A new method for a sterile neutrino search in a 2-reactor 1-detector configuration

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Topics of this talk:

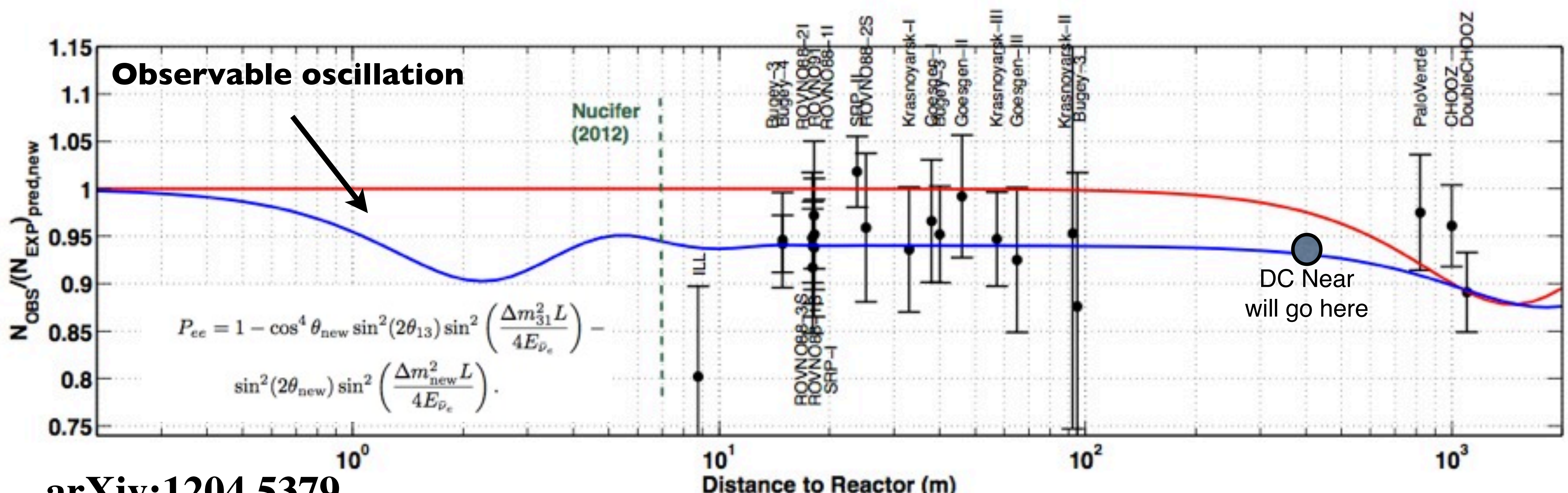
- Sterile neutrinos and the reactor neutrino anomaly
- Difficulties in current analysis techniques
- Describe a 2-reactor 1-detector analysis technique that provides a new approach to searching for sterile neutrinos
- Case Study: apply technique to Double Chooz near detector

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}, but that 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

The rate has a best fit value of ($\sin^2(2\theta_{new})$, δm^2) = (0.12, **0.5 eV²**). The best fit value is ruled out by shape constraint. New best fit value: ($\sin^2(2\theta_{new})$, δm^2) = (0.12, **2 eV²**)

Rate only

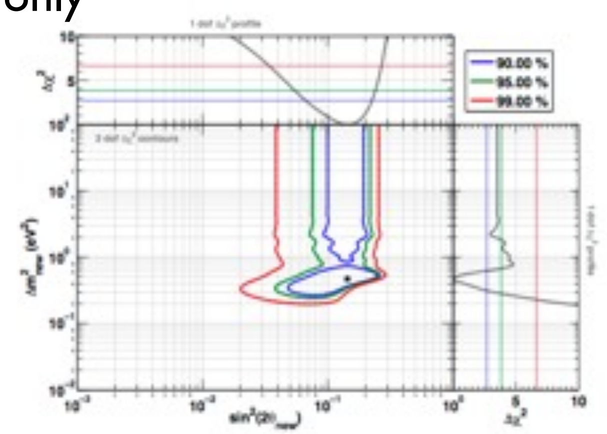


Figure 58. Allowed regions in the $\sin^2(2\theta_{new}) - \Delta m^2_{new}$ plane obtained from the fit of the reactor neutrino data, without any energy spectra information, to the 3+1 neutrino hypothesis, with $\sin^2(2\theta_{13}) = 0$. The best-fit point is indicated by a star.

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Bugey

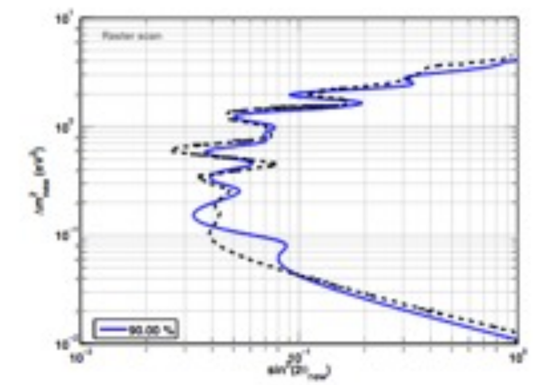

FIG. 2. 90% C.L. exclusion domains obtained in the Δm^2-$\sin^2(2\theta)$ plane from a raster scan of Bugey-3's data. Our result (continuous line) is in good agreement with the original result from [4] (dashed line), excluding oscillations such that $0.06 < \Delta m^2 < 1$ eV² for $\sin^2(2\theta) > 0.05$.

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Rate + Bugey

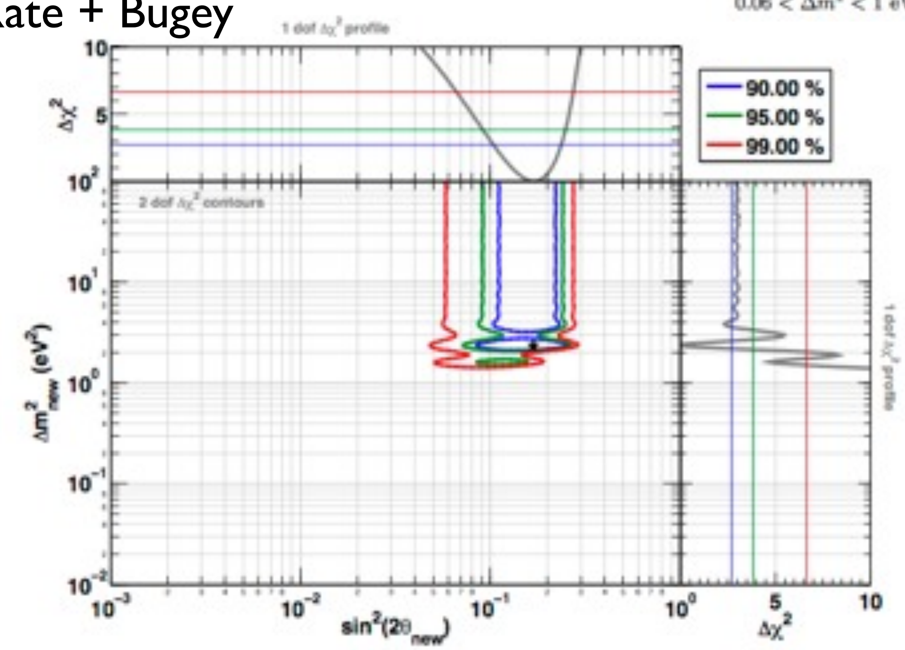
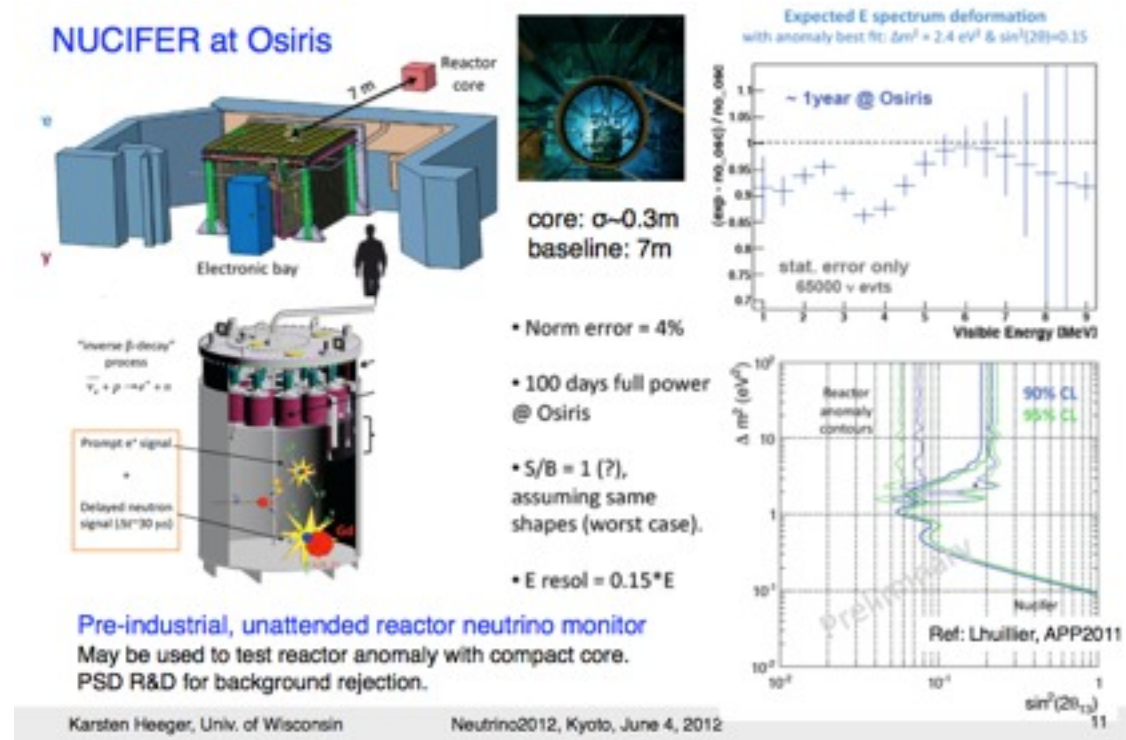


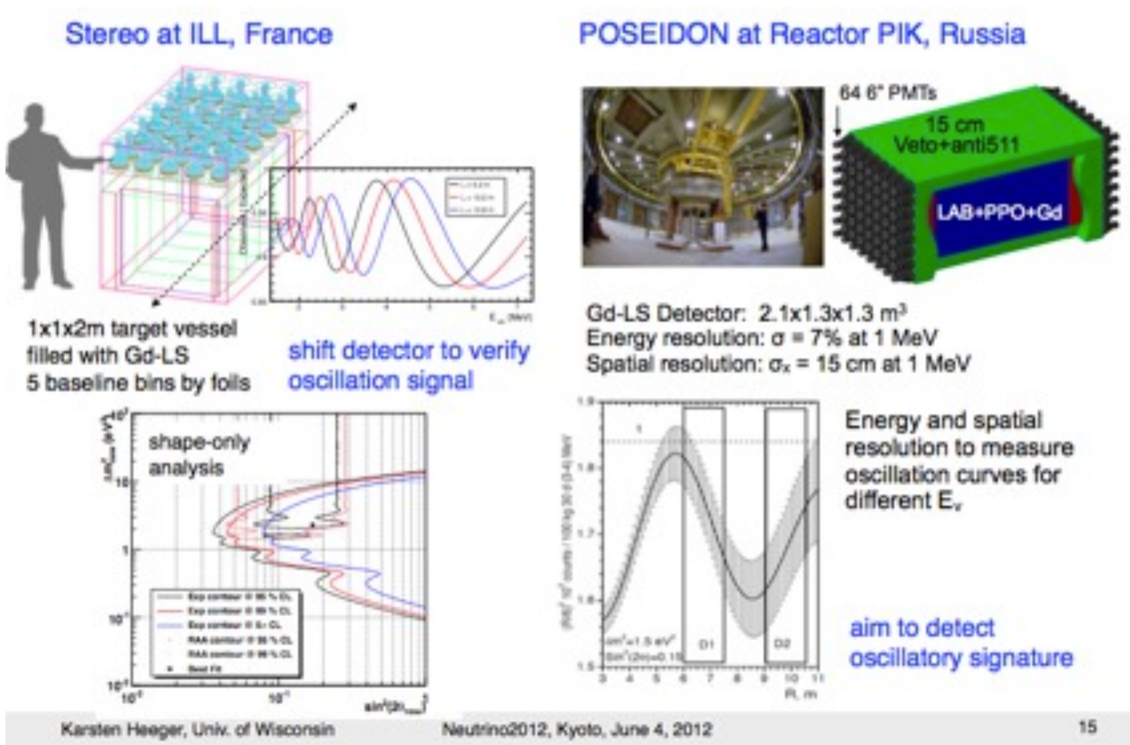
Figure 60. Allowed regions in the $\sin^2(2\theta_{new})$–Δm^2_{new} plane from the combination of reactor neutrino experiments, the Gallex and Sage calibration sources experiments, and the ILL and Bugey-3-energy spectra. The data are well fitted by the 3+1 neutrino hypothesis, while the no-oscillation hypothesis is disfavored at 99.97% C.L (3.6 σ).

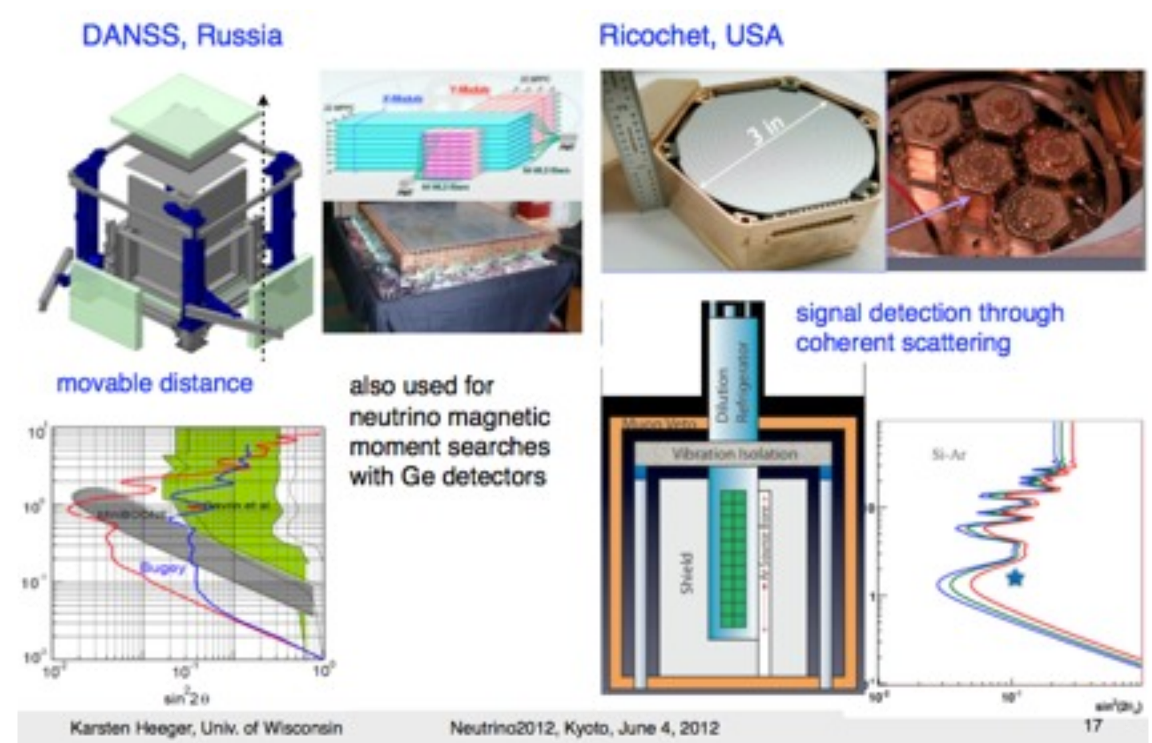
arXiv:1204.5379

Future Experiments to measure L/E oscillation

- Closer to Reactor :
  SCRAAM, Nucifer, Stereo, ...
- Appearance:
  π DAR, K DAR, see J. Spits talk this morning





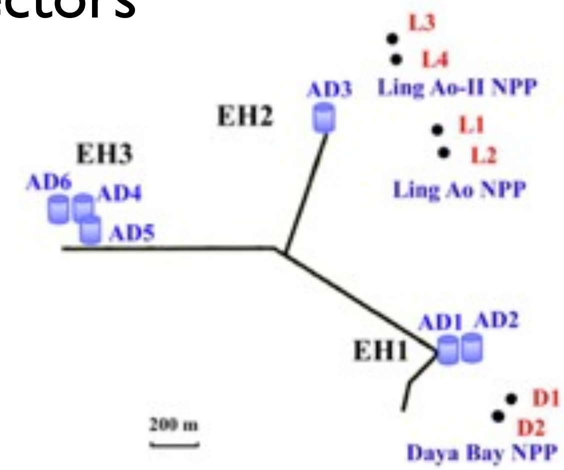


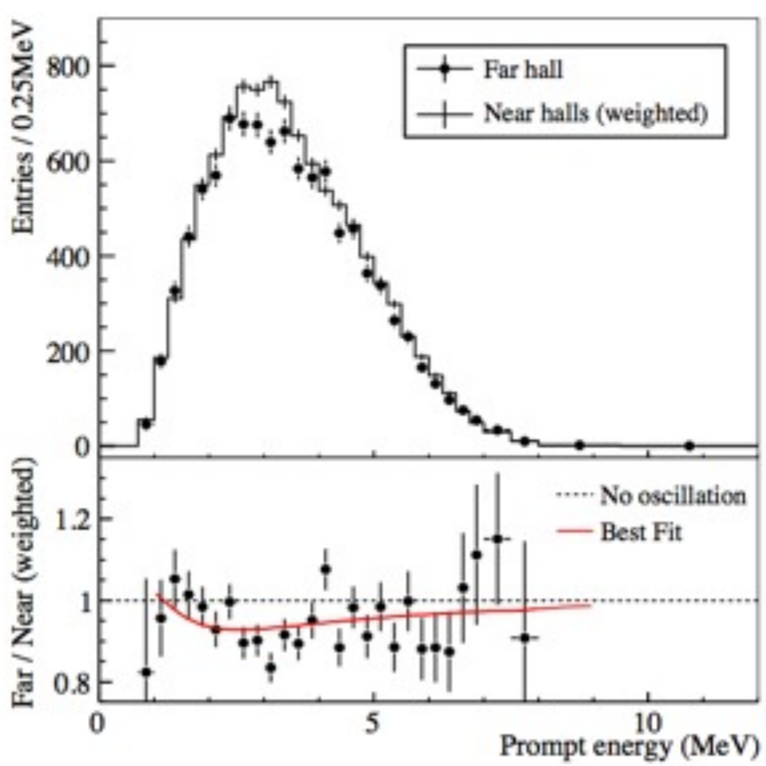
Traditional way of looking at a reactor-detector relationship:

Daya Bay

6 2.9 GWth reactors

6 detectors





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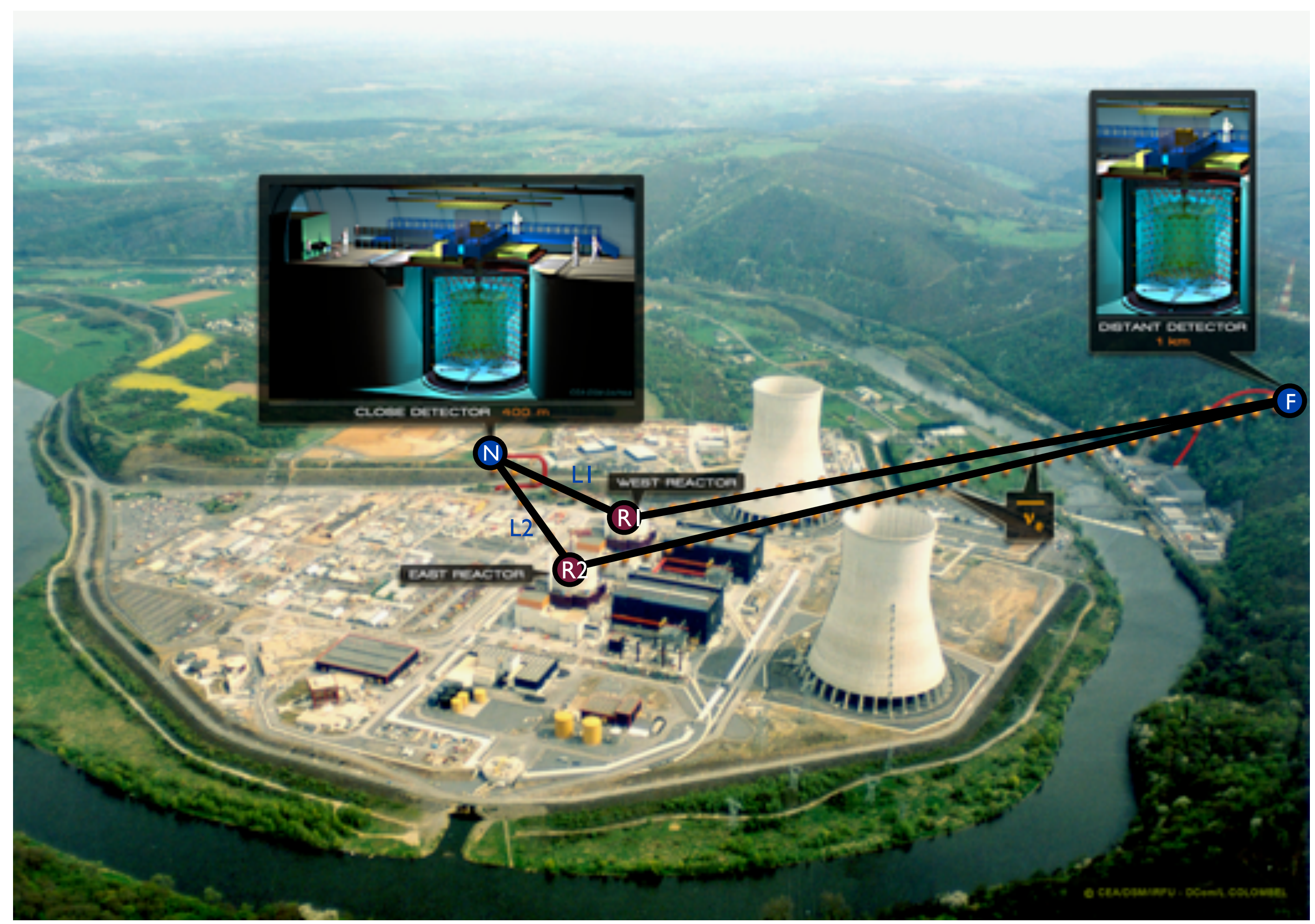
Double Chooz Configuration:

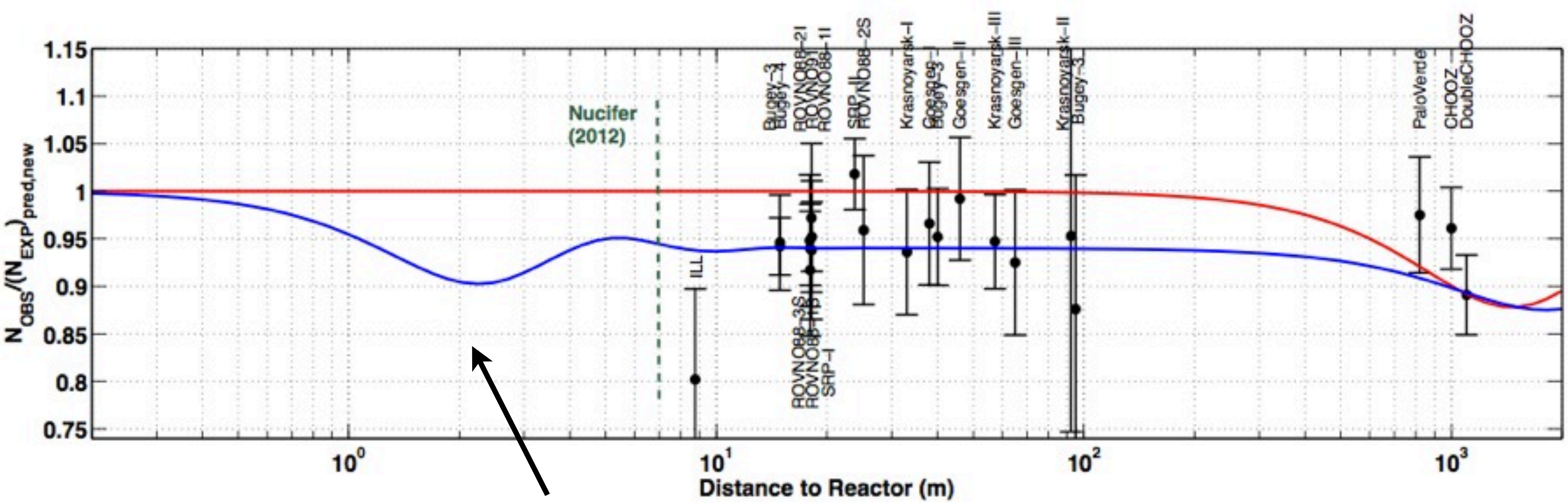
Two 4.25 GWth reactors (**1,2** for this talk)

Two detectors (**Near, Far**)



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 $\sin^2(2\theta_{14})$ term will average out to 1/2 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

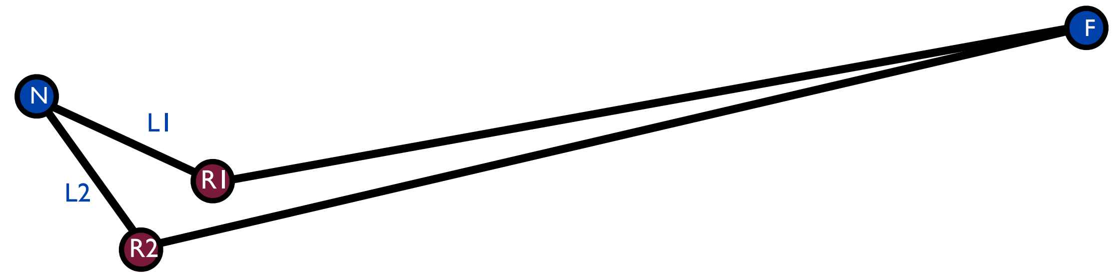


distance dependent rate is difficult

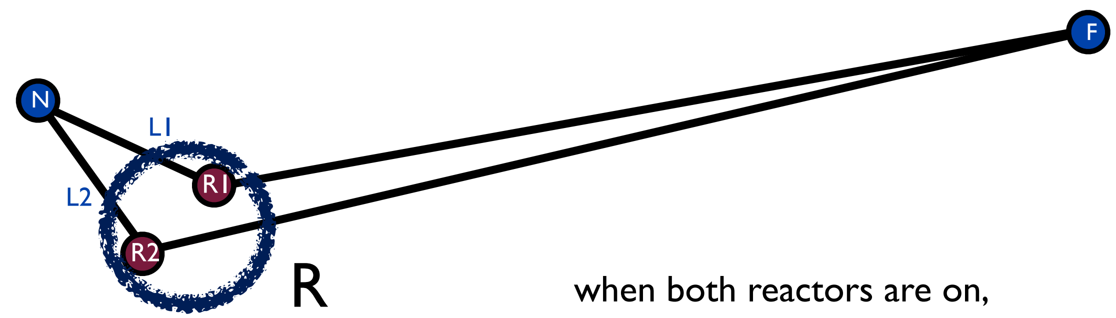
Traditional way of looking at a reactor-detector relationship (DC case study)

Double Chooz:

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



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



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

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

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

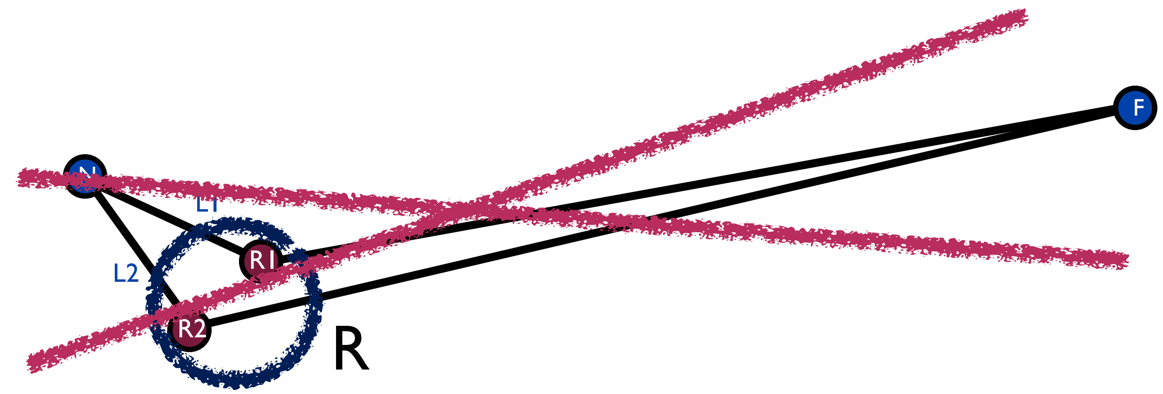
Do not have the two reactor running at the same time (luckily, we don't have to convince anyone, this happens naturally)

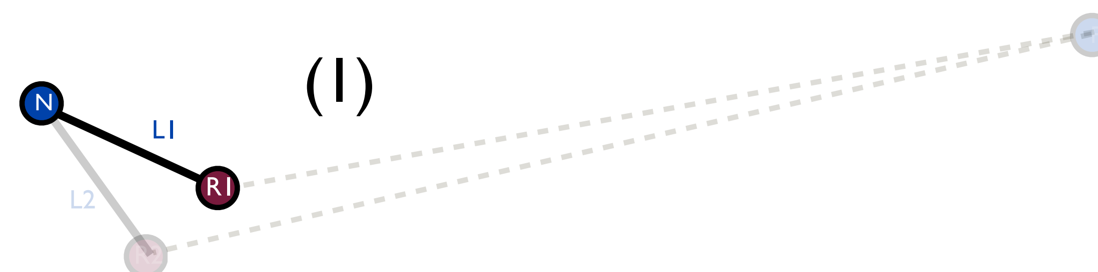
Collect data when Reactor 1 is on and Reactor 2 off and vice versa

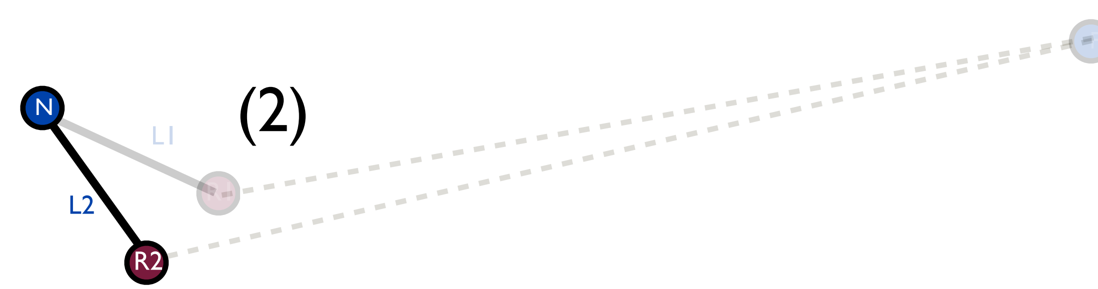
One can then think of a **near and far reactor**

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**





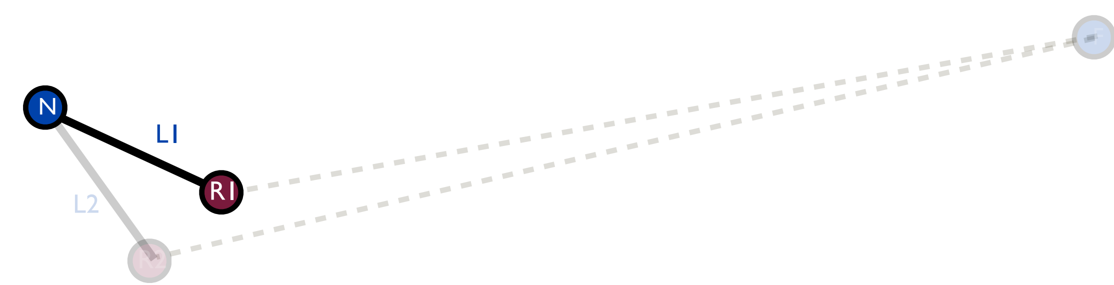


In a shape only analysis, major detector related systematics (fast neutrons, 9Li production, ...) can be constrained

A quantitative case study : DC Near detector

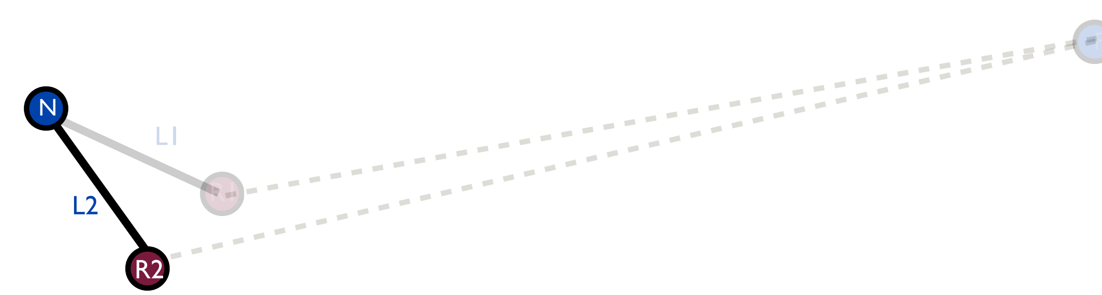
Assumption for this analysis:

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



Reactor 1-Near detector :

- 351 meters away from DC Ndetector
- ~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 from the ratio of the oscillated spectra:

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

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do some math

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

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)

identify 4 baselines

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

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

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

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

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When α is small, the expression simplifies there is 3 important baselines

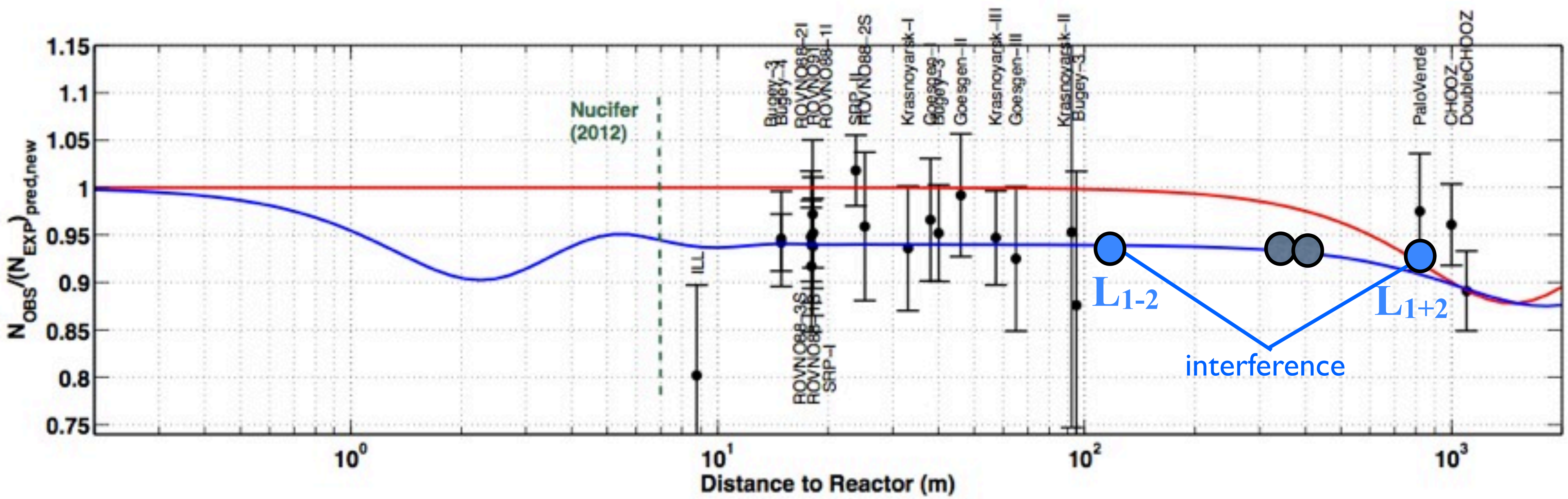
$$\frac{P^{R_1}_{ee}}{P^{R_2}_{ee}} \approx 1 + \left[1-\alpha^2 \sin^2(\beta L_2)\right] \left[\alpha^2 \sin(\beta L_{2-1}) \sin(\beta L_{1+2})\right] + O(6) + ...$$

Interference terms depend on sin and not $\sin^2$

What can be probed with these baselines?

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

Baselines probed by ratio analysis



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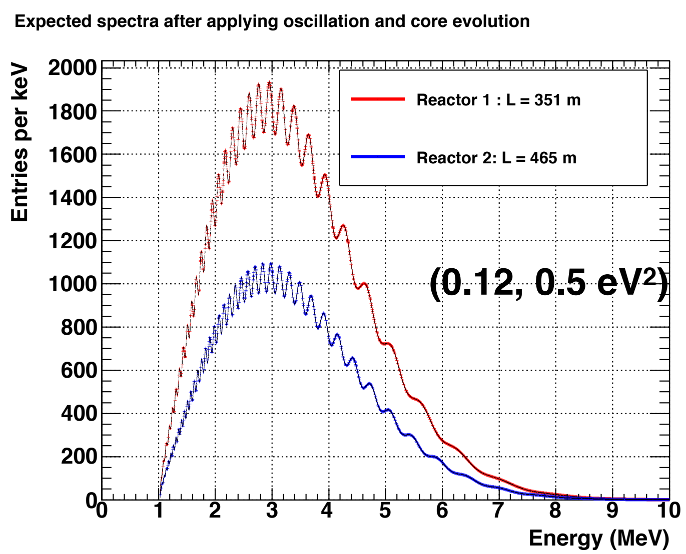
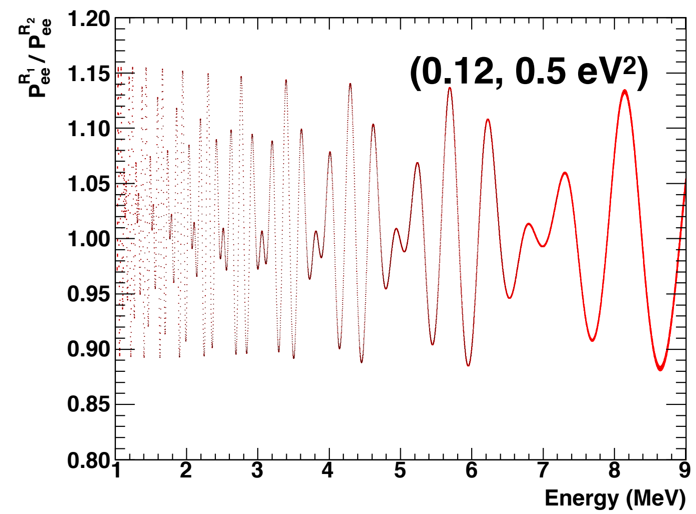
How is this ratio observed in a detector?

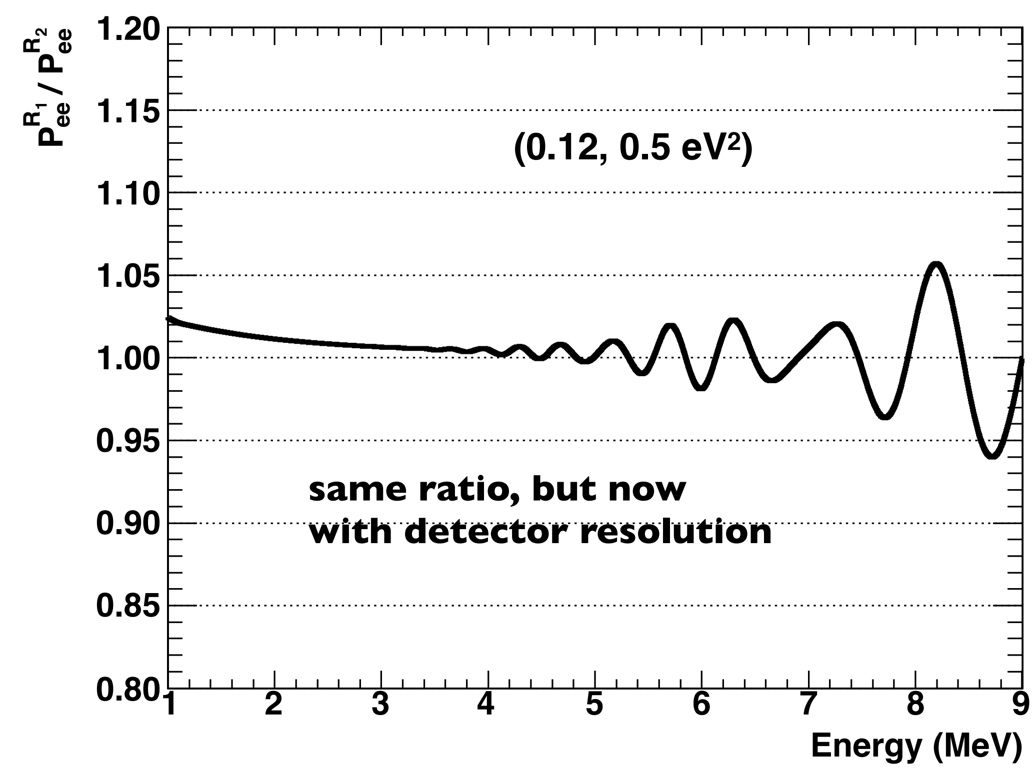
- Convolve 4th neutrino with 3-neutrino oscillation
- Make appropriate livetime, core evolution and distance corrections
- Finally, convolve with detector energy resolution and finite core size



take ratio →



Apply detector resolution



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

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

Rate

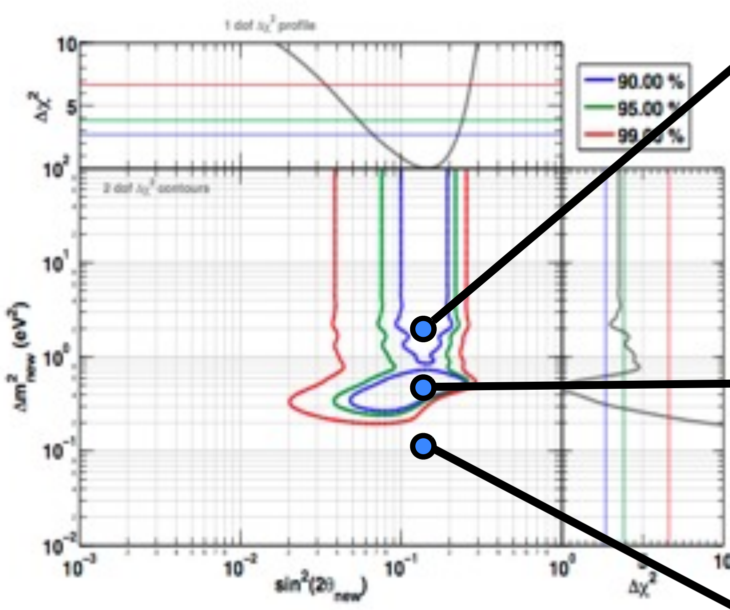
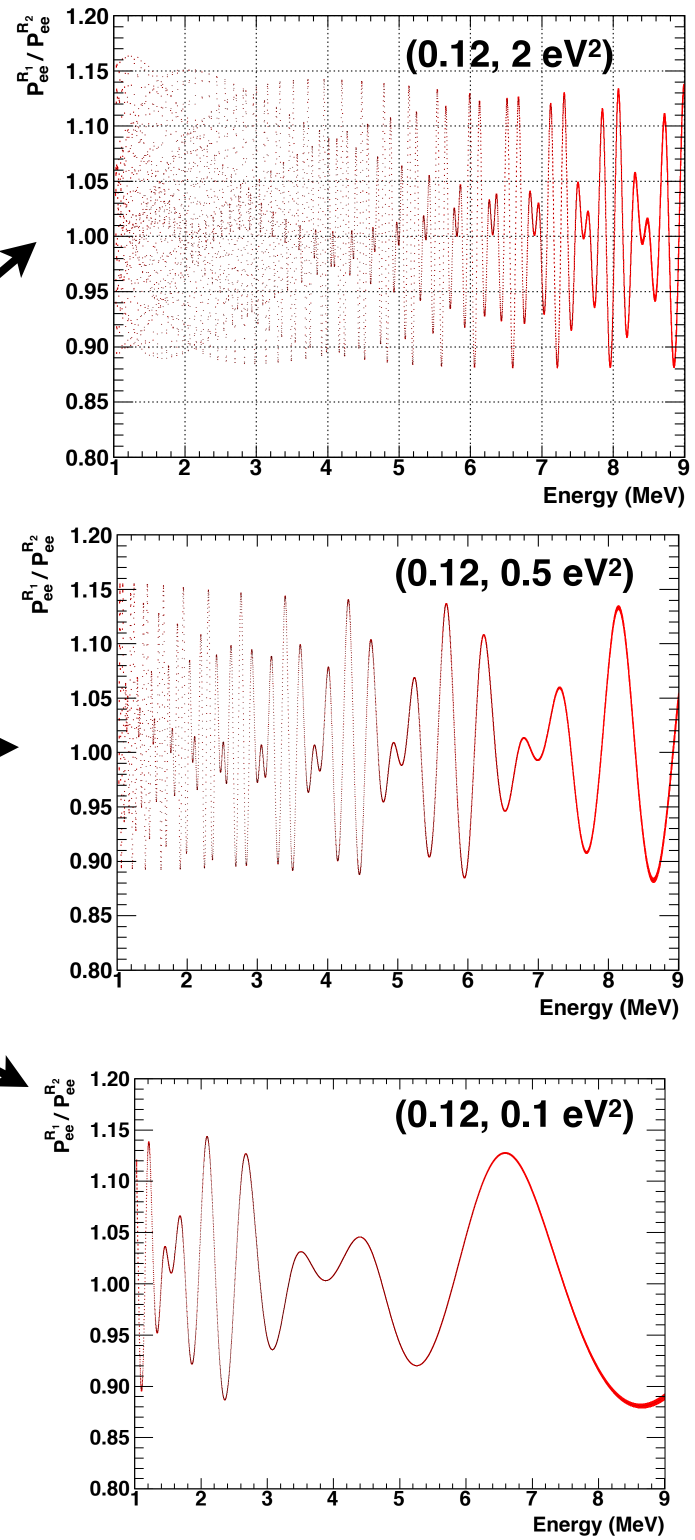
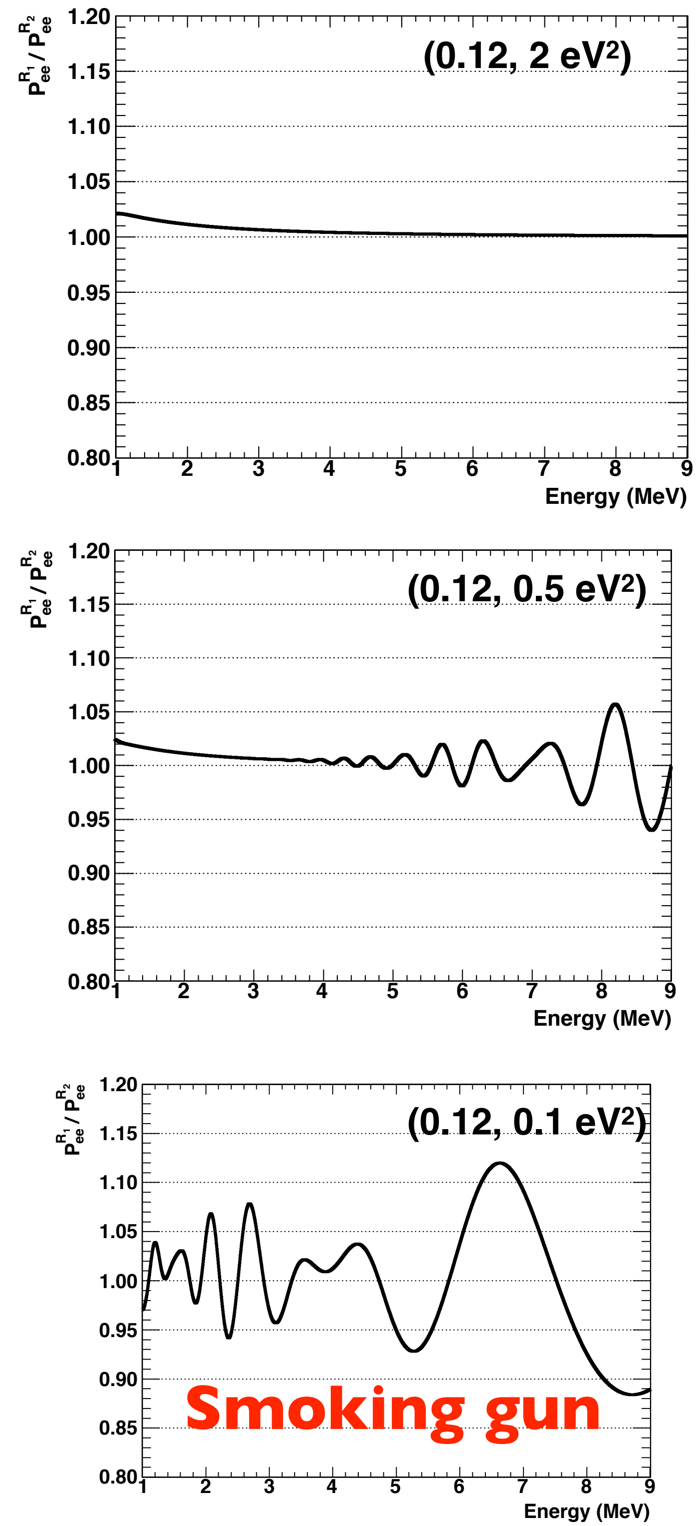


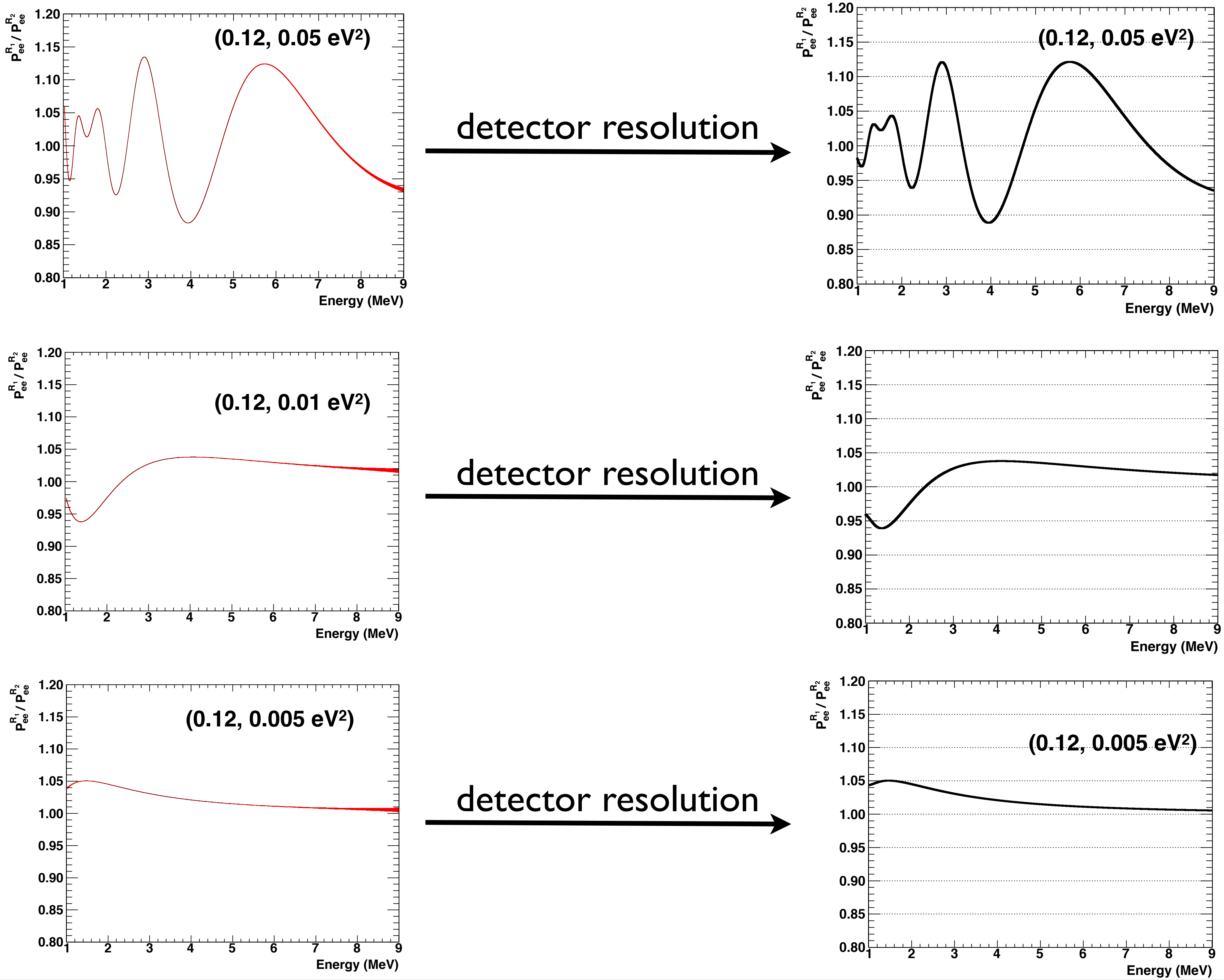
Figure 58. Allowed regions in the $\sin^2(2\theta_{new}) - \Delta m^2_{new}$ plane obtained from the fit of the reactor neutrino data, without any energy spectra information, to the 3+1 neutrino hypothesis, with $\sin^2(2\theta_{13}) = 0$. The best-fit point is indicated by a star.



Detector resolution applied



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

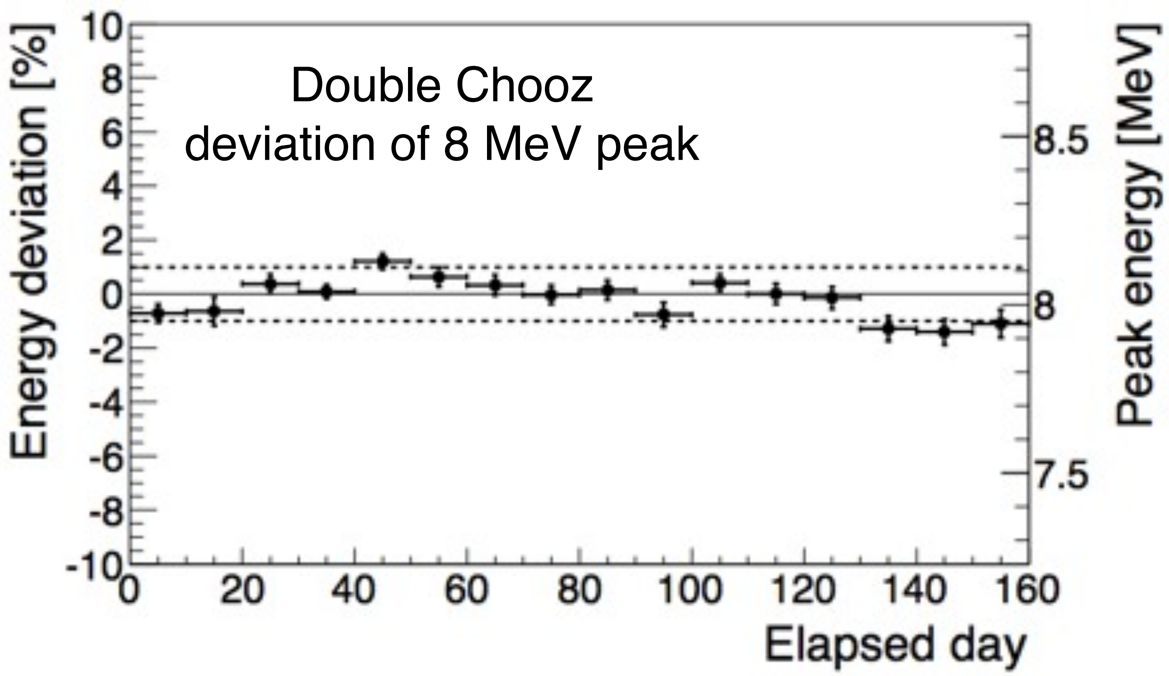


Uncertainties

Shape Uncertainties in ratio: Detector

-resolution used (7 +/- 1)%

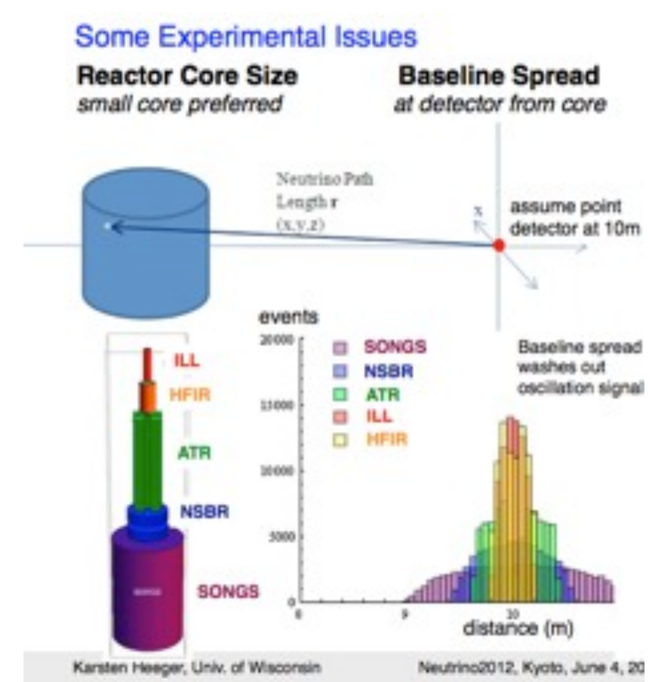
-energy scale stability ~1%



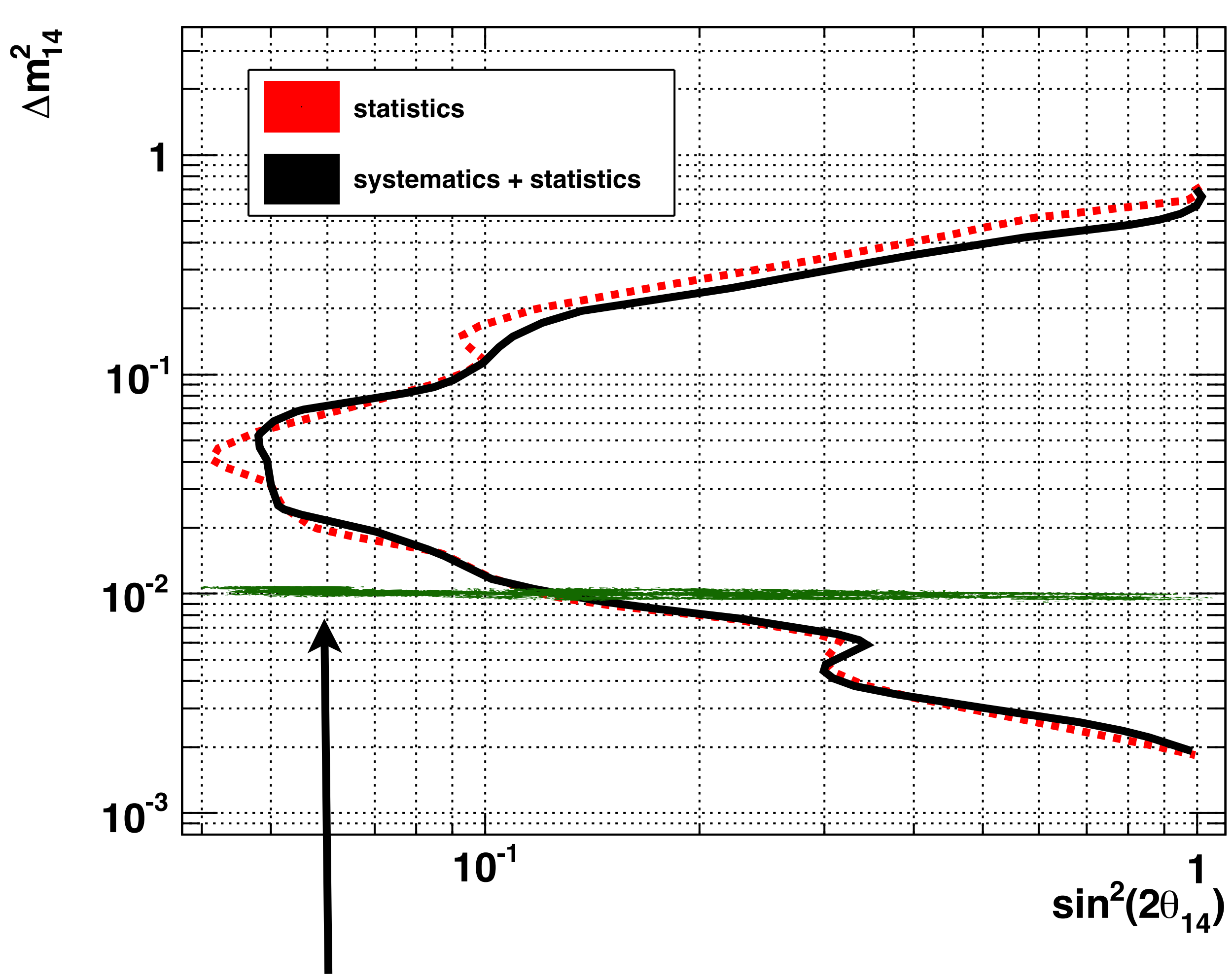
Shape Uncertainties in ratio : Reactor

-Full loading < 0.01%

-Reactor core size of 3.47 meter



Results for this case study: exclusion domain with 5 year of near detector operation + shape systematics



Will gain discrimination power below 0.01 eV²

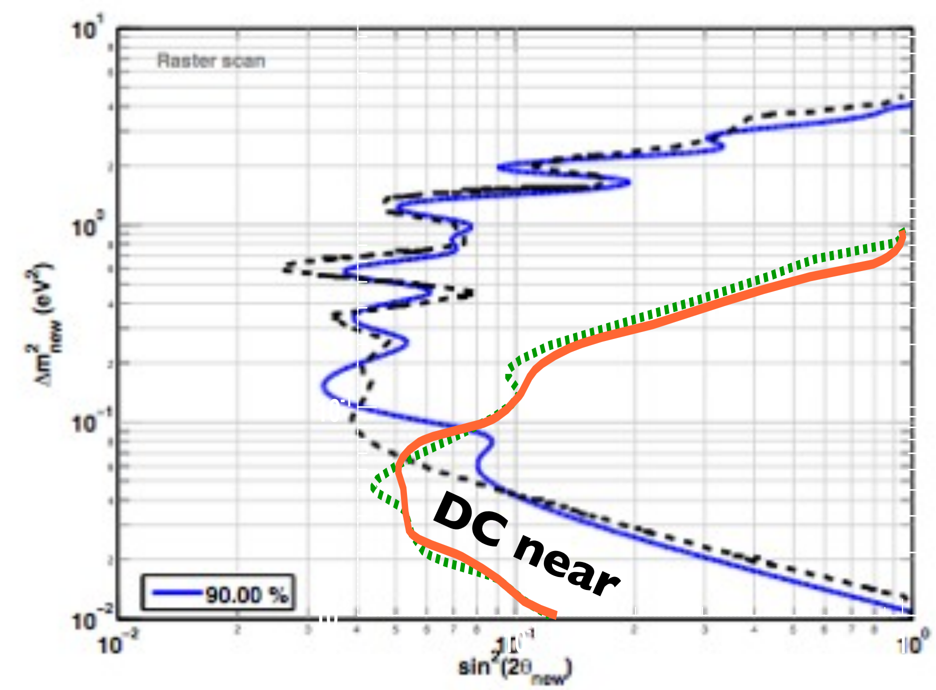


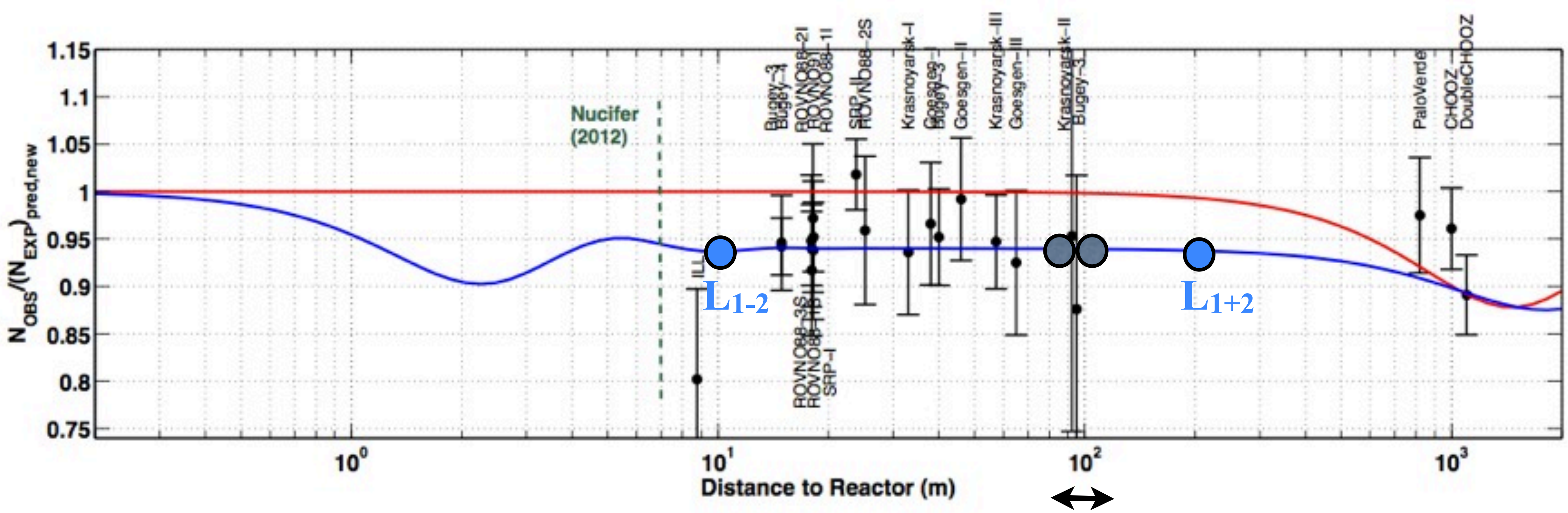
FIG. 2. 90% C.L. exclusion domains obtained in the Δm^2-$\sin^2(2\theta)$ plane from a raster scan of Bugey-3's data. Our result (continuous line) is in good agreement with the original result from [4] (dashed line), excluding oscillations such that $0.06 < \Delta m^2 < 1$ eV² for $\sin^2(2\theta) > 0.05$.

To Do:

- Add rate constraint with appropriate systematics
- 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, however core fission mapping needs to be implemented to assess the effect of core washing out



Backup: Sensitivity map

Going in a unexplored region