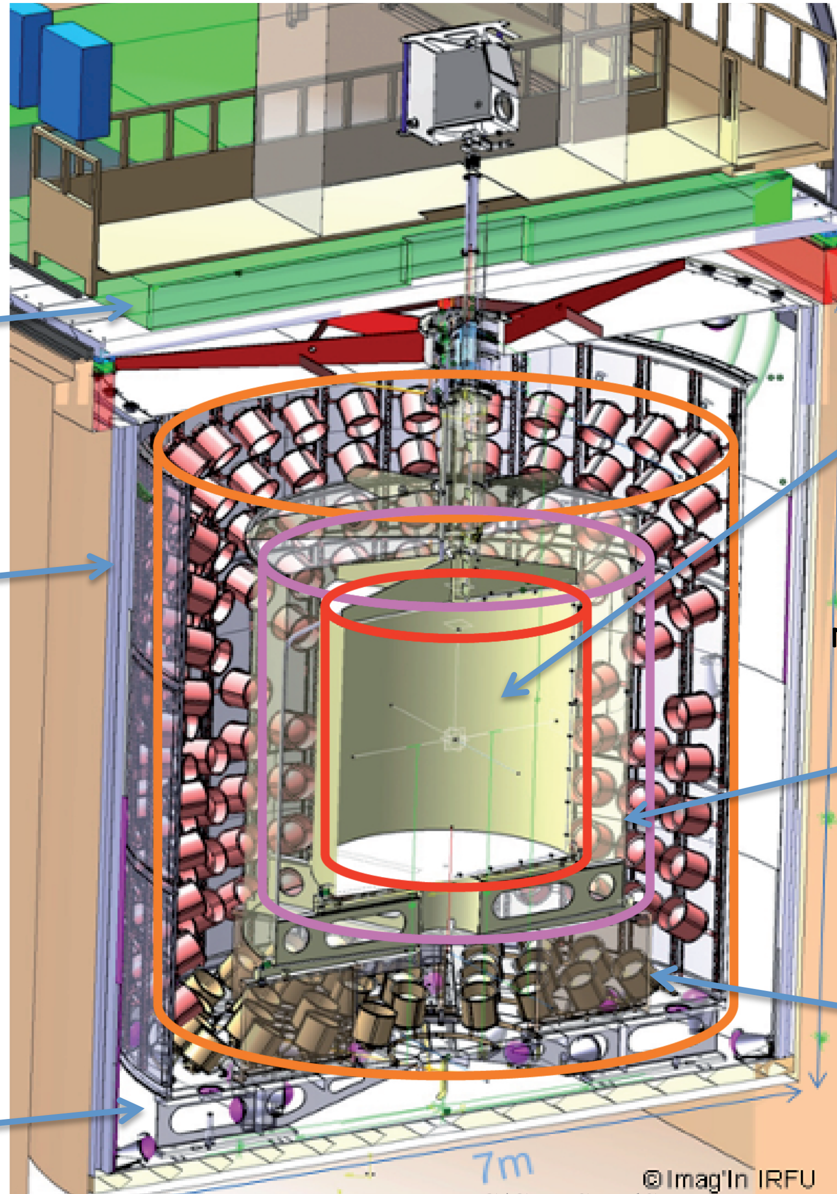
Meanwhile…
New Reactor Projects ready (2011)

Daya Bay (China)	Double Chooz (France)	RENO (South Korea)



	Luminosity in 3 years (ton·GW·y)	Overburden near/far (mwe)	Expected sensitivity	Start of data taking
Daya Bay	4200	270/950	<0.01	August 2011
Double Chooz	210	80/300	0.02~0.03	April 2011
RENO	740	90/440	~0.02	August 2011

Reactor neutrino detectors



Outer Veto
(plastic scintillator)

Shielding
(15 cm steel)

Inner Veto
(liquid scintillator)
78 (8") PMTs

Target (r=1.2 m)
- acrylic vessel (8 mm)
- 8.3 tons Gd-scintillator

Gamma Catcher (e=0.55 m)
- scintillator

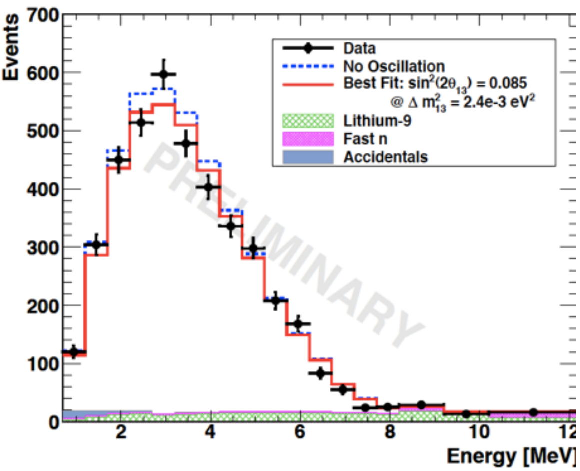
Buffer (e=1.05 m)
- steel (3 mm)
- 80 tons "oil"
- 390 PMTs (10")

Reactor neutrino detectors

θ_{13} is large!!!

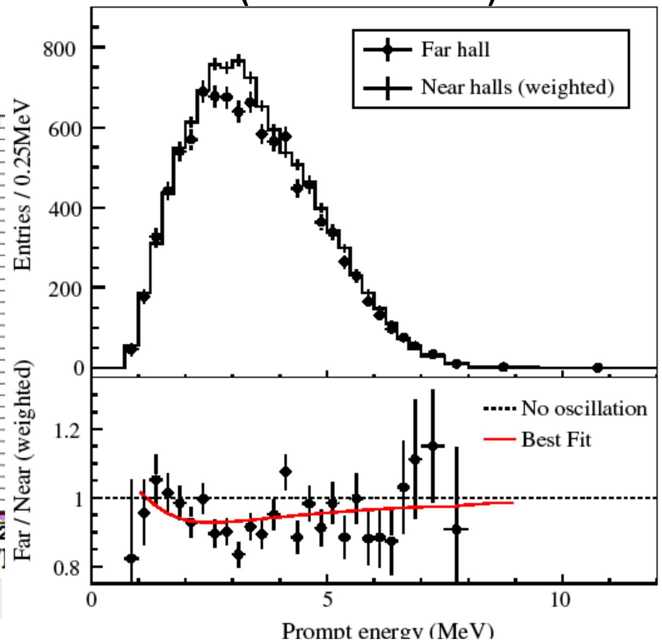
reactor experiments discovery
of the 1→3 oscillation

Double Chooz
with only a far detector
(Nov. 2011)



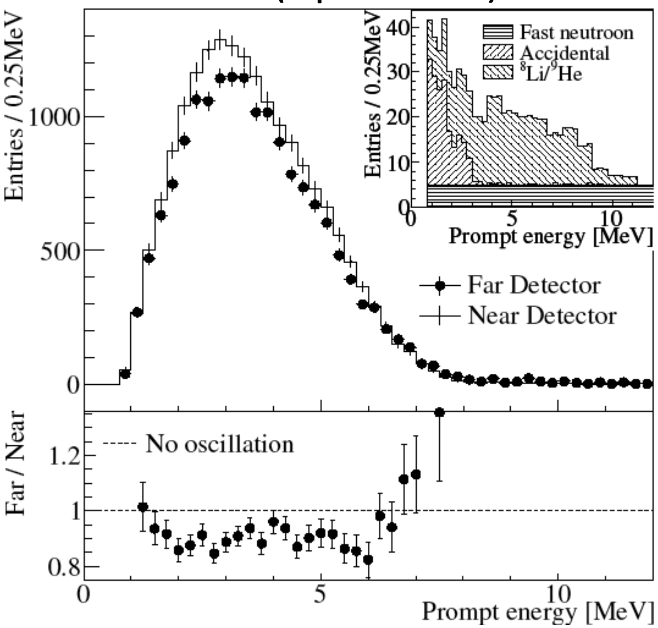
$\sin^2(2\theta_{13})=0.085\pm0.029(stat)\pm0.042(syst)$

Daya Bay
(March 2012)



$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$

RENO
(April 2012)

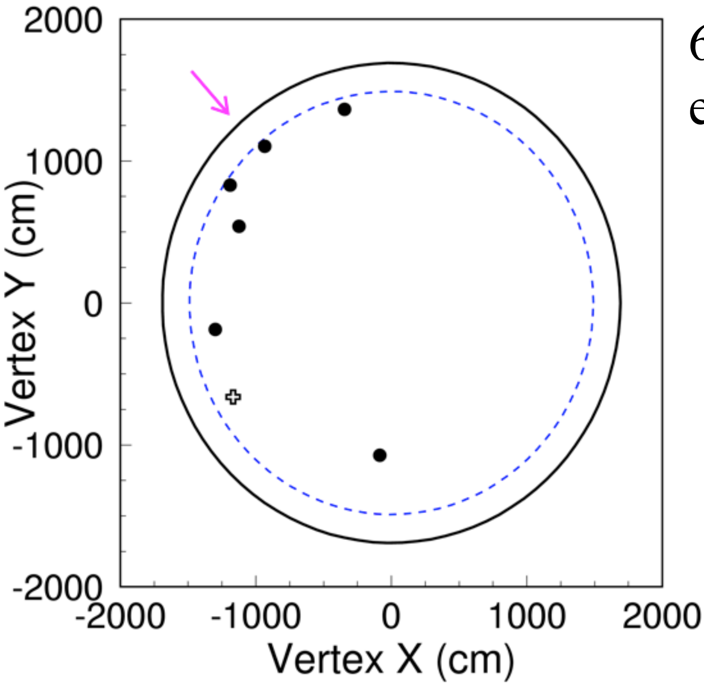


$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$

$\theta_{13}>0$ (C.L. > 5 σ) → proposed LBL beam facilities had to be readjusted…
now, the name of the game is MH and CPV

Do not forget the T2K evidence…

Phys. Rev. Lett. 107, 041801 (2011)



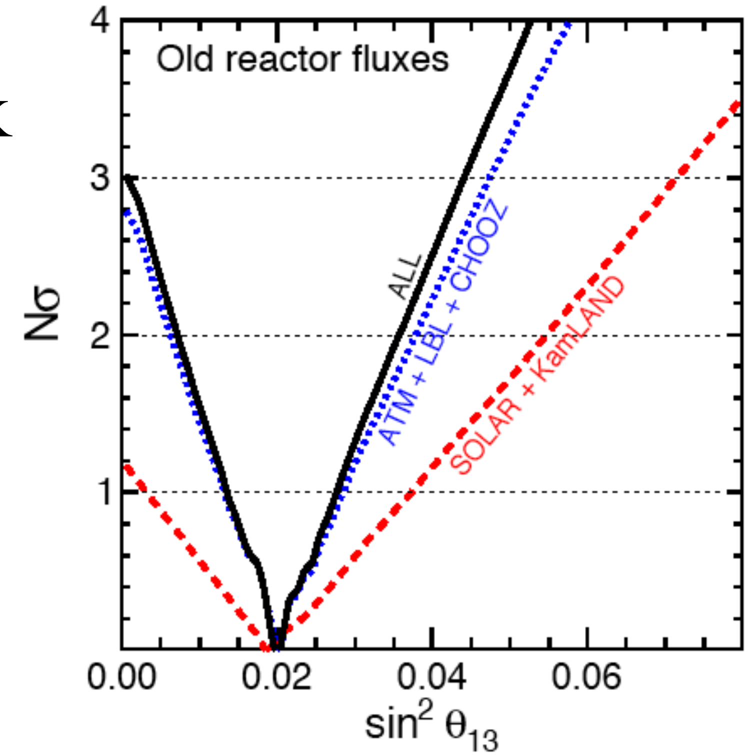
6 electron-like events in SuperK

Normal hierarchy, δ=0:

- Best fit: $\sin^2(2\theta_{13})=0.11$
- $0.03<\sin^2(2\theta_{13})<0.28$ @90% C.L.

$\sin^2 2\theta_{13}>0$ at 2.5 σ

Phys. Rev. D84 (2011) 053007



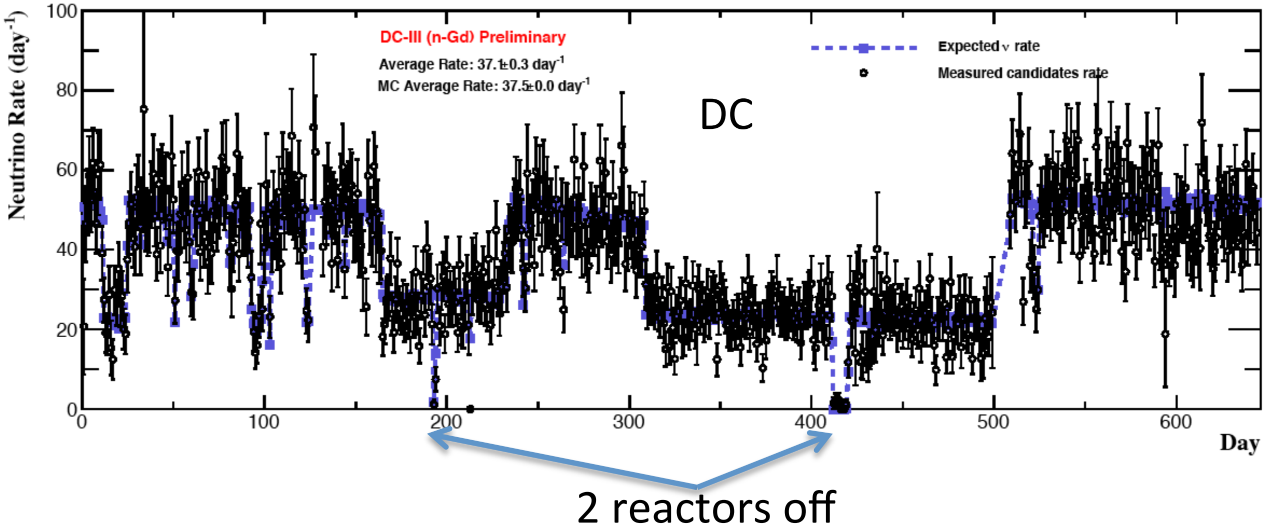
2011 global results:

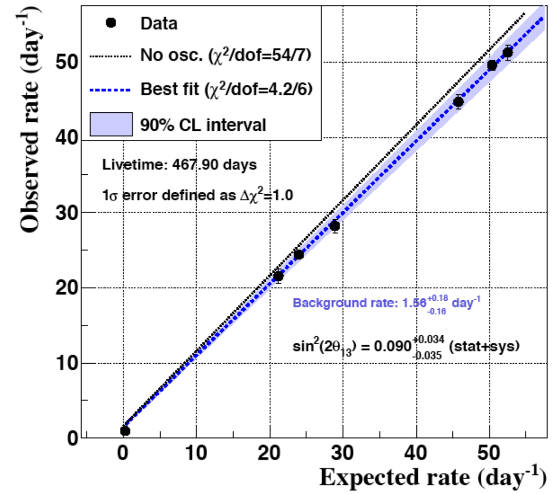
$\sin^2\theta_{13}=0.021\pm0.007$

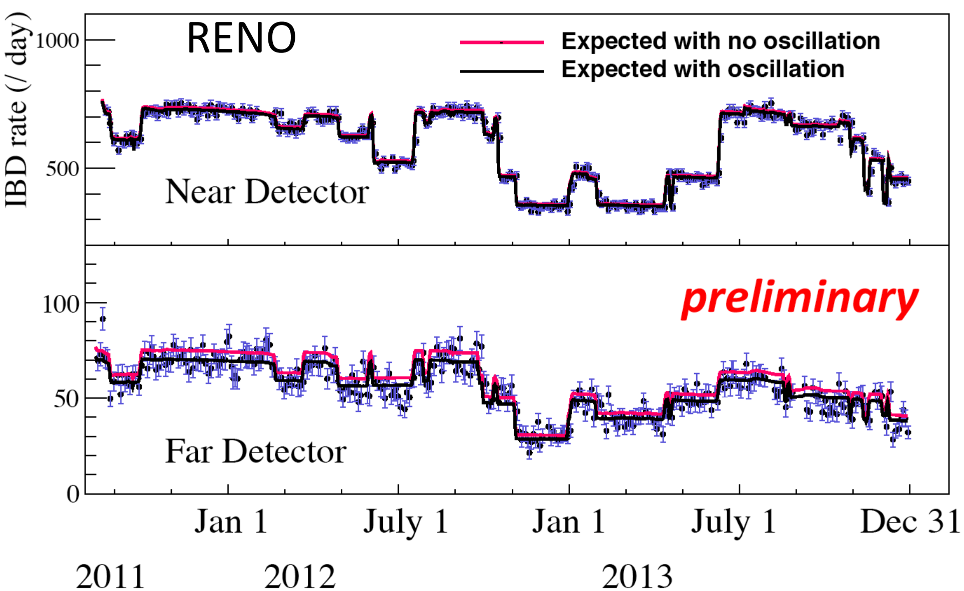
⇒

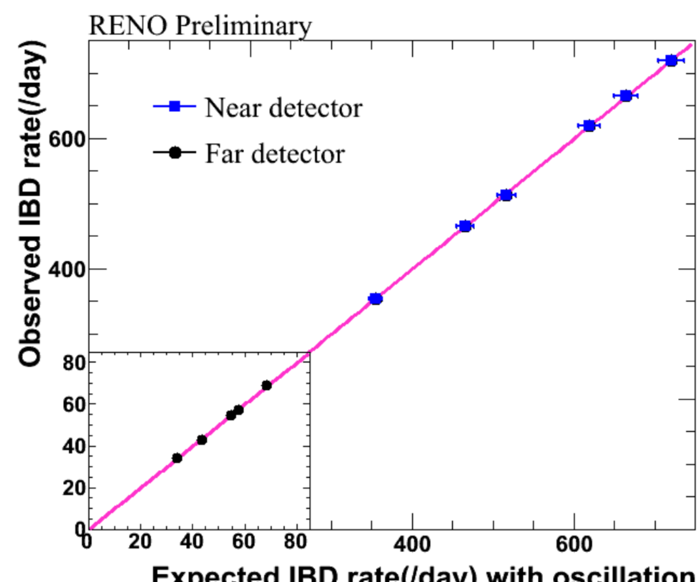
$\sin^2\theta_{13}>0$ with C.L. ~3 σ

Precision era with high statistics

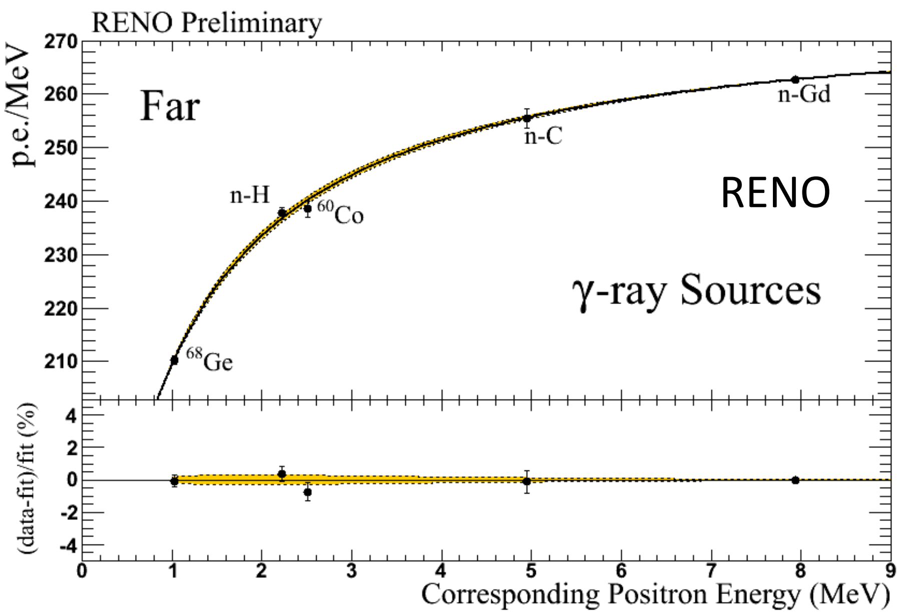


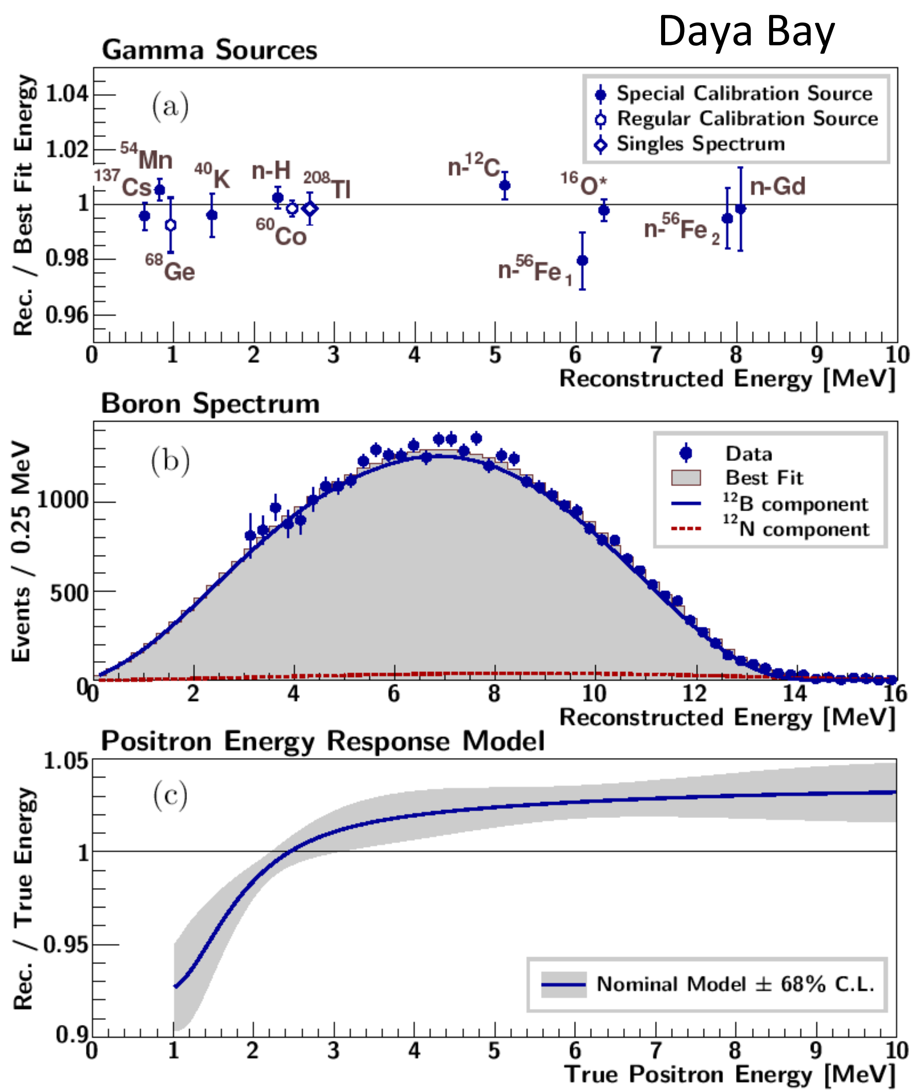


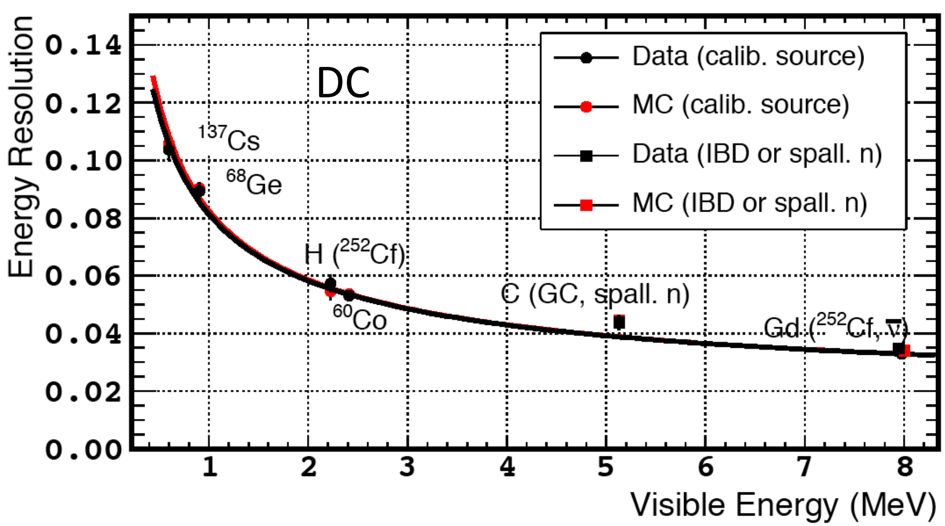




Detector calibration







Systematic errors

(limiting factor)

DC

Source	Uncertainty (%)
Bugey4 measurement	1.4
Fractional fission rate of each isotope	0.8
Thermal power	0.5
IBD cross-section	0.2
Mean energy released per fission	0.2
Distance to reactor core	< 0.1
Total	1.7

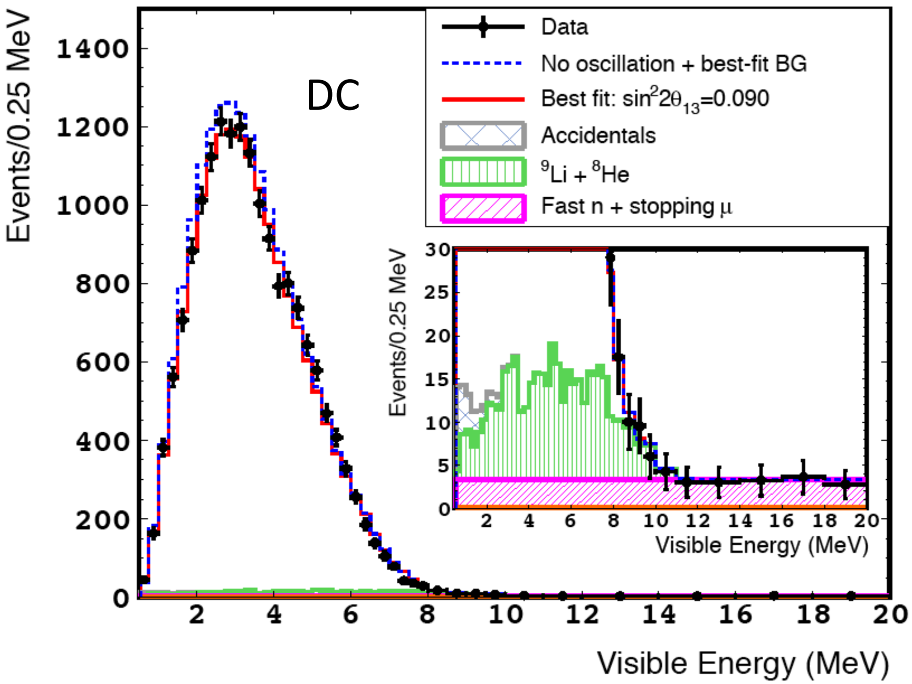
Daya Bay

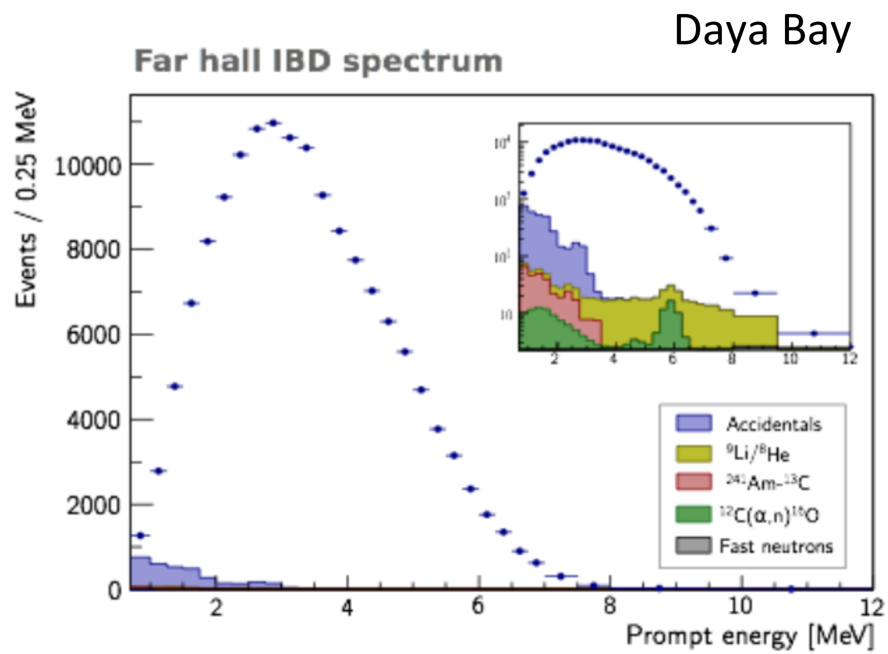
	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

RENO

Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$ Error (fraction)
Statistics (near) (far)	0.21 % 0.54 %	0.008
Isotope fraction	0.7 %	0.003 → 15.6 %
Thermal power	0.5 %	0.002 → 6.9 %
Detection efficiency	0.2 %	0.003 → 15.6 %
Backgrounds (near) (far)	0.14 % 0.51 %	0.006 → 62.3 %

Background



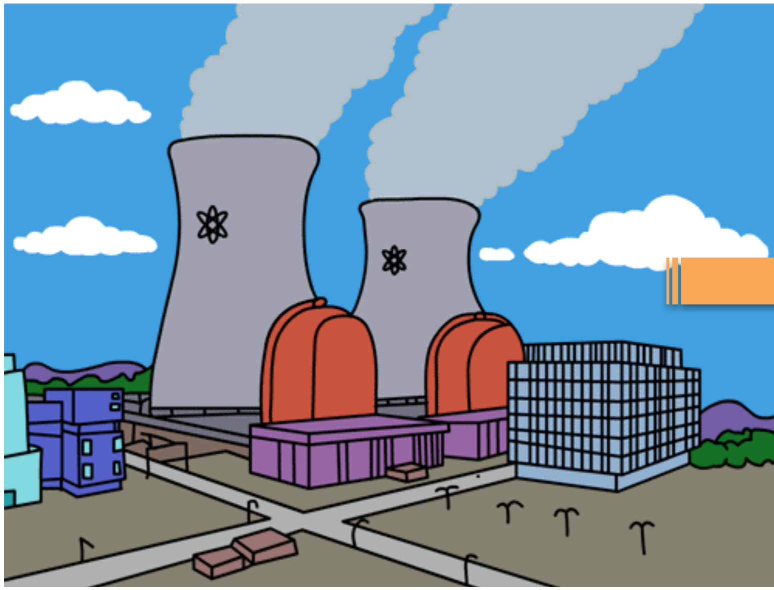


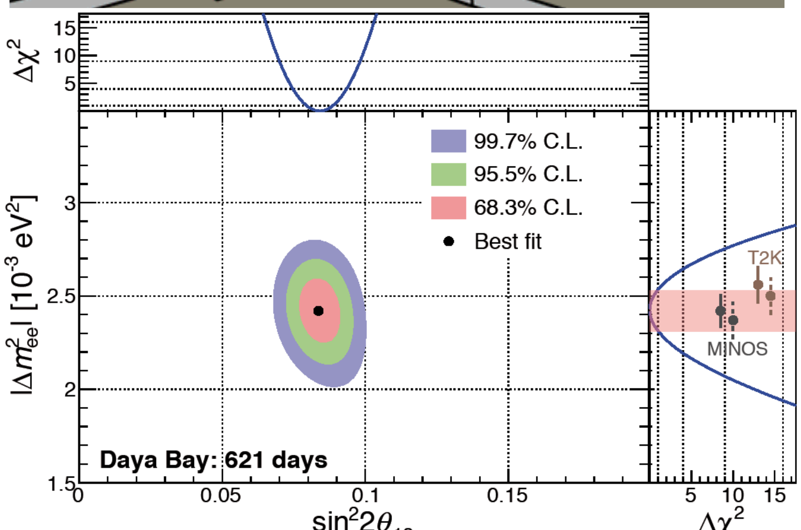
Daya Bay

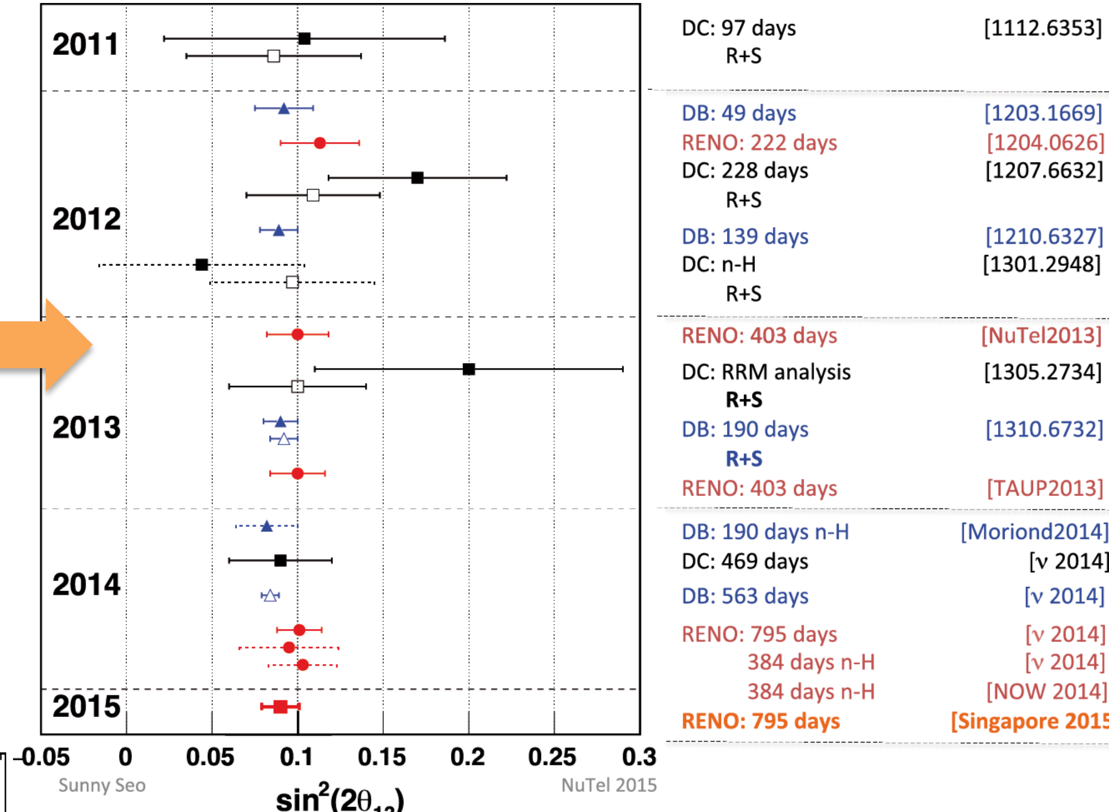
Background	Near	Far	Uncertainty	Method
Accidentals	1.4%	2.3%	negligible	statistically calculated from uncorrelated singles
$^{9}Li/^{8}He$	0.4%	0.4%	50%	measured with after-muon events
^{241}Am-^{13}C	0.03%	0.2%	50%	MC benchmarked with single gamma and strong AmC source
Fast neutrons	0.1%	0.1%	30%	measured from AD/water/RPC tagged muon events
$^{12}C(\alpha, n)^{16}C$	0.01%	0.1%	50%	calculated from measured radioactivity

Present results

(NuTel2015)







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

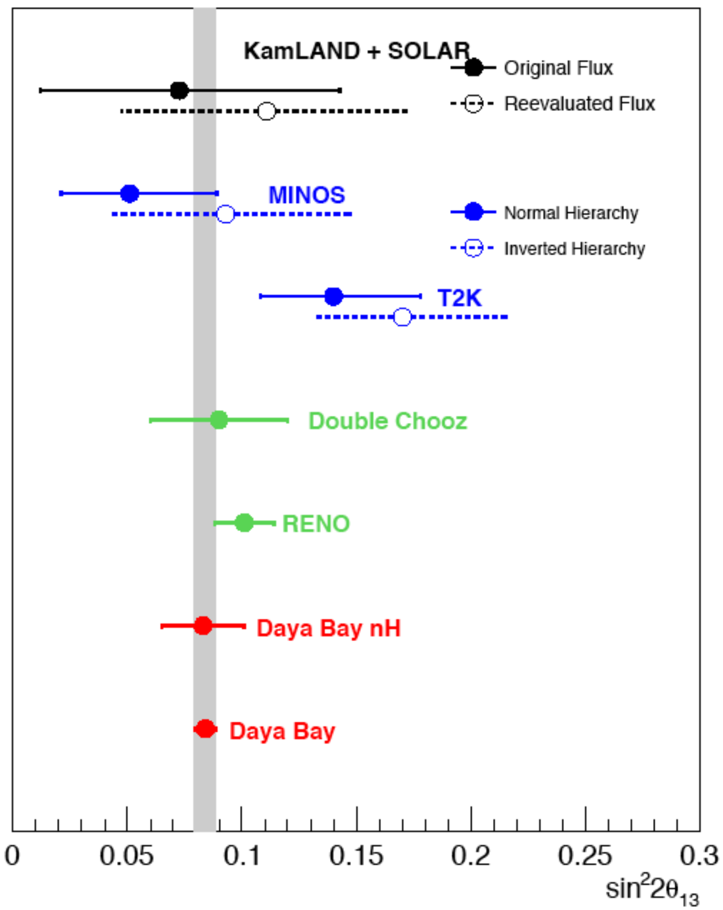
$$\left|\Delta m^2_{ee}\right| = 2.42 \pm 0.11 \times 10^{-3}\ \text{eV}^2$$

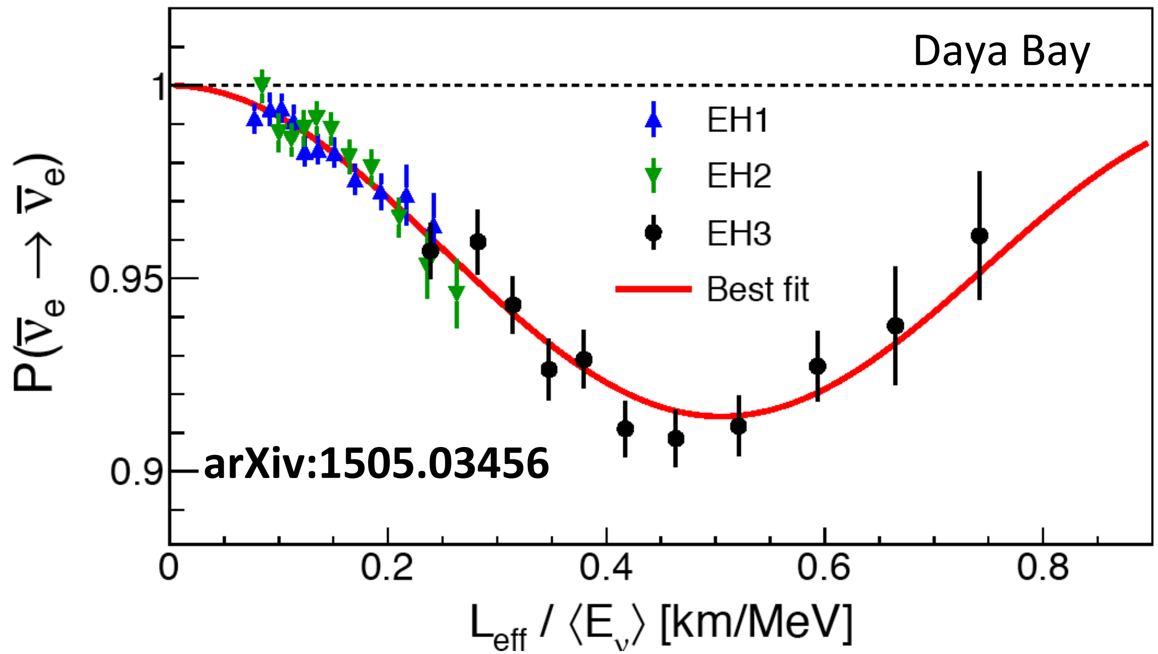
arXiv:1505.03456

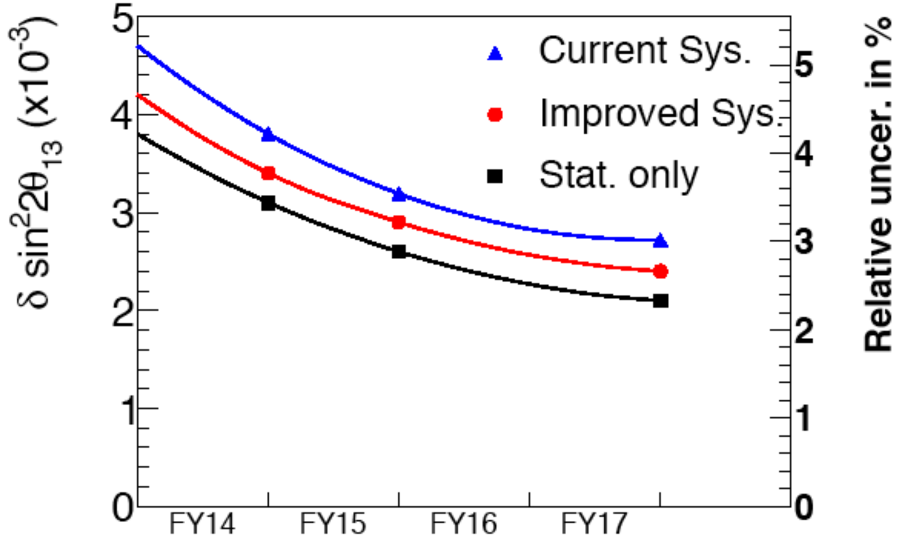
$\sin^2 \Delta_{ee} \equiv \cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$

Precision era

arXiv:1505.01891

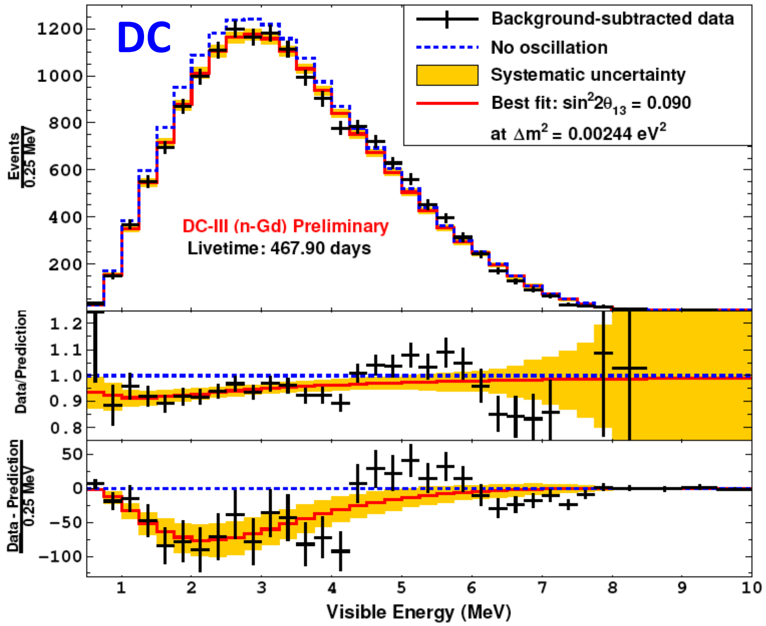


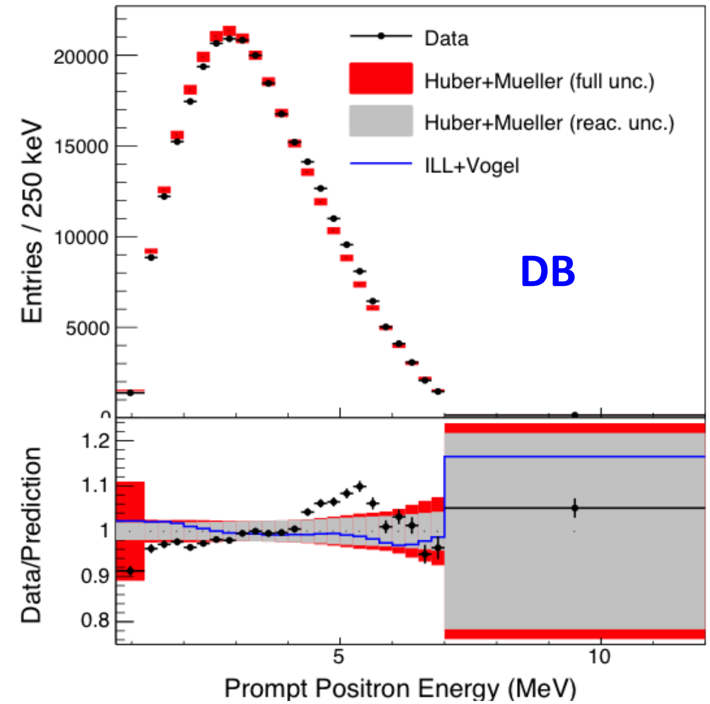


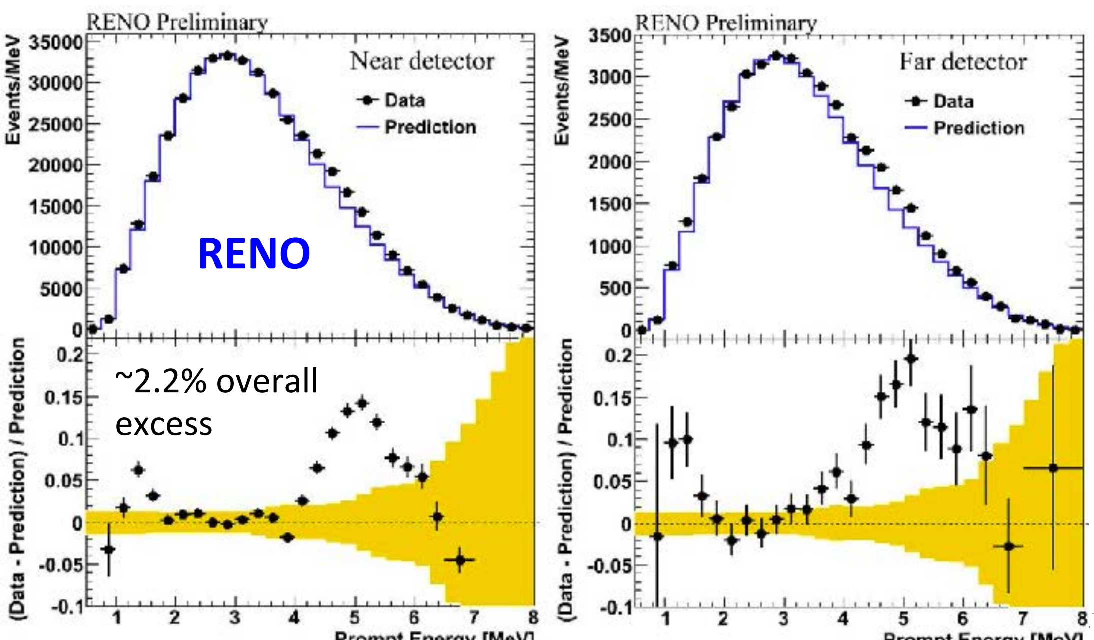


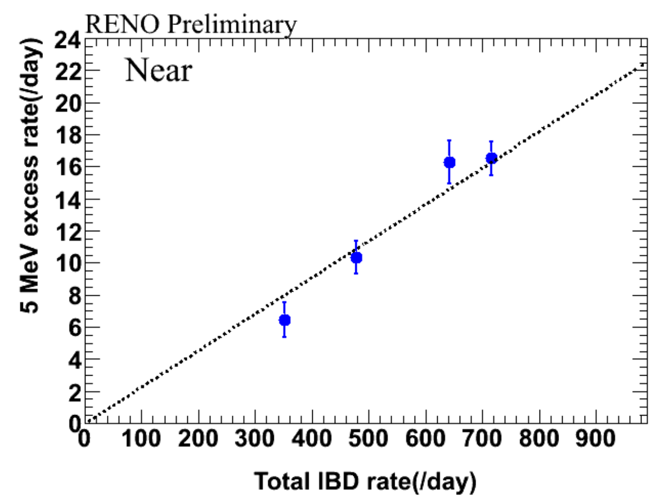
Oups… a problem!

excess for 4<E<6 MeV





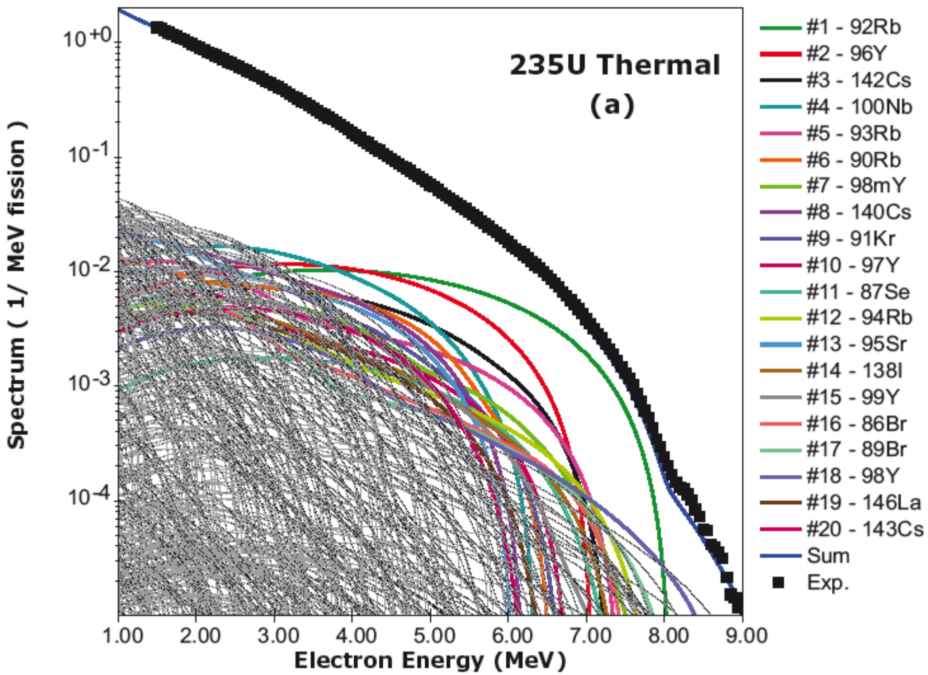




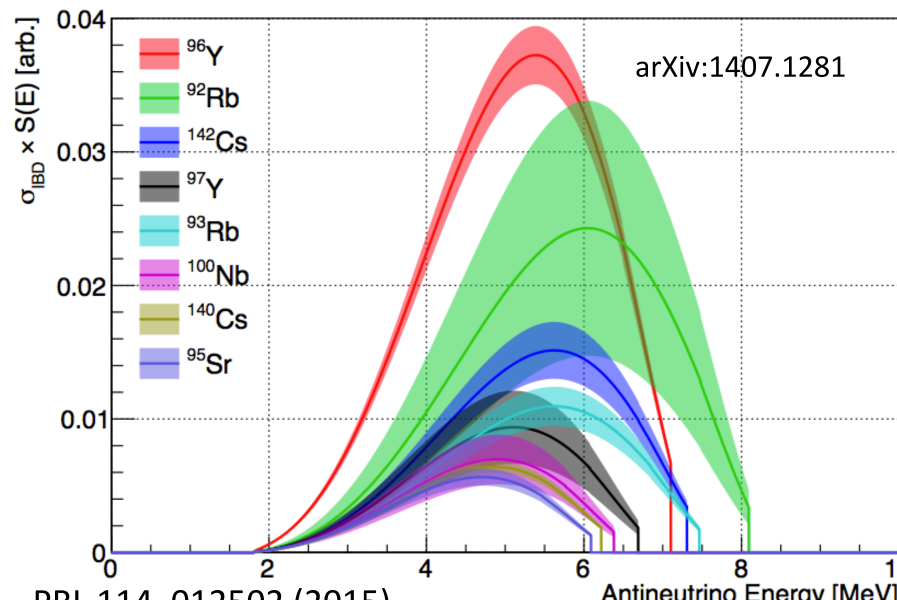
How about the spectrum predictions?

- Significance: globally ~ 2 σ, locally up to 4 σ
- Events depending on reactor power disfavouring unexpected backgrounds
- A single β-branch or mono-energetic line cannot simulate this excess
- A possible explanation:
  - Decays of prominent fission daughter isotopes (~ 42% rate from ^{96}Y, ^{92}Rb, ^{142}Cs, ^{97}Y, ^{93}Rb, ^{100}Nb, ^{140}Cs, ^{95}Sr)

- **No effect to θ_{13} especially if near-far comparison is applied.**
- **Not large enough to explain the reactor anomaly.**



PRC 91, 011301(R) (2015)



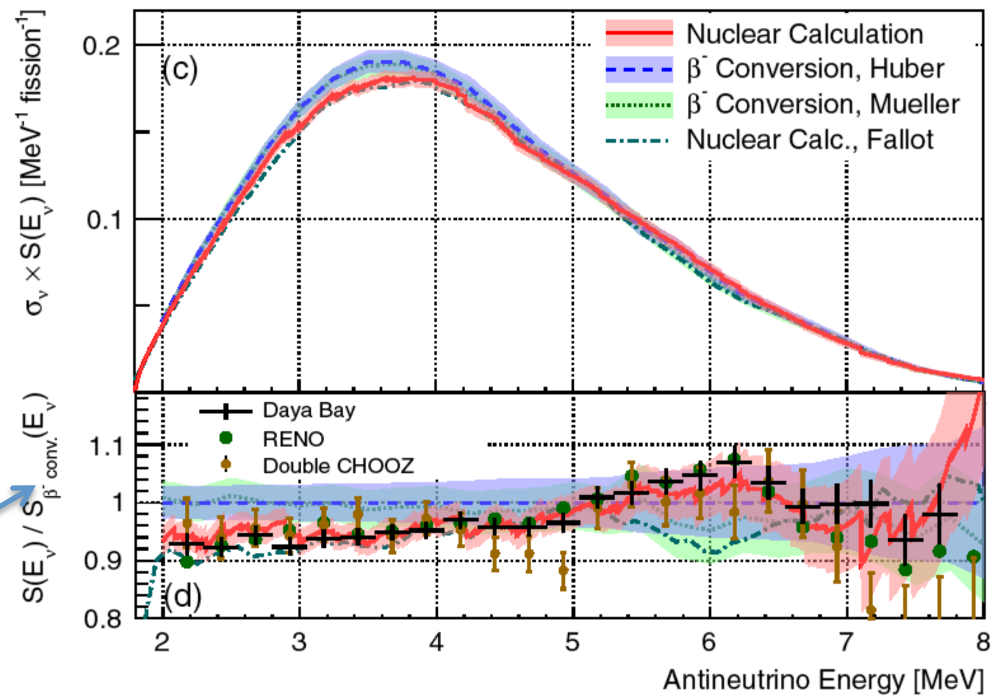
PRL 114, 012502 (2015)

Possible explanations

Two general approaches used to calculate antineutrino spectra:

- **Conversion method**: relies on the measured β spectra from the ILL which are fitted with a set of virtual β branches and then converted into the corresponding antineutrino. spectra.
- **Summation (or ab initio) method**: makes use of all available information on the β decays of each fission fragment, summing each nuclide's individual β spectrum weighted by its yield in fission.

PRL 114, 012502 (2015)

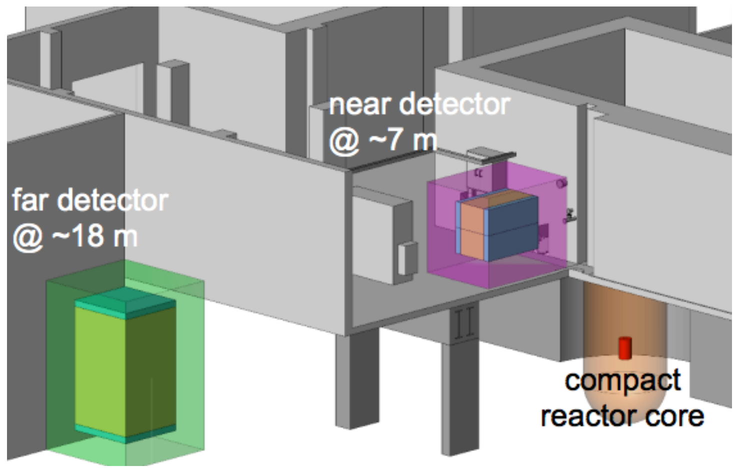


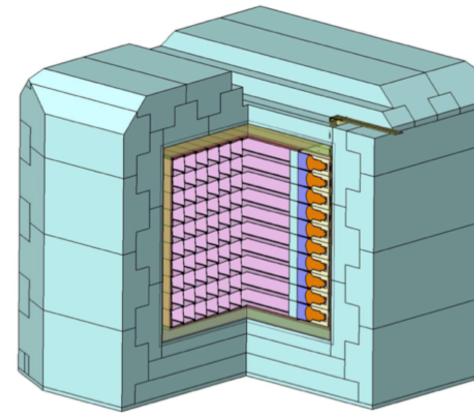
*"illustrative comparison…
the overall agreement between the measurements and ab initio calculation is surprising…"*

Precision measurements of energy spectrum needed

- New Very Short Baseline experiments (mainly for sterile neutrino searches)
- Very good energy resolution needed

PROSPECT



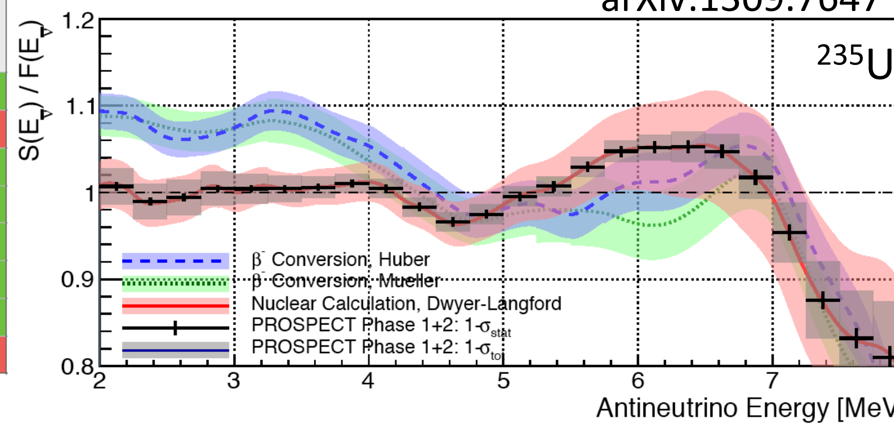


Li loaded Liquid scintillator

Effort	Dopant	Good X-Res	Good E-Res	L Range (meters)	Fuel	Exposure, MW*ton	Move-able?	Running at intended reactor?
PROSPECT	**Li**	**Yes**	**Yes**	**6.5-20**	**HEU**	**185**	**Yes**	**Yes**
NuLat	Li/B	Yes	Yes	TBD	TBD	TBD	Yes	No
Nucifer	Gd	No	Yes	7	HEU	56	No	Yes
STEREO	Gd	Yes	Yes	9-11	HEU	100	No	Yes
SoLid	Li	Yes	No	6-8	HEU	155	No	Yes
DANSS	Gd	Yes	No	9.7-12	LEU	2700	Yes	Yes
Neutrino4	Gd	Yes	No	6-12	HEU	150	Yes	Yes
Hanaro	Li/Gd	No	Yes	20-ish	LEU	30	No	No

B. Littlejohn Fermilab Intesity Frontier Seminar 2015

arXiv:1309.7647



What next?
(mass hierarchy)

$$P\left(\overline{\nu_e} \rightarrow \overline{\nu_e}\right) \simeq 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$- \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

$$P_{ee}(L/E) = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m_{21}^2 \cdot \frac{L}{4E})$$

$$- \sin^2 2\theta_{13} \sin^2(\left|\Delta m_{31}^2\right| \cdot \frac{L}{4E})$$

$$- \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta m_{21}^2 \cdot \frac{L}{4E}) \cdot \cos(2\left|\Delta m_{31}^2\right| \cdot \frac{L}{4E})$$

$$\pm \frac{\sin^2\theta_{12}}{2} \sin^2 2\theta_{13} \sin(2\Delta m_{21}^2 \cdot \frac{L}{4E}) \cdot \sin(2\left|\Delta m_{31}^2\right| \cdot \frac{L}{4E})$$

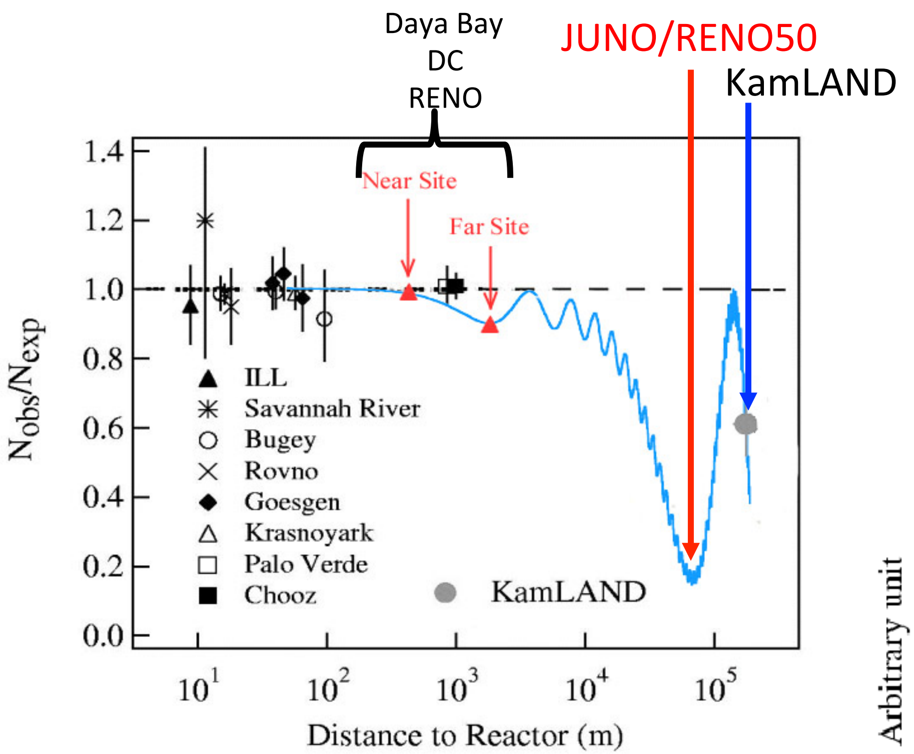
=(2n-1)π/2⇒ max. sens.

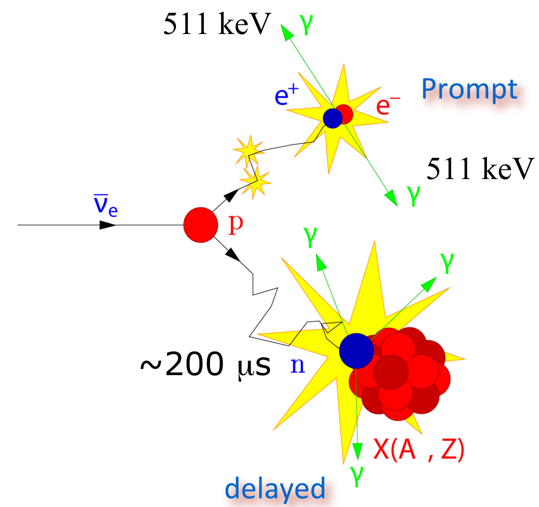
=nπ ⇒ non sensitivity

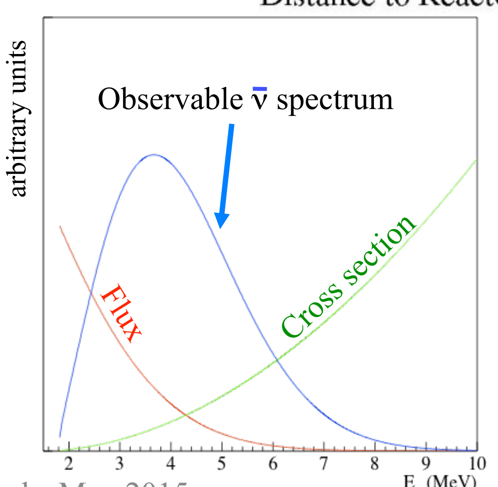
with:

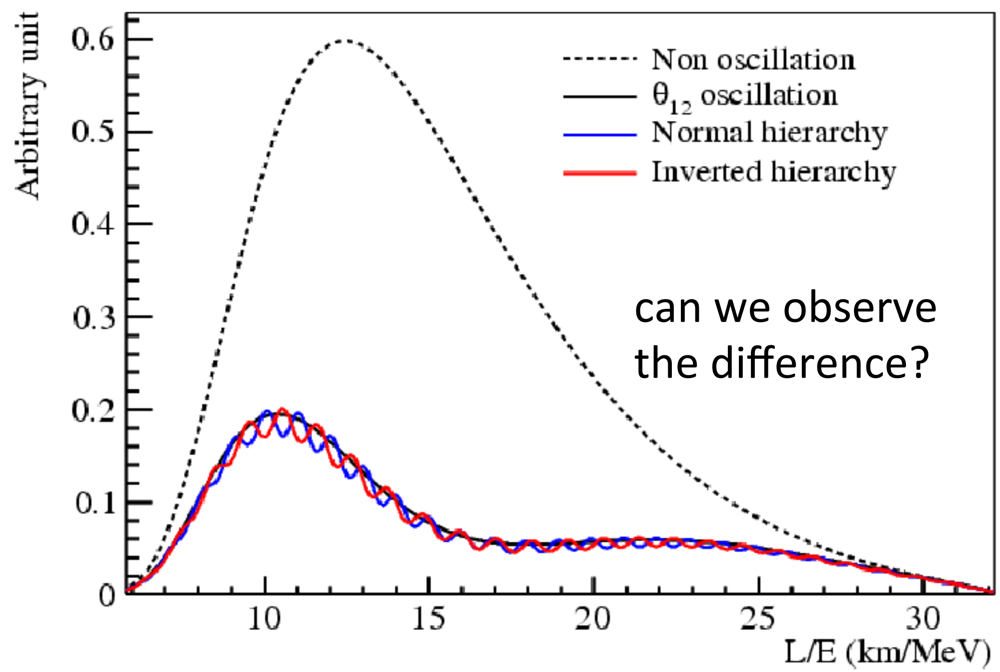
$$\Delta m_{31}^2 \equiv \begin{cases} m_3^2 - m_1^2 > 0 \ \text{(NH)} \\ m_3^2 - m_1^2 < 0 \ \text{(IH)} \end{cases}$$

Neutrino spectrum









Energy resolution

The sensitivity will strongly depend on the energy resolution (E_m: mesured energy)

$$R(E_\nu, E_m) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(E_m - E_\nu)^2}{2\sigma_E^2}}$$

$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{a^2}{E} + b^2 + \frac{c^2}{E^2}$$

stat. (N_{pe})

syst. (non-uniformities, energy leaks…)

noise

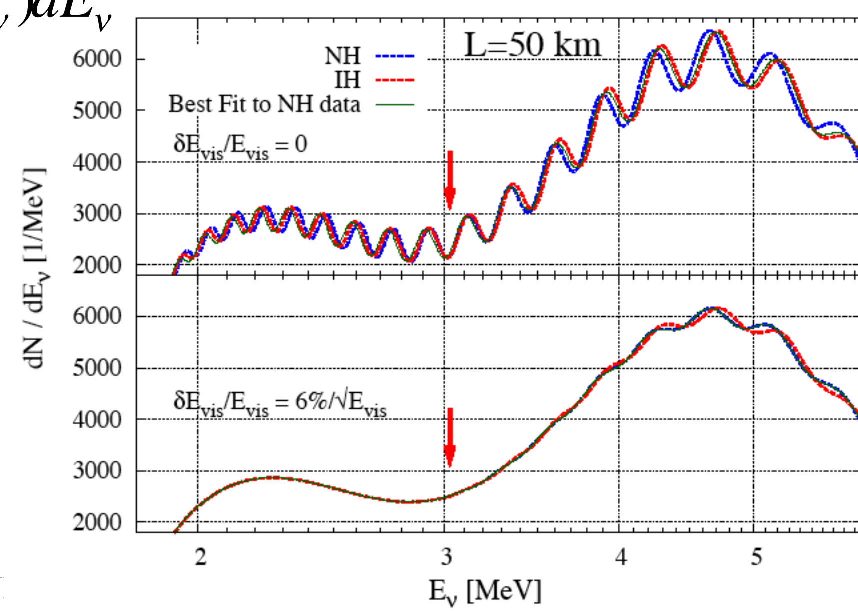
Measured spectrum (without background):

$$N(E_m) = \int R(E_\nu, E_m)\phi(E_\nu) \cdot \sigma(E_\nu) \cdot P_{\bar{\nu}_e \to \bar{\nu}_e}(E_\nu) dE_\nu$$

Shift in energy spectrum of $\sim\Delta m_{21}^2/\Delta m_{31}^2 \sim 3\%$

An energy resolution of ~3% (for E~1 MeV) is needed

JHEP 1305 (2013) 131



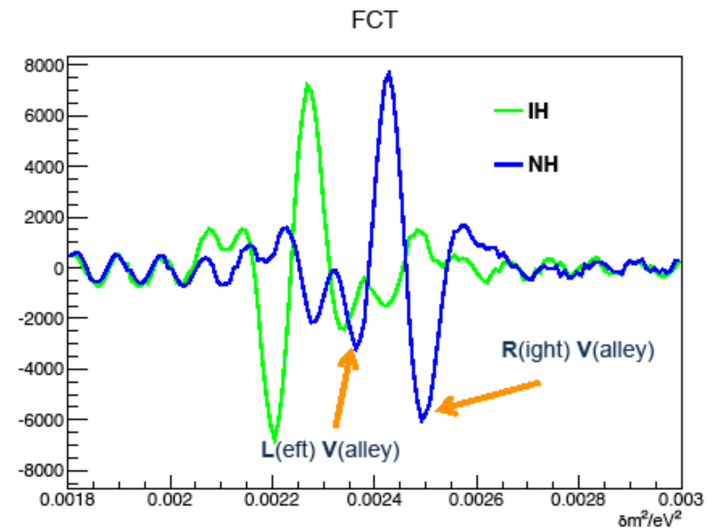
Spectral analysis

PHYS. REV. D 78, 111103(R) (2008)

Fourrier transform of the energy spectrum F(t):
(t=L/E)

$$FCT(\omega) = \int_{t_{\min}}^{t_{\max}} F(t)\cos(\omega t)\,dt$$

$$FST(\omega) = \int_{t_{\min}}^{t_{\max}} F(t)\sin(\omega t)\,dt$$

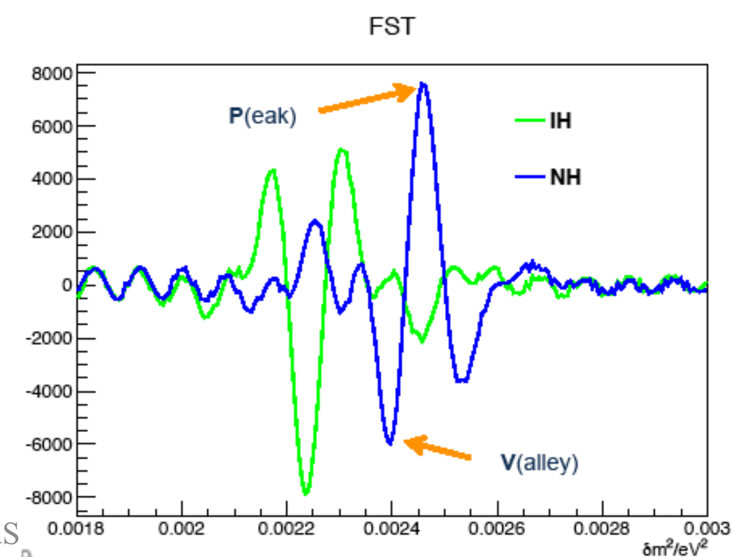


Discriminant variables:

$$RL = \frac{RV - LV}{RV + LV} \quad \text{(for FCT)}$$

$$PV = \frac{P - V}{P + V} \quad \text{(for FST)}$$

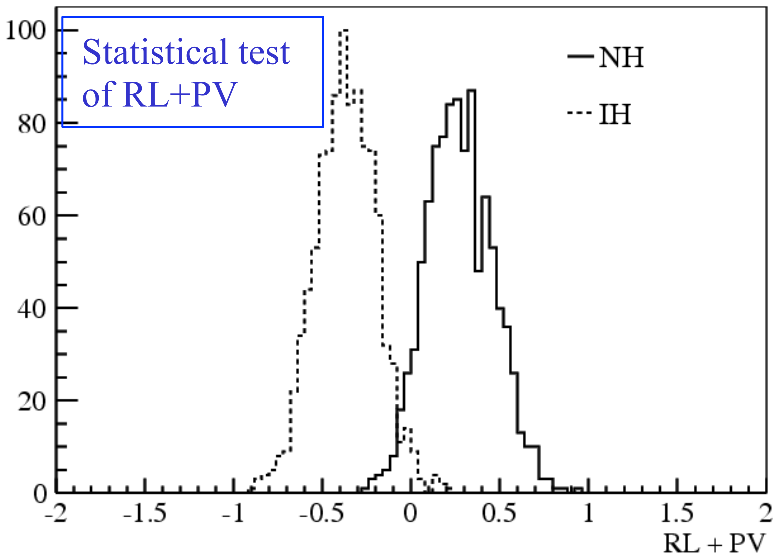
RL>0 and PV>0 →NH
RL<0 and PV<0 →IH



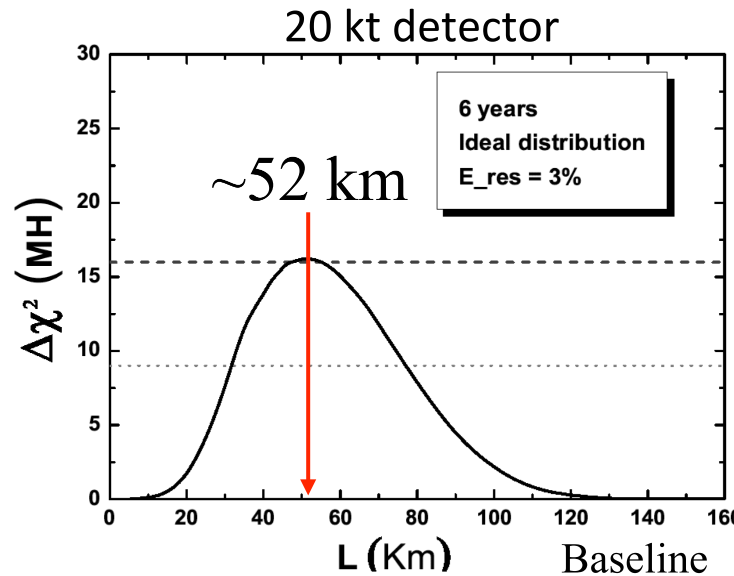
Statistical test of RL+PV

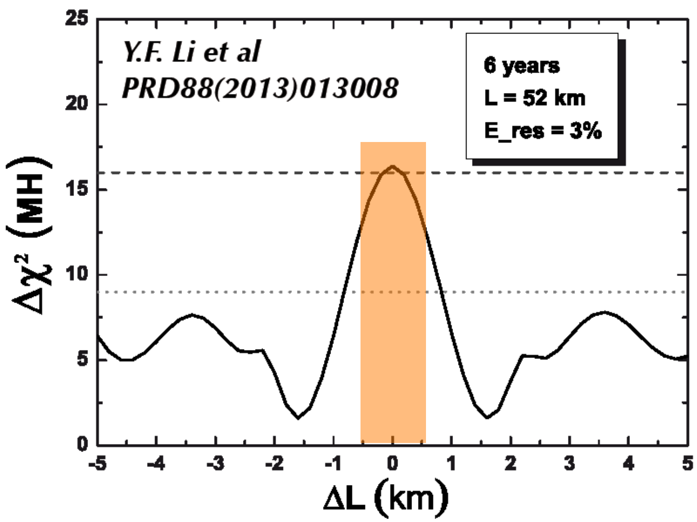
Detector position

PHYS. REV. D 78, 111103(R) (2008)

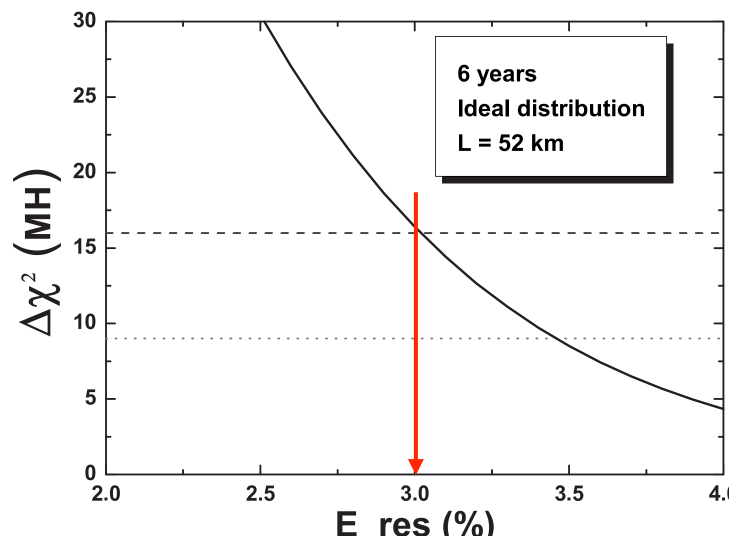


PHYS. REV. D 88, 013008 (2013)

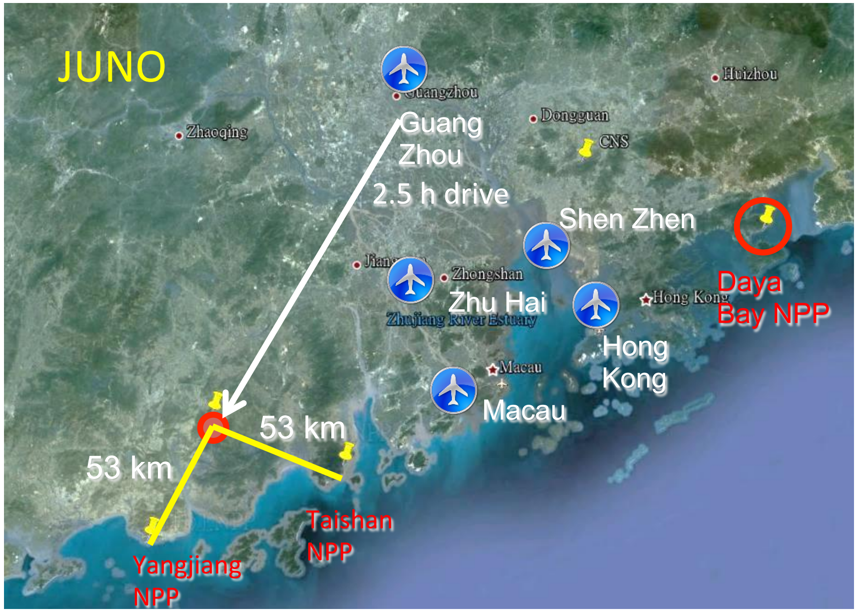


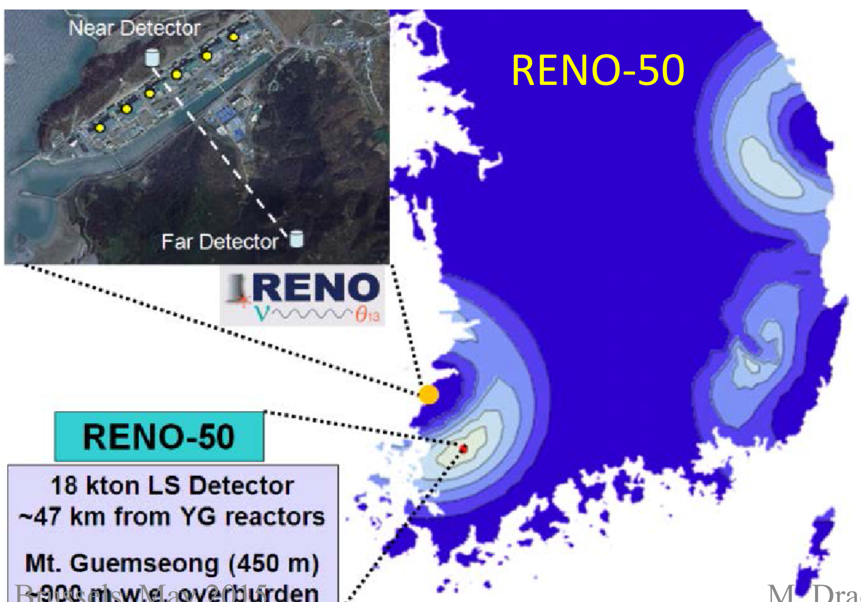


acceptable uncertainty on the distance: ±500 m



JUNO/RENO-50

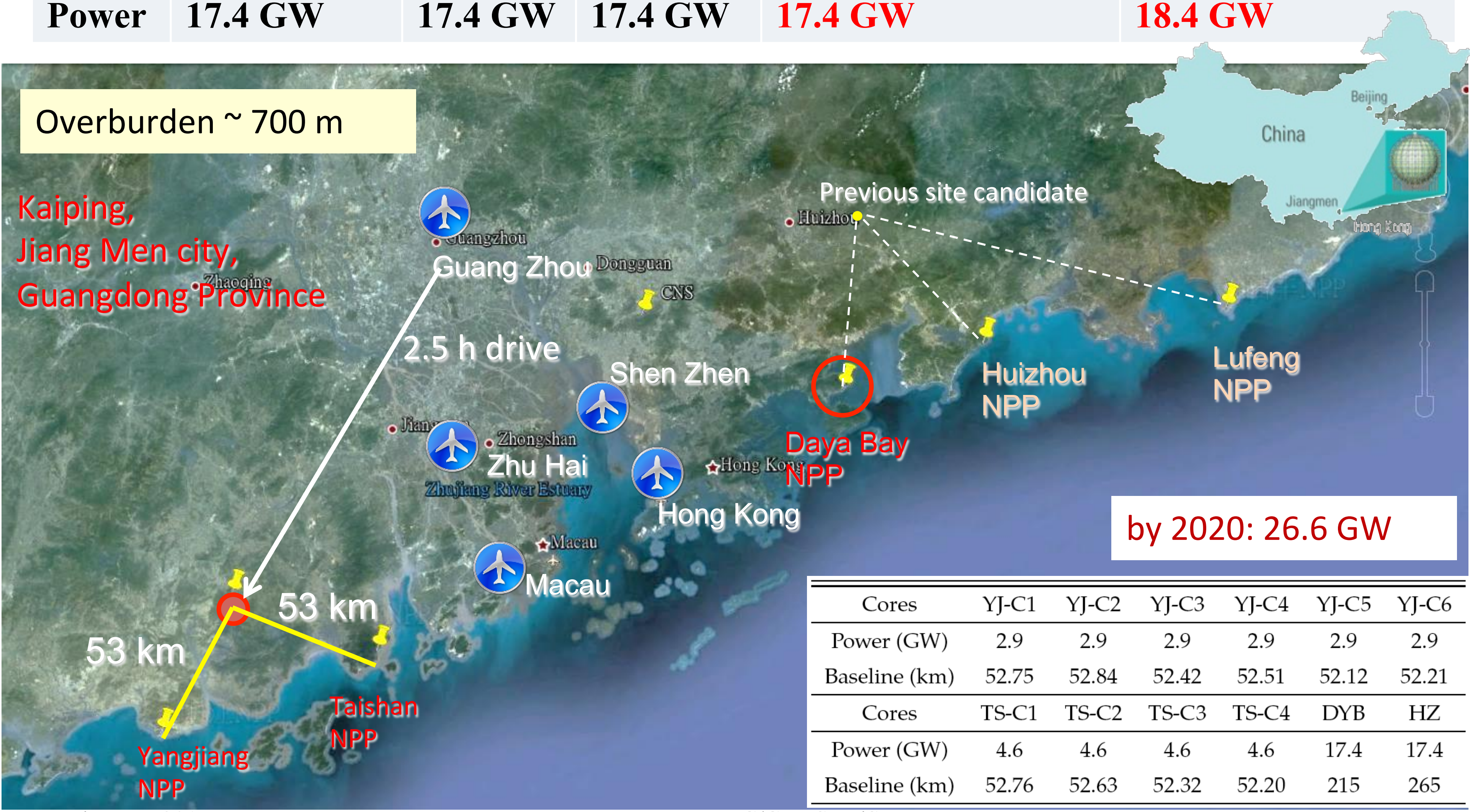




- Rich physics program:
  - Reactor neutrinos
    - Mass Hierarchy
    - precision measurements of oscillation parameters
  - Supernovae neutrinos
  - Geoneutrinos
  - Solar neutrinos
  - Atmospheric neutrinos
  - Exotic searches

JUNO

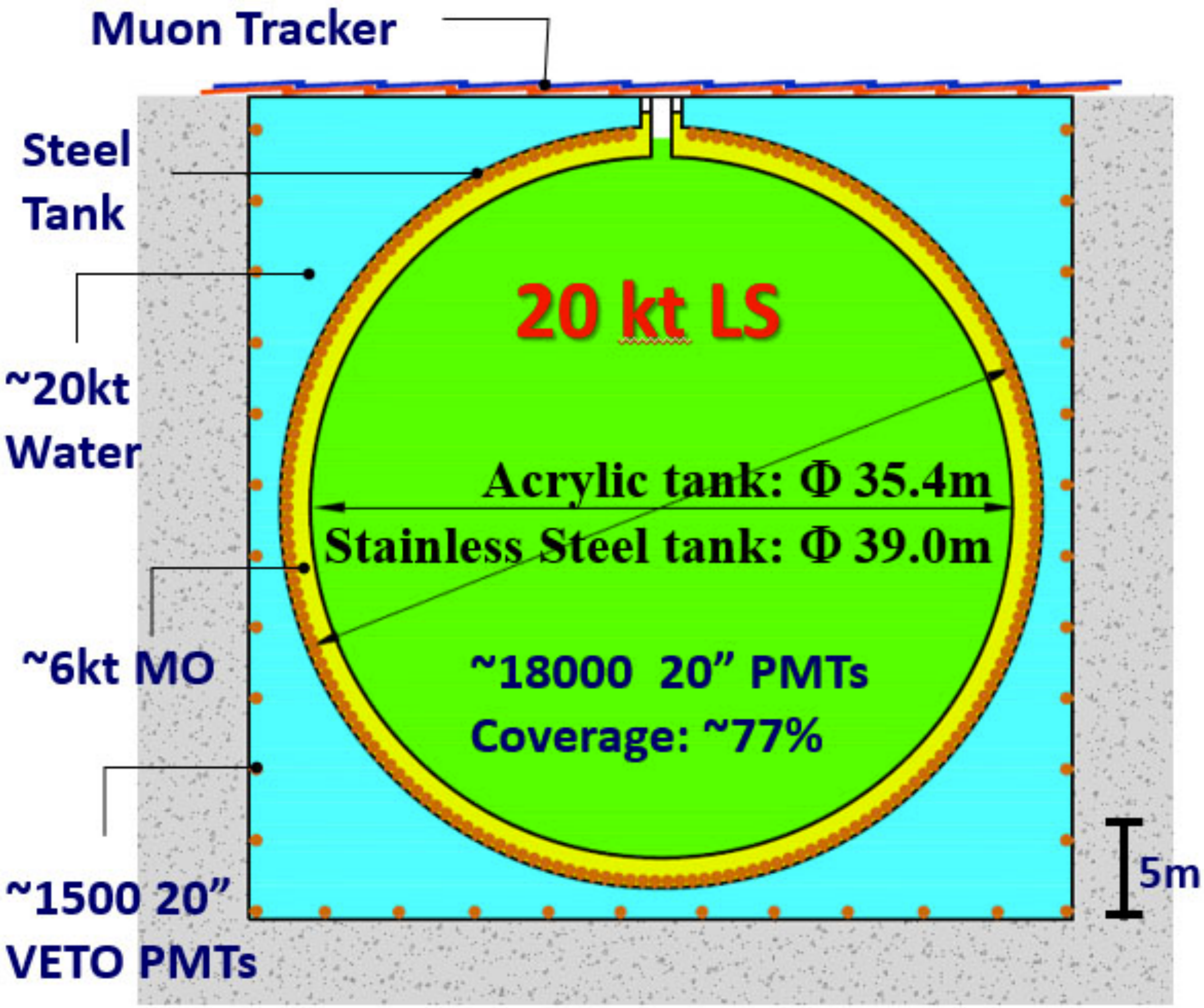
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



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

Experimental site

JUNO detector

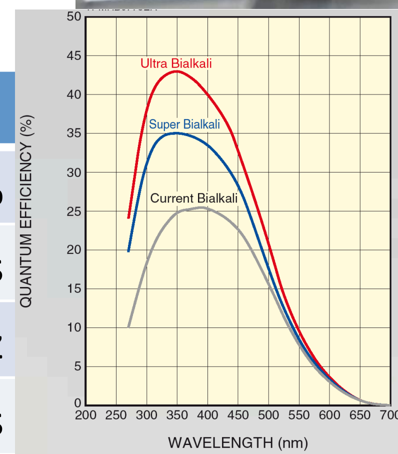


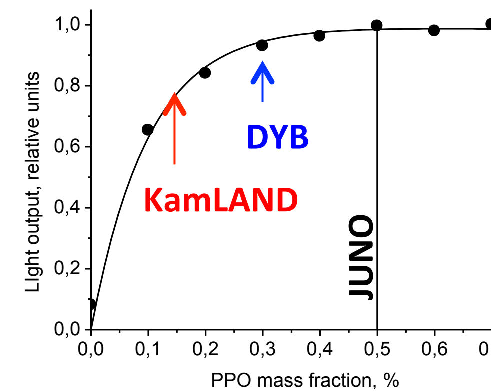
High energy resolution

How to reach the required energy resolution?

- Photocathode coverage: 77% with 20" PMTs
- High PMT QE: ~35%
- Liquid scintillator attenuation length: ~30 m
- High light yield with optimised fluors

	R5912	R5912-100	MCP-PMT
QE@410 nm	25%	35%	25%
Rise time	3 ns	3.4 ns	5 ns
Dark noise	1 kHz	3.5 kHz	2.2 kHz
TTS	5.5 ns	1.5 ns	3.5 ns





	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	6%/√E	5%/√E	3%/√E
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Background

IBD~60/day

Singles

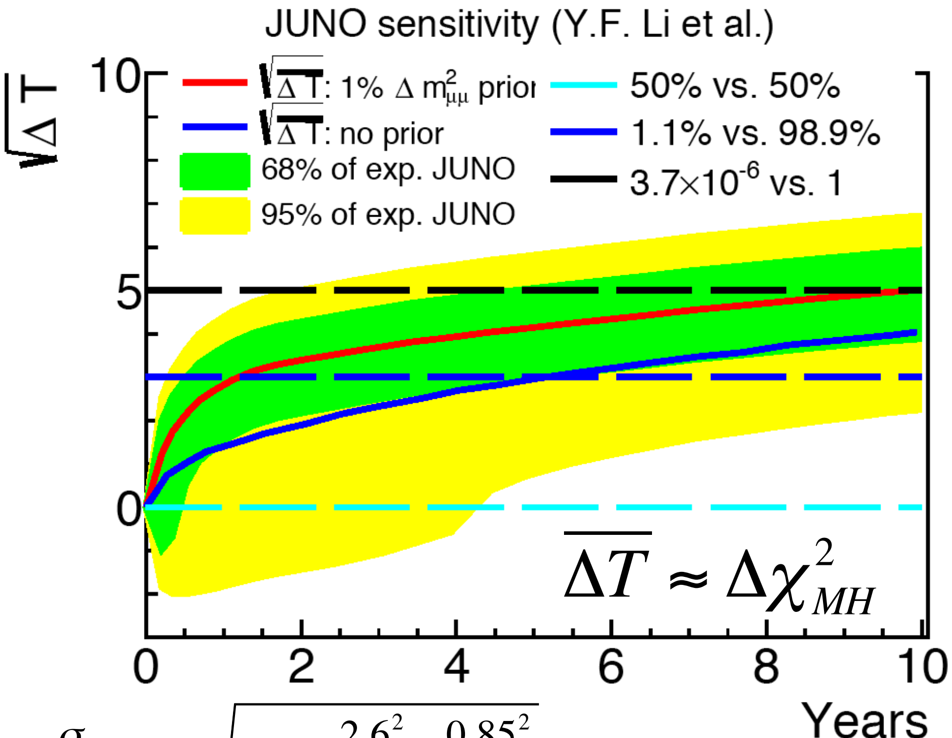
Event Type	Raw rate	Reduction
Radioactivity (in FV <17.2m)	0.4 Hz (PMTs) 2.2 Hz (LS) 3.7 Hz (acrylic) 0.2 Hz (support) 1.3 Hz (Rn) ~ 0.03 (rock)	Use low radioactivity PMTs; LS raw material purification (w/o distillation after LS production)
Cosmogenic isotopes (delayed)	340/day	
Spallation neutron	1.8 Hz	

IBD bkg

Accidentals	~410/day	→ 1.1 /day w/ prompt-delayed distance $R_{p-d} < 1.5$m. Negligible.
Fast neutron	0.01/day	0.01/day (σ=100%)
$^{9}Li/^{8}He$	80/day	1.8/day after muon veto (σ=20%)
(a, n)	3.8/day (acrylic) 0.2/day (balloon)	→ 0.05 /day (acrylic), FV cut (σ=50%) → negligible (balloon), FV cut

Performance

PRD 88 013008 (2013)



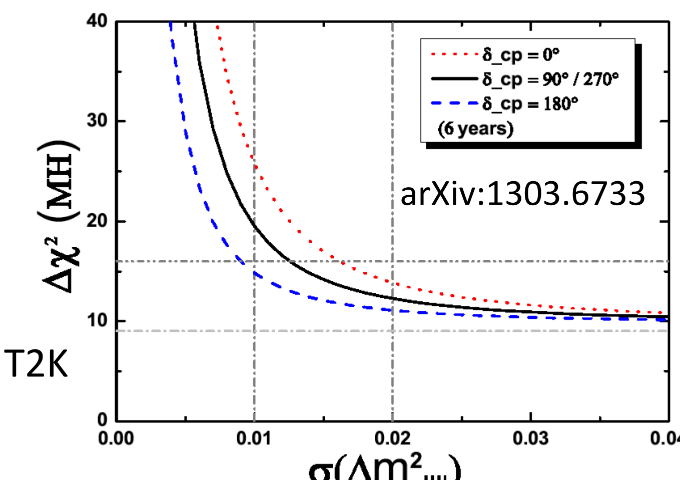
$$\frac{\sigma_E}{E}(\%) \sim \sqrt{0.7^2 + \frac{2.6^2}{E} + \frac{0.85^2}{E^2}}$$

$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32},$$

$$\Delta m^2_{\mu\mu} \simeq \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \sin 2\theta_{12} \sin\theta_{13} \tan\theta_{23} \cos\delta\Delta m^2_{21},$$

- Inputs
  - 100 kevents (6 years)
  - 3% @ 1 MeV energy resolution
  - 1% energy scale uncertainty
  - realistic backgrounds
- Sensitivity
  - JUNO only
    - 50% chance to have 3 σ or higher
    - 2.3% chance to have 5 σ or higher
  - JUNO + 1% $\Delta m_{\mu\mu}^2$
    - 84% chance to have 3 σ or higher
    - 16% chance to have 5 σ or higher

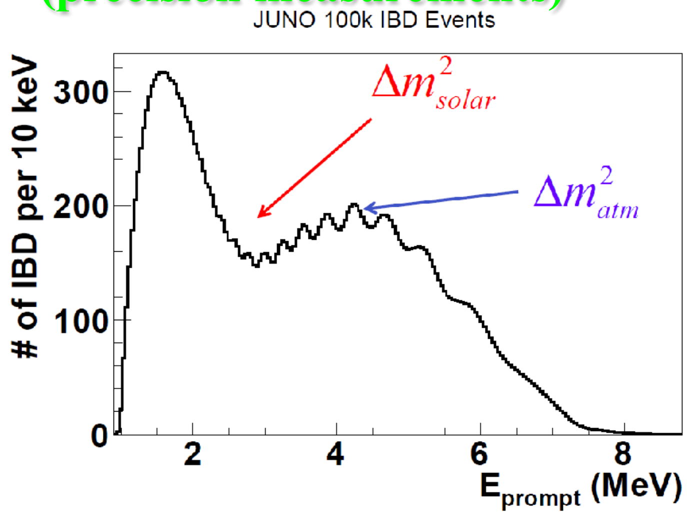
by NOvA, MINOS, T2K

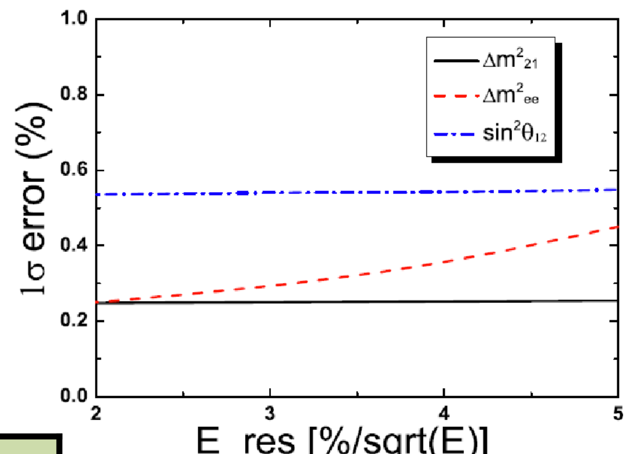


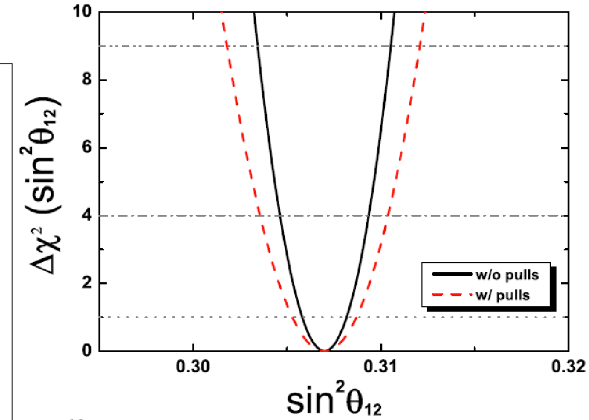
Oscillation parameters

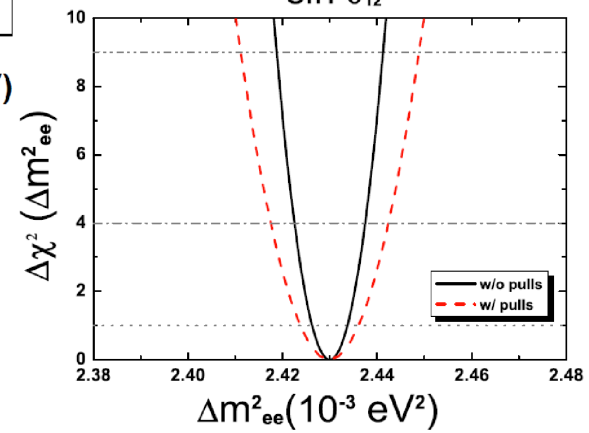
(precision measurements)

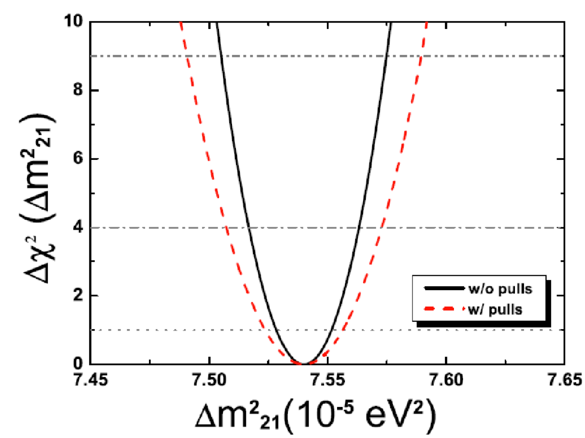
- First experiment to observe:
    - simultaneously "solar" and "atmospheric" oscillations
    - more than two cycles of neutrino oscillations
- Complementary to long baseline accelerator program
- Probing the unitarity of U_{PMNS} to the sub-percent level!











	Current	JUNO
Δm^2_{21}	~3%	~0.6%
Δm^2_{32}	~4%	~0.5%
$\sin^2\theta_{12}$	~7%	~0.7%

better precision than for CKM matrix elements

JUNO schedule

First get-together meeting

Funding(2013-2014) review approved

Geological survey and preliminary civil design

1st 20" MCP-PMT

Collaboration formed

Groundbreaking Ceremony (10 Jan. 2015)

2013

2014

Kaiping Neutrino Research Center established

Civil/infrastructure construction bidding

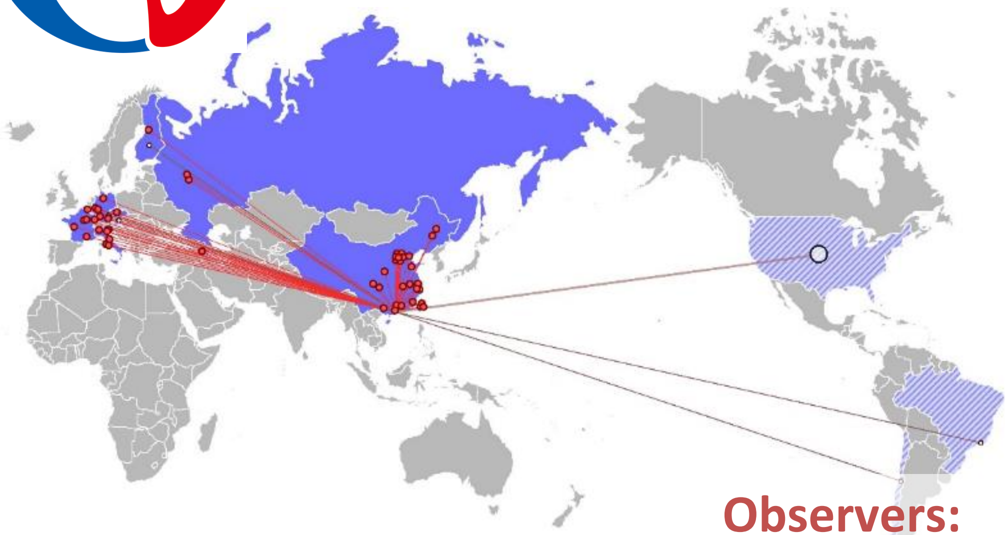
Funding from CAS: "Strategic Leading Science & Technology Programme" approved (~CD1)

Yangjiang NPP started to build the last two cores

Civil design approved

- Civil construction: 2015-2017
- Detector component production: 2016-2017
- PMT production: 2016-2019
- Detector assembly & installation: 2018-2019
- Filling & data taking: 2020

JUNO Collaboration



Asia (28)

BNU
CAGS
CQ U
CIAE
DGUT
ECUST
Guangxi U
HIT
IHEP
Jilin U
Nanjing U
Nankai U
Natl. CT U
Natl. Taiwan U
Natl. United U
NCEPU
Pekin U
Shandong U
Shanghai JTU
Sichuan U
SYSU
Tsinghua
UCAS
USTC
Wuhan U
Wuyi U
Xiamen U
Xi'an JTU

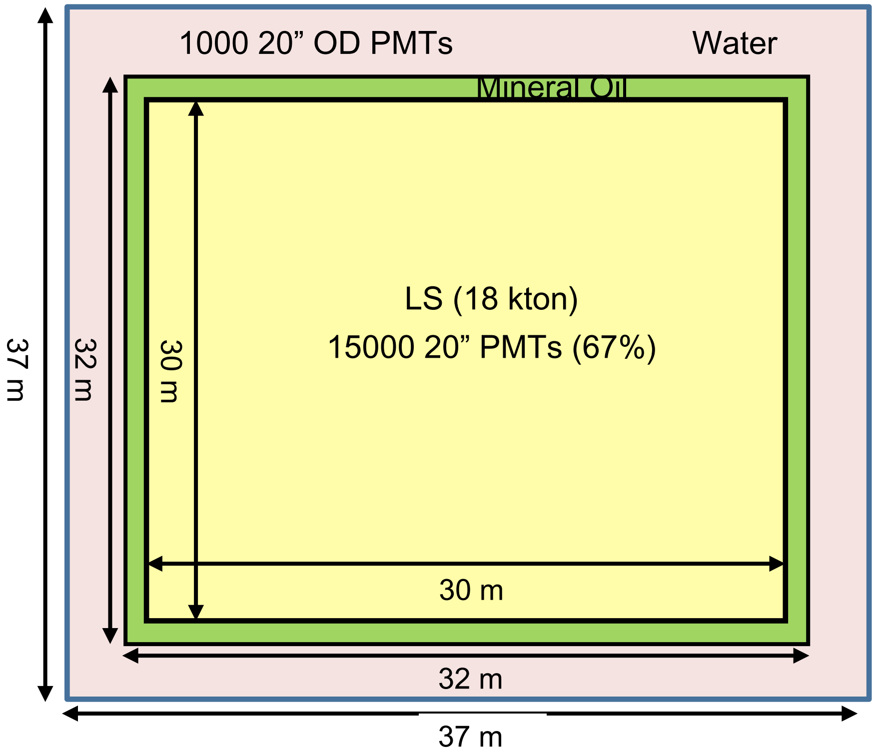
Observers:

US institutions
HEPHY Vienna
PUC Brazil
PCUC Chile
Jyvaskyla U.

Europe (23)

APC Paris
Charles U
CPPM Marseille
FZ Julich
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Padova
INFN-Perugia
INFN-Roma 3
IPHC Strasbourg
INR Moscow
JINR
LLR Paris
RWTH Aachen
Subatech Nantes
TUM
U.Hamburg
ULB
U Mainz
U Oulu
U Tuebingen
YPI Armenia

RENO-50



- 18 kton liquid scintillator underground detector
- 15000 20" PMTs
- R&D funding ($ 2M in 3 years, 2015~2017) given by the Samsung Science & Technology Foundation.
- A proposal has been submitted to obtain construction funding.
- 2015:
  - Group organization
  - Detector simulation & design
  - Geological survey
- 2016 ~ 2017 :
  - Civil engineering for tunnel excavation, Underground facility ready, Structure design,
  - PMT evaluation and order, Preparation for electronics, HV, DAQ & software tools, R&D for liquid scintillator and purification
- 2018 ~ 2020 : Detector construction
- 2021 ~: Data taking & analysis

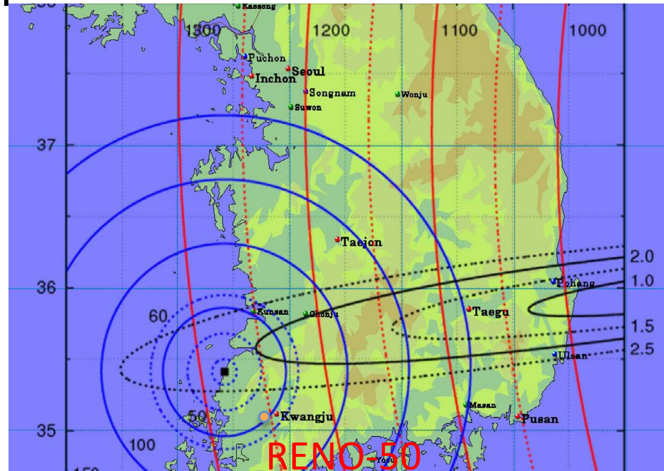
RENO-50 physics

- Determination of neutrino mass hierarchy
  - 3 σ sensitivity from 5 years of data
- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{32}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\%(1\sigma) \qquad \frac{\delta\Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\%(1\sigma) \qquad \frac{\delta\Delta m^2_{32}}{\Delta m^2_{32}} < 1.0\%(1\sigma)$$

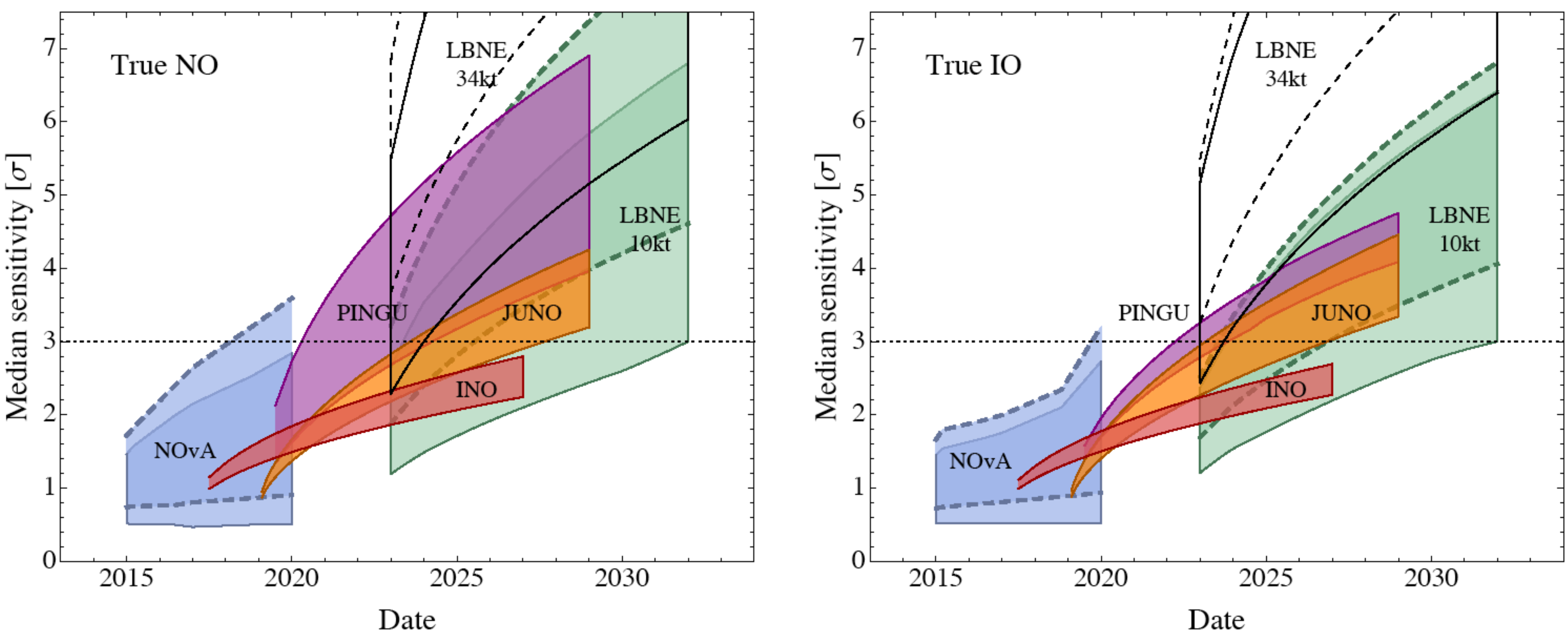
- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc)
- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth
- Solar neutrinos : with ultra low radioactivity
  - MSW effect on neutrino oscillation and solar models

Detection of J-PARC beam (Hyper-K): ~200 events/year



Comparisons and complementarities

arXiv:1311.1822



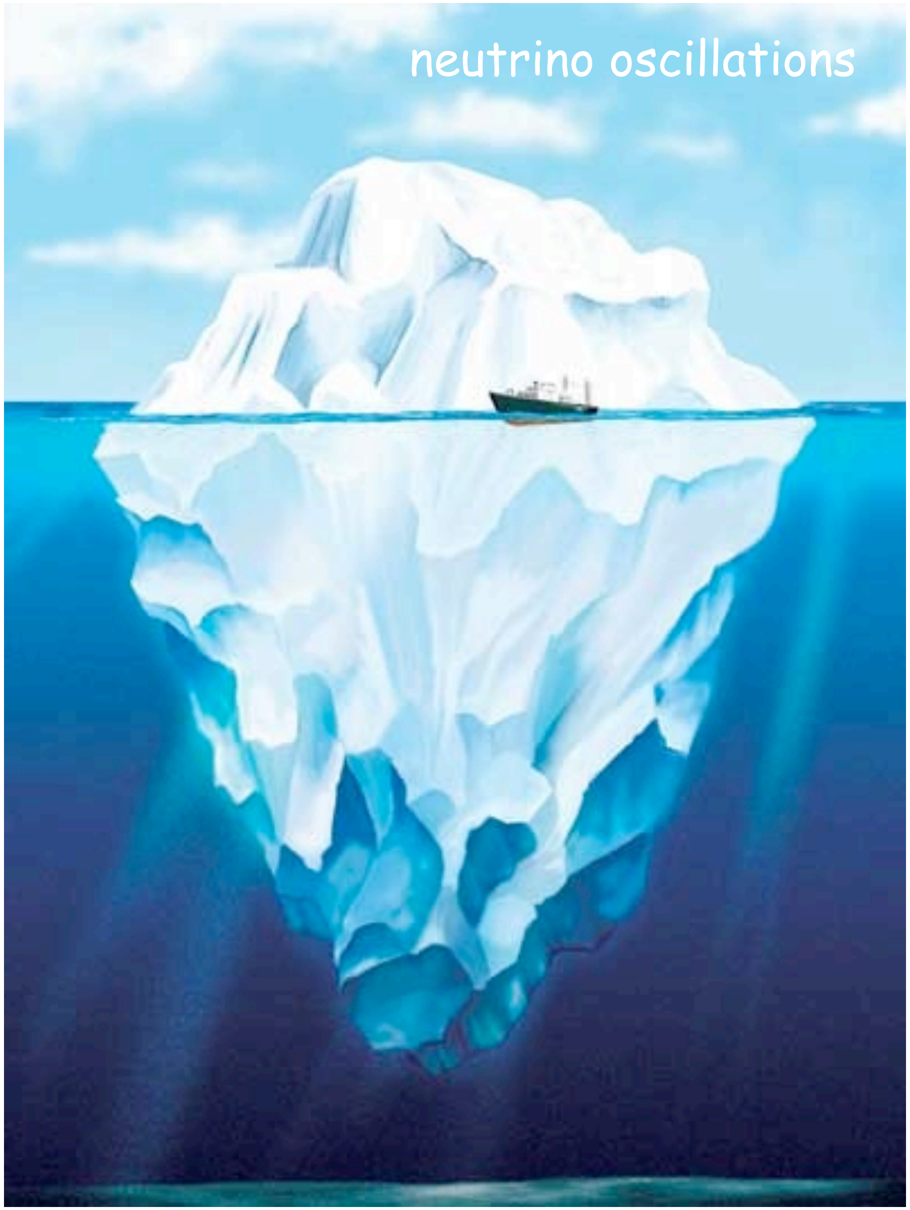
- width of bands due to
  - δ_{CP} (for NOvA and LBNE)
  - $40^o<\theta_{23}<50^o$ (for INO and PINGU)
  - $3.0\%\sqrt{(1\ MeV/E)}<\sigma_E<3.5\%\sqrt{(1\ MeV/E)}$

- complementarities
  - reactors (low energy)
    - LS, antineutrinos
  - LBL (high energy)
    - accelerator and atm. neutrinos
    - LAr, WC, …

Conclusions

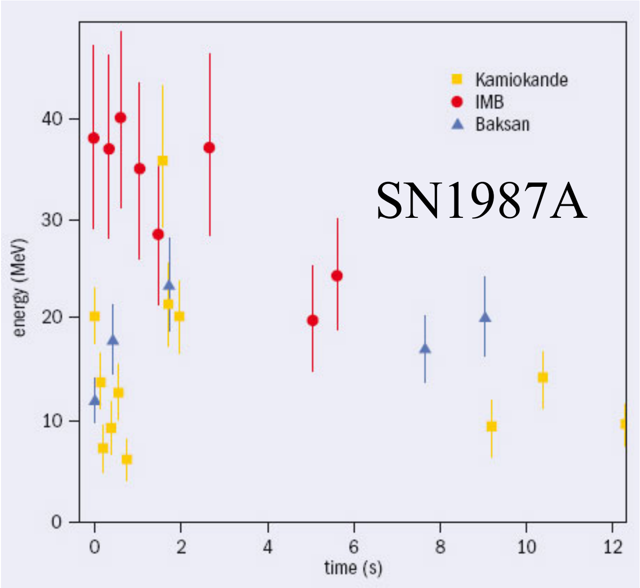
- Reactor experiments allowed the θ_{13} measurement and opened now the door to:
  - neutrino Mass Hierarchy determination
  - observation of a possible CP violation in the lepton sector using conventional neutrino beams.
- Better reactor predictions are needed
  - new very short baseline reactor experiments in preparation will probably do the job.
- New Medium baseline large volume reactor experiments will very probably solve the Mass Hierarchy problem during the next 10 years:
  - High energy resolution is needed.
  - JUNO:
    - Under construction in China
  - RENO-50:
    - In R&D phase in S. Korea.
- Accurate measurement of neutrino oscillation parameters.

Is that all?

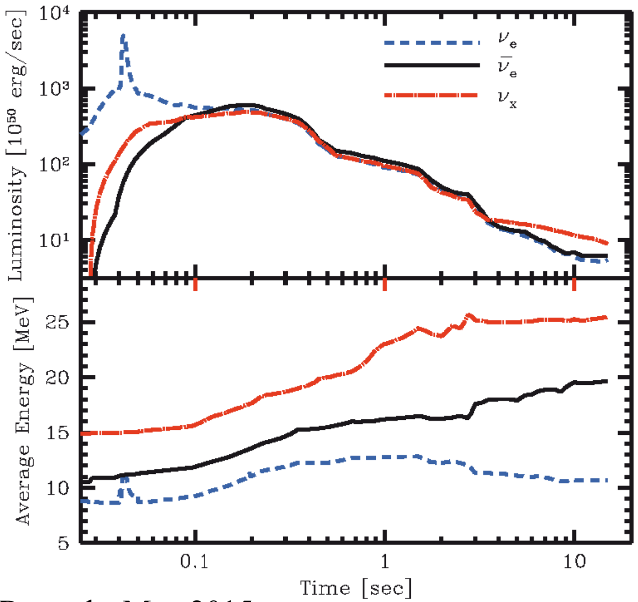


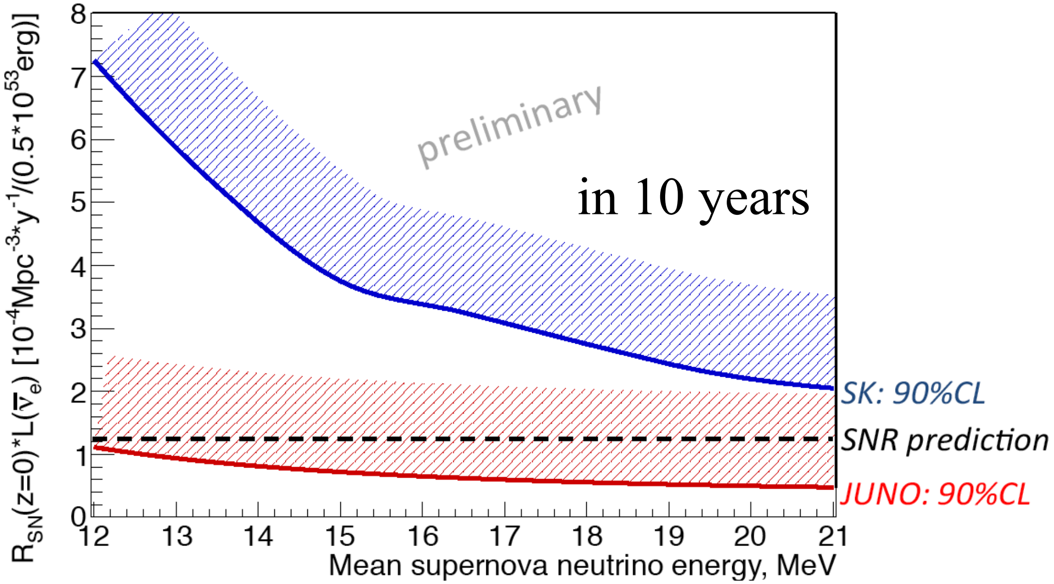
Backup

Supernovae explosions



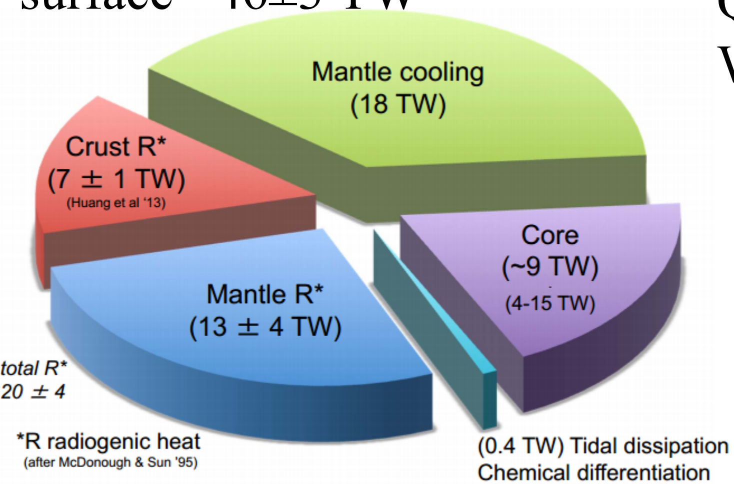
- 5000 ν will be detected by JUNO if explosion at 10 kpc (centre of our galaxy)
  - energy spectrum
  - time distribution
- better understanding of the explosion mechanisms
- detection of relic neutrinos produced by previous explosions





Detection of Geo-neutrinos

Heating at the earth surface ~46±3 TW

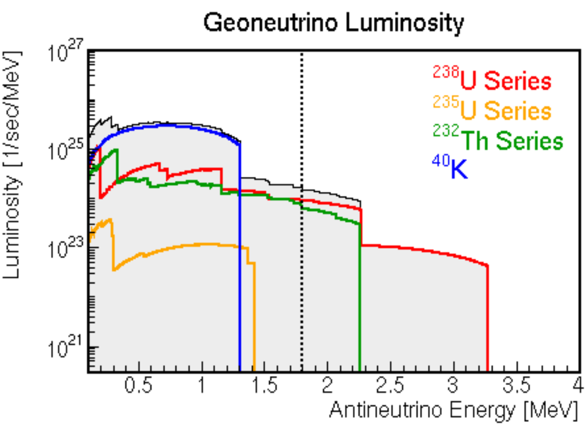


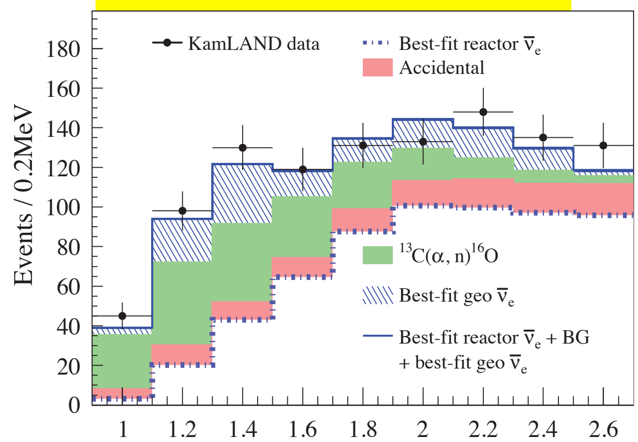
Radiogenic contribution at the earth surface.
Quantity of U and Th in the mantle.
What is it hidden in the centre of the earth?

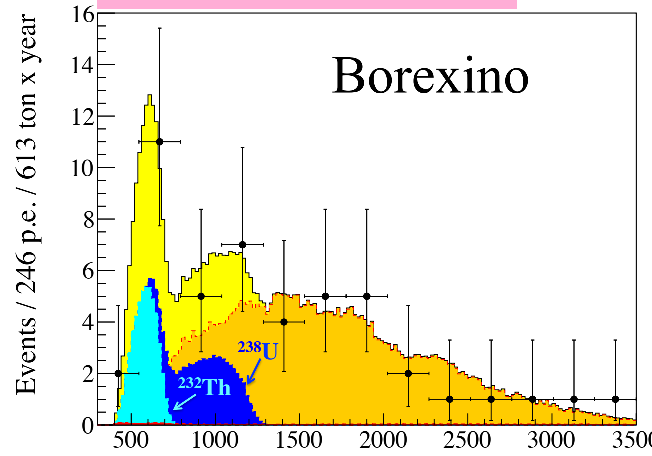
Decay	E_{max} [MeV]	Q [MeV]	Q - $<E_\nu>$ [MeV]
$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6e^- + 6\bar{\nu}_e$	**3.25**	51.7	47.6
$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e$	**2.25**	42.7	40.4
$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e$ (89%)	1.311	1.311	0.59
$^{40}K + e \rightarrow {}^{40}Ar + e^- + \nu_e$ (11%)	0.044	1.505	1.461

N_{geo} = 116±28(10y)
S_{geo} = 28±6.7 TNU
B/S=0.24

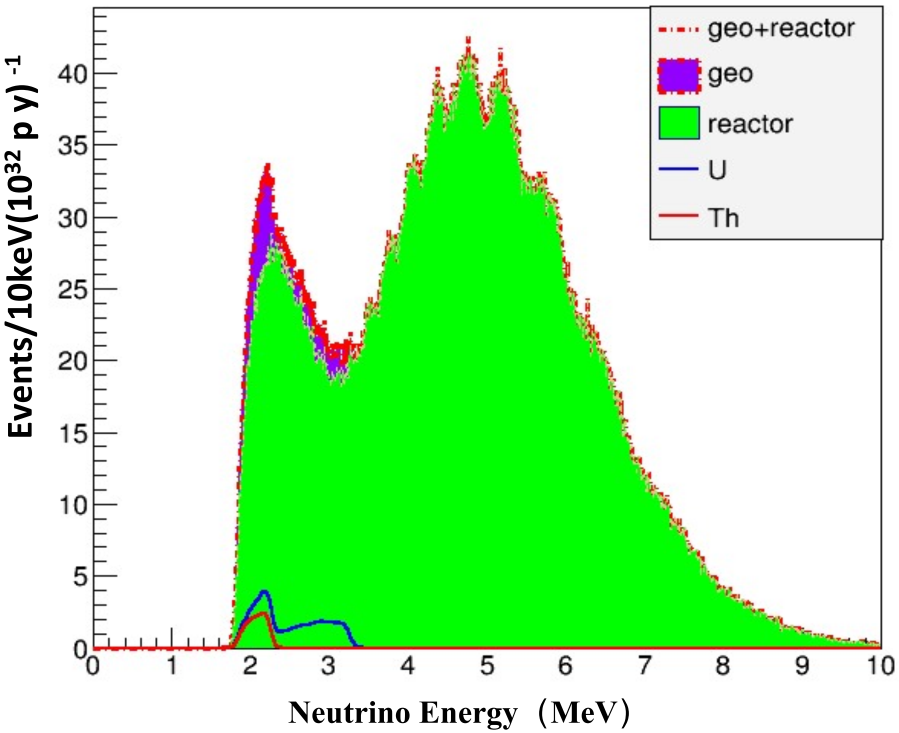
N_{geo}=14.3±4.4 (5y)
S_{geo}= 38.8 ±12.0 TNU
B/S=0.31







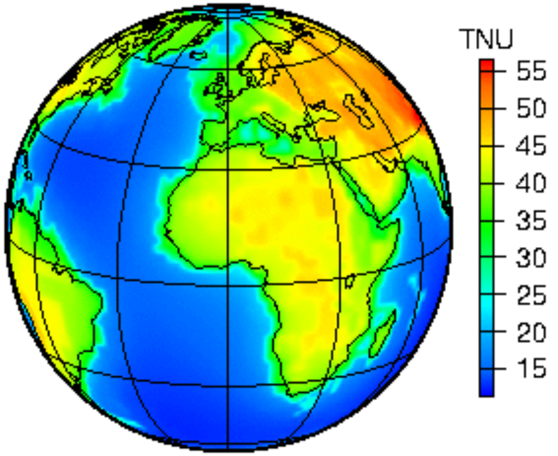
Geo-neutrinos in JUNO



JUNO ~700/year
Kamland 116/10 years
Borexino 14.3/5 years

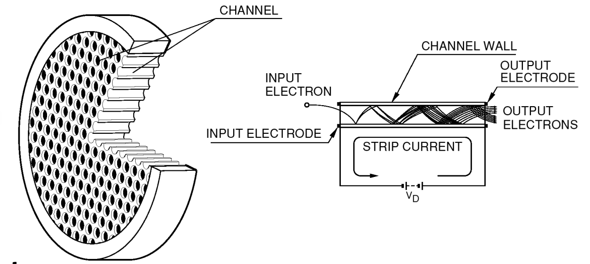
KamLAND: 30±7 TNU
Borexino: 38.8±12.0 TNU
JUNO:
- reach an uncertainty of 3 TNU
- large background from reactors
- Aim: 37 **±10% (stat.) ±10% (syst.)**

1.8-3.4MeV
- Reactor Neutrinos: 14±0.14/day
- Geo-neutrinos 2±0.5/day

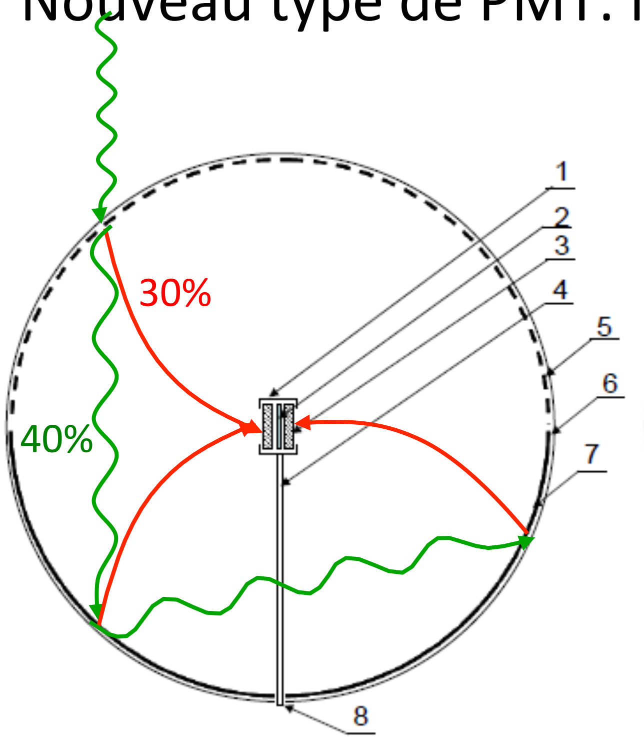


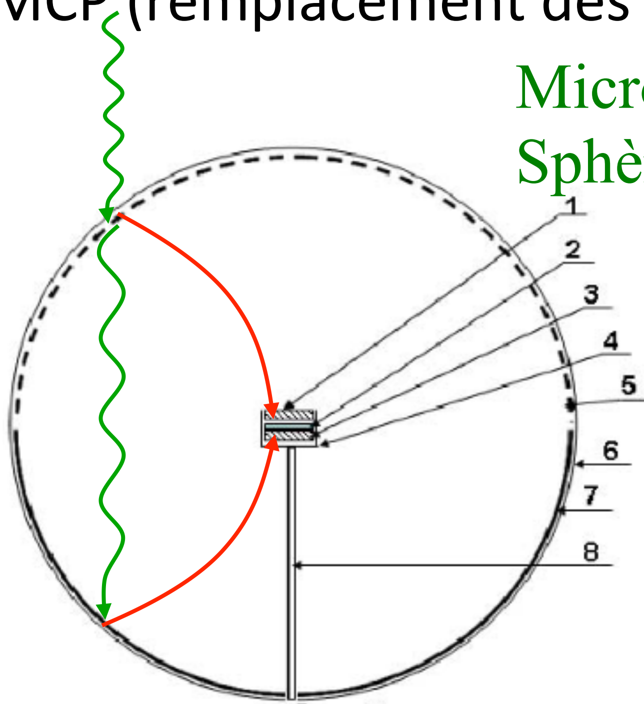
(TNU ~ number of detected ν/year/kt LS (IBD, 10^{32} p)

Photodetectors



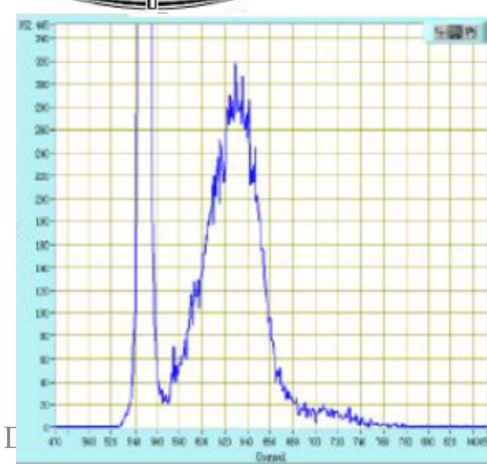
Nouveau type de PMT: MCP (remplacement des dynodes)





MicroChannel Plates
Sphère entièrement active

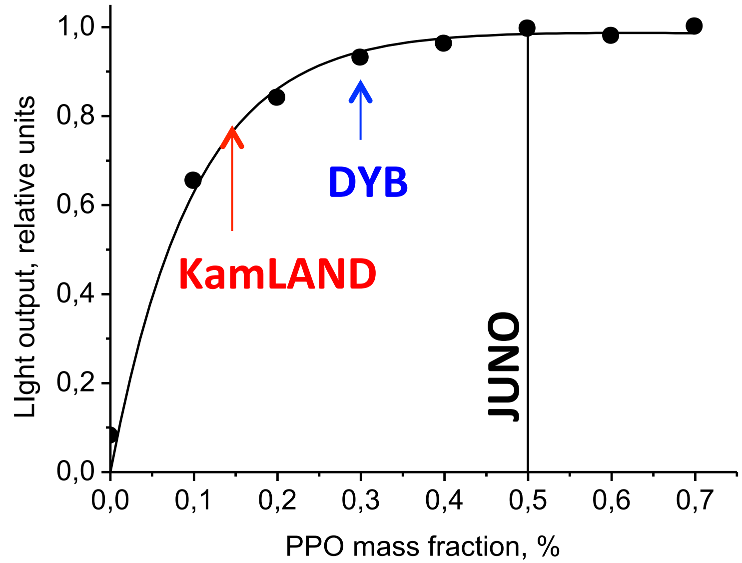
1. Insulated trestle table
2. Anode
3. MCP dodule
4. Bracket of the cables
5. Transmission Photocathode
6. Glass shell
7. Reflection Photocathode
8. Glass joint



Efficacité quantique: 30%
Transmission du verre: 40%
Efficacité de collection: 70%

Liquid scintillator

- **Baseline:**
  LAB+PPO+bisMSB (without Gd)
- **Improvement of the light yield**
  - Optimisation of the fluor concentration
- **Improvement of the transmission**
  - Solvent: LAB
    - ➢ improvement of the production process
  - Handling/purification
    - ➢ distillation, filtration, water extraction, N_2 separation, …
- **Radioactivity reduction**
  - less critical due to Gd absence
  - Singles<3Hz (>0.7MeV), if ^{40}K/U/Th <10^{-15} g/g (preliminary)

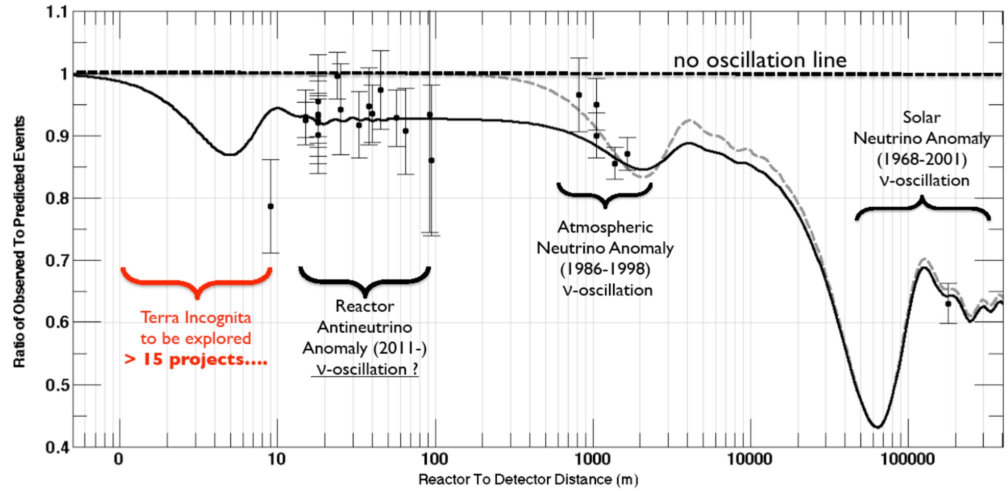


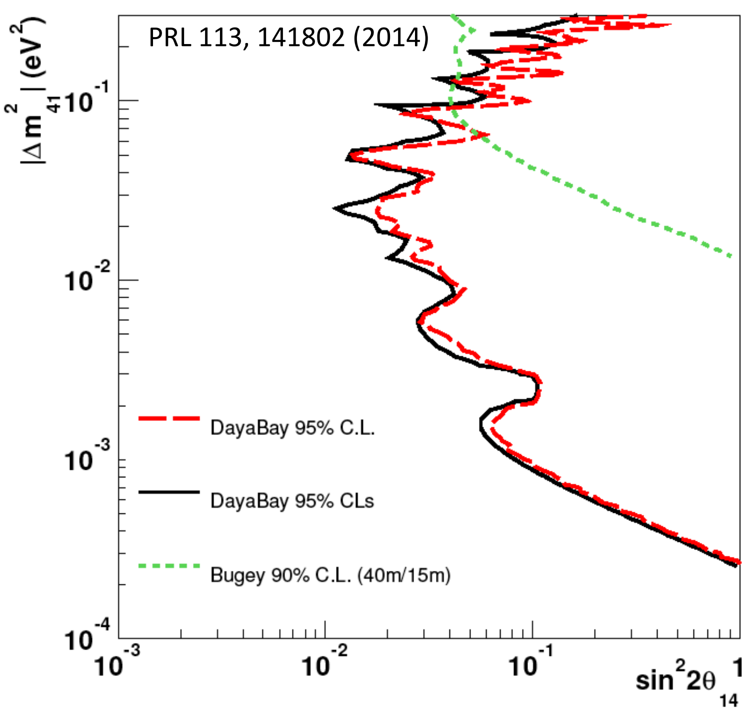
Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 column	18.6 m
Al_2O_3 column	22.3 m
LAB from Nanjing, Raw	20 m
Al_2O_3 column	25 m

Sterile neutrinos in Daya Bay

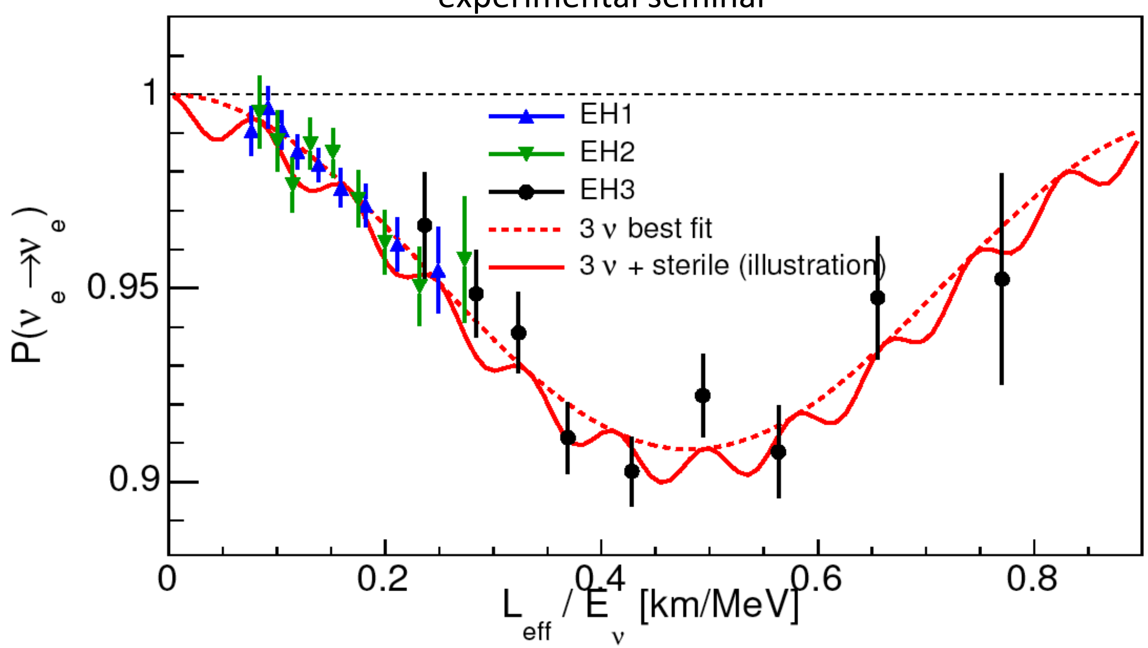
$$P\left(\overline{\nu_e} \rightarrow \overline{\nu_e}\right) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{ee}^2 L}{4E}$$

$$-\sin^2 2\theta_{14}\sin^2\frac{\Delta m_{41}^2 L}{4E}$$



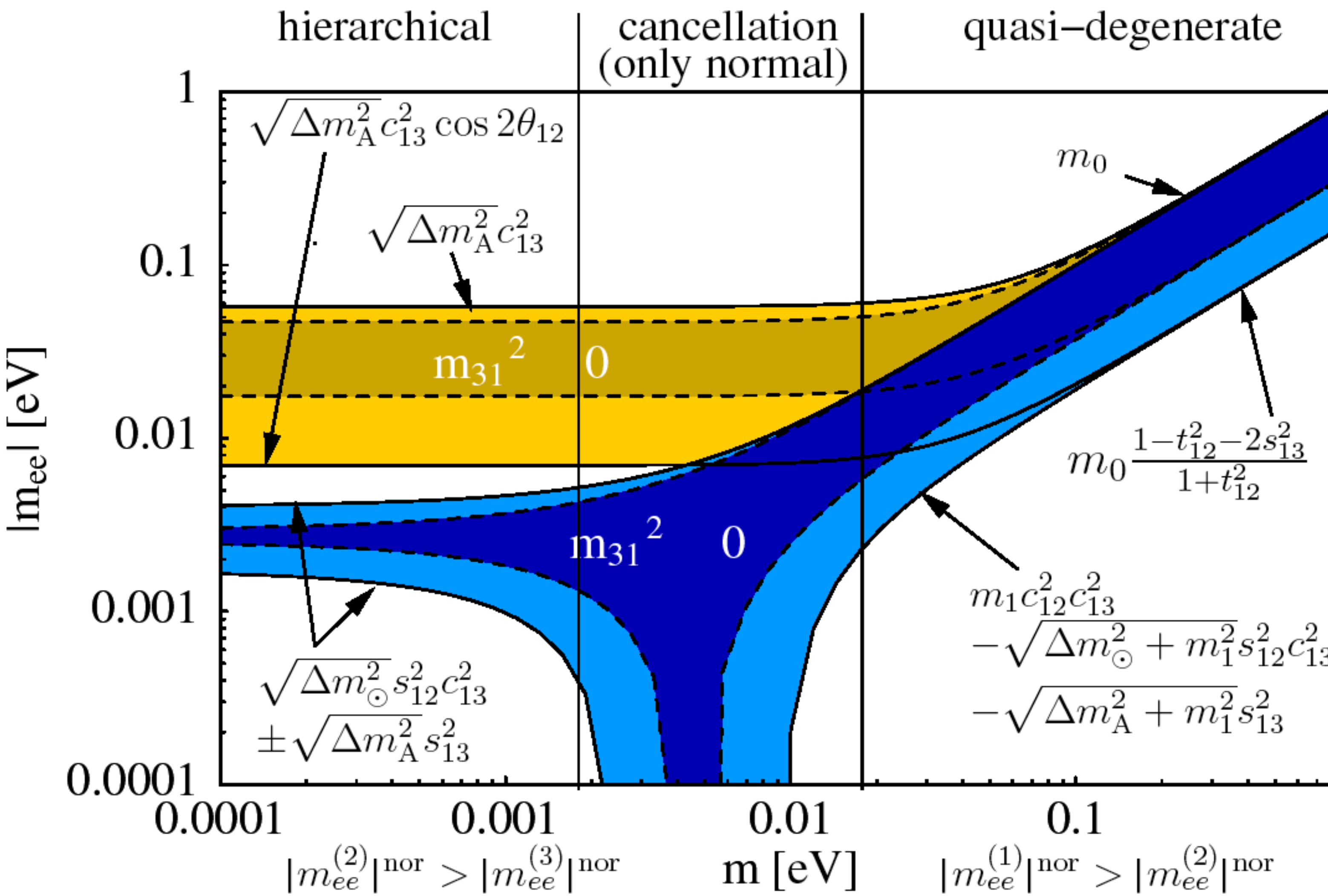


Y. Nakajima, Nov. 18, 2014, SLAC experimental seminar

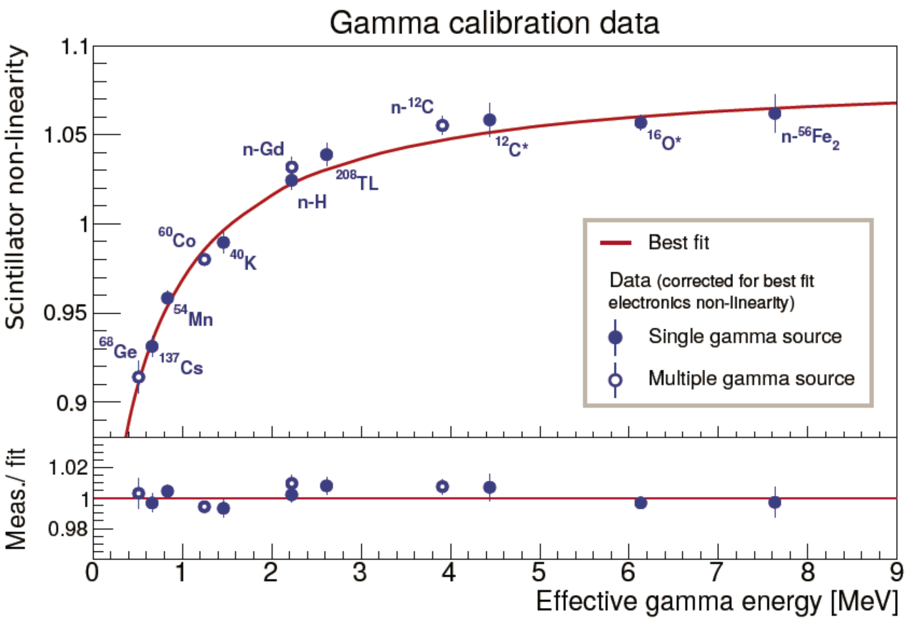


Double beta decay

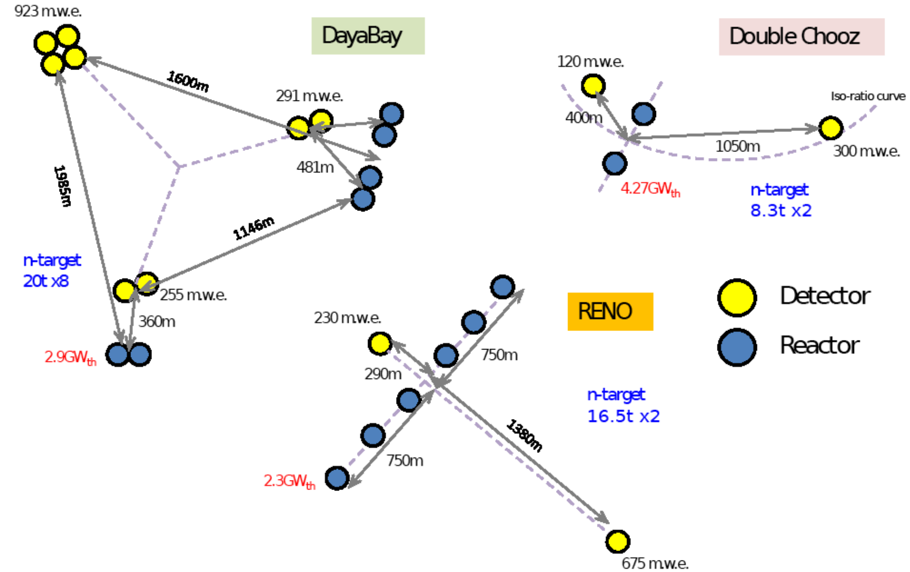
PHYSICAL REVIEW D **73,** 053005 (2006)



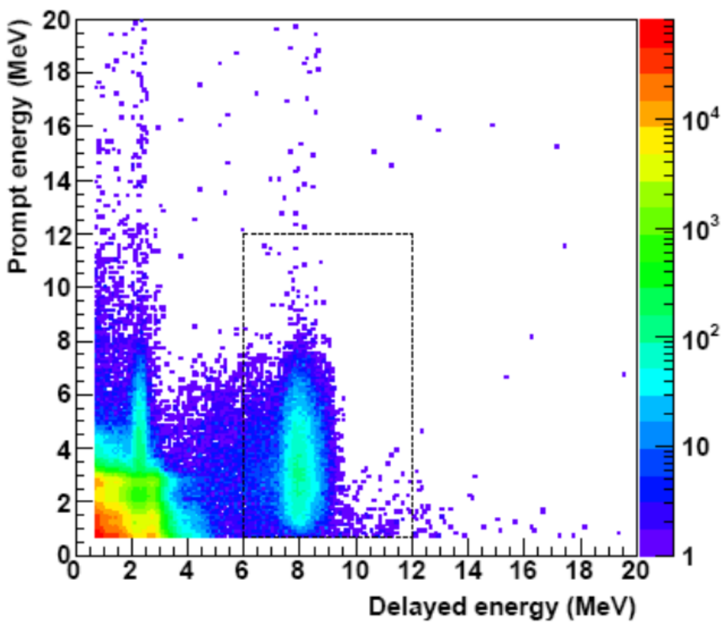
A.O.B.



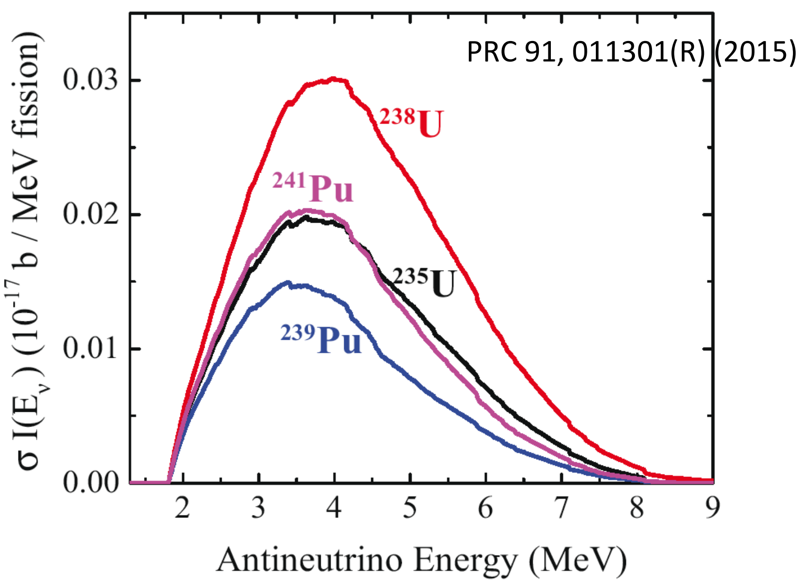
Gamma calibration data
Scintillator non-linearity
Meas./ fit
Effective gamma energy [MeV]
Best fit
Data (corrected for best fit electronics non-linearity)
Single gamma source
Multiple gamma source
n-12C
12C*
16O*
n-56Fe2
n-Gd
n-H
208TL
60Co
40K
54Mn
68Ge
137Cs



DayaBay
Double Chooz
RENO
Detector
Reactor
923 m.w.e.
1600m
291 m.w.e.
481m
1985m
1146m
n-target
20t x8
255 m.w.e.
360m
2.9GWth
120 m.w.e.
400m
Iso-ratio curve
1050m
300 m.w.e.
4.27GWth
n-target
8.3t x2
230 m.w.e.
750m
290m
n-target
16.5t x2
1380m
750m
2.3GWth
675 m.w.e.



Prompt energy (MeV)
Delayed energy (MeV)



PRC 91, 011301(R) (2015)
238U
241Pu
235U
239Pu
σ I(Eν) (10-17 b / MeV fission)
Antineutrino Energy (MeV)