The Self–Calibration Effect and GLoBES

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Workshop on Physics and Applications of the GLoBES software

Outline

1. Basic idea and motivations from neutrino physics
2. Analytical discussion of the CalEffect
3. The (tiny) CalEffect in Reactor Experiments
4. Application of the CalEffect to Earth matter effects on Supernova neutrinos

Outline

Neutrino physics is entering the stage of precision measurements:

- Most of the oscillation parameters are known (except CP–phase δ, the exact value of θ_{13} and the sign of Δm^2_{A}), but not very precisely: e.g. the relative uncertainty of $\sin^2 2\theta_{12}$ is still about 10%.
- Therefore, future experiments will need good background reduction and control of the uncertainties, as well as a good energy resolution and calibration. $\rightarrow$ This is crucial!!!
- The GLoBES software can be used to study the performance of such experiments and is also a tool to judge how much can be gained from different proposed experimental setups.

J. Kopp, M. Lindner, AM: Detector Self–Calibration using characteristic Backgrounds, hep-ph/0702xxx

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Energy calibration of neutrino detectors

There exist different methods for the energy calibration of a neutrino detector:

- radioactive sources with known properties
- accelerated lepton beams
- indirect methods (measurements of secondary particles after the neutrino interaction)

Common: they are all only sensitive to charged particles $\Rightarrow$ uncertainties in the primary neutrino interactions are not taken into account

BETTER (in that sence): direct calibration with neutrinos

PROBLEM: the rates, as usual...

BUT: for future experiments (like e.g. LENA: 50 kt Large Liquid Scintillator Detector), this may be different!

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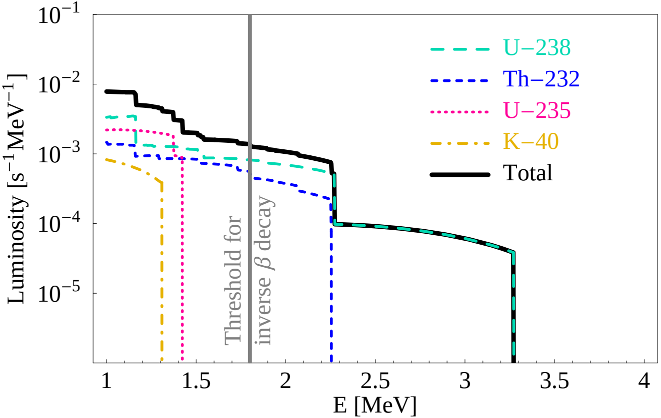
The basic idea

- If there is a natural background with reasonable rates and a characteristic shape, this could be used to perform (or, more realistic: support) the energy calibration.
- For a LLSD, this could be the Geo–neutrino background for $\bar{\nu}_e$'s:



Features of the Geo–neutrino spectrum

- It has characteristic steps (cut–offs) at well–known energies: relevant (above threshold for inverse β–decay) are mostly the Th–232 cutoff at $\approx$ 2.25 MeV and the one from U–238 at $\approx$ 3.3 MeV.
- These steps are (of course) independent of the actual rates. $\Rightarrow$ As long as one can see them, it will be possible to pin down the corresponding energies.
- The Geo–neutrino rates in e.g. LENA should be $\sim$ 1500 events per year, which would be enough. K. A. Hochmuth et al.: hep-ph/0509136

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Outline

The χ^2 function

As usual with GLoBES, we perform a χ^2 analysis. $\Rightarrow$ A simplified (Gaussian approximation, neglecting all errors except spectral distortions a_i and energy calibration b) version of this χ^2 function is:

$$\chi^2 = \sum_i \left[\frac{\left(T_i(a_i, b) - N_i\right)^2}{N_i} + \frac{a_i^2}{\sigma_i^2} \right]$$

$\hookrightarrow$ a_i: nuisance parameters (e.g. global detector normalization (bin–independent in that case))
$\hookrightarrow$ $\sum_i$: sum over all bins
$\hookrightarrow$ $N_i = \sigma_{N_i}^2$: statistical errors of the event rates for each bin
$\hookrightarrow$ T_i & N_i: theoretical and "true" event rates

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Binning and energy calibration

Calculation of the theoretical event rates as usual in GLoBES (for details, see manual... or ask the authors):

$$T_i = (1 + a_i)\tilde{N}_i(b),$$

$$\tilde{N}_i(b) = (1 + b) \cdot \left[\left(N_{\lfloor \delta(i) \rfloor + 1} - N_{\delta(i)} \right) \cdot (\delta(i) - \lfloor \delta(i) \rfloor) + N_{\lfloor \delta(i) \rfloor} \right],$$

$$\delta(i) = b \cdot (i + t_0 + \frac{1}{2}) + i.$$

$\hookrightarrow$ last two lines: can cause wrong binning of the events
ASSUMPTION: We assume no prior knowledge on the energy calibration b (no penalty term). However, we do assume b to be small enough to take $\lfloor \delta(i) \rfloor = i$ (b cannot shift events into the next bin).

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Expansion of the χ^2 function

Combining the normalization and spectral uncertainties gives:

$$T_i = (1 + a_i + b)\left[(N_{i+1} - N_i) \cdot b \cdot (i + t_0 + \frac{1}{2}) + N_i\right]$$

Then, up to first order in the small quantities b^2, a_i^2, and ba_i, the χ^2 function is:

$$\sum_i \left(\frac{1}{N_i}\left[(1 + a_i + b)N_i + b(N_{i+1} - N_i) \cdot (i + t_0 + \tfrac{1}{2}) - N_i\right]^2 + \frac{a_i^2}{\sigma_i^2}\right)$$

$\hookrightarrow$ Neglecting terms such as $\mathcal{O}(b^3)$ an higher in χ^2 means neglecting terms of $\mathcal{O}(b^2)$ and $\mathcal{O}(ba_i)$ in T_i.
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Minimum of the χ^2–function

The energy calibration for the minimum χ^2 function turns out to be

$$b = -\frac{\sum_i \frac{1}{N_i} a_i N_i \gamma_i}{\sum_i \frac{1}{N_i} \gamma_i^2},$$

where $\gamma_i = N_i + (N_{i+1} - N_i)(i + t_0 + \frac{1}{2})$.

Two extreme cases:

- very smooth energy spectrum: $N_{i+1} - N_i \ll N_i \Rightarrow \gamma_i \approx N_i \Rightarrow$ Then, b should be of the same order as a_i.
- energy spectrum with large steps: then, at least for some bins, the difference $(N_{i+1} - N_i)$ must be (much) larger than N_i giving $\gamma_i \gg N_i \Rightarrow$ since γ_i appears two times in the denominator of b, but only one time in the numerator, it must hold that $b \sim \frac{a_i \gamma_i}{\gamma_i^2 / N_i} \to 0$ $\Rightarrow$ CalEffect!

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Reactor experiments with a LLSD

We have discussed the physics potential of a detector like LENA using mobile and stationary reactors (e.g. *SMALL*–scenario: 0.5 $\mathrm{GW_{th}}$, 2 years running time): J. Kopp, M. Lindner, AM, M. Rolinec: JHEP01(2007)053 (hep-ph/0606151)

Modification of GLoBES: user defined χ^2 function to include all complicated backgrounds

$$\chi^2 = \sum_i \frac{1}{N_i}\left[T_i(a_{\rm norm}, a_{\rm det}, a_{\rm reac}, a_{\rm U}, a_{\rm Th}, b) - N_i\right]^2 + \\ + \frac{a^2_{\rm norm}}{\sigma^2_{\rm norm}} + \frac{a^2_{\rm det}}{\sigma^2_{\rm det}} + \frac{a^2_{\rm reac}}{\sigma^2_{\rm reac}} + \frac{a^2_{\rm U}}{\sigma^2_{\rm U}} + \frac{a^2_{\rm Th}}{\sigma^2_{\rm Th}} + \frac{b^2}{\sigma^2_b}$$

$\hookrightarrow$ backgrounds: other reactors, Geo–neutrinos from Th & U

$\hookrightarrow$ This feature is now implemented in the new Version 3.0:

```
glbDefineChiFunction
```

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$$\chi^2 = \sum_i \frac{1}{N_i}\left[T_i(a_{\mathrm{norm}}, a_{\mathrm{det}}, a_{\mathrm{reac}}, a_{\mathrm{U}}, a_{\mathrm{Th}}, b) - N_i\right]^2 + \\ + \frac{a_{\mathrm{norm}}^2}{\sigma_{\mathrm{norm}}^2} + \frac{a_{\mathrm{det}}^2}{\sigma_{\mathrm{det}}^2} + \frac{a_{\mathrm{reac}}^2}{\sigma_{\mathrm{reac}}^2} + \frac{a_{\mathrm{U}}^2}{\sigma_{\mathrm{U}}^2} + \frac{a_{\mathrm{Th}}^2}{\sigma_{\mathrm{Th}}^2} + \frac{b^2}{\sigma_b^2}$$

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`glbDefineChiFunction`

Reactor experiments with a LLSD

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Considered situations for the Geo–neutrino Background

- **No Geo–neutrinos:** Only background from distant reactors. Geo–neutrinos do not exist.
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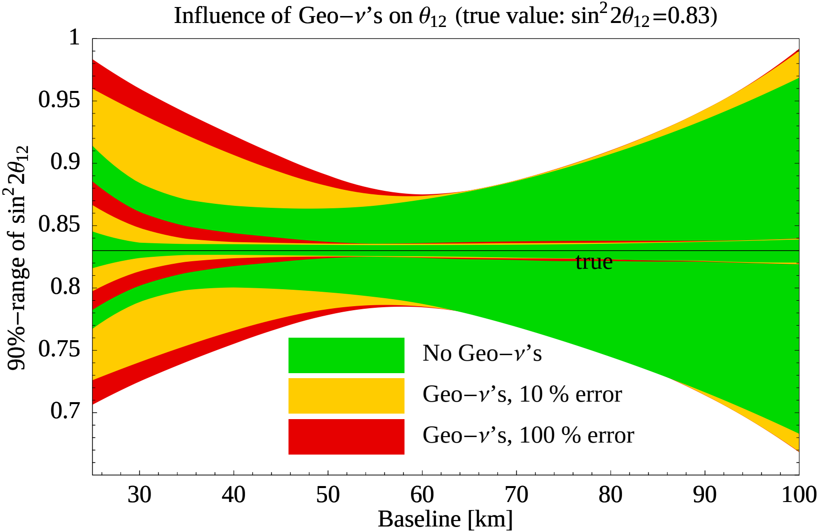
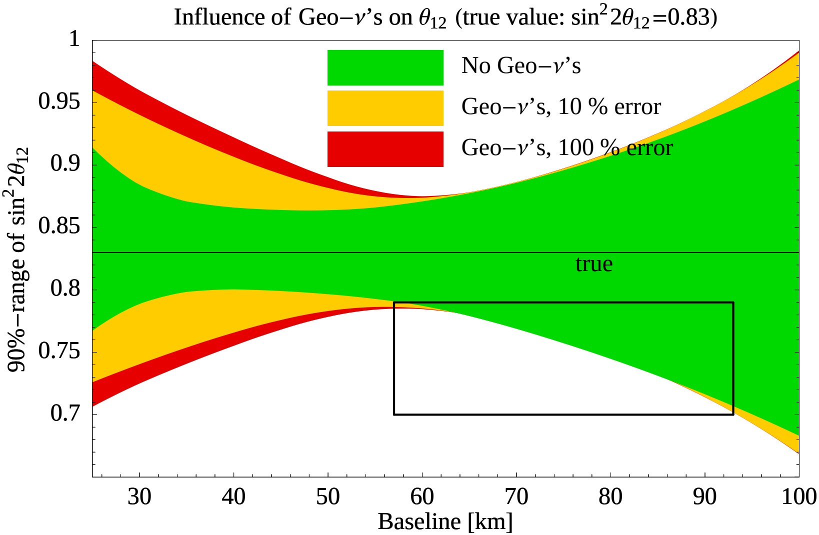
Resulting sensitivity plots

The 90%–range for $\sin^2 2\theta_{12}$ then looks like this:



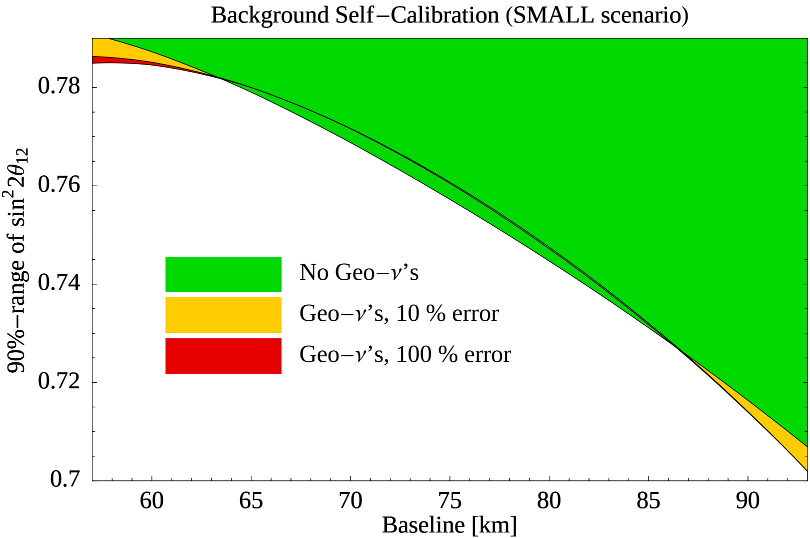
Resulting sensitivity plots

BUT: if one takes a closer look...



Resulting sensitivity plots

... things can be different!!



This is due to the CalEffect!

- In certain regions, the sensitivity of a measurement can be better with background than without.
- The reason for this seemingly paradoxial situation is that the background can give additional information, e.g. by characteristic lines.
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Outline

The (very) basics of SN neutrinos

- a supernova is essentially a neutrino black–body source ⇒ e.g. $\bar{\nu}_e$'s coming from supernovae have a thermal energy spectrum
- the $\bar{\nu}_e$ neutrinos that are produced in a supernova reach us as mass eigenstates $\bar{\nu}_1$ ⇒ the oscillations that appear inside the Earth are essentially $\bar{\nu}_1$–$\bar{\nu}_2$ oscillations
  ↪ therefore, we had to modify the GLoBES source code to implement oscillations of mass eigenstates in matter → interface for the implementation of non–standard physics in the new GLoBES version 3.0
- effect of the Earth matter on the power spectrum of SN neutrinos: "wiggles" on the otherwise smooth spectrum → for the analysis of these effects (e.g. to distinguish the mass orderings), the positions of these peaks are crucial ⇒ can be worsened by a wrong energy calibration ⇒ the CalEffect can help

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The Simulation

- effect of Earth matter: "wiggles" on the thermal energy spectrum of the SN neutrinos $\rightarrow$ better visible in the power spectrum (going to inverse energy units and taking the squared modulus of the Fourier transform of the resulting spectrum) $\Rightarrow$ the different oscillation modes are pointed out
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  $\Rightarrow$ predicts a flux ratio of $\frac{\Phi(\bar{\nu}_e)}{\Phi(\bar{\nu}_x)} = 0.8$
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Different cases for each Earth model

- propagation in vacuum: does not affect the power spectrum (of course, because it is just a travel of the neutrinos in space which is 12742 km longer, as if the Earth would not be present)
- perfect energy calibration: gives the "correct" wiggles due to Earth matter
- energy calibration error of 10%: gives a clearly separated curve with wrong positions of the wiggles
  $\hookrightarrow$ **NOTE:** This error in the energy calibration is clearly much too large for realistic cases!!! However, we wanted to point out the principle validity of the CalEffect and this is simply better visible with this assumption.
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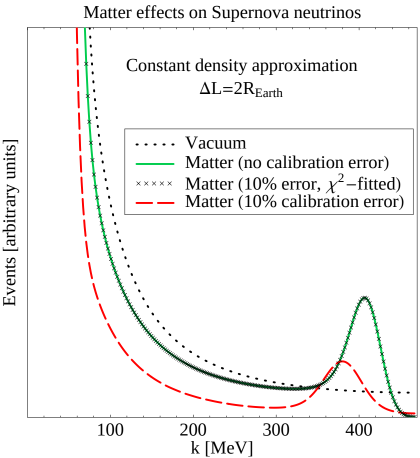
Power spectra of the SN neutrinos



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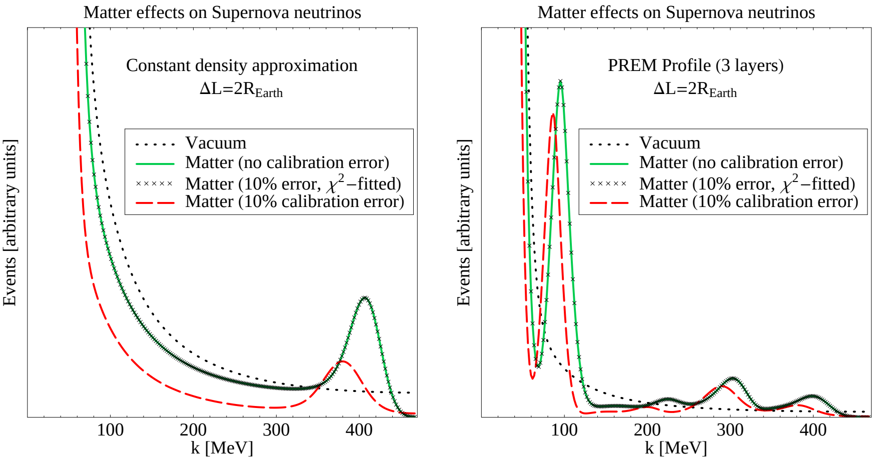

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Conclusions

- the CalEffect is an interesting possibility to exploit natural backgrounds that are present anyway in a neutrino experiment
- the effect applies to all situations with a suitable background source and high enough statistics
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