A new method for a sterile neutrino search

M. Bergevin, UC Davis

Today

Topics of this seminar:

- What are neutrinos and how do we measure them?
- Sterile neutrinos and the reactor neutrino anomaly
- Difficulties in current analysis techniques (the so-called shape anomaly)
- Describe a 2-reactor 1-detector analysis technique that provides a new approach to searching for sterile neutrinos
- Case Study: Double Chooz near detector

Neutrinos: what you need to remember (Cliff notes)

- Neutrinos are produced radioactive decay, nuclear reactions, high energy collision (neutron decay, muon decay, nuclear power operation, cosmic rays hitting the atmosphere, ...)
- We have confirmed there is at least 3 flavors of neutrinos (electron, muon, tau neutrinos)
- These neutrino can oscillate to other flavor of neutrino (electron neutrino can go to muon neutrino), this oscillation is a function of distance traveled over the energy of the neutrino (***L*/*E***)
- There are possible hints **from reactor neutrino experiments** for what are called sterile neutrinos (reactor antineutrino anomaly)

We **measure** low energy neutrinos through Inverse Beta Decay (IMD) and Electron Scattering (ES)

$$\nu_e n \rightarrow p e^- \text{ (IBD)}$$

$$\bar{\nu}_e p \rightarrow n e^+ \text{ (IBD)}$$

$$\nu_e e^- \rightarrow \nu_e e^- \text{ (ES)}$$

Neutrinos: they can oscillate from one to the other

Neutrino oscillations are parameterized by the PMNS matrix, U:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix} 1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavor eigenstates | solar – θ_{12} | atmospheric – θ_{23} | reactor – θ_{13} | mass eigenstates

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

Oscillation probability:

$$P(\bar\nu_\alpha \to \bar\nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\,\sin^2(\Delta_{ij}) - 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\,\sin(2\Delta_{ij})$$

where $\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E_\nu}$ and $\Delta m^2_{ij} \equiv m^2_j - m^2_i$

θ_{12} and Δm^2_{12} -> Probed with Solar + KamLAND data

θ_{23} and Δm^2_{23} -> Probed with SuperK, K2K and MINOS data

θ_{13} -> As of Nov. 2011, weak indication of $\theta_{13} \neq 0$ from Chooz, MINOS and T2K

C. Grant

February 3 - 9, 2013 Aspen Center for Physics - Winter Conference: "New Directions in Neutrino Physics" 2

For reactor anti-neutrino detector close to a reactor, this can be boiled down to:

$$P_{ee} = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_{\bar\nu_e}}\right)$$

Neutrino physicist: we live for those anomalies! (e.g.: Solar neutrino anomaly)

0.5 ^{37}Ar per day for 133 ton ^{37}Cl

Expect 8.6 SNU

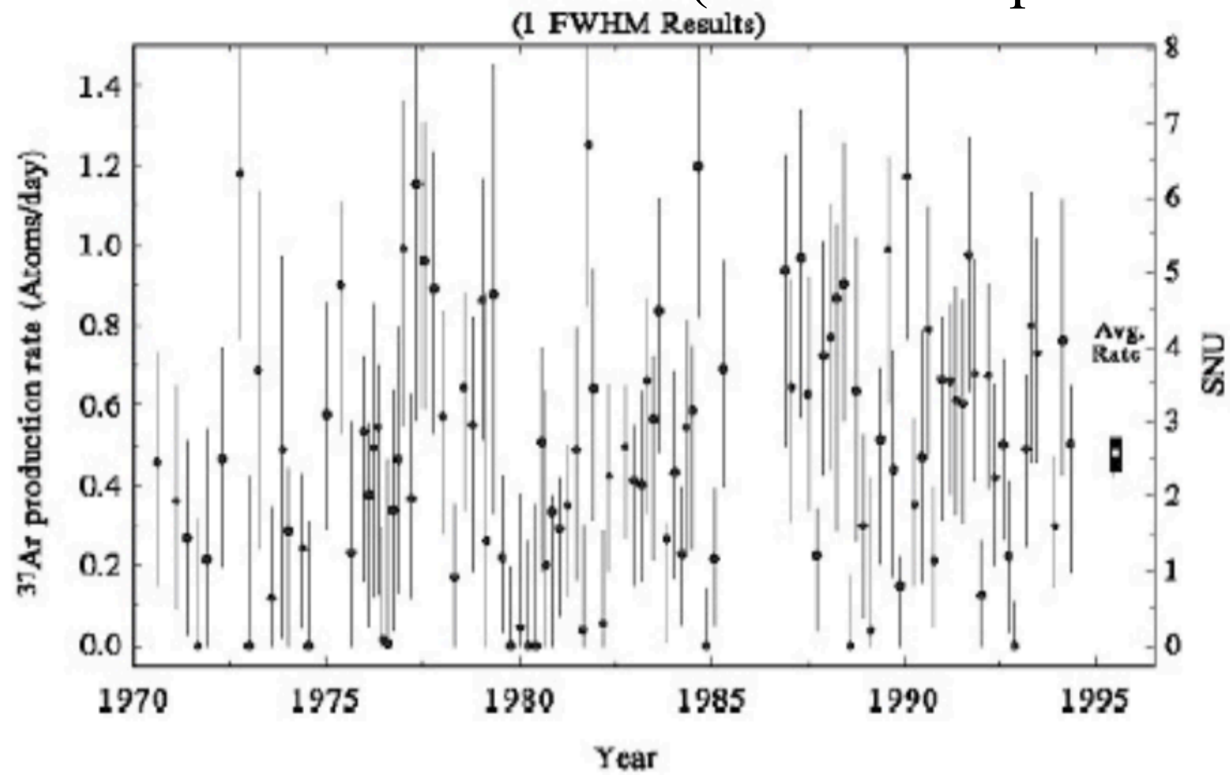
Measure 2.5 SNU

40 year of counting!

$\varphi_{meas} / \varphi_{exp}$ **= 0.301 ± 0.027**

1 SNU = 1 neutrino interaction per second for 10^{36} target atoms

Radiochemical Detectors (Davis Cl experiment)



<u>SuperK neutrino Elastic Scattering measurement</u>

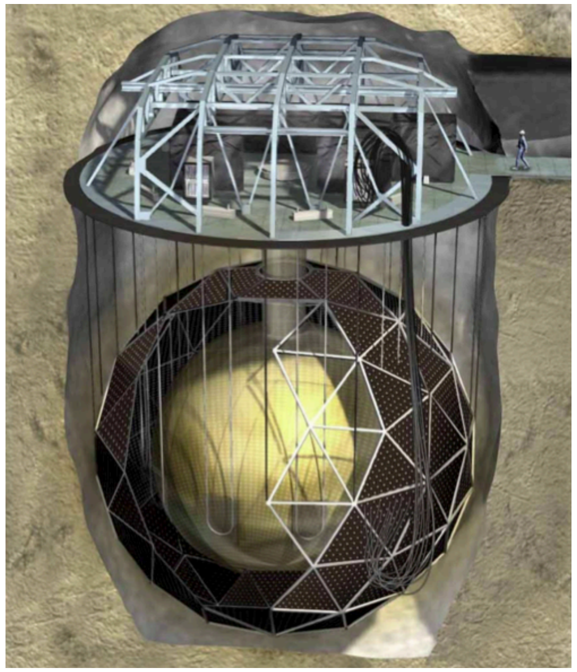
$$\phi_{\mathrm{SK}}^{\mathrm{ES}}(\nu_x) = 2.32 \pm 0.03 \;(\mathrm{stat.})^{+0.08}_{-0.07}\;(\mathrm{sys.}) \times 10^{6}\;\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

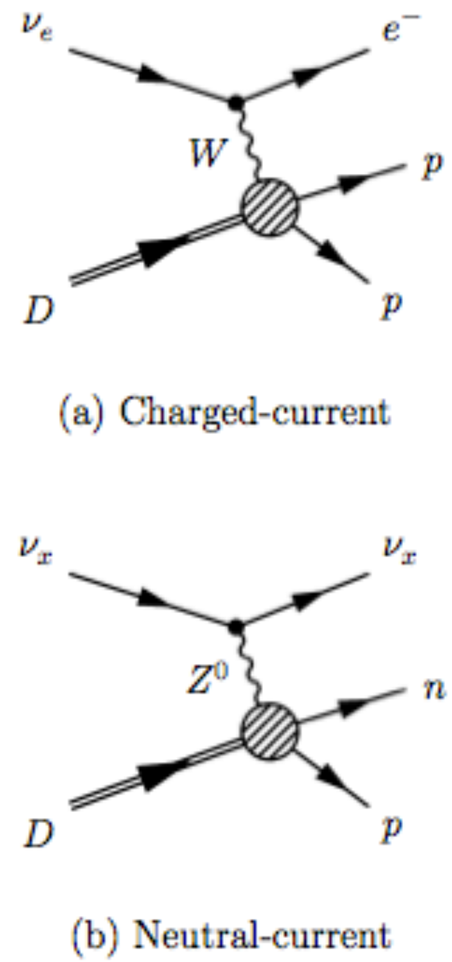
$\varphi_{SK} / \varphi_{solar\ model}$ **= 0.406 ± 0.014**

Hence, the solar neutrino anomaly

How to measure amplitude: $\sin^2(2\theta)$
How we measure solar neutrinos in SNO

One kiloton of D_2O
12 m diameter acrylic
vessel





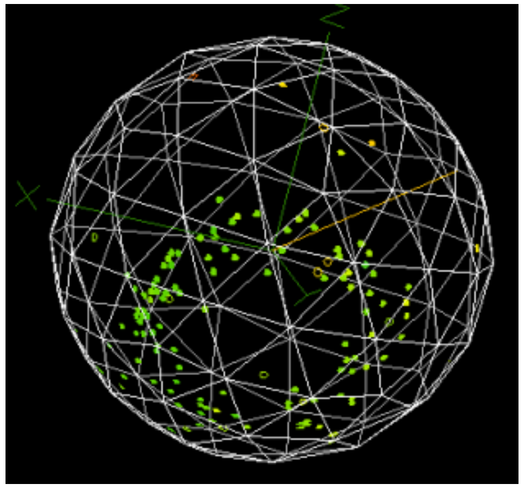
$D = {}^2H = np$

Deuteron is weakly bound together:

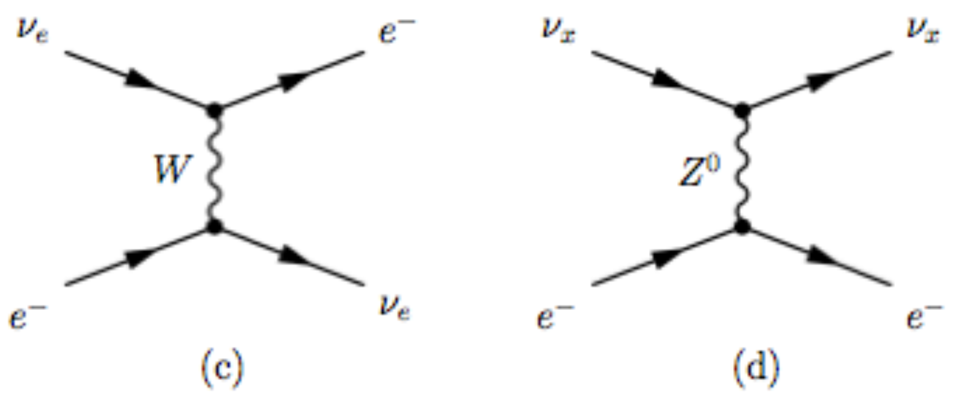
$$\nu_e + d \rightarrow p + p + e^- \text{ (CC)}$$

$$\nu_x + d \rightarrow p + n + \nu_x \text{ (NC)}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \text{ (ES)}$$



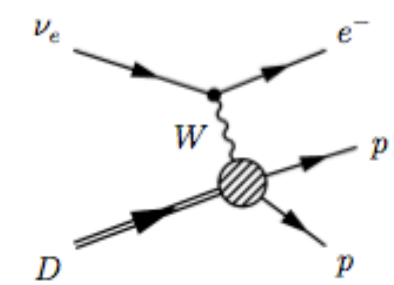
Again, three types of flavor: (electron, muon, tau) neutrino



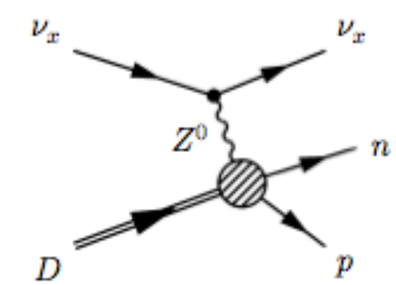
Elastic scattering

How to measure amplitude: $\sin^2(2\theta)$
SNO was able to measure the total rate

Solar neutrino problem solved!



(a) Charged-current



(b) Neutral-current

<u>SNO's first result</u>

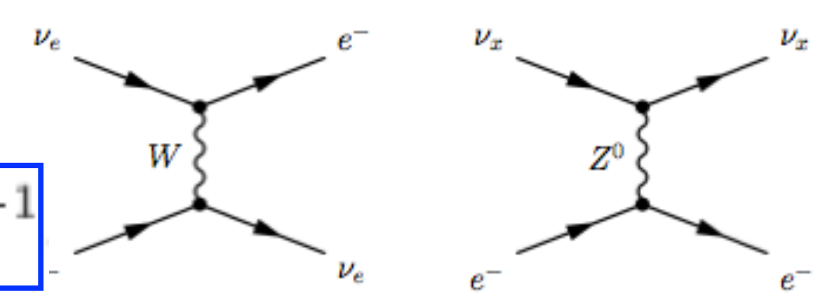
$$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$

$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(\text{stat.})^{+0.12}_{-0.12}\ (\text{syst.})$$

$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(\text{stat.})^{+0.46}_{-0.43}\ (\text{syst.}).$$

<u>SNO's consistent with SuperK ES measurement</u>

$$\phi_{SK}^{ES}(\nu_x) = 2.32 \pm 0.03\ (\text{stat.})^{+0.08}_{-0.07}\ (\text{sys.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

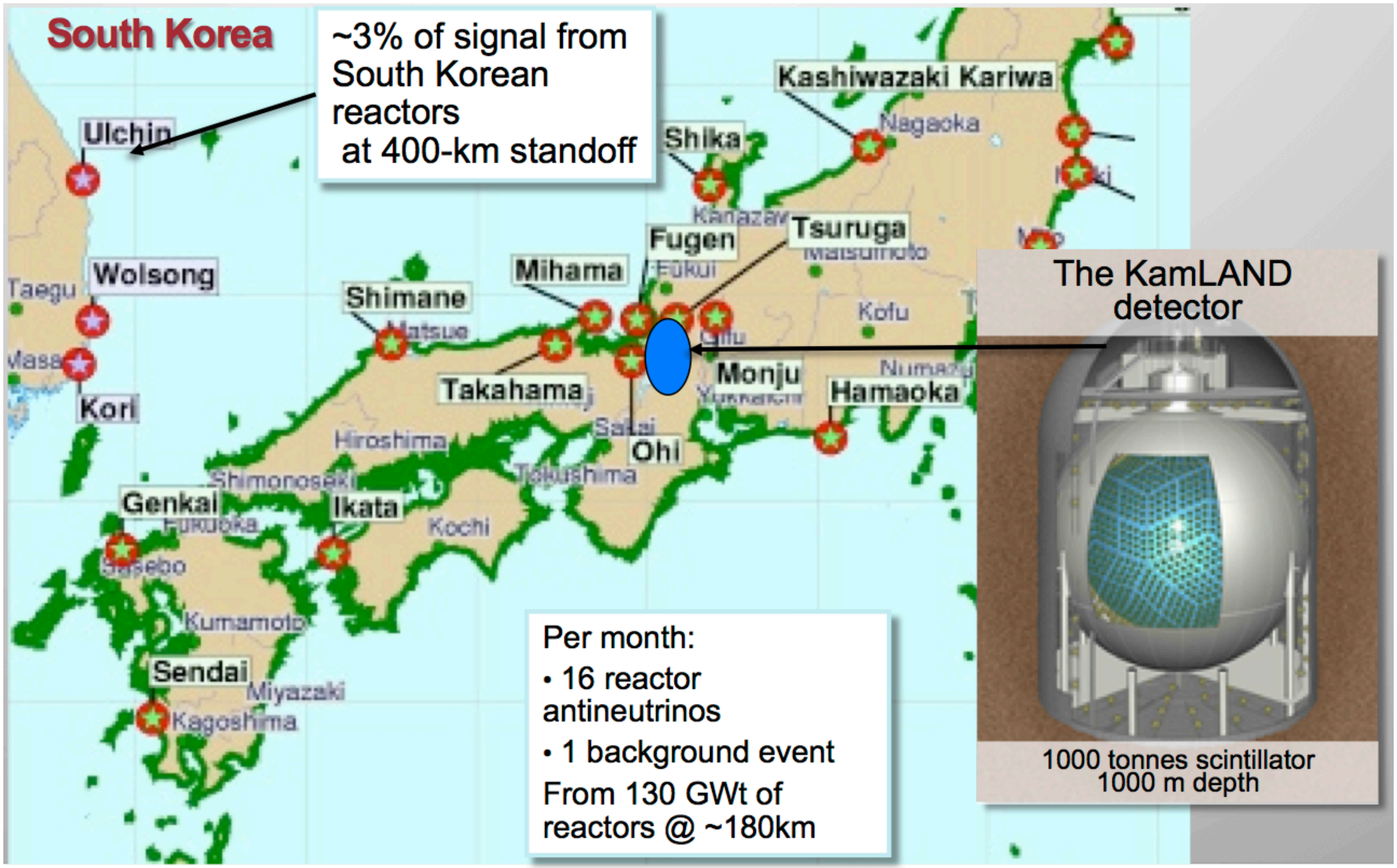


(c) (d)
Elastic scattering

<u>CC/NC is consistent with Chlorine experiment!</u>

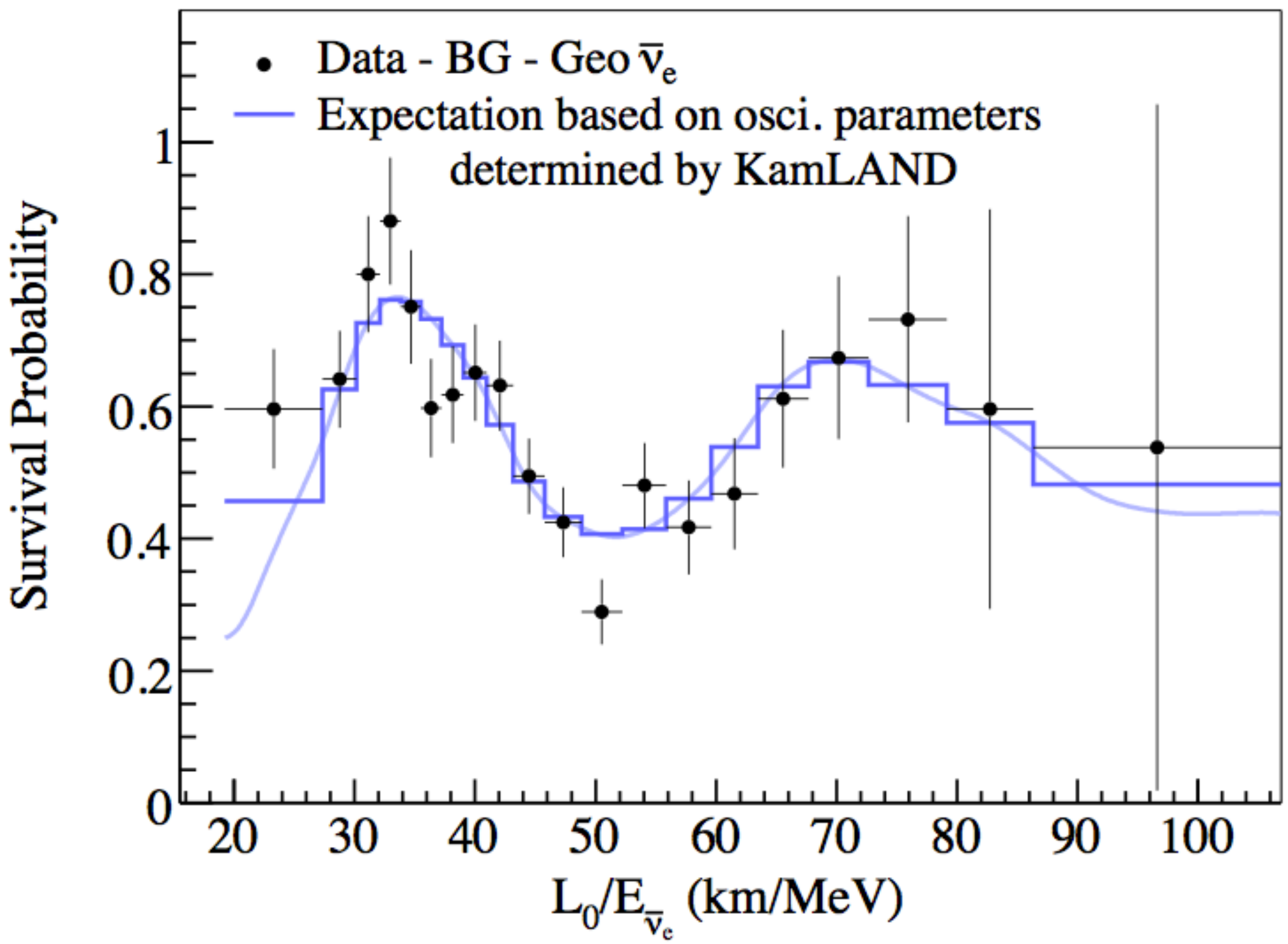
$\phi_{CC}/\phi_{NC} = 0.301 \pm 0.033(total)$ $\qquad$ $\varphi_{Cl}/\varphi_{solar\ model} = 0.301 \pm 0.027$

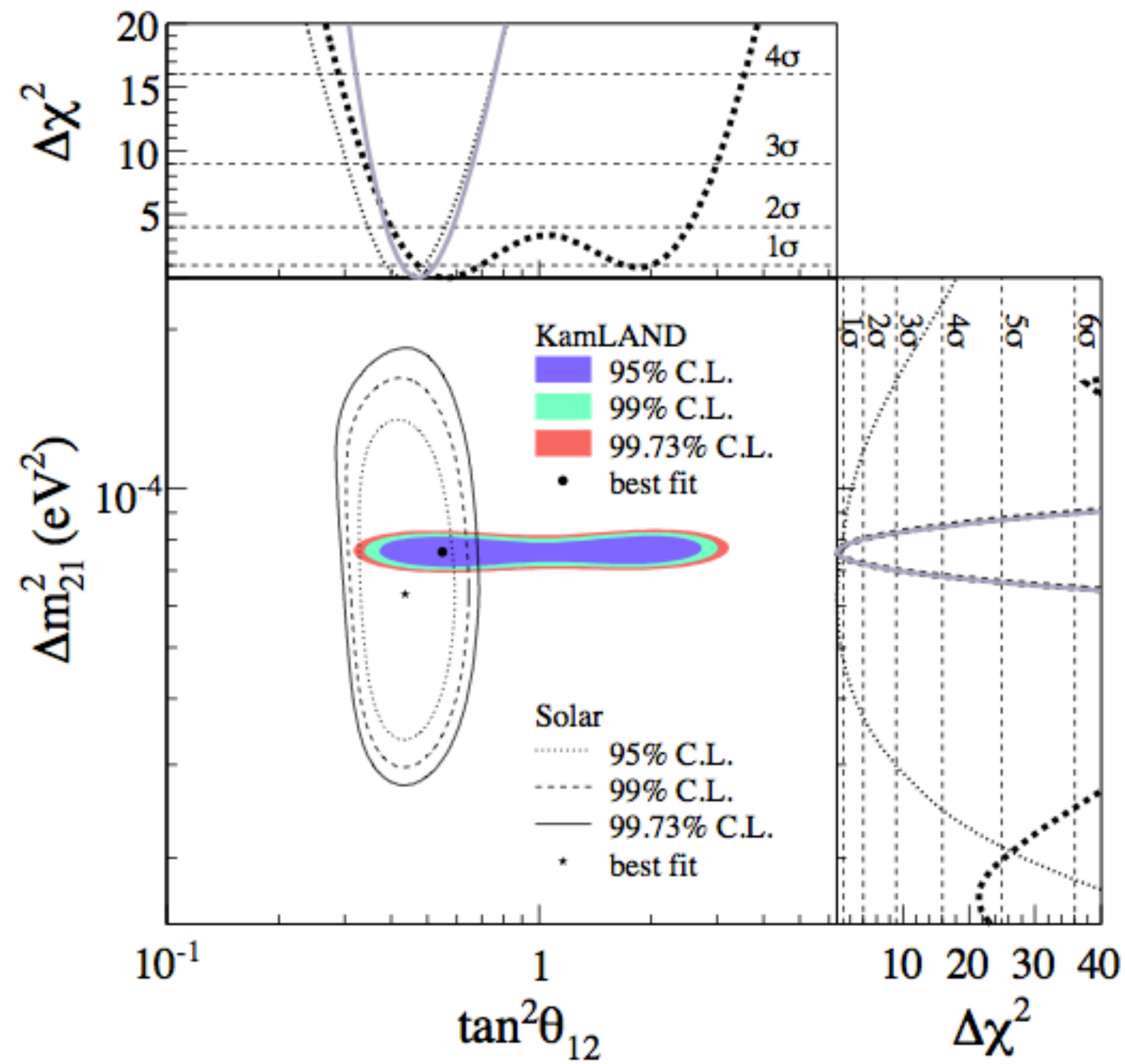
How to measure frequency (Δm^2) KamLAND



How to measure frequency (Δm^2) KamLAND (disappearance experiment)

$$P_{ee} \cong 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_{\bar{\nu}_e}}\right)$$

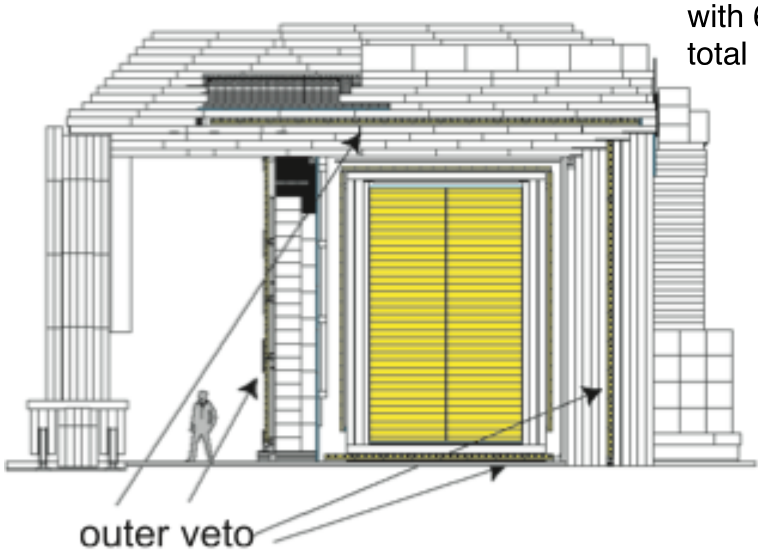




What about appearance experiments? LSND claim (π beam close to rest)

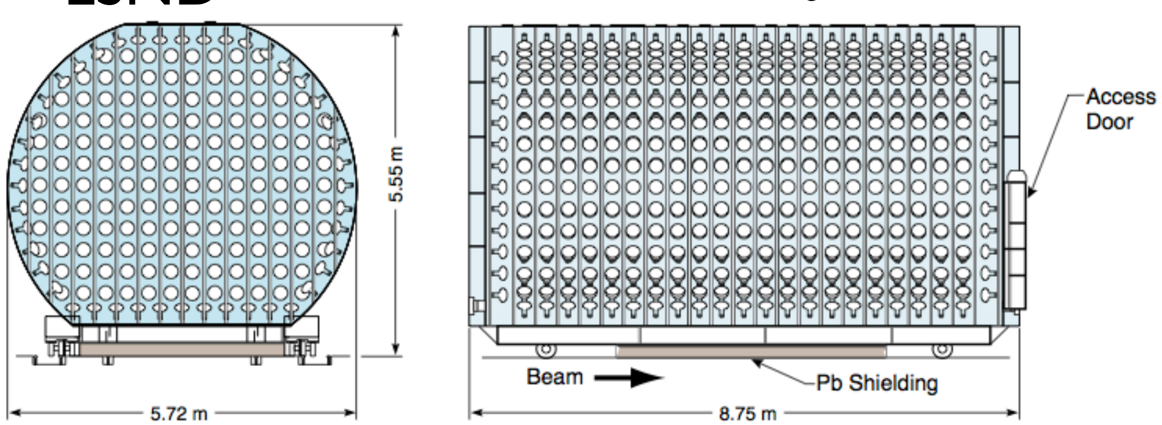
KARMEN

segmented liquid scintillator calorimeter with 608 modules and a total mass of 56 t

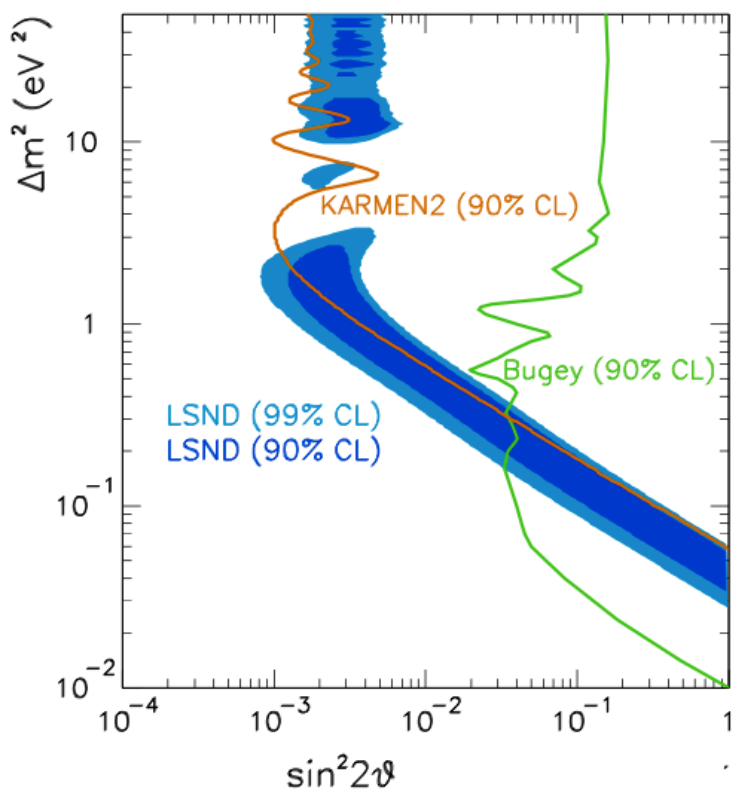


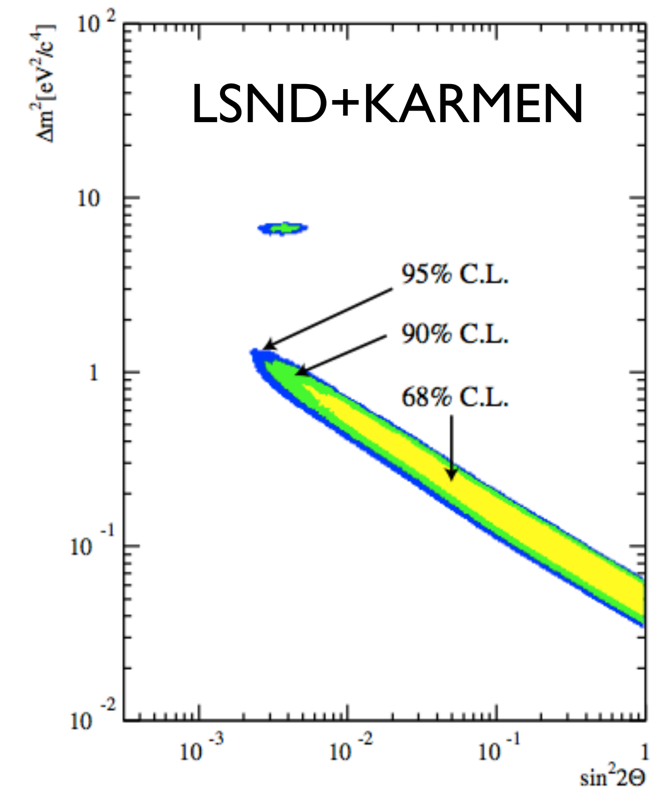
LSND

167 t of liquid scintillator mineral oil and 0.031 g/l of b-PBD



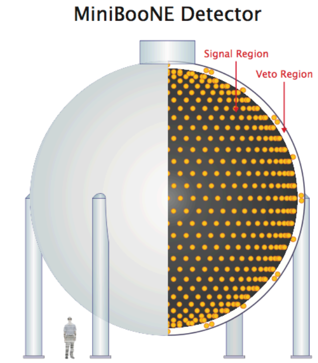
LSND collected 28,896 C on target and observed a 3.8 σ excess of events consistent with $\nu_\mu \to \nu_e$ [P_{osc}= (0.264+/-0.067+/-0.04)]



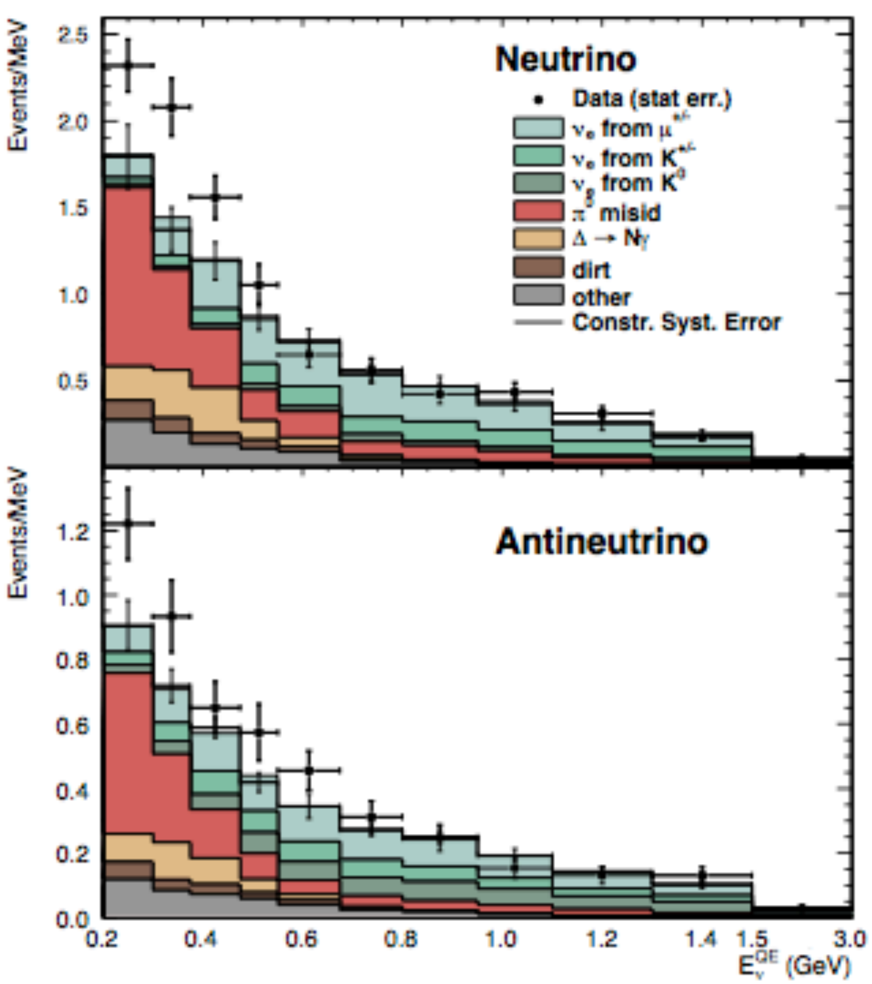


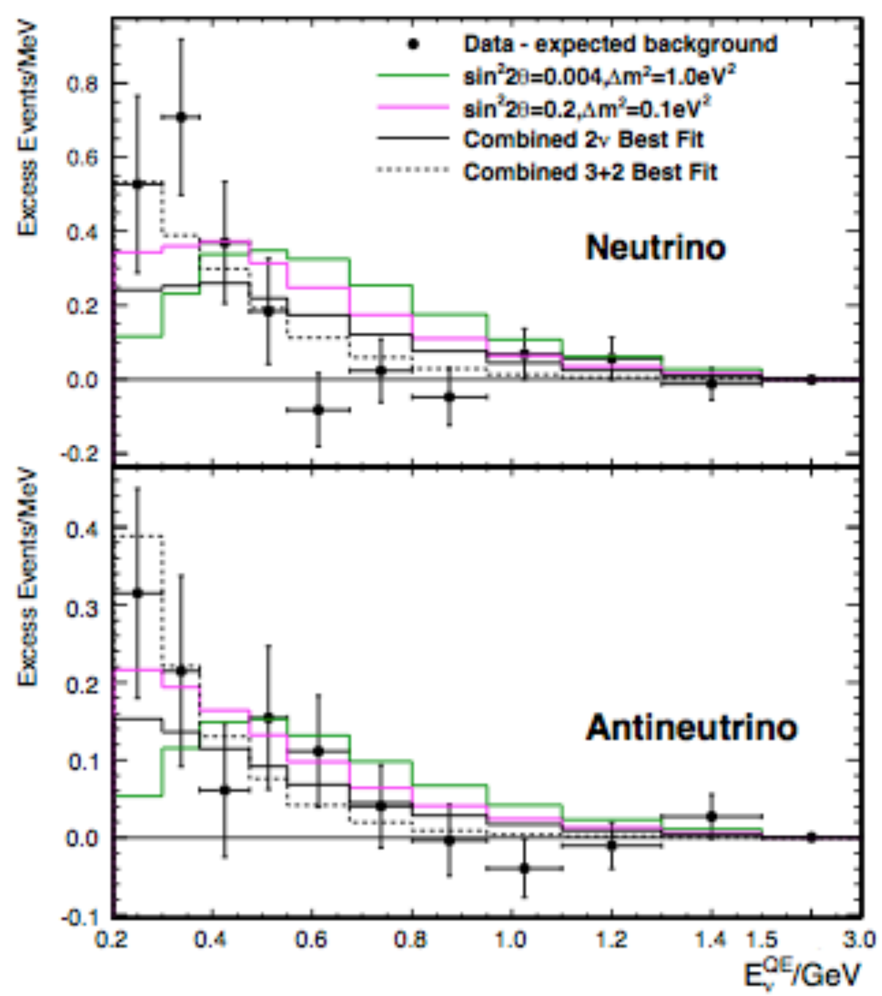
Property	LSND	KARMEN
Proton Energy	798 MeV	800 MeV
Proton Intensity	1000 μA	200 μA
Protons on Target	28,896 C	9425 C
Duty Factor	6×10^{-2}	1×10^{-5}
Total Mass	167 t	56 t
Neutrino Distance	30 m	17.7 m
Particle Identification	YES	NO
Energy Resolution at 50 MeV	6.6%	1.6%
Events for 100% $\bar{\nu}_\mu \to \bar{\nu}_e$ Transmutation	33,300	14,000

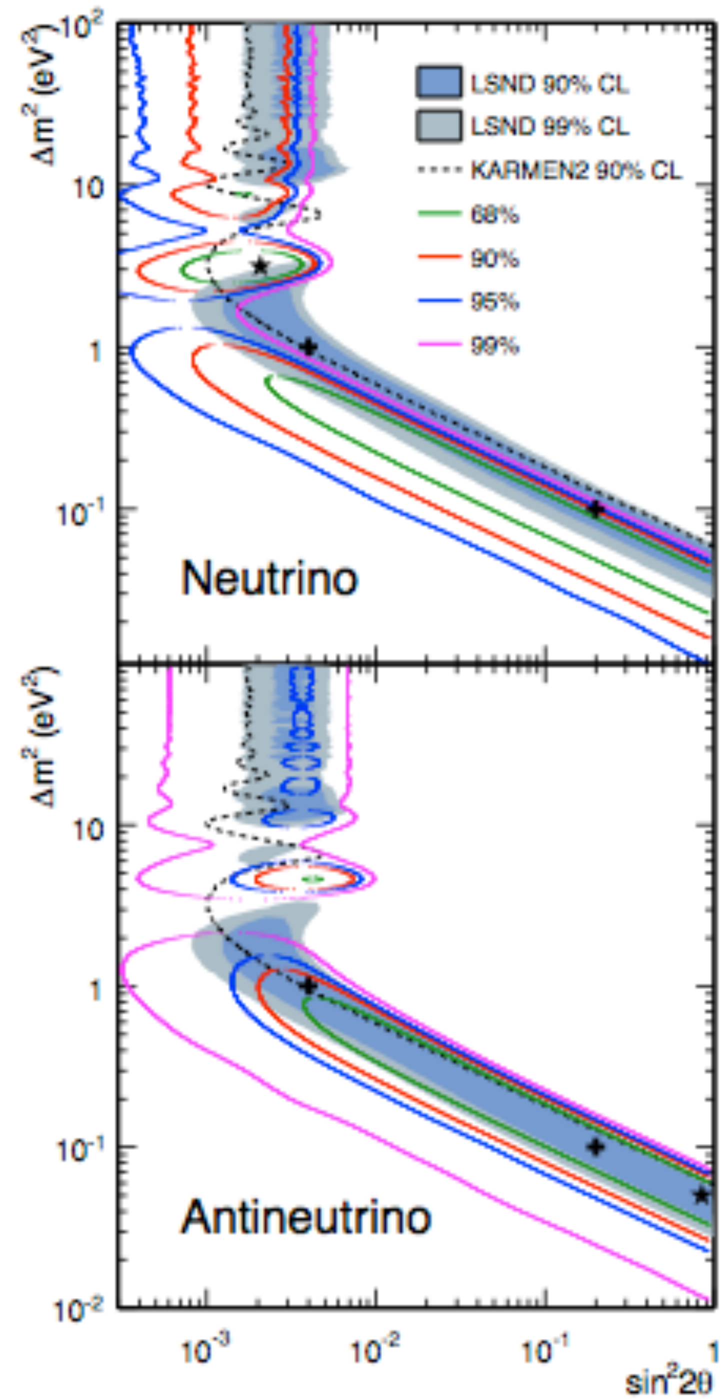
MiniBoone excess



The MiniBooNE experiment at Fermilab reports results from an analysis of the combined ν_e and $\bar{\nu}_e$ appearance data from 6.46×10^{20} protons on target in neutrino mode and 11.27×10^{20} protons on target in antineutrino mode. A total excess of $240.3 \pm 34.5 \pm 52.6$ events (3.8σ) is observed from combining the two data sets in the energy range $200 < E_\nu^{QE} < 1250$ MeV. In a combined fit for CP-conserving $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations via a two-neutrino model, the background-only fit has a χ^2-probability of 0.03% relative to the best oscillation fit. The data are consistent with neutrino oscillations in the $0.01 < \Delta m^2 < 1.0$ eV^2 range and with the evidence for antineutrino oscillations from the Liquid Scintillator Neutrino Detector (LSND).

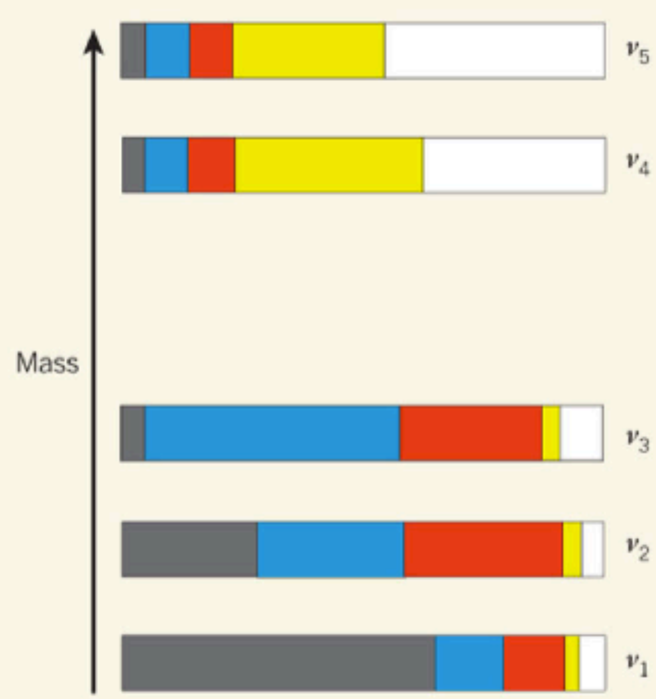






http://arxiv.org/abs/1207.4809v2

Sterile Neutrinos?



N = 2

- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Slide stolen from W. C. Louis
SLAC Intensity Frontier Workshop
March 6, 2

N = 0

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates | solar - θ_{12} | atmospheric - θ_{23} | reactor - θ_{13} | mass eigenstates

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

C. Grant

You mentioned something about a reactor anomaly?

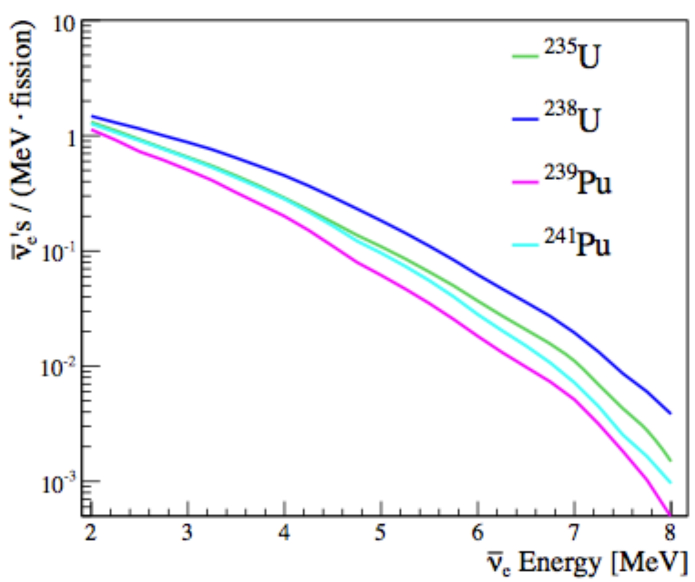
Neutrino: how they are produced in nuclear reactors and measured by detectors?

$\bar{\nu}_e$ Flux Source:

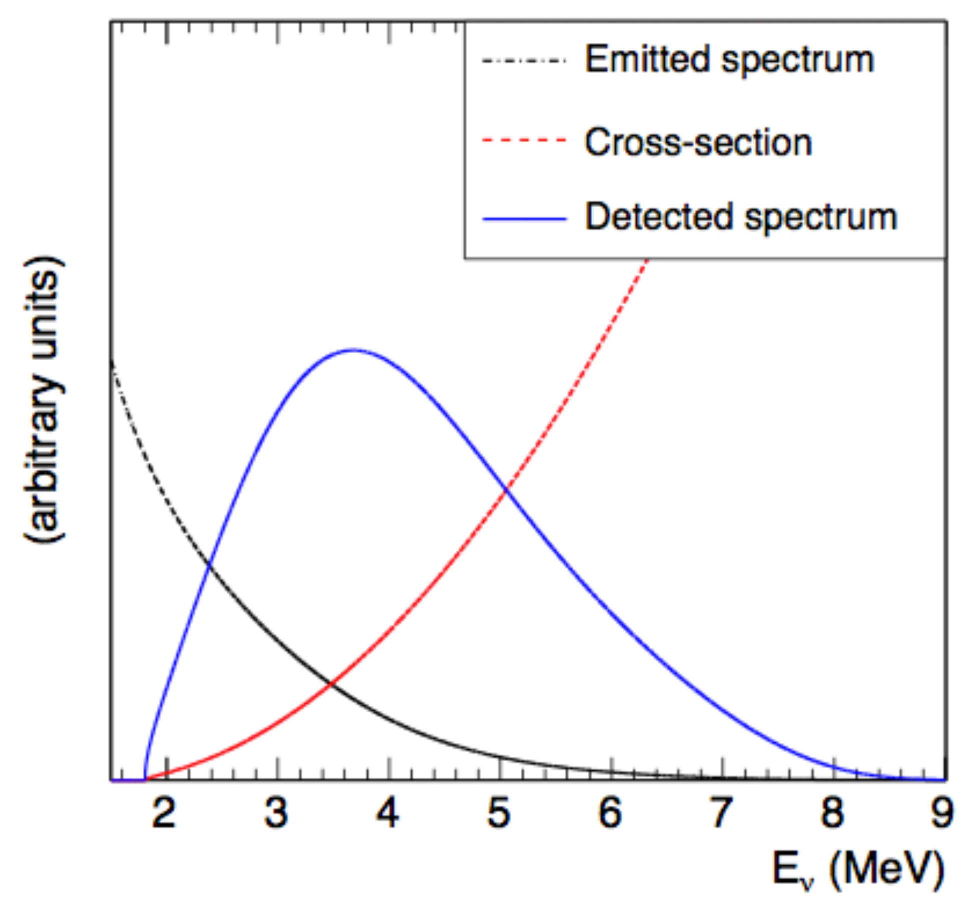
β-decays from neutron-rich fission products in nuclear reactors

- ~ 200 MeV / fission
- ~ 6 anti-nu's / fission
- ~ 2 x 10^{20} anti-nu's / GW_{th}

Data from T. A. Mueller et al., arXiv:1101.2663v3



T. A. Mueller et al., arXiv:1101.2663v3



To calculate fission rates:

Double Chooz uses reactor simulations (MURE and DRAGON) in combination with an anchor point from Bugey4 to minimize systematic uncertainty

C. Grant

What is the reactor anti-neutrino anomaly?

In 2011, re-evaluation of reactor anti-neutrino spectra because
  (a) 3% increased flux of antineutrinos relative to the previous calculations
  (b) experimental neutron lifetime value significantly lower

Previously published experimental result with L< 100 m now show a disappearance not consistent with θ_{13} (could be due to a sterile neutrino oscillation)

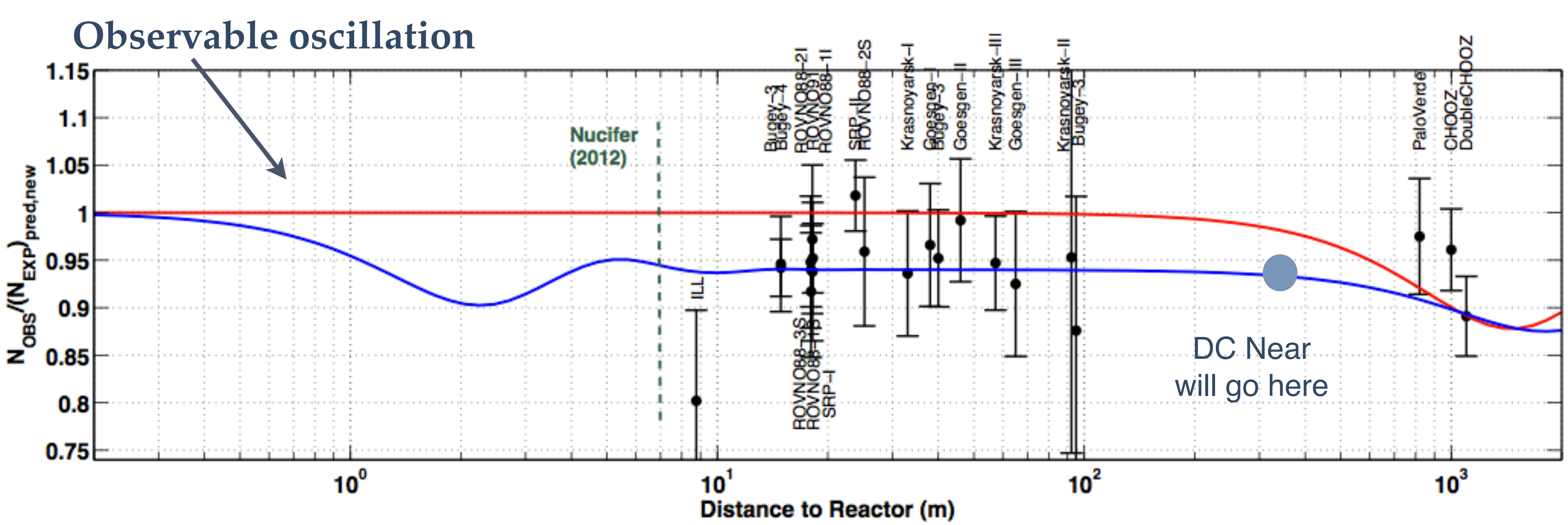
arXiv:1204.5379

What is the reactor anti-neutrino anomaly?

In 2011, re-evaluation of reactor anti-neutrino spectra because
(a) 3% increased flux of antineutrinos relative to the previous calculations
(b) experimental neutron lifetime value significantly lower

Previously published experimental result with L< 100 m now show a disappearance not consistent with θ_{13} (could be due to a sterile neutrino oscillation)

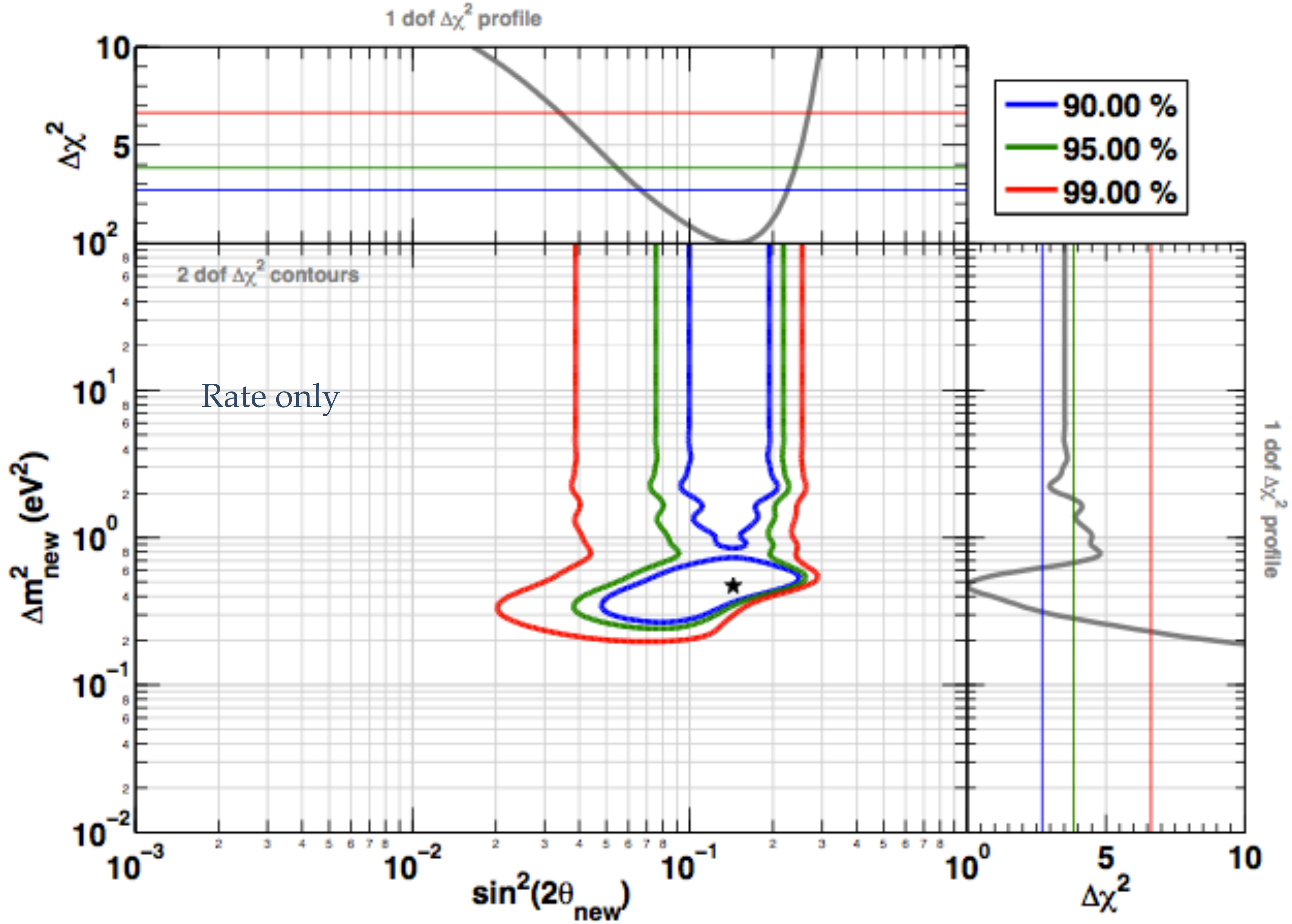
The current reactor experiments probe regions of $\Delta m^2 > 0.3$ eV^2



arXiv:1204.5379

Sterile neutrino allowed mixing parameters for RNA

These different have allowed solutions to the oscillation formula

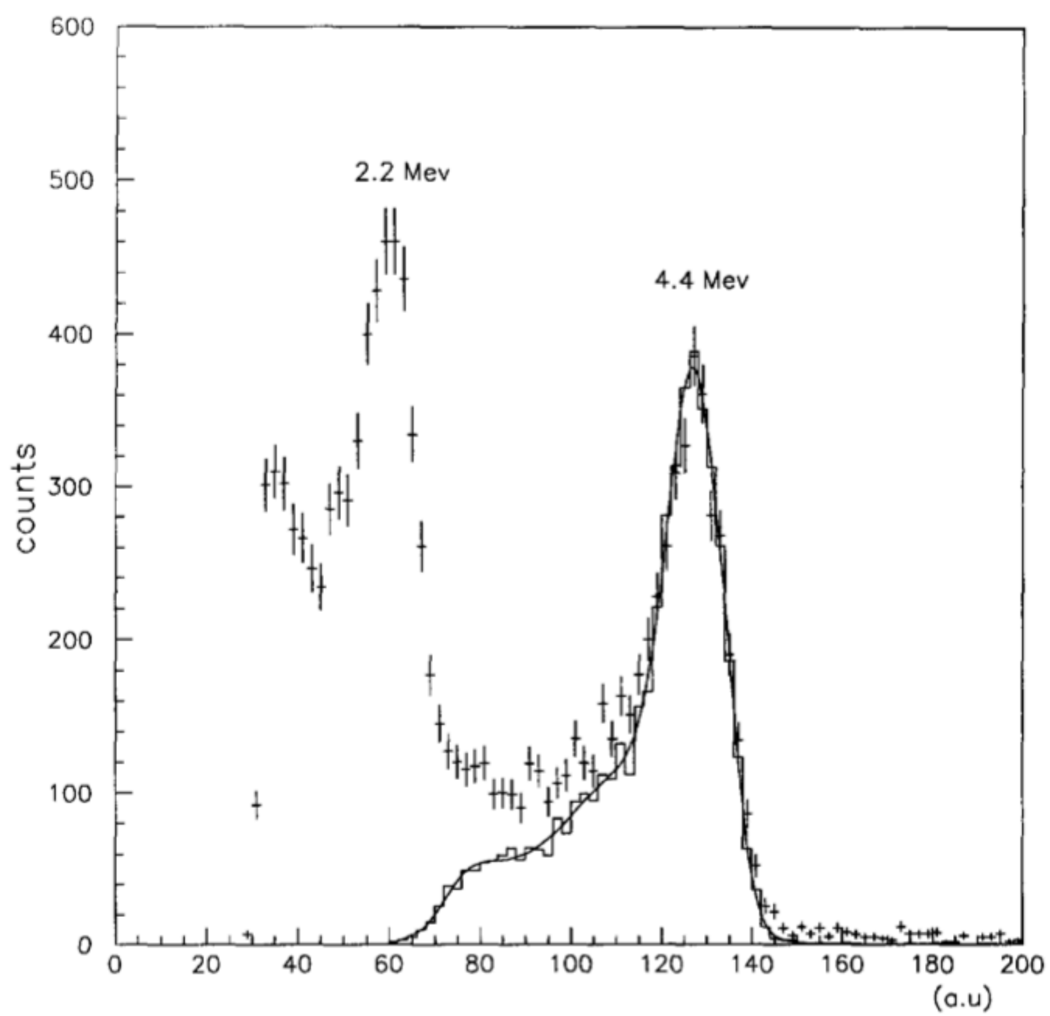


arXiv:1204.5379

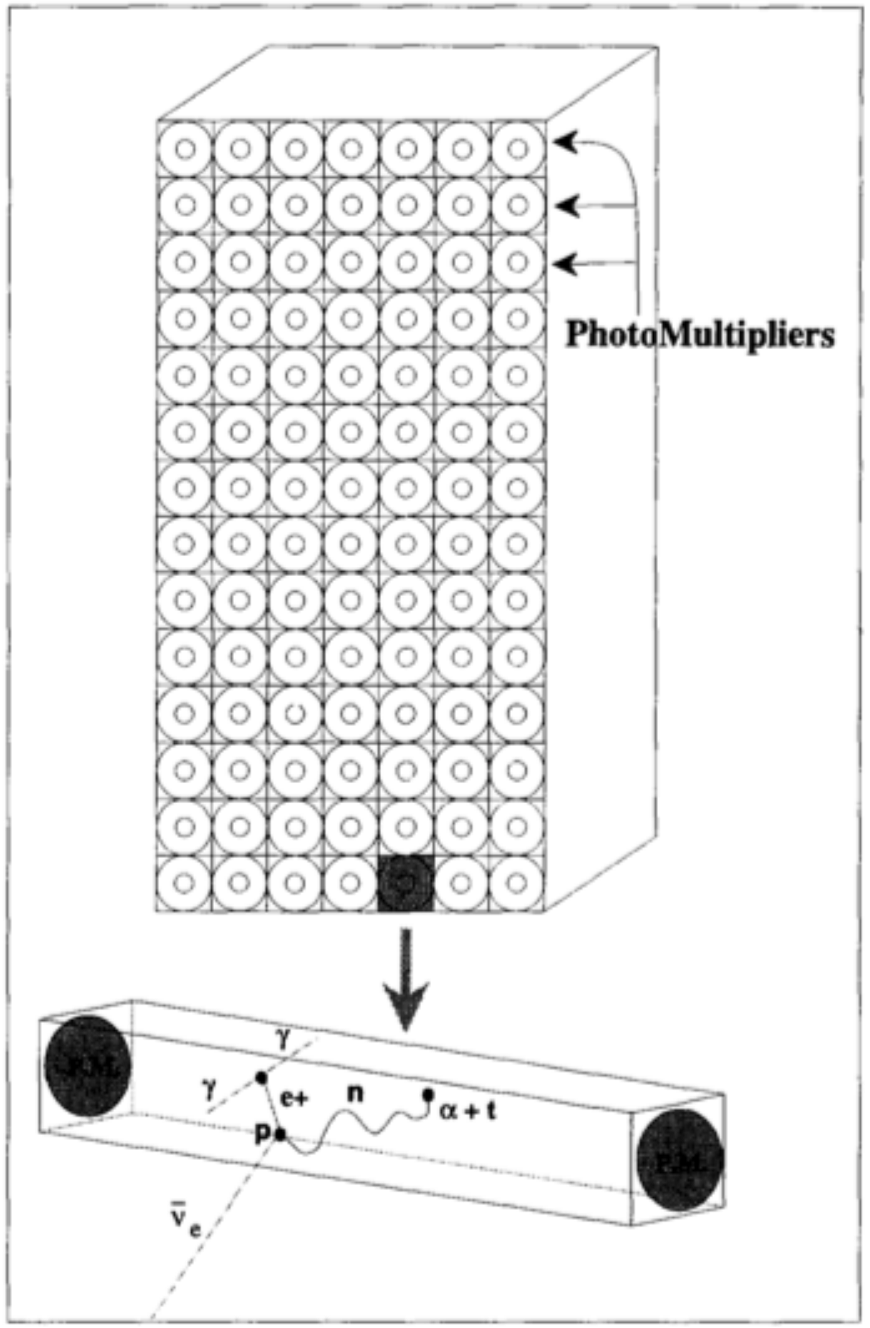
BUGEY-3 measurement of oscillation:

^{6}Li loaded scintillator

$$n + {}^{6}\mathrm{Li} \longrightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H} + 4.8\,\mathrm{MeV}.$$

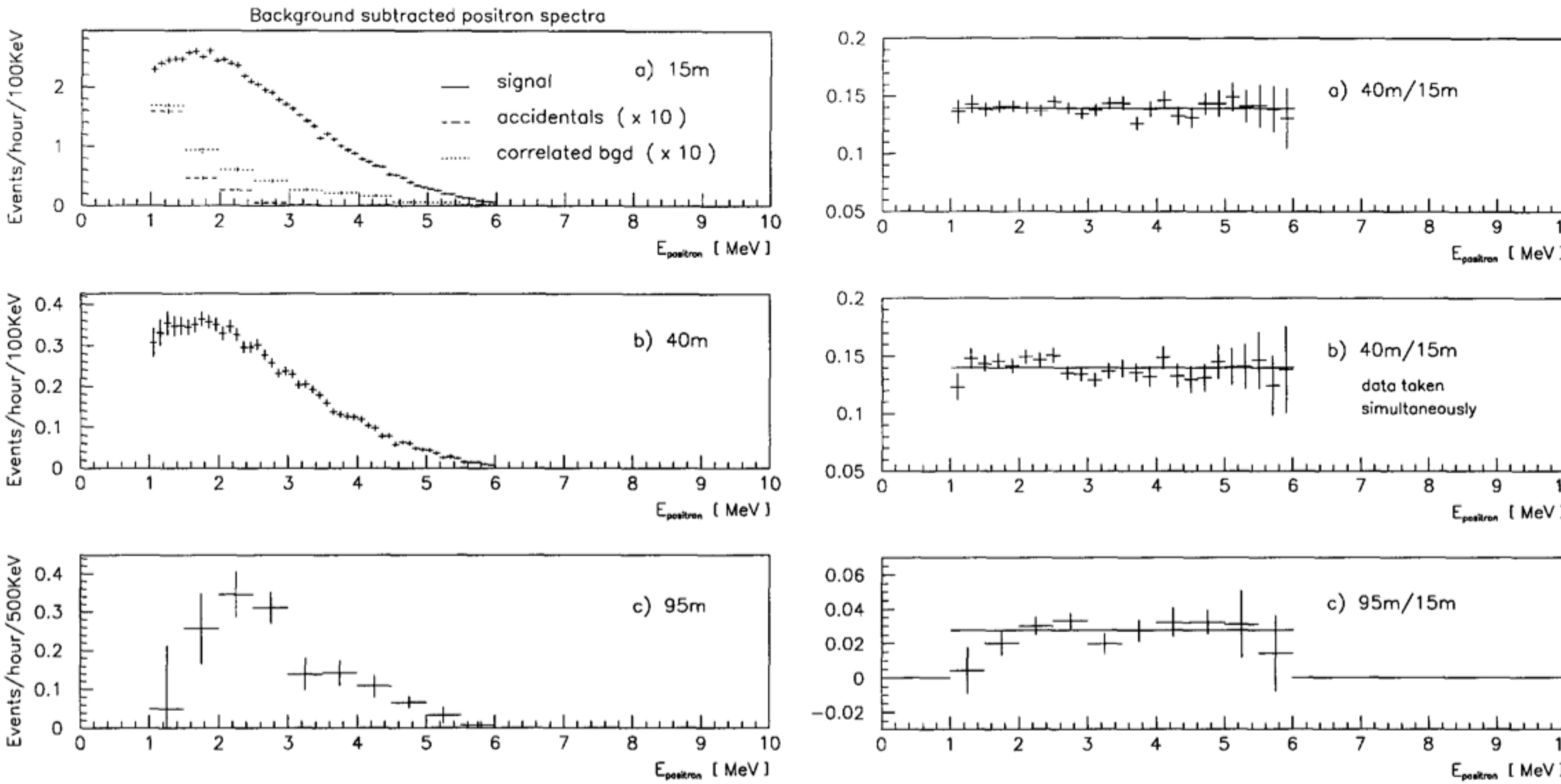


AmBe 4.4 MeV gamma source



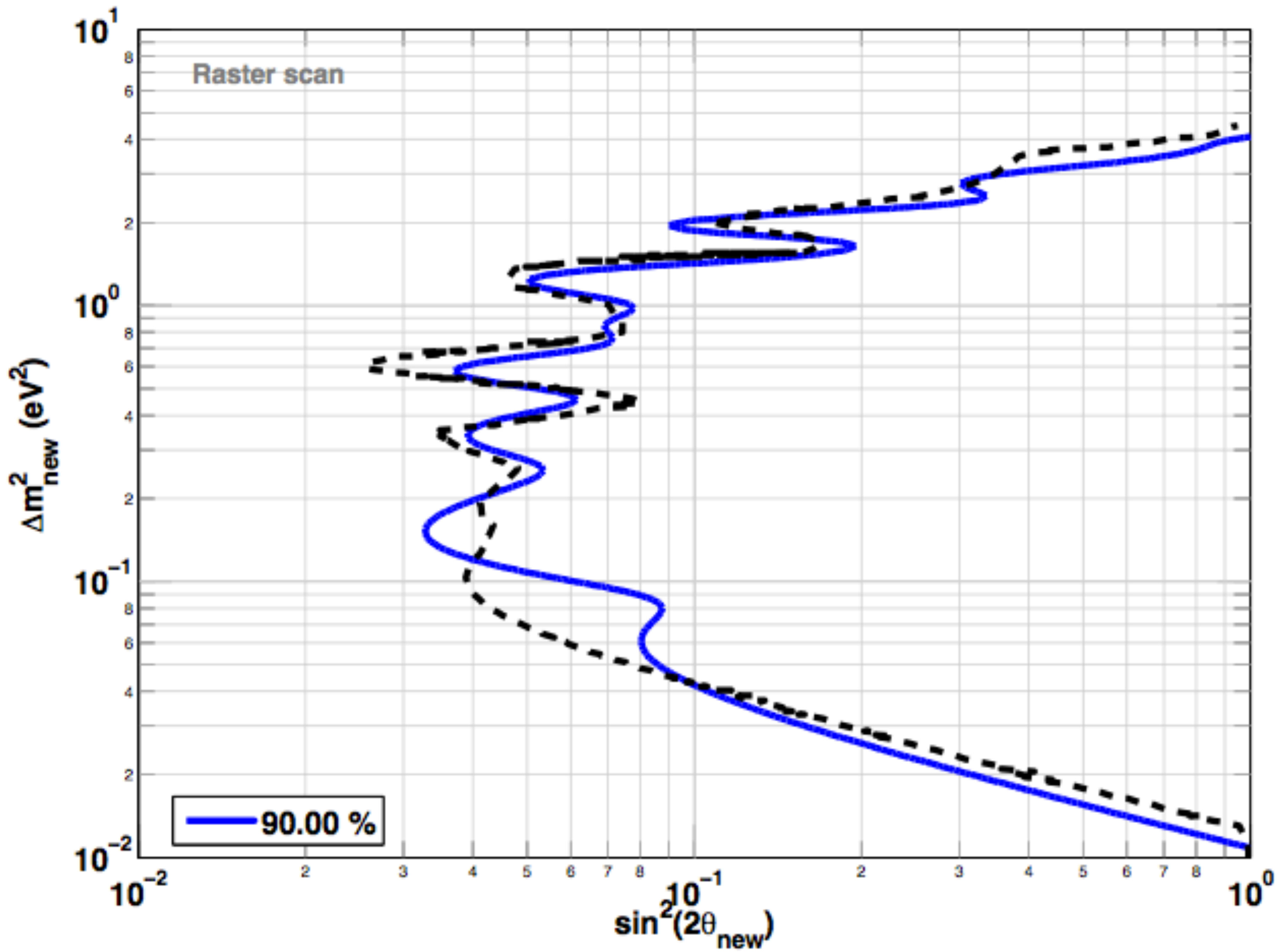
Nuclear Physics B 434 (1995) 503-532

BUGEY-3 measurement of oscillation:



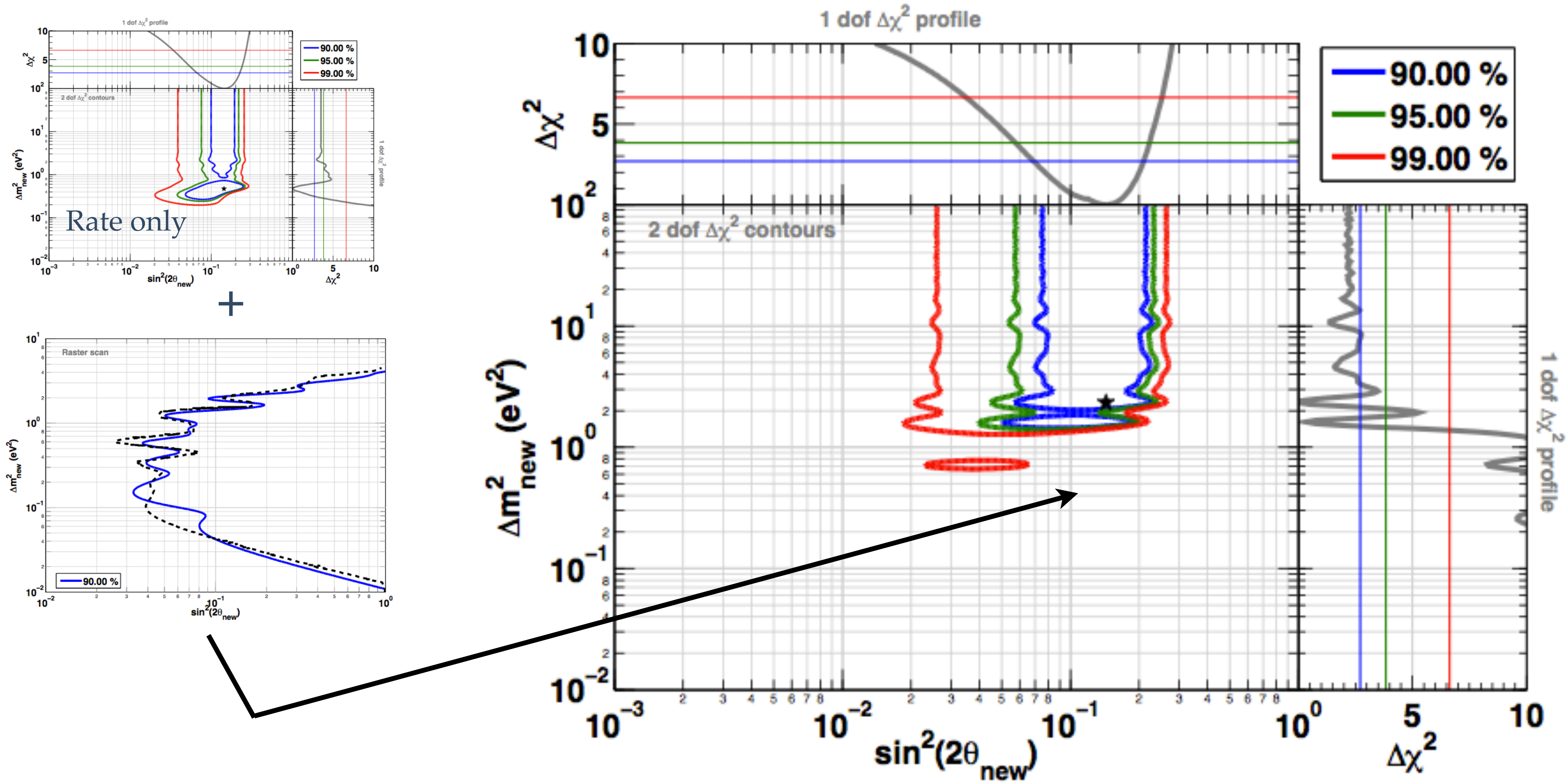
Nuclear Physics B 434 (1995) 503-532

No oscillation was seen: (exclusion plot of solutions)



arXiv:1204.5379

Sterile neutrino allowed mixing parameters for RNA

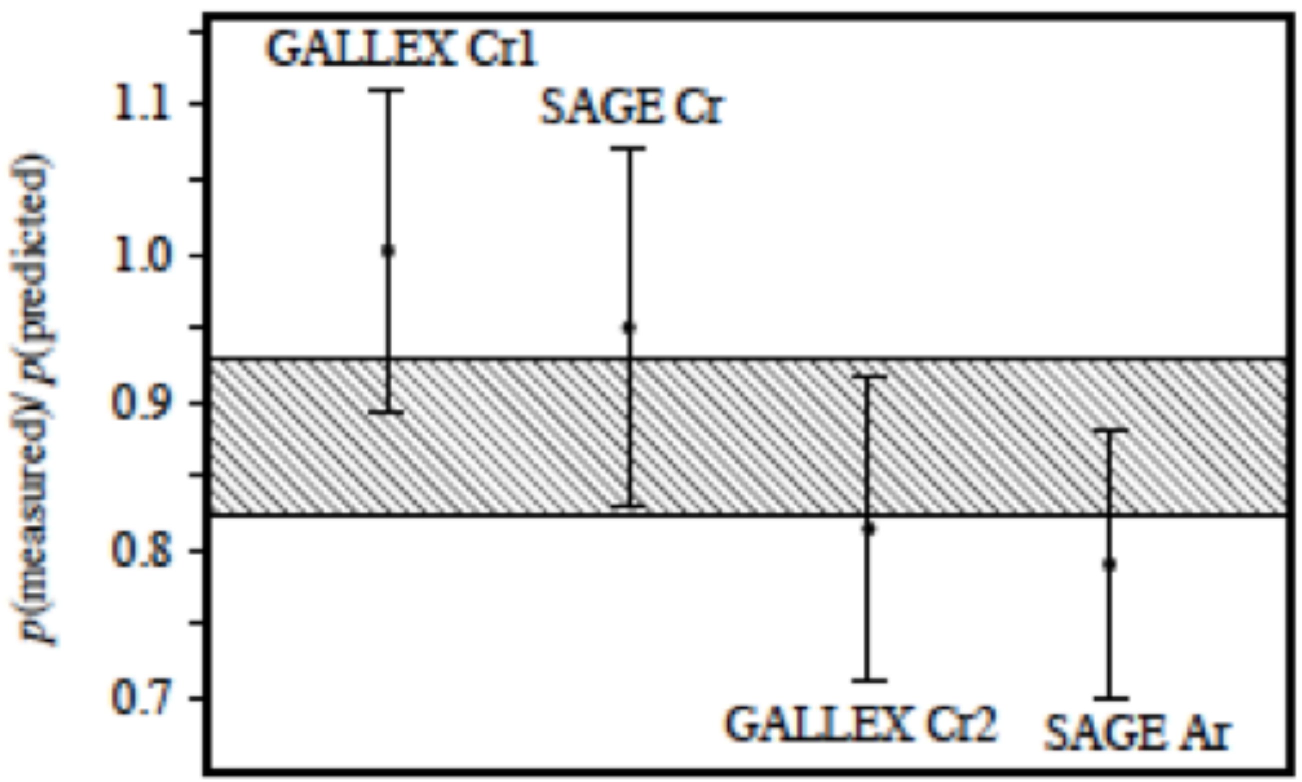


arXiv:1204.5379

Further anomaly? The SAGE/GALLEX study:

Radioactive Neutrino Source Anomaly

SAGE, Phys. Rev. C 73 (2006) 045805



Create a neutrino source close to the detector

$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e\,,$$
$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e\,.$$

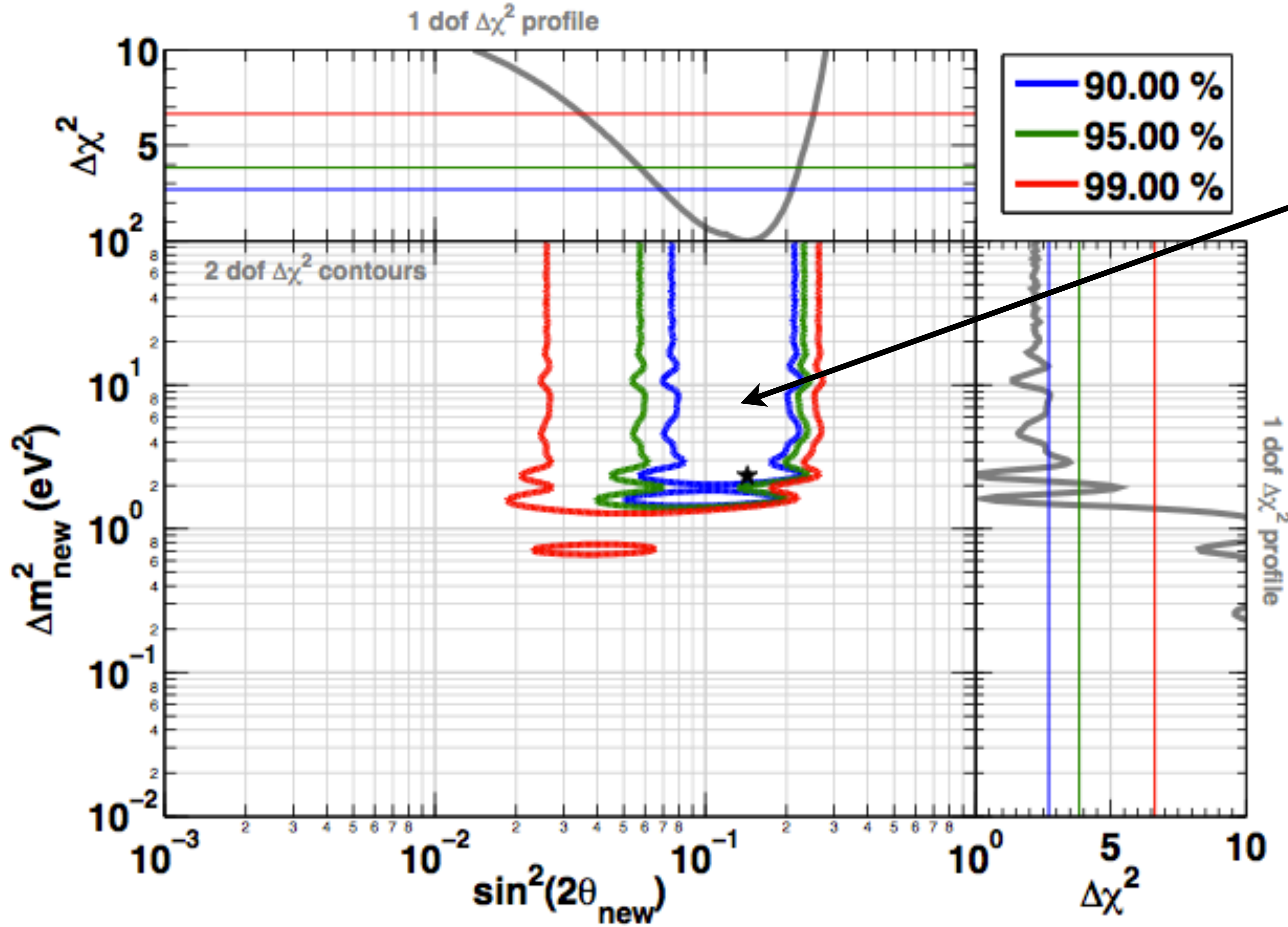
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R^k_{B}	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm {}^{+0.084}_{-0.078}$
R^k_{H}	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm {}^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

R=0.86+-0.05

Slide taken from W. C. Louis
SLAC Intensity Frontier Workshop
March 6, 2

GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos

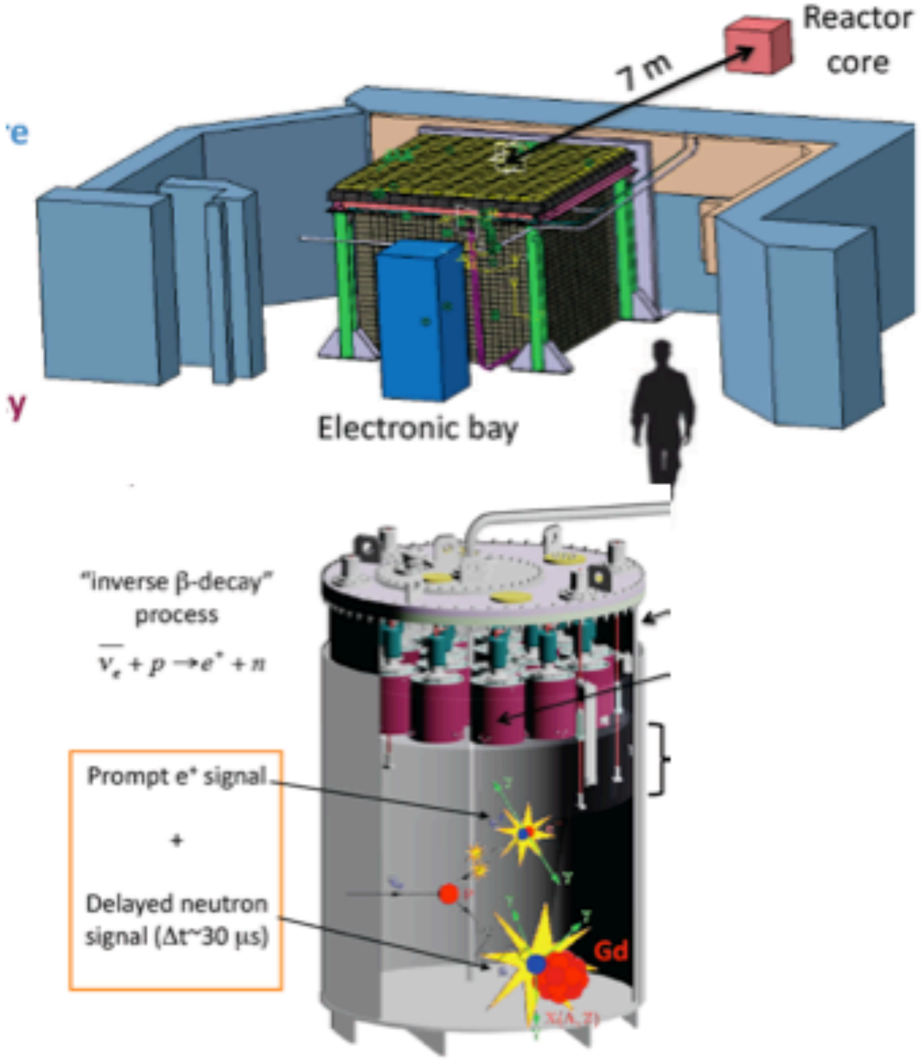
Future Experiments to measure sterile neutrinos?



Build experiments to go at higher modulation frequencies (higher Δm^2)

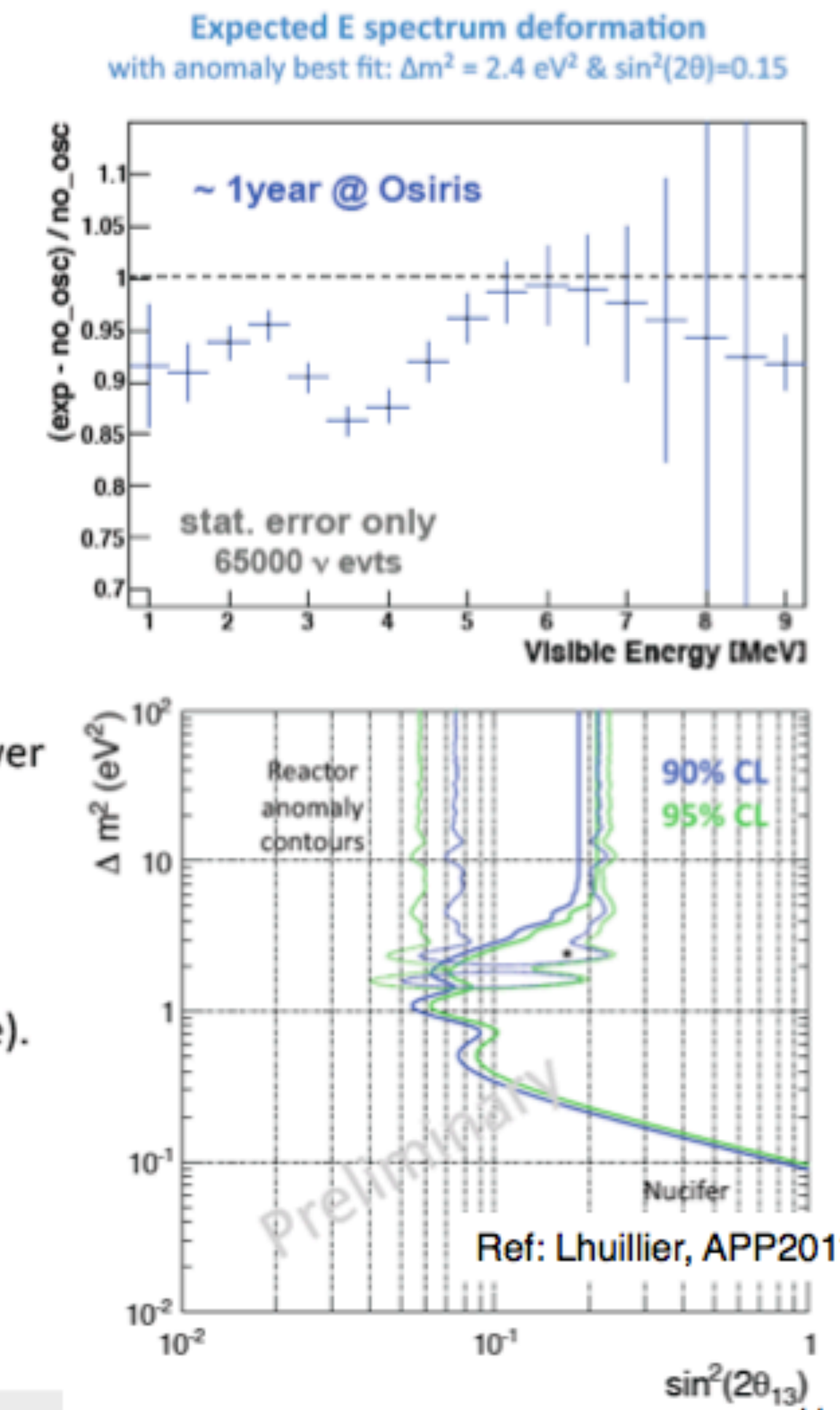
Future Experiments to measure sterile neutrinos?

NUCIFER at Osiris



core: σ~0.3m
baseline: 7m

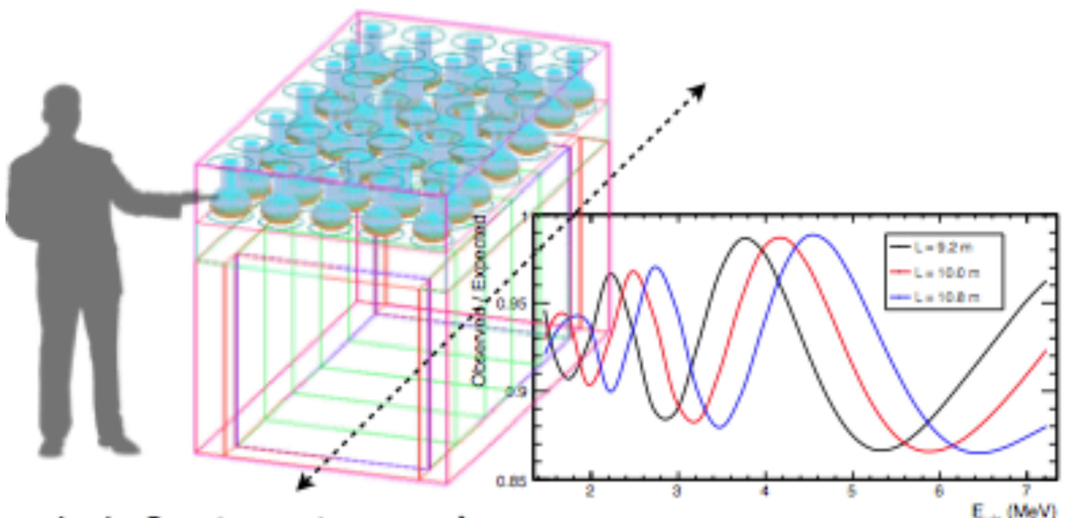
- Norm error = 4%
- 100 days full power @ Osiris
- S/B = 1 (?), assuming same shapes (worst case).
- E resol = 0.15*E



Pre-industrial, unattended reactor neutrino monitor
May be used to test reactor anomaly with compact core.
PSD R&D for background rejection.

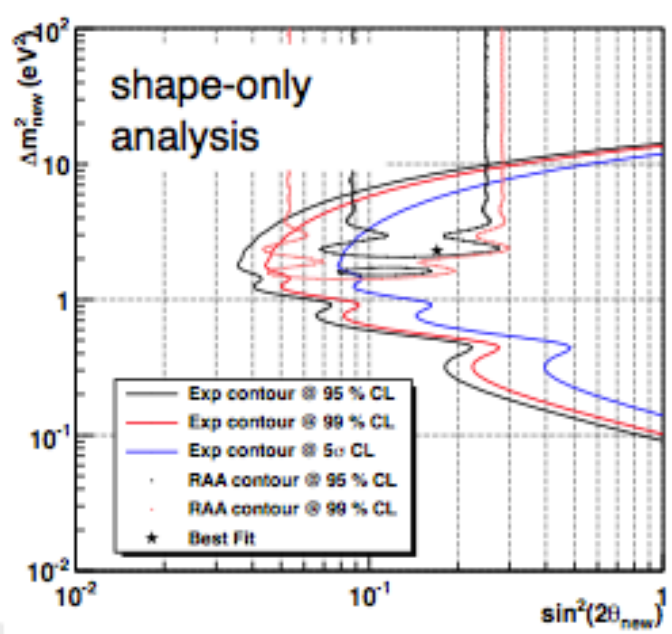
Future Experiments to measure sterile neutrinos?

Stereo at ILL, France

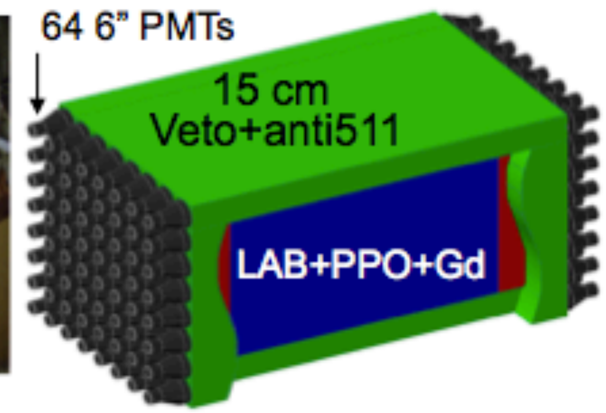


1x1x2m target vessel
filled with Gd-LS
5 baseline bins by foils

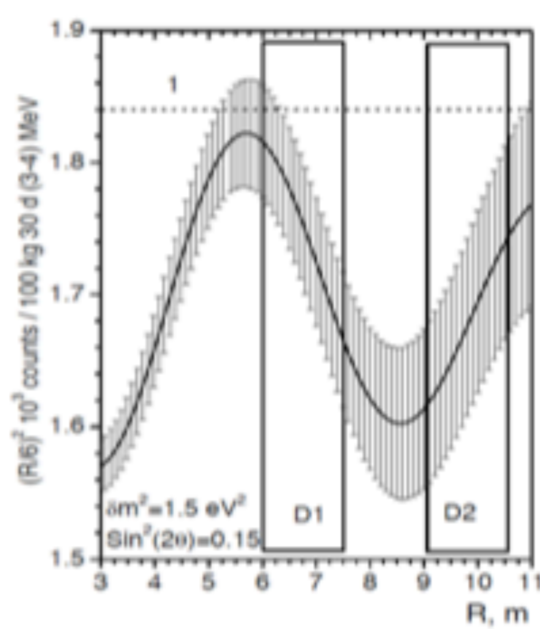
shift detector to verify oscillation signal



POSEIDON at Reactor PIK, Russia



Gd-LS Detector: 2.1x1.3x1.3 m^3
Energy resolution: σ = 7% at 1 MeV
Spatial resolution: σ_x = 15 cm at 1 MeV



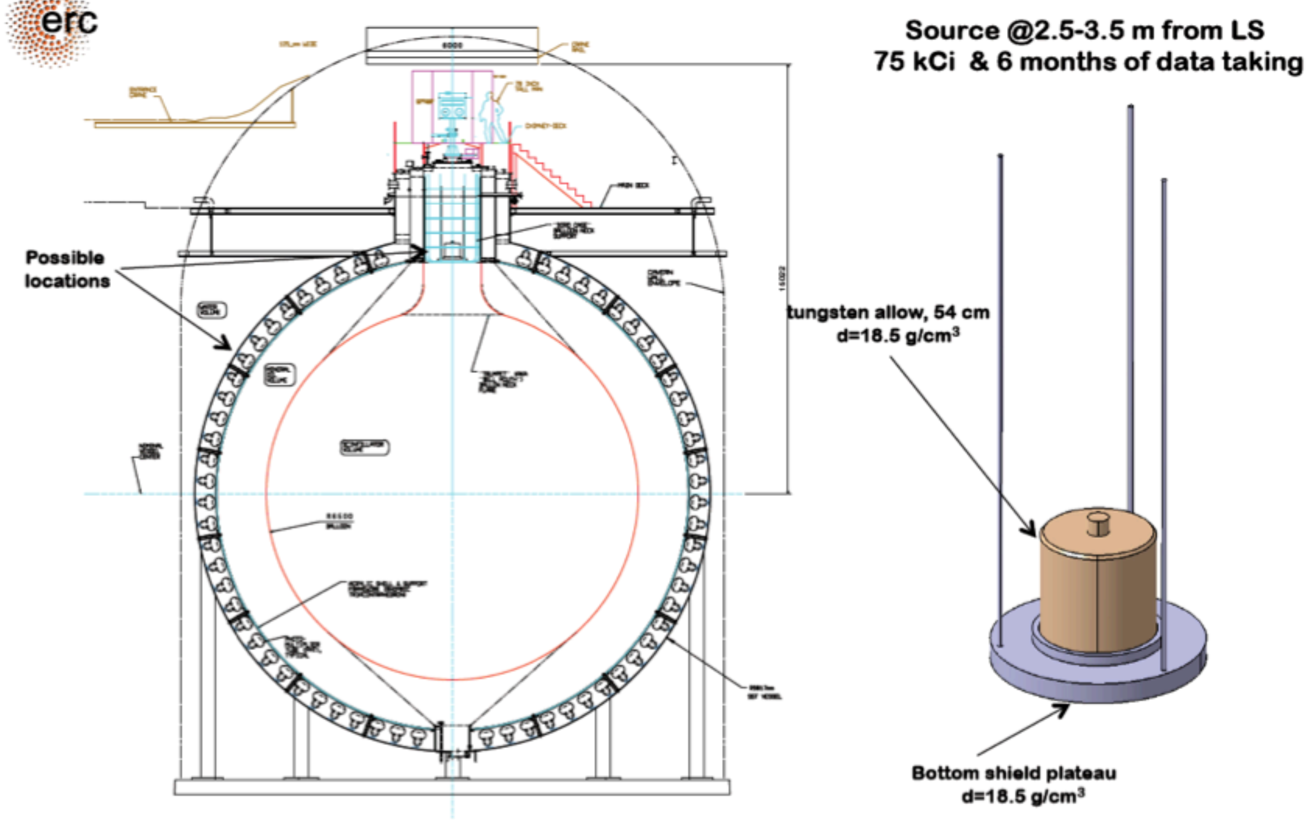
Energy and spatial resolution to measure oscillation curves for different E_ν

aim to detect oscillatory signature

Bring the source to the detector!

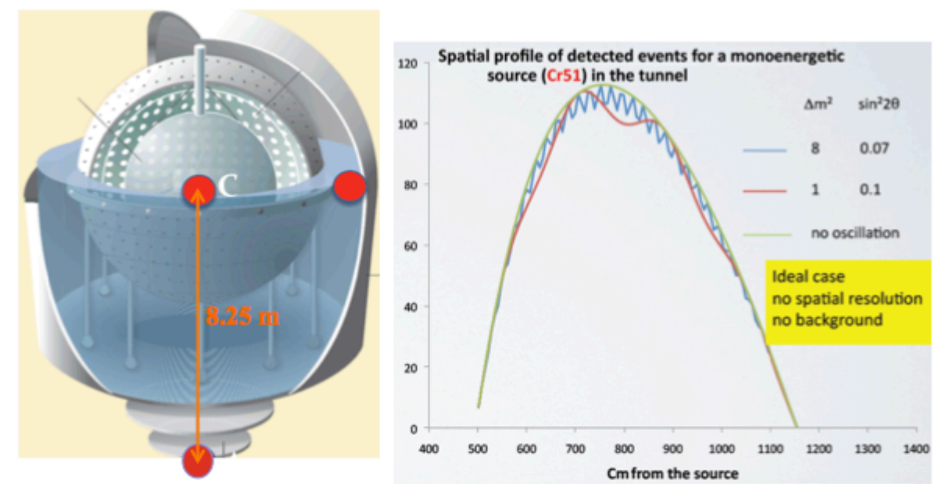
CeLAND Concept with KamLAND Detector

^{144}Ce Source @external + 35 cm W-alloy



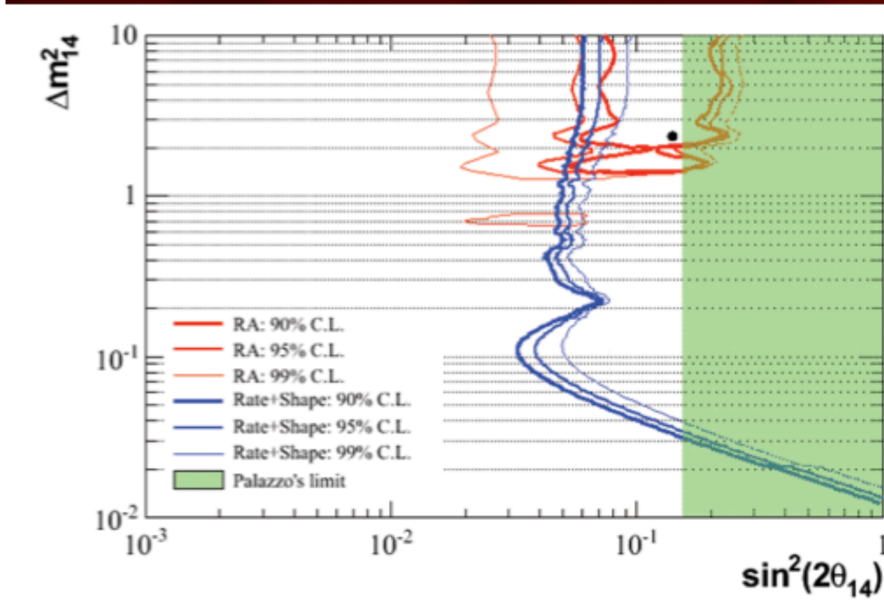
J. Link, SLAC Intensity Frontier Workshop
March 6, 2

Short Distance Oscillations with Borexino Concept



Source Under Detector

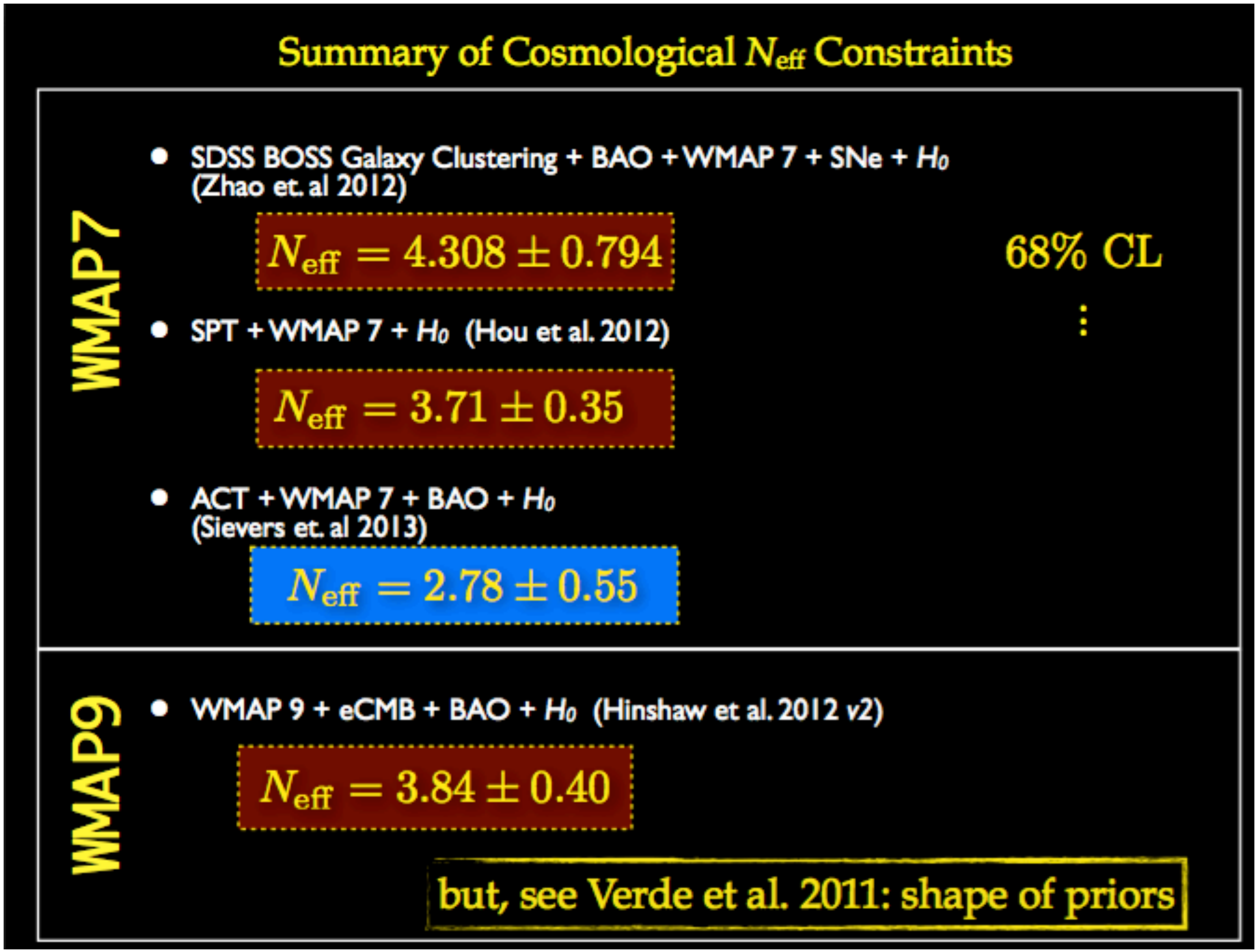
Borexino Sensitivity



10 MCi ^{51}Cr Source with a 100 day exposure

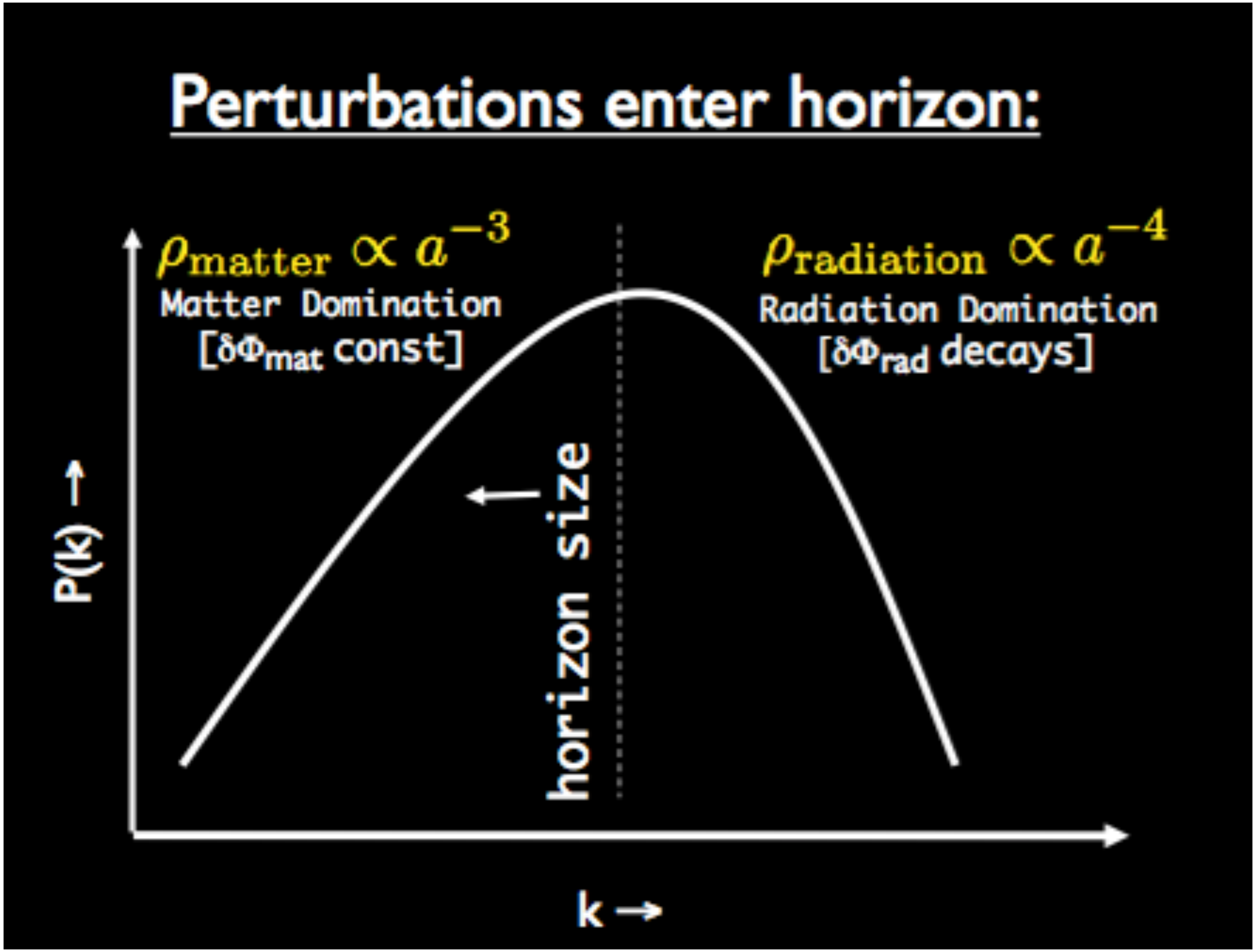
What about the other extreme?
Neutrino evaluated from cosmic measurement

But what about cosmic limits?



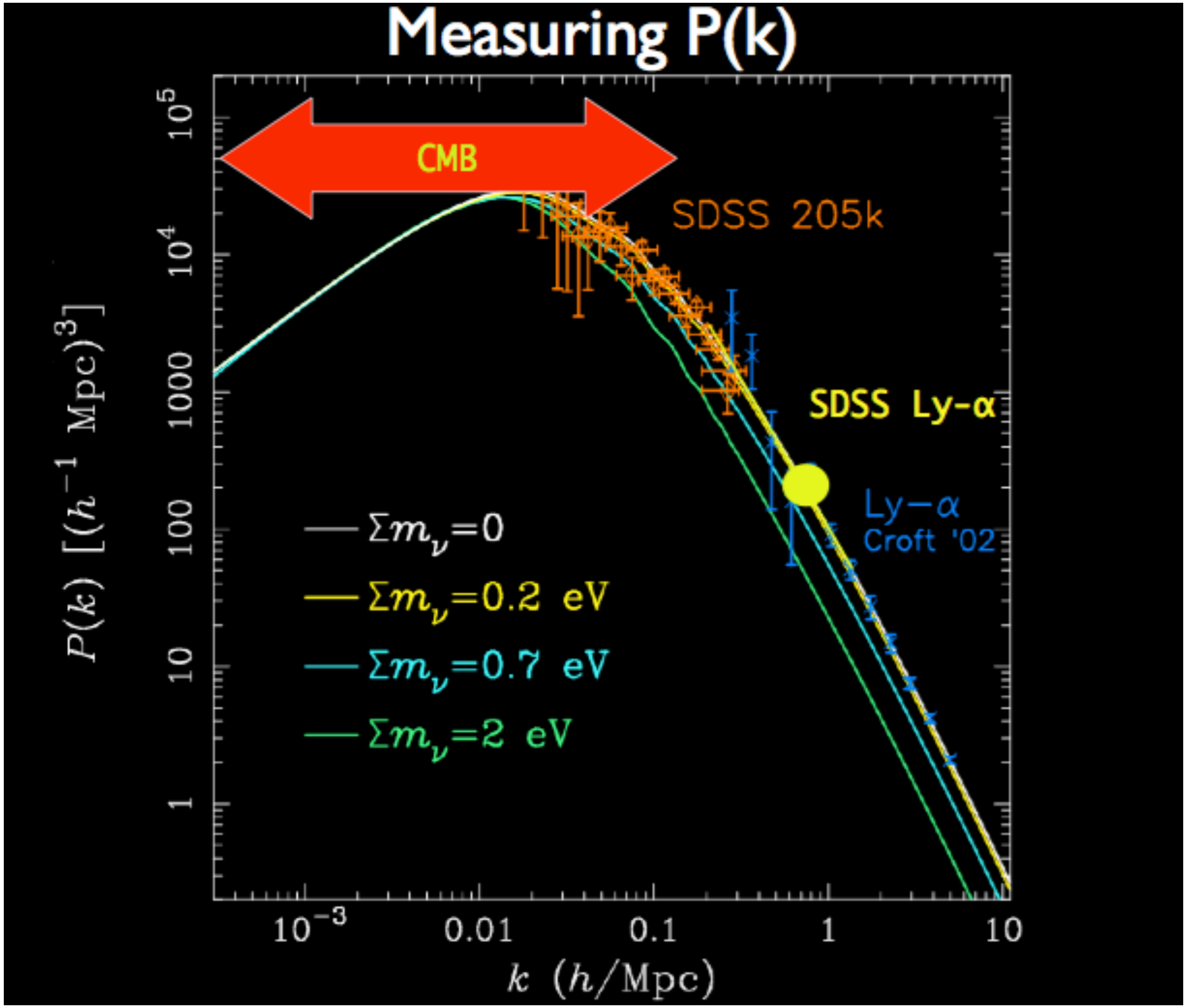
ABAZAJIAN, Kev, Cosmic Frontier SLAC Meeting

But what about cosmic limits?



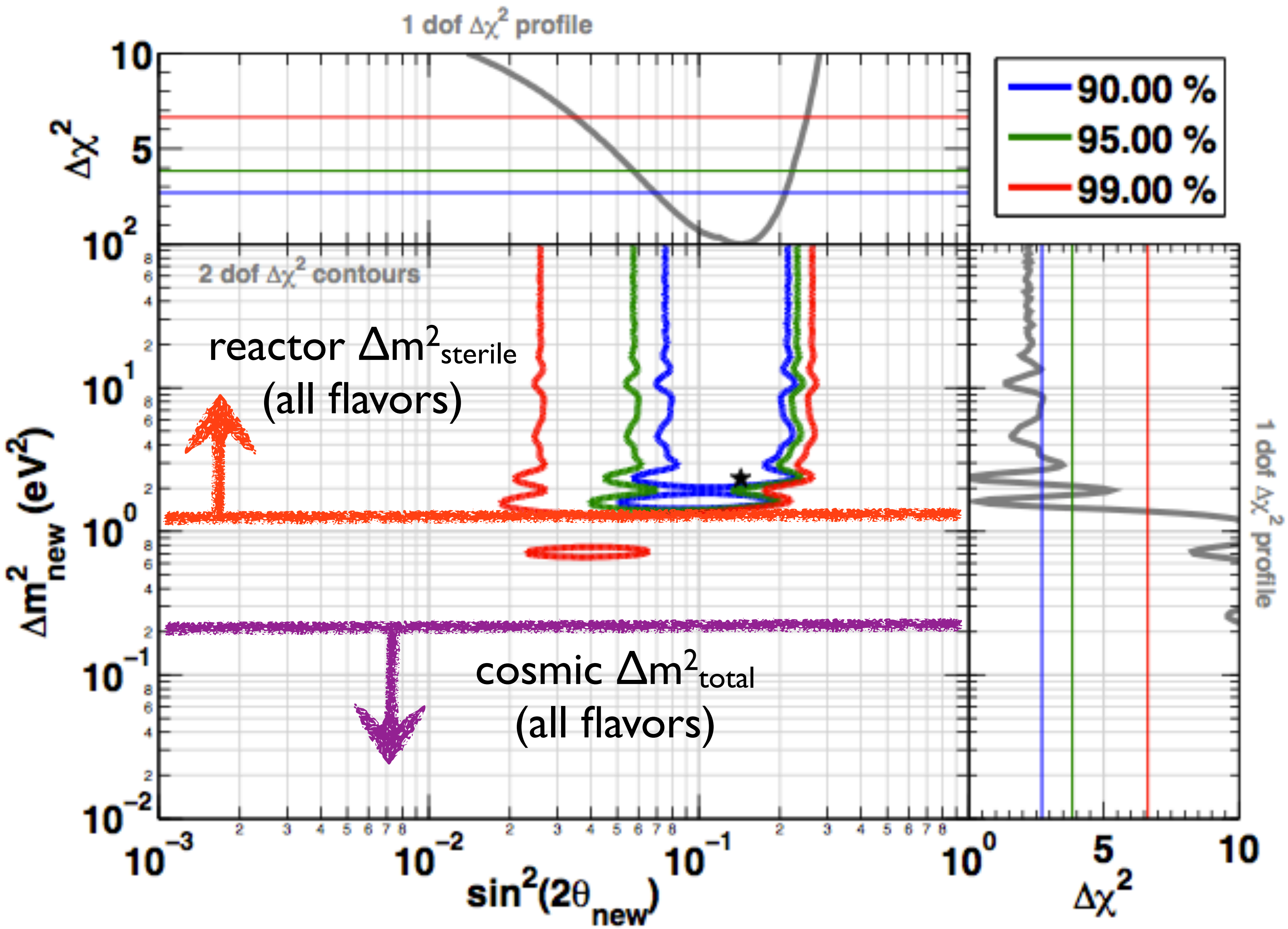
ABAZAJIAN, Kev, Cosmic Frontier SLAC Meeting

But what about cosmic limits?



ABAZAJIAN, Kev, Cosmic Frontier SLAC Meeting

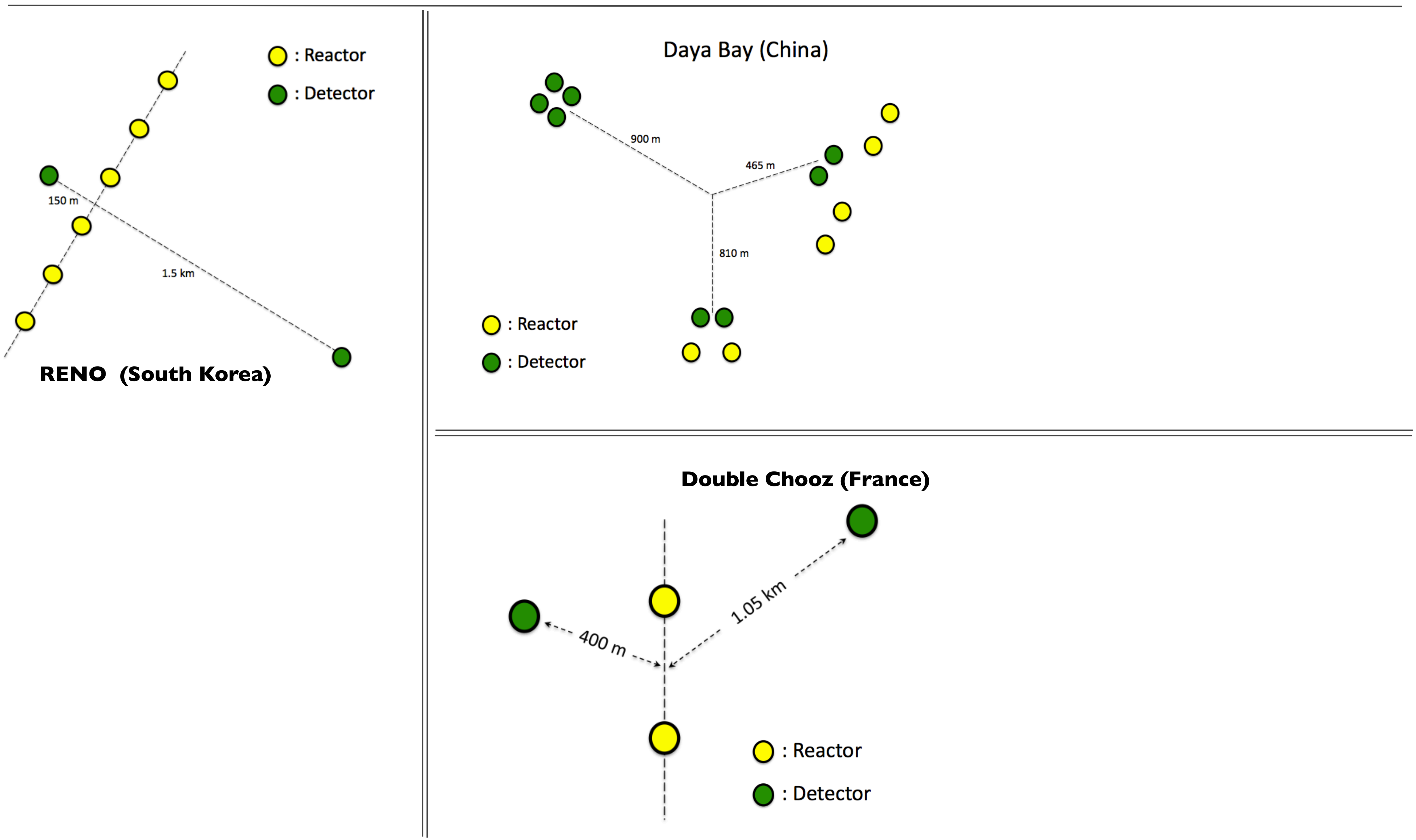
A real anomaly!



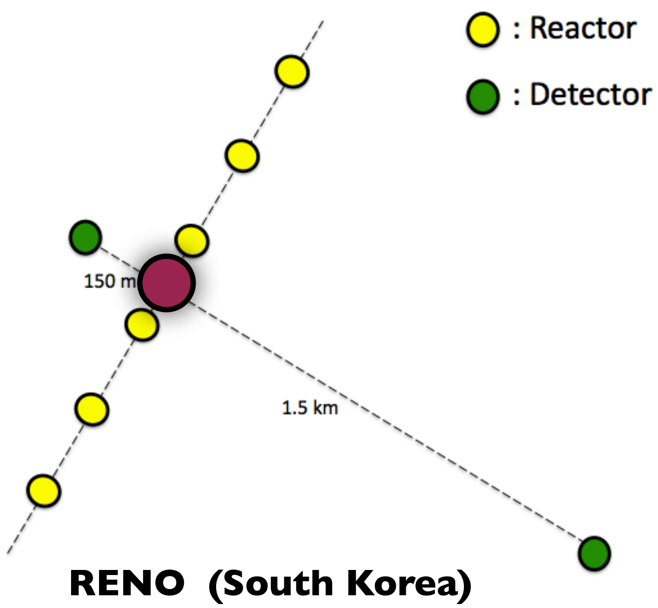
A new method to look for sterile neutrinos

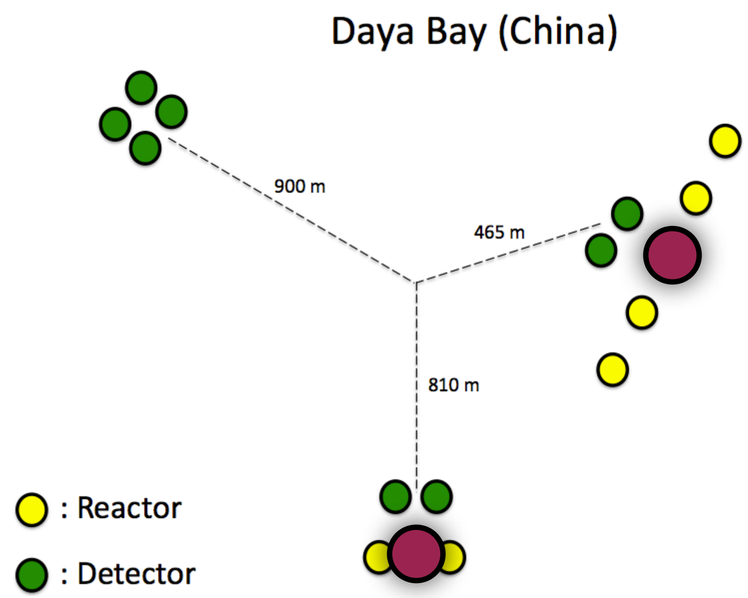
Bergevin, Grant, Svoboda: arxiv.1303.0310v1

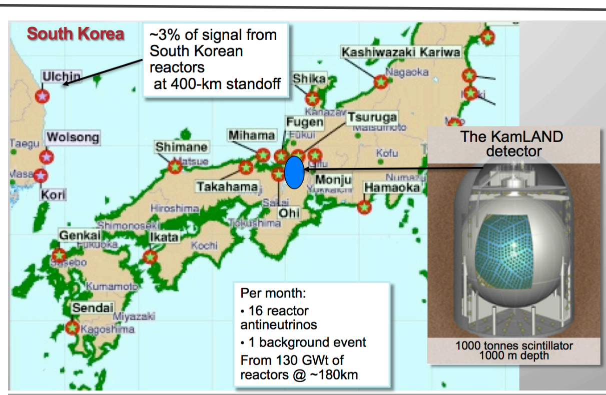
Traditional way of looking at a reactor-detector relationship:

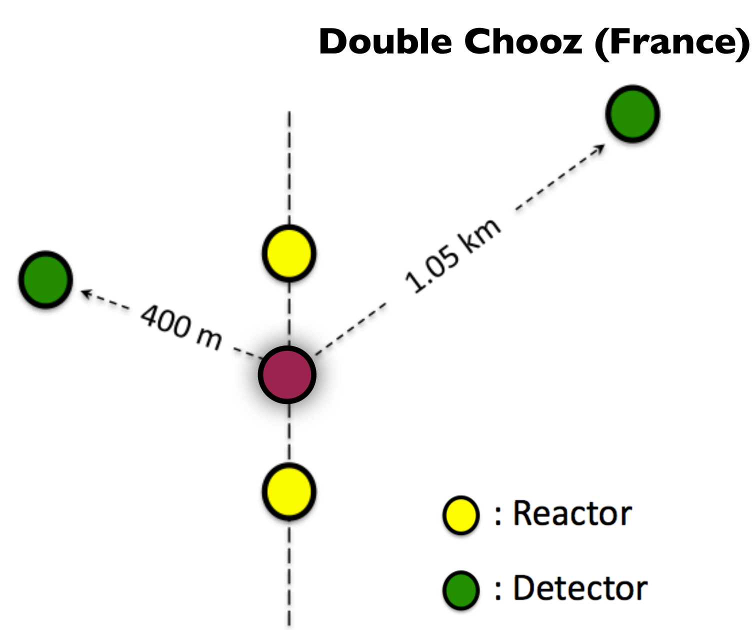


Average the reactors to amplitude evaluation

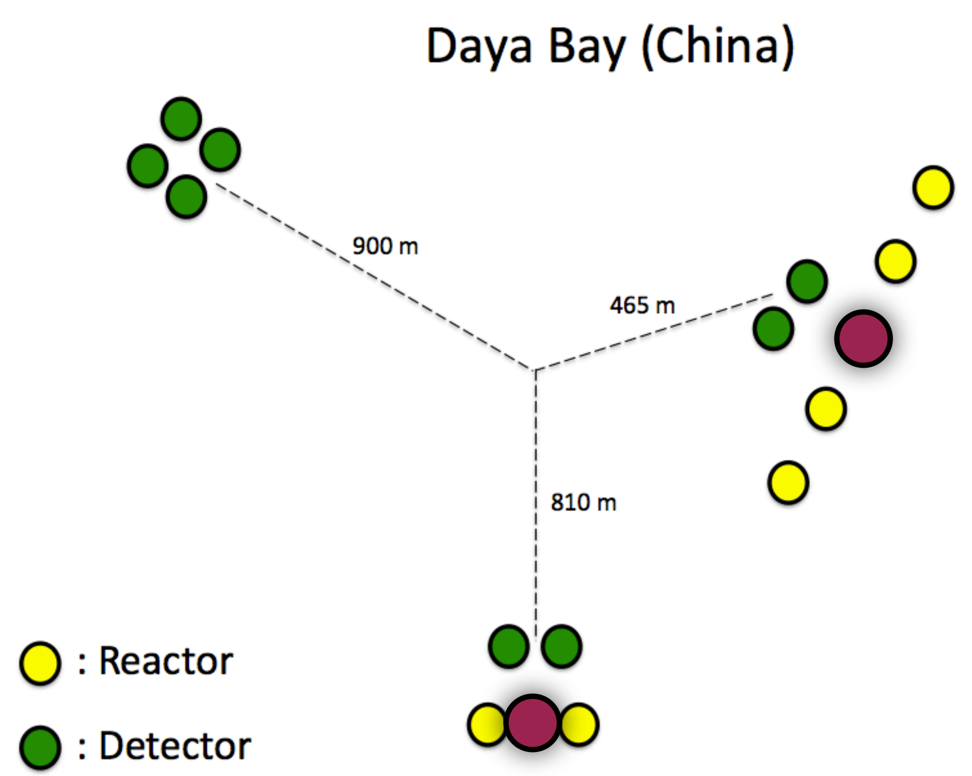


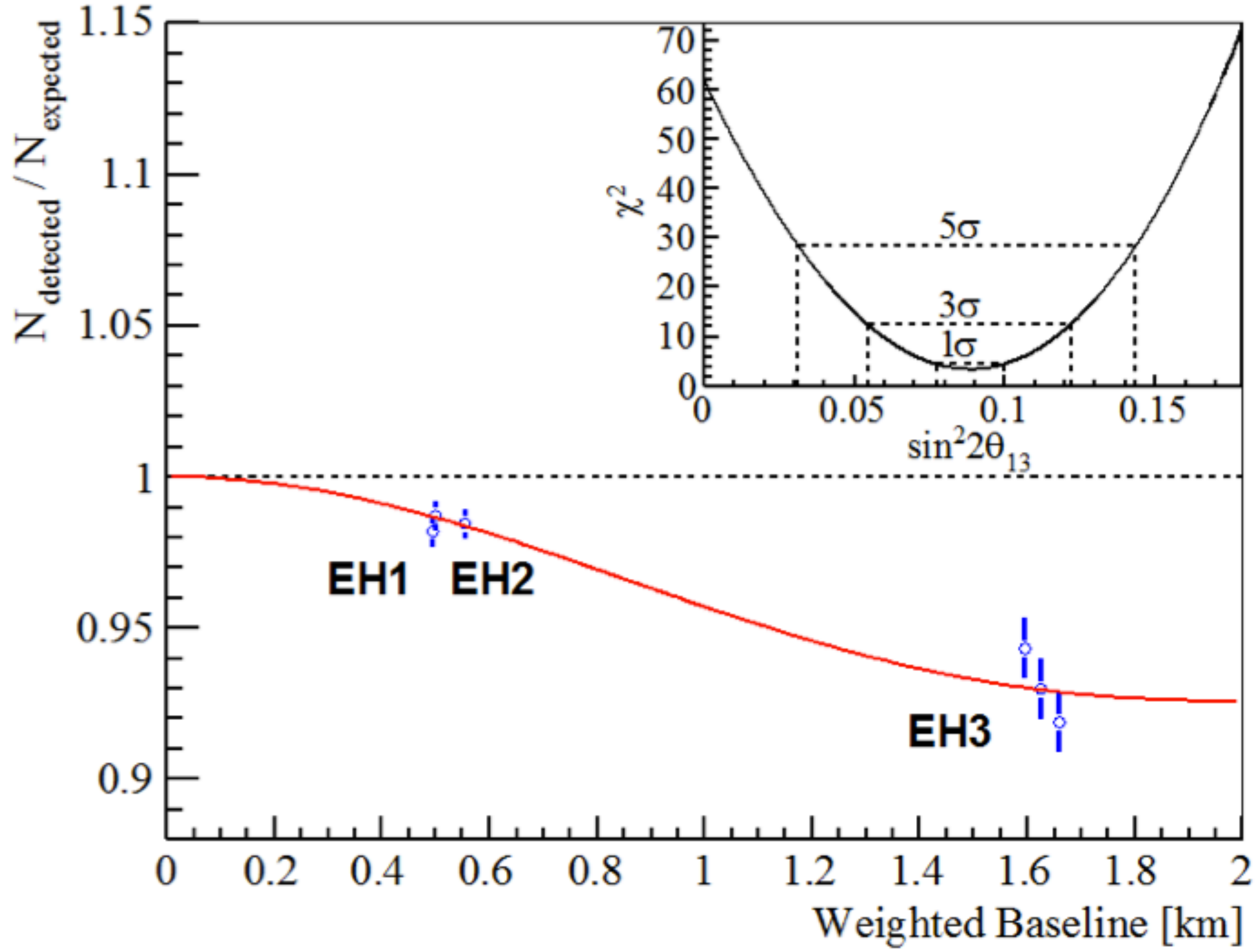




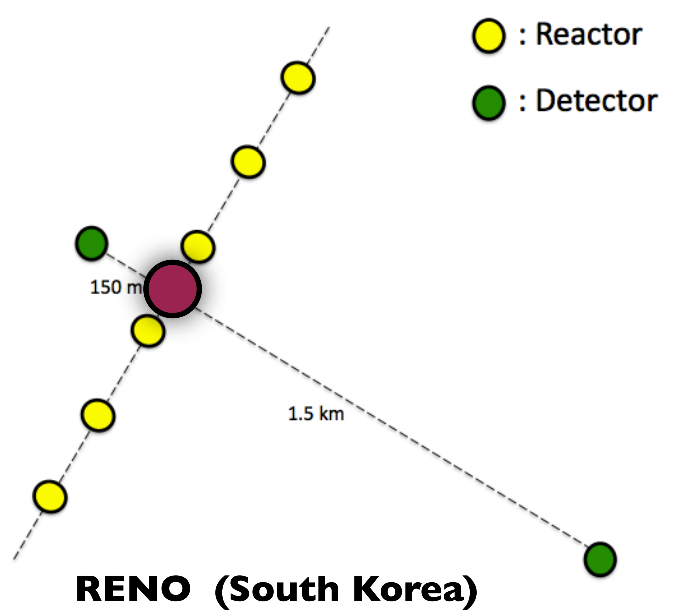


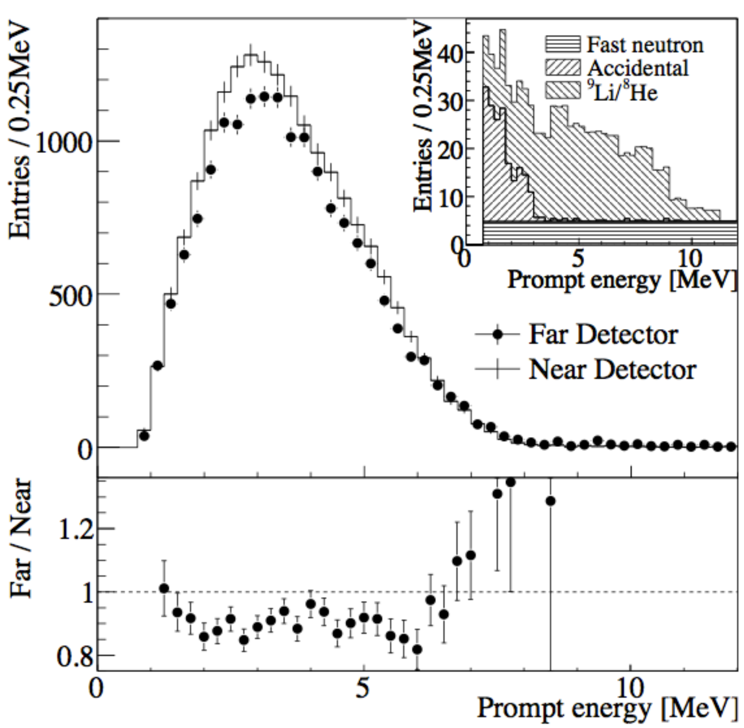
Daya Bay finally called it! (Measured amplitude change)

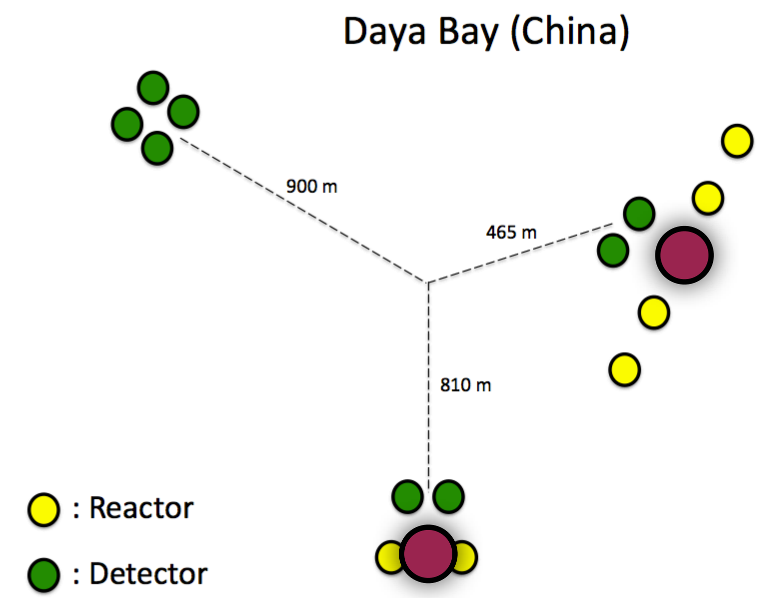


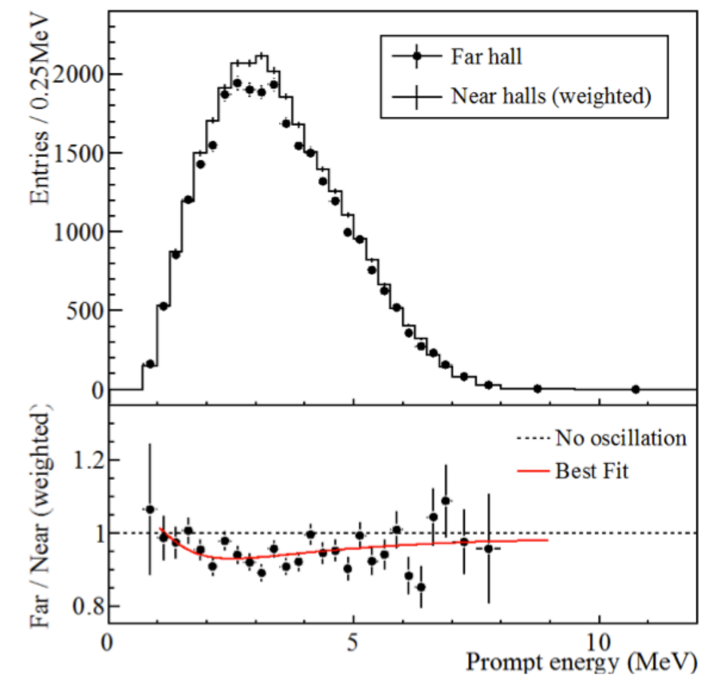


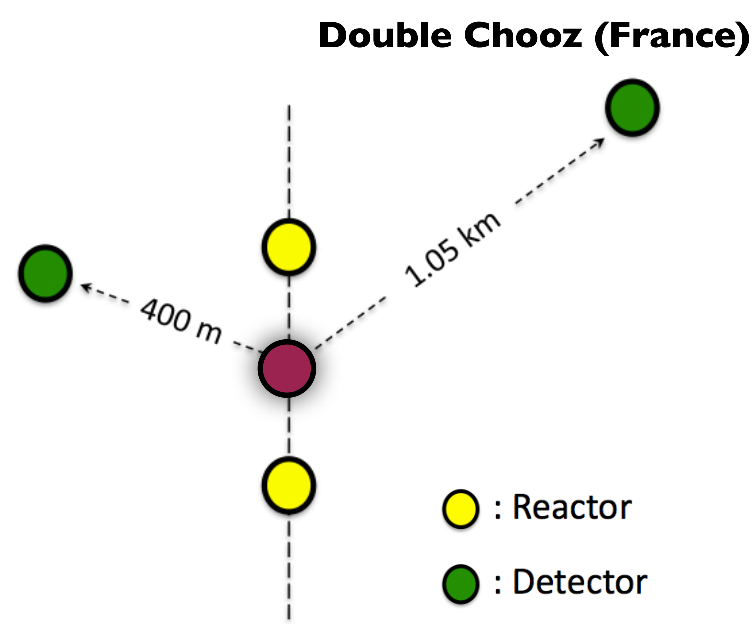
However, taking the ratio leads to strange behaviors(a possible shape anomaly)

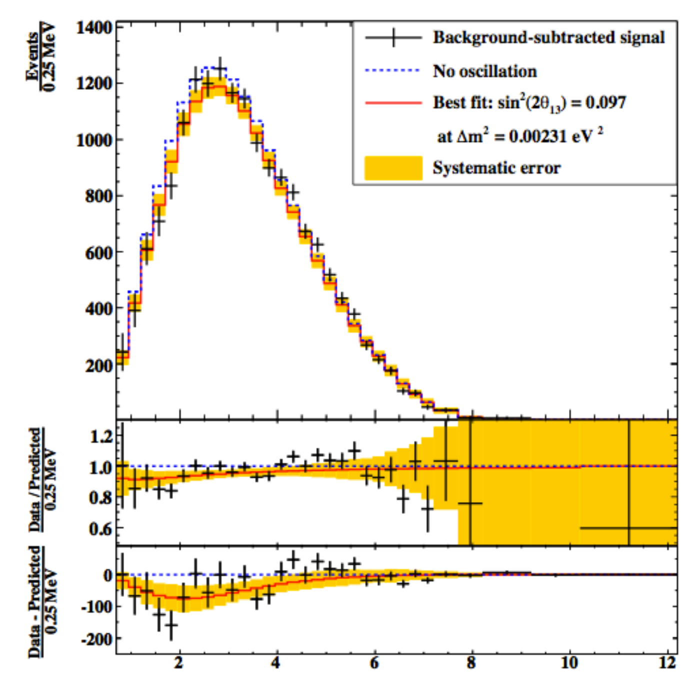








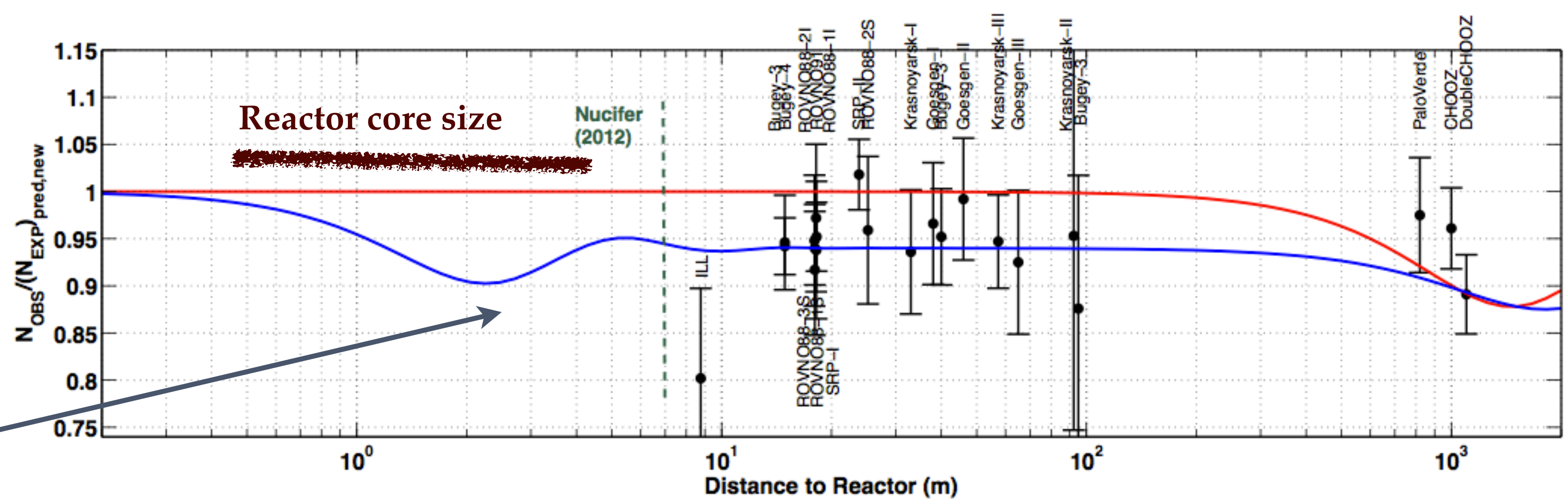




Why the "1"-reactor multi-detector sterile neutrino rate or shape analysis is difficult:

- A traditional rate analysis of the neutrino spectra at each detector may not be sufficient to detect a higher Δm^2_{14} due to systematic uncertainties in the absolute rate
- The **detector resolution will wash out** the large Δm^2 such that the survival probability will average out to $0.5*\sin^2(2\theta_{14})$ for a shape analysis
- In addition, distances implied are on the order of the core size which will also wash it out the oscillation feature in a shape analysis

distance dependent rate is difficult

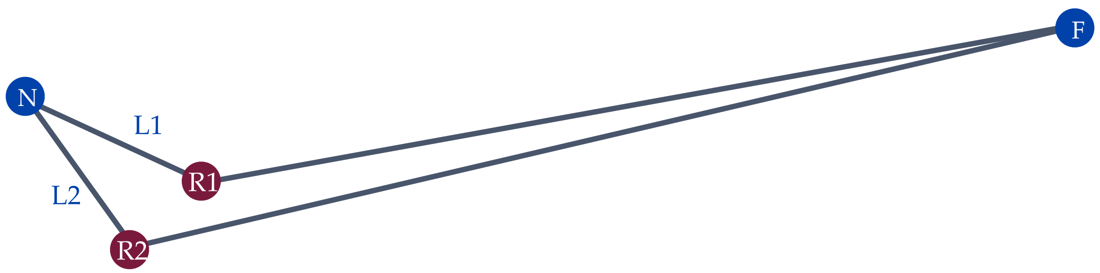


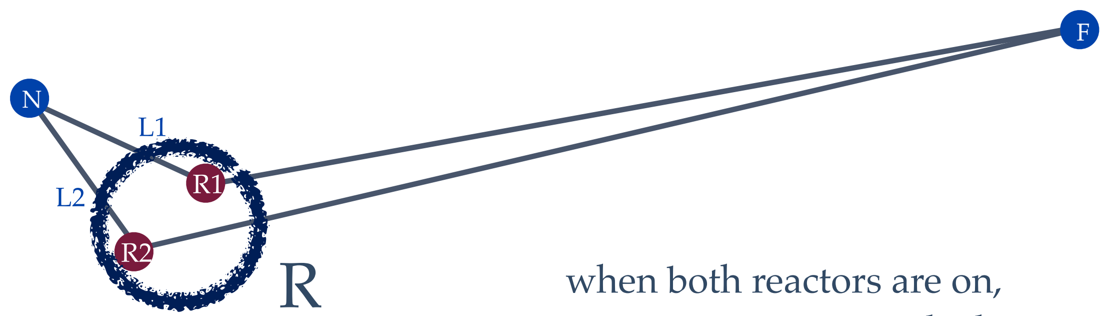
Traditional way of looking at a reactor-detector relationship (DC case study)

As stated before, a 2-reactor 2-detector set-up, it is customary to think of an "average" reactor and multiple detector scenario **("1"-reactor 2-detector)**

In the rare case when both reactors are off, gain better understanding of detector related systematics (^{9}Li, FN)

It is fairly common for one reactor to be on while the other is off. In the case of DC, it is 30% of the time





when both reactors are on, we cannot tell from which reactor the anti-neutrinos are originating

Double Chooz:

- Two 4.25 GWth Reactors (1,2 for this talk)
- 2 Detectors (Near, Far)

New idea of the reactor-detector relationship for a Shape-Only analysis:

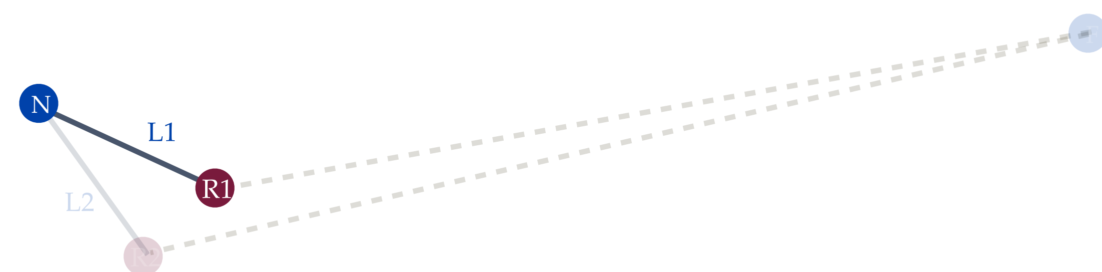
Do not have the two reactor running at the same time (luckily, we don't have to convince anyone, this happens naturally)

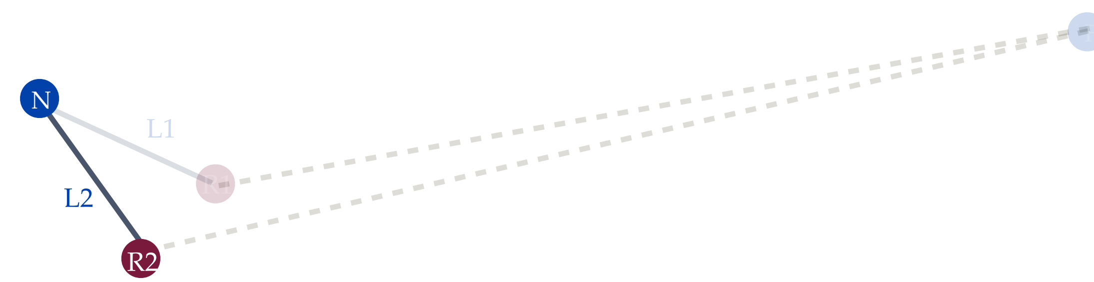
Collect data when Reactor 1 is on and Reactor 2 off and vice versa

One can then think of a **near and far reactor**

Do a ratio of the energy spectra corrected for livetime and distance for near and far reactor:

This can be used in a shape analysis that does **not depend on rate information**





Only works with 2 "identical" reactors

In a shape only analysis, major detector related systematics (fast neutrons, 9Li production, ...) can be constrained

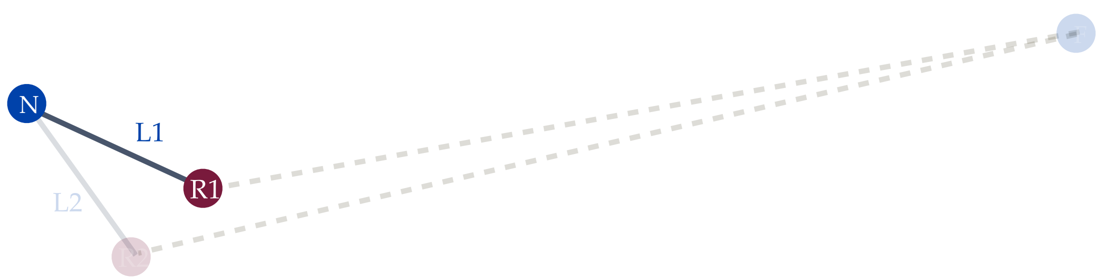
A quantitative case study : DC Near detector

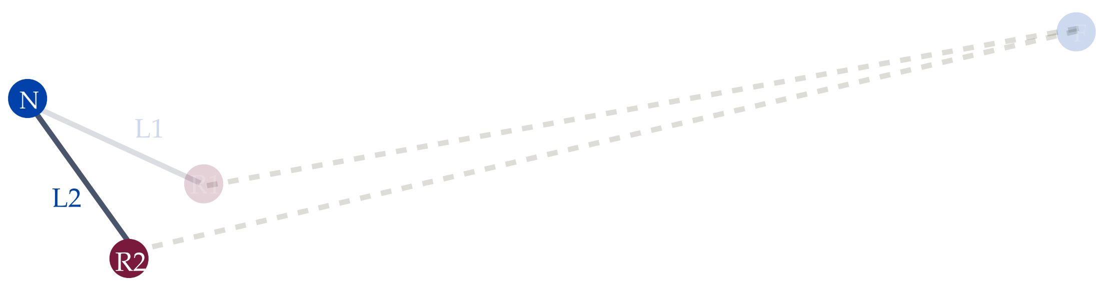
Assumption for this analysis:

~274 days of data per Reactor assuming down cycle of 15% per Reactor. (implies 5 years total of detector operation)

Reactor 1-Near detector :
- 351 meters away from DC detector
- ~460 anti-neutrinos per day

Reactor 2-Near detector :
- 465 meters away from detector
- ~260 anti-neutrinos per day





Only works with 2 "identical" reactors

Do a ratio of the energy spectra corrected for livetime and distance for near and far reactor!

Understanding the shape distortion from the ratio of the oscillated spectra:

$$P_{ee} = 1 - \sin^2(2\theta_{new}) \sin^2\left(\frac{\Delta m^2_{new} L}{4E_{\bar{\nu}_e}}\right) \xrightarrow{\text{ratio + simplify}} \frac{P_{ee}^{R_1}}{P_{ee}^{R_2}} = \frac{1 - \alpha^2 \sin^2(\beta L_1)}{1 - \alpha^2 \sin^2(\beta L_2)}$$

Understanding the shape distortion from the ratio of the oscillated spectra:

$$P_{ee} = 1 - \sin^2(2\theta_{new}) \sin^2\left(\frac{\Delta m^2_{new} L}{4E_{\bar{\nu}_e}}\right) \xrightarrow{\text{ratio + simplify}} \frac{P^{R_1}_{ee}}{P^{R_2}_{ee}} = \frac{1-\alpha^2\sin^2(\beta L_1)}{1-\alpha^2\sin^2(\beta L_2)}$$

do some math

$$\frac{P^{R_1}_{ee}}{P^{R_2}_{ee}} = \frac{1+\alpha^2\sin(\beta L_{2-1})\sin(\beta L_{1+2}) - \alpha^4\sin^2(\beta L_1)\sin^2(\beta L_2)}{1-\alpha^4\sin^4(\beta L_2)}$$

Doing a ratio of two distribution yields an **interference term** with a behavior ~ **sin(γ/E) function** (and not as the square of a sin function)

$(a)\quad L_1 \equiv$ distance from detector to reactor 1

$(b)\quad L_2 \equiv$ distance from detector to reactor 2

$(c)\quad L_{2-1} \equiv L_2 - L_1$

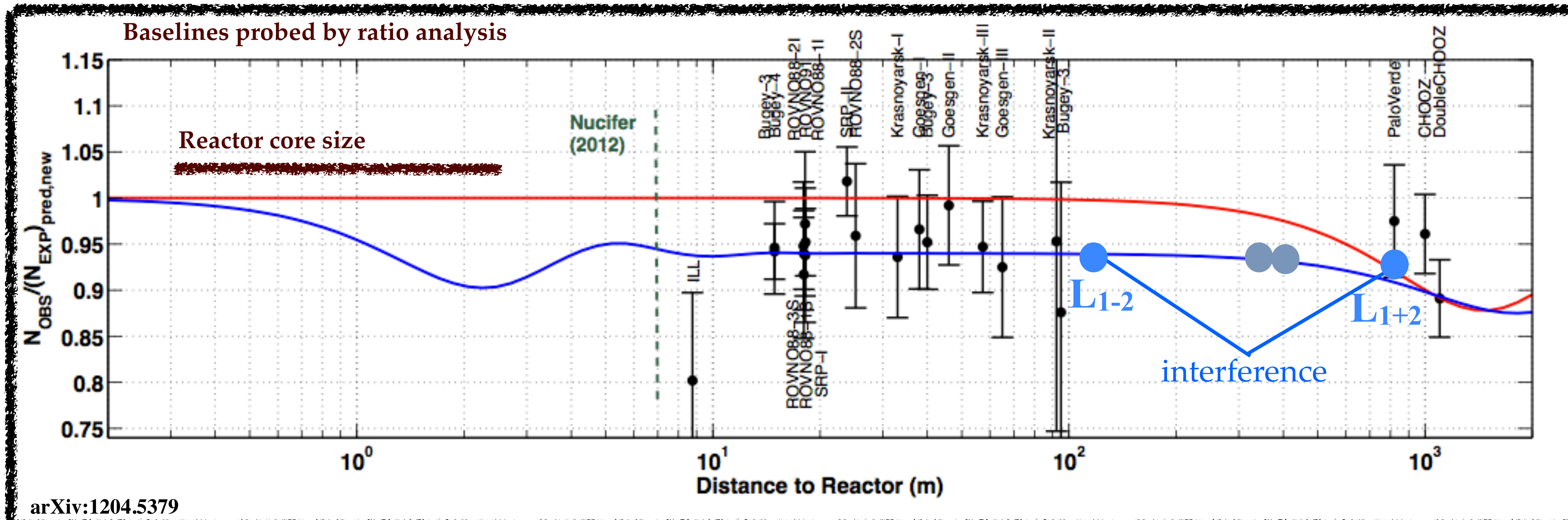
$(d)\quad L_{1+2} \equiv L_1 + L_2$

identify 4 baselines

What can be probed with these baselines?

$$\frac{P_{ee}^{R_1}}{P_{ee}^{R_2}} = \frac{1 + \alpha^2 \sin(\beta L_{2-1}) \sin(\beta L_{1+2}) - \alpha^4 \sin^2(\beta L_1) \sin^2(\beta L_2)}{1 - \alpha^4 \sin^4(\beta L_2)}$$

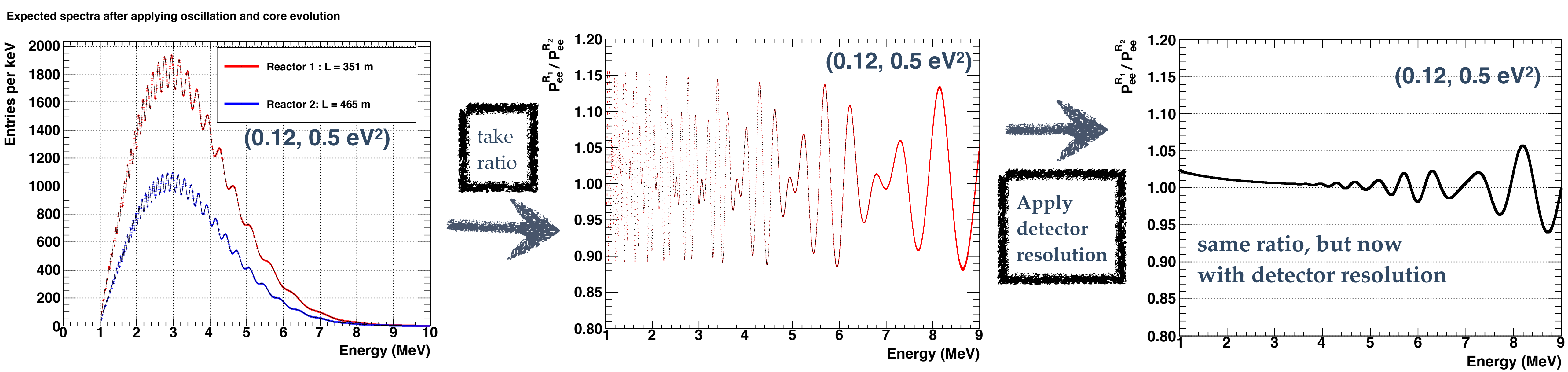
$$\frac{P_{ee}^{R_1}}{P_{ee}^{R_2}} \approx 1 + [1 - \alpha^2 \sin^2(\beta L_2)] [\alpha^2 \sin(\beta L_{2-1}) \sin(\beta L_{1+2})] + O(6) + \ldots$$



How is this ratio observed in a detector?

- Convolve 4th neutrino with 3-neutrino oscillation
- Make appropriate livetime, core evolution and distance corrections
- Finally, convolve with detector energy resolution and finite core size

Adding detector resolution removes many of the features, **but not all!**



How does this ratio change as a function of Δm^2?

Rate

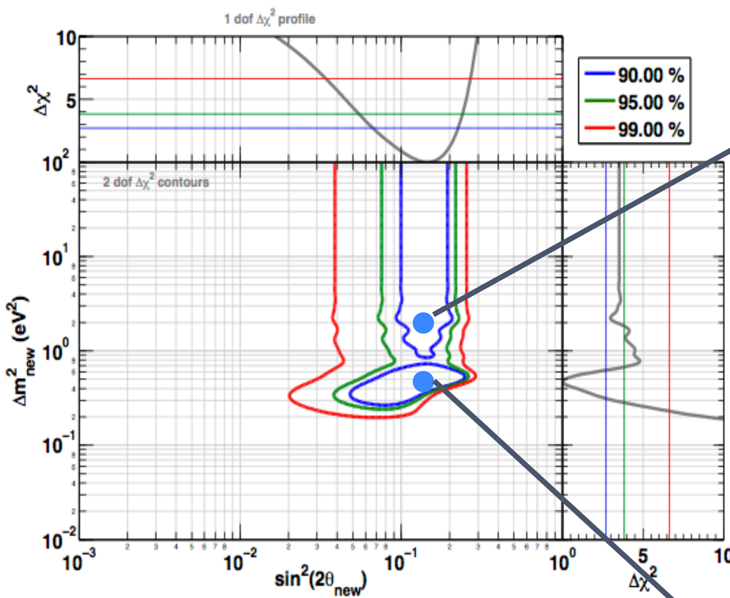
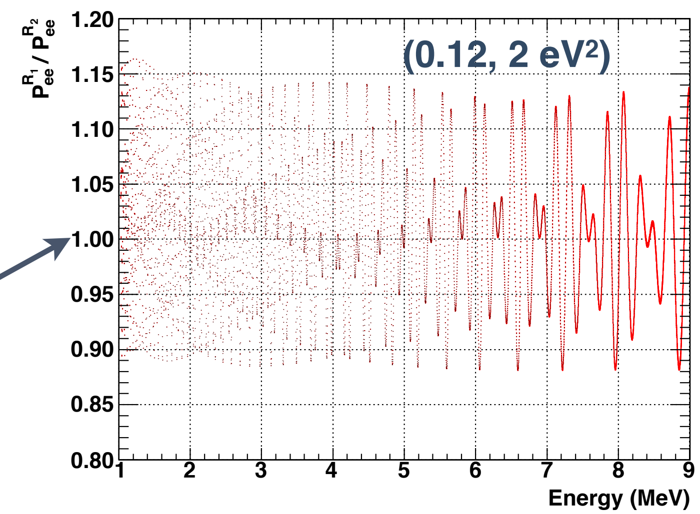
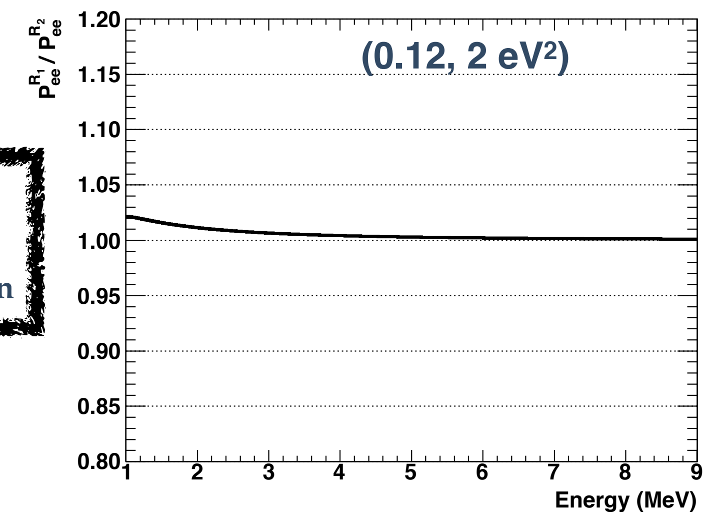
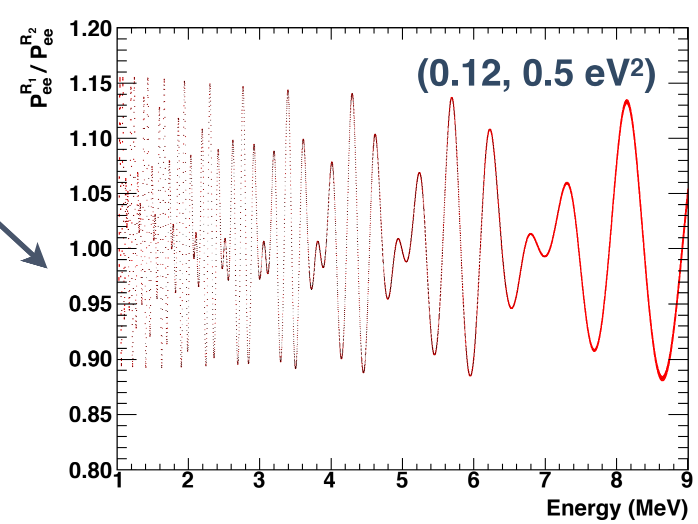


Figure 58. Allowed regions in the $\sin^2(2\theta_{new}) - \Delta m^2_{new}$ plane obtained from the fit of the reactor neutrino data, without any energy spectra information, to the 3+1 neutrino hypothesis, with $\sin^2(2\theta_{13}) = 0$. The best-fit point is indicated by a star.

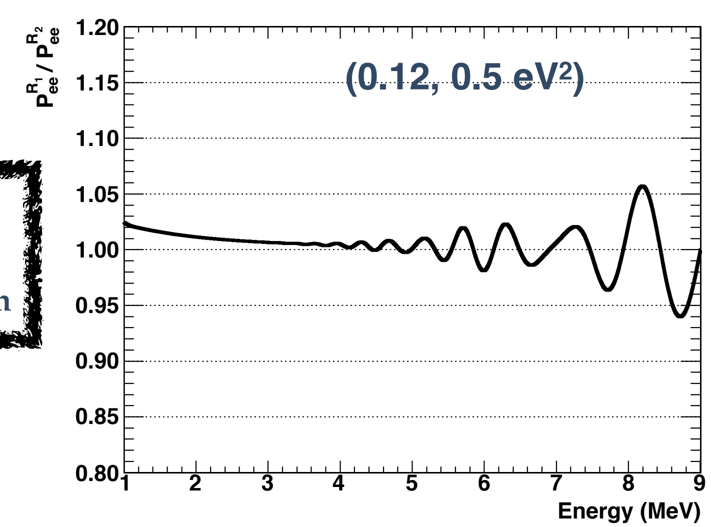


Apply detector resolution





Apply detector resolution



How does this ratio change as a function of Δm^2?

Rate

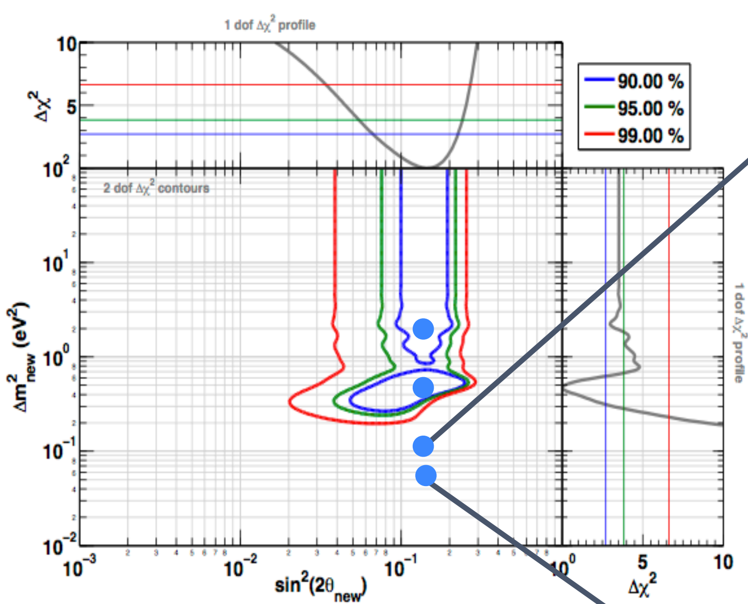
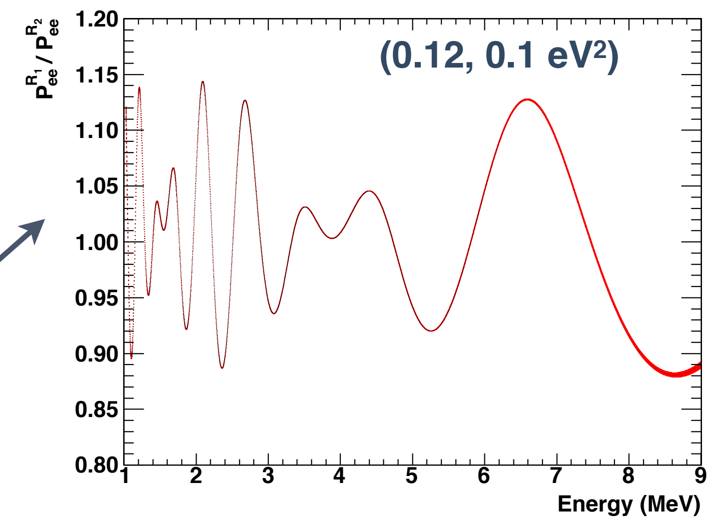
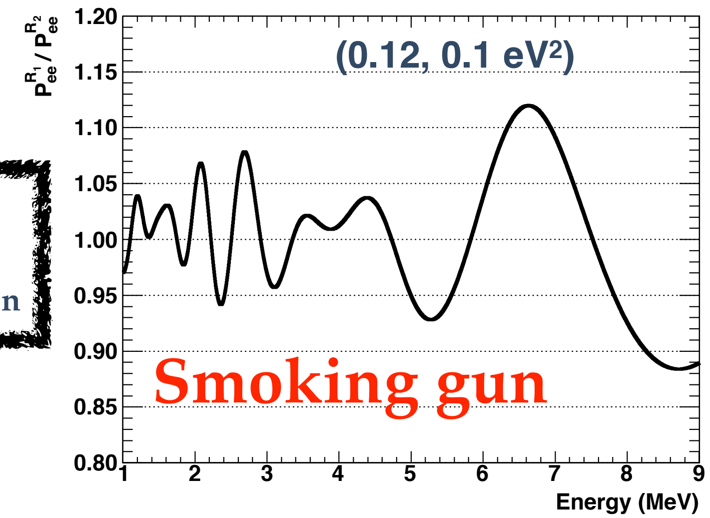
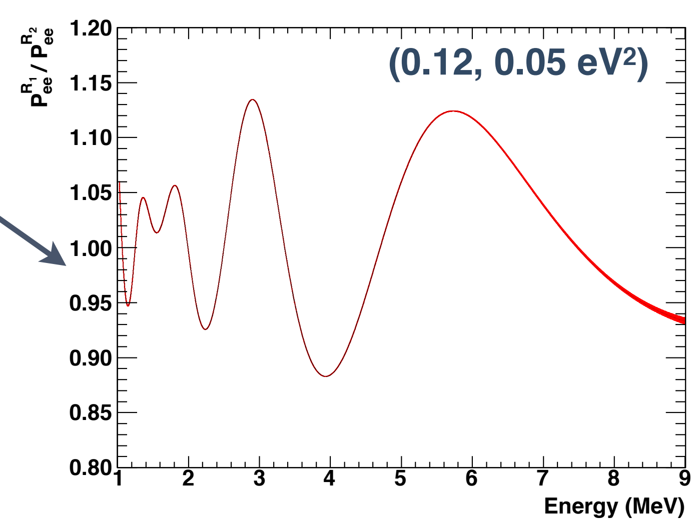


Figure 58. Allowed regions in the $\sin^2(2\theta_{new}) - \Delta m^2_{new}$ plane obtained from the fit of the reactor neutrino data, without any energy spectra information, to the 3+1 neutrino hypothesis, with $\sin^2(2\theta_{13}) = 0$. The best-fit point is indicated by a star.

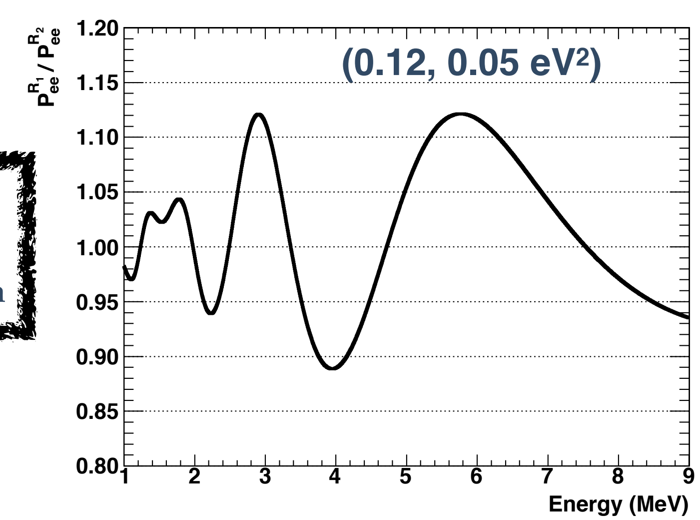


Apply detector resolution

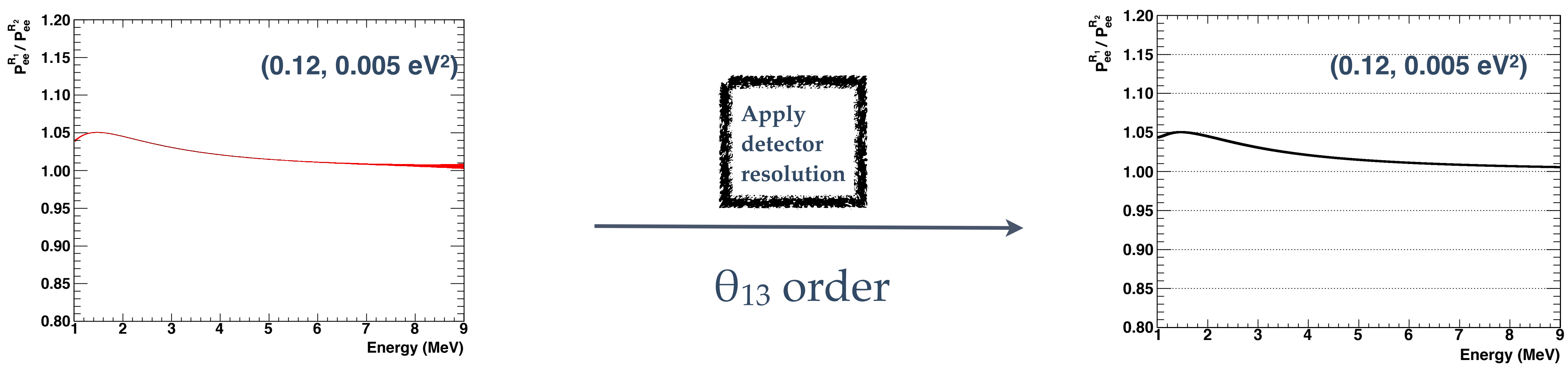




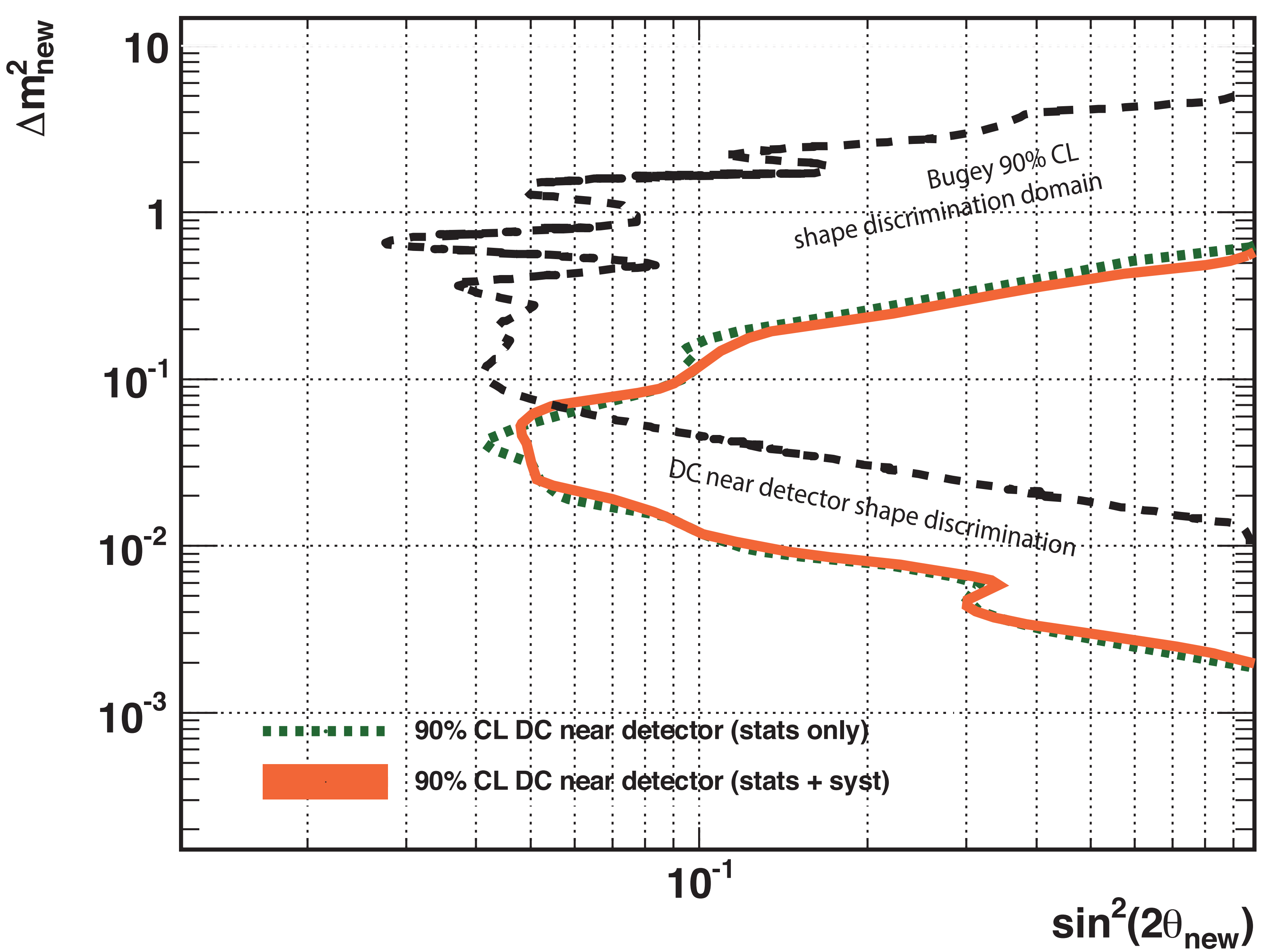
Apply detector resolution



At even lower Δm^2 the detector resolution has less of an impact:



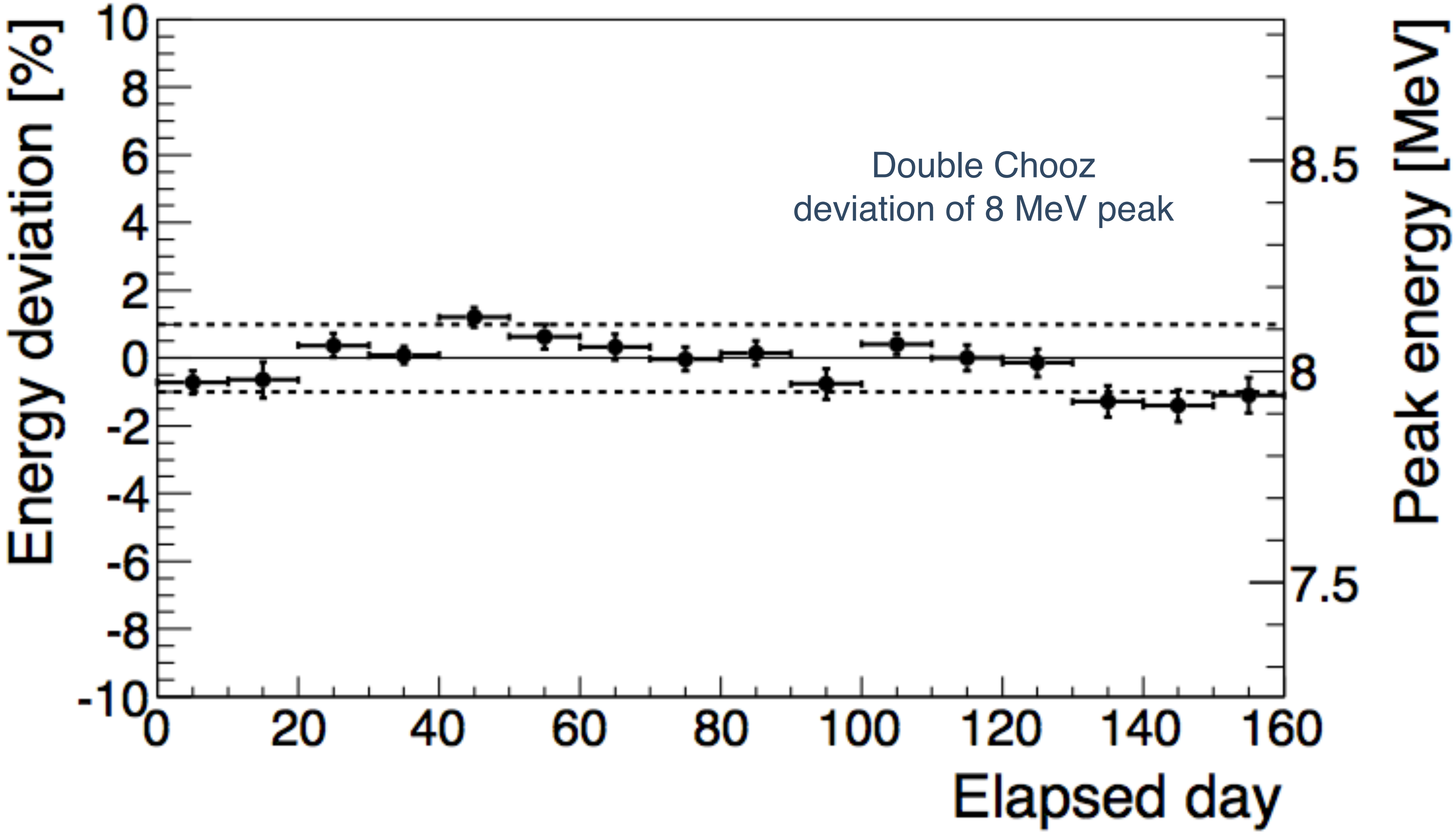
Result first: domain with 5 year of near detector



What are these systematics?

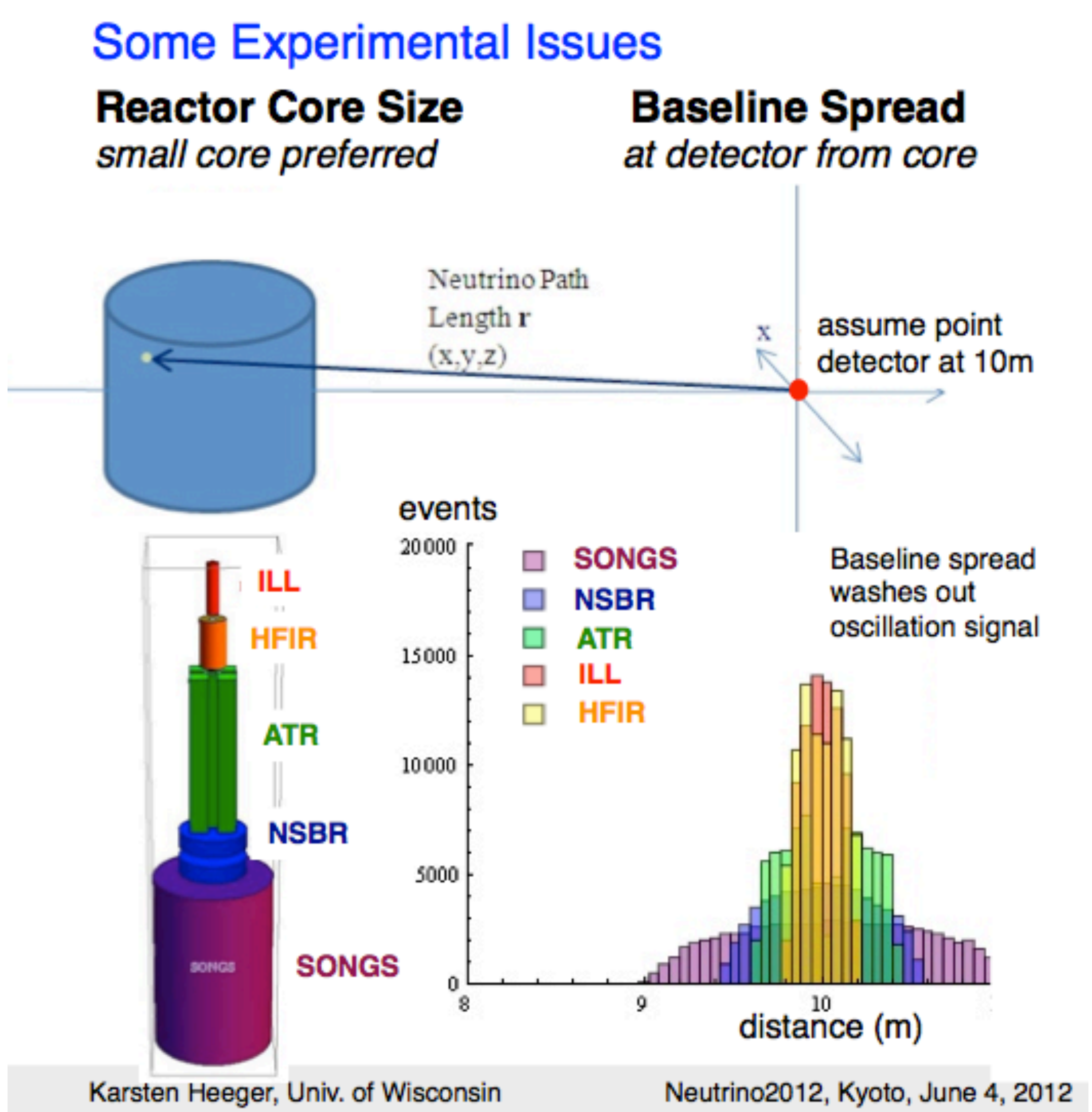
Systematic Uncertainties from the detector

-resolution used (7 +/- 1)%
-energy scale stability ~1%

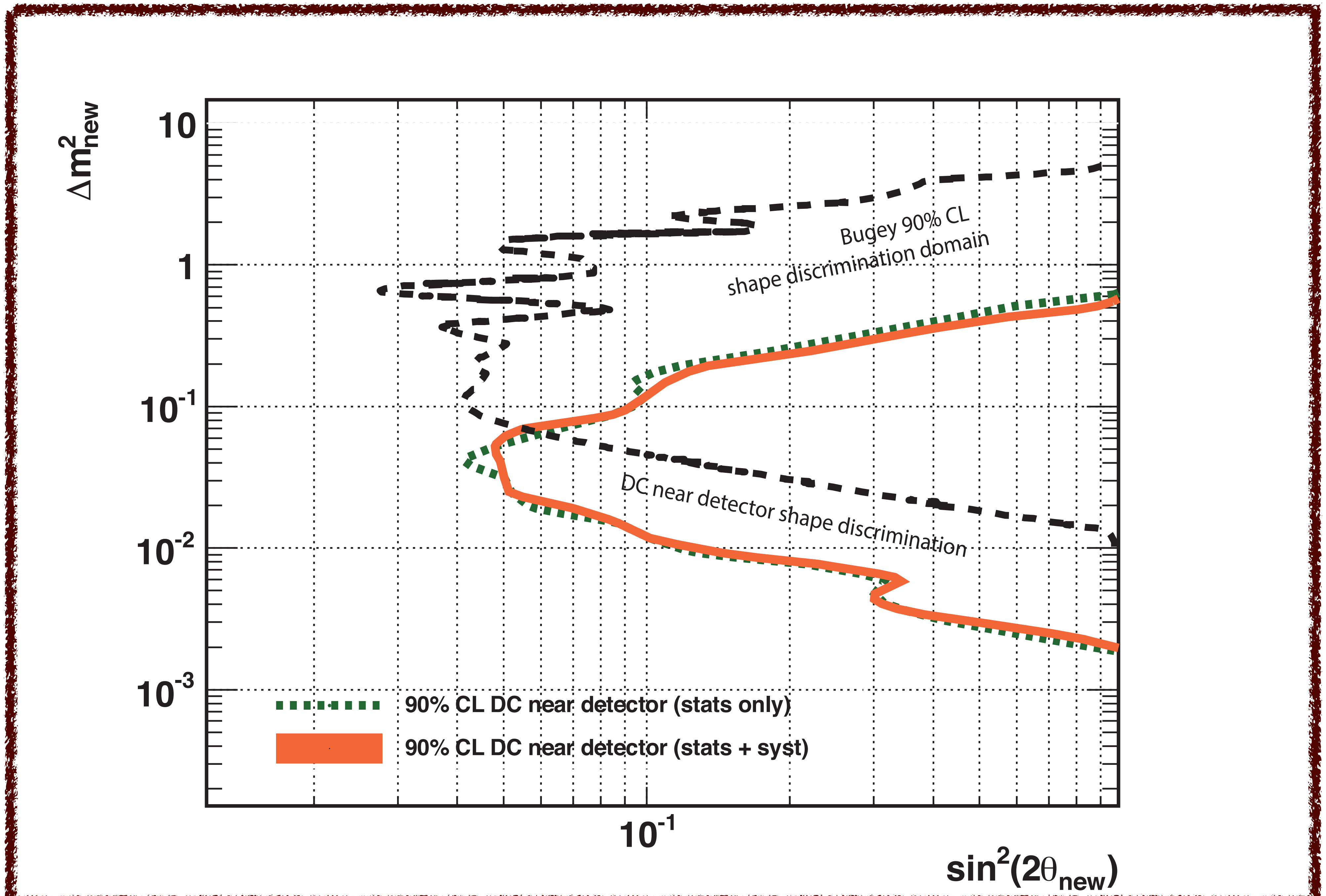


Systematic Uncertainties from the reactor

-Full loading < 0.01%
-Reactor core size of 3.47 meter



Exclusion domain with 5 year of near detector operation + shape systematics

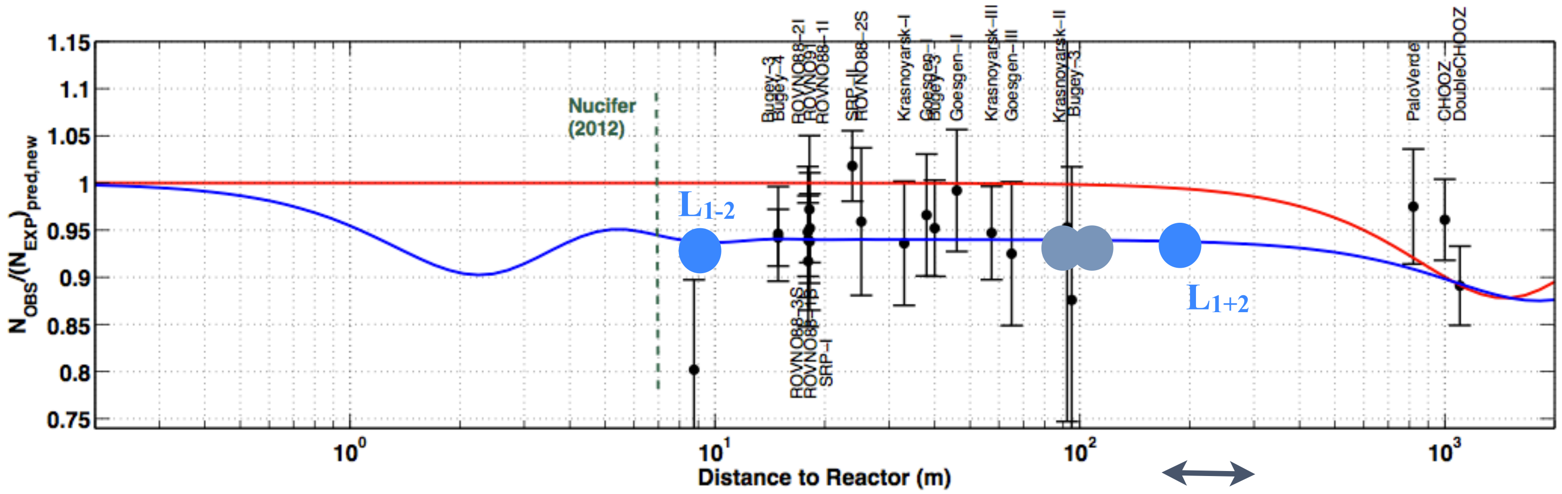


To Do from the Davis group:

- Add rate constraint with appropriate systematics
- Look at better performing detectors (better energy resolutions)
- Try same analysis in L/E instead of as a function of E
- Optimize position for new experiment to probe higher Δm^2
- Optimize binning strategy for different Δm^2 domain

Conclusions

- The DC near detector experiment is being built (no cost) and offers sensitivity in a region of phase space not explored before
- Formalism developed can be applicable for different experimental sites. Braidwood is a good example, 2 identical cores separated by ~100 m
- The choice of the location of the detector is paramount: L_{1-2} and L_{1+2} should be optimized for specific detector set-up: for example **with L_{1-2}=10~15 meters**, the ILL region might be probed by the interference terms



Backup: Sensitivity map

Going in a unexplored region