

# Is it possible to improve our knowledge of $\theta_{13}$ by oscillation experiments at reactors?

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## Summary

- Current status

  - Physics motivations

  - The Chooz result

- What next?

  - Improvement of statistics and systematics

  - Potentialities of two-distance tests

  - The Krasnoyarsk project (Kr2Det)

  - An alternative experimental frame

  - Signal and Background

- Expected sensitivity

  - Rate test

  - Shape test

- Outlook and conclusions

## Physics motivations

- $\nu_\mu \leftrightarrow \nu_\tau$  oscillation hypothesis is dominant for atmospheric  $\nu$ 's

$$1 \times 10^{-3} \leq \delta m_{23}^2 \leq 3 \times 10^{-3} \text{ eV}^2 \quad \leftarrow \text{SK data}$$

but  $\nu_e \leftrightarrow \nu_\mu$  mixing could still be present at a subdominant level

$$(\sin^2(2\theta_{13}) \leq 0.1 \text{ at } \delta m_{13}^2 = 3 \times 10^{-3} \text{ eV}^2)$$

(limited by Chooz results, also SK at a minor extent)

- SK + SNO results (energy spectra, CC rate, day/night effect)  
strongly favour the LMA MSW solution to solar neutrino deficit  
mass hierarchy  $\Rightarrow$

$$(\sin^2(2\theta_{\text{CHOOZ}}) = 4 |U_{e3}|^2 (1 - |U_{e3}|^2)$$

$$(\sin^2(2\theta_{\text{KamLAND}}) = 4 |U_{e1}|^2 |U_{e2}|^2$$

SURVIVAL PROBABILITY  
INDEPENDENT OF ENERGY FOR  
 $\Delta m^2 \gtrsim 2 \times 10^{-4} \text{ eV}^2$

$\Rightarrow$  CONSTRAINT TO LARGE  $\Delta m^2$  VALUES OF  
LMA SOLUTION

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## The Chooz result

$$R = 1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$$

M. Apollonio *et al.*, Phys. Lett. B 466 (1999) 415

$$\sin^2(2\theta_{13}) \leq 0.1 \Leftrightarrow |U_{e3}| \leq 0.025$$

recently confirmed by Palo Verde

$$R = 1.01 \pm 2.4\%(\text{stat}) \pm 5.3\%(\text{syst})$$

F. Boehm *et al.*, hep-ex/0107009

Sensitivity could be lowered to

$$\sin^2(2\theta_{13}) \leq 10^{-3} \text{ at neutrino factories}$$

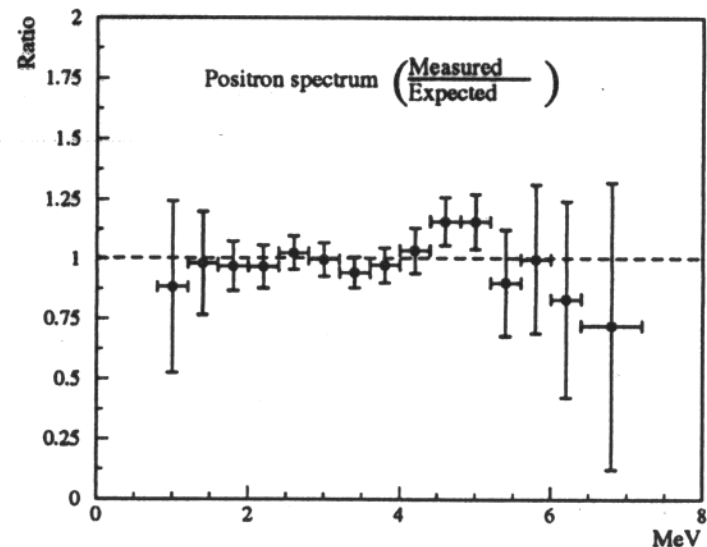
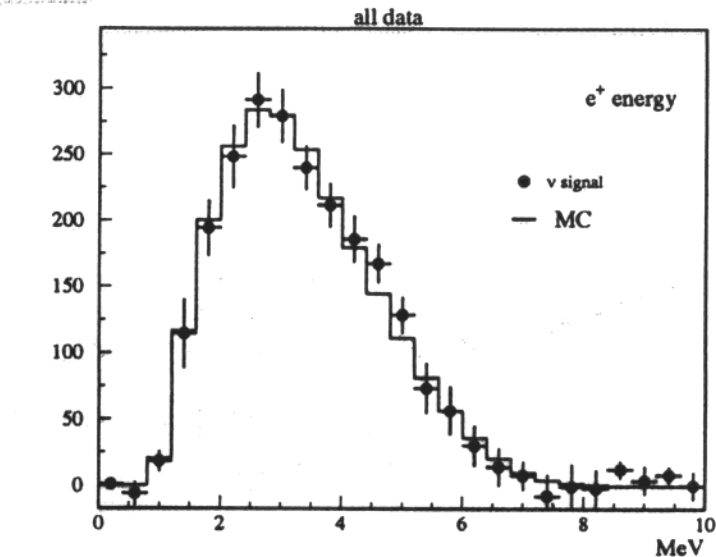
(construction to be started in ~2010)

Is it possible to reach an intermediate

( $\sin^2(2\theta_{13}) \sim 10^{-2}$ ) step by reactor

experiments?

factor 5 improvement  $\Leftrightarrow$  errors must be  $\sim 0.5\%$



## Possible improvements

- systematics

Comparison of neutrino fluxes and spectra at two distances

$L_1 \sim 100 \text{ m}$ ,  $L_2 \sim 1 \text{ Km}$

$\Rightarrow$  independent of absolute normalisation (spectra, cross section, power, burn-up)

which contributed at 2% to the overall systematic uncertainty at Chooz

Identical detectors (detection technique, geometrical shape) or as similar as possible  $\Rightarrow$  minimise differences in efficiencies and calibrations.

- statistics

Large volume detectors (target  $\sim 50 \text{ t}$ )  $\Rightarrow$  signal larger by  $\sim 10$

to be located underground (300 m.w.e)  $\Rightarrow$  neutron background suppression

Detector design suited to shield the target from external radioactivity

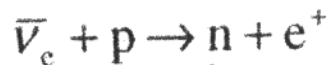
$\Rightarrow$  accidental background suppression

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## A possible detector

Event signature

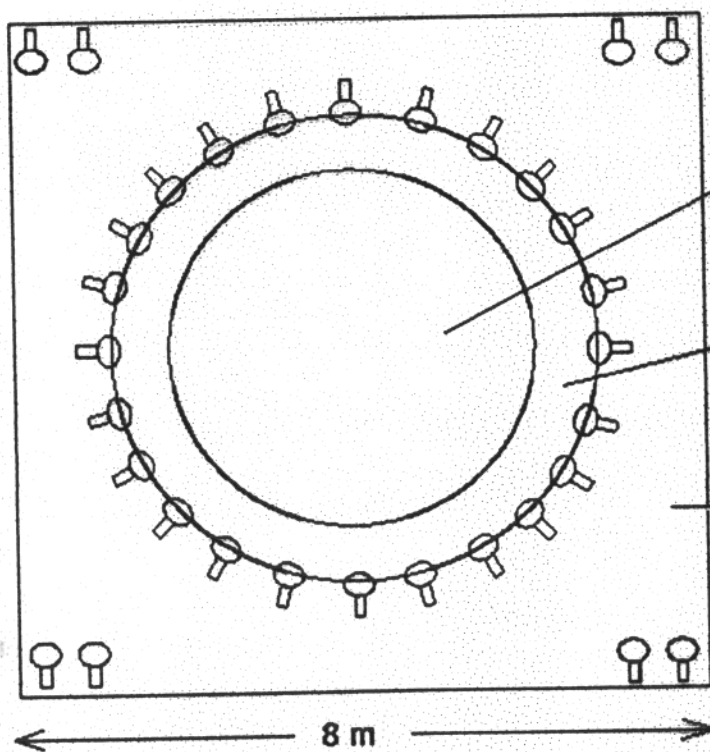
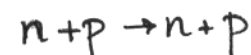
prompt positron signal



delayed neutron signal ( $\tau = 180 \mu\text{s}$ )  $n + p \rightarrow d + \gamma (2.2 \text{ MeV})$

neutron efficiency lower ( $\sim 50\%$ ) than Chooz

BACKGROUND



Mini version of KamLAND (or Borexino)

1 50 t liquid scintillation target (no Gd-doping)  
( $\lambda \sim 10 \text{ m}$ , stable)

2 Mineral oil buffer ( $\sim 1 \text{ m}$  thick)  
shield against PMT radioactivity

3 Active cosmic veto

PURITY  
U  $10^{-14}$   
Th  $10^{-14}$

↓  
SINGLE RATE  $\approx 0.1 \text{ s}^{-1}$   
NOT SO STRINGENT

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## The Kr2Det project

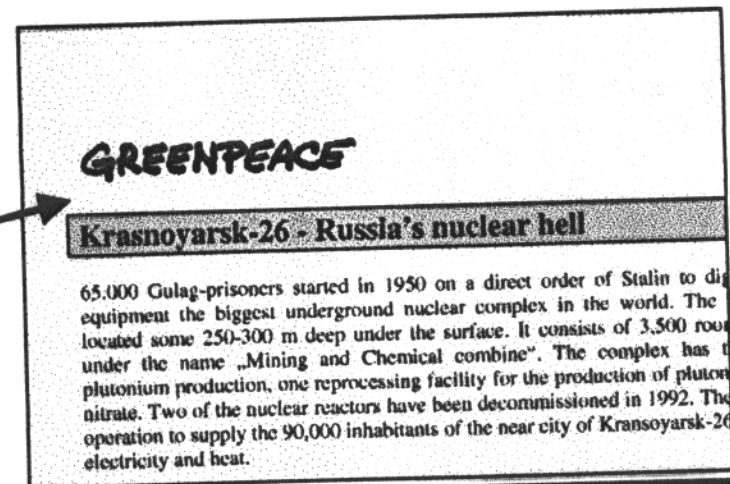
Based on L.V.Mikaelyan's idea

- to be operated by Krasnoyarsk nuclear plant (Russia)  
one (over three) reactor still operating,  $W = 1.6 \text{ GWth}$
- $L_1 = 250 \text{ m}$ ,  $L_2 = 1100 \text{ m}$
- twin detectors (with the possibility to swap their position)  $\Rightarrow \sigma_{\text{syst}} \sim 0.5\%$
- thick rock overburden (600 m.w.e.)  
(neutron flux suppressed by a factor  $\sim 3$  w.r.t. Chooz)
- possibility to measure the background during the reactor stop for refueling
- $\sigma_{\text{stat}} = 0.5\%$  could be reached in  $\sim 3\text{y}$  data taking

but...

plant operating is not guaranteed

Russian authorities are strongly  
demanded to stop reactor operations for  
safety reasons



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## A possible alternative

### Chooz2

- Far detector located in the underground site ( $L_2 \sim 1000$  m, 300 m.w.e.) hosting the previous experiment  $\Rightarrow S/N \sim 10$
- Near detector placed in a new shallow site ( $L_1 \sim 100$  m, 40 m.w.e.), to be built on purpose
  - $\mu$  vertical intensity reduced to only 30% of the surface intensity
  - $\Rightarrow$  near detector must be smaller (else it would be overwhelmed by cosmic rays!)
  - $\Rightarrow$  systematic error could not be better than 1%

5t scintillator target size looks like a reasonable compromise

- signal:

$$R_2^\nu \approx 5R_{CHOOZ}^\nu \approx 125 \text{ ev/d}, \quad R_1^\nu \approx 1250 \text{ ev/d} \quad \text{at full reactor power}$$

- background:

$R_\mu \sim 2$  KHz (2 orders of magnitudes larger than at the underground site)

$N_n \sim 3$  times as low as underground F.Boehm *et al.* PRD 62 (2000) 092005

$\Rightarrow$  neutron flux  $\phi_n \sim 30$  times as large as underground

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## Statistical uncertainties

A realistic plant operation frame

- reactors operating at full power, 90% duty cycle
- alternated stop (~1 month) for refueling

During 3 years data taking one collects:

- 800 d with both reactors ON ("ON" period)  
 $S_2^{\text{ON}} \approx 10^5 \text{ ev}, S_1^{\text{ON}} \approx 10^6 \text{ ev}$
- 200 d with one reactors OFF ("OFF" period)  
 $S_2^{\text{OFF}} \approx 1.35 \times 10^4 \text{ ev}, S_1^{\text{OFF}} \approx 1.25 \times 10^6 \text{ ev}$

$$\Rightarrow R_1 = (625 \pm 2) \text{ ev/d}$$

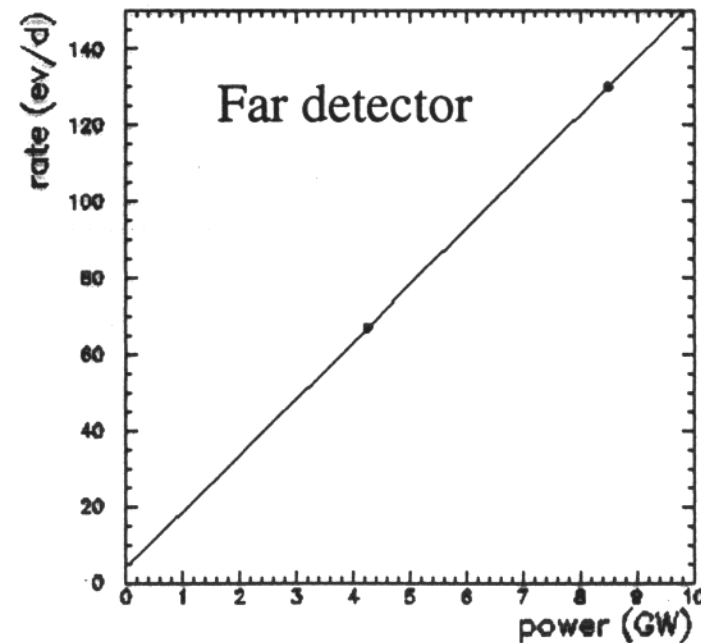
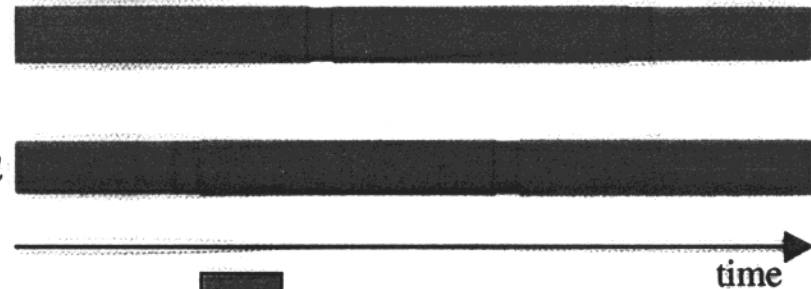
$$R_2 = (63 \pm 0.7) \text{ ev/d}$$

$$\Rightarrow \sigma_{\text{stat}} = 1.1\%$$

limited by background subtraction

reactor 1

reactor 2



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## A more optimistic scenario

Background measurement could be improved if reactors:

- ramp up/down slowly
  - are both OFF for a while
- (both conditions were fulfilled at Chooz)

With 30 d reactor shutdown

$$B_2^{\text{OFF}} \approx (5 \pm 0.4) \text{ ev/d}$$

$$\Rightarrow R_2 = (125 \pm 0.6) \text{ ev/d}$$

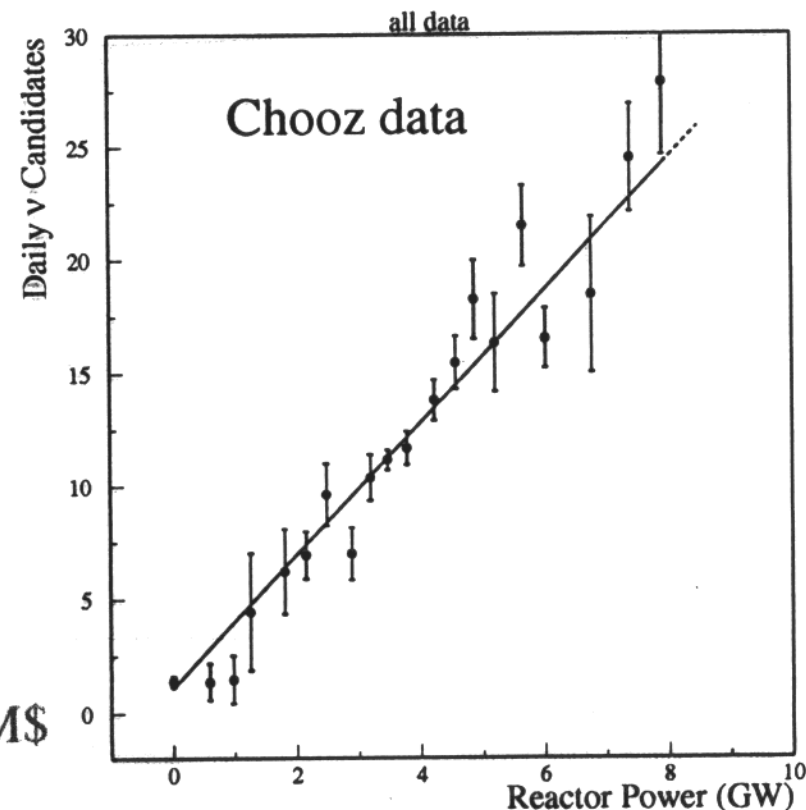
$$\Rightarrow \sigma_{\text{stat}} = 0.5\% \quad \text{OK}$$

How much does it cost?

$$0.05\$/\text{kWh} * 8.5\text{GW} * 0.3 * 24 \text{ h} = 3 \text{ M\$}$$

in 1 day

$$\Rightarrow \sim 100 \text{ M\$ in 1 month}$$



## Rate test

Based on the comparison of integral rates at two distances

$$r = \frac{R_2}{R_1} \cdot \frac{V_1 \epsilon_1 L_2^2}{V_2 \epsilon_2 L_1^2} = \text{test variable (normalised to 1 in absence of oscillations)}$$

↑                      ↑  
statistics          systematics

Use  $\Delta\chi^2$  instead of likelihood ratio for statistic test

(OK in a Gaussian regime)

$$\chi^2 = \left( \frac{r_{\text{meas}} - r_{\text{exp}}(\delta m^2, \theta)}{\sigma} \right)^2 \quad \Delta\chi^2 = \chi^2 - \chi^2_{\text{min}}$$

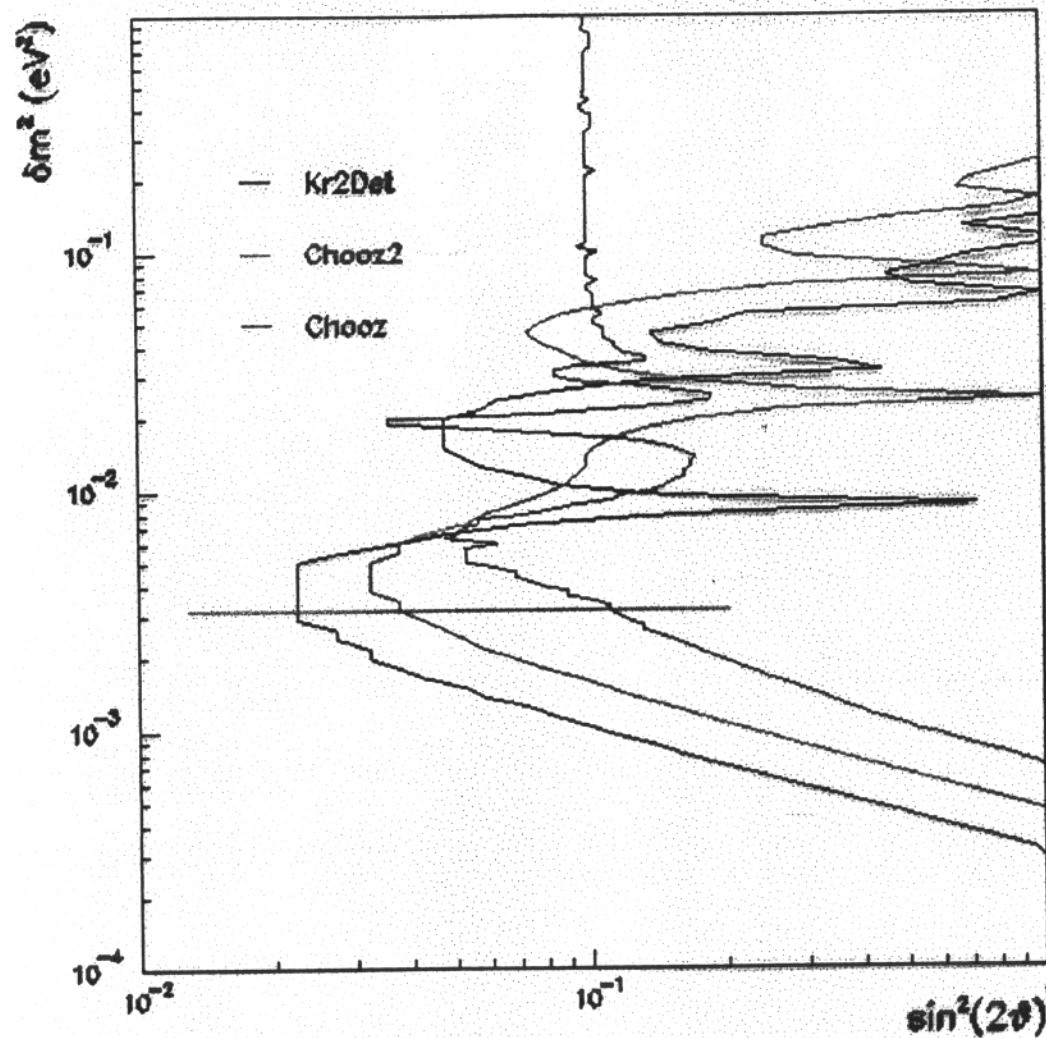
↑  
errors added in quadrature

Apply Feldman-Cousins procedure to determine 90% confidence intervals in  $(\sin^2(2\theta), \delta m^2)$  for:

- Kr2Det
- Chooz2

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## Rate sensitivity plot



At  $\delta m^2 = 3 \times 10^3 \text{ eV}^2$

- Kr2Det  
 $\sin^2(2\theta) \leq 0.02$
- Chooz2  
 $\sin^2(2\theta) \leq 0.04$   
not much encouraging...
- Chooz  
 $\sin^2(2\theta) \leq 0.1$

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## Spectrum test

Based on the comparison of positron spectra at two distances

Improved sensitivity in the “lobe” regions

⇒ more powerful test

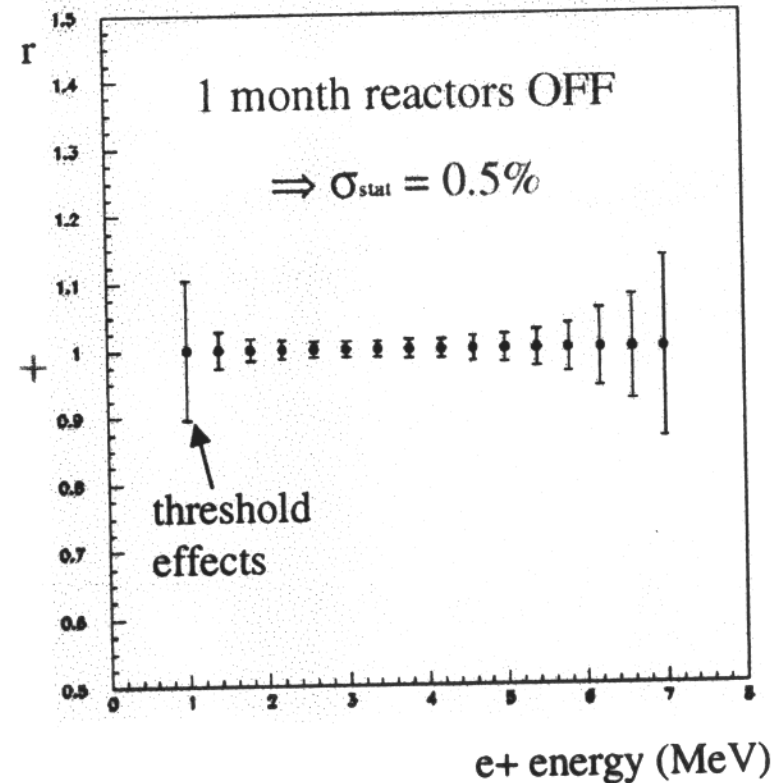
Spectra arranged in 16 bins ( $\Delta E = 0.4$  MeV)

Build statistic as

$$\chi^2 = \sum_{i=1}^n \left( \frac{r_{\text{meas}}(E_i) - \alpha r_{\text{exp}}(gE_i, \delta m^2, \theta)}{\sigma_{\text{stat}}(E_i)} \right)^2 + \left( \frac{\alpha - 1}{\sigma_\alpha} \right)^2 + \left( \frac{g - 1}{\sigma_g} \right)^2$$

↑  
spectra normalisation  
(relative efficiencies,  
target volumes)

↑  
energy scale  
calibration



$$\Delta\chi^2(\delta m^2, \theta) = \min_{\alpha, g} \chi^2(\delta m^2, \theta, \alpha, g) - \chi_{\text{best}}^2 \longrightarrow \text{FC procedure}$$

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## Spectrum test sensitivity

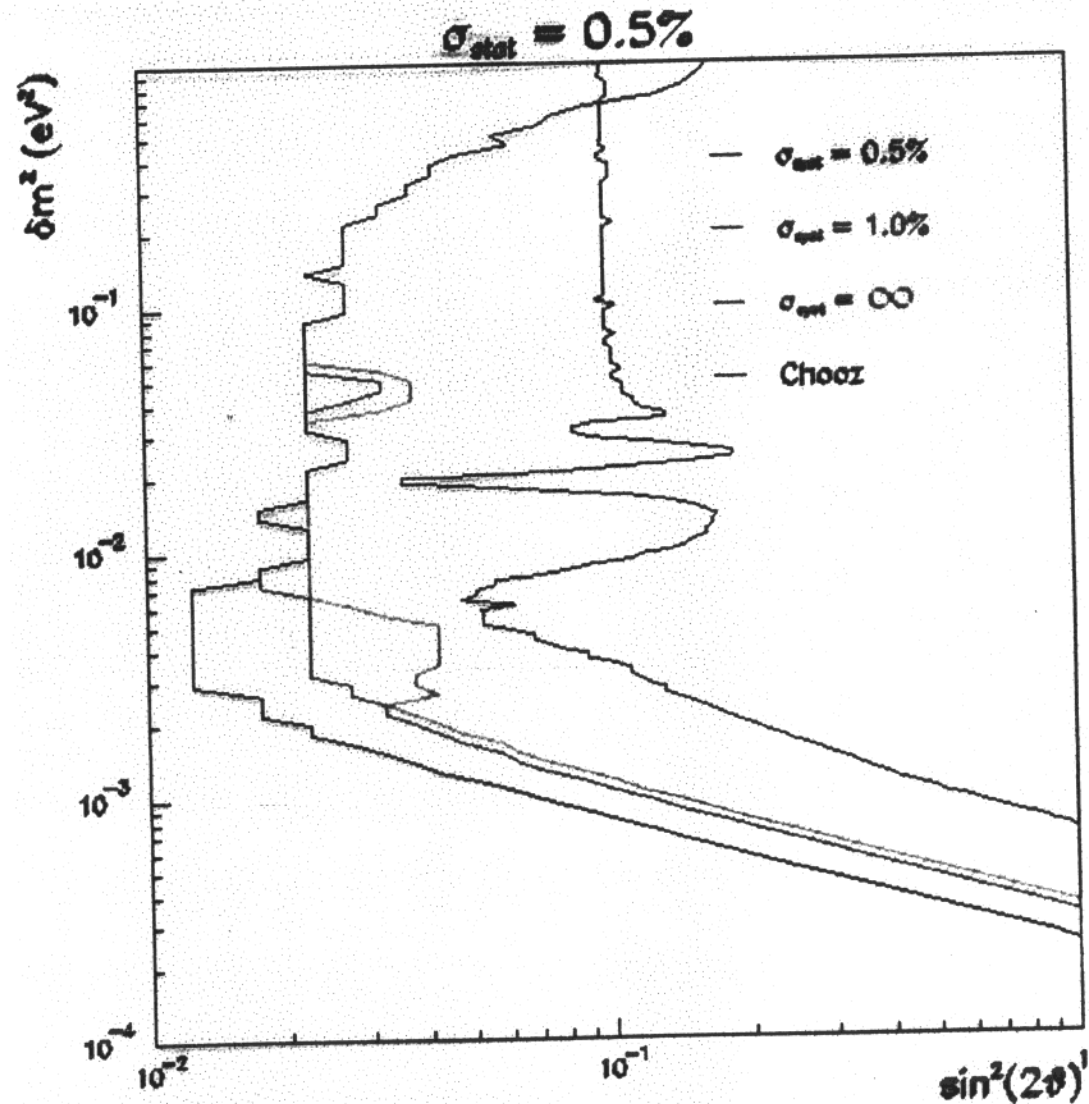
1 month reactors OFF

90% sensitivity contours as  
functions of  $\sigma_\alpha$

( $\sigma_g$  neglected)

At  $\delta m^2 = 3 \times 10^3 \text{ eV}^2$

- $\sigma_\alpha = 0.5\%$   
 $\sin^2(2\theta) \leq 0.015$
- $\sigma_\alpha = 1.0\%$   
 $\sin^2(2\theta) \leq 0.025$
- $\sigma_\alpha = \text{infinite (shape test)}$   
 $\sin^2(2\theta) \leq 0.04$
- Chooz  
 $\sin^2(2\theta) \leq 0.1$



Is it possible to improve our ...

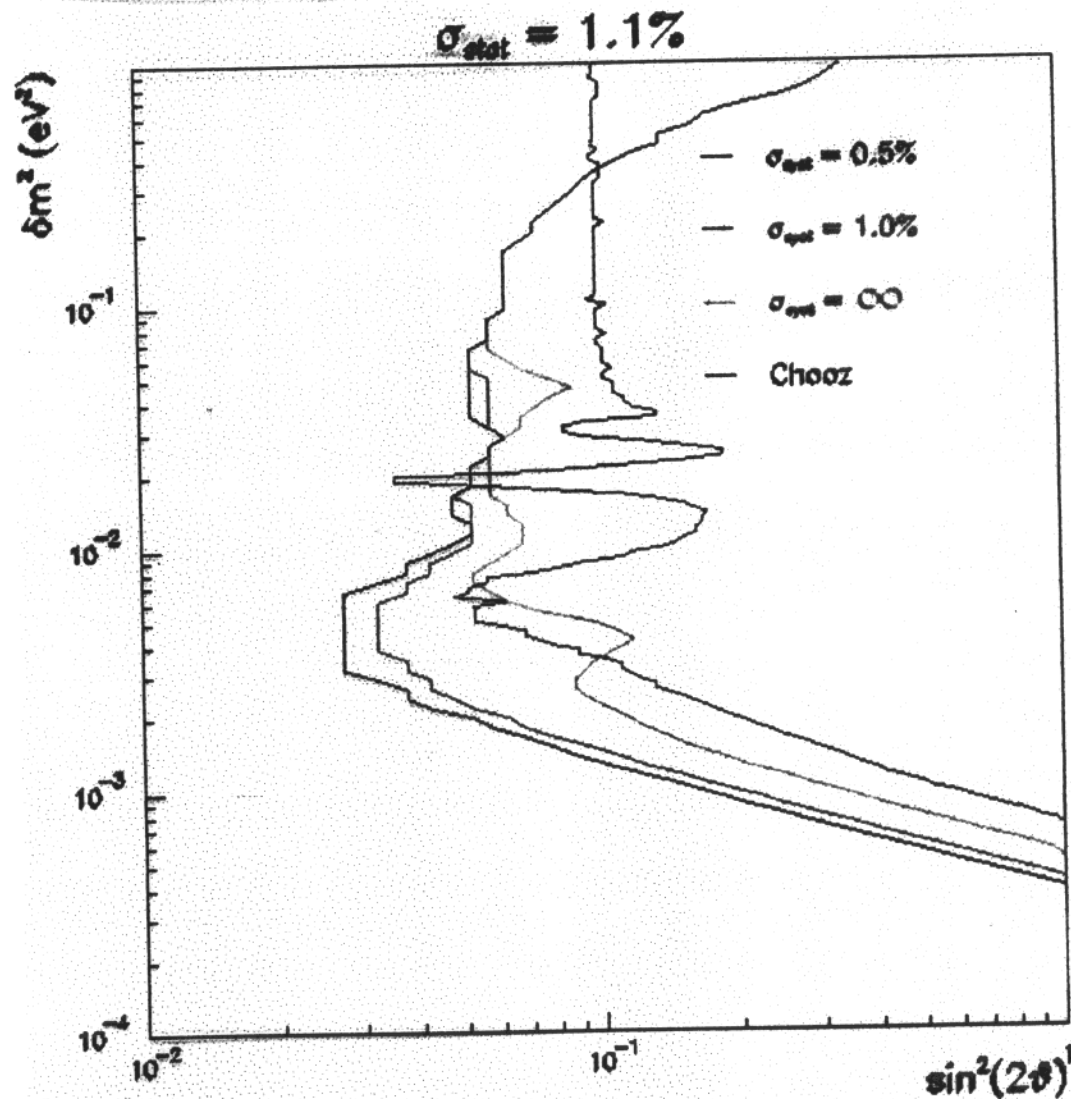
## Spectrum test sensitivity (more realistic)

reactors ON-OFF

90% sensitivity contours as  
functions of  $\sigma_\alpha$   
( $\sigma_g$  neglected)

At  $\delta m^2 = 3 \times 10^3 \text{ eV}^2$

- $\sigma_\alpha = 0.5\%$   
 $\sin^2(2\theta) \leq 0.03$
- $\sigma_\alpha = 1.0\%$   
 $\sin^2(2\theta) \leq 0.04$
- $\sigma_\alpha = \text{infinite (shape test)}$   
 $\sin^2(2\theta) \leq 0.1$
- Chooz  
 $\sin^2(2\theta) \leq 0.1$



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## Outlook and conclusions

- $\nu_e \leftrightarrow \nu_x$  mixing present at subdominant level in the atmospheric  $\nu$  range
  - could influence the solution to the solar  $\nu$  deficit
  - to be investigated at future neutrino factories down to  $\sin^2(2\theta) \leq 10^{-3}$
- Sensitivity at reactor experiments could be pushed to  $\sin^2(2\theta) \leq 0.02$  if:
  - both detectors were located underground  $\Rightarrow \sigma_{\text{syst}} = 0.5\%$
  - background could be measured with reactors OFF  $\Rightarrow \sigma_{\text{stat}} = 0.5\%$   
one reactor plants are preferred, underground if possible Do they exist?
- Else it is difficult to obtain better than 1% accuracy, both statistics and systematics  
 $\Rightarrow$  a factor 2+3 improvement with respect to Chooz