J. BOUCHEZ

CEA - DAPNIA

SACLAY

NO-VE

4/12/2003

θ_{13} measurements
experimental options

- disappearance expts
  - Reactor
  - Tritium
- Appearance at accelerators

THE MIXING MATRIX

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\nu_\mu \leftrightarrow \nu_\tau$ at atm. frequency (Δm^2_{23})
$\theta_{23} \sim 45°$

GENEVA'S ν_e oscillations at atmospheric frequency

Solar ν_e disappearance (LMA)
$\theta_{12} \sim 35°$

CHOOZ = $\theta_{13} \lesssim 12°$ [limit depends upon actual Δm^2_{23} value]

To best determine θ_{13} =
Get to the maximum of atmospheric oscillation ($L/E \sim 500$ km/GeV)
→ look for ν_e disappearance
→ look for ν_e appearance from ν_μ
or ν_μ appearance from ν_e
(or ν_τ appearance from ν_e)

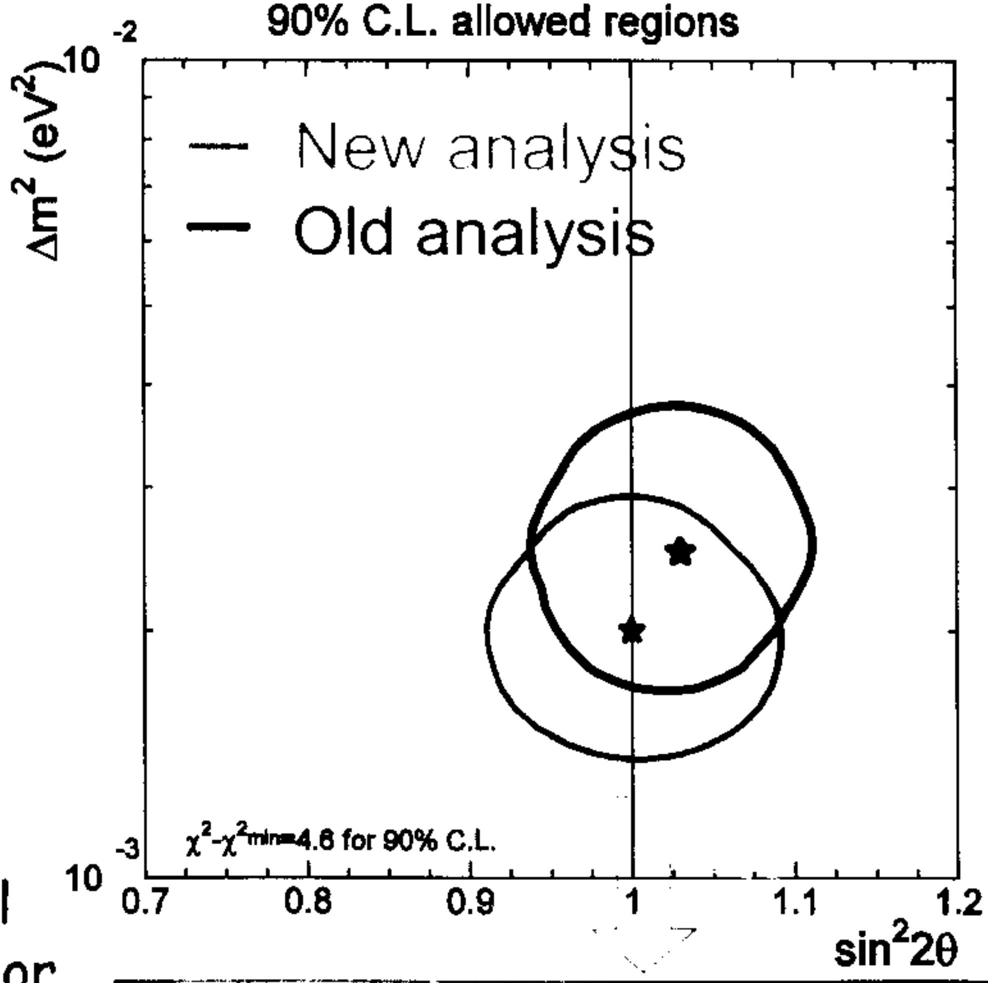
New SuperK analysis

Best fit at $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.0 \times 10^{-3}\ eV^2)$

Allowed @90%CL $\sin^2 2\theta > 0.9$; $1.3\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}\ (eV^2)$

- **Neutrino flux**
  (Honda 1995 Honda 2001)
- **Neutrino interaction models**
  (several improvements,
  → agree with K2K near data)
- **Improved detector simulation**
- **Improved event reconstruction tools**

Each change slightly shifted the allowed region to lower Δm^2



Since the time of the OPERA proposal (2000) the signal decreased by a factor 2.6 ………

This makes life harder for everyone !

CHOOZ : $\bar{\nu}_e \longrightarrow \bar{\nu}_e$

$\sim 1\,km$

$\bar{E}_\nu \sim 2$ Me

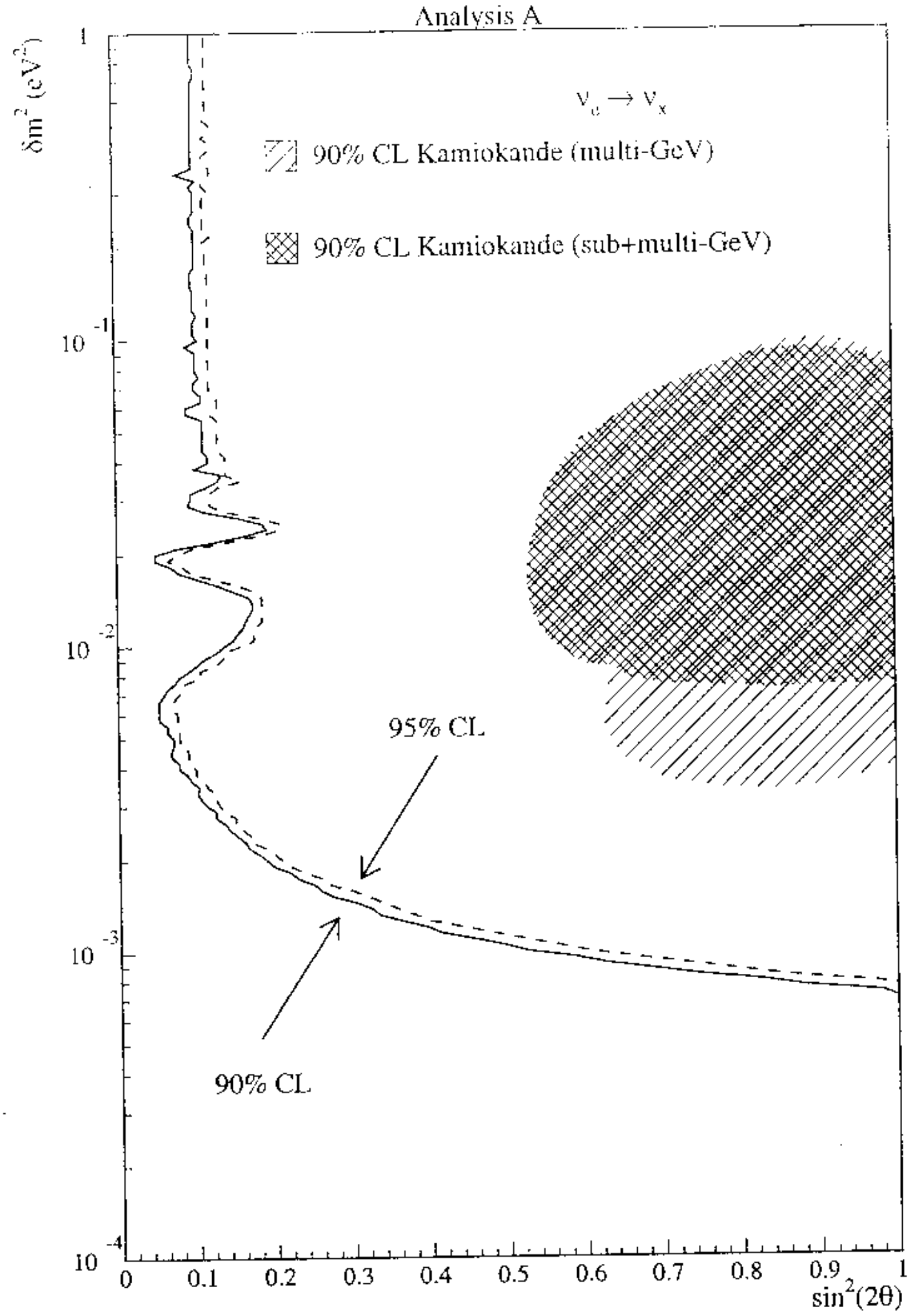


Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.

ν_e DISAPPEARANCE

- Reactor projects
- Tritium source

$$\Delta_{ij} = \frac{(m_j^2 - m_i^2)\,L}{4E}$$

DISAPPEARANCE

$$P_{ee} = 1 - \overbrace{\underset{\text{SMALL}}{\underset{\downarrow}{\sin^2 2\theta_{13}}}\ \underset{\sim 1}{\underset{\downarrow}{\sin^2\Delta_{13}}}}^{\longleftarrow\ \text{Atmosph.}\ \longrightarrow} - \overbrace{\underbrace{\underset{1}{\underset{\downarrow}{c_{13}^4}}\ \underset{\sim 1/3}{\underset{\downarrow}{\sin^2 2\theta_{13}}}\ \underset{\text{SMALL}}{\underset{\downarrow}{\sin^2\Delta_{1}}}}_{4\,10^{-4}\ \text{at}\ L_{opt.}}}^{\longleftarrow\ \text{solar}\ \longrightarrow}$$

Atmospheric term will always be dominant in sensitivity domain

$$P_{ee} = 1 - 4\,\theta_{13}^2\ \sin^2\Delta_{13}$$

- No sensitivity to very low θ_{13}
- No CP effects

⇒ Disappearance experiments will be systematics limited

Rem = $P_{ee} = 1 - 2\,\theta_{\mu e}^2\ \sin^2\Delta_{13}$ should not be used (confusing!)

REACTOR EXPERIMENT

CHOOZ = Single detector
⇒ relies on predicted flux
Active mass
Absolute efficiency

SYSTEMATICS = 2.8%

⇒ USE 2 IDENTICAL DETECTORS TO
LOWER SYSTEMATICS AT 1%
BY COMPARING NEAR AND FAR MEAS

Remarks

- 2 detectors are never "identical"
  - Background rates will be different
    (⇒ dead times will be ≠)
  - S/N will be different

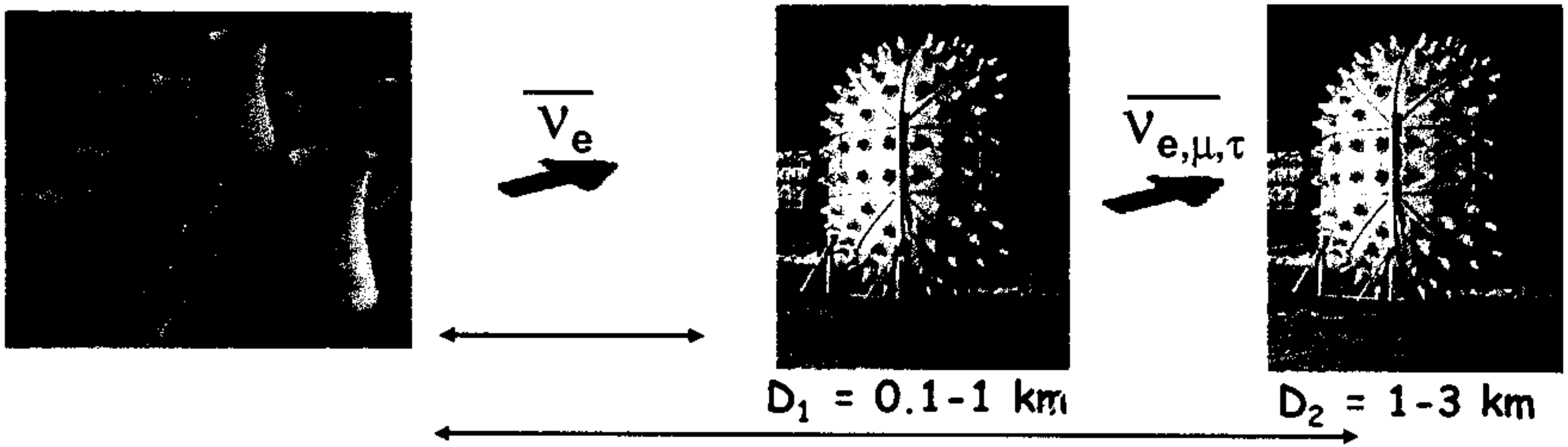
BUGEY3
1.7%

Better design to decrease background.

- Energy scale is very important
  (scale + non linearities)

See H. de KERRET's talk

One nuclear plant & two detectors



$\overline{\nu_e}$

$\overline{\nu_{e,\mu,\tau}}$

D_1 = 0.1-1 km

D_2 = 1-3 km

Nuclear reactor

Near detector

Far detector

1,2 core(s) → ON/OFF : ok
◆ 4 cores → ON/OFF : no !

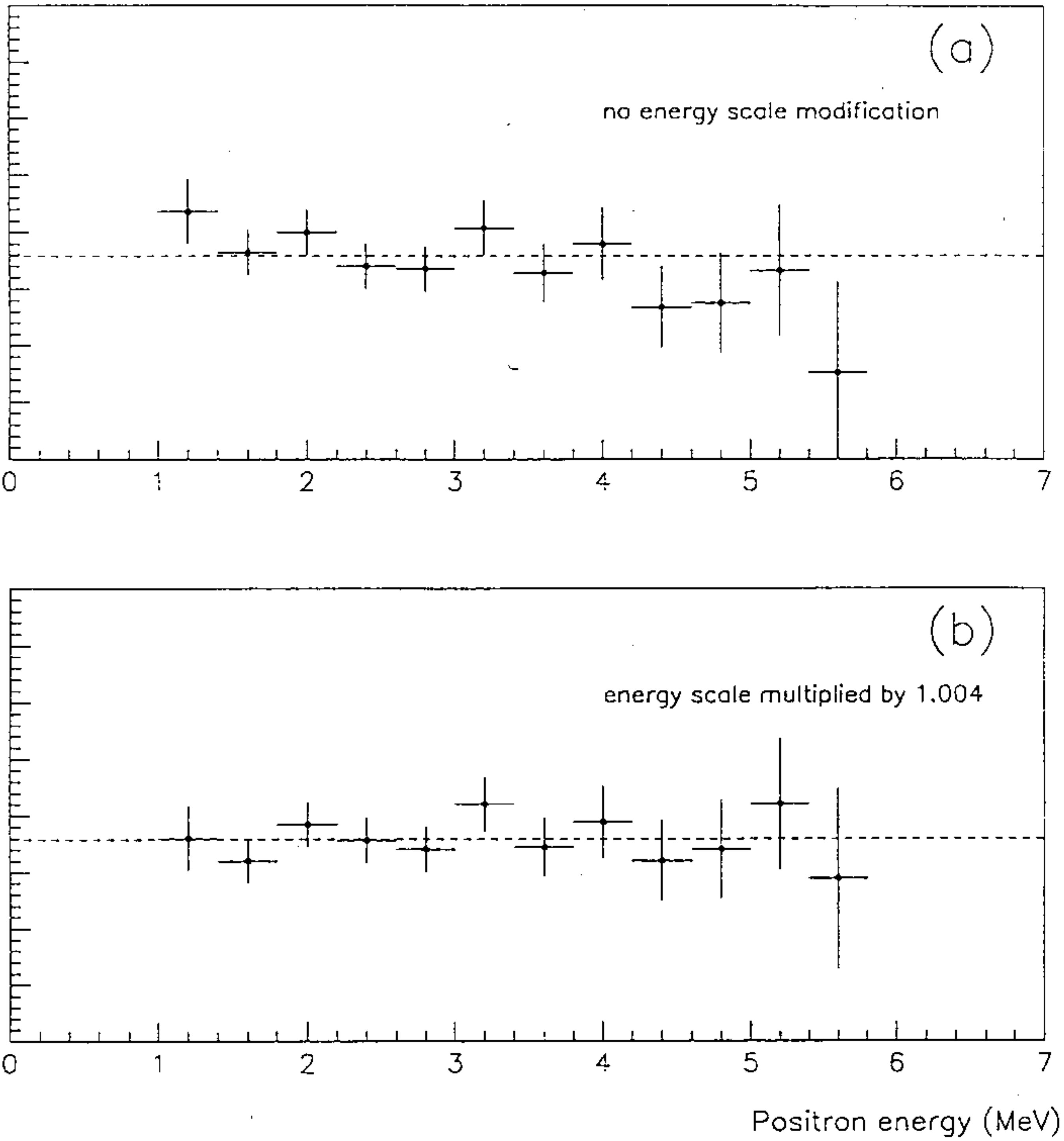
5-50 tons
> 50 mwe

5-50 tons
> 300 mwe

✓ Isotrope ν_e flux (uranium & plutonium fission fragments)
✓ Detection tag : $\nu_e \overline{+} p \rightarrow e^+ + n$, <E>~ 4 MeV, Threshold ~1.8 MeV
✓ Disappearance experiment: suppression+shape distortion between the 2 detectors
✓ 2 IDENTICAL detectors (CHOOZ, KamLAND, BOREXINO/CTF type)
- *Minimise the uncertainties on reactor flux & spectrum (2 % in CHOOZ)*
- *Cancel cross section uncertainties*
- *Challenge: relative normalisation between the two detectors < 1% !*

BUGEY 3 : Comparisons DATA / PREDICTIONS

Phys. letters B 374 (1996) 243



Effect of a 0.4% change on energy scale (syst uncertainty = 0.8%)

TWO COMPETING PHILOSOPHIES

1 - Go fast, to start before or at the same time as LBL (JHF1, NuMI off-axis)

EUROPE
JAPAN

⇒ Detectors at fixed locations
Reuse if possible existing infrastructures (CHOOZ)

2 - No need to hurry, reactors are complementary to LBL appearance exp^{ts}

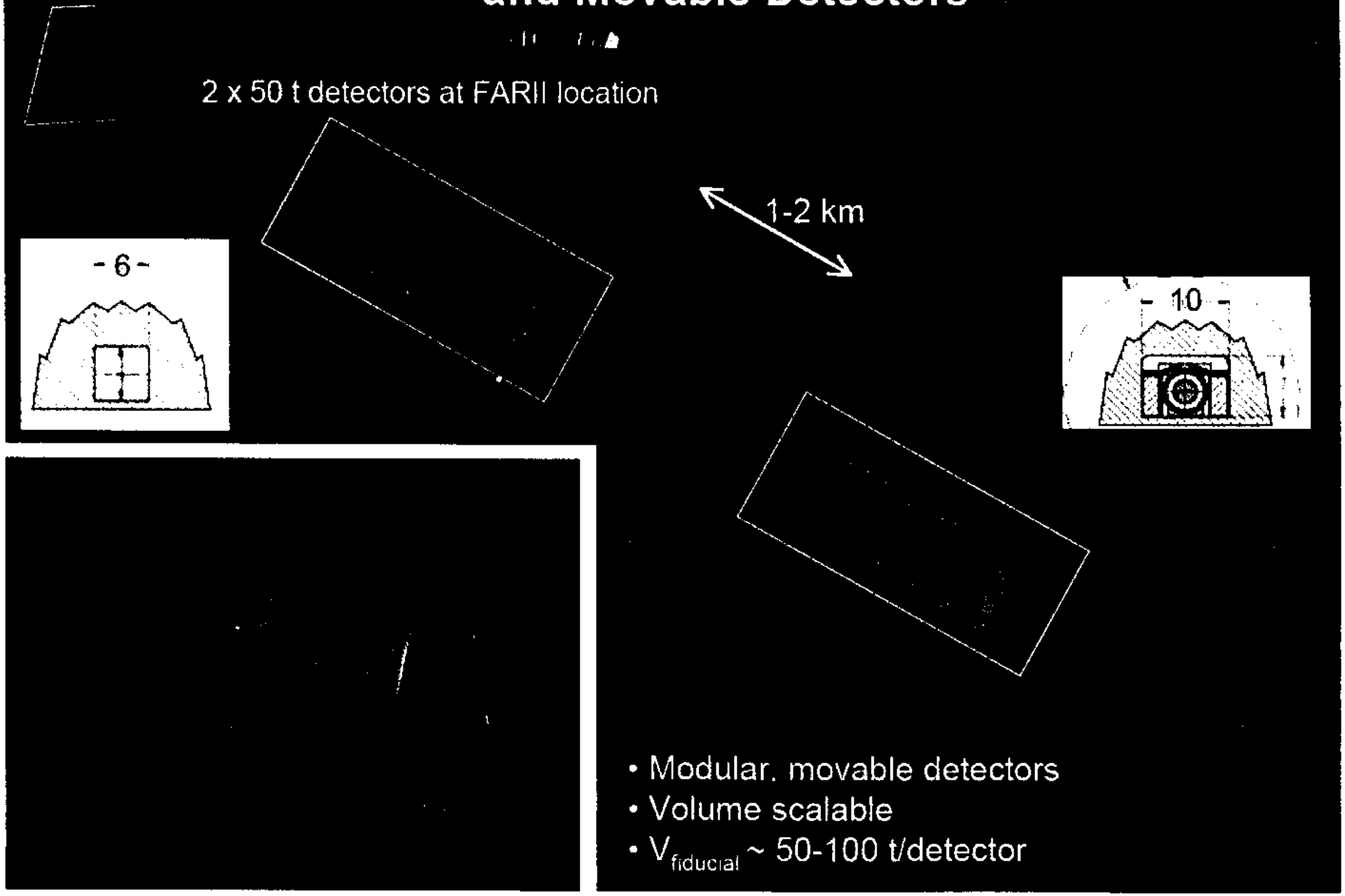
⇒ More sophisticated design (movable detectors)

USA

But more expensive and later start

There is matter for debate.

Tunnel with Multiple Detector Rooms and Movable Detectors

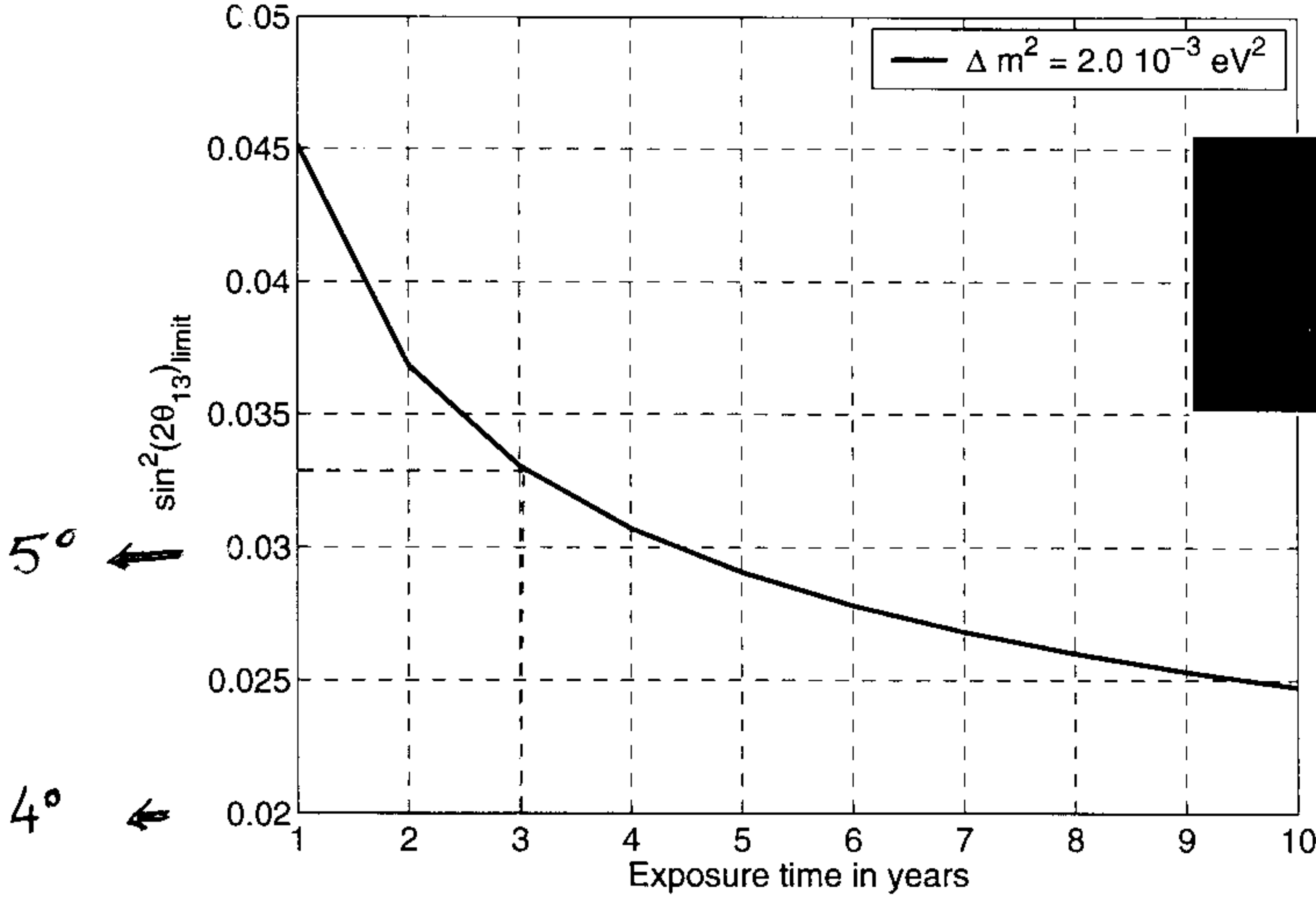


2 x 50 t detectors at FARII location

1-2 km

- Modular, movable detectors
- Volume scalable
- $V_{fiducial}$ ~ 50-100 t/detector

Sensitivity at 90% C.L. if $\sin^2(2\theta_{13})=0$ versus the exposure time



[redacted]

(Pure PXE liquid scintillator)

TRITIUM SOURCE

- Idea = Use a strong tritium source

  20 kg $\Rightarrow$ 200 MCi ($7\ 10^{18}\ \bar{\nu}_e / s$)

  $E^{\nu}_{max} = 18.6$ keV

  Diffusion on e^- $E^{max}_{e^-} \sim 1.3$ keV !

  $E_\nu = 14$ keV $\langle E_{e^-} \rangle = 360$ eV

- Detector = spherical TPC with MicroMegas readout

$-\bar{\nu}_e$ osc.

$$L_{osc}(14\ \text{keV}) = 14\ \text{m} \quad (2.5\ 10^{-3}\ \text{eV}^2)$$
$$17.5\ \text{m} \quad (2\ 10^{-3}\ \text{eV}^2)$$

$-\ \mu_{\nu_e}$ at $10^{-12}\ \mu_B$ level

$-\ \bar{\nu}_e\ e^-$ scattering at low energy

- $\sin^2\theta_W$ at large distances
- Atomic binding effects.

MAIN QUESTION = What will be the background level?

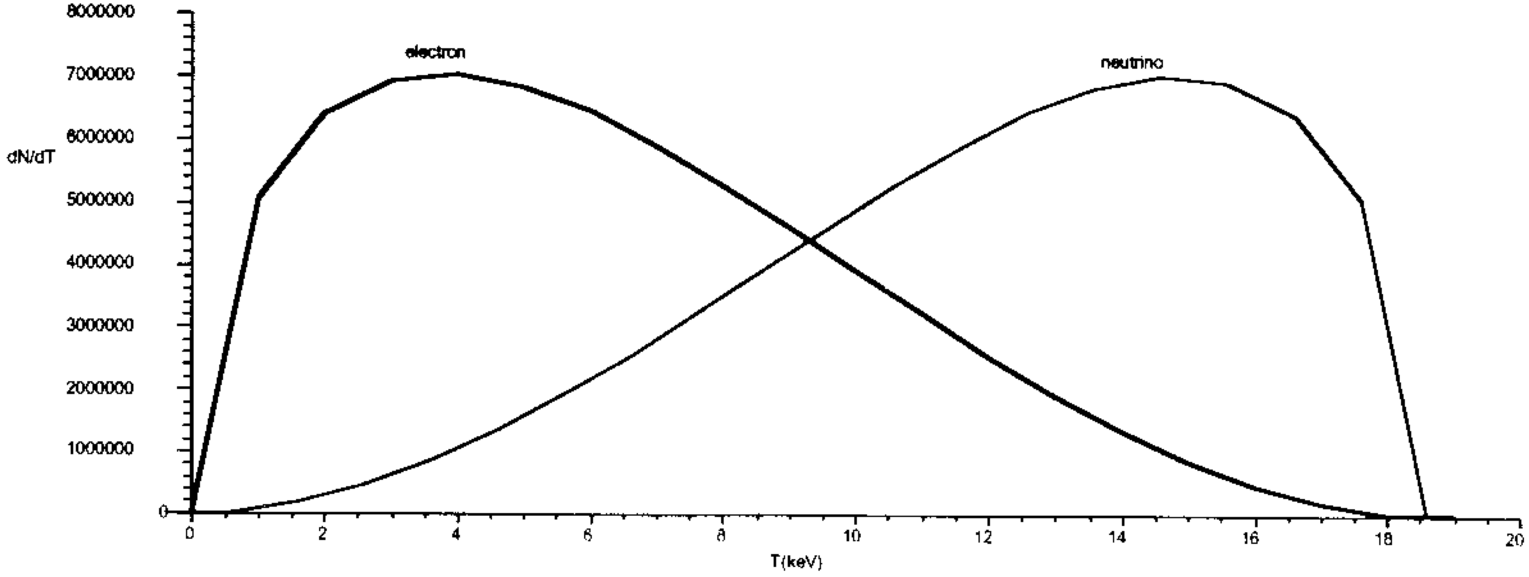
Tritium

- Produced by neutrons on Li^5 or He^3
- Half life 12.26 years, Energy Maximum 18.6 keV,

Average energy 5.7 keV, power 4 kW at t/20 Kgr

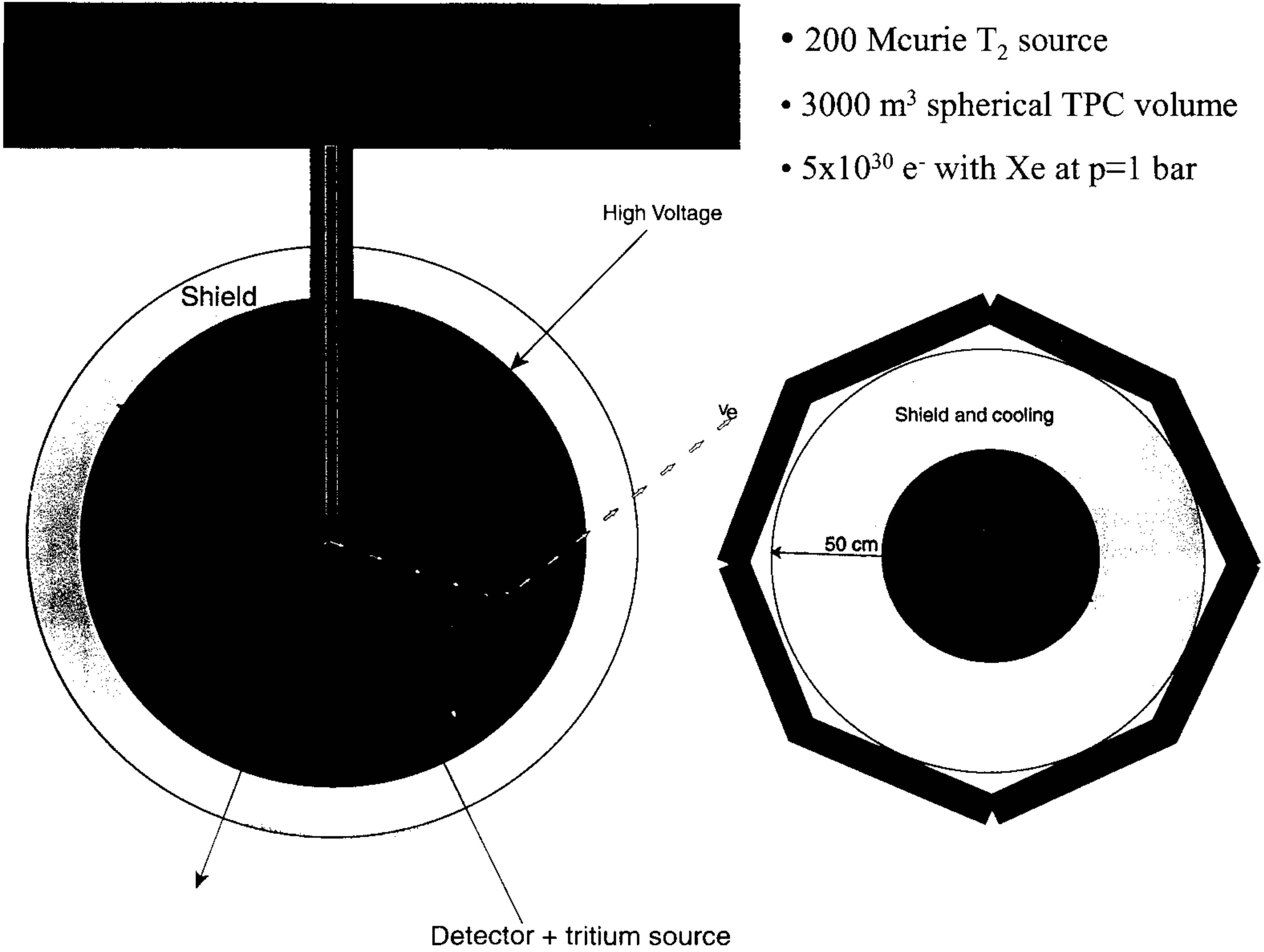
Neutrino production: $7x10^{18}$ s/20 Kgr

$$T \rightarrow He^3 + e^- + \nu$$



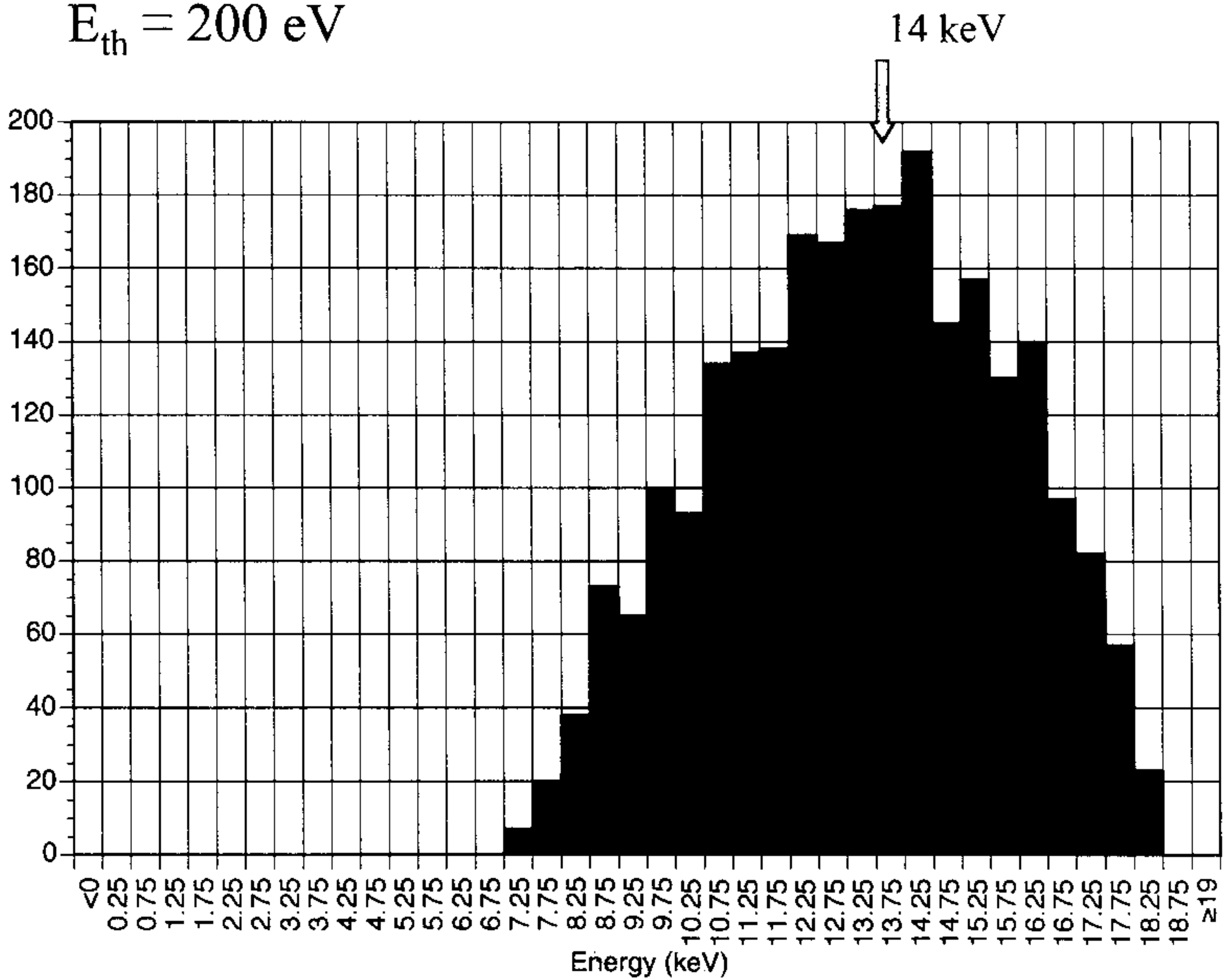
I. GIOMATARIS & VERGADOS

- 200 Mcurie T_2 source
- 3000 m^3 spherical TPC volume
- $5x10^{30}$ e^- with Xe at p=1 bar

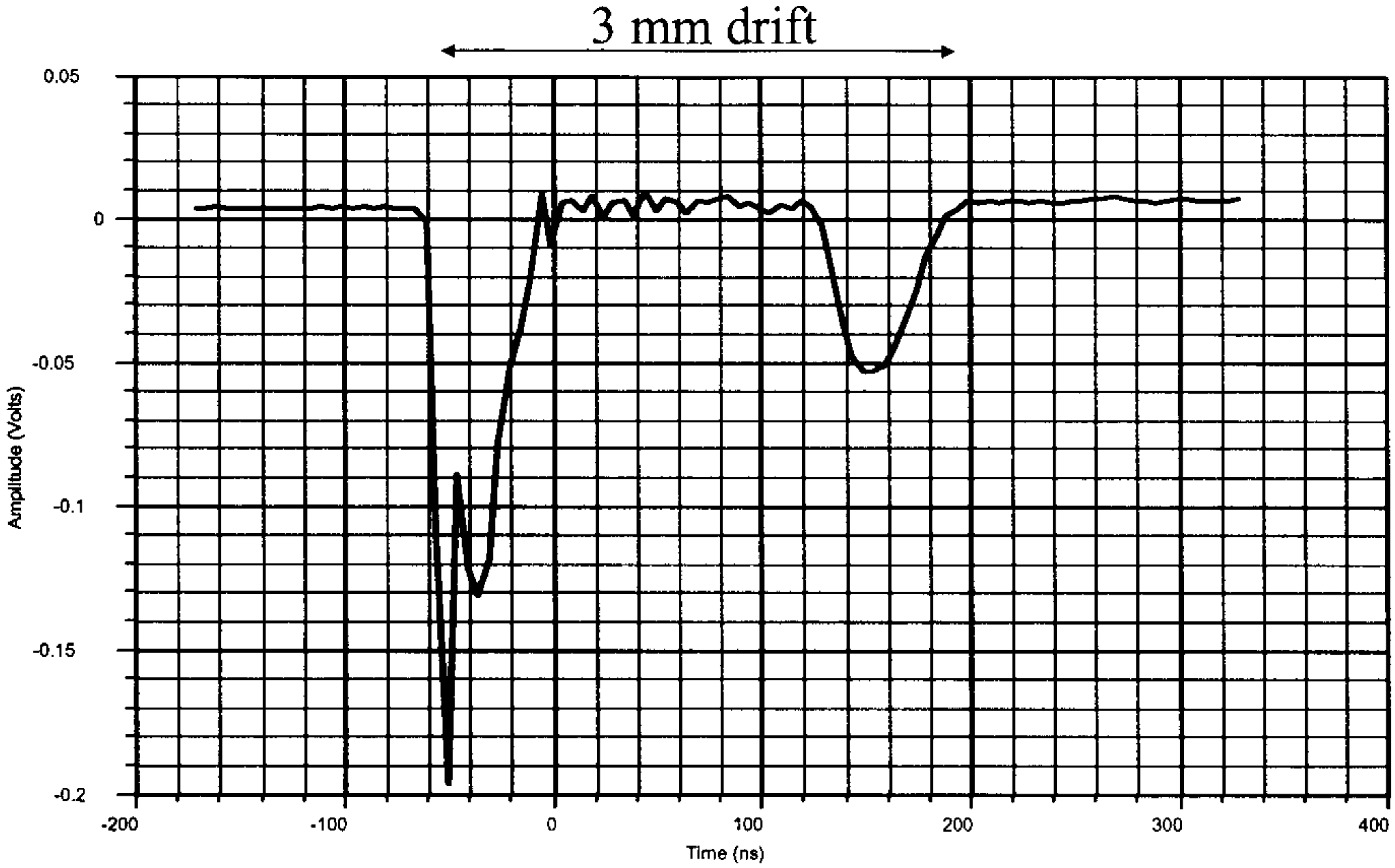


Energy distribution of detected neutrinos,

$E_{th} = 200$ eV



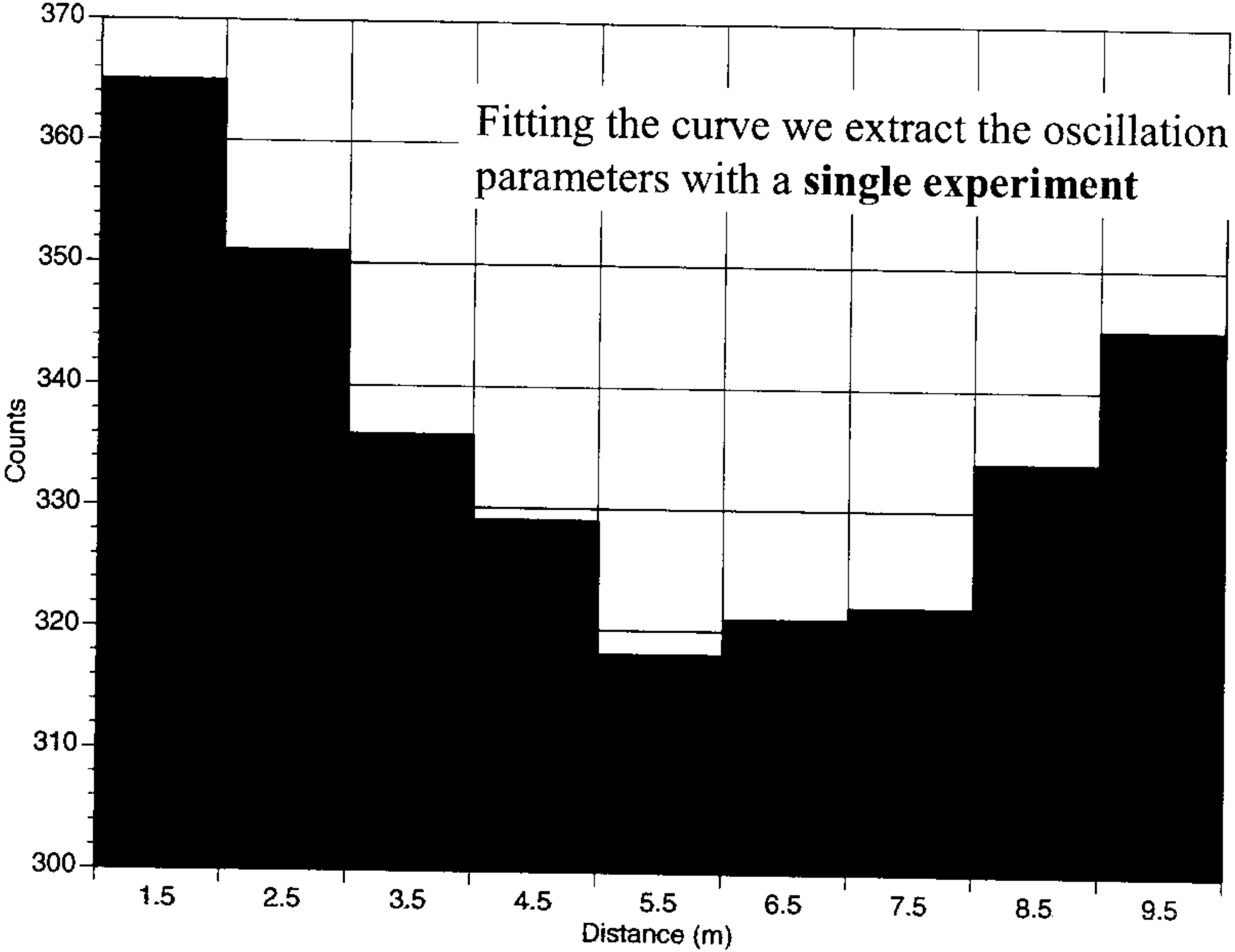
Two Micromegas signals at 3 mm distance in depth



Precise determination of the depth

Detected neutrinos-versus distance, $\sin^2 2\theta_{13}$=.17, E_{th}=200 eV

The effect of the unknown neutrino energy distribution is small

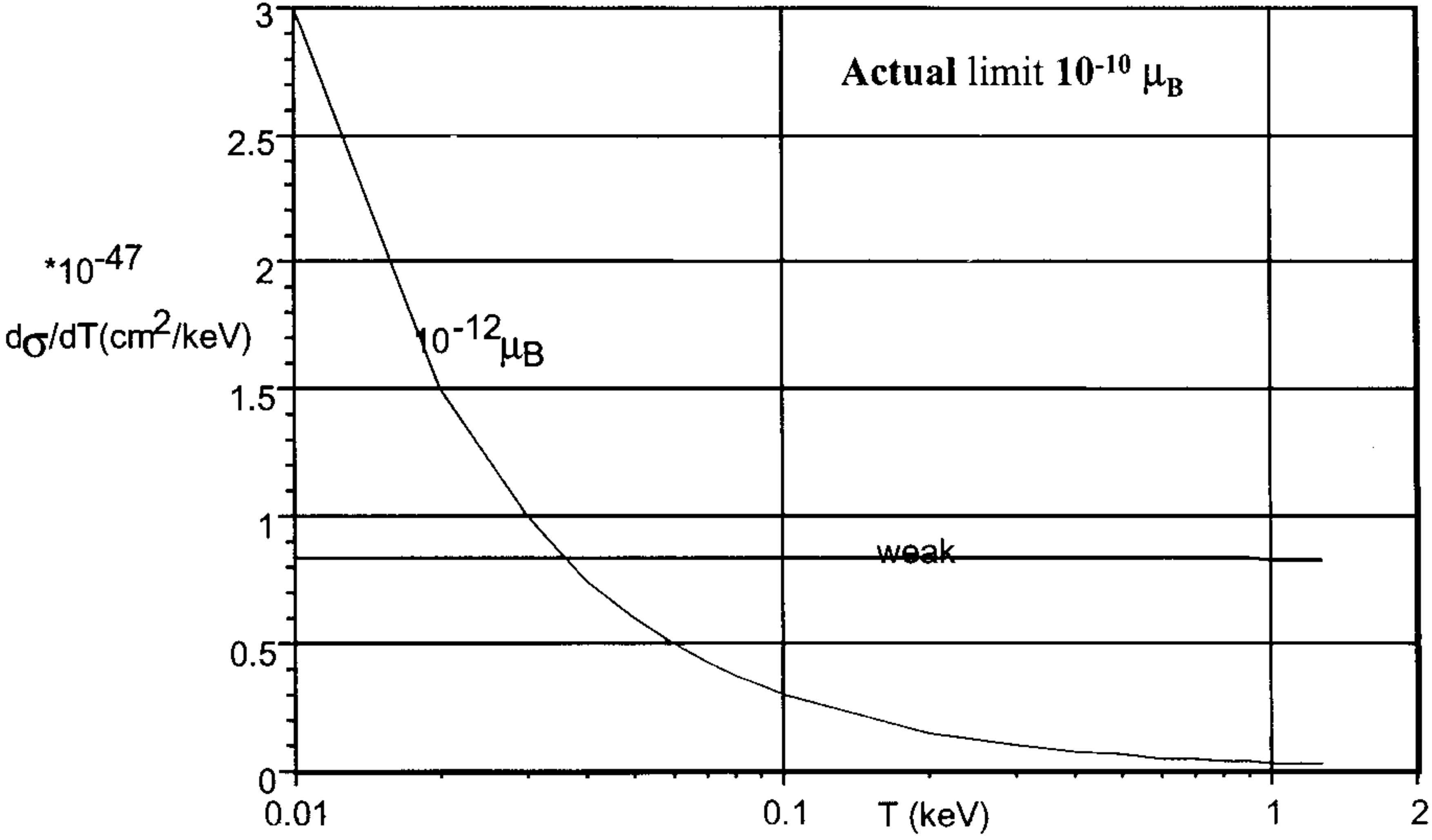


Fitting the curve we extract the oscillation parameters with a **single experiment**

Neutrino magnetic moment sensitivity

$<< 10^{-12}\ \mu_B$

$d\sigma/dT \approx (\mu_\nu)^2(1\text{-}T/E\nu)/T$



$\nu_\mu \leftrightarrow \nu_e$ APPEARANCE EXP^{TS} USING ACCELERATORS

4 phases:

- Phase 1: Use "existing" facilities & detectors (optimized for ν_μ disappearance and/or ν_τ appearance)

  $\theta_{13} > 5^0$

  - MINOS, ICARUS, OPERA
  - gulf of Tarento, horizontal showers

$\theta_{13} > 2.5^\circ$ + CP ?

- Phase 2: 1st generation of superbeams
  - JHF 1, NuMI off axis
- Phase 3: 2nd generation of superbeam

  $\theta_{13} > 1^\circ$ + CP

  - JHF 2, NuMI 2, BNL
  - CERN → Fréjus = Superbeam and betabeam

$\theta_{13} > 0.1^\circ$ + CP

- Phase 4: ν factories, HE β-beams

SUPER BEAMS

Conventional ν_μ beams produced by high intensity proton drivers.

20 kT detectors	• NuMI	400 kW	2005
	• JHF1	750 kW	2008
500 kT detectors	• JHF2	4 MW	2012
	• SPL-SB	4 MW	⩾ 2012

⇒ look for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ appearance at 1st maximum ($L_{opt} \sim 600$ km/GeV

Beam requirements

- Low ν_e contamination
- Good knowledge of $\frac{\nu_e}{\nu_\mu}$
- Good understanding of the beam (near → far extrapol.)

Detector requirements

- Good e^- efficiency
- Good π^0 rejection
- Good understandi of background

LOW ENERGY OR HIGH ENERGY ?

- Superbeams are power-limited
  - Focalisation of ν's $\propto E^2$
  - Solid angle at $L_{opt} \propto \frac{1}{E^2}$
  - ν cross-section $\propto E$
  - ν flux (less protons) $\sim \frac{1}{E}$

$\Rightarrow$ Equivalent at zeroth order. -

Choice will rely on other criteria

LOW ENERGY (E<1GeV)

- Less ν_e below K threshold (depends on p energy)
- Less [illegible]
- Better π^0 tagging
- Fermi momentum
  $\Rightarrow$ Bad E resolution
  Counting exp^t
  or rely on QE dominance
- Water Č technique OK
- No evident advantage for Liquid Argon
- No matter effects

HIGH ENERGY (E>1GeV)

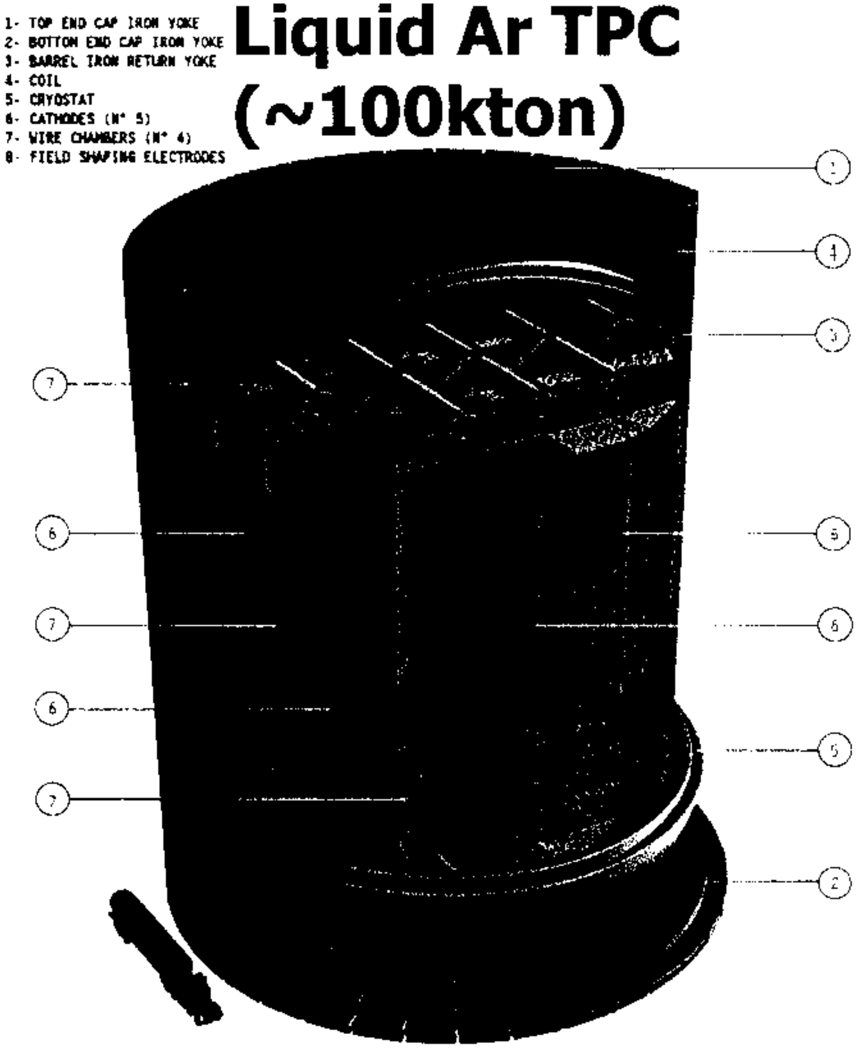
⚠ Stay below ν_τ CC threshold

- Need good tracking detectors (fine grained, LAr)
- Need very good π^0 rejection
- more ν_e background
- good E resolution
- Some matter effects (sign of Δm^2_{13})

Liquid argon is a good choice.

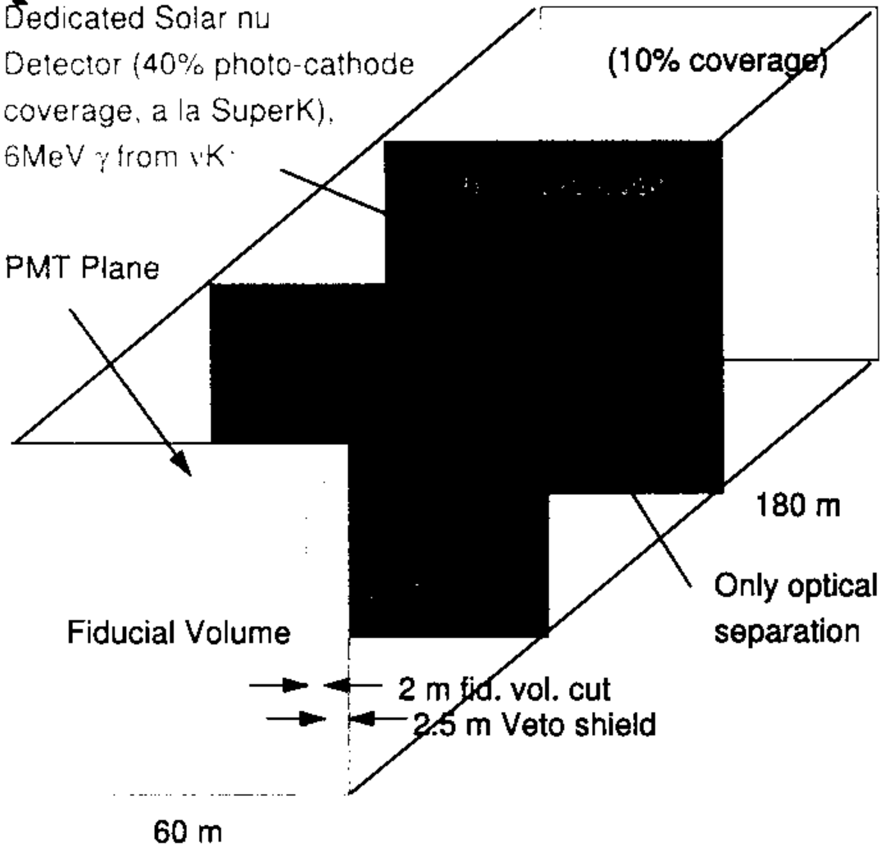
Detectors

Liquid Ar TPC (~100kton)



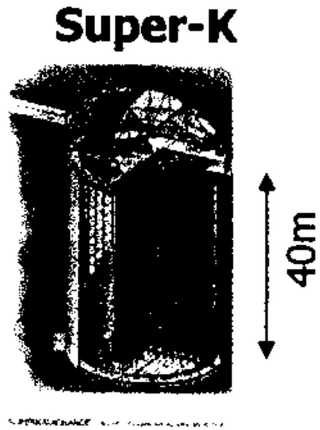
LANNDD
Liquid Argon Neutrino and Nucleon Decay Detector

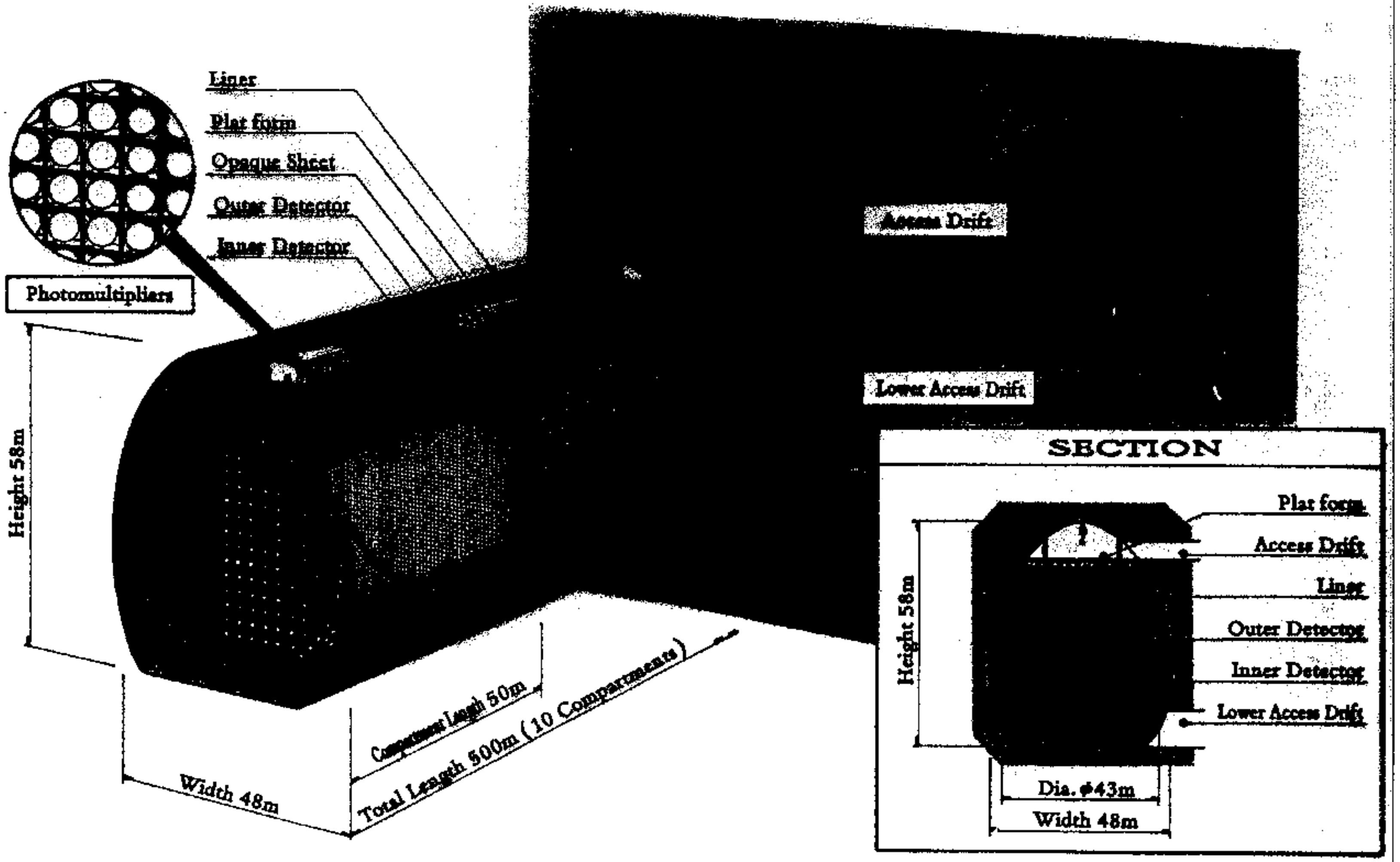
UNO (400kton Water Cherenkov)



Dedicated Solar nu Detector (40% photo-cathode coverage, a la SuperK), 6MeV γ from νK⁺

Schematic drawing of Hyper-Kamiokande

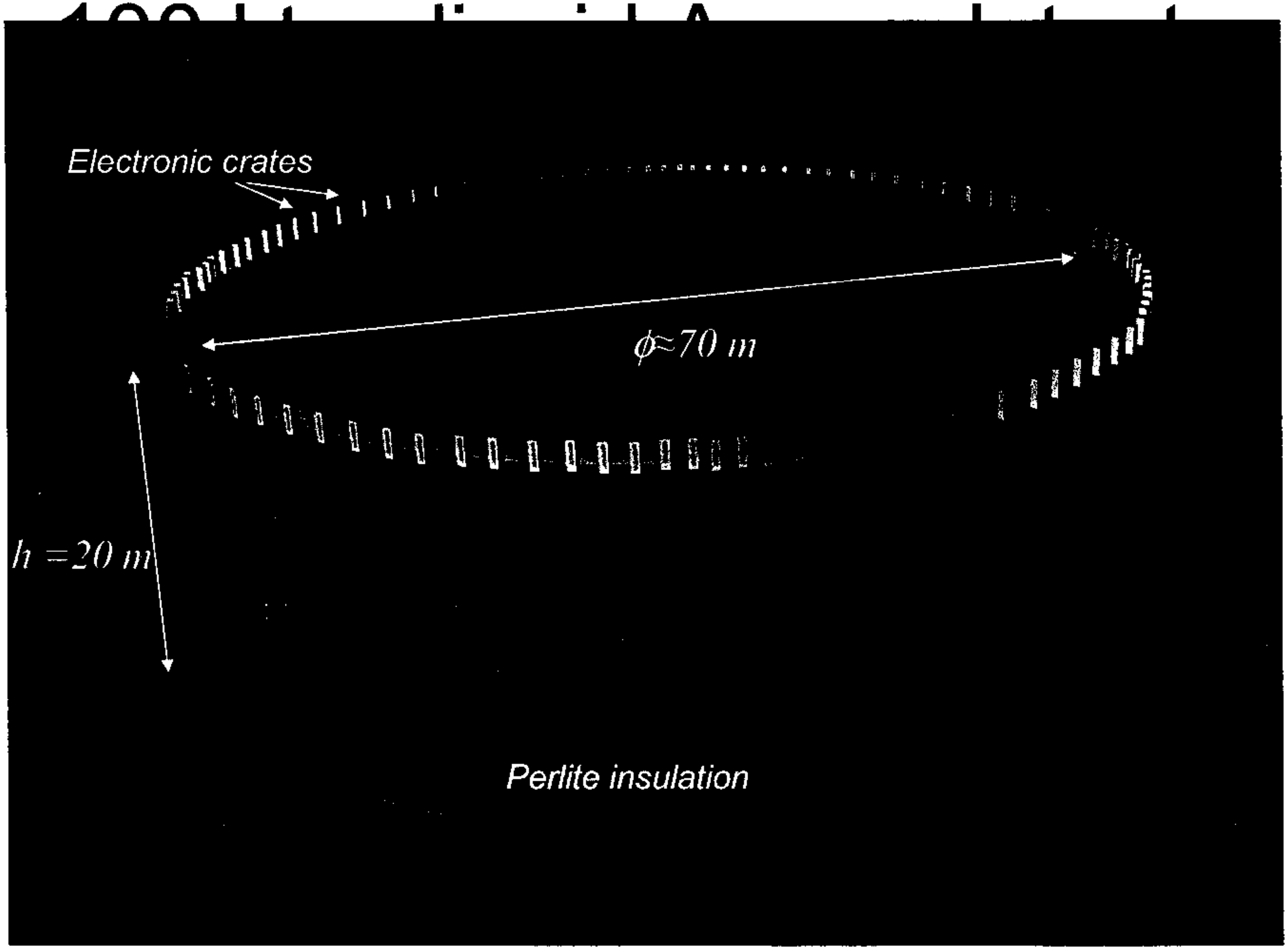




Other major goal: improve proton decay reach

Supernovae until Andromedes, etc...

Excavation will not start until 2011


Electronic crates
$\phi \approx 70\ m$
$h = 20\ m$
Perlite insulation

QUESTION: Should we go underground?

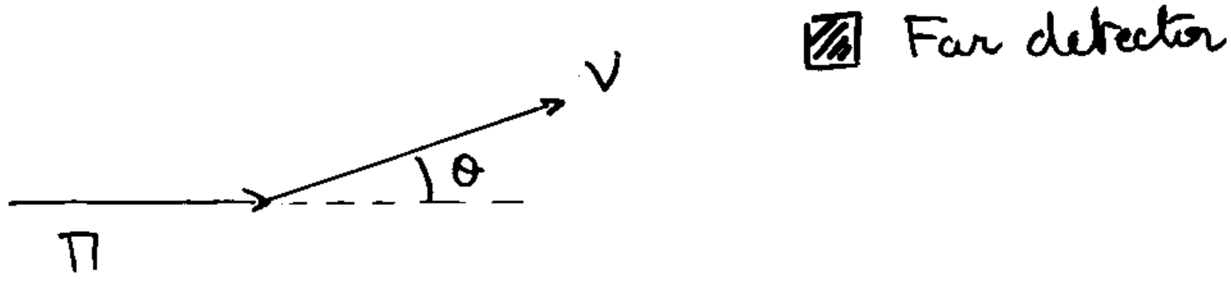
Phase 2 (20kT detectors):

Not necessarily if very low duty cycle.

Phase 3 (~ 500 kT detectors)

A necessity for proton decay search

THE OFF-AXIS TRICK



By kinematics: $E_\nu^{MAX} = \frac{30\ \text{MeV}}{\theta}$

- Jacobian peak at $E = E_\nu^{MAX}$
- Flux enhancement at E_ν^{MAX}
- Strong decrease of high energy tail
- Lower ν_e contamination
- sizeable enhancement only for $E_\nu^{MAX} \geq 500$ MeV

Strategy:

1. Choose $\theta = \frac{30\ \text{MeV}}{E_\nu^{OPT}}$
2. Optimize 0° ν beam for $2 E_\nu^{OPT}$

$\Rightarrow$ QUASI MONOCHROMATIC BEAM!

UNDERSTANDING BEAM WITH NEAR DETECTOR(S)

Poor man solution

→ go to a sufficient distance ($\gtrsim$ 2 km) so that ν source is pointlike

→ Use the same detection technique as the far detector

→ Apply $1/L^2$ law

- sufficient for discovery, not sufficient to measure precisely osc. parameters

⇒ Use near detectors (~300m) to measure ν_μ, ν_e beams. + ν cross-sections (QE, NQE at low energy)

But target is generally ≠ from far detector

Example: C or Ar instead of O

Rich man solution

300 m	2 km	Far det.
A1	A2	
	B1	B2

A1 ↔ A2. Beam understanding

A2 ↔ B1 ≠ in σ_ν and detector response

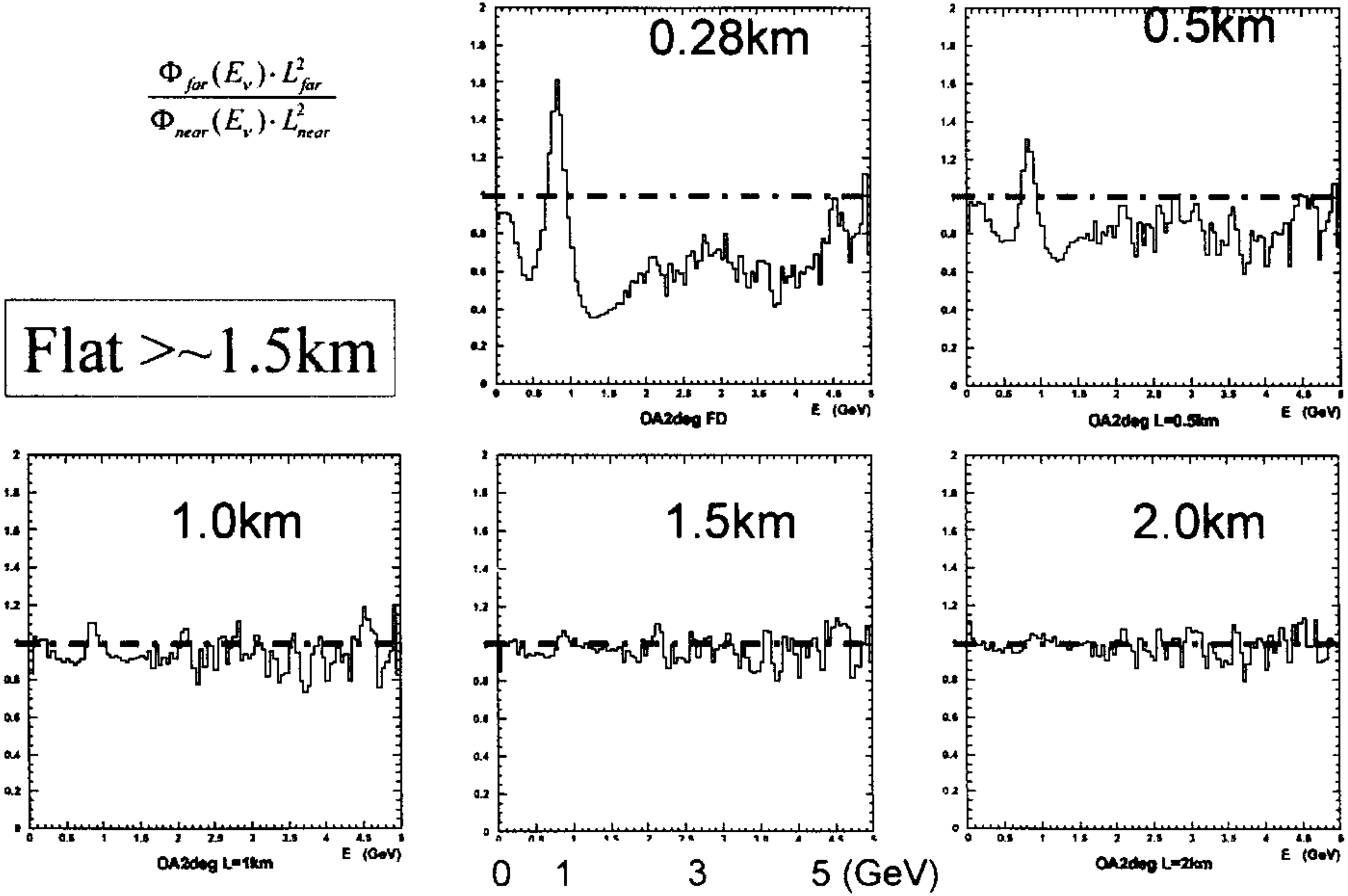
If too expensive, important to study carefully the possible strategies

(more important for phase 3 when systematics become important, while phase 2 is statistics limited)

Far/near flux ratio

$$\frac{\Phi_{far}(E_\nu)\cdot L_{far}^2}{\Phi_{near}(E_\nu)\cdot L_{near}^2}$$

Flat >~1.5km



EXTRAPOLATING FROM NEAR (300 m) TO FAR

- Usual method : double ratio

$$\mathrm{Far} = \mathrm{Near}(\mathrm{data}) \times \frac{\mathrm{Far}(\mathrm{MC})}{\mathrm{Near}(\mathrm{MC})}$$

Sensitive to modelization defects

- A better method : Transfer matrix

$$\mathrm{Far})_i = \underset{\overset{\nearrow}{\text{MC}}}{T_{ij}} \; \underset{\overset{\uparrow}{\text{data}}}{\mathrm{Near})_j}$$

hadrons feeding Near (j) will feed several Far bins = Matrix is non diagonal

⇒ Less sensitive to modelization defects

(A. Para and

APPEARANCE AND θ_{13} SENSITIVIT

Appearance amplitudes depend upon θ_{13} and δ (correlations)

θ_{13} upper limit if no signal
θ_{13} value if significant signal } will depend upon the value of δ

This does not limit θ_{13} sensitivity, but θ_{13} determination.

⇒ Appearance sensitivity should be shown in θ_{13}, δ plane

δ is not a nuisance parameter, it is a physical quantity!

JECTS

NuMI off axis G. Feldman

BNL → Homestake (UNO)

θ_{13} sensitivity = 3°

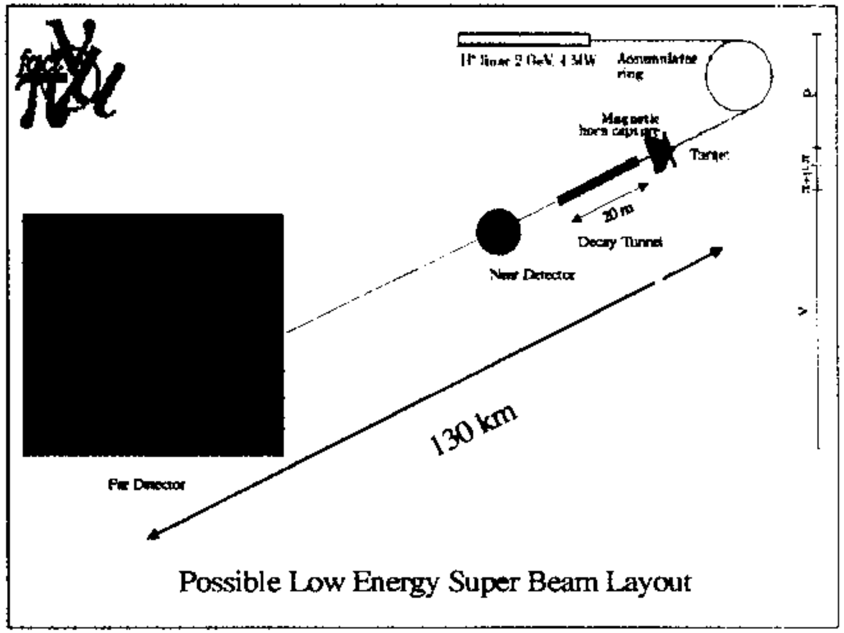
JHF1 and 2 K. Nishikawa

Superbeam CERN- Frejus

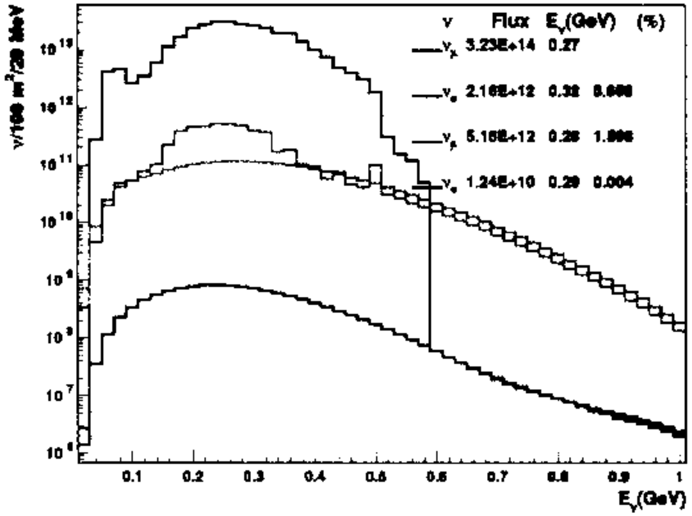
β-beam CERN-Frejus M. Mezzett.

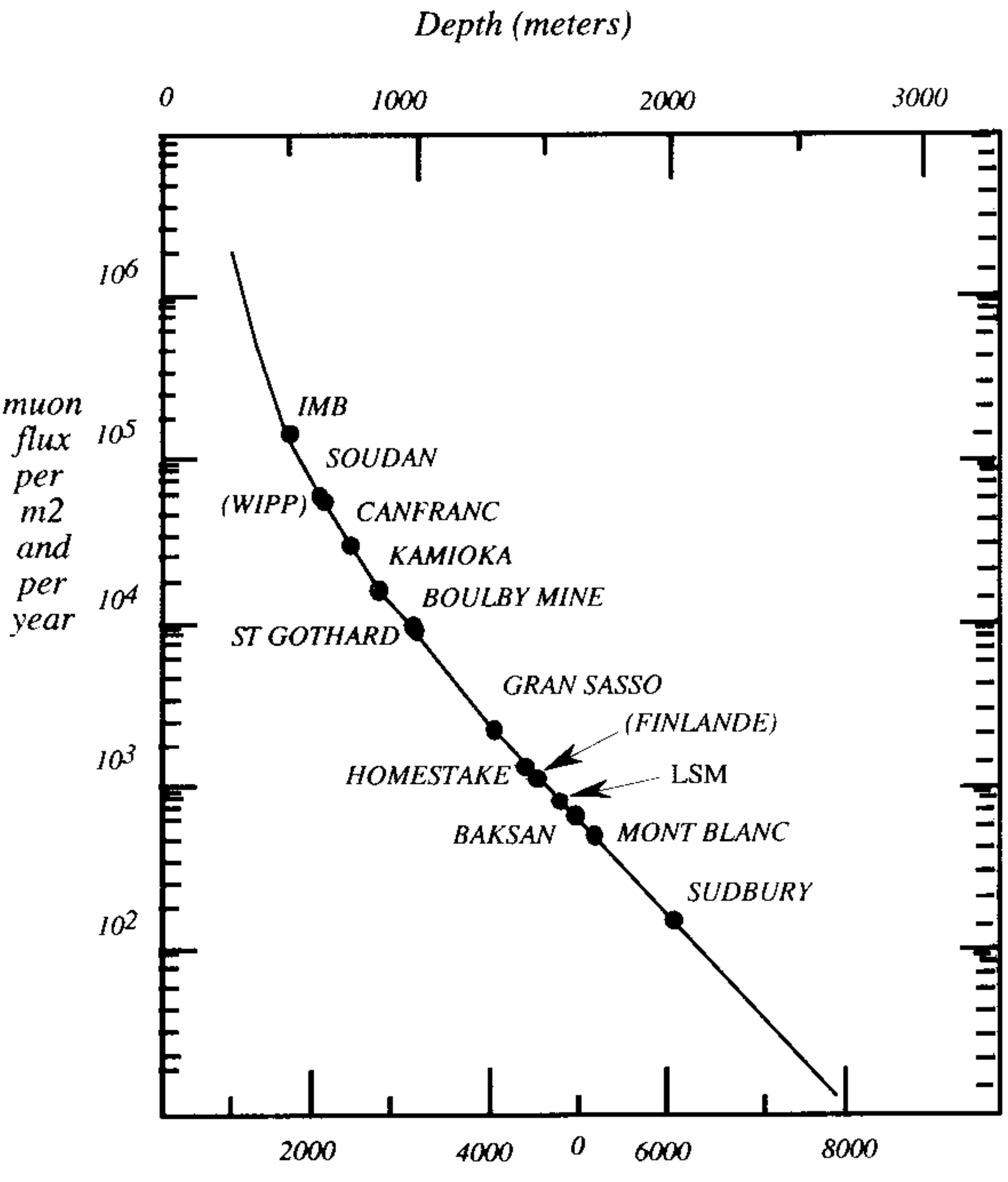
SPL-SuperBeam at CERN

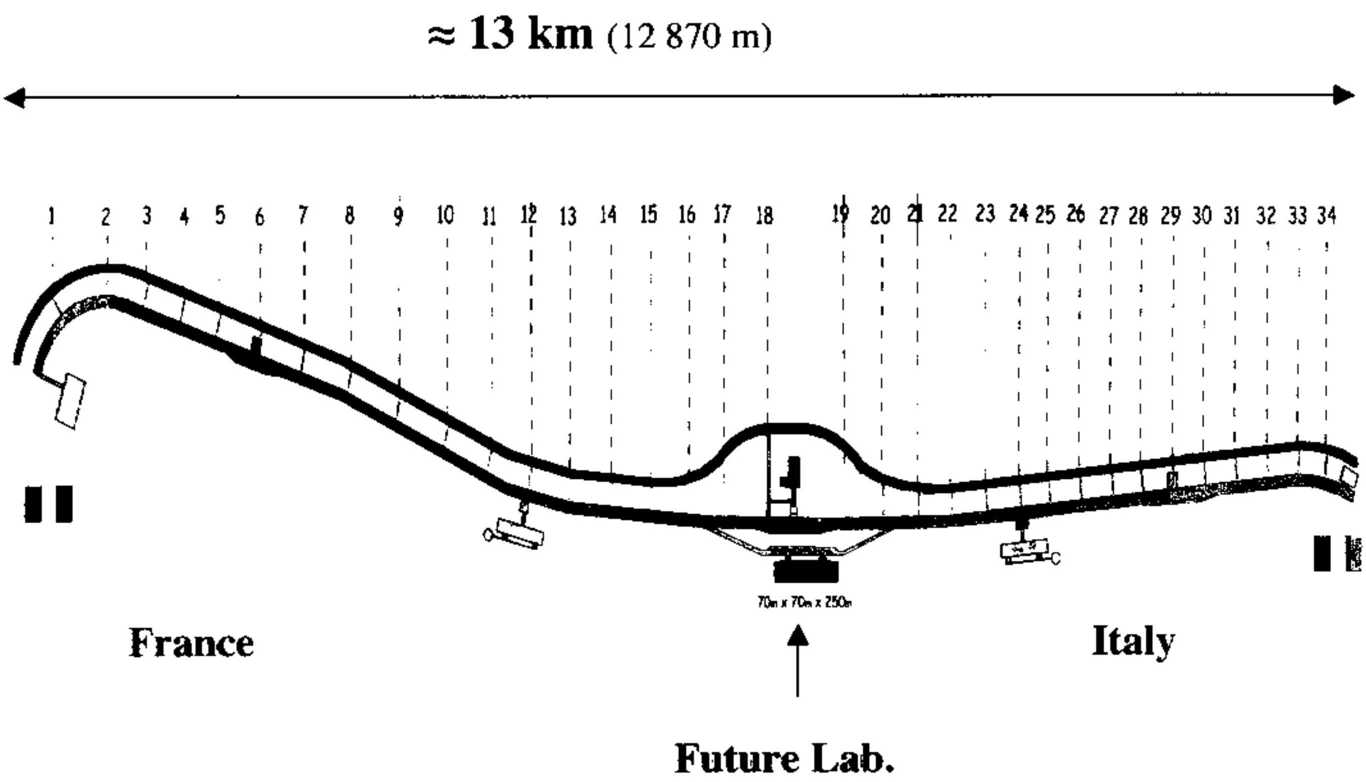
A feasibility study of the CERN possible developments



Possible Low Energy Super Beam Layout




Depth (meters)
0
1000
2000
3000
muon flux per m2 and per year
10^6
10^5
10^4
10^3
10^2
IMB
SOUDAN
(WIPP)
CANFRANC
KAMIOKA
BOULBY MINE
ST GOTHARD
GRAN SASSO
(FINLANDE)
HOMESTAKE
LSM
BAKSAN
MONT BLANC
SUDBURY
2000
4000
0
6000
8000
Depth (meters of water equivalent)



Present road Tunnel at Fréjus (grey)
and
future Tunnel (black) for safety (*)
and for an independent access to the Fréjus Lab(s)

(*) with 34 bypasses (shelters) connecting the two Tunnels

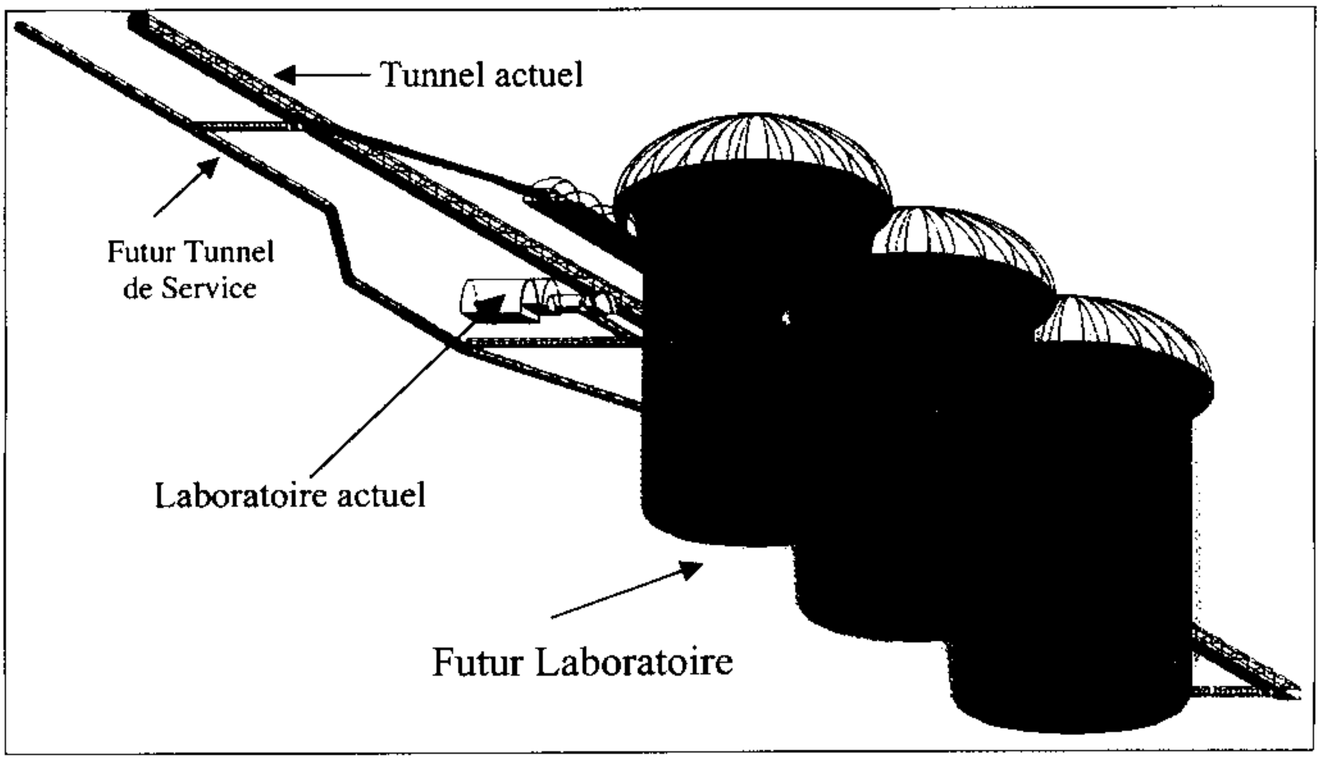


Figure 10. Présentation "artistique" de l'ensemble constitué par l'actuel Tunnel Autoroutier, par le Tunnel de Service de prochaine réalisation.(2003-2008) et par un Grand Laboratoire International, actuellement en phase d'étude.

Sensitivity to θ_{13} with a UNO like detector

5 ans

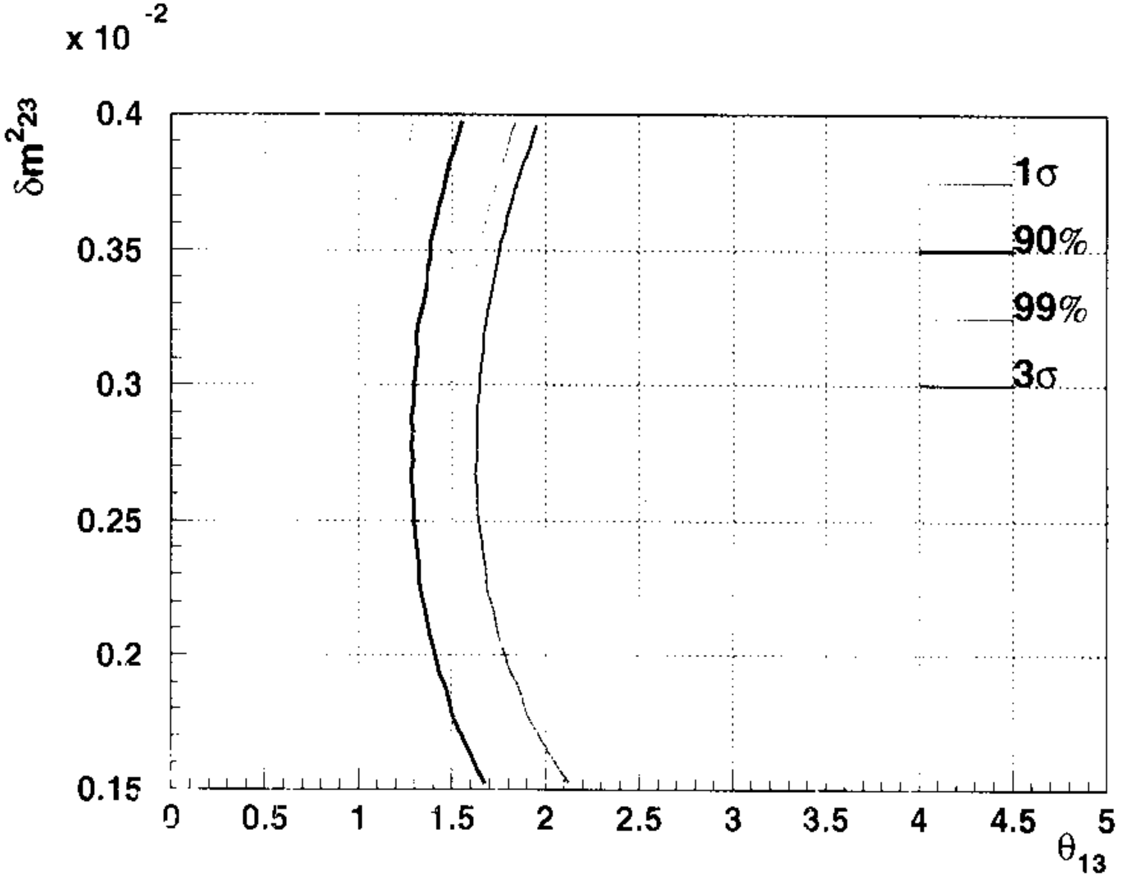
For the JHF limit: $\sin^2 2\theta_{13} = 0.006$ ($\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$, solar SMA solution):

ν_μ^{CC} (no osc.)	76782
Beam ν_e	294
NC	32
μ/e	44
Signal	138 (> 5σ)

θ_{13} 90%CL sensitivity: $\theta_{13} = 1.2°$

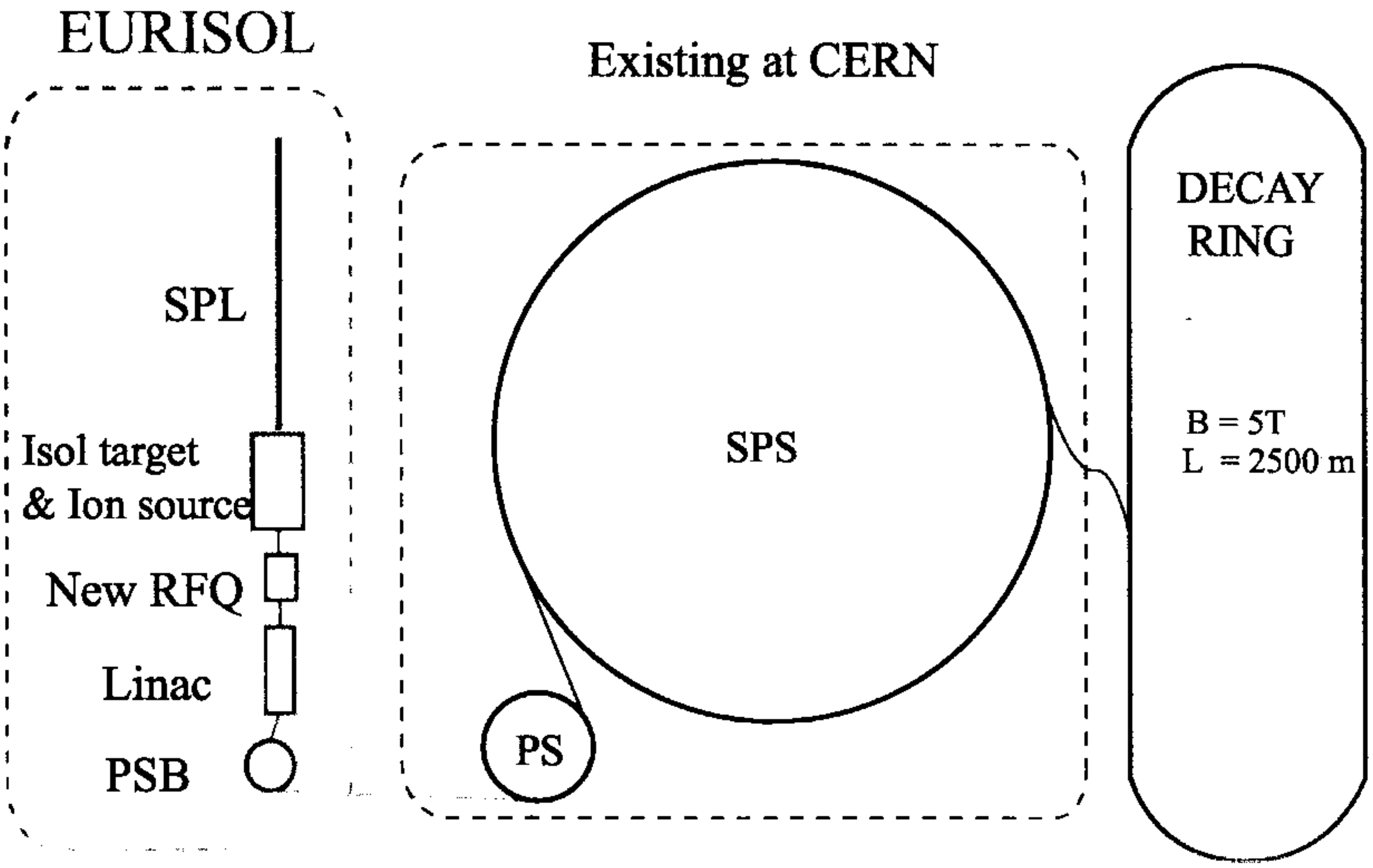
JHF 90%CL sensitivity: $\theta_{13} = 2.3°$ (Phase 1)

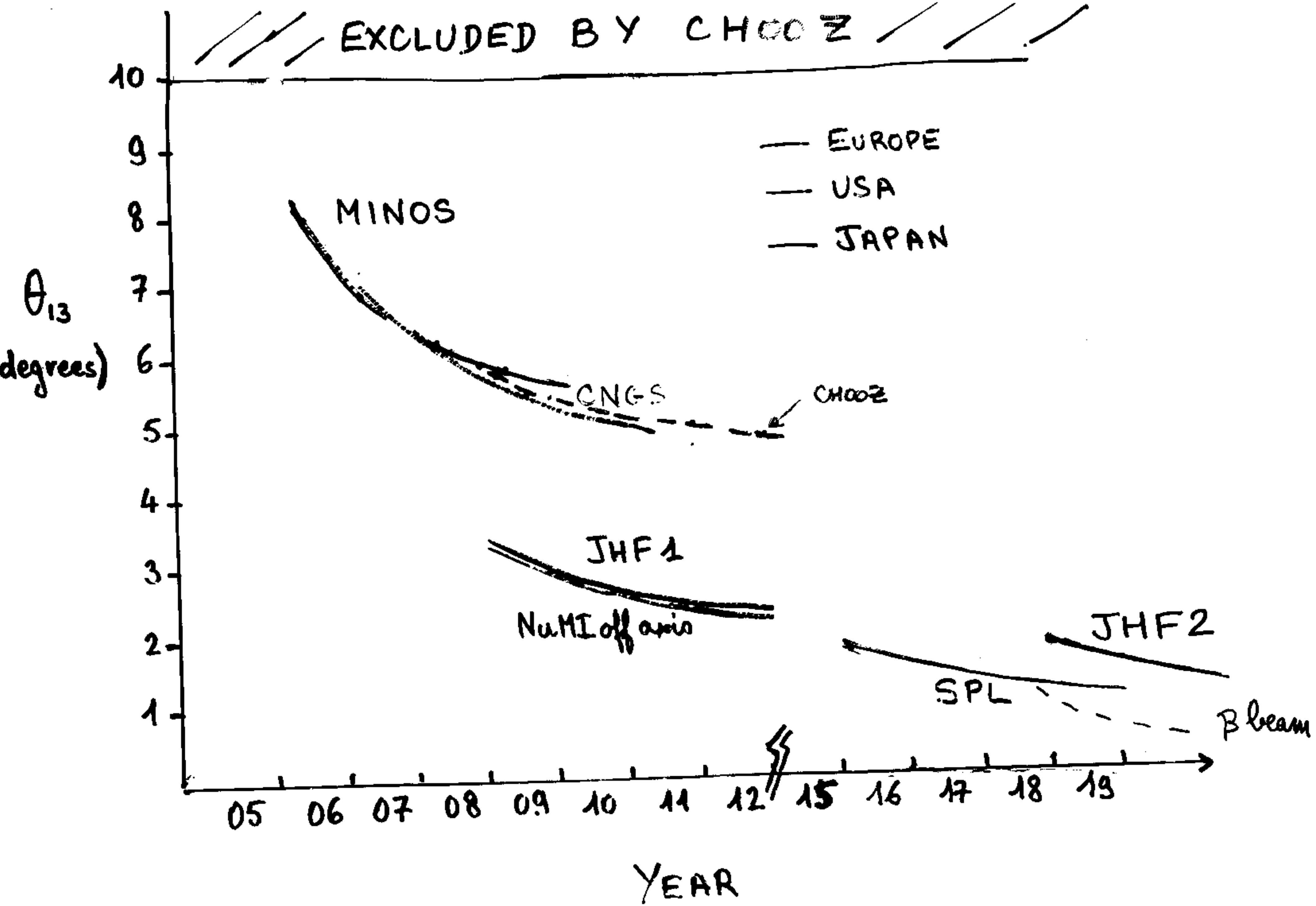
(Factor 3.7 better on $\sin^2 2\theta_{13}$)



35 ν_μ CC /(kT × an)

β- beams (idée originale de Piero Zucchelli)




EXCLUDED BY CHOOZ
EUROPE
USA
JAPAN
MINOS
CNGS
CHOOZ
JHF1
NuMI off axis
JHF2
SPL
β beam
θ_{13} (degrees)
10
9
8
7
6
5
4
3
2
1
05
06
07
08
09
10
11
12
15
16
17
18
19
YEAR

CONCLUSIONS

- Europe has no phase 2 projects
- CERN beams and Frejus lab. offer an opportunity to propose a very competitive phase 3 project
- A working group at european level already exists

• Need a careful study to compare Water Cerenkov / Liquid argon

• Write an EoI

- Important date = 2008, when digging machines meet in the middle of the tunnel.