The significance of the third neutrino mixing angle θ_{13} and the reactor experiments searching for it

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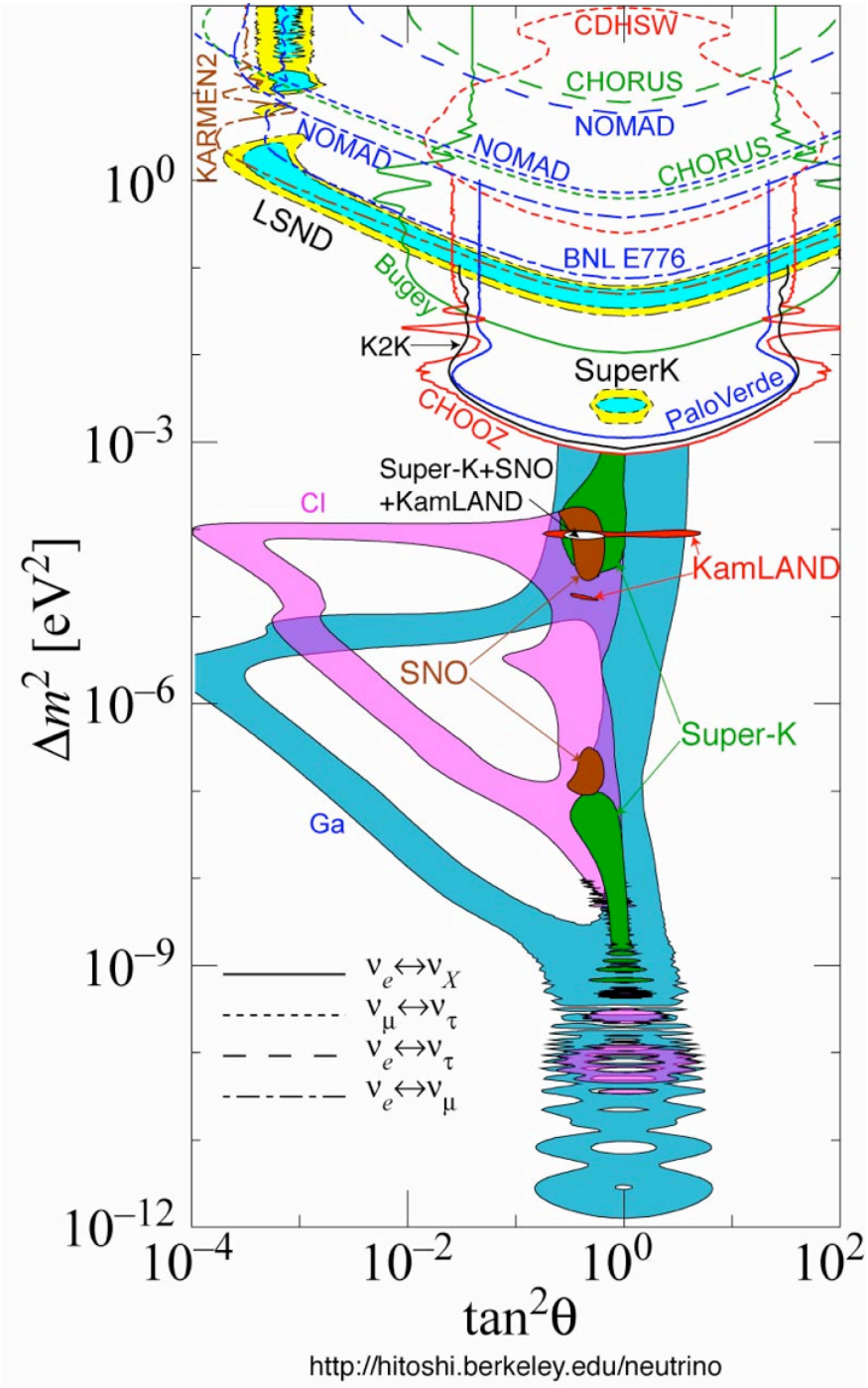
SLAC Summer Institute 2008

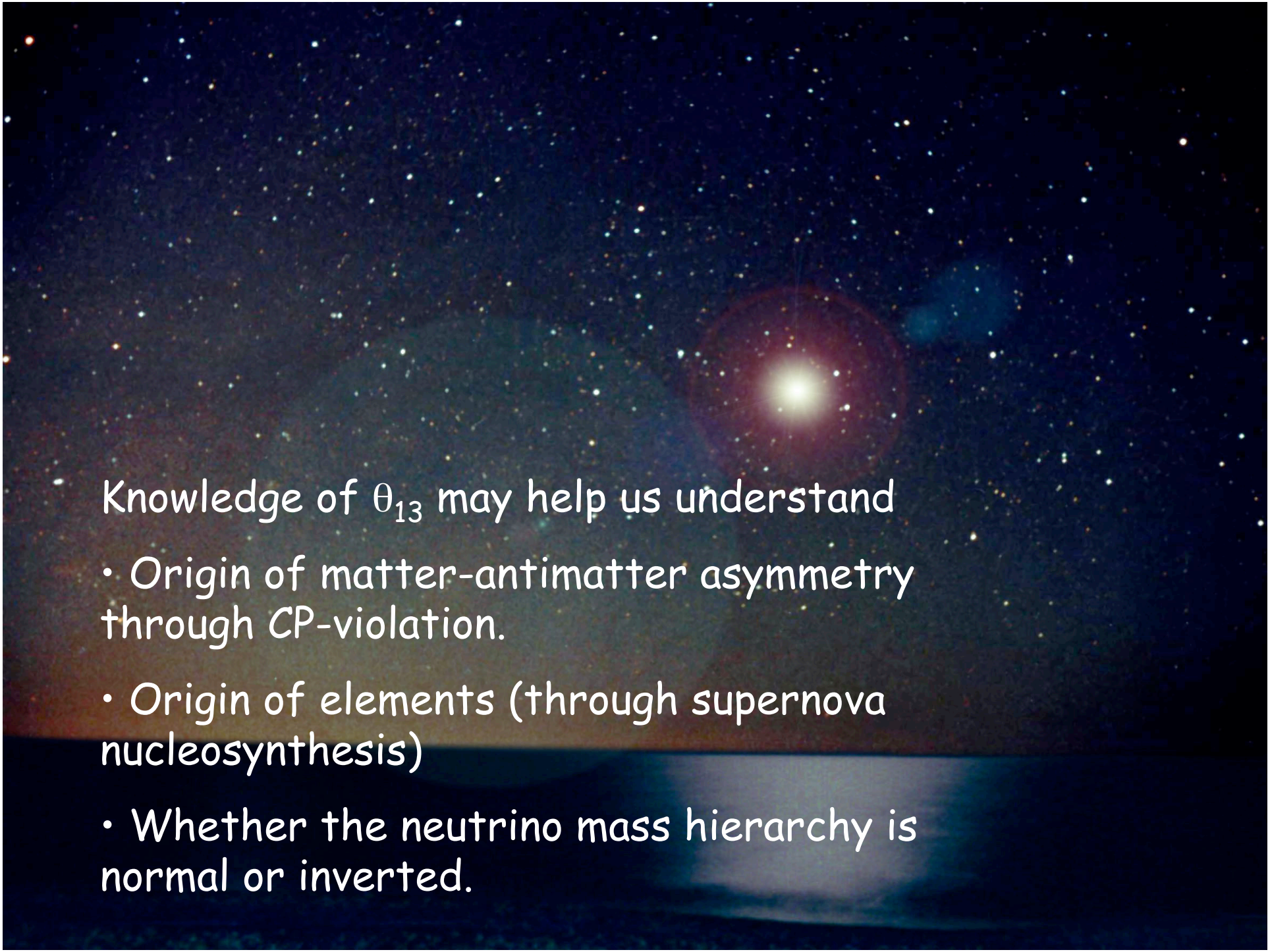


We learned a lot about ν-mixing from recent experiments!

$\theta_{atmospheric}$ (primarily θ_{23})

θ_{solar} (primarily θ_{12})

Yet our current knowledge of θ_{13} is very limited!



Knowledge of θ_{13} may help us understand

- Origin of matter-antimatter asymmetry through CP-violation.
- Origin of elements (through supernova nucleosynthesis)
- Whether the neutrino mass hierarchy is normal or inverted.

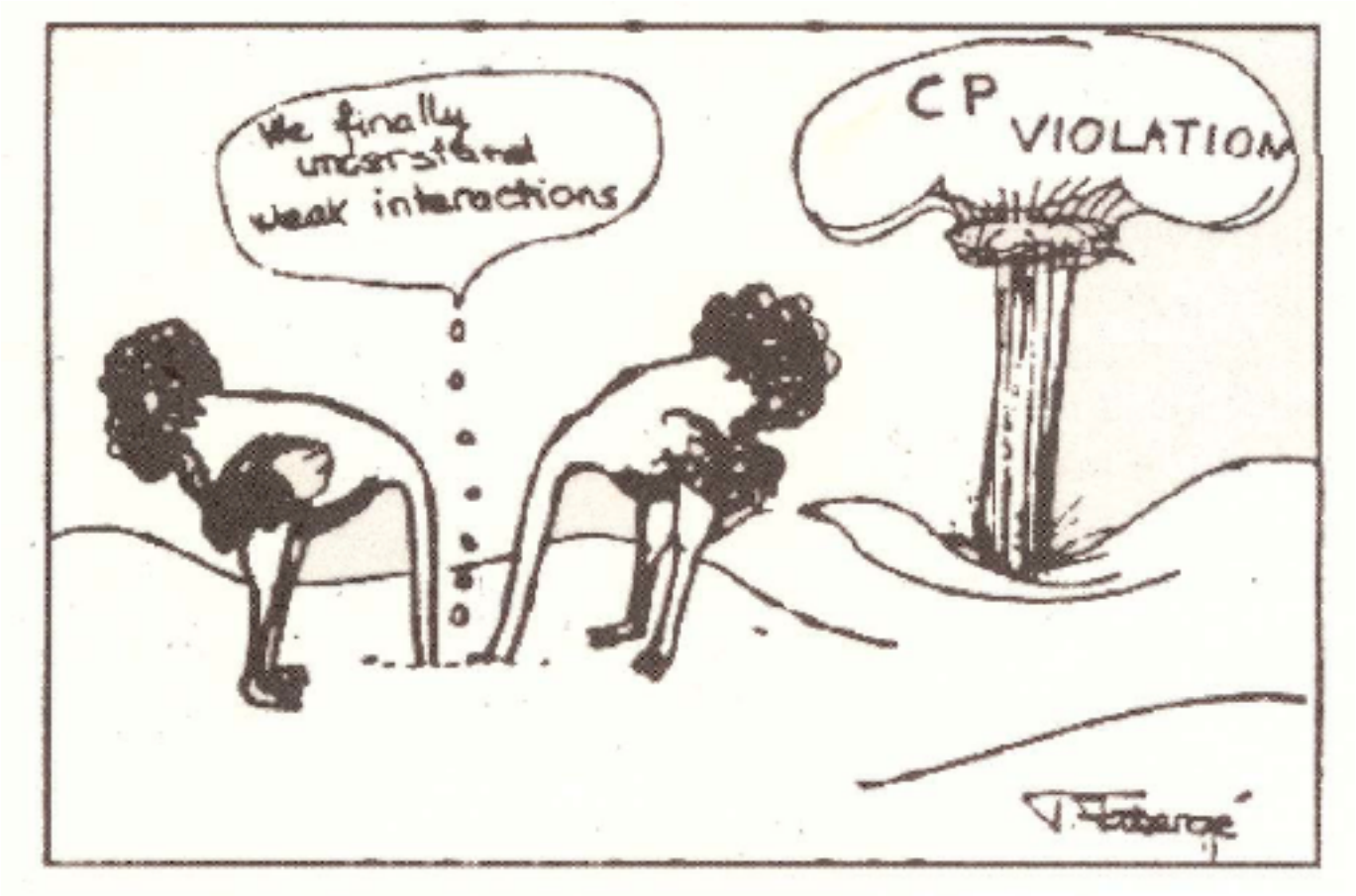
CP-asymmetry was proposed by Okubo in 1958.

In 1967, Sakharov wrote: "From S. Okubo's effect at high temperature a coat is tailored for the Universe to fit its skewed shape".

He proposed the conditions under which one can achieve matter-antimatter asymmetry via baryogenesis:

- C and CP-violation
- B violation
- Deviation from thermal equilibrium

In 1986 Fukugita & Yanagida explored conditions for leptogenesis. For example heavy partners of neutrinos in the see-saw mechanism must have been produced in the Early Universe. If their decays are CP-violating they may have given rise to particle-antiparticle asymmetry.



CP-violation is observed in neutral kaon decays, but what is seen there is not big enough to provide baryon-antibaryon asymmetry!

Atmospheric Reactor, long-baseline solar

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

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana phases

CP-violating phases

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

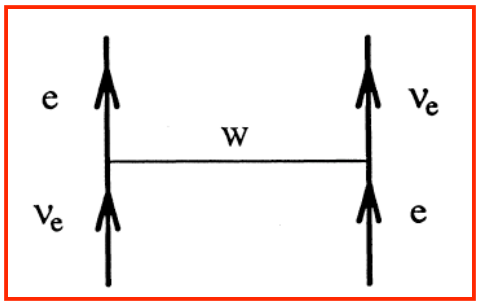
A direct search for CP-violation by neutrinos would search for $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)$ using neutrino factories, superbeams, beta beams, etc. Those efforts are beyond the scope of this talk.

MSW effect

In vacuum: $E^2 = p^2 + m^2$

In a potential: $(E-\Phi)^2 = p^2 + m^2 \Rightarrow E^2 = p^2 + m_{eff}^2$, $m_{eff}^2 \approx m^2 + 2E\Phi$

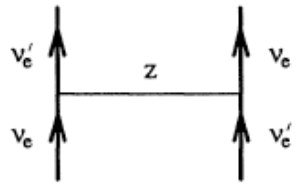
The potential is provided by the coherent forward scattering of ν_e's off the electrons in dense matter.

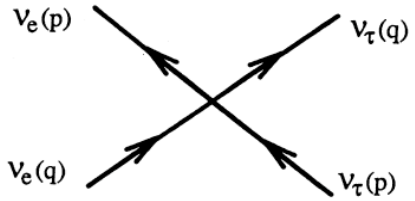


There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute to phase differences *unless* we invoke a sterile neutrino.

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_e\\ \psi_x\end{pmatrix} = \begin{pmatrix}-\frac{\delta m^2}{4p}\cos 2\theta + \frac{1}{\sqrt{2}}G_F N_e & \frac{\delta m^2}{4p}\sin 2\theta\\ \frac{\delta m^2}{4p}\sin 2\theta & \frac{\delta m^2}{4p}\cos 2\theta - \frac{1}{\sqrt{2}}G_F N_e\end{pmatrix}\begin{pmatrix}\psi_e\\ \psi_x\end{pmatrix}$$

If the neutrino density itself is also very high then one has to consider the effects of neutrinos scattering off other neutrinos. This is the case for a core-collapse supernova.





In core-collapse supernovae particle abundances are the isospin-mirror of the abundances for Big-bang nucleosynthesis!

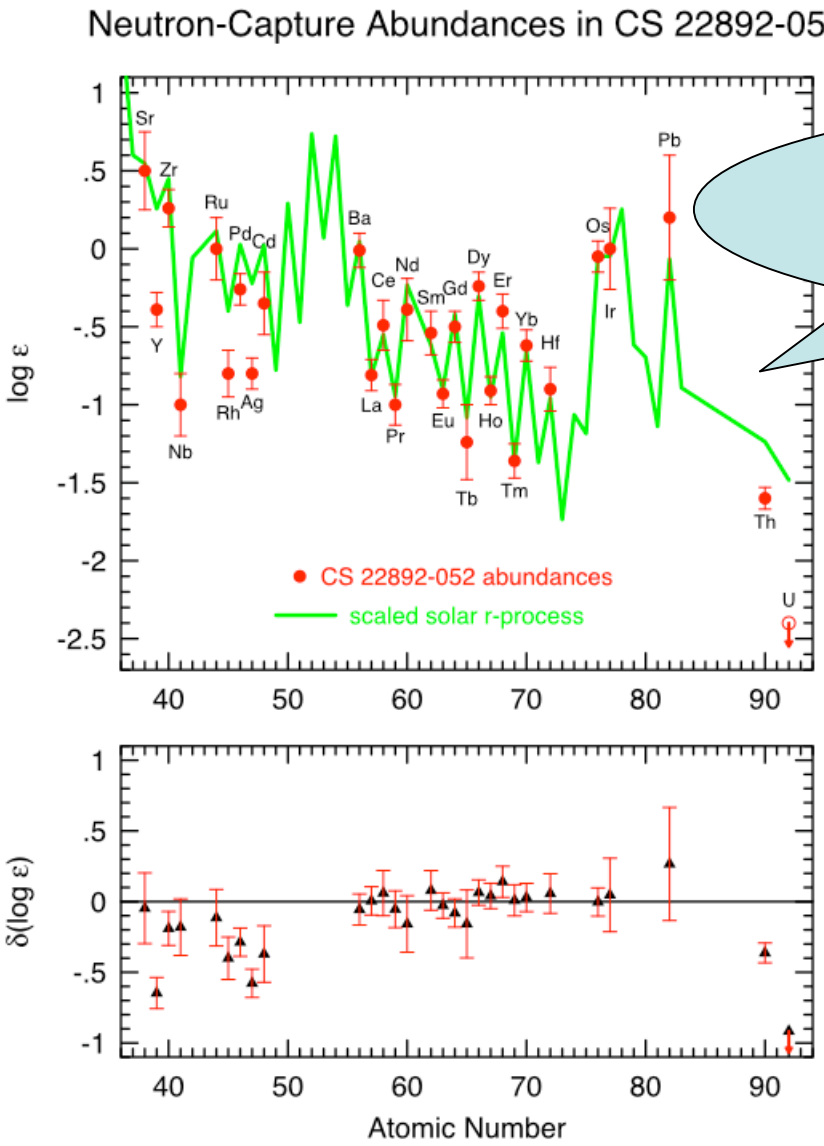
Big-Bang: $n/p \ll 1$

Core-collapse SN: $n/p \gg 1$

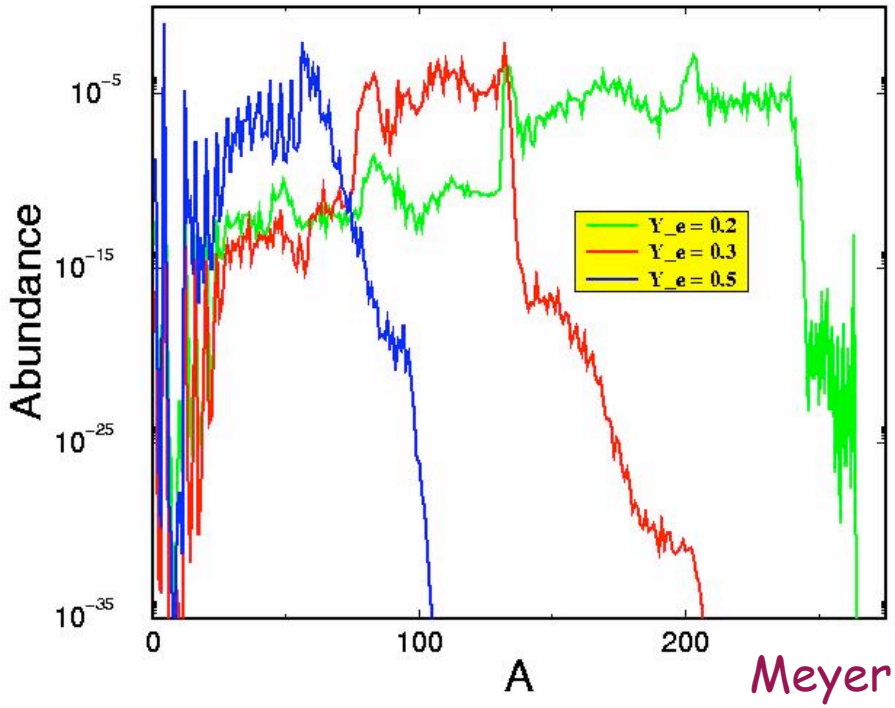
This makes core-collapse supernovae an ideal site for r-process nucleosynthesis which requires a lot of neutrons!

[Fe/H] ≈ -3.1

r-process abundances



A > 100 abundance pattern fits the solar abundances well



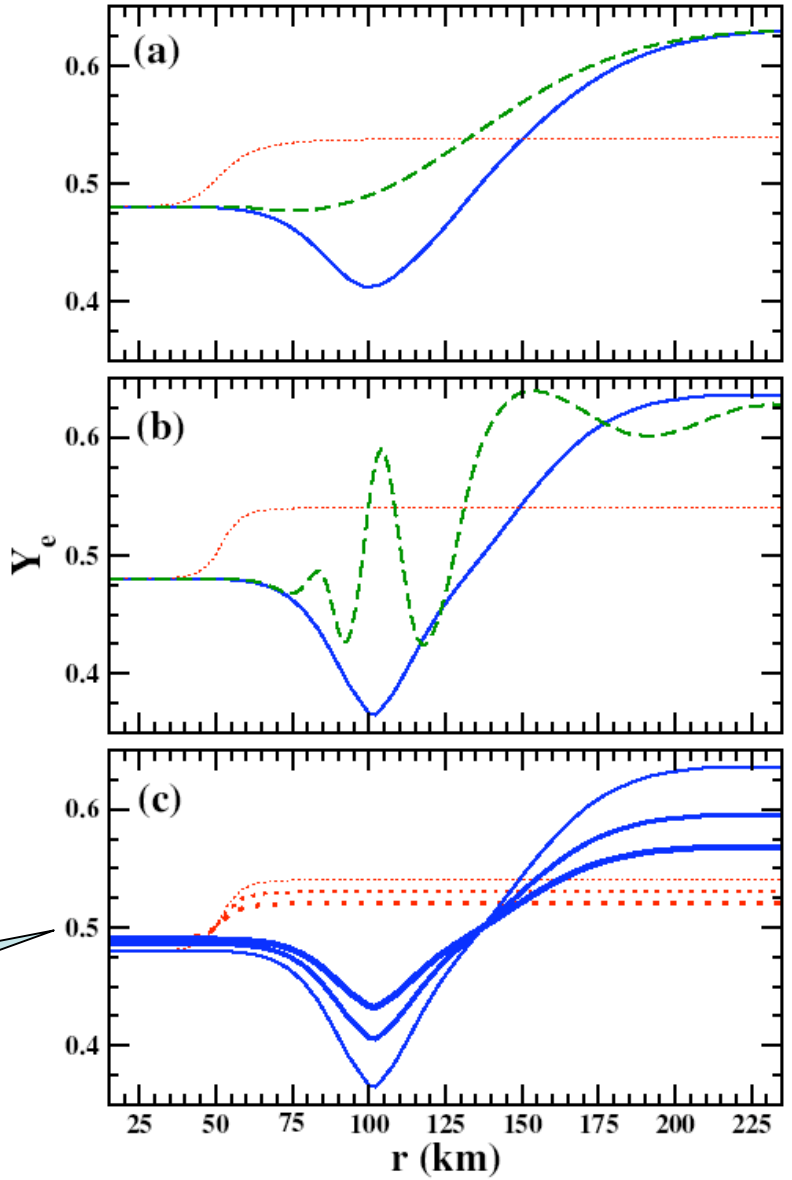
Meyer

One finds large-scale, collective flavor oscillations deep in the supernova envelope, which is sensitive to the value of θ_{13}.

Fuller, Qian, Raffelt, Duan, Sigl, Balantekin, Pehlivan, Carlson,....

ν luminosity:
L^{51} = 0.001, 0.1, 50

Alpha abundance:
X_α= 0, 0.3, 0.5 (thin, medium, thick lines)



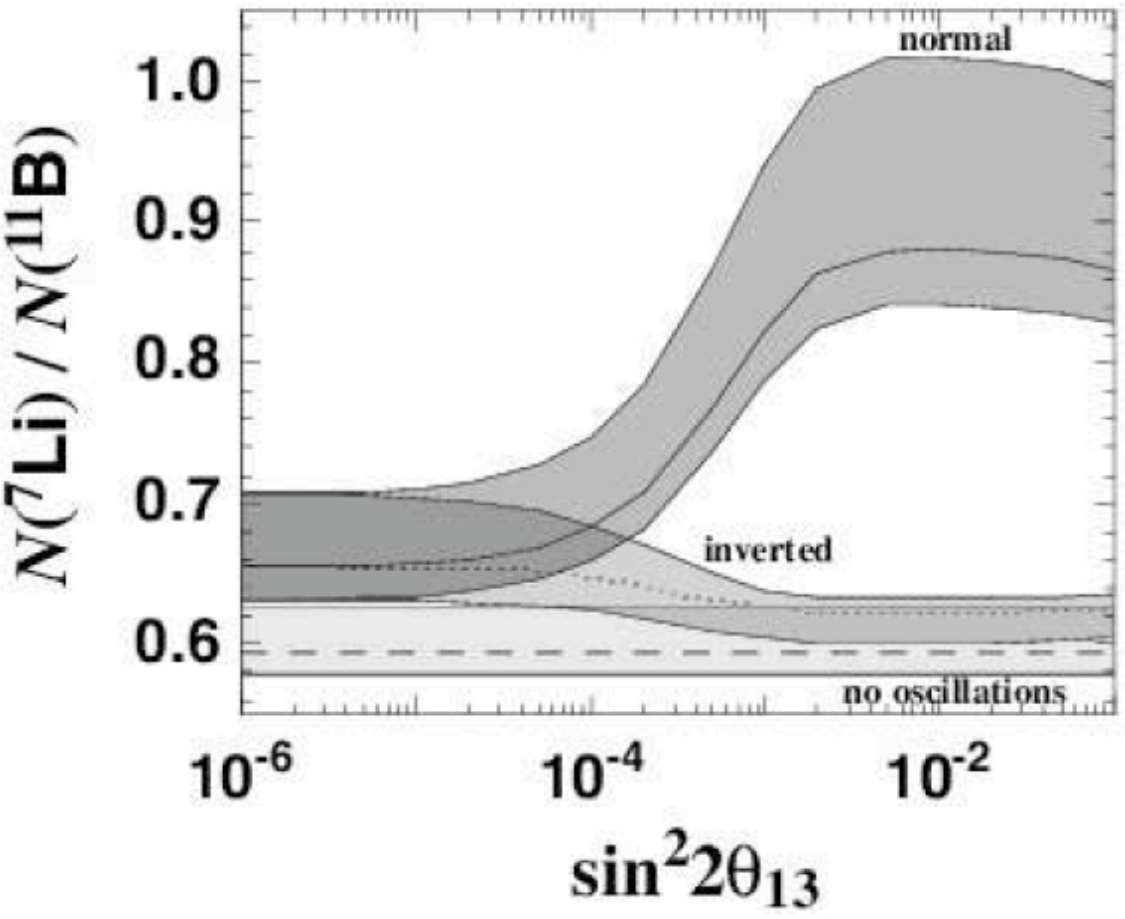
θ_{13}~ π/10

θ_{13}~ π/20

θ_{13} ~ π/20
with α effect

Balantekin and Yuksel, New J. Phys. 7, 51 (2005)

The value of θ_{13} may also effect light-element production through the so-called ν-process:



Yoshida *et. al.*, Astrophys.J. **649** 319 (2006)

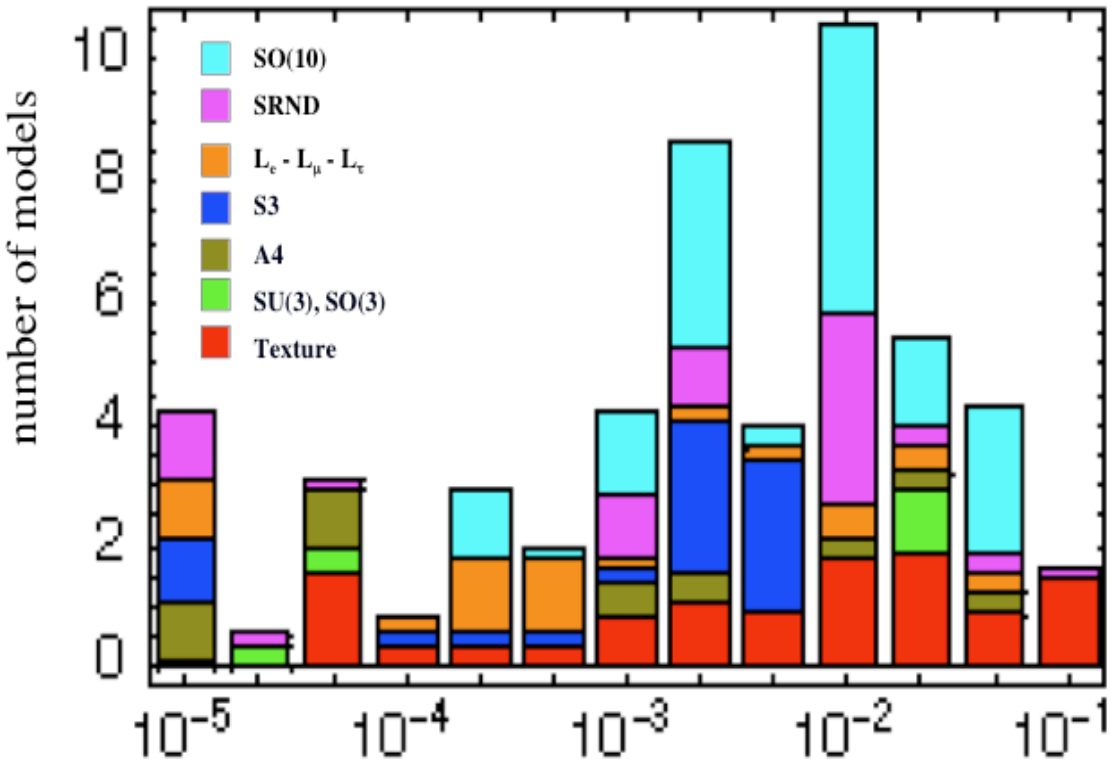
Consider the combinations

$\tilde{\nu}_\mu = \cos 2\theta_{23}\, \nu_\mu - \sin 2\theta_{23}\, \nu_\tau$

$\tilde{\nu}_\tau = \sin 2\theta_{23}\, \nu_\mu + \cos 2\theta_{23}\, \nu_\tau$

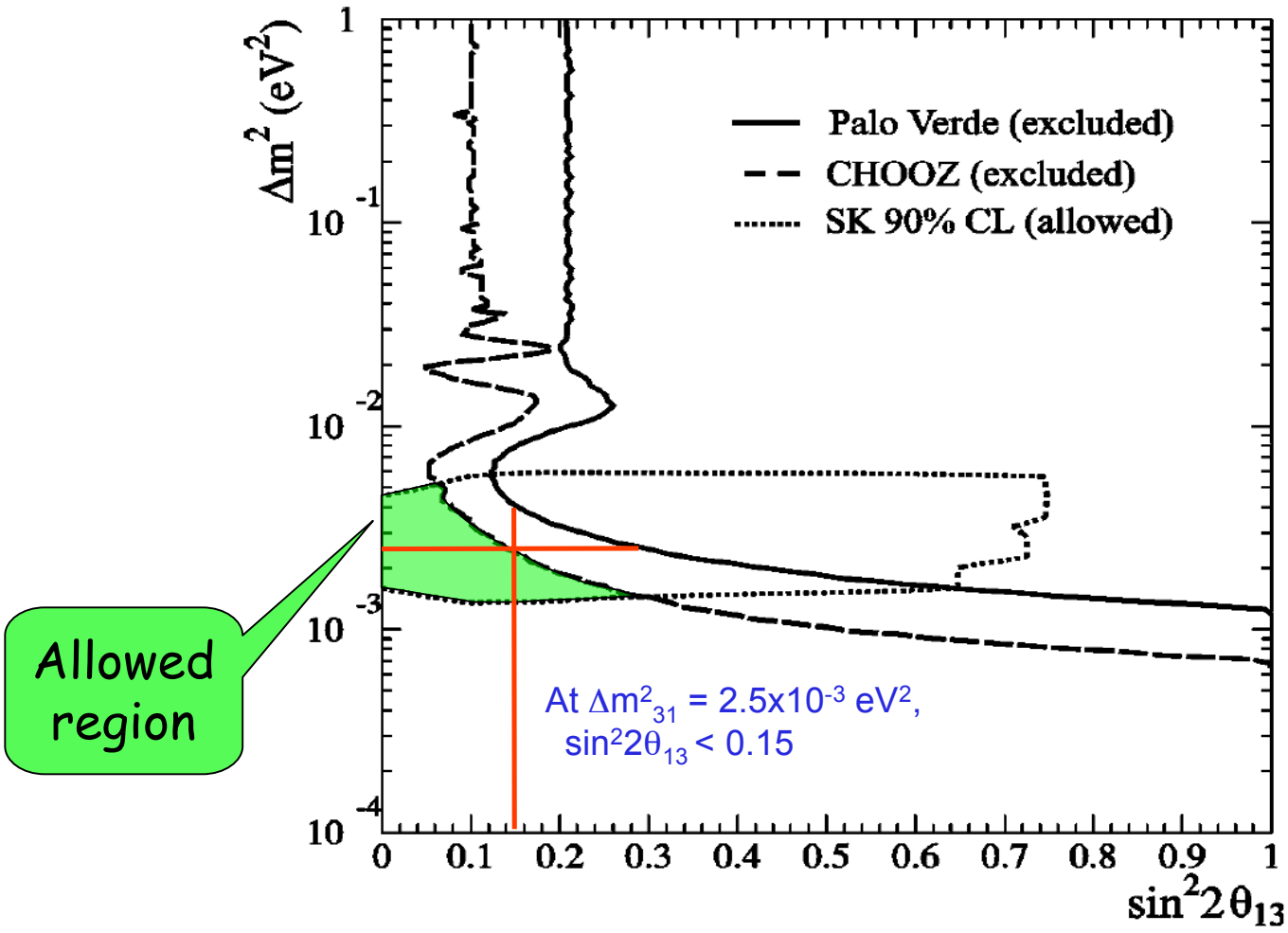
If θ_{13} were zero, ν_e only mixes with $\tilde{\nu}_\mu$. Thus for neutrino experiments below the muon threshold (i.e. for solar, reactor, and supernova neutrinos) knowing the value of θ_{13} is useful to distinguish normal from inverted hierarchy.

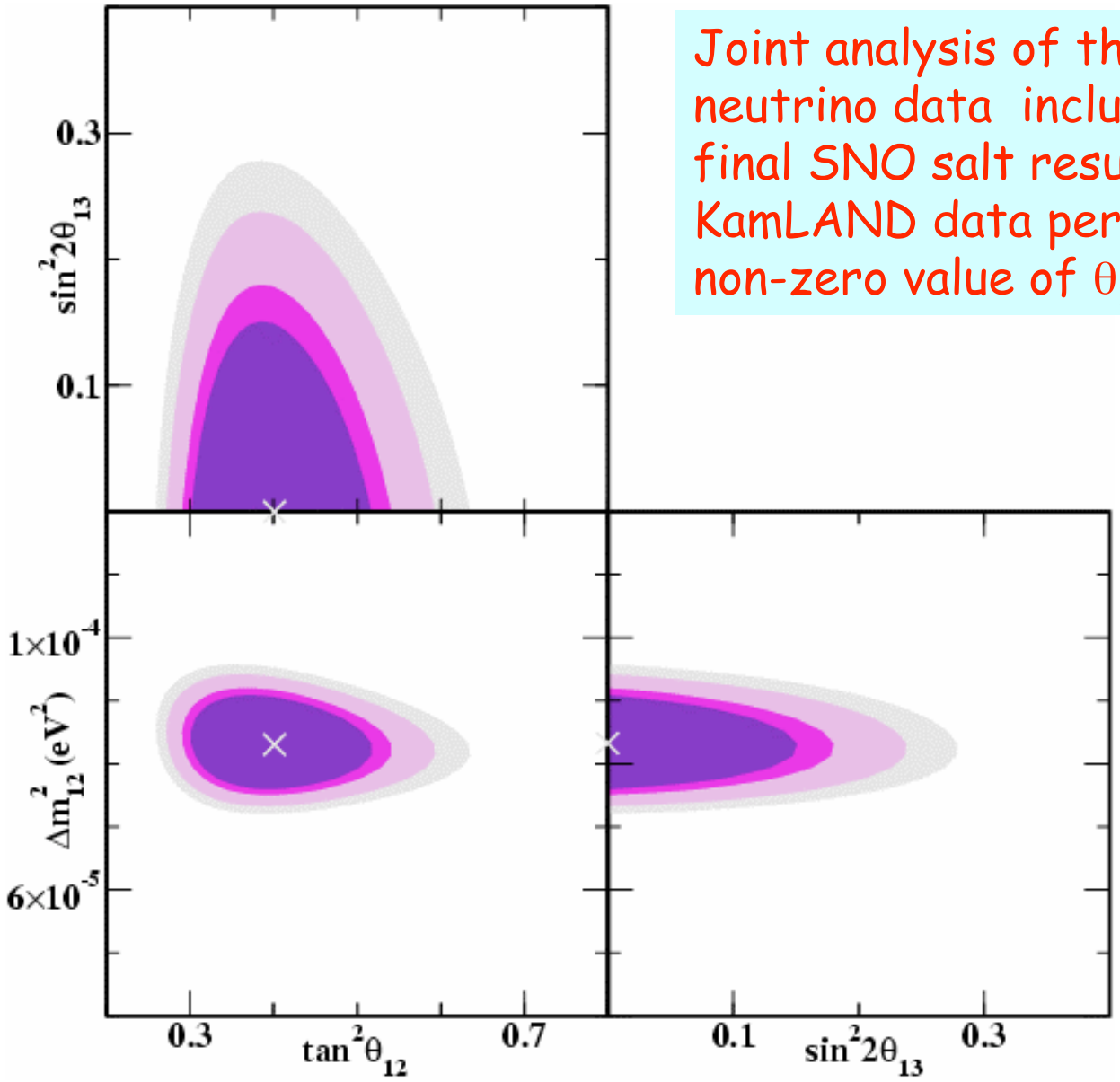
Theory is yet not of much help:



Albright and Chen

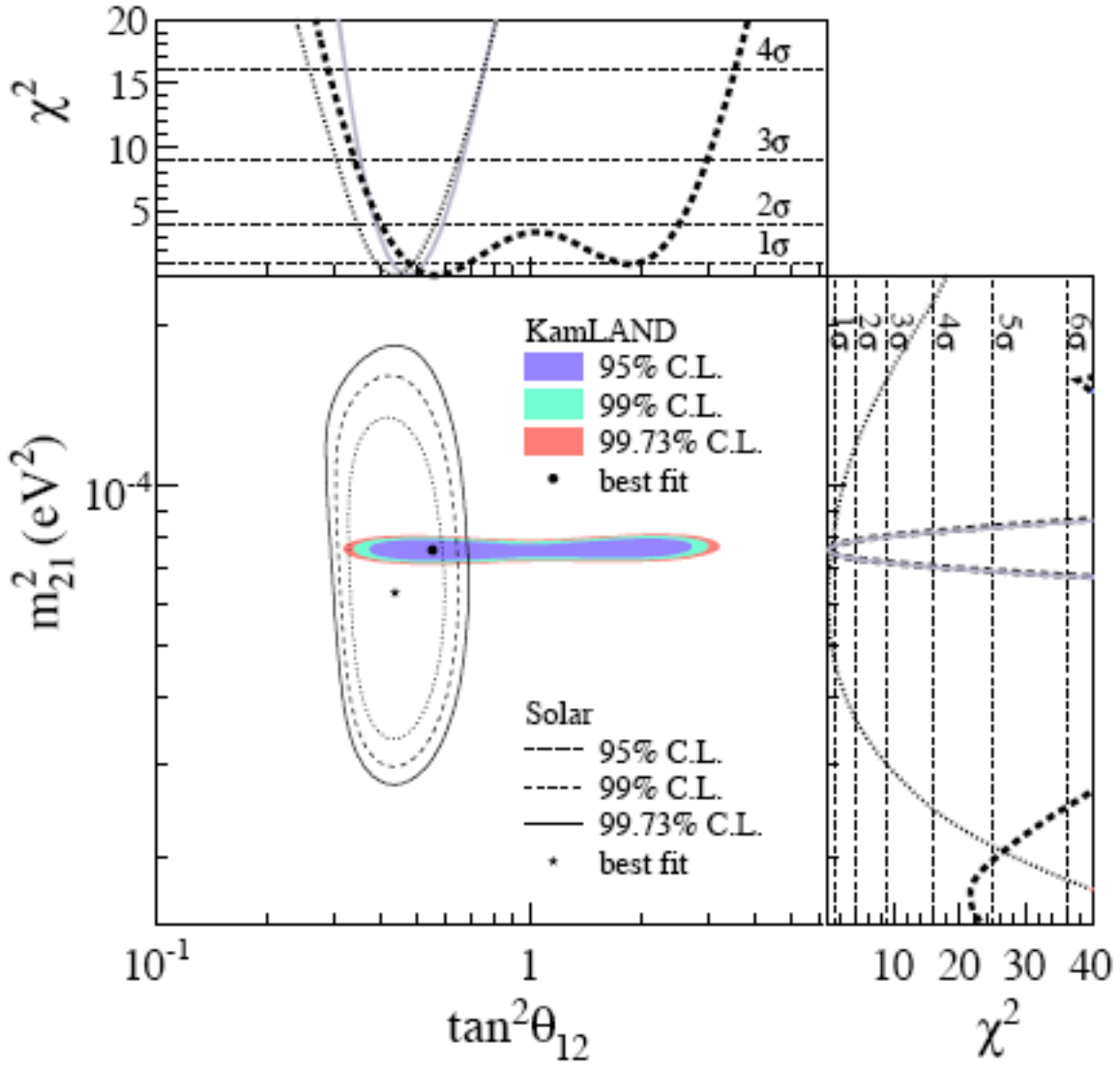
Current direct search limits





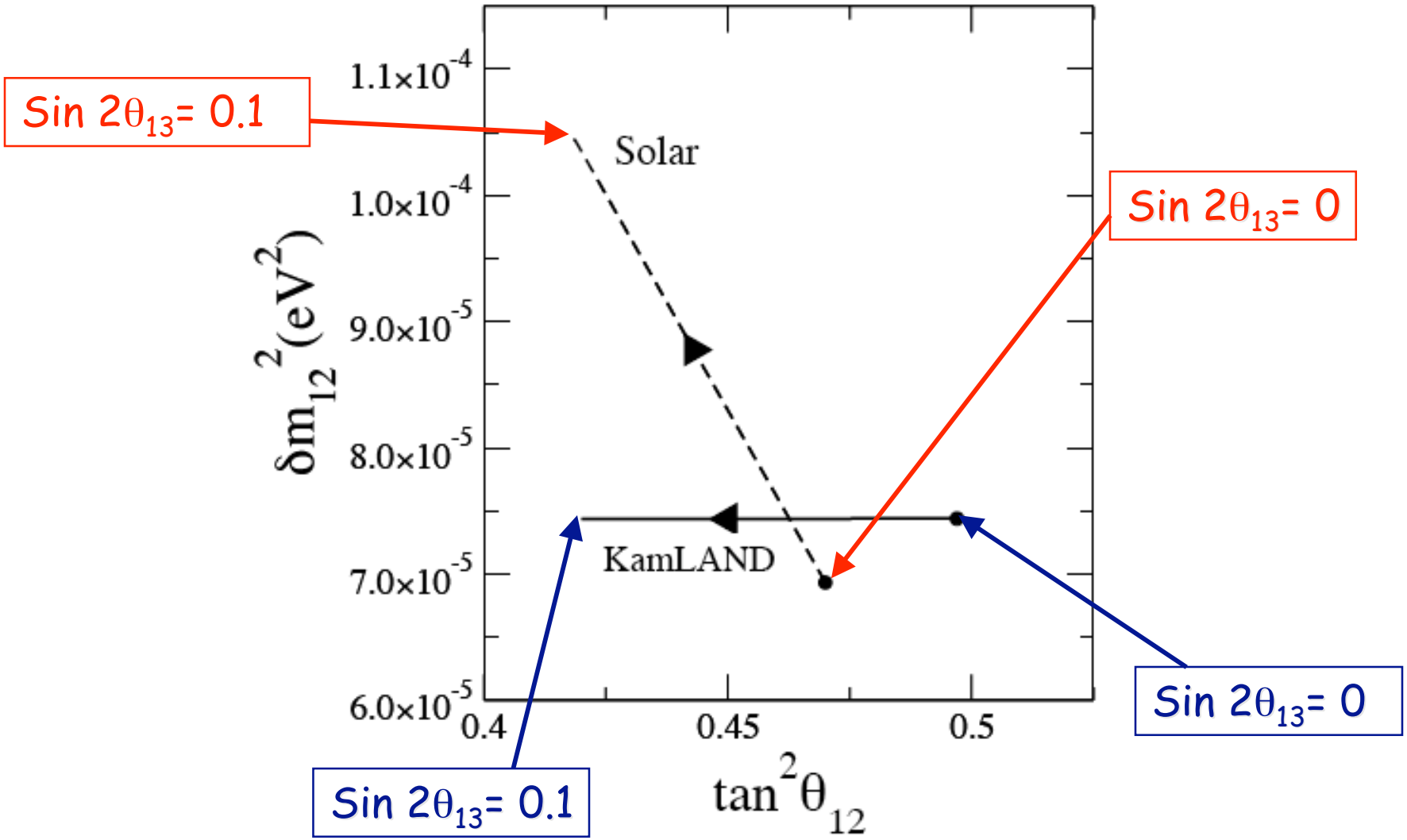
Joint analysis of the solar neutrino data including final SNO salt results and KamLAND data permits a non-zero value of θ_{13}:

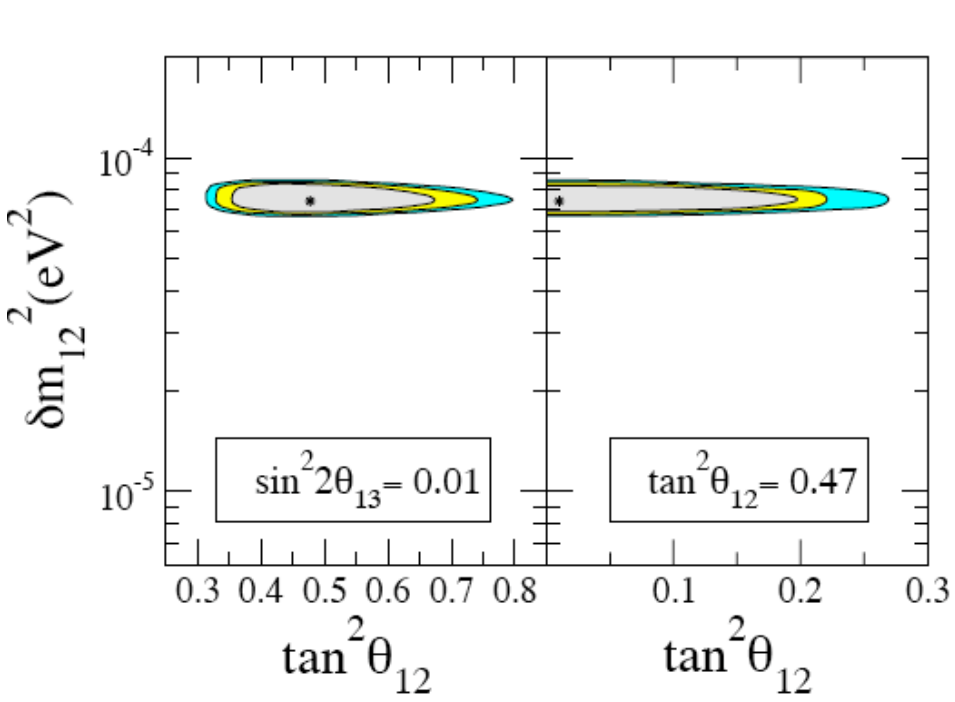
Balantekin, et al., PLB 613, 61 (2005)



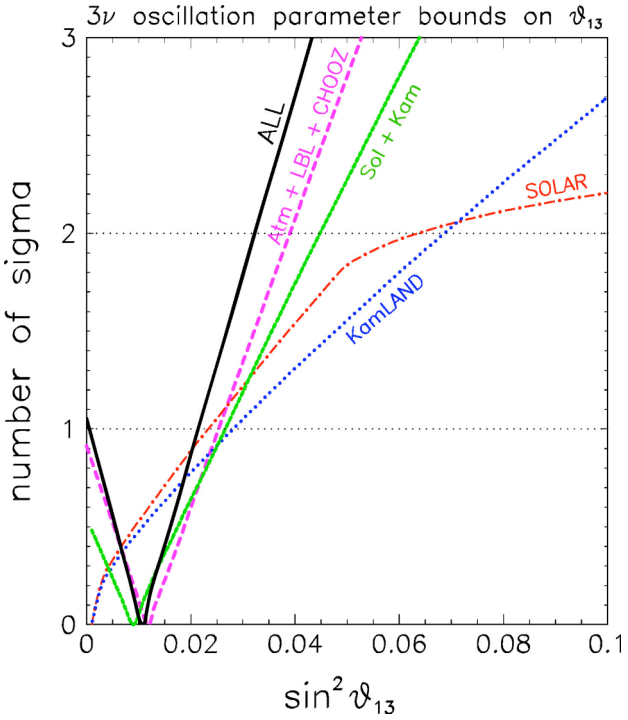
KamLAND and solar best fit values are not the same!
CPT-violation? Other new physics?

….or is it simply ignoring θ_{13} ?



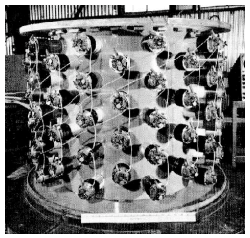


Balantekin & Yilmaz, J. Phys. *G* **35**, 075007 (2008) (arXiv:0804.3345 [hep-ph]).



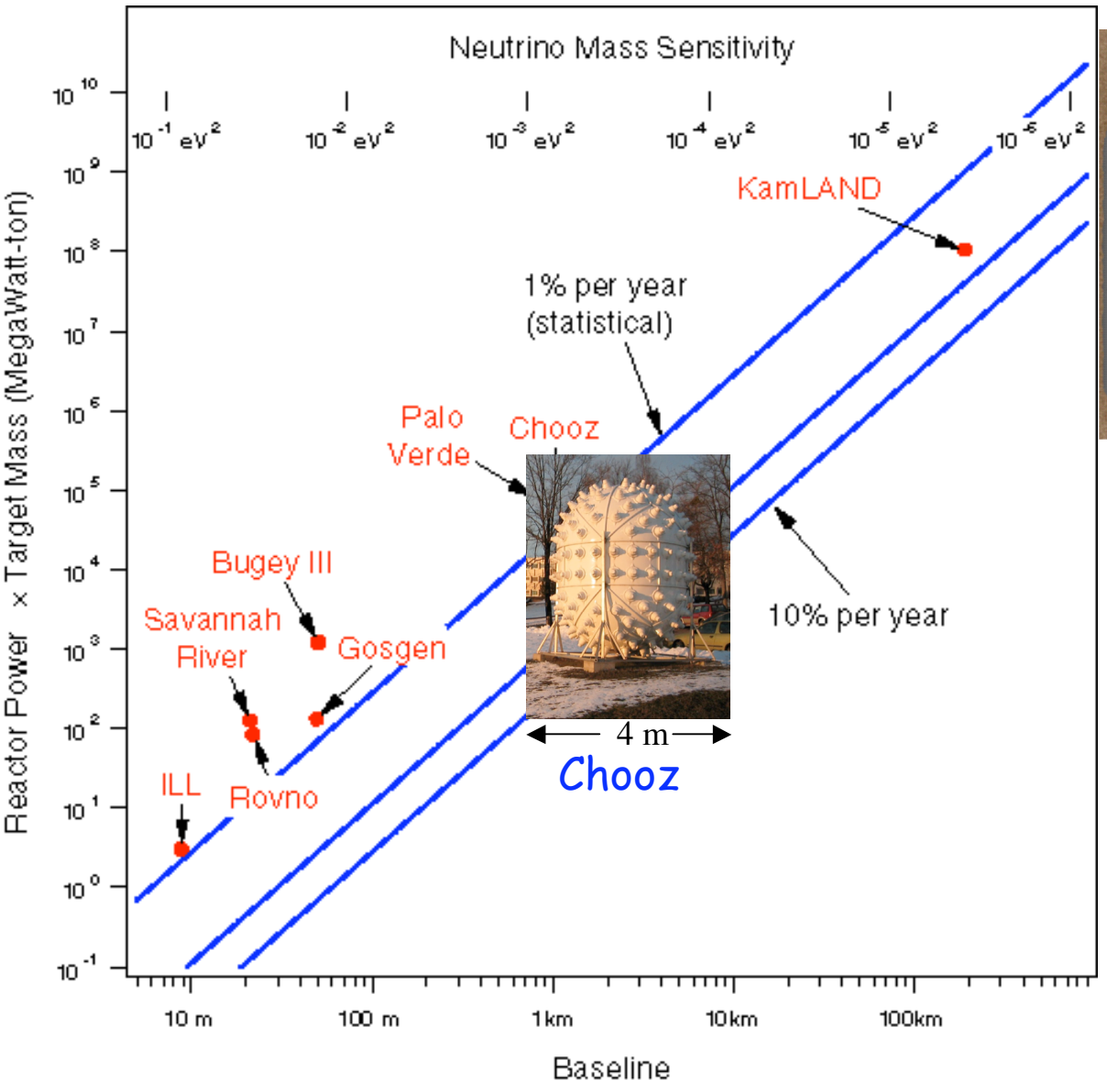
Fogli *et al.*, Venice ν-oscillation workshop(2008) and arXiv:0806.2649 [hep-ph]

Reactor (Anti)neutrino Experiments



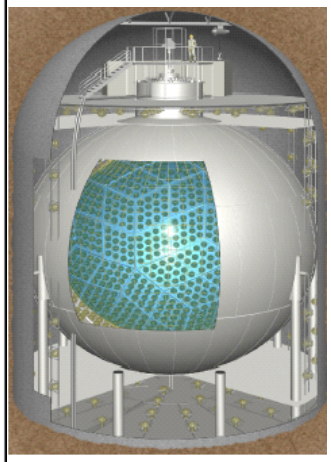
1m

Poltergeist



4 m

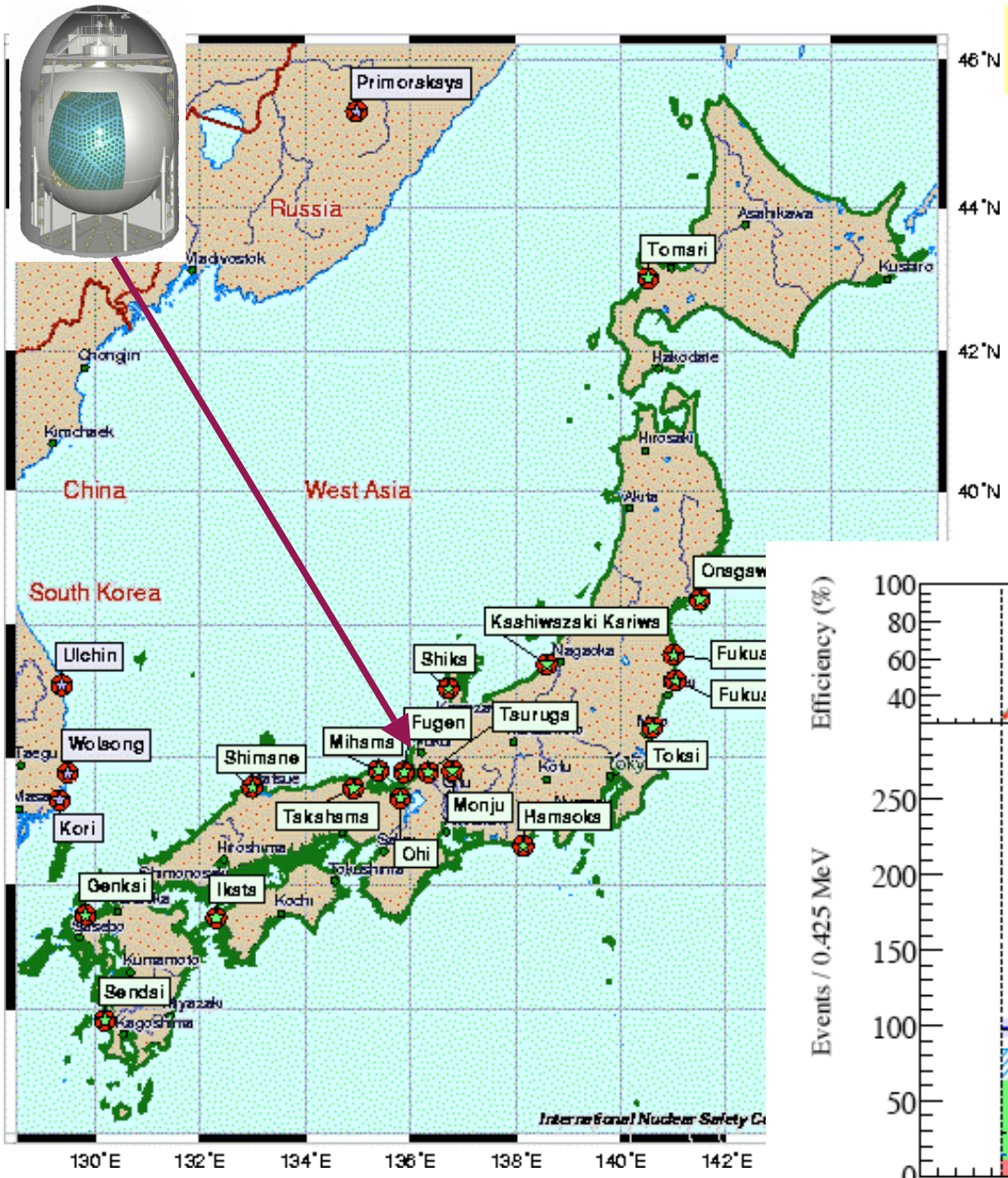
Chooz



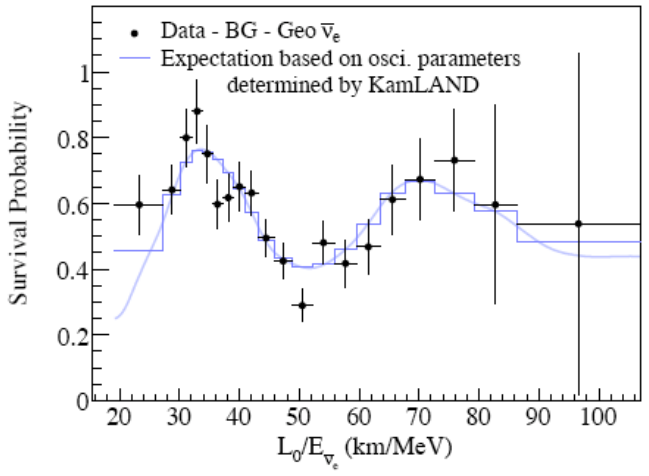
20 m

KamLAND

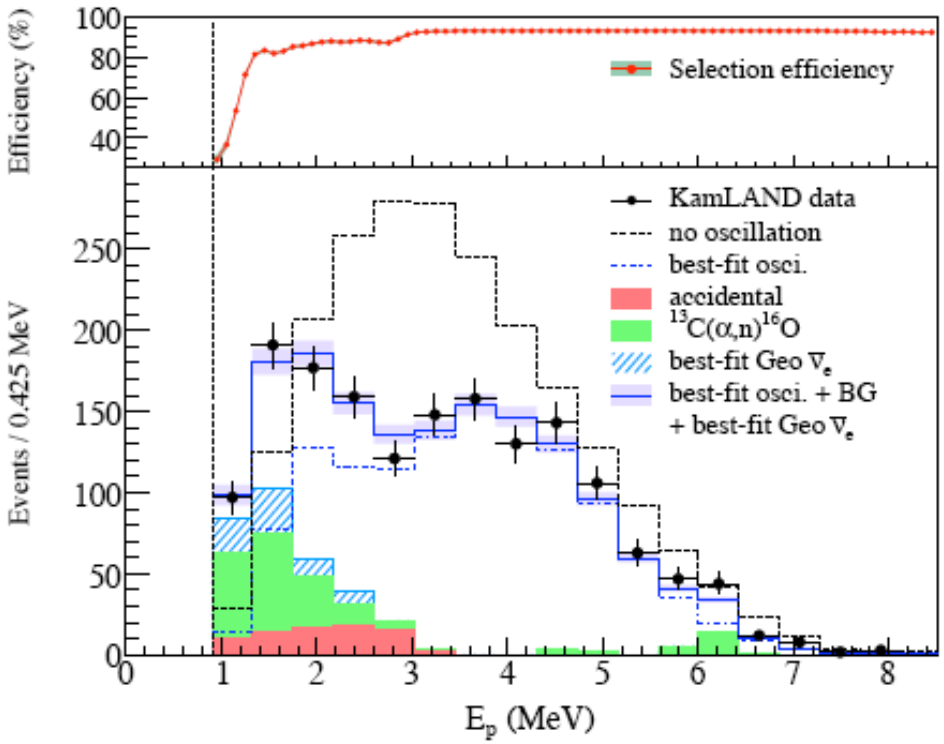
KamLAND



Primorskaya
Russia
Vladivostok
Tomari
Asahikawa
Kushiro
Chongjin
Kimchaek
Hakodate
Hirosaki
Akita
China
West Asia
South Korea
Onagawa
Kashiwazaki Kariwa
Nagaoka
Ulchin
Shika
Fukus
Fugen
Tsuruga
Wolsong
Shimane
Mihama
Toksi
Kotu
Kori
Takahama
Monju
Hamaoka
Ohi
Hiroshima
Genkai
Ikata
Kochi
Kumamoto
Sendai
Kagoshima
International Nuclear Safety C
46°N
44°N
42°N
40°N
130°E
132°E
134°E
136°E
138°E
140°E
142°E

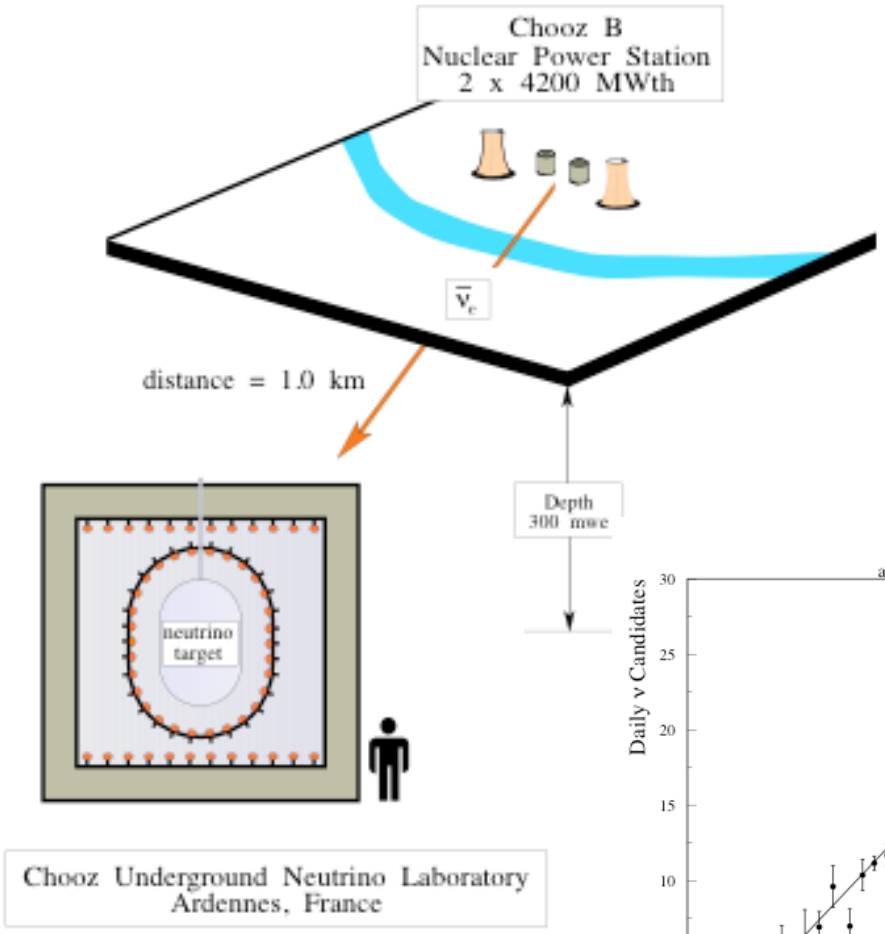


Data - BG - Geo $\bar{\nu}_e$
Expectation based on osci. parameters determined by KamLAND
Survival Probability
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

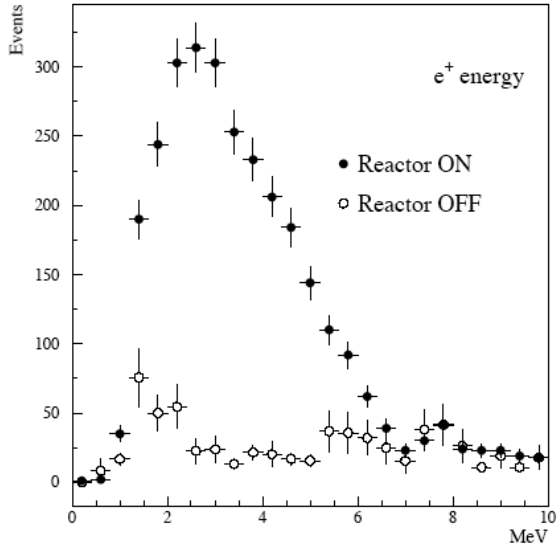


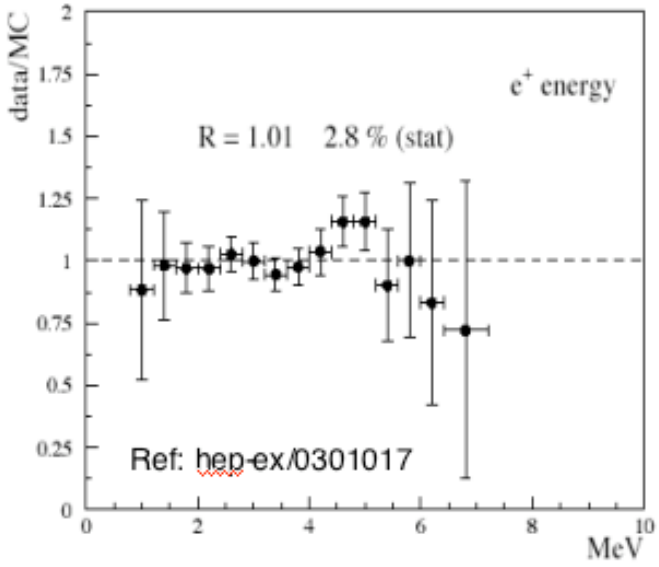
Efficiency (%)
Selection efficiency
KamLAND data
no oscillation
best-fit osci.
accidental
$^{13}C(\alpha,n)^{16}O$
best-fit Geo $\bar{\nu}_e$
best-fit osci. + BG
+ best-fit Geo $\bar{\nu}_e$
Events / 0.425 MeV
E_p (MeV)

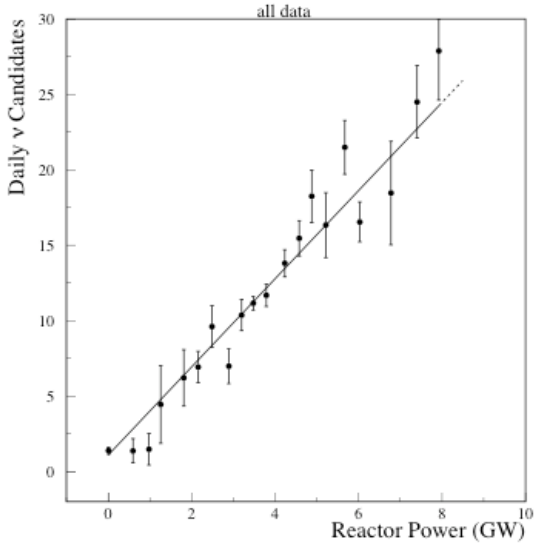
CHOOZ



Chooz Underground Neutrino Laboratory
Ardennes, France



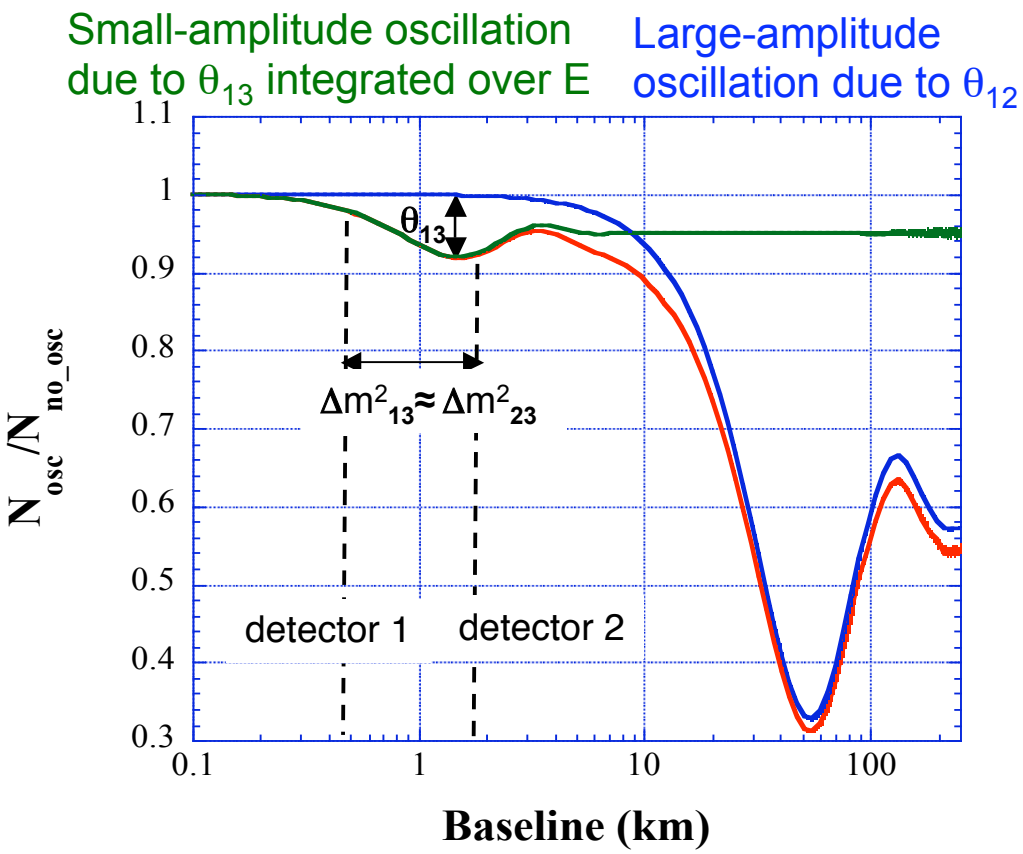




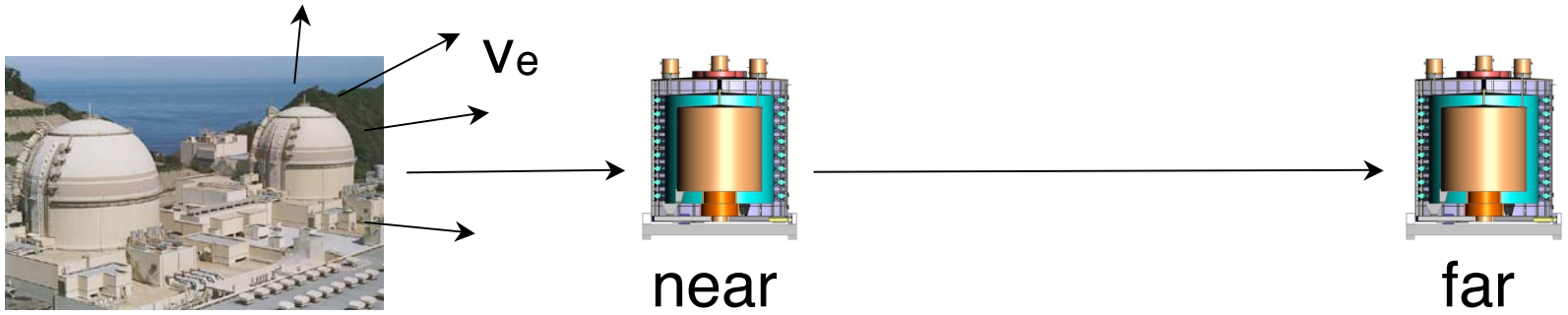
Measuring θ_{13} with Reactor Antineutrinos

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- Reactor neutrino energies are too low to produce muons. Hence this is an antineutrino disappearance experiment (also no matter effects).
- Measure ratio(s) of interaction rates in two or more detectors to cancel systematic errors.
- Those detectors will never be identical, hence one should try to control mass differences, detection efficiencies, etc.



From K. Heeger

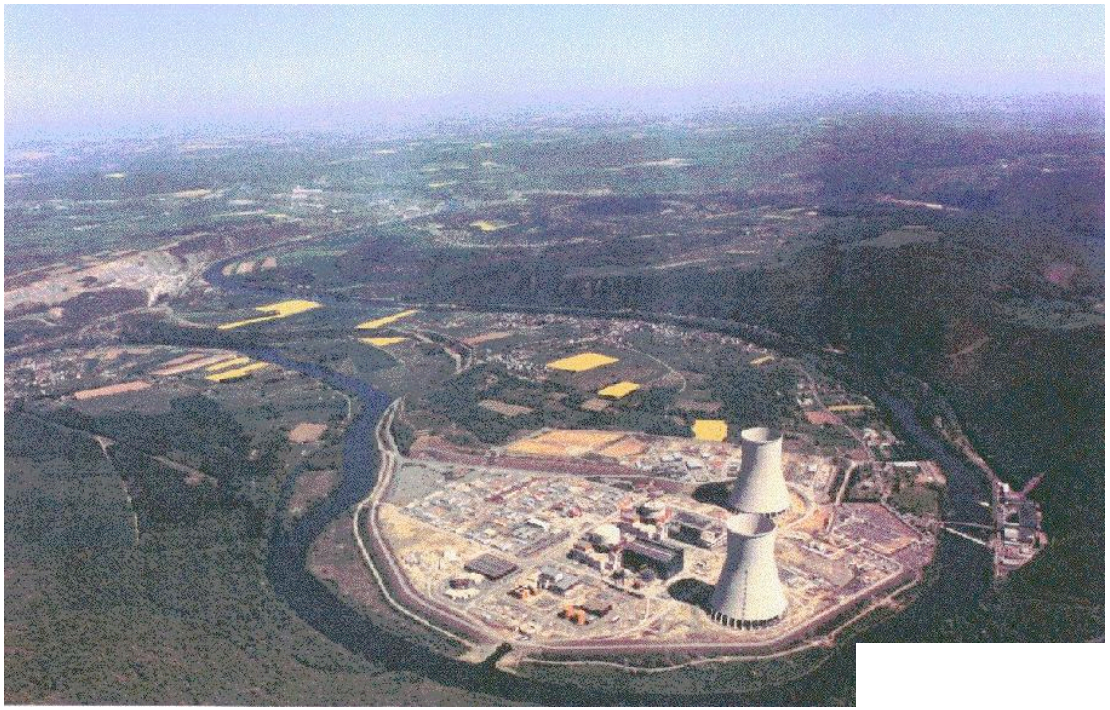


$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

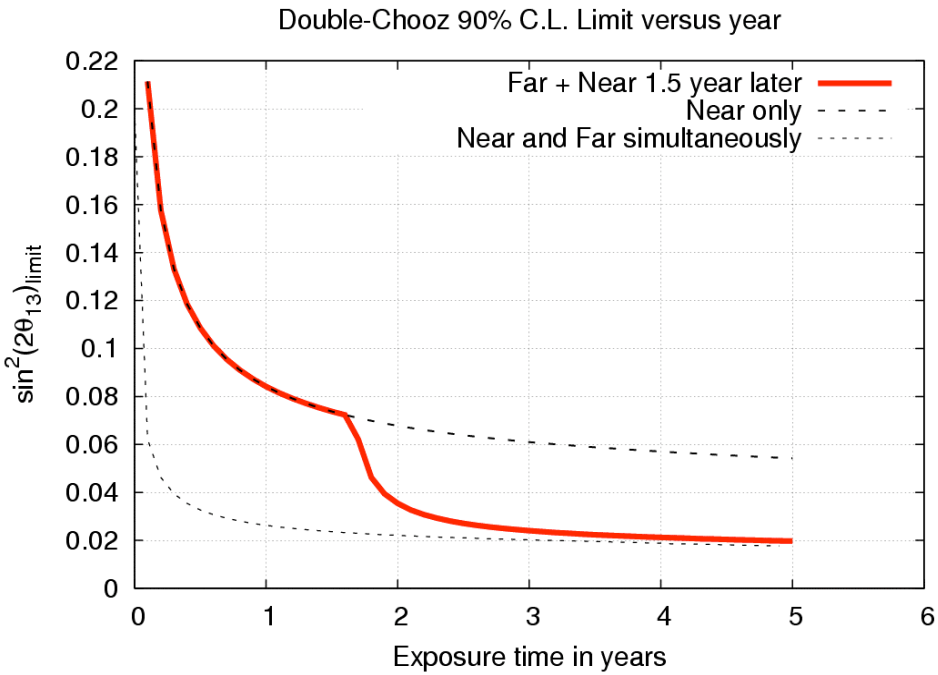
Ratio of detector masses

Ratio of detector efficiencies

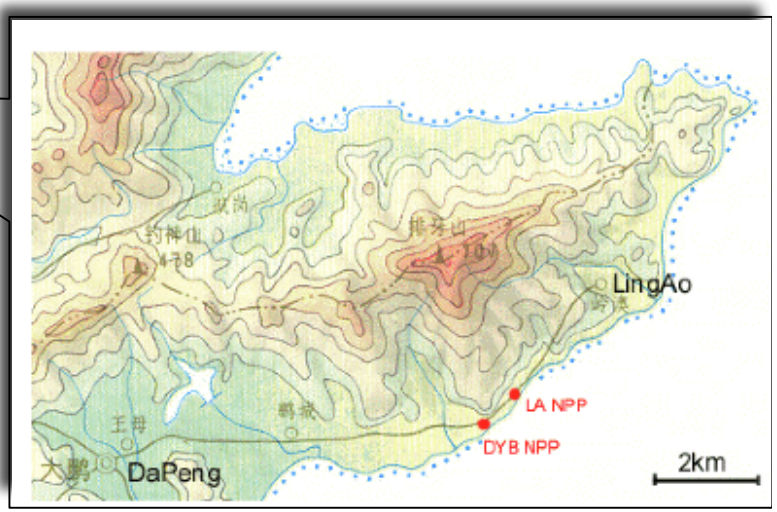
$\sin^2 2\theta_{13}$



Double Chooz



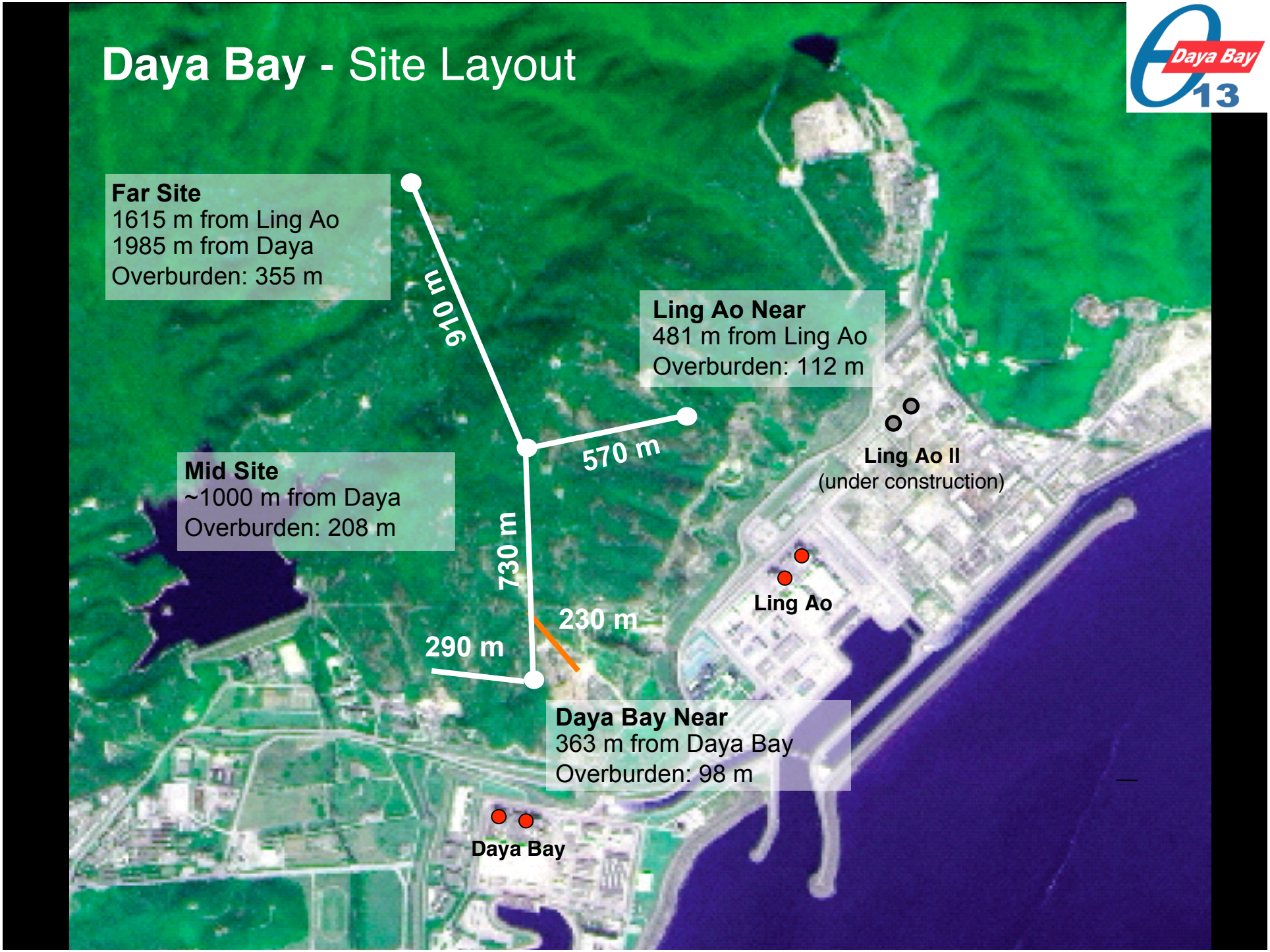
Daya Bay, China

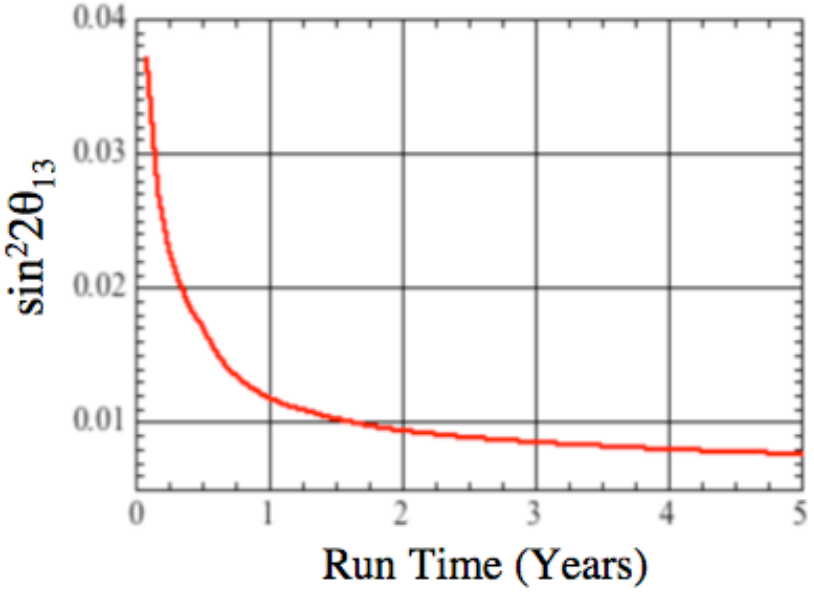


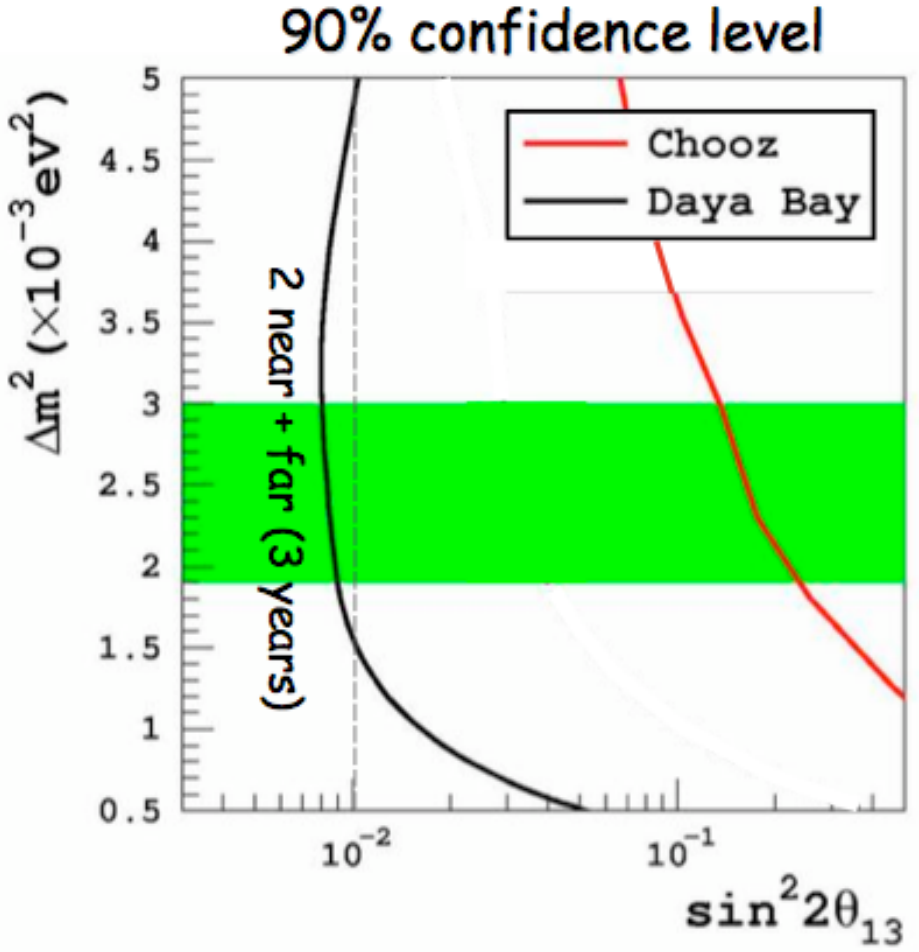
Multiple reactor cores.
(at present 4 units 11.6 $GW_{th,}$ in 2011 6 units with 17.4 GW_{th})

Up to 1000 mwe overburden nearby.
Adjacent to mountains.

http://dayawane.ihep.ac.cn/

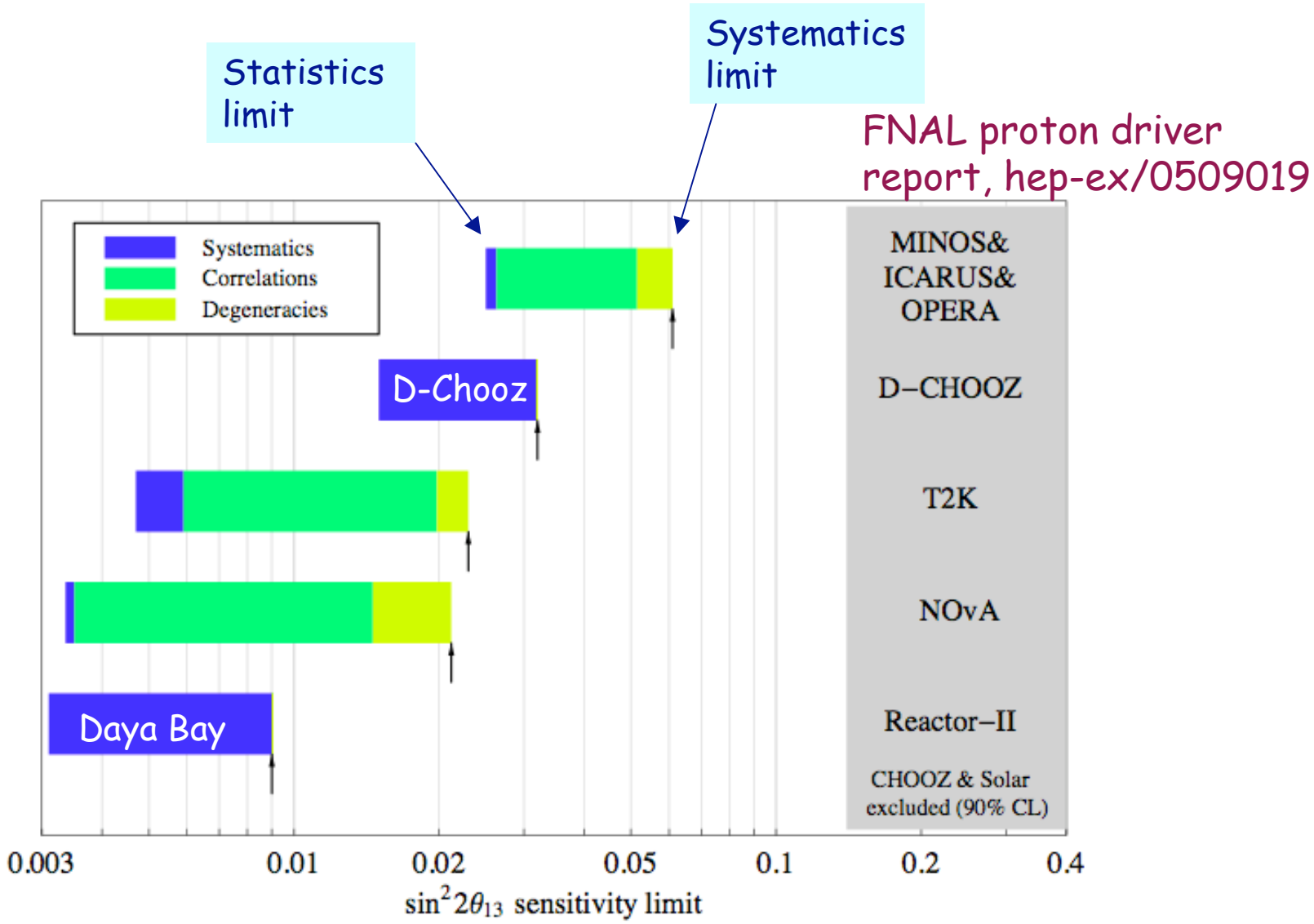

Daya Bay - Site Layout
Far Site
1615 m from Ling Ao
1985 m from Daya
Overburden: 355 m
Ling Ao Near
481 m from Ling Ao
Overburden: 112 m
Mid Site
~1000 m from Daya
Overburden: 208 m
Daya Bay Near
363 m from Daya Bay
Overburden: 98 m
910 m
570 m
730 m
230 m
290 m
Ling Ao II
(under construction)
Ling Ao
Daya Bay


0.04
0.03
0.02
0.01
$\sin^2 2\theta_{13}$
0
1
2
3
4
5
Run Time (Years)


90% confidence level
Chooz
Daya Bay
2 near + far (3 years)
Δm^2 ($\times 10^{-3}$ eV^2)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
10^{-2}
10^{-1}
$\sin^2 2\theta_{13}$

Highlights of recent progress

- DOE CD-3B approval on Aug. 6, 2008.
- Civil construction started blasting on Feb. 19, 2008.
- Daya Bay Ground Breaking Ceremony (Oct. 13, 2007).



$\mathrm{Sin}^2 2\theta_{13}$ sensitivity limits