Solar Neutrinos: Theory and Experiment

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Introduction

The Sun is source of neutrinos of different origins

- Nuclear reactions responsible for generation of energy in the Sun

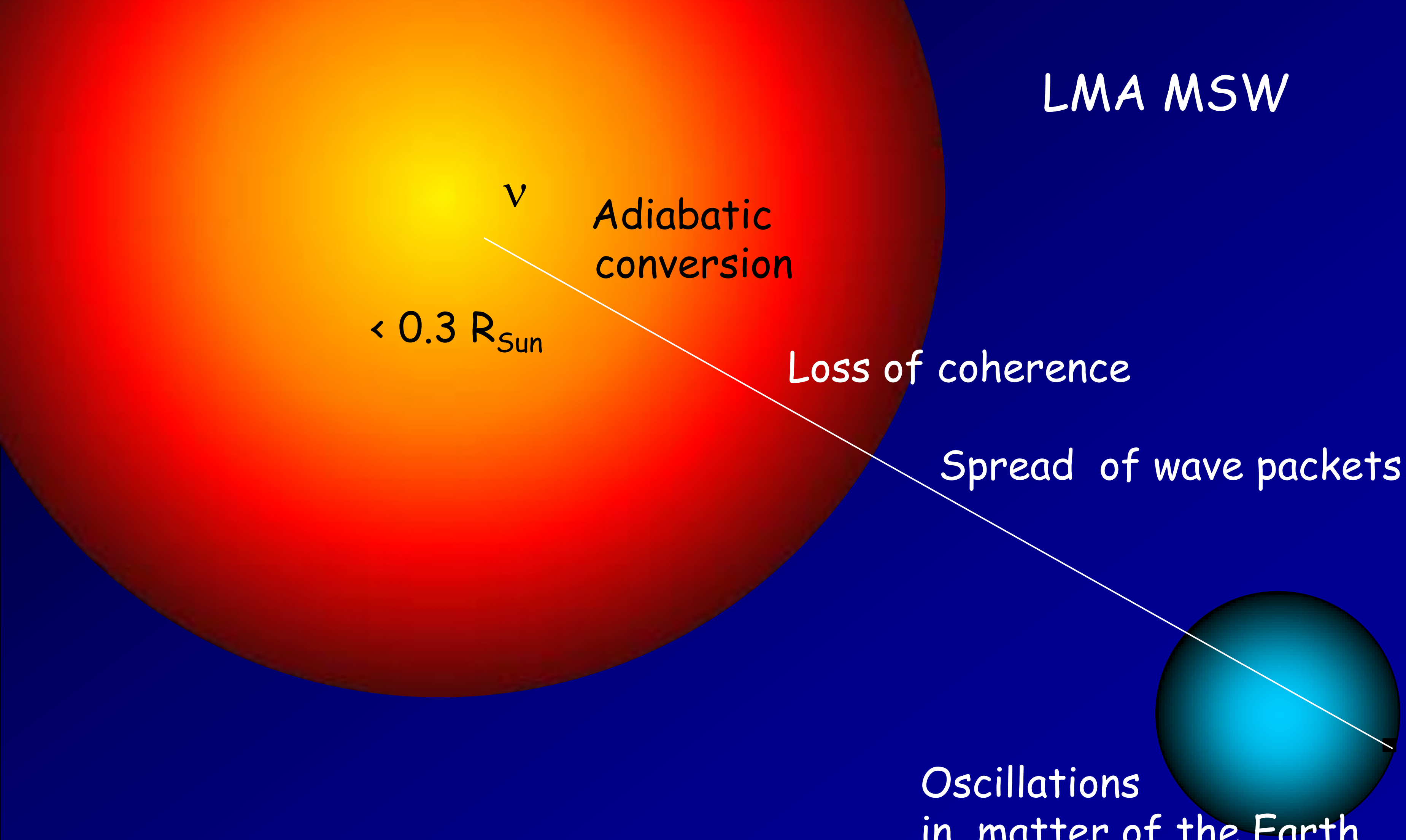
High energy cosmic rays interacting with outer layers of the Sun "Solar atmospheric neutrinos"

Thermal (kev energies) neutrinos

Solar flare Neutrinos from pions decays produced in solar flares

Neutrinos from annihilation of Dark matter particles accumulated in the Sun

Fate of solar neutrinos



7 min

LMA MSW

ν

Adiabatic
conversion

$< 0.3\ R_{Sun}$

Loss of coherence

Spread of wave packets

Oscillations
in matter of the Earth

Aspects

Astrophysics, Studies of the Sun

Nuclear reactions in the solar environment, production of neutrinos

Neutrino properties: masses mixing, interactions

The Sun a Neutrino Laboratory

Applications: neutrinos as tools

Searches for new physics

Interactions at very low energies

Tomography of the Earth

Known fluxes of neutrinos with known properties

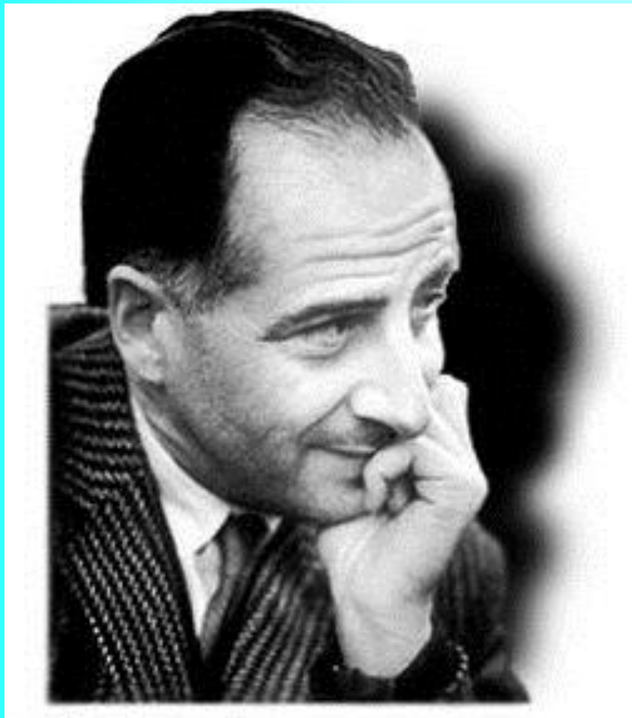
Solar neutrinos as background for DM and double beta decay experinmnts

Content

Review

M. Maltoni, A. Y. S., "Solar neutrinos and neutrino physics", 1507.05287

Pontecorvo and solar neutrinos



Бруно Понтекорво

1946

Proposal of Cl-Ar method

Discussed detection of solar neutrinos

1957

Proposal of neutrino mixing and oscillations

1967

Oscillations of solar neutrinos
Anticipation of the solar neutrino problem

"If the oscillation length is large ...
from the point of view of detection
possibilities an ideal object is the Sun"

I. Production

Hydrogen burning

via chain of nuclear reactions

$4p + 2e^- \rightarrow {}^4He + 2\nu_e + n\gamma$

$n = 2, 3$

with energy release $Q = 26.73$ MeV

in form of gammas, neutrinos and kinetic energy of nuclear products

Formation of the Helium core → neutronization of medium

Only neutrinos no antineutrinos (lepton number conservation)

Only electron neutrinos no other flavors

Important feature:

$T \ll Q_i \ll m_N$

Fundamental reaction

The starting reaction of the dominant chain of reactions

$$p + p \rightarrow d + e^+ + \nu_e$$

Weak interaction: β^+-decay of proton in the presence of another proton

Coulomb barrier

Double suppression → $t \sim 10^{10}$ years (in the center of the Sun)

The largest time, other reactions are much faster (apart from pep)

→ determines duration of whole chain

→ Determines lifetime of the Sun

Produces the pp-neutrinos -- dominant flux

Continuous energy spectrum with endpoint $Q_{pp} = 0.42$ MeV

Flux- Luminosity relation

Neutrino

EM

Average neutrino energy:

$$\langle E\rangle = \Sigma_i\, E_i \frac{F_i}{F^{tot}} = 0.265 \text{ MeV}$$

$$F^{tot} = \Sigma_i\, F_i$$

Neutrino escape the Sun without interactions carrying 2<E> = 0.53 MeV energy per chain

Each chain

Two neutrinos

Energy deposit Q – 2<E>

Neutrino flux F_ν

Luminosity L_{Sun}

→ Number of chains per unit of time: $L_{sun}/(Q - 2\langle E\rangle)$

Neutrino flux:

$$F_\nu = \frac{2\, L_{sun}}{Q - 2\langle E\rangle}$$

Assumptions

Test of the relation – test of these assumptions

1. Photon diffusion time: $t_{diff} \sim 10^5$ years →

$$\boxed{F_\nu(t_0)} \Leftrightarrow \boxed{L_{sun}(t_0 + t_{diff})}$$

The present luminosity can be used if changes in the energy release and diffusion parameters can be neglected

2. No additional sources of energy exist.

3. Fraction of unterminated chains is negligible.

they exist in outer parts
of production region

Standard Solar Model Code

Local instantaneous output

Number of ν_e events in detector produced by neutrinos from k reaction:

$$N^{(k)} \sim \int dr\, P_{ee}\,[n_e(r)]\, \underbrace{4\pi r^2 R_\nu^{(k)}(r)}_{}$$

ν_e –survival probability

electron number density

flux generated in a shell with radius r

If i and j – colliding particles in the k-reaction, the rate of k-reaction:

$$R_\nu^{(k)}\,(r) = \langle v_{ij}\,(T)\,\sigma_{ij}(T)\rangle\, \underbrace{n_i(r)\; n_j(r)}_{}\, [1 + \delta_{ij}]^{-1}$$

relative velocity

cross-section

number densities of i and j particles

Kronecker index (remove double counting)

Taken in the present epoch

Averaged over Maxwell-Bolzmann distribution

Cross-sections

$$\sigma_{ij} = S_{ij}(E)\ E^{-1}\ e^{-2\pi\eta(ij)}$$

Astrophysical factor

kinetic energy of colliding nuclei

Gamow penetration factor

$$\eta(ij) = Z_i Z_j\ \alpha/v_{ij}$$

Z_i Z_j - electric charges of nuclei, α - fine structure constant

In solar medium $S_{ij}(E) = S_{ij}(0)$

Interaction occur due to QM tunneling
(penetration under Coulomb barrier)

σ_{ij} - main source of uncertainties

Programs of experimental measurements in underground labs.

LUNA.
Gran-Sasso

Abundances of elements

For $n_i(r, t)$ -- system of coupled differential equations

$$\frac{dn_i(r,t)}{dt} = - \Gamma_i(T, n_m)\, n_i(r,t) + f_{ijk}(T)\, n_j(r,t)\, n_k(r,t) + \ldots$$

absorption, decay   creation

It should be also in the energy space

Thermal and gravitational diffusion of elements - neglected

$T(r, t)$, $n_i(r,t)$ from

- Equation of hydrostatic equilibrium (balance of the thermal motion, radiation and gravity
- Equation of state (equation for ideal gas with corrections)
- Equation of energy transport (depends on opacity, parameters of diffusion and convection –depend on chemical composition)

Initial conditions. Tuning parameters

Initial conditions:

Slowly contracting protostar with mass M_{Sun}

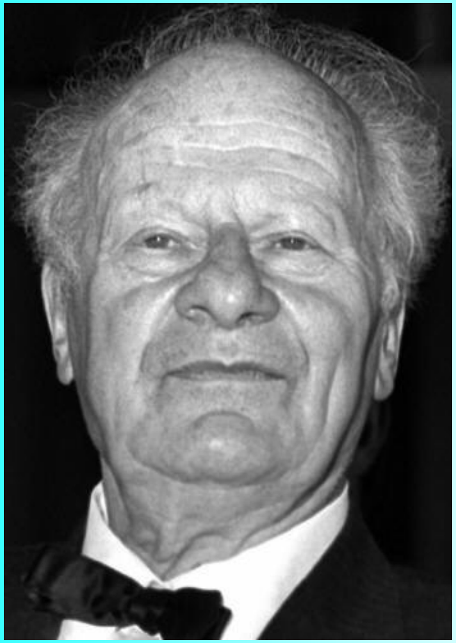
Uniform chemical composition similar to that at the surface of the Sun now

Tuning parameters:

Radius
Age of the Sun
Depth of convective zone

Chains and cycles

of nuclear reactions



Following evolution of individual nuclei

Scanning of all possible interactions of a given nuclei – identifying the most probable reactions, e.g.

p +

P → …

d → …

^{3}He → …

^{4}He → …

e p → …

^{12}C → …

G. Gamov,
V. Weizecker

H. Bethe
H. Bethe and
C. Critchfield

Only few possibilities are found which have character of chains and cycles of reactions

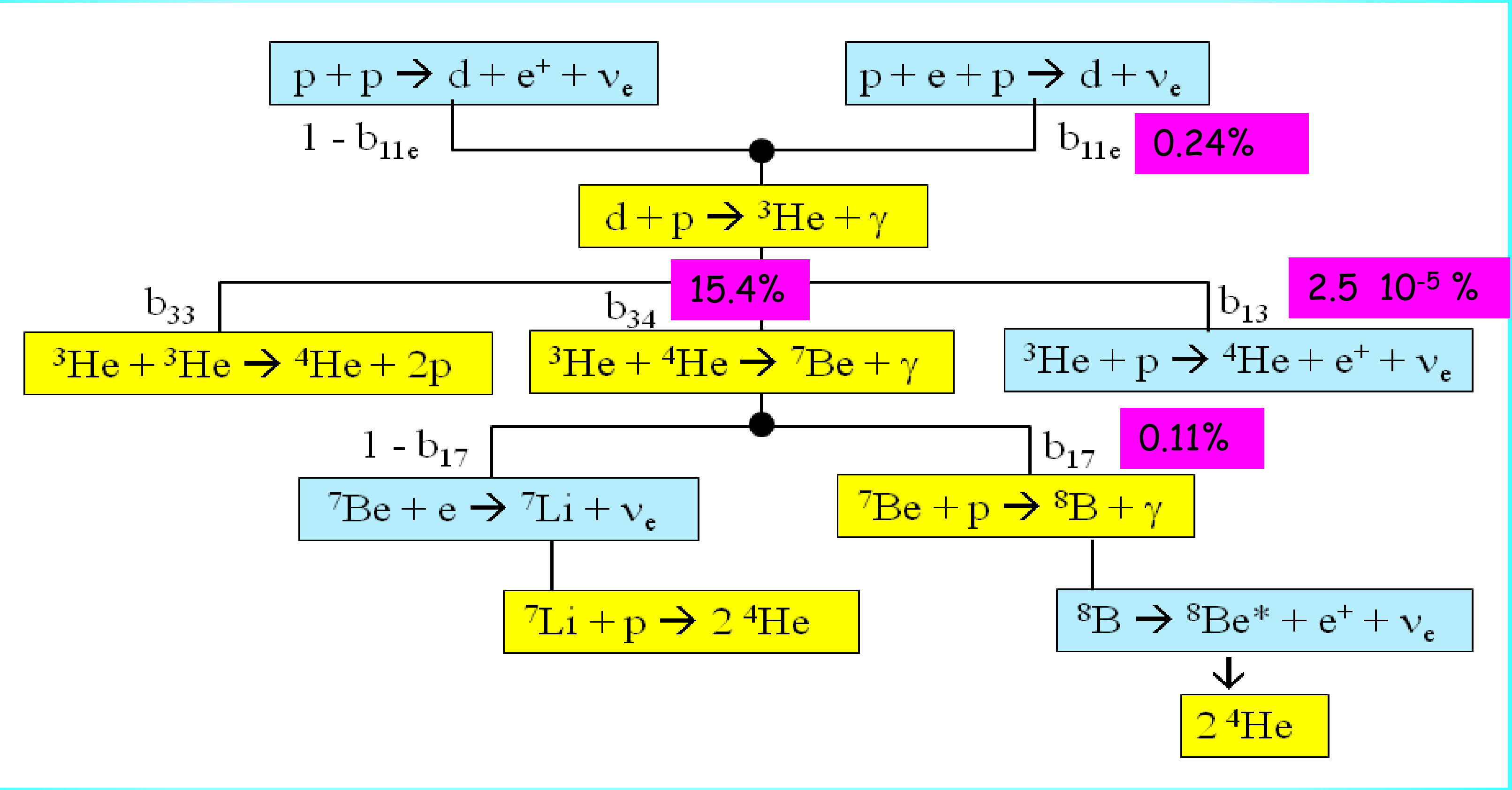
To compute neutrino fluxes it is enough to know:

Total neutrino flux

Branchings

Terminations of chains/cycles

The pp-chain



$p + p \rightarrow d + e^+ + \nu_e$

$p + e + p \rightarrow d + \nu_e$

$1 - b_{11e}$

b_{11e} 0.24%

$d + p \rightarrow {}^3He + \gamma$

15.4%

b_{33}

b_{34}

b_{13} 2.5 10^{-5} %

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

$1 - b_{17}$

b_{17} 0.11%

${}^7Be + e \rightarrow {}^7Li + \nu_e$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow 2\ {}^4He$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$2\ {}^4He$

Two branchings:

${}^3He$: $b_{34} = b_{34}(\sigma, T, n)$

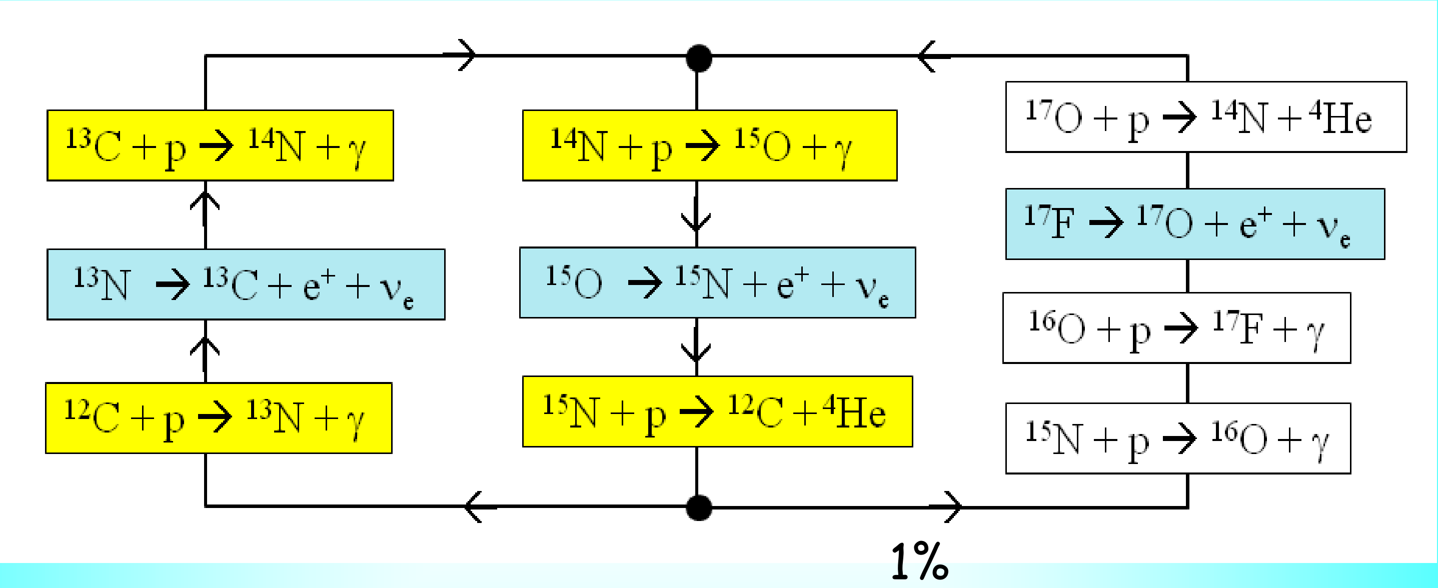
${}^7Be$: $b_{17} = b_{17}(\sigma, T, n)$

Branchings averaged over production regions

CNO-cycles

1.6% of energy generation

bi-cycle



$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$

$^{12}C + p \rightarrow {}^{13}N + \gamma$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$

$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

$^{17}O + p \rightarrow {}^{14}N + {}^{4}He$

$^{17}F \rightarrow {}^{17}O + e^{+} + \nu_e$

$^{16}O + p \rightarrow {}^{17}F + \gamma$

$^{15}N + p \rightarrow {}^{16}O + \gamma$

^{12}C, ^{14}N, ^{16}O – catalizers of cycles

^{12}C, ^{16}O – initial abundances

^{14}N – abundance changes during evolution

Fluxes and branchings

Branches
Terminations
Flux – Luminosity relation and normalization of neutrino flux

$$\frac{F_{pep}}{F_{pp}} = b_{11e} = 2.4\ 10^{-3}$$

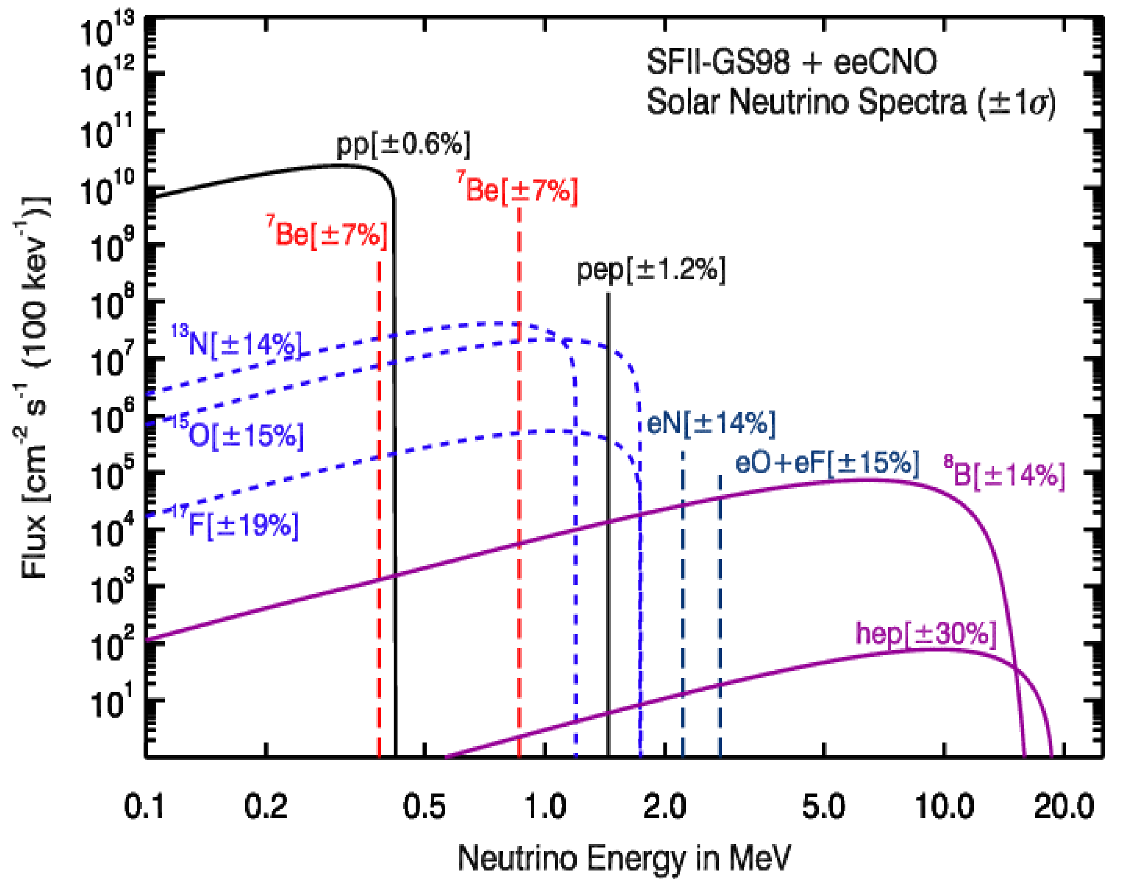
$$\frac{F_{Be}}{F_{pp}} = \frac{b_{34}}{2 - b_{34}} = 0.081$$

$$\frac{F_{B}}{F_{Be}} = b_{17} = 1.1\ 10^{-3}$$

branchings can be estimated but exact values should be computed using SSM code

Solar neutrino spectrum

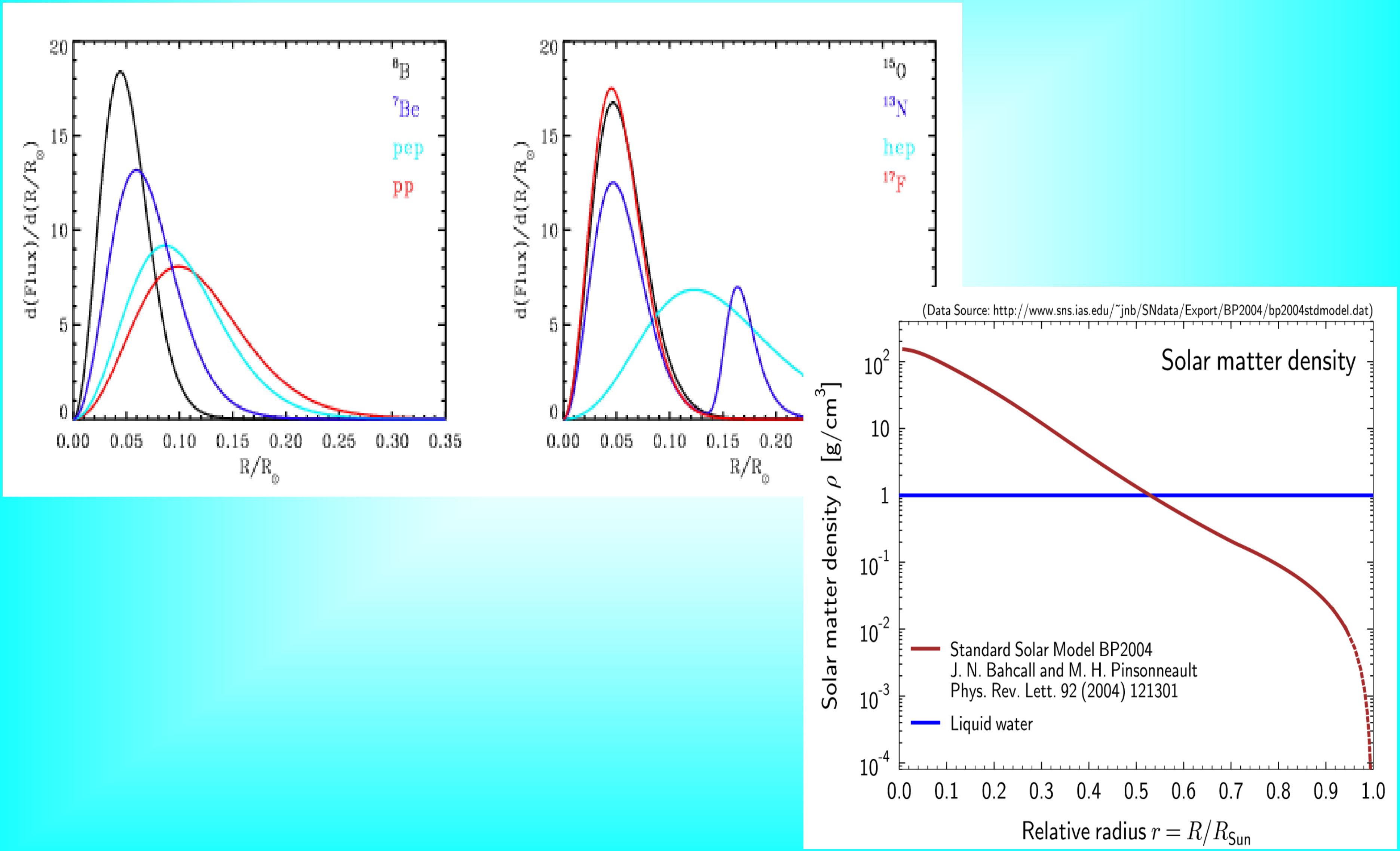
A. Serenelly



pp-, N-, O- asymmetric with sharp decrease after maximum

Be-, Hep – symmetric spectra due to final state

Neutrino production region



(Data Source: http://www.sns.ias.edu/~jnb/SNdata/Export/BP2004/bp2004stdmodel.dat)

Neutrino fluxes

N. Vinyolis et al,
1611.09867 astro-ph.SR

Models with high and low metallicities

Flux	GS98	AGSS09met	Experiment
pp	5.98 (1 +/- 0.006)	6.03 (1 +/- 0.005)	5.97 (1+0.006/-0.005)
pep	1.44 (1 +/- 0.01)	1.46 (1 +/- 0.009)	1.45 (1+0.009)
hep	7.98 (1 +/- 0.30)	8.25 (1 +/- 0.30)	19 (1+0.63/-0.47)
^{7}Be	4.93 (1 +/- 0.06)	4.50 (1 +/- 0.06)	4.80 (1+0.050/-0.046)
^{8}B	5.46 (1 +/- 0.12)	4.50 (1 +/- 0.12)	5.16 (1+0.025/-0.017)
^{13}N	2.78 (1 +/- 0.15)	2.04 (1 +/- 0.14)	< 13.7
^{15}O	2.05 (1 +/- 0.17)	1.44 (1 +/- 0.16)	< 2.8
^{17}F	5.29 (1 +/- 0.20)	3.26 (1 +/- 0.18)	< 85

pp: × 10^{10} cm^{-2} s^{-1} pep, ^{13}N, ^{15}O: × 10^{8}

^{7}Be : × 10^{9} ^{8}B, ^{17}F: × 10^{6} hep: × 10^{3}

Before BOREXINO phase II release

Solar metallicity problem

New 3D models of solar atmosphere (include effects of stratification, inhomogeneities ,etc)

Better agreement with absorption line shapes

Consistent with observations of neighboring stars

Predict 40% lower abundances of heavy elements (heavier than ^{4}He) in photosphere

Lower the temperature and density gradients → profiles

Disagreement with helioseismology

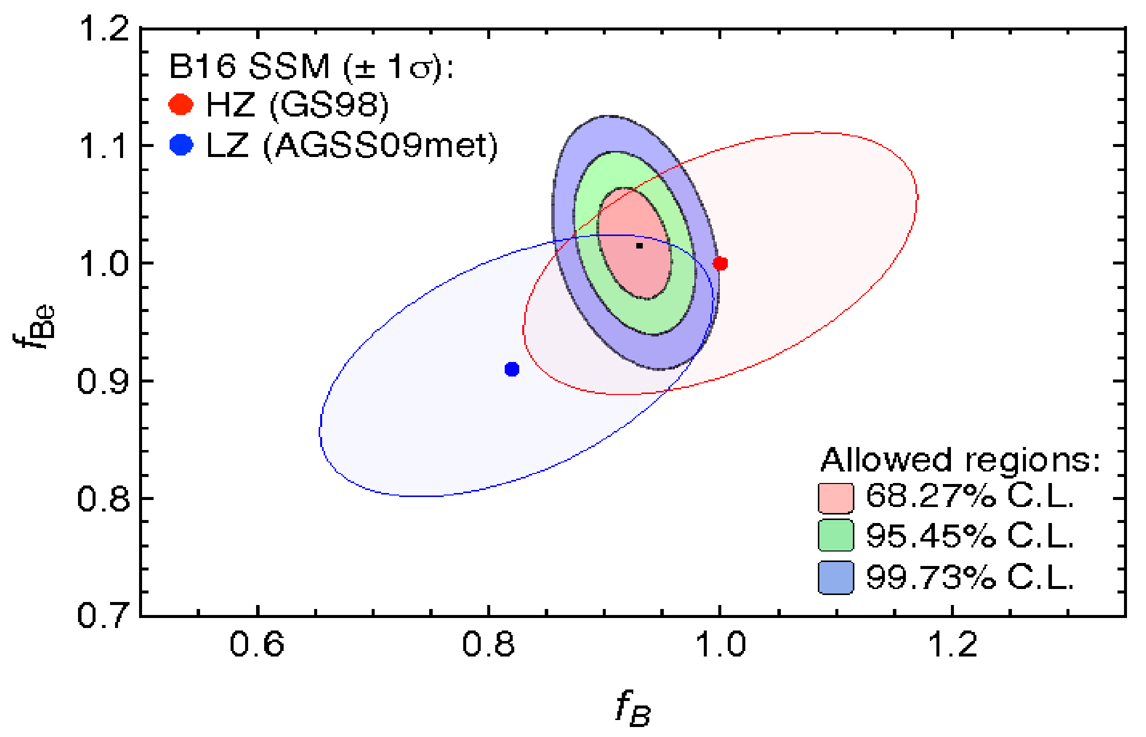
Reduces the central temperature of the Sun

Affects solar neutrino fluxes

Be: -10%   B: -20%   N, O: -40%

pp: +…%   → to satisfy the luminosity constraint

Distinguishing models with neutrinos

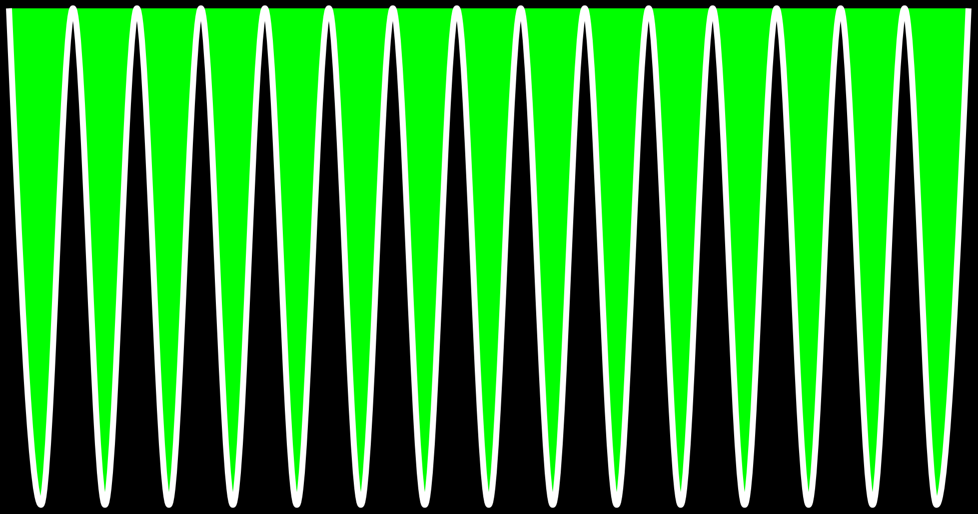


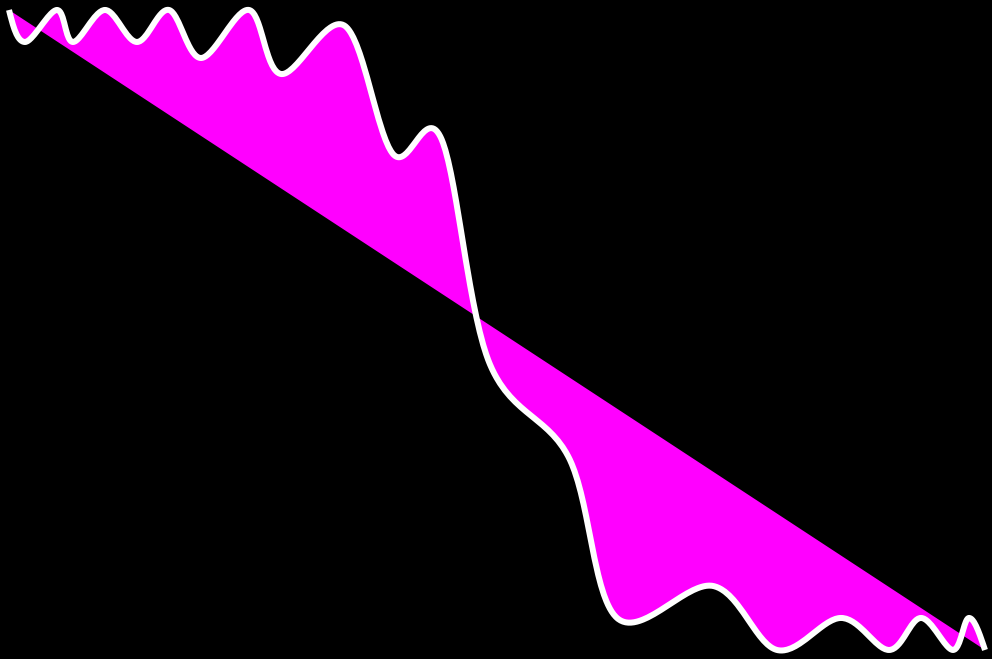
Borexino Collaboration
(Agostini, M. et al.)
arXiv:1707.09279 [hep-ex]

Theoretical uncertainties should be reduced

Allowed contours of *f*Be-*f*B obtained by combining the new result on 7Be ν's with solar and KamLAND data. The 1σ theoretical prediction are shown for low metallicity (blue), high metallicity (red). For fixed sin2θ13 = 0.02: Φ(7Be) = (5.00 ±0.15)× 109 cm-2 s−1; Φ(8B) = (5.08 ± 0.10) ×106 cm-2 s−1; tan2θ12 =0.47 ± 0.03; Δm212 = 7.5×10−5± 0.2 eV2.

II. Propagation





Flavor transformations

Absorption, inelastic interactions of neutrinos on the way to a detector can be neglected

Masses, Mixing

refraction

Key concept:
mixing in matter and eigenstates of neutrinos in matter

Mixing in vacuum

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

$(\nu_e , \nu_\mu , \nu_\tau)^T$

Flavor states

Mixing matrix in vacuum

$(\nu_1 \ \nu_2 \ \nu_3)^T$

Mass states

Standard parametrization

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

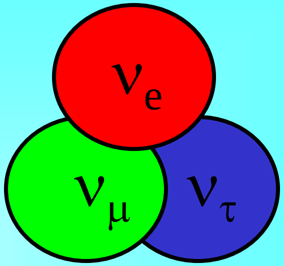
Diagonalizes the mass matrix in the flavor basis M:

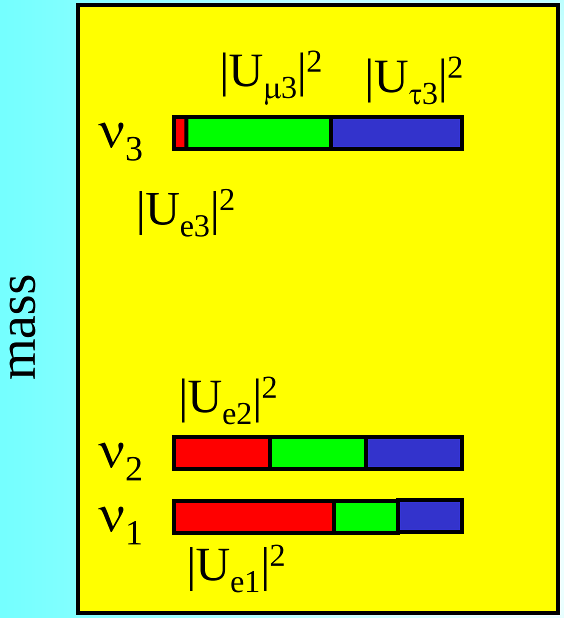
$$U_{PMNS}^{+} \; M^{+} M \; U_{PMNS} = M^{diag\ 2}$$

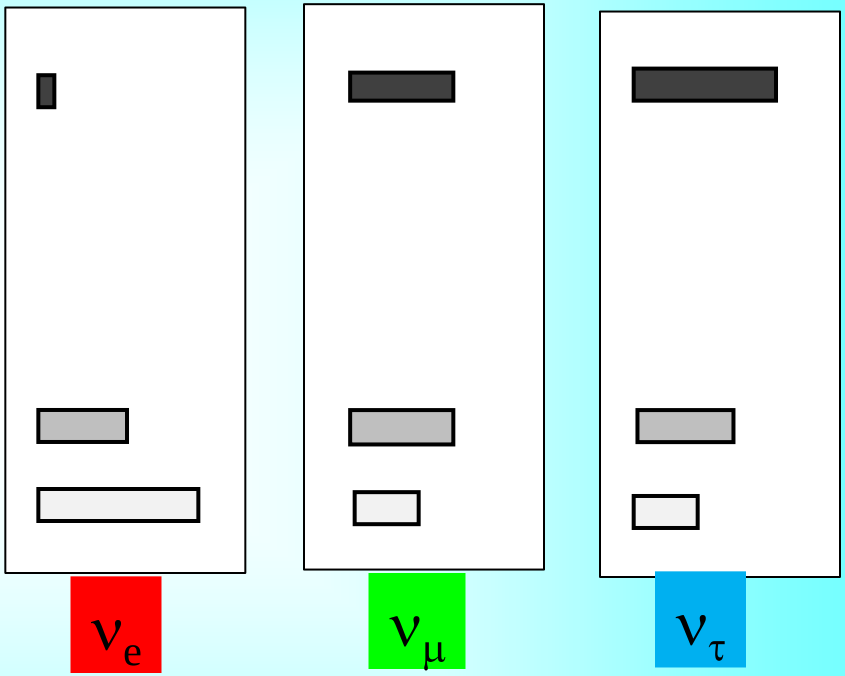
$$M^{diag\ 2} = diag\ (m_1^2, \ m_2^2, \ m_3^2)$$

Mixing

Dual
role







Flavor content of
mass states

$$\nu_{mass} = U_{PMNS}^{+} \nu_f$$

Mass content of flavor states

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

Standard parametrization

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

$I_{\delta} = \mathrm{diag}\,(1,\ 1,\ e^{i\delta})$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ s_{12}c_{23} + c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & - s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} + s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$, etc.

δ is the Dirac CP violating phase

θ_{12} is the ``solar" mixing angle

θ_{23} is the ``atmospheric" mixing angle

θ_{13} is the mixing angle determined by T2K, Daya Bay, CHOOZ, DC…

Evolution equation

$$\boxed{i \frac{d \nu_f}{d t} = H_0 \nu_f}$$

$$H_0 = \frac{M^+ M}{2E}$$

generalization for single ultra relativistic neutrino

$$H = E \sim p + \frac{m^2}{2E}$$

p is omitted, $m^2 \rightarrow M^+ M$

U_{PMNS} diagonalizes Hamiltonian in vacuum

Mass states are the eigenstates of the Hamiltonian in vacuum

Since U_{PMNS} constant, it diagonalizes also equation of motion -- splits it into three independent equations for mass states

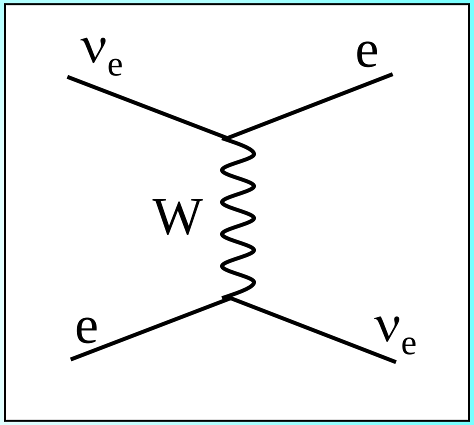
Mass states are eigenstates of propagation → propagate independently in vacuum

Refraction. Matter potential

L. Wolfenstein, 1978

at low energies Re A >> Im A
inelastic interactions can be neglected

Elastic forward scattering ⇨ $V_e,\ V_\mu,\ V_\tau$ potentials



Refraction index:

$$n - 1 = V / p$$

for E = 10 MeV

$$n - 1 = \begin{cases} \sim 10^{-20} & \text{inside the Earth} \\ < 10^{-18} & \text{inside the Sun} \end{cases}$$

$V \sim 10^{-13}$ eV inside the Earth

difference of potentials

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

Electron number density

$$V_\mu = V_\tau$$

Refraction length:

$$l_0 = \frac{2\pi}{V}$$

Mixing in matter – dynamical variable

S.P. Mikheyev, A.Y.S. 1985

Hamiltonian in matter: $H_0 \rightarrow H\ (n_e, E\ ) = H_0 + V\ (n_e)$

Mass states are no more the eigenstates of Hamiltonian and propagation
They mix and oscillate

Eigenstates of Hamiltonian in matter: $\nu_k \rightarrow \nu_{mk}$

Mixing in matter is determined with respect to eigenstates in matter

$\nu_f = U^m\ \nu_m$ $U_{PMNS} \rightarrow U^m(n_e, E)$

U^m diagonalizes the Hamiltonian in matter

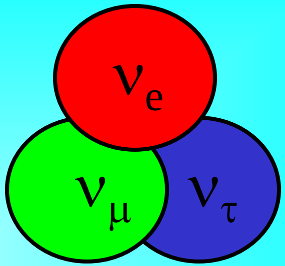
$U^{m+}\ H\ U^m = H^{diag}$ $H^{diag} = diag\ (H_{1m},\ H_{2m},\ H_{3m})$

eigenvalues of the Hamiltonian

Inverting:

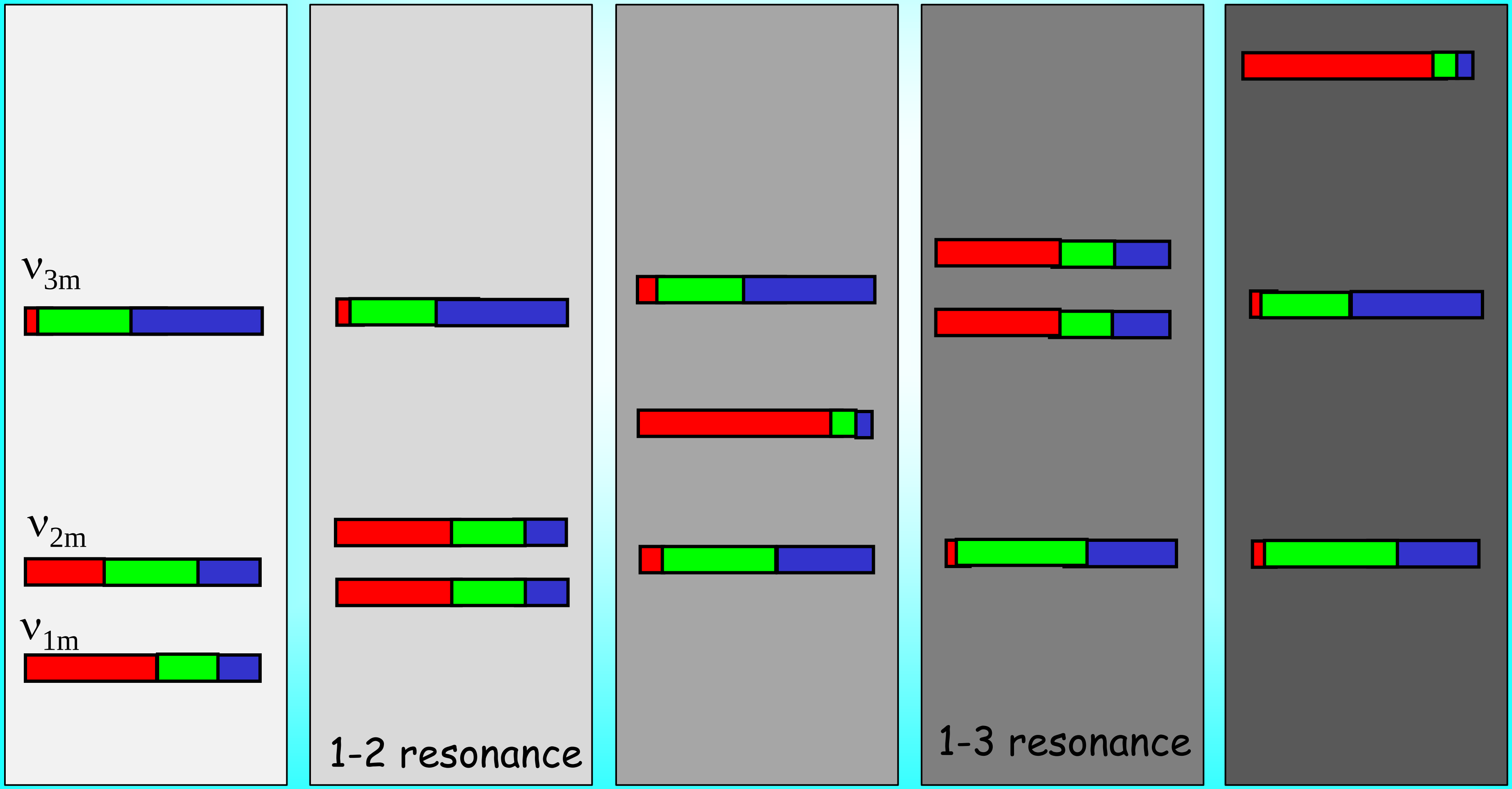
$\nu_m = U^{m+}(n_e, E)\ \nu_f$ → flavor of eigenstates depends on n_e and E

Flavor in matter

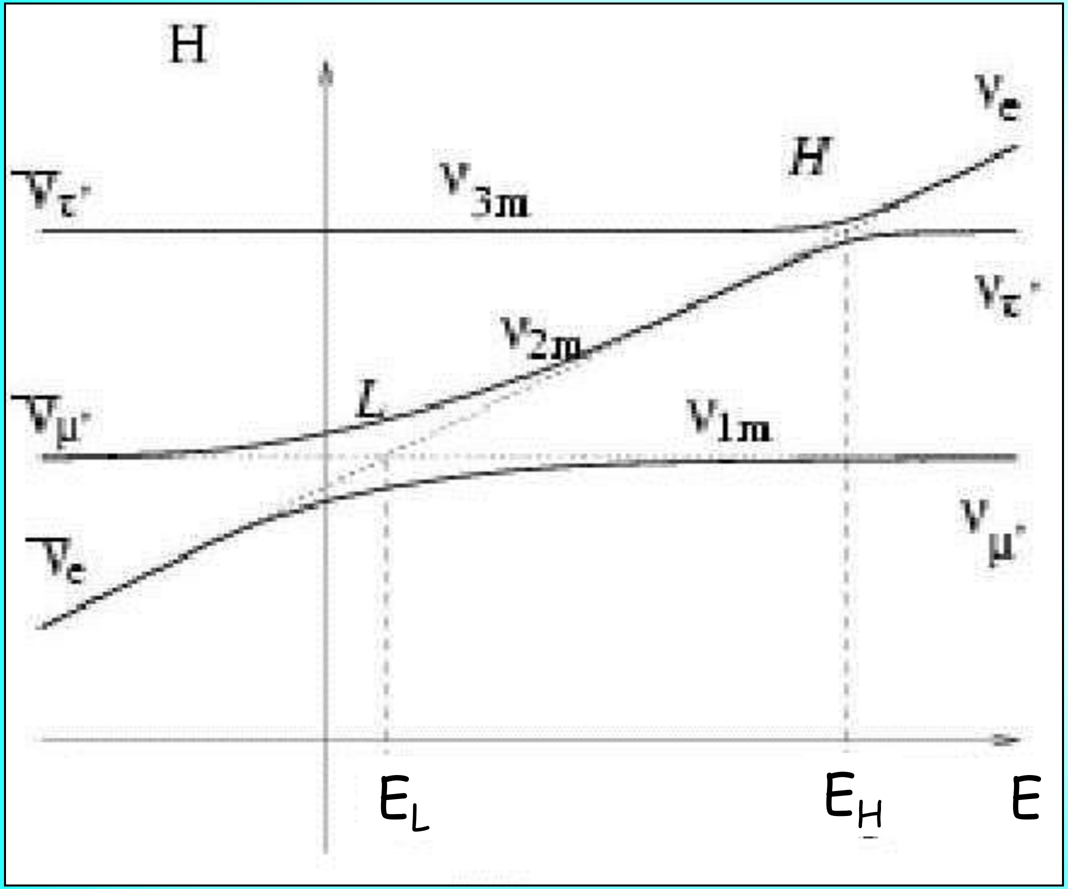


Density increase →

Normal mass hierarchy, neutrinos



Level crossings



0.1 GeV

6 GeV

Resonance region

High energy range

Normal mass hierarchy

Constant density case

Similarly to vacuum evolution has a character of oscillations with parameters determined by mixing and eigenvalues of H

Since $U^m(n_e, E)$ is constant

ν_m diagonalize the evolution equation (split into three independent eqiuations for each eigenstate)

$$i \frac{d\nu_m}{dt} = H^{diag} \nu_m$$

Solution is trivial: $\nu_{mk}(t) = e^{-i\,\phi_k(t)} \nu_{mk}$

where the phase $\phi_k(t) = H_{km}\, t$

Then evolution of ν_e

$\nu_e = \Sigma_k U_{ek}^m (n)\, \nu_{mk}$ ➡ $\nu(t) = \Sigma_k U_{ek}^m (n) e^{-i\,\phi_k(t)} \nu_{mk}$

Lead to oscillations → effect of phase difference increase $\phi_k(t) - \phi_j(t)$

Varying density $U_{ek}^m = U_{ek}^m (n(t))$ and ν_m are no more the eigenstates of propagation

Evolution equation for eigenstates. Adiabaticity

Inserting in evolution equation for the flavor states $\nu_f = U^m \nu_m$

$$\boxed{i \frac{d\nu_m}{dt} = \left(H^{diag} + i\, U^{m+} \frac{dU^m}{dt} \right) \nu_m} \quad H^{diag} = diag(H_{1m}, H_{2m}, H_{3m})$$

off - diagonal

If density changes slowly enough, so that

$$\boxed{\left(U^{m+} \frac{dU^m}{dt} \right)_{ij} << H_{im} - H_{jm}}$$

adiabaticity condition

equation for the eigenstates splits:

$$i \frac{d\nu_m}{dt} = H^{diag} \nu_m$$

The eigenstates evolve independently, transitions between them

$\nu_{im} \Leftrightarrow \nu_{jm}$ are absent as in constant density case

In contrast to constant density case the flavor of ν_{im} changes according to density change

LMA MSW solution

Refers to certain region of oscillation parameters Δm^2 - $\sin^2\theta$

Established 1968 - 2003

KAMLAND reactor experiment was planned to check the LMA solution

Inside the Sun

Density profile of the Sun is such that for LMA oscillation parameters the adiabaticity condition is fulfilled down to very small densities n_f , where matter effect on mixing can be neglected and therefore the eigenstates in matter coincide with mass states:

$$\nu_{im}(n_f) = \nu_i$$

Adiabatic propagation means that transitions between the eigenststes can be neglected and they propagate independently (in the same way as mass states in vacuum)

$$\nu_{im} \not\rightarrow \nu_{jm}$$

Therefore the adiabatic evolution in the Sun means that

$$\nu_{im}(n_0) \rightarrow \nu_{im}(n_f) = \nu_i$$

initial density n_0

Flavor content (composition) of the eigenstates changes according to (mixing) density change.

Inside the Sun

ν_e is produced at some central density n_0

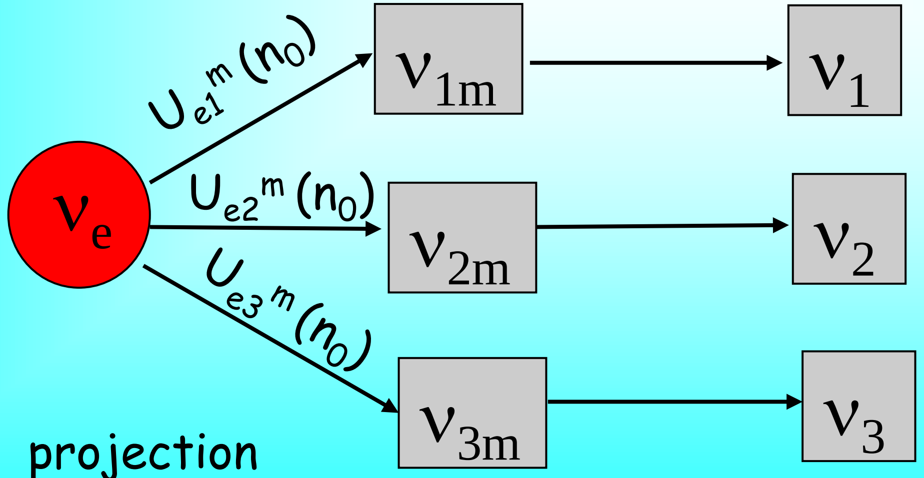
It can be expanded onto eigenstates in the production point:

$$\nu_e = \Sigma_i \, U_{ei}^m (n_0) \, \nu_{im} (n_0)$$

Evolving to the surface of the Sun adiabatically $\nu_{im}(n_0) \rightarrow \nu_i$

$$\nu_e \rightarrow \Sigma_i \, U_{ei}^m (n_0) \, \nu_i$$

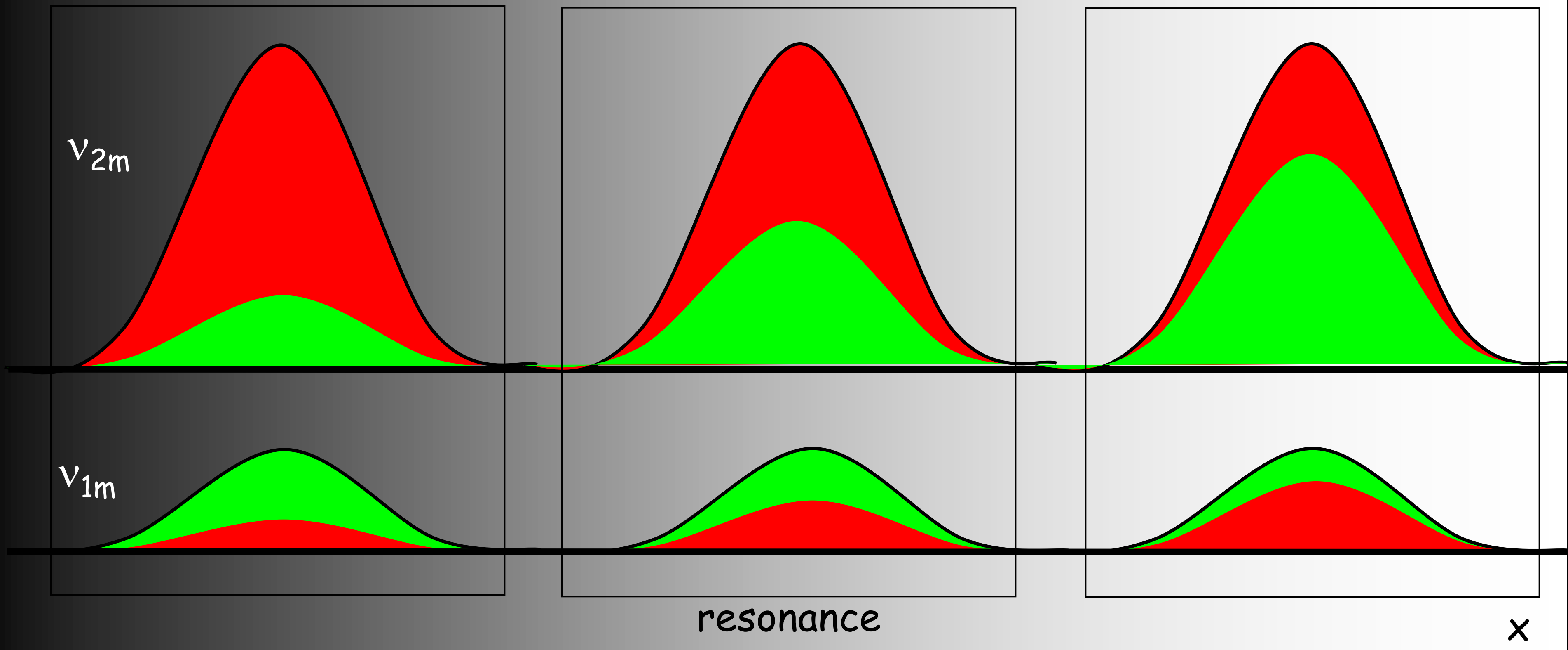
Admixtures of the eigenstates do not change being determined by the initial mixing



Adiabatic propagation

But flavors of eigenstates change

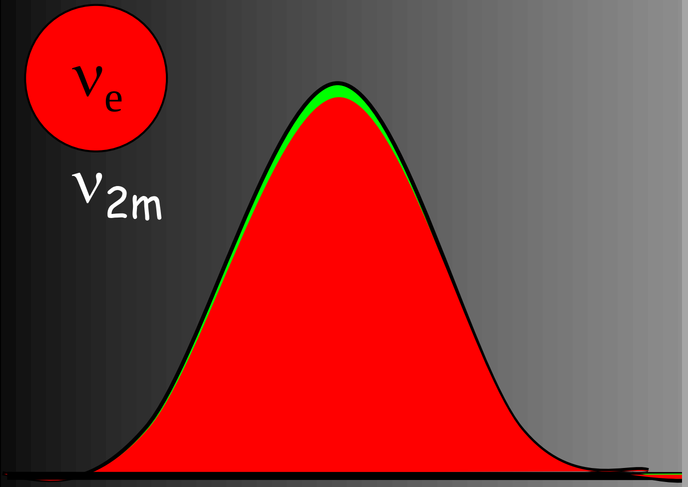
Adiabatic conversion



if density
changes
slowly

- the amplitudes of the wave packets do not change
-flavors of the eigenstates being determined by mixing
angle follow the density change

Non-oscillatory transition



Single eigenstate:
→no interference
→no oscillations
→phase is irrelevant

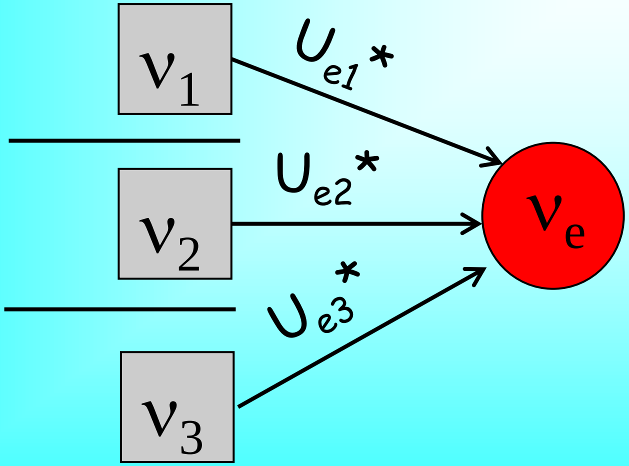
This happens when mixing is very small in matter with very high density

From the Sun to the Earth

1. Loss of the propagation coherence between the eigenstates

In position (configuration) space:
the wave packets of different eigenstates have different group velocities (due to different masses).
They are separated already at distances 0.1 – 10 R_{sun} (depending on energy). Absence of the overlap - no interference.

Incoherent fluxes of mass states arrive at the Earth



The probability to find ν_e

$$P_{ee} = \Sigma_i | U_{ei}^m(n_0, E) U_{ei}* |^2$$

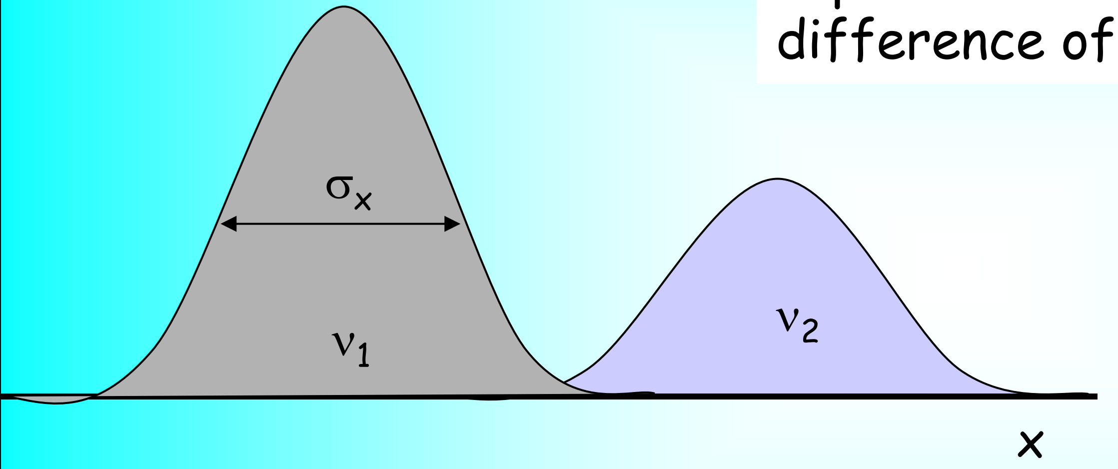
$$= \Sigma_i | U_{ei}^m(n_0 , E)|^2 |U_{ei}|^2$$

Contributions from different eigenstates sum up in the probability

2. Spread in space of individual wave packets

Coherence in propagation

In the configuration space: separation of the wave packets due to difference of group velocities



$\Delta v_{gr} = \Delta m^2 / 2E^2$

separation: $\Delta v_{gr} L = \Delta m^2 L/2E^2$

no overlap: $\Delta v_{gr} L > \sigma_x$

coherence length: $L_{coh} = \sigma_x E^2/\Delta m^2$

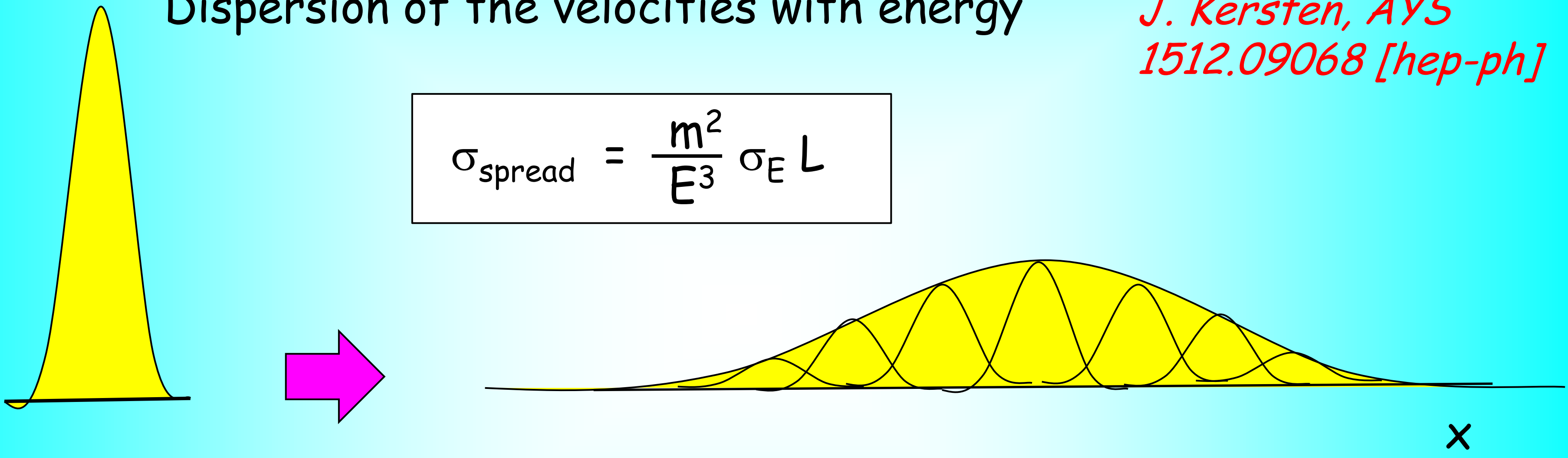
Spread of wave packets

Due to presence of waves with different energies in the packet

Dispersion of the velocities with energy

J. Kersten, AYS
1512.09068 [hep-ph]

$$\sigma_{spread} = \frac{m^2}{E^3} \sigma_E L$$



Beryllium neutrino line:

$\sigma_x = 2\pi / \Gamma_{Be} = 6\ 10^{-8}$ cm → $\sigma_{spread} \sim 4\ 10^{-6}$ cm

$\Delta x_{sep}{}^S \sim 2\ 10^{-3}$ cm → $\Delta x_{sep}{}^S >> \sigma_{spread}$

$\Delta x_{sep}{}^E \sim 5\ 10^{-8}$ cm → $\sigma_x \sim \Delta x_{sep}{}^E << \sigma_{spread}$

Oscillations of mass states in the Earth

Loss of coherence: YES NO?

Remarks

$$P_{ee} = \Sigma_i |U_{ei}{}^m(n_0, E)|^2 \; |U_{ei}|^2$$

Is final result for the survival probability, which describes the signal during the day when the earth effect can be neglected

It does not depend on phase and distance

Oscillations did not even mentioned

Oscillations - interference effect which is determined by phase is irrelevant here

Complete interpretation is production of eigenstates which evolve independently without interference

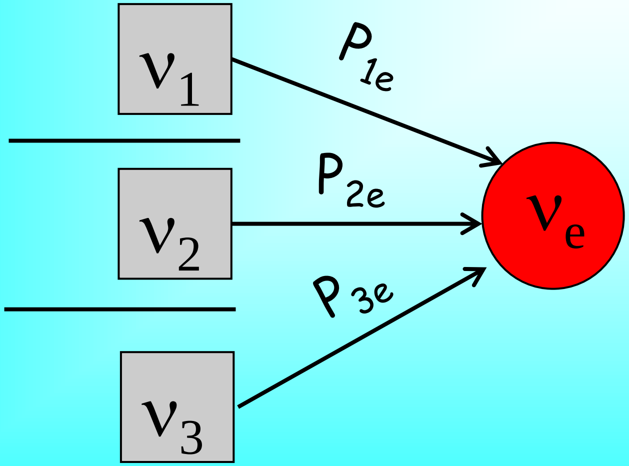
The problem is reduced to determination of mixing parameters $U_{ei}{}^m(n_0, E)$ in the production point

Oscillations in the Earth

In matter of the Earth mass states split into eigenstates and start to oscillate

Projections of ν_k on ν_e should be substituted by the oscillation probabilities $| U_{ei}|^2 \rightarrow P_{ie}$

$$P_{ee} = \Sigma_i | U_{ei}^m(n_0 , E)|^2 P_{ie}$$



$$P_{3e} = |U_{e3}|^2 = s_{13}^2$$

Unitarity

$$P_{2e} = 1 - P_{1e} - s_{13}^2$$

Pure Earth matter effect:

$$f_{reg} = |U_{e1}|^2 - P_{1e}$$

called the regeneration factor

Final result

Using the same standard parametrization for mixing matrix in matter:

$U_{e1}^m = c_{13}^m \cos\theta_{12}^m$ $U_{e2}^m = c_{13}^m \sin\theta_{12}^m$ $|U_{e3}^m| = s_{13}^m$

($c_{13} = \cos\theta_{13}$, $c_{13}^m = \cos\theta_{13}^m$, etc.)

and regeneration factor one finds from general formula

$$P_{ee} = c_{13}^2 c_{13}^{m2} P_2^{ad} + s_{13}^2 s_{13}^{m2} - c_{13}^{m2} \cos 2\theta_{12}^m f_{reg}$$

$$P_2^{ad} = \sin^2\theta_{12} + \cos 2\theta_{12} \cos\theta_{12}^m$$

or $P_2^{ad} = \frac{1}{2}(1 + \cos 2\theta_{12} \cos 2\theta_{12}^m)$

The mixing parameters in matter $\theta_{ij}^m = \theta_{ij}^m(n_0, E)$

Should be computed in the neutrino production point

Find in terms of Vacuum mixing and potential V

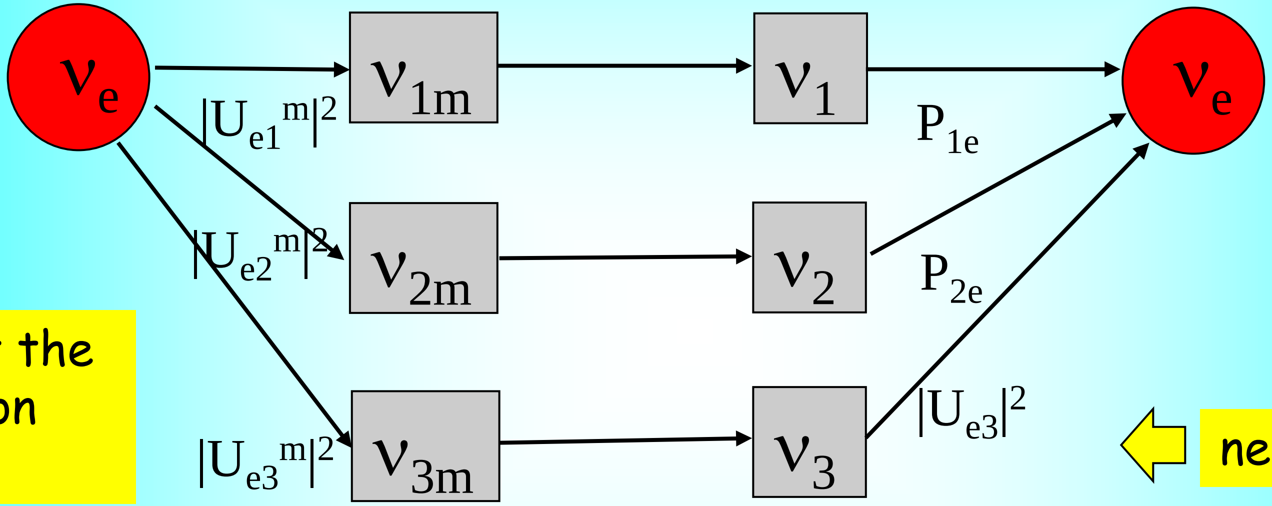
Scheme of transitions

and between the
Sun and the Earth

projection

propagation
in the Sun

propagation
in the Earth



ν_e

$|U_{e1}{}^m|^2$ $\quad$ ν_{1m} $\quad$ ν_1 $\quad$ P_{1e}

$|U_{e2}{}^m|^2$ $\quad$ ν_{2m} $\quad$ ν_2 $\quad$ P_{2e}

$|U_{e3}{}^m|^2$ $\quad$ ν_{3m} $\quad$ ν_3 $\quad$ $|U_{e3}|^2$

ν_e

mixing at the
production
point n_0

adiabatic
conversion

oscillations
in multi-layer
medium

nearly decouples

$$P_{ee} = \Sigma_i |U_{ei}{}^m(n_0)|^2 P_{ie}$$

during the day $\quad$ $P_{ie} = |U_{ei}|^2$ $\quad$ scale invariant

Finding oscillation parameters: $3\nu \rightarrow 2\nu$

Simple expressions of parameters involved can be found reducing 3ν to 2ν evolution problem

For solar neutrinos this can be done "decoupling" the heavies state ν_{3m} from the rest of the system using inequalities

$$V \sim \Delta m_{21}^2/2E \ll \Delta m_{31}^2/2E$$

1. Go to the "propagation basis"

$$\nu_f = U_{23} I_\delta \tilde{\nu}$$

$$\tilde{\nu} = (\nu_e , \tilde{\nu}_\mu , \tilde{\nu}_\tau)^T$$

ν_e is not affected

The Hamiltonian in this basis:

$$\tilde{H} = U_{13}\, U_{12}\, H_0^{diag}\, U_{12}^T\, U_{13}^T + V$$

$$H_0^{diag} = diag(0, \Delta m_{21}^2, \Delta m_{31}^2)/2E$$

potential is not affected,
dependence on 23-mixing and CP phase disappear

...continued

2. Make 1-3 rotation U_{13}^m on angle θ_{13}^m which vanishes elements H_{13}, H_{31}

$$\theta_{13}^m \simeq \theta_{13} + \delta\theta_{13} \qquad \delta\theta_{13} = \theta_{13} \frac{4V\,E}{\Delta m_{21}^2}$$

vacuum angle

matter correction

In new basis $\nu' = (\nu_e', \tilde{\nu}_\mu, \nu_\tau')^T$ $\qquad \nu_f = U_{23} I_\delta U_{13}^m \nu'$

the Hamiltonian

$$H' \simeq \begin{pmatrix} H^{(2)} & 0 \\ 0 & H_{3m} \end{pmatrix}$$

small induced H_{23} are neglected

the third state ν_τ' decouples

$$H^{(2)} = \frac{\Delta m_{21}^2}{4E} \begin{array}{cc} \begin{pmatrix} -\cos 2\theta_{12} + 2\varepsilon_{12}\, c_{13}^{m2} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} & \begin{array}{c} \nu_e' \\ \tilde{\nu}_\mu \end{array} \end{array} \qquad \varepsilon_{12} = \frac{2V\,E}{\Delta m_{21}^2}$$

Standard 2ν Hamiltonian in matter with $V \rightarrow c_{13}^{m2}\, V \simeq c_{13}^2\, V$

1-2 mixing in matter

Diagonalization of the Hamiltonian:

$$\sin^2 2\theta_{12}{}^m = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - c_{13}{}^2\, 2EV/\Delta m_{21}{}^2)^2 + \sin^2 2\theta_{12}}$$

$$V = \sqrt{2}\, G_F\, n_e$$

Mixing is maximal $\sin^2 2\theta_{12}{}^m = 1$ if

$$c_{13}{}^2\, V = \cos 2\theta_{12} \frac{\Delta m_{21}{}^2}{2E}$$

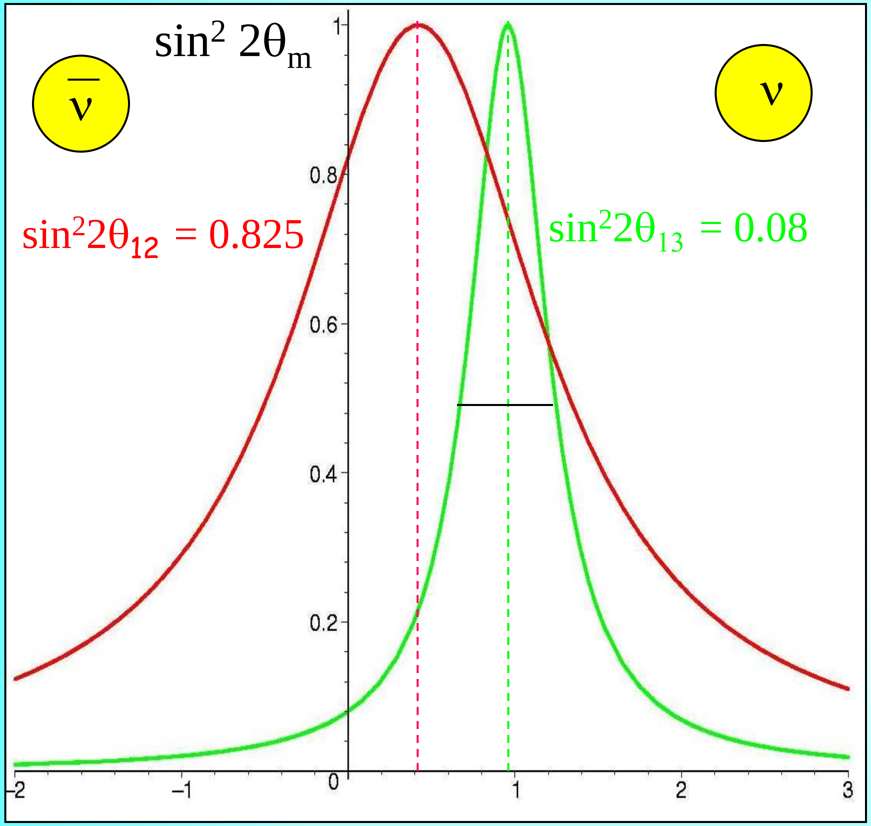
Resonance condition

Difference of the eigenvalues

$$H_{2m} - H_{1m} = \frac{\Delta m_{21}{}^2}{2E}\sqrt{(\cos 2\theta_{12} - c_{13}{}^2\, 2EV/\Delta m_{21}{}^2)^2 + \sin^2 2\theta_{12}}$$

Resonance

Dependence of mixing on density, energy has a resonance character



In resonance: $\sin^2 2\theta_m = 1$

Flavor mixing is maximal

$l_\nu = l_0 \cos 2\theta$

Vacuum oscillation length ≈ Refraction length

Resonance width: $\Delta n_R = 2n_R \tan 2\theta$

density $l_\nu / l_0 \sim n E$

$\theta_m \rightarrow 0$

$\theta_m = \theta$

$\theta_m = \pi/4$

$\theta_m \rightarrow \pi/2$

Mixing is suppressed at high densities

$$|V| \gg \frac{\Delta m^2}{2E}$$

⇒ Flavor states coincide with eigenstates and vice versa

Adiabaticity in 2ν - system

In non-uniform medium the Hamiltonian depends on time: $H_{tot} = H_{tot}(n_e(t))$

$$\boxed{i \frac{d\nu_f}{dt} = H_{tot}\,\nu_f}$$

$$\nu_f = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \qquad \nu_m = \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

Inserting $\nu_f = U(\theta_m)\,\nu_m$ $\qquad \theta_m = \theta_m(n_e(t))$ $\qquad$ Here $\theta_m = \theta_{12}^m$

$$i \frac{d}{dt}\begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} = \begin{pmatrix} 0 & i \frac{d\theta_m}{dt} \\ -i \frac{d\theta_m}{dt} & H_{2m} - H_{1m} \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

off-diagonal terms imply transitios

$\nu_{1m} \Leftrightarrow \nu_{2m}$

However

if $\left|\frac{d\theta_m}{dt}\right| \ll H_{2m} - H_{1m}$

off-diagonal elements can be neglected
no transitions between eigenstates
propagate independently

Adiabatic parameter

$$\gamma = \frac{\left| \frac{d\theta_m}{dt} \right|}{H_{2m} - H_{1m}}$$

Adiabaticity condition:

$\gamma << 1$

most crucial in the resonance where the mixing angle in matter changes fast

$$\gamma_R = \frac{l_R}{2\pi \, \Delta r_R}$$

$\Delta r_R = h_n \tan 2\theta$ is the width of the resonance layer

$h_n = \frac{n}{dn/dx}$ is the scale of density change

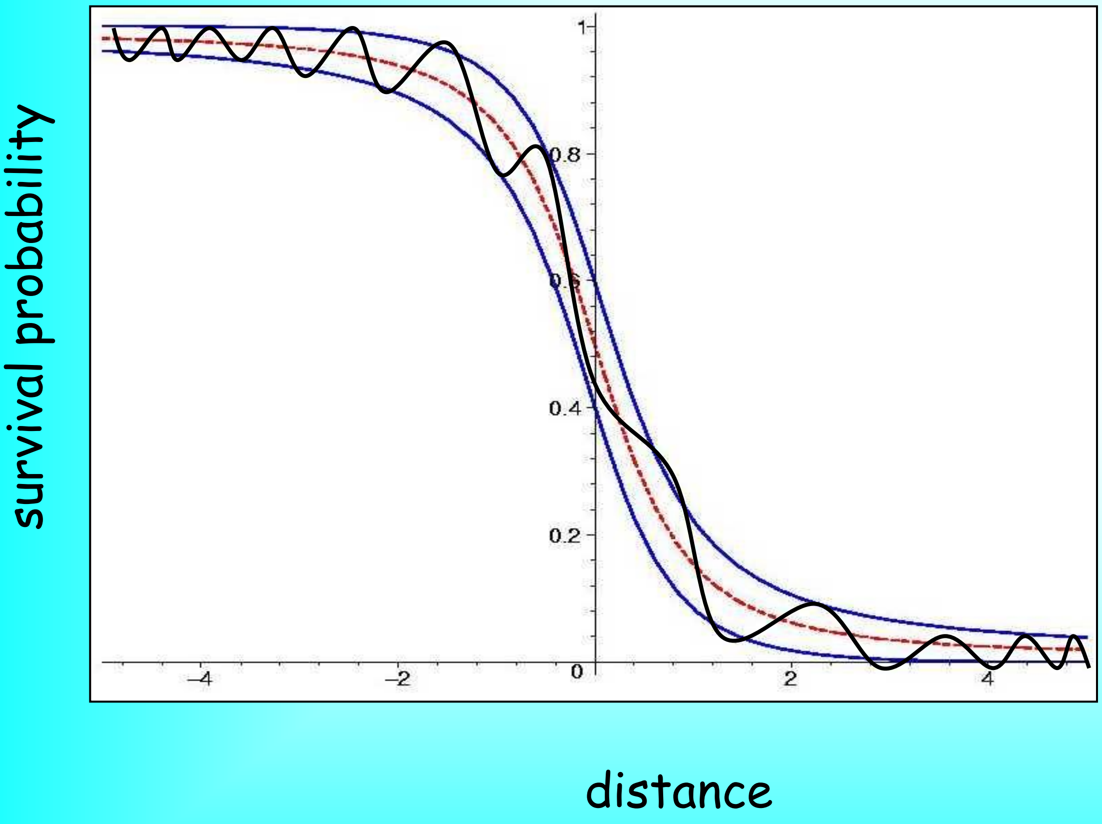
$l_R = l_\nu / \sin 2\theta$ is the oscillation length in resonance

Explicitly:

$$\gamma_R = \frac{4\pi E \cos 2\theta}{\Delta m^2 \sin^2 2\theta \, h_n}$$

Spatial picture

Adiabatic conversion



interplay of adiabatic conversion and oscillations

Non-oscillatory transition is modulated by oscillations

Mixing in matter

Thus, the total mixing matrix

$$U^m = U_{23} I_\delta U_{13}^m U_{12}^m$$

Thus the angles θ_{12}^m and θ_{13}^m determined via reduction of the 3ν to 2ν problem are the mixing angles in whole 3ν framework

They should be used in our general formula for the probability

Oscillations in the Earth

Incoherent fluxes of mass state arrive at the Earth.
They split into eigenstates in matter and oscillate.
Due to unitarity (and small energies) it is enough to compute only one oscillation probability P_{1e} or regeneration factor f_{reg}

$(f_{reg} = |U_{e1}|^2 - P_{1e})$

Mixing of mass states in matter

$$U^{mass} = U_{PMNS}^{+} U^{m}$$

For 2ν case

$$\sin 2\theta' = \frac{c_{13}^2 \varepsilon_{21} \sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - c_{13}^2 \varepsilon_{21})^2 + \sin^2 2\theta_{12}}} = c_{13}^2 \varepsilon_{21} \sin 2\theta_{12}^{m}$$

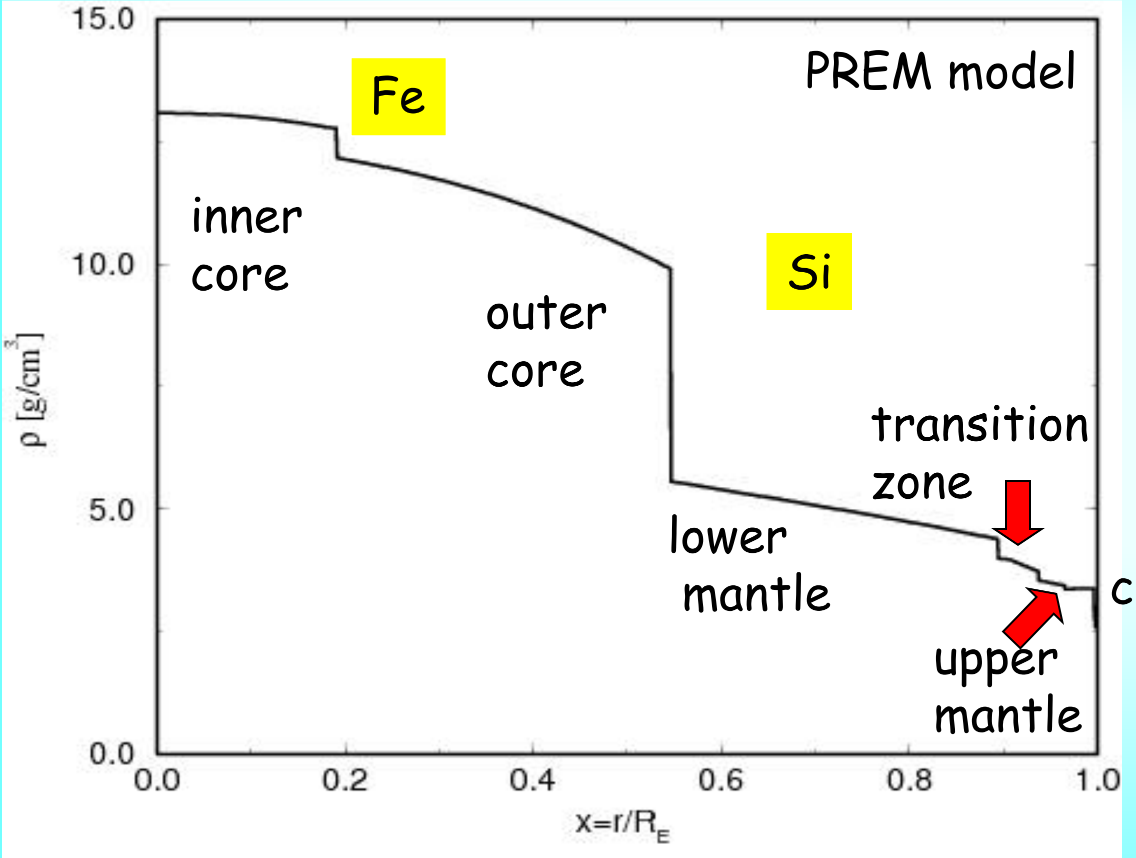
$$\varepsilon_{21} = \frac{2V E}{\Delta m_{21}^2} = 0.03\, E_{10}\, \rho_{2.6}$$

MeV g/cm^3

determines smallness of effects

Low density regime

The earth density profile



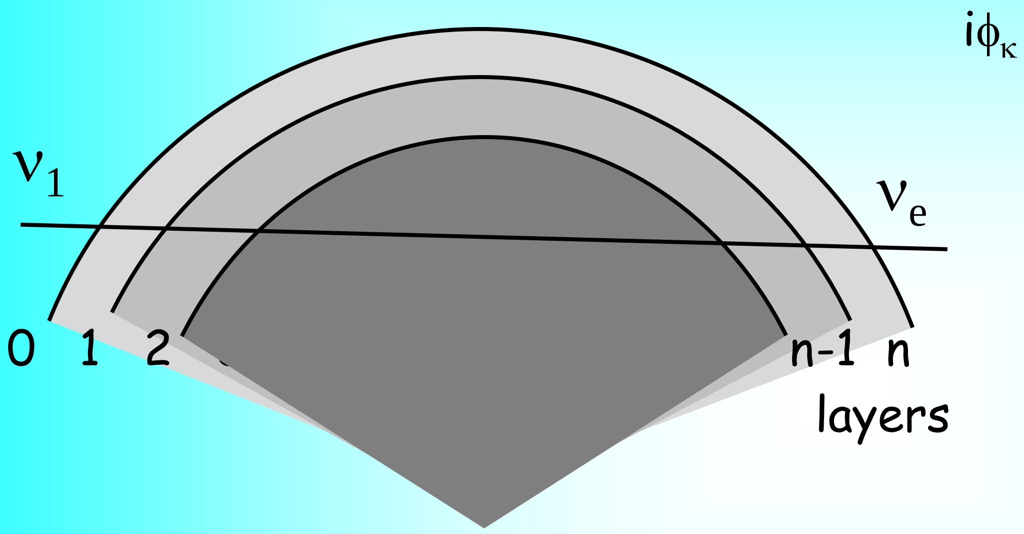
A.M. Dziewonski
D.L Anderson 1981

(phase transitions in silicate minerals)

R_e = 6371 km

solid liquid

Regeneration



Layers with slowly
changing density
and density jump

Evolution matrix (matrix
of transition amplitudes)

$$S = U^m_n \, \Pi_k \, D_k U_{k,k-1}$$

U^m_n - flavor mixing matrix, projects onto flavor state in the end

D_k - describe the adiabatic evolution within layers

$$D_k = \mathrm{diag}\,(e^{-0.5i\phi_\kappa},\ e^{0.5i\phi_\kappa})$$

$$\phi_\kappa = \int dx (H_{2m} - H_{1m})$$

adiabatic phase
acquired in k layer

$U_{k,k-1}$ - describes change of basis of eigenstates between k and k-1 layers

$$U_{k,k-1} = U(-\Delta\theta_{k-1})$$

$\Delta\theta_{k-1}$ -change of the mixing angle in matter after k-1 layer

...continued

~

$$P_{1e} = c_{13}^2|S_{e1}|^2$$

due to transition to 3ν basis

Approximate (lowest order in ε) result

$$U_{k,k-1} \simeq I - i\sigma_2 \sin \Delta\theta_{k-1}$$

Inserting this expression into formula for S and taking the lowest order terms in $\sin\Delta\theta_{k-1} \sim \varepsilon$

$$P_{1e} = c_{13}^2 \cos^2\theta_n^f + c_{13}^2 \sin 2\theta_n^f \, \Sigma_{j = 0 \, ...n-1} \sin \Delta\theta_j \cos \phi_j^{after}$$

the 1-2 angle in matter near detector

sum over jumps

total phase acquired after jump j

$$\sin \Delta\theta_j \simeq c_{13}^2 \sin 2\theta_{12} \, \Delta V_j \, \frac{E}{\Delta m_{21}^2}$$

ΔV_j - j density jump

The lowest order plus waves emitted from different jumps

Integral formula

Substituting summation (with small spatial intervals) by integration:

$$f_{reg} = - \tfrac{1}{2}\, c_{13}{}^4 \sin^2 2\theta_{12} \int_{x_0}^{x_f} dx\, V(x) \sin \phi^m(x \rightarrow x_f)$$

The phase acquired from the point x to the final point of trajectory (phase after)

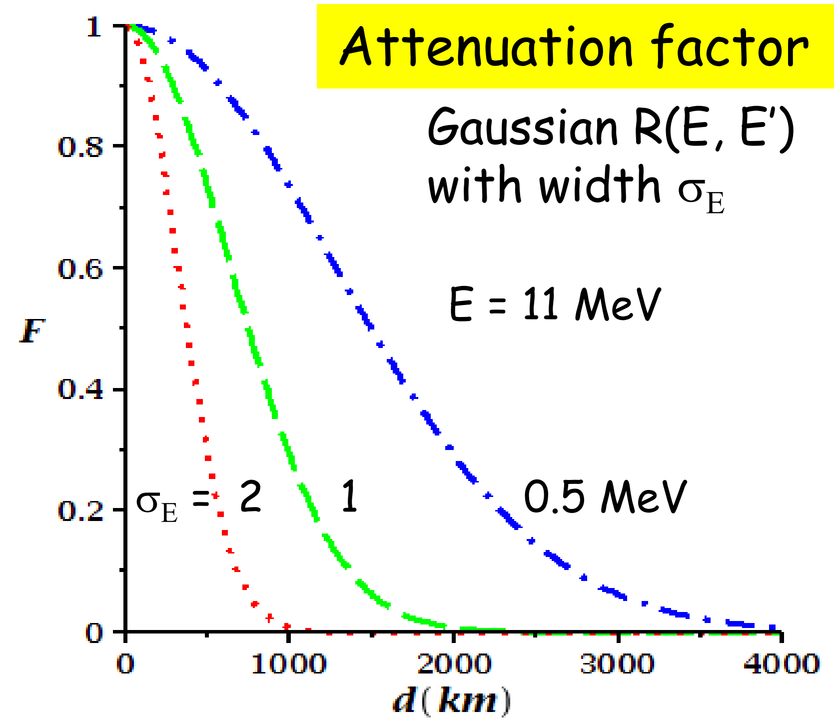
Attenuation effect

Integration with the energy resolution function R(E, E'):

$$\langle f_{reg} \rangle = \int dE' \, R(E, E') \, f_{reg}(E')$$

$$\langle f_{reg} \rangle = 0.5 \sin^2 2\theta \int_{x_0}^{x_f} dx \, F(x_f - x) \, V(x) \, \sin\Phi^m(x \rightarrow x_f)$$

F(d)



The sensitivity to remote structures d > λ_{att} is suppressed

Attenuation length

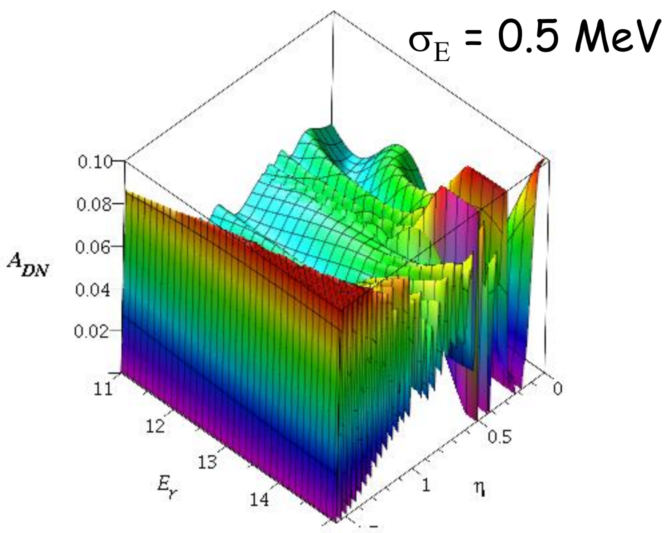
$$\lambda_{att} = l_\nu \frac{E}{\pi\sigma_E}$$

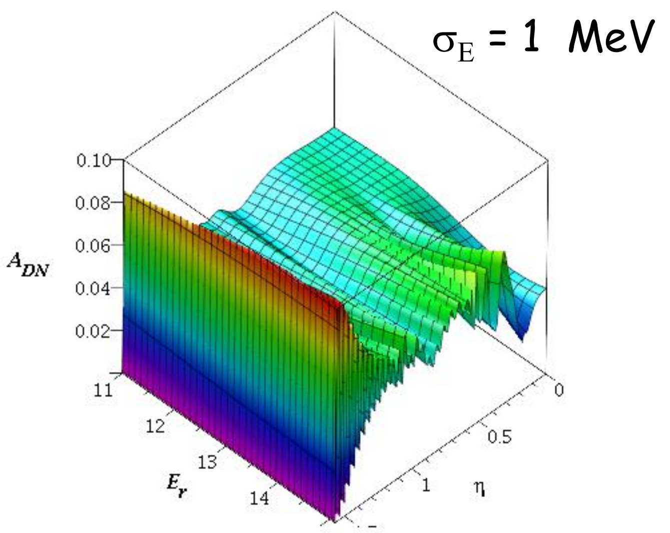
l_ν is the oscillation length

The better the energy resolution, the deeper penetration

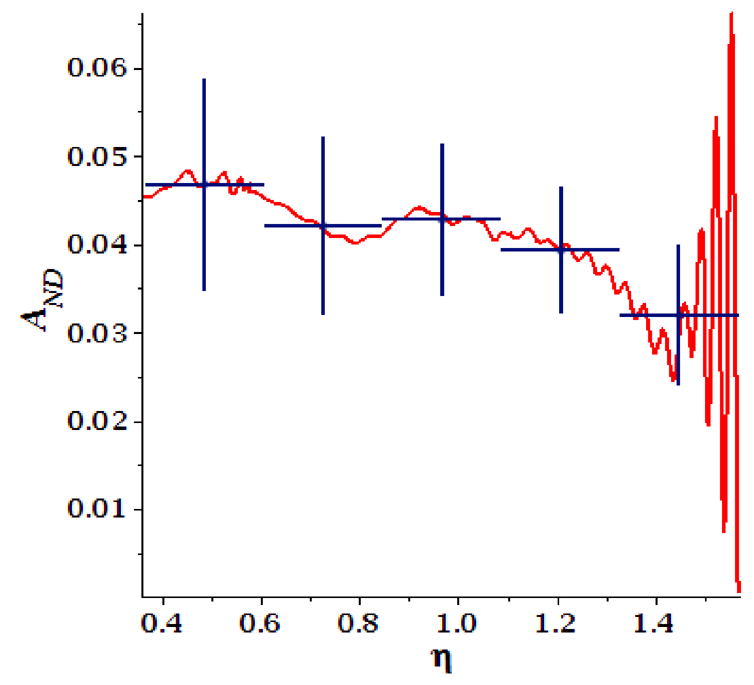
Attenuation effect

A. Ioannisian, A.Y.S., D. Wyler
1702.06097 [hep-ph]





$$A_{DN} = \frac{N - D}{D}$$



Relative excess of the night events integrated over E > 11 MeV
Sensitivity of DUNE experiment

The Nobel Prize in Physics 2015

Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

SNO Collaboration
Queen's University, Kingston, Canada

" for the discovery of neutrino oscillations, which shows that neutrinos have mass"

SNO has discovered almost non-oscillatory flavor transition

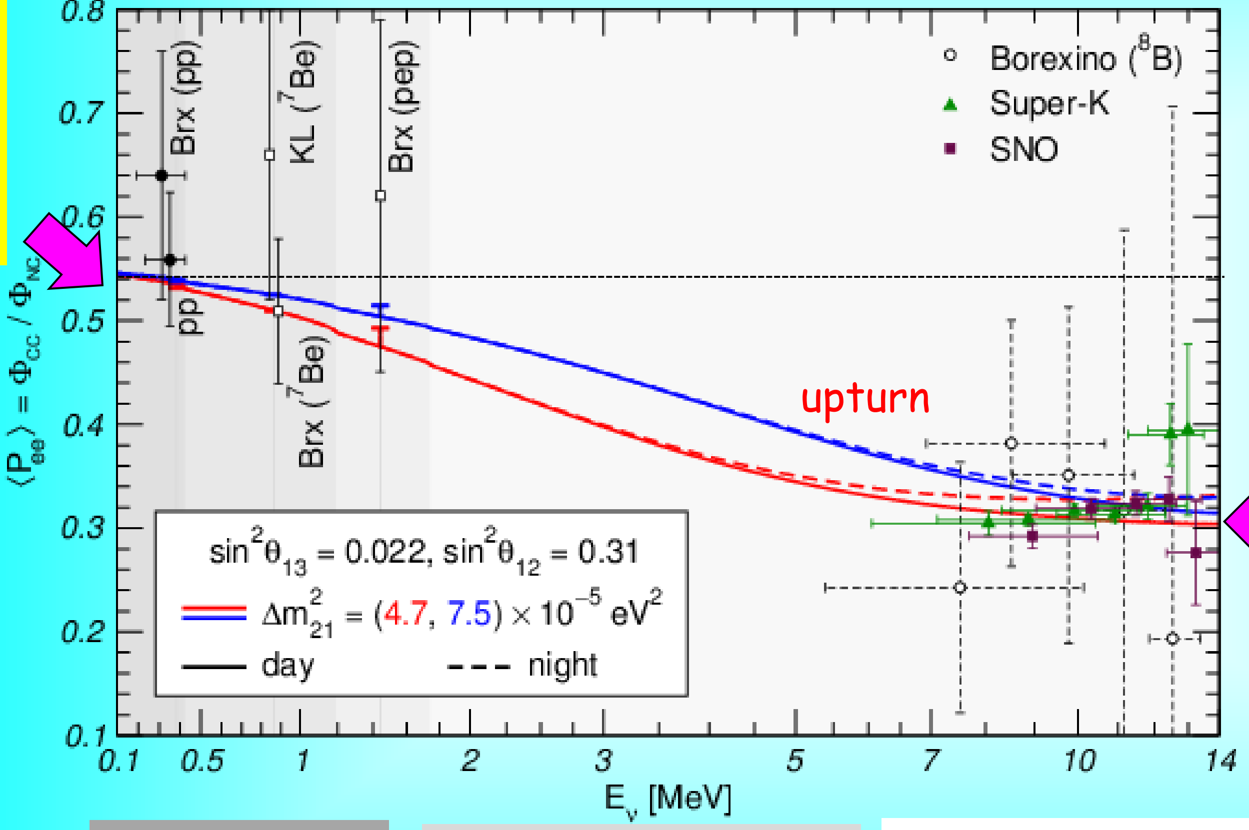
Oscillations do not imply the mass immediately

Energy profile

M. Maltoni, A.Y.S.
1507.05287 [hep-ph]

potential V vs. $\frac{\Delta m_{21}^2}{2E}$ kinetic

$1 - 0.5 \sin^2 2\theta_{12}$



LMA MSW predicion for two different values of Δm_{21}^2

best fit value from solar data

best global fit

$\sin^2 \theta_{12}$

Vacuum dominated

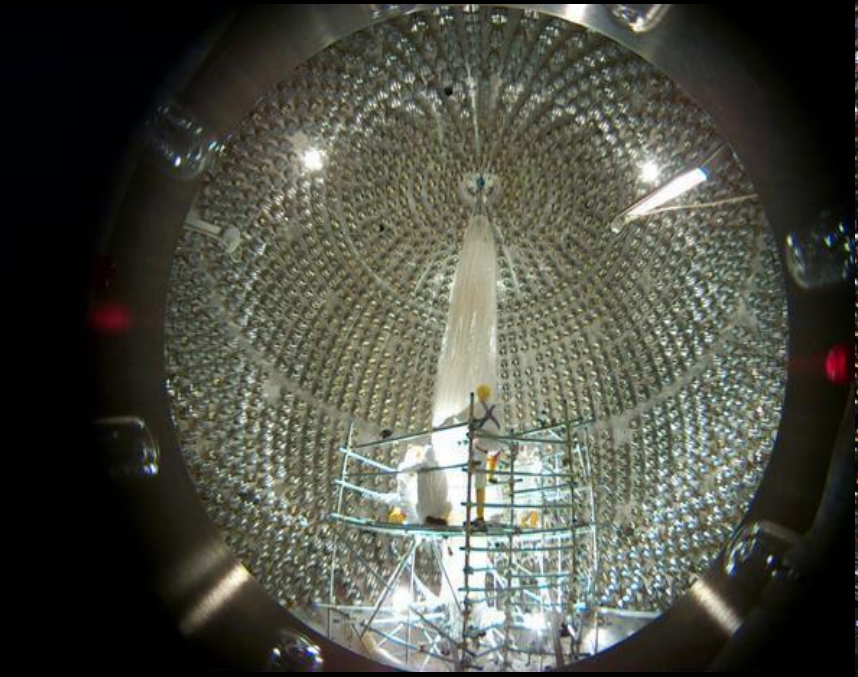
Transition region resonance turn on

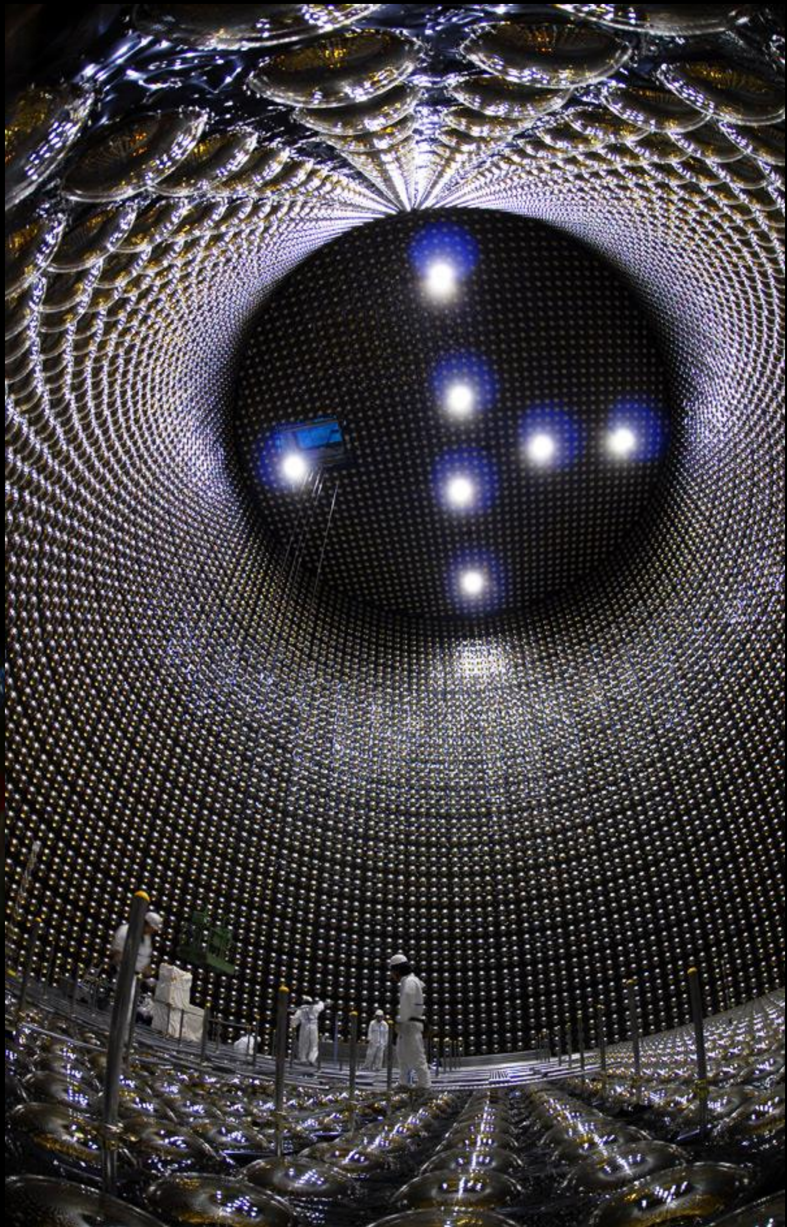
Matter dominated region

determined by n_0 and Δm_{21}^2

Reconstructed exp. points for SK, SNO and BOREXINO at high energies

III. Detection





Three phases

1. Establishing the problem. Some hints

Homestake
Kamiokande
SAGE, Gallex

2. The solution

Super-Kamiokande
SNO

KamLAND
reactor

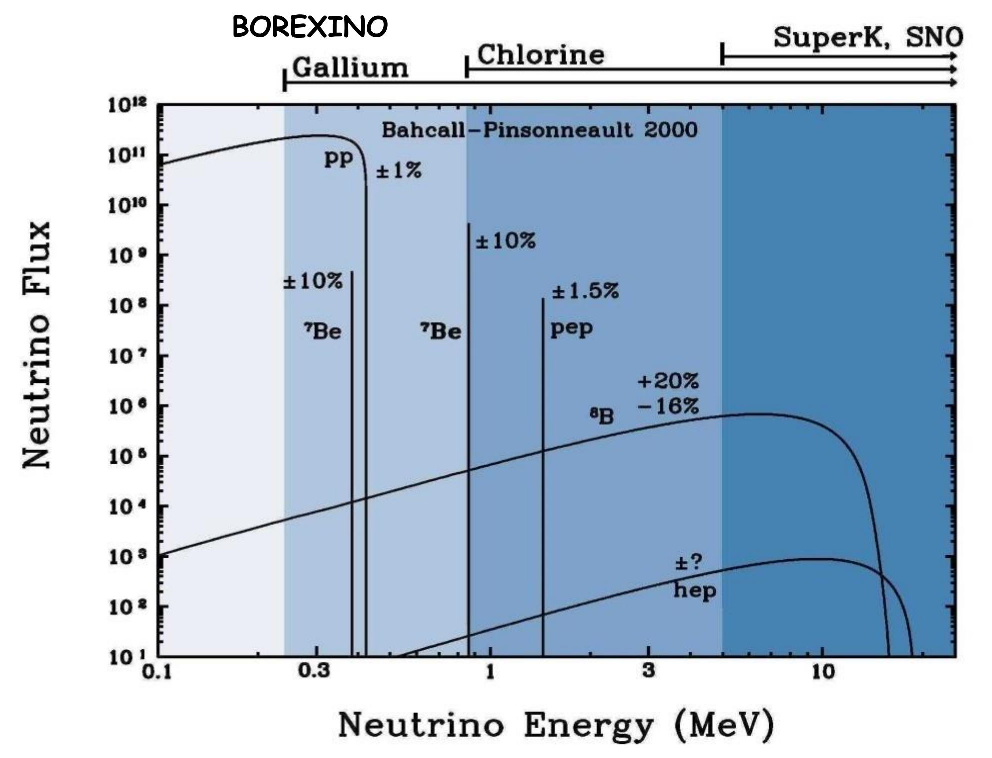
3. Further tests. Detailed studies. Consolidation of results

Super-Kamiokande
BOREXINO

Reviews

A Ianni, Prog. Part.Nucl. Phys. 2017
M Wurm,1704.06331

Experiments and thresholds



Consequence of finite energy resolution /reconstruction function

Homestake experiment

R. Davis Jr.

B. Pontecorvo 1946

Radiochemical Cl-Ar method

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$

E^{th} = 0.814 MeV 77% (^8B), 14% (^7Be), ...

Extraction of atoms of ^{37}Ar produced during exposure (about 40 days)

^{37}Ar decays: by K electron capture deexitation emission of Auger electrons

detected in proportional counter

615 tons of tetrachoroethylene C_2Cl_4

Homestake Gold Mine in Lead, 4200 m.w.e

Homestake: Results

Ar-production rate (average over 108 runs)

Q_{Ar} = 2.56 +/- 0.16 +/-0.16 SNU

SNU = 10^{-36} captures /nucleus/sec

SSM prediction: Q_{Ar}^{SSM} = 8 +/- 1 SNU

$$R_{Ar} = \frac{Q_{Ar}}{Q_{Ar}^{SSM}} = 0.32 +/- 0.05$$

deficit of signal

SSM + LMA:

Q_{Ar}^{LMA} = 3.1 SNU 2σ larger

Time variations with about 11 years period
(in anticorrelation with solar activity)
which can not be explained by statistical fluctuation

Systematics, new problem?

Kamiokande II, III. First hints

Water Cherenkov detector (2140 t of water, 948 PMT)

$\nu + e \rightarrow \nu + e$

Signal: recoil electron, E > 7 MeV

$$R_{\nu e} = \frac{\text{observed}}{\text{expected}} = 0.49 - 0.64$$

deficit

$R_{\nu e} > R_{Ar}$

Weaker deficit

I. Barabanov

Can be explained by $\nu_e \rightarrow \nu_\mu , \nu_\tau$ transformations

Since ν_μ , ν_τ contribute to signal via Neutral Currents

(they do not contribute to the Ar production rate)

Contribution from NC: 6.5 times smaller than from CC

Gallium experiments

V. Kuzmin

SAGE

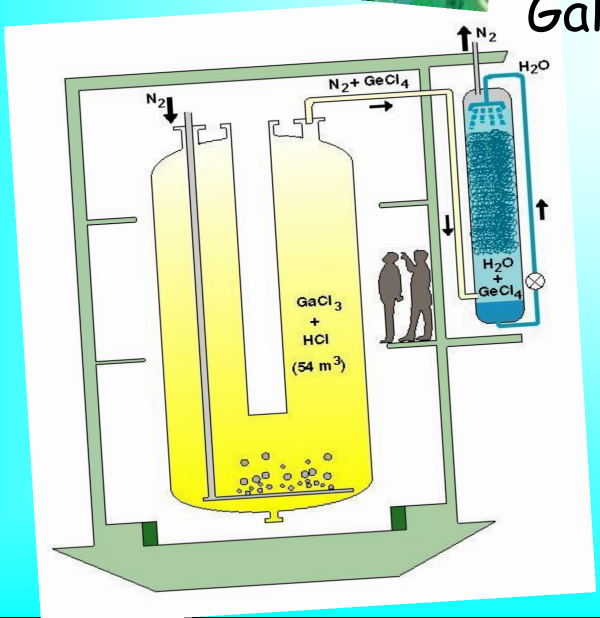
$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$

E^{th} = 0.233 MeV

53% (pp), 26% (Be), 11% (B) ...

Radiochemical method:
Counting of number of produced ${}^{71}Ge$ atoms (extraction, detection in proportional counter)

Gallex,GNO



SAGE: Baksan, liquid metal form, 60 t

Gallex: $GaCl_3$ 30 t

were first announcing nonzero signal

Gallium experiments

Germanium production rate

SSM prediction Q_{Ge}^{SSM} = 128 +/- 5 SNU

SAGE: Q_{Ge} = 65.4 +3.1/-3.0 (stat) + 2.6/-2.8(syst) SNU

Gallex GNO: Q_{Ge} = 67.13 +4.64/- 4.63 SNU

Combined: Q_{Ge} = 66.2 +/- 3.1 SNU

$$R_{Ge} = \frac{Q_{Ge}}{Q_{Ge}^{SSM}} = 0.52 +/-0.03$$

deficit

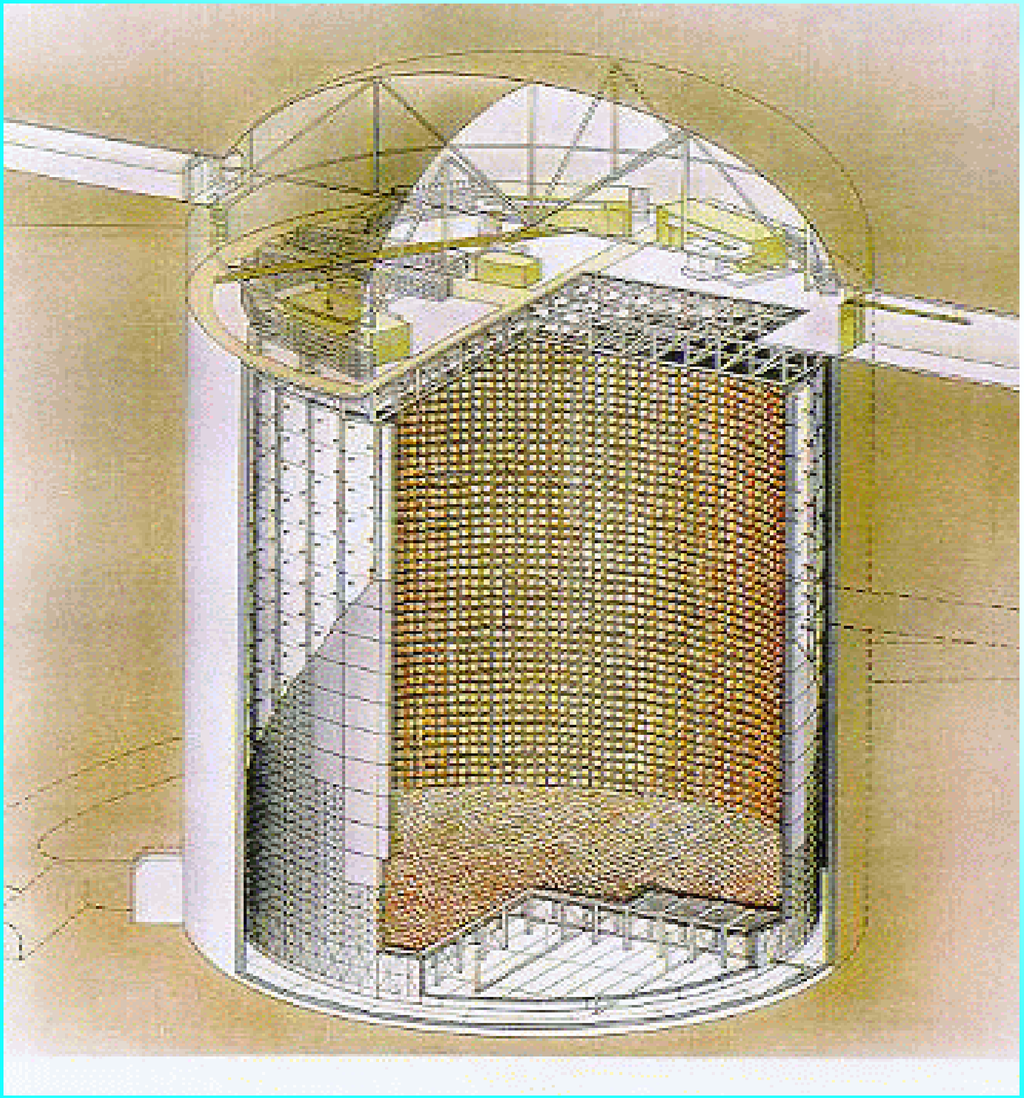
Q_{Ge}^{pp} = 67.8 SNU + measured contributions from Be, pep, B → Q_{Ge}^{min} = 83 SNU

luminocity

More than 3σ above exp. result

disfavoring (excluding?) astrophysical solutions

SuperKamiokande



Depth: 2700 m. v.e

50 kiloton water Cherenkov detector
11,146 photomultiplier tubes (PMTs)
inner 22.5 kiloton fiducial volume

2 m thick outer detector instrumented with 1885 outward-facing PMTs - to veto entering particles and to tag exiting tracks.

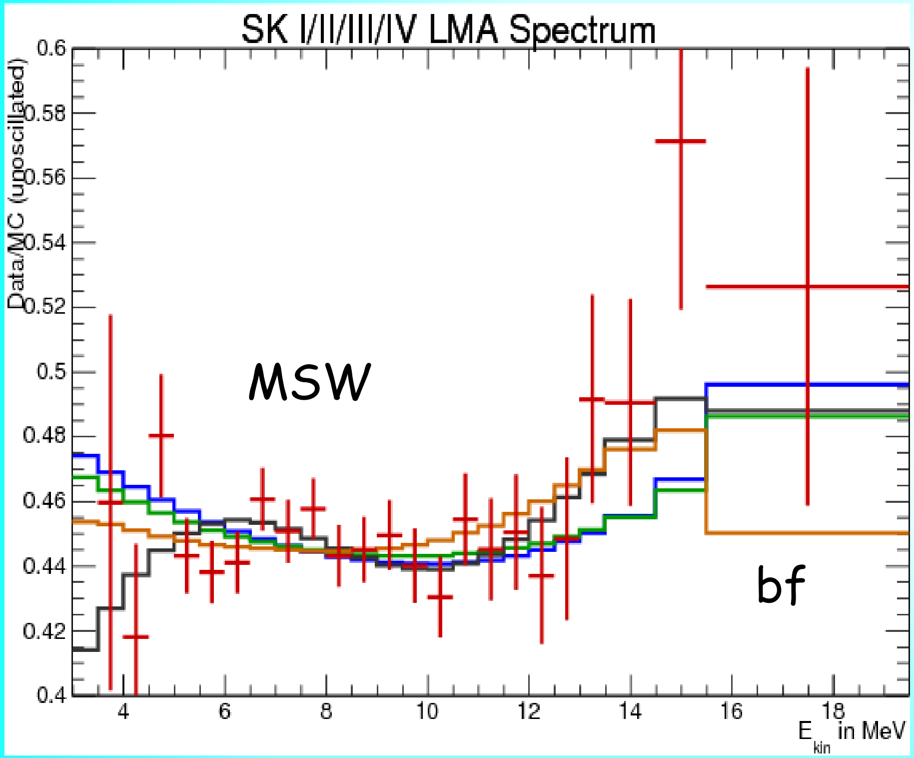
h = 41 m, D = 39.3 m

$\nu + e \rightarrow \nu + e$

SK results

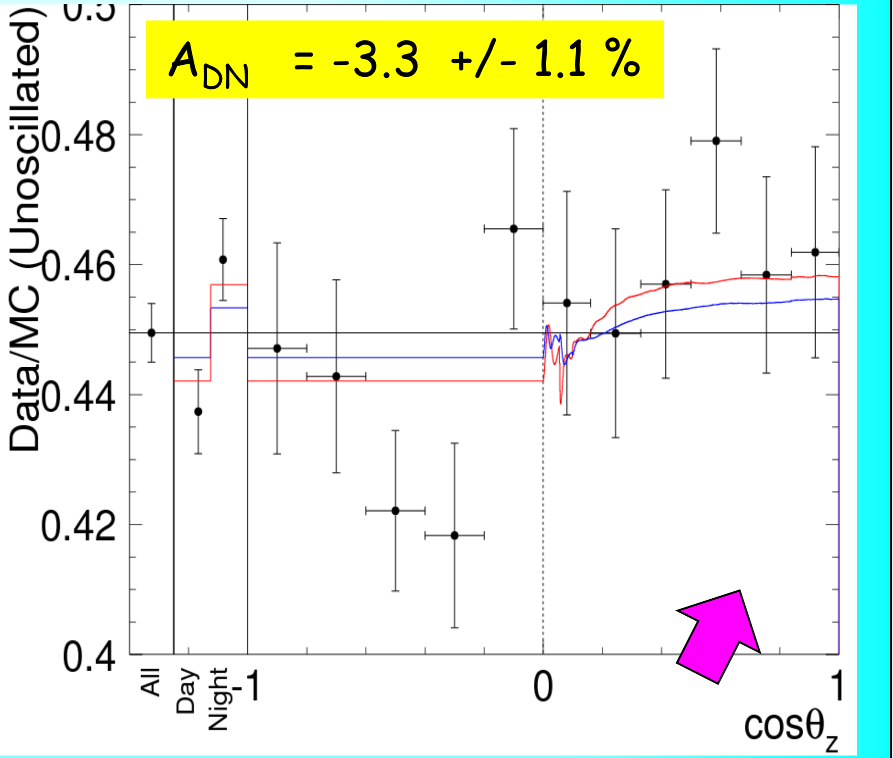
SK Collaboration (Abe, K. et al.)
arXiv:1606.07538 [hep-ex]

Recoil electron energy spectrum



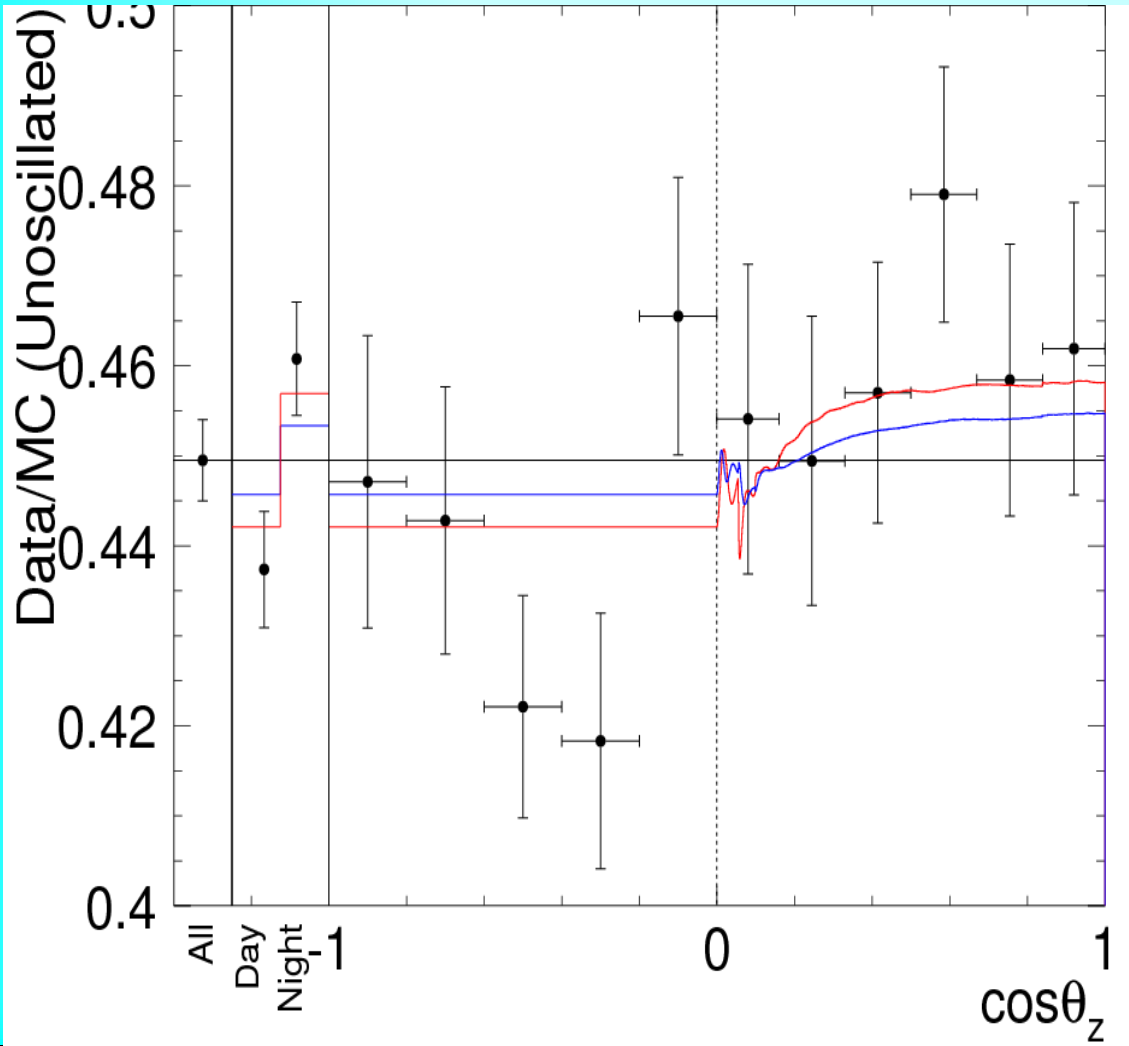
— bf of data
— MSW (low dms)
— MSW (high dms)

SK-IV solar zenith angle dependence



No enhancement for core crossing trajectories (last bin) -- attenuation effects

Day-Night asymmetry



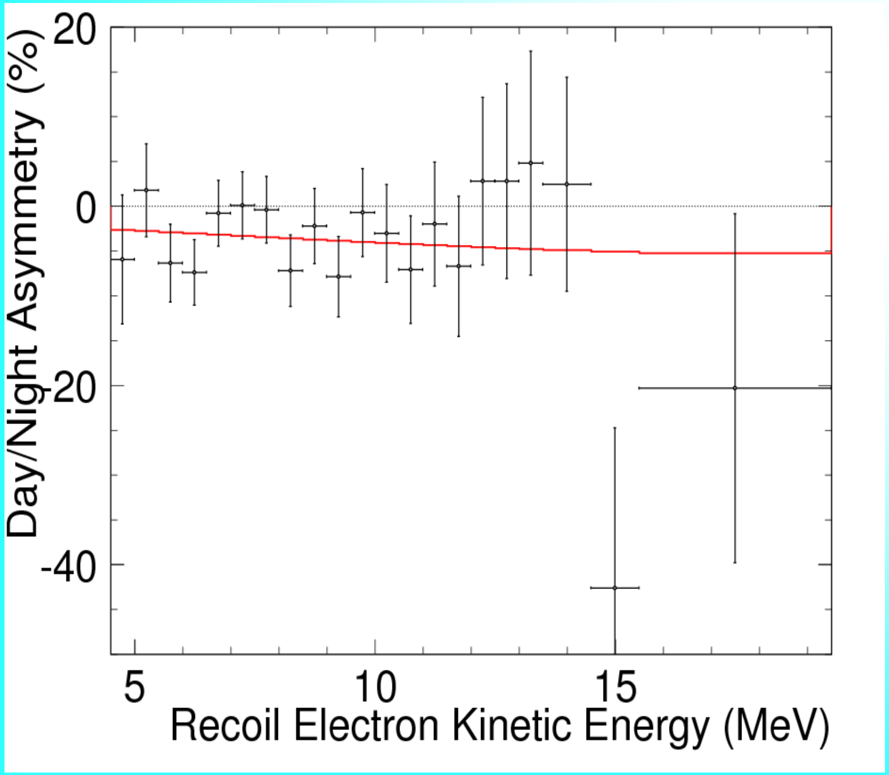
SK-IV solar zenith angle dependence of the solar neutrino data/MC (unoscillated) interaction rate ratio (4.49-19.5 MeV). Red (blue) lines are predictions when using the solar neutrino data (solar neutrino data+KamLAND) best-fit oscillation parameters. The error bars are statistical uncertainties only.

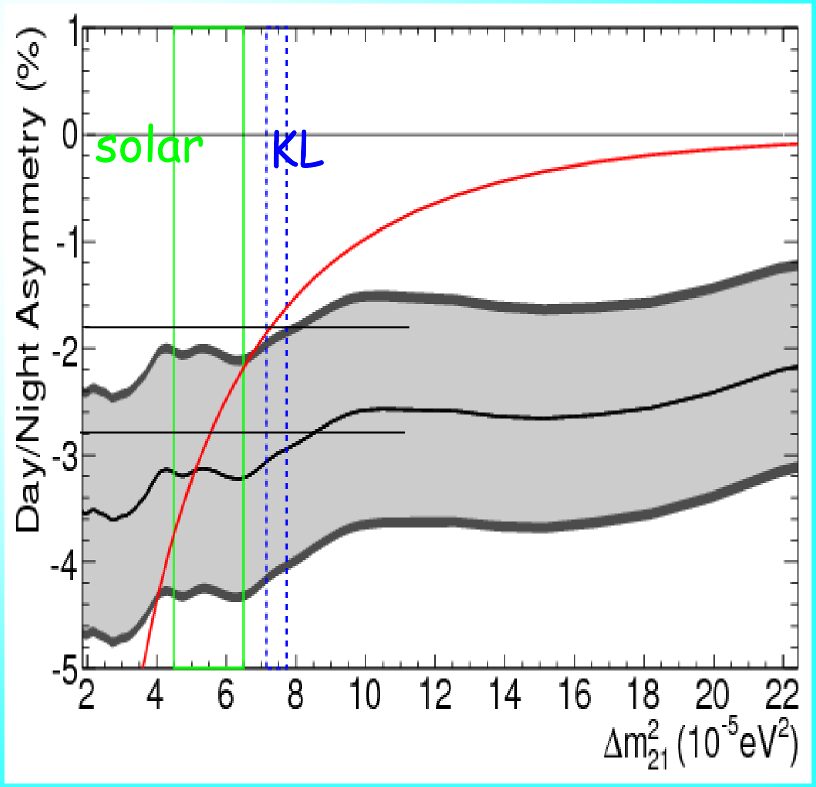
Day-Night effect

First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

Super-Kamiokande collaboration (Renshaw, A. et al.) Phys.Rev.Lett. 112 (2014) 091805 arXiv:1312.5176

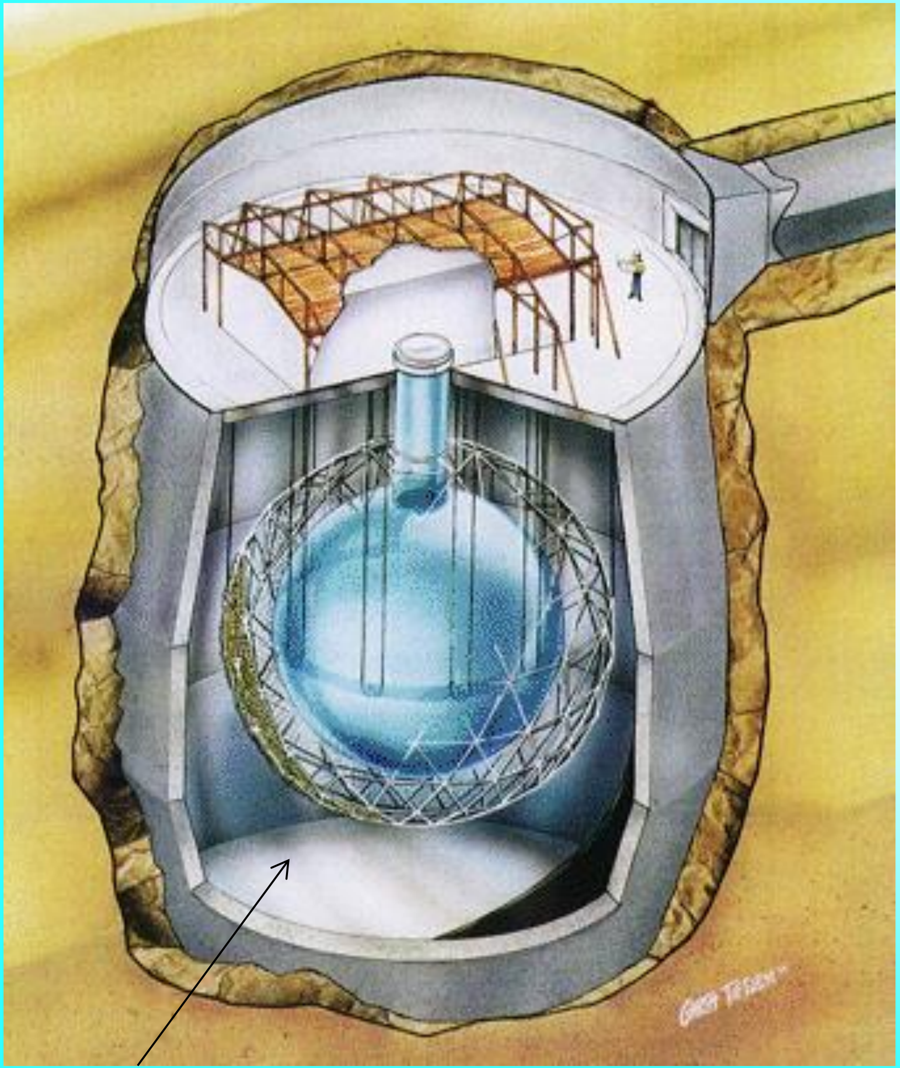
> 3 σ





SNO detector

Sudbury Neutrino Observatory



light water

in the INCO, Ltd. Creighton mine
near Sudbury, Ontario, Canada.

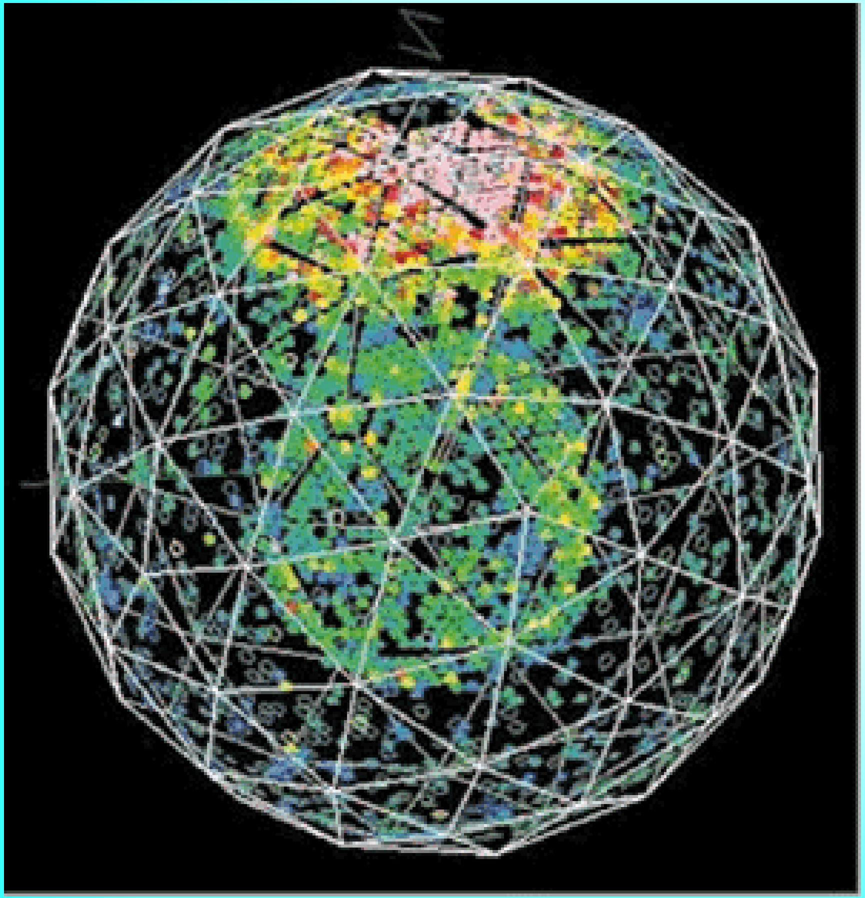
SNO Collaboration: 170 member
from Canada, US, UK

Proposed by Herb Chen, 1984

- Water Cherenkov detector
- Depth: 2092 m of 5890 m of w.e,
- 1000 tonnes of heavy water, D_2O
in a transparent acrylic spherical
shell 12 m in diameter.

9456 photomultiplier tubes (PMTs)
mounted on a stainless steel
geodesic sphere 17.8 m in diameter.

SNO events



Charged current interactions

$\nu_e + d \rightarrow e + p + p$

measure ν_e – flux only

Neutral current interactions

$\nu + d \rightarrow \nu + n + p$

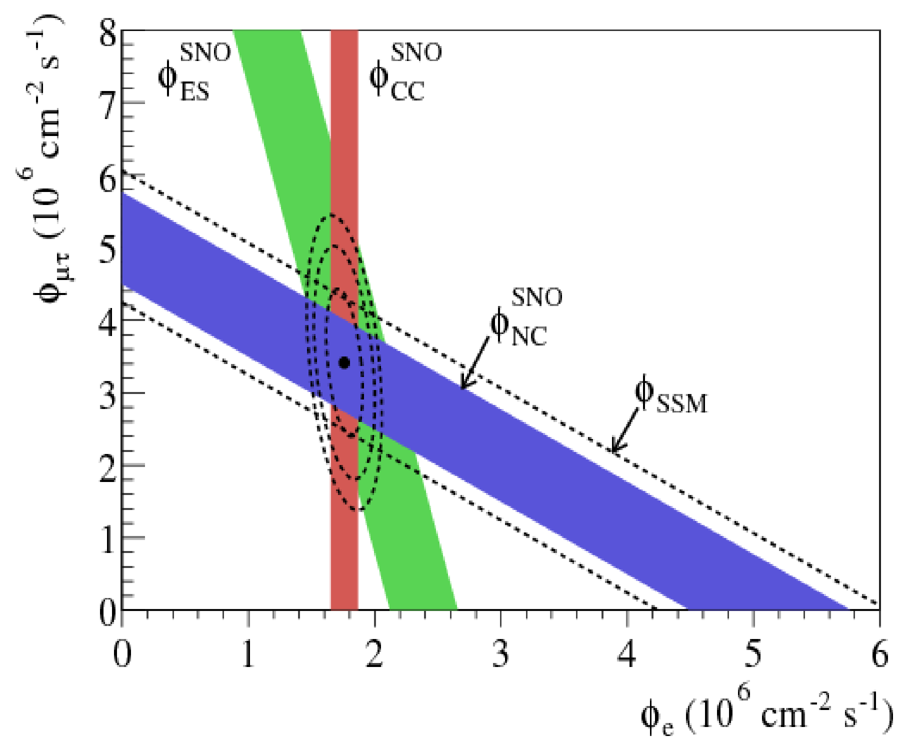
measure total flux of all ν species –insensitive to flavor transformations

$\nu + e \rightarrow \nu + e$

sensitive to all neutrino species but mainly to ν_e

SNO results

$\nu_e \rightarrow \nu_\mu , \nu_\tau$ transformations

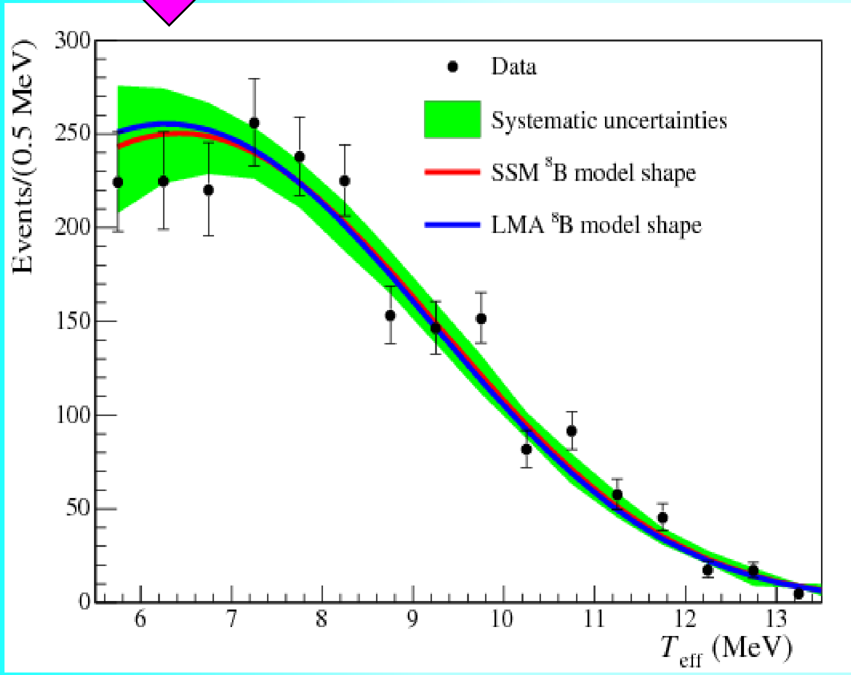


$$P_{SNO} = \frac{\Phi_e}{\Phi_{NC}} = 0.34$$

ν_e - survival probability

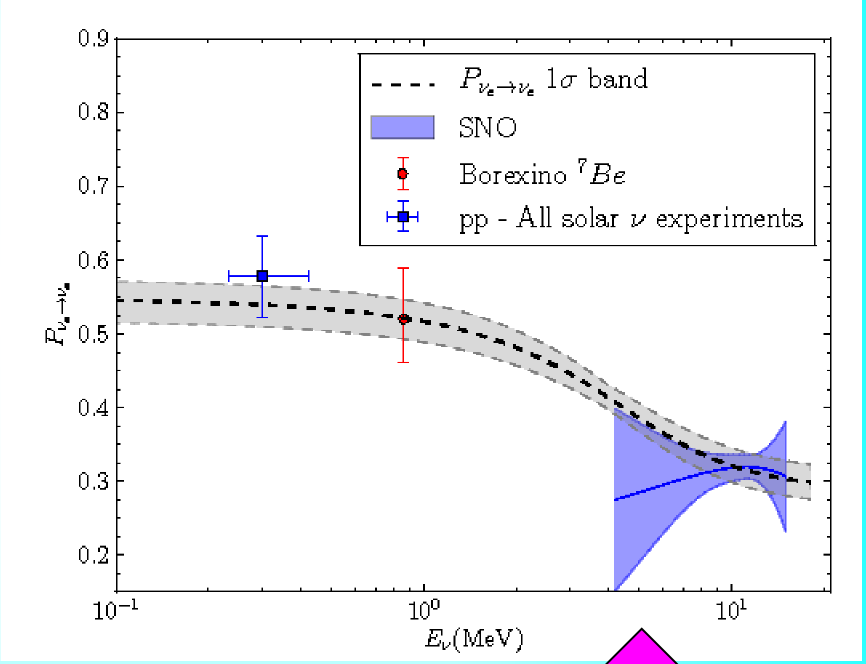
Using different characteristics →
disentangled 3 types of events

SNO results



CC events: no substantial spectrum distortion nearly constant suppression

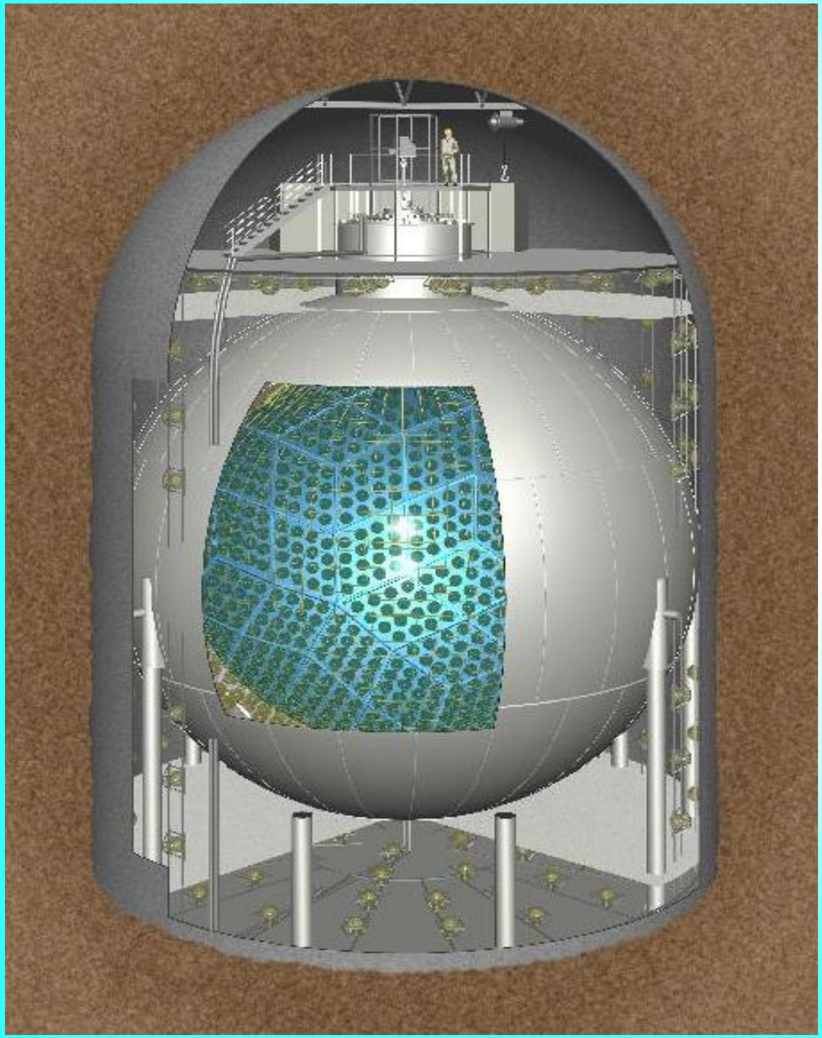
Survival probability



Turn down?

KamLAND

Kamioka Liquid Anti Neutrino Detector



53 atomic reactors

$\langle L \rangle \sim 180$ km

Scintillator detector

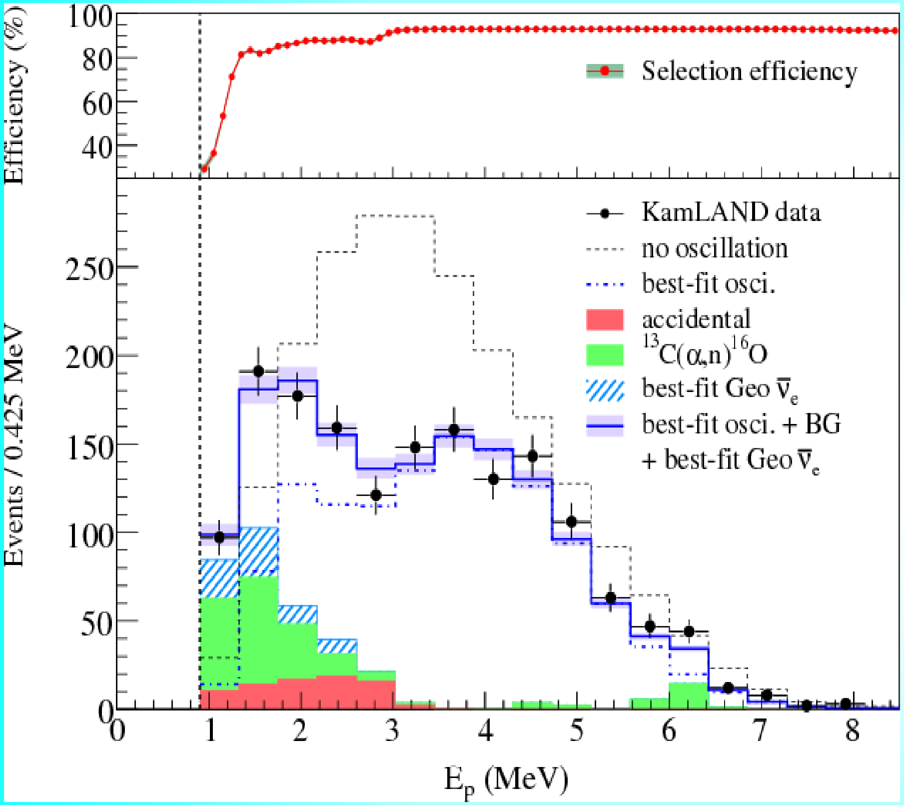
1000 ton of mineral oil

D = 18 m

1879 PMT

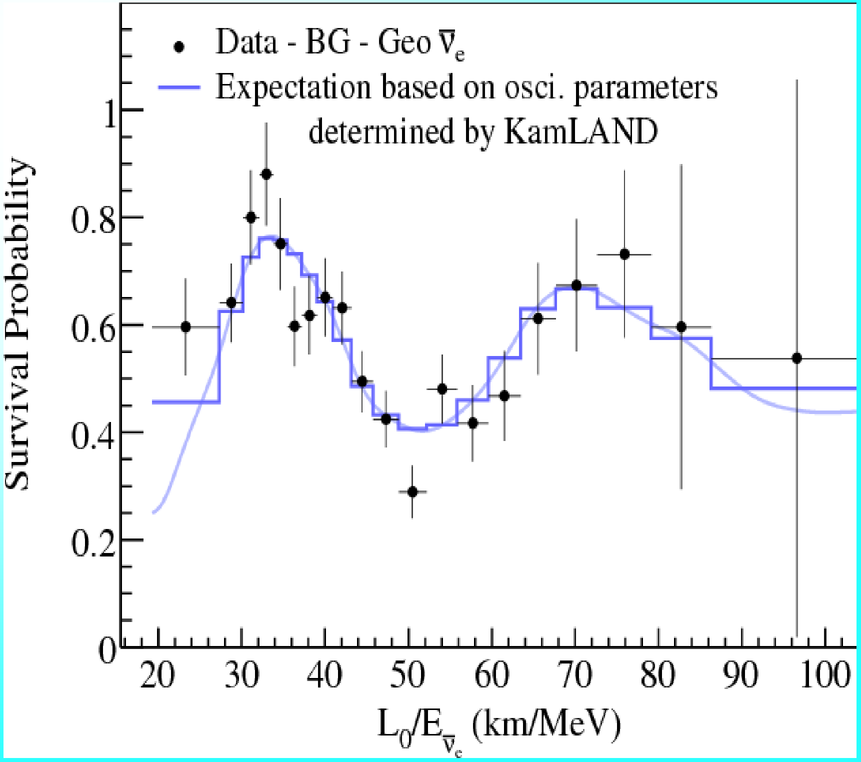
$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

KamLAND result

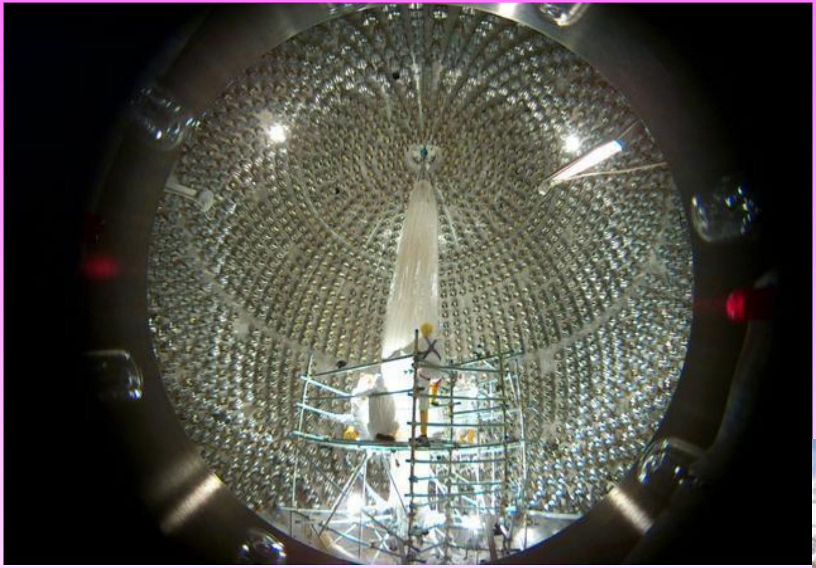


Observed vacuum oscillations of $\overline{\nu_e}$

consistent with parameters
of the LMA MSW solution



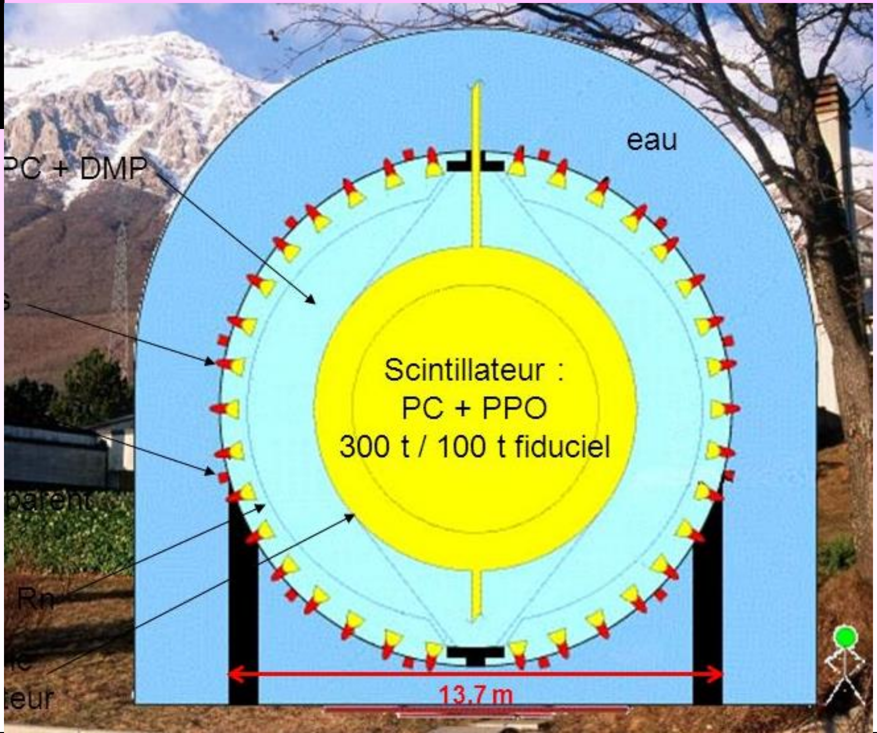
BOREXINO



Scintillator
1 kton pseudocumene

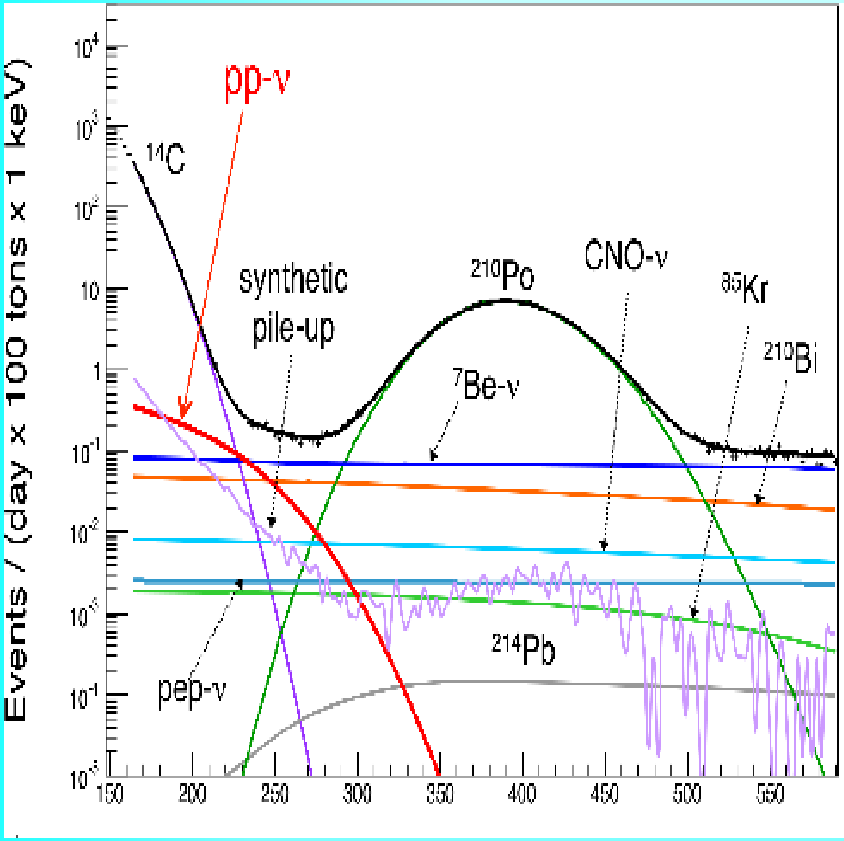
2212 8-inch PMT

$\nu + e \rightarrow \nu + e$

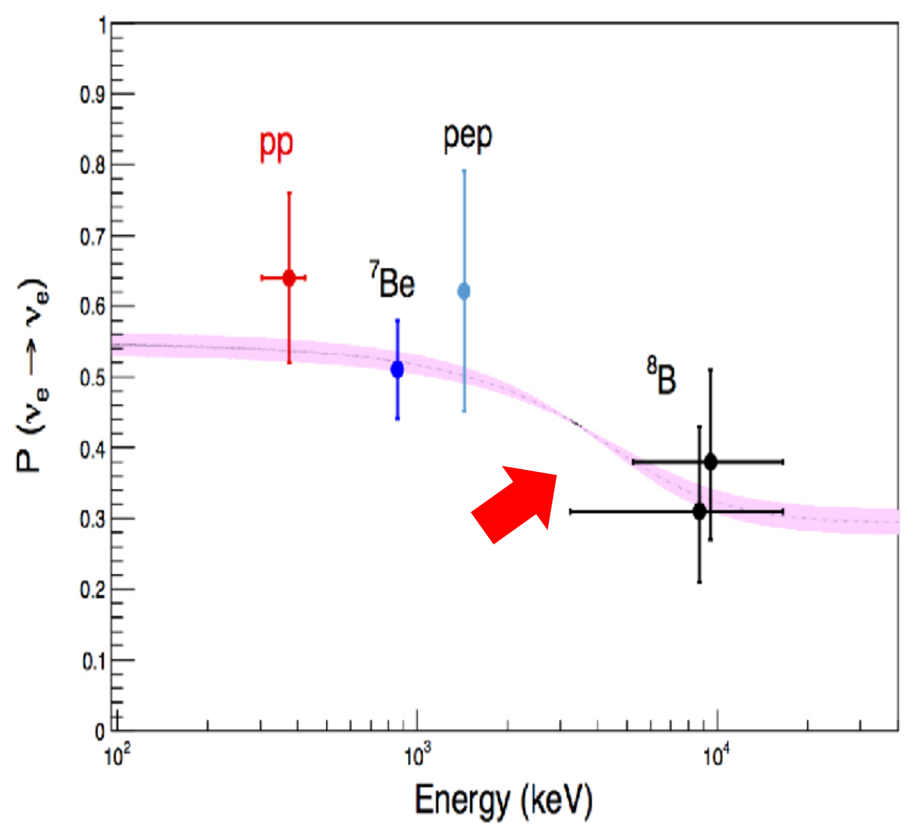


Solar pp-neutrinos

Neutrinos from the primary pp-reactions in the Sun
BOREXINO Collaboration
(G. Bellini et al.)
Nature 512 (2014) 7515, 383



Energy (keV)

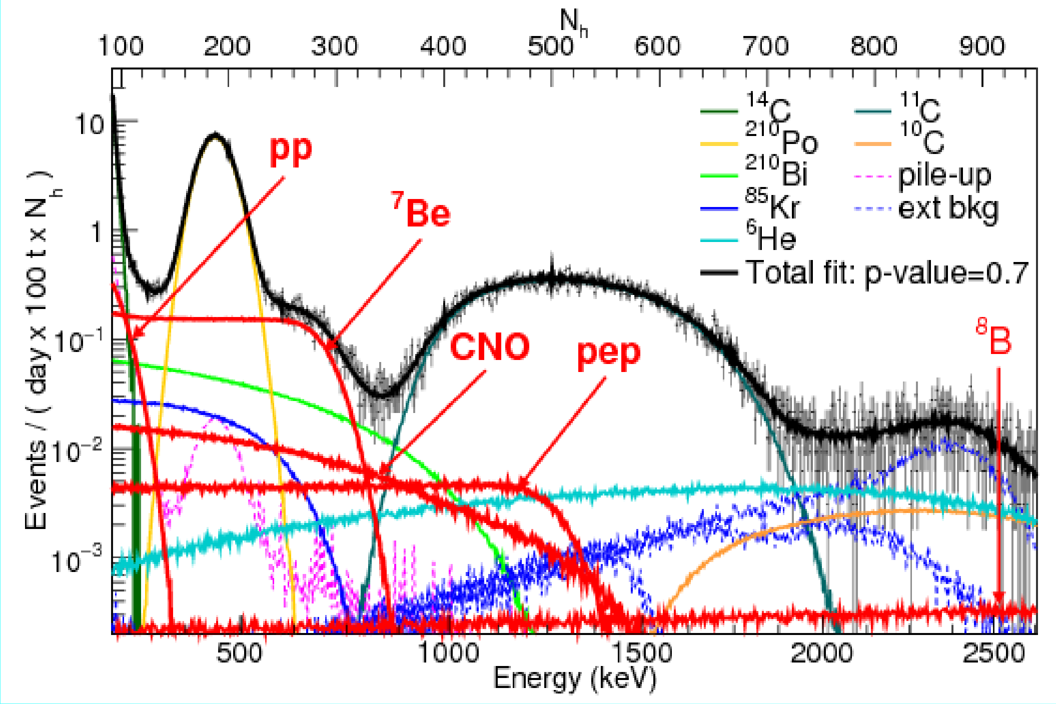


$$\cos^4\theta_{13}(1 - \tfrac{1}{2}\sin^2 2\theta_{12}) + \sin^4\theta_{13}$$

BOREXINO spectroscopy

Borexino Collaboration
(Agostini, M. et al.)
arXiv:1707.09279 [hep-ex]

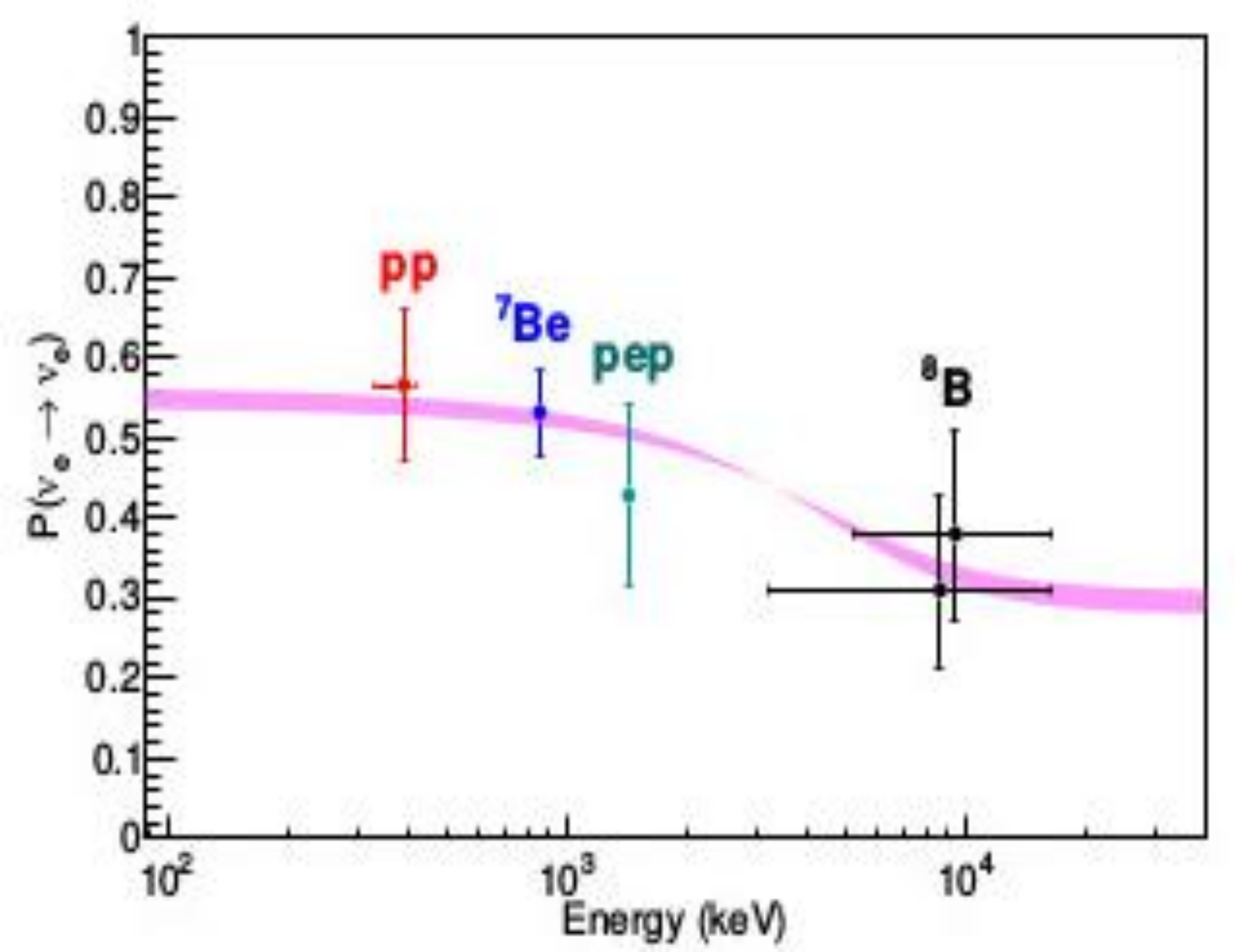
First Simultaneous Precision Spectroscopy of *pp*, 7Be, and *pep* Solar Neutrinos with Borexino Phase-II



Multivariate fit results (an example obtained with the MC method) for the TFC-tagged energy spectra, with residuals. The sum of the individual components from the fit (black lines) are superimposed on the data (grey points).

BOREXINO and LMA MSW

Borexino Collaboration
(Agostini, M. et al.)
arXiv:1707.09279 [hep-ex]



Status of the LMA MSW Solution

Good agreement with all available data,
especially if solar neutrino results only are used

Some deviations at about 2 -3σ – level exist if global best fit value of Δm_{21}^2 (dominated by KamLAND) is used

Absence of upturn of the spectrum

Large D-N asymmetry

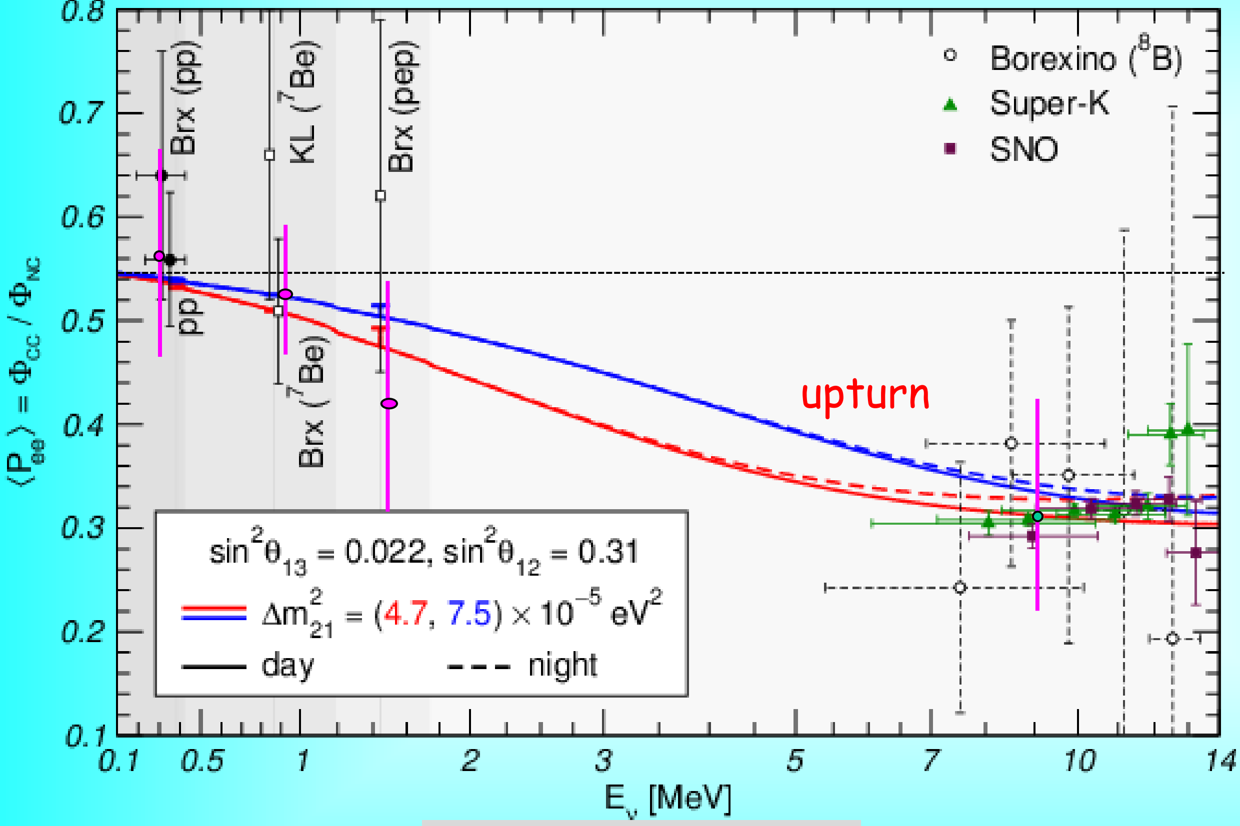
Difference of values of Δm^2_{21} extracted from solar and KamLAND data

Large value of matter potential extracted from global fit

Can be related

LMA MSW vs. Experiment

M. Maltoni, A.Y.S.
1507.05287 [hep-ph]



Transition region
resonance turn on

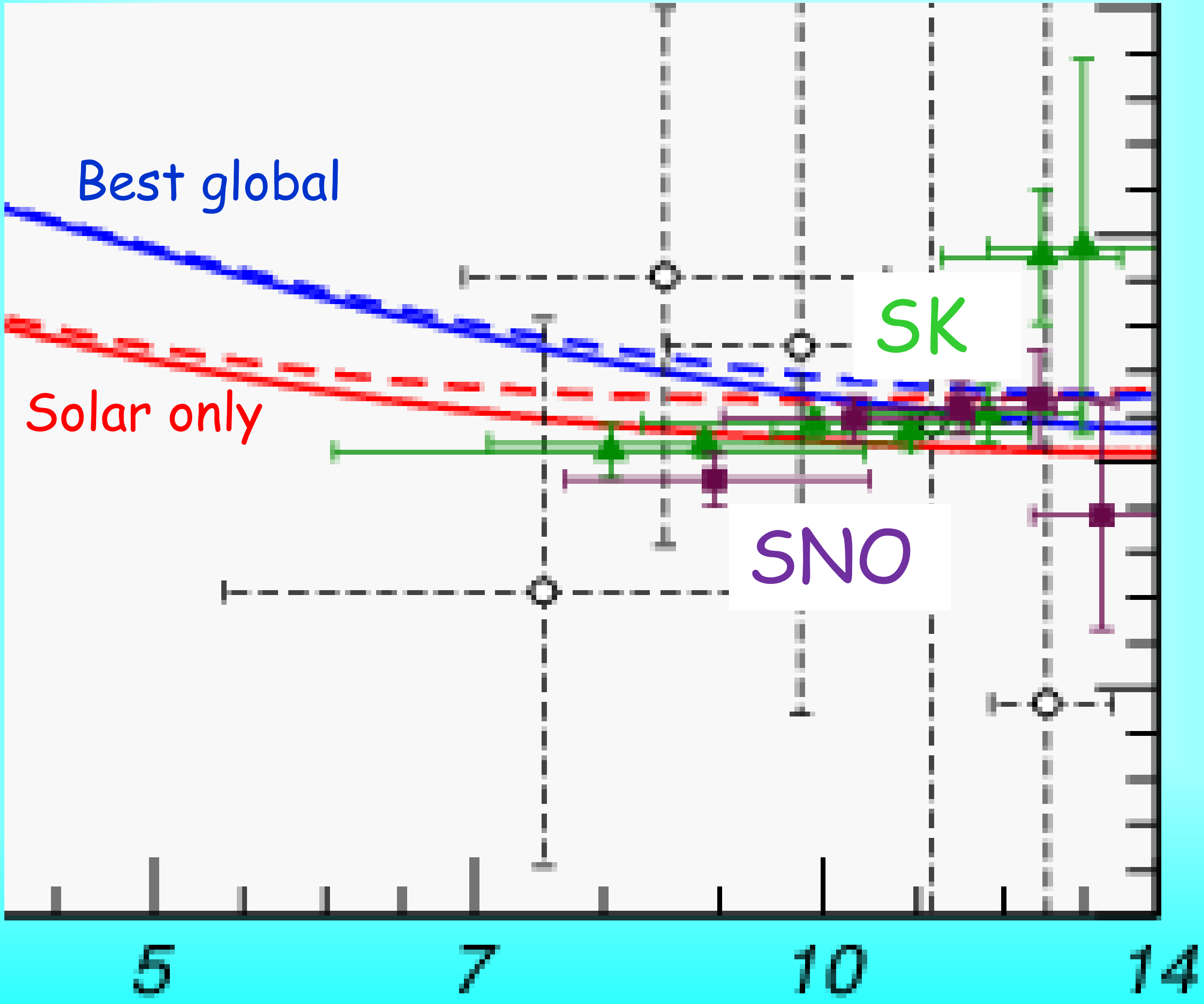
LMA MSW predicion
for two different
values of Δm_{21}^2

best fit value
from solar data

best global fit

Reconstructed
exp. points for
SK, SNO and
BOREXINO
at high energies

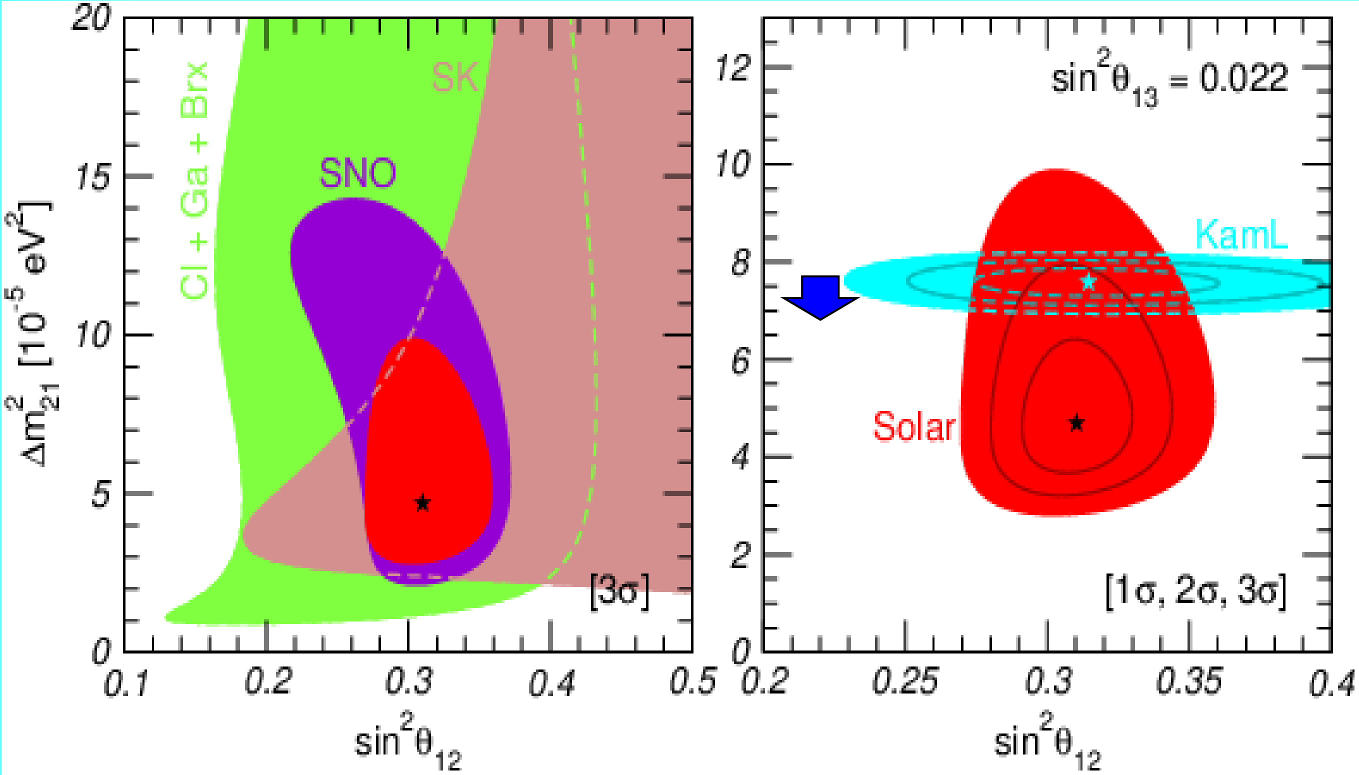
Upturn?



SNO+

Neutrino parameters

M. Maltoni, A.Y.S.
1507.05287 [hep-ph]



Red: all solar neutrino data

Δm^2_{21} (KL) > Δm^2_{21} (solar)

2 σ

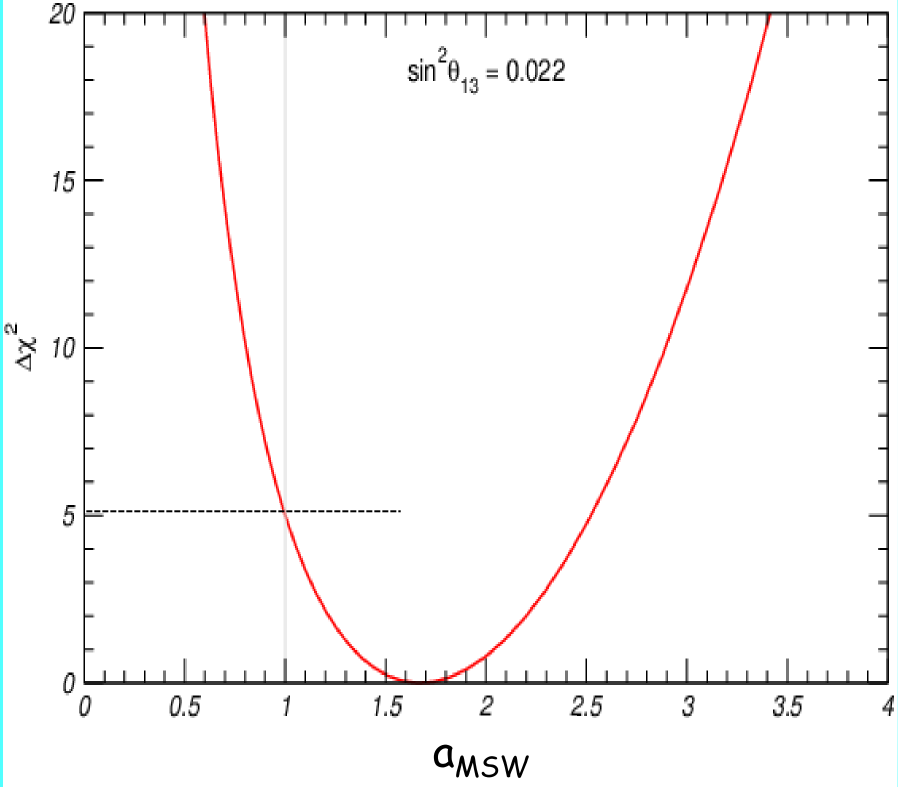
KamLAND data reanalized in view of reactor anomaly (no front detector) bump at 4 -6 MeV

→

Δm^2_{21} decreases by 0.15 10^{-5} eV^2

Matter potential

G. L Fogli et al hep-ph/0309100
C. Pena-Garay, H. Minakata,
hep-ph 1009.4869 [hep-ph]
M. Maltoni, A.Y.S.
1507.05287 [hep-ph]



$V = a_{MSW} V_{stand}$

a_{MSW} = 0 is disfavoured by > 15 σ

the best fit value a_{MSW} = 1.66

a_{MSW} = 1.0 is disfavoured by > 2 σ

related to discrepancy of Δm^2_{21} from solar and KamLAND:

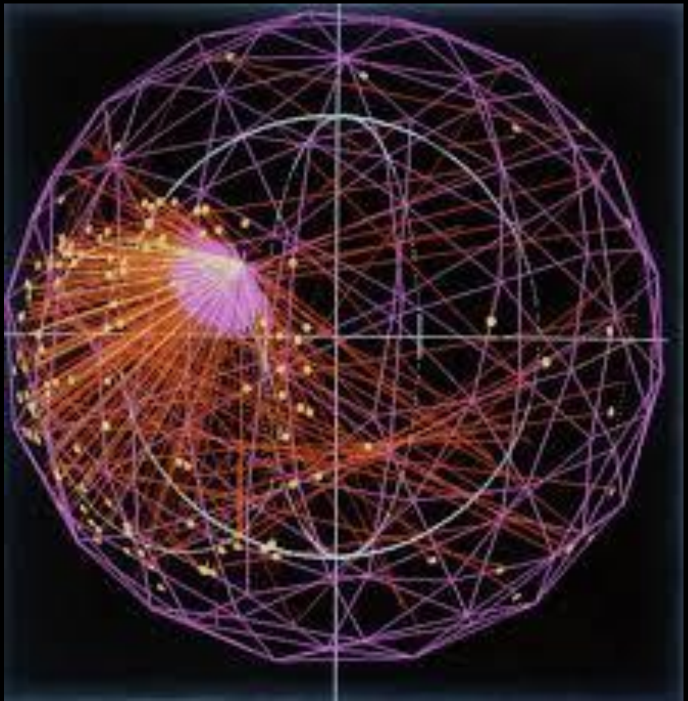
$$\frac{\Delta m^2_{21}\,(KL)}{\Delta m^2_{21}\,(Sun)} = 1.6$$

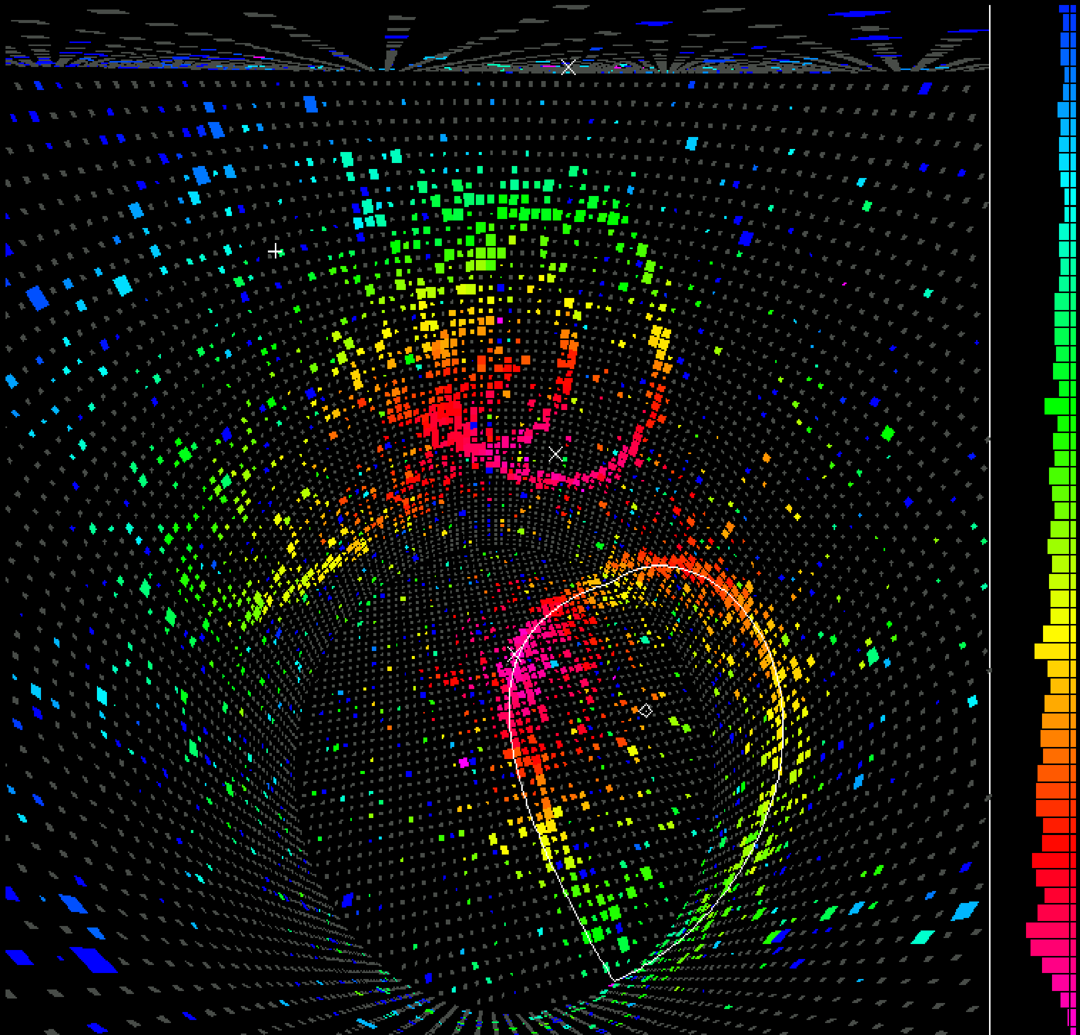
Potential enters the probability in combination

$$\frac{V}{\Delta m^2_{21}}$$

Determination of the matter potential from the solar plus KamLAND data using a_{MSW} as free parameter

IV. New physics Searches





New physics: bounds and hints

- Sterile neutrinos
- Non-standard interactions
- New long range forces
- Neutrino decays
- Large magnetic moments
- Extra dimensions
- Non-standard decoherence
- Mass varying neutrinos
- Violation of fundamental symmetries
  - Lorentz invariance
  - CPT invariance

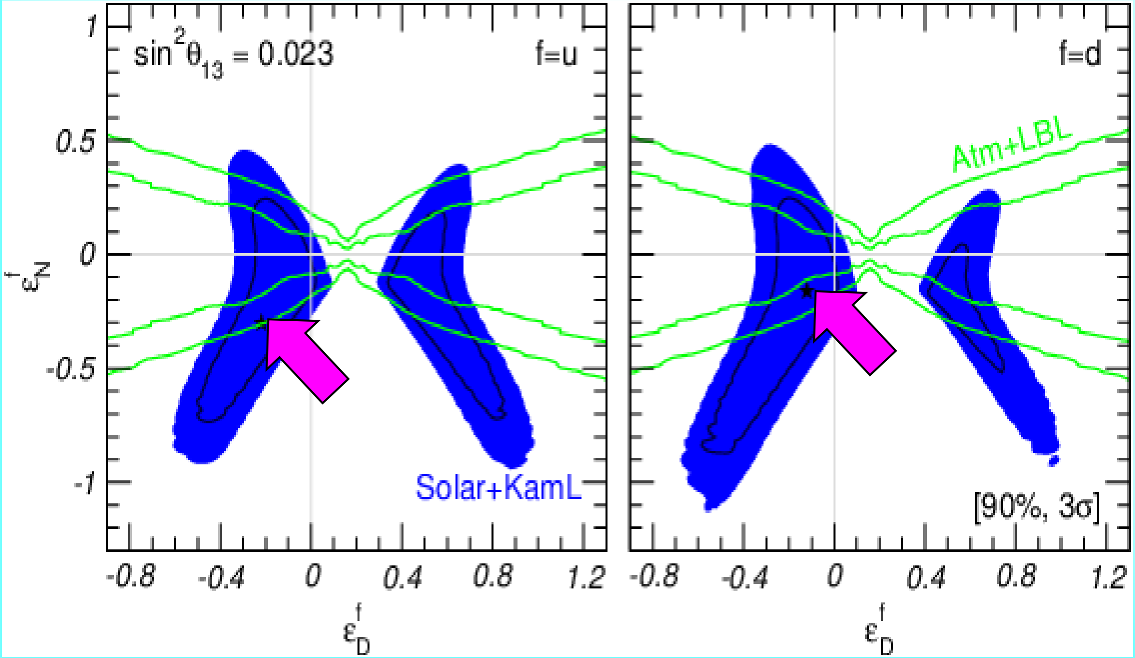
Effects in the Sun
Interactions in detectors

Non-standard interactions

Additional contribution
to the matrix of potentials
in the Hamiltonian

M C. Gonzalez-Garcia ,
M. Maltoni
arXiv 1307.3092

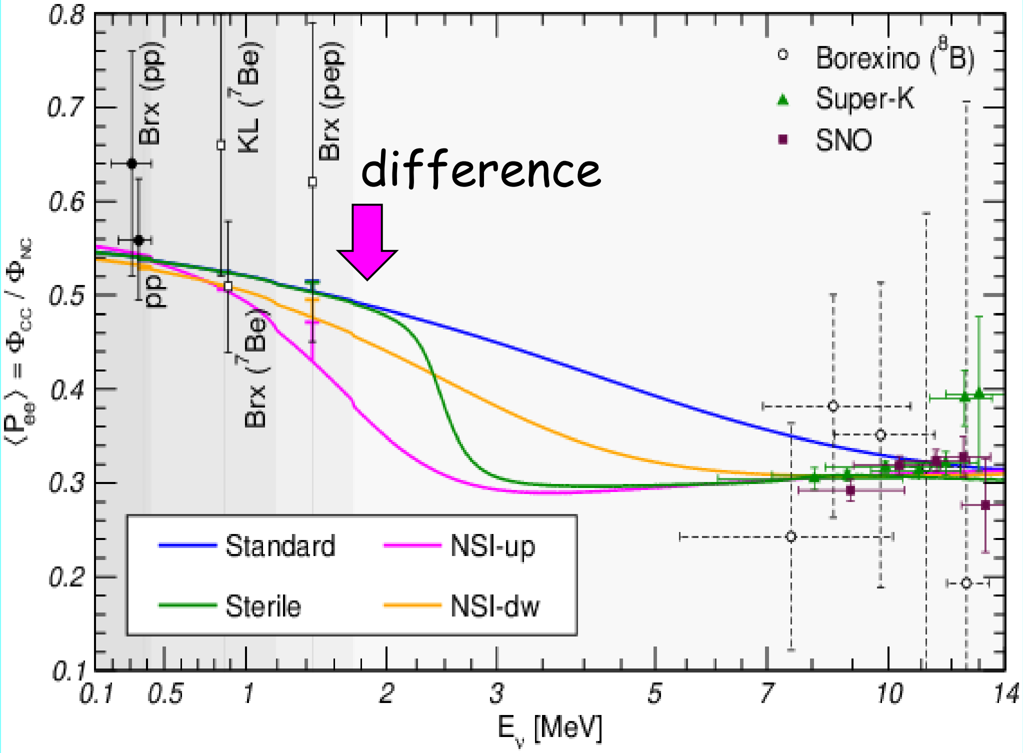
$$V_{NSI} = \sqrt{2}\, G_F\, n_f \begin{pmatrix} \varepsilon^f_D & \varepsilon^f_N \\ \varepsilon^f_N & \varepsilon^f_D \end{pmatrix} \qquad f = e, u, d$$



In the best fit points the D-N asymmetry is 4 - 5%

Allowed regions of parameters of NSI

New physics effects

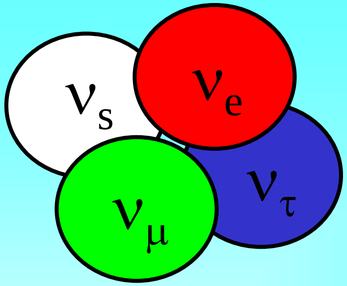


M. Maltoni, A.Y.S.
1507.05287 [hep-ph]

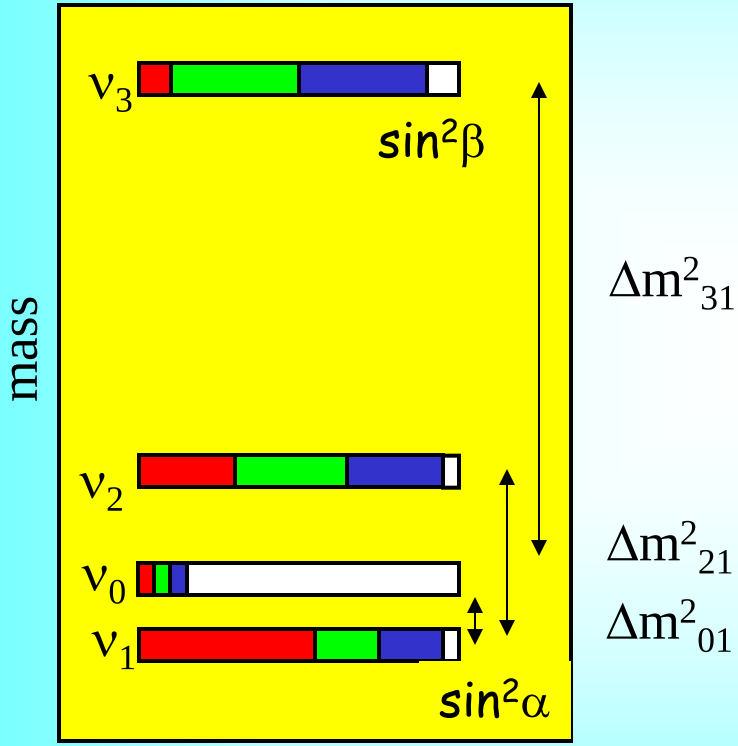
Extra sterile neutrino with
$\Delta m^2_{01} = 1.2 \times 10^{-5}$ eV^2, and
$\sin^2 2\alpha = 0.005$

Non-standard interactions with
$\varepsilon^u_D = -0.22$, $\varepsilon^u_N = -0.30$
$\varepsilon^d_D = -0.12$, $\varepsilon^d_N = -0.16$

meV physics



sterile neutrino $m_0 \sim 0.003$ eV



Adiabatic conversion
for small mixing angle
Adiabaticity violation

Allows to explain absence of upturn and reconcile solar and KAMLAND mass splitting but not large DN asymmetry

additional radiation
in the Universe if mixed in ν_3

no problem with LSS
bound on neutrino mass

For solar nu: $\sin^2 2\alpha \sim 10^{-3}$

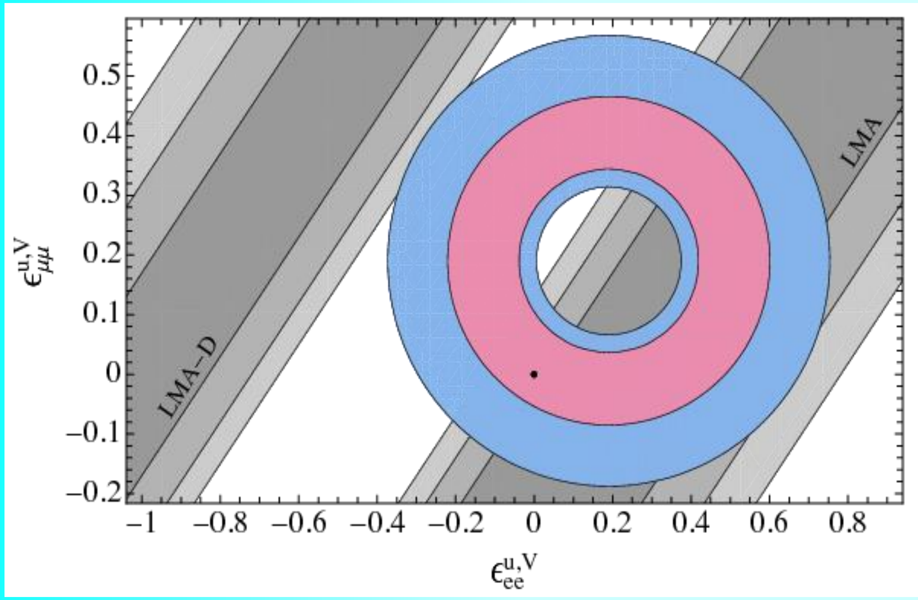
For dark radiation

$\sin^2 2\beta \sim 10^{-3}$ (NH)

$\sin^2 2\beta \sim 10^{-1}$ (IH)

NSI bounds

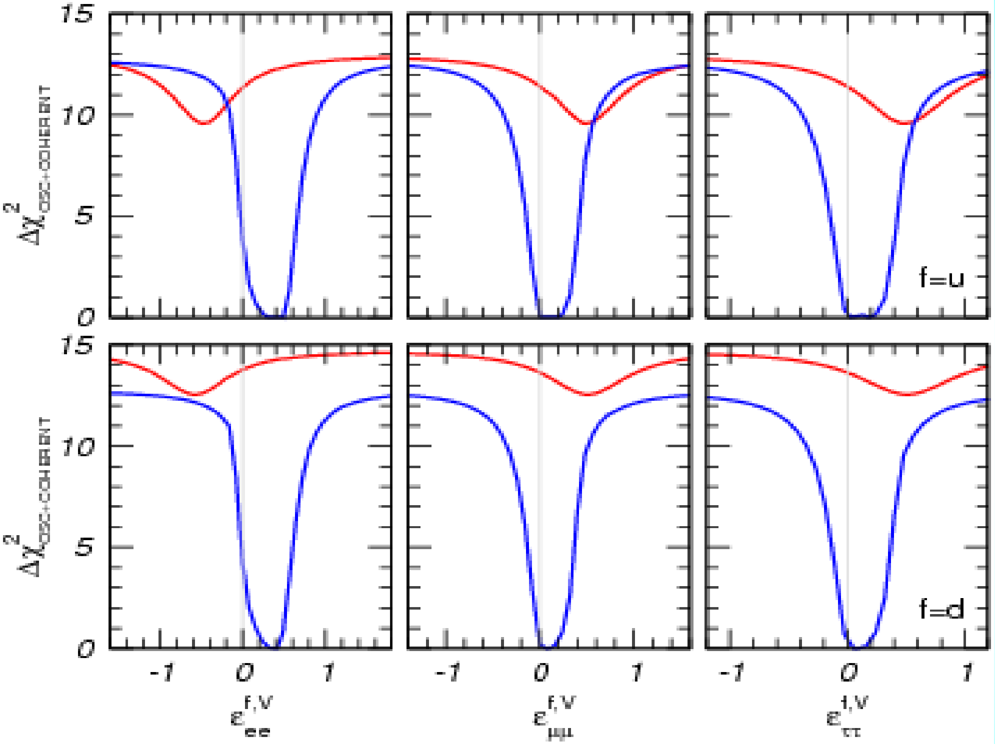
P. Coloma, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, 1708.02899 [hep-ph]



Allowed regions from the COHERENT experiment and allowed regions from the global oscillation fit.

Diagonal shaded bands correspond to the LMA and LMA-D regions as indicated, at 1σ, 2σ, 3σ (2~dof).
The COHERENT regions are at 1σ and 2σ only. 3σ region extends beyond the boundaries of the figure

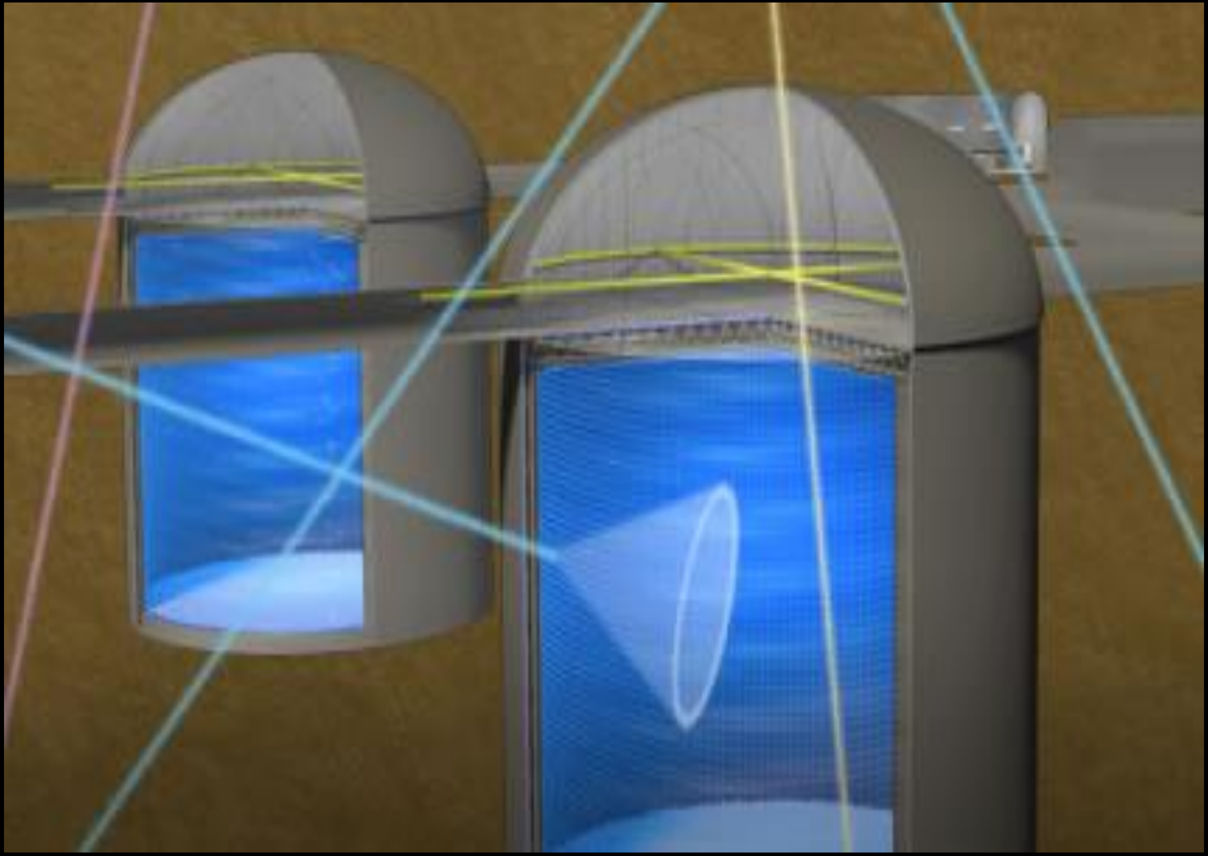
Bounds on NSI



Bounds on the flavour diagonal NSI parameters from the global fit to oscillation plus COHERENT data. Blue lines correspond to the LMA solution ($\theta 12<\pi/4$), while the red lines correspond to the LMA-D solution ($\theta 12>\pi/4$).

COHERENT experiment, in combination with global oscillation data, excludes the NSI degeneracy at the 3.1σ (3.6σ) CL for NSI with up (down) quarks.

V. Future and outlook



Problems, future

Absence of upturn of the spectrum

Large D-N asymmetry

Difference of values of Δm^2_{21} extracted from solar and KamLAND data

Large value of matter potential extracted from global fit

at about 2 -3σ - level

Can be related

Another reactor anomaly or new physics in solar neutrinos?

Detection of CNO neutrinos to shed some light on the problem of SSM: controversy of helioseismology data and abundance of heavy elements

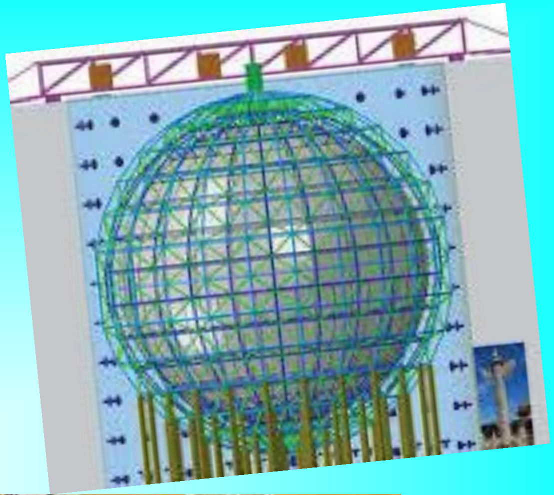
High precision measurements of the pp- and Be- neutrino fluxes

Detailed study of the Earth matter effect

Future experiments

SNO+

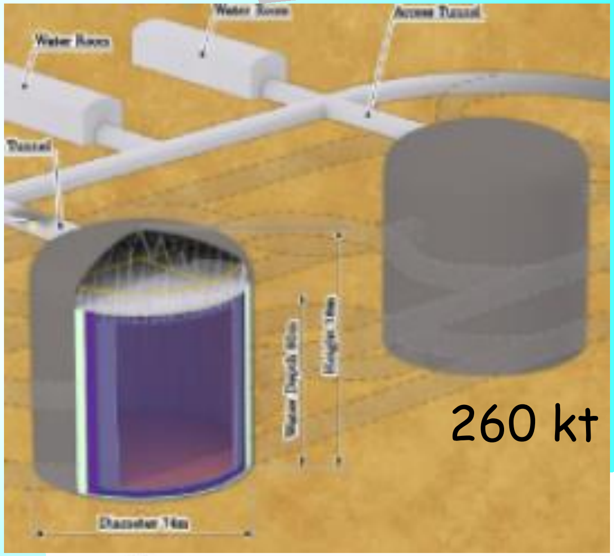
870 tons
Double beta decay of Te
Simultaneously solar with E > 3 MeV, upturn
later pep- CNO- later



JUNO

LS 20 kt, too shallow,background?

HyperKamiokande



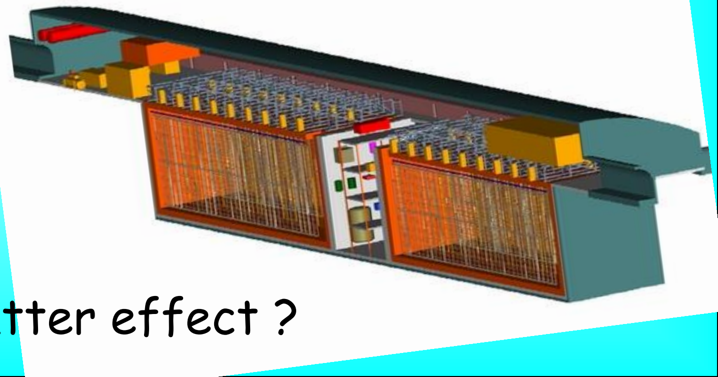
260 kt each

17 times larger SK. 100 000 νe events/y, lower PMT coverage, E > 4-5 MeV shallower than SK, larger background, > 5 σ D-N in 10 y

DUNE

4 x 11.6 kt (fv) LiAr TPC

$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e$



Earth matter effect ?

... continued

JinPing

The deepest lab - lowest background

$\nu + e \rightarrow \nu + e$

ASDC (WbLS)

(water based Liquid scintillator)

Combining advantages of scintillator (good energy resolution) and cherenkov (directionality) experiments

$\nu + e \rightarrow \nu + e$

Theia

30 t f.v. also 1% Li doped

$\nu_e + {}^7Li \rightarrow {}^7Be + e$

pep, N, O, B Be

DARWIN

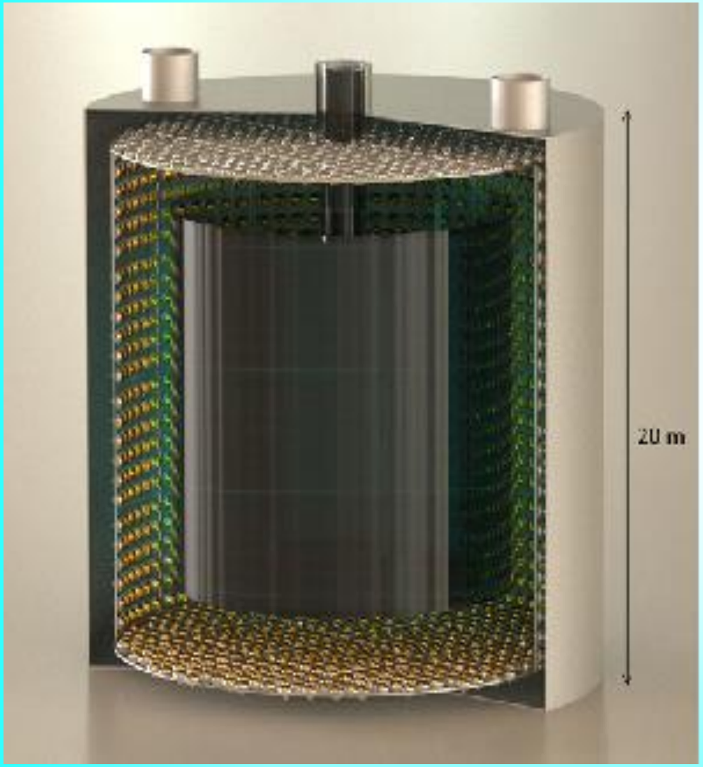
DM experiments hitting neutrino floor
Liquid Xe TPC, 30 t fiducial volume

$\nu + e \rightarrow \nu + e$

pp (1%)

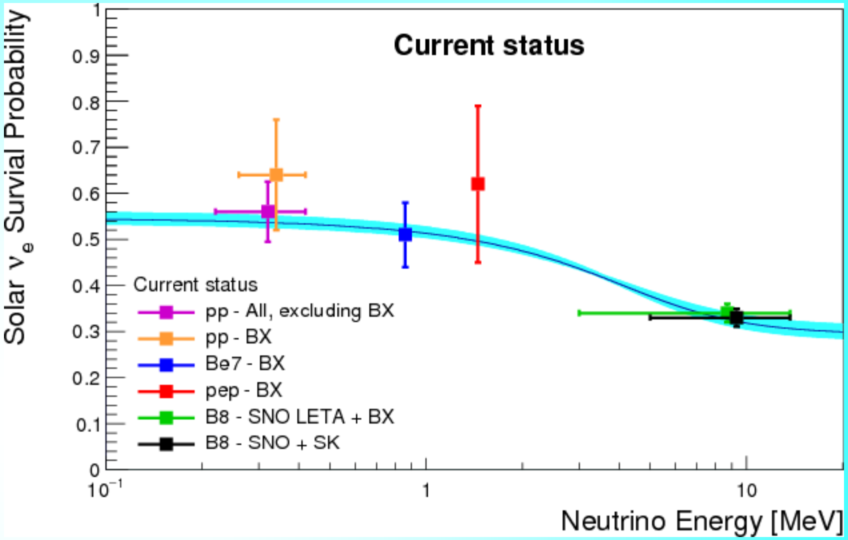
JinPing underground lab

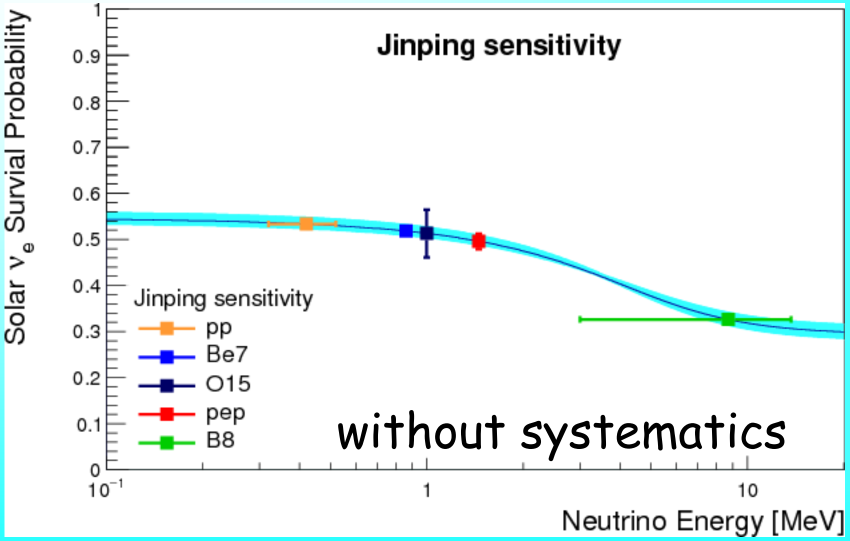
scintillator uploaded
water detectors?



FV: 100 times bigger than BOREXINO

Deeper than SNO





without systematics

... in conclusion

Only one lecture on solar neutrinos

Opinion: Physics of solar neutrinos is essentially done. Problem solved, what is left is just further checks, small corrections...

Actually, there is continuous progress in the field with new important experimental and theoretical results

Rich physics of neutrino propagation (much richer than e.g. of reactor neutrinos)

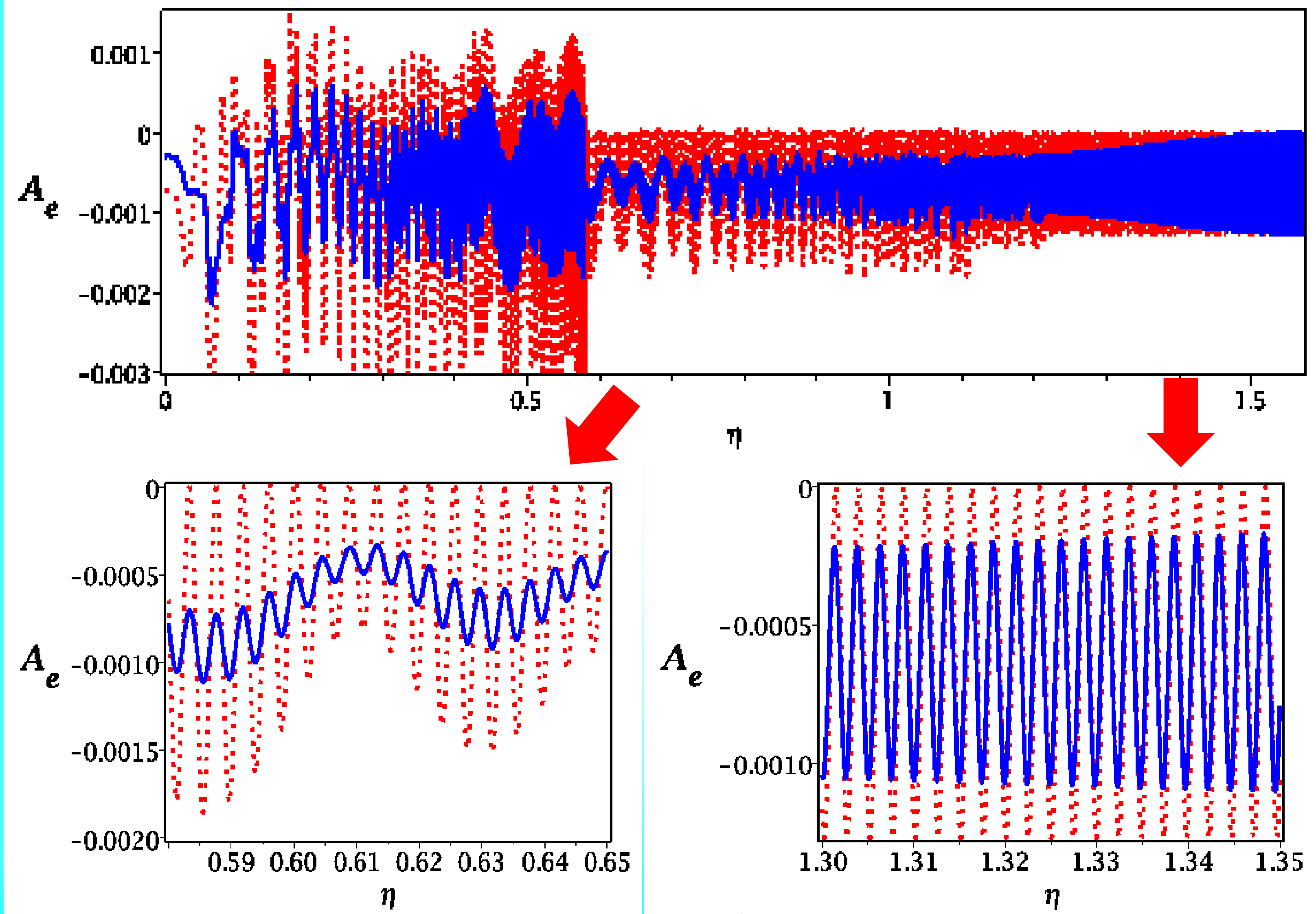
Interesting physics of neutrino production

Applications

New phase of the field with % - sub % accuracy

New physics, new opportunities,
In particular, full 3 neutrino framework is the must

Variations of the Be flux



Nadir angle

From the Sun to the Earth

1. Loss of the propagation coherence between the eigenstates

In position (configuration) space:
the wave packets of different eigenstates have different group velocities (due to different masses).
They are separated already at distances 0.1 – 10 R_{sun} (depending on energy). Absence of the overlap - no interference.

In the energy space:
due to long propagation period of oscillatory modulations of the energy spectrum is so small that these modulations is averaged out due to uncertainty in energy at production (or finite energy resolution)

$$P_{ee} = \Sigma_i | U_{ei}^m(n_0)|^2 P_{ie}$$

Adiabaticity violation

SN shock waves

If sterile neutrinos with small mixing exist

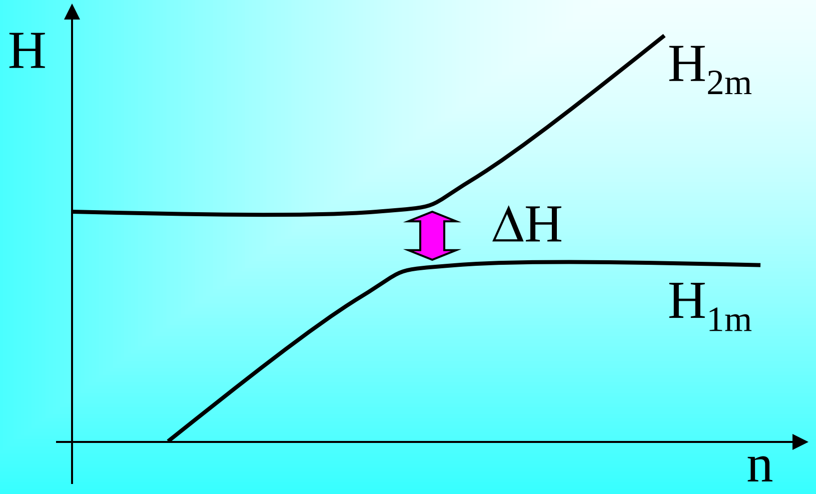
If density $n_e(t)$ changes fast $\left|\frac{d\theta_m}{dt}\right| \sim |H_{2m} - H_{1m}|$

the off-diagonal terms in the Hamiltonian can not be neglected

transitions $\boxed{\nu_{1m} \Leftrightarrow \nu_{2m}}$

Admixtures of ν_{1m} ν_{2m} in a given propagating neutrino state change

``Jump probability" = penetration under barrier: $\boxed{P_{12} = e^{-\frac{\Delta H}{E_n}}}$



$E_n = d\theta_m/dt \sim 1/h_n$

is the energy associated to change of density

$$\boxed{P_{12} = e^{-2\pi/\gamma_R}}$$

Landau-Zenner

γ_R - adiabaticity parameter

3ν probabilities

$P(\nu_e \rightarrow \nu_\mu) = |\cos\theta_{23} A_{e2} e^{-i\delta} + \sin\theta_{23} A_{e3}|^2$

$= |\cos\theta_{23} |A_{e2}| e^{i(-\delta+\phi)} + \sin\theta_{23} |A_{e3}||^2$

$\phi = \arg(A_{e2} A_{e3}{}^*)$

$P_{int} = 2 s_{23} c_{23} |A_{e2}||A_{e3}| \cos(\phi - \delta)$

For constant density and E > 0.5 GeV

$|A_{e2}| \sim \cos\theta_{13} \sin 2\theta_{12}{}^m \; \sin\phi_{12}{}^m$

$|A_{e3}| \sim \sin 2\theta_{13}{}^m \; \sin\phi_{13}{}^m$

Below 1-3 resonance and above 1-2 resonance $\xi_{12} >> 1 >> \xi_{13}$

$\xi_{ij} = 2EV/\Delta m_{ij}{}^2$

$\sin 2\theta_{13}{}^m \sim \sin 2\theta_{13} / (1 - \xi_{13})$
$\phi_{13}{}^m \sim \phi_{13} (1 - \xi_{13})$

small matter corrections

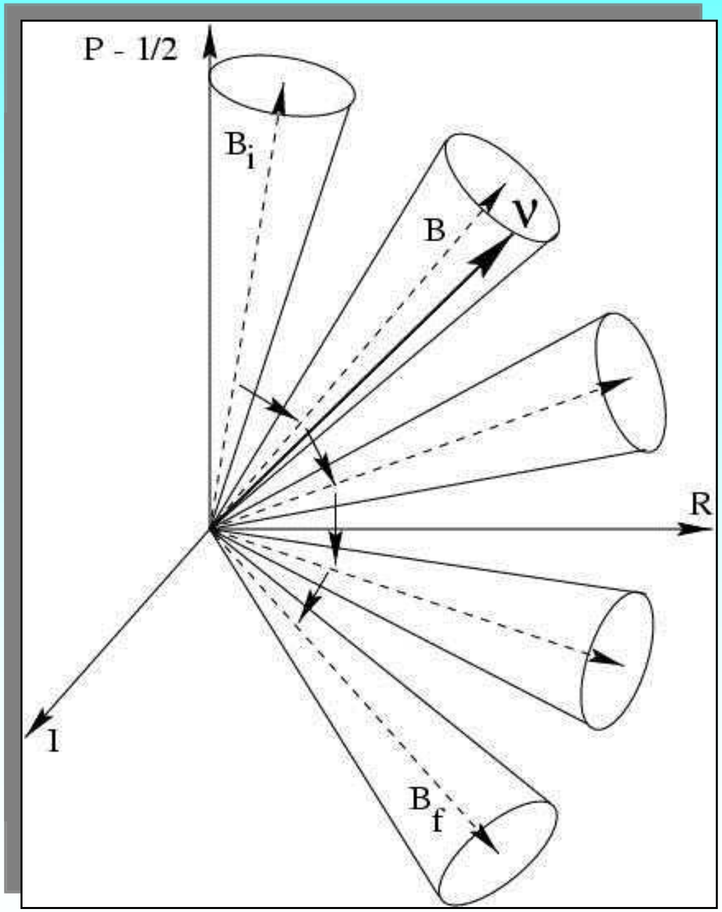
$\sin 2\theta_{12}{}^m \sim \sin 2\theta_{12} / \xi_{12}$
$\phi_{12}{}^m \sim \phi_{12}\, \xi_{12} = VL/2$

matter dominated limit
If phase is small - vacuum mimicking

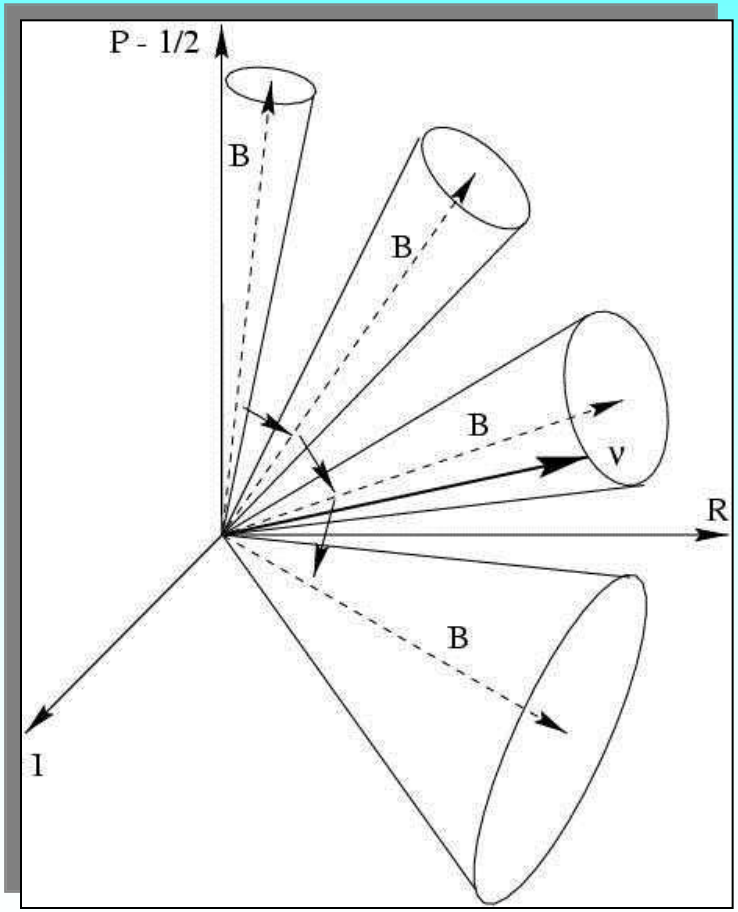
gives formula which appears in all Long baseline experiment papers

Adiabatic conversion

Pure adiabatic conversion



Partialy adiabatic conversion



Propagation in matter

L. Wolfenstein, 1978

At low energies – refraction phenomena

Refraction index: $n - 1 = V / p$

V - potential

Difference of potentials for ν_e ν_μ

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

Fermi constant

Electron number density

$V \sim 10^{-13}$ eV inside the Earth

$E = 10$ MeV $\quad n - 1 = \begin{cases} \sim 10^{-20} & \text{inside the Earth} \\ < 10^{-18} & \text{inside the Sun} \end{cases}$

Refraction length: $l_0 = \dfrac{2\pi}{V}$

- distance at which additional phase is 2π

Mixing in matter

Mixing is determined with respect to the eigenstates of propagation

in vacuum:

H_0

U_{PMNS}

ν_f $\quad \nu_e \quad \nu_\mu \quad \nu_\tau$

U^m

in matter:

$H(n_e, E) = H + V$

ν_{mass} $\quad \nu_1 \quad \nu_2 \quad \nu_3$

ν_H $\quad \nu_{1m} \quad \nu_{2m} \quad \nu_{3m}$

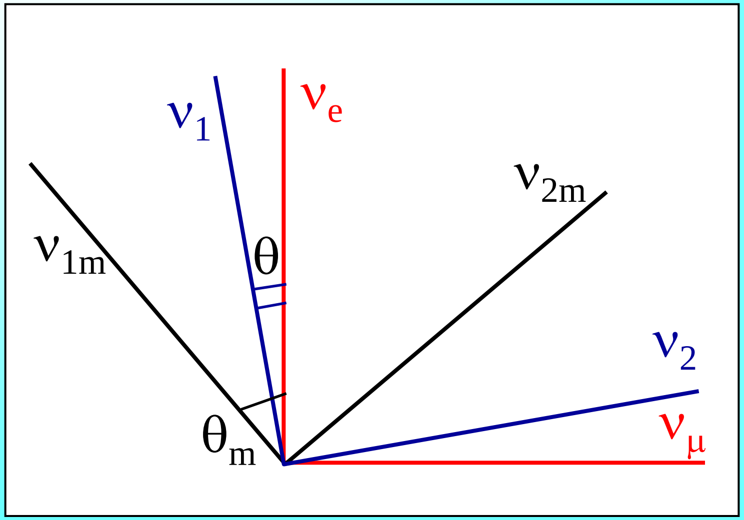
Eigenstates in vacuum H_0

Eigenstates in medium

Mixing angle determines flavors (flavor content) of eigenstates of propagation

θ_m depends on n_e, E

Flavor basis is the same,
Eigenstates basis changes



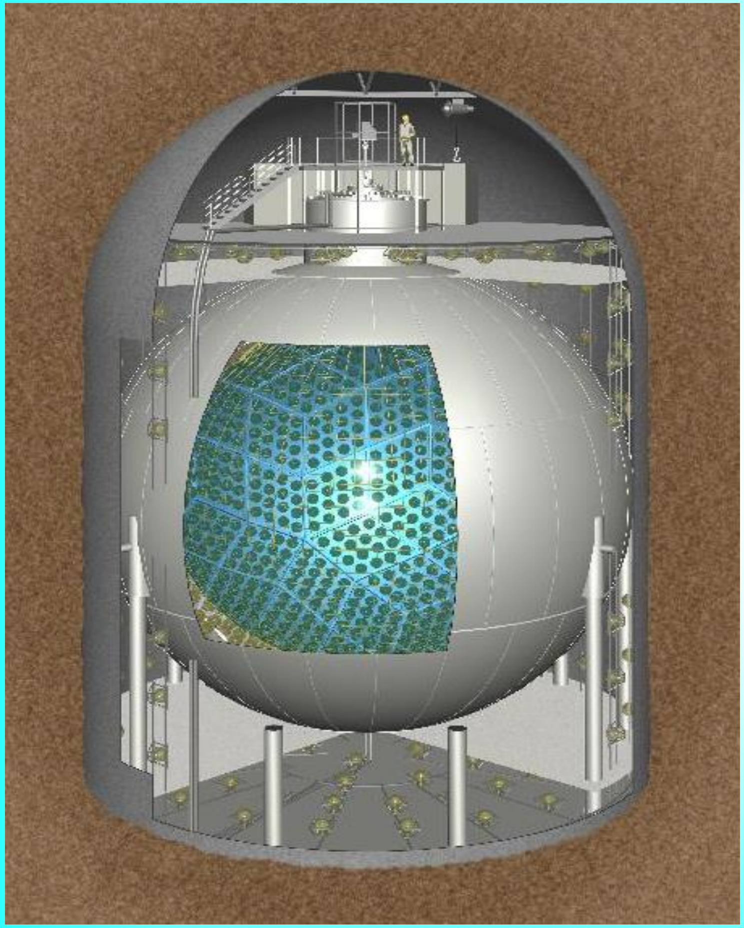
KamLAND

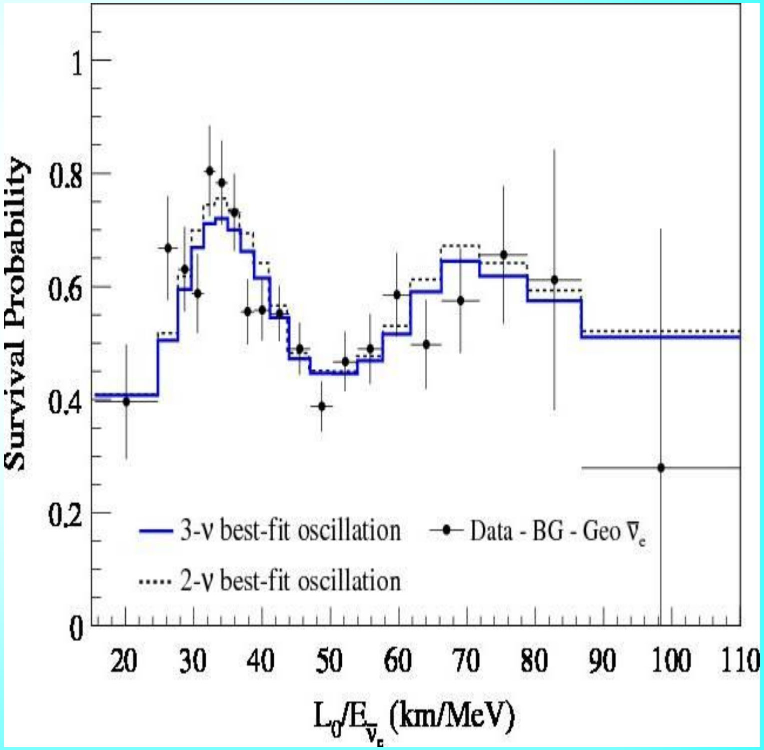
Decisive experiment

scintillator

reactors

<L> ~ 180 km





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

Adiabatic conversion probability

Sun, Supernova

Initial state: $\nu(0) = \nu_e = \cos\theta_m{}^0\, \nu_{1m}(0) + \sin\theta_m{}^0\, \nu_{2m}(0)$

Mixing angle in matter in production point

Adiabatic evolution to the surface of the Sun (zero density):

$\nu_{1m}(0) \rightarrow \nu_1$

$\nu_{2m}(0) \rightarrow \nu_2$

Final state: $\nu(f) = \cos\theta_m{}^0\, \nu_1 + \sin\theta_m{}^0\, \nu_2\; e^{i\phi}$

Probability to find ν_e averaged over oscillations

$$P_{ee} = |\langle\nu_e|\nu(f)\rangle|^2 = (\cos\theta\, \cos\theta_m{}^0)^2 + (\sin\theta\, \sin\theta_m{}^0)^2$$

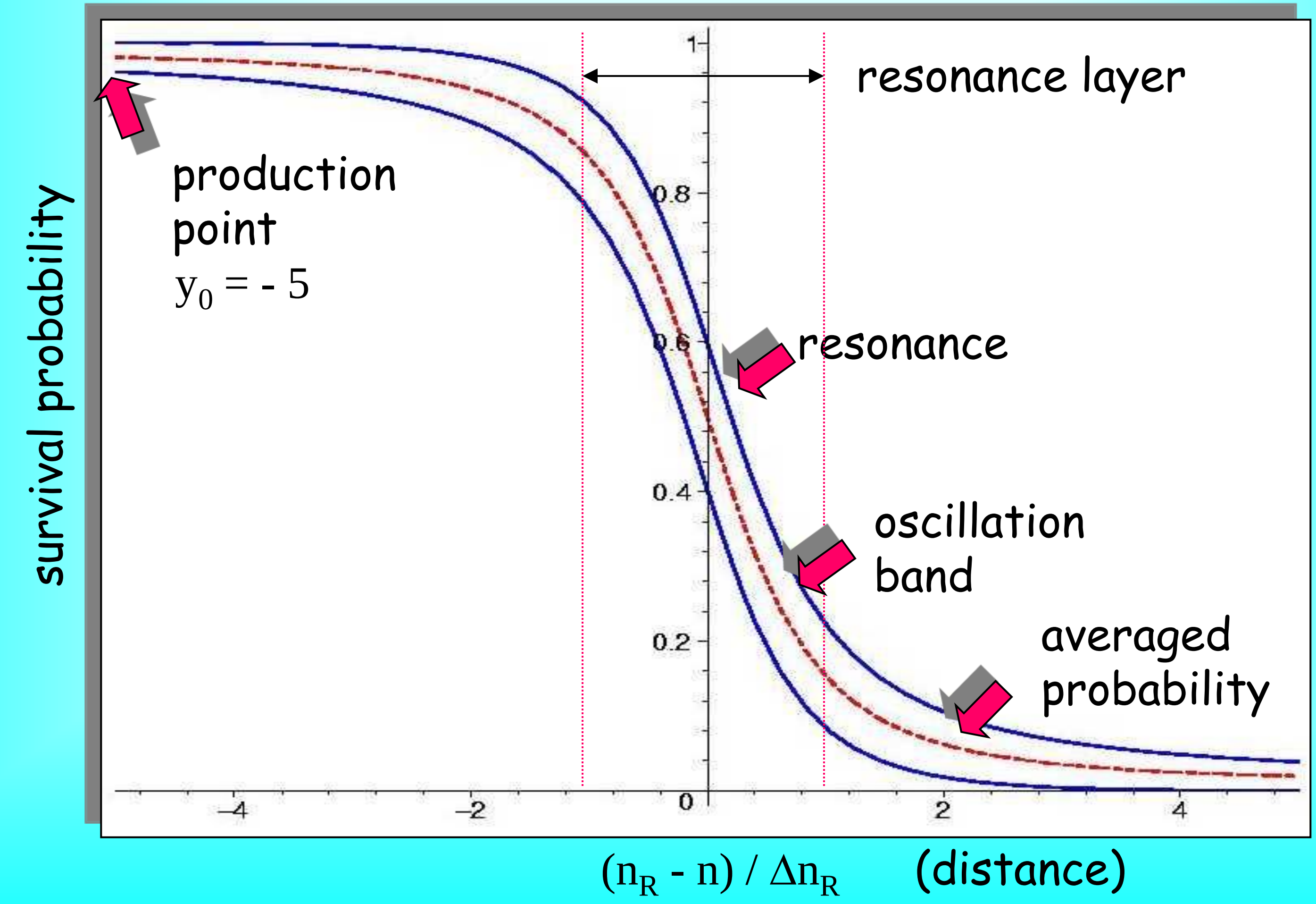
$$= 0.5[\, 1 + \cos 2\theta_m{}^0 \cos 2\theta\,]$$

or

$$P_{ee} = \sin^2\theta + \cos 2\theta \cos^2\theta_m{}^0$$

Spatial picture

The picture is universal in terms of variable $y = (n_R - n) / \Delta n_R$
no explicit dependence on oscillation parameters, density distribution, etc.
only initial value y_0 matters



A Yu Smirnov

Oscillations versus adiabatic conversion

Different degrees of freedom

Oscillations

Vacuum or uniform medium with constant parameters

Phase difference increase between the eigenstates

$\phi(t)$

Mixing does not change

$\theta_m (E)$

Adiabatic conversion

Non-uniform medium or/and medium with varying in time parameters

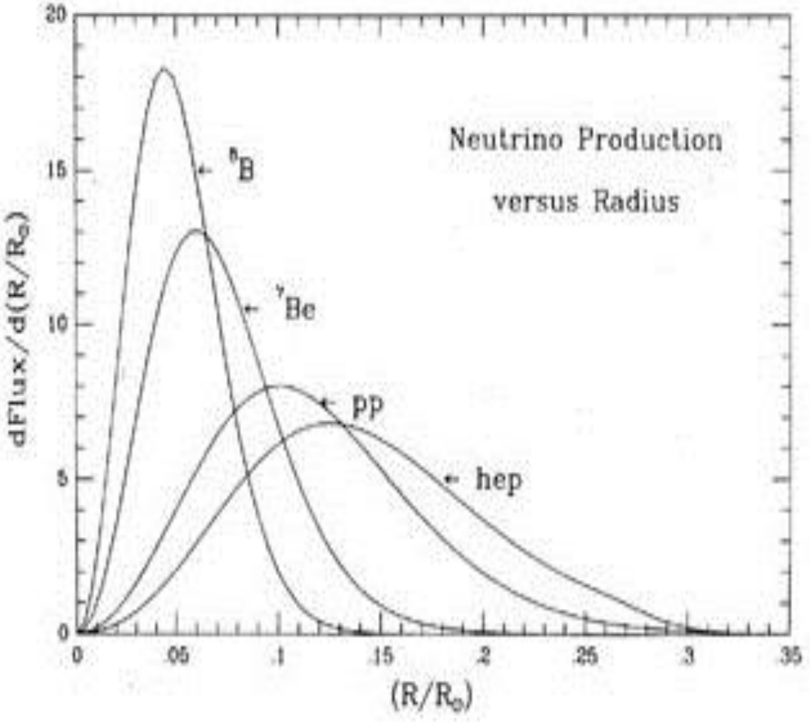
Change of mixing in medium = change of flavor of the eigenstates

$\theta_m (t)$

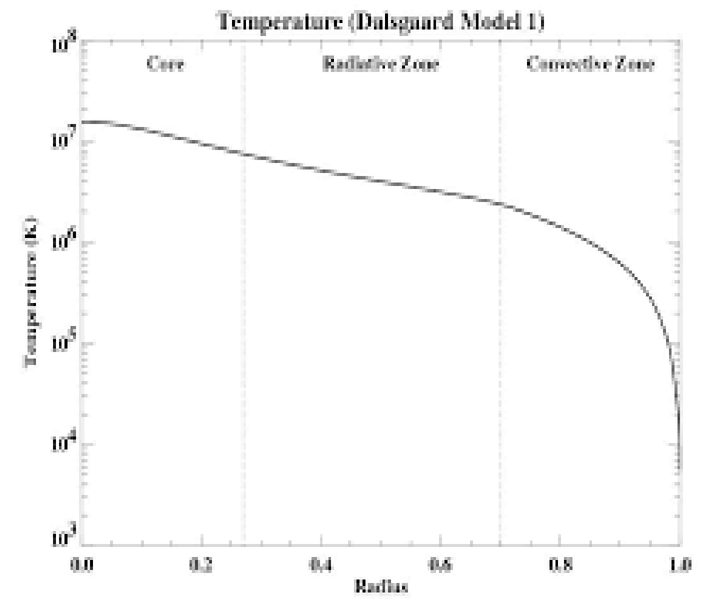
Phase is irrelevant

In non-uniform medium: interplay of both processes

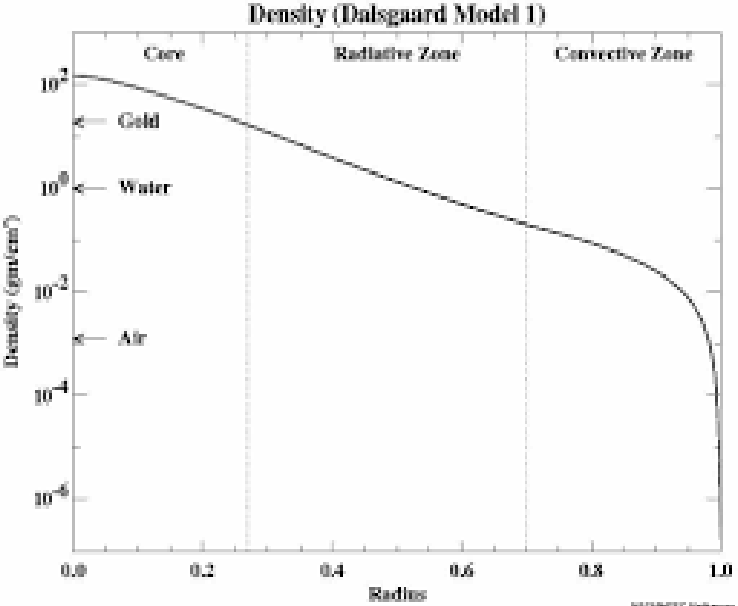
Neutrino production



Neutrino production as a function of radius



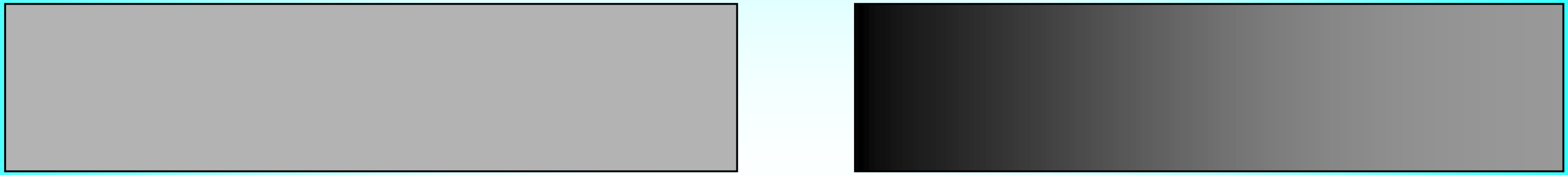
NASA/MSFC Hathaway

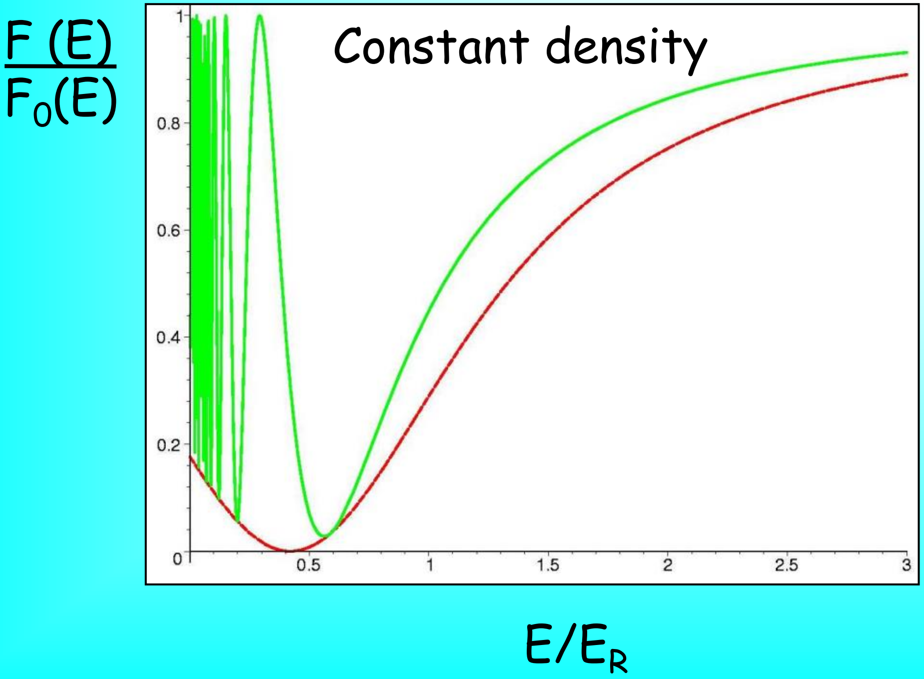


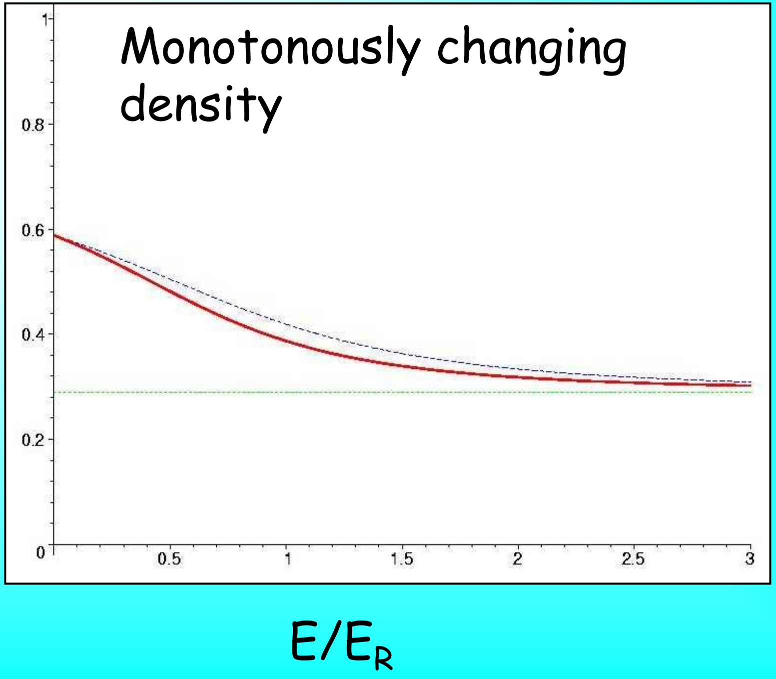
NASA/MSFC Hathaway

Resonance oscillations vs. adiabatic conversion

Passing through the matter filter ν







Scaling **

Inside the Sun highly adiabatic conversion →

The averaged survival probability is scale invariant = no dependence on distance, on scales of the density profile, etc.

Function of the combinations $\varepsilon_{12} = \frac{2VE}{\Delta m_{21}^2}$ $\varepsilon_{13} = \frac{2VE}{\Delta m_{31}^2}$ Very weak dependence

With oscillations in the Earth $P_{ee} = P_{ee}(\varepsilon_{12}, \varepsilon_{13}, \phi_E)$

$\phi_E = \Delta m_{21}^2 L / 2E$

L – the length of the trajectory in the Earth

If oscillations in the Earth are averaged $P_{ee} = P_{ee}(\varepsilon_{12}, \varepsilon_{13}) = P_{ee}(\varepsilon_{12})$

Invariance: $\Delta m_{ij}^2 \rightarrow a\, \Delta m_{ij}^2$, $V \rightarrow a\, V$

$\Delta m_{ij}^2 \rightarrow b\, \Delta m_{ij}^2$, $E \rightarrow b\, E$

a = -1 flip of the mass hierarchy

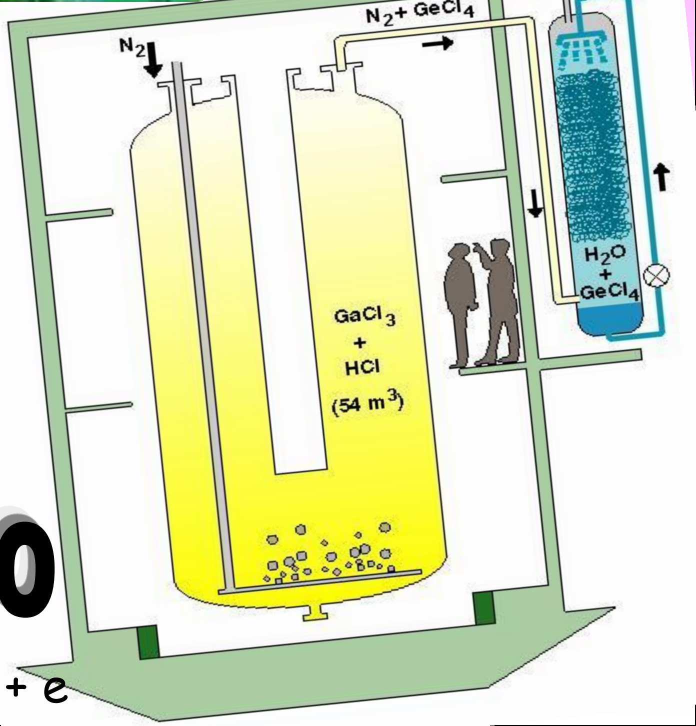
Homestake

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$

SAGE

Solar neutrino fluxes

Ga-calibration experiments anomaly



Gallex, GNO

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$

Mixing in matter – dynamical variable

S.P. Mikheyev, A.Y.S. 1985

Mixing in matter is determined with respect to eigenstates in matter

$\nu_f = U^m \nu_m$

$U_{PMNS} \rightarrow U^m(n_e, E)$

$\nu_m = U^{m+}(n_e, E)\, \nu_f$

Flavor of eigenstates depends on n_e E

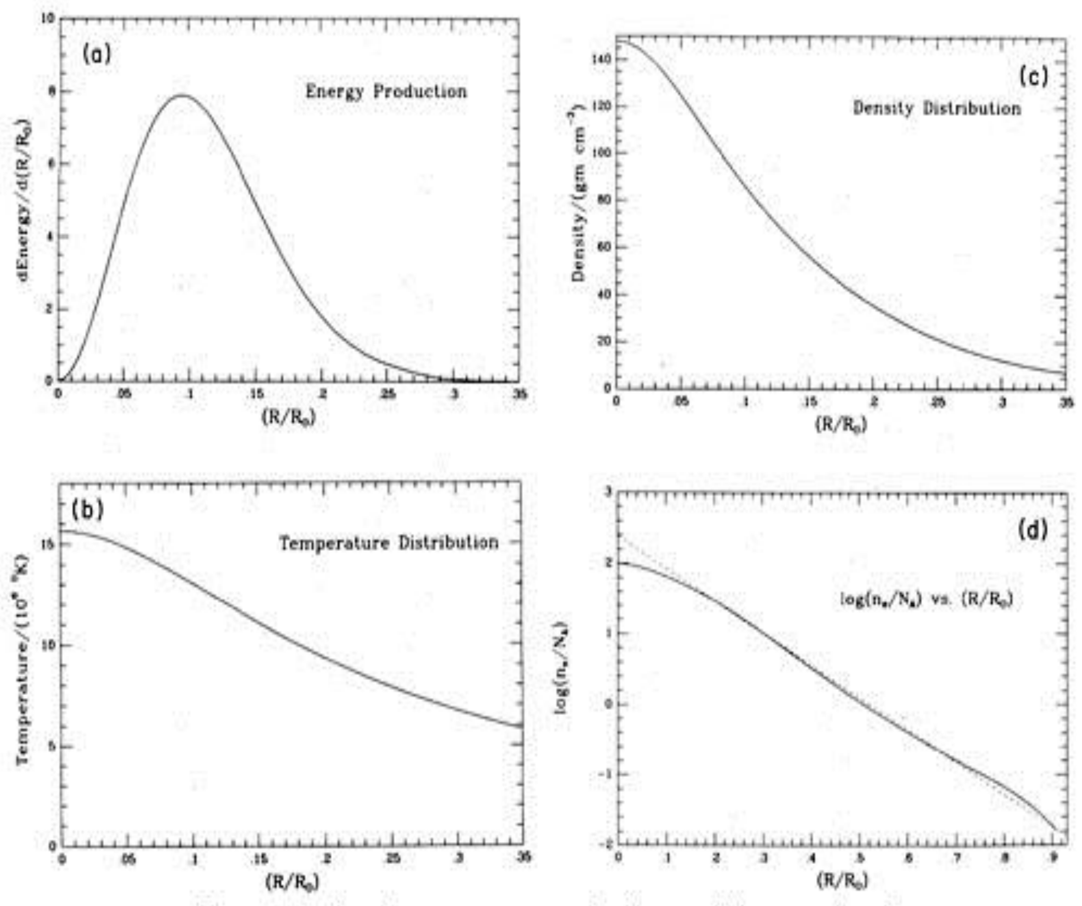
High density
mixing suppressed

$l_\nu = l_0 \cos 2\theta$

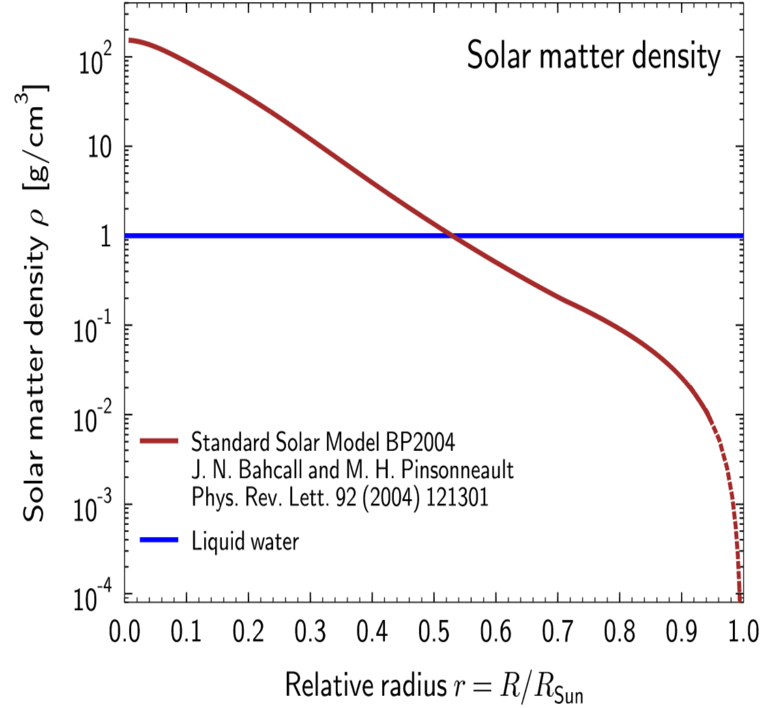
Resonance:
maximal mixing

Low density
vacuum mixing

Temperature and density profiles



Energy production, temperature, density, and electron density


(Data Source: http://www.sns.ias.edu/~jnb/SNdata/Export/BP2004/bp2004stdmodel.dat)

JUNO

Also RENO-50

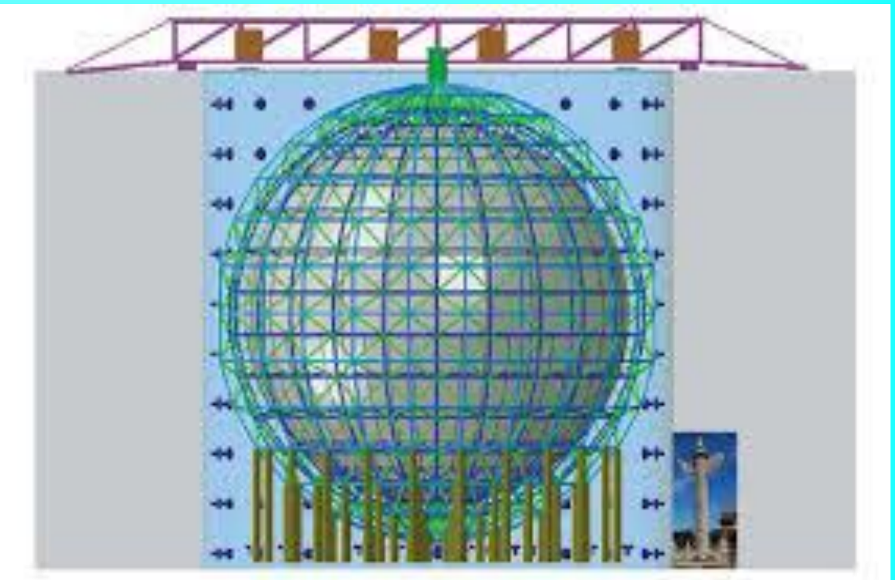
Jiangmen Underground
Neutrino Observatory

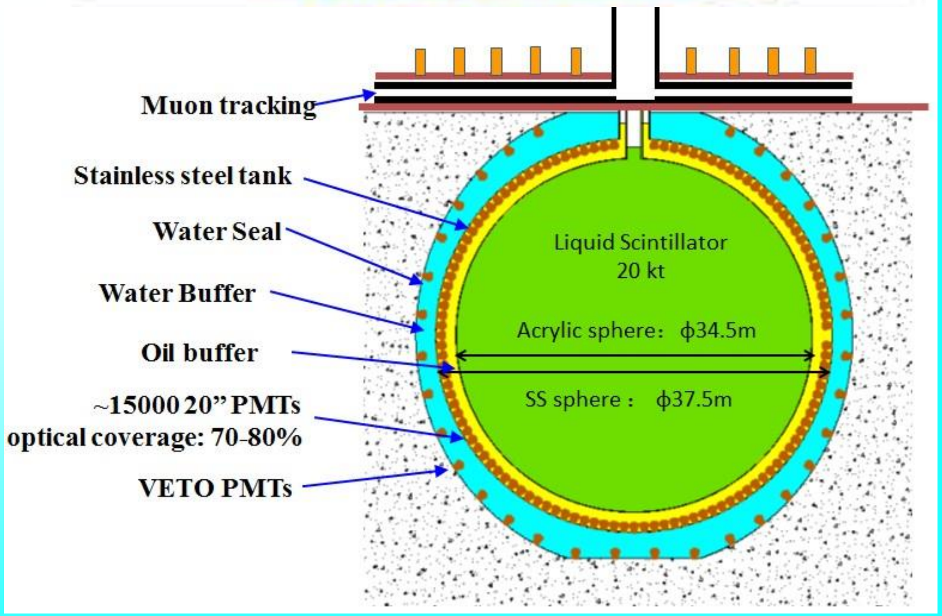
d = 700 m, L = 53 km, P = 36 GW

20 kt LAB scintillator

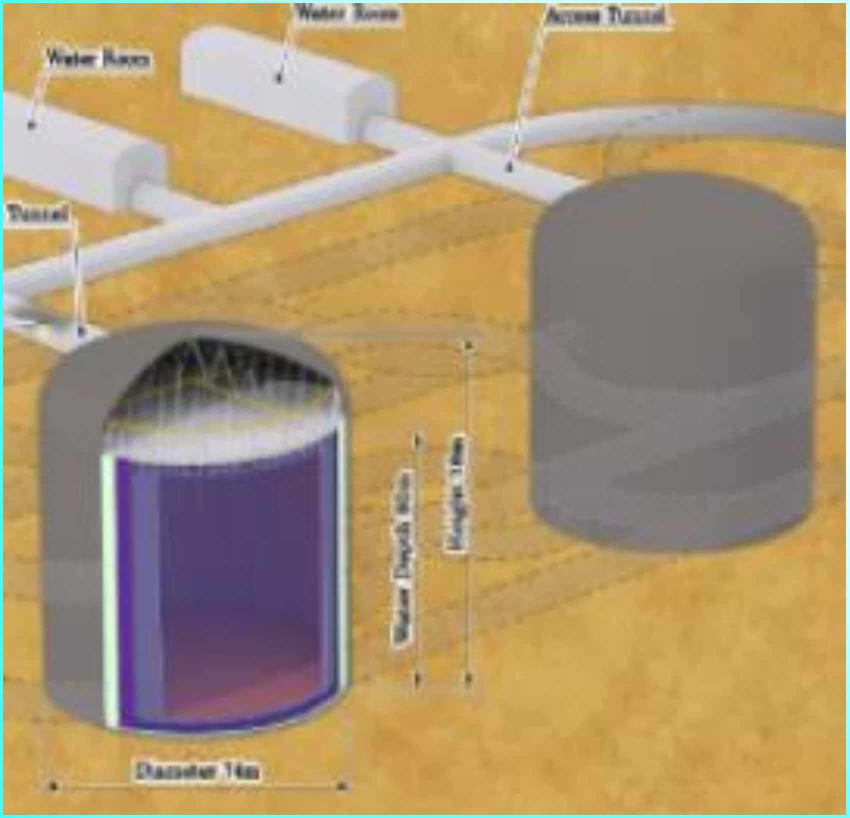
$n + p \rightarrow d + \gamma$

Key requirement:
energy resolution 3% at 1 MeV





Hyper-Kamiokande



Problems, future

Intermediate energy range upturn, D-N asymmetry

Detection of CNO neutrinos to shed some light on the problem of the SSM: controversy of helioseismology data and metallicity

High precision measurements of the pp- and Be- neutrino fluxes
Checks of flux- luminosity relations

Detailed study of the Earth matter effect
Oscillation tomography

Experiments:

DARWIN

SK

JUNO

JinPing

ASDC Theia (WbLS)

SNO+

Hyper-K

DUNE