Neutrino Physics

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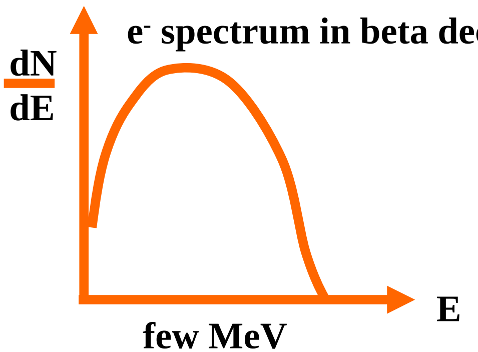
1. What are neutrinos and how do we know ?
2. The neutrino questions
3. Neutrino mass and neutrino oscillations
3. Future neutrino experiments
4. Conclusions

Consider $^{6}He^{++} \to {}^{6}Li^{++}\ \nu_e\ e^-$

Q=3.5078 MeV T/2 ≈ 0.8067 s

1930 Neutrinos: *the birth of the idea*

Pauli's letter of the 4th of December 1930



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 Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" 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 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 beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli

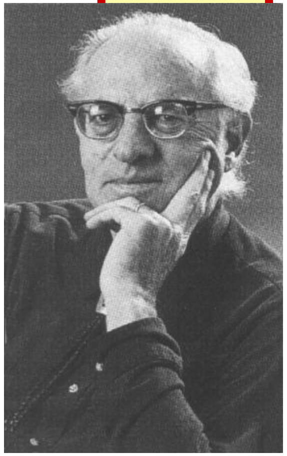
Wolfgang Pauli

Neutrinos: *direct detection*

Reines and Cowan

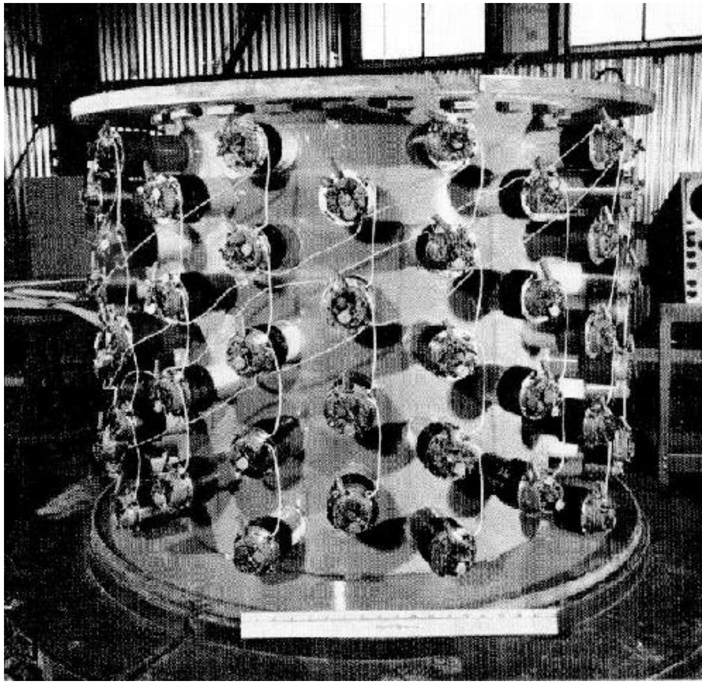
1953 -56

The target is made of about 400 liters of water mixed with cadmium chloride



The anti-neutrino coming from the nuclear reactor (beta-decays) interacts with a proton of the target, giving a positron and a neutron.

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



The positron annihilates with an electron of target and gives two simultaneous photons ($e^+ + e^- \rightarrow \gamma\gamma$) .
The neutron slows down before being eventually captured by a cadmium nucleus, that gives the emission of 2 photons about 15 microseconds after those of the positron.

All those 4 photons are detected and the 15 microseconds identify the "neutrino" interaction.

4-fold delayed coincidence

1956 Parity violation in Co beta decay: electron is left-handed (C.S. Wu et al)

1957 Neutrino helicity measurement (M. Goldhaber et al):

neutrinos have <u>negative helicity</u>
(If massless this is the same as left-handed)

γ polarization is detected by absorbtion in (reversibly)magnetized iron

$$e^- + \mathrm{Gd} \rightarrow \nu_\mathrm{e} + \mathrm{Sm}^* \\ \downarrow \\ \mathrm{Sm} + \gamma$$

1959 Ray Davis established that
(anti) neutrinos from reactors do not interact with chlorine to produce argon

reactor : n $\rightarrow$ p e^- ν_e or $\bar{\nu}_e$?

these ν_e do not do $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$
they are anti-neutrinos

Neutrinos
the properties

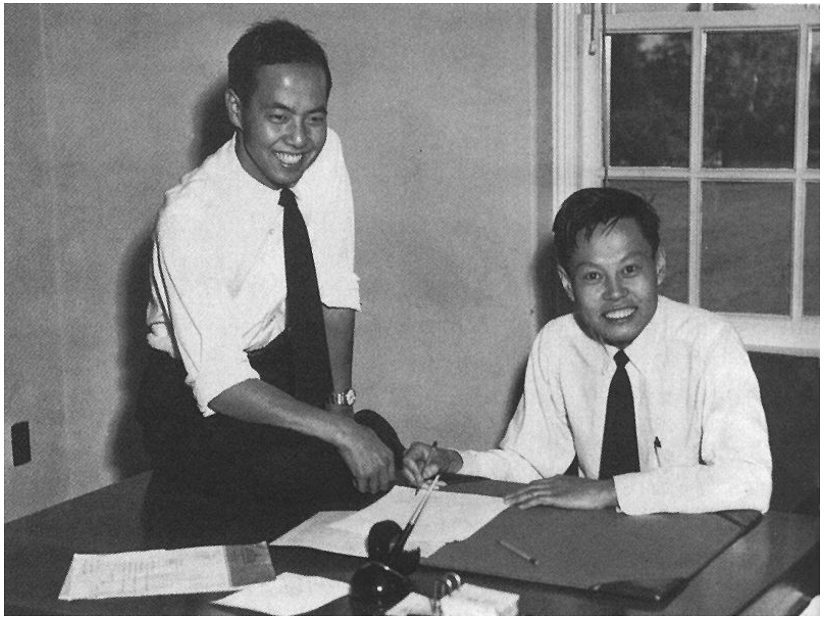
1960

In 1960, Lee and Yang realized that if a reaction like

$$\mu^- \rightarrow e^- + \gamma$$

is not observed, this is because two types of neutrinos exist ν_μ and ν_e

otherwise $\mu^- \rightarrow e^- + \nu + \bar{\nu}$ has the same Quantum numbers as $\mu^- \rightarrow e^- + \gamma$



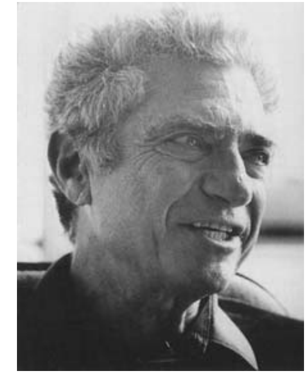
Lee and Yang

Two Neutrinos

1962

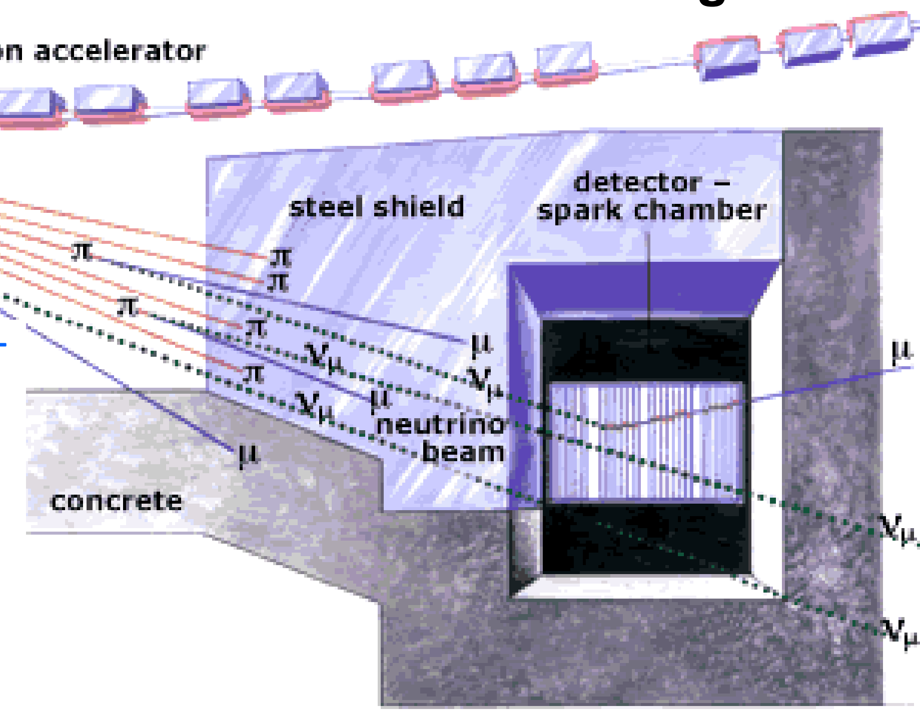
Schwartz

Lederman

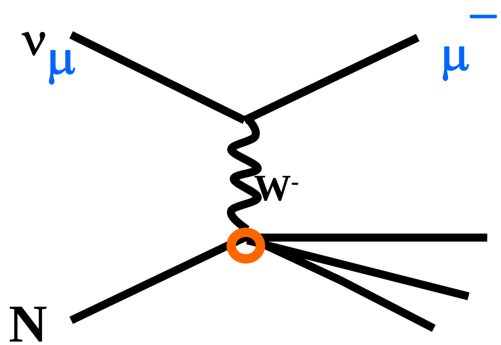


Steinberger

AGS Proton Beam



Neutrinos from π-decay only produce muons (not electrons)



hadrons

when they interact in matter

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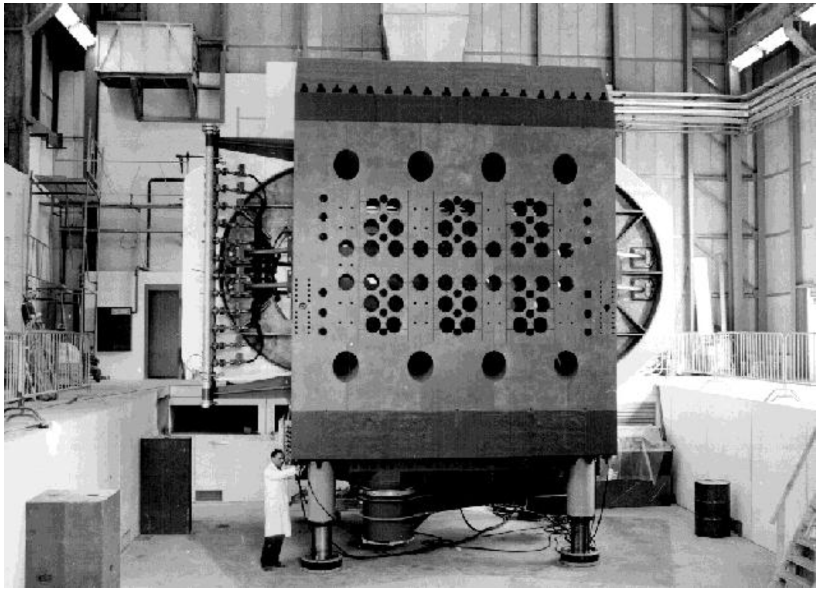
Neutrinos

the weak neutral current



Gargamelle Bubble Chamber CERN

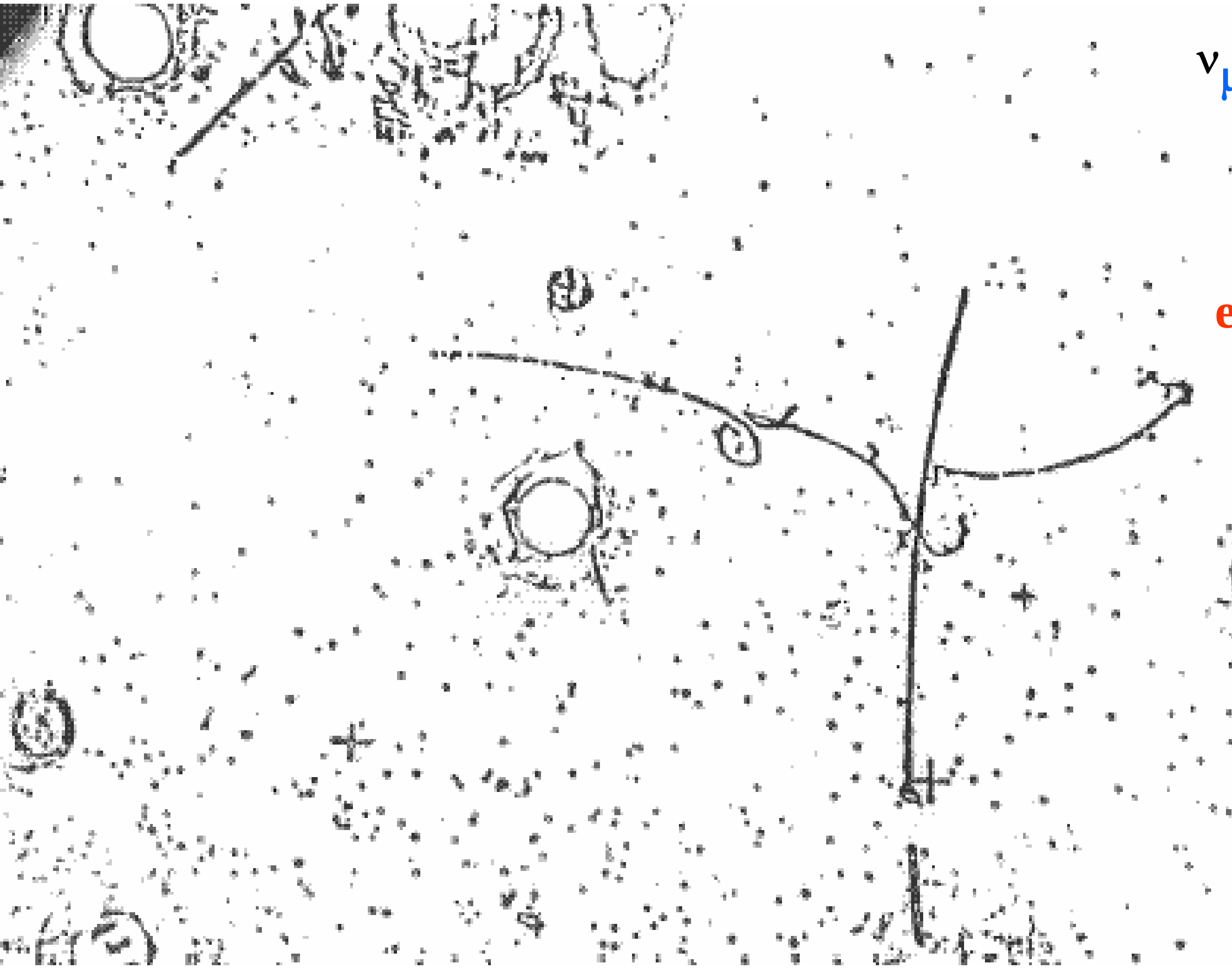
Discovery of weak neutral current

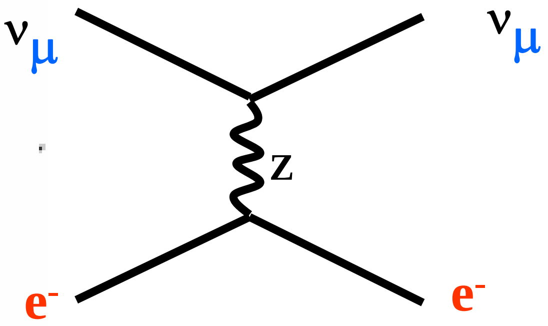
$\nu_\mu + e \rightarrow \nu_\mu + e$

$\nu_\mu + N \rightarrow \nu_\mu + X$ (no muon)

previous searches for neutral currents had been performed in particle decays (e.g. $K^0 \to \mu\mu$) leading to extremely stringent limits (10^{-7} or so)

early neutrino experiments had set their trigger on final state (charged) lepton!





elastic scattering of neutrino off electron in the liquid

1973 Gargamelle

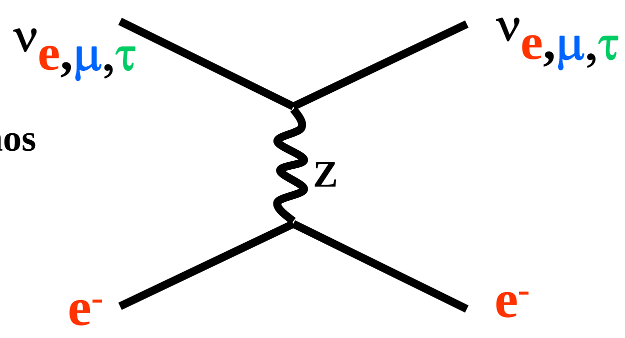
experimental birth of the Standard model

The Standard Model: 3 families of spin 1/2 quark and leptons interacting with spin 1 vector bosons (γ, W&Z, gluons)

charged leptons	e	μ	τ
	mc^2=0.0005 GeV	0.106 GeV	1,77 GeV
neutral leptons = neutrinos	ν_e	ν_μ	ν_τ
	mc^2 ?=? <1 eV	<1 eV	<1 eV
quarks	d	strange	beauty
	mc^2=0.005 GeV	0.200 GeV	5 GeV
	u	charm	top
	mc^2=0.003 GeV	1.5 GeV	mc^2=175 GeV
	First family	Seconde family	Third family

Neutrino cross-sections

at all energies



NC reactions (Z exchange) are possible for all neutrinos

CC reactions

very low energies(E<~50 MeV): $\nu_e + {}_A^Z N \to e^- + {}_A^{Z+1}N$ **inverse beta decay of nuclei**

medium energy (50<E<700 MeV) **quasi elastic reaction on protons or neutrons**

$\nu_e + n \to e^- + p$

or

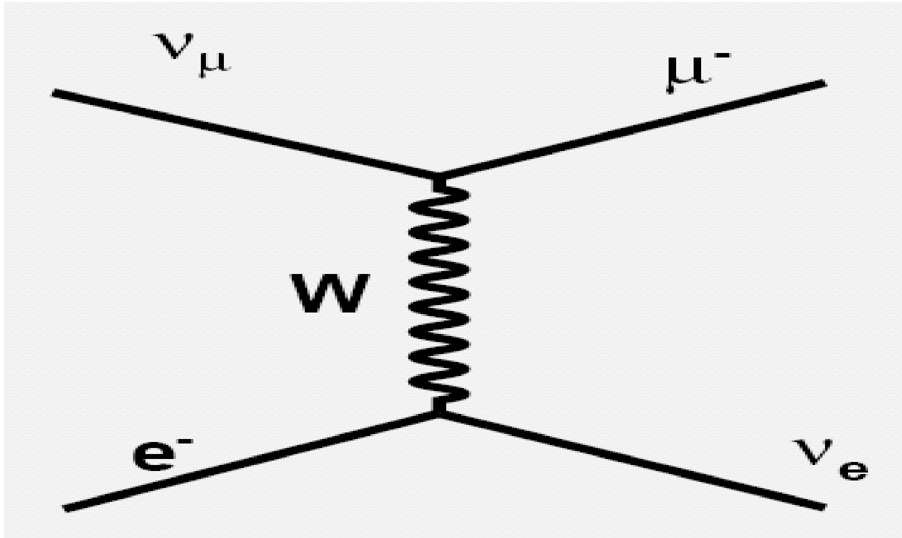
$\bar{\nu}_e + p \to e^+ + n$

Threshold for muon reaction 110 MeV

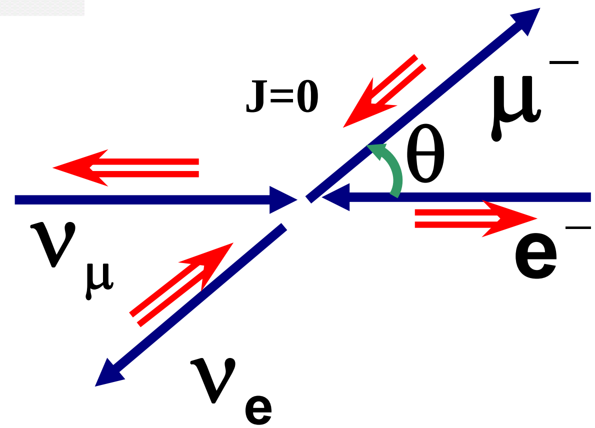
Threshold for tau reaction 3.5 GeV

above 700 MeV pion production becomes abundant and
above a few GeV deep inelastic (diffusion on quark folloed by fragmentation) dominates

Quasielastic scattering off electrons ("Leptons and quarks" L.B.Okun)



$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



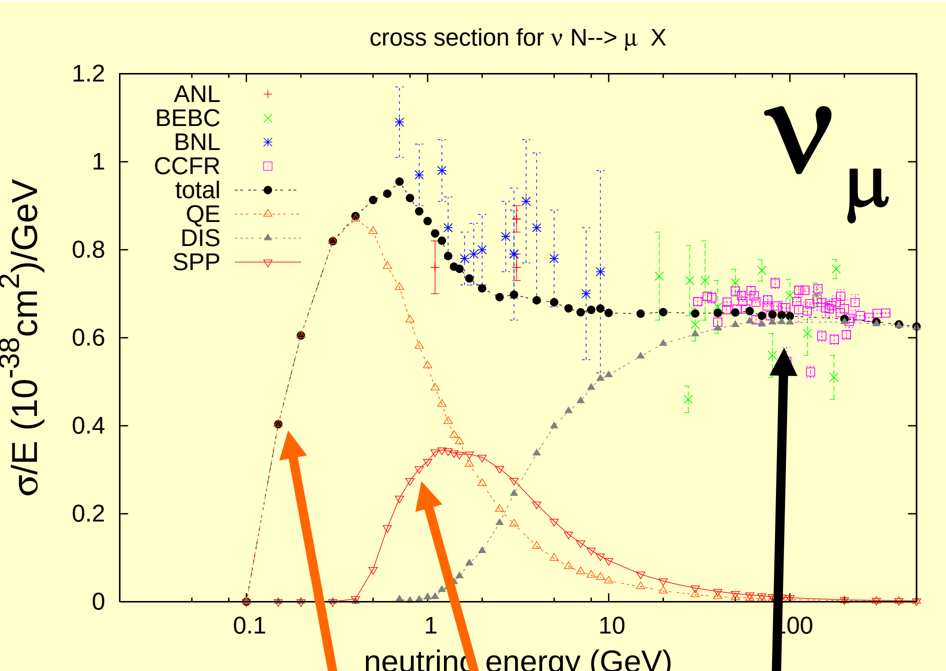
J=0 ==> Cross section is isotropic in c.m. system

$$\sigma = \frac{G_F^2}{\pi} \frac{\left(s - m_\mu^2\right)^2}{s}$$

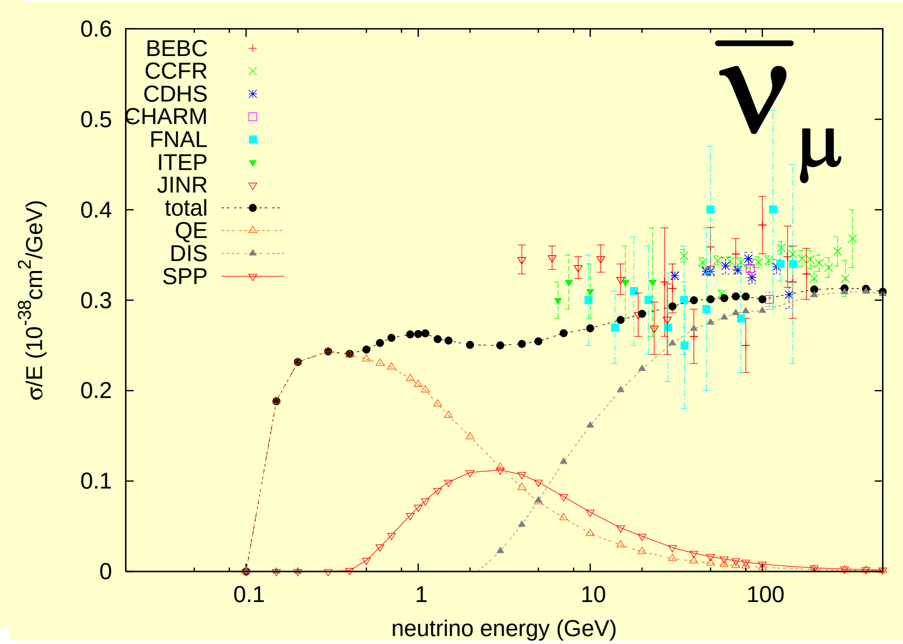
high energy limit :
(neglect muon mass)

$$\sigma = \frac{G_F^2}{\pi} s = \frac{2 G_F^2}{\pi} m_e E_\nu$$

Total neutrino – nucleon CC cross sections



neutrino



anti-neutrino

We distinguish:

- quasi-elastic
- single pion production („RES region”, e.g. W<=2 GeV)
- more inelastic („DIS region”)

Below a few hundred MeV neutrino energies: quasi-elastic region.

Plots from Wrocław MC generator

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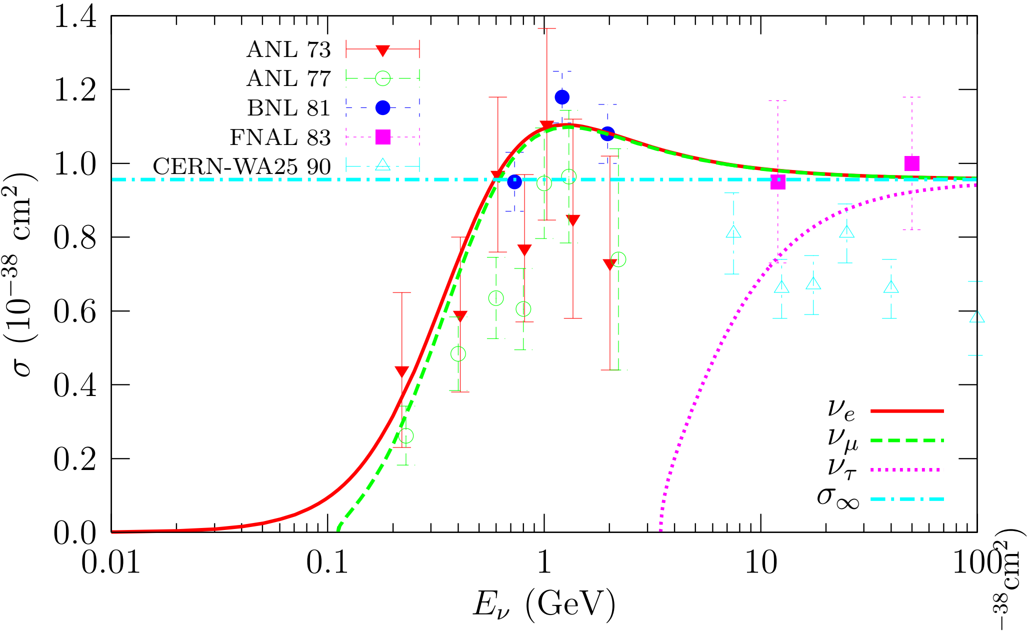
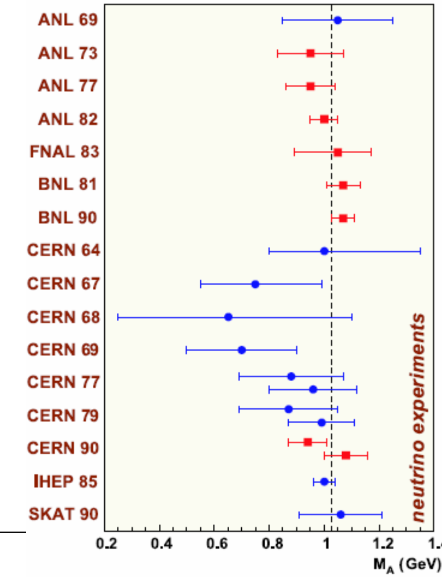
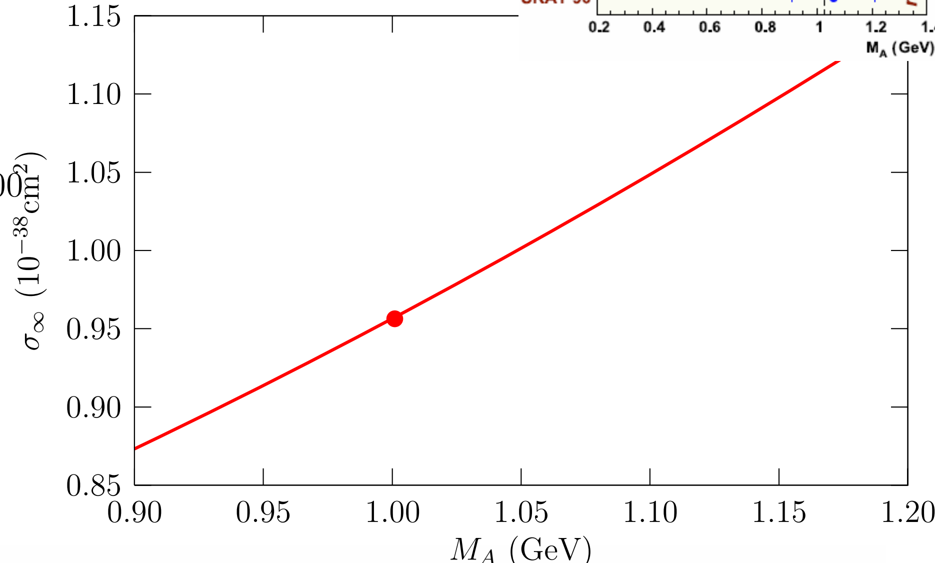
Quasi-elastic reaction



(from Naumov)





Huge experimental uncertainty

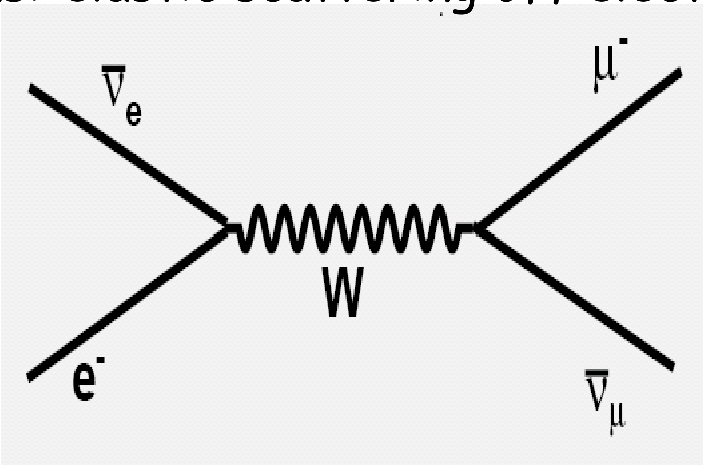
The limiting value depends on the axial mass

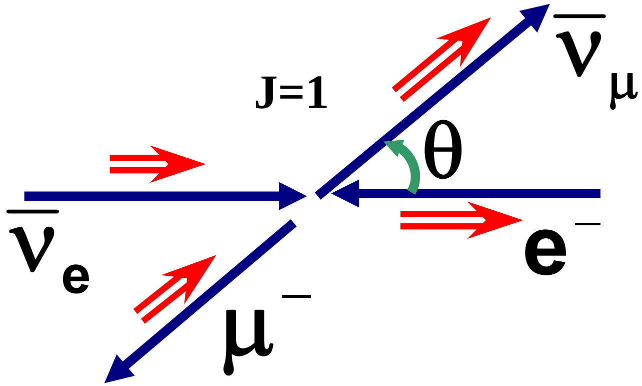
Under assumption of dipole vector form-factors:

$$\sigma_\infty = \frac{G_F^2 \cos^2\theta_C}{6\pi}\Big[M_V^2 + g_A^2 M_A^2 + \frac{2\xi(\xi+2)M_V^4}{(4M^2-M_V^2)^2}(M^2 - M_V^2) + \frac{3\xi(\xi+2)M_V^8}{(4M^2-M_V^2)^3}\Big(\frac{4M^2}{4M^2-M_V^2}\ln\frac{4M^2}{M_V^2} - 1\Big)\Big].$$

(A. Ankowski)

Quasi-elastic scattering off electrons





$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

Differential cross section in c.m. system

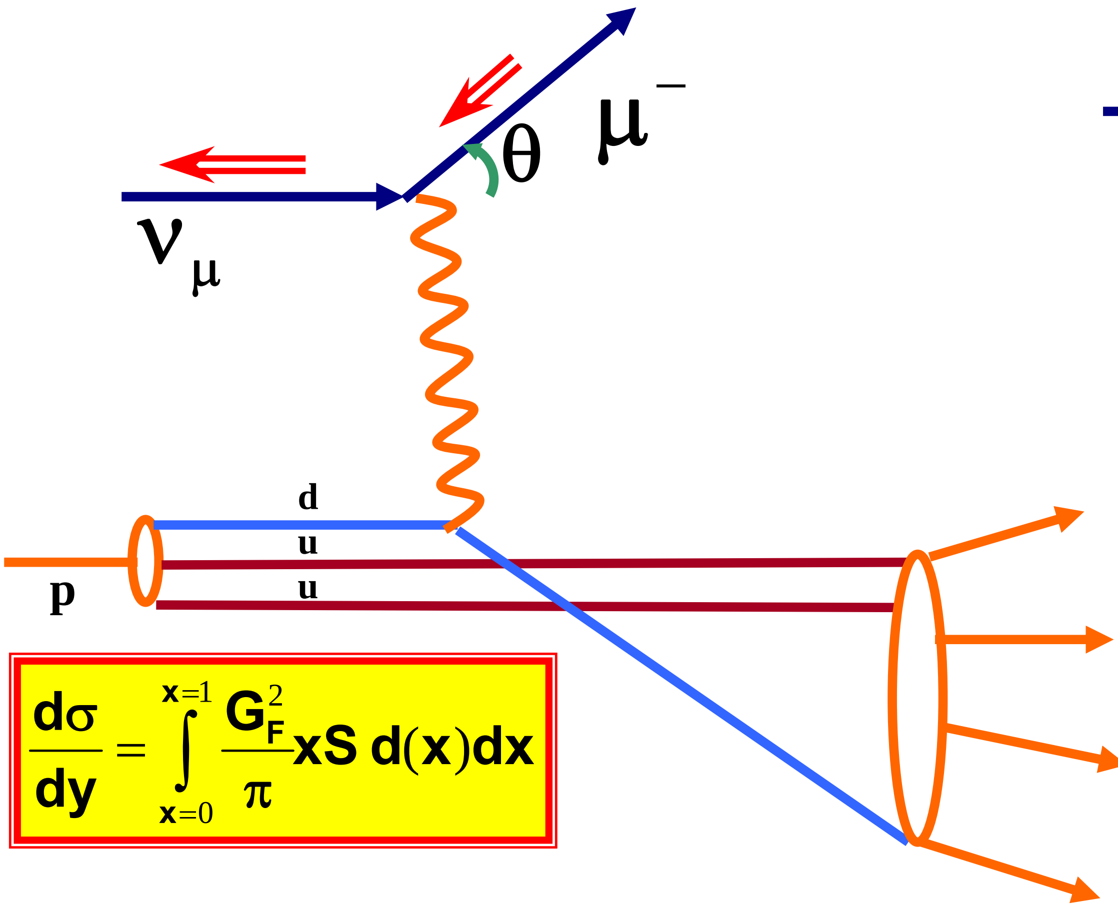
$$\frac{d\sigma}{d\cos\theta} = \frac{2G_F^2}{\pi}\frac{\left(s-m_\mu^2\right)^2 E_e E_\mu}{s^2}\left(1+\frac{s-m_e^2}{s+m_e^2}\cos\theta\right)\left(1+\frac{s-m_\mu^2}{s+m_\mu^2}\cos\theta\right)$$

Total cross section

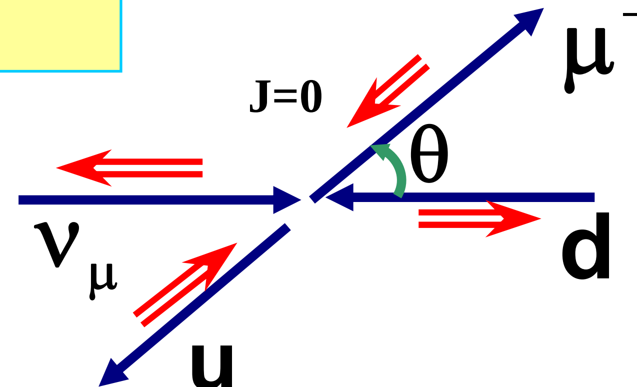
$$\sigma = \frac{2G_F^2}{\pi}\frac{\left(s-m_\mu^2\right)^2 (E_e E_\mu + 1/3 E_{\nu 1} E_{\nu 2})}{s^2}$$

At high energies interactions on quarks dominate:
DIS regime: neutrinos on (valence) quarks

x= fraction of longitudinal momentum carried by struck quark
y= (1-cosθ)/2
for J=0 isotropic distribution
d(x)= probability density of quark d with mom. fraction x
<u>neglect all masses!</u>



$$\frac{d\sigma}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\, d(x)dx$$



$s = xS = 2mE_\nu x$

$$\frac{d\sigma(x)}{dy} = \frac{G_F^2}{\pi} xS$$

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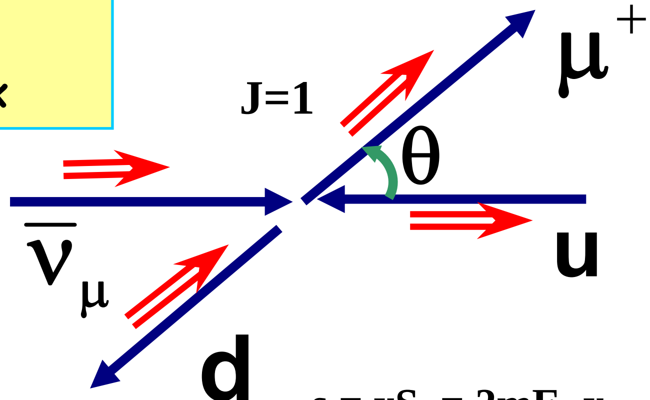
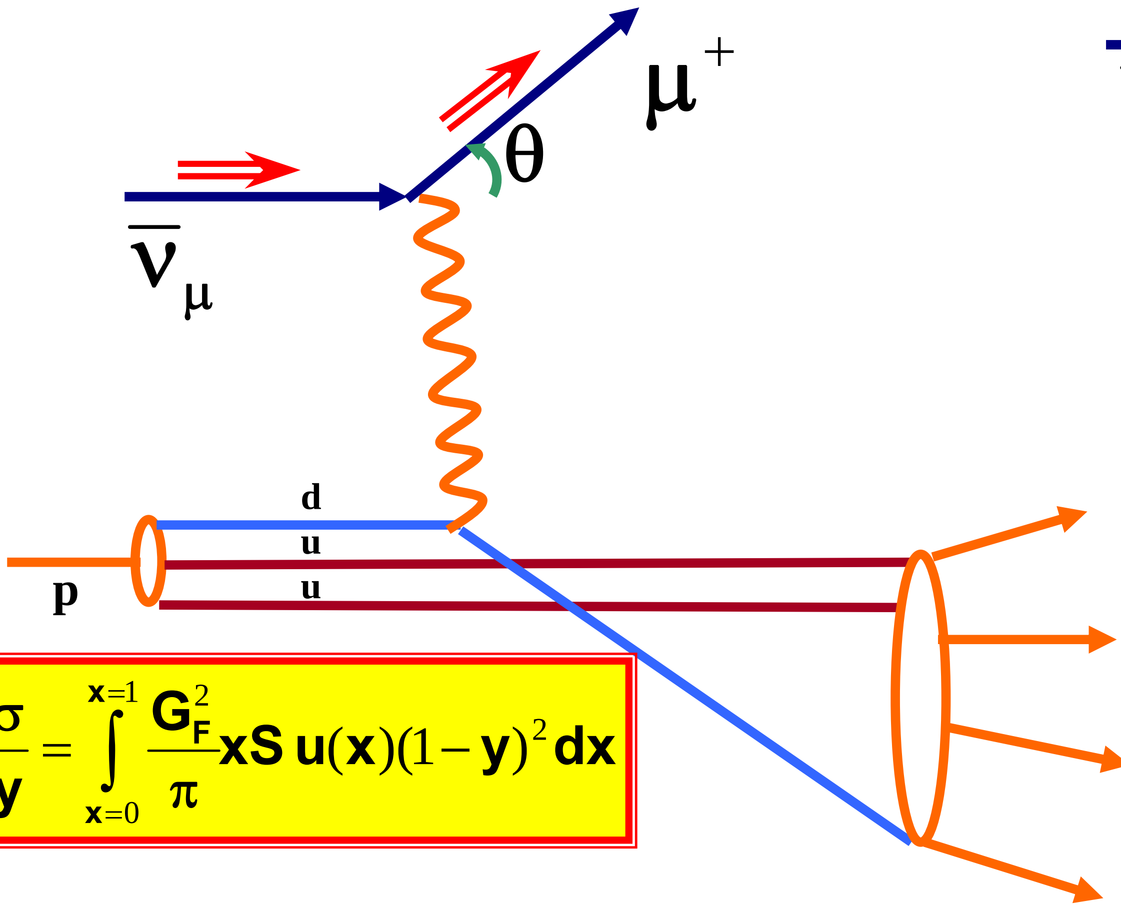
At high energies interactions on quarks dominate: DIS regime: anti-neutrinos on (valence) quarks

x= fraction of longitudinal momentum carried by struck quark
y= $(1-\cos\theta)/2$
for J=1 distribution prop. to $(1-y)^2$ (forward favored)
u(x)= probability density of quark u with mom. fraction x



$s = xS = 2mE_\nu x$

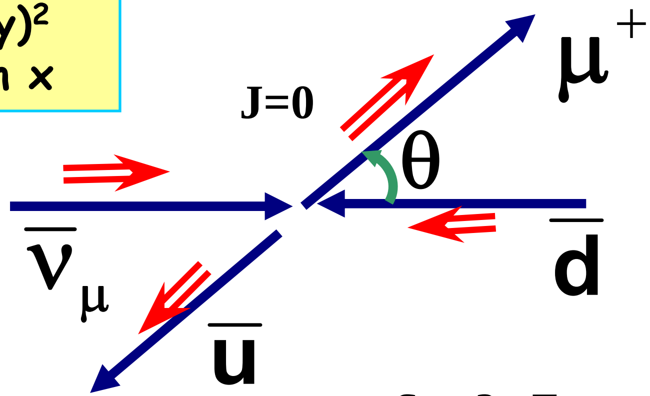
$$\frac{d\sigma(x)}{dy} = \frac{G_F^2}{\pi} xS\,(1-y)^2$$



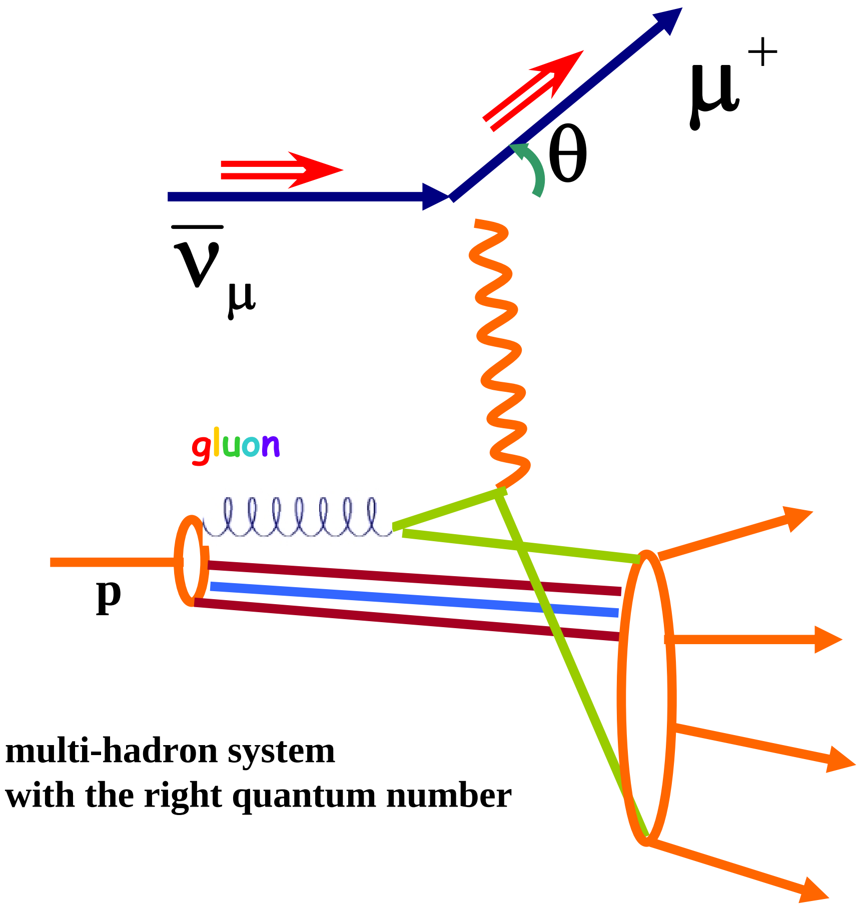
$$\frac{d\sigma}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,u(x)(1-y)^2 dx$$

there are also (gluons) and anti-quarks at low x (sea)
(anti)neutrinos on sea-(anti)quarks

for J=0 (neutrino+quarks or antineutrino+antiquarks) isotropic
for J=1 (neutrino+antiquarks or antineutrino+quarks) $(1-y)^2$
$q_i(x)$, = probability density of quark u with mom. fraction x



$s = xS = 2mE_\nu x$



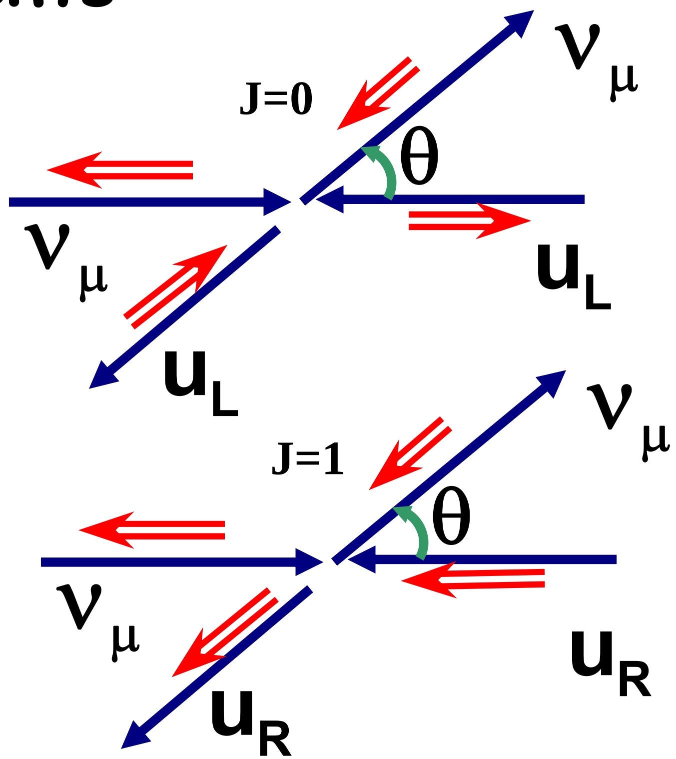
$$\frac{d\sigma^{\nu}}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,(\bar{q}(x)(1-y)^2 + q(x))dx$$

$q = d, s, (b)$ and $\bar{q} = \bar{u}, \bar{c}, (\bar{t})$

$$\frac{d\sigma^{\bar{\nu}}}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,(q(x)(1-y)^2 + \bar{q}(x))dx$$

$q = u, c, (t)$ and $\bar{q} = \bar{d}, \bar{s}, (\bar{b})$

Neutral Currents



electroweak theory

CC: $g = e/\sin\theta_W$
NC: $g' = e/\sin\theta_W \cos\theta_W$

NC fermion coupling = $g'(I^3 - Q\sin\theta_W)$

I^3= weak isospin =
+1/2 for Left handed neutrinos & u-quarks,
-1/2 for Left handed electrons muons taus, d-quarks
0 for right handed leptons and quarks

Q= electric charge
θ_W= weak mixing angle.

$g_L^u = 1/2 - 2/3 \sin\theta_W$

$g_R^u = \quad - 2/3 \sin\theta_W$

$$\frac{d\sigma(x)}{dy} = \frac{G_F^2 \rho^2}{\pi} x S\left({g_L^u}^2 + {g_R^u}^2 (1-y)^2\right)$$

(sum over quarks and antiquarks as appropriate)

the parameter ρ can be calculated by remembering that for these cross sections we have the W (resp Z) propagator, and that the CC/NC coupling is in the ratio $\cos\theta_W$
thus $\rho^2 = m_W^4 / (m_Z^4 \cos\theta_W) = 1$ at tree level in the SM, but is affected by radiative corrections sensitive to e.g. m_{top}

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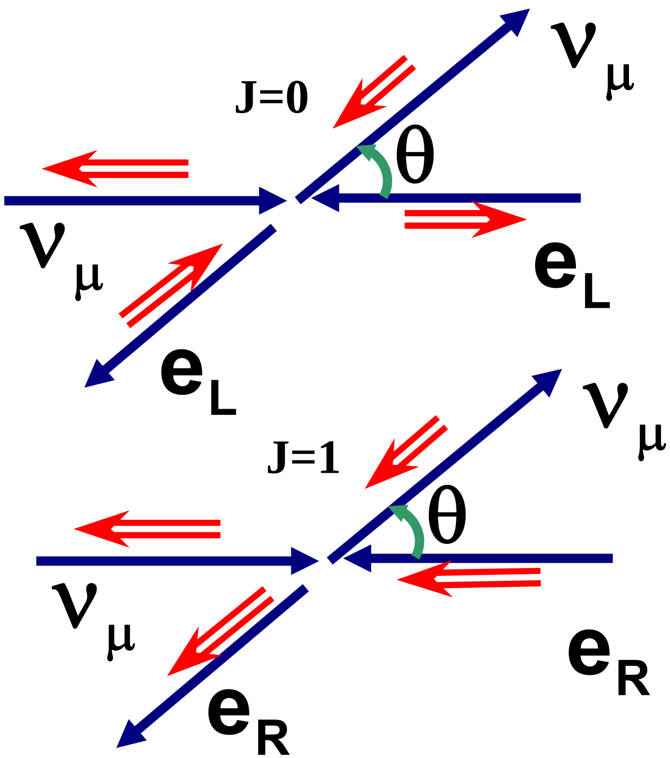
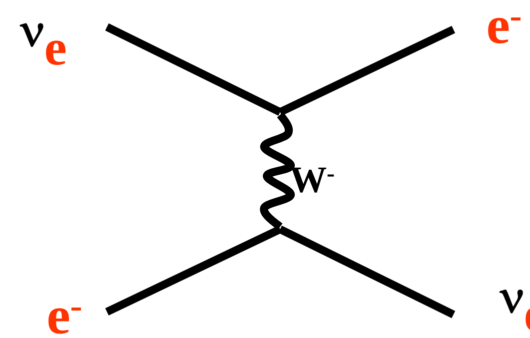
scattering of ν_μ on electrons:
(invert the role of R and L for antineutrino scattering)



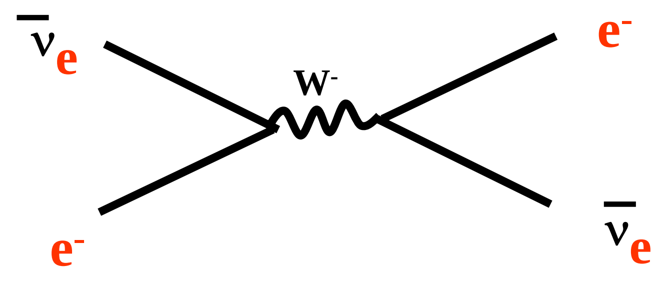
$$\frac{d\sigma}{dy} = \frac{G_F^2 \rho^2}{\pi} S\left(g_L^{e\,2} + g_R^{e\,2}(1-y)^2\right)$$

$$\sigma = \frac{G_F^2 \rho^2}{\pi} S\left(g_L^{e\,2} + 1/3\, g_R^{e\,2}\right)$$

the scattering of electron neutrinos off electrons is a little more complicated (W exchange diagram)



only electron neutrinos



only electron anti- neutrinos

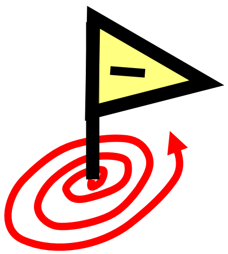
some remarkable symmetries:

each quark comes in 3 colors

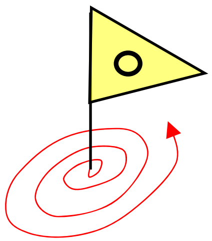
sum of charges is

$$-1 + 0 + 3 \times (2/3 \ - 1/3) = 0$$

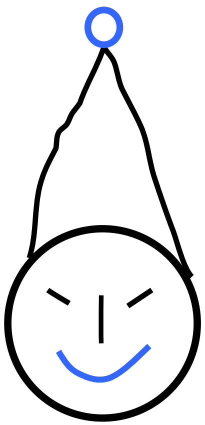
this turns out to be a necessary condition
for the stability of
higher order radiative corrections



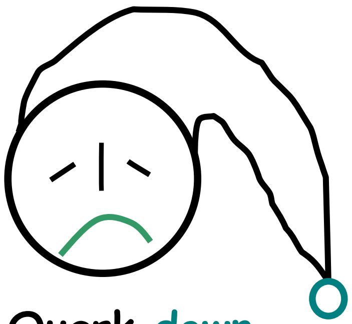
Electron
charge -1



Neutrino
charge 0



Quark up
charge 2/3

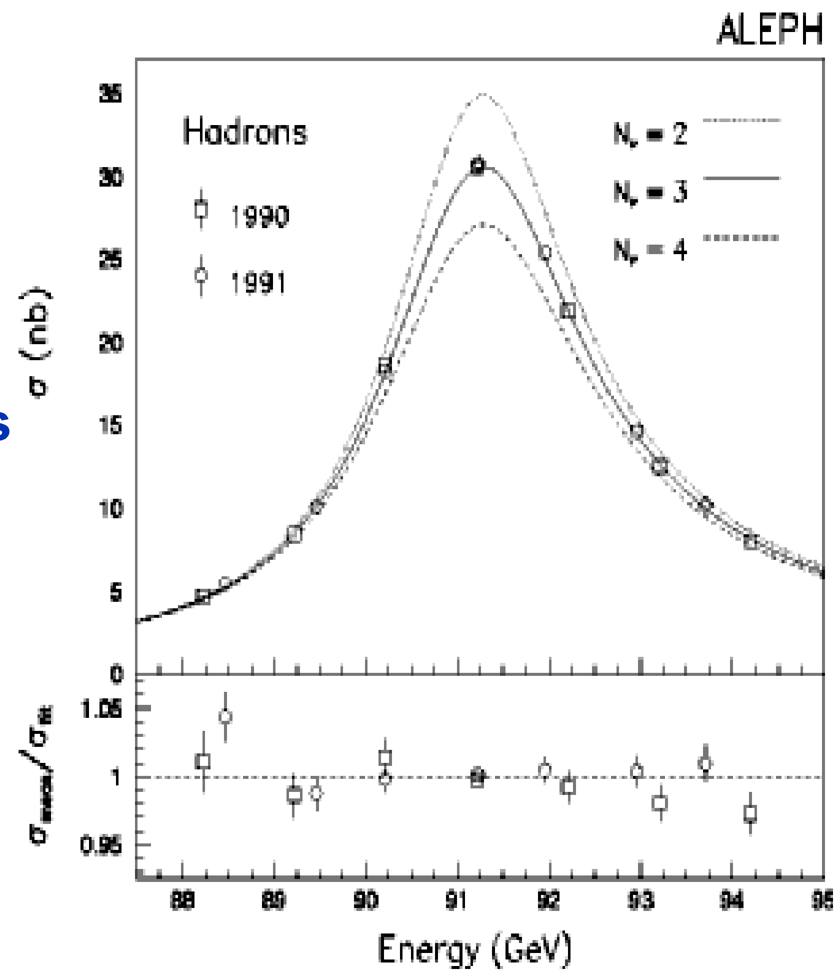


Quark down
charge -1/3

1989 The Number of Neutrinos

collider experiments: LEP

- **N_ν determined from the visible Z cross-section at the peak (most of which are hadrons):**
the more decays are invisible the fewer are visible:
hadron cross section decreases by 13% for one more family of neutrinos



in 2001: N_ν = 2.984 ±0.008

Neutrino mysteries

1. Neutrinos have mass (we know this from oscillations, see later…)

2. neutrinos are massless or nearly so
   mass limit of 2.2eV/c^2 from beta decay
   mass limit of <~ 1 eV/c^2 from large scale structure of the universe

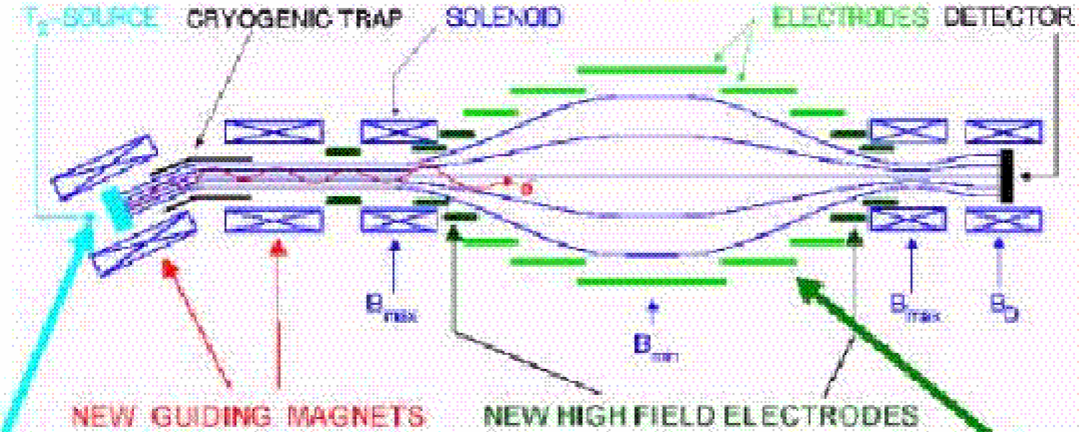
3. neutrinos appear in a single helicity (or chirality?)
   but of course weak interaction only couples to left-handed particles
   and neutrinos have no other known interaction…
   So… even if right handed neutrinos existed,
   they would neither be produced nor be detected!

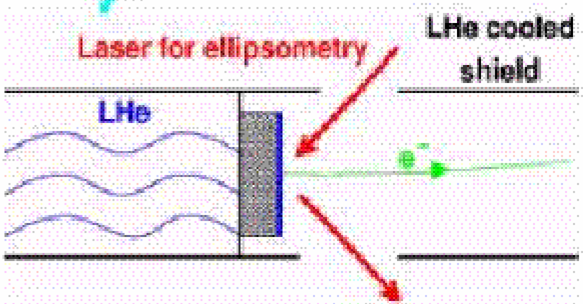
4. if they are not massless why are the masses so different from those of other quark and leptons?

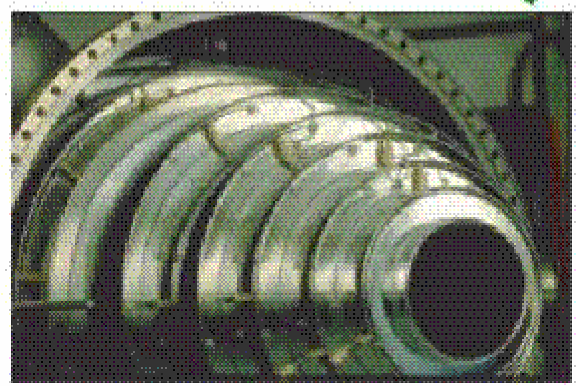
5. 3 families are necessary for CP violation, but why only 3 families?

……

Mainz Neutrino Mass Experiment since 1997







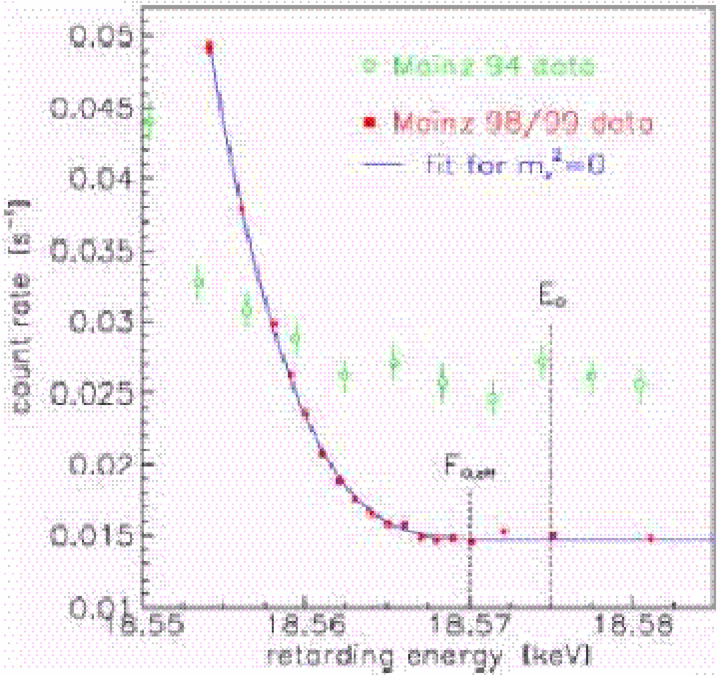
Mainz
ν group
2001:

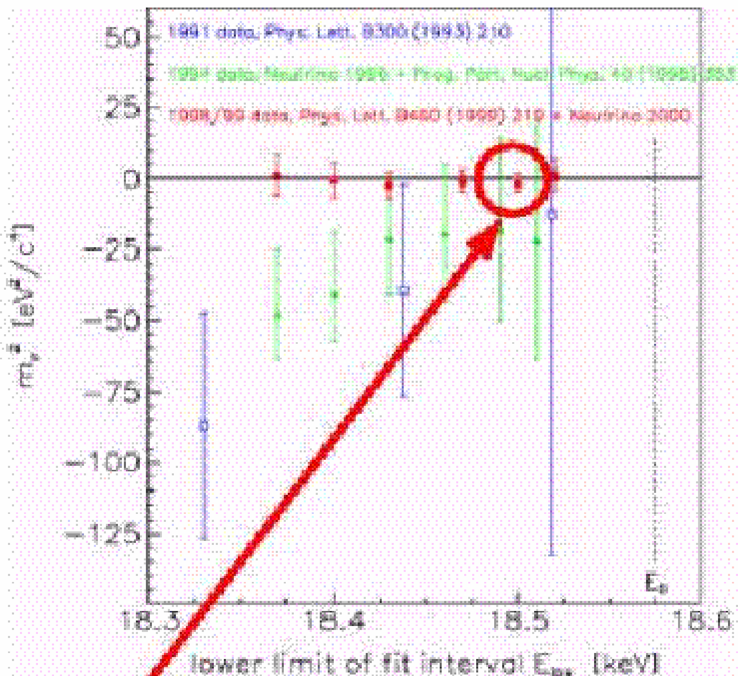
J. Bonn
B. Bornschein*
L. Bornschein
B. Flatt
Ch. Kraus
B. Müller
E.W. Otten
J.P. Schall
Th. Thümmler**
Ch. Weinheimer**

* → FZ Karlsruhe
** → Univ. Bonn

- T_2 Film at 1.86 K
- quench-condensed on graphite (HOPG)
- 45 nm thick (≈130ML), area 2cm²
- Thickness determination by ellipsometry

Mainz data of 1998,1999





$m^2(\nu) = -1.6 \pm 2.5 \pm 2.1\ eV^2$ (χ^2/d.o.f. = 125/121)

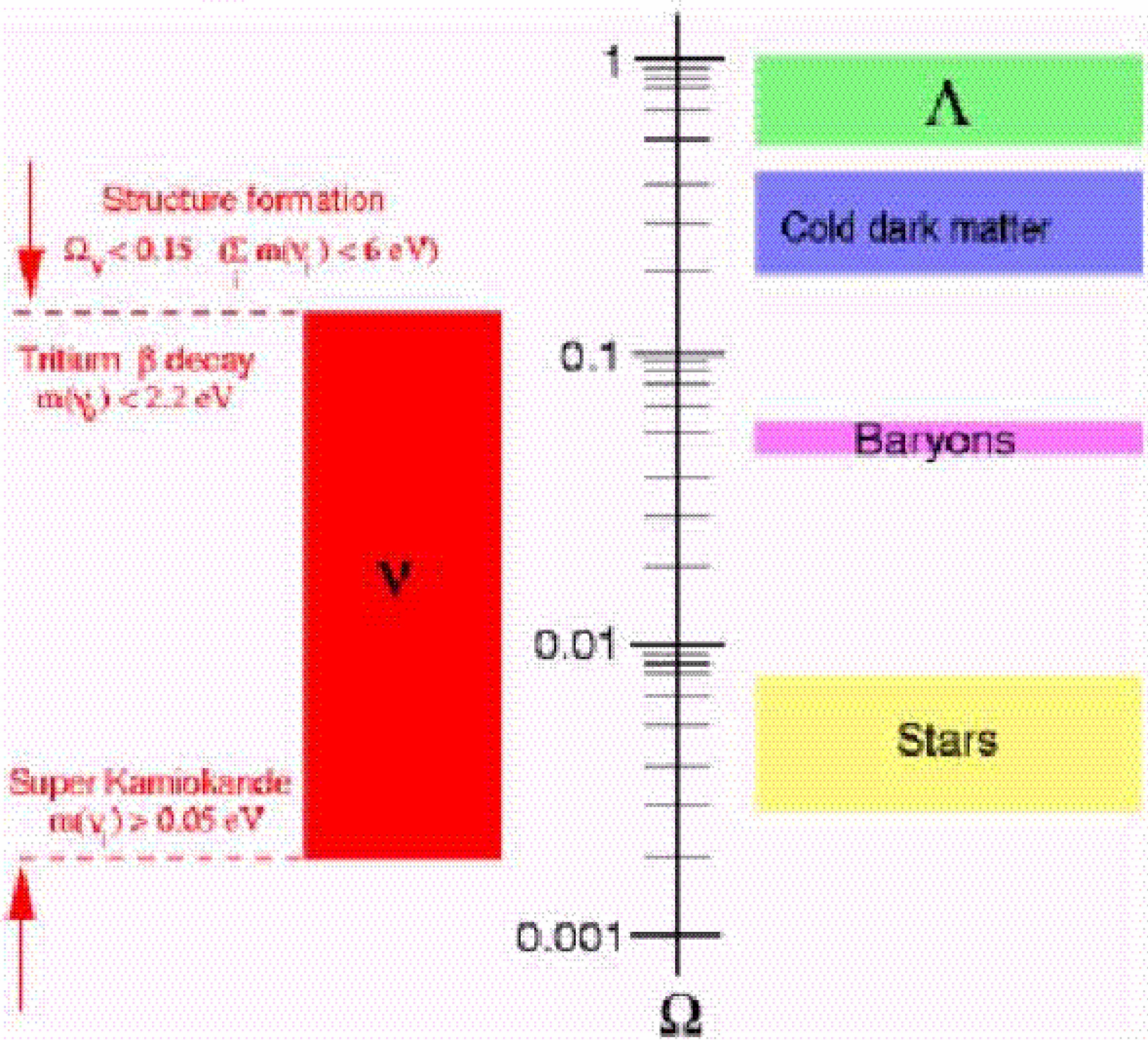
$\Rightarrow$ $m(\nu) < 2.2$ eV (95% C.L.)

(J. Bonn et al., Nucl. Phys. B (Proc. Suppl.) 91 (2001) 273)

KATRIN experiment programmed to begin in 2008. Aim is to be sensitive to $m_{\nu\ e} < 0.2$ eV

What IS the neutrino mass?????

Cosmology and neutrino mass



There is a long way to go to match direct measurements of neutrino masses with oscillation results and cosmological constraints

Direct exploration of the Big Bang -- Cosmology

measurements of the large scale structure of the universe
using a variety of techniques

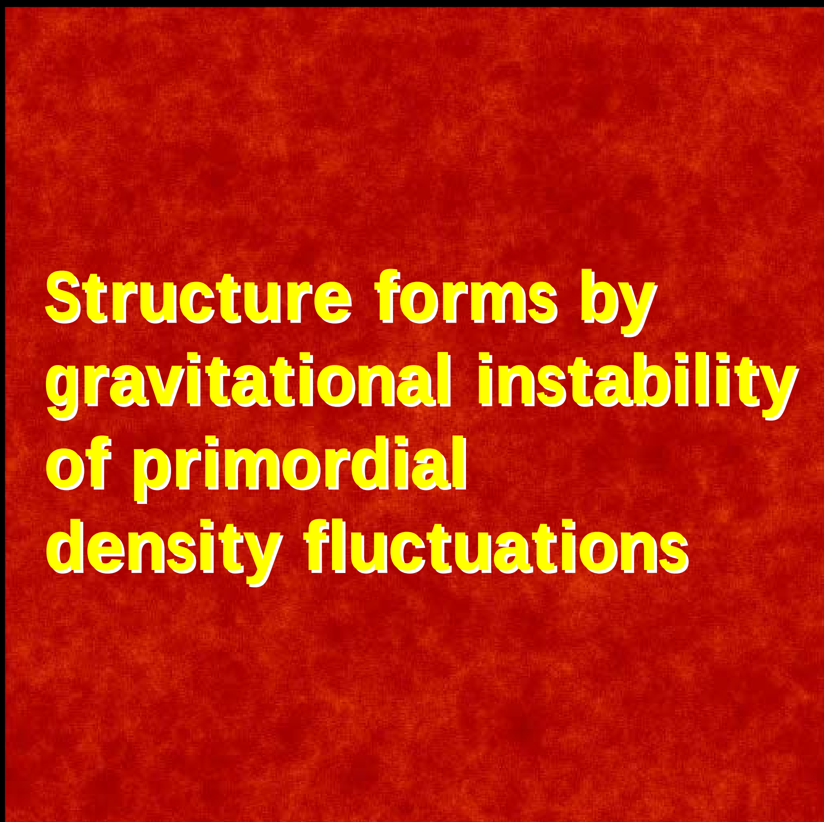
-- Cosmic Microwave Background
-- observations of red shifts of distant galaxies with a variety of candles.
Big news in 2002 : Dark Energy or cosmological constant

→large scale structure in space, time and velocity
is determined by early universe fluctuations, thus by mechanisms of energy release
(neutrinos or other hot dark matter)

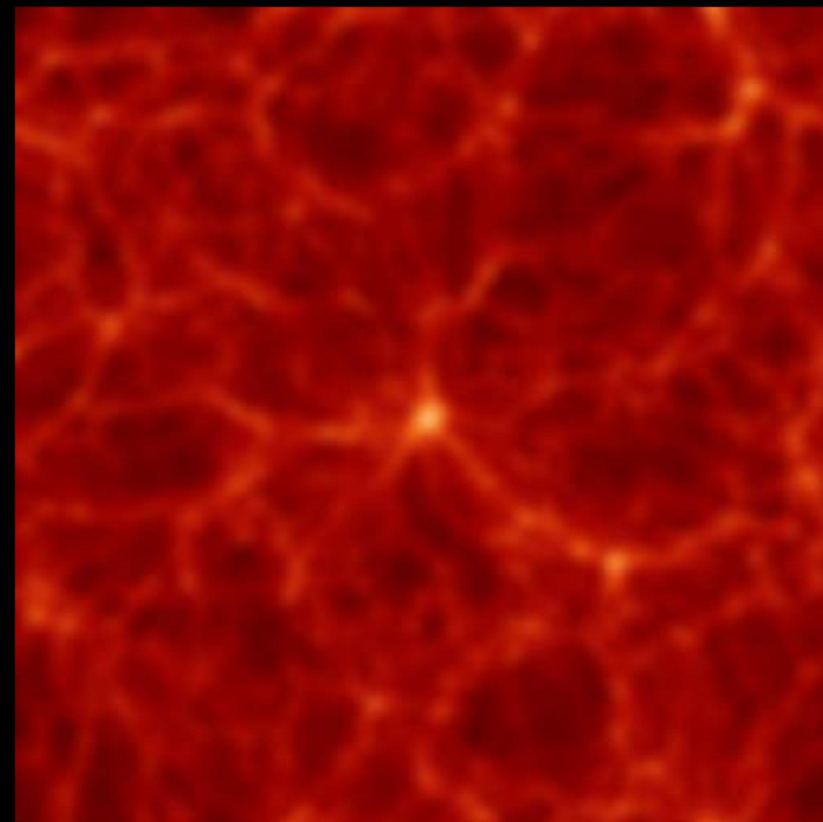
the robustness of the neutrino mass limits….

Formation of Structure

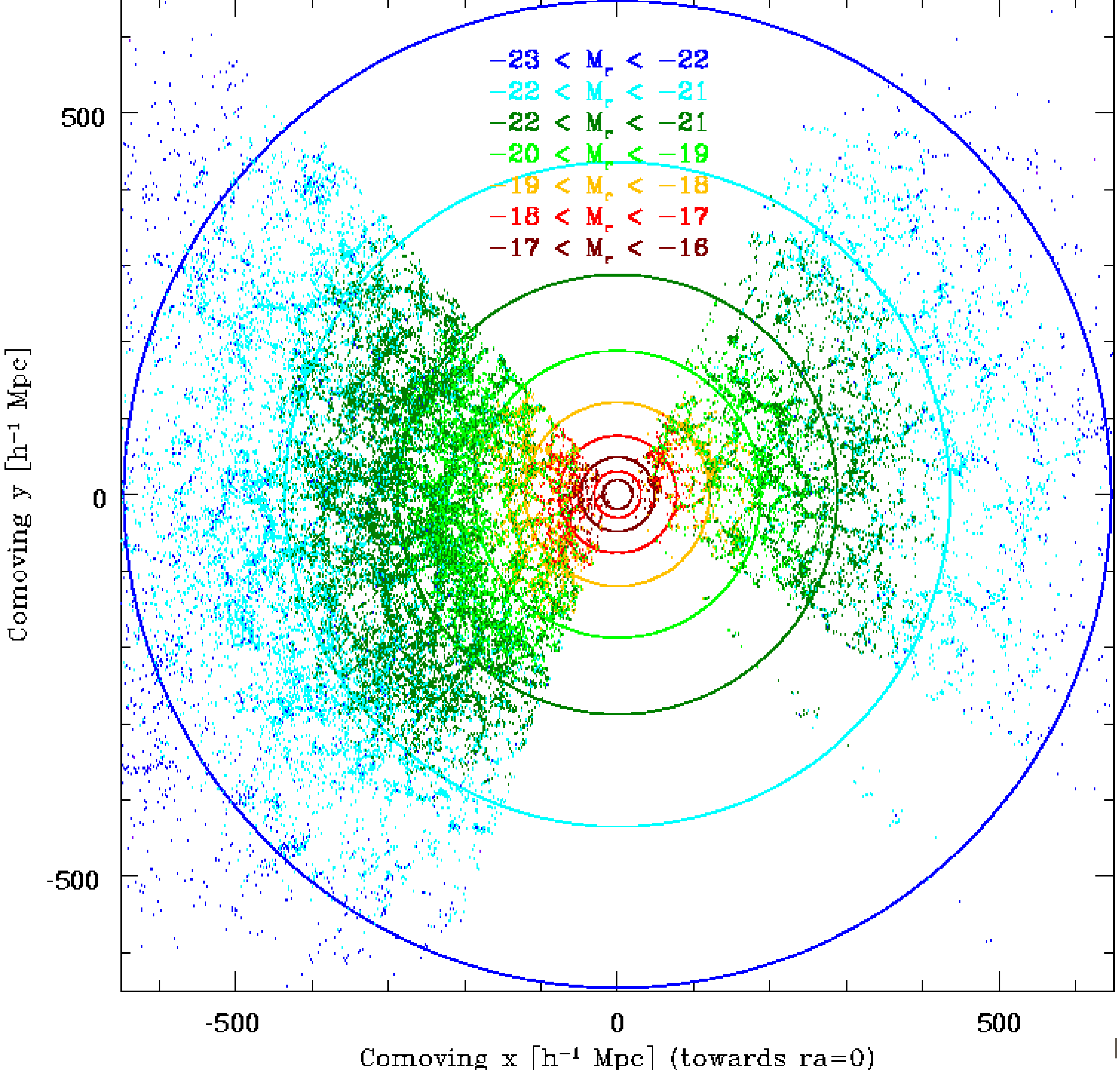
Smooth	→	Structured



Structure forms by gravitational instability of primordial density fluctuations



A fraction of hot dark matter suppresses small-scale structure

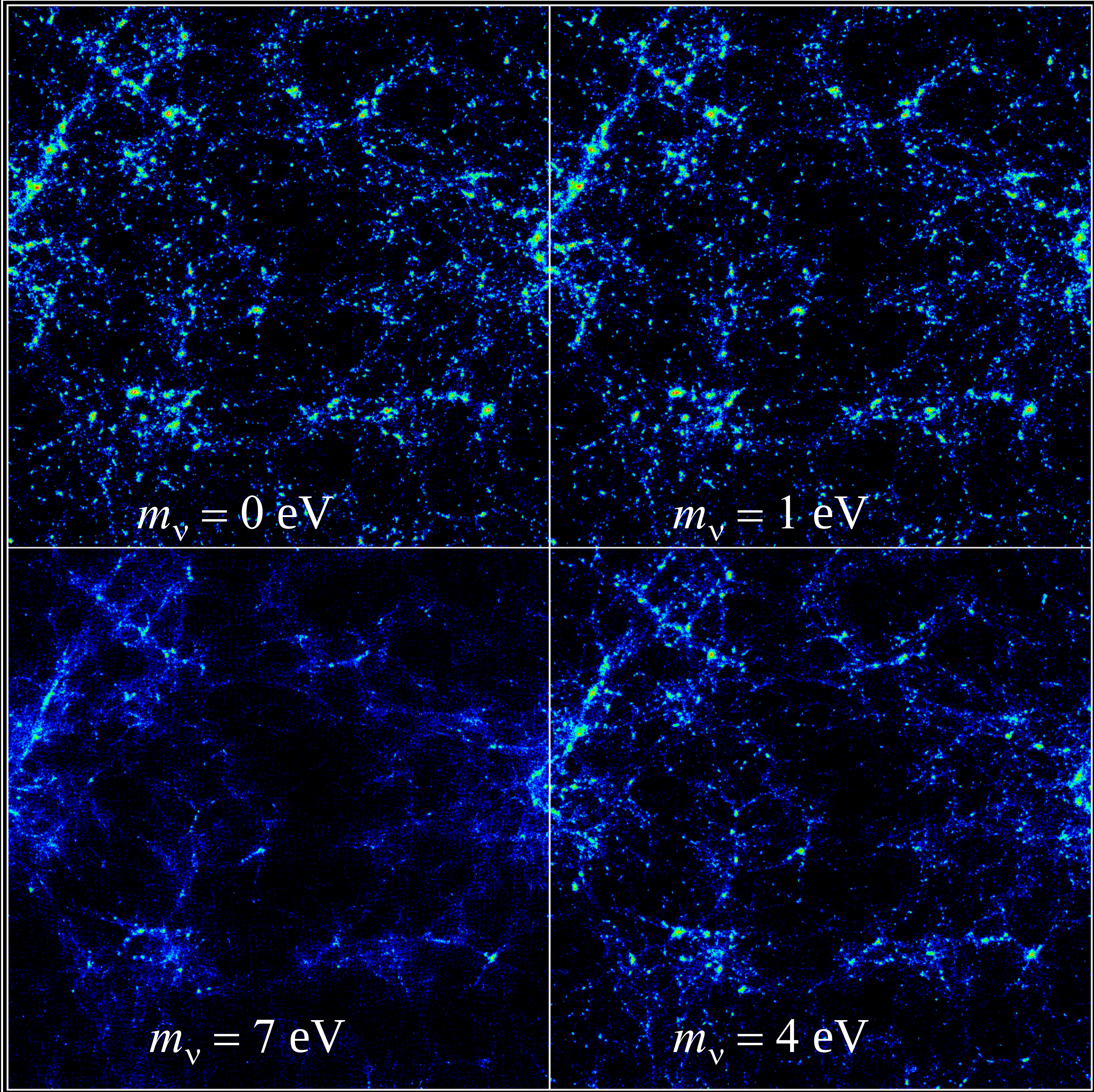


−23 < M_r < −22
−22 < M_r < −21
−22 < M_r < −21
−20 < M_r < −19
−19 < M_r < −18
−18 < M_r < −17
−17 < M_r < −16
500
0
-500
-500
0
500
Comoving y [h⁻¹ Mpc]
Comoving x [h⁻¹ Mpc] (towards ra=0)

lel

Halzen

adding hot neutrino dark matter erases small structure



Halzen

Authors	Σm_ν / eV (limit 95%CL)	Data / Priors
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP, CMB, 2dF, σ_8, HST
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP, CMB, 2dF, HST
Tegmark et al. 2003 [astro-ph/0310723]	1.8	WMAP, SDSS
Barger et al. 2003 [hep-ph/0312065]	0.75	WMAP, CMB, 2dF, SDSS, HST
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP, SDSS, SN Ia gold sample, Ly-α data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP, SDSS, Bias, Ly-α data from SDSS sample

NB Since this is a large mass this implies that the largest neutrino mass is limit/3

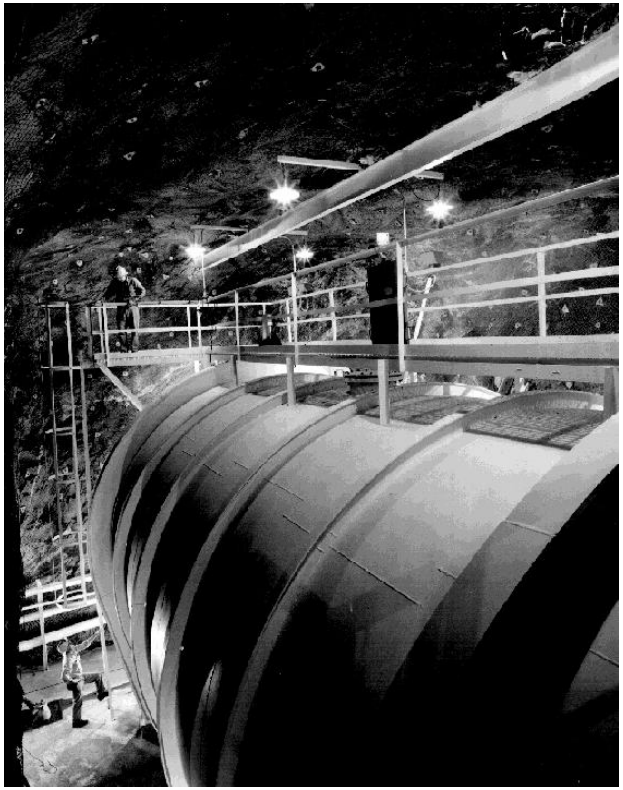
Neutrinos

astrophysical neutrinos

Ray Davis

since ~1968

Homestake Detector



Solar Neutrino Detection
600 tons of chlorine.

- **Detected neutrinos E> 1MeV**
- **fusion process in the sun**

solar : pp $\rightarrow$ pn e^+ ν_e (then D gives He etc…)

these ν_e <u>do</u> ν_e + $^{37}Cl \rightarrow {}^{37}Ar$ + e^-

they are neutrinos

- **The rate of neutrinos detected is three times less than predicted!**

solar neutrino 'puzzle' since 1968-1975!

solution: 1) solar nuclear model is wrong or 2) neutrino oscillate

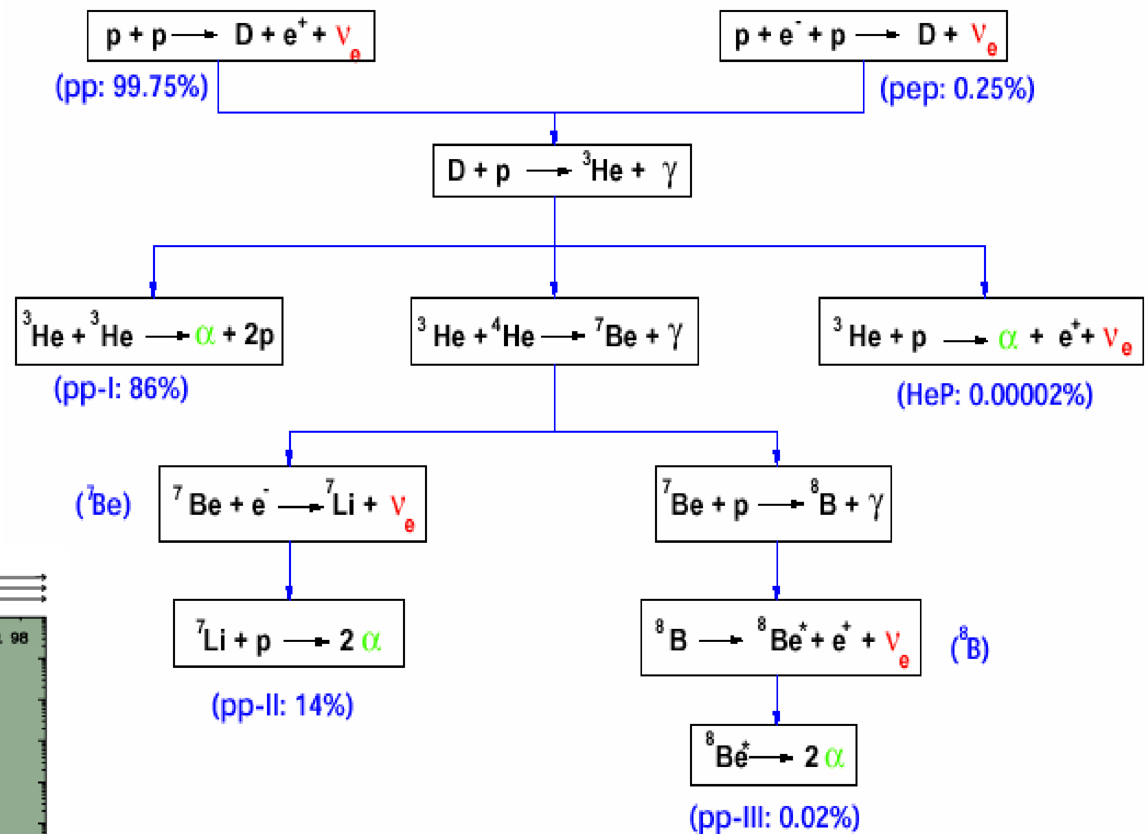
ν_e solar neutrinos

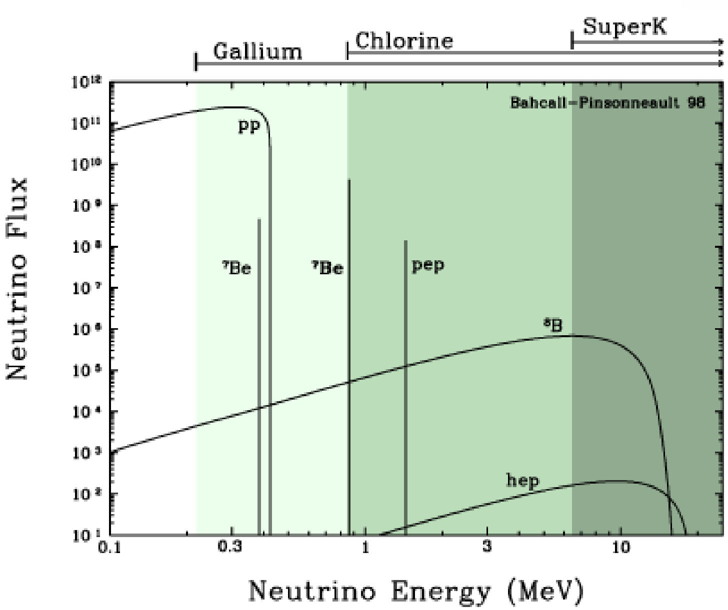
Sun = Fusion reactor

Only ν_e produced

Different reactions

Spectrum in energy





Counting experiments vs flux calculated by SSM

BUT …

Alain Blondel

The Pioneer: Chlorine Experiment

The interaction

$^{37}Cl(\nu_e,e)^{37}Ar$ (E_{thr} = 813 keV)

K_{shell} **EC** τ = **50.5** d

$\rightarrow$ ^{37}Cl + 2.82 keV (*Auger* e^-, *X*)

ν Signal Composition:
(BP04+N14 SSM+ ν osc)

pep+hep	0.15 SNU	(4.6%)
^{7}Be	0.65 SNU	(20.0%)
^{8}B	2.30 SNU	(71.0%)
CNO	0.13 SNU	(4.0%)
Tot	3.23 SNU ± 0.68 1σ	

Expected Signal
(BP04 + N14)

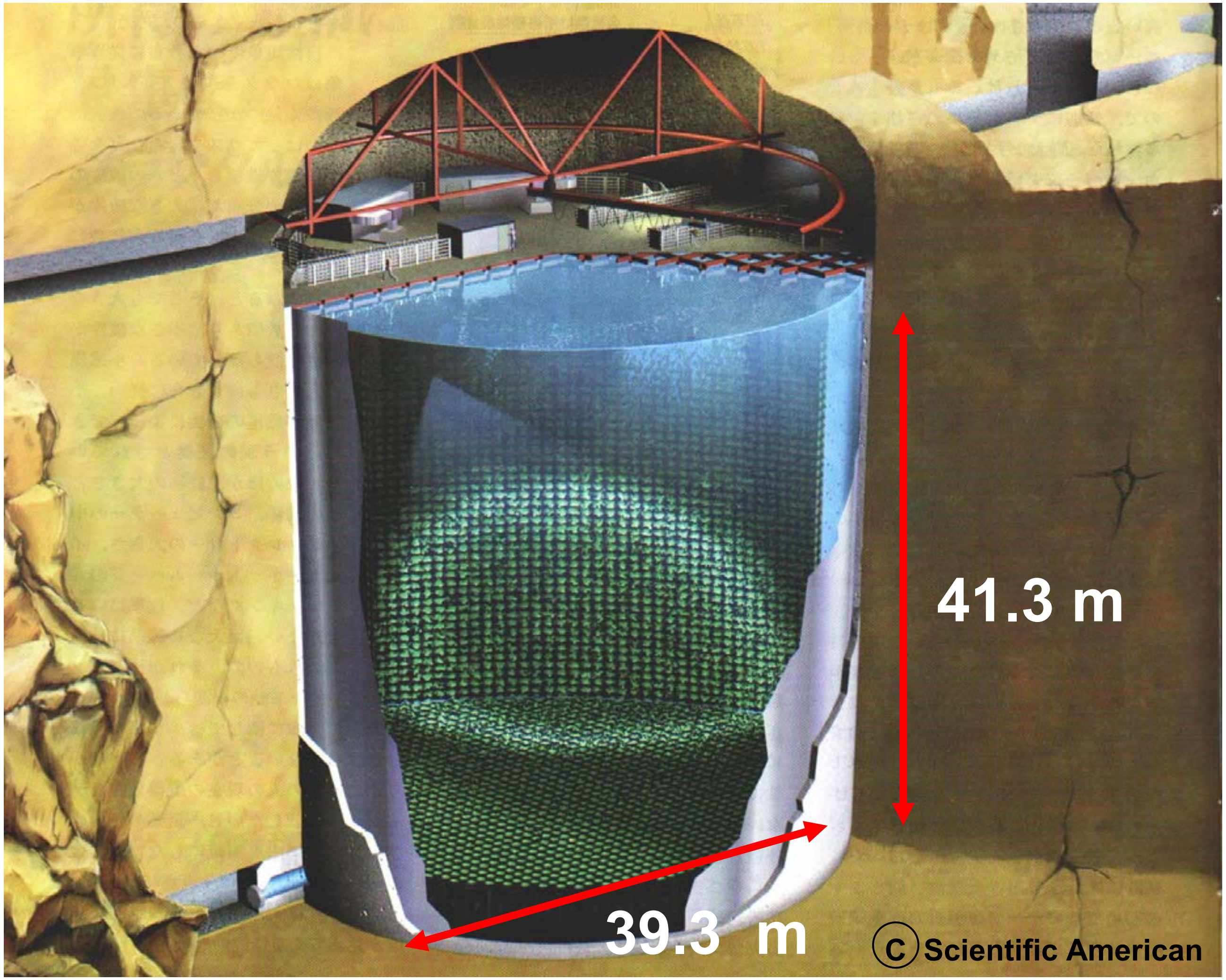
8.2 SNU $^{+1.8}_{-1.8}$ 1σ

expected
(no osc)

Generalities on radiochemical experiments

	Data used for R determination	N runs	Average efficiency	Hot chem check	Source calib	R_{ex} [SNU]
Chlorine (Homestake Mine); South Dakota USA	1970-1993	106	0.958 ± 0.007	^{36}Cl	*No*	2.55 ± 0.17 ± 0.18 *6.6% 7%* ***2.6* ± 0.3** 8.5+-1.8
GALLEX/GNO LNGS Italy	1991-2003	124	??	^{37}As	*Yes twice* ^{51}Cr *source*	69.3 ± 4.1 ± 3.6 *5.9% 5%* 131+-11
SAGE Baksan Kabardino Balkaria	1990-ongoing	104	??	*No*	*Yes* ^{51}Cr ^{37}Ar	70.5 ± 4.8 ± 3.7 *6.8% 5.2%* ***70.5* ± 6.0** 131+-11

Super-K detector



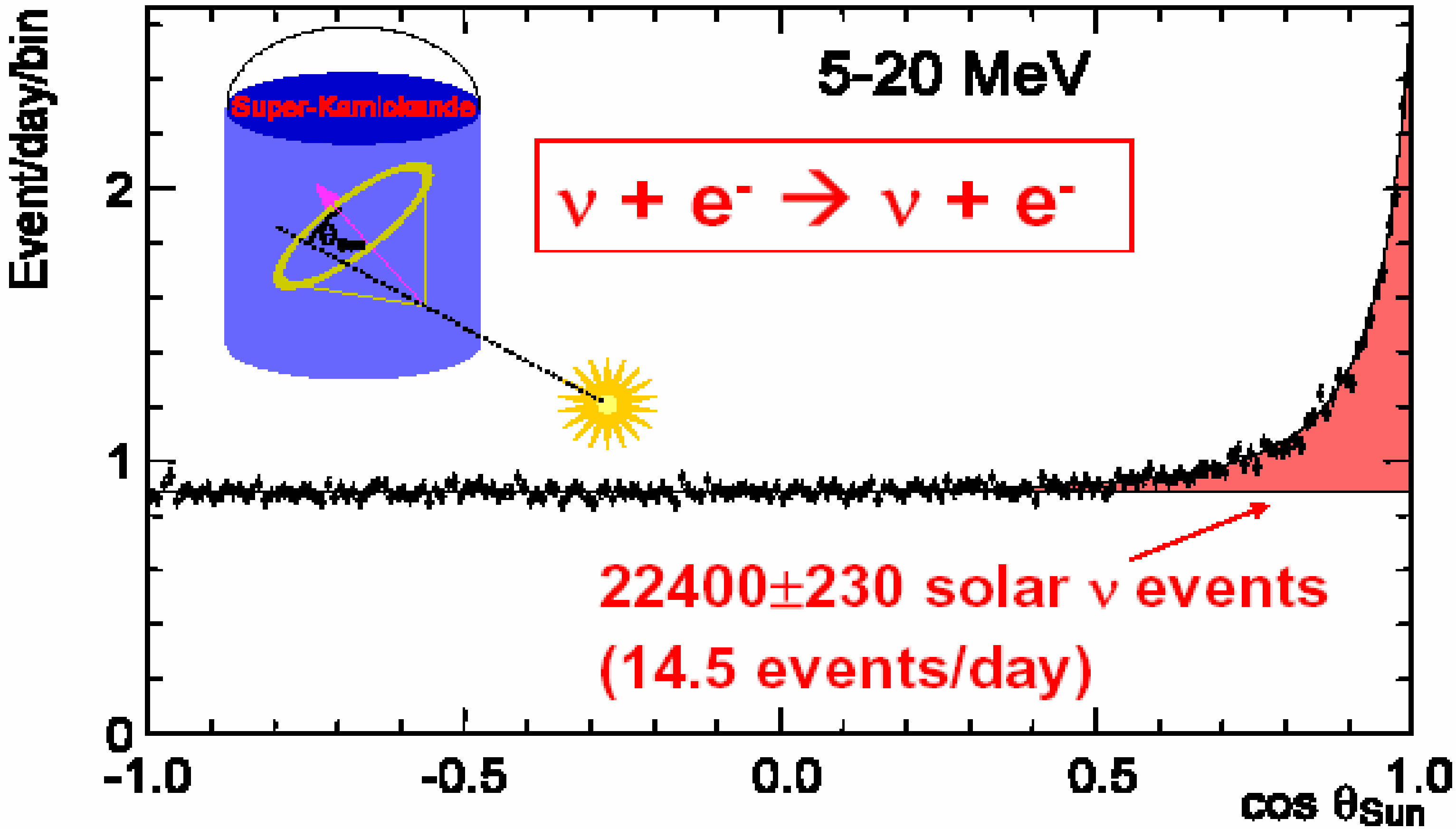
Water Cerenkov detector

50000 tons of pure light water

≈10000 PMTs

Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)



^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \; {}^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

Missing Solar Neutrinos

Only fraction of the expected flux is measured !

Possible explications:

wrong SSM

NO. Helio-seismology

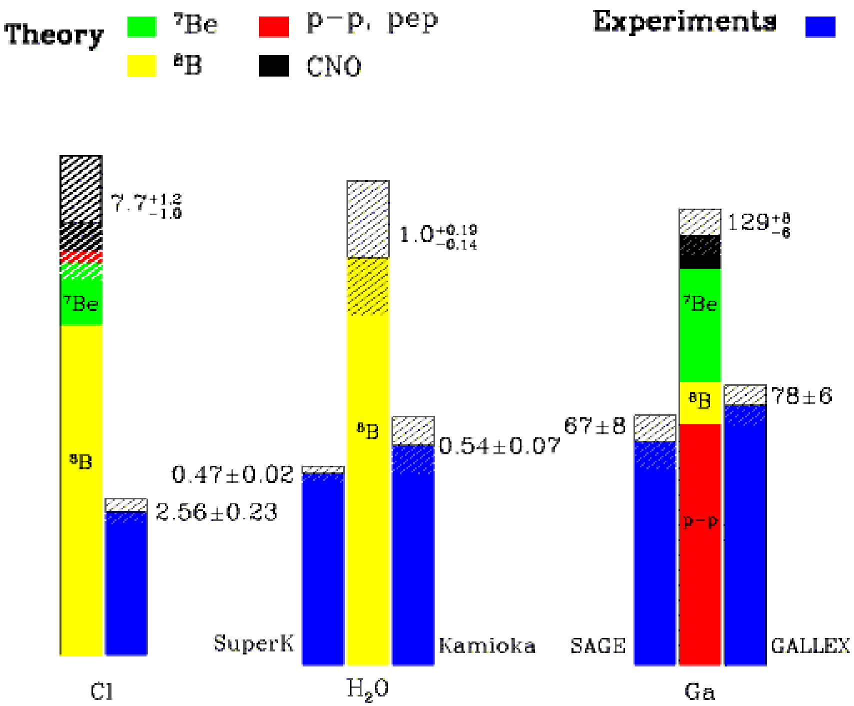
wrong experiments

NO. Agreement between different techniques

or

ν_e's go into something else

Oscillations?



Total Rates: Standard Model vs. Experiment
Bahcall−Pinsonneault 98

neutrino definitions

the electron neutrino is present in association with an electron (e.g. beta decay)

the muon neutrino is present in association with a muon (pion decay)

the tau neutrino is present in association with a tau ($W \to \tau\nu$ decay)

these flavor-neutrinos are not (as we know now) quantum states of well defined mass (neutrino mixing)

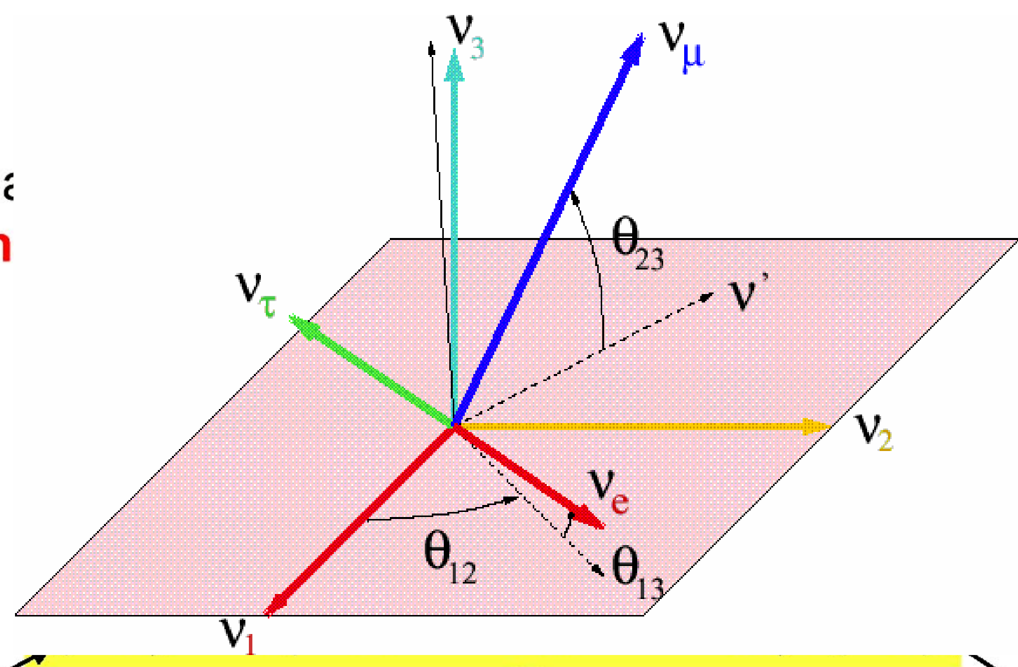
the mass-neutrino with the highest electron neutrino content is called ν_1

the mass-neutrino with the next-to-highest electron neutrino content is ν_2

the mass-neutrino with the smallest electron neutrino content is called ν_3

Lepton Sector Mixing

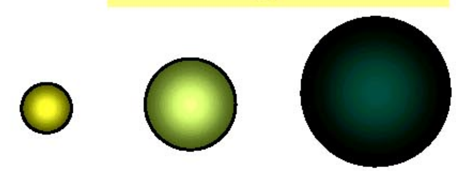
⋆ If neutrinos a[...] the
mass eigen[...]e same:



Weak eigenstates
„flavor eigenstates"

3 independent parameters
+ 1 complex phase

Mass eigenstates

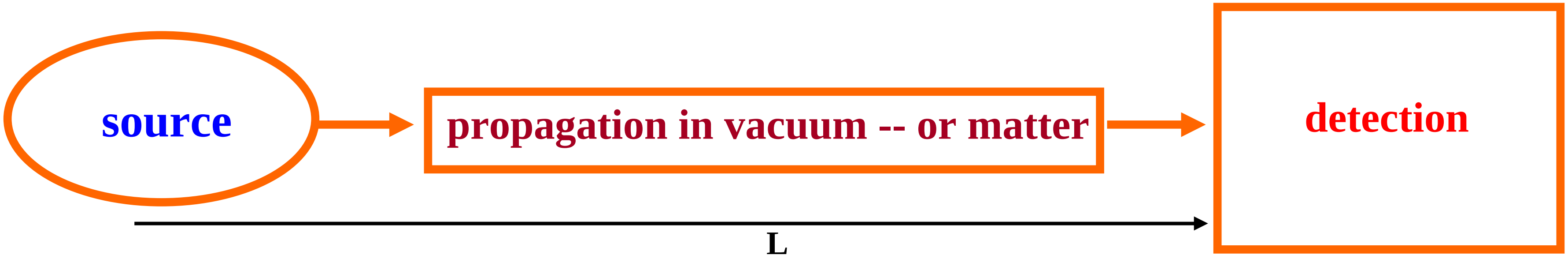


m_1 m_2 m_3

Pontecorvo 1957

Alain Blondel

Neutrino Oscillations (Quantum Mechanics lesson 5)



weak interaction produces 'flavour' neutrinos

e.g. pion decay $\pi \rightarrow \mu\nu_\mu$

$$|\nu_\mu\rangle = \alpha\,|\nu_1\rangle + \beta\,|\nu_2\rangle + \gamma\,|\nu_3\rangle$$

α is noted $U_{1\mu}$

β is noted $U_{2\mu}$

γ is noted $U_{3\mu}$ etc….

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = \alpha\,|\nu_1\rangle\ \exp(i E_1 t) + \beta\,|\nu_2\rangle\ \exp(i E_2 t) + \gamma\,|\nu_3\rangle\ \exp(i E_3 t)$$

t = proper time $\propto$ L/E

detection and identification by weak interaction: (CC)

$\nu_\mu\ N \rightarrow \mu^-\ X$

or $\nu_e\ N \rightarrow e^-\ X$

or $\nu_\tau\ N \rightarrow \tau^-\ X$

$$P(\mu \rightarrow e) = |\langle \nu_e | \nu(t)\rangle|^2$$

Alain Blondel

Oscillation Probability

- The case with two neutrinos:
  - A mixing angle: θ
  - A mass difference:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

- The oscillation probability is:

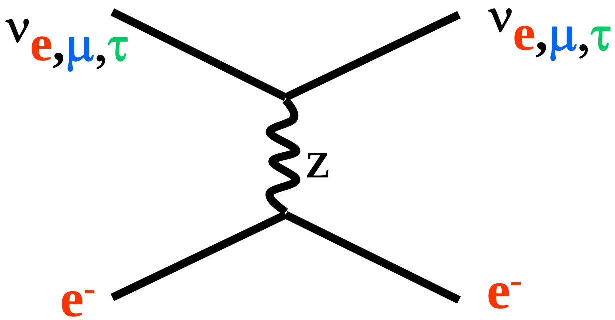
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

Δm^2 in eV^2
L in km
E in GeV

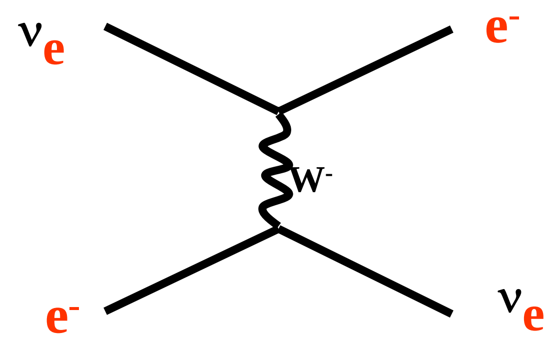
where L = distance between source and detector
E = neutrino energy

Hamiltonian= E = sqrt($p^2 + m^2$) = p + $m^2 / 2p$
for a given momentum, eigenstate of propagation in free space are the mass eigenstates!

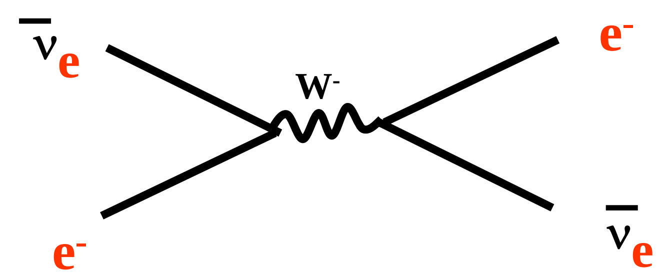
To complicate things further:
matter effects
elastic scattering of (anti) neutrinos on electrons



all neutrinos and anti neutrinos do this equally



only electron neutrinos



only electron anti- neutrinos

These processes add a forward amplitude to the Hamiltonian,
which is proportional to the number of elecrons encountered
to the Fermi constant and to the neutrio energy.
The Z exchange is diagonal in the 3-neutrino space
this does not change the eigenstates
The W exchange is only there for electron neutrinos
It has opposite sign for neutrinos and anti-neutrinos (s vs t-channel exchange)

$D = \pm 2\sqrt{2}\, G_F\, n_e E_\nu$

THIS GENERATES A FALSE CP VIOLATION

$$D = \pm 2\sqrt{2}\, G_F\, n_e E_\nu$$

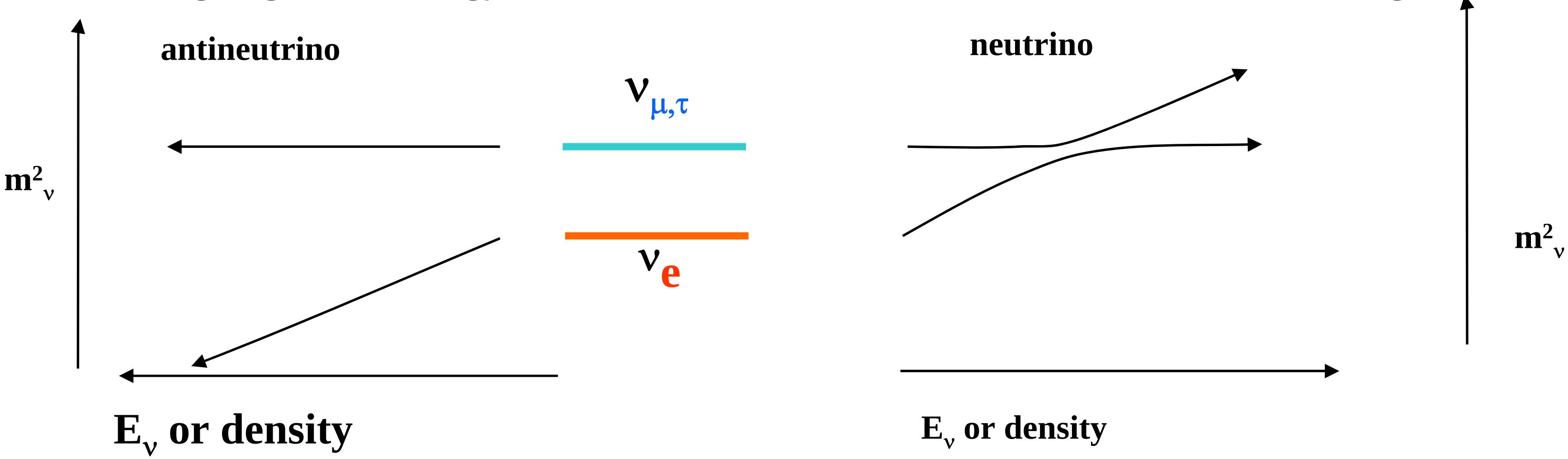
$$H_{\text{flavour base}} = U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} D & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

This is how YOU can solve this problem: write the matrix, diagonalize, and evolve using,

$$i \frac{\partial \psi}{\partial t} = H\psi$$

This has the effect of modifying the eigenstates of propagation!

Mixing angle and energy levels are modified, this can even lead to level-crossing. ***MSW effect***



oscillation is further suppressed **resonance… enhances oscillation**

oscillation is enhanced for neutrinos if $\Delta m^2_{1x} > 0$, and suppressed for antineutrinos

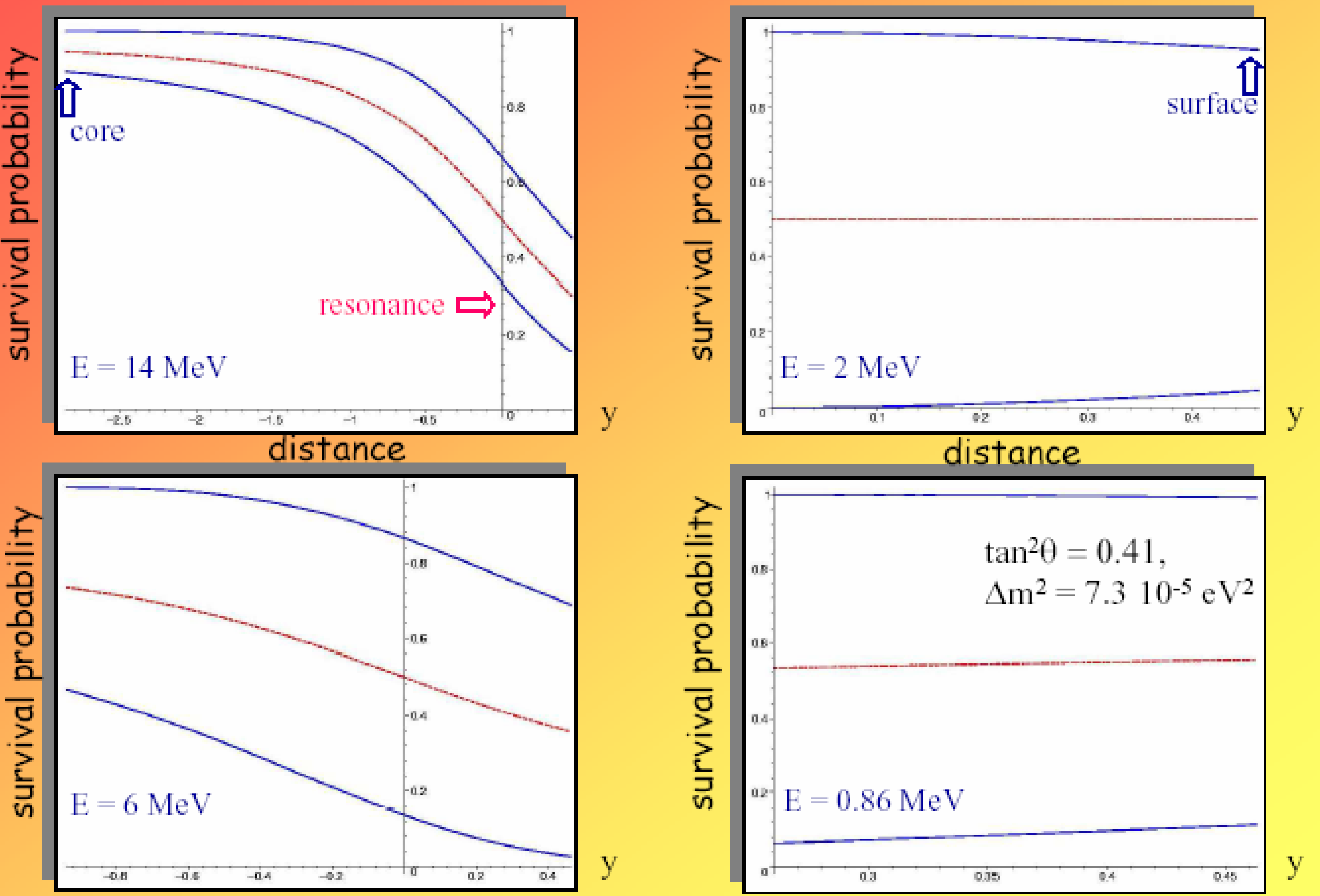
oscillation is enhanced for antineutrinos if $\Delta m^2_{1x} < 0$, and suppressed for neutrinos

since T asymmetry uses neutrinos it is not affected

Alain Blondel

MSW conversion inside the Sun

SMIRNOV



Solar Models *R* previsions for Radiochemical experiments

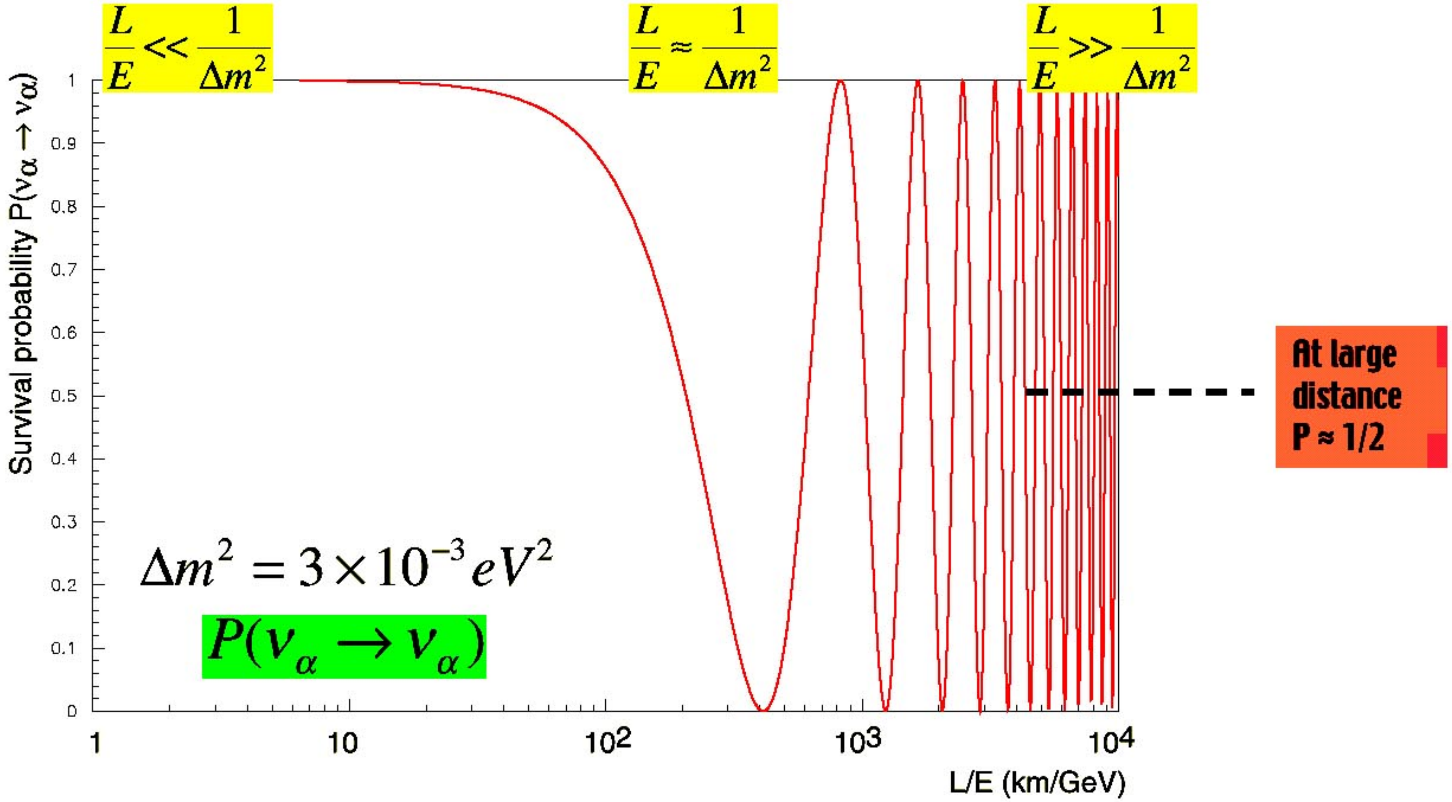
from LUNA experiment on $^{14}N(p,\gamma)^{15}O$
New $S_0(^{14}N+p) = 1.77$ keV $\pm$ 0.2

Flux ($cm^{-2}s^{-1}$)	BP00	BP04	BP04 + N14	$BP04^{+}$ + N14	P_{ee} $\Delta m^2 = 7.1\times10^{-5}$ eV^2 $\theta_{12} = 32.5$
pp (10^9)	59.5 *(± 1%)*	5.94 *(± 1%)*	59.8	60.3	0.578 (vac)
pep (10^8)	1.40 *(± 2%)*	1.40 *(± 2%)*	1.42	1.44	0.531(vac)
hep (10^3)	9.24	7.88 *(± 16%)*	7.93	8.09	~ 0.3 matter
^{7}Be (10^9)	4.77 *(± 10%)*	4.86 *(± 12%)*	4.86	4.65	0.557 vac
^{8}B (10^6)	$5.05^{+20\%}_{-16\%}$	5.79 *(± 23%)*	5.77	5.24	0.324 matter
^{13}N (10^8)	$5.48^{+21\%}_{-17\%}$	5.71	$3.23^{+37\%}_{-35\%}$	2.30	0.557 vac
^{15}O (10^8)	$4.80^{+25\%}_{-19\%}$	5.03	$2.54^{+43\%}_{-39\%}$	1.79	0.541 vac
^{17}F (10^6)	$5.63^{+25\%}_{-25\%}$	5.91	$5.85^{+44\%}_{44\%}$	3.93	

increased accuracy in $^7Be(p,\gamma)^8B$ measurement

Columns 2,3,4 from BP04

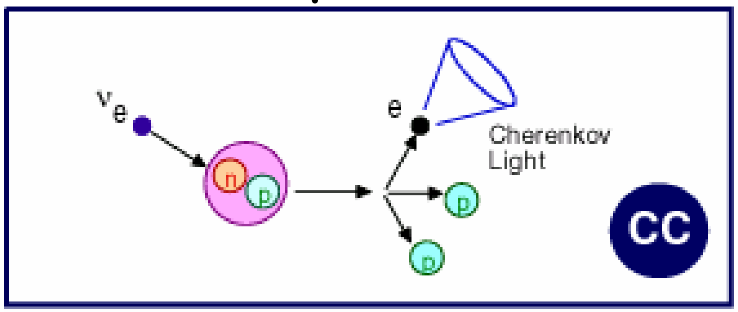
Oscillation Phenomena



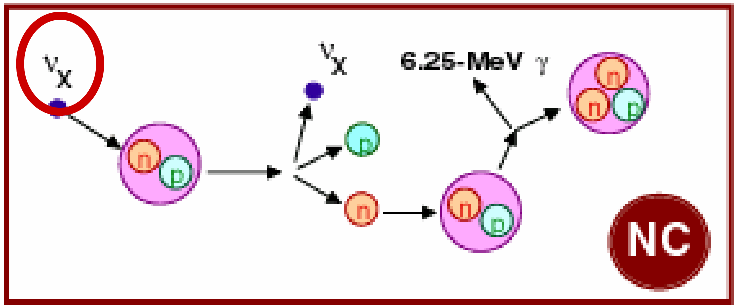
SNO detector

Aim: measuring non ν_e neutrinos in a pure solar ν_e beam

How? Three possible neutrino reaction in heavy water:

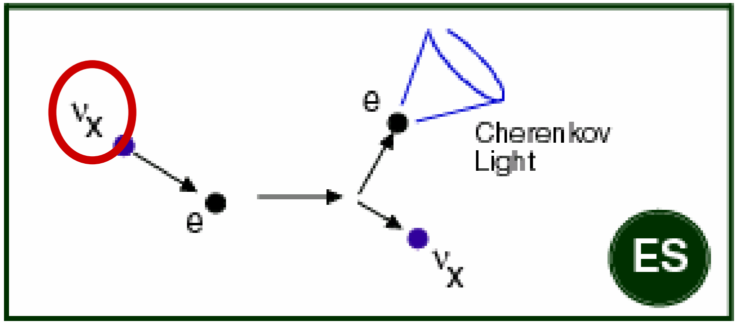


only ν_e



equally

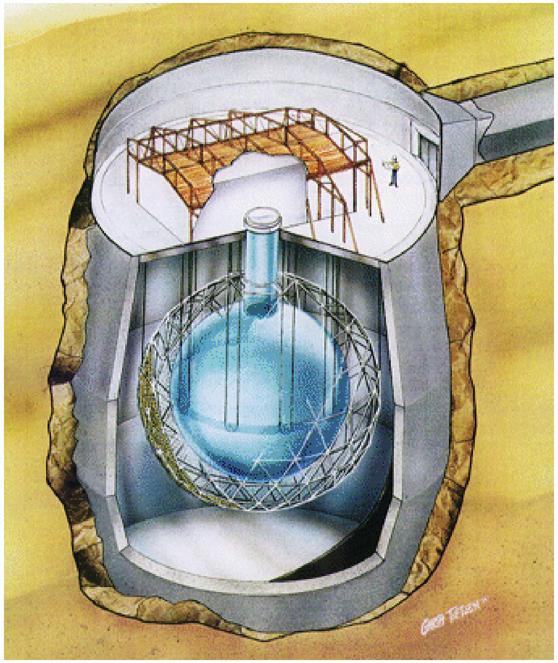
$\nu_e + \nu_\mu + \nu_\tau$



in-equally

$\nu_e +$

$0.1\,(\nu_\mu + \nu_\tau)$



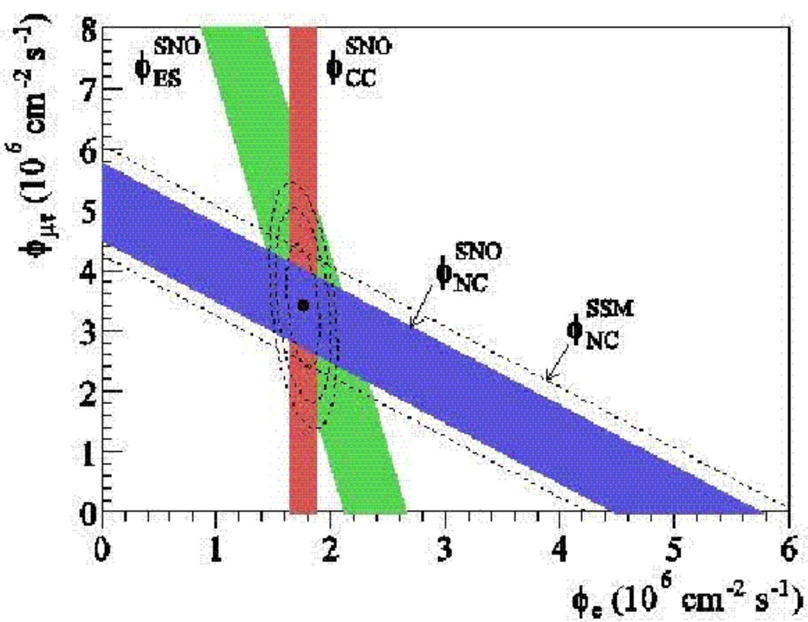
1000 ton of D_2O

12 m diam.

9456 PMTs

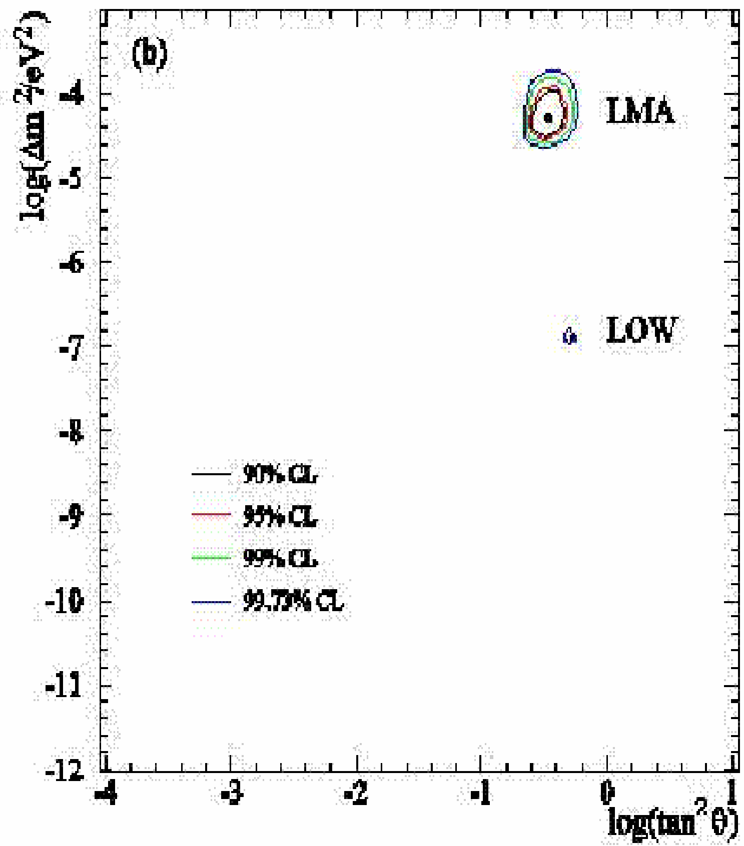
Physics Implication Flavor Content

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44\,+0.46}_{-0.43\,-0.43}$



Strong evidence of flavor change

Combining All Experimental and Solar Model information

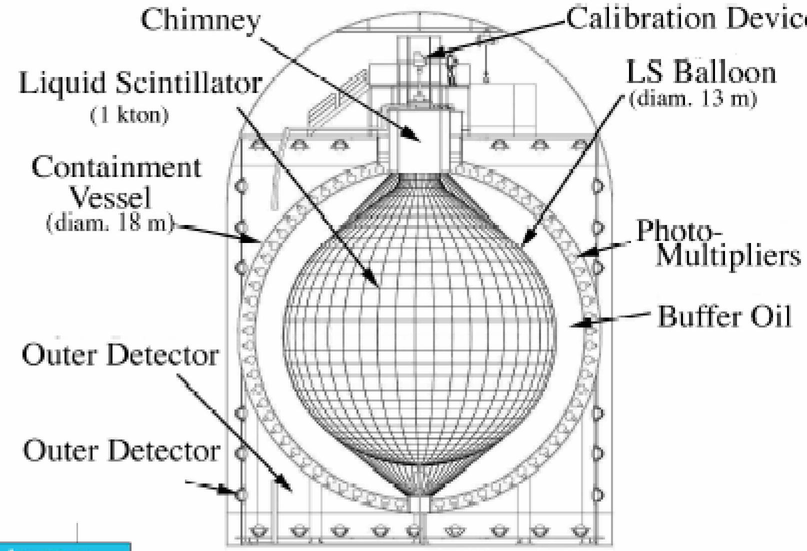


Charged current events are depleted (reaction involving electron neutrinos)

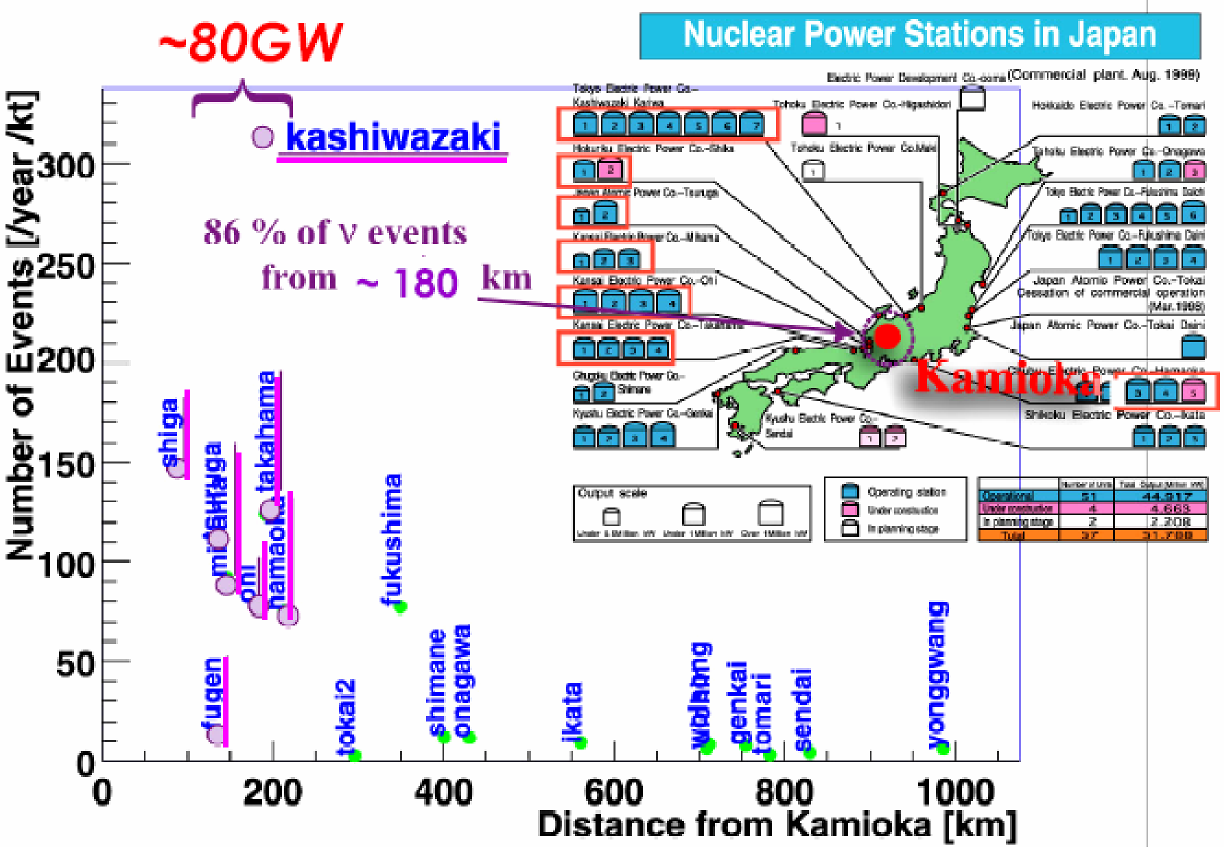
Neutral current reaction agrees with Solar Model (flavour blind)

SSM is right, neutrinos oscillate!

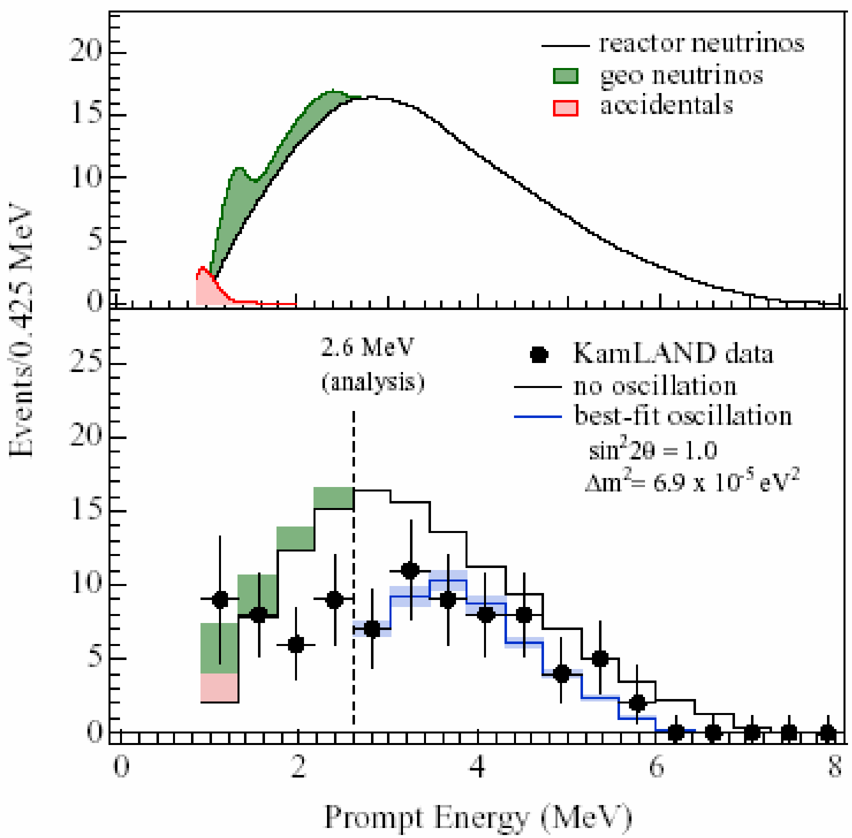
Kamland 2002

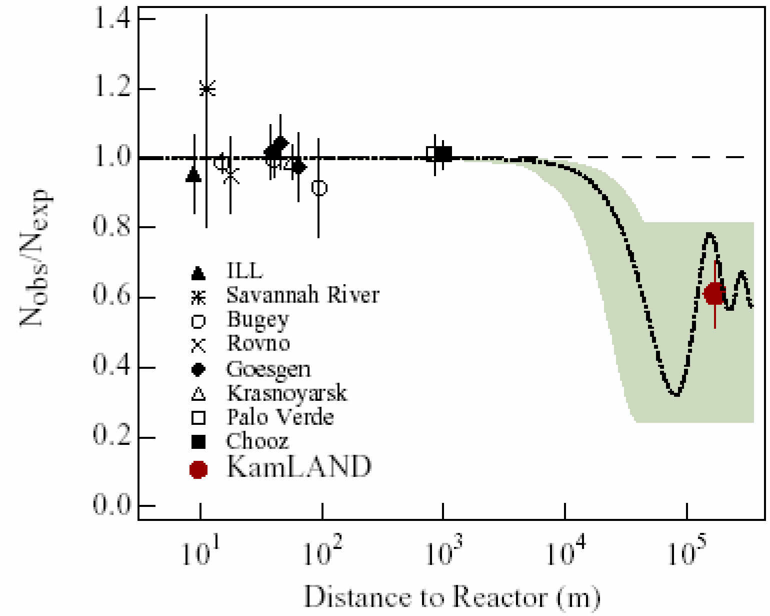


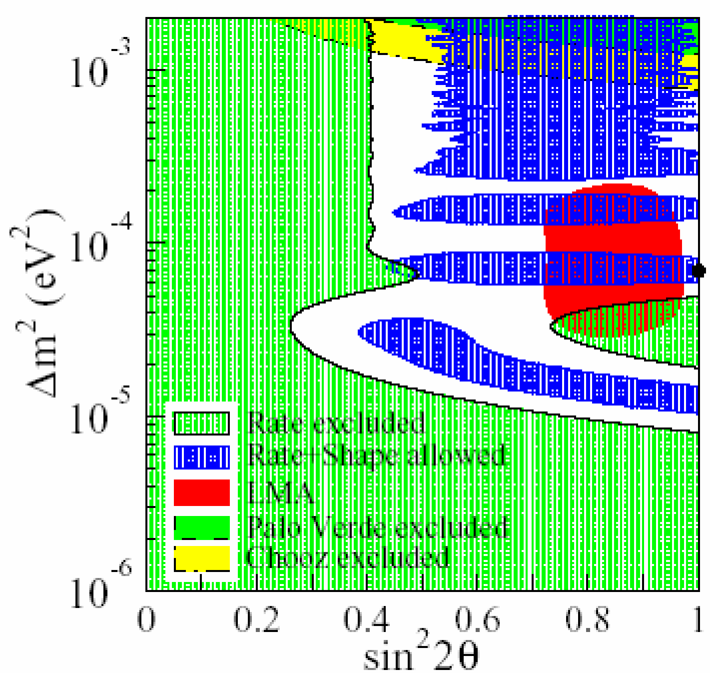
20 % of world nuclear power



KamLAND: disappearance of antineutrinos from reactor
(few MeV at ~100 km)

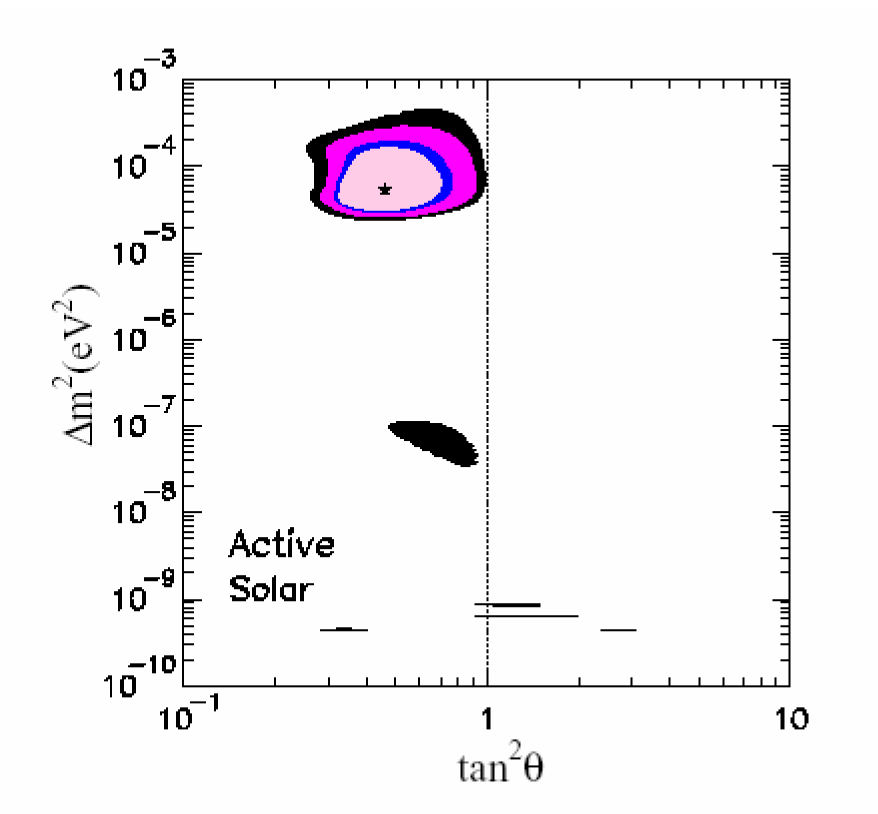




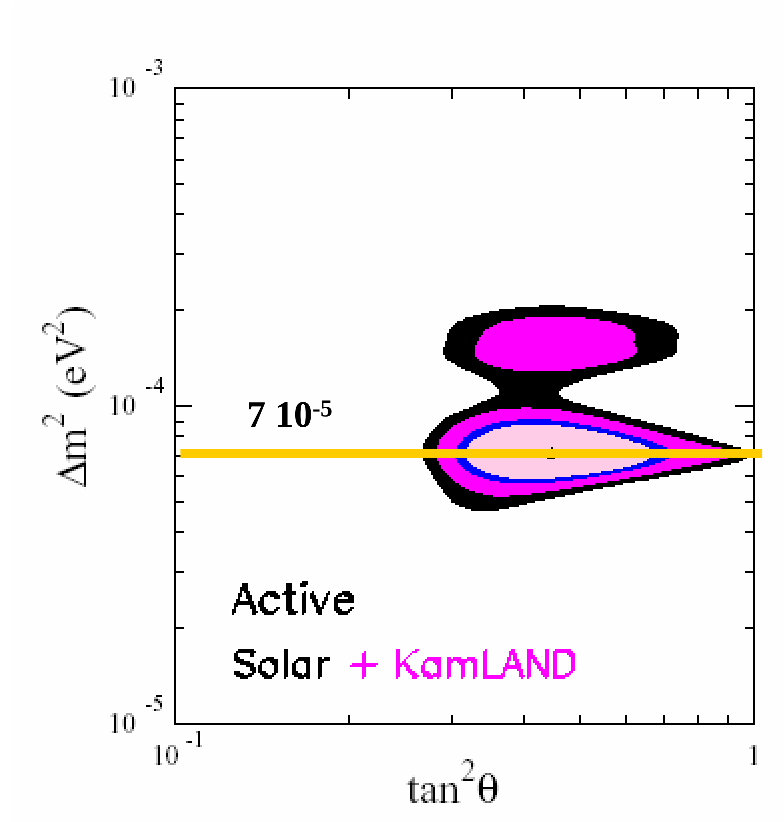


Prerequisite for CP violation in neutrinos: Solar LMA solution

Before KamLAND

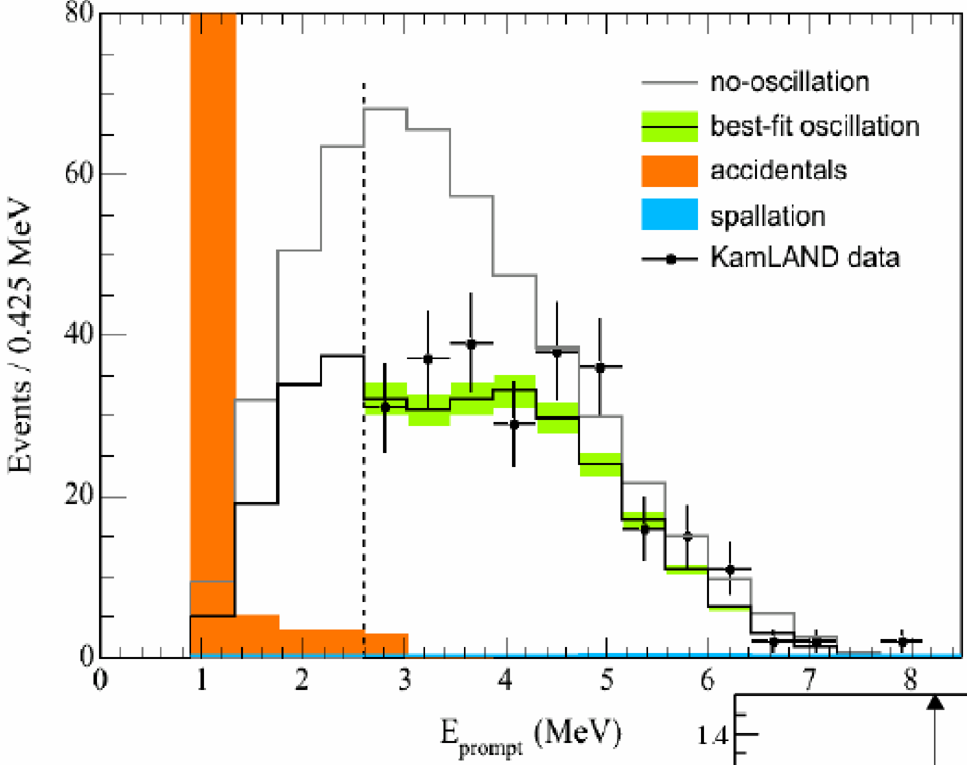


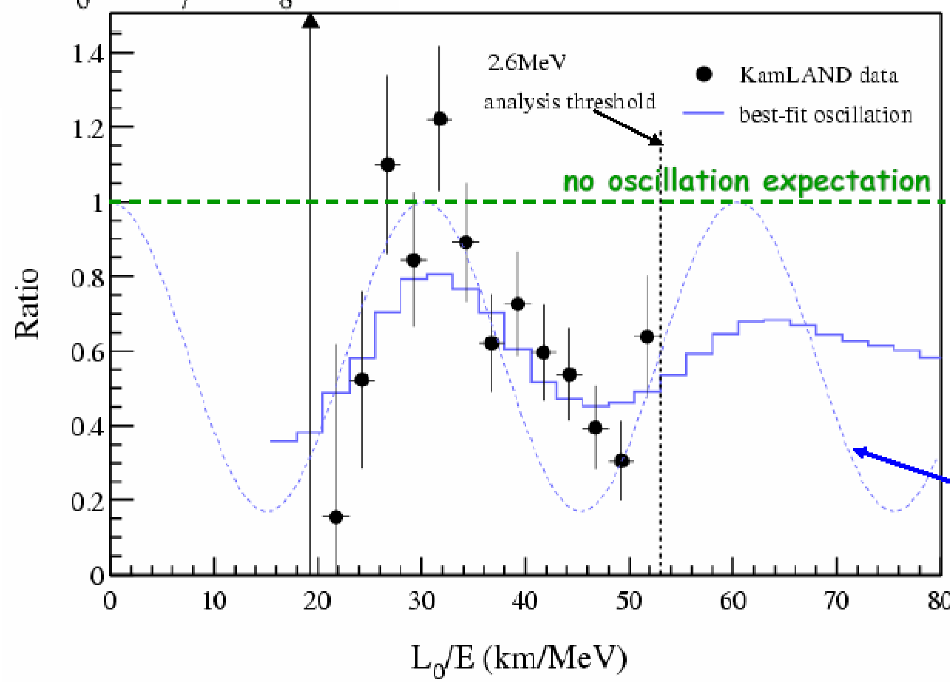
After KamLAND



This will be confirmed and Δm^2_{12} measured precisely by KAMLAND and maybe Borexino in next 2-4 yrs

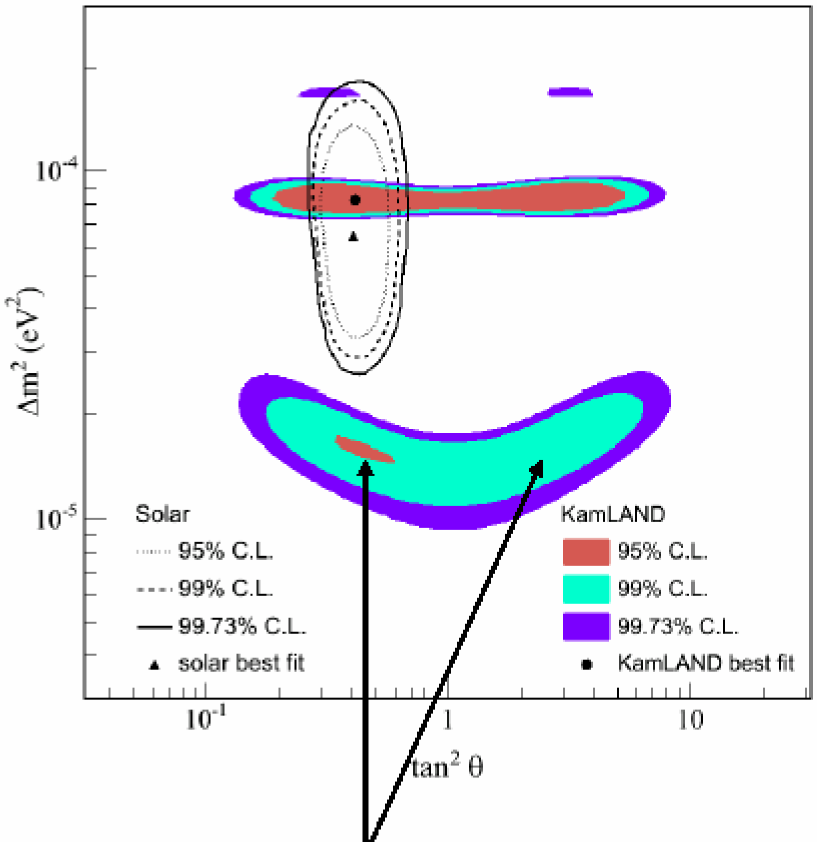
Kamland 2004





Hypothetical single 180km baseline experiment

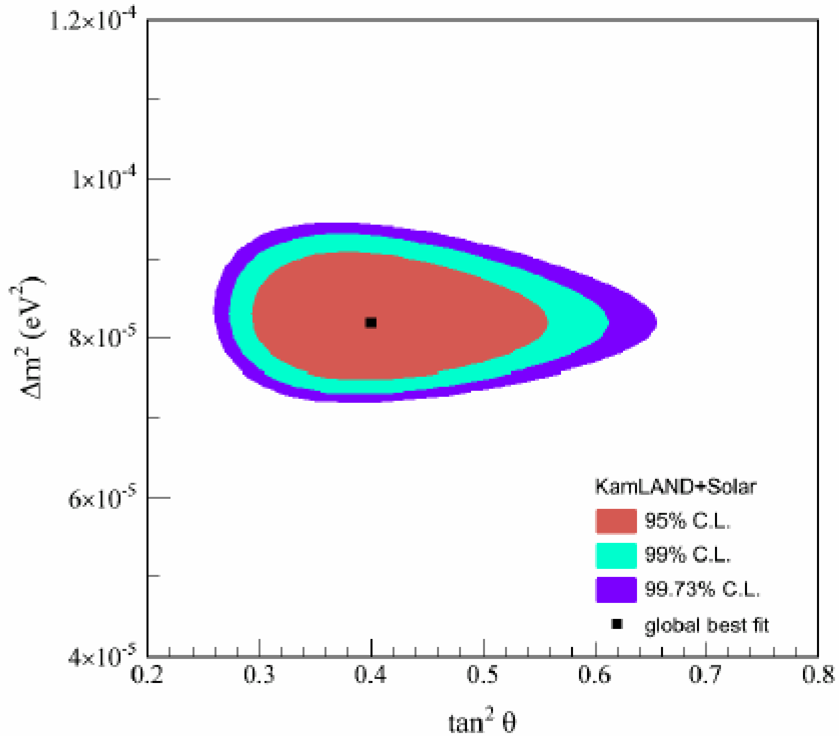
Kamland 2004



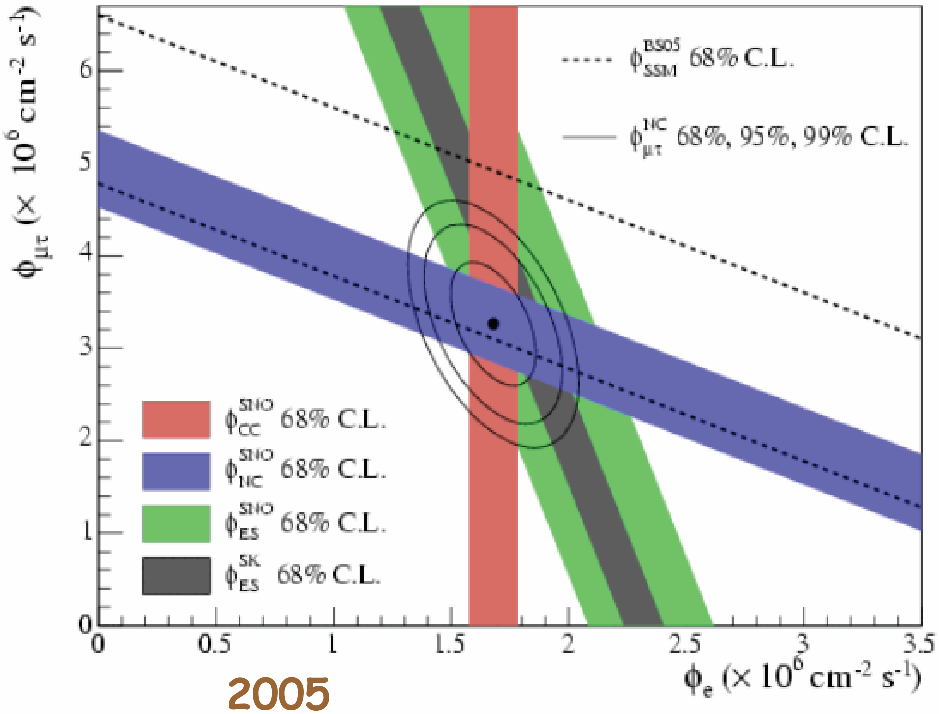
Includes (small) matter effects

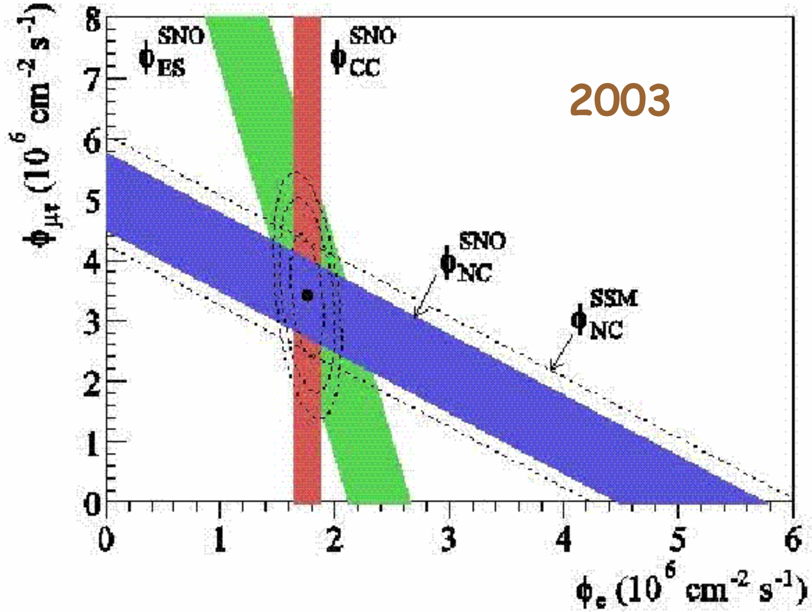
$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

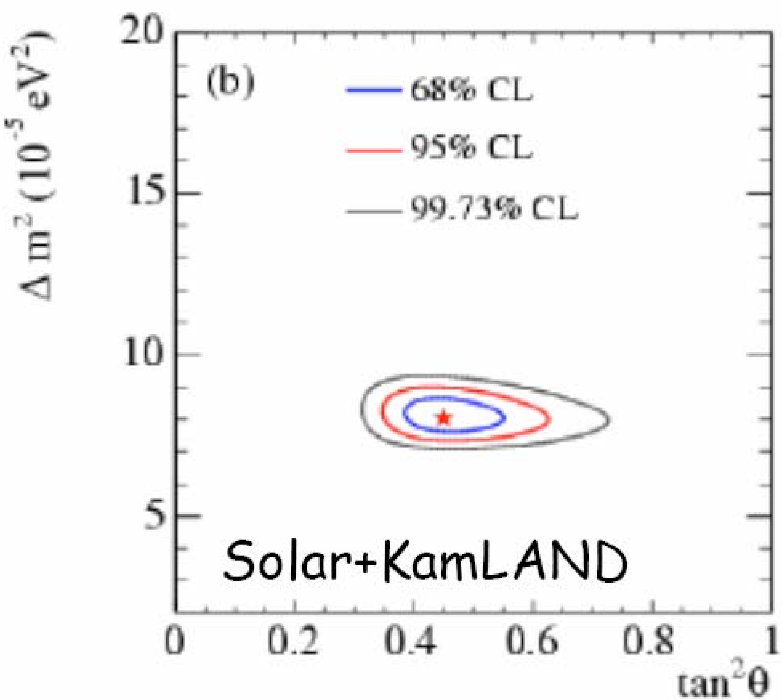
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



Flavor content of solar flux.







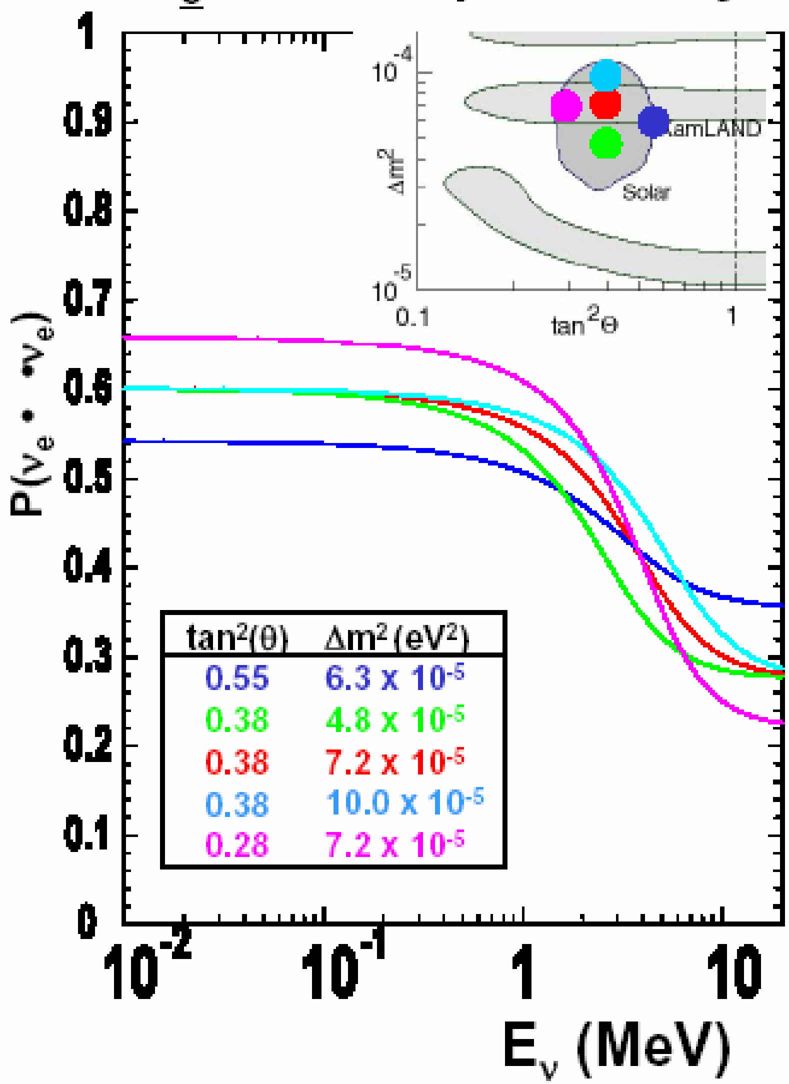
Solar oscillation parameters now at 10-20% precision.

(Maximal mixing excluded at >5 s)

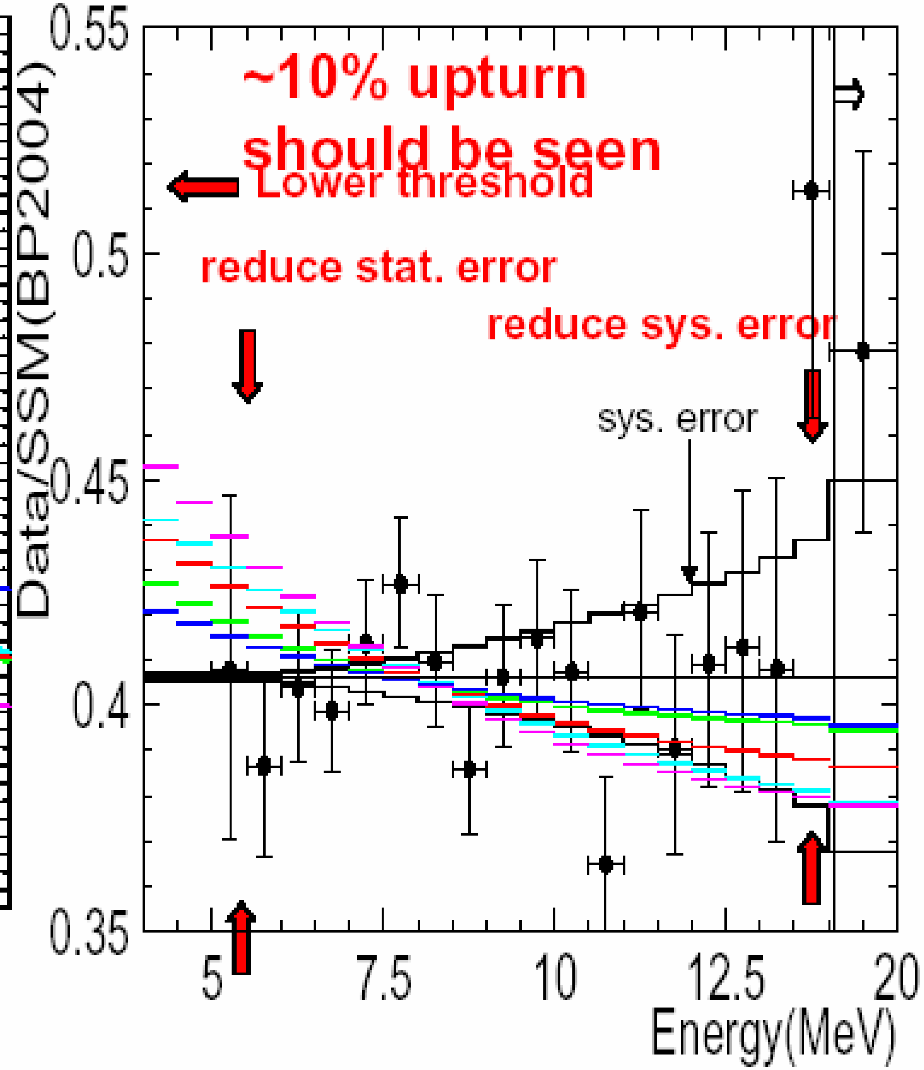
Future prospects towards SK-III

Possibility of detecting spectrum distortion

ν_e survival probability

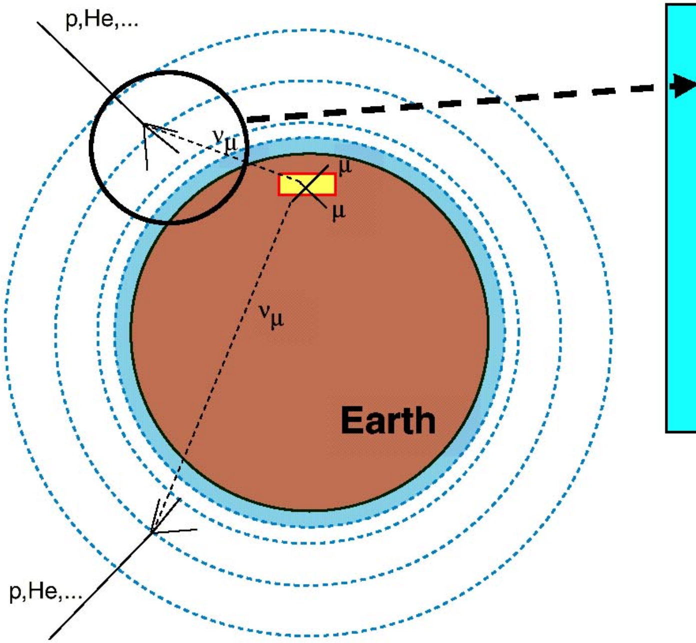


Recoil electron spectrum

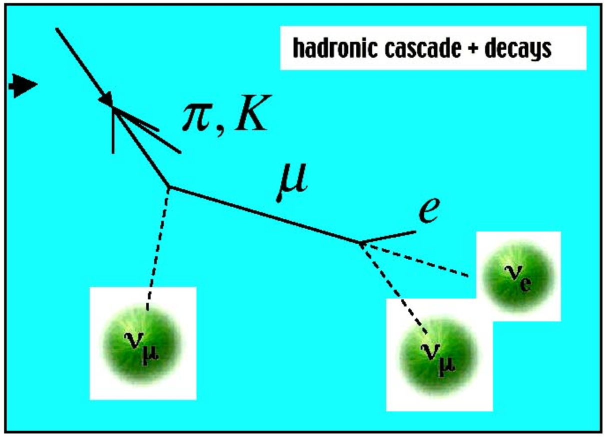


Atmospheric Neutrinos

Path length from ~20km to 12700 km



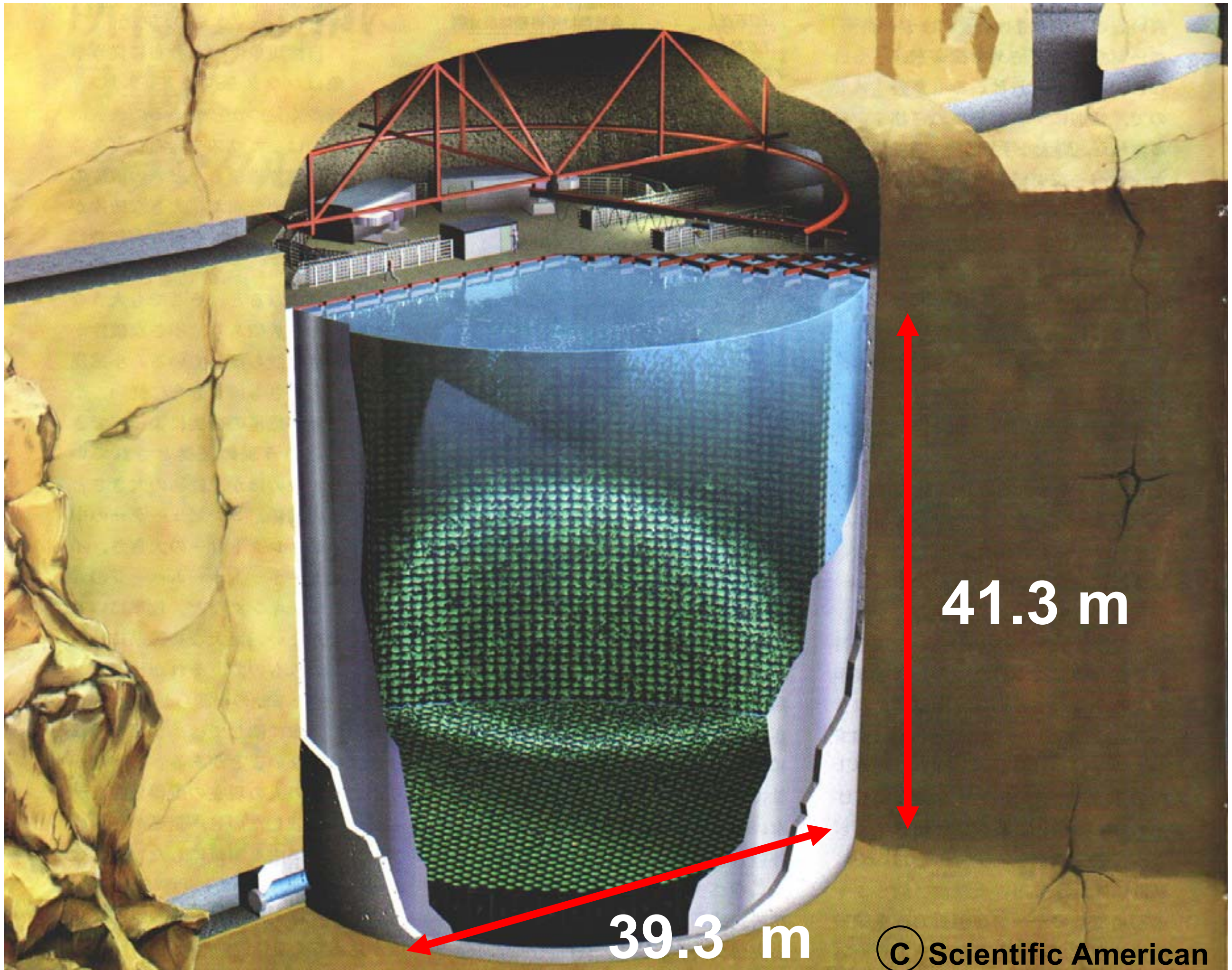
almost isotropic source
(geomagnetic effects)



$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

Predicted ratio of muon to electron neutrinos

Super-K detector



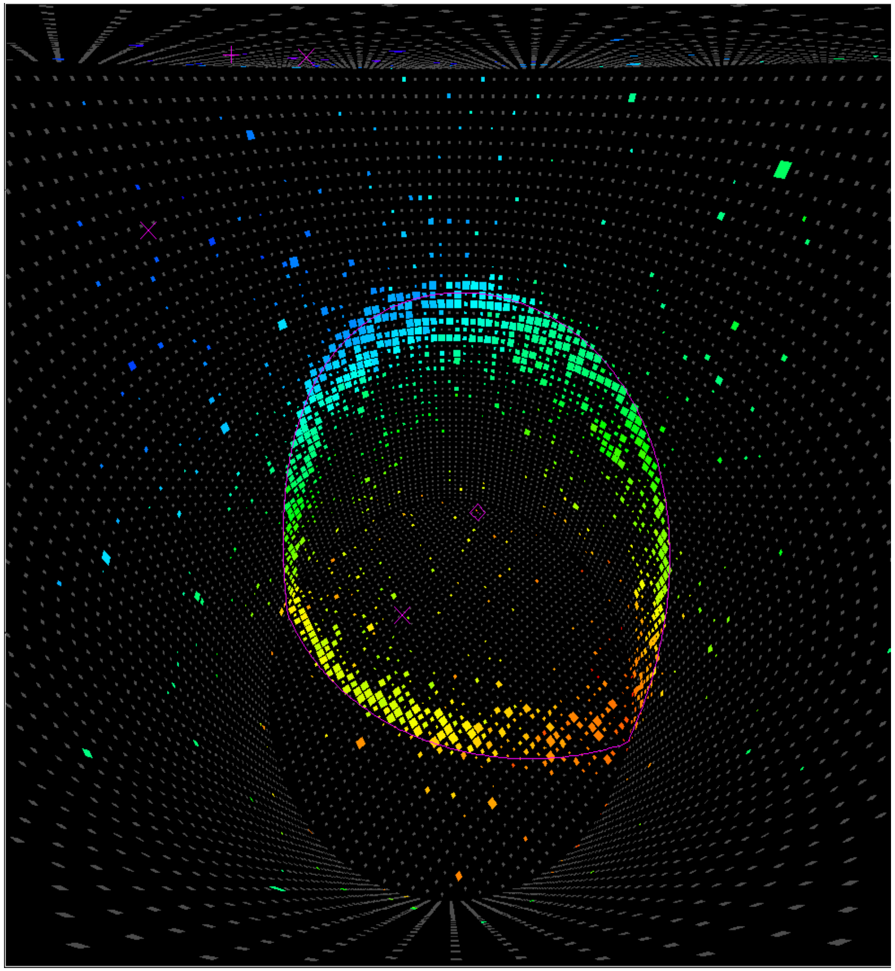
Water Cerenkov detector

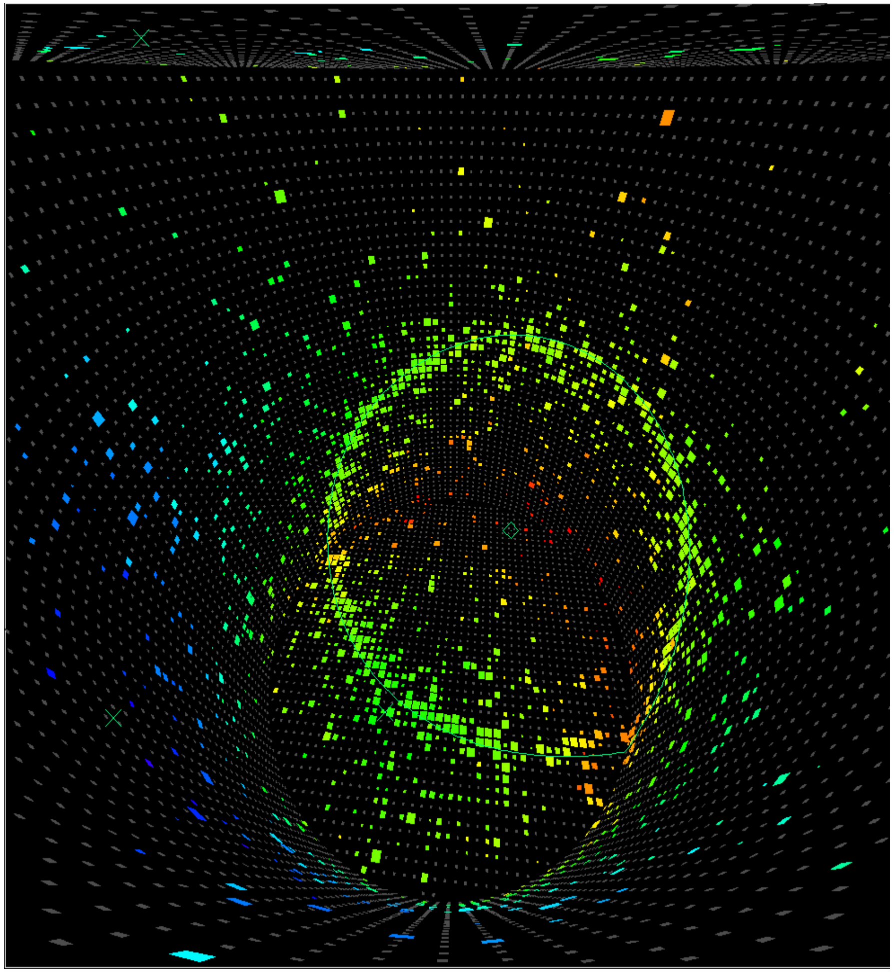
50000 tons of pure light water

≈10000 PMTs

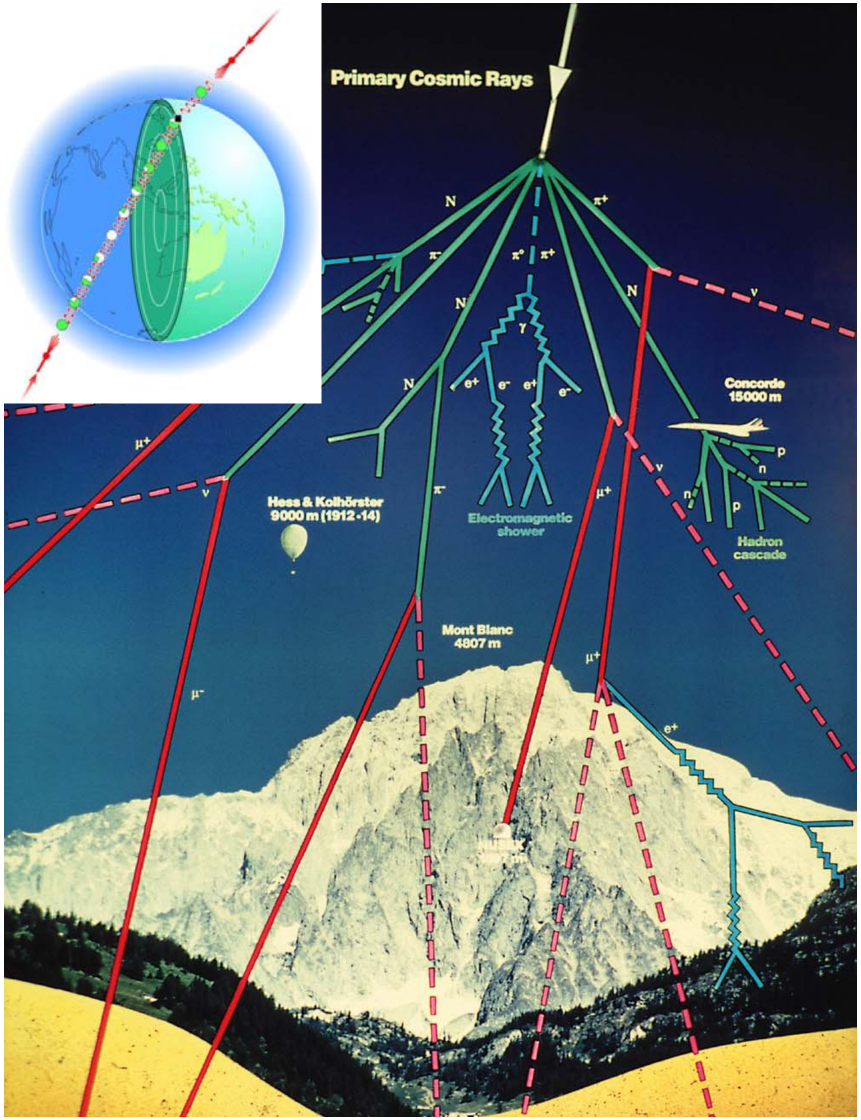
μ/e Background Rejection

e/mu separation directly related to granularity of coverage.
Limit is around 10^{-3} (mu decay in flight) SKII coverage OKOK, less maybe possible



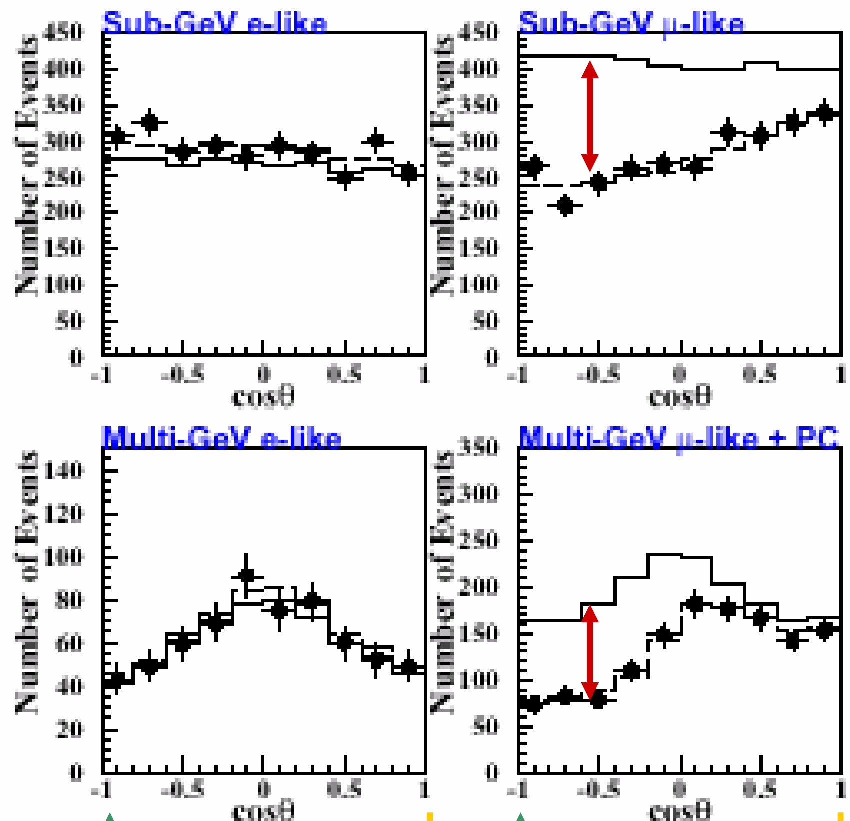


Atmospheric ν : up-down asymmetry



Super-K results

ν_e ν_μ



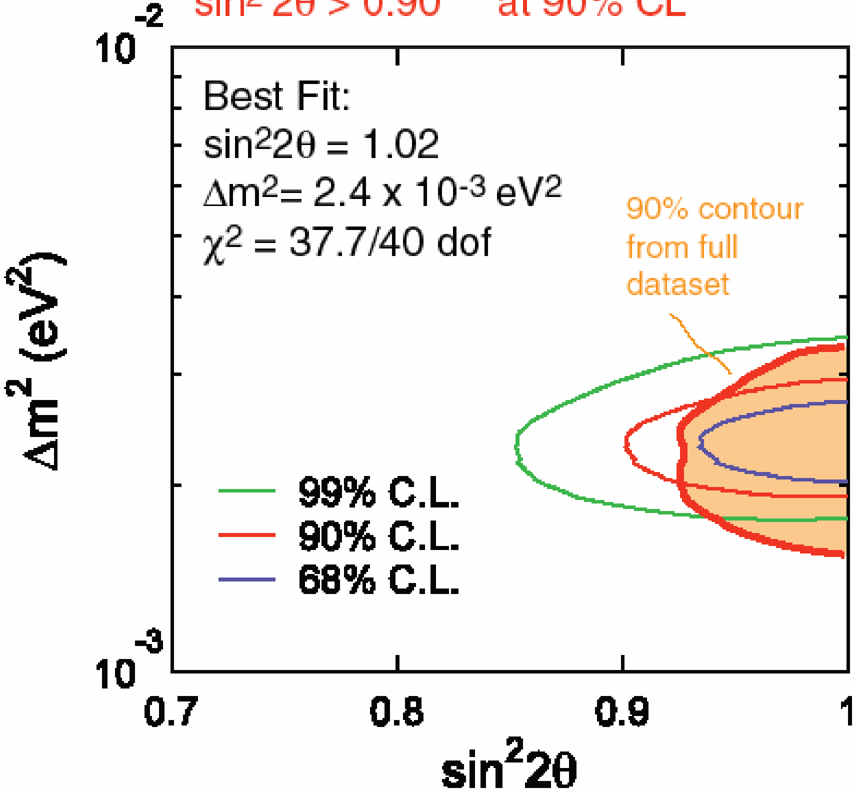
up down

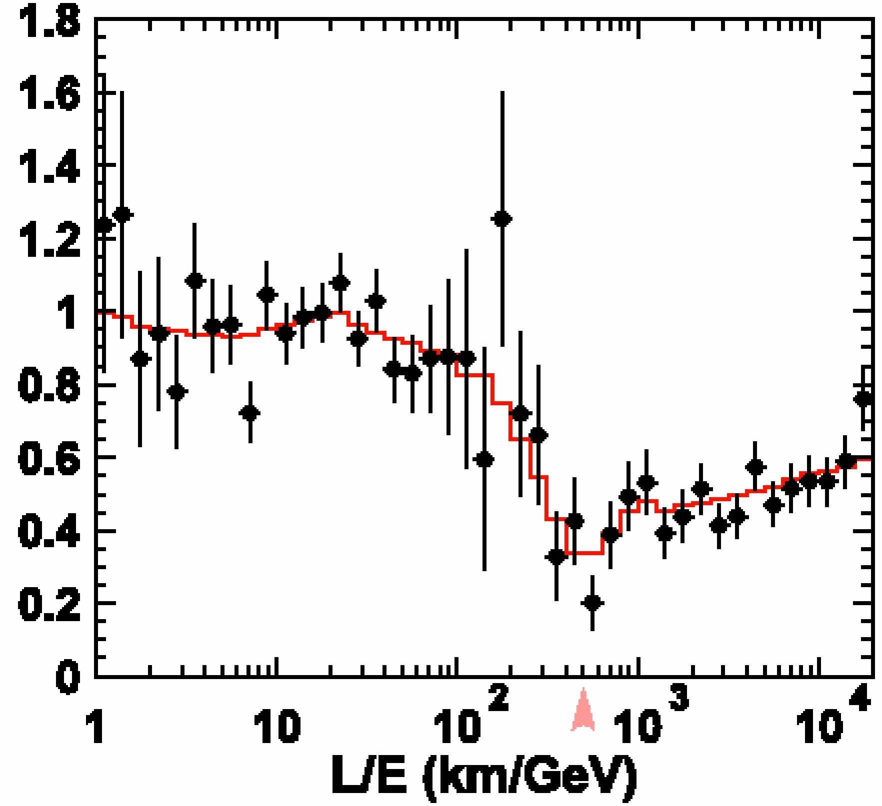
Atmospheric Neutrinos

SuperKamiokande Atmospheric Result

$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.0 \times 10^{-3}\ eV^2$

$\sin^2 2\theta > 0.90$ at 90% CL





K2K Collaboration

JAPAN: High Energy Accelerator Research Organization (KEK) / Institute for Cosmic Ray Research (ICRR), Univ. of Tokyo / Kobe University / Kyoto University / Niigata University / Okayama University / Tokyo University of Science / Tohoku University

KOREA: Chonnam National University / Dongshin University / Korea University / Seoul National University

U.S.A.: Boston University / University of California, Irvine / University of Hawaii, Manoa / Massachusetts Institute of Technology / State University of New York at Stony Brook / University of Washington at Seattle

POLAND: Warsaw University / Solton Institute

Since 2002

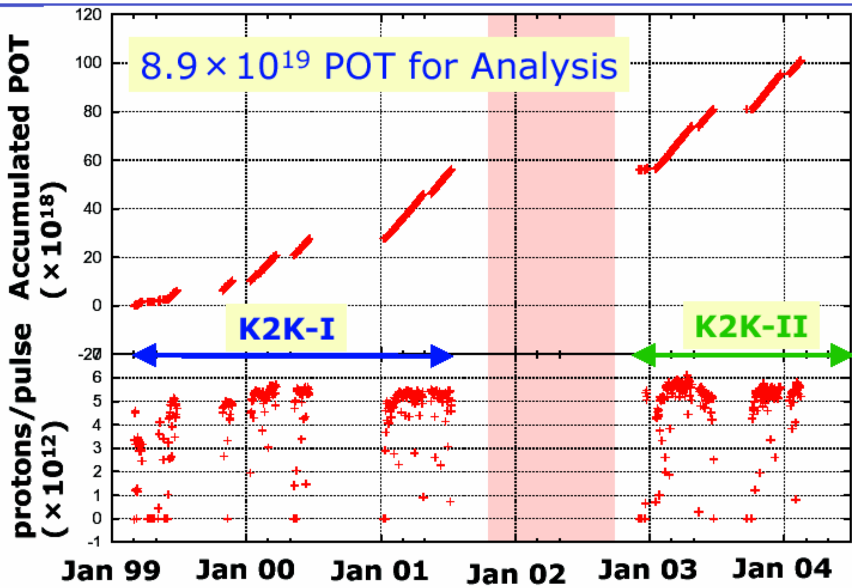
JAPAN: Hiroshima University / Osaka University **U.S.A.:** Duke University

CANADA: TRIUMF / University of British Columbia

ITALY: Rome **FRANCE:** Saclay **SPAIN:** Barcelona / Valencia **SWITZERLAND:** Geneva

RUSSIA: INR-Moscow

Accumulated POT (Protons On Target)



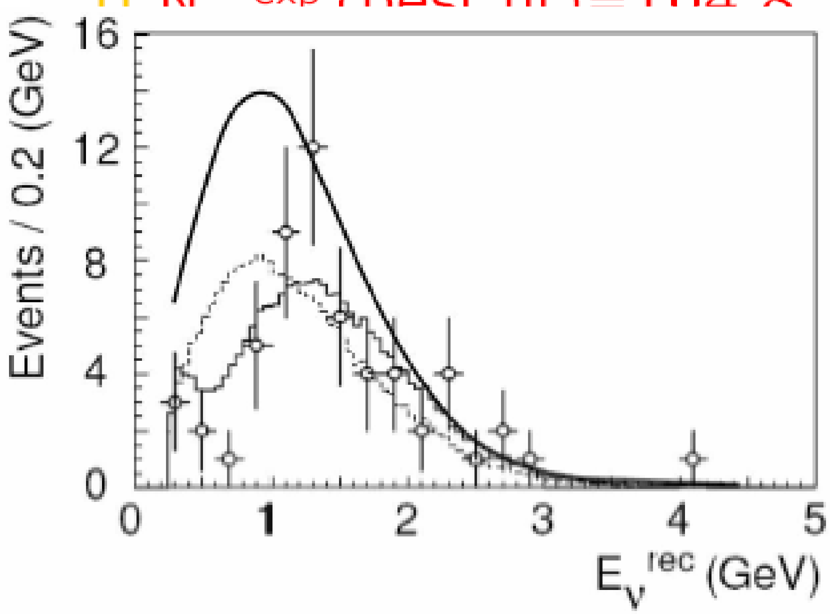
K2K-SK events

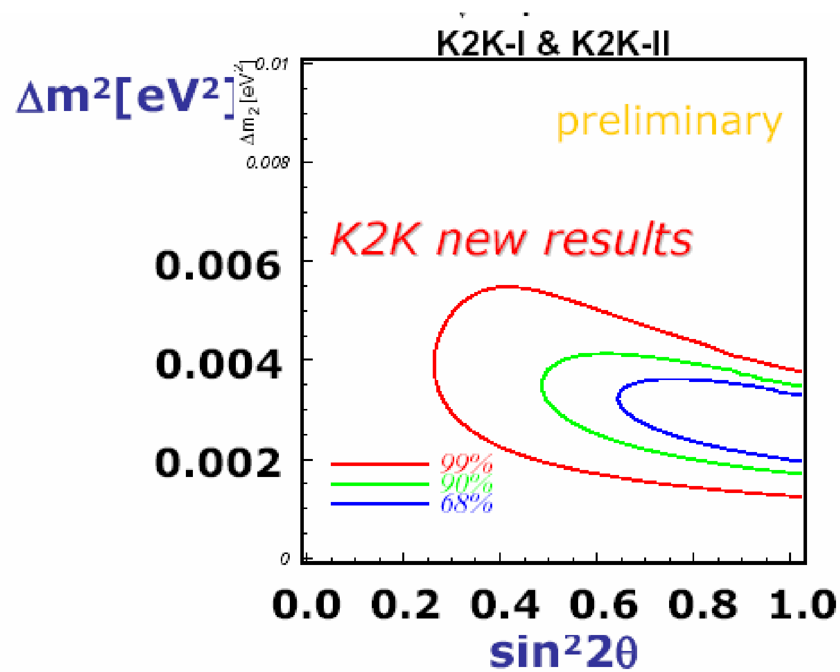
preliminary

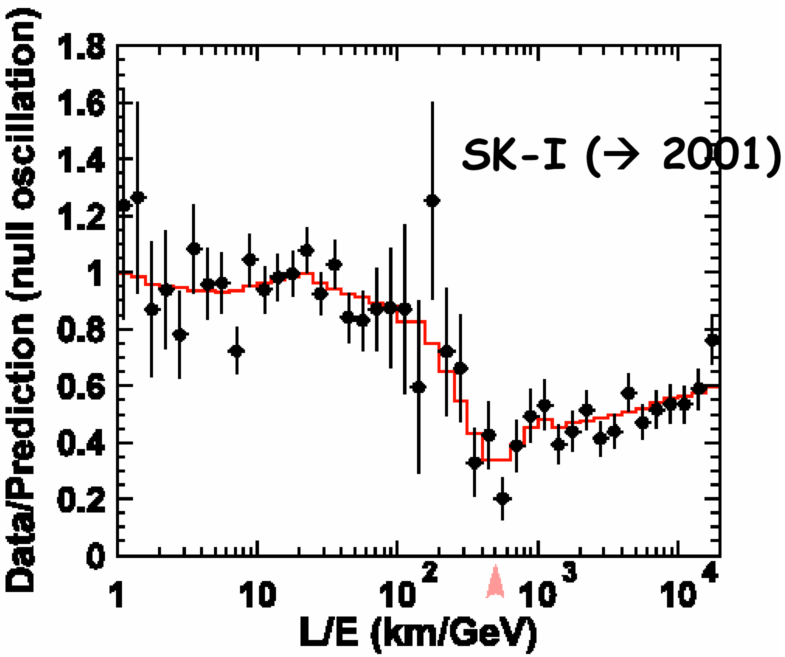
K2K-alll (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	**108** (56, 52)	**150.9** (79.1*, 71.8)
1ring	**66** (32, 34)	**93.7** (48.6, 45.1)
μ-like (for E_ν^{rec})	**57 (56)** (30, 27)	**84.8** (44.3, 40.5)
e-like	**9** (2, 7)	**8.8** (4.3, 4.5)
Multi Ring	**42** (24, 18)	**57.2** (30.5, 26.7)

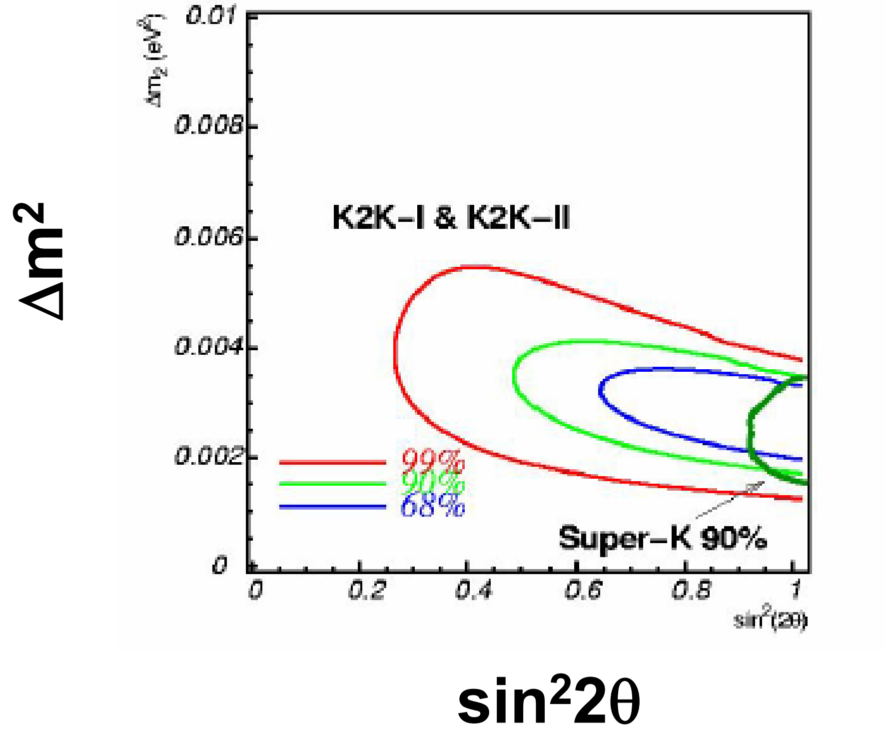
Ref; K2K-I(47.9×10^{18}POT), K2K-II(41.2×10^{18}POT) 23
*: The number is changed from the previous one.

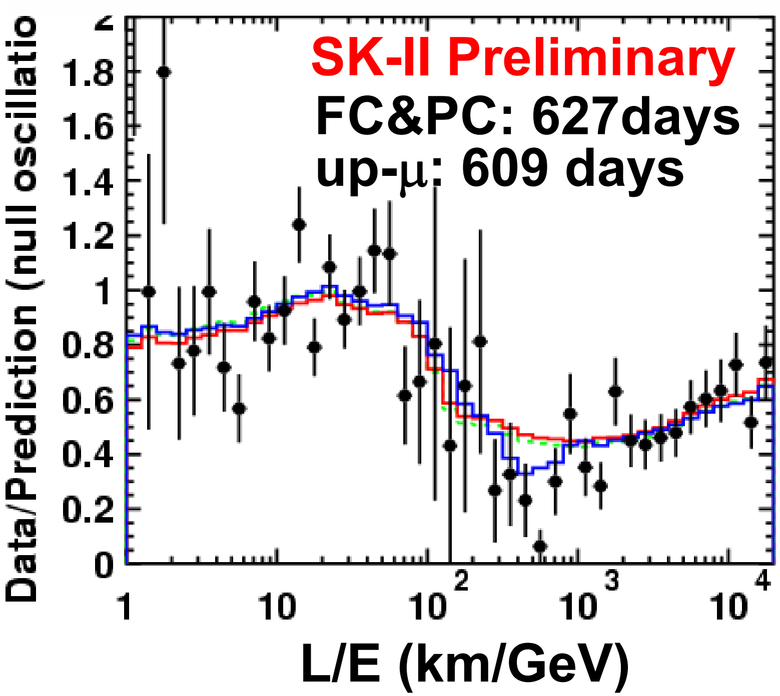
- $N_{SK}^{obs}=108$
- N_{SK}^{exp} (best fit)=104.8











Guide Line χ^2

for $\Delta m^2 = 2.4\times10^{-3}\ eV^2$, $\sin^2 2\theta = 1.02$

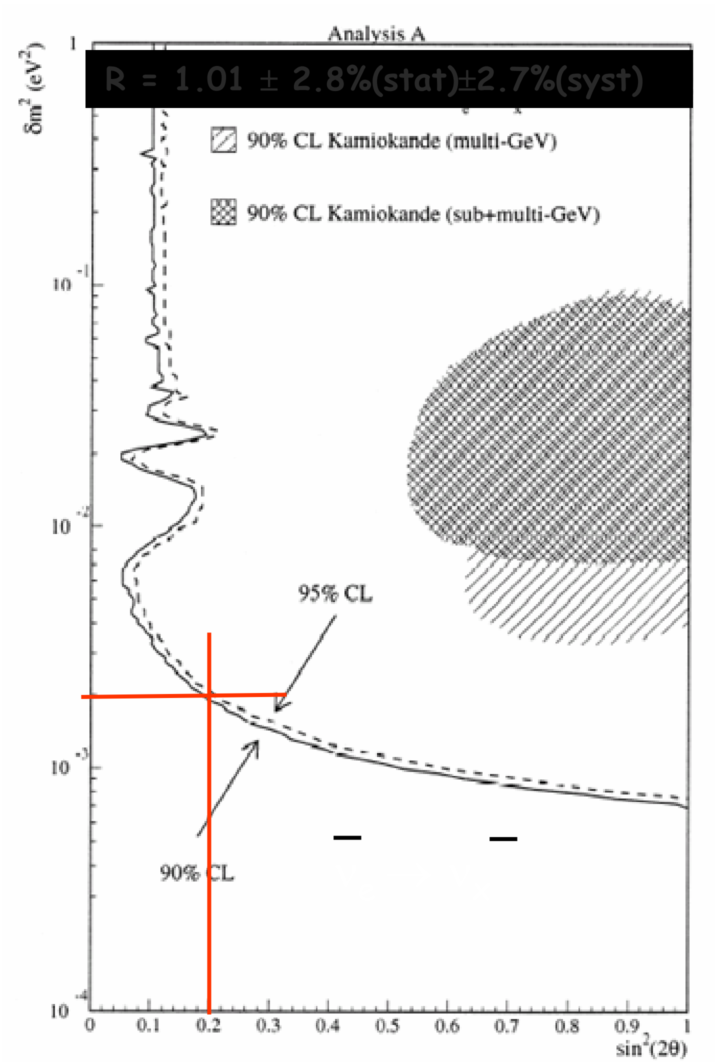
χ^2_{osc} = 42.9/42 d.o.f. (43%)

neutrino decay $\Delta\chi^2 = 16.5$ (4.1σ)

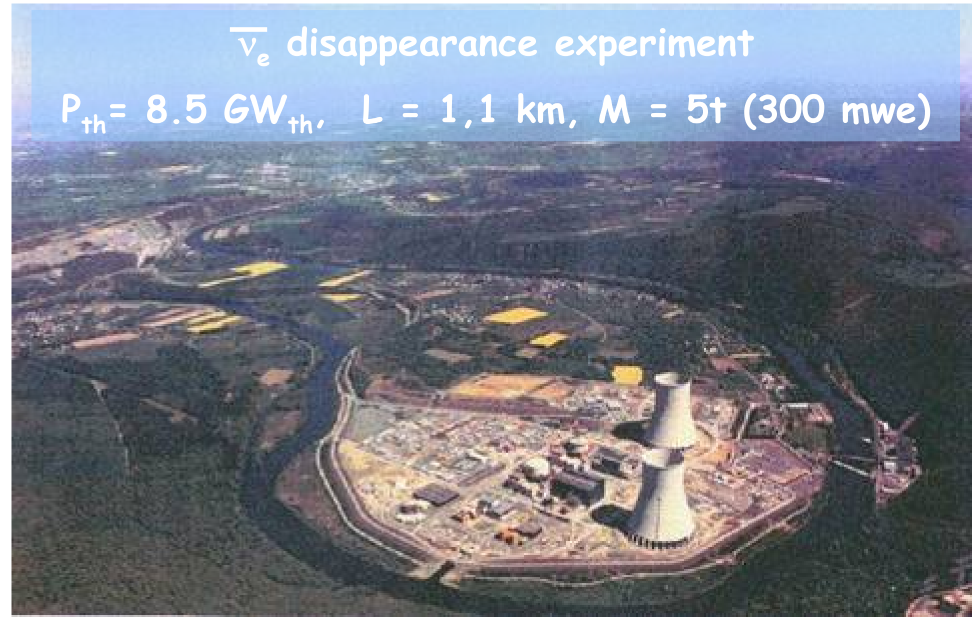
de-coherence $\Delta\chi^2 = 20.9$ (4.6σ)

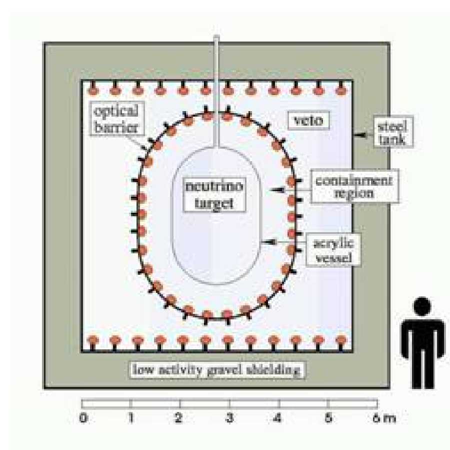
combination will certainly exceed 5 sigma..

θ_{13} : Best current constraint: CHOOZ



M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374





World best constraint !

$@\Delta m^2_{atm}=2\ 10^{-3}\ eV^2$

$\sin^2(2\theta_{13})<0.2$

(90% C.L)

General framework :

1. **We know that there are three families of active, light neutrinos** ***(LEP)***
2. **Solar neutrino oscillations are established** ***(Homestake+Gallium+Kam+SK+SNO)***
3. **Atmospheric neutrino (ν_μ –>) oscillations are established** ***(IMB+Kam+SK+Macro+Sudan)***
4. **At that frequency, electron neutrino oscillations are small** ***(CHOOZ)***

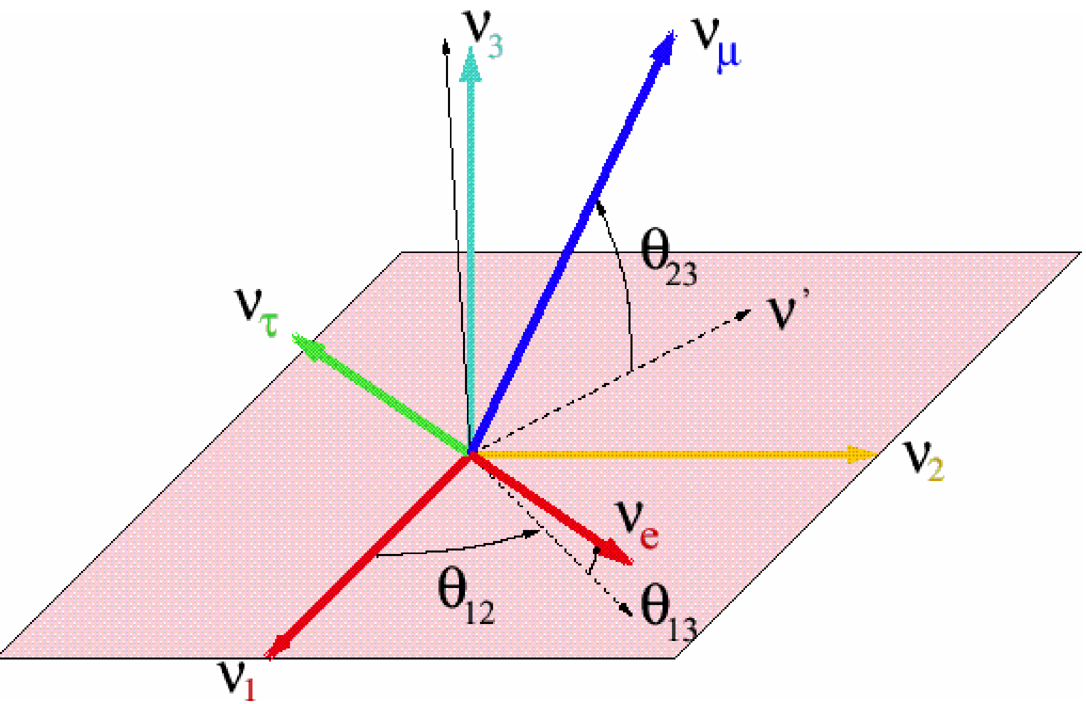
This allows a consistent picture with 3-family oscillations
preferred:
LMA: θ_{12} ~30^0 Δm_{12}^2~$8\ 10^{-5} eV^2$, θ_{23} ~45^0 $\Delta m_{23}{}^2$~ $\pm 2.5\ 10^{-3} eV^2$, $\theta_{13} <\sim 10^0$
with several unknown parameters
=> an exciting experimental program for at least 25 years *)
including leptonic CP & T violations

5. **There is indication of possible higher frequency oscillation (LSND) to be confirmed (miniBooNe)**
This is not consistent with three families of neutrinos oscillating, and is not supported (nor is it completely contradicted) by other experiments.
(Case of an unlikely scenario which hangs on only one not-so-convincing experimental result)
If confirmed, this would be even more exciting

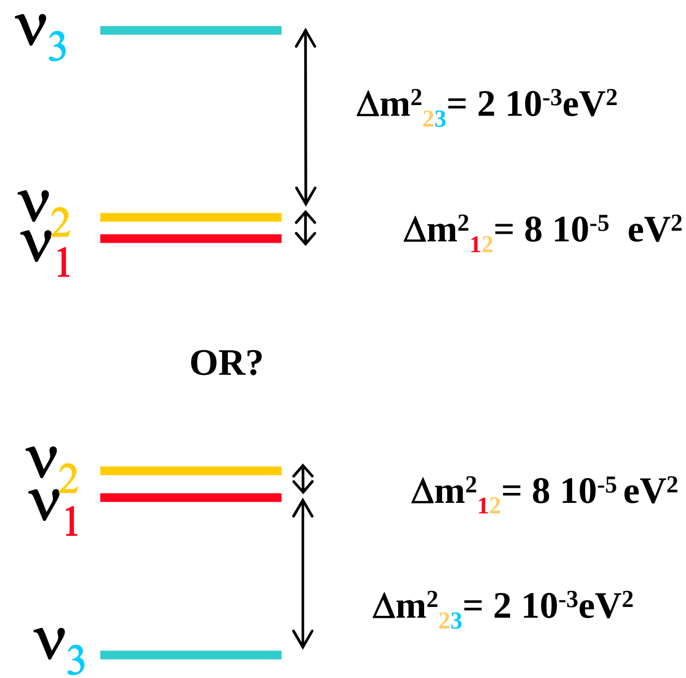
(I will not explore this here, but this has been done. See *Barger et al PRD 63 033002*)

***)to set the scale: CP violation in quarks was discovered in 1964**
and there is still an important program (K0pi0, B-factories, Neutron EDM, BTeV, LHCb..) to go on for 10 years…i.e. a total of ~50 yrs.
and we have not discovered leptonic CP yet!

The neutrino mixing matrix: 3 angles and a phase δ



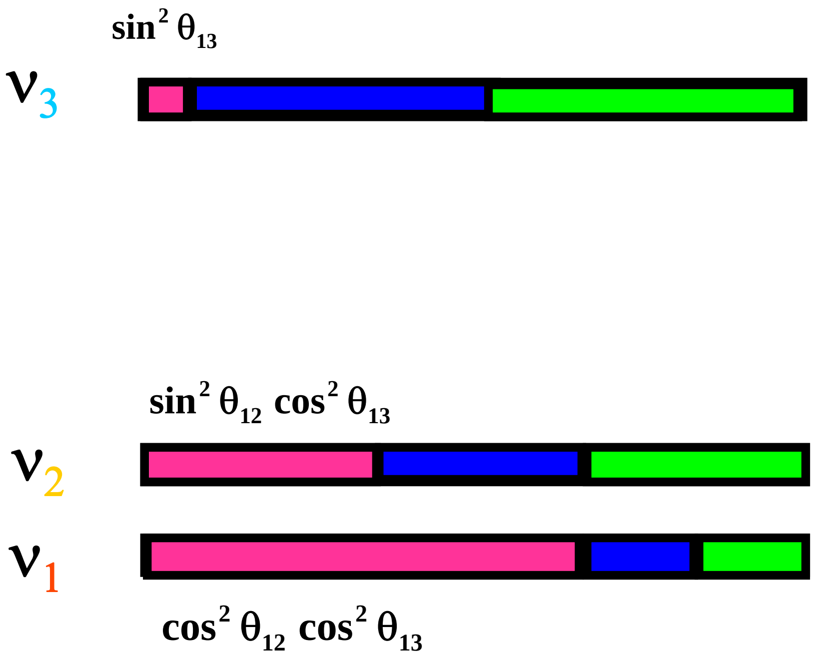
θ_{23} (atmospheric) = 45^0 , θ_{12} (solar) = 32^0 , θ_{13} (Chooz) < 13^0

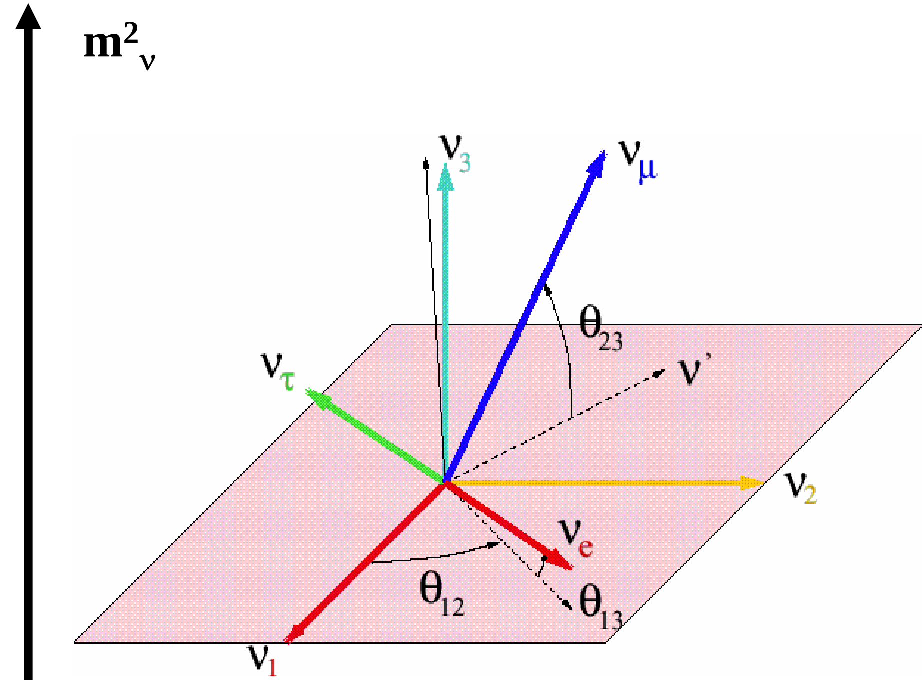


$$U_{MNS} : \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known even after approved program:
θ_{13} , phase δ , sign of Δm^2_{13}

neutrino mixing (LMA, natural hierarchy)





$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

ν_e is a (quantum) mix of

ν_1 (majority, 65%) and ν_2 (minority 30%)

with a small admixture of ν_3 (< 13%) (CHOOZ)

Neutrinos have mass and mix

This is NOT the Standard Model

why cant we just add masses to neutrinos?

Majorana neutrinos $\nu_i = \overline{\nu}_i$

or

Dirac neutrinos? $\nu_i \neq \overline{\nu}_i$

e+ ≠ e− since Charge(e+) = − Charge(e−).
But neutrinos may not carry any conserved charge-like quantum number.
There is NO experimetal evidence or theoretical need for a conserved Lepton Number L as
L(ν) = L(l−) = −L(ν̄) = −L(l+) = 1

then, nothing distinguishes ν_i from $\overline{\nu}_i$

violation of fermion number…. !

Adding masses to the Stadard model neutrino 'simply' by adding a Dirac mass term

$$m_D \nu_L \overline{\nu_R}$$

implies adding a right-handed neutrino.

No SM symmetry prevents adding then a term like

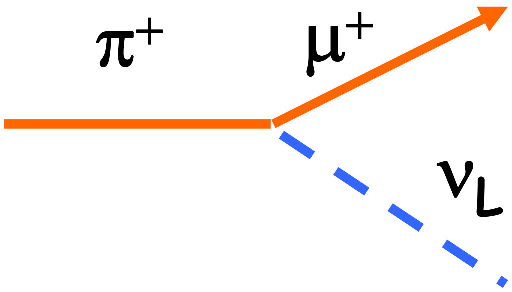
$$m_M \overline{\nu_R{}^c}\, \nu_R$$

and this simply means that a neutrino turns into a antineutrino
(the charge conjugate of a right handed antineutrino is a left handed neutrino!)

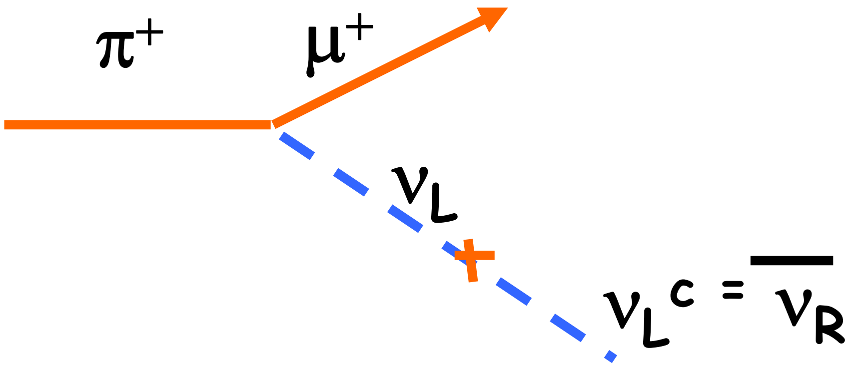
this does not violate spin conservation since a left handed field has a component of the opposite helicity (and vice versa)

$\nu_L \approx \nu_- + \nu_+ \, m/E$

Pion decay with massive neutrinos



+



1

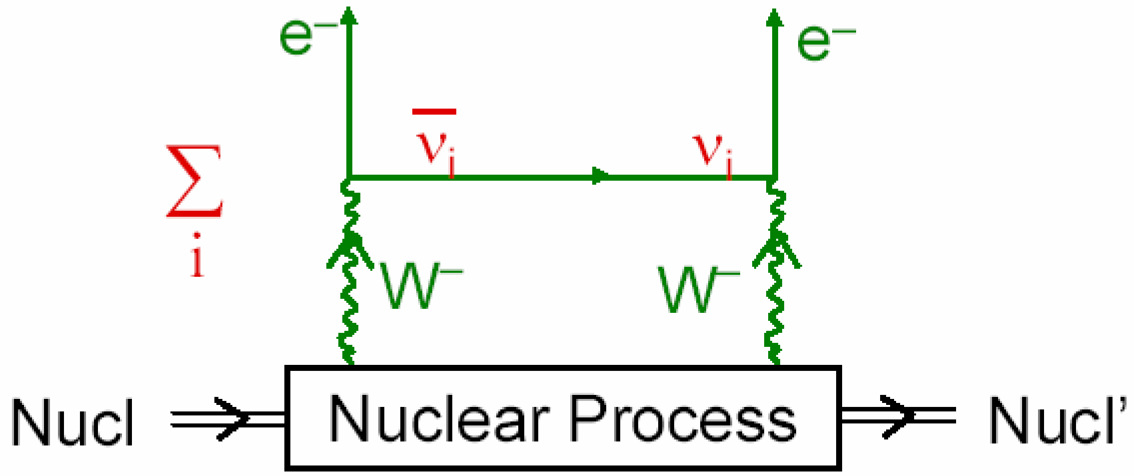
$(m_\nu /E)^2$

$(.05/30\ 10^6)^2 = 10^{-18}$

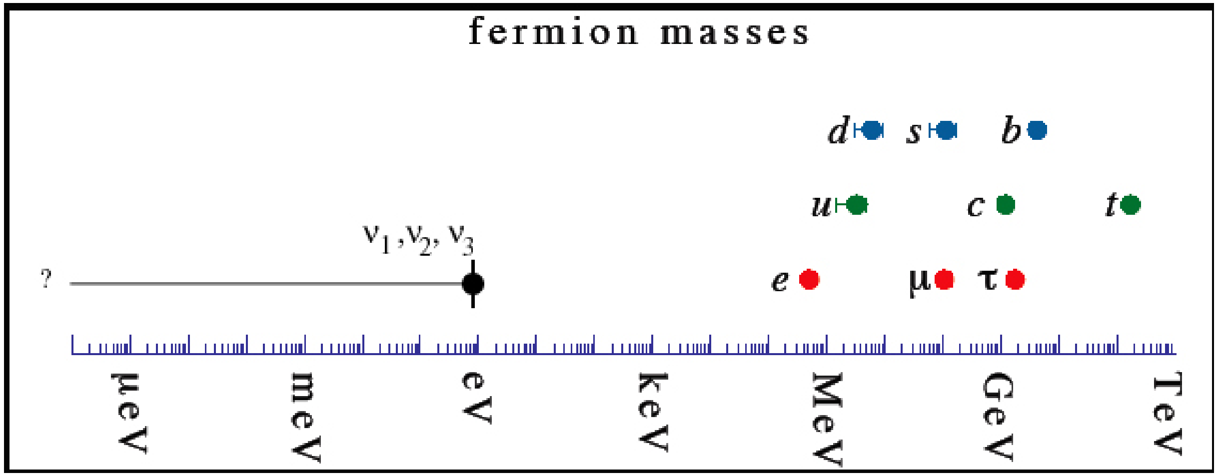
no problem

The Idea That Can Work —

Neutrinoless Double Beta Decay [0νββ]



By avoiding competition, this process can cope with the small neutrino masses.



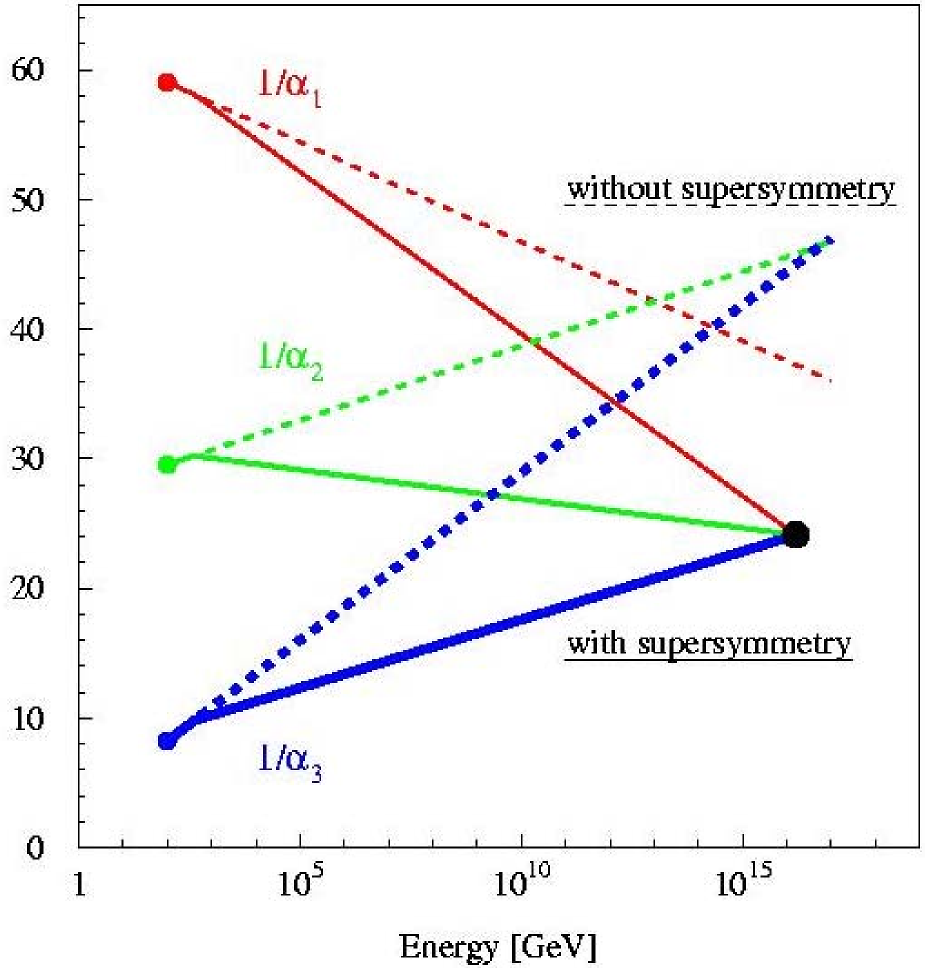
The mass spectrum of the elementary particles. Neutrinos are 10^{12} times lighter than other elementary fermions. The hierarchy of this spectrum remains a puzzle of particle physics.

Most attractive wisdom: via the see-saw mwchanism,
the neutrinos are very light because they are low-lying states
in a split doublet with heavy neutrinos of mass scale interestingly
similar to the grand unification scale.

$m_{\nu.}\, M = \langle v \rangle^2$ with $\langle v \rangle \sim= m_{top} = 174$ GeV

$m_{\nu.} = O(10^{-2})$ eV

$M \sim 10^{15}$ GeV


60
50
40
30
20
10
0
1/α1
1/α2
1/α3
without supersymmetry
with supersymmetry
1
10^5
10^10
10^15
Energy [GeV]

food for thought: (simple)

what result would one get if one measured the mass of a ν_e (in K-capture for instance)?

what result would one get if one measured the mass of a ν_μ (in pion decay)?

Is energy conserved when neutrinos oscillate?

future experiments on neutrino masses

-- neutrinoless double beta decay
-- oscillations and CP violation