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T30d Theoretische Elementarteilchenphysik

Physics Potential of Future Reactor Neutrino Experiments

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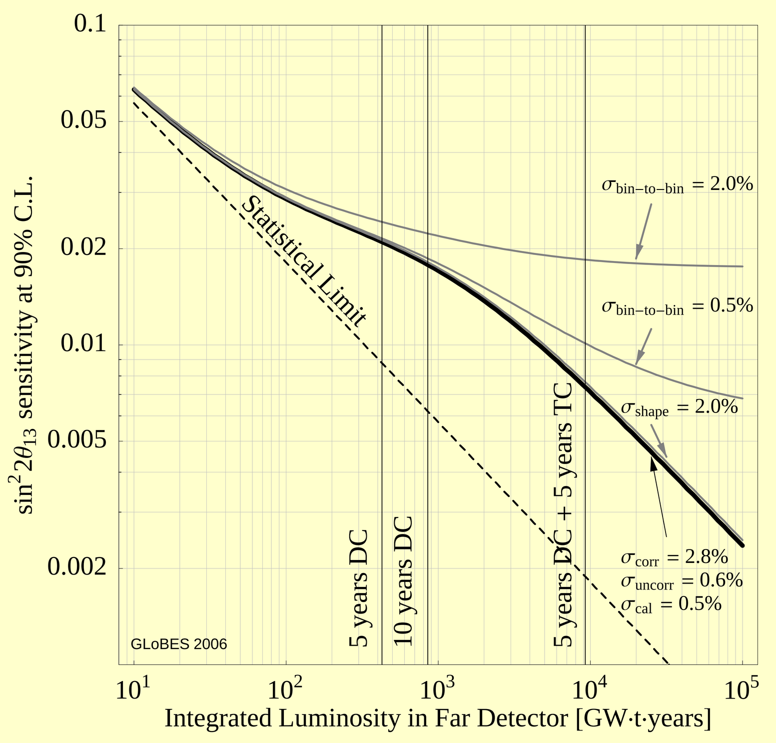
The main limitation for the precise determination of θ_{13} in a reactor neutrino experiment are systematical uncertainties. After giving an overview of the impact of different types of errors, we apply our considerations to near/far detector setups such as Double Chooz (and its possible upgrade, Triple Chooz), where the errors associated with the neutrino source cancel. This allows a sensitivity to $\sin^2 2\theta_{13}$ of ≈ 0.02 at the 90% C.L. Additionally we discuss more elaborate scenarios which turn out to be robust also to most errors associated with the detectors. We find that a realistic reactor experiment can reach a sensitivity of the order of $\sin^2 2\theta_{13} \approx 10^{-3}$. This will lead to a discussion of the role of reactor experiments in the global neutrino research program, in particular their complementarity to superbeams, and their impact on $0\nu\beta\beta$ decay experiments.

Systematical Errors

Next generation reactor neutrino experiments will have excellent statistics, so their sensitivity to θ_{13} is ultimately limited by systematical errors.

	Corr.	Typ. value
Reactor flux normalization	yes	2.0%
Reactor spectrum	yes	2.0% per bin
Cross Sections	yes	
Scintillator Properties	yes	2.0%
Spill-in/spill-out	yes	
Analysis cuts	yes	
Fiducial mass	no	
Rel. Detector normalization	no	0.6%
Rel. Energy calibration	no	0.5%
Backgrounds	partly	1.0%

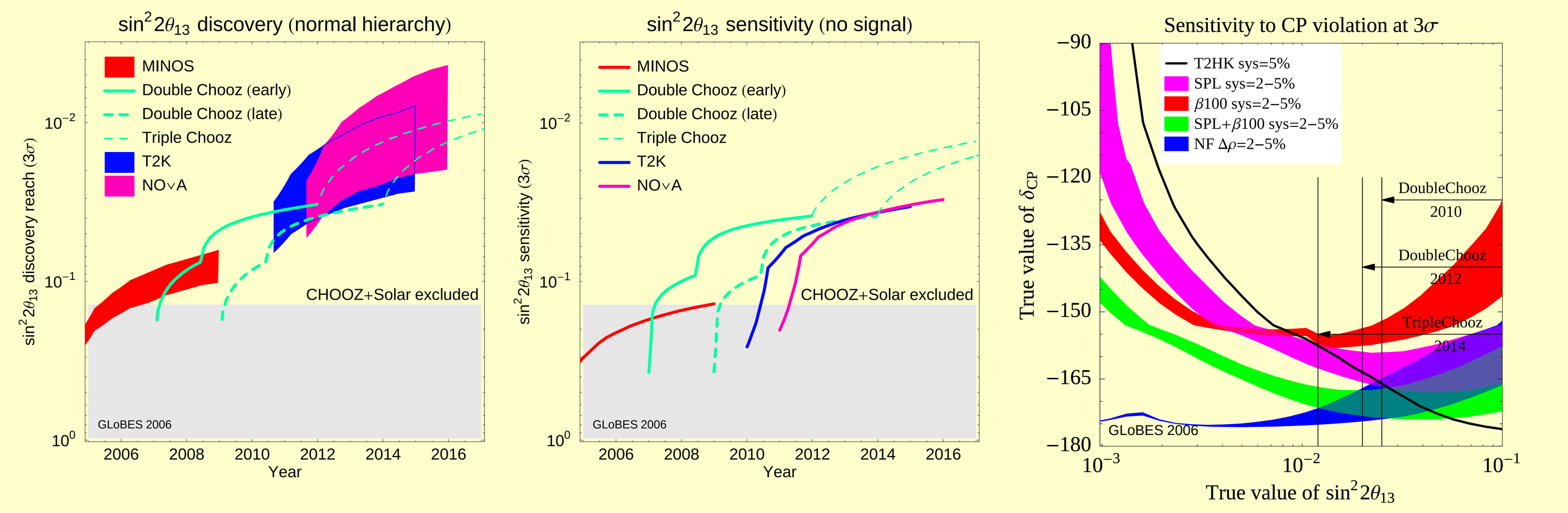


In a setup with identical near and far detectors, errors that are correlated between the detectors cancel.

The impact of systematical errors on the θ_{13} sensitivity in such a setup depends on the total exposure:

- *Low exposure:* The sensitivity is limited by the statistical uncertainty in the total event rate.
- *Medium exposure:* The sensitivity is limited by uncorrelated systematical normalization errors.
- *High exposure:* The sensitivity is limited by the statistics in each energy bin. Systematical normalization errors are eliminated by spectral information. Only errors that are uncorrelated between detectors *and* bins can spoil the performance.

Role in the Global Neutrino Research Program



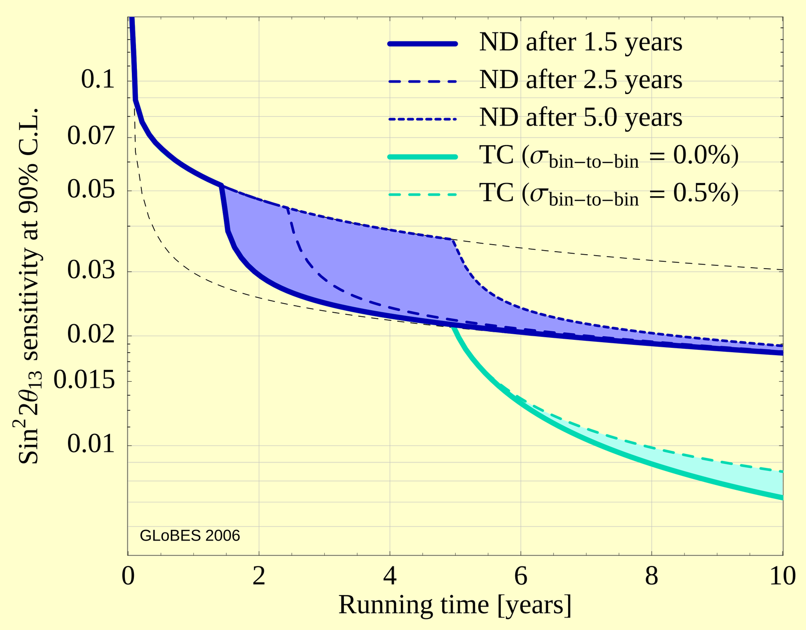
Reactor experiments achieve a θ_{13} discovery reach (defined as the potential to distinguish $\theta_{13} \neq 0$ from the zero hypothesis) and a sensitivity (defined as the limit that can be achieved if the true value is zero) that can well compete with superbeam experiments (left and middle plots). Superbeams suffer from parameter correlations between θ_{13} and δ_{CP}, therefore their sensitivity is actually worse than that of a reactor experiment. Their discovery reach may be better, depending on the true value of δ_{CP} (colored bands). For large θ_{13}, a precise measurement from a large reactor experiment can break correlations in the superbeams and thus improve their sensitivity to CP violation.

Furthermore, reactor experiments will help to select the optimum technology for future beam experiments (right plot). If $\sin^2 2\theta_{13}$ is below 10^{-2}, only a neutrino factory can achieve a good sensitivity to CP violation. If $\sin^2 2\theta_{13} > 10^{-2}$, the performance of accelerator setups depends crucially on systematical errors (superbeams and β-beams) or on the uncertainty in the Earth matter density (neutrino factory), as indicated by the colored bands. By 2010, the envisaged timeframe for a decision about second-generation beam facilities, reactor experiments will have reached the branching point $\sin^2 2\theta_{13} \approx 10^{-2}$.

Double Chooz and Triple Chooz

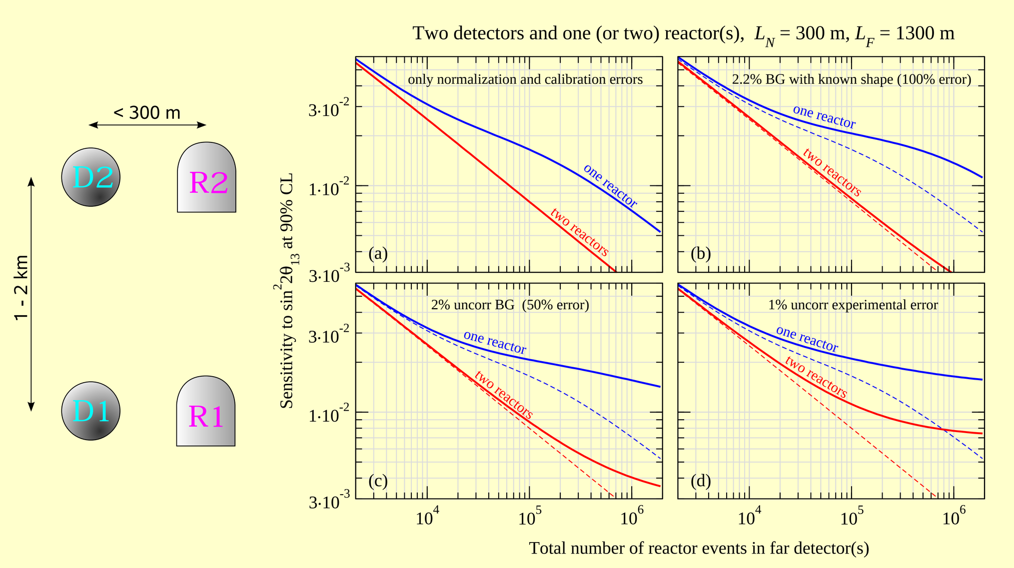
Double Chooz, currently the most advanced reactor neutrino project, will use near and far detectors to eliminate the uncertainties in the reactor flux and spectrum. Although the near detector will be operational 1.5 years after the far detector, the overall sensitivity of $\sin^2 2\theta_{13} \approx 0.02$ remains unchanged.

Triple Chooz is an upgrade option for Double Chooz using an existing underground cavern for the construction of a 200 t detector, which could reach a sensitivity of $\sin^2 2\theta_{13} < 0.01$.



Note also the dedicated posters by the Double Chooz collaboration.

The R2D2 Setup

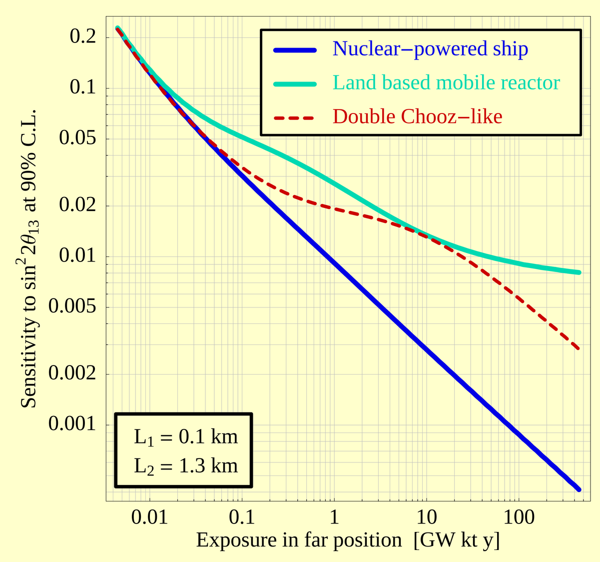


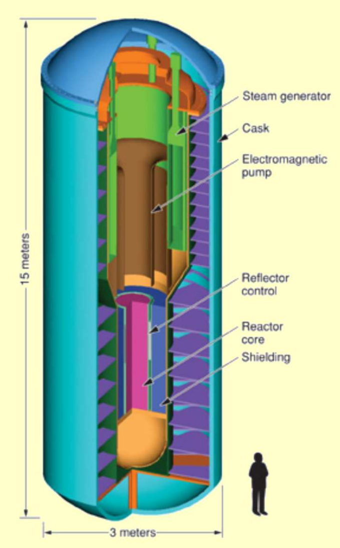
In a symmetrical setup with 2 reactors and 2 detectors (**R2D2**), errors associated with the reactors *and* erros associated with the detectors cancel because each detector acts both as near and as far detector. Only completely uncorrelated bin-to-bin errors (which are expected to be very small) can spoil the performance. It is, however, crucial to separate events from the two reactors. If both are running simultaneously this might in principle be possible on a statistical basis since the spatial distribution of secondary neutron interaction vertices is slightly biased in the forward direction with respect to the primary neutrino vertex.

Mobile Reactor Scenarios

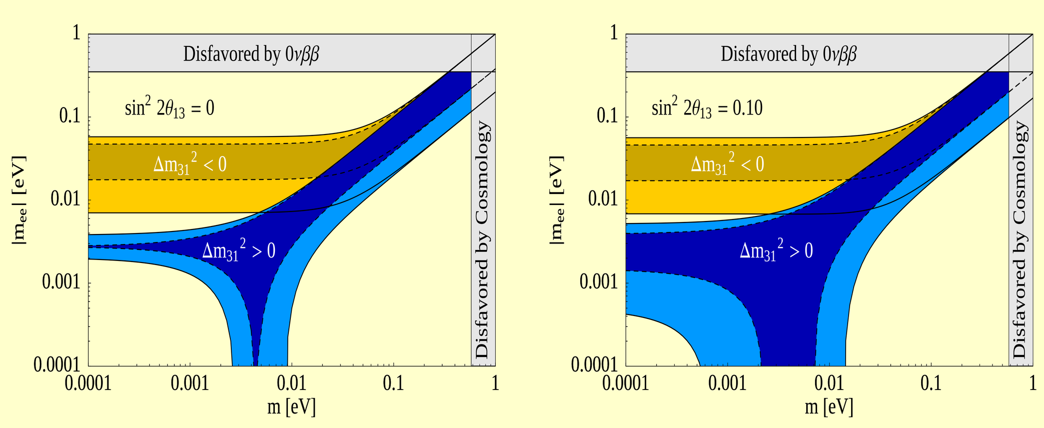
By placing a **mobile nuclear reactor** at two different baselines consecutively, a cancellation of systematical errors can be achieved with *one* reactor and *one* detector. Two scenarios are possible:

- *Nuclear ship:* Flux and spectrum remain unchanged when the reactor is moved. Therefore all errors are correlated and cancel.
- *Land-based mobile reactor:* Only detector-side errors remain correlated. At high exposures, where the sensitivity comes from spectral information, this scenario is limited by the uncorrelated uncertainty in the reactor spectrum. This could be circumvented by employing a (small & cheap) near detector.





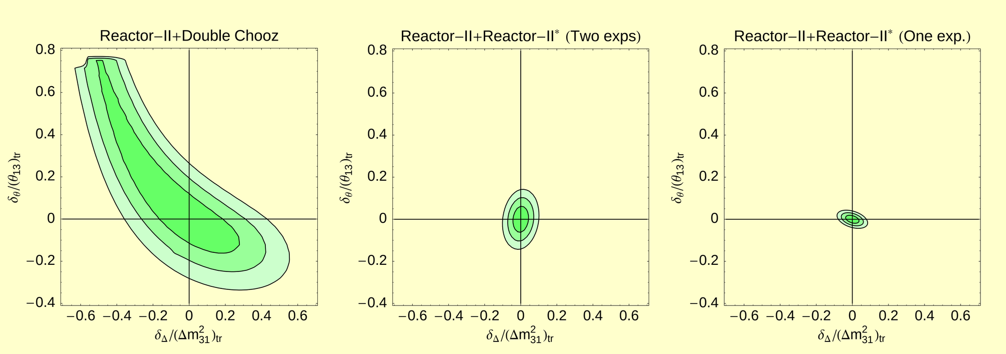
Impact on $0\nu\beta\beta$ Decay Experiments



The rate of $0\nu\beta\beta$ decay depends on the effective mass $|m_{ee}| = |\sum_i m_i U_{ei}^2|$, where m_i are the neutrino mass eigenvalues and U_{ei} are the elements of the PMNS matrix. From current bounds on the oscillation parameters, one obtains two bands of allowed values for $|m_{ee}|$. The shape of the normal hierarchy (NH, blue) band depends strongly on θ_{13}. Precise knowledge about this parameter is necessary to predict the physics potential of future searches for $0\nu\beta\beta$ decay and to potentially rule out $\Delta m_{31}^2 < 0$. Small θ_{13} implies:

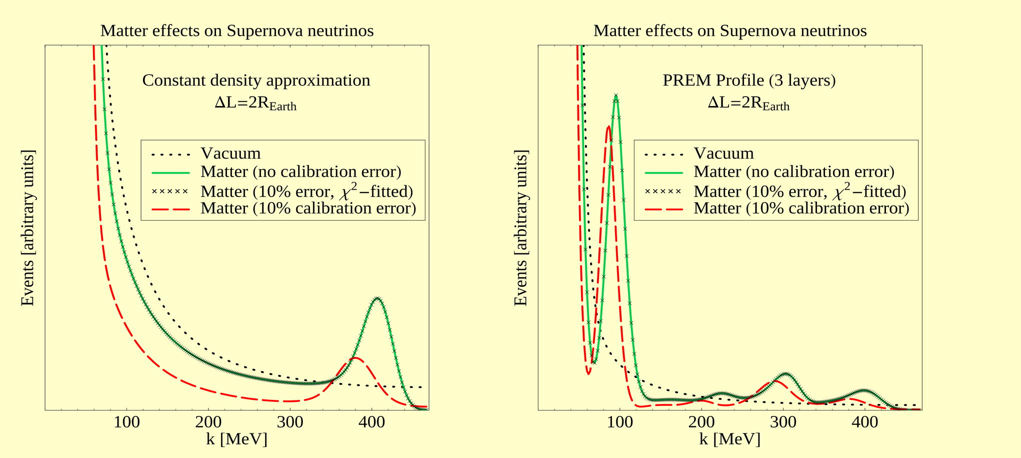
- Large gap between the bands for $\Delta m_{31}^2 > 0$ and $\Delta m_{31}^2 < 0 \Rightarrow$ Determination of the mass hierarchy from $0\nu\beta\beta$ decay is easy.
- The NH band is narrow $\Rightarrow$ Strong bounds on the absolute neutrino mass scale both for observation and non-observation of $0\nu\beta\beta$ decay.

Testing Mass-Varying Neutrinos



Mass-varying neutrinos (MVNs) imply that the neutrino oscillation parameters in air and matter could be very different. Since reactor experiments do have different paths in air and matter, a direct test of MVNs using reactor experiments may be possible. In `hep-ph/0511177`, a different parameterization of θ_{13} and Δm_{31}^2 has been adopted for air and matter. Since the Double Chooz baseline is partly in air, Double Chooz will constrain MVNs when combined with beam or reactor data in matter. Higher sensitivities can be obtained by comparing new experiments in matter (Reactor-II) and largely in air (Reactor-II*) or even physically moving the material between near and far detector (one experiment) in order to cancel systematics almost completely.

The self-calibration effect



A typical low-energy background for future low-energy neutrino detectors are Geo-neutrinos. Due to their characteristic spectral shape, one can use them to calibrate the energy reconstruction for $\overline{\nu}_e$ events, provided that at least several thousand Geo-neutrinos are detected. A similar self-calibration for ν_e events is possible with solar neutrinos. The plots show the impact of Earth matter effects on the peaks in the inverse power spectrum of supernova neutrinos: a wrong energy calibration worsens the determination of the peak positions, or can even lead to a misidentification of certain peaks. If the energy calibration is determined by a χ^2-fit to the Geo-neutrino background, this error will go to zero. Thus, a measurement with background can yield better results than one without.

[1] P. Huber, M. Lindner, and T. Schwetz, JHEP **02**, 029 (2005), `hep-ph/0411166`.
[2] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter (2006), `hep-ph/0601266`.
[3] T. Schwetz and W. Winter, Phys. Lett. **B633**, 557 (2006), `hep-ph/0511177`.
[4] M. Lindner, A. Merle, and W. Rodejohann, Phys. Rev. **D73**, 053005 (2006), `hep-ph/0512143`.