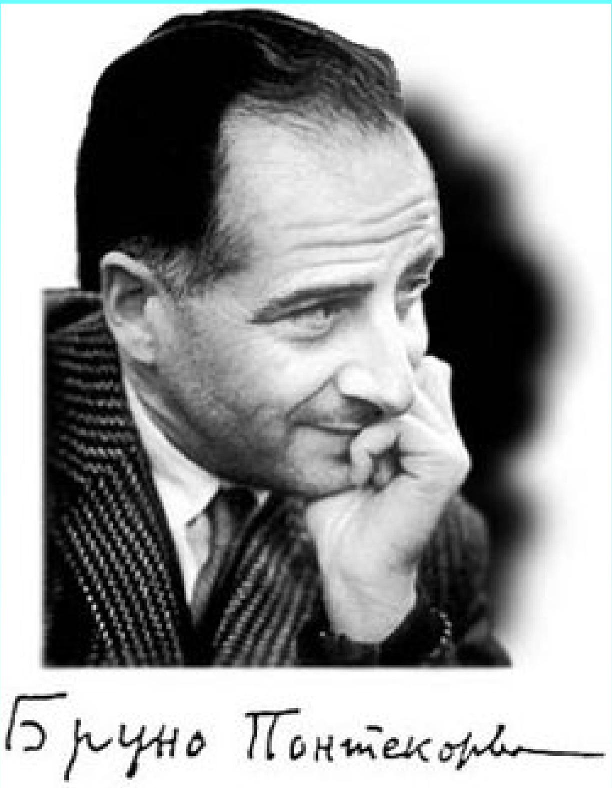
Neutrinos and New physics world

A. Yu. Smirnov

International Centre for Theoretical Physics, Trieste, Italy
Institute for Nuclear Research, RAS, Moscow, Russia

50 years ago...



B. Pontecorvo

``Mesonium and antimesonium"

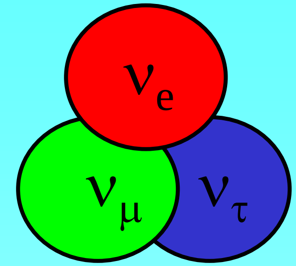
Zh. Eksp.Teor. Fiz. 33, 549 (1957)
[Sov. Phys. JETP 6, 429 (1957)] translation

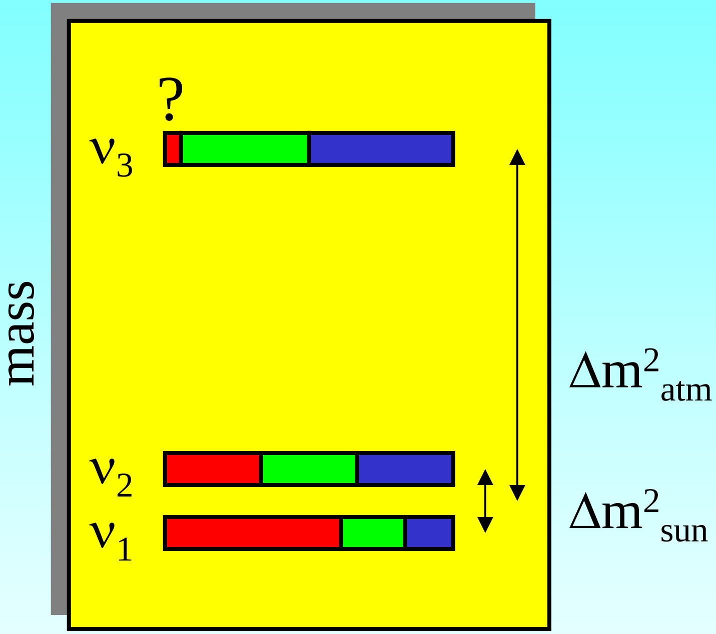
mentioned a possibility of neutrino mixing and oscillations

Results of Wu experiment, 1957:
Parity violation → V-A theory,
two-component massless neutrino

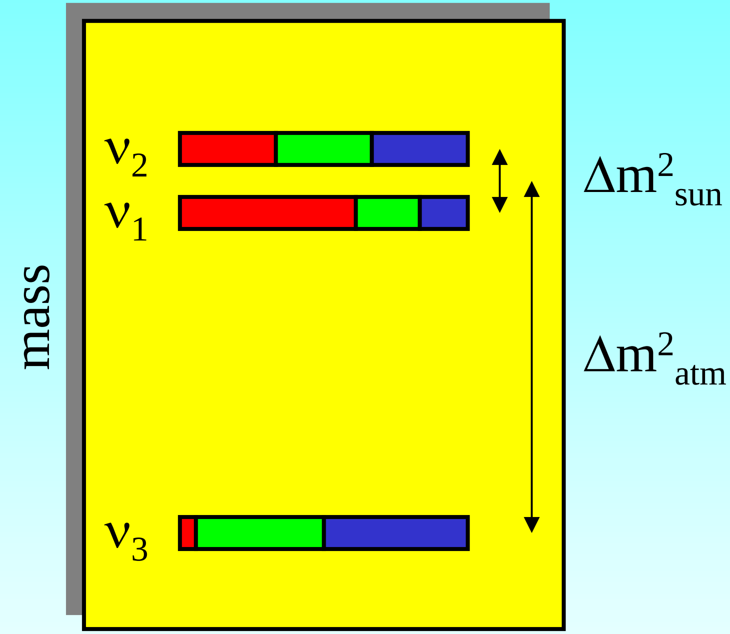
...and now

Mass and flavor spectrum





?



Normal mass hierarchy

Inverted mass hierarchy

$\nu_f = U_{PMNS}\, \nu_{mass}$

$U_{PMNS} = U_{23}\, I_\delta\, U_{13}\, I_{-\delta}\, U_{12}$

The first phase

of studies of neutrino mass and mixing is essentially over

The main results:

Discovery of non-zero neutrino masses

Determination of the dominant structure of the lepton mixing:
discovery of two large mixing angles

Establishing strong difference of the quark and lepton mass spectra and mixing patterns

New phase will start with new series of experiments in 2008 – 2010
the main objectives
- determination of the absolute scale of neutrino mass;
- subdominant structures of mixing matrix;
- identification of the mass hierarchy, etc.

Plan:

Give explanation of statements above
and discuss their possible implications

Part I: Determination of neutrino mass and mixing

- Effects
- Experiments
- Summary of results
- Leptons versus quarks

Part II: To interpretation of the results:

- Neutrinos and new physics

- Grand Unification & neutrino mass
- Quark-lepton complementarity
- Flavor symmetry tri-bimaximal mixing
- Extra dimensions

Masses and Mixing

Flavors and masses

Flavor neutrino states:

ν_e ν_μ ν_τ

e μ τ

- correspond to certain charged leptons
- interact in pairs
- eigenstates of the CC weak interactions

ν_s Sterile neutrinos?

Mass eigenstates

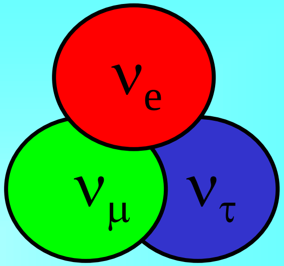
ν_1 ν_2 ν_3

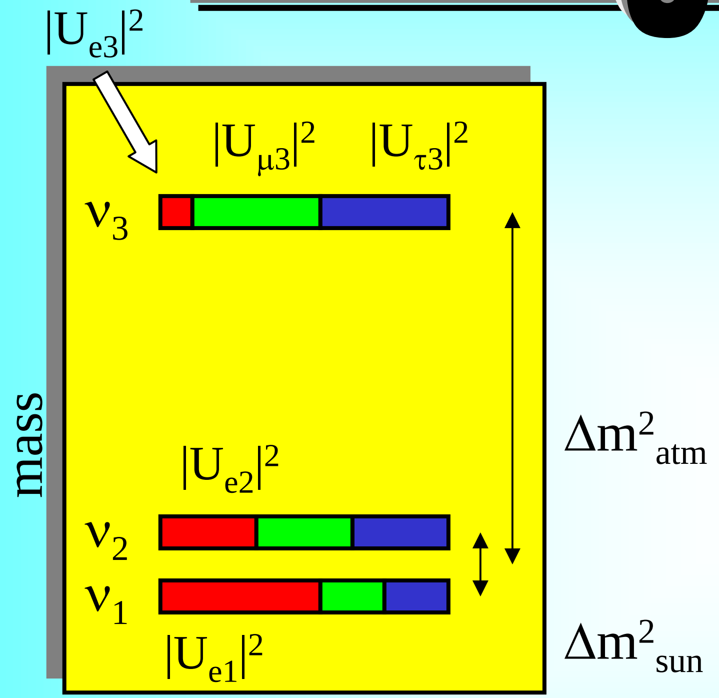
m_1 m_2 m_3

Mixing

Flavor states $\neq$ Mass eigenstates

Mixing angles





Normal mass hierarchy

Moduli of mixing elements are paremeterization independent

$$\tan^2\theta_{12} = |U_{e2}|^2 \;/\; |U_{e1}|^2$$

$$\sin^2\theta_{13} = |U_{e3}|^2$$

$$\tan^2\theta_{23} = |U_{\mu3}|^2 \;/\; |U_{\tau3}|^2$$

$$\Delta m^2_{atm} = \Delta m^2_{32} = m^2_3 - m^2_2$$

$$\Delta m^2_{sun} = \Delta m^2_{21} = m^2_2 - m^2_1$$

Rotation in 3D space

Mixing matrix

$$\nu_f = U_{PMNS}\, \nu_{mass}$$

where $\nu_f = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$ $\nu_{mass} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

the matrix is unitary:

$$U_{PMNS}^{+}\, U_{PMNS} = I$$

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix

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

$$U_{\alpha i} = |U_{\alpha i}|\, e^{i\phi_{\alpha i}}$$

Due to unitarity and possibility to renormalize wave functions of neutrinos and charge leptons only one phase is physical

Two effects

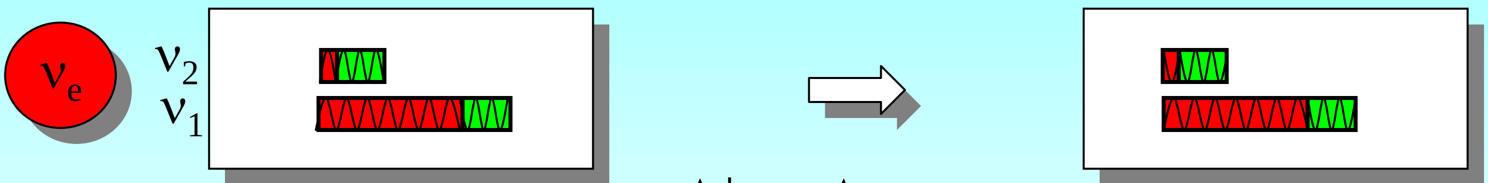
Oscillations
in vacuum
and in matter

Adiabatic
conversion
in matter
MSW effect

Vacuum oscillations

- Flavors of mass eigenstates do not change
- Admixtures of mass eigenstates do not change: no ν_1 <-> ν_2 transitions

} Determined by θ



$\Delta\phi = 0$

$\Delta\phi = \Delta v_{phase}\, t$

- Due to difference of masses ν_1 and ν_2 have different phase velocities → phase difference

$$\Delta\phi = \frac{\Delta m^2}{2E} L$$

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

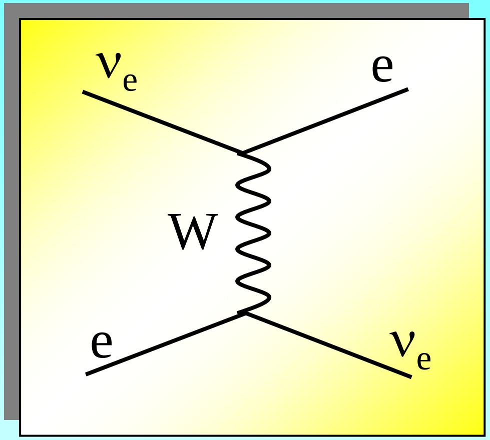
oscillations: effects of the phase difference increase which changes the interference pattern

Refraction

L. Wolfenstein, 1978

Elastic forward scattering → Potentials V_e, V_μ

for ν_e ν_μ



- $V \sim 10^{-13}$ eV inside the Earth for E = 10 MeV
- difference of potentials

$$V_e - V_\mu = \sqrt{2}\, G_F n_e$$

- Refraction index:

$$n - 1 = V / p$$

- Refraction length:

$$l_0 = 2\pi / (V_e - V_\mu) = \sqrt{2}\, \pi / G_F n_e$$

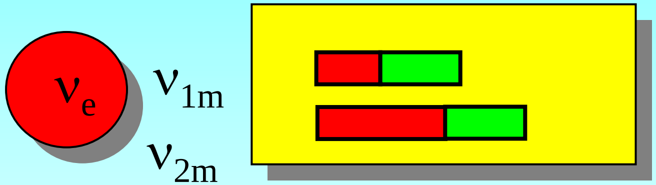
- n – 1 =
  - ~ 10^{-20} inside the Earth
  - < 10^{-18} inside the Sun
  - ~ 10^{-6} inside the neutron star

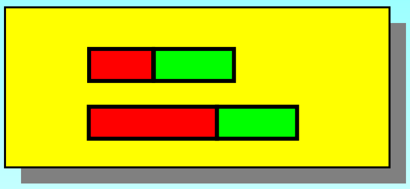
- Neutrino optics → focusing of neutrinos fluxes by stars, complete internal reflection, etc

Oscillations in matter

In uniform matter (constant density)
mixing is constant $\theta_m(E, n) = \text{constant}$

Dynamics of propagation
is the same as in vacuum
-> oscillations





$\Delta\phi_m = 0$

$\Delta\phi_m = (H_2 - H_1)\, L$

Parameters of oscillations
(depth and length)
are determined by mixing in matter
and by effective energy split in matter

$\sin^2 2\theta, \quad l_\nu$ → $\sin^2 2\theta_m, \; l_m$

Adiabatic conversion

- Admixtures of the eigenstates do not change (adiabaticity)

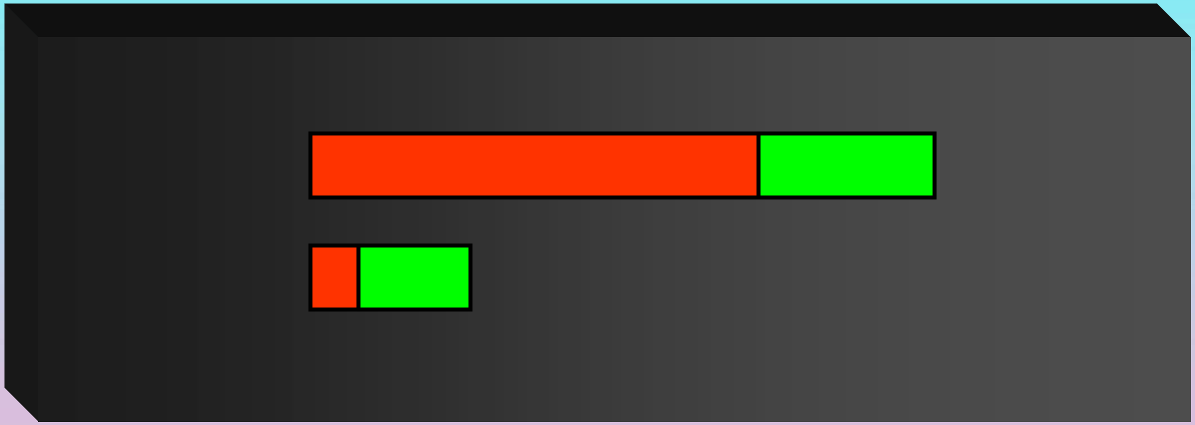
  Determined by mixing θ_m^0 in the production point

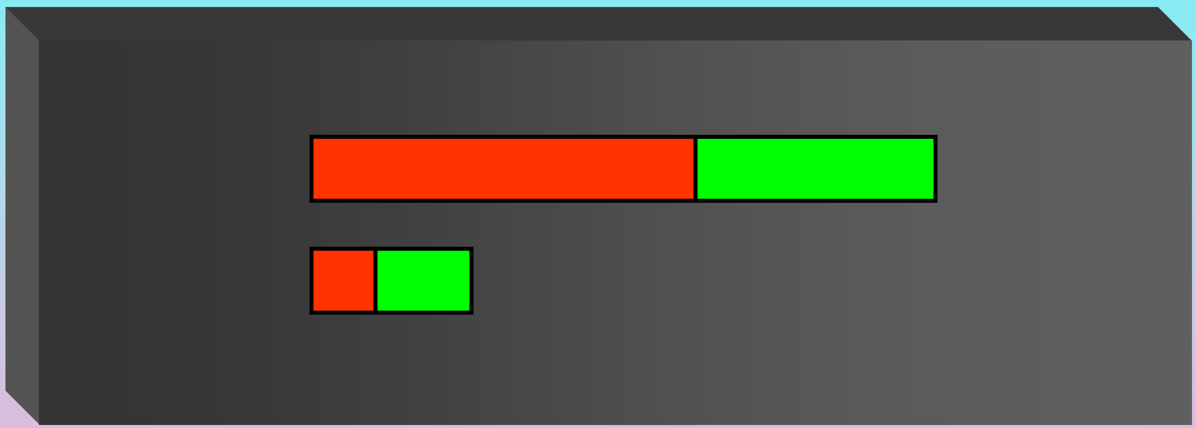
- Flavors of the eigenstates follow the density change

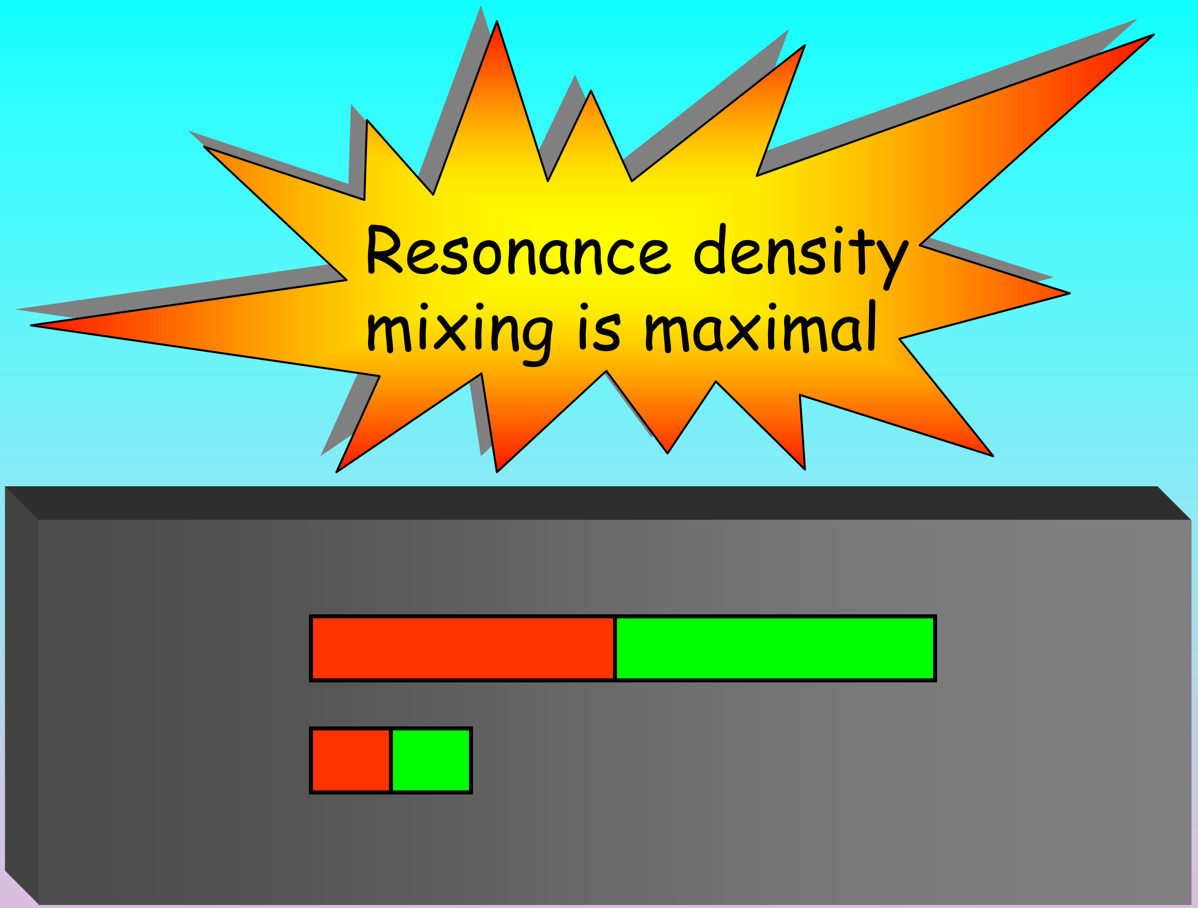
  Flavor: $\theta_m = \theta_m(\rho(t))$

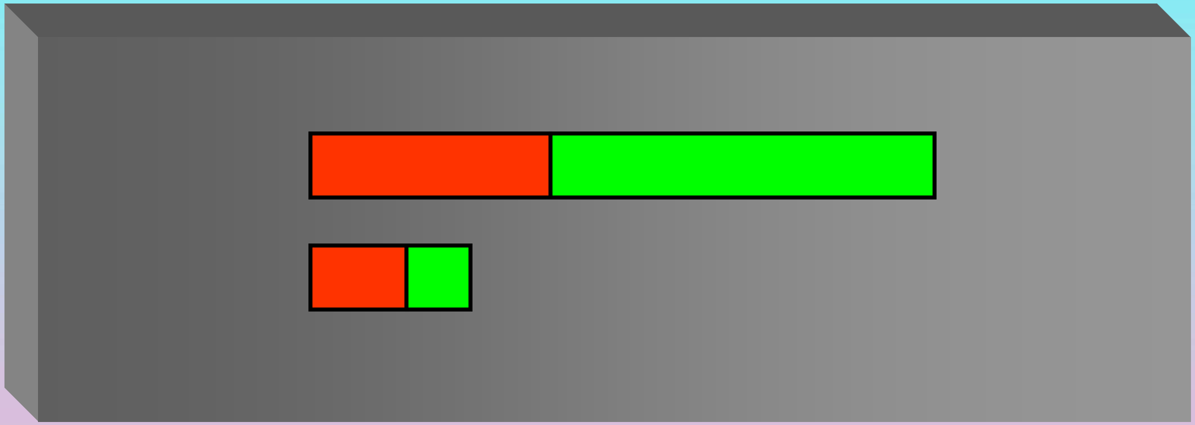
- Phase difference of the eigenstates changes leading to oscillations

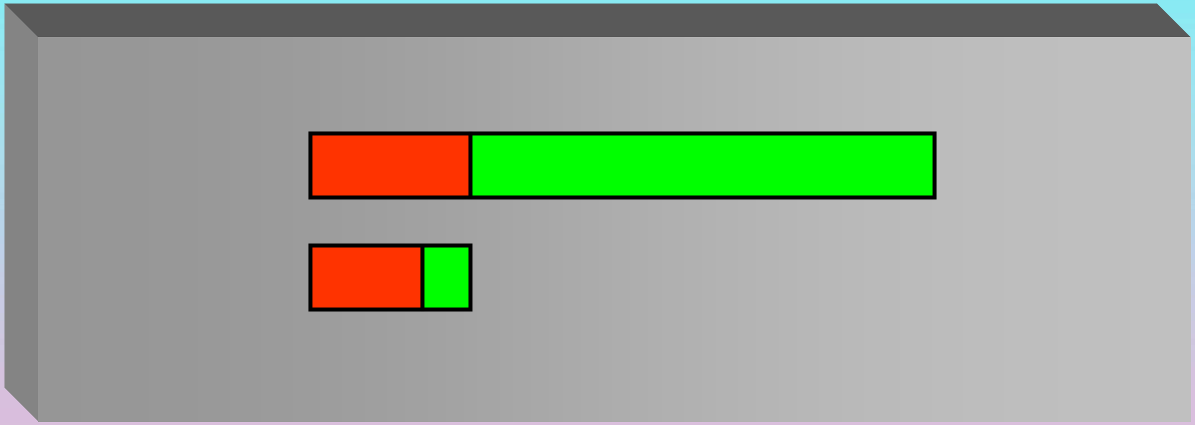
  $\phi = (H_1 - H_2)\, t$






Resonance density
mixing is maximal

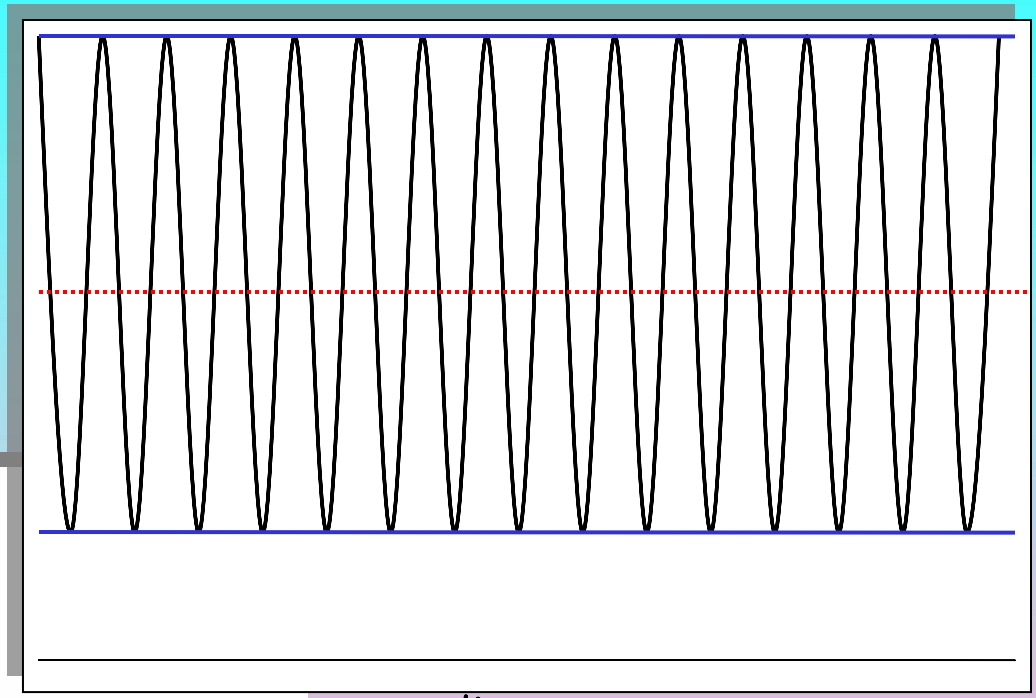




Spatial picture

Oscillations

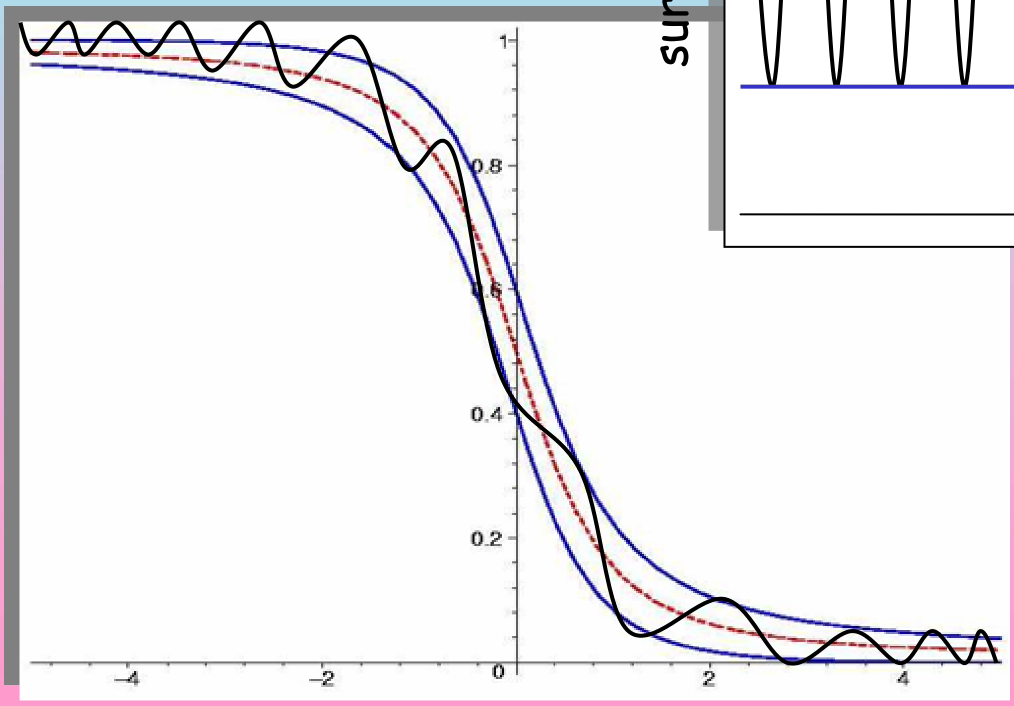
survival probability



distance

Adiabatic conversion

survival probability



distance

Experiments and Results

Solar Neutrinos

$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 26.73\ MeV$

electron neutrinos are produced

$F = 6\ 10^{10}\ cm^{-2}\ c^{-1}$

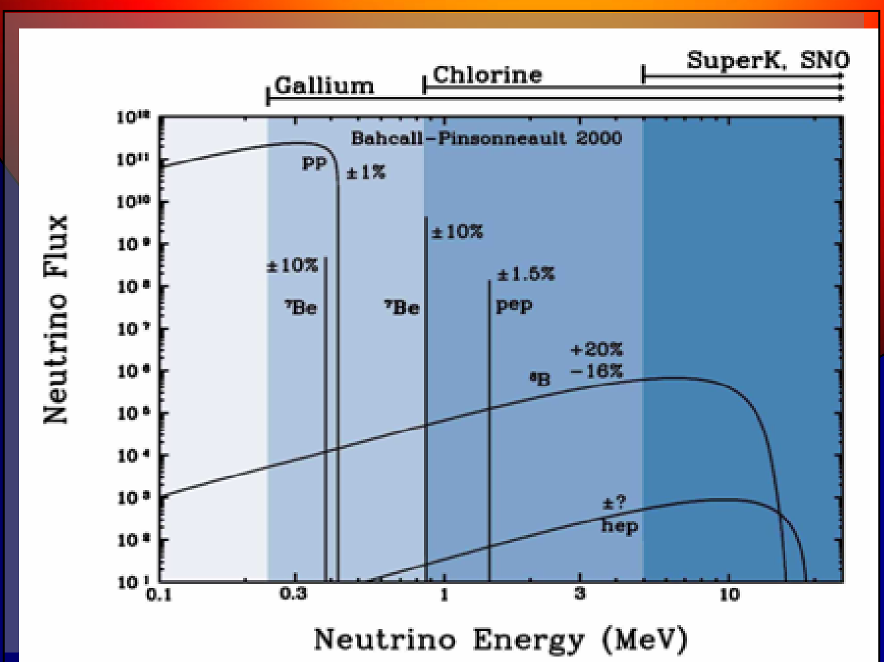
total flux at the Earth

Adiabatic conversion

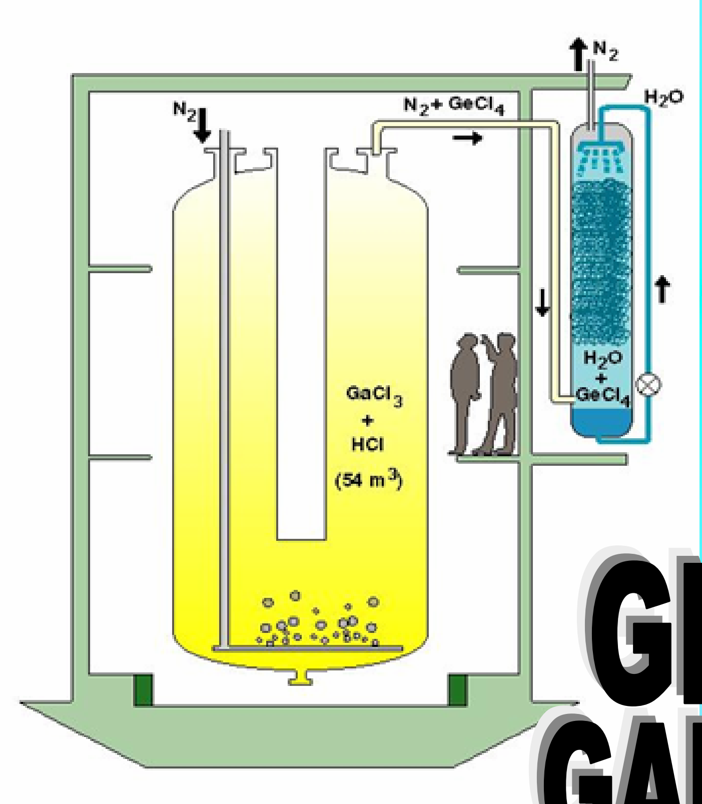
ν

Oscillations in matter of the Earth

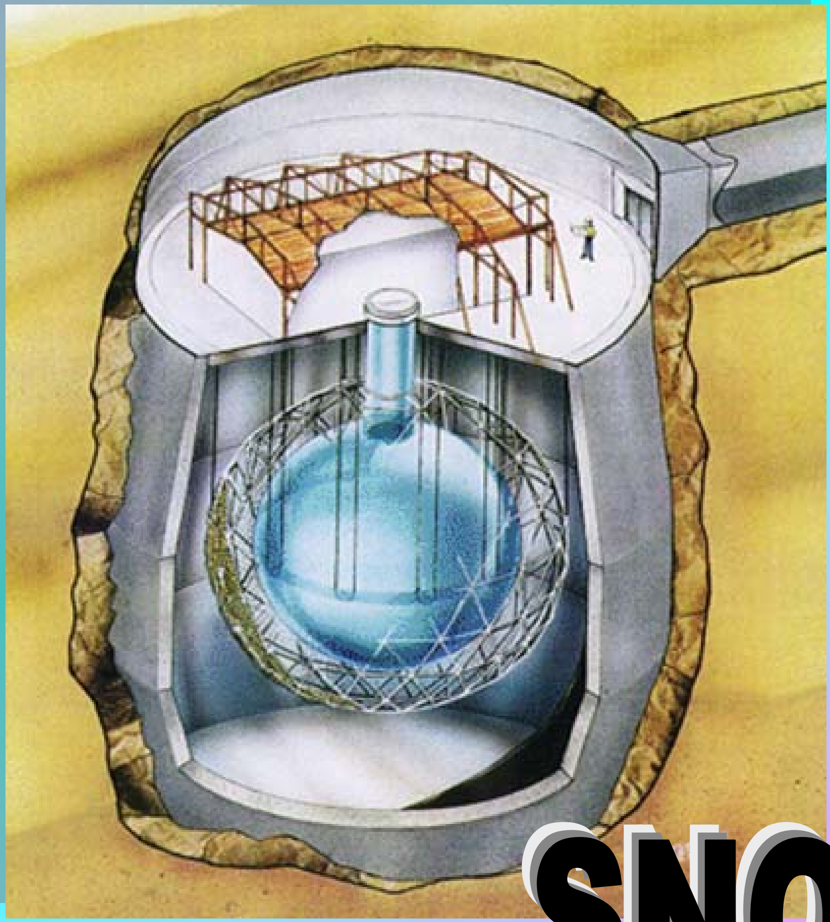
ρ : (150 ⇨ 0) g/cc



Homestake
Kamiokande
SAGE

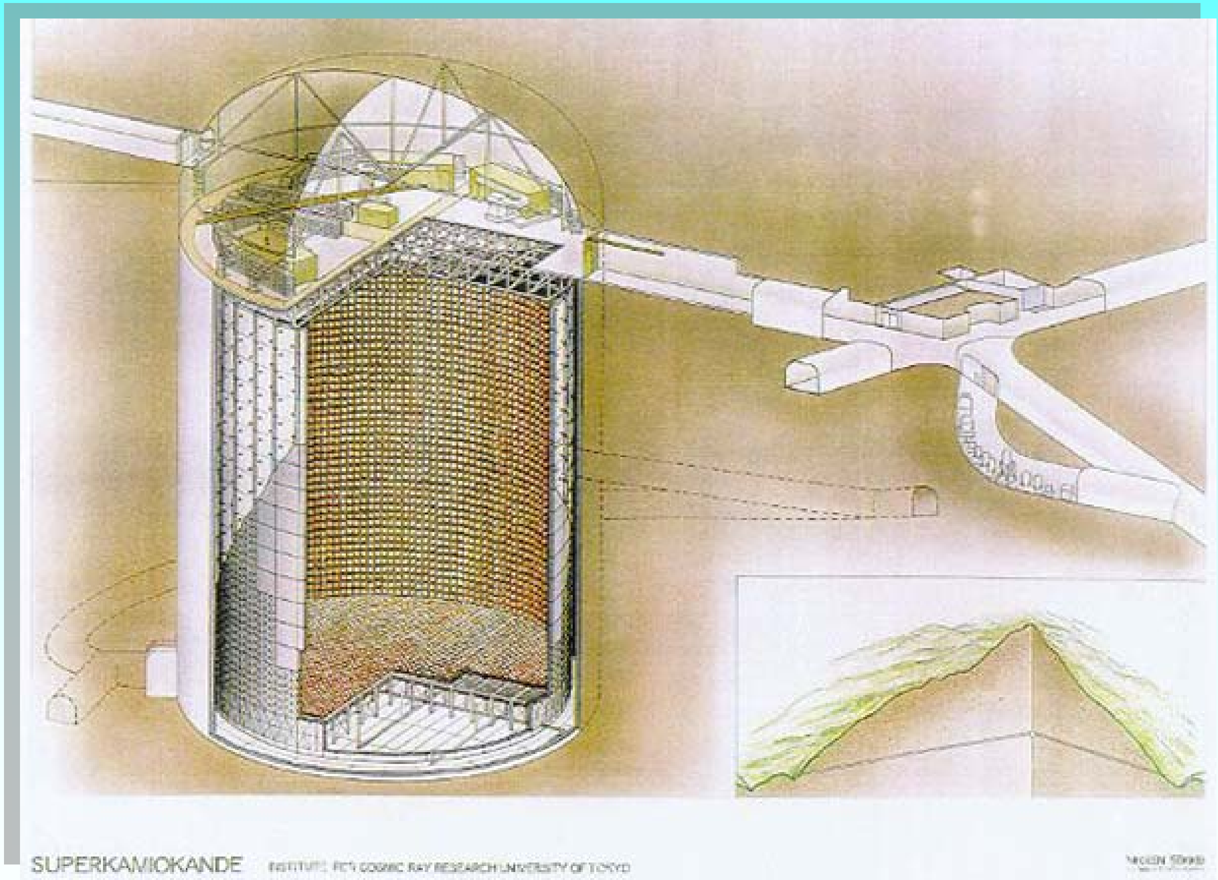


GNO
GALLEX



SNO
SuperKamiokande

SuperKamiokande



50 kt water
Cherenkov detector

ν e –> ν e

KamLAND

Kamioka
Large Anti-Neutrino Detector

- Reactor long baseline experiment
  150 - 210 km

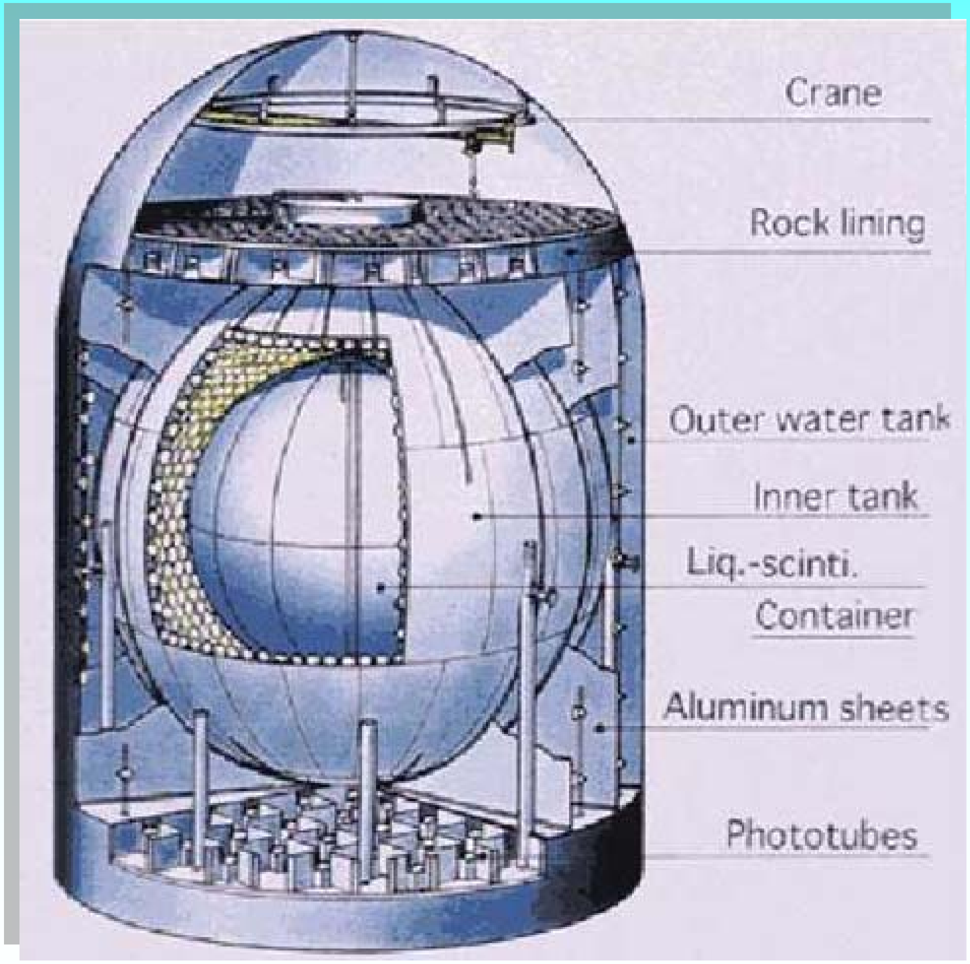
- $\bar{\nu}_e + p \rightarrow e^+ + n$

  $E_{pr} > 2.6$ MeV

- Data: total rate
  energy spectrum of events

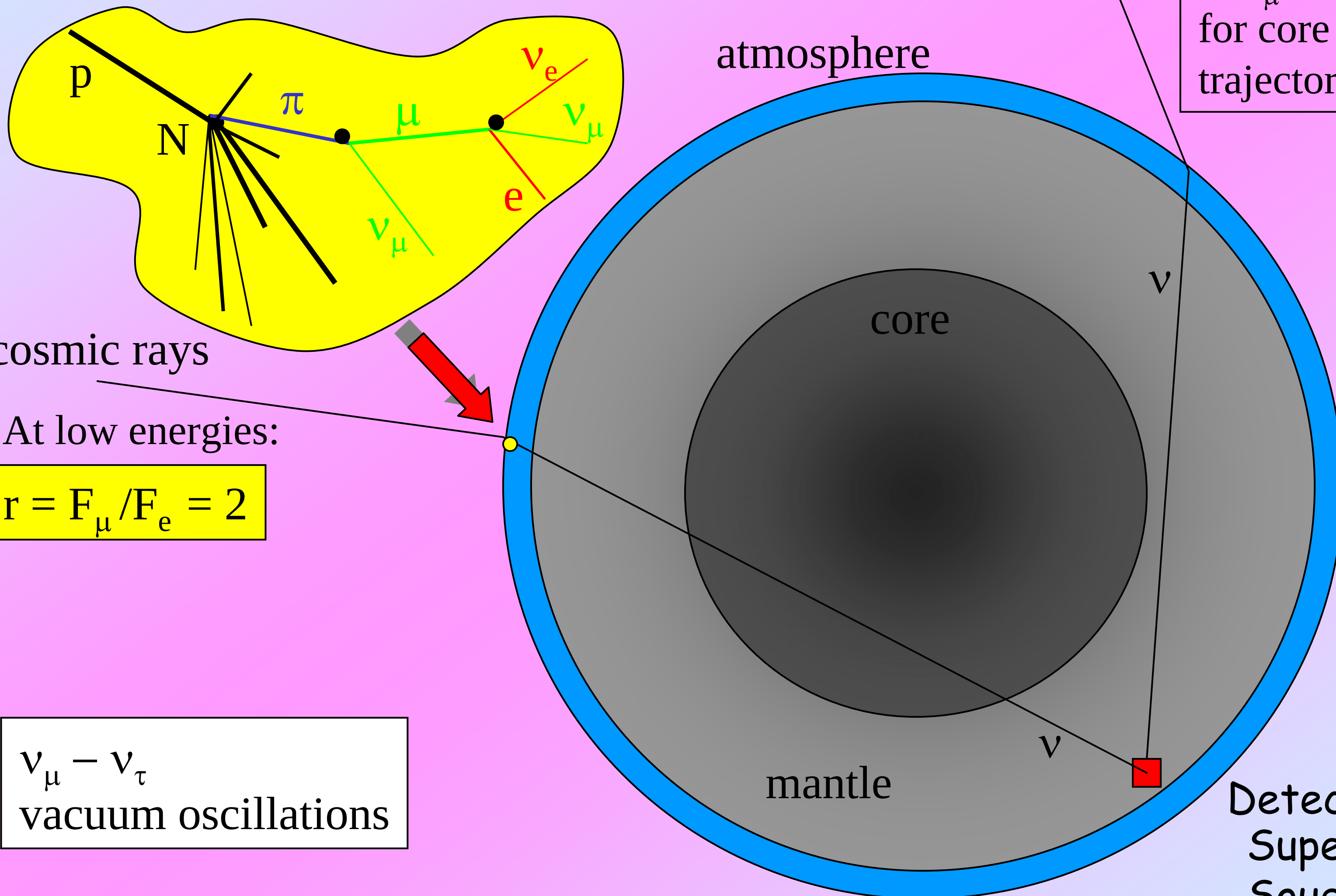
- Vacuum oscillations

- Detection of the Geo-neutrinos
  $E_{pr} > 1.3$ MeV



1 kton of Liquid scintillator

Atmospheric neutrinos



Parametric effects in $\nu_\mu - \nu_e$ oscillations for core crossing trajectories

$\nu_\mu - \nu_e$ oscillations in matter

At low energies:

$r = F_\mu / F_e = 2$

$\nu_\mu - \nu_\tau$ vacuum oscillations

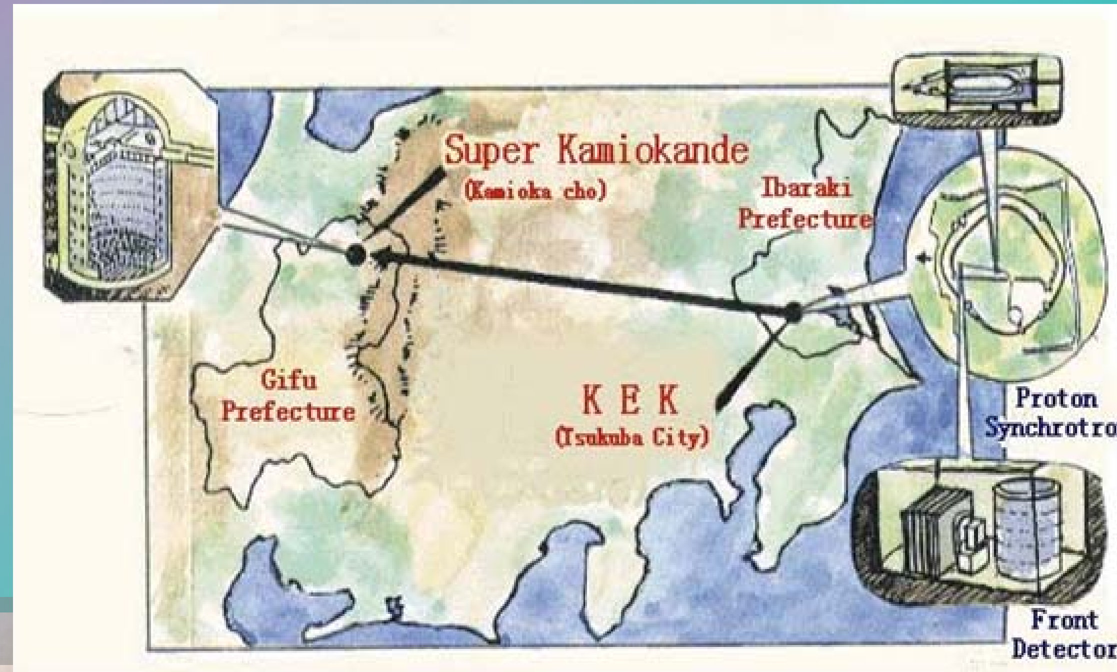
Detector
SuperKamikande
Soudan
MACRO

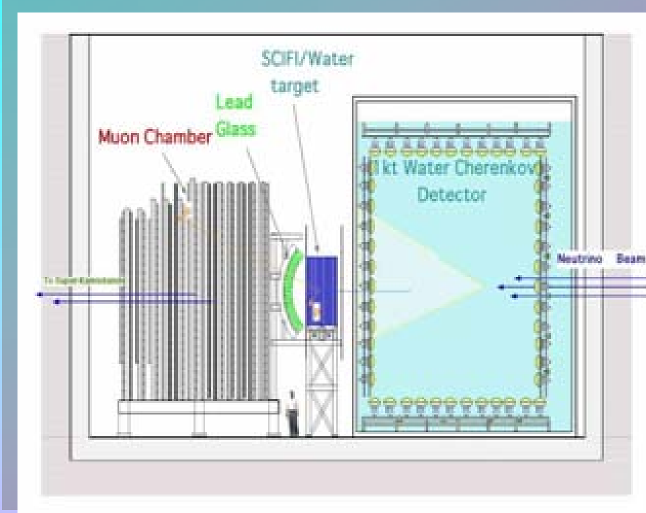
K2K

KEK to Kamioka

$\nu_\mu \rightarrow \nu_\mu$

Vacuum oscillations





SuperKamiokande

MINOS

Main Injector Neutrino Oscillation Search

LBL: Fermilab – SOUDAN mine

Near detector (1km):
1 kton

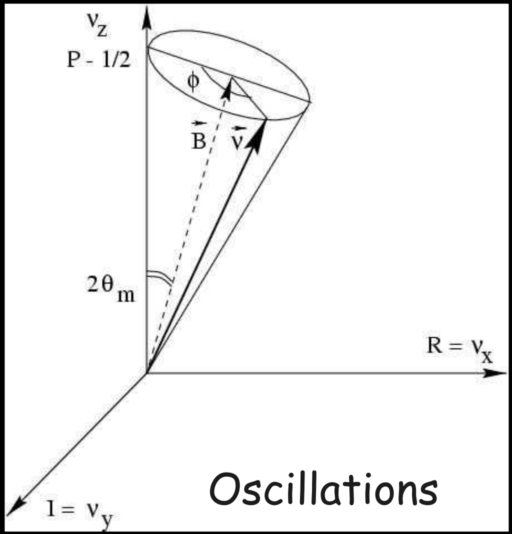
Far detector (735 km)
5400 t, steel,
sampling calorimeter

Beam: 120 GeV protons
2.5 10^{20} p/year
-> 1 - 10 GeV neutrinos

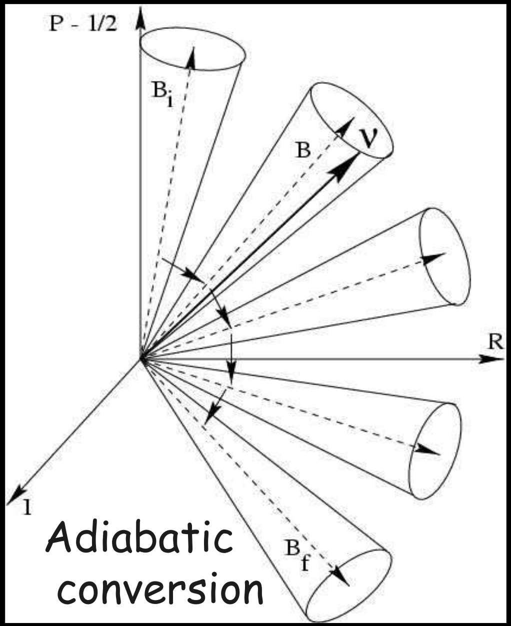
Vacuum oscillations

Other effects

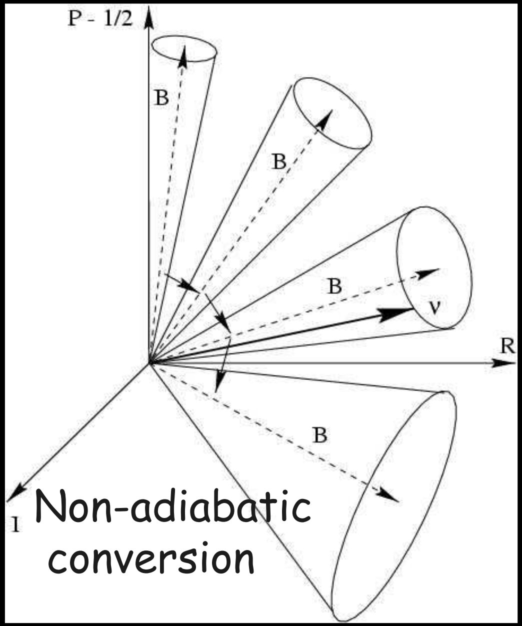
Graphical representation



Oscillations

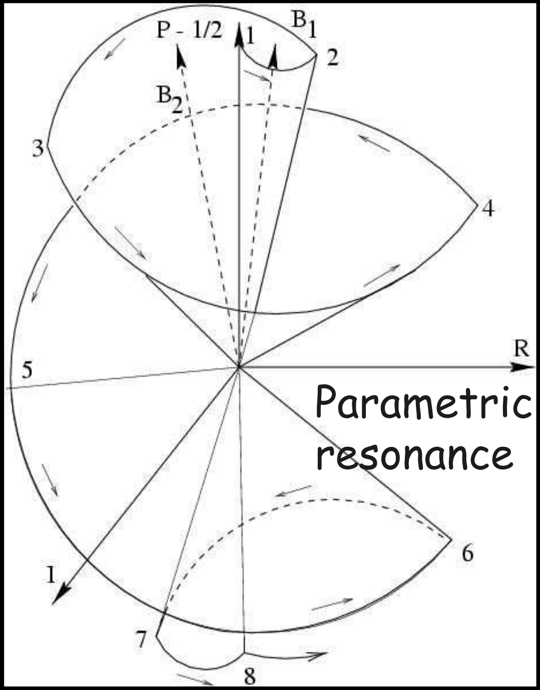


Adiabatic conversion



Non-adiabatic conversion

Collective effects in neutrino gases
→ non-linear physics,
Synchronized oscillations,
bi-polar oscillations, etc.
Applications: supernovae, early universe

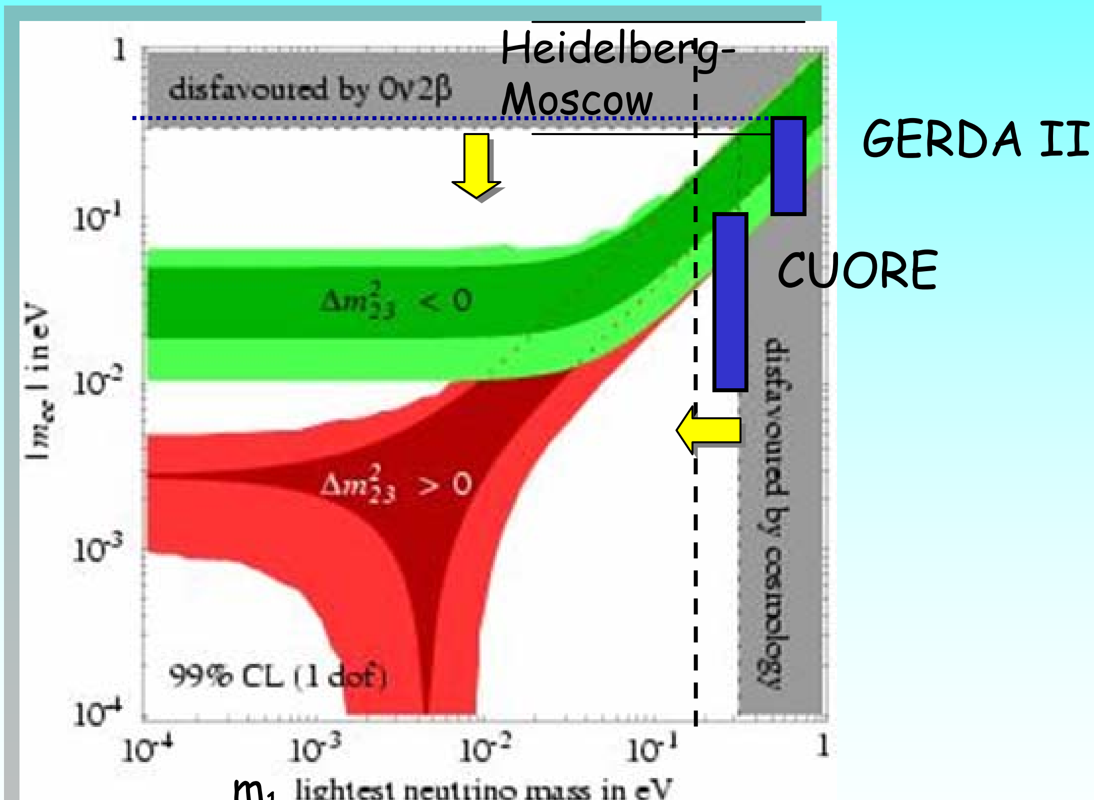


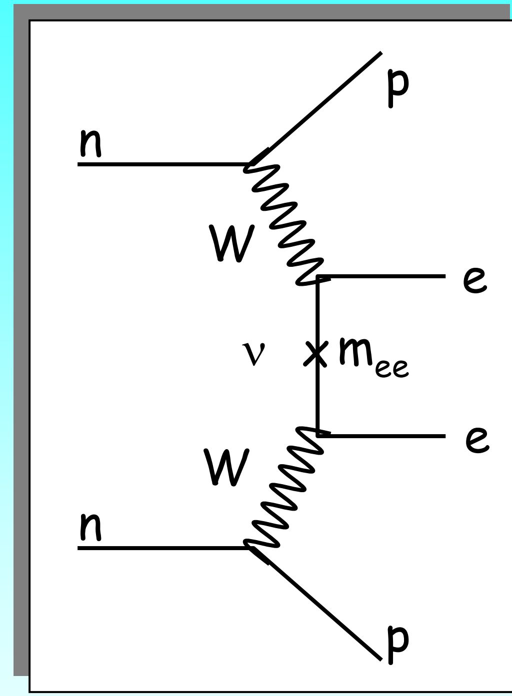
Parametric resonance

Absolute scale of mass

A. Strumia, F. Vissani

Neutrinoless double beta decay





$$m_{ee} = \Sigma_k U_{ek}^2 m_k e^{i\phi(\kappa)}$$

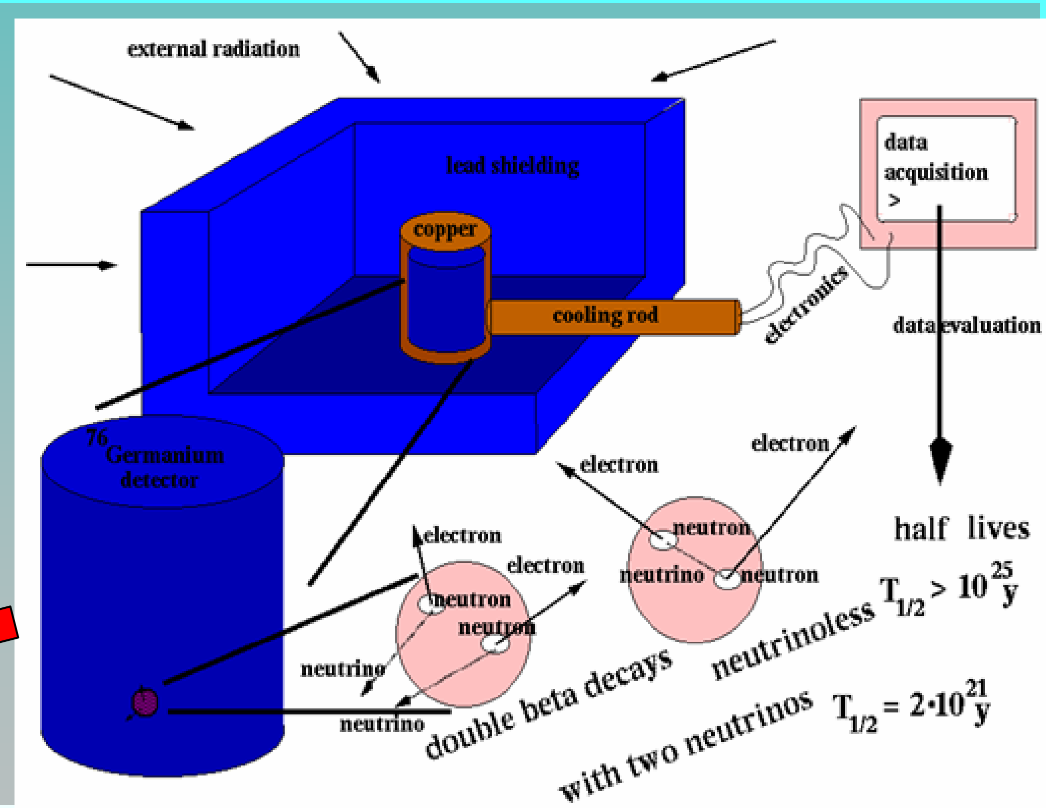
Kinematic searches, cosmology

Both cosmology and double beta decay have similar sensitivities

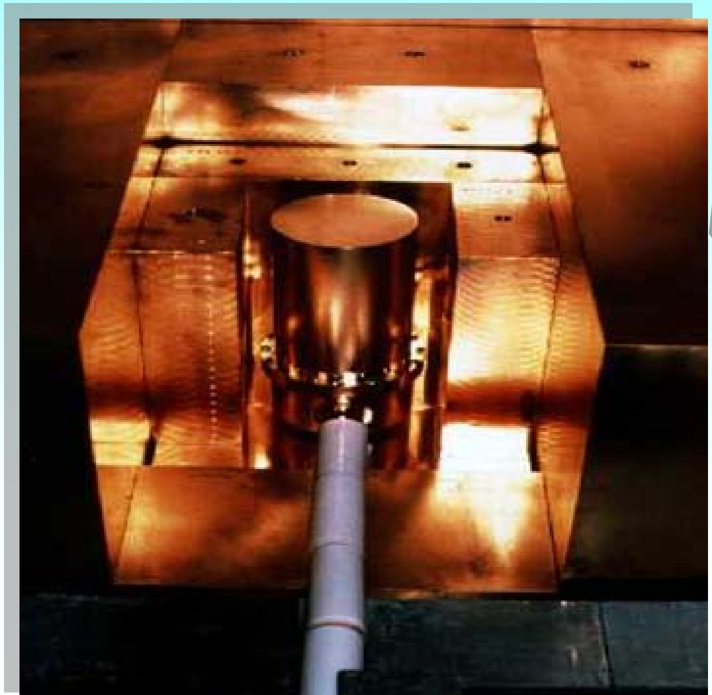
Double beta decay

$^{76}Ge \rightarrow {}^{76}Se + e + e$

Heidelberg-Moscow experiment

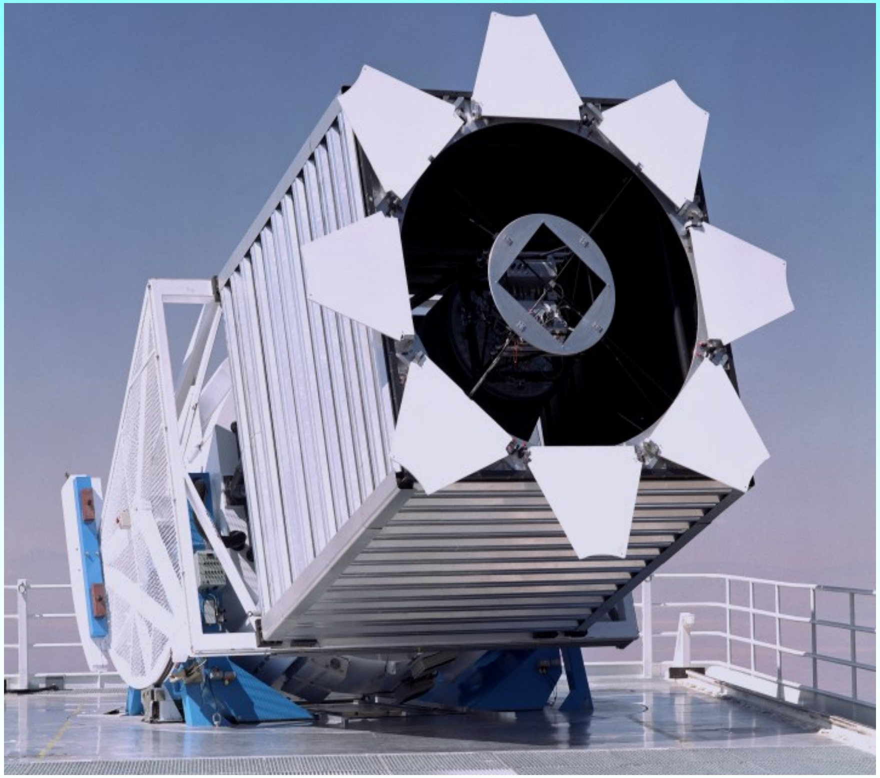


Fifth detector



Evidence
Cosmology?
If $2\beta\ 0\nu$ -> mechanism?

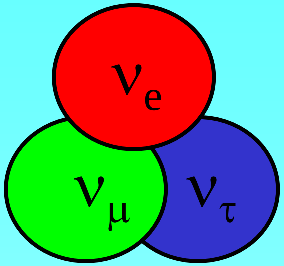
Cosmological bounds

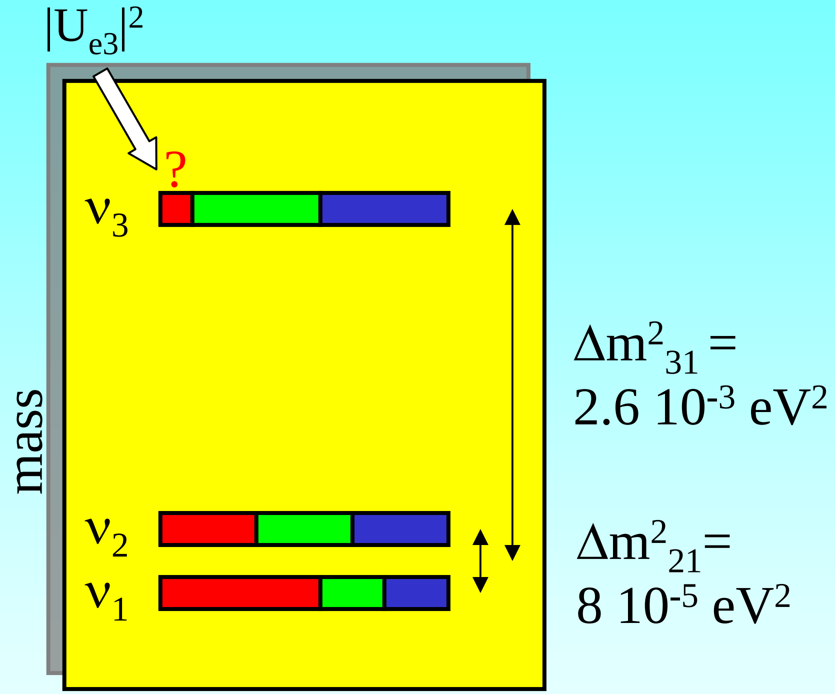


SDSS

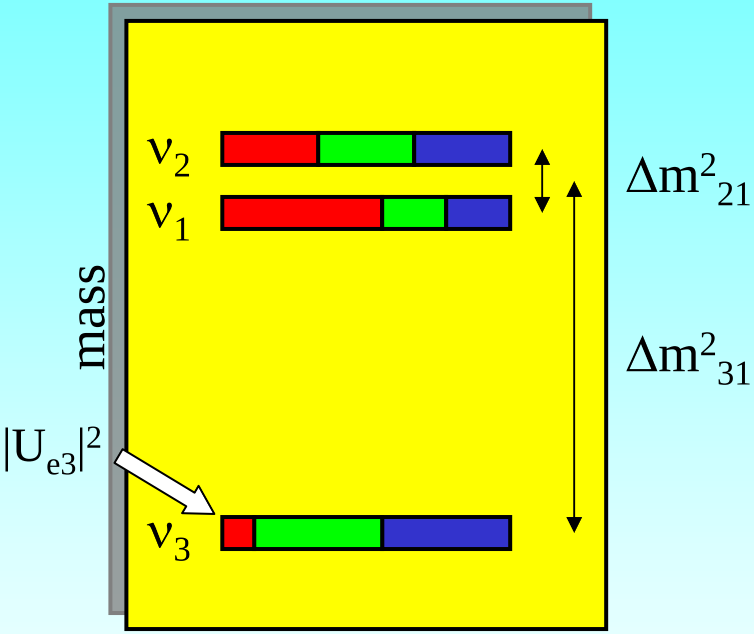
Summary of results

Mass spectrum and mixing





Normal mass hierarchy



Inverted mass hierarchy

- Type of mass spectrum: with Hierarchy, Ordering, Degeneracy ➡ absolute mass scale
- Type of the mass hierarchy: Normal, Inverted
- $U_{e3} = ?$
- More neutrino states?

Mixing: summary

M.C. Gonzalez-Garcia, M. Maltoni, Moriond, March 2007 (Phys. Rep.)

The angles 1σ (3 σ)

	1σ	(3 σ)
$\theta_{12}^{o} = 33.7$	+/- 1.3	(+ 4.3, - 3.5)
$\theta_{23}^{o} = 43.3$	+ 4.3, - 3.8	(+ 9.8, - 8.8)
$\theta_{13}^{o} = 0.0$	+ 5.3, - 0.0	(+ 11.5, - 0.0)

small shift from maximal mixing

b.f. value is zero; stronger upper bound

Mixing matrix (moduli of matrix elements)

$$U_{PMNS} = \begin{pmatrix} 0.81 - 0.85 & 0.53 - 0.58 & 0.00 - 0.12 \\ 0.32 - 0.49 & 0.52 - 0.69 & 0.60 - 0.76 \\ 0.27 - 0.46 & 0.47 - 0.64 & 0.65 - 0.80 \end{pmatrix}$$

90 % C.L.

Masses: summary

Global oscillation fit:

$$\Delta m_{31}^2 = 2.6 +/- 0.2 \;\; (0.6) \times 10^{-3} \;\; eV^2$$

$$\Delta m_{21}^2 = 7.90 \,^{+0.27}_{-0.28} \left(^{+1.10}_{-0.89}\right) \times 10^{-5} \;\; eV^2$$

M. Gonzalez-Garcia, M. Maltoni, 2007

⇨ the weakest mass hierarchy $|m_2 / m_3| > 0.18$

Cosmology:

$\Sigma_i \; m_i < 0.42$ eV (95% C.L.)

$\Sigma_i \; m_i < 0.17$ eV (95% C.L.)

U. Seljak et al

< 0.6 eV

S. Hannestadt

⇨ at least for one neutrino: $m \sim 0.05 - 0.10$ eV

Heidelberg-Moscow: $m_{ee} = 0.24 - 0.58$ eV

if confirmed, other than light neutrino mass mechanism?

"Standard" neutrino model

1. There are only 3 types of light neutrinos

2. Interactions are described by
   the Standard (electroweak) model

3. Masses and mixing have pure vacuum origin;
   they are generated at the EW and probably
   higher mass scales

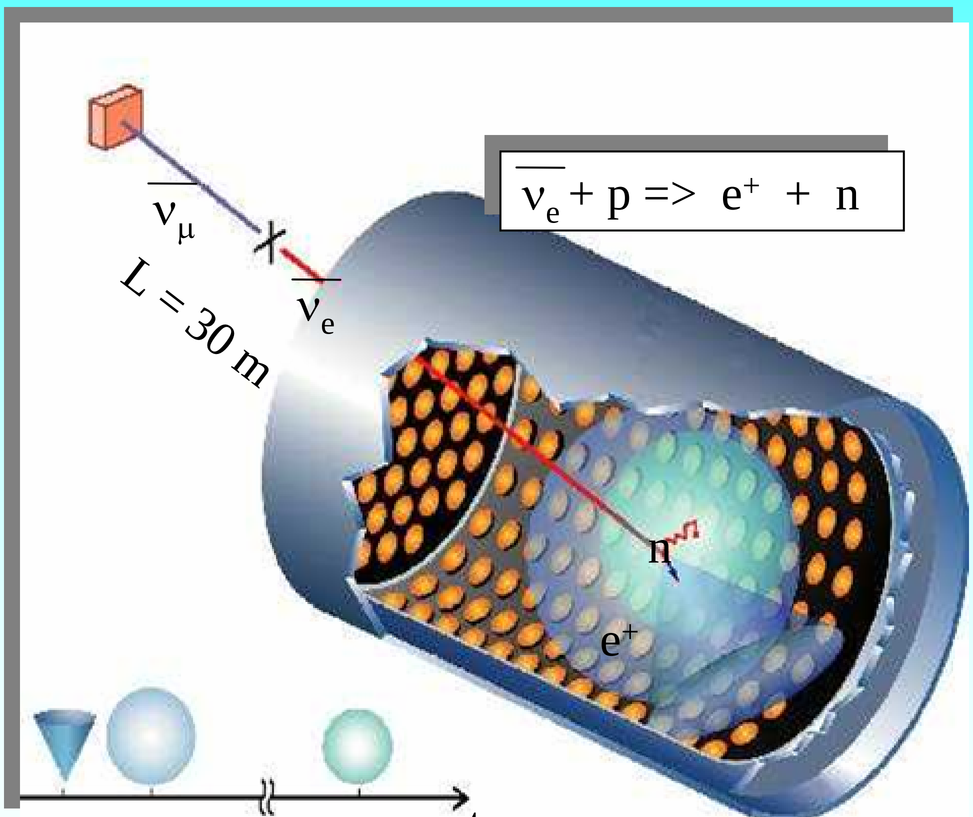
= ``Hard" masses

Tests of these statements;
Search for physics beyond

LSND

Large Scintillator Neutrino Detector

Los Alamos Meson Physics Facility



Cherenkov cone + scintillations

200 t mineral oil scintillator

$p \rightarrow$
$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

decay at rest

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$P = (2.64 \pm 0.67 \pm 0.45)\, 10^{-3}$

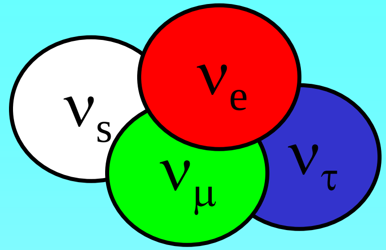
Oscillations?

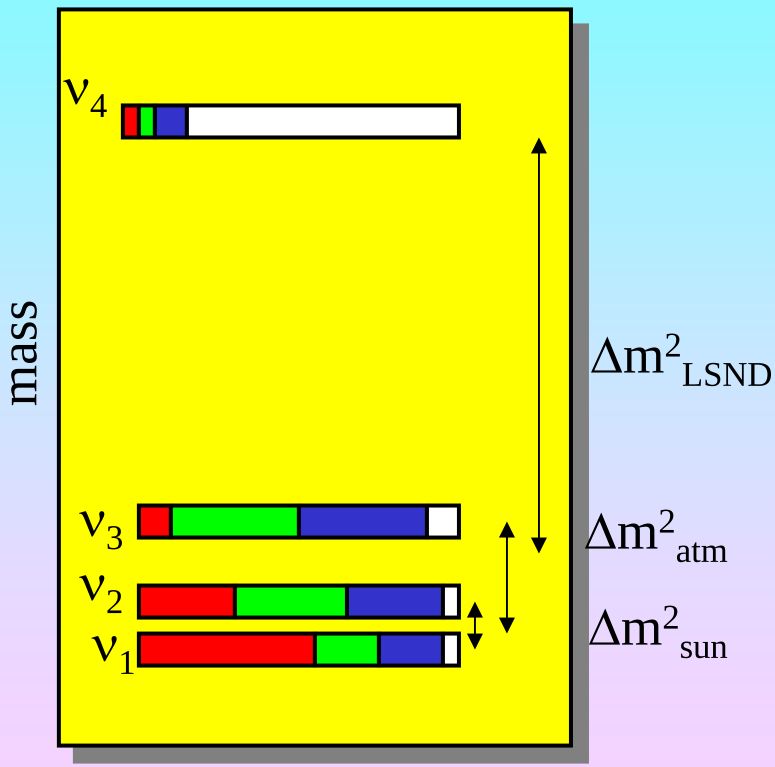
$\Delta m^2 > 0.2\ eV^2$

Beyond ``standard" picture:

- new sector,
- new symmetry

(3 + 1) scheme





The problem is

$$P \sim |U_{e4}|^2 \; |U_{\mu 4}|^2$$

Restricted by short baseline experiments CHOOZ, CDHS, NOMAD

2 - 3s below the observed probability

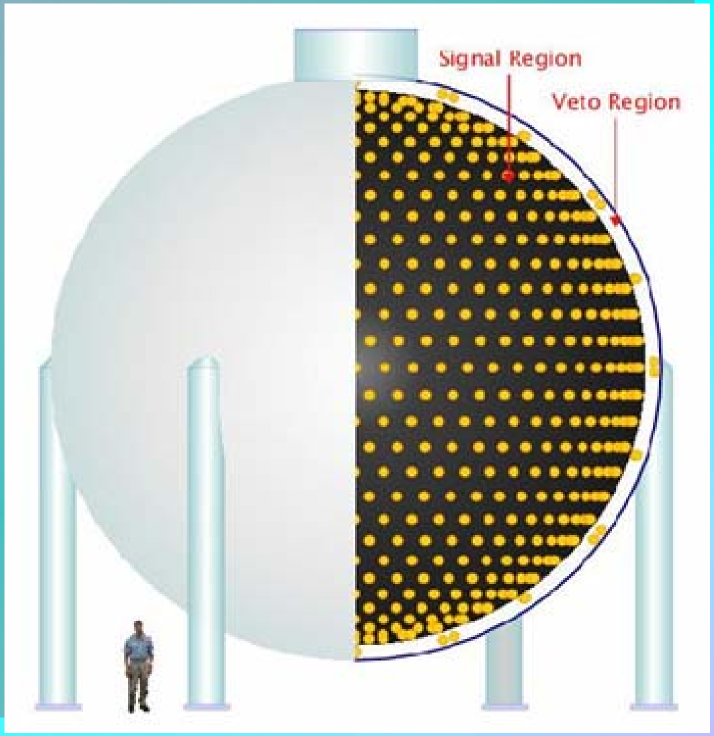
1-3 subsystem of levels is frozen

MiniBooNE

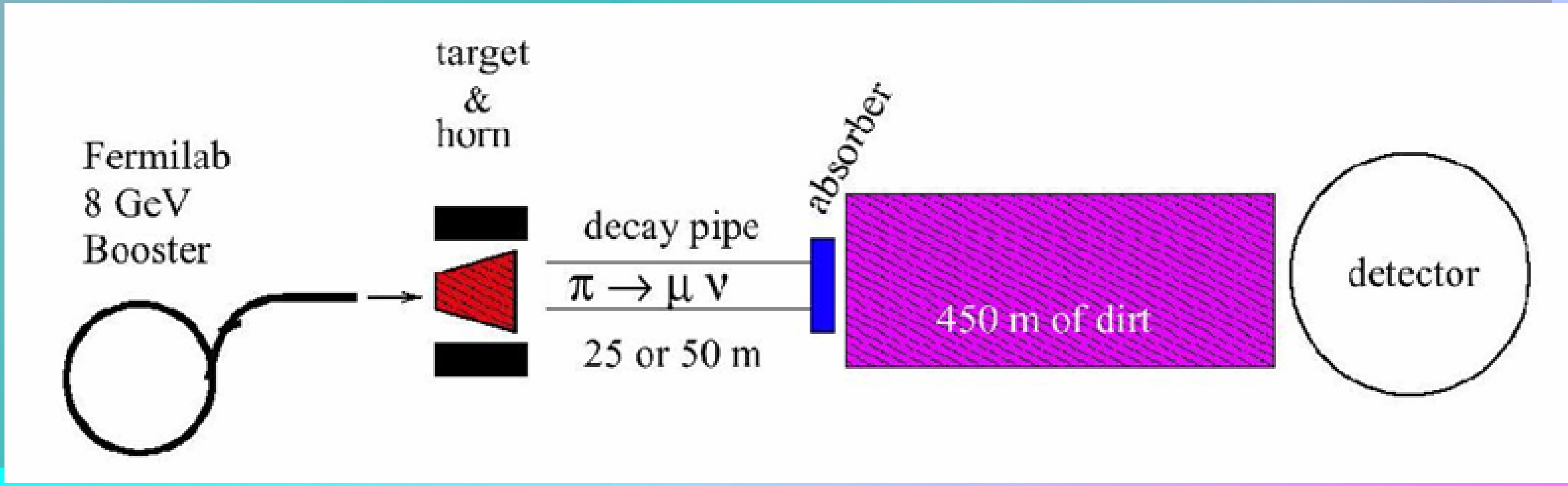
Search for ν_e appearance

12 m diameter tank

450 t (mineral oil)
1280 PMT



L = 541 m, $\langle E_\nu \rangle$ ~ 800 MeV



Leptons vs Quarks

Understanding Fermion Masses

Unification of particles and forces GUT's, Strings...

Two fundamental issues

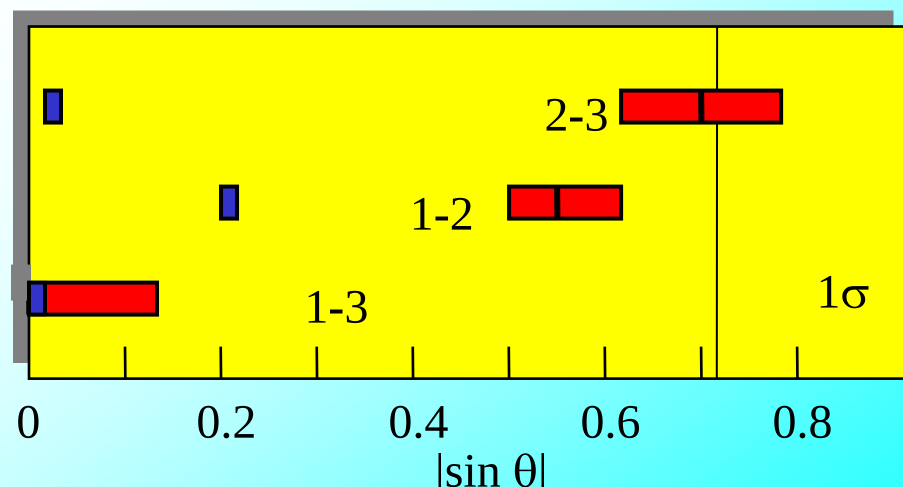
Mixing

Mixing	Quarks	Leptons
1-2, θ_{12}	13^o	34^o
2-3, θ_{23}	2.3^o	42^o
1-3, θ_{13}	$\sim 0.5^o$	$< 8^o$

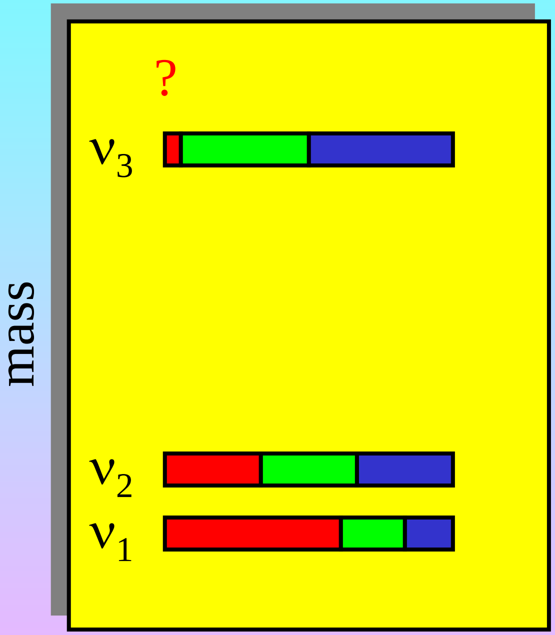
Complementarity

$\theta_{12} + \theta_C = 46.7^o \; +/- \; 2.4^o$

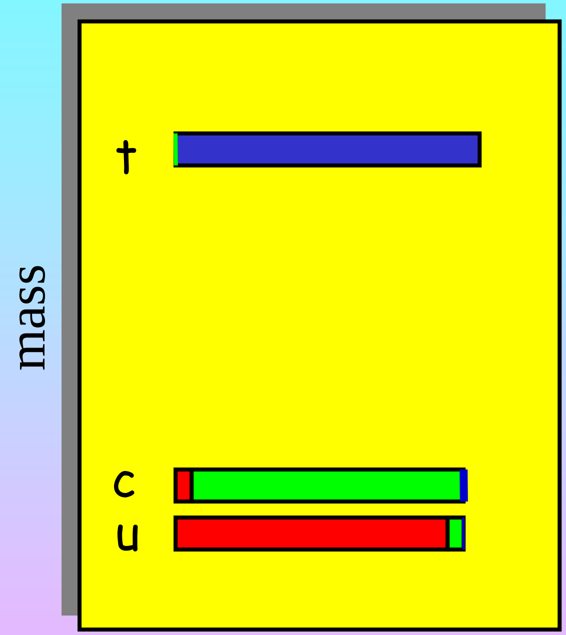
$\theta_{23} + V_{cb} = 43.9^o \; + 5.1/-3.6^o$



Mass spectrum and mixing



Leptons



Quarks

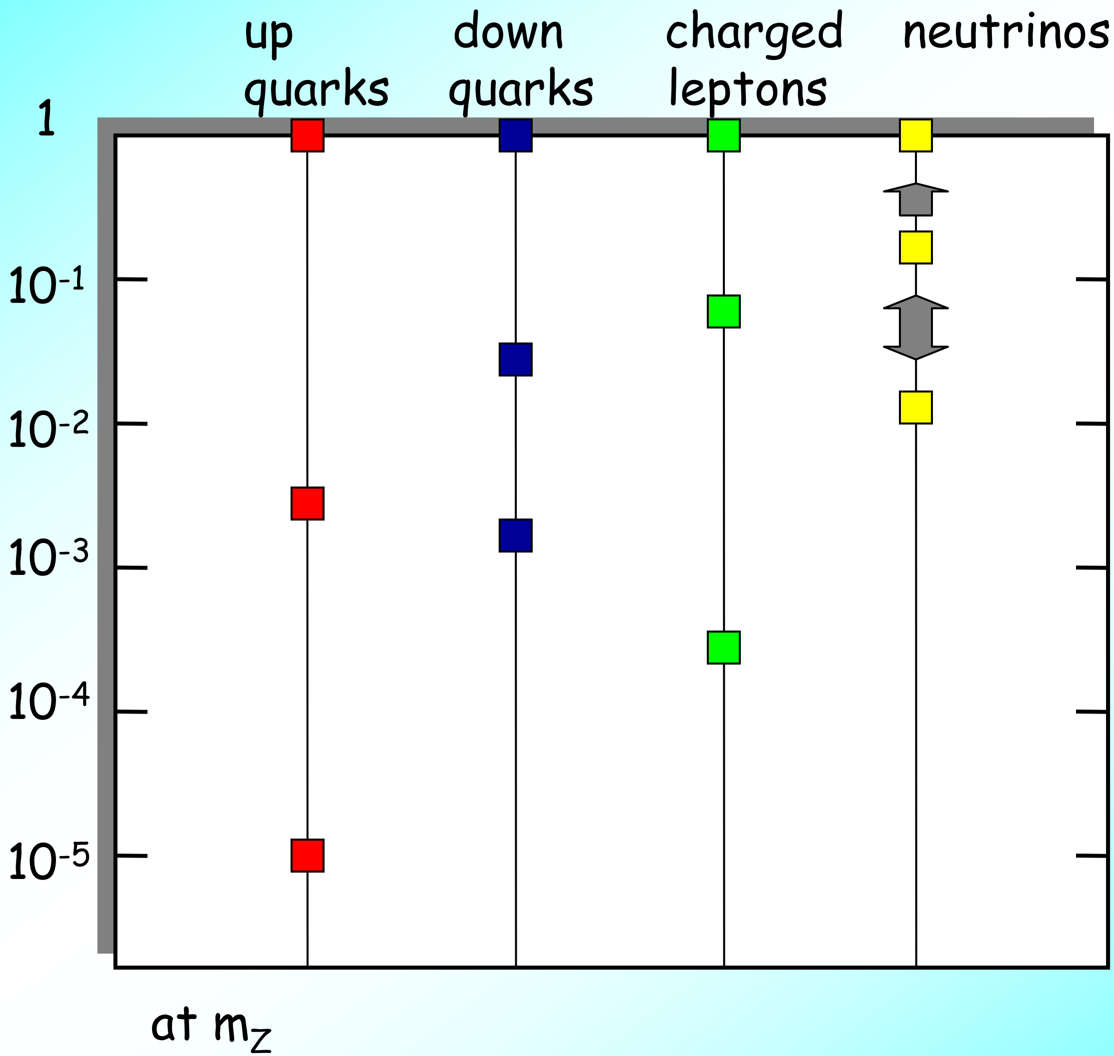
$\nu_f = U_{PMNS}\, \nu_{mass}$

$U_{PMNS} = U_{23}\ I_\delta\ U_{13}\ U_{12}$

$U_d = U_{CKM}^{+}\, U$

$U = (u, c, t)$

Mass Ratios



Regularities?

$m_u\, m_t \;=\; m_c^{\,2}$

$V_{us}\, V_{cb} \sim V_{ub}$

Gatto –Sartori-Tonin relation

$\sin\theta_C \sim \sqrt{m_d/m_s}$

Koide relation ?

New physics world

Neutrino mass is the first manifestation of physics beyond the Standard Model

to appreciate this statement

Standard Model of electroweak interactions
the Glashow-Salam-Weinberg model - accomplished in 1967 - 1968

About 40 years of desperate searches of deviations from the SM –
→ searches new physics

Abdus Salam
developed various
scenarios of
physics beyond the SM:

- unification of quarks and leptons
  (quark- lepton symmetry)
- aspects of supersymmetry
- physics of extra dimensions

Why neutrinos?

SM has some other problems that can not be resolved in the SM

- Three different couplings
- Gravity
- Scale of masses

- No dark matter candidate
- Baryon asymmetry in the universe
- inflation

Observed pattern of the quark masses and mixing also has no explanation in the SM.

Scale of neutrino mass

m = (0.04 – 0.10) eV

$$\frac{m_3}{m_\tau} \sim (0.3 - 1)\ 10^{-10}$$

$$\frac{m_\tau}{m_t} \sim 10^{-2}$$

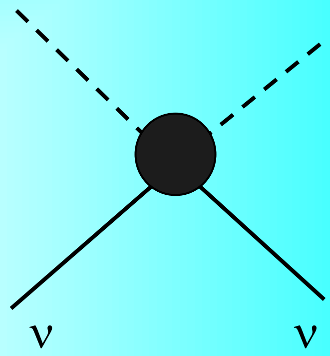
Effective scales

S. Weinberg

No new light particles
→ effective operator

$$\frac{h}{\Lambda} \, L L H H$$

Λ is the scale of new physics



generates
Majorana mass

$m_\nu = h \langle H \rangle^2 / \Lambda$

$h \sim 1$
$\Lambda \sim M_{Pl}$

→ $m_\nu \sim 10^{-5}$ eV

Too small to explain data

Still can produce
observable effects

$\Lambda \sim 10^{14}$ GeV

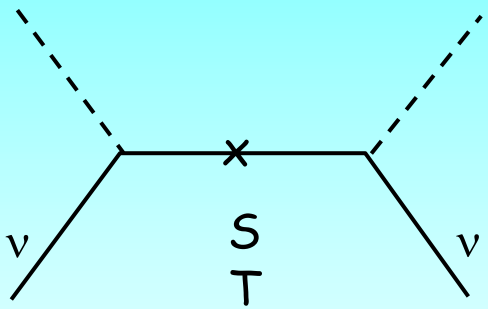
enhanced effective
h >> 1 ?

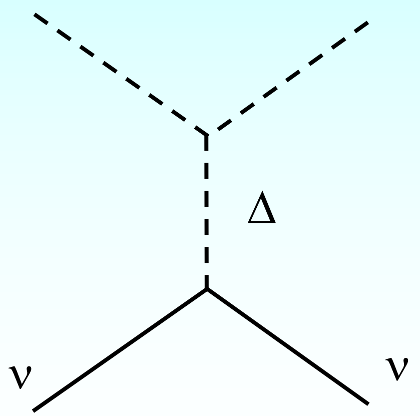
New scale of physics
GUT?

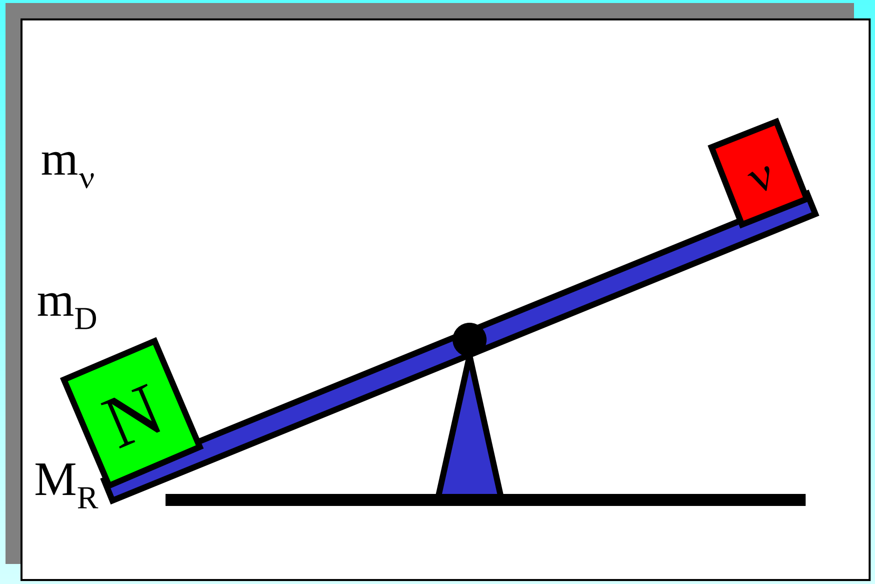
See-saw

P. Minkowski
T. Yanagida
M. Gell-Mann, P. Ramond, R. Slansky
S. L. Glashow
R.N. Mohapatra, G. Senjanovic

Realization of the effective operator







- $$\begin{array}{c} \\ \nu \\ N \end{array} \begin{array}{c} \nu \quad\quad N \\ \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \end{array}$$ $m_D = Y\langle H\rangle$
- If $M_R \gg m_D$

$$m_n = - m_D^T M_R^{-1} m_D$$

The same mechanism explains large lepton mixing

High vs. Low mass scales

Low scale mechanisms

EW scale?

kev-scale mechanisms?

10^{-6} GeV

Intermediate scale

10^{10} GeV

Grand unification

$M_3 \sim M_{GUT}$

10^{16} GeV

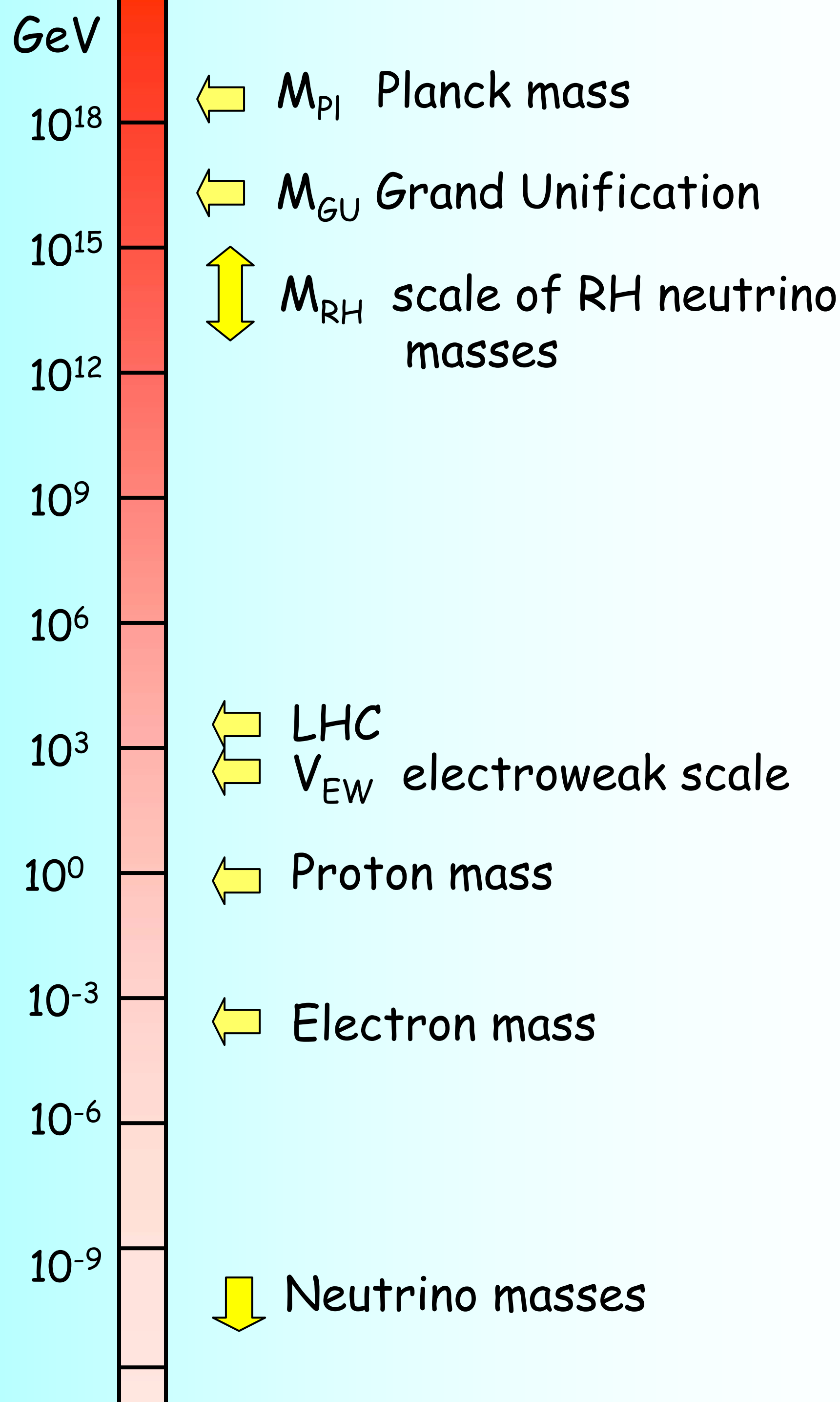
Planck scale

With many O(100) RH neutrinos

10^{19} GeV

25 orders of magnitude!

Energy and mass scales



Mapping the high energy Physics on to low energy observables

Grand Unification

Quark-Lepton symmetry

Correspondence:

u_r , u_b , u_j <-> ν
d_r , d_b , d_j <-> e

color

Pati-Salam

Symmetry:

Leptons as 4th color

Unification:

form multiplet of the extended gauge group, in particular, 16-plet of SO(10)

GUT

Can it be accidental?

More complicated connection between quarks and leptons?

Universality is not excluded

GUT's

generically

Give relations between masses of leptons and quarks

$m_b = m_\tau$

In general: ``sum rules"

b - τ unification ⟺ large 2-3 leptonic mixing

Provide with all the ingredients necessary for seesaw mechanism

- RH neutrino components
- Large mass scale
- Lepton number violation

But - no explanation of the flavor structure

Quark-Lepton Complementarity

A.S.
M. Raidal
H. Minakata

$\theta^l_{12} + \theta^q_{12} \sim \pi/4$

$\theta_{12} + \theta_C = 46.7^o$ +/- 2.4^o

$\theta^l_{23} + \theta^q_{23} \sim \pi/4$

$\theta_{23} + V_{cb} = 43.9^o + 5.1/-3.6^o$ 1σ

H. Minakata, A.S.
Phys. Rev. D70: 073009 (2004)
[hep-ph/0405088]

Difficult to expects exact equalities
but qualitatively

- 2-3 leptonic mixing is close to maximal because 2-3 quark mixing is small

- 1-2 leptonic mixing deviates from maximal substantially because 1-2 quark mixing is relatively large

accidental?

Possible implications

``Lepton mixing = bi-maximal mixing – quark mixing"

Quark-lepton symmetry

Existence of structure which produces bi-maximal mixing

See-saw? Properties of the RH neutrinos

In the lowest approximation:

$V_{quarks} = I, \quad V_{leptons} = V_{bm}$
$m_1 = m_2 = 0$

Bi-maximal mixing

F. Vissani
V. Barger et al

$U_{bm} = U_{23}^m U_{12}^m$

Two maximal rotations

$$U_{bm} = \begin{pmatrix} \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \sqrt{\frac{1}{2}} \\ \frac{1}{2} & -\frac{1}{2} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

as dominant structure?
Zero order?

$U_{PMNS} = U_{bm}$

- maximal 2-3 mixing
- zero 1-3 mixing
- maximal 1-2 mixing
- no CP-violation

⇐ contradicts data at (5-6)σ level

New symmetry?

Neutrino symmetry?

Maximal 2-3 mixing

Can both features be accidental?

Zero 1-3 mixing

$\nu_\mu - \nu_\tau$ permutation symmetry

Neutrino mass matrix in the flavor basis:
For charged leptons: D = 0

$$\begin{pmatrix} A & B & B \\ B & C & D \\ B & D & C \end{pmatrix}$$

Often related to equality of neutrino masses

Discrete symmetries S_3, D_4

Can this symmetry be extended to quark sector?

Are quarks and leptons fundamentally different?

Tri/bimaximal mixing

L. Wolfenstein

P. F. Harrison
D. H. Perkins
W. G. Scott

$U_{tbm} = U_{23}(\pi/4)U_{12}$

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & -\sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

ν_3 is bi-maximally mixed

ν_2 is tri-maximally mixed

- maximal 2-3 mixing
- zero 1-3 mixing
- no CP-violation

$U_{tbm} = U_{mag}\, U_{13}(\pi/4)$

$\sin^2\theta_{12} = 1/3$ in agreement with 0.315

In flavor basis…
relation to masses?
No analogy in the
Quark sector?
Implies non-abelian
symmetry

Possible implications

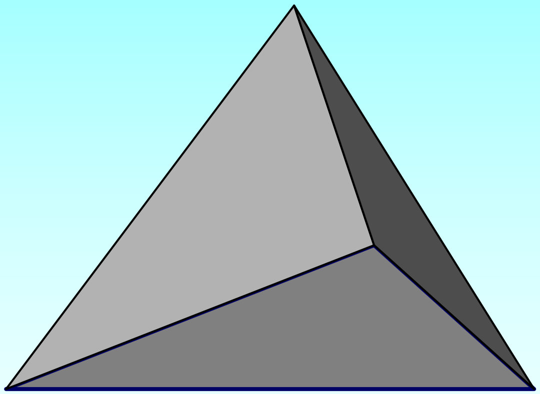
$U_{tbm} = U_{mag}\, U_{13}(\pi/4)$

E. Ma

$$U_{mag} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix}$$

$\omega = \exp(-2i\pi/3)$

tetrahedron



Symmetry:

A_4 symmetry group of even permutations of 4 elements

representations: $\underline{3}$, $\underline{1}$, $\underline{1'}$, $\underline{1''}$

Other possibilities:

T', D_4, S_4, $\Delta(3n^2)$ ...

Extended higgs sector,
Auxiliary symmetries,
Flavor alignment,
Extra dimensions?

Relation to masses?
No analogy in the quark sector?
Unification?

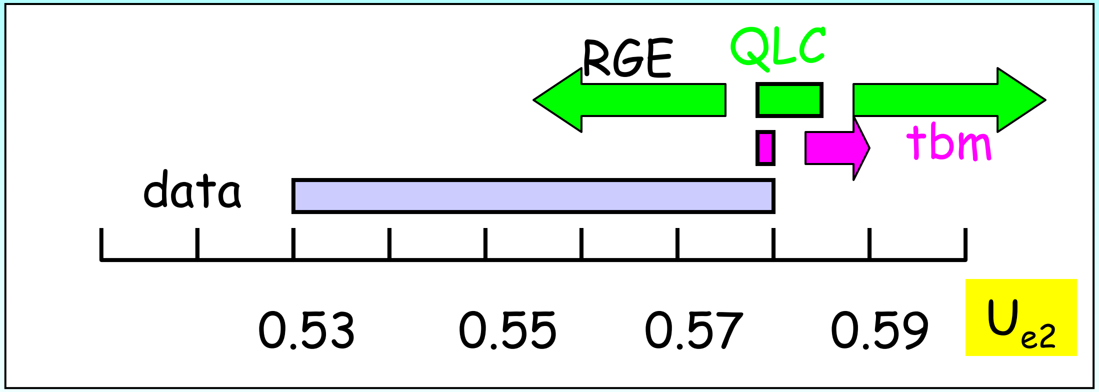
tbm vs. QLC

Physical parameter $U_{e2} = \cos\theta_{13} \sin\theta_{12}$

Global fit: 0.53 - 0.58 (90% C.L.)

tbm: 0.577

QLC: 0.576 - 0.584 (depending on Majorana CP -phases)



RGE for tbm:
A. Dighe, S. Goswami, W. Rodejohann
hep-ph/0512328

tbm: RGE $\theta_{13} < 10^{-3}$ for hierarchical nu
→ 0.1 for degenerate nu

Perturbative approach

Fermion mass matrices

$$M_f = M_0 + \delta M_f$$

$f = u, d, l, \nu$

Determined by symmetry?

corrections
due to new interactions
Planck scale effects...

What is zero order structure?
What it should explain?

- third generation masses
- 2-3 mixing
- 1-3 mixing

The rest:
from perturbations?

M_0 - can be the same for all fermions and whole difference of Q and L mixing and masses can come from corrections

Universality?

"Flavored GUT's"

From the bottom & from the top

Data

no simple relations
between masses
and mixing →

can not be described in
terms of a few parameters

No simple
``one-step''
explanations

→ data look complicated

String theory

* GUT
* Existence of a number O(100) of singlets of SM and GUT symmetry group
* Several U(1) gauge factors
* Discrete symmetries
* Heavy vector-like families
* Non-renormalizable interaction
* Selection rules for interactions
* Explicit violation of symmetry
* Incomplete GUT multiplets

How one can get from this complicated structure simple pattern we observed at low energies?

→ data look too simple

Framework

``String inspired…"

Non-abelian flavor (family symmetry) G with irreducible representation $\underline{3}$

$16_F \sim \underline{3}$

SO(10)
3 fermionic families in complete representations 16_F, 10_H, 16_H

leads to Q-L difference

No higher representations
no 126_H

Singlet sector:
several (many ?) singlets (fermionic and bosonic) of SO(10), S,
additional symmetries

Heavy vector-like families of 10_F, 16_F

their mixing corrects masses of charged fermions

Non-renormalizable interactions

C. Hagedorn
M. Schmidt
A.S.

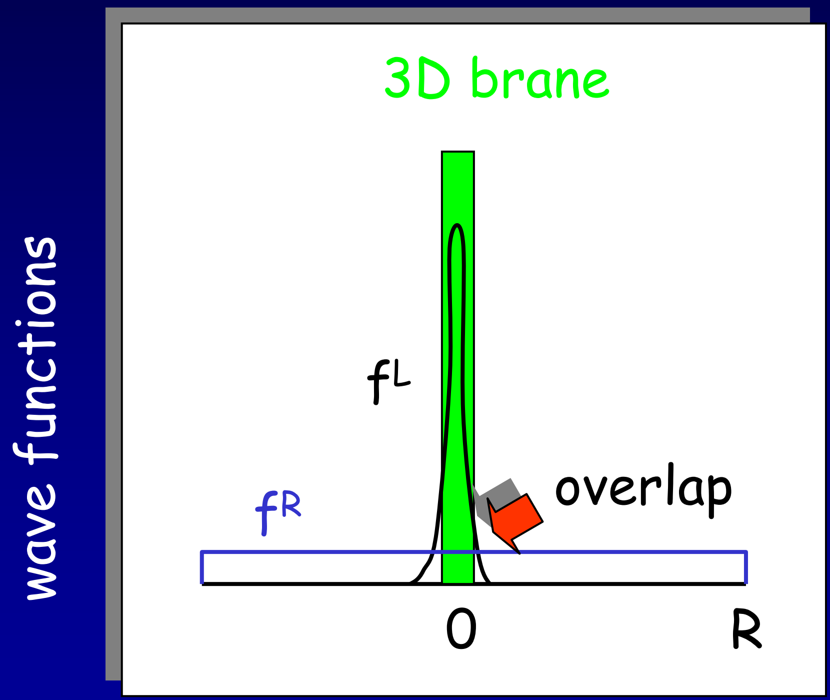
Something completely different?

Extra Dimensions

New mechanism of generation
of small Dirac masses:
overlap suppression

Right-handed components of neutrinos have no SM interactions

...in large flat extra D



RH neutrinos propagate in the bulk

Small Dirac masses due to ``overlap suppression"

Mass term: $m \bar{f}^L f^R$ + h. c.

If left and right components are localized differently in extra dimensions → suppression:

$m \, \varepsilon \, f^L f^R$ + h. c.

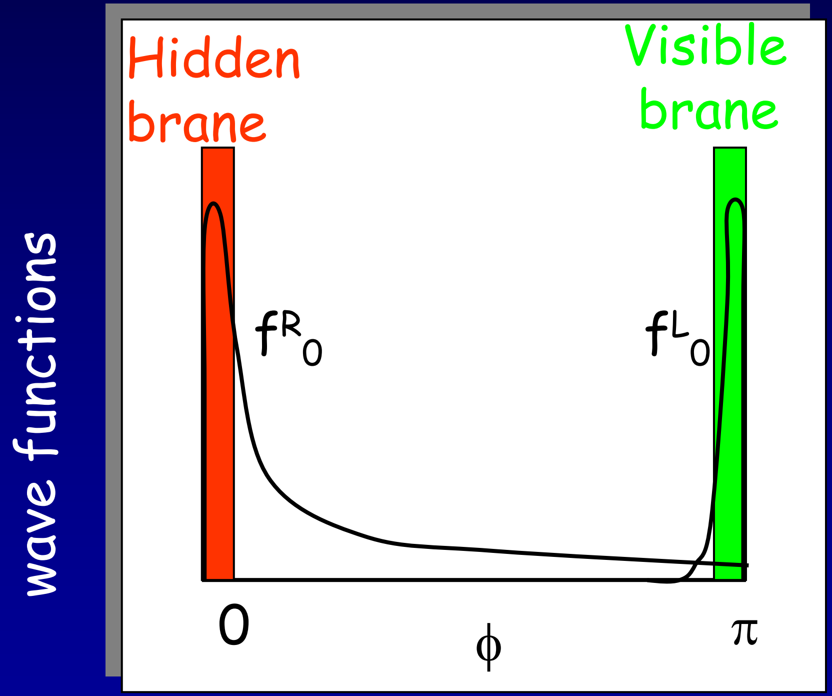
amount of overlap in extra D

Arkani-Hamed, Dvali, Dimopoulos

Large extra D + 3D brane

...in warped extra D

Grossman
Neubert
Huber, Shafi...



RH neutrinos - bulk zero mode localized on the hidden brane

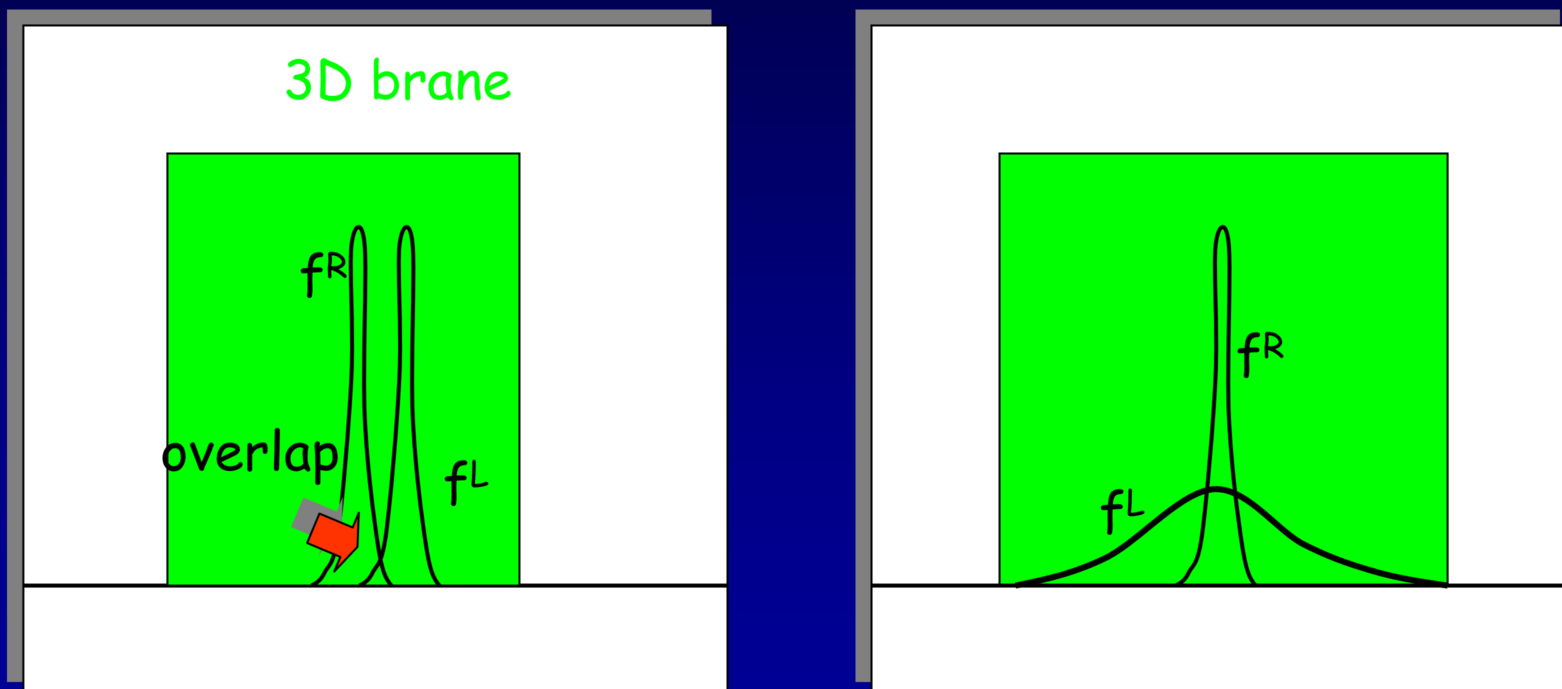
In Randall -Sundrum (non-factorizable metric)

Setting: 1 extra D S^1/Z_2

... on the fat brane

Arkani-Hamed, Schmaltz

wave functions



Summary

Recent progress in neutrino physics and particle physics in general was related to discovery of neutrino mass and mixing.
Consistent picture: interpretation of all * the results in terms of vacuum mass and mixing of three neutrinos.

LSND ?

Still unknown parameters: 1-3 mixing, hierarchy, CP phase
→ future program of phenomenological and experimental studies

Strong difference of quark and lepton mixing patterns
Data are well described by tri-bimaximal mixing or quark-lepton complementarity – with different implications
Hints of special neutrino symmetry?

Theoretical interpretation: no unique and compelling interpretation and the answer may not be simple.

One should consider neutrinos in wider context (SUSY, GUT, extraD?), connect with other phenomena...

It may happen that something important (in principles or context) is still missed

Input from high energy experiments (first of all LHC), from astrophysics and cosmology is crucial

Next generation of LBL experiments

project	baseline L	mean energy $\langle E_\nu \rangle$	goal 90% C.L.	status
T2K : JPARC → SuperKamiokande accelerator, off-a $\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_e$	295 km	0.7 GeV	$\sin^2\theta_{13} < 0.005$ $\delta(\Delta m_{23}^2) \sim 0.0001$ eV $\delta(\sin^2 2\theta_{23}) \sim 0.01$ Hierarchy ?	2009 start
NOνA Fermilab → Ash River accelerator, off-a $\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_e$	810 km	2.2 GeV	$\sin^2\theta_{13} < 0.006$ Δm_{23}^2 Hierarchy	2010 start ?
Double CHOOZ reactor $\bar{\nu}_e \to \bar{\nu}_e$	1.05 km	0.004 GeV	$\sin^2\theta_{13} < 0.005 - 0.008$	2008 start - 2011
Daya Bay	Moving detectors	0.004 GeV	$\sin^2\theta_{13} < 0.002 - 0.003$	2010

Future projects

- determination of mass hierarchy
- 1-3 mixing
- deviation of 2-3 mixing from maximal (and quadrant)
- CP violation
- Earth tomography

- Icecube (1000 Mton)
- Underwater detectors NEMO, ANTARES
- INO - Indian Neutrino observatory — 50 kton iron calorimenter
- HyperKamiokande — 0.5 Megaton whater Cherenkov detectors
- TITAND (Totally Immersible Tank Assaying Nuclear Decay)

  2 Mt and more

...but

Koide relation

$$\frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = 2/3$$

Y. Koide, Lett. Nuov. Cim. 34 (1982), 201

with accuracy 10^{-5}

$$\tan\theta_C = \sqrt{3}\,\frac{\sqrt{m_\mu} - \sqrt{m_e}}{2\sqrt{m_\tau} - \sqrt{m_\mu} - \sqrt{m_e}}$$

all three families are substantially involved!

Both relations can be reproduced if

$$m_i = m_0(z_i + z_0)^2$$

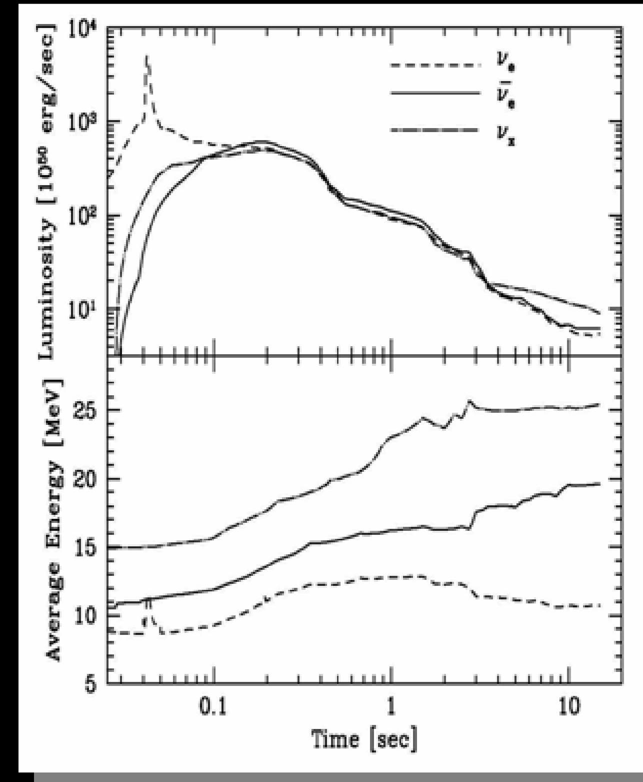
$$\Sigma_i\, z_i = 0$$

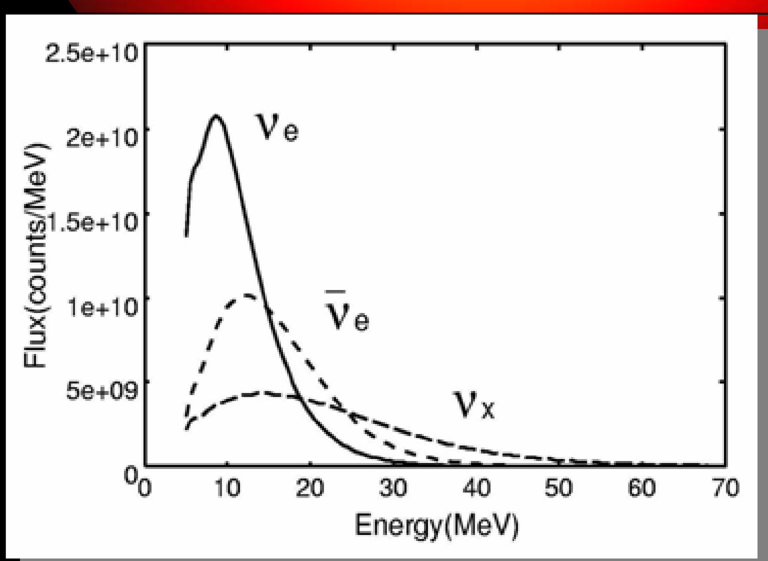
$$z_0 = \sqrt{\Sigma_i\, z_i^2 / 3}$$

C A Brannen

Neutrinos, hierarchical spectrum

Supernova neutrinos





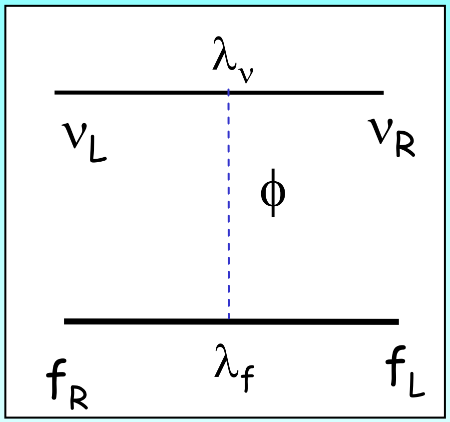
$\rho \sim (10^{11} - 10^{12})$ g/cc ➡ 0

$E(\nu_e) < E(\bar{\nu}_e) < E(\nu_x)$

"Soft" neutrino mass?

Are neutrino masses usual?

in the context
of MaVaN scenario



Exchange by
very light scalar

$m_\phi \sim 10^{-8} - 10^{-6}$ eV

$f = e, u, d, \nu$

D B Kalplan, E. Nelson,
N. Weiner , K. M. Zurek
M. Cirelli, M.C. Gonzalez-Garcia,
C. Pena-Garay
V. Barger, P Huber, D. Marfatia

chirality flip –
true mass:

$$m_{soft} = \lambda_\nu \lambda_f n_f / m_\phi$$

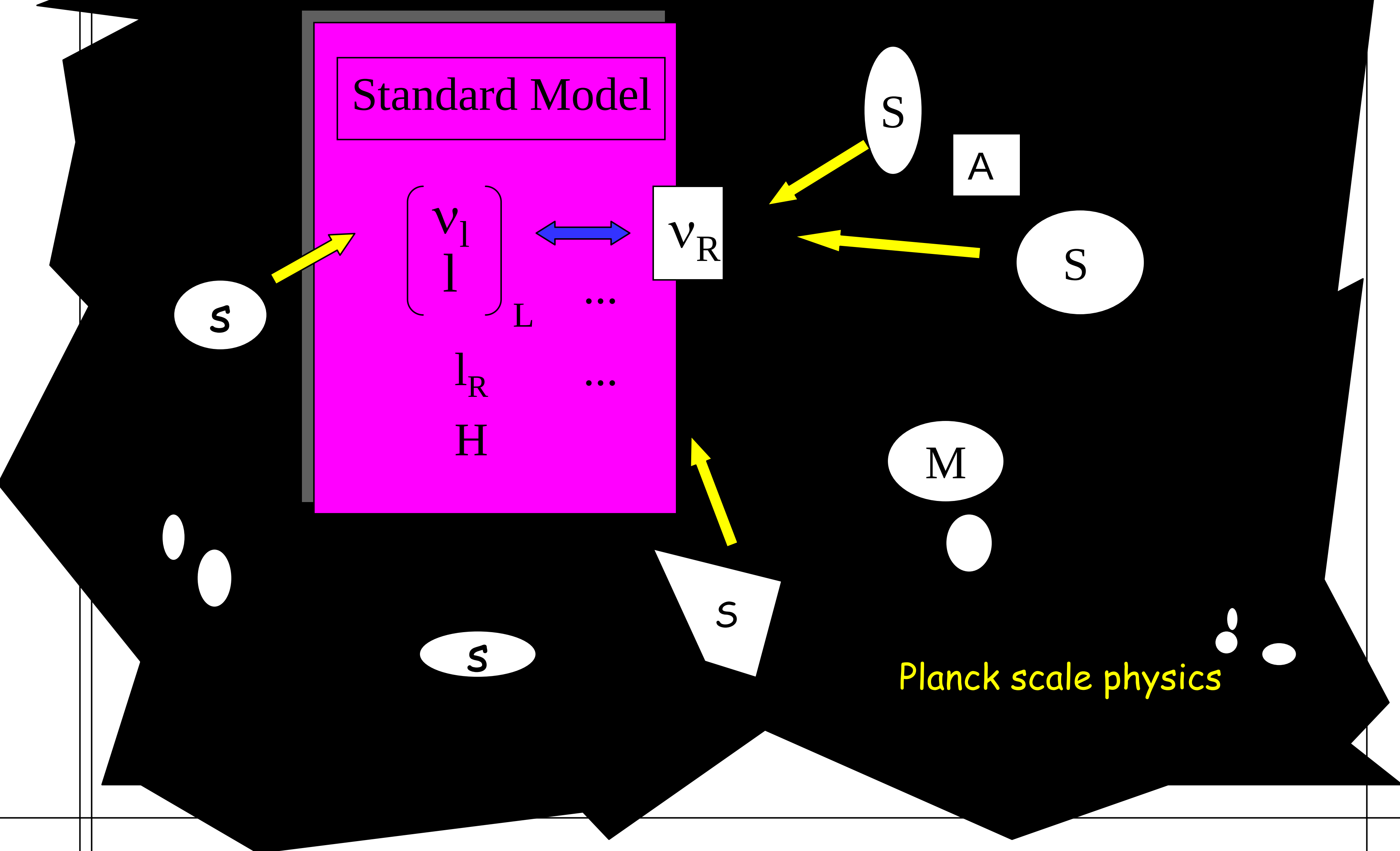
$\lambda_f \sim \phi / M_{Pl}$

In the evolution equation: $m_{vac} \rightarrow m_{vac} + m_{soft}$

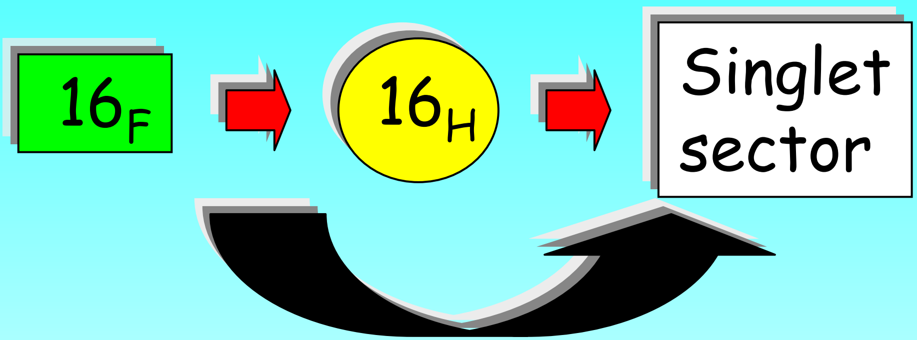
generated by some short range
physics (interactions) EW scale VEV

medium and energy
dependent mass

General picture



Singlet sector



C. Hagedorn
M. Schmidt,
A.S. in progress

- several (many ?) singlets (fermionic and bosonic) of SO(10),
- additional symmetries (U(1), discrete) →
  hierarchy of masses and couplings with neutrinos from 16
- some singlets can be light – sterile neutrinos

Due to symmetries only certain restricted subset is relevant for neutrino mass and mixing

Mixing of singlets with neutrinos (neutral components of 16).
responsible for neutrino mass and mixing
and strong difference of quark and lepton patterns

Easier realizations of symmetries

Neutrinos & LHC

The EW-scale mechanisms of neutrino mass generation

HE scale: seesaw

New Higgs bosons at the EW scale

Zee, Babu-Zee radiative mechanisms

R-parity violation

Double charged bosons

New fermions?

?

Seesaw at LHC

W. Buchmuller, D. Wyler

Can RH neutrinos be detected at LHC?

Type-I: RH neutrinos- singlets of the SM symmetry group

RH neutrinos can be produced/decay

Via mixing with light neutrinos

Additional interactions

Negligible unless strong cancellation occurs

- RH gauge bosons in LR models
- New higgs bosons

Type-III seesaw

Summary

Status: ``standard" model of neutrino mass and mixing – further confirmations/checks. Deviations?

ti-bimaximal mixing;
possible presence of special
leptonic (neutrino) symmetries

Q-L complementarity:
bi-maximal mixing and
Q-L symmetry/unification

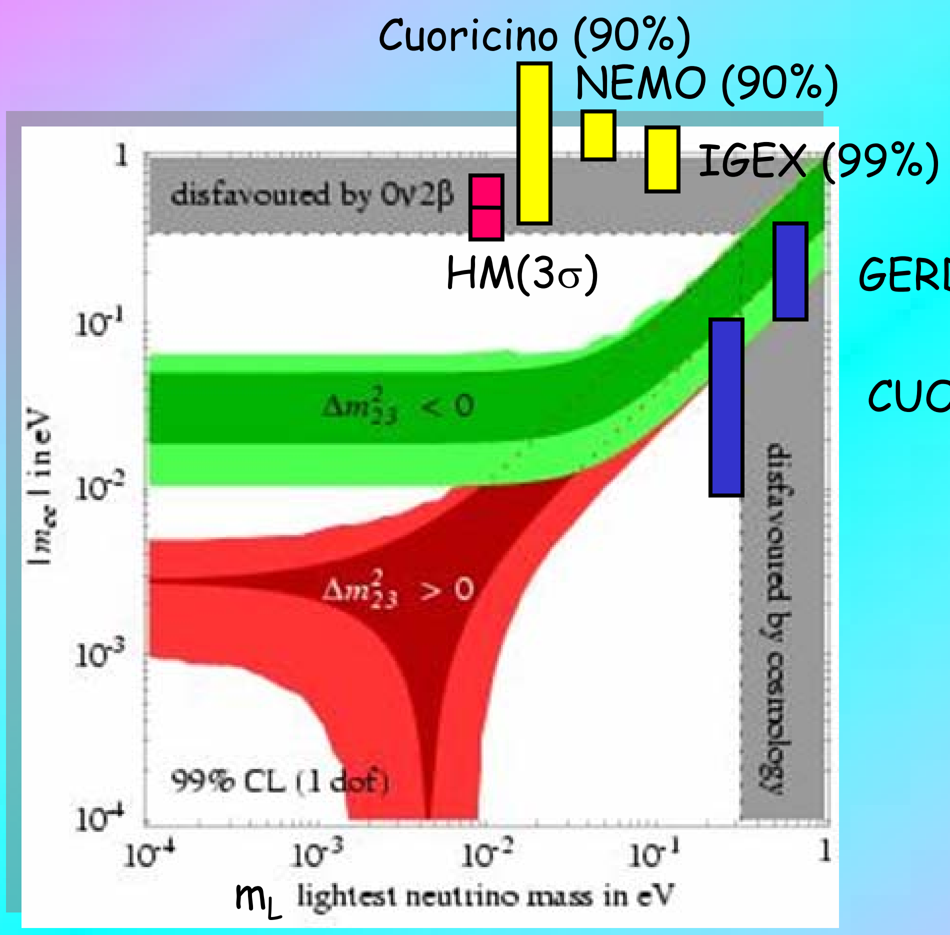
?

Real or accidental?

GUT + flavor (ultimate unification?): string inspired framework with extended singlet sector, non-renormalizable interactions ?

Can LHC help?

Present and future limits



A. Strumia, F. Vissani

Comments

NEMO: ^{100}Mo

Cuoricino, CUORE: ^{130}Te

GERDA: ^{76}Ge

Masses

- Hierarchy of masses:

Quarks

$|m_c / m_t| \sim 0.005$

$|m_s / m_b| \sim 0.02 - 0.03$

Leptons

$|m_2 / m_3| > 0.18$ Neutrinos

$|m_\mu / m_\tau| = 0.06$

Neutrino mass hierarchy is the weakest one

- $m_u : m_c : m_t = \lambda^4 : \lambda^2 : 1$

  $m_d : m_s : m_b \sim \lambda^2 : \lambda : 1$

Upper and down fermions have different mass hierarchies