Experiments to detect θ_{13}

M.Apollonio
Universita' di Trieste e INFN

Layout of the talk

- θ_{13} and motivations to its measurement
- Chooz limit
- Appearance and disappearance experiments
  - Accelerators (A)
  - Nuclear Reactors (R)
- (A)
  - Approved projects (Phase I)
  - Phase II
  - Phase III
- (R)
  - Double-Chooz and similar

θ_{13}

- Scenario: MiniBoone disfavouring LSND
- "standard picture"
  - 2 Δm^2_{ij} (Δm^2_{12}, Δm^2_{23}) indipendent
  - 3 mixing angles (θ_{12}, θ_{23}, θ_{13})
  - 1 ~~CP~~ phase
- Mixing Matrix PMNS
  - 1-2 solar mixing
  - 2-3 atmospheric mixing
  - 1-3 o e3 mixing: θ_{13} describes oscillations ν_e at the atmospheric frequency
  - δ_{CP} → introduces CP violation effects

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Current experimental results:

- $\Delta m^2_{23} \sim 2\times10^{-3}\ eV^2$
- $\Delta m^2_{12} \sim 7\times10^{-5}\ eV^2$
- $\Delta m^2_{23} >> \Delta m^2_{12}$
- $\theta_{12} \sim 35^o$
- $\theta_{23} \sim 45^o$

Why measuring θ_{13}?

- The least known among the parameters in PMNS
- Coupled to $e^{i\delta}(U_{e3})$

  $\theta_{13}>0$ would allow to access δ
- CP violation in the lepton sector

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.7 & 0.7 & s_{13}e^{i\delta} \\ 0.5 & 0.5 & 0.7 \\ 0.5 & 0.5 & 0.7 \end{pmatrix}$$

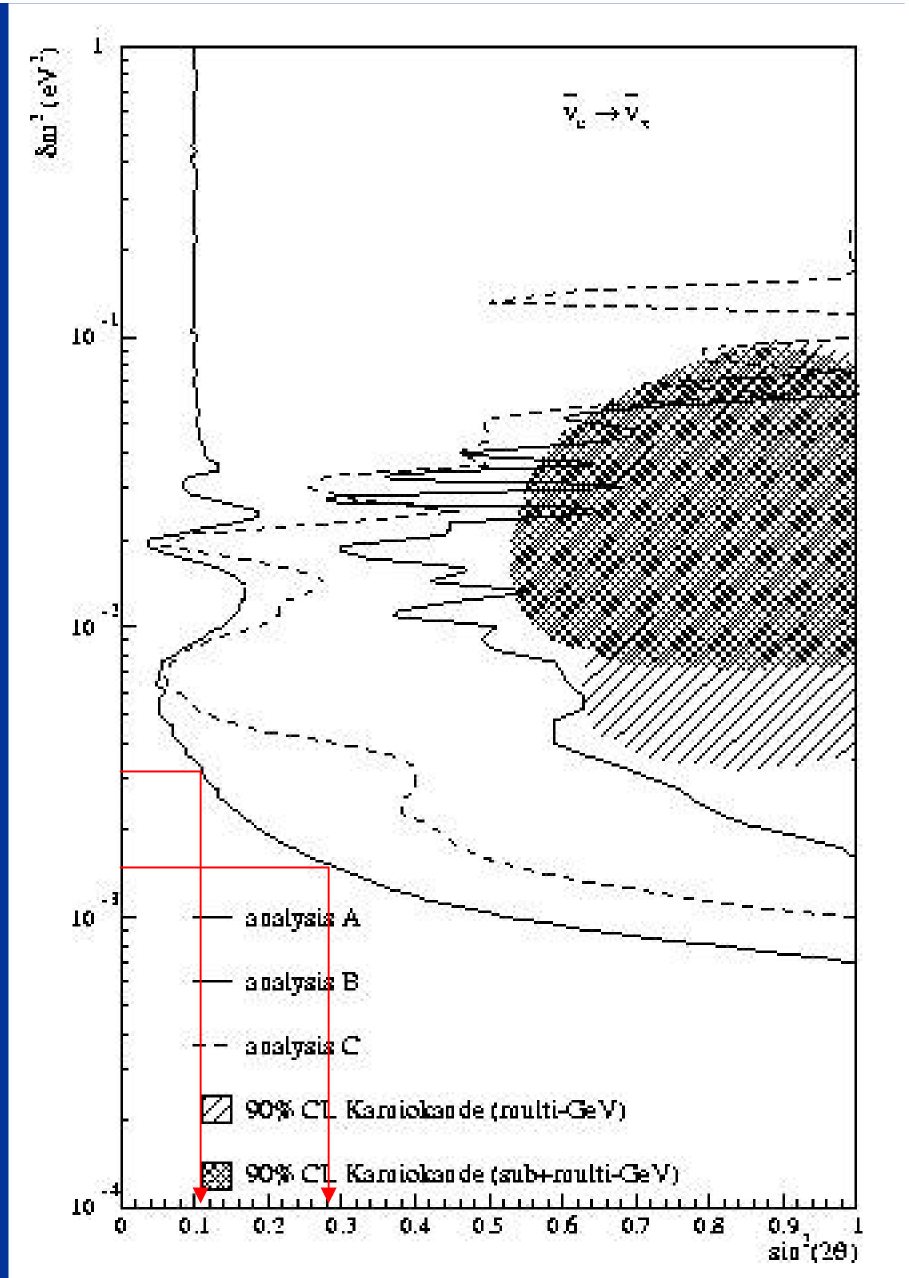
What do we know about θ_{13} today?

1. θ_{13} must be small (maybe null)
2. The best limit up to date comes from the reactor experiment CHOOZ:

   $\theta_{13} < 10^o\text{-}17^o$

   $(1.3\times10^{-3} < \Delta m_{23}^2 < 3\times10^{-3})$

   [J.Bouchez, NO-VE 2003]



[CHOOZ coll., Eur.Phys.J.C27(2003),331-374]

3 families scenario: appearance experiments

- Accelerators
- **NB**: P sensitive to δ (correlated with θ_{13})

$$\mathbf{P}(\nu_\mu \to \nu_e) =$$
$$= \sin^2 2\theta_{13} \cdot A_1$$
$$- \sin\delta \cdot \sin 2\theta_{13} \cdot \alpha \cdot A_2$$
$$+ \cos\delta \cdot \sin 2\theta_{13} \cdot \alpha \cdot \cos\Delta \cdot A_3$$
$$+ \alpha^2 \cdot A_4$$

$$A_1 = \sin^2\theta_{23} \cdot \frac{\sin^2\left[(1-\hat{A})\Delta\right]}{(1-\hat{A})}$$

$$A_2 = \xi \cdot \sin(\Delta) \cdot \frac{\sin(\hat{A}\Delta)}{\hat{A}} \cdot \frac{\sin\left[(1-\hat{A})\Delta\right]}{(1-\hat{A})}$$

$$A_3 = \xi \cdot \cos(\Delta) \cdot \frac{\sin(\hat{A}\Delta)}{\hat{A}} \cdot \frac{\sin\left[(1-\hat{A})\Delta\right]}{(1-\hat{A})}$$

$$A_4 = \cos^2\theta_{23} \cdot \sin^2 2\theta_{12} \cdot \frac{\sin^2(\hat{A}\Delta)}{\hat{A}}$$

$$\Delta = \Delta m^2_{13}\left(L/4E\right)$$

$$\xi = c_{13} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

- α should be considered
- sign(Δm^2_{13}) is present in $\hat{A}$

[P.Migliozzi, F.Terranova arXiv:hep-ph/0302274]

Accelerators

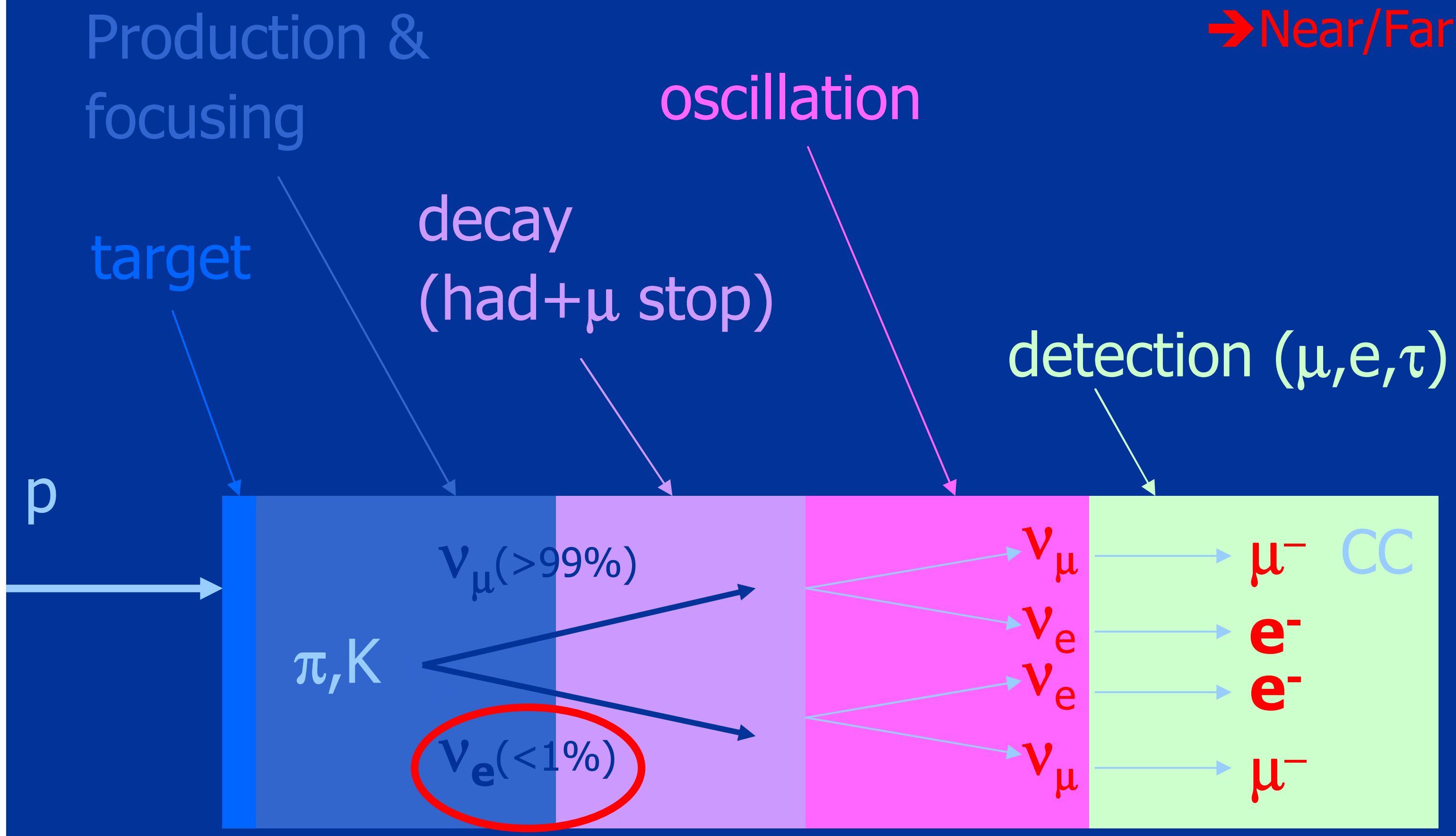
- general concept: conventional beam
  - Broad band (BBB)
  - Narrow band (NBB)
- Super Beam (SB)
- Off-Axis Beam (OA)
- β-Beam (βB)
- Neutrino Factory (NF)

(A) General concept

Main backgrounds:

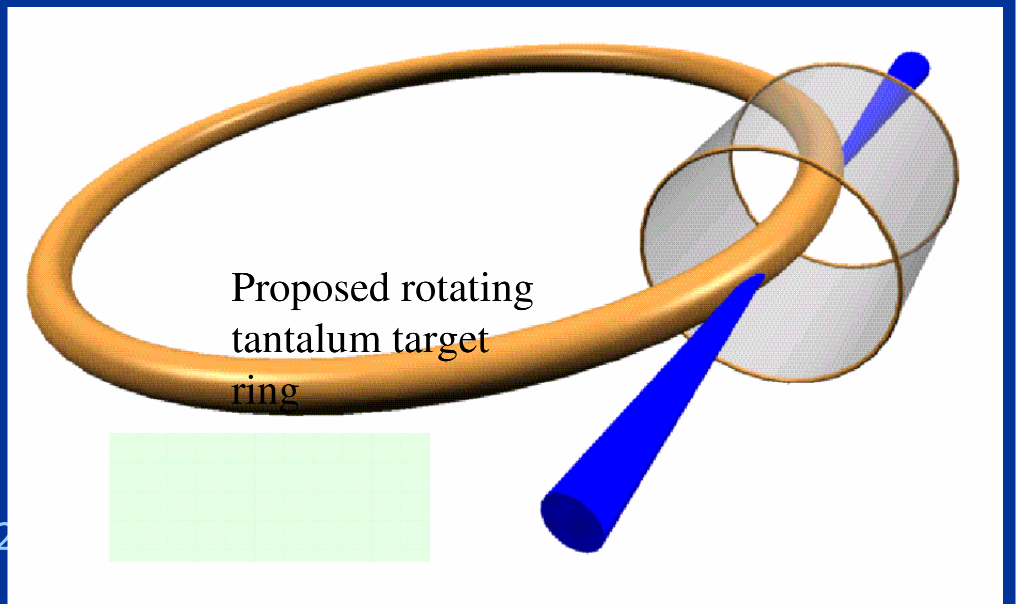
- Initial ν_e contamination in the beam
- π^0 production (NC)

➔Near/Far detection



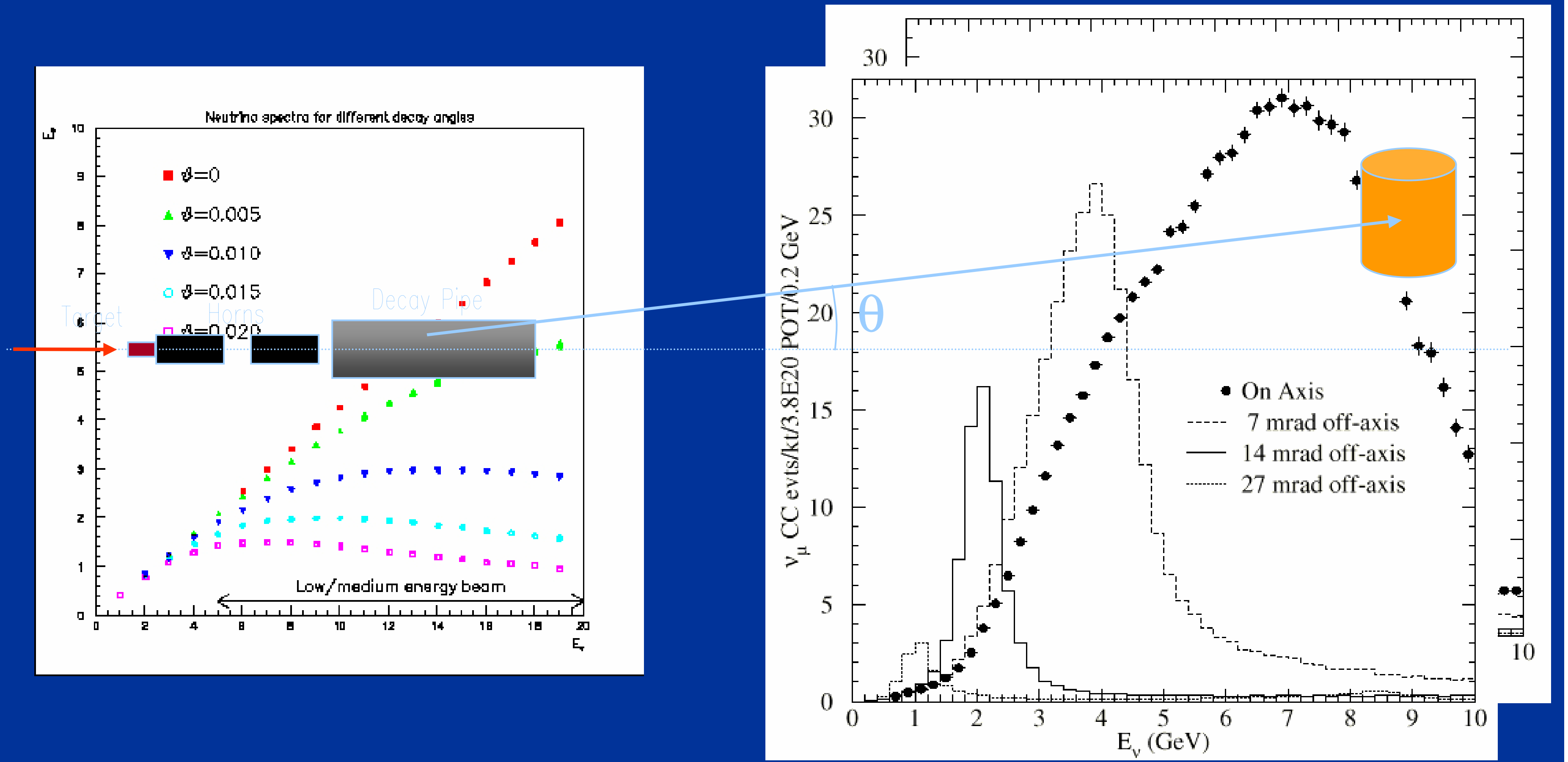
(A)-SB

- It is a conventional proton beam whose power is of the order of MW
- Produces ν_μ ($\bar{\nu}_\mu$)
- Proton-driver: technically feasible
  - →PB: target
  - →Sol.: R&D



(A)-OA

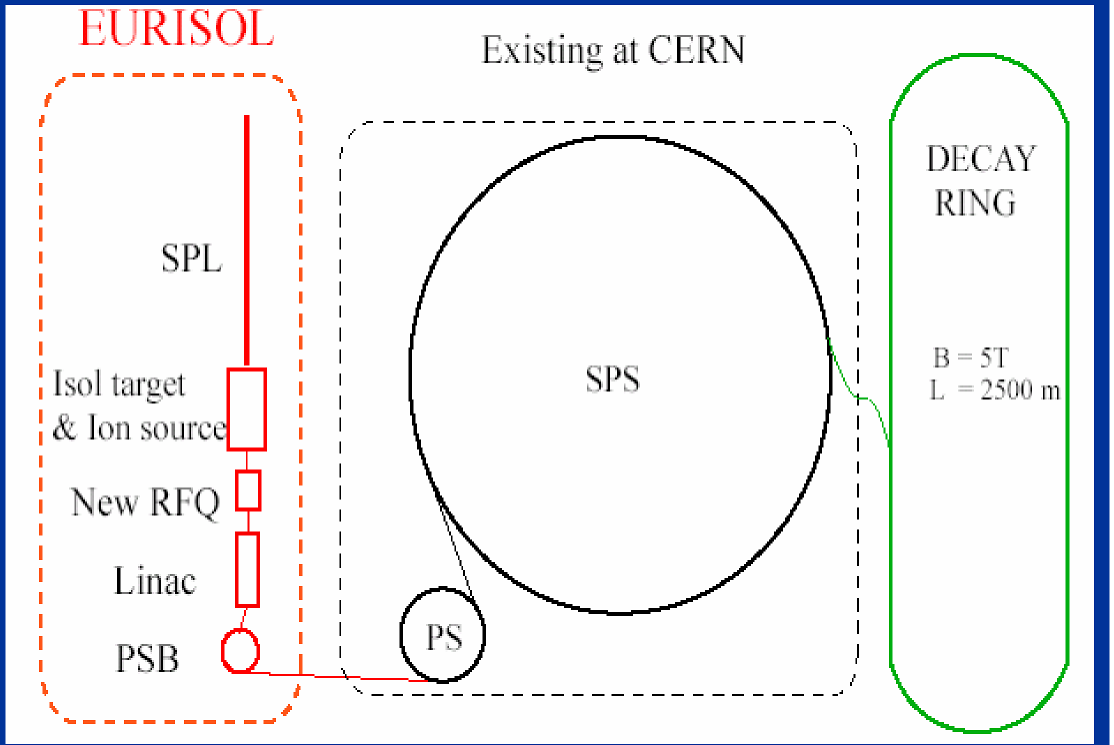
- Detector laying out of the main beam axis



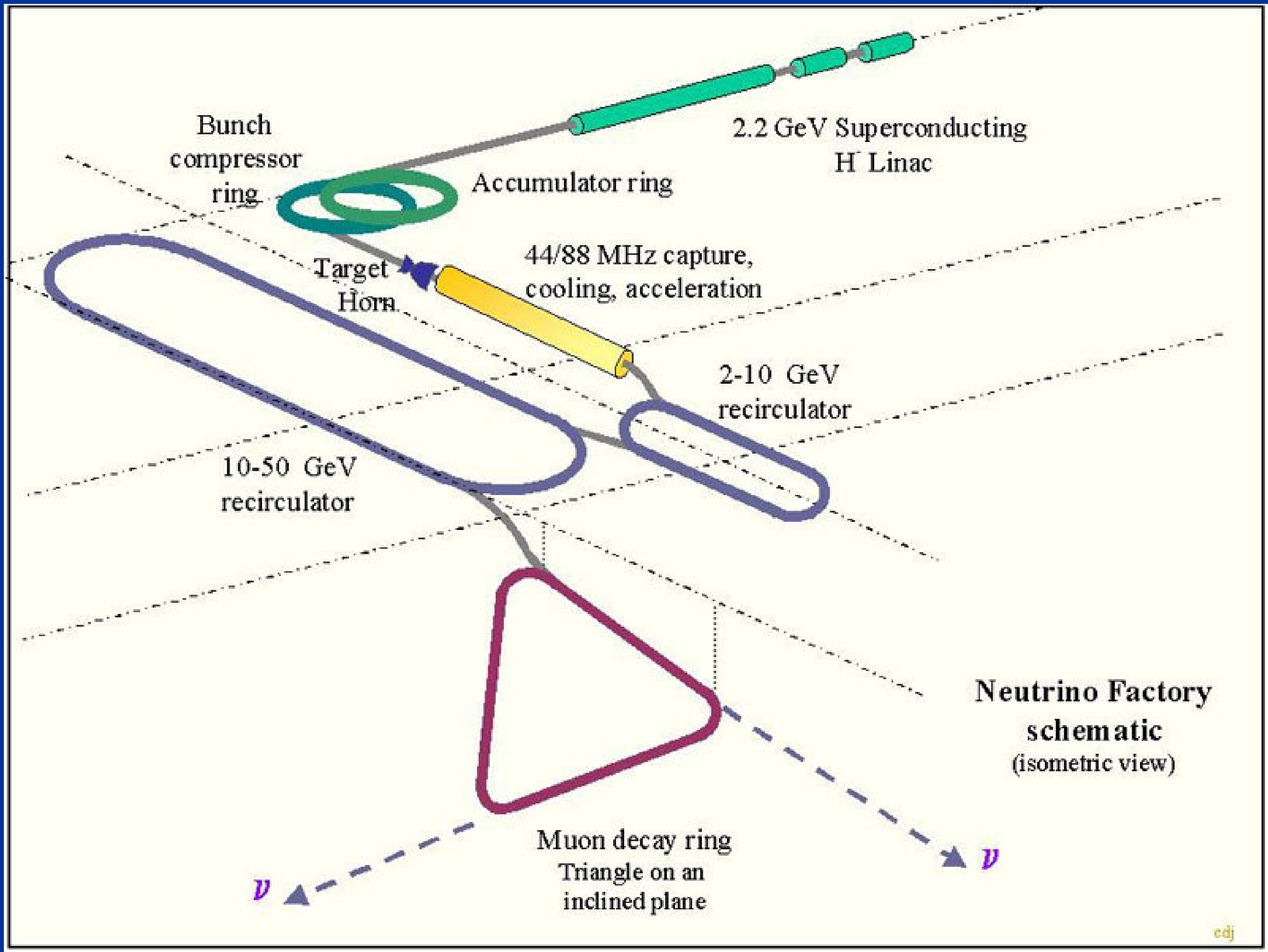
(A)β-Beams

[P.Zucchelli, Phys.Lett. B532:166,2002]

- Original solution: radioactive ions with short lifetime
  - acceleration
  - storage
  - decay
- Es.: β^- (^{6}He) → $\bar{\nu}_e$, β^+ (^{18}Ne) → ν_e



(A)-NF



Bunch compressor ring
Accumulator ring
2.2 GeV Superconducting H- Linac
Target
Horn
44/88 MHz capture, cooling, acceleration
2-10 GeV recirculator
10-50 GeV recirculator
Neutrino Factory schematic
(isometric view)
Muon decay ring
Triangle on an inclined plane
ν
ν
cdj

(A) Experiments [J.Bouchez, NO-VE 2003]

Phase	Experiment	Power (MW)	E (GeV)	L (km)	detector	Sens to θ_{13}	Starting date
Phase I	MINOS	0.4	3	730	Calorimeter	5^o	2005
Phase I	OPERA	0.17	20	732	Emulsion	7^o	2006
Phase I	ICARUS	0.17	20	732	L-Ar	5^o	2006
Phase II	NuMI-OA	0.4	2	700/ 900	Fine grained calorimeter[20kT]	2.5^o	2008 ?
Phase II	T2K (OA)	0.8	0.7	295	WC (SuperK) [20kT]	2.3^o	2009
Phase III	T2K-II (OA)	4.0	0.7	295	WC (HyperK) [500kT]	1^o	2020 ?
Phase III	SPL-SB	4.0	0.27	130	WC/L-Ar [500kT]	1^o	~2015
Phase III	β-Beam	0.2	0.3-0.6	130	WC/L-Ar [500kT]	0.5^o	2018 ?

(A) Experiments (cont'd)

- Requirements for Super-Beams ($\nu_\mu \rightarrow \nu_e$ appearance case)
  - Beam side:
    - Low ν_e contamination
    - Good knowledge of ν_e/ν_μ
    - Good understanding of the beam (near to far)
  - Detector side:
    - Good e- efficiency
    - Good π^0 rejection
    - Good understanding of bkg

Which energy?

- Low or high?
  - Focalisation of neutrinos $\sim\gamma^2\sim E^2$
  - Solid angle factor @ L $\sim 1/\gamma^2 \sim 1/E^2$
  - $\sigma(\nu) \sim \gamma \sim E$
  - p flux $\sim 1/\gamma \sim 1/E$

  $\rightarrow \sim 1$
- The 0th order approximation cannot help that much in the choice
- Other considerations mandatory

Low (E<1GeV) or High (E>1GeV) ?
[choice related to bkg considered]

intrinsic ν_e contamination and π^0 mimicking e-

- WC technique gives a good π^0 (NC) vs e- separation (2-ring vs 1-ring)
- Less ν_e (below K threshold)
- Fermi momentum ➔ poor E resolution
- No matter effects

- Better use fine grained detectors or L-Ar TPC
- Need good π^0 rejection
- More ν_e bkg
- Better resolution in E
- Matter effects can arise ➔ sign(Δm^2_{13})

caveat: stay below τ threshold

Underground or not?

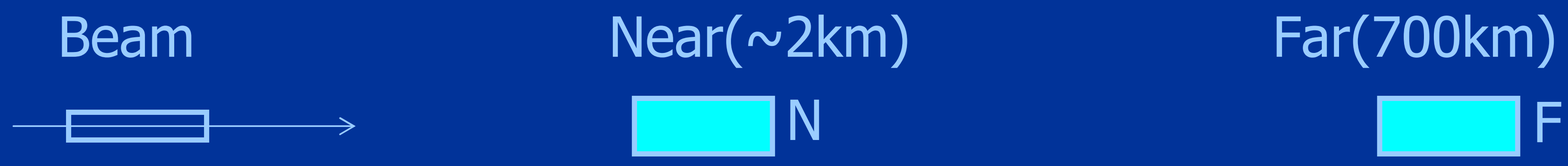
- In principle not: just a matter of choosing the right (low) duty cycle [phase II, 20 kton]
- BUT it is a must if your detector is "multi-purpose" (e.g. searching for other effects like proton decay) [phase III, 500 kton]

Near/Far

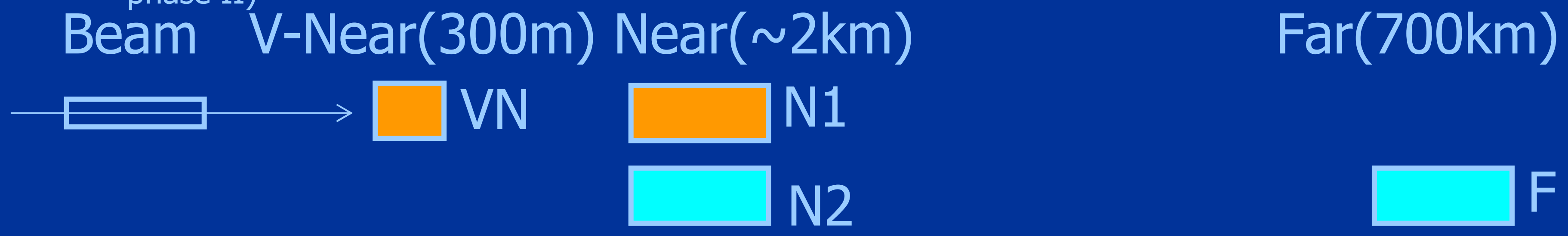
- Best way to determine ν_e bkg: measure it at a near location (before oscillation)
- Try to ensure equality of conditions between near and far detectors: i.e. same beam, same target nuclei (cross sections and π^0 production do depend on nuclei)
- Near detector sufficiently far from the source → point-like assumption (~ 2 km)
  - If you go closer then the source is not point-like anymore
- Near detector able to understand the different ν interactions (QE/non-QE)
- Ideally TWO near detectors (~300 m, ~2 km):
  - One giving a clear clue about ν interactions
  - The other as much as identical to the FAR detector

Near/Far (cont'd): strategies for beam understanding

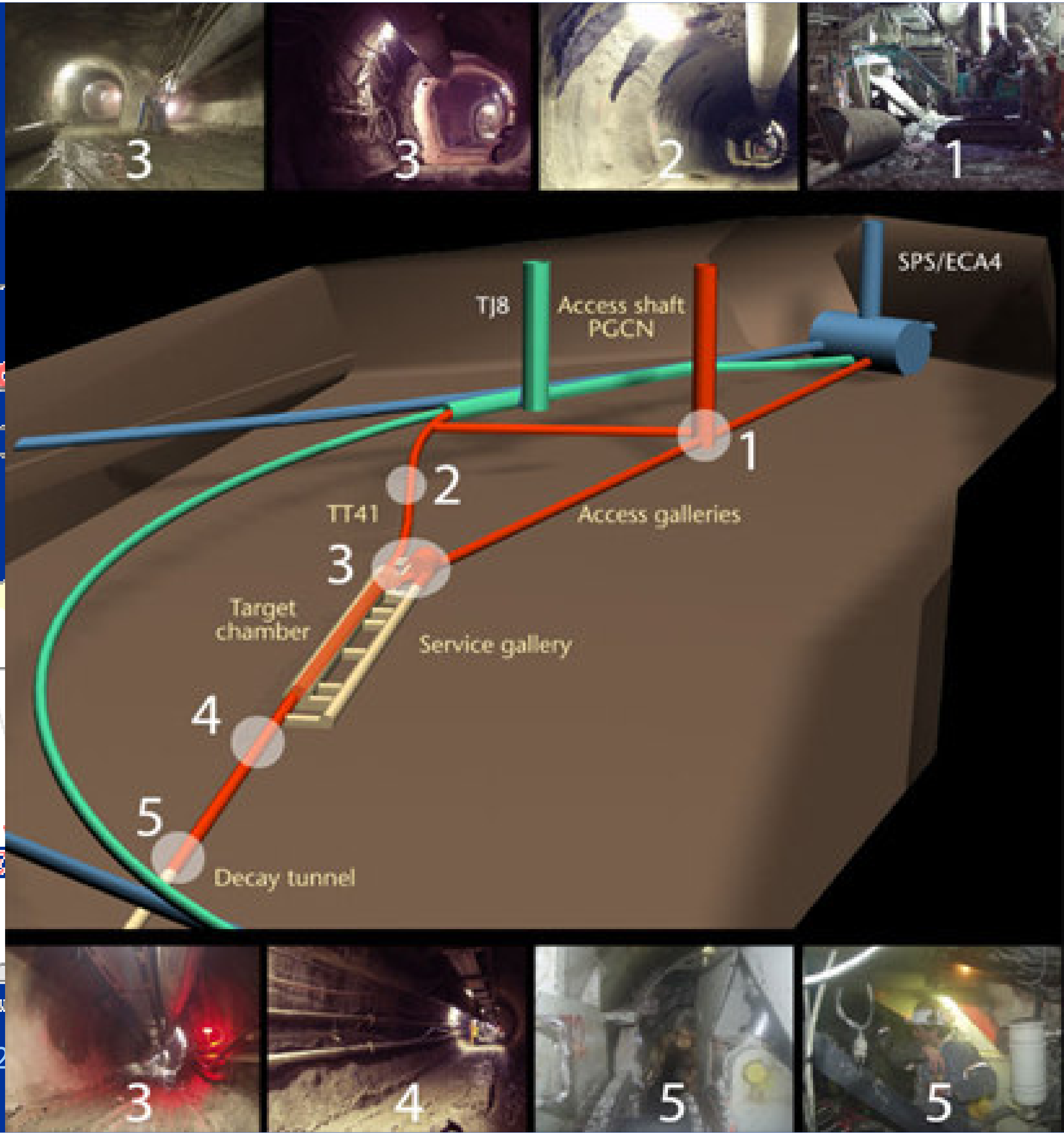
- Cheap solution:
  - N sees a point-like source
  - F and N use the same detection technique ($1/L^2$ law)
  - Good for discovery though it does not allow a precise measurement of θ_{13}



- "Pricey" solution:
  - VN ←→ N1: similar detection techniques allowing beam understanding
  - N1 ←→ N2: different in $\sigma(\nu)$ and detector performances → can be compared
  - F and N2 using the same detection technique
  - Should be optimal for high statistics phase III where you want to reduce systematics (less dramatic for phase II)



Time to have a look at some projects …



France

CE

from the desk of (Your Na

CNGS

full mixing, 5 years run
@ 6.76×10^{19} pot/year

- Tuned to reach max sensitivity to ν_τ appearance (off-peak) ➔ $E > E_{thre}(\tau) \sim 17$ GeV ➔ $\Delta_{CNGS} \sim \mathbf{O}(10^{-1})$ ➔ $\Delta^2 \sim \mathbf{O}(10^{-2})$

$$\mathbf{P}(\nu_\mu \to \nu_\tau) \approx \cos^4\theta_{13} \cdot \sin^2 2\theta_{23} \cdot \Delta^2$$

← Suppression factor

- They open a window to θ_{13}

$$\mathbf{P}(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \cdot \sin^2\theta_{23} \cdot \sin^2\Delta$$

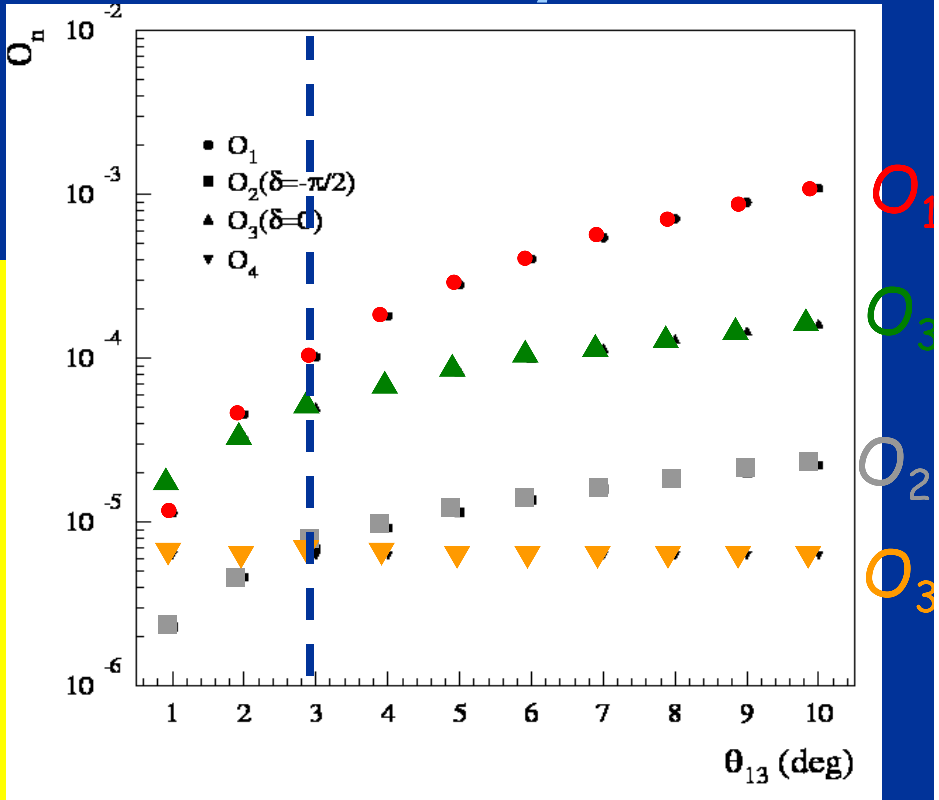
NB:

- High cross sections $\sigma(\nu_\tau$-CC), $\sigma(\nu_e$-CC)
- High granularity (and detection of $\tau \to e$ processes): high BKG suppression (NC(π^0), $\nu_\mu \to \nu_\tau \to \tau(\to e)X$)

Relative importance of the terms in P: case OFF-PEAK: $\Delta \neq \pi/2$

$A_i \sim O(1)$, $\hat{A}_{CNGS} \sim 1.6$

$|1-\hat{A}|\Delta << 1 \rightarrow \sin^2[(1-\hat{A})\Delta]/(1-\hat{A})^2 \sim \Delta^2$



- Effect $(\delta-\theta_{13}) \rightarrow O_3$
- Sign(Δm^2_{13})

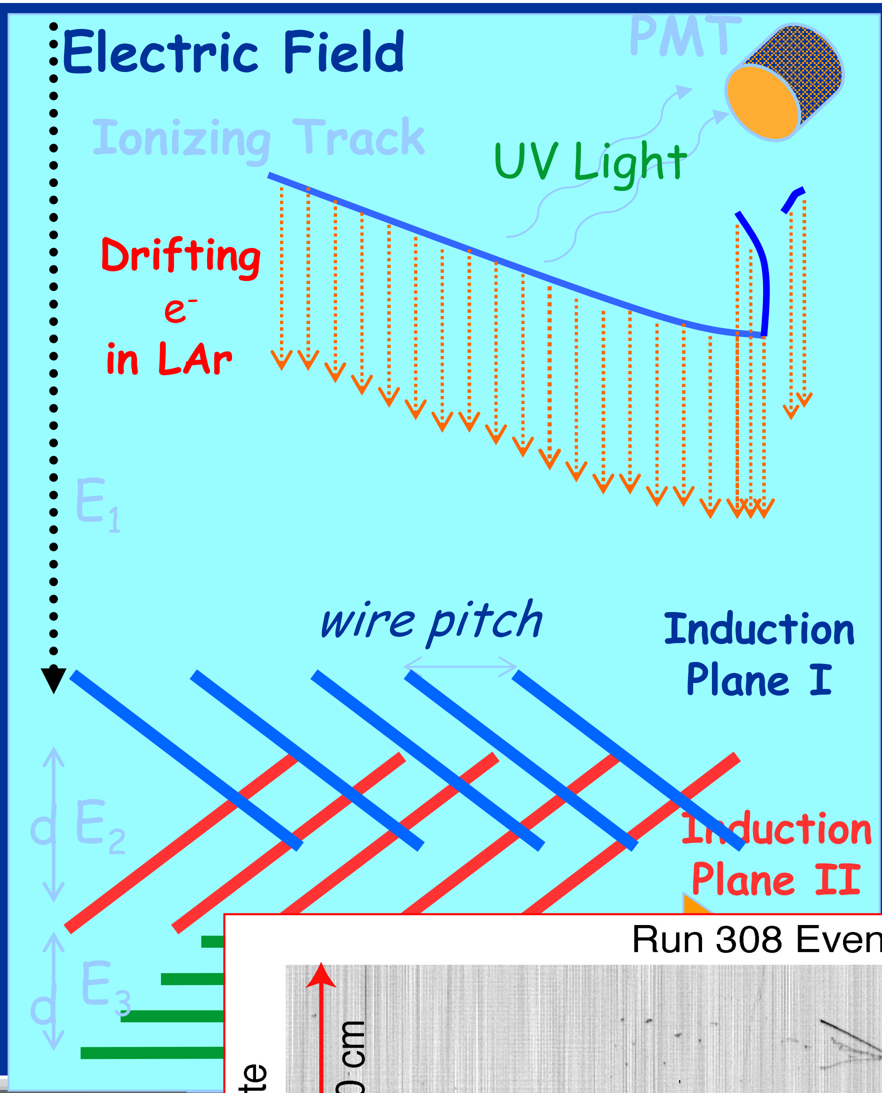
[P.Migliozzi, NO-VE 2003]

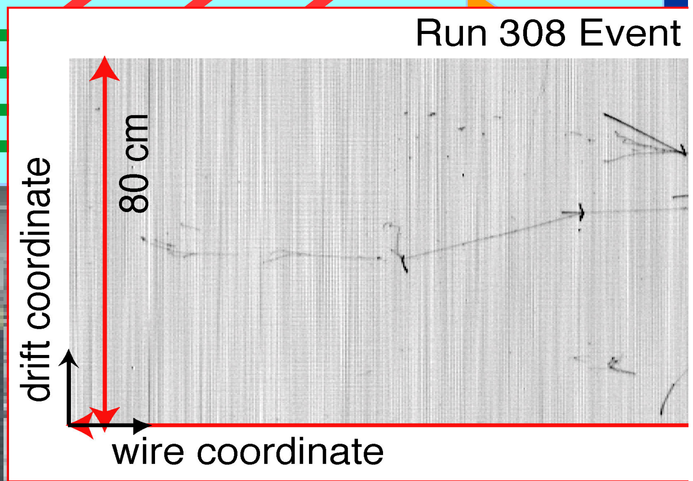
Deterioration effect from

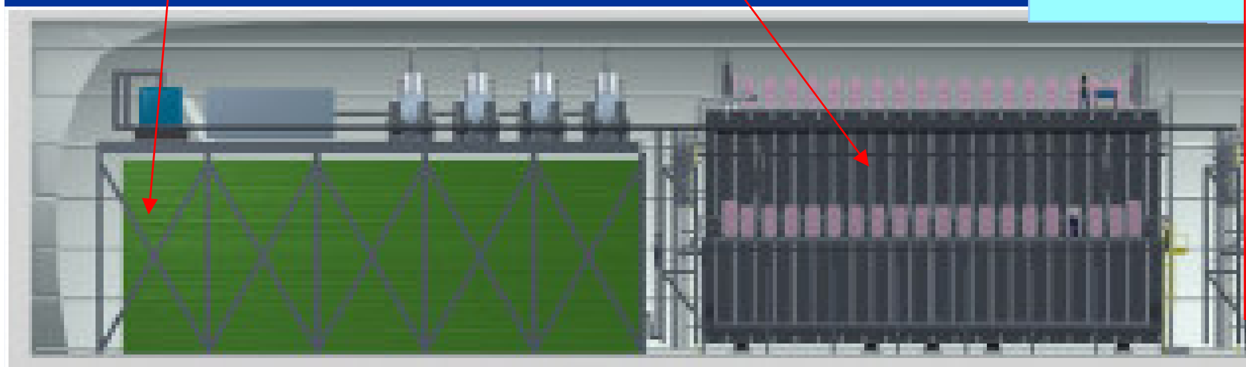
$\theta_{13} \sim 3^o$

Icarus:Lar-TPC

- T~89K, E~.5 kV/cm
- tracking, dE/dX, e.m. + had. calorimetry
- e/γ id // e/π separation
  σE/E~13%/sqrt(E) (e.m.)
  σE/E~30%/sqrt(E) (had)
- Conceived to detect events with τ production ➔ allows detection of e and therfore the study of channel νμ→ντ
- Being built @ LNGS
  - T600
  - 2xT1200 → T3000







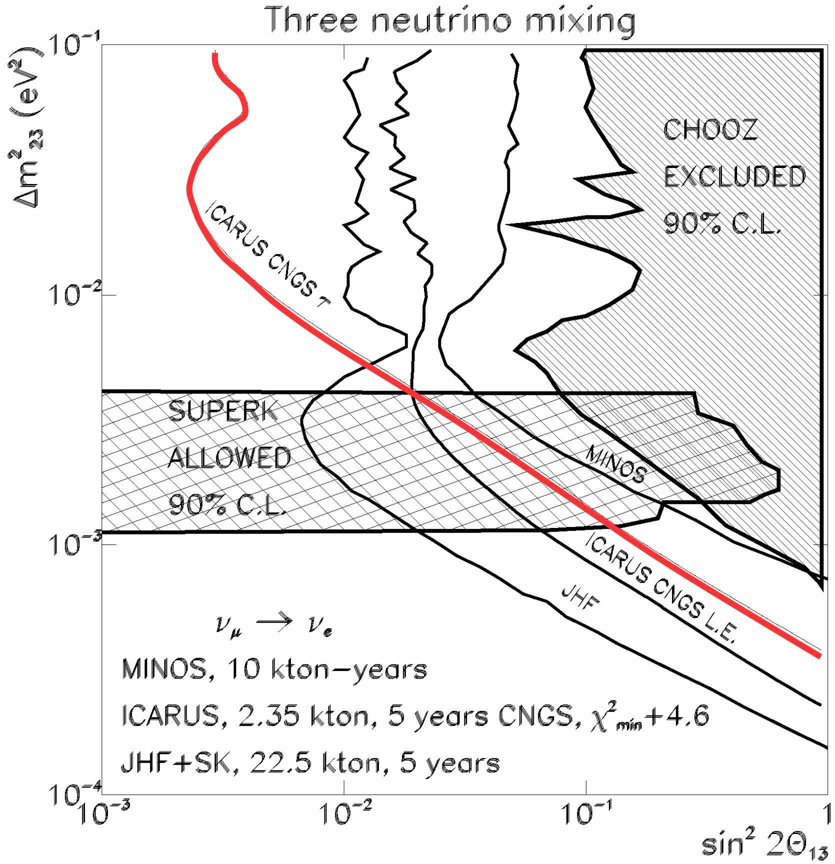
Icarus: expected results for θ_{13}

@ $\Delta m^2_{23} = 2.5 \times 10^{-3}$

$$(\sin^2 2\theta_{13})_{CNGS,\tau} < 0.04 \quad \text{or} \quad \theta_{13} < 6^\circ$$

$$(\sin^2 2\theta_{13})_{CHOOZ} < 0.14 \quad \text{or} \quad \theta_{13} < 11^\circ$$

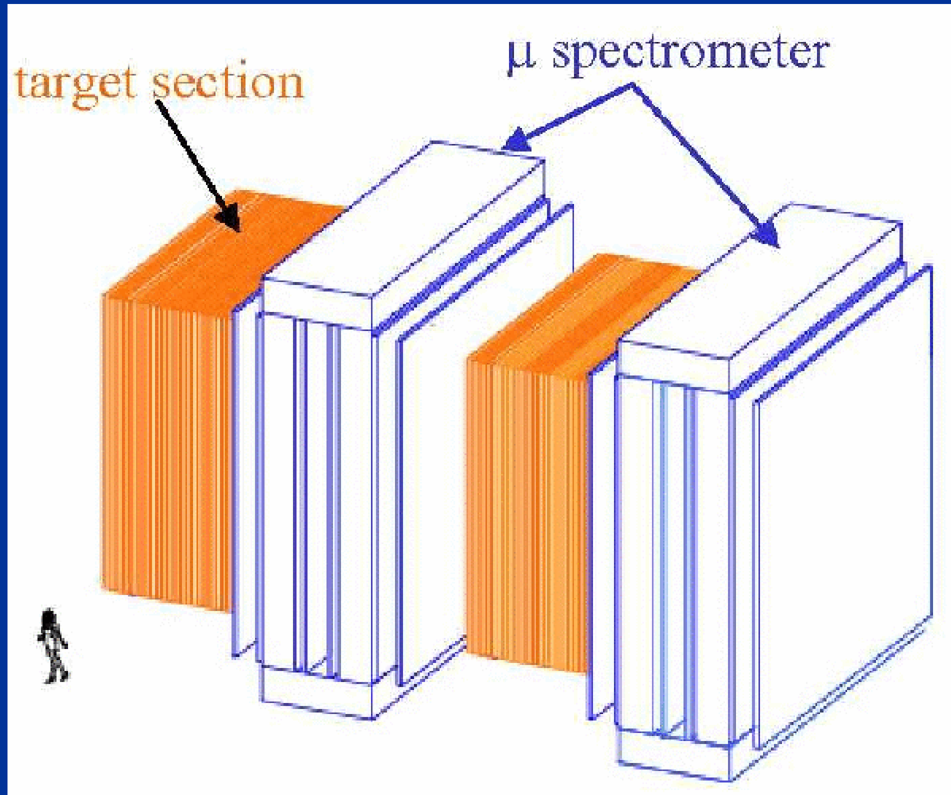
$$(\sin^2 2\theta_{13})_{MINOS} < 0.06 \quad \text{or} \quad \theta_{13} < 7^\circ$$



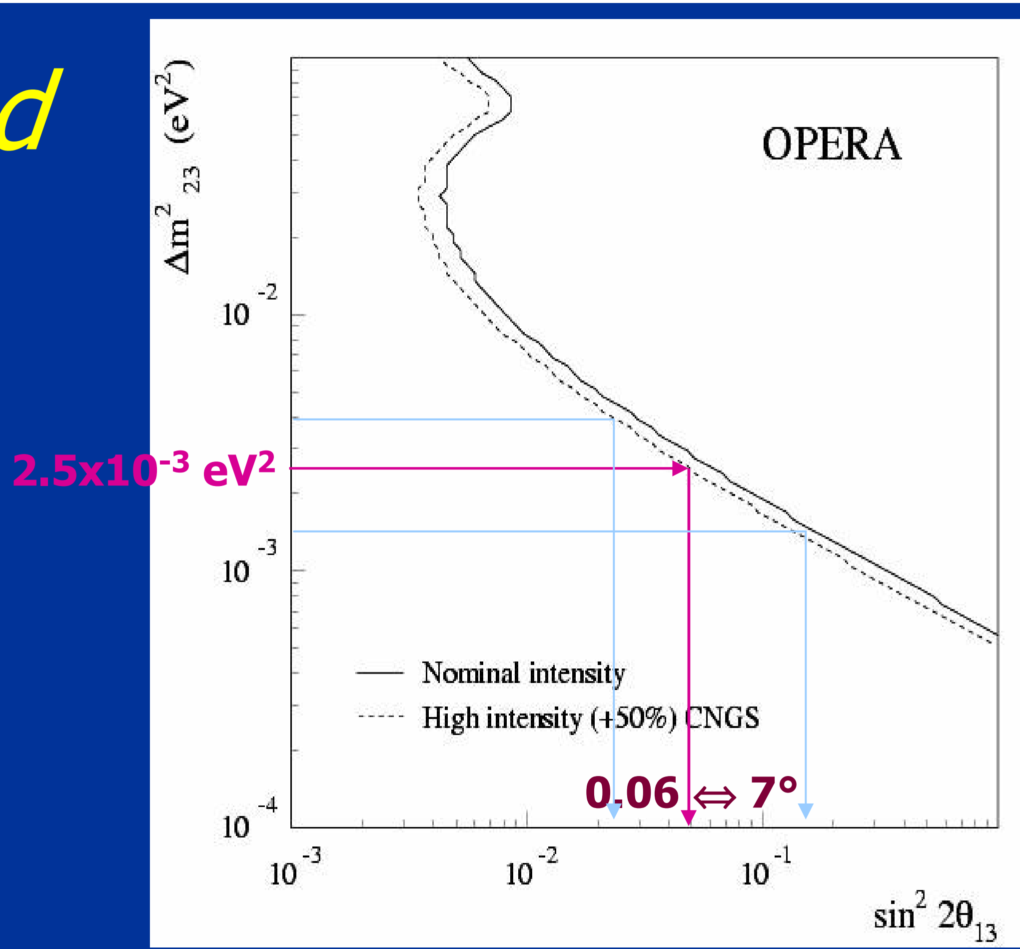
C.Montanari-LNGS, 22-marzo-2004

Opera: emulsions + μ-spectrometer

- Direct observation of the decay products from τ (CC)
- High granularity: ~ μm (track separation)
- $\sigma_E/E \sim 20\%/\mathrm{sqrt}(E)$ (e.m.)



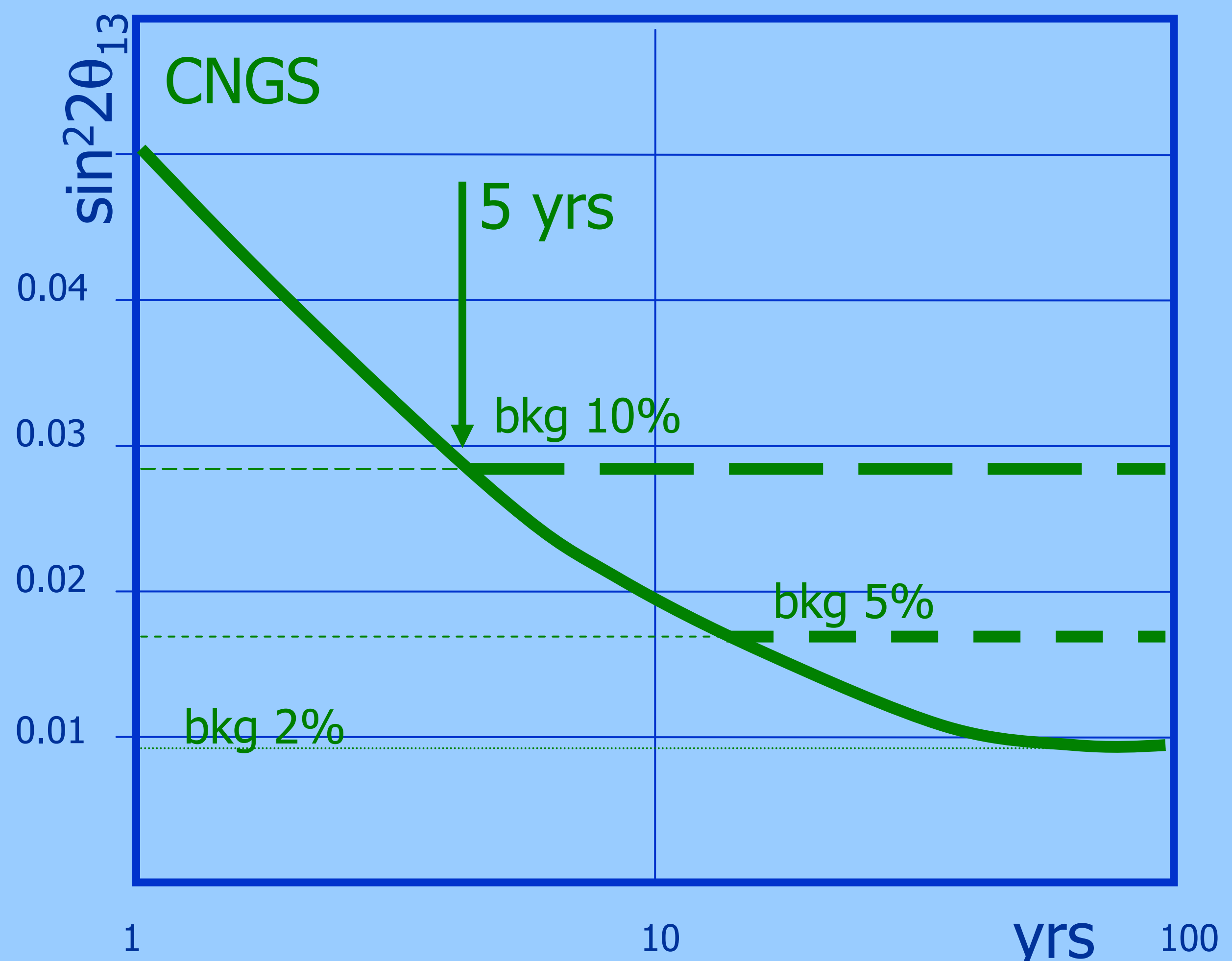
Opera: expected results for θ_{13}



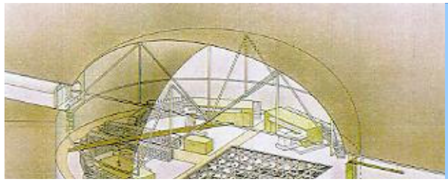
τ detection	signal ($\Delta m^2 = 1.3 \times 10^{-3}\ eV^2$)	signal ($\Delta m^2 = 2.0 \times 10^{-3}\ eV^2$)	signal ($\Delta m^2 = 3.0 \times 10^{-3}\ eV^2$)	BKGD
Final Design	4.7	11.0	24.6	1.06

CNGS (cont'd)

- Sensitivity to θ_{13} (sign(Δm^2)&δ effects):

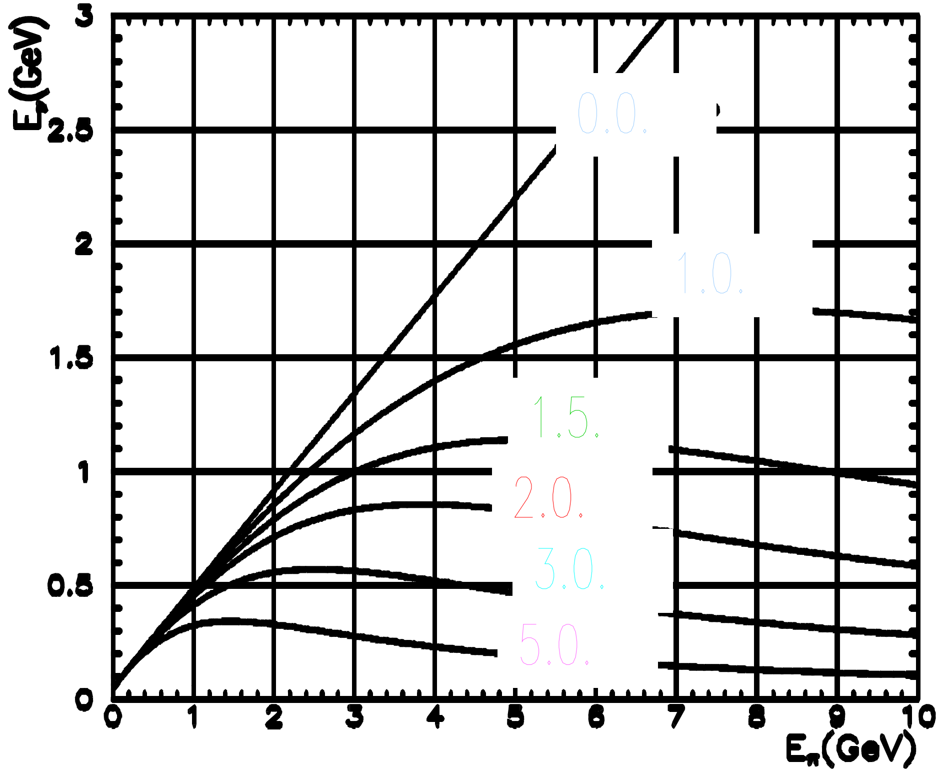


[P.Migliozzi, F.Terranova arXiv:hep-ph/0302274]



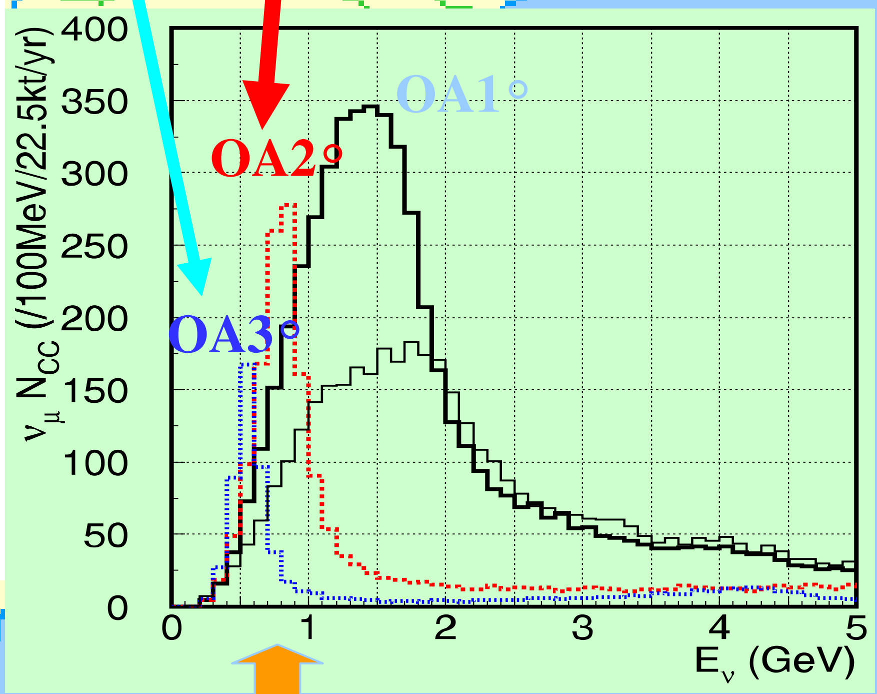
T2K [I/II]

E_π vs. E_ν

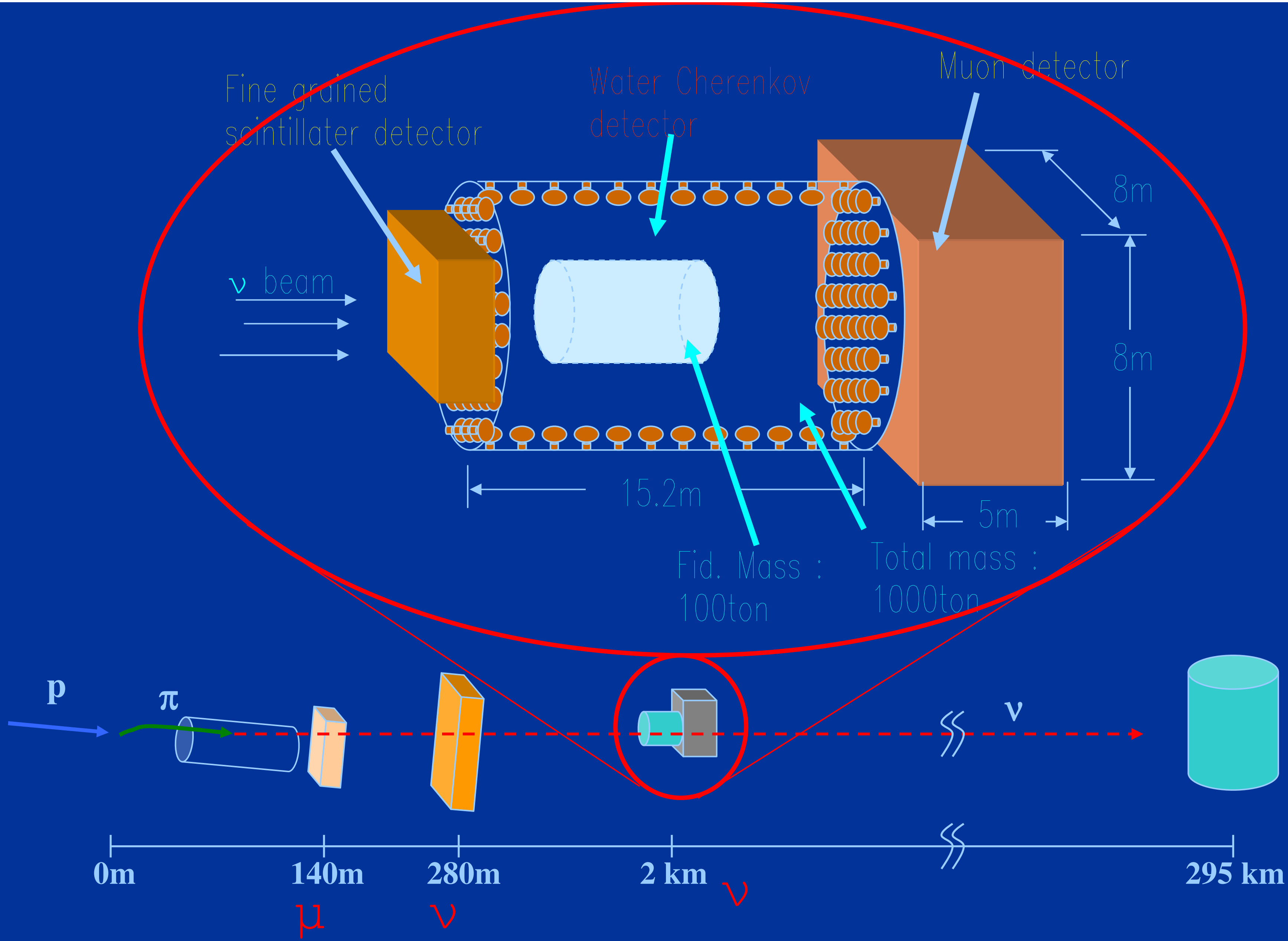


800 CC ν_μ / year

2200 CC ν_μ / year



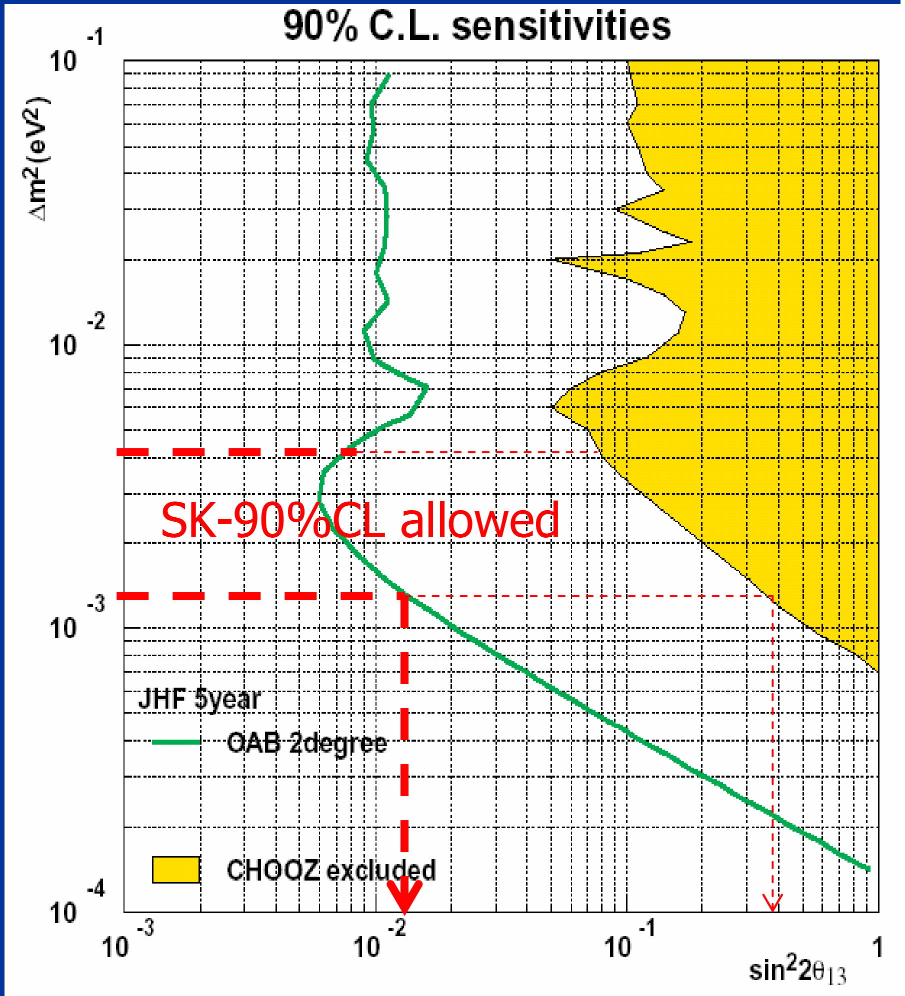
Max. osc. energy for 3×10^{-3} eV^2


Fine grained
scintillater detector
Water Cherenkov
detector
Muon detector
ν beam
8m
8m
15.2m
5m
Fid. Mass :
100ton
Total mass :
1000ton
p
π
ν
0m
140m
280m
2 km
295 km
μ
ν
ν

SuperKamiokande

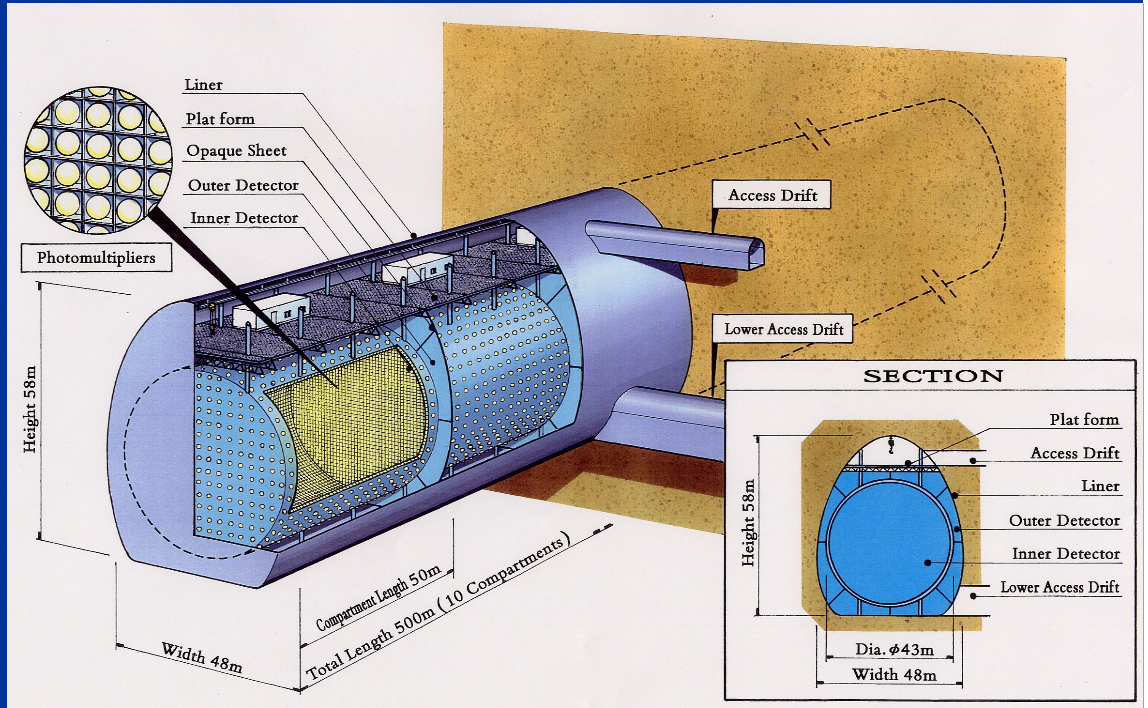
- Water Cerenkov detector
  - Sub-GeV → good π^0/el. separation
  - θ_{13}: 2.5° sensitivity after 5 yrs of data taking

T. Kajita, Fermilab – May 2003



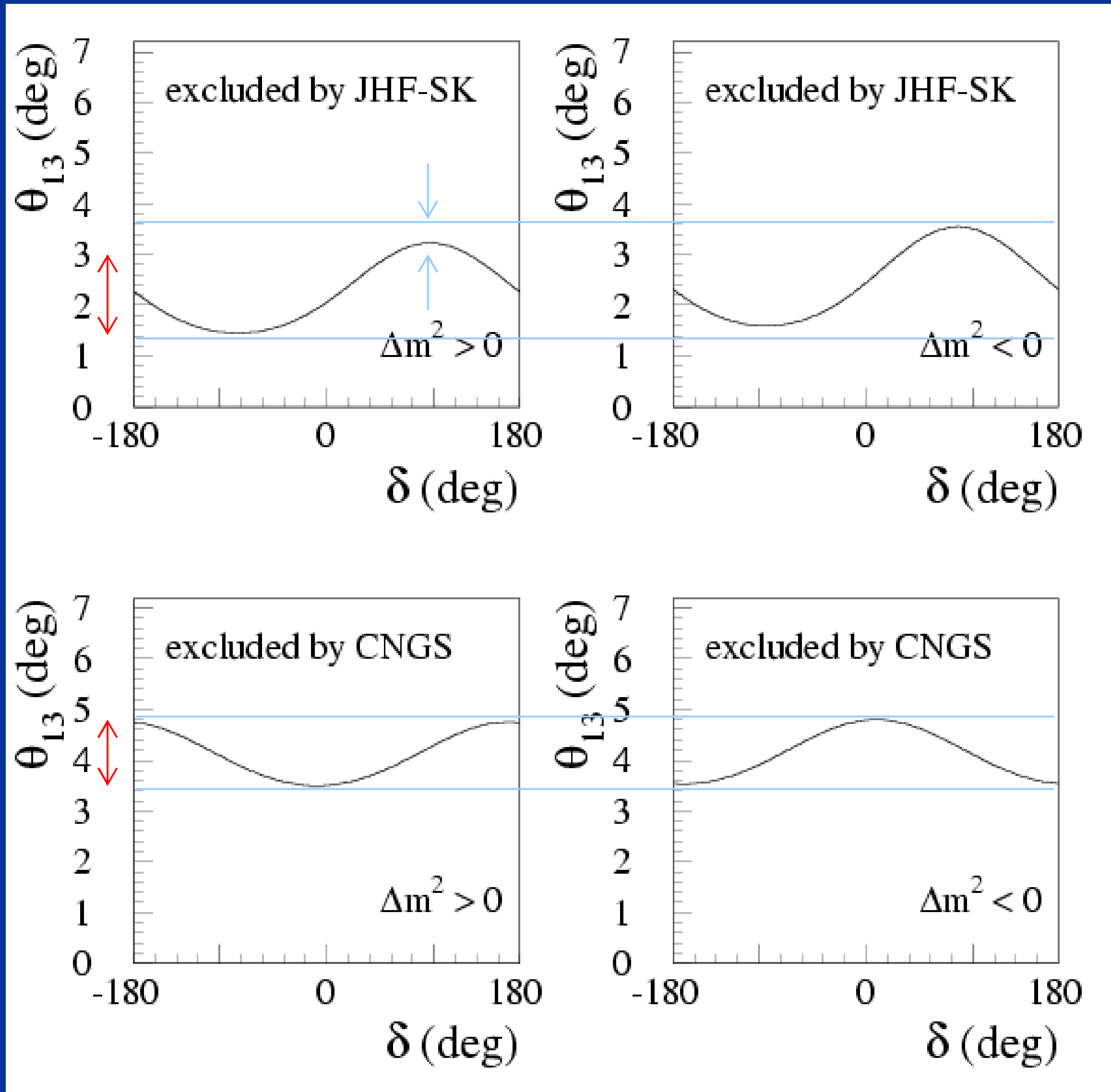
HyperKamiokande

- Goals:
  - Improve θ_{13} sensitivity
  - Go for CP violation measurement



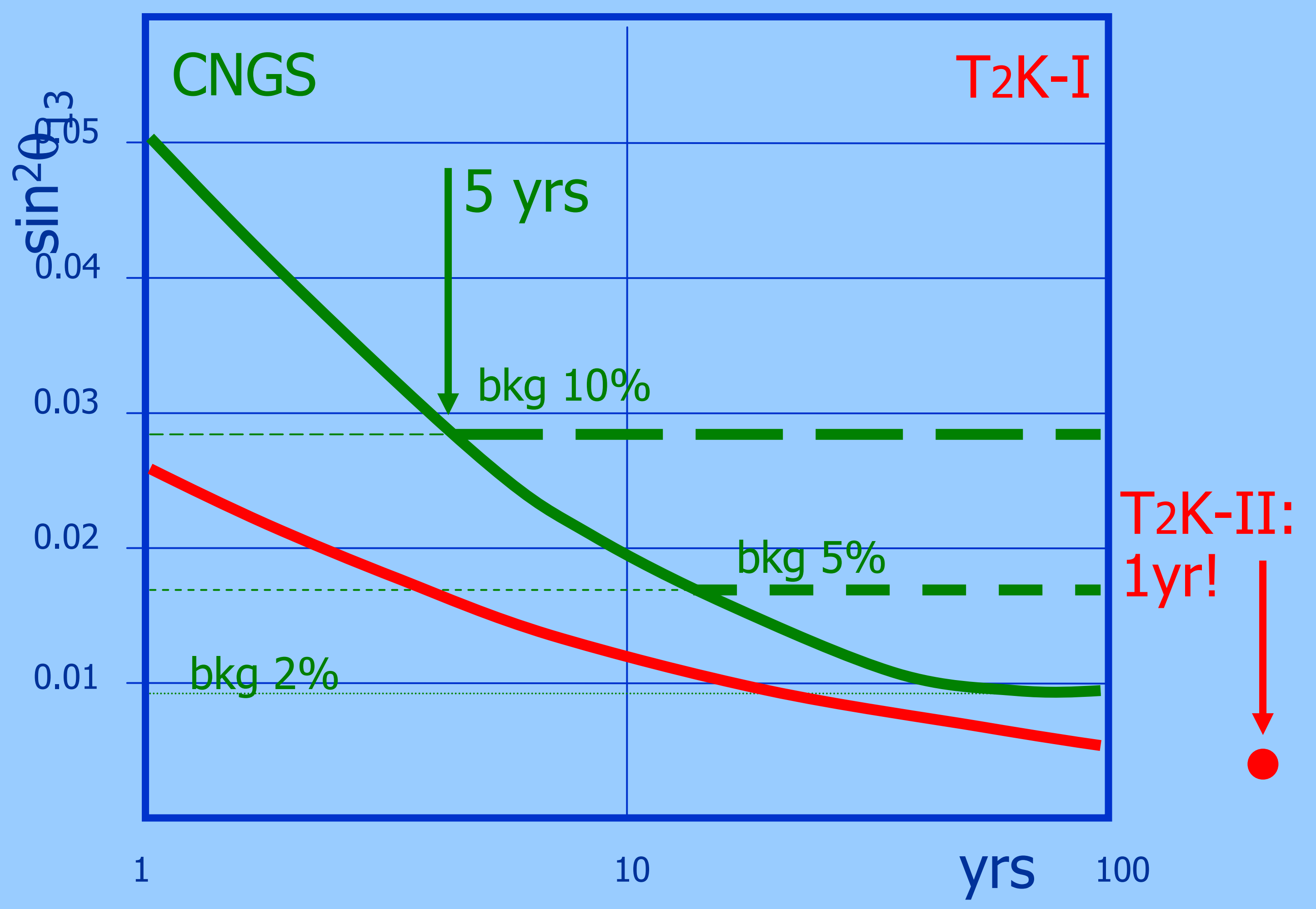
T2K-I vs CNGS

- Sensitivity to θ_{13} as a function of δ
- T2K: O_2 even in Δ
- CNGS: O_3 odd in Δ



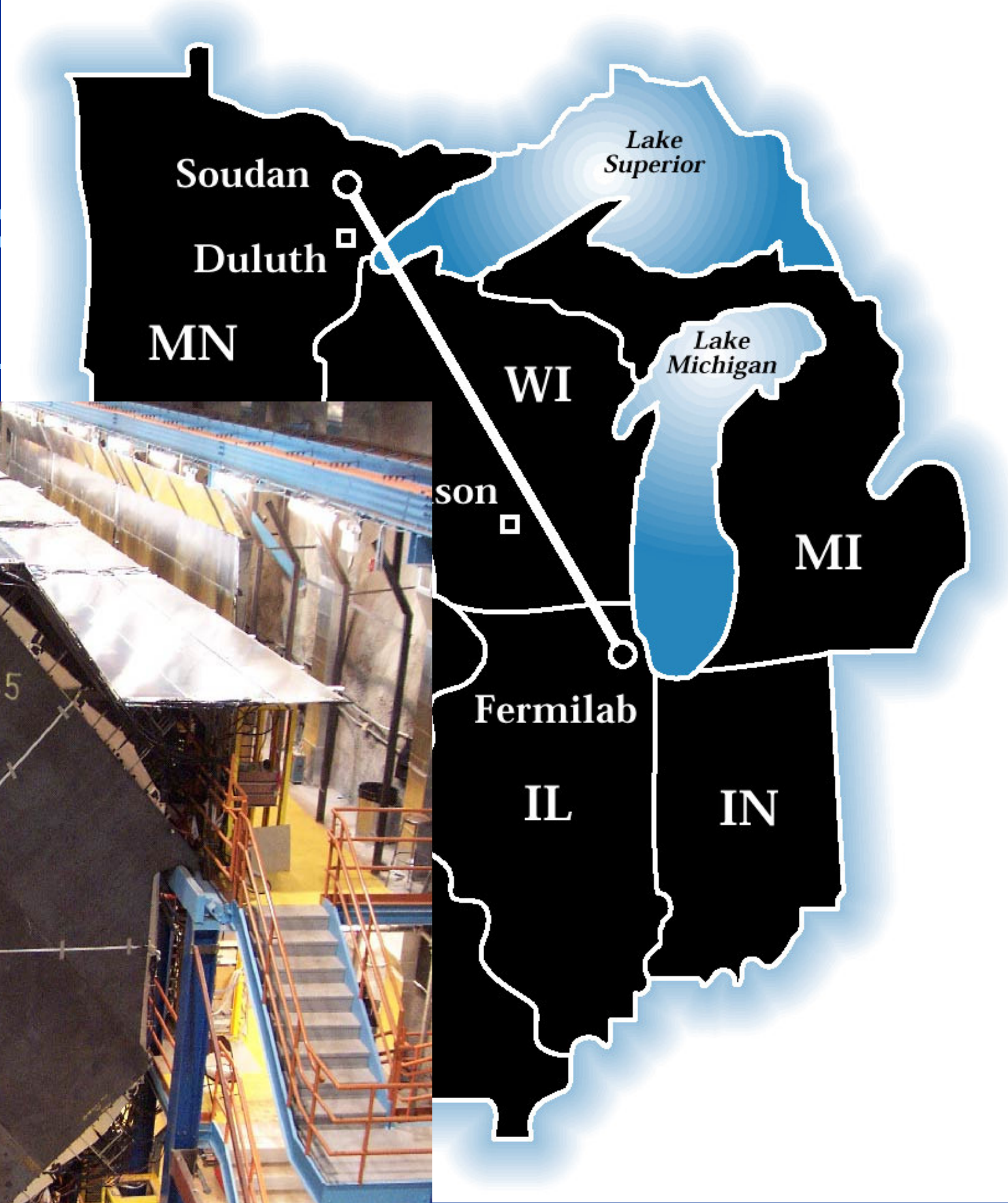
T2K I/II vs CNGS

- Sensitivity to θ_{13}:



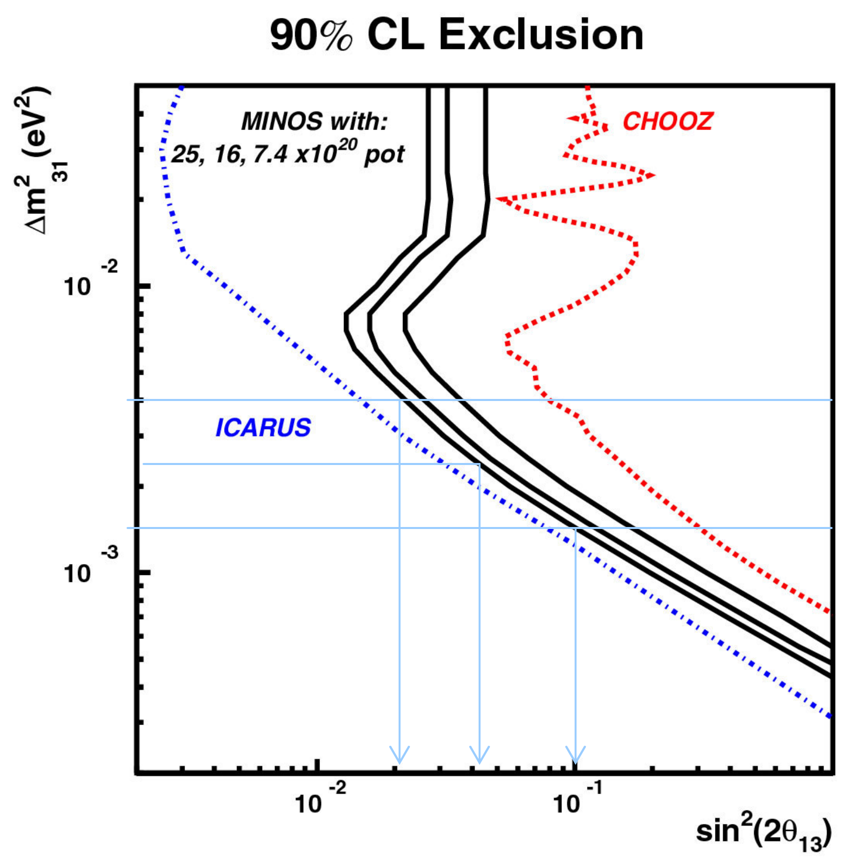
Minos

- L/E tuned to the first MAX
  (~730km/3GeV)
- Magnetized (1.5 T) calorir

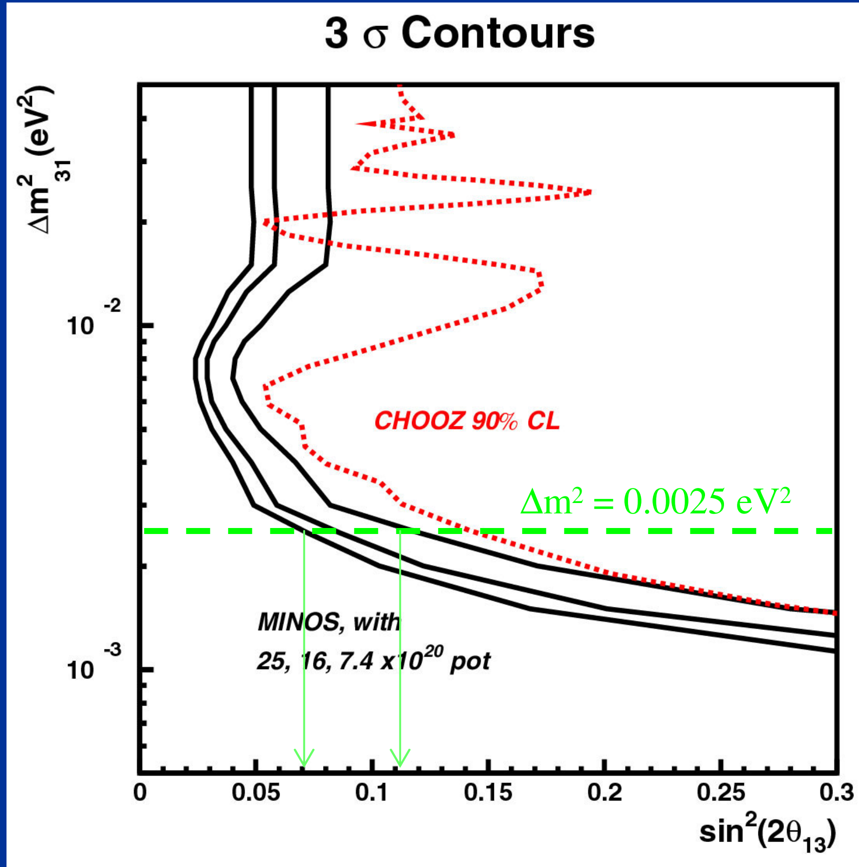


Minos (cont'd)

Sensitivity to θ_{13}



MINOS 3σ discovery limits

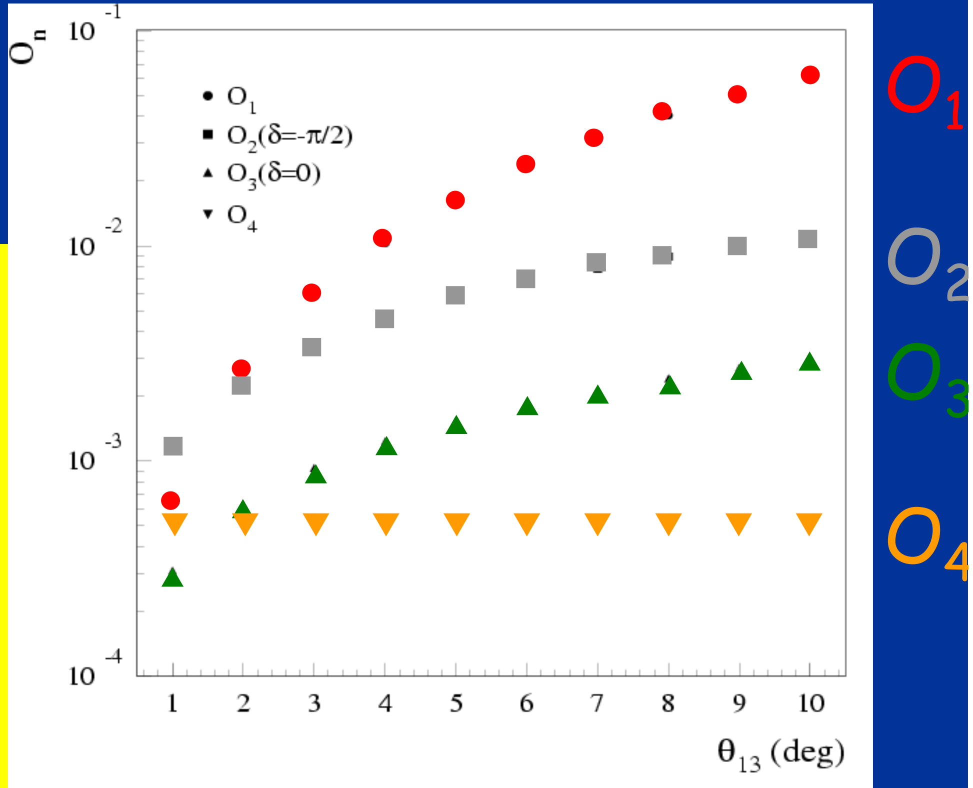


NuMI-OA

- OA: θ~0.7º
- L~712 km, <E>~2.2 GeV → on peak
- |A|~0.2 → matter effects NOT negligible → sensitivity to sign(Δm^2_{13})

Relative importance of terms in P: case ON-PEAK:$\Delta \sim \pi/2$

$A_i \sim O(1)$, $\hat{A}_{JPARC} \sim 0$



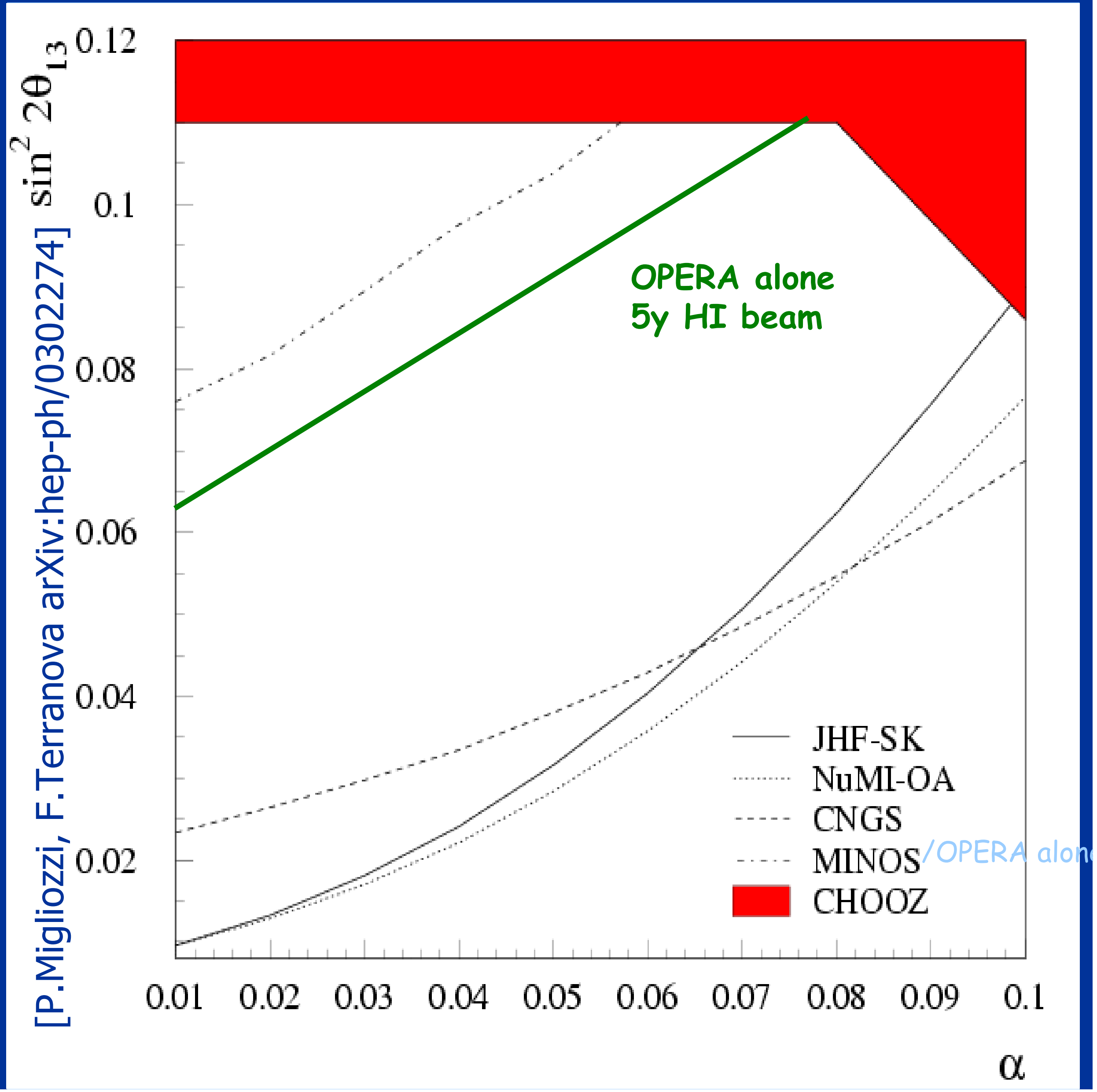
- $A_i \sim O(1)$
- Effect (δ-θ_{13})

Deterioration effect from

$\theta_{13} \sim 3^o$

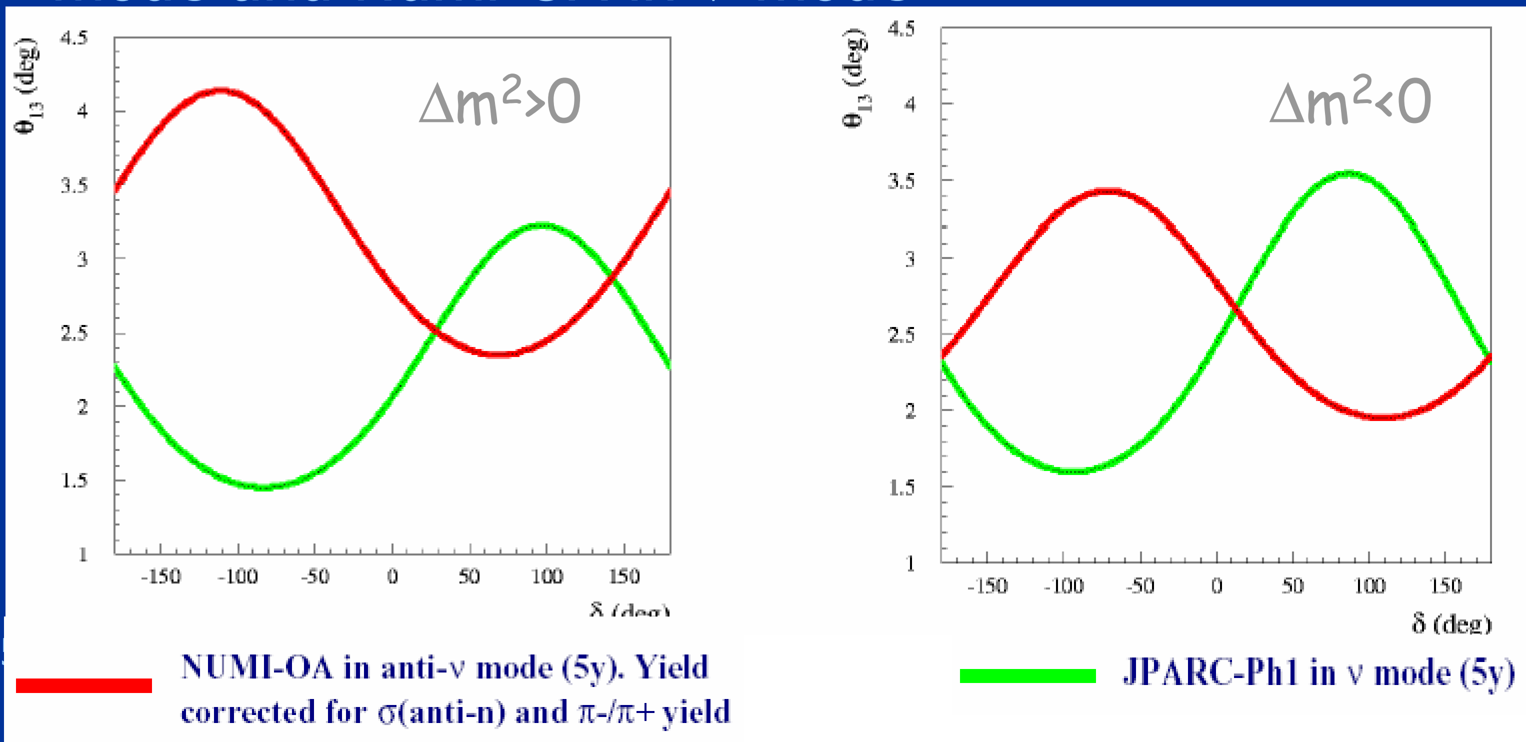
(A) sensitivity to θ_{13} (90% C.L.)

- as a function of α

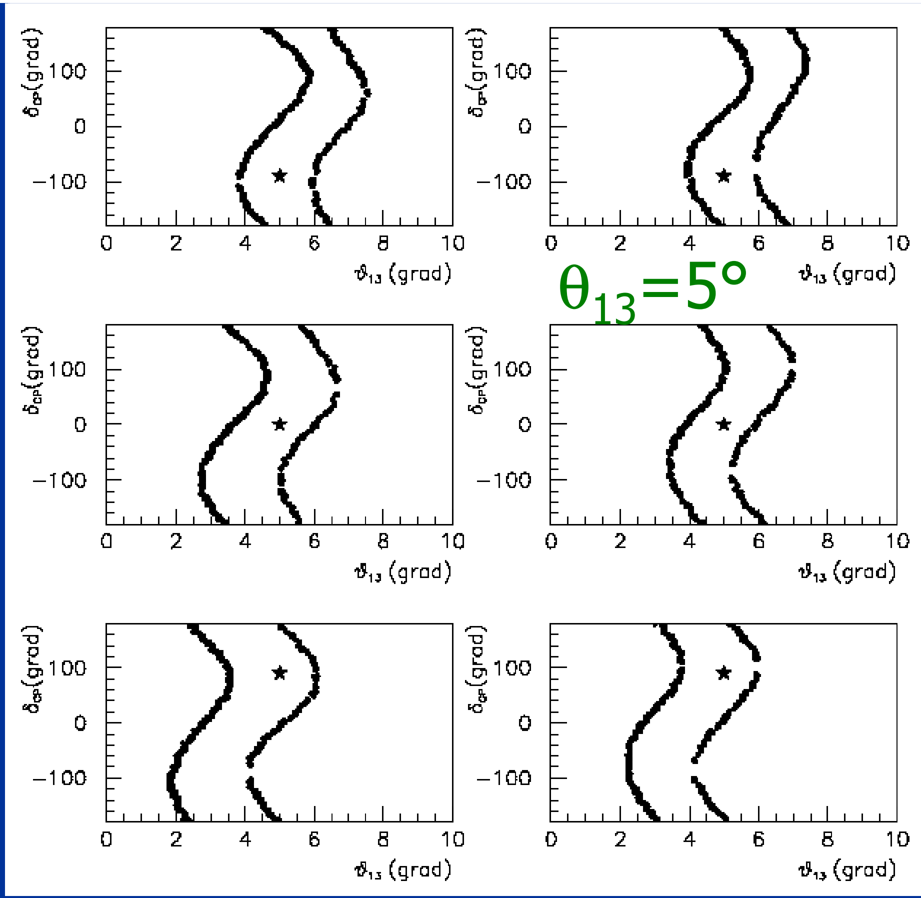


θ_{13} at (A)

- Measurement made difficult by matter effects and CP violation
- Sensitivity to θ_{13} strongly depends on δ
- Synergies among different experiments could help
- Ex.: sens. to θ_{13} in T_2K + Numi-OA: start T_2K in ν-mode and Numi-OA in $\bar{\nu}$-mode



- If $\theta_{13}>7^o$ then: indication of appearance at 90% C.L.
- Ex1: $\theta_{13}=10^o$
- CNGS: 3 yrs of data taking (T_2K-I start), $\Delta m^2<>0$
- 8 yrs CNGS d.t. + 5 yrs T2K d.t.
- Ex2: $\theta_{13}=5^o$

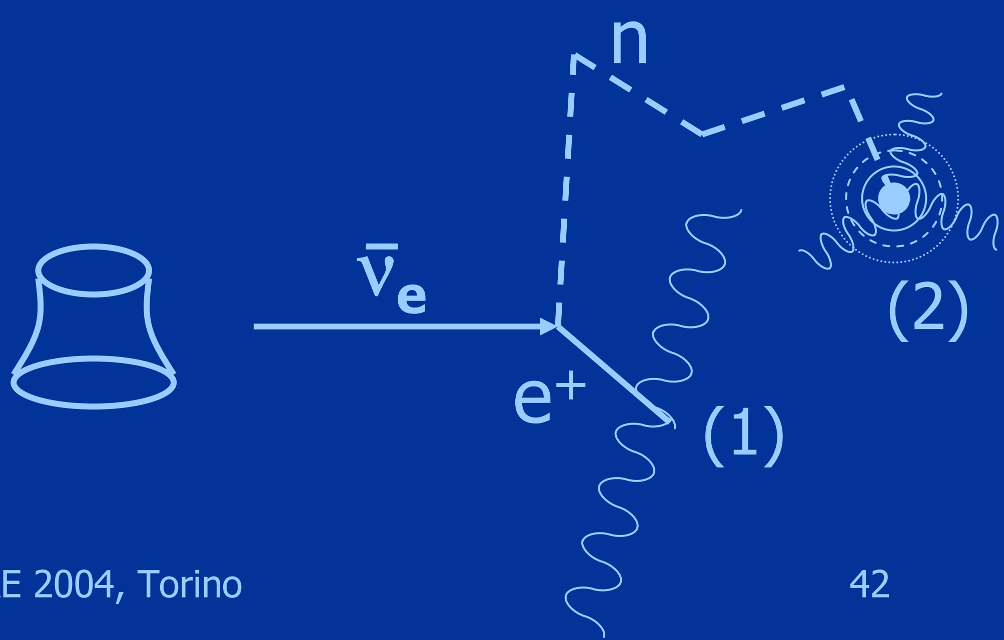


disappearance exp.: Reactors

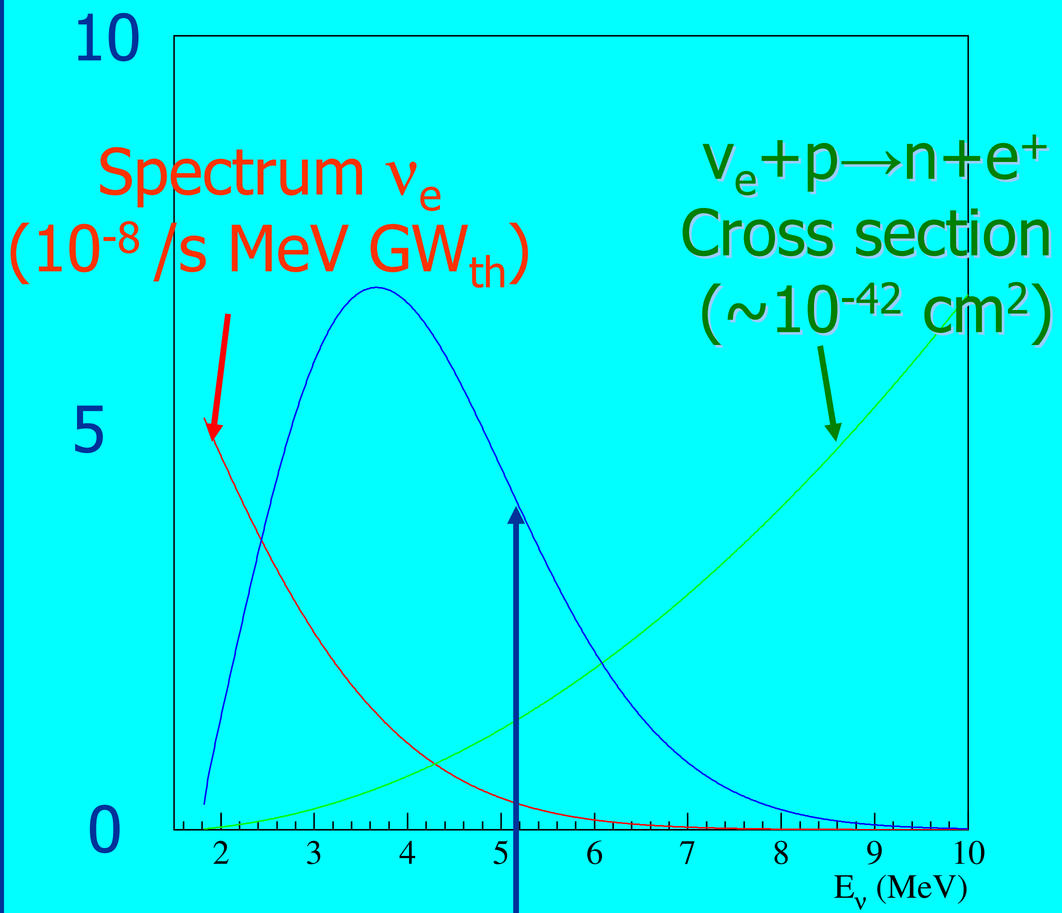
- Reactors: P NOT sensitive to δ → can do a pure measurement of θ_{13}
- Tipical reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Detection: "prompt" signal from positron (1) + delayed capture of n on Gd (p) (2) [a la Chooz]

$$\mathrm{P}(\nu_e \rightarrow \nu_e) =$$
$$= 1 - \sin^2 2\theta_{13} \cdot A_1 + \alpha^2 \cdot A_2$$
$$A_1 = \sin^2 \Delta$$
$$A_2 = \cos^4 \theta_{13} \cdot \sin^2 2\theta_{12} \cdot \Delta^2$$
$$\Delta = \Delta m^2_{13} \left(L/4E \right)$$
$$\alpha = \frac{\Delta m^2_{21}}{\left|\Delta m^2_{31}\right|}$$

[F.Dalnoki-Veress, La thuile 2004]



Chooz



Observed spectrum (interactions/MeV ton day)

$$E_{\bar{\nu}} \cong E_{e^+} + E_n + (M_n - M_p) + m_{e^+}$$

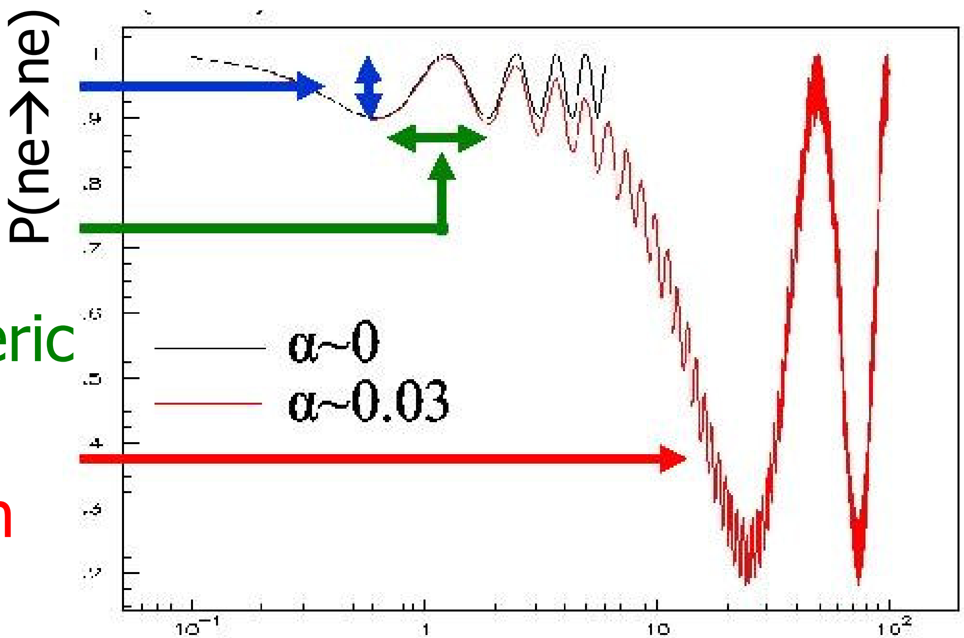
$P(\nu_e \to \nu_e)$

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \cdot A_1 + \alpha^2 A_2$$

θ_{13}: amplitude

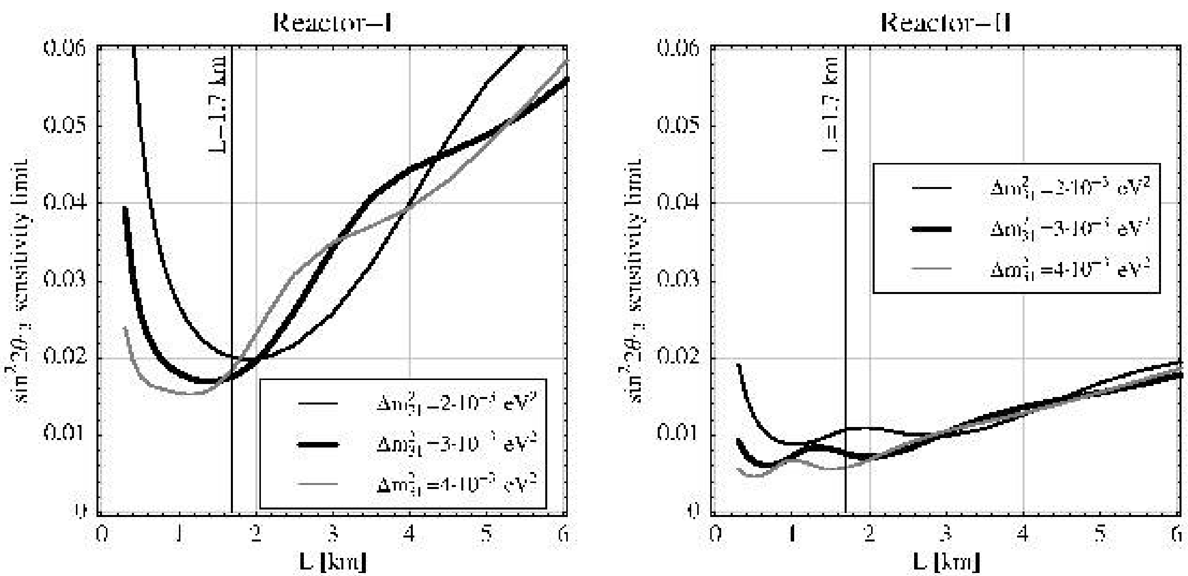
$A_1 = A_1(\Delta)$: atmospheric modulation

A2: solar modulation



[F.Dalnoki-Veress, La thuile 2004]

RI 400 t GW y
RII 8000 t GW y



[Huber at al., hep-ph/0303232]

Chooz: an example of reactor experiment

- Relied on
  - calculation of ν_e flux from the two reactor cores
  - computation of the active mass of the target
  - evaluation of the absolute efficiency
  - knowledge of ν_e cross section
- Systematics kept at 2.8% ← finally limited the experimental result

- The key for a successful new reactor experiment (measuring θ_{13}) is reducing the systematics (<1%) and reach enough statistics (<0.5%)
- This can be achieved by using a pair of "identical" detectors (near/far technique)
- Some ideas are being pursued:
  - A case: Double Chooz
- CAVEAT-1: you never have 2 identical detectors!
  - Different bkg (and dead times)
  - S/N different
- CAVEAT-2:energy scale and relative non-linearities to be held into account

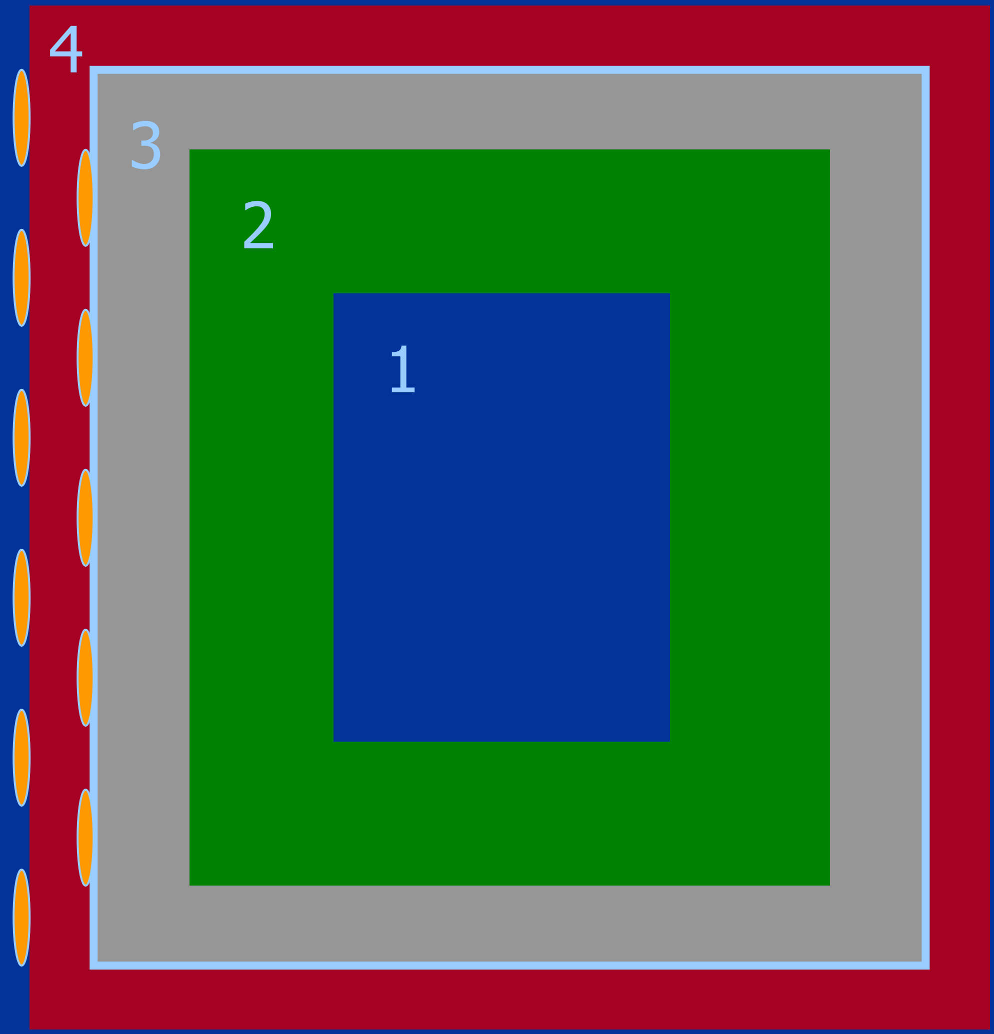
strategies

- Faster:
  - Use existing facilities/places with proper "refurbishing"
  - Try to get some result before or at the same time as LBL exp's (e.g. T2K-I, Numi-OA)
- Reactors complementarity:
  - No need to go faster: try instead to perform a highly precise measurement
  - Build new brand detectors (sophisticated too: e.g. with movable baselines)
  - You pay it with a later start

from CHOOZ to double-CHOOZ

- Detector Basics: 2 identical detectors (12.6 m^3) at
  - 150 m
  - 1050 m
1. Gd (0.1%) loaded LS
   - ~ 10 ton
2. LS buffer
3. Non-scintillating buffer
4. VETO

H.deKerret, NO-VE 2003



K.Anderson et al., arXiv:hep-ex/0402041 v1 26 Feb 2004

From CHOOZ to Double-CHOOZ

Mainly canceled using the near/far technique

systematics	CHOOZ	D-CHOOZ
Reactor flux	1.9%	-
Reactor power	0.7%	-
E/fission	0.6%	-

systematics	CHOOZ	D-CHOOZ
LS density	0.3%	-
%H	1.2%	-
Np target	0.8%	0.2%
ε(Ee+)	1.5%	0.5%
Target volume	0.3%	0.2%

Relative error: σ_{rel}~0.6%

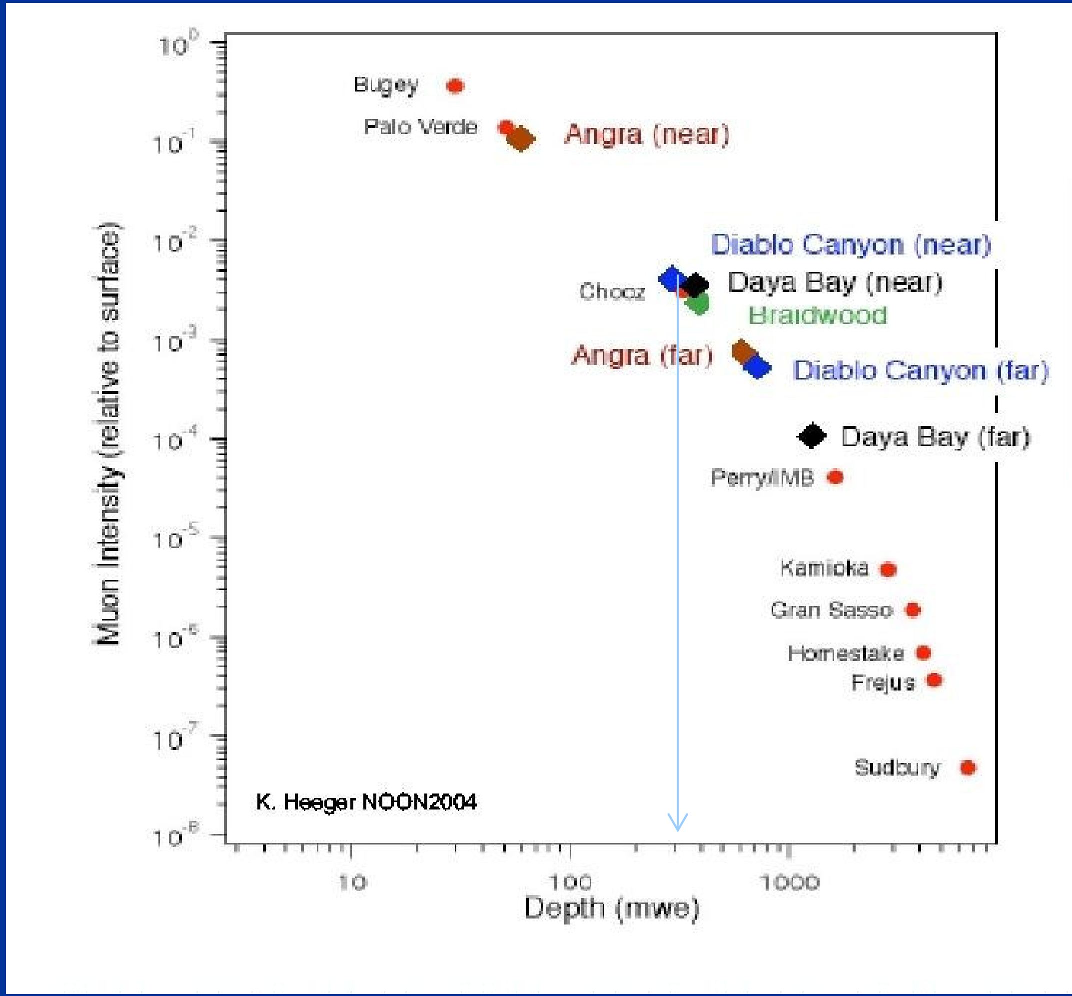
σ_{sist}~1%

Using the same LS/LS+Gd should help a lot to improve these systematics

[F.Dalnoki-Veress, La thuile 2004/H.De Kerret, NO-VE 2003]

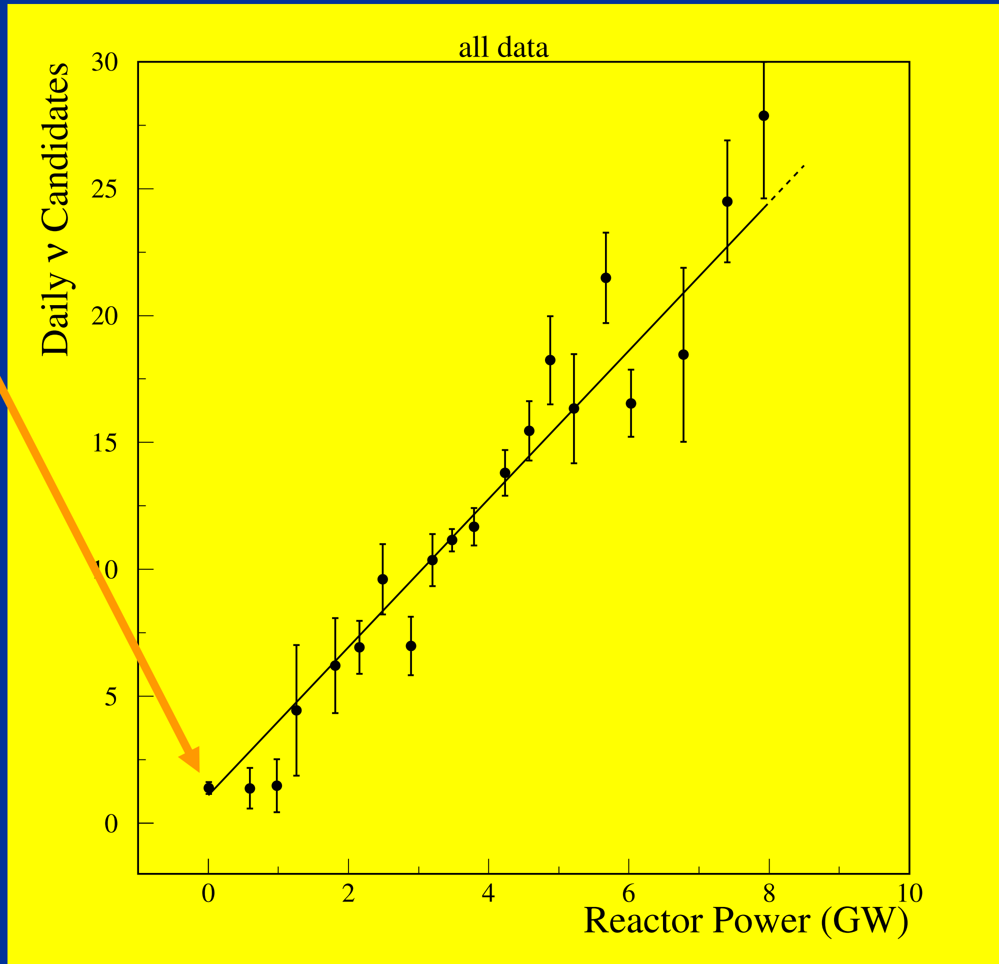
from CHOOZ to double-CHOOZ

- Important: reduce the muon flux → main cause of correlated background!
- Also present the accidental background from natural radioactivity → LS buffer + veto
- BKG can be measured when (if) reactor is OFF



CHOOZ: rate_n vs thermal power

•NB: when GW→0 you get the bkg (accid.+correlated)



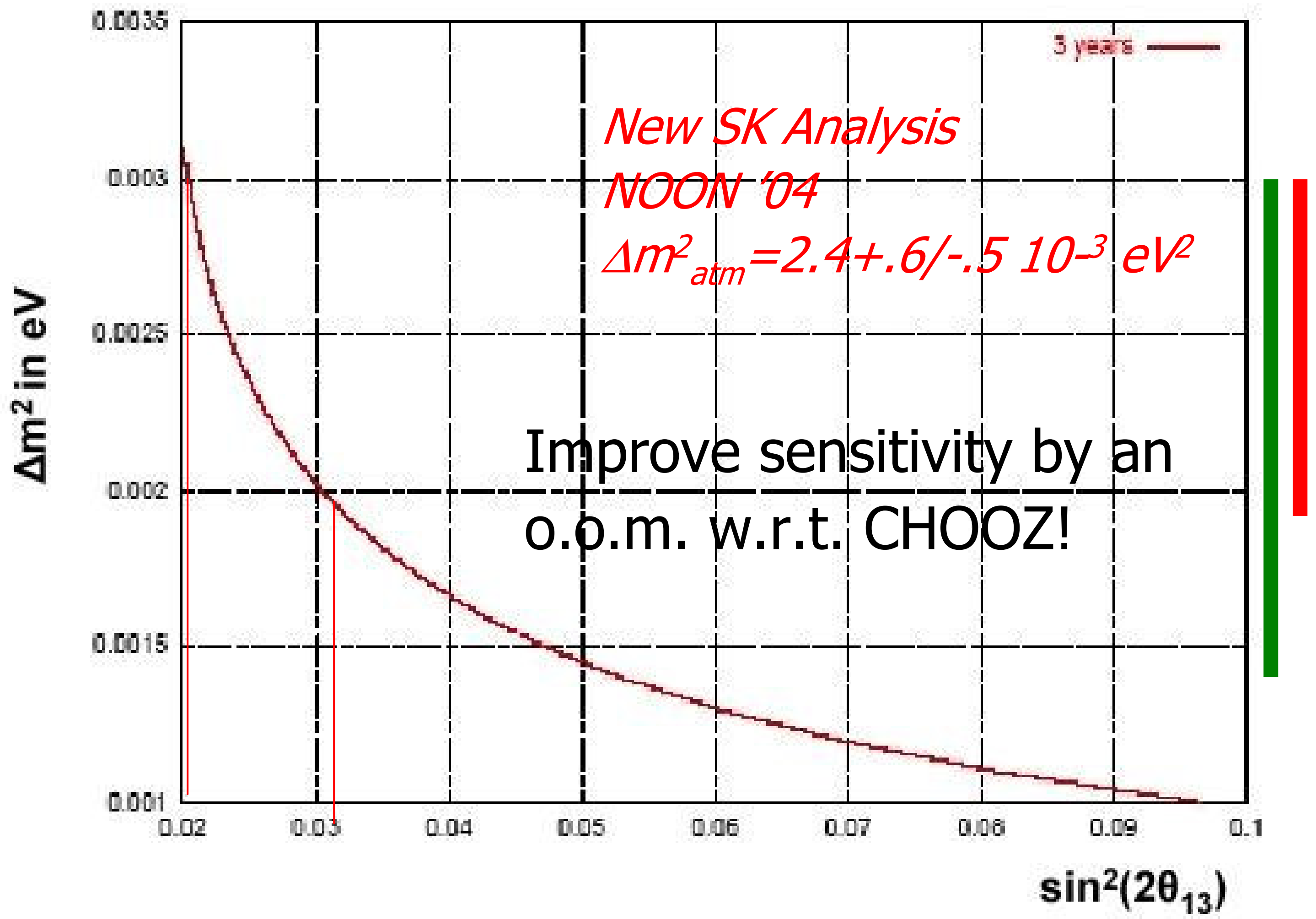
D-CHOOZ

- S/B>100 (in Chooz ~ 18)
- Increase S by a factor 2.2 (from 5 to 11 tons)
- Reduce B by a factor 3 with a careful design of the detector (double buffer)

schedule

- 2006: FAR detector
- 2007: NEAR detector
- 2008 first results

Sensitivity to θ_{13} (R): D-CHOOZ



Other reactor experiments:

Site	Near/Far (tons)	Expected starting date	Sensitivity to θ_{13}
Angra dos reis	25t/50t	?	<0.02-0.03
Diablo canyon	25t/50t	2009	<0.01-0.02
Braidwood	25t/50t	2009	<0.02-0.03
Daya Bay	50t	2009	0.012
Kashiwazaki	8.5t/8.5t	2008	0.026
Krasnoyarsk	46t/46t	?	0.016

Summary

- I have considered two categories of experiments investigating about θ_{13}
  - Accelerator based
  - Reactor Based
- (A) many possible phases and time scales (2006→2020)
  - In general sensitivity to θ_{13} spoiled by our ignorance of δ CP term (and sign(Δ))
  - Synergies between different experiments to reduce this effect
  - Reachable sensitivities
    - Phase I (2005-2006): ~ 5^o
    - Phase II (2008-2009): ~ 2.5^o
    - Phase III (2015-2020): ~ 0.5^o-1^o
- (R) several projects as well and time-scales (though less spread)
  - Here δ CP term not involved: pure measurement of θ_{13}
  - But the hard thing is reducing detector systematics: if this is done at the <1% then
  - Reachable sensitivies:
    - In the range [3^o-5^o]
- Ex.: CNGS starting in 2006+5 yrs of data taking → $\theta_{13}<5^o$ in 2011
  D-CHOOZ starting in 2006+3 yrs of d.t. → $\theta_{13}<5^o$ in 2009/2010

The End