

Neutrinos the MSW effect and MORIOND

A. Yu. Smirnov

*International Centre for
Theoretical Physics, Trieste*

*60 years of Rencontres de Moriond,
Paris, January 16 - 17, 2026*



Outline

1. Neutrinos at MORIOND

2. 86 Workshop on Massive Neutrinos

3. Then and Now

I have attended Rencontres (Moriond, Blois) many times but two participations were the most memorable which I will talk about mostly

Neutrinos at MORIOND



Rencontres

Neutrino physics and astrophysics - **important component** of Rencontres de Moriond

- Electroweak parts of MORIOND: sections devoted to neutrinos
- Special workshops on neutrinos

They cover in **very comprehensive** way

- recent experimental results and projects,
- new detectors and technologies,
- the latest theoretical developments

and also provide with useful private information, rumours, etc...

The beginning of the year - important factor: fresh efforts

Using Moriond proceedings one can write history of neutrino physics after 1966

Moriond “miracle”

My first participation was in 1980: 4 years before MSW
Two remarkable things happened

That was my first trip abroad

Unbelievable for those who knew the background:

- immediately in the western country,
- I was travelling alone,
- I was not married, and not a member of the Communist party.

Even now I don't understand completely how it could happen.

Probably the key role was played by

Alexander Alexandrovich Pomansky -

who was that time the Director of Baksan Neutrino Observatory
He knew Jean Tran Thanh Van personally (participated in Morionds before) and proposed to invite me.
I suspect that Pomansky vouched for me to the authorities.

Missed talk

I was supposed to give a talk on my results (paper in preparation) on neutrino decay

$$\nu \rightarrow \nu' \phi$$

where the scalar particle ϕ is the Goldstone boson related to spontaneous breaking of symmetry of lepton number.

Month before the Moriond I learned about the PRL paper by Chigashige, Mohapatra and Peccei with similar content in which the scalar was coined Majoron.

I was so depressed that eventually, already during the workshop decided to cancel my talk.

Still I gave a talk at Moriond 80

a talk and missed discovery

That time I became interested in the theory of neutrino oscillations. Knowing this experimentalist from our INR department asked me to present

"The first results of searches of oscillations of the atmospheric neutrinos" obtained at the Baksan neutrino telescope.

The analysis was performed by S. Mikheyev

The results based on study of the **angular distribution of muons** were negative and I have shown the bounds on the oscillation parameters.

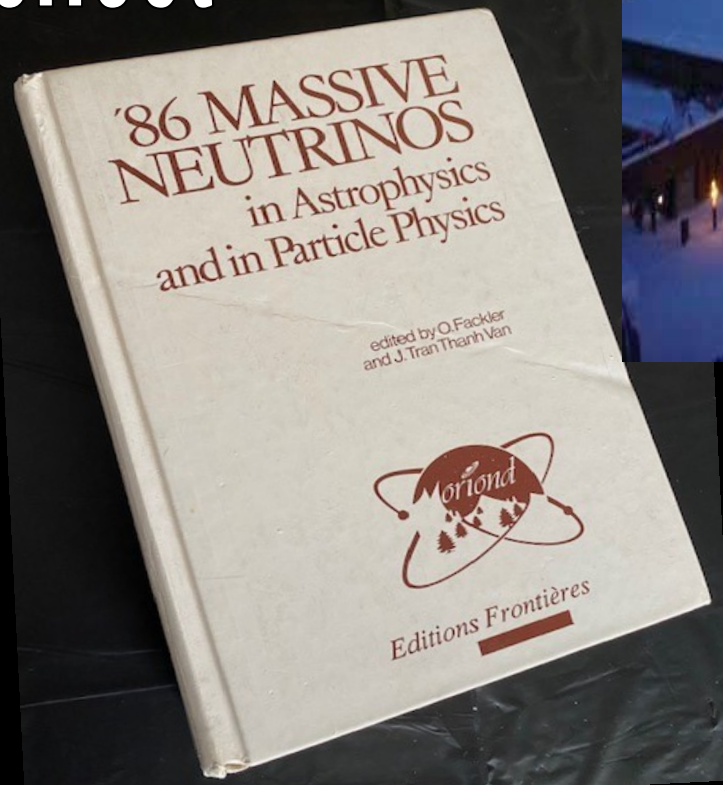
Unfortunately, even later no clear effect of oscillations was found. Baksan missed discovery of oscillations.



Stas Mikheyev

That was my first scientific contact with Stas Mikheyev which eventually led to work on MSW, again in connection to the atmospheric ν

86 Moriond Workshop in Tignes. The MSW effect



On the way to Tignes

I was invited to Moriond 86 again by recommendation of A.A. Pomansky .

I was given 15 min to talk on oscillations in matter at one of evening sessions and was very much surprised that the "Introductory talk" by Peter Rosen was mostly devoted to "the Mikheyev-Smirnov effect". (In proceedings Peter changed the title).

Things changed already on the way from Burg Sain Maurice to Tignes: Rosen learned that I am also in the bus and he asked to introduce himself. He told me that he is going to talk on Solar neutrinos and his slab model of resonance oscillations (paper with Gelb).

After arrival at Tignes, the organizers (Orrin Fackler, apparently by recommendation of Peter) told me that they will find time for my longer talk in one of the morning sessions.

Even more talks

After Rosen's introduction the organizers told me that, if needed, they can arrange my another presentation and **I can talk as much as I want!**

Eventually I gave **two long** (half an hour) **talks** on oscillations in matter and yet another talk on Baksan data (muons) on Cygnus X-3.

Most of results I have presented for the first time.
They included

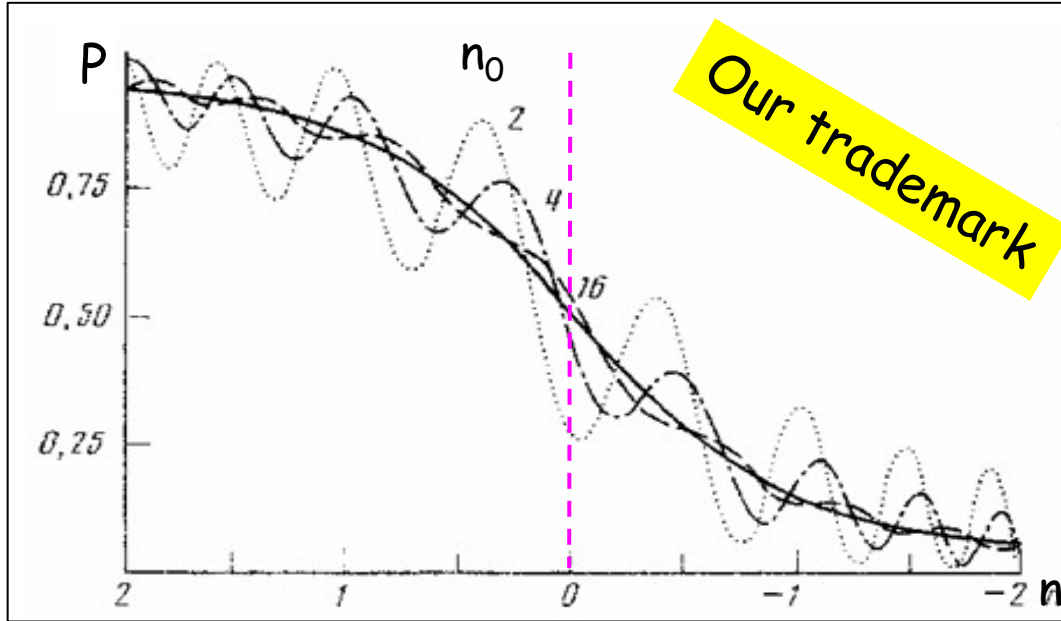
Complete theory of adiabatic conversion:

- equation of motion,
- analytic solutions
- detailed properties of the solutions

and **various applications.**

Let me flash some pictures from slides

Adiabatic conversion



Survival probability as function of n for different initial values of n_0

With increase of n_0 the amplitude of oscillations decreases. P converges to non-oscillatory form (solid).

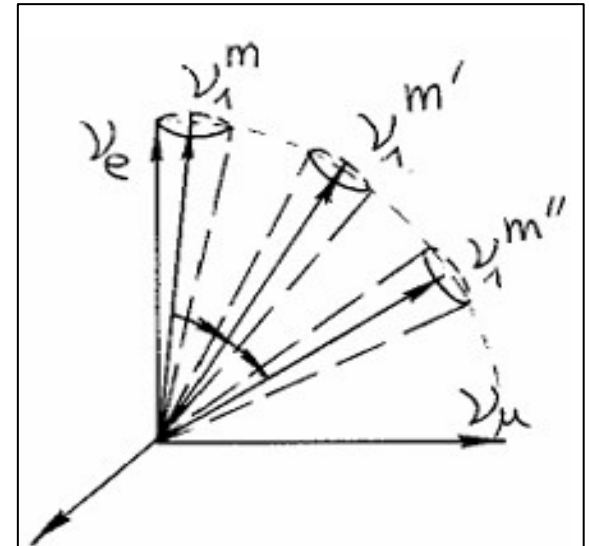
$$P(n)_{\text{non-osc}} = \frac{1}{2} [1 + n (n^2 + 1)^{-1/2}]$$

If $\rho \rightarrow 0$, $n \rightarrow -1/\tan 2\theta$ $P \rightarrow \sin^2\theta$

Universal form in terms of

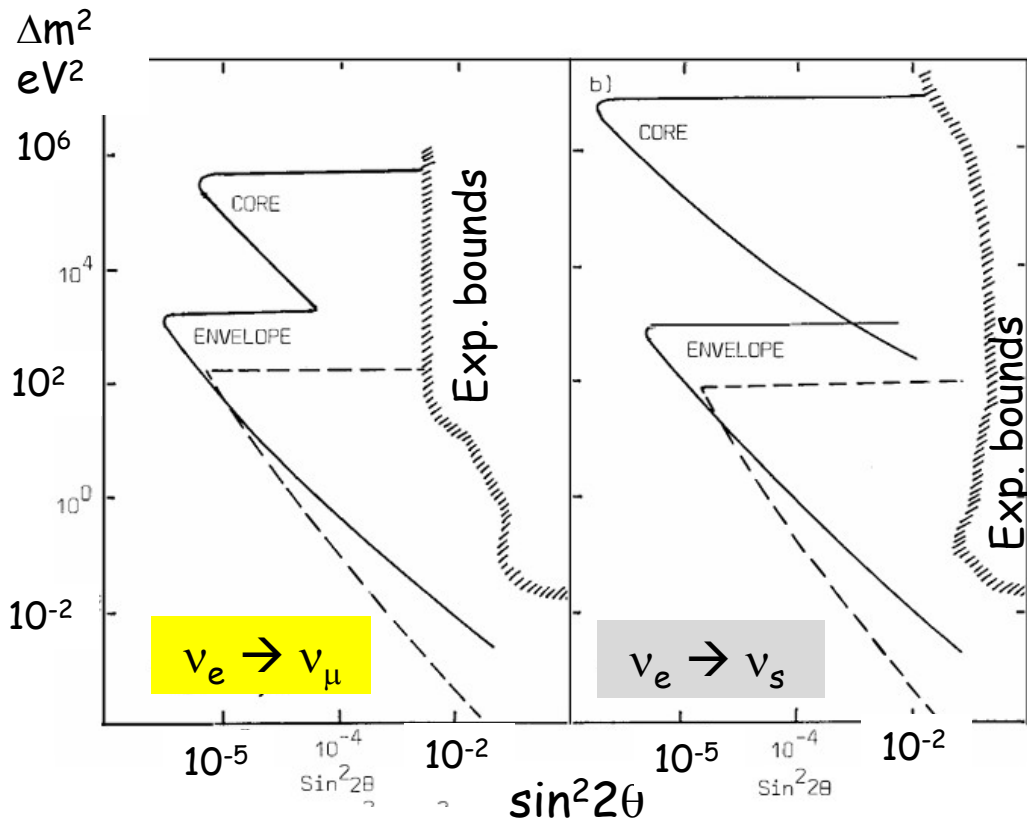
$$n = (\rho - \rho_R) / \Delta\rho_R$$

- distance in density scale
 $\Delta\rho_R$ - width of resonance



Geometric representation of neutrino oscillations in the adiabatic regime.

Conversion of supernova neutrinos



The region of strong conversion effects
Dashed lines, correspond to $t = 10$ sec
and show effect of envelope expansion.

Observable effects:

Exchange of energy spectra

$$\nu_e \leftrightarrow \nu_\alpha \quad \text{or} \quad \bar{\nu}_e \leftrightarrow \bar{\nu}_\alpha$$

$$\alpha = \mu, \tau$$

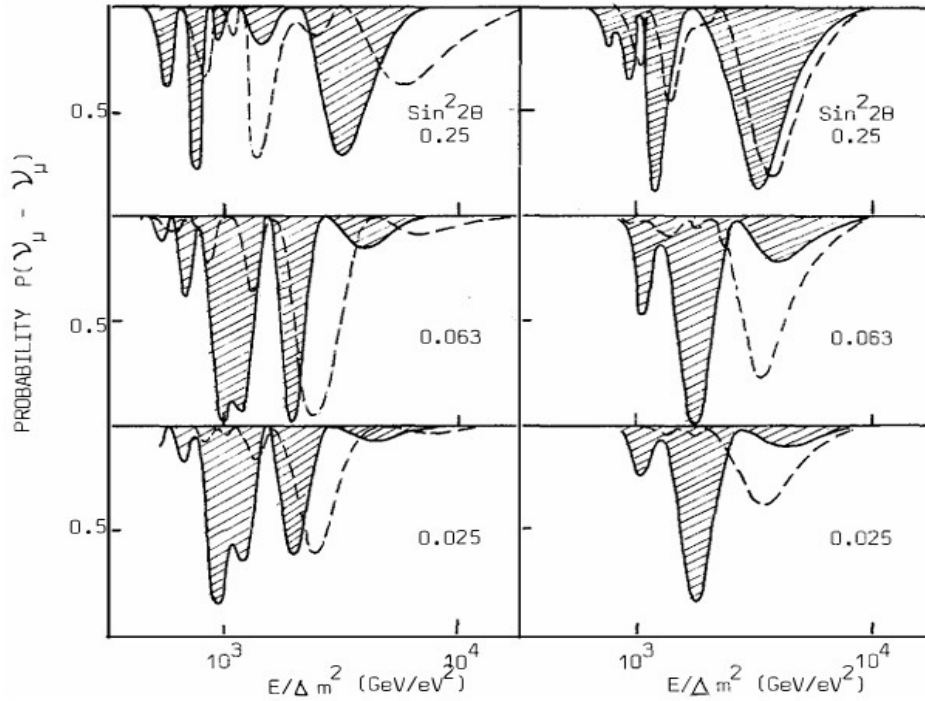
Harder spectra of ν_e (or $\bar{\nu}_e$)
→ more events.

Increase of energy release
in the envelope → explosion

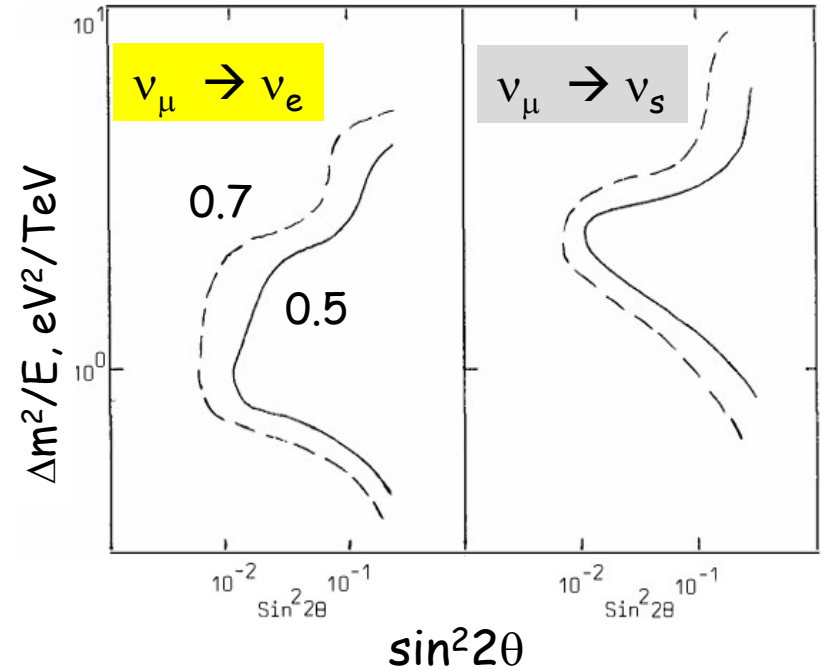
In the case of $\nu_e \rightarrow \nu_\tau$
suppression of the ν_e -flux

The potential has opposite
sign in the core and envelope
→ strong effect for both ν_e
and $\bar{\nu}_e$ at different energies

Earth matter effect



The **suppression factor** due to $\nu_e \rightarrow \nu_\mu$ (full curves) and $\nu_e \rightarrow \nu_s$ (dashed curves) oscillations, for zenith angle $\cos \psi = 1$ (core and mantle crossing, left) and $\cos \psi = 0.8$ (mantle crossing, right)



Borders of region of oscillations parameters in which the survival probability is smaller than 0.7 (dashed) and 0.5 (full curves).

Earth matter effect: Applications

Atmospheric and accelerator neutrinos:

study the Earth density profile

Supernova neutrinos:

with two or more detectors determination of direction to SN

Solar neutrinos:

regeneration of the ν_e - flux, day-night modulations of the signal due to rotation of the Earth.

The first presentation, never published in Journal, we refer to Moriond 86 proceedings as to the original source

Analytic results for solar neutrinos presented at MORIOND 87 which take into account

- lost of coherence on the way from the Sun to the Earth and
- mass to flavor oscillations $\nu_i \rightarrow \nu_e$ inside the Earth

The formula used later by Baltz and Weneser

Other results

Effects in the Early Universe

Few important things had been understood

$$\nu_e \rightarrow \nu_s$$

Initially effect is triggered by the lepton asymmetry which increased due to development of neutrino asymmetry

The problem becomes non-linear

$$V_{\text{eff}} = V_{B,L} + V(P_\nu - P_{\bar{\nu}})$$

Potential depends on oscillation probability and it enters equation for probability

Furthermore, one should consider system of equations for neutrinos and antineutrinos simultaneously

But thermal term was overlooked...

Albert Messiah: theory of the adiabatic conversion

Derived evolution equation for the evolution matrix $U_H(x, x')$ (equivalent to the eigenstates in matter ν_{im}) with separation of the adiabatic and non-adiabatic parts.

$$\text{Adiabatic condition: } \omega = \frac{d\theta_m/dx}{2W} \ll 1$$

mixing angle in matter level spacing

Corrections to the adiabatic solution $\sim \omega^2$

Introduced amplitude of transition between eigenstates $\beta = A(\nu_{2m} \rightarrow \nu_1)$

Derived formula for the survival probability:

$$P_{ee}(x) = \frac{1}{2} [1 + (1 - 2|\beta|^2) \cos 2\theta \cos 2\theta_m(x)]$$

$|\beta|^2 = P_c$ - jump or flop probability, x - the production point

Adiabatic solution: $\beta = 0$

Known as Parke's formula (published few months later)

→ Fair to call Messiah - Parke formula

Messiah: The MSW effect

He did not like the term "resonance oscillations", in framework of solar neutrinos claiming that the effect can be readily deduced from the adiabatic solution of the equation of flavor evolution.

Messiah said: MS call it the "resonant amplification effect" - somewhat misleading denomination.

I will call it the MSW effect

For the first time I heard this term. Later Peter Rosen written "As a matter of historical record, I think it is fair to say that the MSW effect received its name at the January 86 Moriond Workshop."

My reply to Messiah was that I agree, "oscillations" (at least in connection to solar neutrinos) is confusing, but insisted on importance of the resonance and resonance condition.

I said: in our next paper we clarify the terminology.

Messiah replied: no way, now "oscillations" will be forever

He turned to be right! (see e.g. Nobel 2015 citations)

Other related presentations and discussions

Peter Rosen

- Slab model for oscillations in matter
- survival probabilities for solar neutrinos for different values of mixing angle
- The MSW triangles for ^{37}Cl and ^{71}Ga experiments

Michel Spiro

J. Bouchez, M. Cribier,
J. Rich, D. Vignaud,
W. Hampel

Neutrino oscillations in matter and solar neutrino experiments. Conditions for strong matter effect (resonance, slow change of density adiabaticity), survival probability, triangle for ^{71}Ga and ^{37}Cl experiments

Till Kirsten

Possible outcome of Gallium experiment in view of MSW conversion

and more

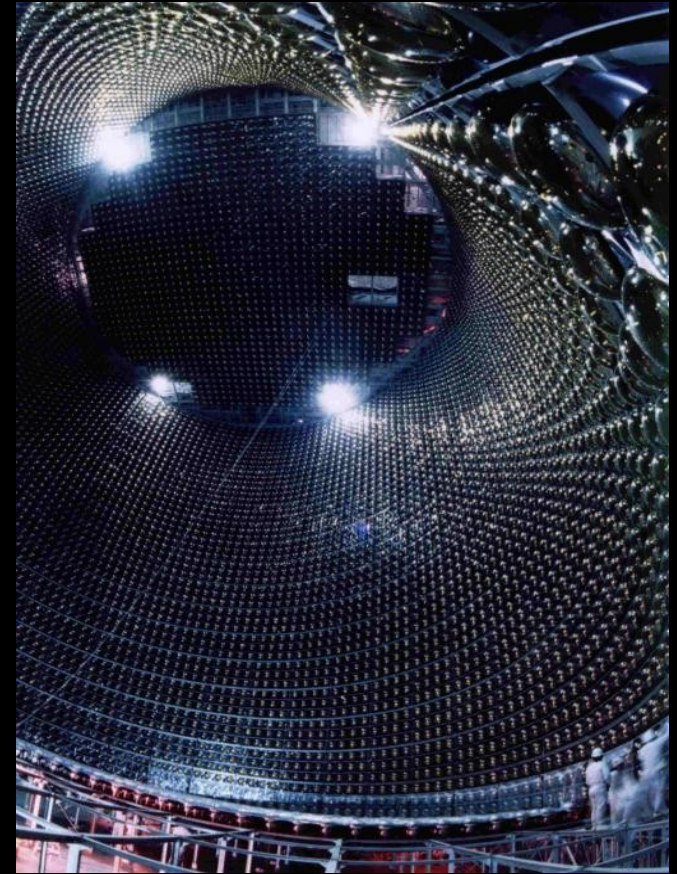
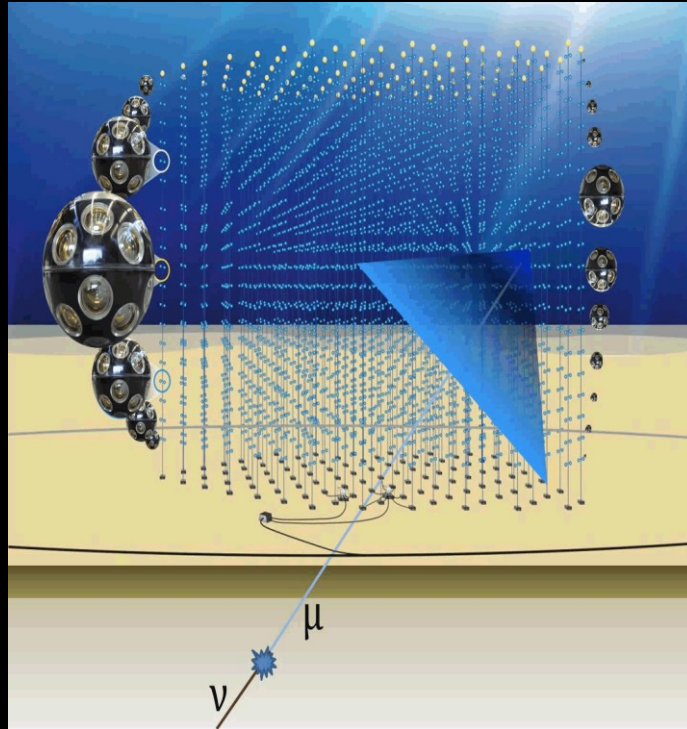
J.J Simpson

Proposal of SNO: Sudbury Neutrino Observatory experiment (H. H. Chen 85), "in view of recent interest in neutrino matter oscillations"

G. Steigman

Theoretical summary. Born again neutrinos. The most exciting new work discussed at this workshop ... The *MSW* mechanism. Overview of results presented at the Workshop...

Then and Now Follow up



Over Years. Other Moriond meetings

Many important things were already presented at Moriond 86.
Related papers at other Morionds.

1987 7th Moriond Workshop: Searches for New and Exotic Phenomena

AS: "New aspects of neutrino oscillations in matter (3 ν case)

S.P. Mikheyev, "Neutrino oscillations in matter"

J. Rich, M. Cribier, M. Spiro, D. Vignaud W. Hampel "The MSW Effect and Radiochemical Solar Neutrino Experiments".

1988 5th Force: Neutrino Physics

P. Toshev, "Resonant amplification of neutrino transitions in the Sun: **exact analytical results**" (Improved theory of Non-adiabatic transitions - beyond Landay -Zenner)

P.I. Krastev S.T. Petcov, "**Analytic description** of two neutrino transitions of solar neutrinos in the Sun"

M. Koshiba, Recent neutrino results from **Kamiokande-II** and future

1989

9th Moriond Workshop: Tests of Fundamental Laws (Particle Physics, Astrophysics, Atomic Physics)

P.I. Krastev, A.Yu.S. "Parametric effects in neutrino oscillations"

S. Toshev, "What happens with Dirac phase in matter?"

1990

10th Moriond Workshop: New and Exotic Phenomena

P.I. Krastev, "Variations of solar neutrino signals and resonant conversion"

M. Spiro, D. Vignaud, "Solar Model Independent Neutrino Oscillation Signals in the Forthcoming Solar Neutrino Experiments?"

S. P. Rosen, "Review of solar neutrinos and the MSW effect"

M. Nakahata, "Super-Kamiokande"

1991 11th Moriond Workshop: Tests of Fundamental Laws in Physics

A.Yu.S. "Berry phase and the solar neutrino problem"

S. Toshev, "Resonant amplification of T violating effects in matter neutrino oscillations".

E. K. Akhmedov, "Resonant spin-flavor precession and the solar neutrino problem"

V.N. Gavrin, SAGE Collaboration, "First measurement of the integral solar neutrino flux by the Soviet-American Gallium experiment"

D. Vignaud, "Report on the Gallex experiment"

Yoichiro Suzuki, "Kamiokande-II results on solar neutrinos and the Super-Kamiokande experiment"

E. Meroni, Borexino Collaboration, "The Borexino project to study the solar neutrinos"

1992

12th Moriond Workshop, Progress in atomic physics, neutrinos and gravitation

P.I. Krastev, "Solar neutrinos in **twisting magnetic fields**"

1993

28th Rencontres de Moriond: Perspectives in Neutrinos, Atomic Physics and Gravitation,

E. K. Akhmedov, S.T. Petcov, A.Yu.S. "Pontecorvo's original oscillations revisited"

1995

30th Rencontres de Moriond: Electroweak Interactions and Unified Theories

A.Yu.S. "Solar neutrinos and lepton mixing"

etc., etc.

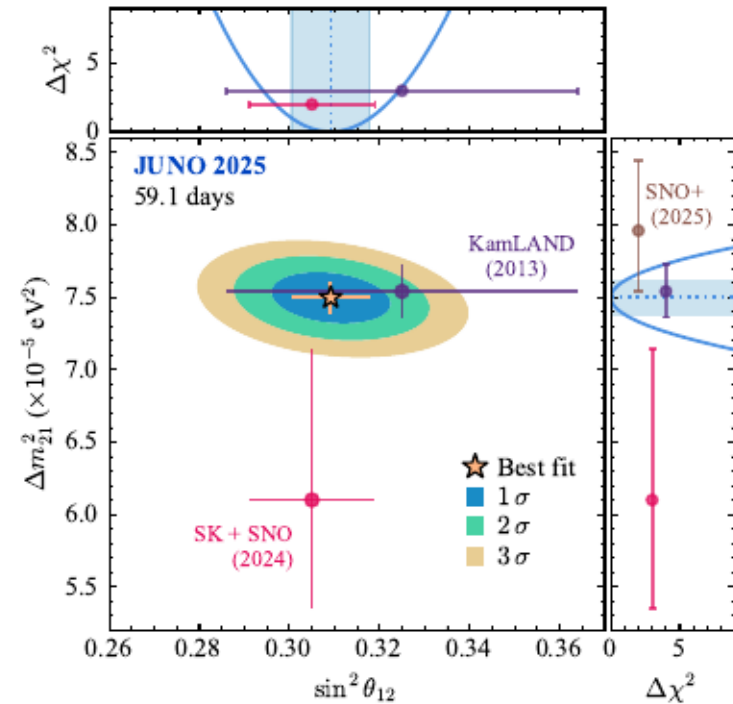
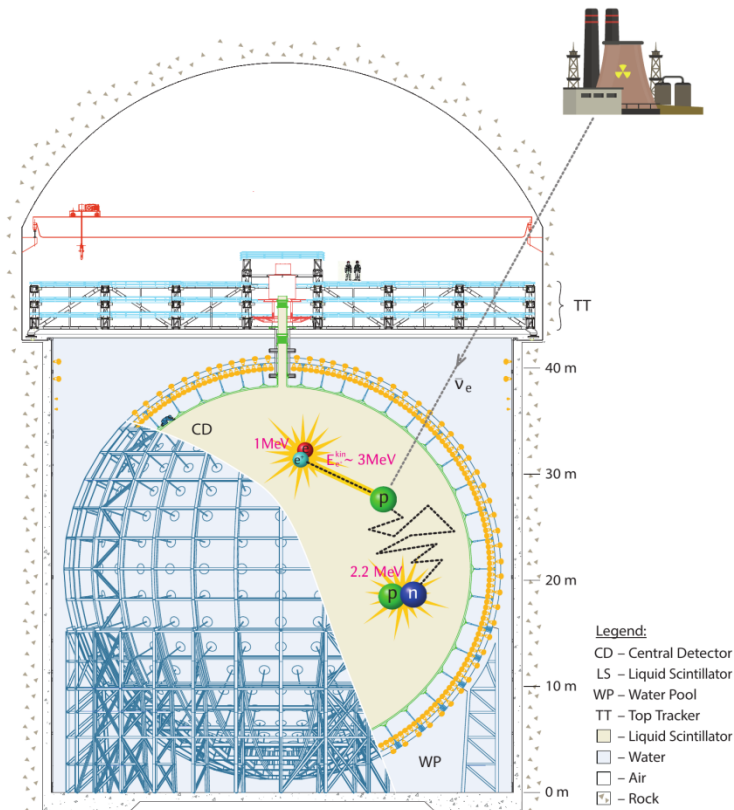
Things discussed in 80ies still actual now

30 years later: Two recent results

First measurement of reactor neutrino oscillations at JUNO arXiv:2511.14593 [hep-ex]

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087$$

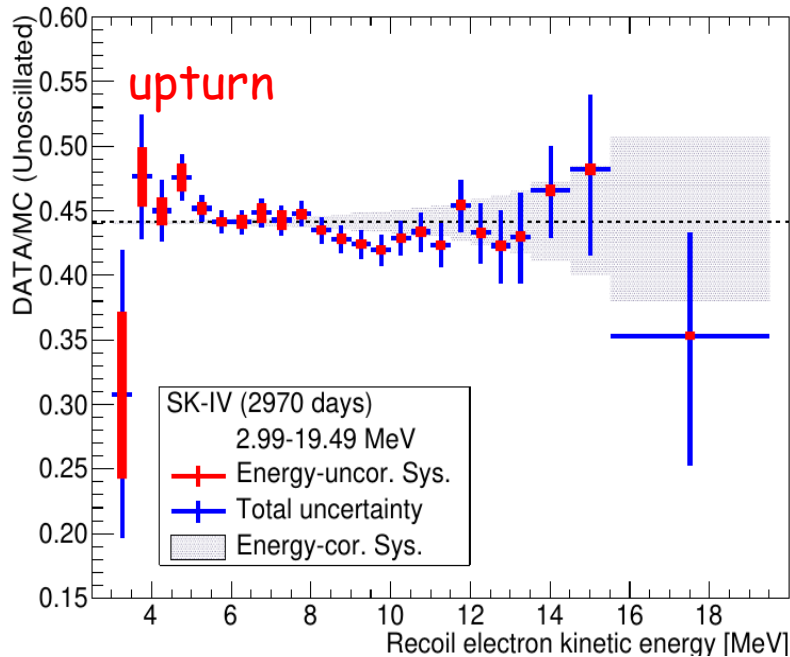
$$\Delta m^2 = (7.50 \pm 0.12) \times 10^{-5} \text{ eV}^2$$



and

Measurement of solar neutrino interaction rate below 3.49 MeV in **Super-Kamiokande-IV** arXiv:2512.19887 [hep-ex]

Solar neutrinos: signal dominated by the MSW effect



Energy spectrum of recoil electrons
versus unoscillated spectrum

Data to unoscillated MC ratio:

$$R = 0.307 +0.112/-0.111$$

According to the MSW

$$R = \sin^2\theta_{12}$$

JUNO: 0.3092 ± 0.0087

Day-Night asymmetry:

Observed at more than 3σ

In conclusions

Rencontres de Moriond played substantial role in developments of neutrino physics

... in particular, in establishing and promotion of the MSW effect and its applications

Many results were presented at Morionds for the first time

Morionds played special role in my personal carrier.

Great appreciation and gratitude for this to the founder Jean Tran Thanh Van and to his collaborators!

Congratulation with 60th anniversary!

Back-up

Before Moriond 86

After my short talk and N. Cabibbo summary at WIN-85 (Savonlinna) we continued to work on matter effects and by fall of 1985 complete understanding of conversion phenomenon was achieved.

The paper on the adiabatic solution and supernova neutrinos had been submitted in the fall of 1985 to ZhETP Letter. It was rejected (do not required of quick publication), resubmitted to ZHETP, published in 1986. **MORIOND 86 talk was based on this paper.**

In "Perestroyka" time the rule was introduced that a paper could be submitted to a foreign journal only after it was published in Soviet Journal. That would take 1 - 2 years

We decided to present our results at conferences (and then publish everything in a single review) and Moriond 86 in Tignes had given the first such a chance.

And Now

Solar neutrino problem solved

LMA MSW is identified as the solution

SN neutrino fluxes from Galactic collapses still approaching the Earth

KamLAND → JUNO

SNO → SNO+

SK → HK

ORCA

Resonance oscillations in the Earth
identification of neutrino mass ordering

MSW gained prominence in 80ies largely thanks to extensive discussions at Moriond

We put all the results later in review *Uspechi Fiz. Nauk* (1987) and in *Prog. in Nucl. and Part. Phys.* (1988)

Moscow - Moriond - Moscow fine but 2 days and nights in Paris are wonderful !

Other contributions

A.Yu.S. 1991 "Present status of the resonant flavor conversion"
S.T. Petcov, "Neutrino oscillations in vacuum and the solar neutrino problem" (1992)

S.T. Petcov, "Averaging the matter-enhanced oscillations of solar neutrinos" (1989)

John F. Wilkerson, SAGE Collaboration, "Measurement of solar proton proton fusion neutrinos with a Soviet-American Gallium Experiment at Baksan: A Status report" (1990).

R. Bernabei, **Gallex** Collaboration, "The Gallium solar neutrino experiment at Gran Sasso" (1990)

W.F. Davidson, **SNO** Collaboration, "The Sudbury Neutrino Observatory project". (1990)

D. Vignaud, "Some facts and some dreams about solar models and solar neutrinos" (1991)

R.E. Lanou, "Prospects for cryogenic detection of solar neutrinos" (1991)

E. K. Akhmedov, "Resonant spin flavor precession of neutrinos as a possible solution to the solar neutrino problem"(1992)

S. Toshev, "Analytical formulae for resonant neutrino spin rotation in twisting magnetic field" (1992)

Messiah: theory of the adiabatic conversion

Derived evolution equation for evolution matrix $U_H(x, x')$ (equivalent to the eigenstates in matter v_{im}) with separation of adiabatic and non-adiabatic parts:

$$i \frac{dU_H}{dx}(x, x') = \left[\underbrace{W(x)}_{\text{level spacing}} \underbrace{\sigma_w(x')}_{\sigma_3} + \frac{d\theta_m}{dx} \underbrace{\sigma_k}_{\sigma_2} \right] \underbrace{U_H(x, x')}_{v_m}$$

Adiabatic solution when second term can be neglected

Adiabatic condition $\omega = \frac{d\theta_m/dx}{2W} \ll 1$

Corrections to the adiabatic solution $\sim \omega^2$

Introduced amplitude of transition between eigenstates $\beta = A(v_{2m} \rightarrow v_1)$

$$P_{ee}(x) = \frac{1}{2} [1 + (1 - 2|\beta|^2) \cos 2\theta \cos 2\theta_m(x)]$$

$|\beta|^2 = P_c$ jump, flop probability

Known as Parke formula

Adiabatic solution: $\beta = 0$

Adiabaticity violation: Landau-Zenner

Fast density change, high energy. Based on the level crossing picture
Transitions between the levels are described by the Landau - Zenner probability valid for linear dependence of density on distance

$$P_c = |\beta|^2 = P_{LZ} = e^{-\pi\gamma/2}$$

γ is the adiabaticity parameter, $\gamma = \pi / \kappa_R$

Similar to level crossing problem in atomic physics.

W.C.Haxton Along diagonal line of the MSW triangle in the $\Delta m^2 - \sin^2 2\theta$ plane with $\theta_m \sim \pi/2$ for $\theta \sim 0$

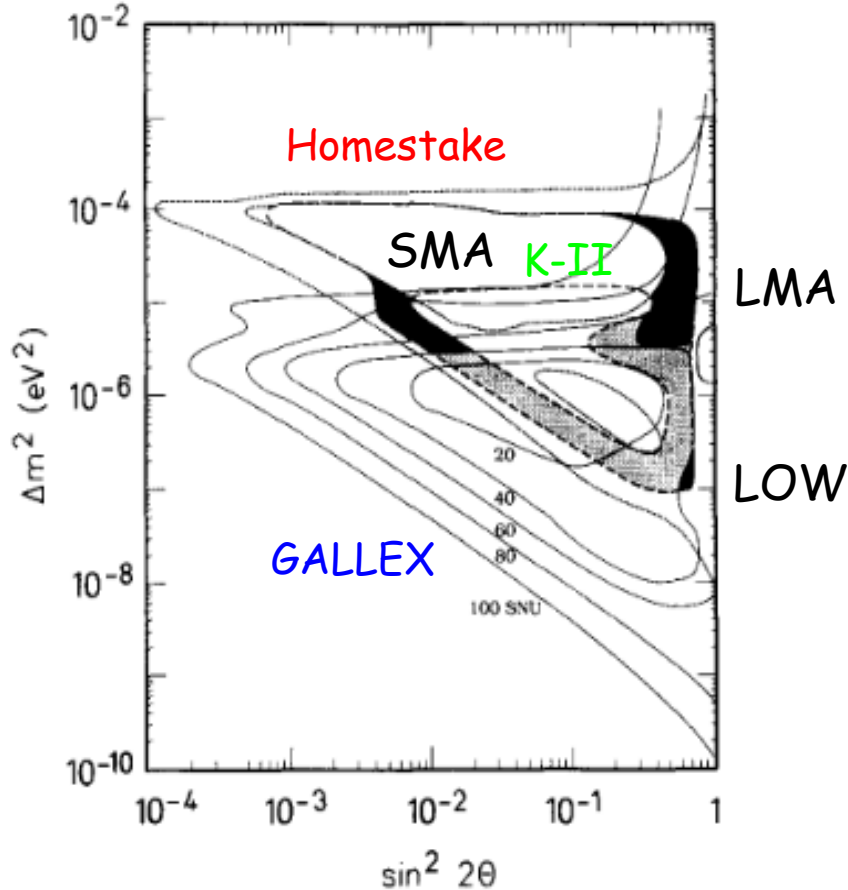
$$P_{ee} = 1 - P_c$$

S.J. Parke General expression for $\theta_m \neq \pi/2$ and non-zero θ
The same expression as in Messiah paper

E. W. Kolb, M. S. Turner T. P. Walker Another (non-adiabatic) solution
refined formulas also for large angle, for different density profiles, in particular, exponential. S. Petcov ...

The MSW triangle. SMA, LMA and LOW solutions

Ga + Homestake + Kamiokande



Three solutions in the corners of the triangle

Terminology introduced by J. Bahcall

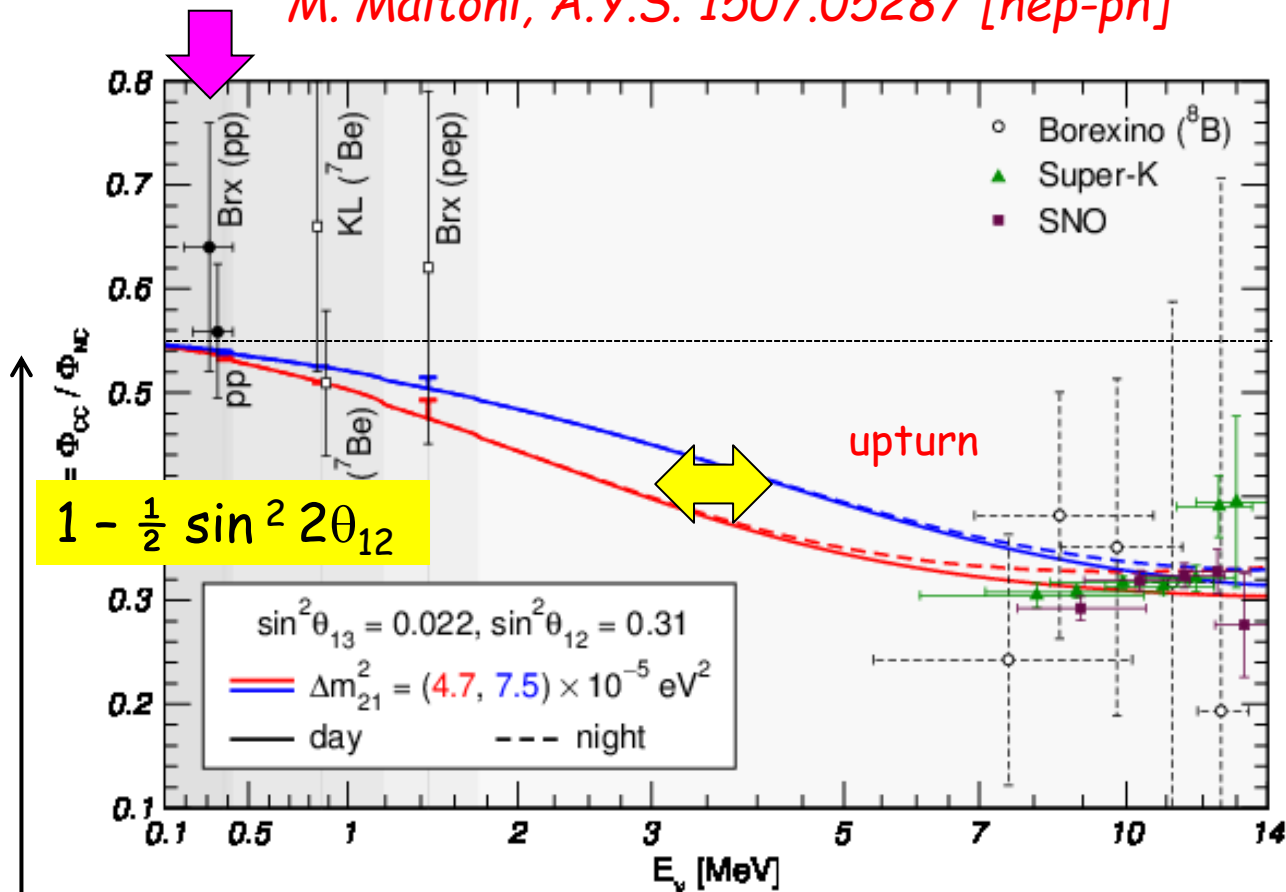
Signatures of the solutions: distortion of the energy spectrum, time variations, Earth matter effect, Day-Night asymmetry

Solid - GALLEX
Dotted - Homestake
Dashed - K-II

Possible intervals of neutrino masses and mixing fixed!

Energy profile of the LMA-MSW

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



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

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

Graphic representation

Graphical representation which uses analogy with electron spin precession in the magnetic field

*J. Bouchez M. Cribier, W Hampel,
J. Rich, M Spiro, D. Vignaud,
Z.Phys. C 32, (1986) 499*

In the space of components of neutrino polarization vector (P, R, I) - components of the density matrix

