A Different Kind of Long Baseline:

Reactor Neutrino Oscillation Experiments

--When Nature is kind--*

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The Stan Wojcicki Scientific Symposium
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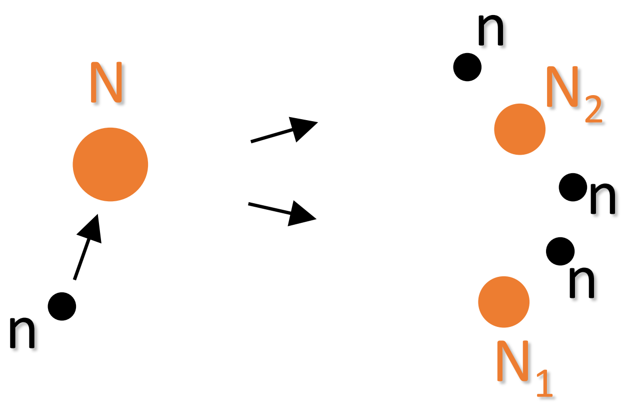
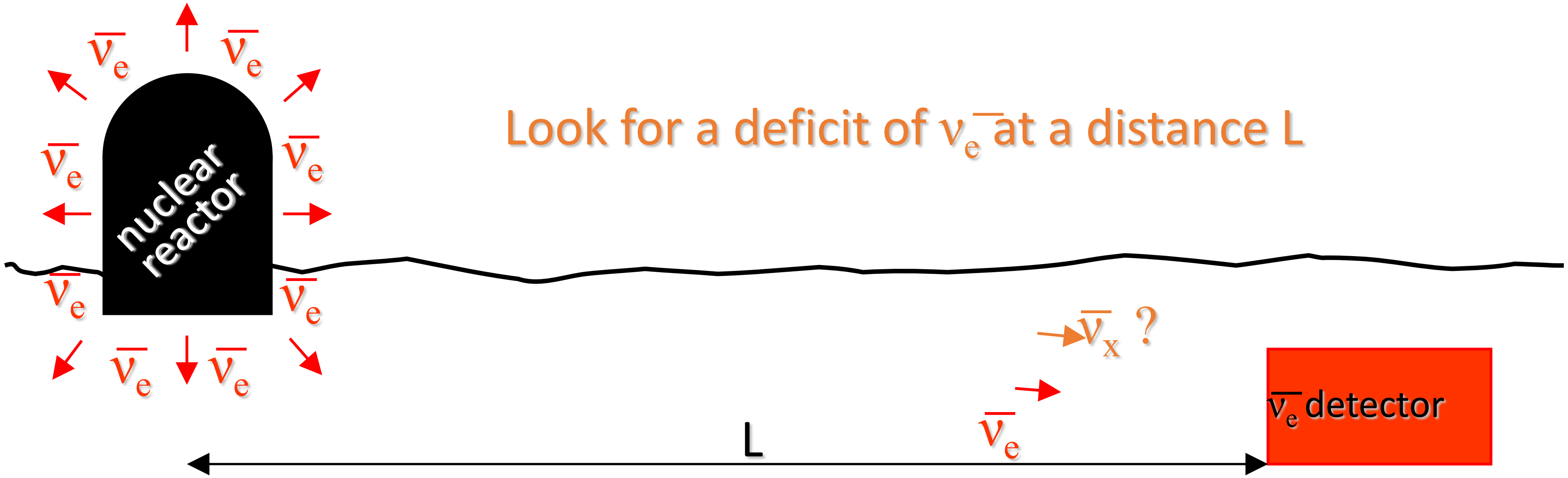
**** In my career I have seen Nature being kind thrice: twice with reactor neutrinos and one… you will hear from Barry about it***

Nuclear reactors are very intense sources of ν_e deriving from beta-decay of the neutron-rich fission fragments



N_1 and N_2 still have too many neutrons and decay

$N_2 \rightarrow N_3 + e^- + \nu_e$



Look for a deficit of $\bar{\nu}_e$ at a distance L

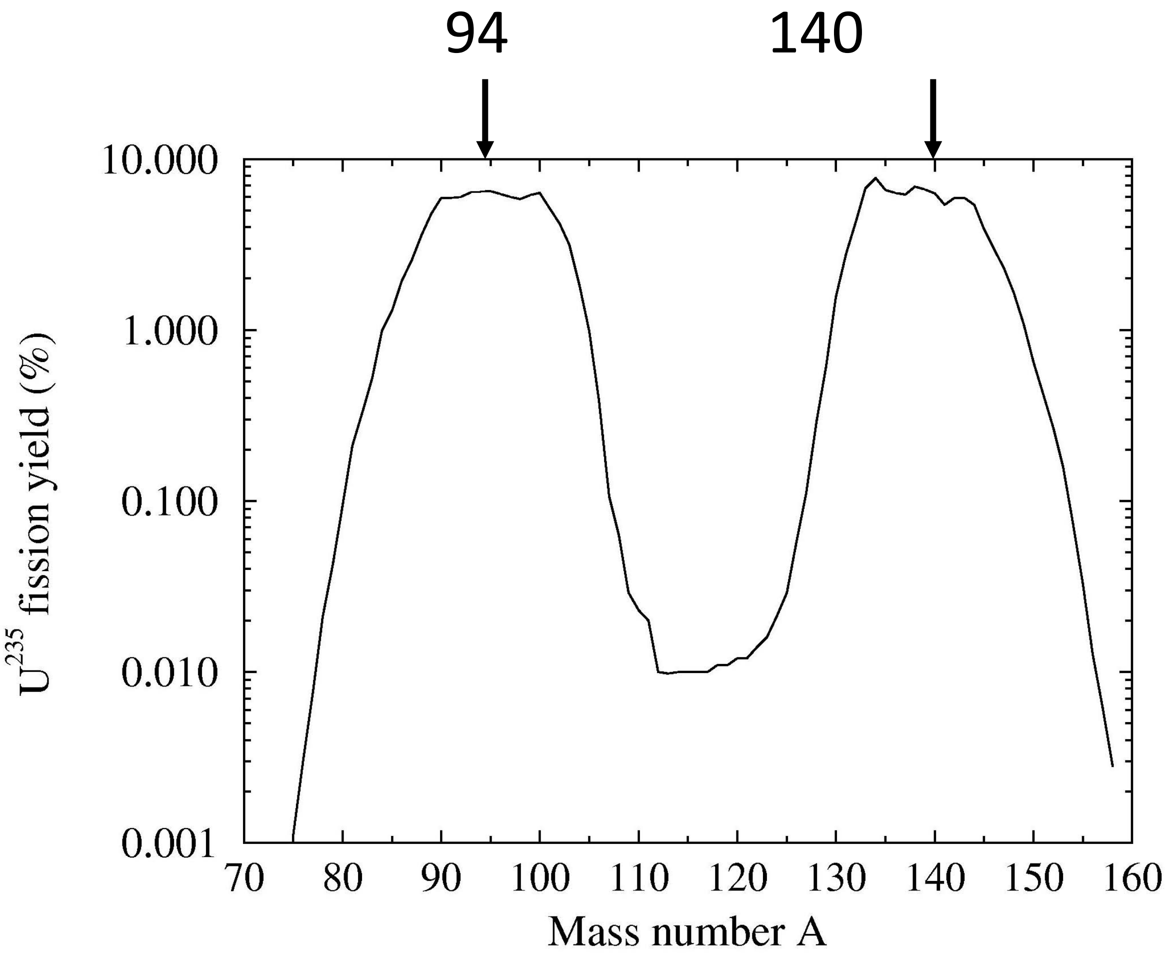
Example: ^{235}U fission

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

stable nuclei with A
most likely from fission

$$^{94}_{40}Zr \qquad ^{140}_{58}Ce$$

together these have
98 protons and
136 neutrons



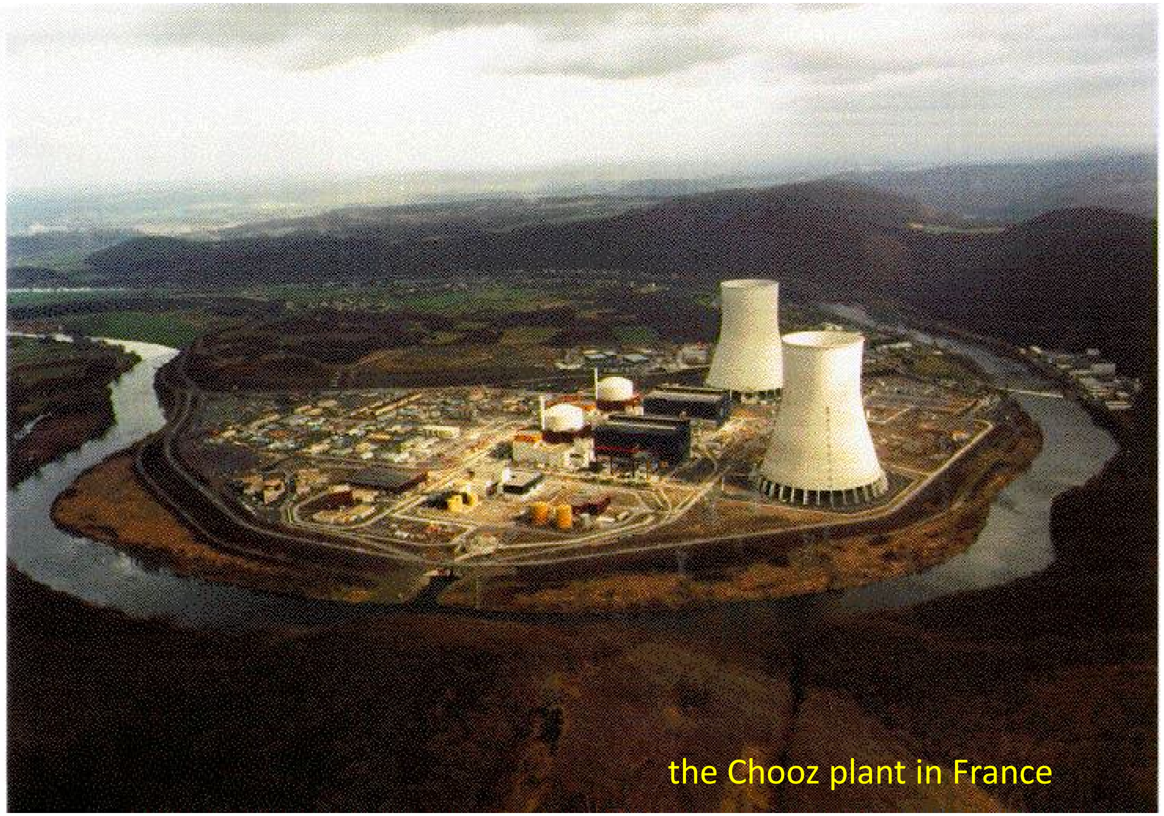
so, on average 6 n have to turn into 6 p to reach stable matter

Power/commercial reactors are generally used since only requirement is to have large power

$$200 MeV / fission$$

$$6\bar{\nu}_e / fission$$

A typical large power reactor produces
3 GW$_{thermal}$ and
6•10^{20} antineutrinos/s



the Chooz plant in France

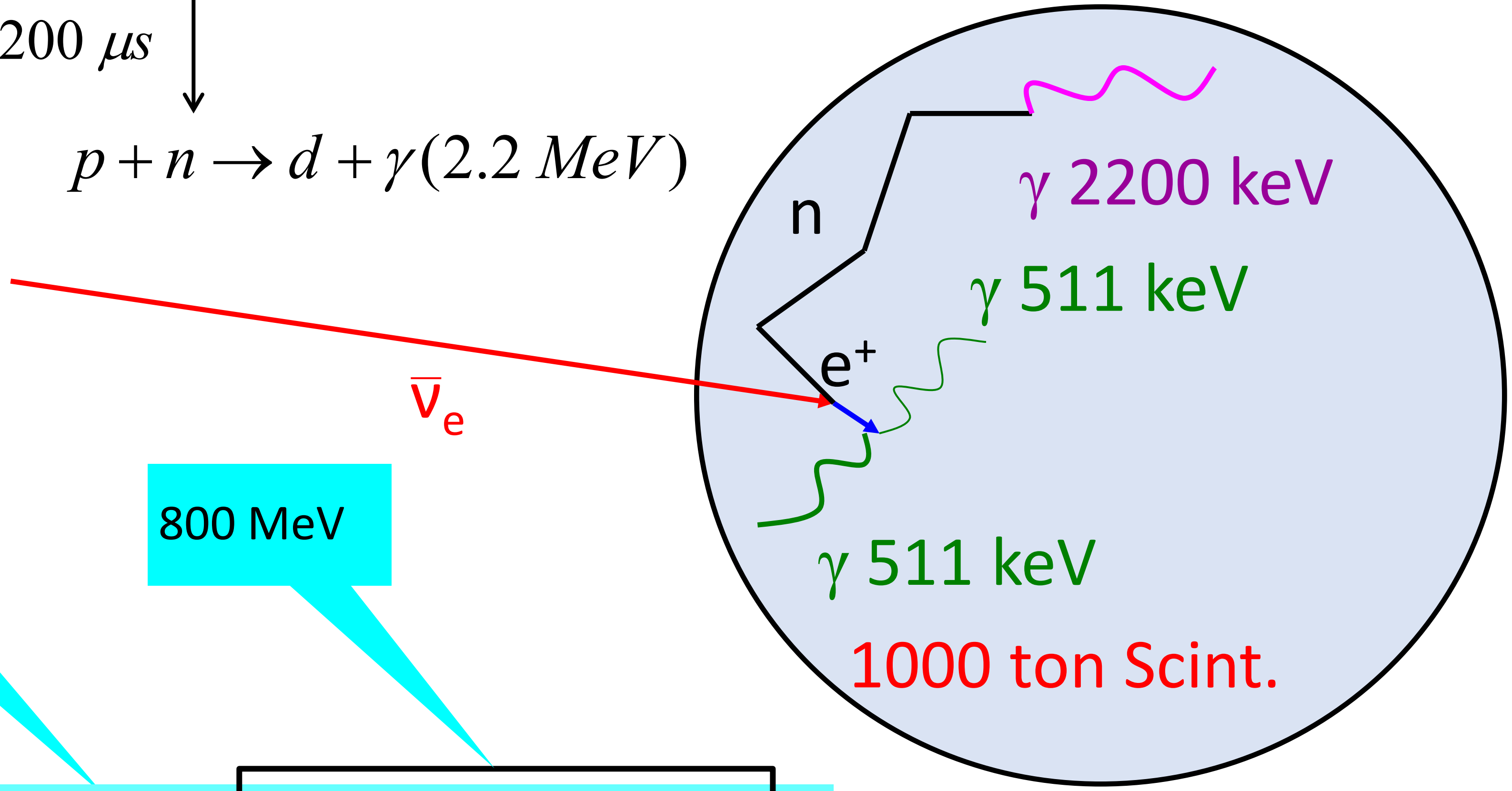
ν det. at low energy is hard: but inverse β decay provides specific signature

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

$$\downarrow \tau \approx 200\ \mu s$$

$$p + n \rightarrow d + \gamma(2.2\ MeV)$$

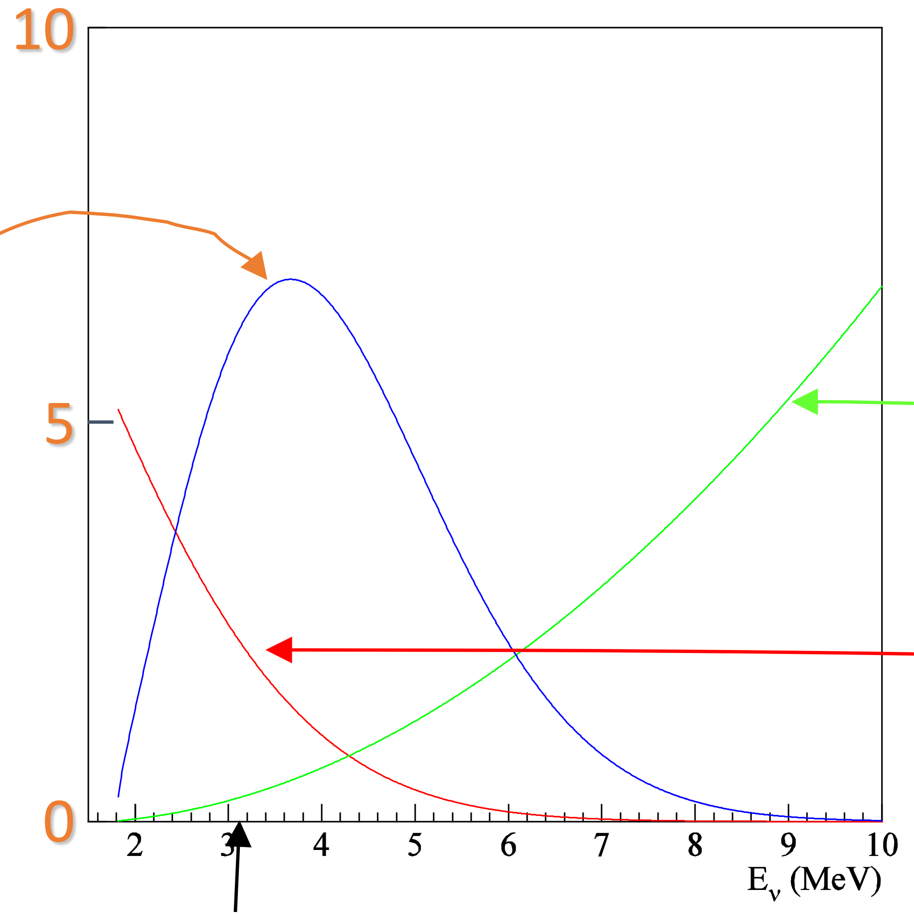
Event tagging by delayed coincidence
in energy, time and space



$$E_{\bar{\nu}} \cong E_{e^+} + \overset{\text{10-40 keV}}{E_n} + \overbrace{(M_n - M_p) + m_{e^+}}^{\text{800 MeV}} \Rightarrow E_\nu \text{ measurement}$$

The $\bar{\nu}_e$ energy spectrum

Observed spectrum (int./MeV ton day)



$\bar{\nu}_e + p \rightarrow n + e^+$
cross section
(~10^{-42} cm^2)

Calculated reactor $\bar{\nu}_e$ spectrum (10^{-8} /s MeV GW$_{th}$)

Neutrinos with E<1.8 MeV are not detected

So, in practice, only ~1.5 neutrinos/fission can be detected above threshold

Indeed, neutrinos were first observed from nuclear reactors

Fred Reines (?) "fixing" a neutrino detector (circa 1953)

…and it is fair to say that the initial data was not particularly clear and, at times, confusing.

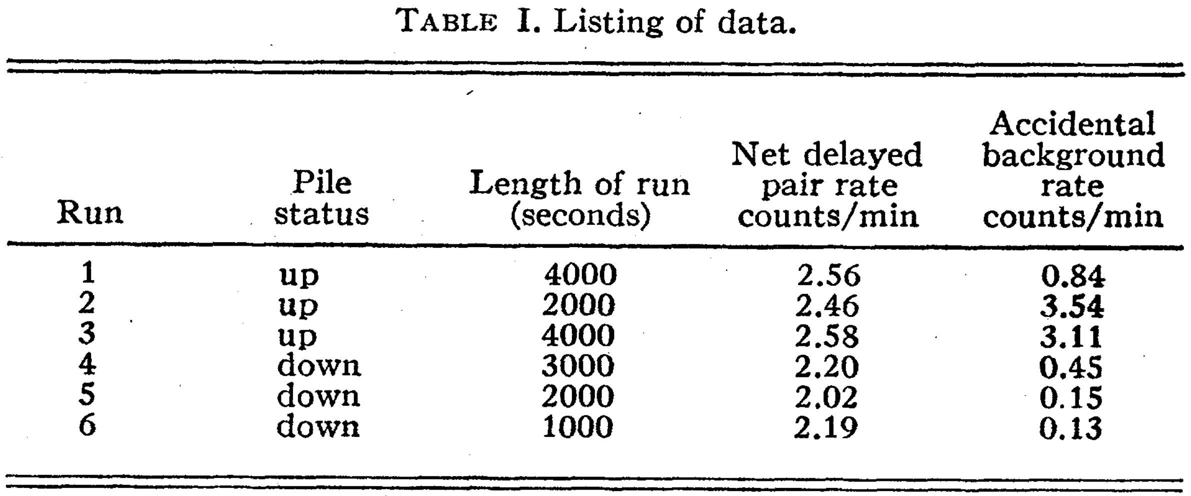
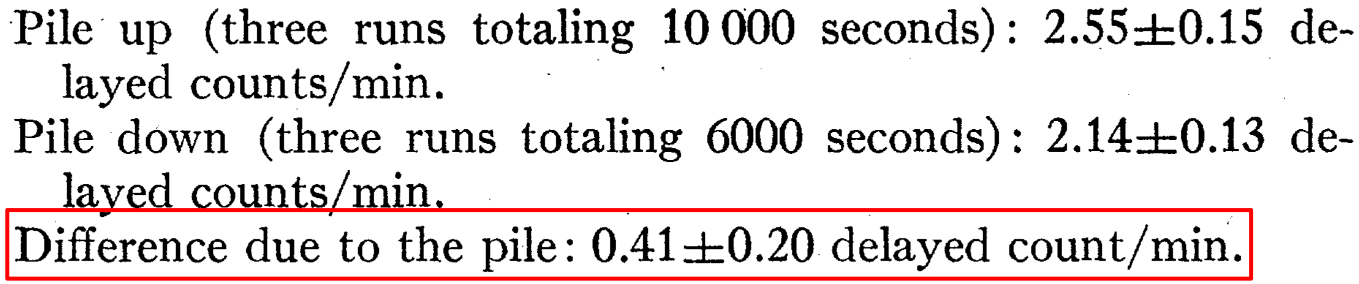


TABLE I. Listing of data.

Run	Pile status	Length of run (seconds)	Net delayed pair rate counts/min	Accidental background rate counts/min
1	up	4000	2.56	0.84
2	up	2000	2.46	3.54
3	up	4000	2.58	3.11
4	down	3000	2.20	0.45
5	down	2000	2.02	0.15
6	down	1000	2.19	0.13



Pile up (three runs totaling 10 000 seconds): 2.55±0.15 delayed counts/min.

Pile down (three runs totaling 6000 seconds): 2.14±0.13 delayed counts/min.

Difference due to the pile: 0.41±0.20 delayed count/min.

F. Reines and C. L. Cowan, Jr. Phys. Rev. 92 (1953) 830

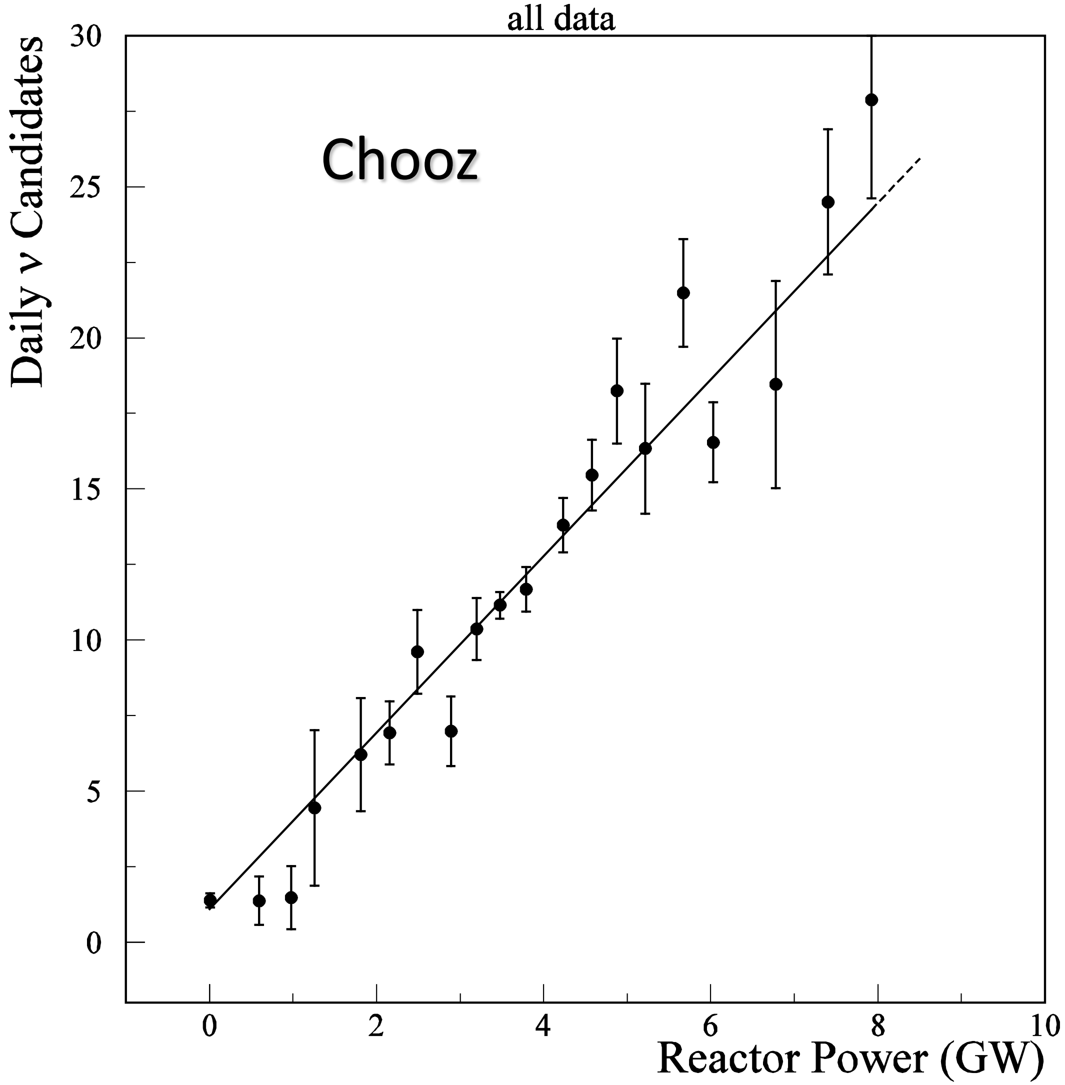
Reactors for disappearance (anti)neutrino oscillation experiments

I am claiming that the “modern era” started with Chooz and Palo Verde

(also, those are the last experiments not to see an oscillation signal)

We were younger… and concerned that maybe we did not understand backgrounds well enough.

Chooz managed to start data taking before the reactors were fully commissioned, this provided zero power measurements and the demonstration that the detected neutrino rate is proportional to the reactor's thermal power



The full mixing matrix is a complicated affair

$$\mathbf{U} = \begin{pmatrix} \mathbf{U}_{e1} & \mathbf{U}_{e2} & \mathbf{U}_{e3} \\ \mathbf{U}_{\mu 1} & \mathbf{U}_{\mu 2} & \mathbf{U}_{\mu 3} \\ \mathbf{U}_{\tau 1} & \mathbf{U}_{\tau 2} & \mathbf{U}_{\tau 3} \end{pmatrix} =$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix}$$

But, the fact that there are two rather different Δm² allows one to write a simplified form, allowing to build some intuition:

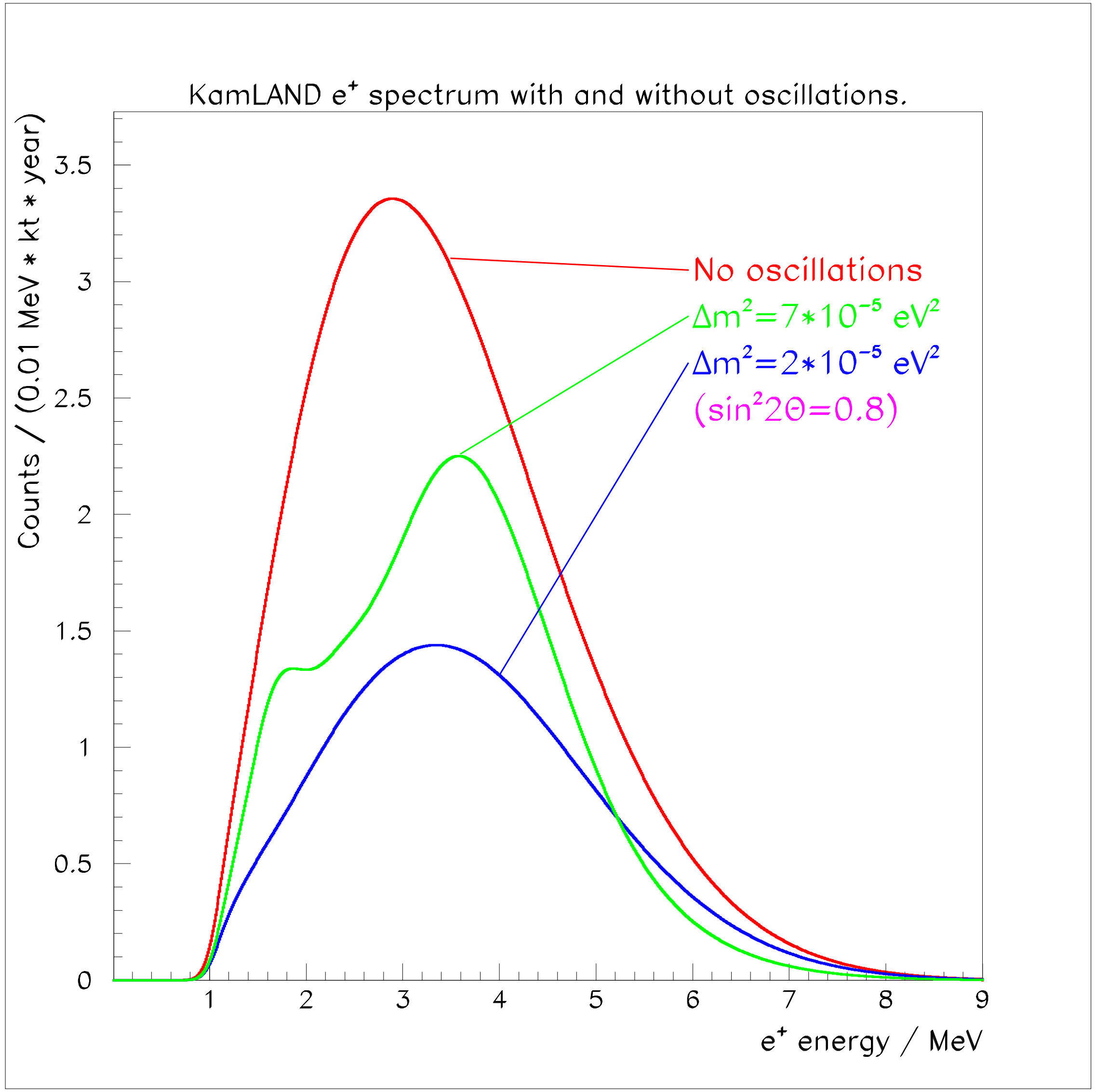
$$P_{osc}(\nu_a \to \nu_b) = sin^2 2\theta \; sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

E_ν in MeV, Δm^2 in eV², L in meters (pardon the units)

→ "how difficult" the measurement is also depends on how kind Nature is

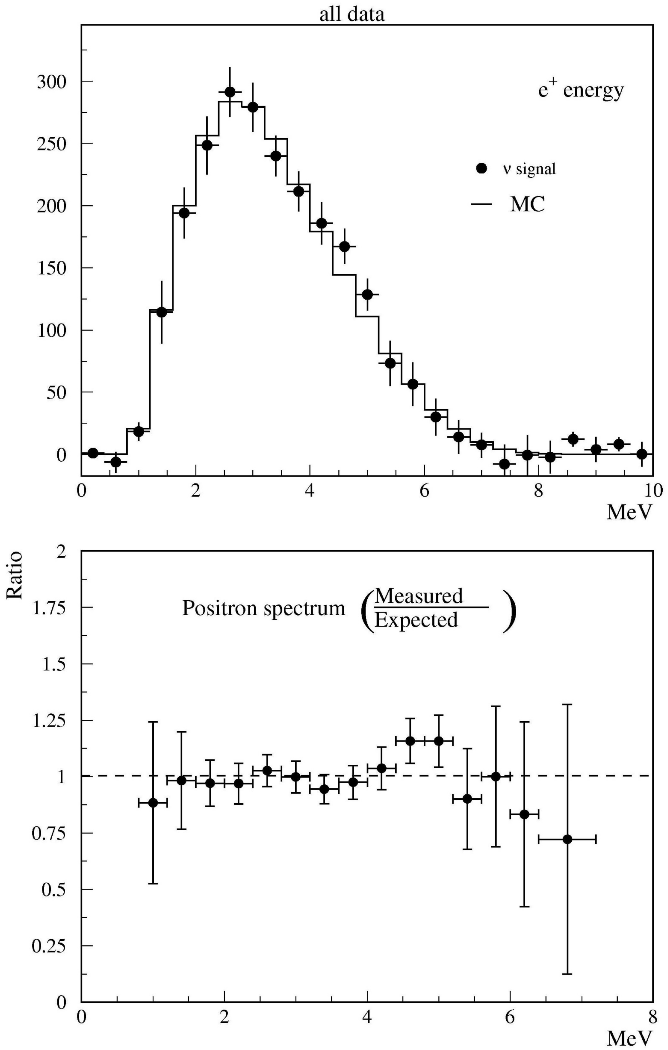
$$P_{osc}(\nu_a \rightarrow \nu_b) = sin^2 2\theta \, sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- **Small θ generally makes things difficult**
- **But, for a broad, smooth energy spectrum, one can hit just the right $\frac{\Delta m^2 L}{E_\nu}$ to produce a "hole" in the middle of the spectrum.**

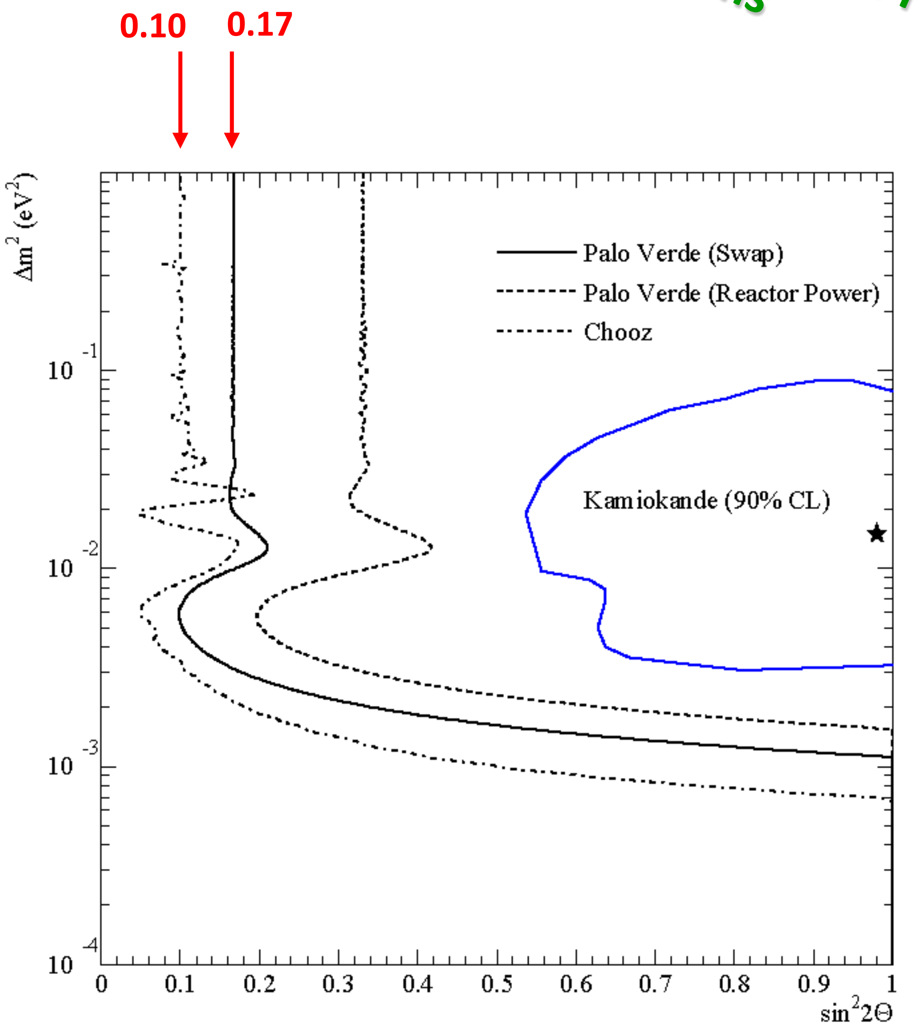


Alas, this was not the case for Chooz or Palo Verde, with ~1km baseline

…so this time we do not see oscillations



Apollonio et al (Chooz) Phys.Lett.B 466 (1999) 415-430

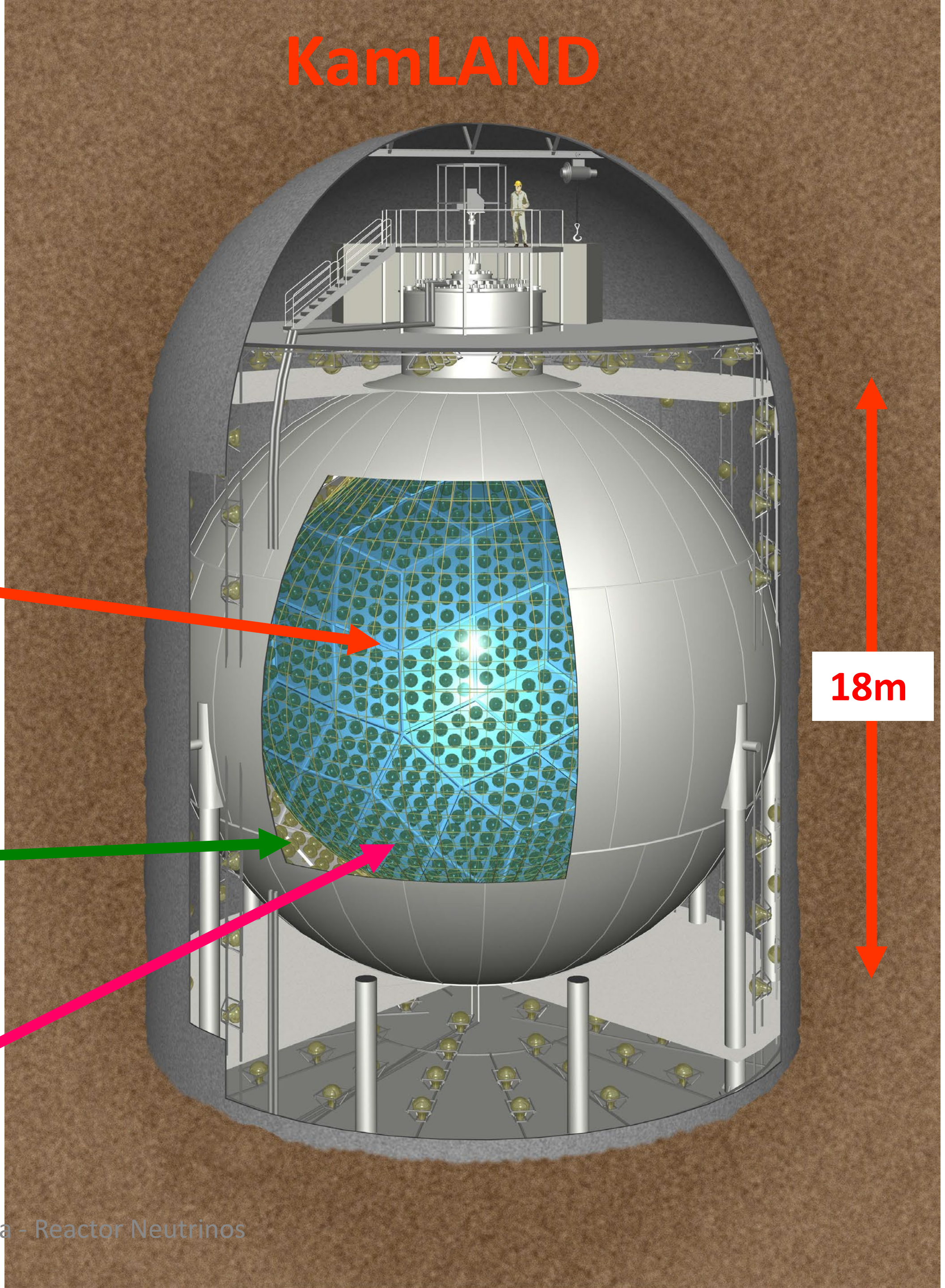


F. Boehm et al (Palo Verde) Phys.Rev.D 64 (2001) 112001

But, it did happen for KamLAND

~1 km high
Mt Ikenoyama

Detectors tend to be large and require extensive shielding against natural radioactivity



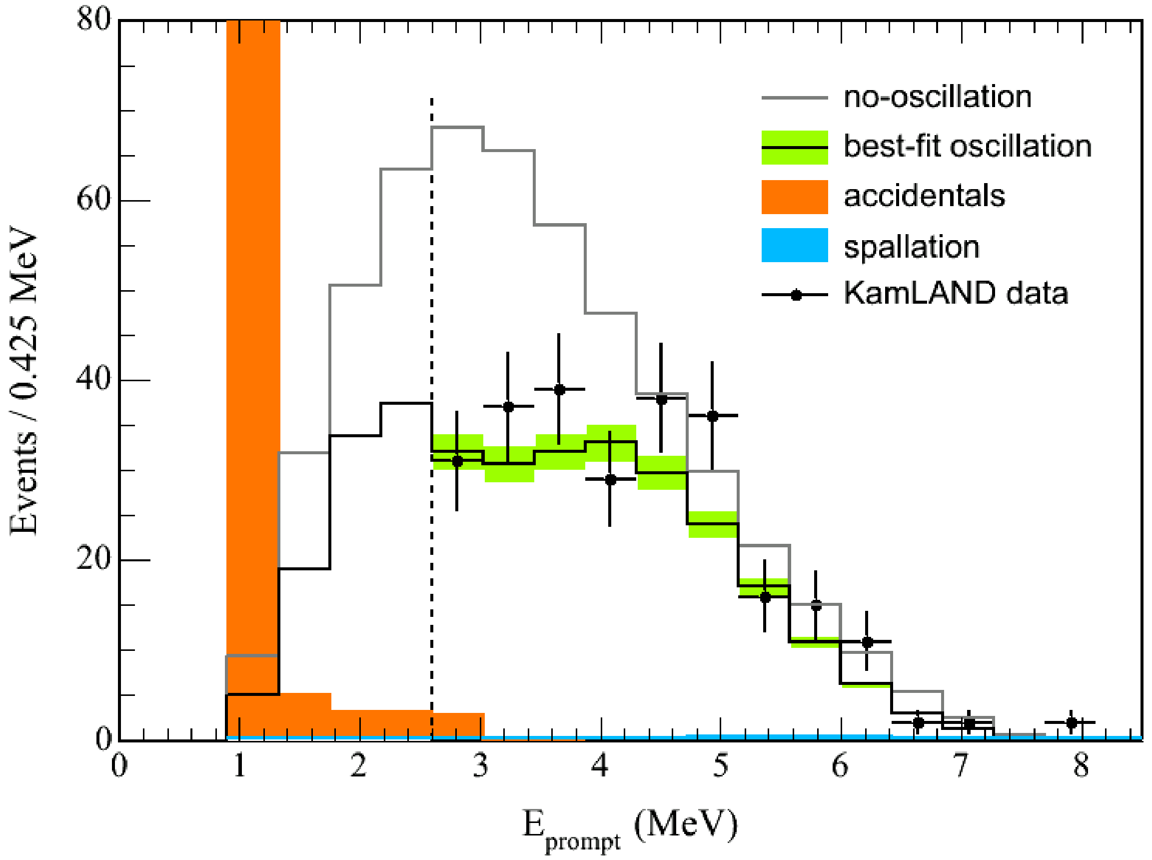
Material where neutrinos interact and are detected (1000 tons liquid scintillator

Shielding oil (2.5 m thick, or about 2 kton)

2000 photomultipliers (20 inch diameter)

Installing 17” and 20” PMTs in KamLAND (Summer 2000)

First KamLAND result



Best fit to oscillations:

$\Delta m^2 = 8.3 \cdot 10^{-5}\ eV^2$

$\sin^2 2\theta = 0.83$

Straightforward χ^2 on the histogram is 19.6/11

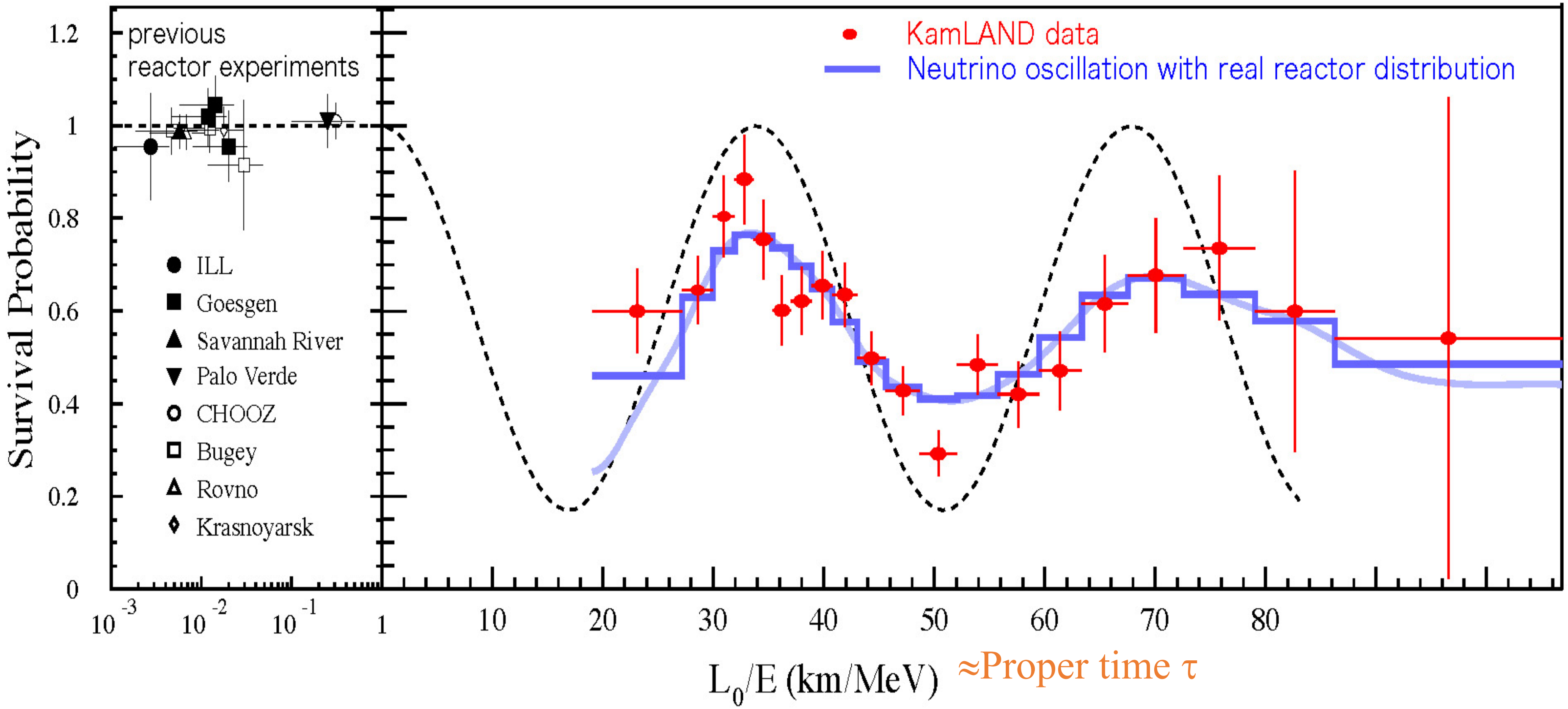
Using equal probability bins $\chi^2/dof = 18.3/18$ ***(goodness of fit is 42%)***

A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

A. Gando et al. (KamLAND) Phys. Rev. D ***83*** *(2011) 052002*

“The oscillatory behavior of neutrino oscillation”

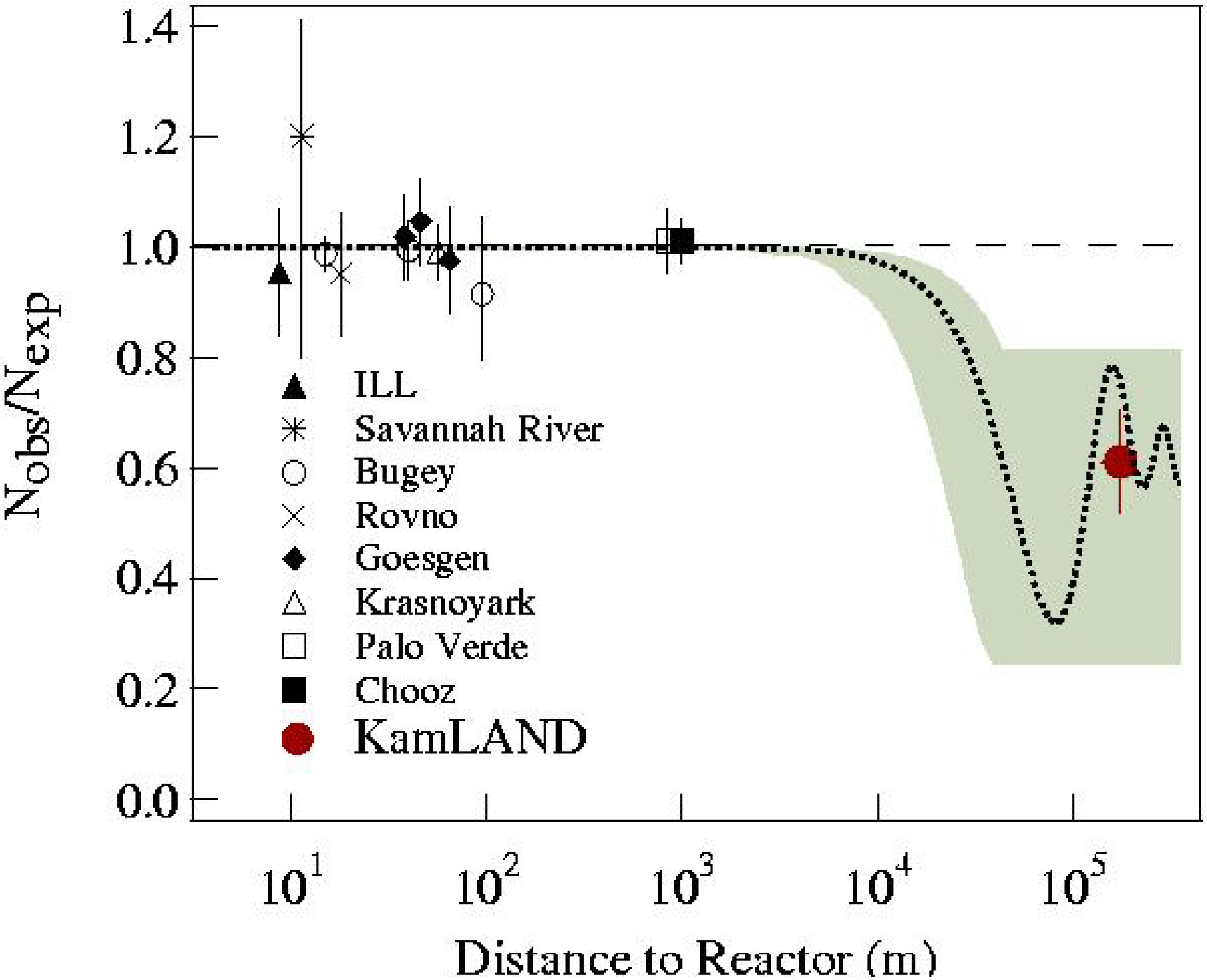
(we did not have the guts to use this as title of the paper (SuperK did))



≈Proper time τ

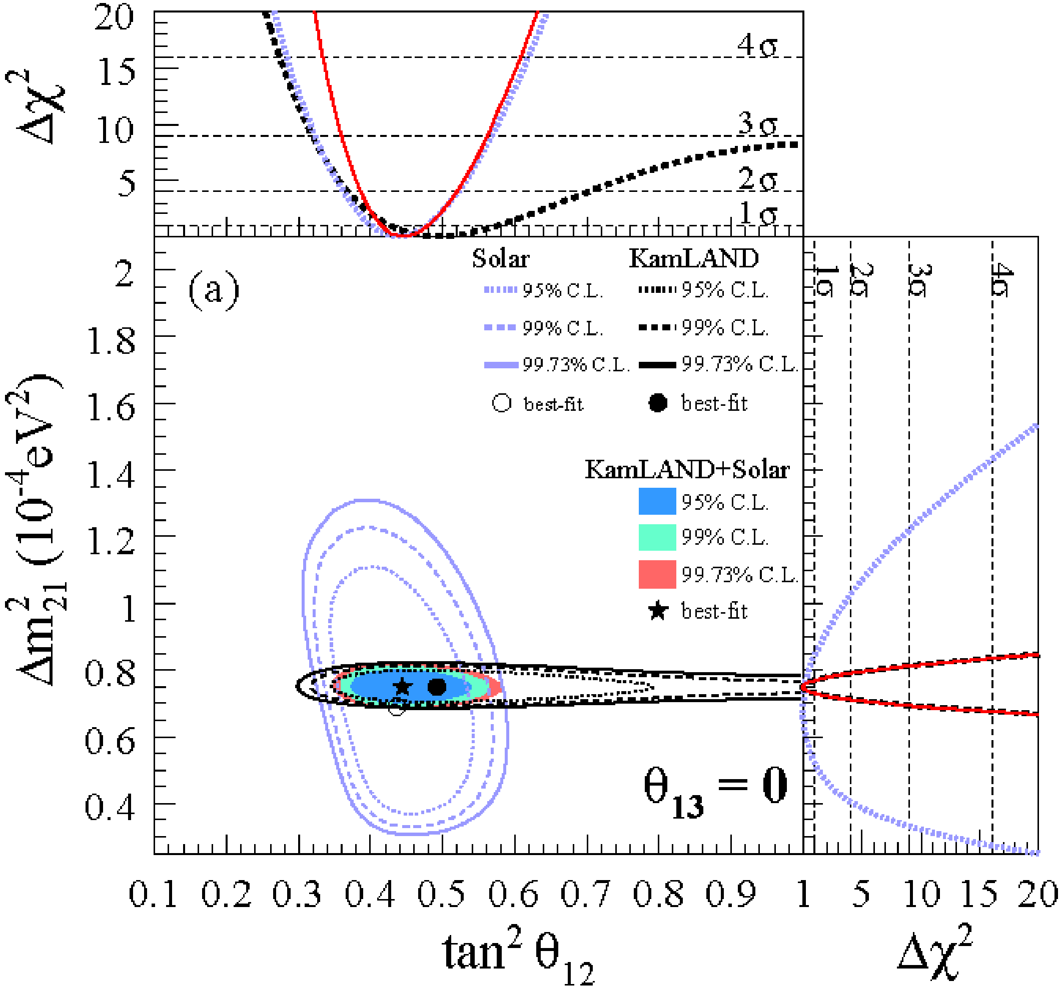
L_0=180 km

This is really what happened!



Note that KamLAND measures very well Δm^2 (the position of the “hole” in the spectrum) **but not so well θ_{12}** (measuring absolute rates is hard)

$$P_{osc}(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



A. Gando et al. (KamLAND) Phys. Rev. D **83** (2011) 052002

How to go after θ_{13} ? This ought to be hard, as Chooz and Palo Verde did not have a signal.

Below is an old slide about this

Method 2: Reactor

Disappearance $\bar{\nu}_e \rightarrow \bar{\nu}_e$

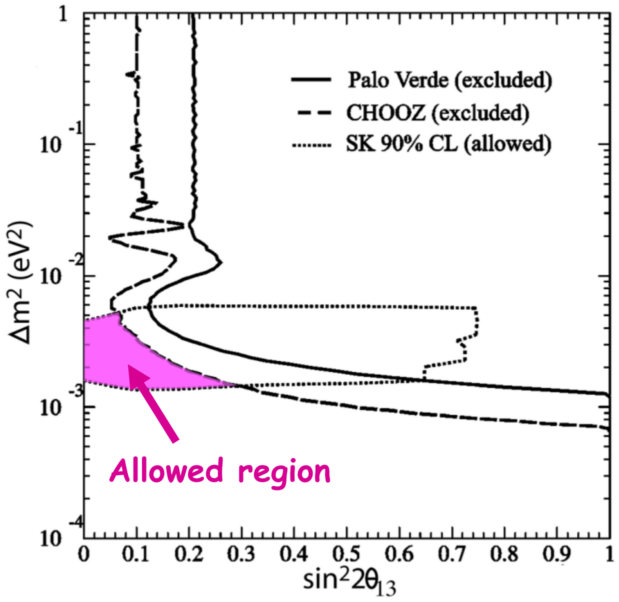
$$1 - P_{\bar{e}\bar{e}} \cong \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(\alpha^2)$$

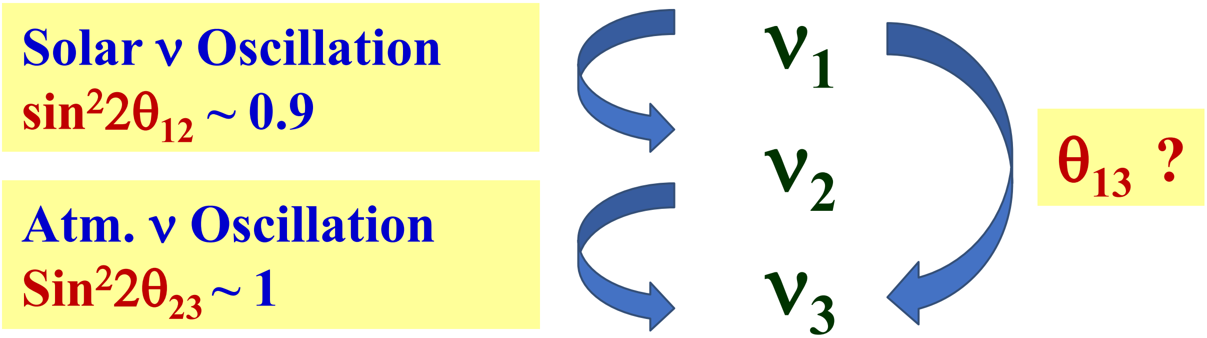
- **Use a near detector to measure reactor flux, spectrum and detector efficiency to cancel “all systematics”**
- **Look for small deviation from $1/r^2$ with plenty of reactor signal**
- **Possibly more limited in sensitivity but maybe “good enough”**
- **Cheaper than superbeam but limited in scope**
- **Very clean θ_{13} measurement**
  (no degeneracy, no matter effects)

First explicit discussion of a ϑ_{13} measurement using reactors:
L.A. Mikaelyan, V.V. Sinev, Phys. Atom. Nucl. 63 No.6 (2000) 1002

θ_{13} for the Neutrino Oscillation

- Key to complete the picture of the neutrino oscillation
- A fundamental parameter of the SM
- Important for future neutrino experiments

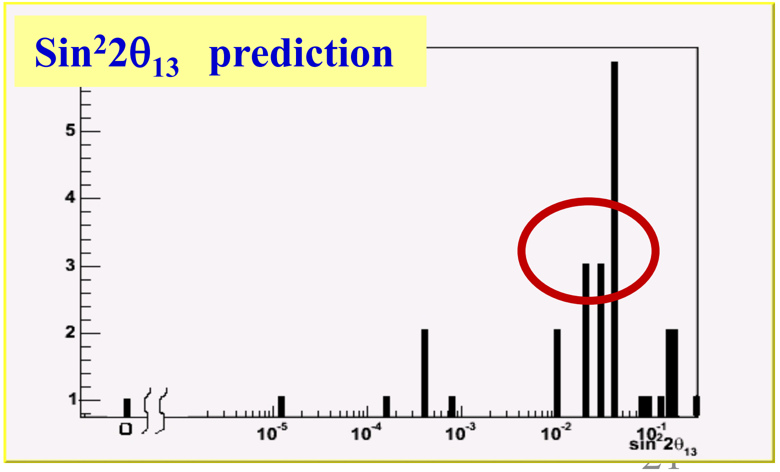




Solar ν Oscillation
$\sin^2 2\theta_{12} \sim 0.9$

Atm. ν Oscillation
$\sin^2 2\theta_{23} \sim 1$

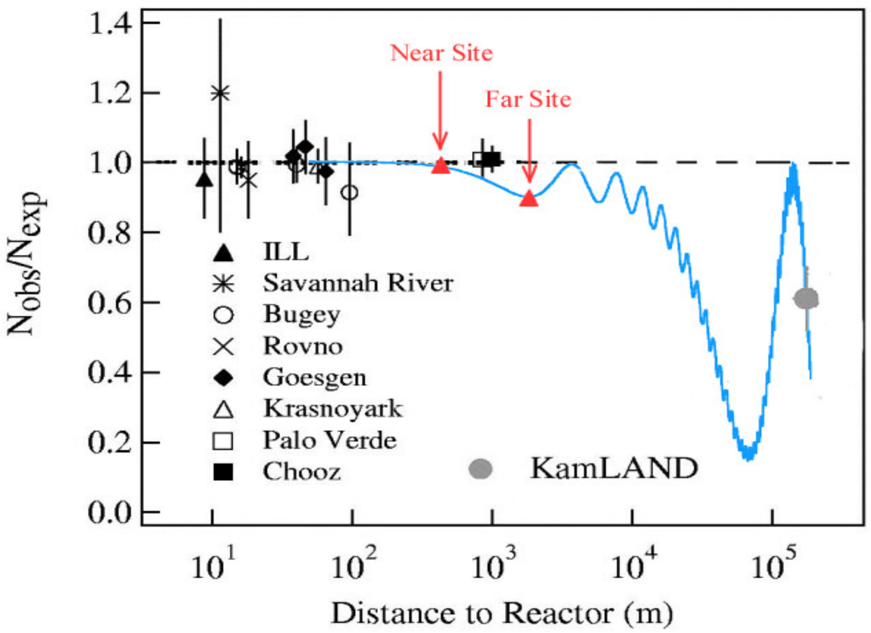
θ_{13} ?

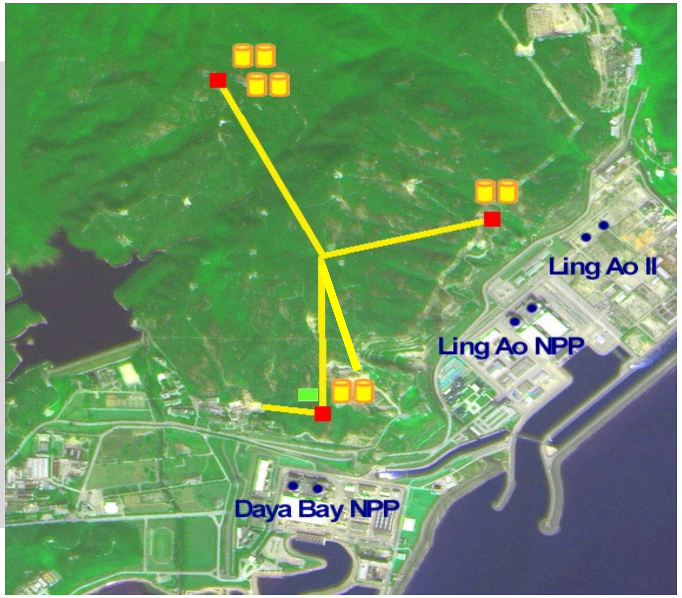


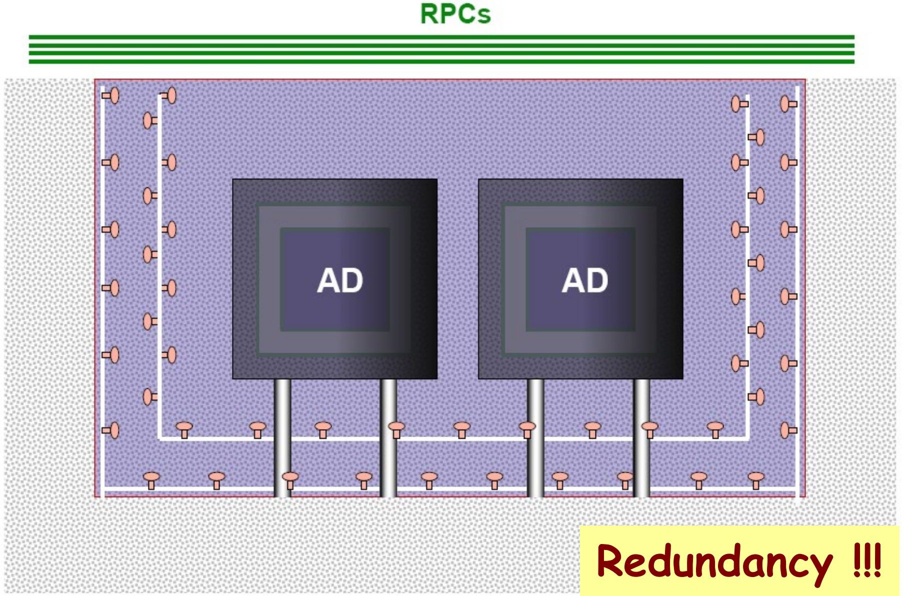
$\sin^2 2\theta_{13}$ prediction

- Sensitivity goal:
  0.01@90%CL for $\sin^2 2\theta_{13}$

Daya Bay Experiment: Concept







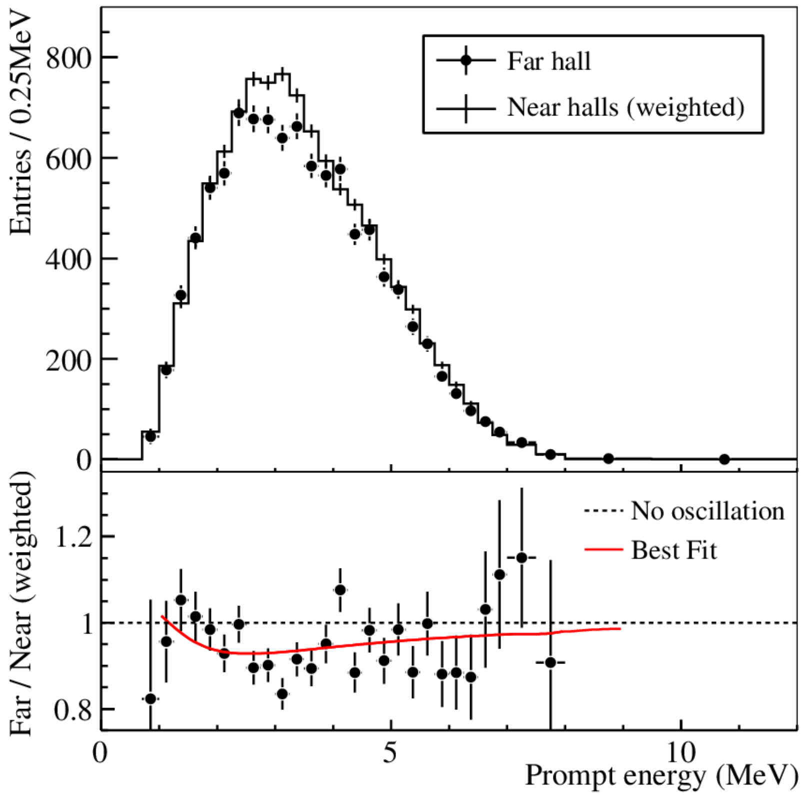
Redundancy !!!

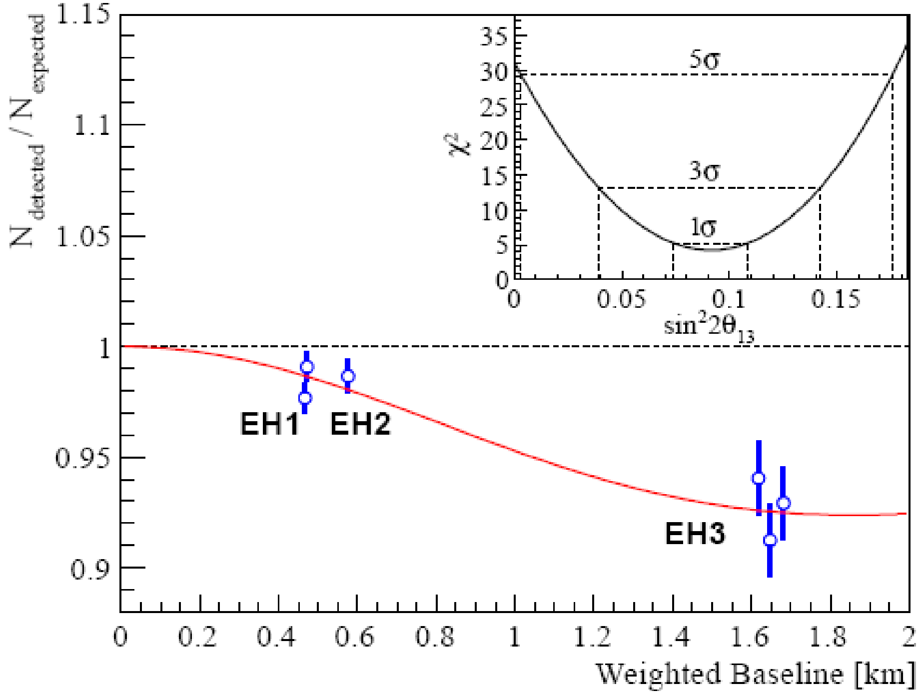
- **Relative measurement (far over near) to cancel Corr. Syst. Err.**
  - 2 near sites, 1 far site
- **Multiple modules at each site to reduce Uncorr. Syst. Err. (1/√N)**
  - Far: 4 modules， near: 2 modules: efficient target mass, flexibility, redundancy, cross check, …
- **Multiple muon detectors to reduce veto ineff. ➔ goal 0.5%**
  - Water Cherenkov： 2 layers
  - RPC： 4 layers at the top + telescopes

X.H. Guo et al., hep-ex/0701029 and ref.s therein

And… Nature was kind again

Electron anti-neutrino disappearance: **R = 0.940 ±0.011 (stat) ±0.004 (syst)**





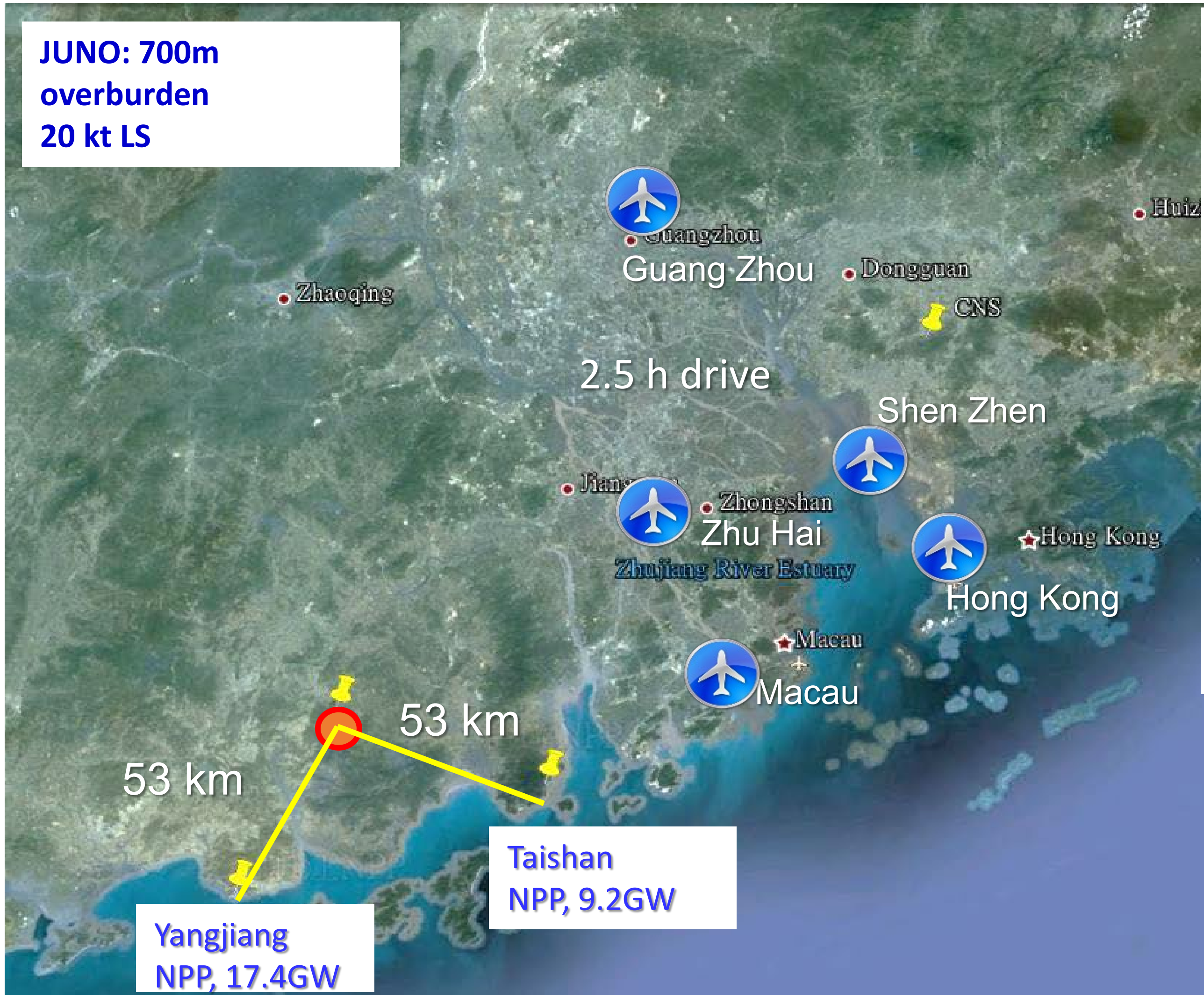
$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
$\chi^2/\text{NDF} = 4.26/4$, 5.2 σ for non-zero θ_{13}

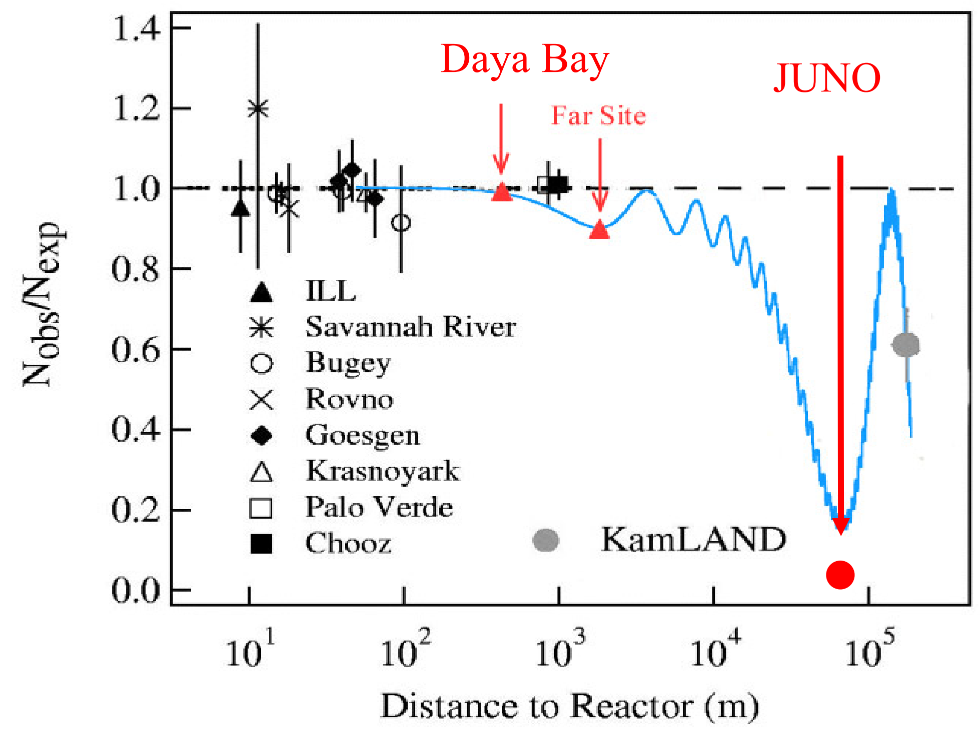
F.P. An et al. (Daya Bay), Phys. Rev. Lett. 108, (2012) 171803

Similar results from Reno (Korea) and Double Chooz (France)

Next Generation Experiment: JUNO

JUNO: 700m
overburden
20 kt LS

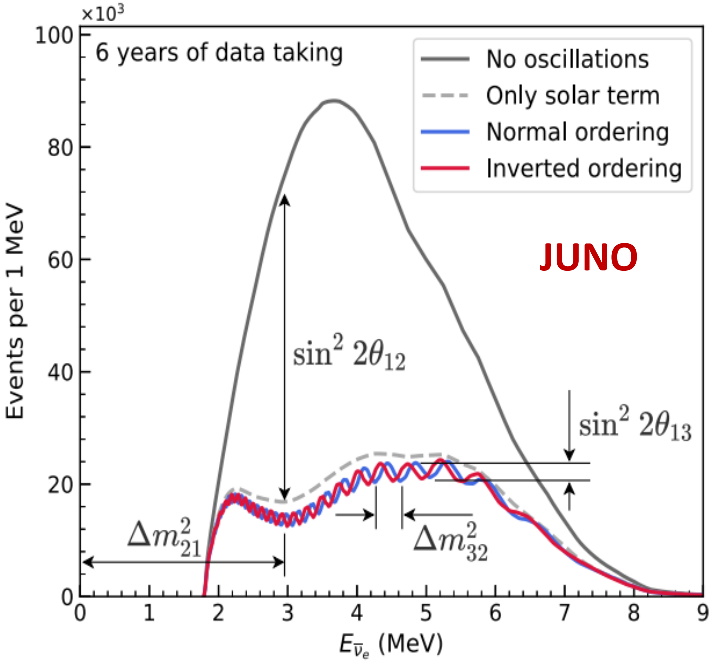




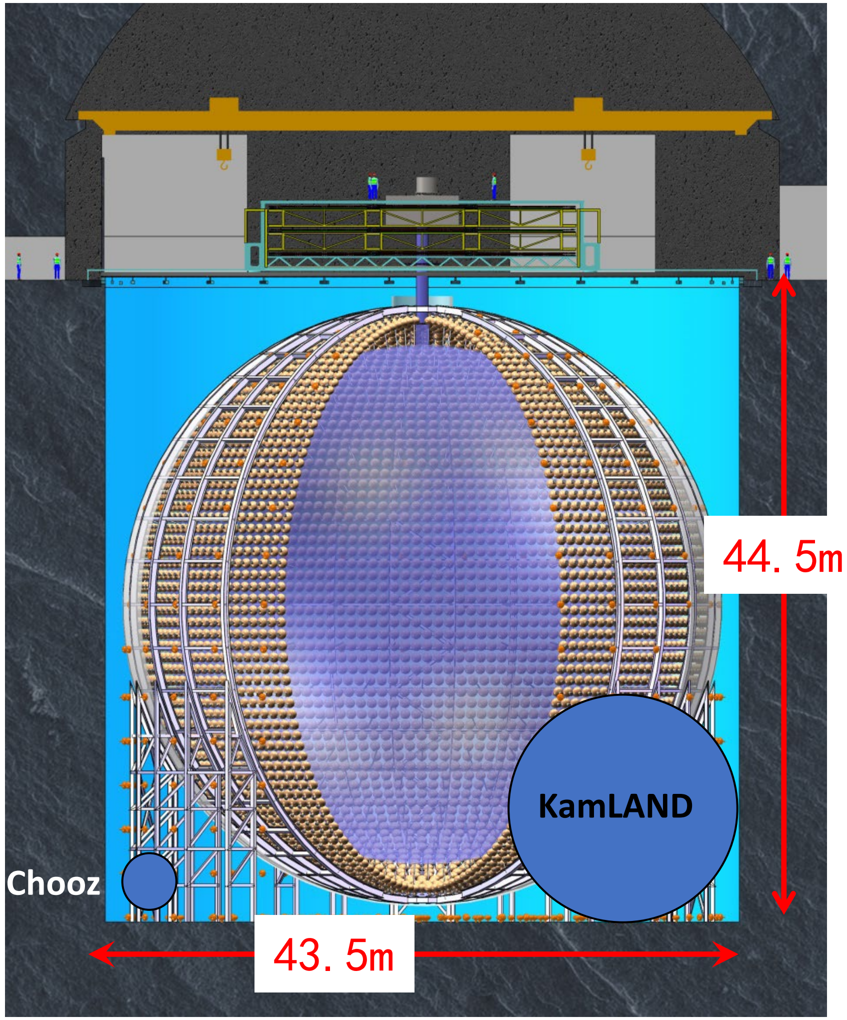
JUNO Detector and Challenges

- Mass hierarchy up to 4σ in 6 years,
- Oscillation parameters to sub-percent,
- Supernova, solar, atmospheric and geo-neutrinos (large detector)

- The very large size is required to get sufficient statistics
- The details of the reactor spectrum don't matter
- The small features require excellent energy resolution

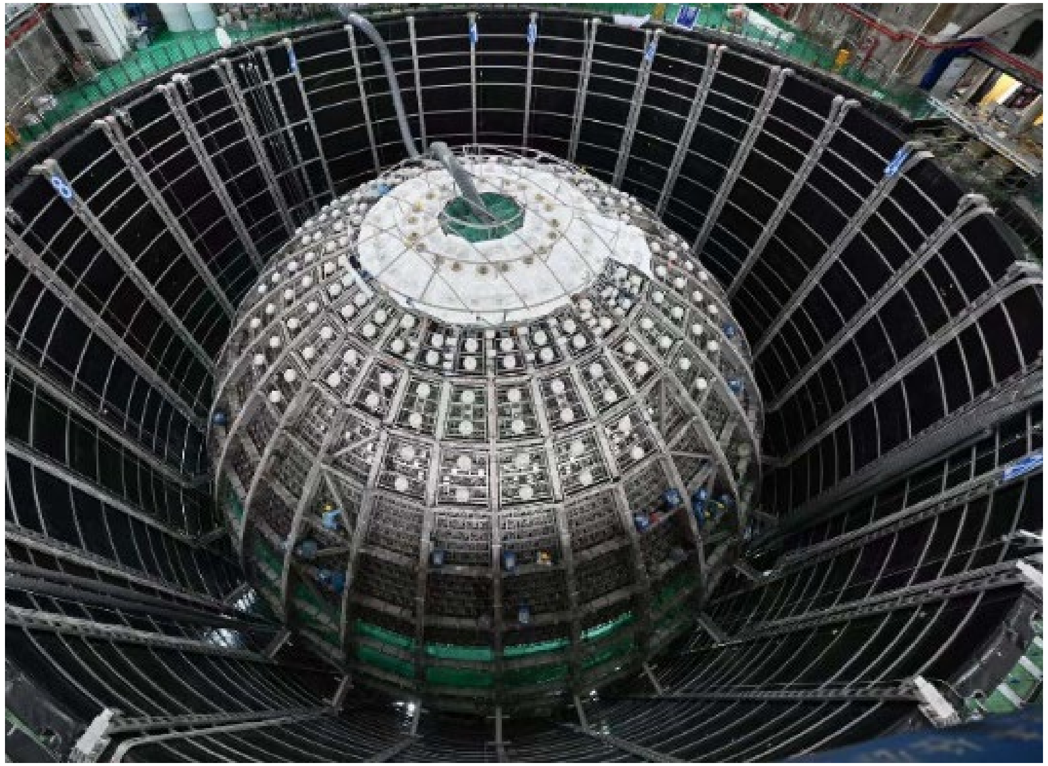


(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)



JUNO Detector and Challenges

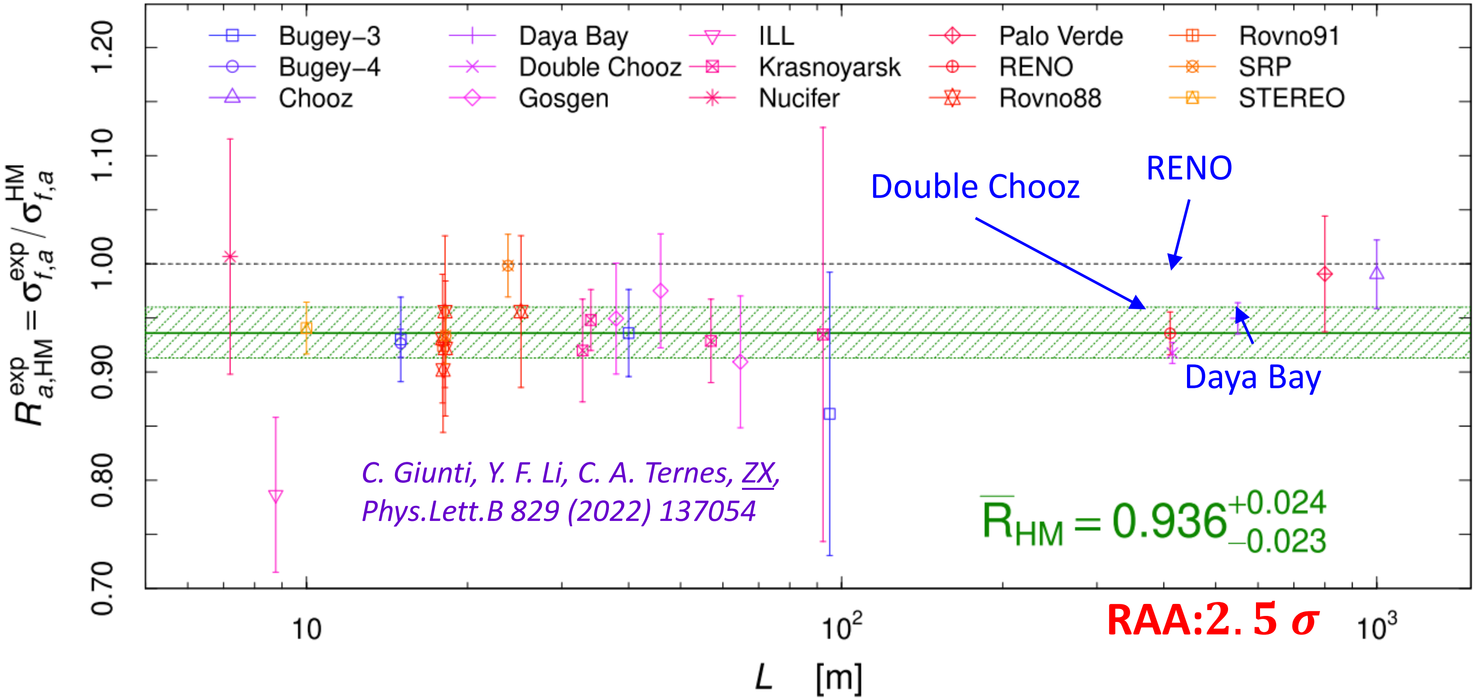
- Largest LS detector ➔ × 20 KamLAND， × 40 Borexino
- High light yield required to obtain sufficient resolution to detect the phase of rapid oscillations: Highest light yield ➔ × 2 Borexino， × 5 KamLAND



Construction will complete in 2024

Yet, not all is good

Now that we have lots of data, with ever shrinking uncertainties,
there seems to be an overall shortage of (anti)neutrinos.

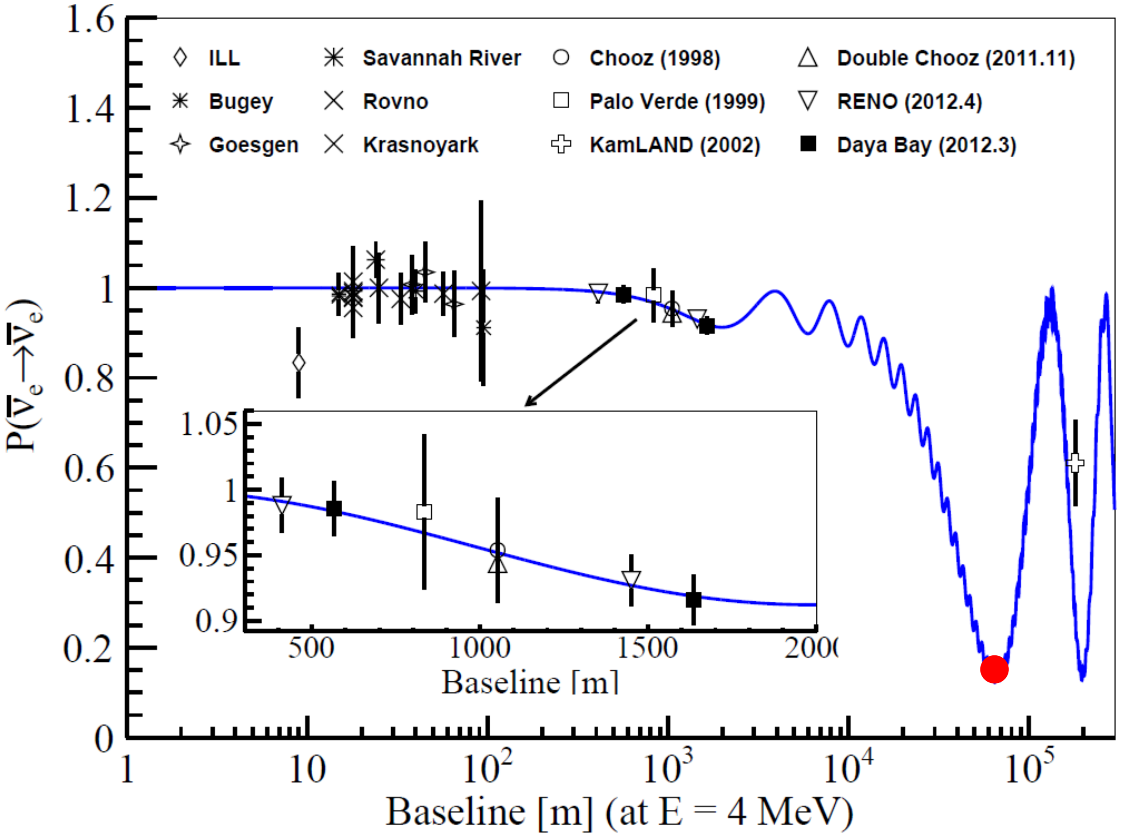


C. Giunti, Y. F. Li, C. A. Ternes, ZX,
Phys.Lett.B 829 (2022) 137054

RAA:$2.5\,\sigma$

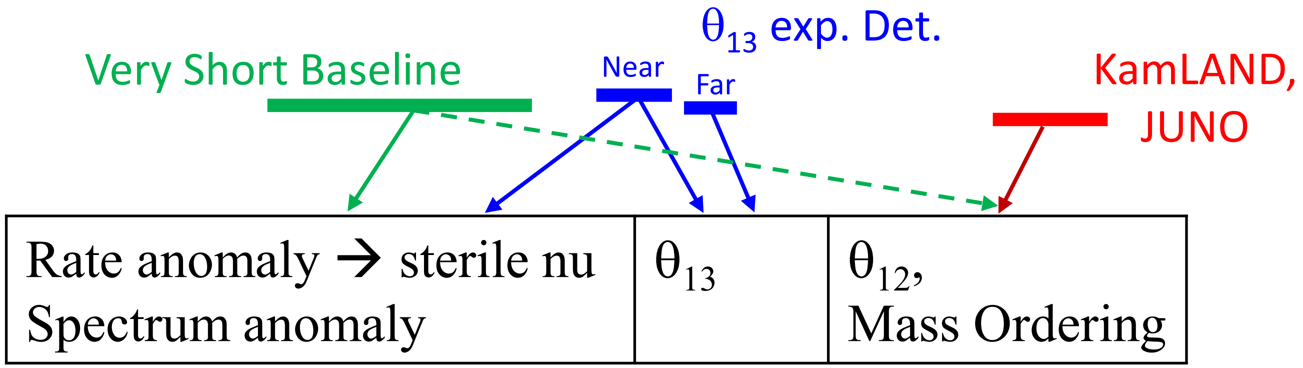
- **The "anomaly" is at short baseline, if nothing else because there is where the statistically more powerful data is.**
- **A revolutionary conclusion would be that this is due to some sterile neutrino, mixing with very large Δm^2 and tiny angle.**
- **A more mundane (and, in my opinion, likely) explanation is that we do not understand the reactor flux to the few % level.**
- **Work in progress…**

Summarizing



- Reactors are not only good at making electricity!
- Not only this is where neutrinos were discovered but…
- This is also a great platform to study flavor mixing.
- After some initial skepticism, they have become a…

  powerhouse for the field.



Rate anomaly → sterile nu Spectrum anomaly	θ_{13}	θ_{12}, Mass Ordering

Thanking many colleagues and, especially, Yifang Wang and Liangjian Wen, for some of the slides