Neutrino Physics

in Next 10 Years

§ Where are we?

§ The Dark Side

§ $\nu_\mu \rightarrow \nu_\tau, \nu_s$

§ $\nu_e \leftrightarrow \nu_\mu$

§ $\nu_e \leftrightarrow \nu_\tau$

§ 3 ν parameter space

§ Dirac vs Majorana

§ Conclusions

Public letter to the group of the Radioactives at the district society meeting in Tübingen:

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dec. 1930
Gloriastr.

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"[3] of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin $\frac{1}{2}$ and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. – The continuous β-spectrum would then become understandable by the assumption that in β-decay, a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant. Now the question that has to be dealt with is which forces act on the neutrons? The most likely model for the neutron seems to me, because of wave mechanical reasons (the details are known by the bearer of these lines), that the neutron at rest is a magnetic dipole of a certain moment μ. The experiments seem to require that the effect of the ionization of such a neutron cannot be larger than that of a γ-ray and then μ should not be larger than $e * 10^{-13}$ cm.

For the moment, however, I do not dare to publish anything on this idea and I put to you, dear Radioactives, the question of what the situation would be if one such neutron were detected experimentally, if it

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Our method may be illustrated by the following simple example: take a nucleus A (spin $I=0$) which decays by allowed orbital electron capture, to an excited state of a nucleus $B(I=1)$, from which a γ ray is emitted to the ground state of $B(I=0)$. The conditions necessary for resonant scattering are best fulfilled for those γ rays which are emitted opposite to the neutrino, which have an energy comparable to that of the neutrino, and which are emitted before the recoil energy is lost. Since the orbital electrons captured by a nucleus are almost entirely s electrons (K, L_I, $\cdots$ electrons of spin $S=\frac{1}{2}$), the substates of the daughter nucleus

All neutrinos left-handed

$\Rightarrow$ massless

ν_L 

$$\frac{\vec{S}\cdot\vec{p}}{|\vec{p}|} = -\frac{1}{2}$$

if $m_\nu \neq 0$, $v < c$

you can pass it and look back

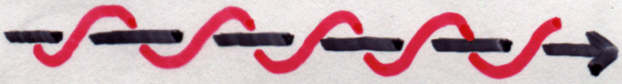
"ν_R" 

$$\frac{\vec{S}\cdot\vec{p}}{|\vec{p}|} = +\frac{1}{2} \quad ??$$

contradiction

All anti-neutrinos right-handed

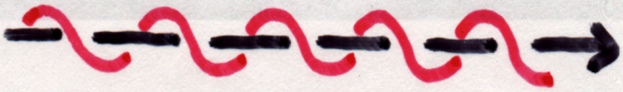
CPT theorem

ν_L  exists

P

ν_R  doesn't exist

T

ν_R  doesn't exist

C

$\bar{\nu}_R$  exists

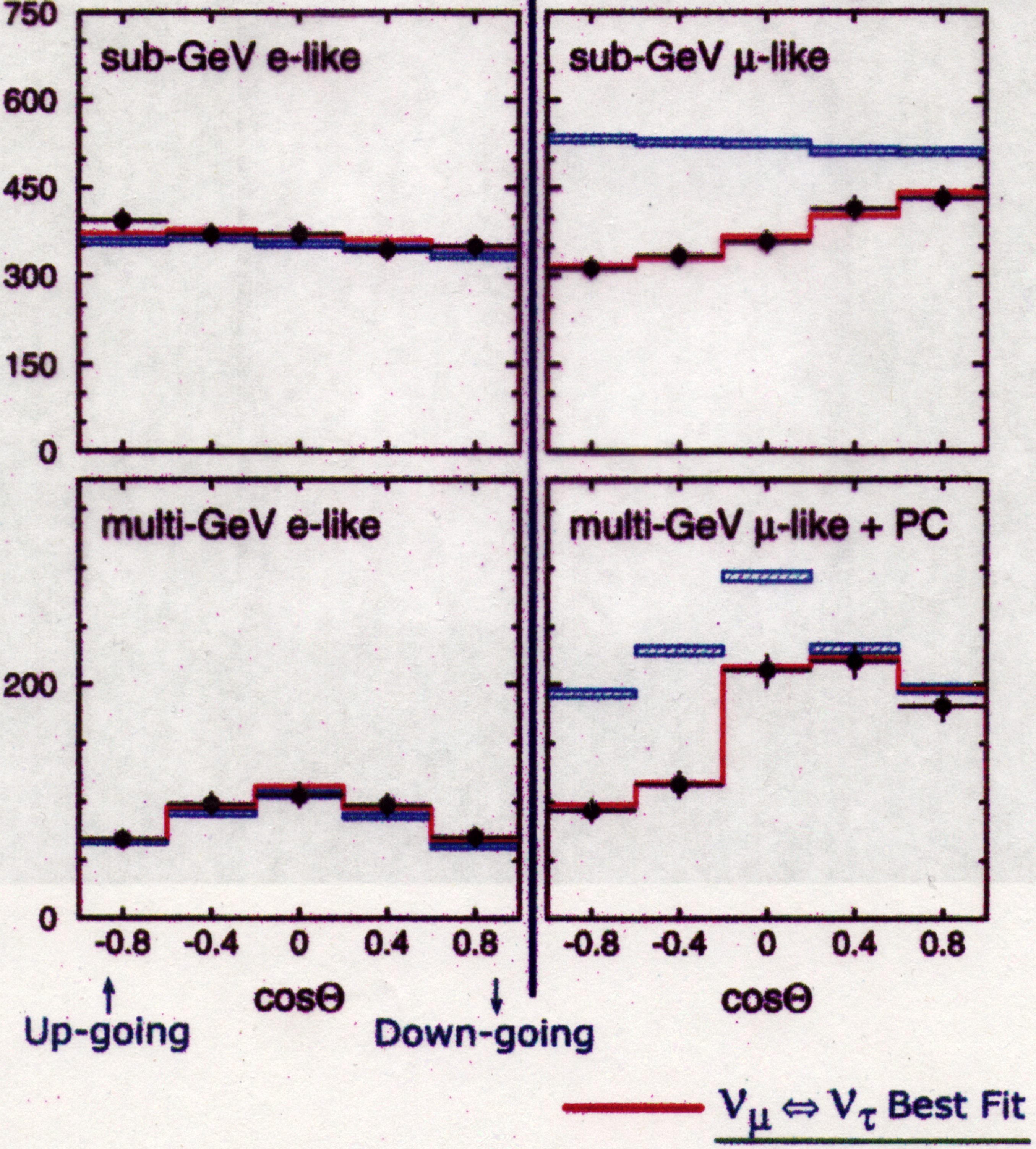
848 days = 52 kty

Zenith Angle Distributions:

ν_e's - No angular distortion

ν_μ's - "disappear" !

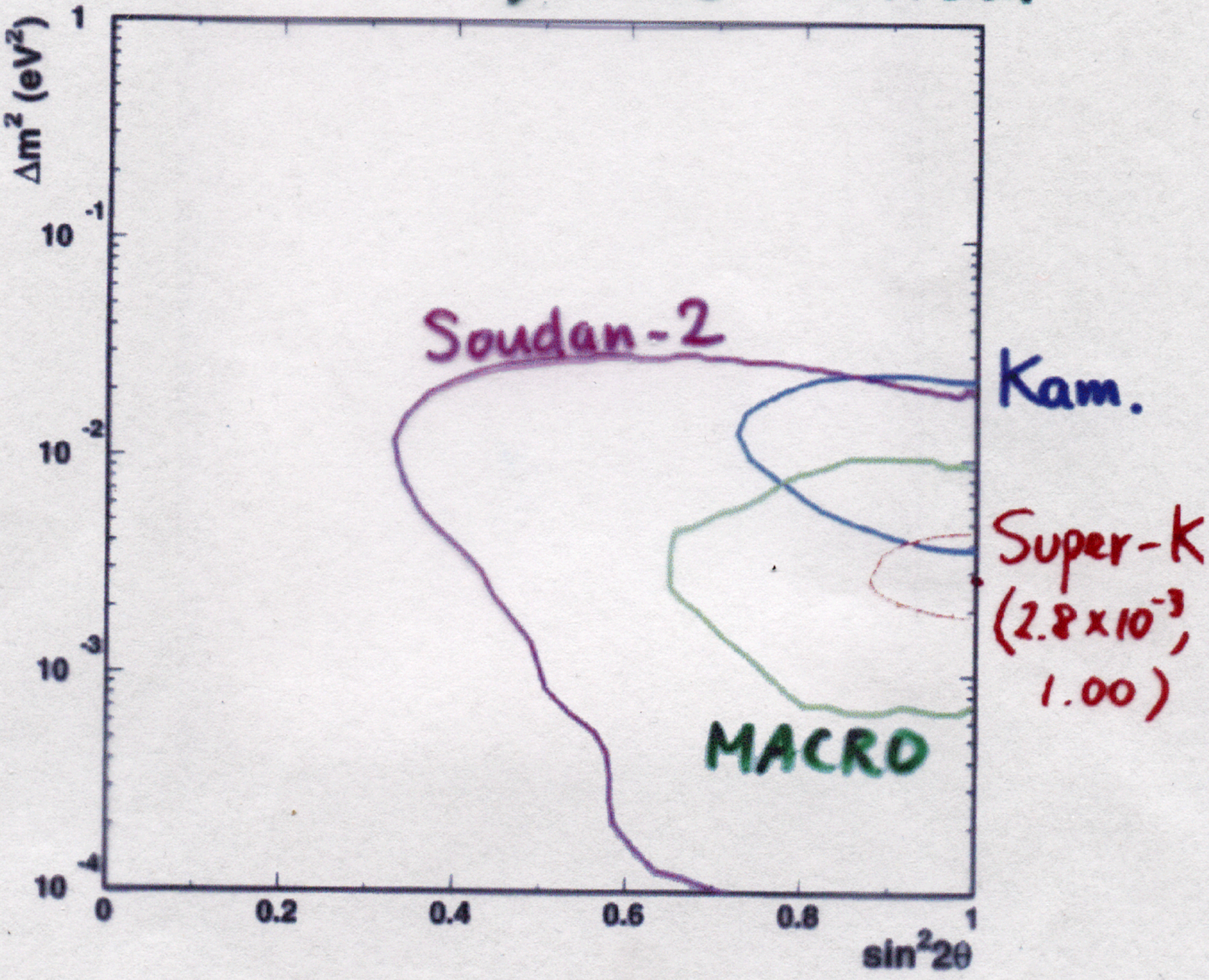
Dependence on $\Theta_z \Rightarrow$ L and E_ν



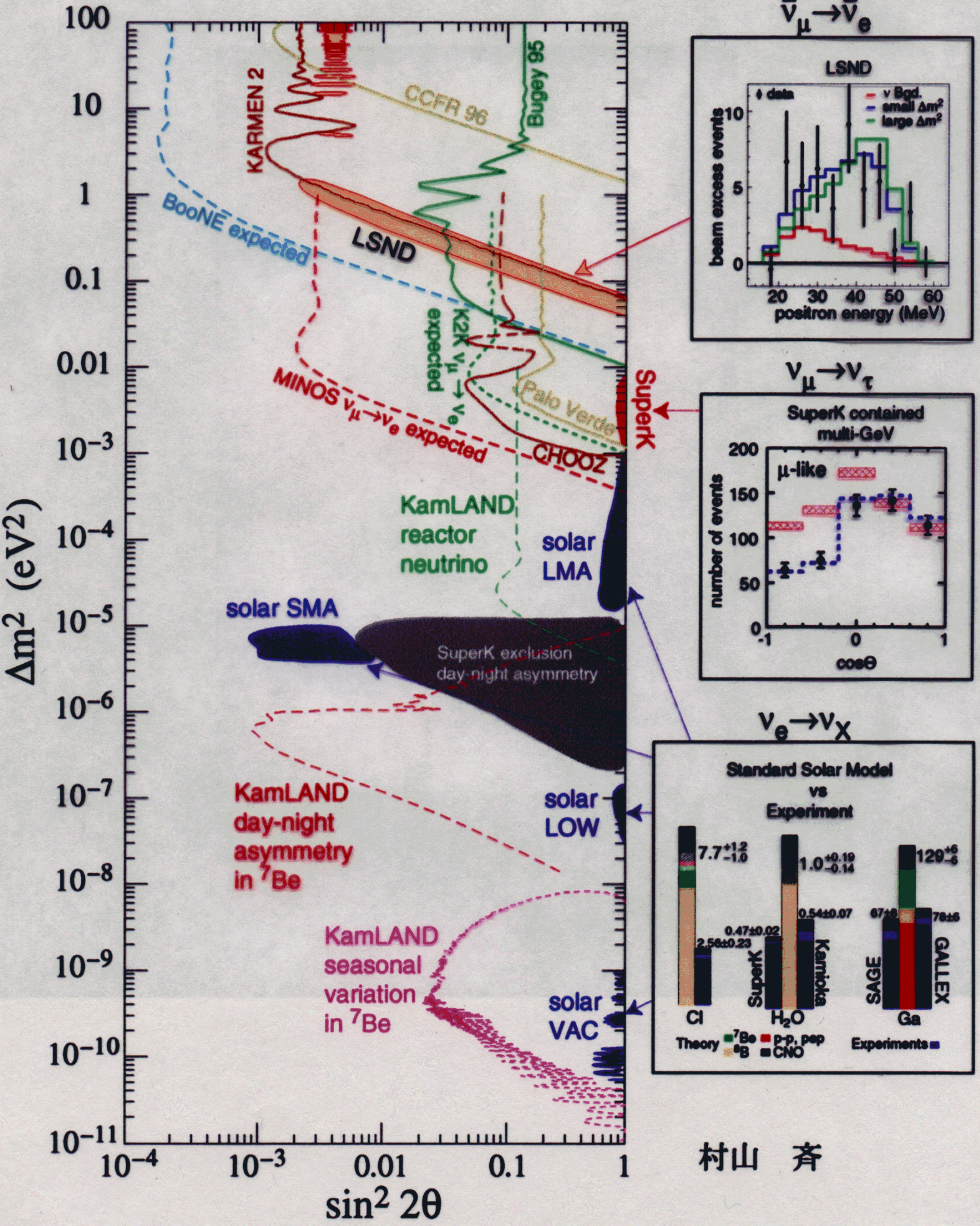
Allowed region from each exp.

(Contained events + up-going μ's)

$\nu_\mu \to \nu_\tau$ 90% C.L.

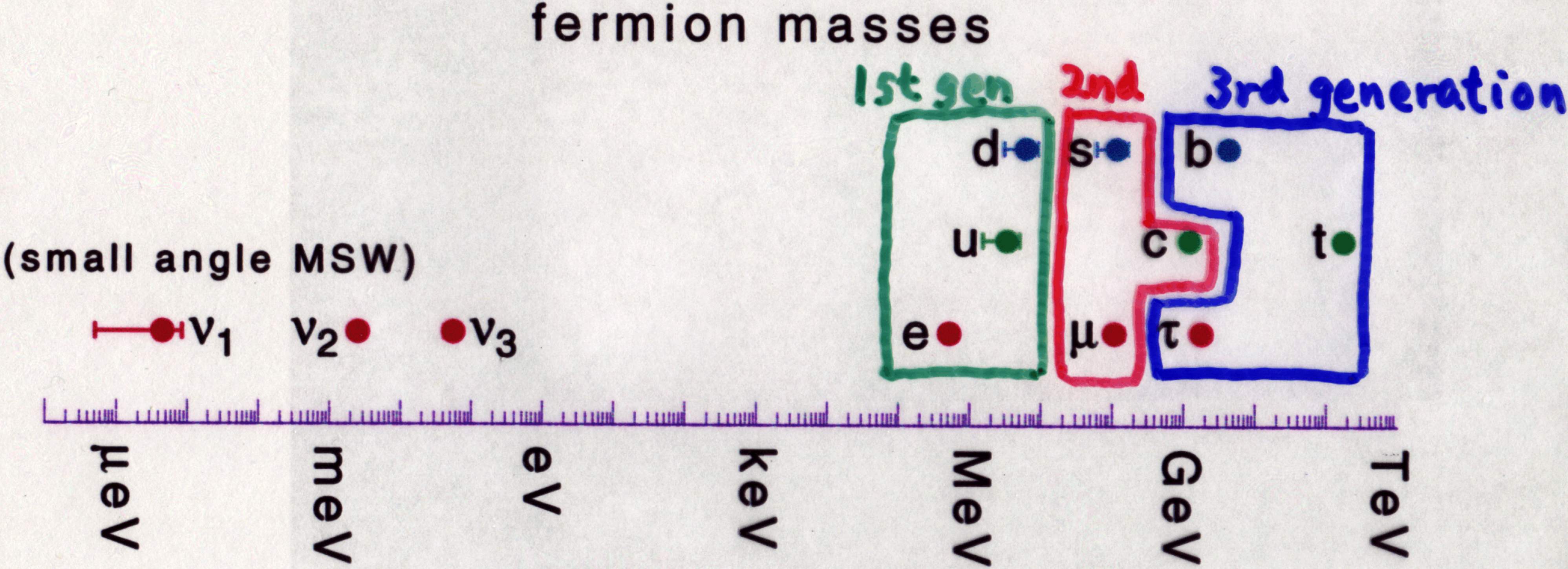


$$\begin{cases} \Delta m^2 \sim (2 \sim 5) \times 10^{-3}\,eV^2 \\ \sin^2 2\theta \gtrsim 0.88 \end{cases}$$



$\bar{\nu}_\mu \to \bar{\nu}_e$
LSND
data
ν Bgd.
small Δm²
large Δm²
beam excess events
positron energy (MeV)
$\nu_\mu \to \nu_\tau$
SuperK contained multi-GeV
μ-like
number of events
cosΘ
$\nu_e \to \nu_X$
Standard Solar Model vs Experiment
Cl
H₂O
Ga
SuperK
Kamioka
SAGE
GALLEX
Theory
⁷Be
⁸B
p-p, pep
CNO
Experiments
KARMEN 2
CCFR 96
Bugey 95
BooNE expected
LSND
K2K $\nu_\mu \to \nu_e$ expected
MINOS $\nu_\mu \to \nu_e$ expected
Palo Verde
CHOOZ
SuperK
KamLAND reactor neutrino
solar LMA
solar SMA
SuperK exclusion day-night asymmetry
solar LOW
KamLAND day-night asymmetry in ⁷Be
KamLAND seasonal variation in ⁷Be
solar VAC
Δm^2 (eV²)
$\sin^2 2\theta$

村山 斉


fermion masses
1st gen
2nd
3rd generation
d
s
b
u
c
t
e
μ
τ
(small angle MSW)
ν1
ν2
ν3
μeV
meV
eV
keV
MeV
GeV
TeV

$$\sum_{i<j} (a_{ri} + i a_{ii})(b_{ri} - i b_{ii}) + (a_{ri} - i a_{ii})(b_{ri} + i b_{ii})$$

$$= 2(a_r b_r + a_i b_i)$$

~~$\sum_{i>j} \left[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* e^{i(E_i - E_j)t} + c.c. \right]$~~

$$\sum_{i>j} \left[U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j} e^{-i(E_i - E_j)t} + c.c. \right]$$

= same but $i>j$ now and $\Delta m_{ij}^2 > 0$ now

$\Rightarrow$ Im part flipped as well as Δm_{ij}^2.

$m_\nu \neq 0$

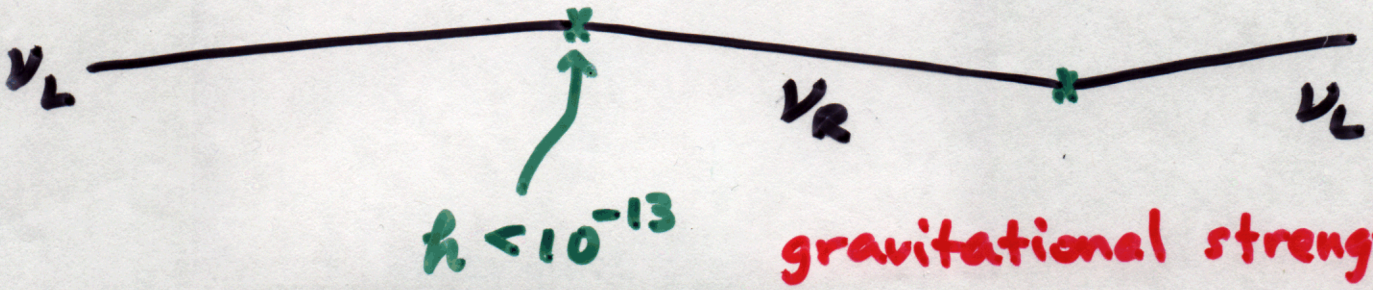
Standard Model clearly incomplet

How can it be fixed up?

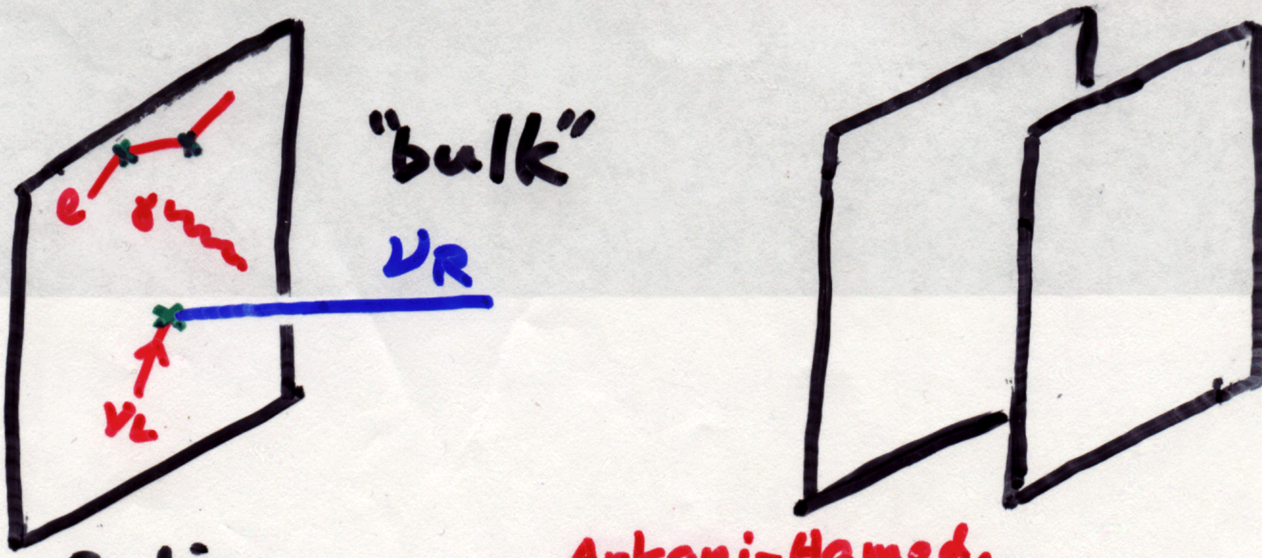
① Dirac neutrino

there actually exists ν_R

we've been missing it because it interacts too weakly



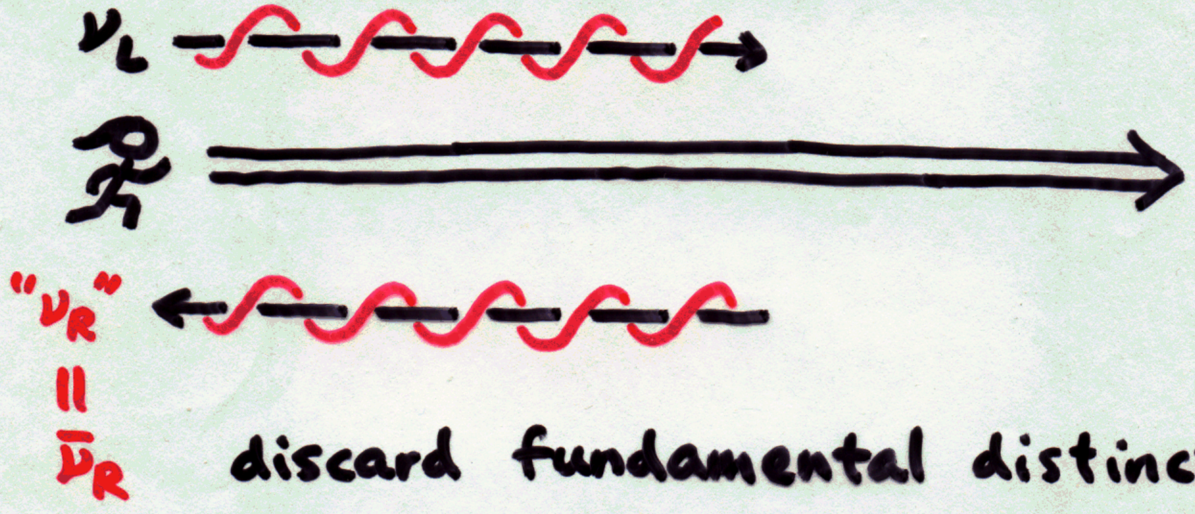
gravitational strengt



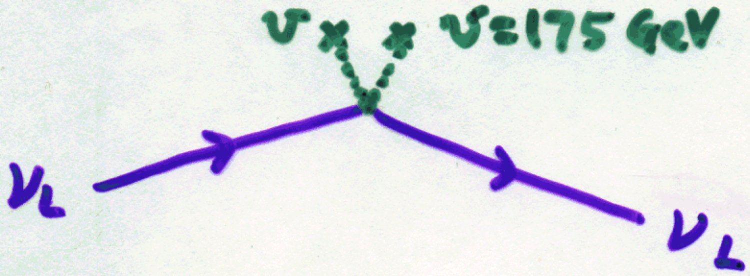
3-dim "brane"

Arkani-Hamed, Dimopoulos, March-Russe

② Majorana neutrino



discard fundamental distinction between ν + $\bar{\nu}$ ⇒ lepton-number violation



$$m_\nu = \frac{v^2}{M}$$

M: new mass (energy) scale in physics

atmospheric ν data

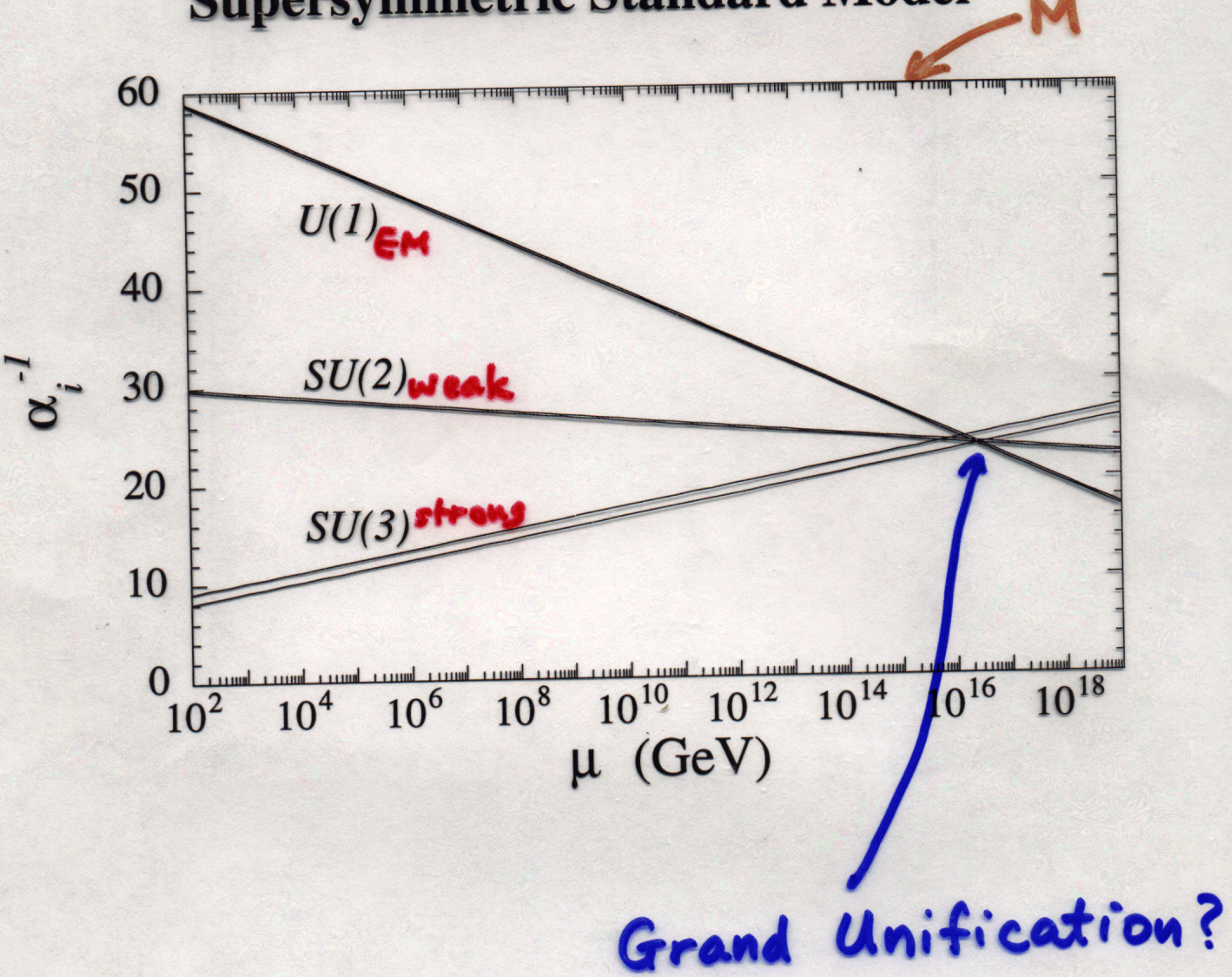
$$\Rightarrow M \simeq 10^{15}\ \text{GeV}/c^2$$

$$\frac{\hbar}{Mc} \simeq 10^{-29}\ \text{cm}$$

extremely short distance physics

hierarchy $M \gg v$ ⇒ need supersymmetry

Supersymmetric Standard Model



Dimopoulos
Raby
Wilczek

Dine
Fischler

large angle(s)

surprise to most theorists

conventional wisdom

hierarchy $m_e \ll m_\mu \ll m_\tau$ 0.0003 : 0.06 : 1

$m_d \ll m_s \ll m_b$ 0.001 : 0.02 : 1

$m_u \lll\ll m_c \lll\ll m_t$ 0.000006 : 0.007 : 1

small angles $V_{us} \sim \lambda \sim 0.22$

$V_{cb} \sim \lambda^2 \sim 0.04$

$V_{ub} \sim \lambda^3 \sim 0.002$

expansion in small parameters breaking flavor symmetry

$$M \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix} \text{ etc}$$

⇒ both hierarchy + small angles

$$V_{us} \sim \sqrt{\frac{m_d}{m_s}} \sim 0.22$$

$$V_{cb} \sim \sqrt{\frac{m_c}{m_t}} \sim 0.08$$

⇒ neutrino mass should also be hierarchical and mixings small esp. w/ GUT

How do we get $\sin^2\theta_{atm} \sim 1$?

conservatives: hierarchy, flavor symmetry, order

e.g. $M_\nu \sim \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \Rightarrow \theta = 45^\circ$

$$M_l \sim \begin{pmatrix} \epsilon^2 & \epsilon \\ \epsilon & 1 \end{pmatrix} \Rightarrow \theta_l \sim \sqrt{\frac{m_\mu}{m_\tau}} \sim 0.24$$

$$M_\nu \sim \begin{pmatrix} \epsilon'^2 & \epsilon' \\ \epsilon' & 1 \end{pmatrix} \Rightarrow \theta_\nu \sim \sqrt{\frac{m_\odot}{m_{atm}}} \sim 0.21$$

$$\theta = \theta_l + \theta_\nu \sim 0.45 \qquad \sin^2 2\theta \sim 0.6$$

$\Rightarrow$ tend to prefer SMA

radicals: "anarchy", no order, random
(Hall, HM, Weiner)

$$M_\nu = M_D M_R^{-1} M_D \quad \text{seesaw}$$

$$M_D \sim \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \quad M_R \sim \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

all comparable
+ random

$$\Rightarrow \frac{\Delta m^2_\odot}{\Delta m^2_{atm}} \sim \frac{1}{10} \text{ natural, angles large}$$

$\Rightarrow$ prefer LMA

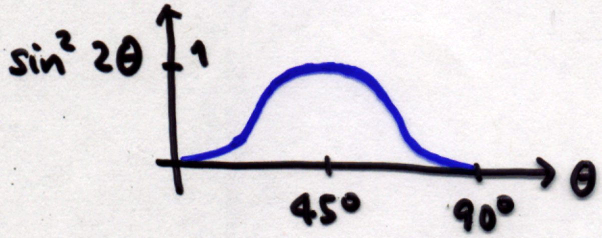
§ The Dark Side of Solar ν Oscillation

expt'l data → fit on $(\Delta m^2, \sin^2 2\theta)$

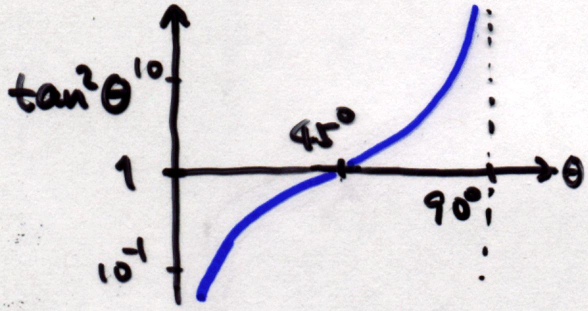
covers only a half of the param space

in presence of matter effects

θ : $0° \to 90°$

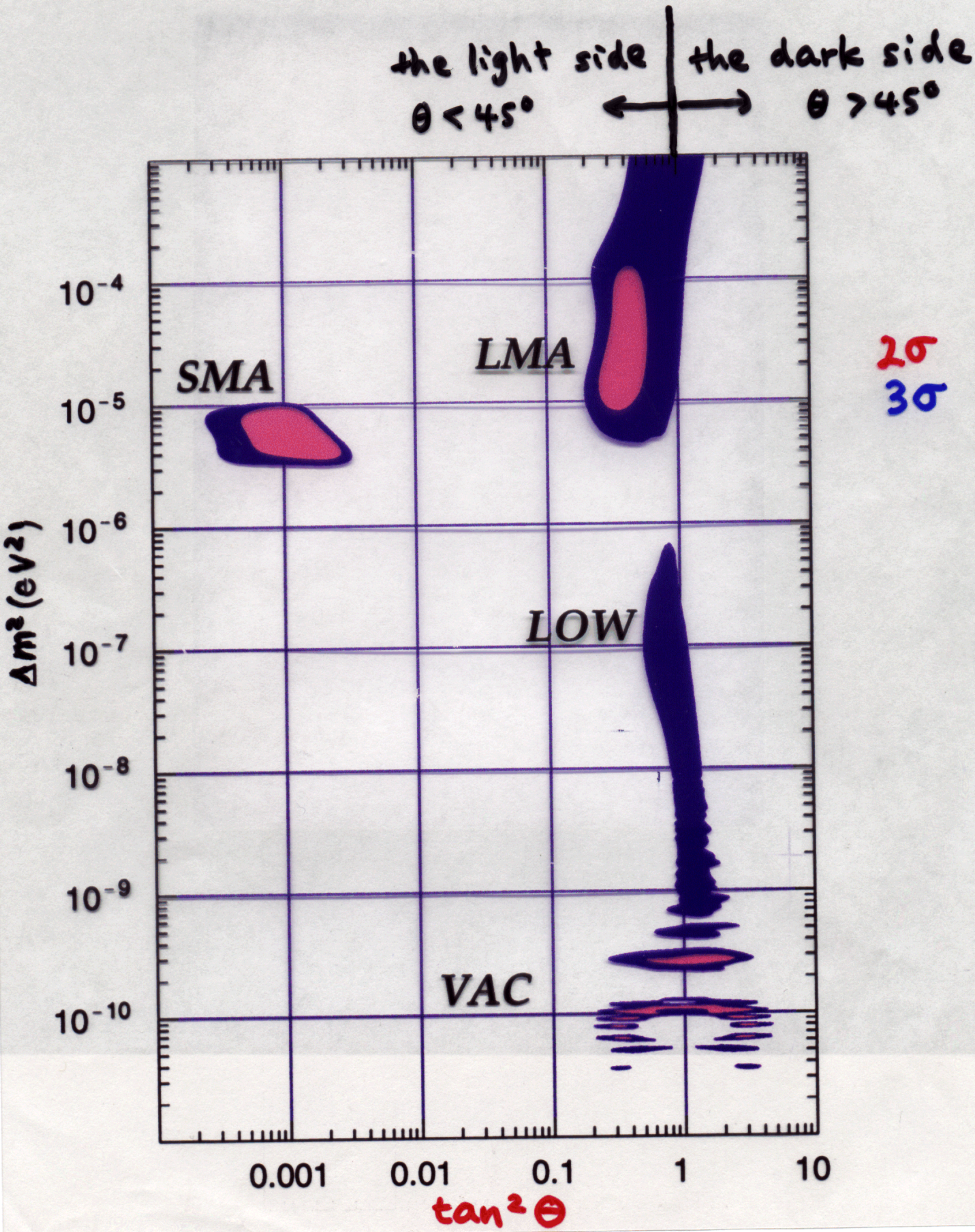


better parameter



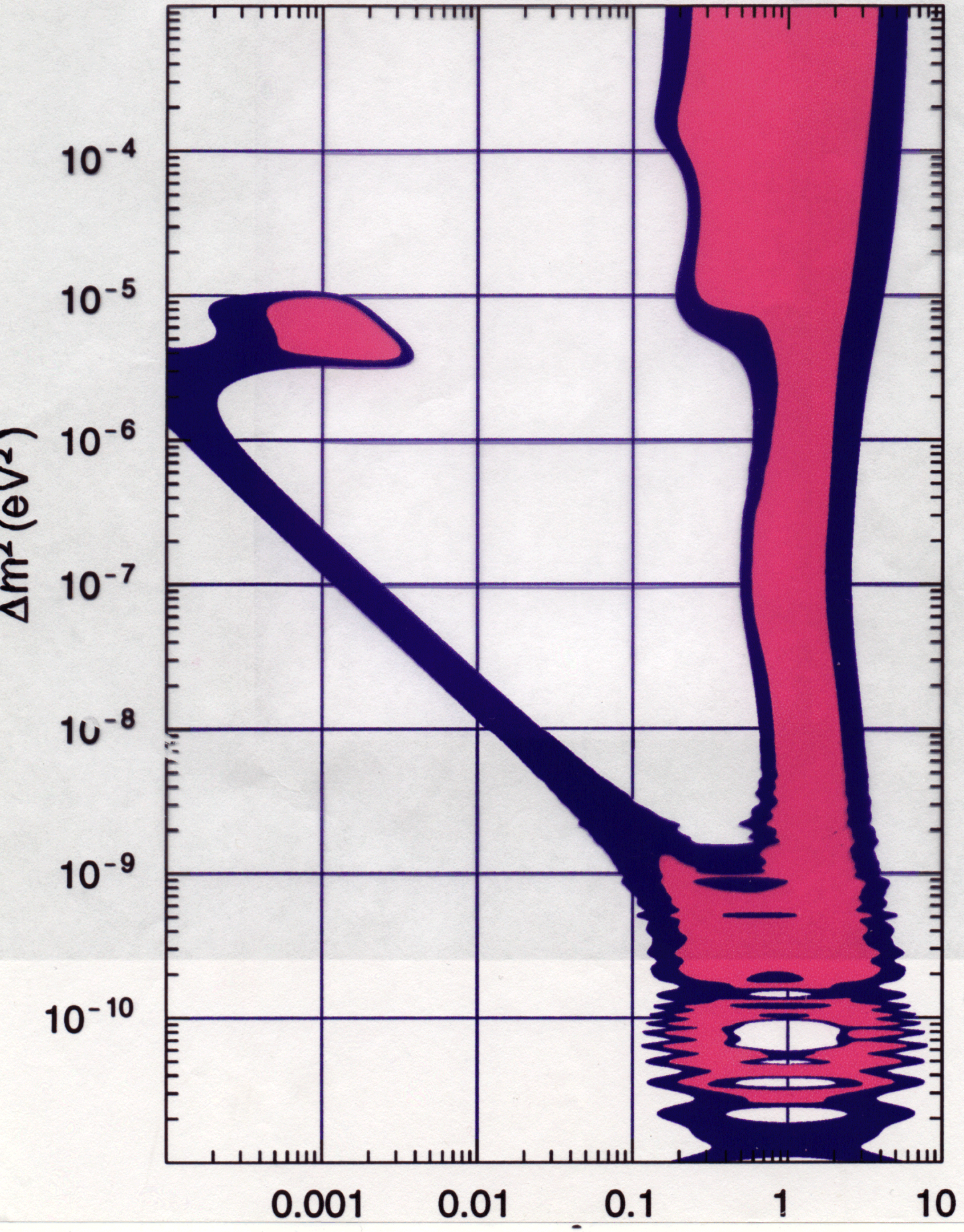
⇒ Alex Friedland

also matter effects in VAC regio



the light side
the dark side
θ < 45°
θ > 45°
SMA
LMA
LOW
VAC
2σ
3σ
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
Δm² (eV²)
0.001
0.01
0.1
1
10
tan²θ

dropped Homestake from the fit



§ $\nu_\mu \to \nu_\tau, \nu_s$

SuperK

Δm^2, $\sin^2 2\theta$

don't know how much improvement

FC ⇒ limited stat @ horizontal
angular res

up μ ⇒ larger theor. systematics

dflux/dE, σ_ν etc

guess : not much change

ν_μ vs ν_s

prospect good

1. $\frac{(\pi^0/e)_{data}}{(\pi^0/e)_{MC}} = 1.11 \pm 0.06 \pm 0.02 \pm 0.25$

stat, MC stat, sys

sys ← $\sigma(\nu N \to \nu N \pi^0)$

K2K ⇒ 0.05

$\nu_\tau \Rightarrow 1$

$\nu_s \Rightarrow 0.8$

} 3σ discriminatio

2. $\frac{\text{up } \pi^0}{\text{down } \pi^0}$ statistics limited

$\sim 2.5\,\sigma$ level in 5 yrs?

3. matter effect in $\nu_\mu \to \nu_s$

use high E_ν s.t. $\frac{\Delta m^2}{E} \sim G_F\, n_n$

PC
up μ
FC multi ring

] ν_s disfavored @ 99% CL

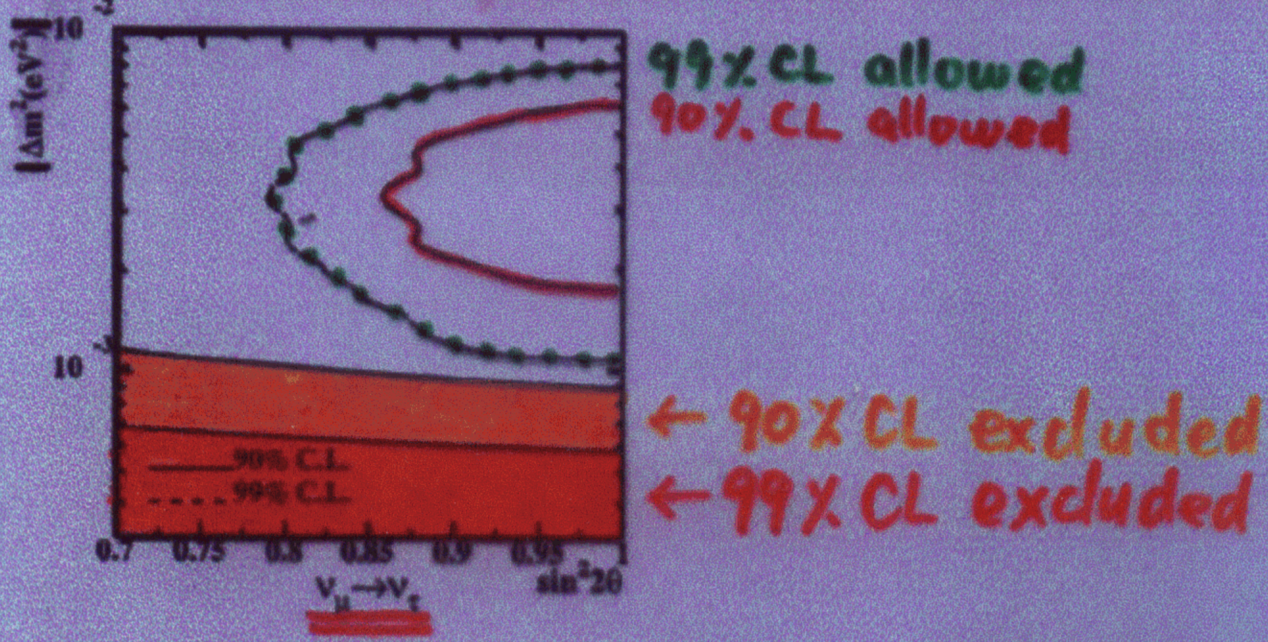
will improve further

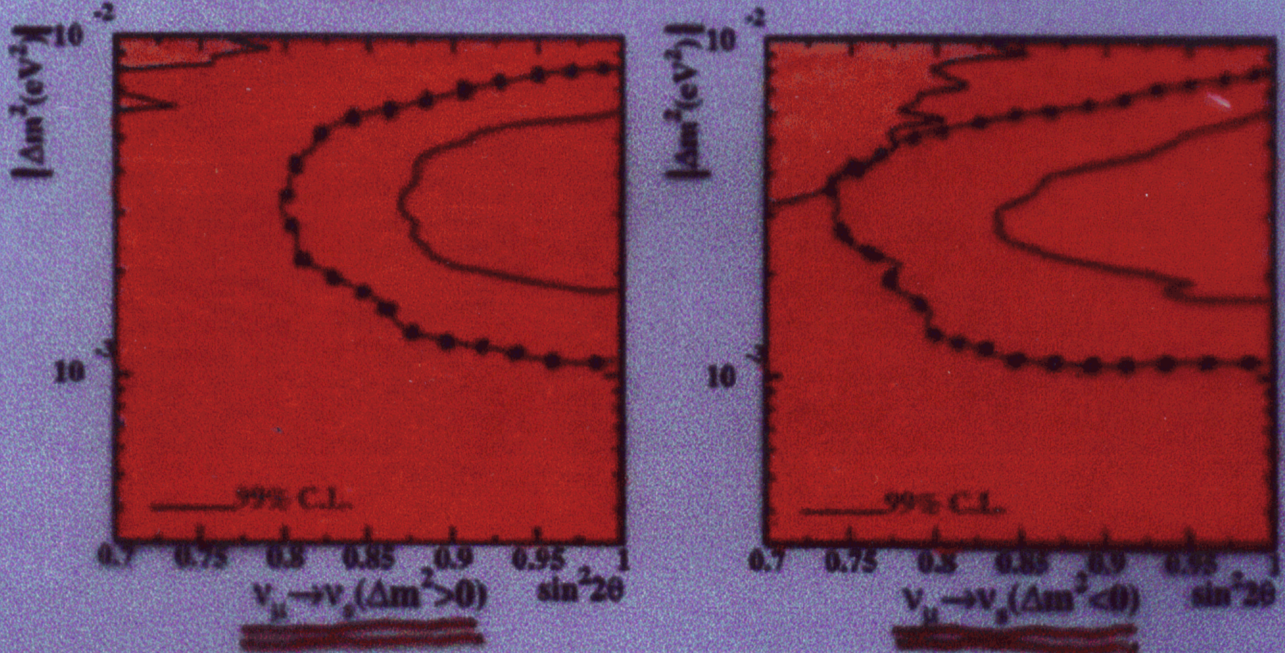
many handles

$\Rightarrow$ could well be settled by SuperK alone in 5 yrs

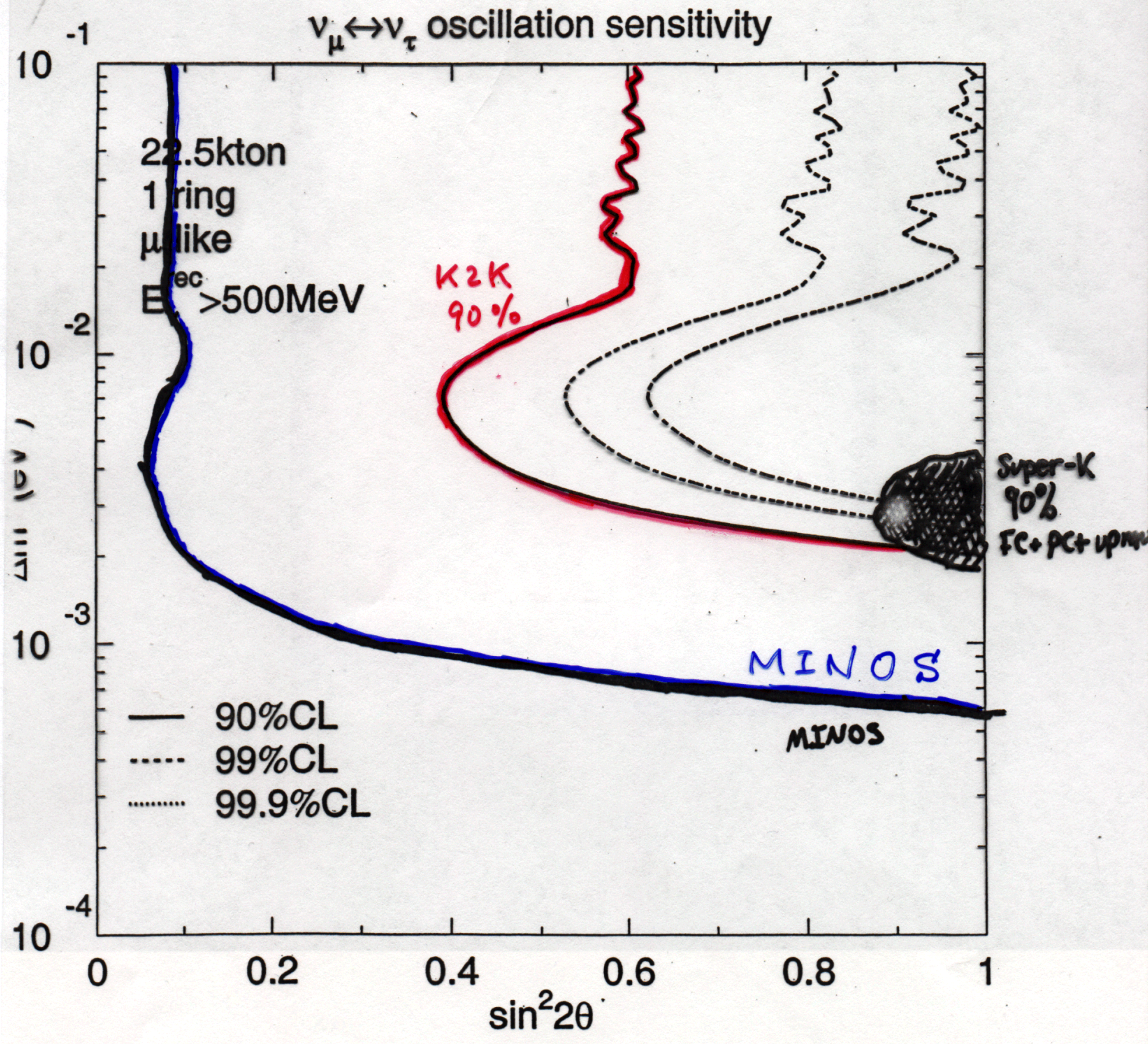
$\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_{sterile}$: Summary

$$\chi^2 = \chi^2_{\left(\frac{UP}{Horiz.}\right)_{Up\text{-}\mu}} + \chi^2_{\left(\frac{UP}{Down}\right)_{PC}} + \chi^2_{\left(\frac{UP}{Down}\right)_{mul}}$$

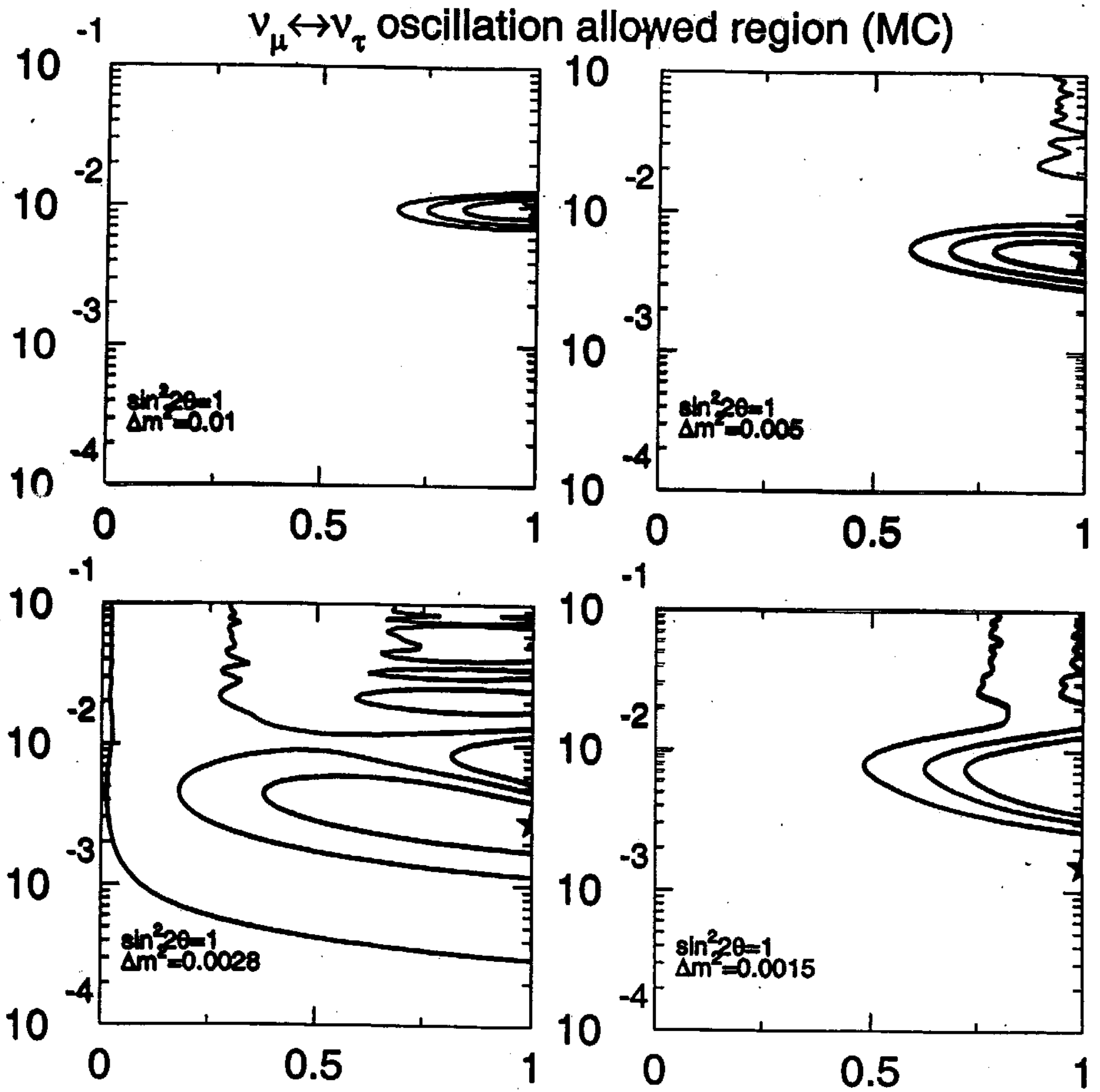




→ $\nu_\mu \to \nu_{sterile}$ oscillations are disfavored



$\nu_\mu \leftrightarrow \nu_\tau$ oscillation sensitivity
22.5kton
1 ring
μ-like
E^{rec} >500MeV
K2K 90%
Super-K 90%
FC+PC+upmu
MINOS
MINOS
90%CL
99%CL
99.9%CL
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta$



$\nu_\mu \leftrightarrow \nu_\tau$ oscillation allowed region (MC)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1
$\sin^2 2\theta=1$
$\Delta m^2=0.01$
$\sin^2 2\theta=1$
$\Delta m^2=0.005$
$\sin^2 2\theta=1$
$\Delta m^2=0.0028$
$\sin^2 2\theta=1$
$\Delta m^2=0.0015$

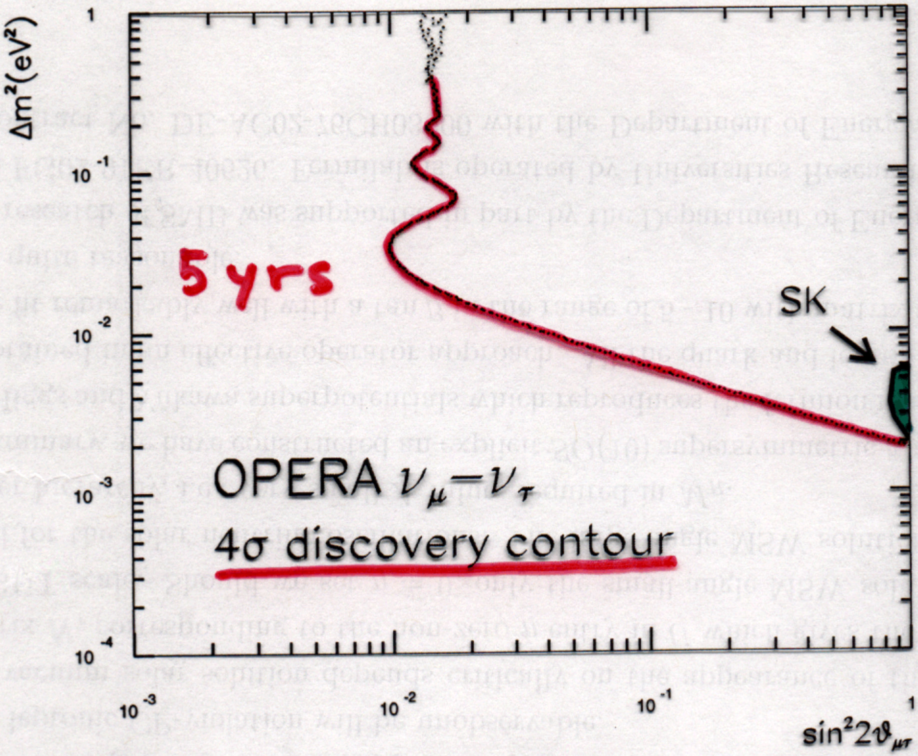
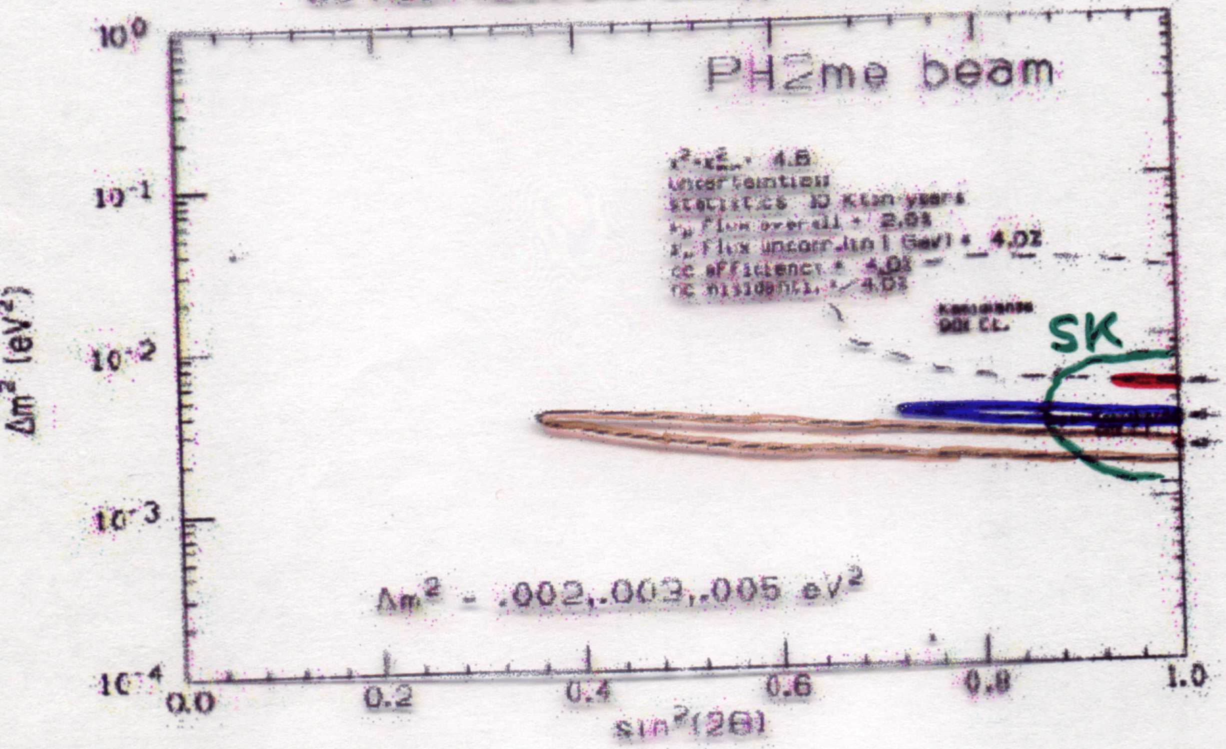


Figure 2.29: Four σ discovery potential of OPERA in the search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations (2.25×10^{20} *pot*).

MINOS Measurement Capability

CC Muon Neutrino Disappearance Test



KEK → SuperK

K2K

ν_μ disappearance

MINOS

FNAL → Soudan

→ verify atm ν oscillation

measure params

MINOS NC/CC

MINOS + emulsion

OPERA
ICANOE
} CERN → Gran Sasso

→ confirm ν_τ

probably well covered

<u>except</u> the unfortunate case

of $\Delta m^2 \sim 1 \times 10^{-3}$ eV^2

(allowed at 99% CL)

MONOLITH

calorimeter expt on atmos ν 25 kt

AQUARICH

novel water Cherenkov 1 Mt

MONOLITH
4 yrs

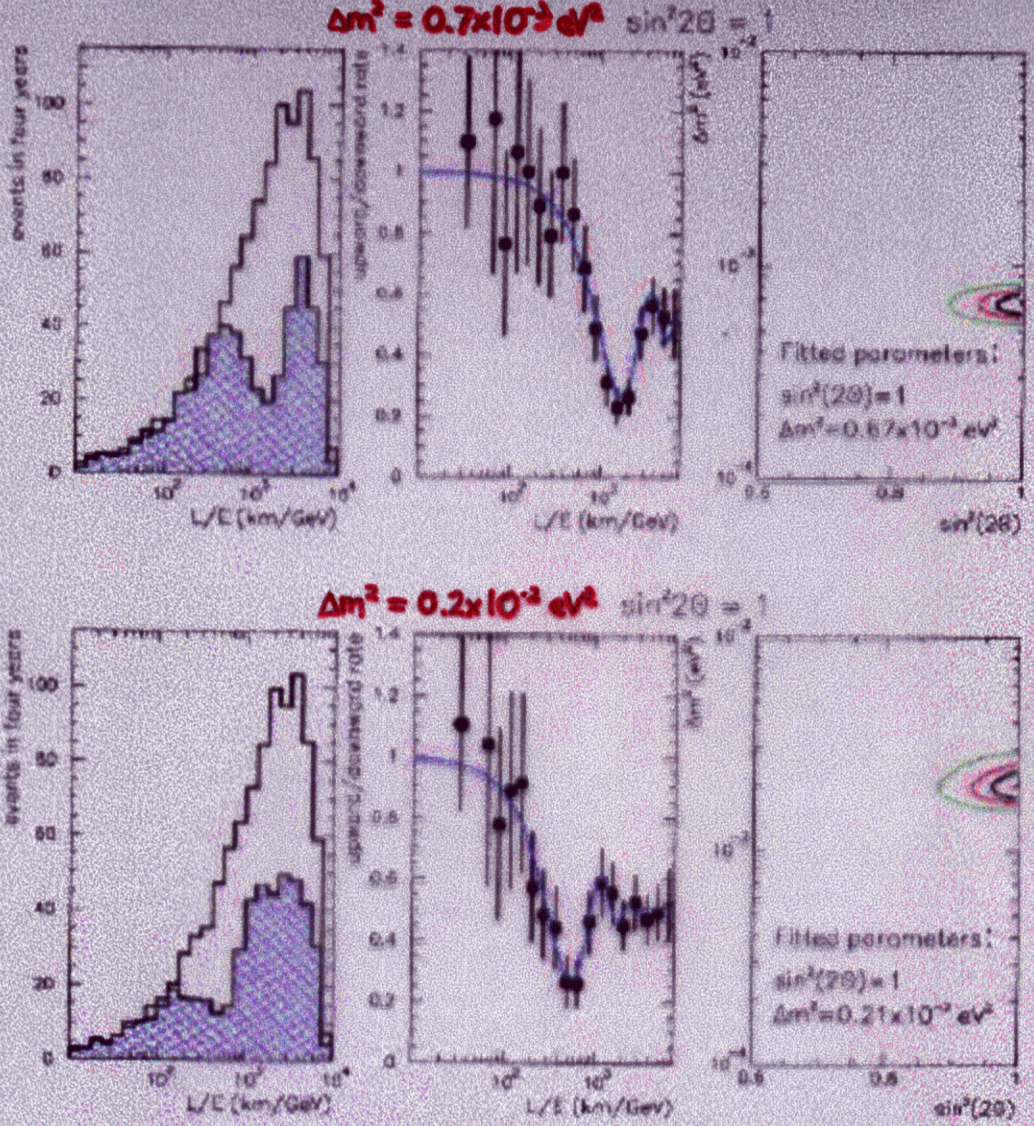
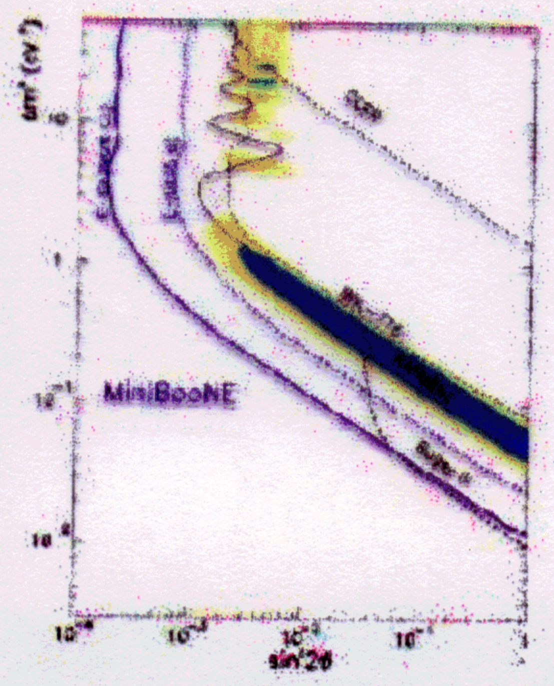


Figure 5.3: Results of the L/E analysis on a simulated sample in presence of $\nu_\mu \to \nu_\tau$ oscillations, with parameters $\Delta m^2 = 7 \times 10^{-4}\ eV^2$ and $\sin^2(2\Theta) = 1.0$ (top) and $\Delta m^2 = 2 \times 10^{-3}\ eV^2$ and $\sin^2(2\Theta) = 1.0$. The figures show from left to right: L/E spectra for upward muon events (hatched area) and downward ones (open area); their ratio with the best-fit superimposed (the first point is integrated over the first six bins) and the result of the fit with the corresponding allowed regions for oscillation parameters at 68%, 90% and 99% C.L. Simulated statistics correspond to 25 years of data taking, rate normalisation, error bars and errors entering in the best fit procedure correspond to 4 years

Expectations for the BooNE Experiment:

Phase 1: MiniBooNE – a single detector experiment

- Goal: verify or rule out LSND signal
- Schedule:
  - Construction begins for detector: Sept 9, 1999
  - All construction (beam & detector) complete: late 2001
  - Results to be presented at conferences in early 2003



Phase 2: If a signal is observed...

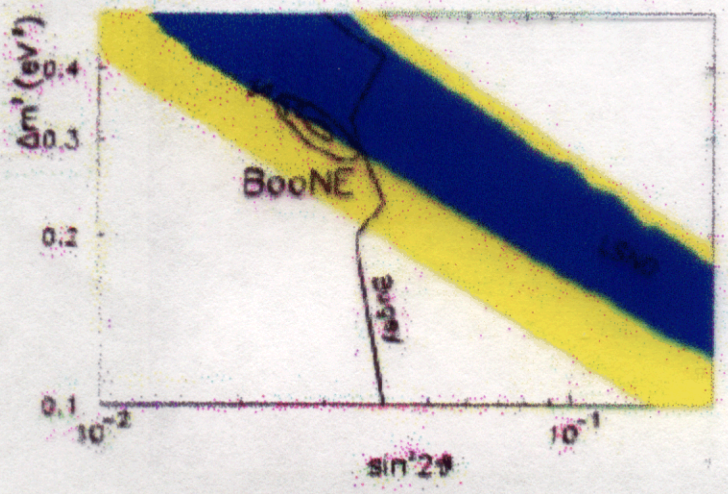
- Install a second detector
- Goal: accurately measure Δm^2

A "Measurement" Experiment!

Two examples for MiniBooNE (1 detector) measurements:

Δm_0^2	$\sin^2 2\theta_0$	$\delta(\Delta m^2)$	$\delta(\sin^2 2\theta)$	Signal Signif.
0.3 (eV^2)	0.03	0.10 (eV^2)	0.02	44 σ
2.0 (eV^2)	0.002	0.10 (eV^2)	0.0002	15 σ

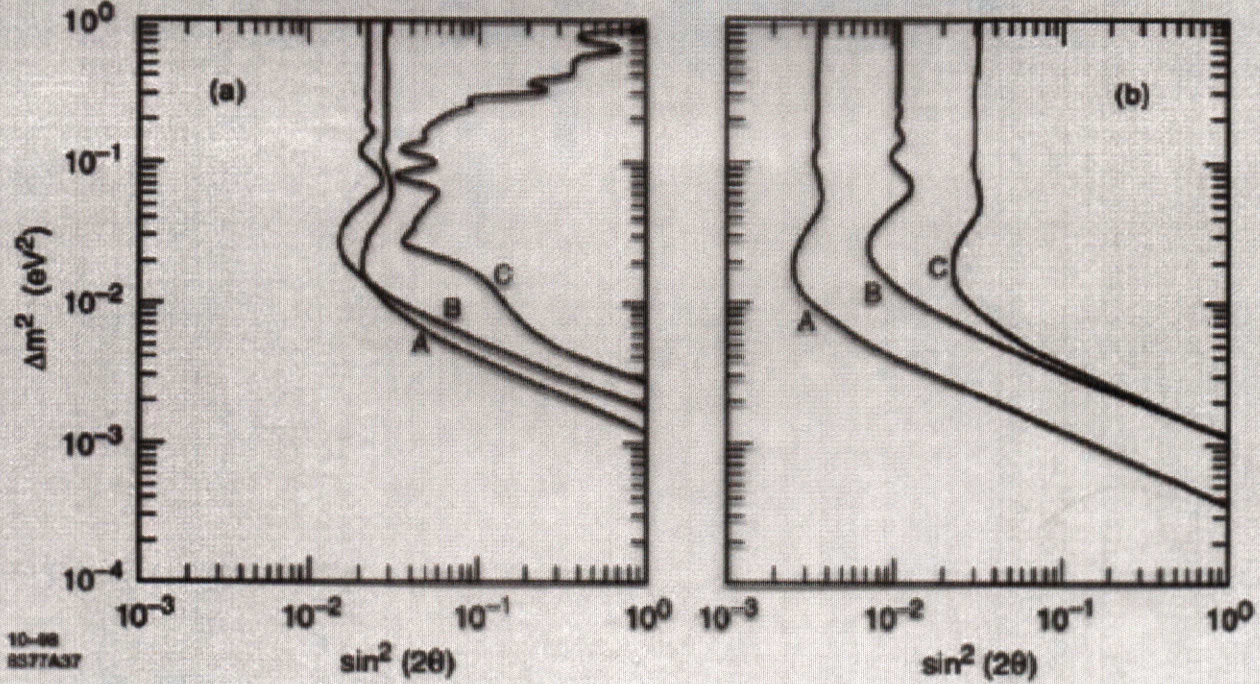
Example BooNE (2 detector) measurement



And tests of CP violation with ν and $\bar{\nu}$ running

Sensitivity

$\nu_\mu \rightarrow \nu_\tau$ $\nu_\mu \rightarrow \nu_e$



A - Disappearance
B - NC/CC rate test
C - CC-event energy test

A - Electron appearance
B - NC/CC rate test
C - Disappearance

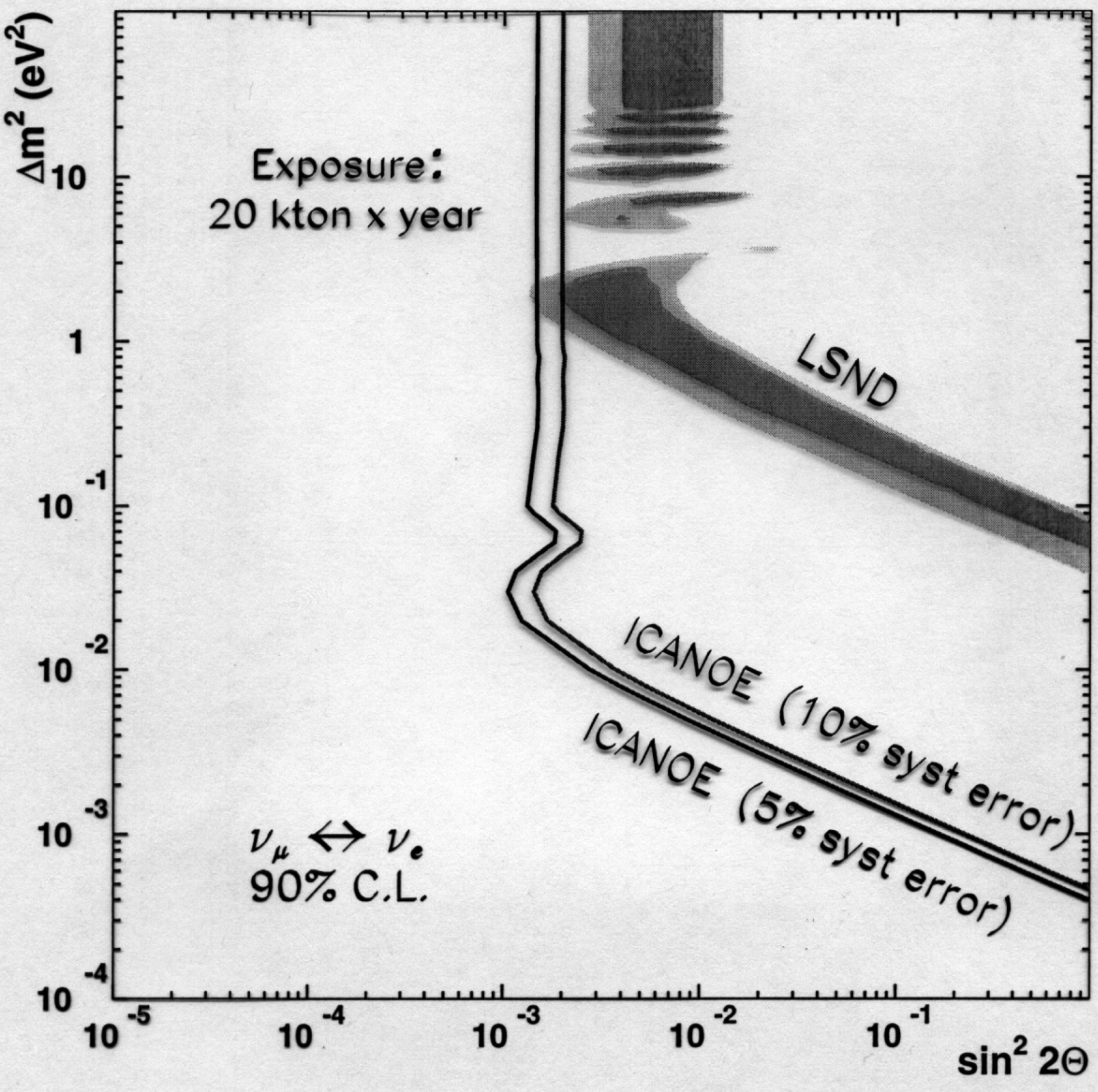
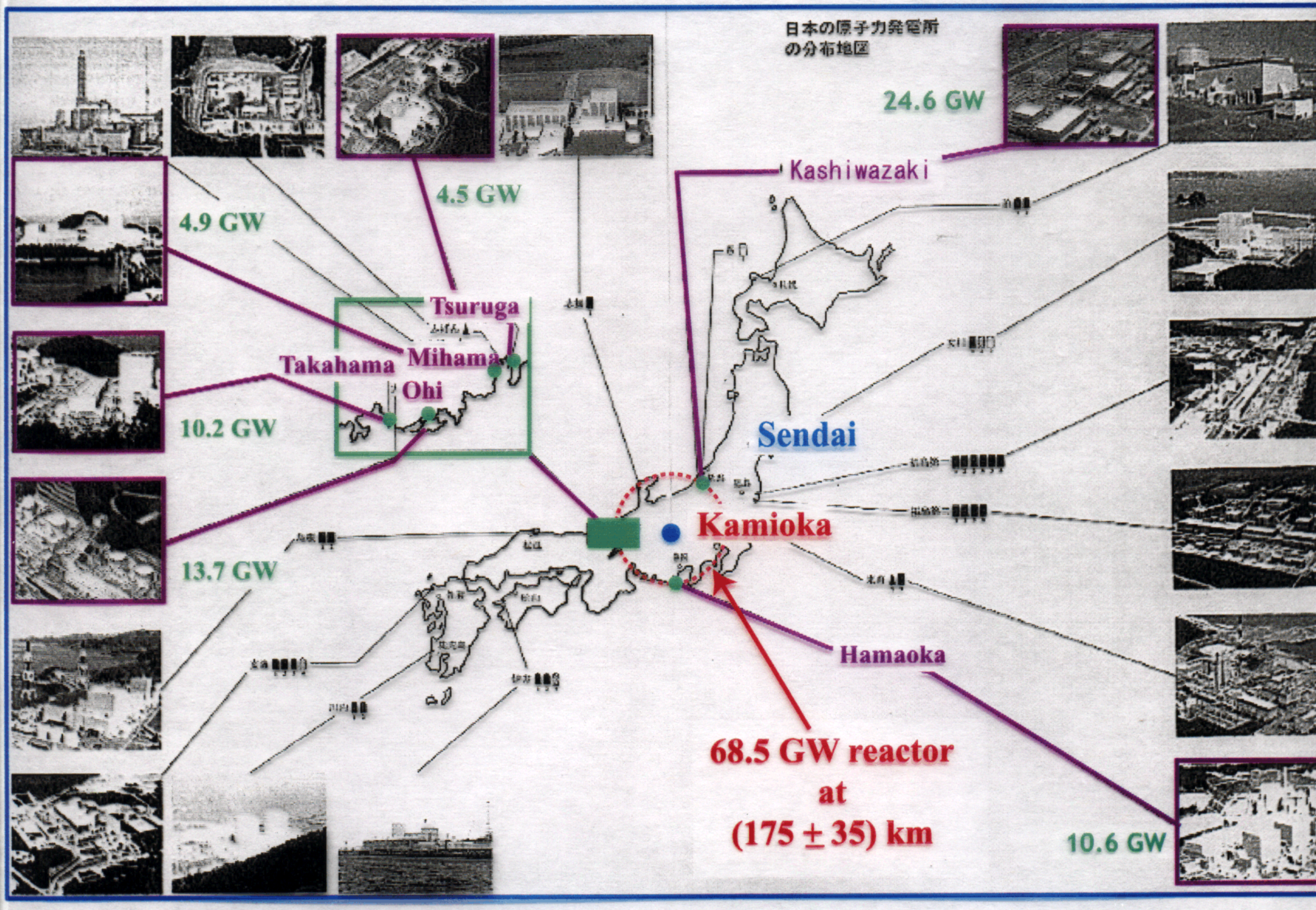


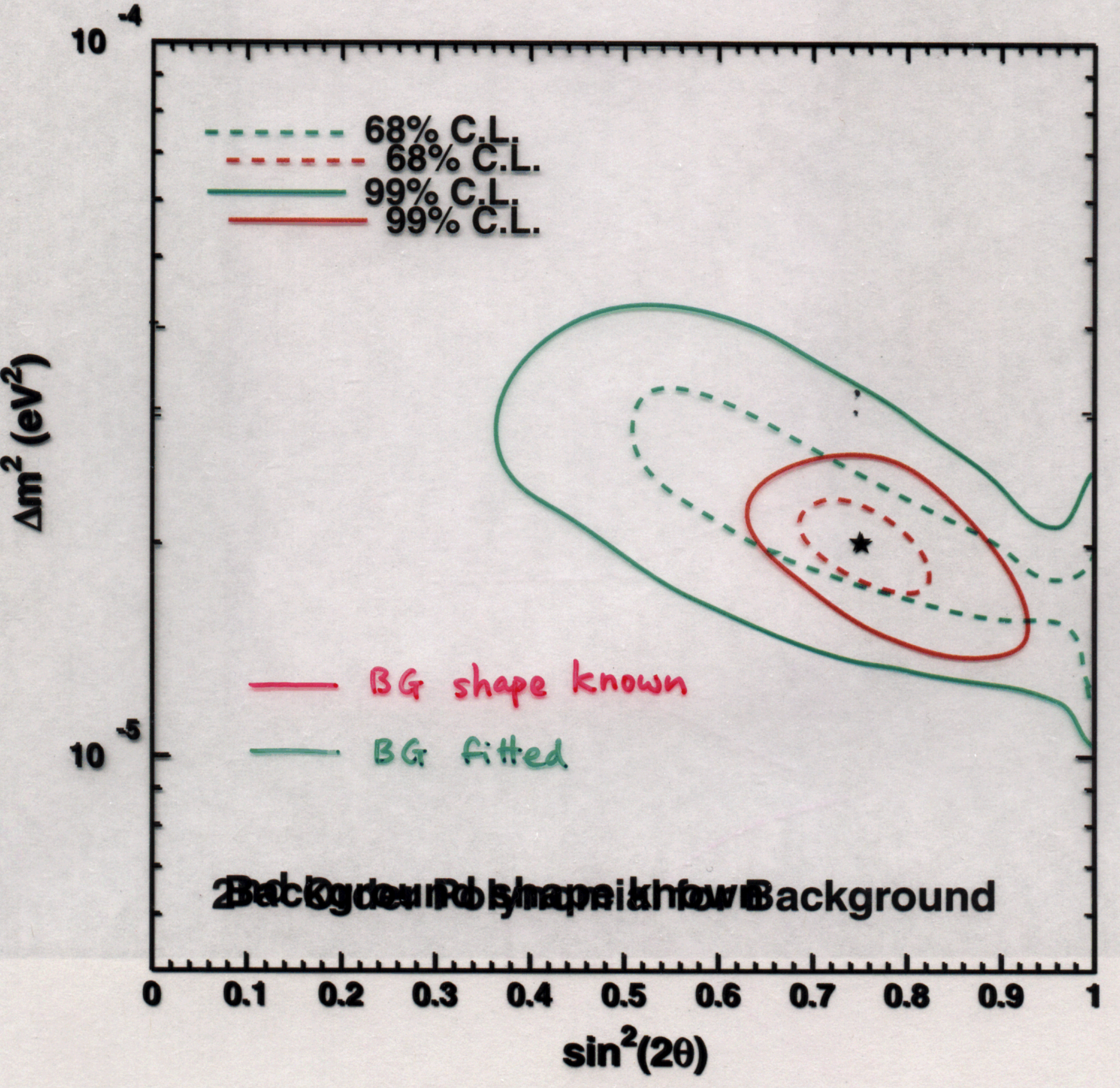
Figure 5.17: *ICANOE* 90% C.L. exclusion region in case no $\nu_\mu \to \nu_e$ are experimentally observed.

Map of Japanese Reactors



KamLAND reactor $\bar{\nu}_e$

$\Delta m^2 = 2 \times 10^{-5}\ eV^2$ (bottom end of LMA)



§ $\nu_\mu \longleftrightarrow \nu_e$

· large $\Delta m^2 \gtrsim 0.1\, eV^2$ (LSND)

Mini-BooNE safely covers LSND region

· $\Delta m^2 \sim 10^{-3} - 10^{-2}\, eV^2$

atmospheric ν

solar ν

need $U_{e3} \neq 0$

MINOS
ICANOE cover $\sin^2 2\theta \gtrsim 10^{-2}$
OPERA for $\Delta m^2 \sim (\Delta m^2)_{atm}$
JHF → SuperK

· $\Delta m^2 \gtrsim 10^{-5}\, eV^2$ (solar LMA)

KamLAND $\bar{\nu}_e$ disappearance

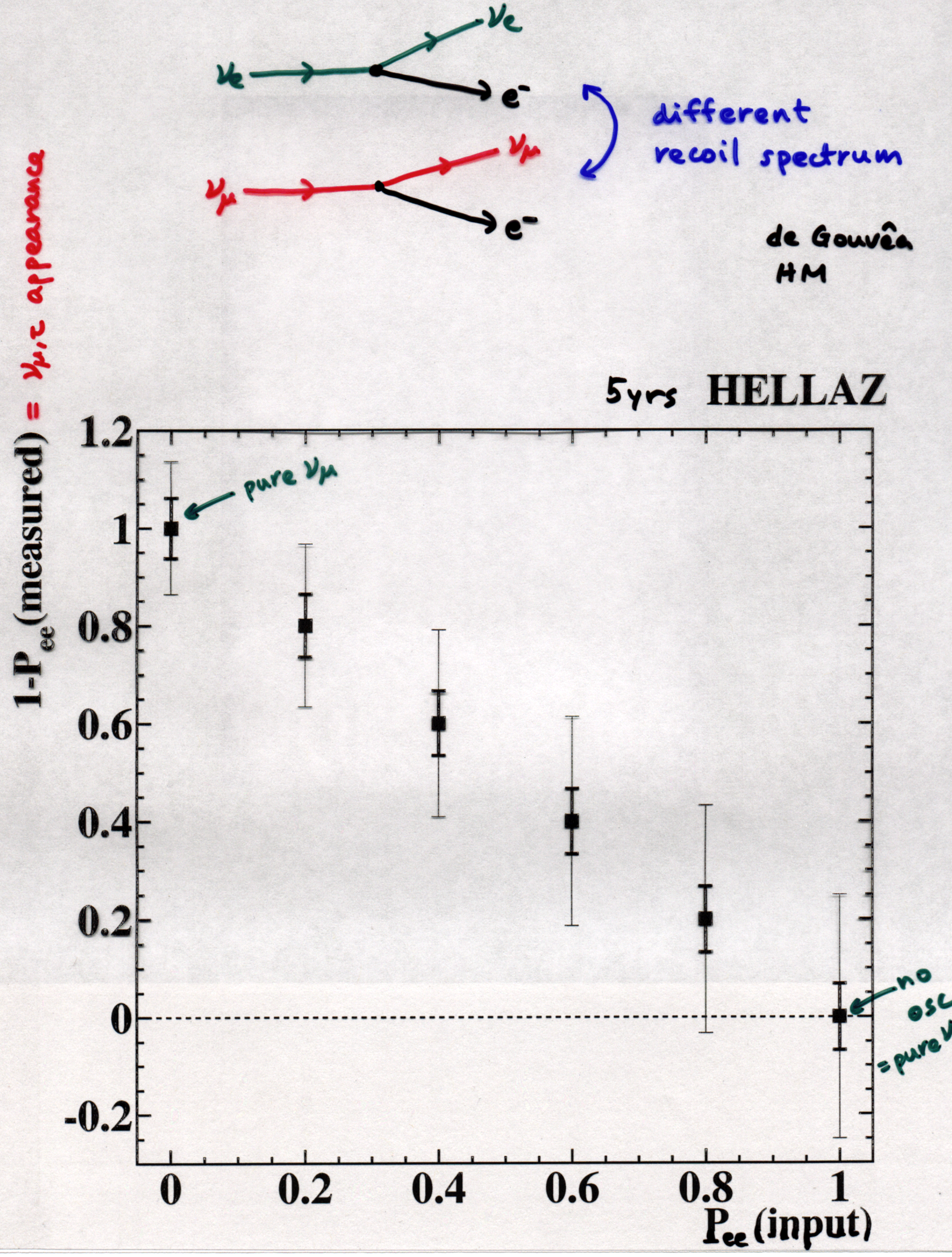
covers $\Delta m^2 \gtrsim 10^{-5}\, eV^2$, $\sin^2 2\theta \gtrsim 0.1$

· $\Delta m^2 \lesssim 10^{-5}\, eV^2$ (solar SMA, LOW, VAC)

SNO $\nu_e \to \nu_\mu$ or ν_τ NC/CC

Borexino/KamLAND day/night → LOW
seasonal → VAC

+HELLAZ recoil spectra ν_e vs $\nu_{\mu,\tau}$
(de Gouvêa, HM)



νe
νe
e⁻
νμ
νμ
e⁻
different recoil spectrum
de Gouvêa
HM
νμ,τ appearance = 1-Pee (measured)
5yrs HELLAZ
pure νμ
no osc =pure ν
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
Pee (input)

§ $\nu_e \longrightarrow \nu_\tau$

mostly solar ν expts

$\Rightarrow$ can't tell $\nu_e \to \nu_\tau$ from $\nu_e \to \nu_\mu$

MINOS, OPERA, ICANOE?

in principle possible à la CCFR/NuTeV

not much discussions

should be there with

$\Delta m^2 \simeq (\Delta m^2)_{atm}$ if $U_{e3} \neq 0$

§ 3ν params

Δm^2_{12} , Δm^2_{23}

three angles

one phase

assume atmos + solar data

$U_{\mu 3}$

$\Delta m^2_{23} \sim 3\times 10^{-3}\, eV^2$, $\sin^2 2\theta \sim 1$

well covered by planned expts

sign of Δm^2_{23} ?

$\Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23}$

MINOS, OPERA, ICANOE $\nu_\mu \to \nu_e$

$\sin^2 2\theta \gtrsim 10^{-3} - 10^{-2}$

U_{e3} how far down do we need to go?

$\Delta m^2_{12} \sim$? $\sin^2 2\theta \sim$?

solar expts $\to U_{e2}$

If signal simultaneous

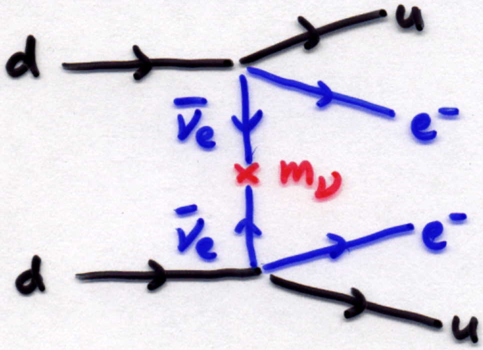
How do we disentangle them?

C̸P ?

§ Dirac vs Majorana

only idea available:

nuclear $0\nu\beta\beta$ decay



$\Delta L = 2$

possible only w/ Majorana

GENIUS

Xe TPC w/ laser

$\Rightarrow (m_\nu)_{ee} \lesssim 10^{-2}$ eV

reaching LMA region

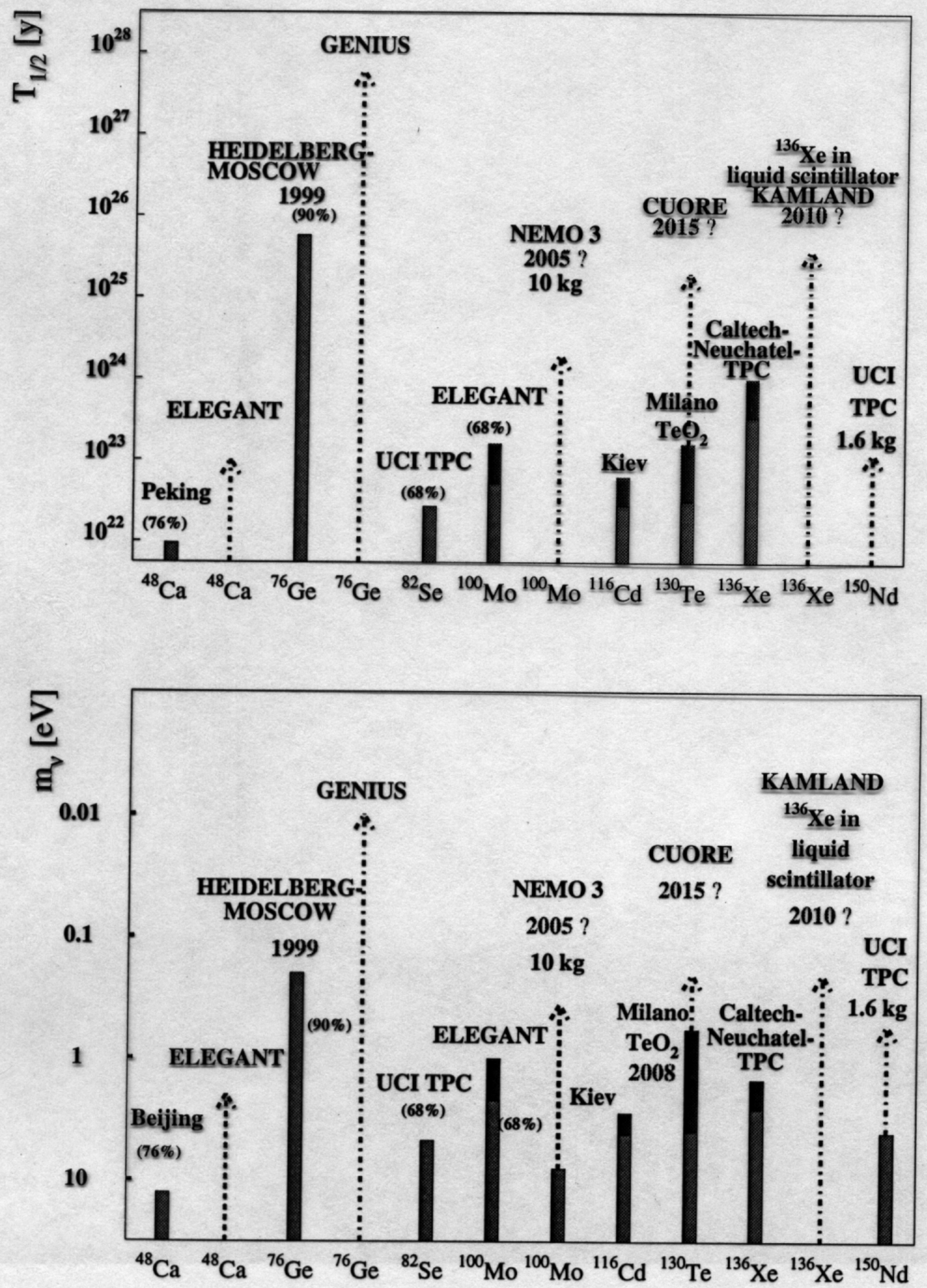


Figure 1.20: Present situation, 1999, and expectation for the near future and beyond, of the most promising $\beta\beta$-experiments concerning accessible half life (a) and neutrino mass limits (b). The light-shaded parts of the bars correspond to the present status, the dark parts of the bars to expectations for running experiments, dashed lines to experiments under construction and dash-dotted lines to proposed experiments.

§ Conclusion

Exciting time for ν physics

first evidence of physics beyond the SM

far reaching implications

$\Rightarrow$ even cosmological matter anti-matter asymmetry

Crucial data in Next 10 yrs

establish $\nu_\mu \to \nu_\tau$ w/ $\Delta m^2 \sim 3\times10^{-3}\ eV^2$

establish solar ν oscillation

select which sol'n

Need More

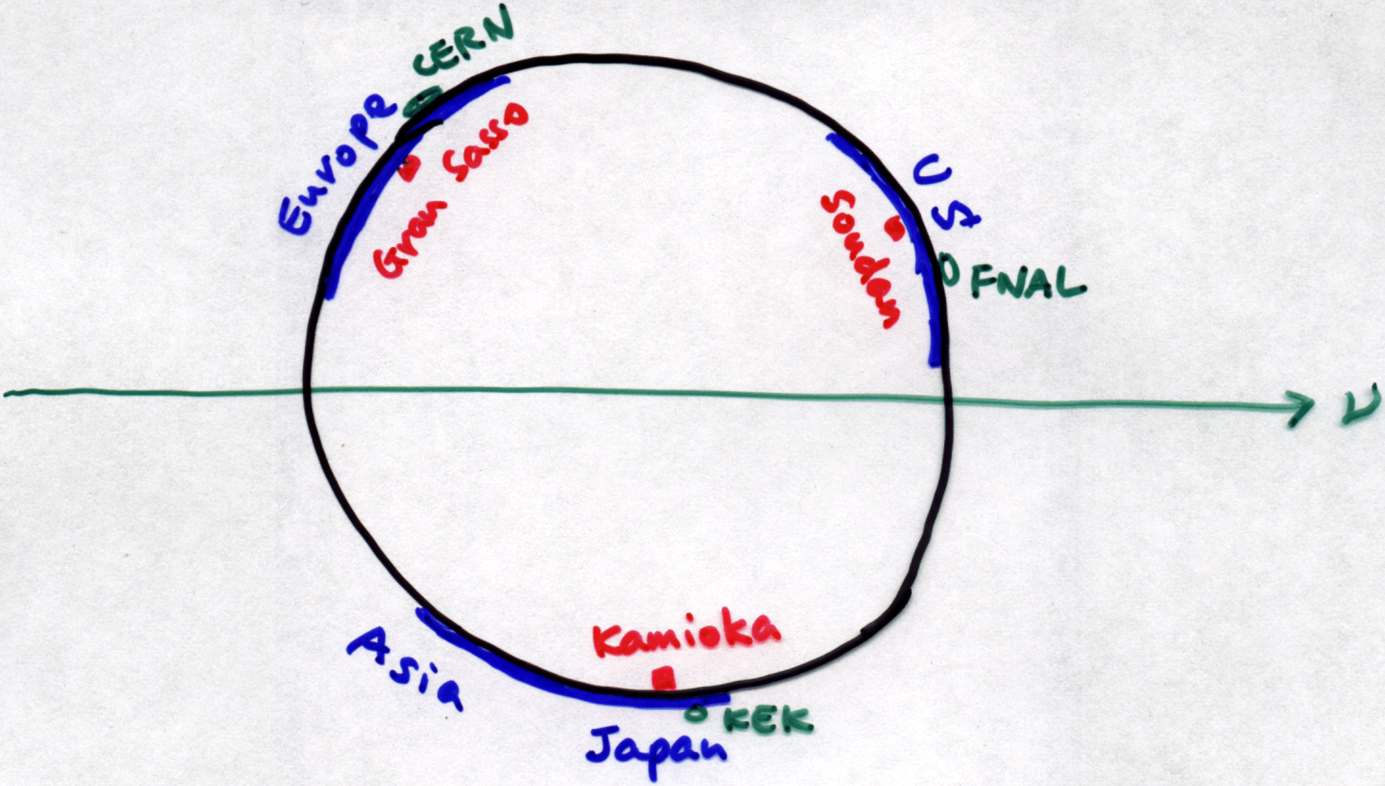
$U_{e3} \neq 0$ $\quad \nu_e \to \nu_\mu$ w/ $(\Delta m^2)_{atm}$ $\quad$ MINOS, ICANOE, OPERA, JHF→SK ?

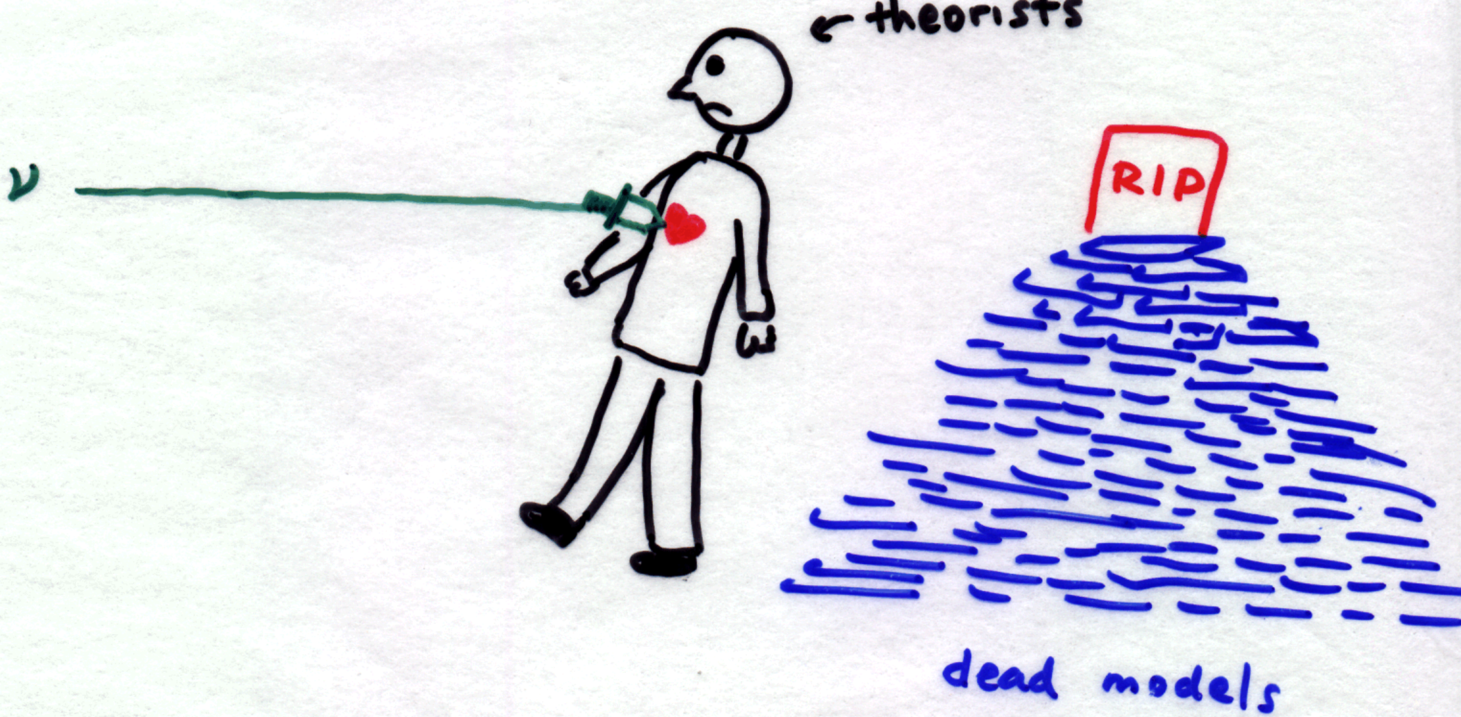
$\qquad\qquad \nu_\tau$ "

signs of Δm^2

CP̸

Dirac vs Majorana


CERN
Europe
Gran Sasso
US
Soudan
FNAL
ν
Asia
Kamioka
KEK
Japan



ν
theorists
RIP
dead models