

# Neutrinos, Messengers in the Universe: the Puzzle of Neutrino Masses and Neutrino Mixing

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## Basic Literature

1. S. M. Bilenky and S. T. Petcov,  
“Massive Neutrinos and Neutrino Oscillations,”  
Reviews of Modern Physics 59 (1987) 671,  
doi:10.1103/RevModPhys.59.671.
2. K. Nakamura and S.T. Petcov,  
“Neutrino Masses, Mixing and Oscillations” ,  
in M. Tanabashi *et al.* [Particle Data Group], “Review of Particle Physics,”  
Phys. Rev. D 98 (2018) 030001, pp. 251 - 286,  
doi:10.1103/PhysRevD.98.030001.
3. C. Giunti and C.W. Kim,  
“Fundamentals of Neutrino Physics and Astrophysics” ,  
Oxford University Press, 2007.

The present lecture will be about **NEUTRINOS** - the most amazing and interesting particles in the zoo of elementary particles. Neutrino physics - vast field of research with beautiful physics and many still unanswered fundamental questions.

We live in a sea of neutrinos.

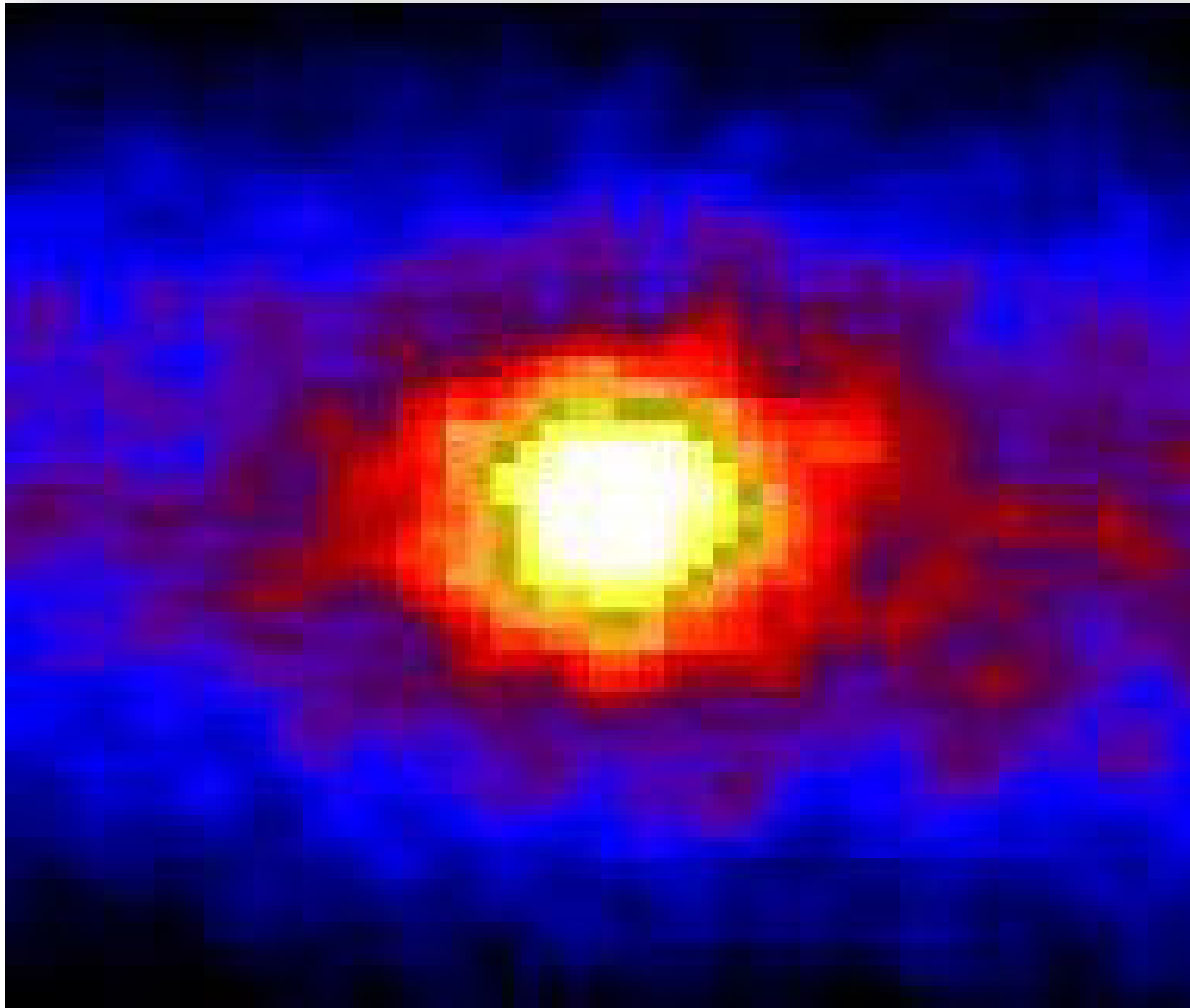
Through an area of our body of  $1 \text{ cm}^2$  orthogonal to the direction of the Sun, every second, during our life, day and night, there pass  $\sim 6.5 \times 10^{10}$  neutrinos emitted by the Sun (i.e., solar neutrinos).

These neutrinos are very “timid” - most have a relatively low energy  $E_\nu \lesssim 1 \text{ MeV}$  ( $\max(E_{\nu_\odot}) \sim 18 \text{ MeV}$ ), exceedingly small cross section (i.e., probability of interacting with neutrons and protons), and thus they do not “bother” us when they traverse our bodies. Actually, they do not “notice” us, and we do not notice them.

However, being produced in the central spherical region of the Sun having a radius of  $\sim 0.2 R_\odot$ ,  $R_\odot = 6.96 \times 10^5 \text{ km}$ , where also the energy in the form of photons (i.e., light) emitted by the Sun is being produced, they carry precious and unique information about the physical conditions in the central part of the Sun, which are so important for the existence of life on Earth.

It takes the  $\gamma$ s produced in the central part of the Sun between 40000 to 100000 y to reach the surface of the Sun and to be emitted.

It takes solar neutrinos, emitted in the same central part of the Sun, just about 8 minutes 22 seconds to reach the Earth.



The Sun seen at night with solar neutrinos by the Super-Kamiokande water Cerenkov neutrino detector in Japan. Super-Kamiokande: 50000 t ultra-pure water observed by 11000 PMS,  $\nu_{\odot} + e^{-} \rightarrow \nu_{\odot} + e^{-}$ .

# Neutrinos: “born” on December 4, 1930, W. Pauli

*Original - Photograph of Pauli 0393*  
Abschrift/15.12.56 PW

Offener Brief an die Gruppe der Radioaktiven bei der  
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut  
der Eidg. Technischen Hochschule  
Zürich

Zürich, 4. Dez. 1930  
Usterstrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich baldvollet  
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich  
angesichts der “falschen” Statistik der  $N$ - und  $Li-6$  Kerne, sowie  
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg  
verfallen: um den “Wechselstich” (1) der Statistik und den Energiesatz  
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale  
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,  
welche den Spin  $1/2$  haben und das Ausschliessungsprinzip befolgen und  
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie  
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen  
würde von derselben Grössenordnung wie die Elektronenmasse sein und  
jedenfalls nicht grösser als  $0,01$  Protonenmasse. Das kontinuierliche  
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim  
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert  
wird, derart, dass die Summe der Energien von Neutron und Elektron  
konstant ist.



Pauli:  $\nu$ s have spin  $1/2$ , neutral, very light, “sit” in  $(A, Z)$  ( ${}^6\text{Li}$  (spin 1)); called  $\nu$ s “neutrons”; “the idea of  $\nu$ s is probably wrong, but only those who wager can win.”

The neutron was discovered in 1932 by J. Chadwick.

Fermi, 1934, theory of  $\beta$ -decay,  $n \rightarrow p + e^- + \bar{\nu}_e$ :  
 $\bar{\nu}_e$  - created. On the suggestion of E. Amaldi called  $\nu$ s “neutrinos”.

$\nu$  - mass :  ${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$  (KATRIN experiment)

Bethe, Peierls, 1934:  $E \sim 1$  MeV,  $\nu$  - **impossible to detect** ( $\sigma(\nu_e + n \rightarrow p + e^-)$ )

$E \sim 1$  MeV,  $L_f \sim 5 \times 10^{11}$  km;  $R_E = 6371$  km

$E \sim 1$  GeV,  $L_f \sim 5 \times 10^5$  km

Pontecorvo 1946: nuclear reactors, Sun - copious sources of  $\nu$ 's,  $\nu$ 's can be detected using “sufficiently large” detectors. Proposed the  ${}^{37}\text{Cl} - {}^{37}\text{Ar}$  method of solar  $\nu_e$  detection (used by R. Davis et al.).

Reines, Cowan, 1956:  $\nu$ 's from reactor detected



(F. Reines, Nobel Prize for Physics in 1995)

Markov, Pontecorvo, Schwarz, 1959: fluxes of  $\nu$ 's at  $p$  accelerators can be used to study WI.

Pontecorvo (1959), Schwarz (1960):  $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ,  $\nu_e$  from  $\beta$ -decay:  $\nu_e \equiv \nu_\mu$ ? Proposed:  $\nu_\mu + n \rightarrow p + \mu^-$  or  $p + e^-$ ?

BNL, 1962:  $\nu_e \neq \nu_\mu$ ; J. Schwarz, L. Lederman, J. Steinberger - Nobel Prize for Physics in 1988.

The studies of the  $\nu$ -properties - important role is establishing the (Lorentz) structure of the WI.

Starting from the 1970'ies  $\nu$  beams used to study the (quark) structure of the  $p$  and  $n$ .

Experimental studies in 1970'ies and 1980'ies - the interaction of  $\nu$ 's with other particles well understood: described by the Standard Theory.

M. Pearl, 1975:  $\tau^\pm$  lepton discovered (Nobel Prize for Physics in 1995);  $\nu_\tau$  observed (much later).

# Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS

**matter constituents**  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	<1×10 <sup>-8</sup>	0	u up	0.003	2/3
e electron	0.000511	-1	d down	0.006	-1/3
$\nu_\mu$ muon neutrino	<0.0002	0	c charm	1.3	2/3
$\mu$ muon	0.106	-1	s strange	0.1	-1/3
$\nu_\tau$ tau neutrino	<0.02	0	t top	175	2/3
$\tau$ tau	1.7771	-1	b bottom	4.3	-1/3

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25} \text{ GeV s} = 1.05 \times 10^{-34} \text{ J s}$ .

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ), where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$ . The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

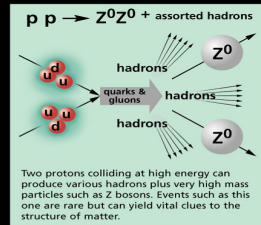
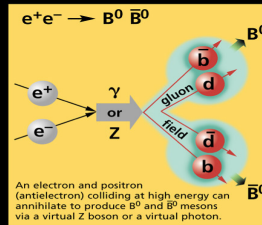
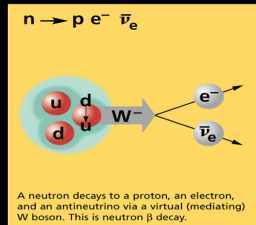
Baryons qq $\bar{q}$ and Antibaryons $\bar{q}q\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
$\Lambda$	lambda	uds	0	1.116	1/2
$\Omega^-$	omega	sss	-1	1.672	3/2

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ ), but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



### The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:

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## BOSONS

**force carriers**  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	g gluon	0	0
$W^-$	80.4	-1			
$W^+$	80.4	+1			
$Z^0$	91.187	0			

### Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and  $W$  and  $Z$  bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

### Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

## PROPERTIES OF THE INTERACTIONS

Property	Interaction	Gravitational	Weak	Electromagnetic	Strong	
		Mass - Energy	(Electroweak)		Fundamental	Residual
Acts on:		All	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	$W^+ W^- Z^0$	$\gamma$	Gluons	Mesons
Strength relative to electromag for two u quarks at:	$10^{-18} \text{ m}$ $3 \times 10^{-17} \text{ m}$ for two protons in nucleus	$10^{-41}$	0.8	1	25	Not applicable to quarks
		$10^{-41}$	$10^{-4}$	1	60	
		$10^{-36}$	$10^{-7}$	1	Not applicable to hadrons	20

Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$\pi^+$	pion	$u\bar{d}$	+1	0.140	0
$K^-$	kaon	$s\bar{u}$	-1	0.494	0
$\rho^+$	rho	$u\bar{d}$	+1	0.770	1
$B^0$	B-zero	$d\bar{b}$	0	5.279	0
$\eta_c$	eta-c	$c\bar{c}$	0	2.980	0

$$SM: SU(3)_c \times SU(2)_L \times U(1)_{Y_W}; \quad m_\nu = 0.$$

### 3 Families of Fundamental Particles - Quarks and Leptons

$$\begin{pmatrix} \nu_e & u \\ e & d \end{pmatrix} \quad \begin{pmatrix} \nu_\mu & c \\ \mu & s \end{pmatrix} \quad \begin{pmatrix} \nu_\tau & t \\ \tau & b \end{pmatrix} + \text{their antiparticles}$$

- $|p\rangle = |uud\rangle$ ,  $|n\rangle = |ddu\rangle$ ,  $|\pi^+\rangle = |u\bar{d}\rangle, \dots$
- **Electromagnetic interaction: the photon  $\gamma$  ( $q, l^\pm$ )**
- **Strong interaction: 8 Gluons  $G$  (quarks)**
- **Weak interaction:  $W^\pm, Z^0$  (all)**
- **Gravitational interaction: the graviton  $g$  (all)**

**Electromagnetic, Strong and Gravitational Interactions have a symmetry: *particle*  $\leftrightarrow$  *antiparticle*;**  
**not respected by Weak Interactions.**

**Universe: there are no antiparticles.**

### 3 Families of Fundamental Particles

$$\begin{pmatrix} \nu_e & u \\ e & d \end{pmatrix} \quad \begin{pmatrix} \nu_\mu & c \\ \mu & s \end{pmatrix} \quad \begin{pmatrix} \nu_\tau & t \\ \tau & b \end{pmatrix} \quad + \text{ their antiparticles}$$

- 3 types (flavours) of active  $\nu$ 's and  $\bar{\nu}$ 's
- The notion of “type” (“flavour”) - dynamical;

$$\nu_e: \nu_e + n \rightarrow e^- + p; \quad \nu_\mu: \pi^+ \rightarrow \mu^+ + \nu_\mu; \text{ etc.}$$

- The flavour of a given neutrino is Lorentz invariant.
- $\nu_l \neq \nu_{l'}, \tilde{\nu}_l \neq \tilde{\nu}_{l'}, l \neq l' = e, \mu, \tau; \nu_l \neq \tilde{\nu}_{l'}, l, l' = e, \mu, \tau.$

The states must be orthogonal (within the precision of the corresponding data):  $\langle \nu_{l'} | \nu_l \rangle = \delta_{l'l}, \langle \bar{\nu}_{l'} | \bar{\nu}_l \rangle = \delta_{l'l}, \langle \bar{\nu}_{l'} | \nu_l \rangle = 0.$

- Data (relativistic  $\nu$ 's):  $\nu_l$  ( $\bar{\nu}_l$ ) - predominantly LH (RH).  
Standard Theory:  $\nu_l, \bar{\nu}_l - \nu_{lL}(x)$ ;

$\nu_{lL}(x)$  form  $SU(2)_L$  doublets with  $l_L(x)$ ,  $l = e, \mu, \tau$ :

$$\begin{pmatrix} \nu_{lL}(x) \\ l_L(x) \end{pmatrix}, \quad l = e, \mu, \tau.$$

- No (compelling) evidence for existence of (relativistic)  $\nu$ 's ( $\bar{\nu}$ 's) which are predominantly RH (LH):  $\nu_R$  ( $\bar{\nu}_L$ .)

If  $\nu_R, \bar{\nu}_L$  exist, must have much weaker interaction than  $\nu_l, \bar{\nu}_l$ :  $\nu_R, \bar{\nu}_L$  - "sterile", "inert".

B. Pontecorvo, 1967

In the formalism of the ST,  $\nu_R$  and  $\bar{\nu}_L$  - RH  $\nu$  fields  $\nu_R(x)$ ; can be introduced in the ST as  $SU(2)_L$  singlets.

No experimental indications (no absolute proofs) exist at present that the SM should be minimally extended to include  $\nu_R(x)$ , and if it should, how many  $\nu_R(x)$  should be introduced.

$\nu_R(x)$  appear in many extensions of the ST, notably in  $SO(10)$  GUT's.

The RH  $\nu$ 's can play crucial role

- i) in the generation of  $m(\nu) \neq 0$ ,
- ii) in understanding why  $m(\nu) \ll m_l, m_q$ ,
- iii) in the generation of the observed matter-antimatter asymmetry of the Universe (via leptogenesis).

The simplest hypothesis is that to each  $\nu_{lL}(x)$  there corresponds a  $\nu_{lR}(x)$ ,  $l = e, \mu, \tau$ , although models with two or more than three  $\nu_{aR}(x)$  are also being considered.

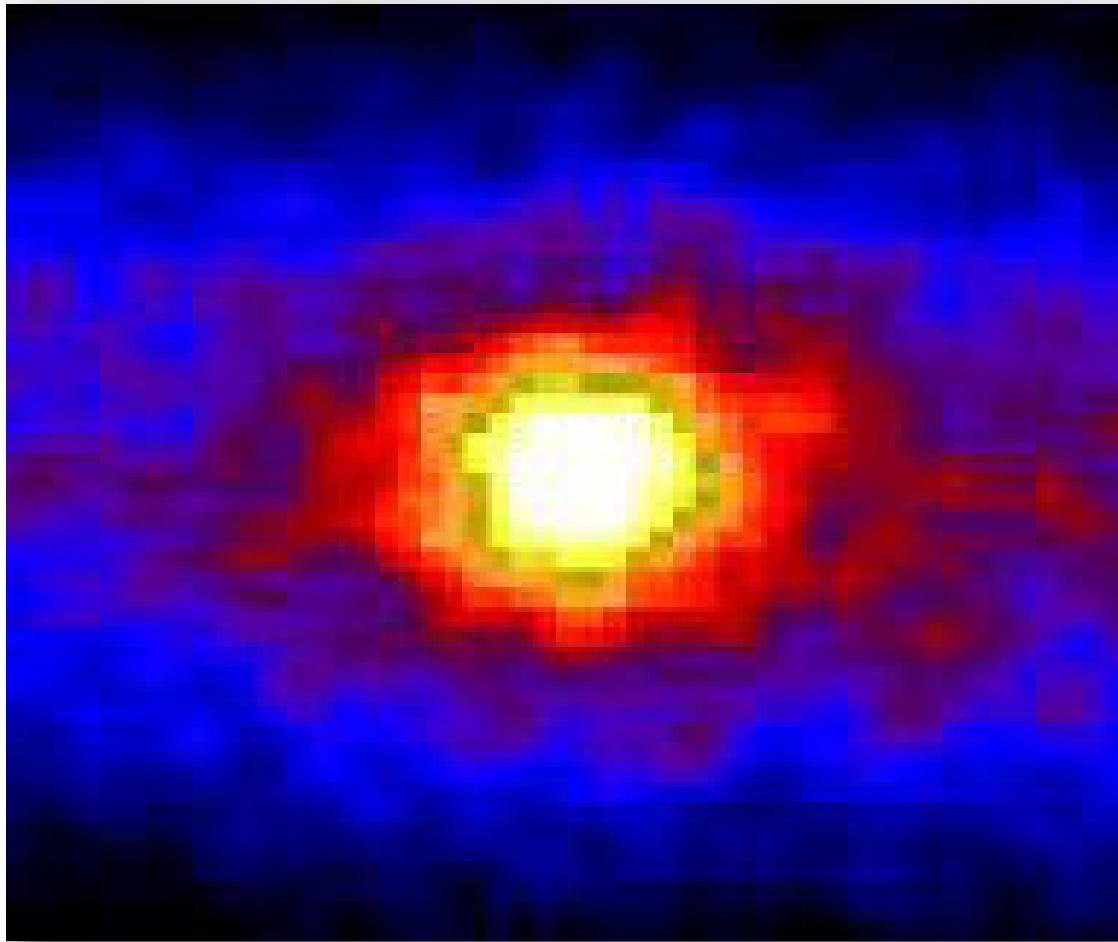
ST +  $m(\nu) = 0$ :  $L_l = \text{const.}$ ,  $l = e, \mu, \tau$ ;  
 $L \equiv L_e + L_\mu + L_\tau = \text{const.}$

## Natural Sources of Neutrinos

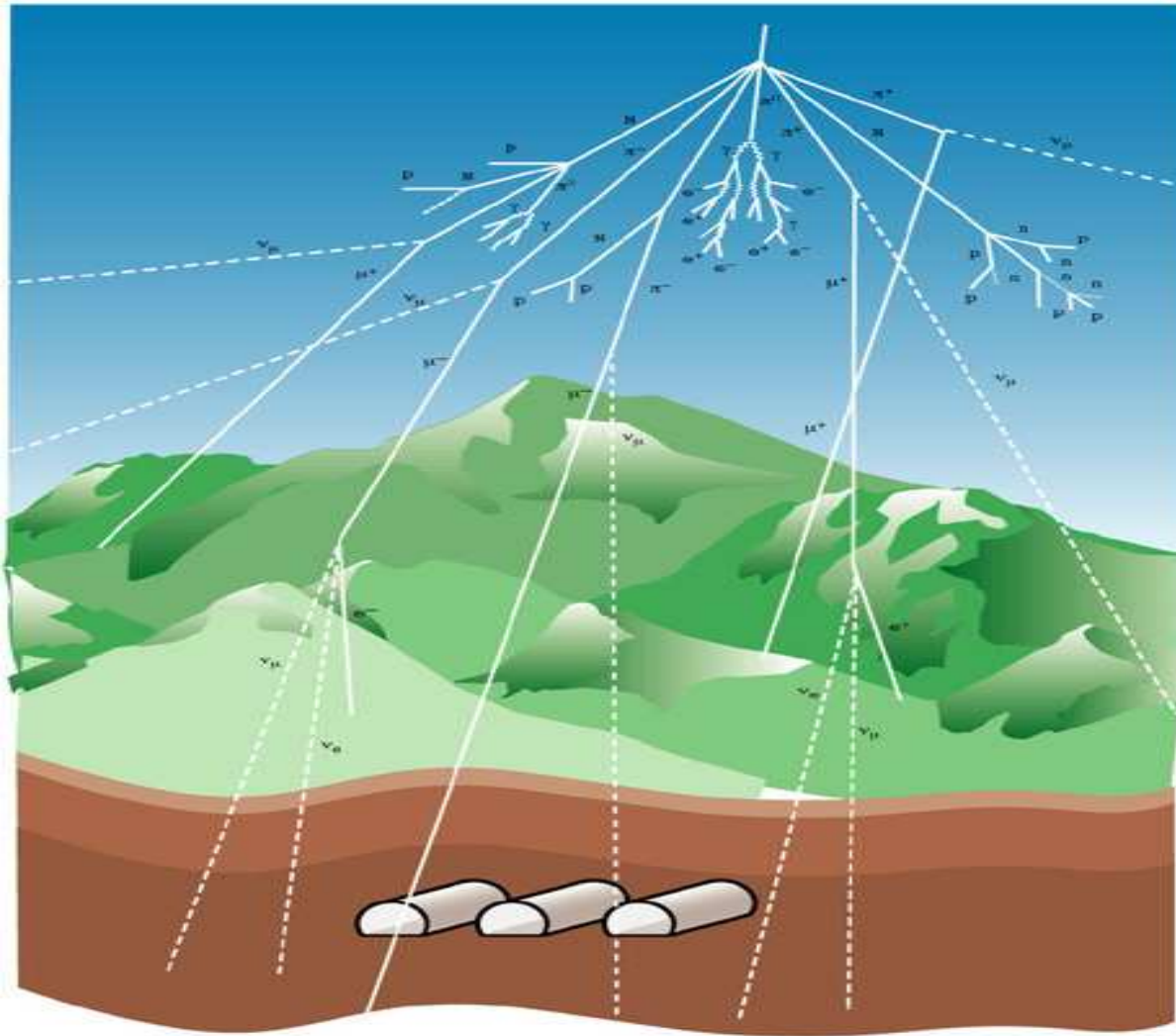
Neutrinos are produced in nuclear reactions of fusion,  $p + p \rightarrow D + e^+ + \nu_e$ ,  $\beta$ -decays of the neutron and many nuclei,  $n \rightarrow p + e^- + \bar{\nu}_e$ ,  $^{26}\text{Al} \rightarrow ^{26}\text{Mg} + e^+ + \nu_e$ ,  $^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + \bar{\nu}_e$ ,  $^{238}\text{U}$  chain of decays 6 of which are  $\beta$ -decays,  $^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e$ , decays of elementary particles,  $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ,  $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$ , etc. .

**Natural** sources of neutrinos are the Sun, the Earth atmosphere bombarded by cosmic rays, the Earth itself, the supernovae, the Early Universe, and some unidentified sources of extremely high energy neutrinos observed by the IceCube and KM3NET experiments.

**Artificial** sources of neutrinos are nuclear reactors (e.g., of nuclear power stations); meson ( $\pi^\pm$ ,  $K^\pm$ ) factories, particle accelerators, artificially produced unstable ( $\beta$ -decay) isotopes.

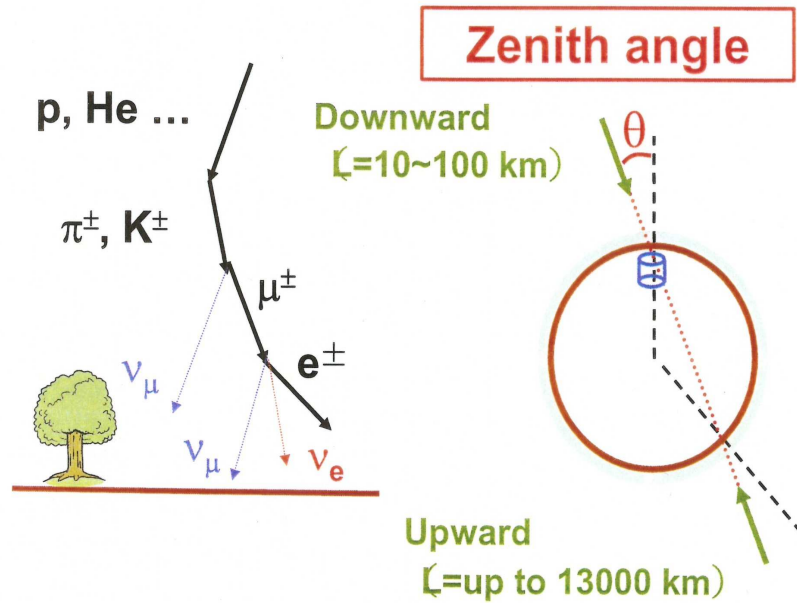


**The Sun (solar neutrinos):**  $\nu_{\odot} = \nu_e$ ;  $E_{\nu} \lesssim 18$  MeV. Detected first by R. Davis et al. using the Pontecorvo  $^{37}\text{Cl} - ^{37}\text{Ar}$  method (R. Davis: Nobel Prize for Physics in 2002). Energies of detected  $\nu_{\odot}$ :  $0.29 \leq E_{\nu} \leq 14.4$  MeV. In the Sun:  $4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e$ , pp-chain (principal source of  $E_{\odot}$  (95%) and  $\nu_e$ ).

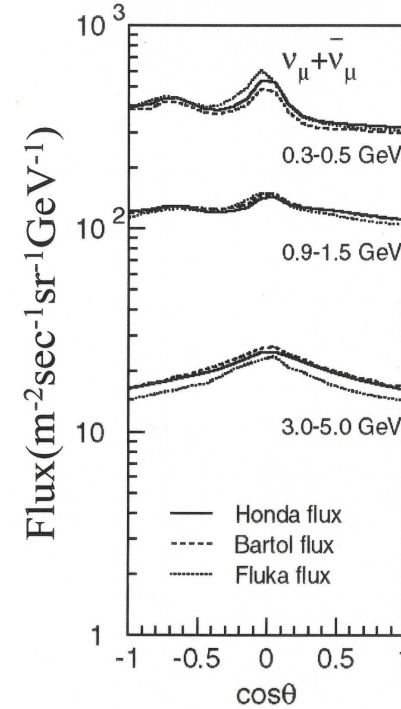


**Cosmic rays bombarding the Earth atmosphere produce atmospheric neutrinos:  $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ .**

# Atmospheric neutrinos



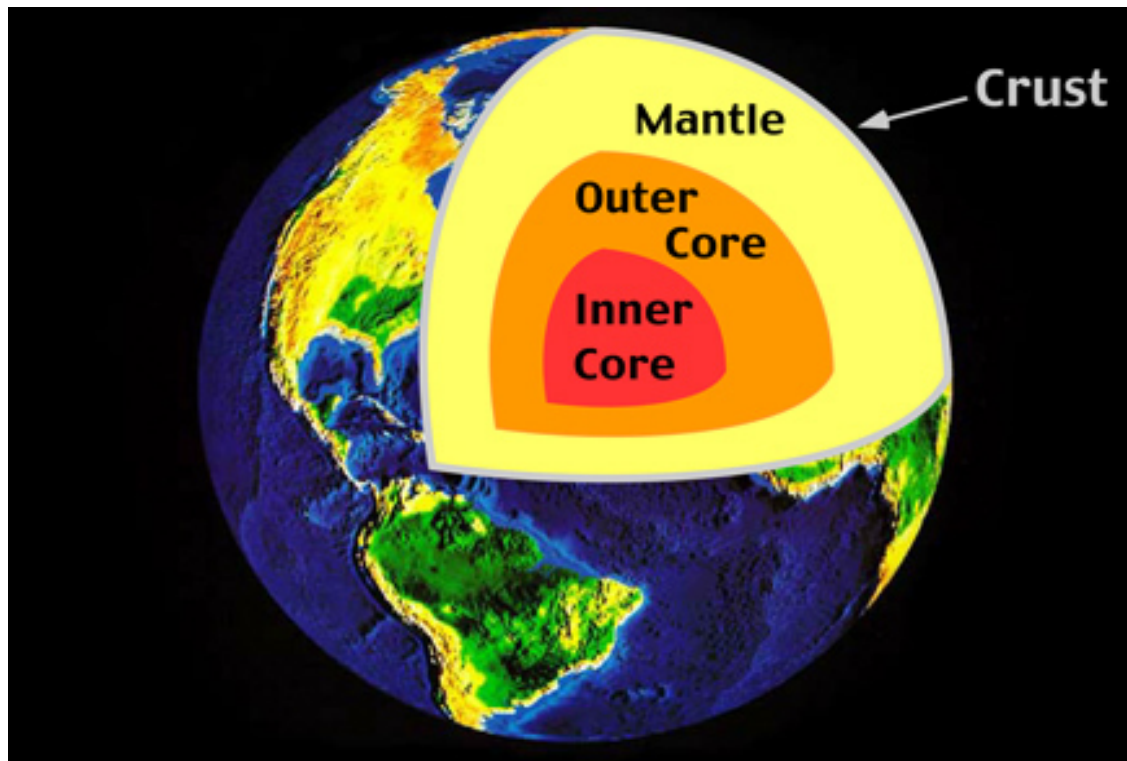
Zenith angle dist. of Atmospheric ν flux



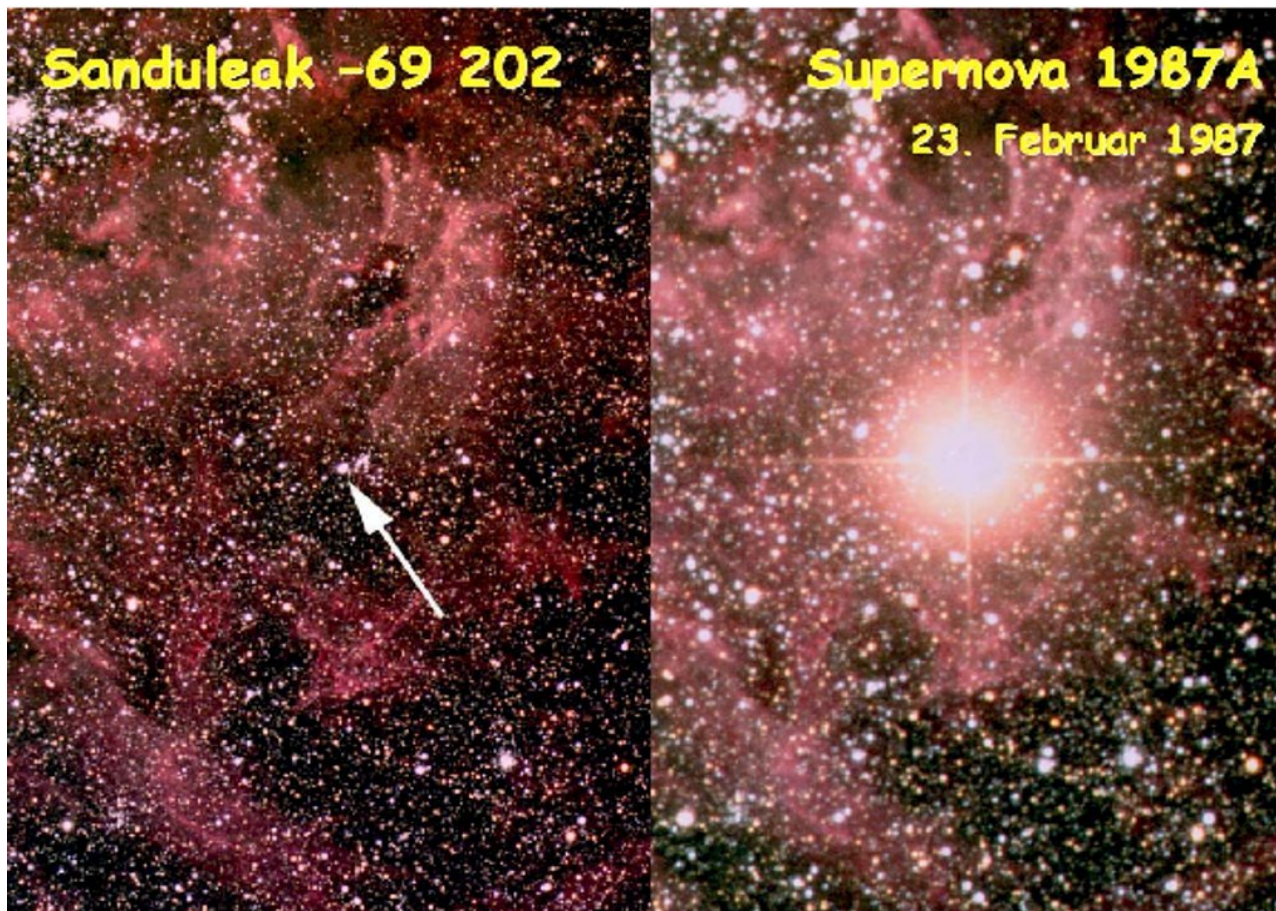
**E<sub>ν</sub> > a few GeV**  
**Up/Down Symmetry**

The atmospheric  $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$  have a wide range of energies spanning the interval from a few MeV to multi-GeV to multi-TeV.

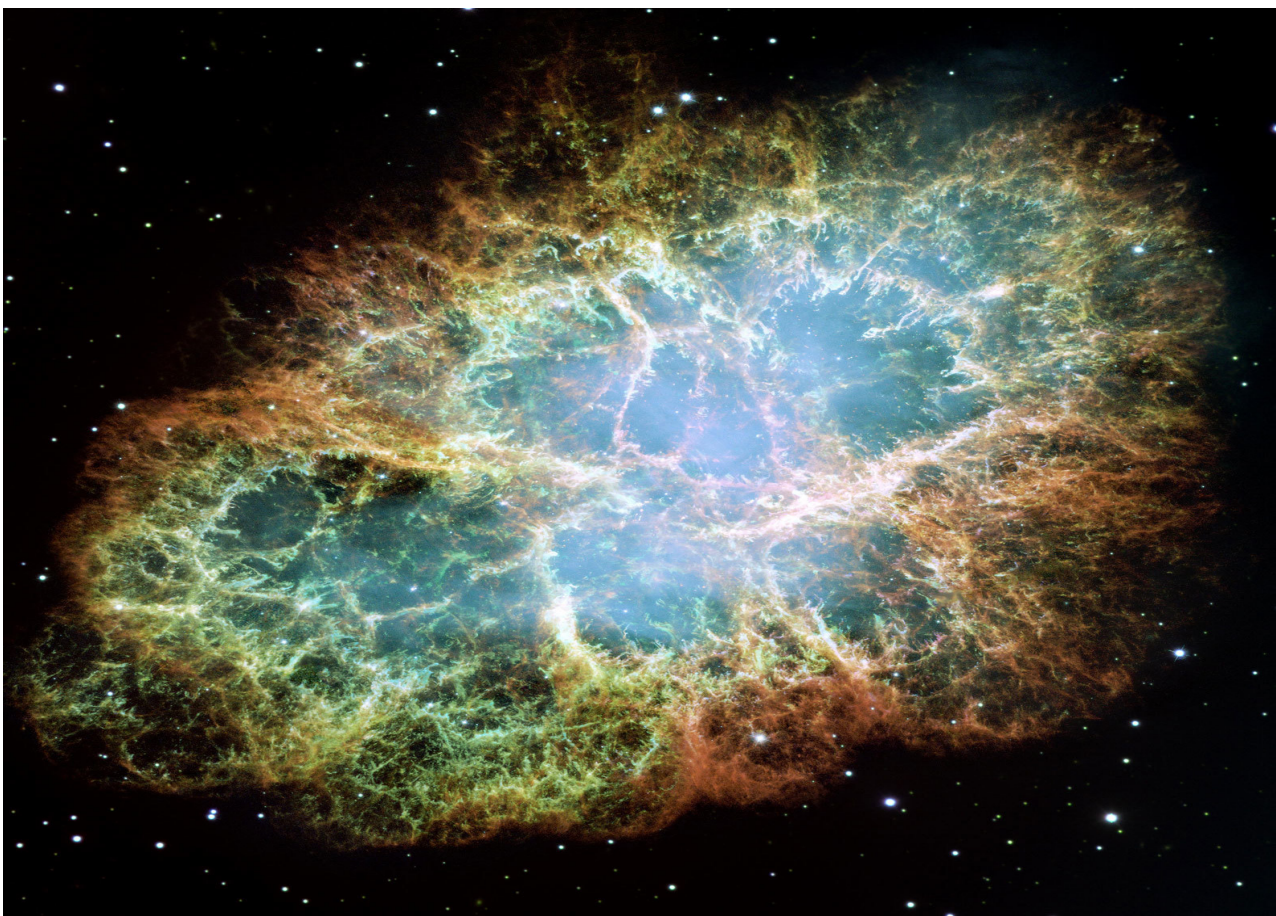
Detected:  $E_\nu \cong (0.1 - 2 \times 10^4)$  GeV. The fluxes are much smaller than the flux of solar neutrinos; fall-off as  $\sim E_\nu^{-2.7}$ .



**The Earth emits geo neutrinos:**  $\bar{\nu}_e$  with  $E_{\bar{\nu}_e} \lesssim 10$  MeV from the decays of naturally-occurring radioactive isotopes  $^{232}\text{Th}$  ( $T_{1/2} = 1.40 \times 10^{10}$  y),  $^{238}\text{U}$  ( $T_{1/2} = 4.468 \times 10^9$  y),  $^{235}\text{U}$  ( $T_{1/2} = 7.040 \times 10^8$  y),  $^{40}\text{K}$  ( $T_{1/2} = 1.248 \times 10^9$  y) in the Earth crust. The study of geo  $\nu$ s provides an independent method to get information about the matter composition of the Earth crust and to assess the Earth heat budget. Earth's age:  $4.453 \times 10^9$  y. The Earth is a planet shining essentially in a flux of  $\bar{\nu}_e$  with a luminosity  $L \sim 10^{25} \text{ s}^{-1}$ .



Supernovae (SN): 99% of the gravitational energy of  $10^{53}$  ergs released in the explosion of the dying star is in the form of a burst lasting tens of seconds of  $\sim 10^{57}$  neutrinos of all flavours,  $\nu_l, \bar{\nu}_l$ ,  $l = e, \mu, \tau$ , with  $E_\nu \sim (10 - 20)$  MeV. Neutrinos from SN1987A (Large Magellanic Cloud, 51 kpc away) were detected by the Kamiokande, IMB and Baksan Observatory experiments: of the total of  $10^{57}$  (!) neutrinos emitted, a total of 25 SN neutrino events in an interval of 13 sec were observed. For their detection the Kamiokande leader Prof. M. Koshiba received the Nobel Prize for Physics in 2002.

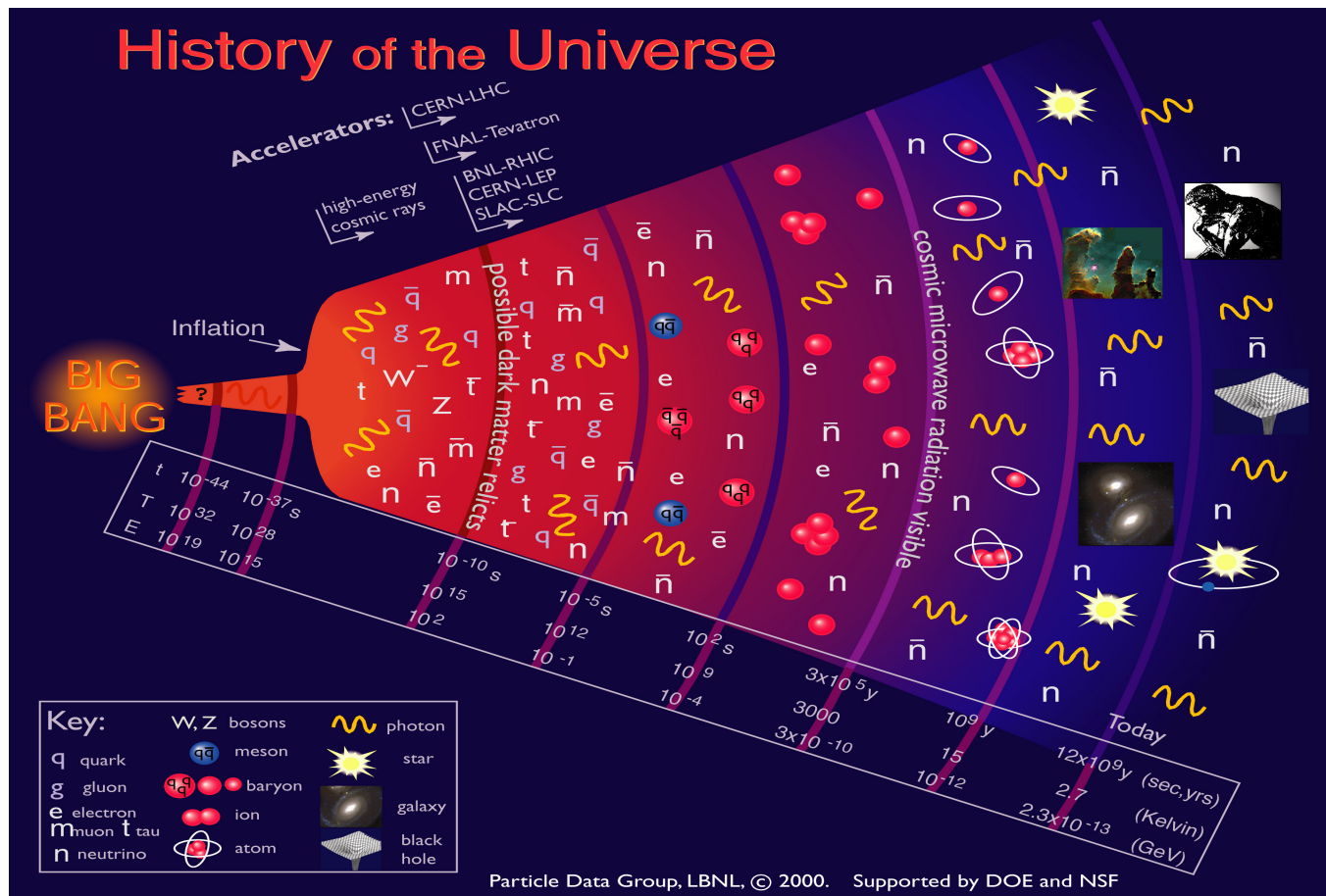


### **The Crab Nebula: remnant of a SN explosion in 1024.**

Since SN  $\nu$ s originate deep inside the stellar core, they are a relatively reliable messenger of the supernova explosion mechanism, which is still not fully understood. They can provide information about  $\nu$  properties as well.

A cosmic background of (anti)neutrinos formed by the accumulation of  $\nu$ s emitted from all past core-collapse supernovae - Diffuse Supernova Neutrino Background (DSNB) - should also exist. The Super-Kamiokande experiment is aiming to detect it.

# History of the Universe



**The Early Universe.** According to the Big Bang Theory, at  $t_U \sim 1$  sec, neutrinos in the plasma decoupled from the other particles (p, n,  $e^-$ ) forming the Cosmic (or Relic) Neutrino Background ( $C\nu B$ ).

Theoretical calculations: today, in every  $1 \text{ cm}^3$  volume of space there should be approximately 336  $\nu$ s (112 of each type). They have very low energy,  $E_\nu \sim 10^{-4}$  eV, temperature  $T \sim 1.95$  K, and so far no viable method of observing them has been found. If observed, could provide information about the state of the Universe when it was 1 second old.

**There have been remarkable discoveries in neutrino physics in the last  $\sim 28$  years.**

# Proofs for $\nu$ -Oscillations

–  $\nu_{\text{atm}}$ : **SK** UP-DOWN ASYMMETRY

$\theta_{23}$ -,  $L/E$ - dependences of  $\mu$ -like events ( $L \sim (15 - 12742)$  km)

Dominant  $\nu_{\mu} \rightarrow \nu_{\tau}$ ; **confirmed by:** K2K (L=250 km), MINOS (L=735 km), T2K (L=295 km); OPERA (CERN–LNGS, L=730 km)

–  $\nu_{\odot}$ : Homestake, Kamiokande, SAGE, GALLEX/GNO

Super-Kamiokande, SNO, BOREXINO; KamLAND

Dominant  $\nu_e \rightarrow \nu_{\mu, \tau}$ ;  $L \sim 1.5 \times 10^8$  km

–  $\bar{\nu}_e$  (from reactors): Daya Bay, RENO, Double Chooz (L $\sim$ (1 - 2) km)

Dominant  $\bar{\nu}_e \rightarrow \bar{\nu}_{\mu, \tau}$

T2K, MINOS, NO $\nu$ A ( $\nu_{\mu}$  from accelerators):  $\nu_{\mu} \rightarrow \nu_e$

T2K, NO $\nu$ A ( $\bar{\nu}_{\mu}$  from accelerators):  $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$

## The $\nu$ -Oscillation Data: $m_\nu \neq 0$ , $\nu$ mixing

$$|\nu_l\rangle = \sum_{j=1}^n U_{lj}^* |\nu_j\rangle, \quad \nu_j : m_j \neq 0; \quad l = e, \mu, \tau; \quad n \geq 3;$$

$$\nu_{lL}(x) = \sum_{j=1}^n U_{lj} \nu_{jL}(x), \quad \nu_{jL}(x) : m_j \neq 0; \quad l = e, \mu, \tau.$$

B. Pontecorvo, 1957; 1958; 1967;

Z. Maki, M. Nakagawa, S. Sakata, 1962;

$U$  is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix.

$\nu_j, m_j \neq 0$ : Dirac or Majorana particles.

Data: at least 3  $\nu$ s are light:  $\nu_{1,2,3}, m_{1,2,3} \lesssim 0.5$  eV.

## The Charged Current Weak Interaction Lagrangian:

$$\mathcal{L}^{CC}(x) = -\frac{g}{2\sqrt{2}} \sum_{l=e,\mu,\tau} \bar{l}(x) \gamma_\alpha (1 - \gamma_5) \nu_{lL}(x) W^\alpha(x) + \text{h.c.},$$

$$\nu_{lL}(x) = \sum_{j=1}^n U_{lj} \nu_{jL}(x), \quad \nu_{jL}(x) : m_j \neq 0; \quad l = e, \mu, \tau.$$



Dr. T. Kajita, Prof. A. McDonald, Nobel Prize for Physics winners, 2015



## LAUREATES

[Breakthrough Prize](#) [Special Breakthrough Prize](#) [New Horizons Prize](#) [Physics Frontiers Prize](#)

2016 [2015](#) [2014](#) [2013](#) [2012](#)



[Kam-Biu Luk and the  
Daya Bay Collaboration](#)



[Yifang Wang and the  
Daya Bay Collaboration](#)



[Koichiro Nishikawa and  
the K2K and T2K  
Collaboration](#)



[Atsuto Suzuki and the  
KamLAND Collaboration](#)



[Arthur B. McDonald and  
the SNO Collaboration](#)



[Takaaki Kajita and the  
Super K Collaboration](#)



[Yoichiro Suzuki and the  
Super K Collaboration](#)



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S.T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026

# Neutrino Oscillations (Quantum Mechanics in Action)

**Pontecorvo, 1957, 1958:**

$$\nu(x) = \frac{\chi_1 + \chi_2}{\sqrt{2}}, \quad \bar{\nu}(x) = \frac{\chi_1 - \chi_2}{\sqrt{2}}, \quad m_1 \neq m_2 > 0, \eta_{1CP} = -\eta_{2CP}$$

$\chi_{1,2}$  - Majorana, maximal mixing;  $\nu \leftrightarrow \bar{\nu}$  possible.

**Pioneering ideas: existence of fermion mixing in  $\mathcal{L}^{CC}(x)$ ,  $m_\nu \neq 0$ , and existence of neutrino oscillations.**

The idea of neutrino oscillations involving  $\nu_e$  and  $\nu_\mu$  - developed further in 1967, where Pontecorvo predicted that due to oscillations of the solar  $\nu_e$ , in R. Davis et al. experiment, which can detect only  $\nu_e$  and was under preparation, a deficit of solar  $\nu_e$  will be observed (which was confirmed).

**Maki, Nakagawa, Sakata, 1962 (specific model) with  $\nu_\mu \neq \nu_e$  (BNL):**

$$\nu_{eL}(x) = \Psi_{1L} \cos \theta_C + \Psi_{2L} \sin \theta_C,$$

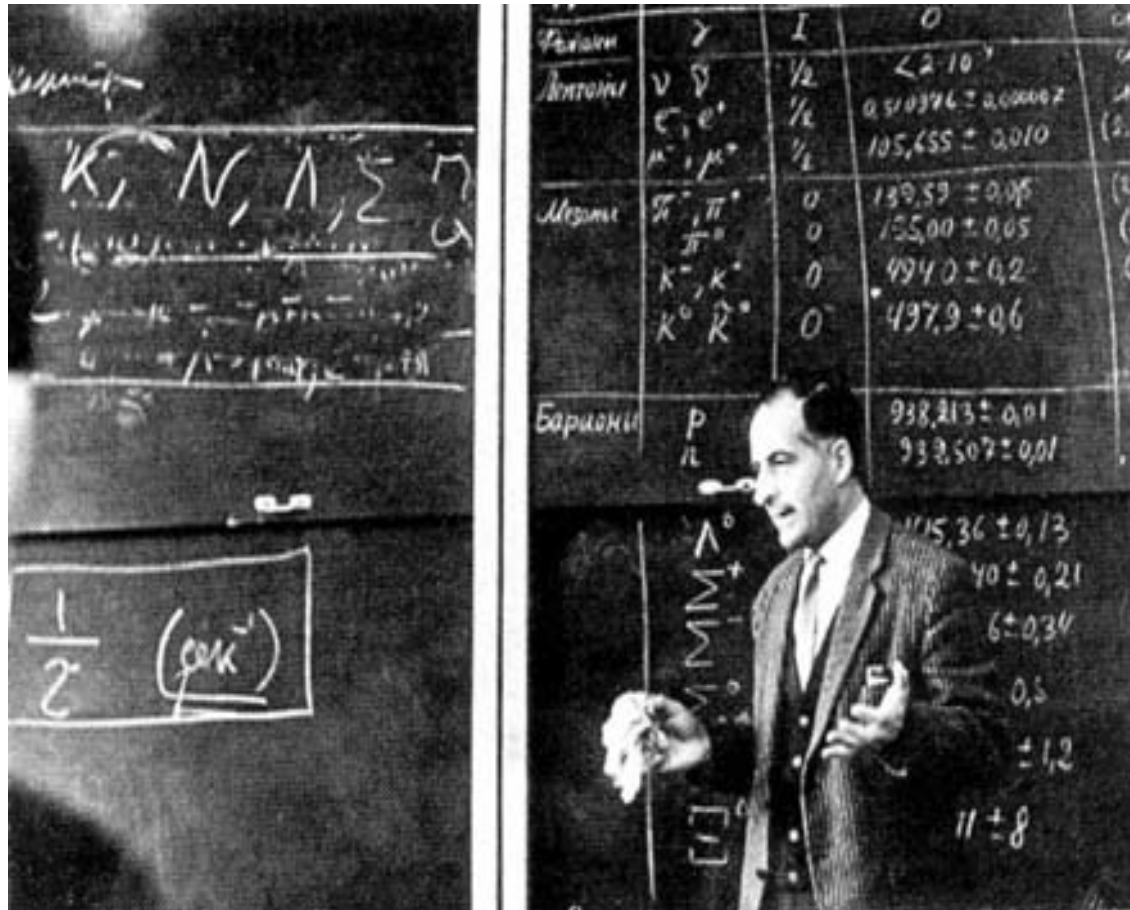
$$\nu_{\mu L}(x) = -\Psi_{1L} \sin \theta_C + \Psi_{2L} \cos \theta_C,$$

$\Psi_{1,2}$  - Dirac,  $\theta_C$ - the Cabbibo (Gell-Mann, Levy) angle.

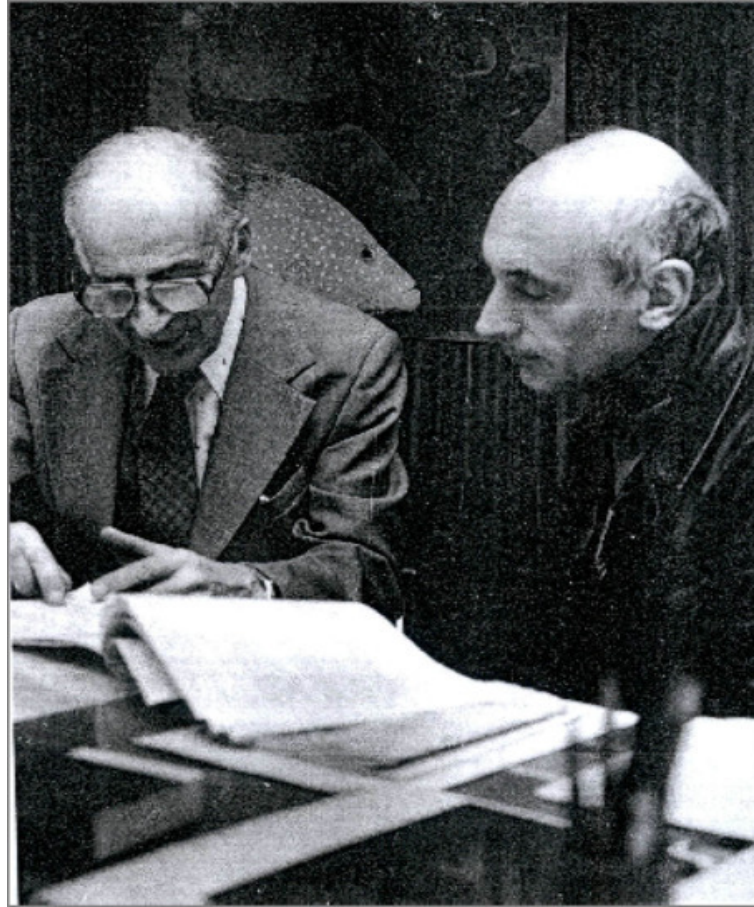
**Idea of "virtual transmutations" of neutrinos.**



**B. Pontecorvo (1913 - 1993) attending a seminar at JINR, Dubna, Russia.**



**B. Pontecorvo giving a talk at a seminar at JINR.**



**S.M. Bilenky and B. Pontecorvo (JINR, Dubna).**

# Solar Neutrinos $\nu_e$ , $E \sim 1$ MeV: B. Pontecorvo 1946



R. Davis et al., 1968 - 1996: 615 t  $\text{C}_2\text{Cl}_4$ ; 0.5 Ar atoms/day, exposure 60 days ( ${}^{37}\text{Ar}$ : K-capture,  $\tau \cong 35$  d).



Kamiokande (1986-1994), Super-Kamiokande (1996 -), SNO (2000 - 2006), BOREXINO (2007 - 2020);



Super-Kamiokande: 50000t ultra-pure water;

SNO: 1000t heavy water ( $D_2O$ )



SAGE (60t), 1990-; GALLEX/GNO (30t, LNGS), 1991-2003

Atmospheric Neutrinos  $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e, E \sim 1 \text{ GeV}$  (0.20 GeV - 20 TeV)

$$\nu_\mu + N \rightarrow \mu^- + X, \quad \bar{\nu}_\mu + N \rightarrow \mu^+ + X$$

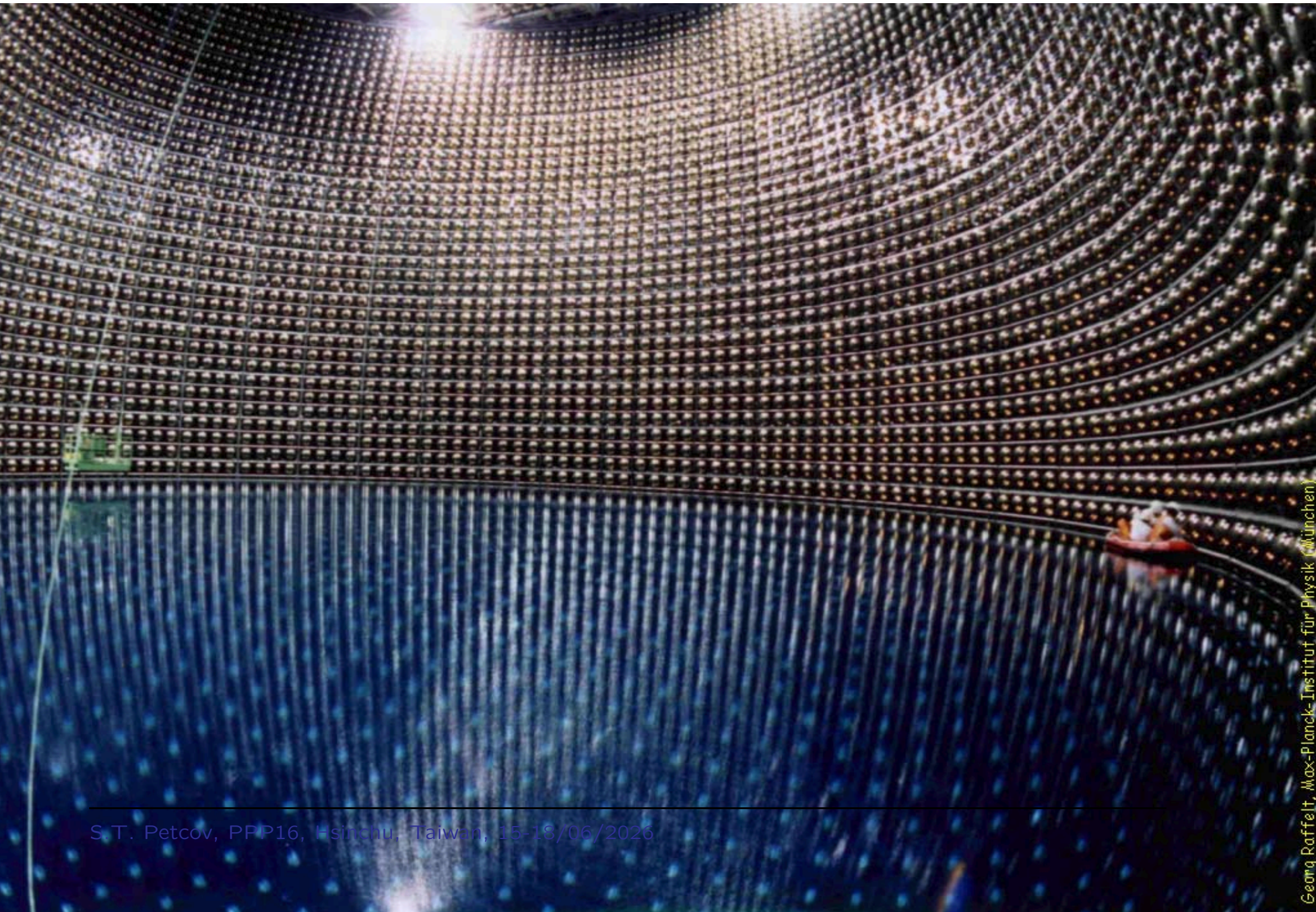
$$\nu_e + N \rightarrow e^- + X, \quad \bar{\nu}_e + N \rightarrow e^+ + X$$

K2K, MINOS, T2K, NO $\nu$ A,  $\nu_\mu$  ( $\bar{\nu}_\mu$ ),  $E \sim 1 \text{ GeV}$

$$\nu_\mu + N \rightarrow \mu^- + X \quad (\nu_e + N \rightarrow e^- + X)$$

Reactor  $\bar{\nu}_e$ : CHOOZ, KamLAND, Double Chooz, RENO, Daya Bay, JUNO (after 1990) ( $E \cong 2 - 10 \text{ MeV}$ )

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



S. T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026



T2K,  $L = 295$  km, active; detector: SK.



**NO $\nu$ A, active:** Fermilab - site in Minnesota, 810 km

**T2K**: Tokai - Super Kamiokande; off-axis  $\nu$  beam,  $E = 0.6 \text{ GeV}$ ,  $L \cong 295 \text{ km}$ , 50 kt water Cherenkov detector.

**NO $\nu$ A**: Fermilab - site in Minnesota; off-axis  $\nu$  beam,  $E = 2 \text{ GeV}$ ,  $L \cong 810 \text{ km}$ , 14 kt liquid scintillator detector.

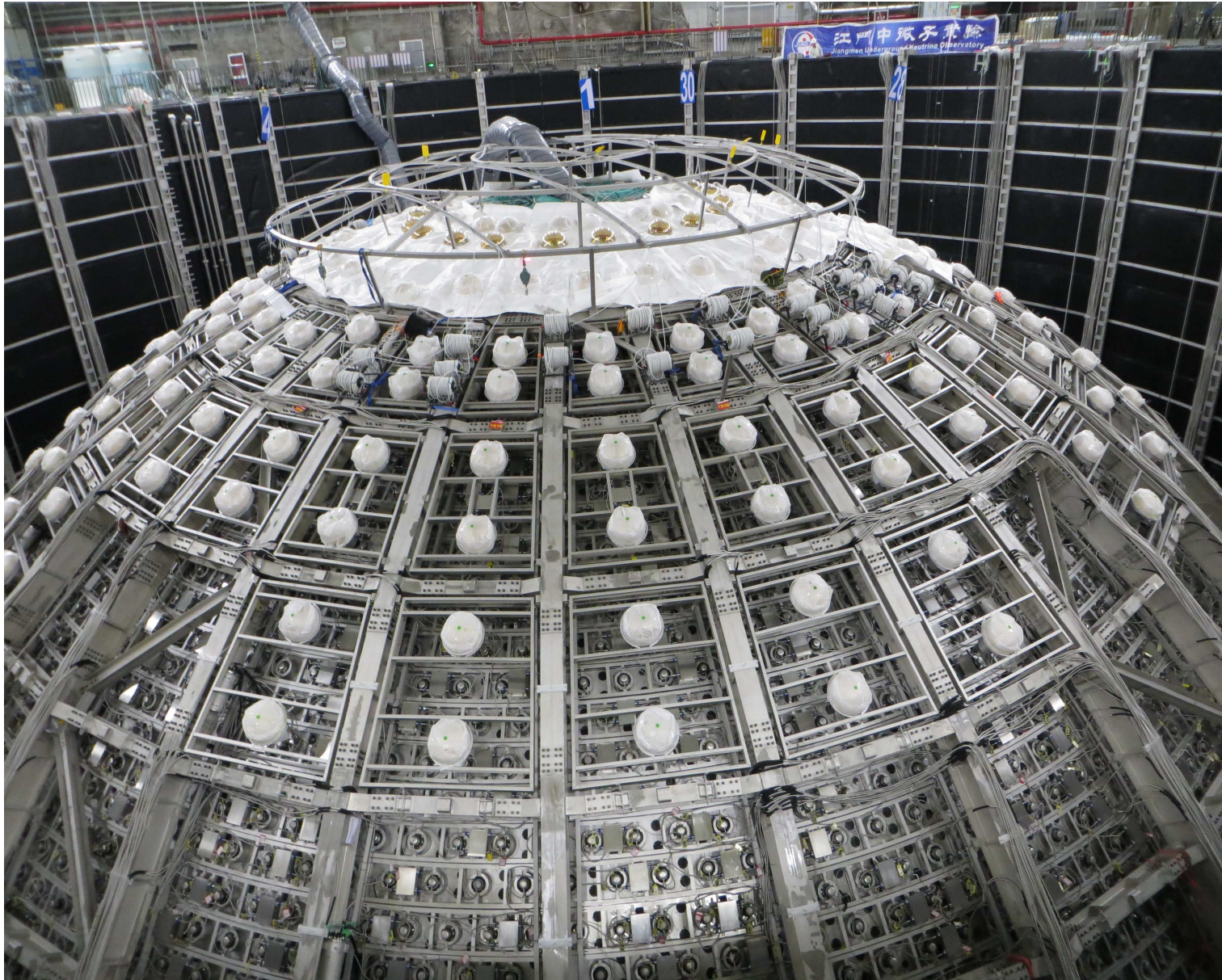
**SK** experiment studying atmospheric  $\nu_\mu$ ,  $\tilde{\nu}_\mu$ ,  $\nu_e$ ,  $\tilde{\nu}_e$  ( $E \cong 0.1 \div 100 \text{ GeV}$ ), and solar  $\nu_e$  ( $E \cong 5 \div 14 \text{ MeV}$ ) oscillations.

**IceCube** experiment at the South Pole, using cubic km of deep pristine Antarctic ice to study very high energy cosmic neutrinos and atmospheric  $\nu_\mu$ ,  $\tilde{\nu}_\mu$ ,  $\nu_e$ ,  $\tilde{\nu}_e$  ( $E_{\text{atm}} \cong 0.1 \div 20 \times 10^3 \text{ GeV}$ ).

**Day Bay:** NPP (six  $2.9 \text{ GW}_{th}$  reactors) near Shenzhen, China, reactor  $\bar{\nu}_e$ ;  $E = (2 - 10) \text{ MeV}$ , 3 near (two at 470 m and one at 576 m) + 2 far (1648 m) liquid scintillator detectors; measured and obtained high precision data on  $\sin^2 \theta_{13}$ .

**JUNO:**  $\bar{\nu}_e$  flux from two NPP ( $26.6 \text{ GW}_{th}$ );  $E = (2 - 10) \text{ MeV}$ ; sphere with diameter of 35 m containing 20 kt of liquid scintillator observed by about 46000 PM;  $L = 53 \text{ km}$ . Started taking data on August 26, 2025; first results published on November 19, 2025 (only 59.1 days of data had already strong impact).





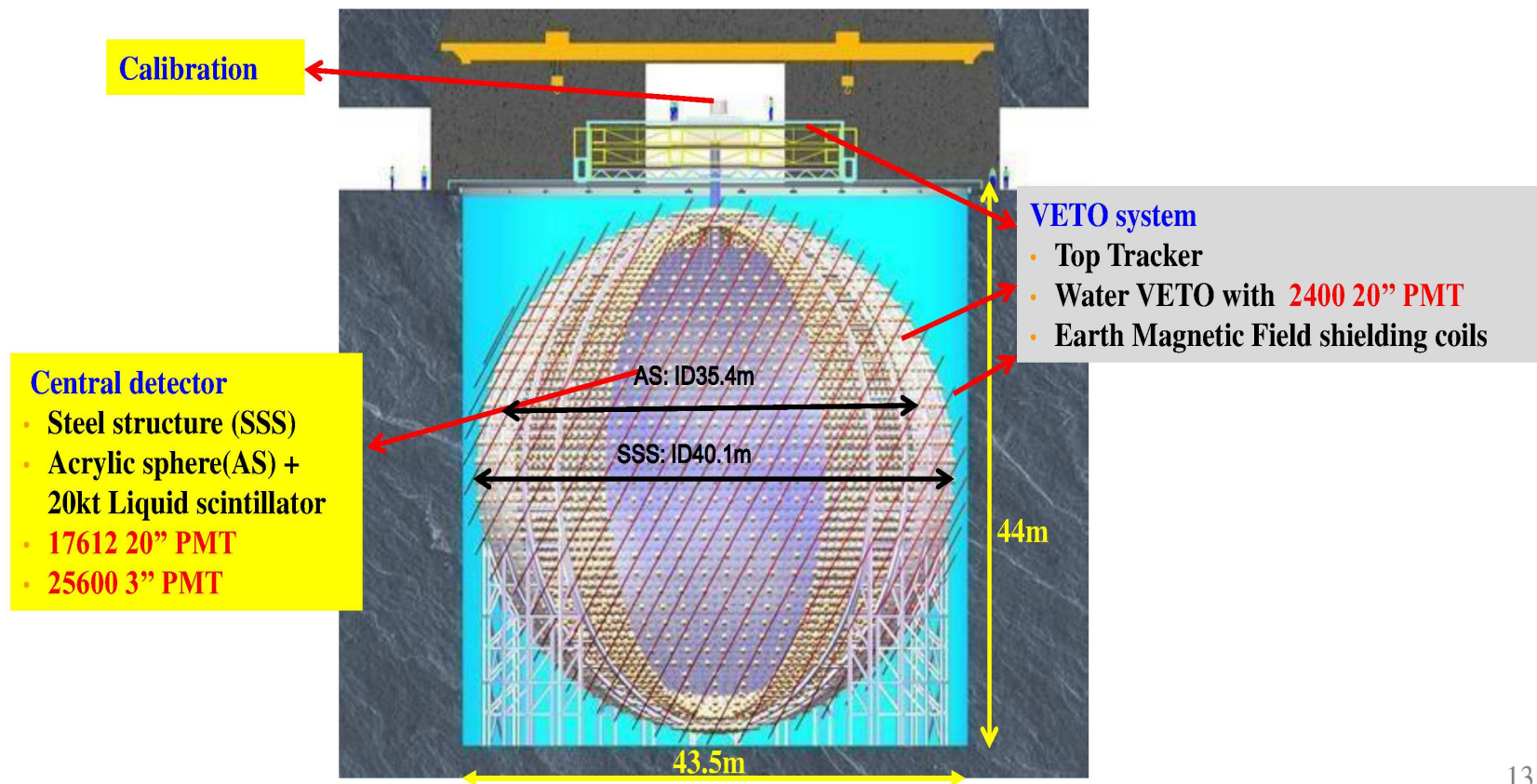
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S.T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026

# Concept of JUNO for Mass Ordering



- Two-layer structure for simplicity and cost: stainless steel frame + Acrylic tank
- Water as VETO and Buffer → radiopurity control of water



# Neutrino Oscillations in Vacuum

Suppose at  $t = 0$  in vacuum

$$|\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta,$$

$$|\nu_{\mu(\tau)}\rangle = -|\nu_1\rangle \sin\theta + |\nu_2\rangle \cos\theta; \quad \nu_{1,2}: m_{1,2} \neq 0$$

After time  $t$  in vacuum

$$|\nu_e\rangle_t = e^{-iE_1 t} |\nu_1\rangle \cos\theta + e^{-iE_2 t} |\nu_2\rangle \sin\theta, \quad E_{1,2} = \sqrt{p^2 + m_{1,2}^2}$$

$$A(\nu_e \rightarrow \nu_{\mu}; t) = \langle \nu_{\mu} | \nu_e \rangle_t = \frac{1}{2} \sin 2\theta (e^{-iE_2 t} - e^{-iE_1 t})$$

$$P(\nu_e \rightarrow \nu_{\mu}; t) = \frac{1}{2} \sin^2 2\theta (1 - \cos(E_2 - E_1)t)$$

$$P(\nu_e \rightarrow \nu_e; t) \equiv P_{ee} = 1 - P(\nu_e \rightarrow \nu_{\mu}; t)$$

V. Gribov, B. Pontecorvo, 1969

Neutrinos are relativistic:  $t \cong L$ ,  $E_2 - E_1 \cong (m_2^2 - m_1^2)/(2p)$   
 $(E_2 - E_1)t \cong (m_2^2 - m_1^2)L/(2p) = 2\pi \frac{L}{L_{osc}^{vac}}$ ,  $L_{osc}^{vac} \equiv \frac{4\pi E}{\Delta m^2}$

$$P(\nu_e \rightarrow \nu_\mu; t) = \frac{1}{2} \sin^2 2\theta \left(1 - \cos 2\pi \frac{L}{L_{osc}^{vac}}\right), \quad L_{osc}^{vac} \equiv \frac{4\pi E}{\Delta m^2}$$

$$L_{osc}^{vac} \cong 2.5 \text{ m} \frac{E[\text{MeV}]}{\Delta m^2[\text{eV}^2]}$$

$$E \cong 3 \text{ MeV}, \quad \Delta m^2[\text{eV}^2] \cong 8 \times 10^{-5} : \quad L_{osc}^{vac} \cong 100 \text{ km}$$

$$E \cong 1 \text{ GeV}, \quad \Delta m^2[\text{eV}^2] \cong 2.5 \times 10^{-3} : \quad L_{osc}^{vac} \cong 1000 \text{ km}$$

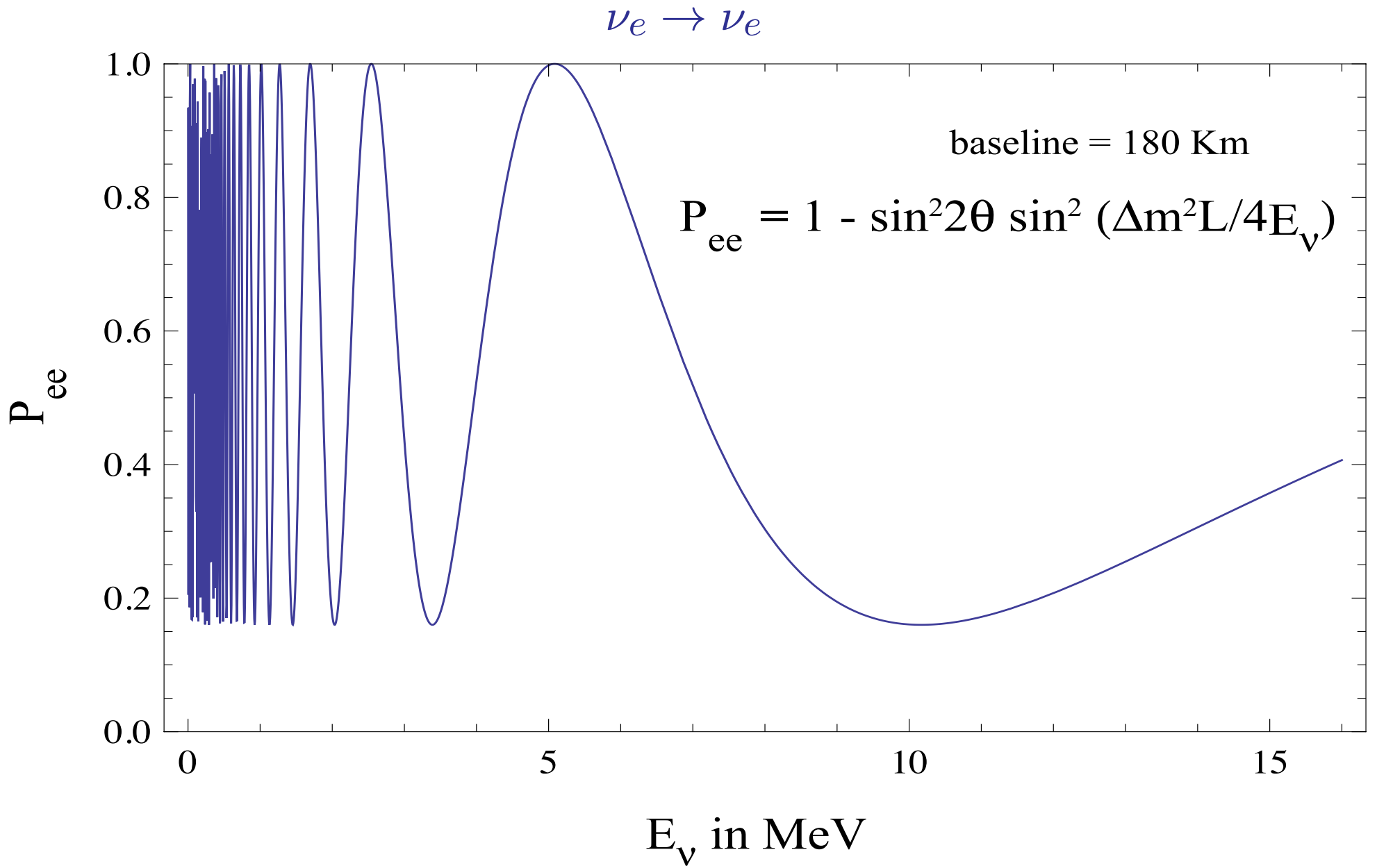
Effects of oscillations observable if

$$\sin^2 2\theta - \text{sufficiently large}, \quad 2\pi L \gtrsim L_{osc}^{vac}$$

Two basic parameters:  $\sin^2 2\theta$ ,  $\Delta m^2$

SK, K2K, MINOS; CNGS (OPERA): dominant  $\nu_\mu \rightarrow \nu_\tau$

KamLAND:  $\bar{\nu}_e \rightarrow \bar{\nu}_e$ ;  $\bar{\nu}_e \rightarrow (\bar{\nu}_\mu + \bar{\nu}_\tau)/\sqrt{2}$



Source	Type of $\nu$	$\bar{E}$ [MeV]	$L$ [km]	$\min(\Delta m^2)$ [eV <sup>2</sup> ]
Reactor	$\tilde{\nu}_e$	$\sim 1$	<b>1</b>	$\sim 10^{-3}$
Reactor	$\tilde{\nu}_e$	$\sim 1$	<b>100</b>	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \tilde{\nu}_\mu$	$\sim 10^3$	<b>1</b>	$\sim 1$
Accelerator	$\nu_\mu, \tilde{\nu}_\mu$	$\sim 10^3$	<b>1000</b>	$\sim 10^{-3}$
Atmospheric $\nu$ 's	$\nu_{\mu,e}, \tilde{\nu}_{\mu,e}$	$\sim 10^3$	$10^4$	$\sim 10^{-4}$
Sun	$\nu_e$	$\sim 1$	$1.5 \times 10^8$	$\sim 10^{-11}$

Correspond to: CHOOZ, Double Chooz, RENO, Daya Bay ( $L \sim 1$  km), KamLAND ( $L \sim 100$  km);  $\tilde{\nu}_e$  disappearance;  $E = (1.8 \div 8.0)$  MeV;

to accelerator experiments - past ( $L \sim 1$  km);

**past, current:** K2K ( $L \sim 250$  km), MINOS ( $L \sim 730$  km),  $\nu_\mu$  disappearance; OPERA ( $L \sim 730$  km),  $\nu_\mu \rightarrow \nu_\tau$ ; T2K ( $L \sim 295$  km), NO $\nu$ A ( $L \sim 800$  km),  $\nu_\mu$  disappearance,  $\nu_\mu \rightarrow \nu_e$ ;  $E \sim 1$  GeV;

SK experiment studying atmospheric  $\nu_\mu, \tilde{\nu}_\mu, \nu_e, \tilde{\nu}_e$  ( $E \cong 0.1 \div 100$  GeV), and solar  $\nu_e$  ( $E \cong 5 \div 14$  MeV) oscillations, and to the solar  $\nu$  experiments ( $E \cong 0.29 \div 14$  MeV).

It is possible to show that, in general,

$$A(\nu_l \rightarrow \nu_{l'}) = \sum_j U_{l'j} \exp\left(-i \frac{m_j^2}{2p} L\right) U_{jl}^\dagger, \quad l, l' = e, \mu, \tau,$$

**Three neutrino mixing:**

$$P(\nu_l \rightarrow \nu_{l'}) = \left| e^{-i m_1^2 L / (2p)} \left( U_{l'1} U_{1l}^\dagger + U_{l'2} e^{-i \Delta m_{21}^2 L / (2p)} U_{2l}^\dagger + U_{l'3} e^{-i \Delta m_{31}^2 L / (2p)} U_{3l}^\dagger \right) \right|^2, \quad l, l' = e, \mu, \tau$$

$$P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}): U_{l'j}, U_{lj}^* \rightarrow U_{l'j}^*, U_{lj}$$

The phase  $\Delta m_{jk}^2 L / (2p)$  is Lorentz invariant.

$$m^2 = E^2 - p^2: \quad \sigma_{m^2} = \sqrt{(2E\sigma_E)^2 + (2p\sigma_p)^2}$$

The condition for producing coherently  $\nu_1, \nu_2, \dots$ :

$$\sigma_{m^2} > |\Delta m_{jk}^2|$$

The equation used above corresponds to a plane wave description of the propagation of neutrinos  $\nu_j$ . It accounts only for the movement of the center of the wave packet describing  $\nu_j$ . In the wave packet treatment of the problem, the interference between the states of  $\nu_j$  and  $\nu_k$  is subject to a number of conditions, the localisation condition (in space and time) and the condition of overlapping of the wave packets of  $\nu_j$  and  $\nu_k$  at the detection point being the most important. For relativistic neutrinos, the localisation condition in space reads:  $\sigma_{xP}, \sigma_{xD} < L_{jk}^v / (2\pi)$ ,  $\sigma_{xP(D)}$  being the spatial width of the production (detection) wave packet. Thus, the interference will not be suppressed if the spatial width of the neutrino wave packets determined by the neutrino production and detection processes is smaller than the corresponding oscillation length in vacuum. In order for the interference to be nonzero, the wave packets describing  $\nu_j$  and  $\nu_k$  should also overlap in the point of neutrino detection. This requires that the spatial separation between the two wave packets at the point of neutrinos detection, caused by the two wave packets having different group velocities  $v_j \neq v_k$ , satisfies  $|(v_j - v_k)T| \ll \max(\sigma_{xP}, \sigma_{xD})$ . If the interval of time  $T$  is not measured,  $T$  in the preceding condition must be replaced by the distance  $L$  between the neutrino source and the detector.

## Examples

- Spatial localisation condition

$\Delta L$  - dimensions of the  $\nu$ - source (and/or detector):

$$2\pi\Delta L/L_{jk}^{\nu} \lesssim 1.$$

- Time localisation condition

$\Delta E$  - detector's energy resolution:

$$2\pi(L/L_{jk}^{\nu})(\Delta E/E) \lesssim 1.$$

If  $2\pi\Delta L/L_{jk}^{\nu} \gg 1$ , and/or  $2\pi(L/L_{jk}^{\nu})(\Delta E/E) \gg 1$ ,

$$\bar{P}(\nu_l \rightarrow \nu_{l'}) = \bar{P}(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) \cong \sum_j |U_{l'j}|^2 |U_{lj}|^2$$

## 3- $\nu$ Oscillations Probabilities in Terms of 2- $\nu$ Oscillation Probabilities

**Suppose:**  $\Delta m_{21}^2 L / (2p) \ll 1$

$$e^{-i \Delta m_{21}^2 L / (2p)} = \cos\left(\frac{\Delta m_{21}^2 L}{2p}\right) - i \sin\left(\frac{\Delta m_{21}^2 L}{2p}\right) \simeq 1.$$

$$P(\nu_l \rightarrow \nu_{l'}) =$$

$$\begin{aligned} & \left| \left( U_{l'1} U_{1l}^\dagger + U_{l'2} U_{2l}^\dagger + U_{l'3} e^{-i \Delta m_{31}^2 L / (2p)} U_{3l}^\dagger \right) \right|^2 \\ & = \left| \delta_{l'l} - U_{l'3} U_{3l}^\dagger \left( 1 - e^{-i \Delta m_{31}^2 L / (2p)} \right) \right|^2, \quad l, l' = e, \mu, \tau \end{aligned}$$

$l = \mu, l' = \tau$ :  $U_{\tau 3} U_{3\mu}^\dagger = \frac{1}{2} \cos^2 \theta_{13} \sin 2\theta_{23}$ ; accel. exp., SK atm. nus.

$l = e, l' = e$ :  $U_{e3} U_{3e}^\dagger = \sin^2 \theta_{13}$ ; CHOOZ, Double Chooz, Daya Bay, RENO:  $L \sim 1$  km.

Suppose:  $\Delta m_{31}^2 L/(2p) \gg 1$

Localisation condition in space and/or time not fulfilled for the oscillations due to  $\Delta m_{31}^2$ , these oscillations are "averaged out", i.e., strongly suppressed.

Terms involving  $e^{-i \Delta m_{31}^2 L/(2p)}$  in  $P(\nu_l \rightarrow \nu_{l'})$  are  $\sim 0$ .

$$P(\nu_l \rightarrow \nu_{l'}) \cong |U_{l'3} U_{3l}^\dagger|^2 + \left| U_{l'1} U_{1l}^\dagger + U_{l'2} e^{-i \Delta m_{21}^2 L/(2p)} U_{2l}^\dagger \right|^2.$$

$l = e, l' = e$ :

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong |U_{e3}|^4 + (1 - |U_{e3}|^2)^2 P^{2\nu}(\bar{\nu}_e \rightarrow \bar{\nu}_e) \\ = \sin^4 \theta_{13} + \cos^4 \theta_{13} P^{2\nu}(\theta_{12}, \Delta m_{21}^2), \quad \sin^2 \theta_{13} = \mathbf{0.022};$$

$$P_{\text{KL}}^{2\nu} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}, \quad \mathbf{KamLAND, L \sim 180 \text{ km.}}$$

$$P_{\odot}(\nu_e \rightarrow \nu_e) = \sin^4 \theta_{13} + \cos^4 \theta_{13} P_{\odot}^{2\nu},$$

$$P_{\odot}^{2\nu} = P_{\odot}^{2\nu}(\theta_{12}, \Delta m_{21}^2; N_e \cos^2 \theta_{13}), \quad \mathbf{solar \ neutrino \ exp.}$$

## Two-Neutrino Oscillations in Vacuum

SK ((100-12742) km), K2K (250 km); CNGS (OPERA), MINOS (730 km); T2K (295 km); dominant  $\nu_\mu \rightarrow \nu_\tau$ ;

$$P(\nu_\mu \rightarrow \nu_\tau; L) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau; L) \cong \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E};$$
$$P(\nu_\mu \rightarrow \nu_\mu; L) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu; L) = 1 - P(\nu_\mu \rightarrow \nu_\tau; L).$$

KamLAND ( $\sim 180$ km):  $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e; L) \cong 1 - \frac{1}{2} \sin^2 2\theta_{12} \left(1 - \cos \frac{\Delta m_{21}^2 L}{2E}\right).$$

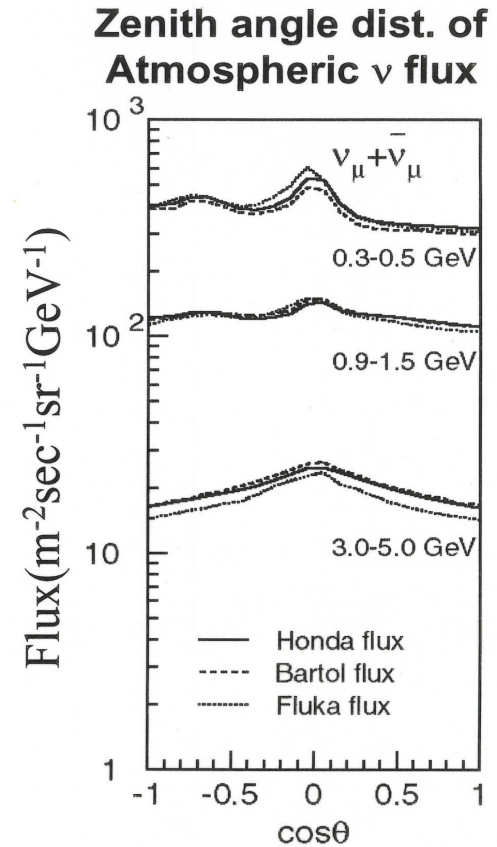
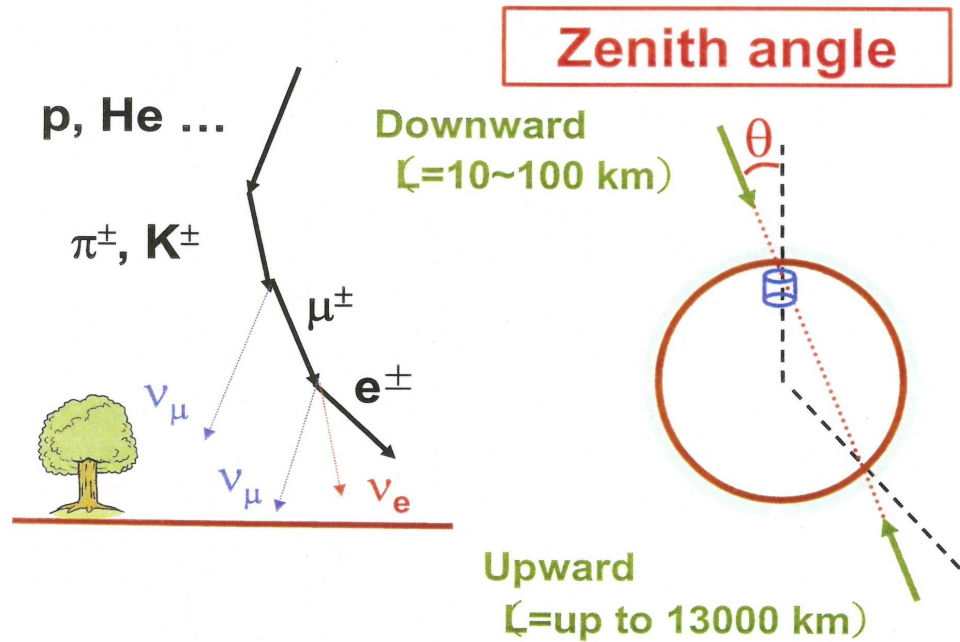
CHOOZ, Double Chooz, Daya Bay, RENO ( $\sim 1$  km):  
 $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e; L) \cong 1 - \frac{1}{2} \sin^2 2\theta_{13} \left(1 - \cos \frac{\Delta m_{31}^2 L}{2E}\right).$$

# Observing the Oscillations of Neutrinos

# Super-Kamiokande Atmospheric Neutrino Data

# Atmospheric neutrinos

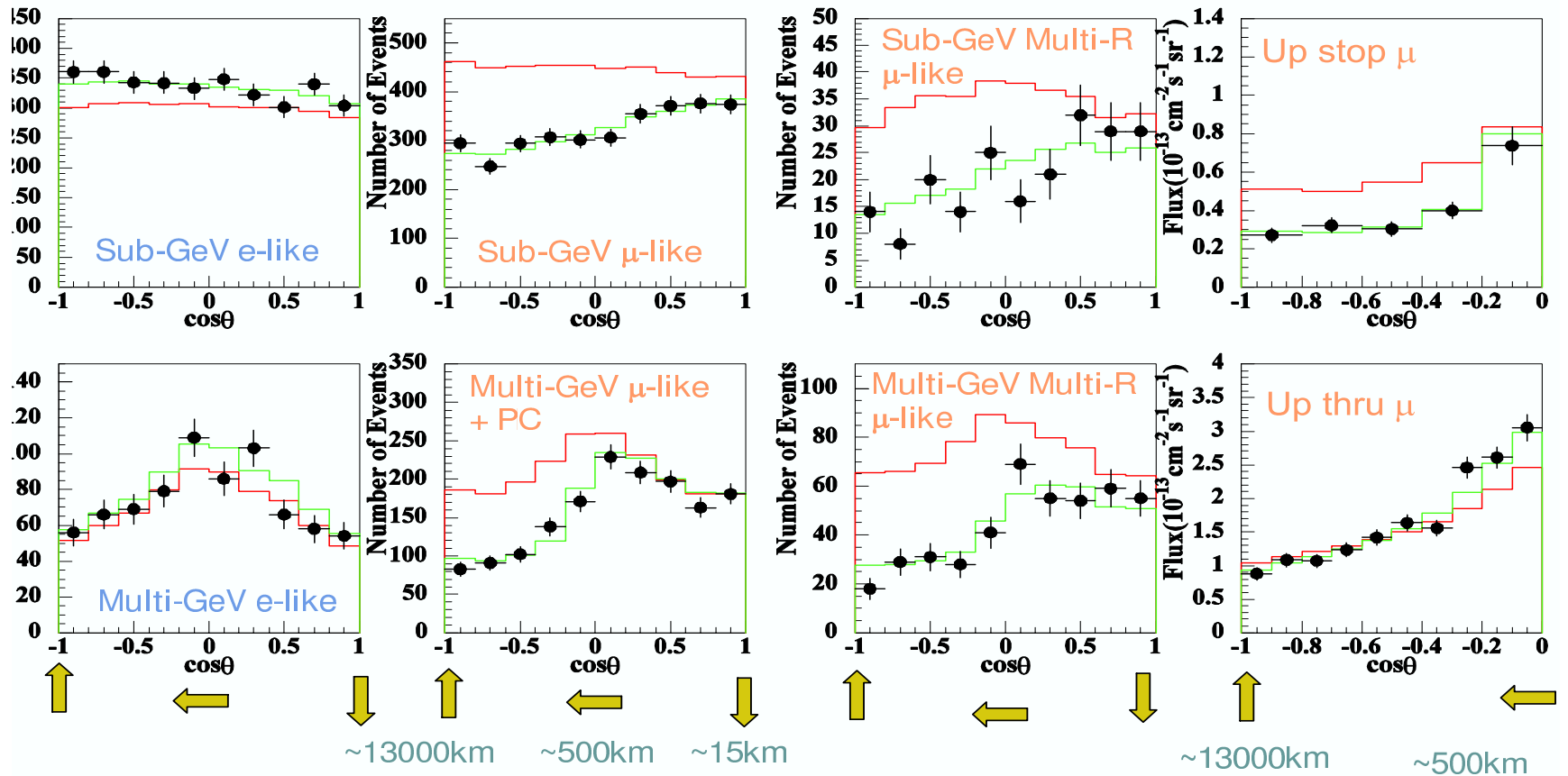


**$E_\nu > \text{a few GeV}$**   
**Up/Down Symmetry**

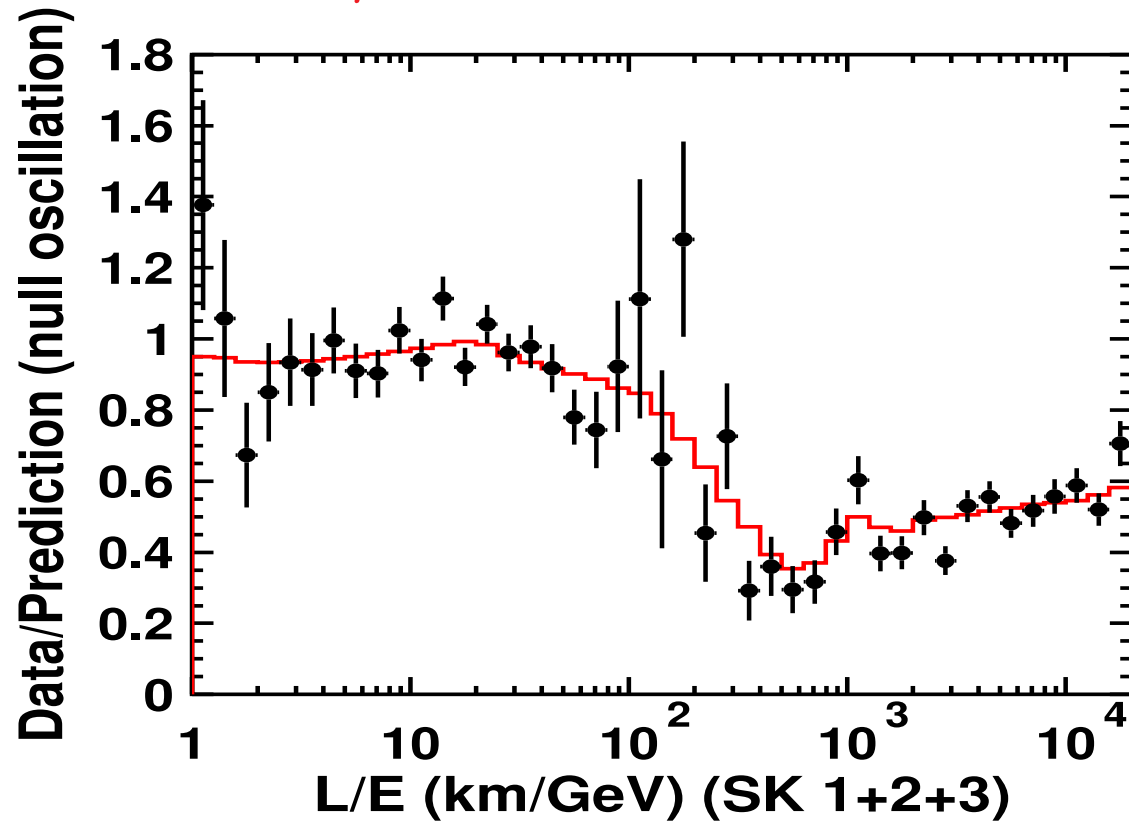
# Zenith angle distributions

$\nu_\mu \leftrightarrow \nu_\tau$   
2-flavor oscillations

Best fit  
 $\sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3} \text{ eV}^2$   
Null oscillation



# SK: L/E Dependence, $\mu$ -Like Events

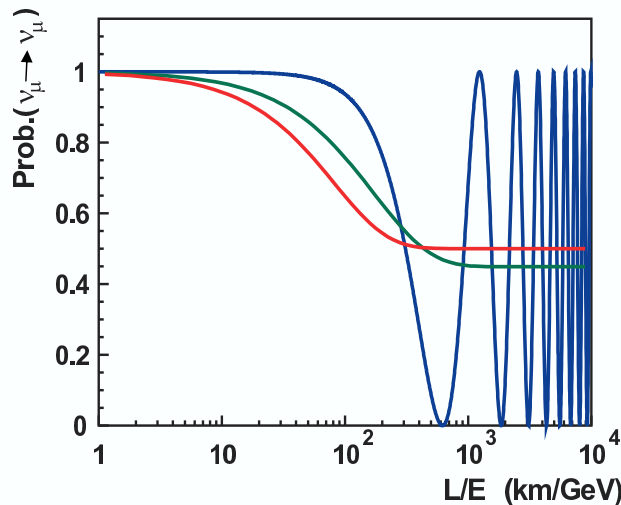


## L/E analysis

Neutrino oscillation :  $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$

Neutrino decay :  $P_{\mu\mu} = \left(\cos^2 \theta + \sin^2 \theta \times \exp\left(-\frac{m}{2\tau} \frac{L}{E}\right)\right)^2$

Neutrino decoherence :  $P_{\mu\mu} = 1 - \frac{1}{2} \sin^2 2\theta \times \left(1 - \exp\left(-\gamma_0 \frac{L}{E}\right)\right)$



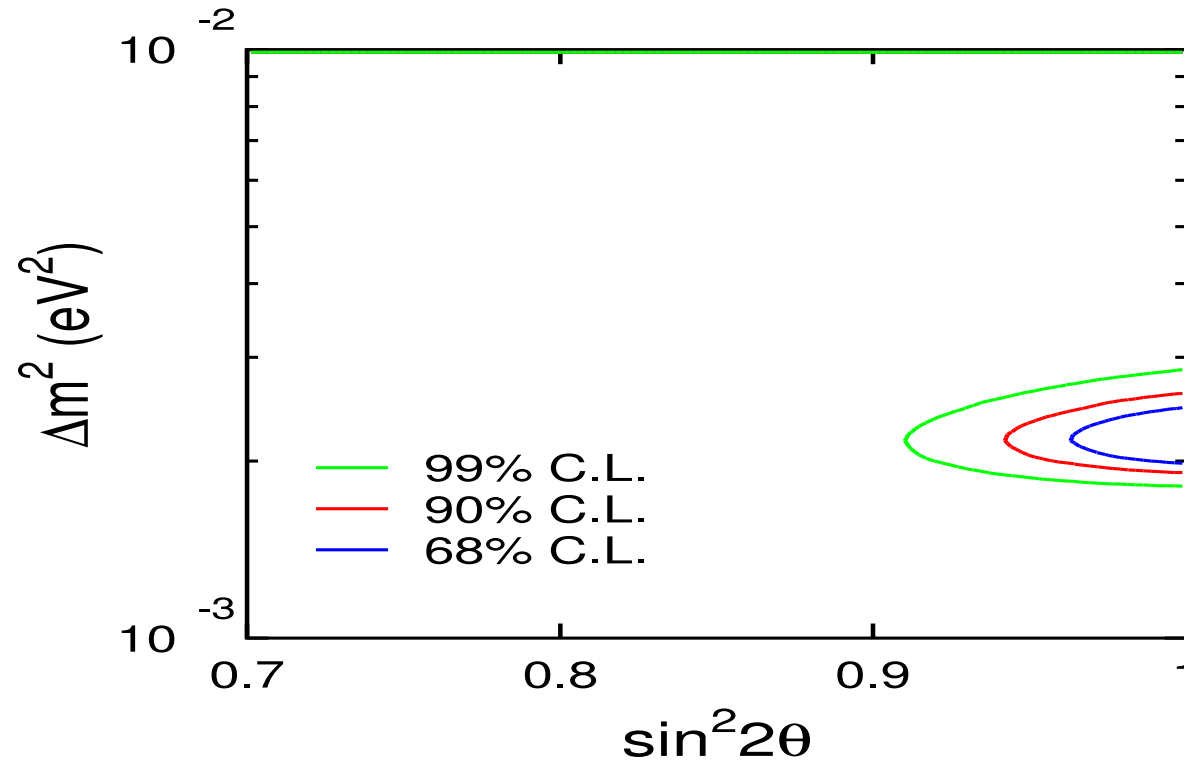
Use events with high resolution in L/E



The first dip can be observed

- Direct evidence for oscillations
- Strong constraint to oscillation parameters, especially  $\Delta m^2$  value

## SK: Atmospheric $\nu$ Data



$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{\text{atm}} \equiv \sin^2 2\theta_{23} = 1.0 ;$$

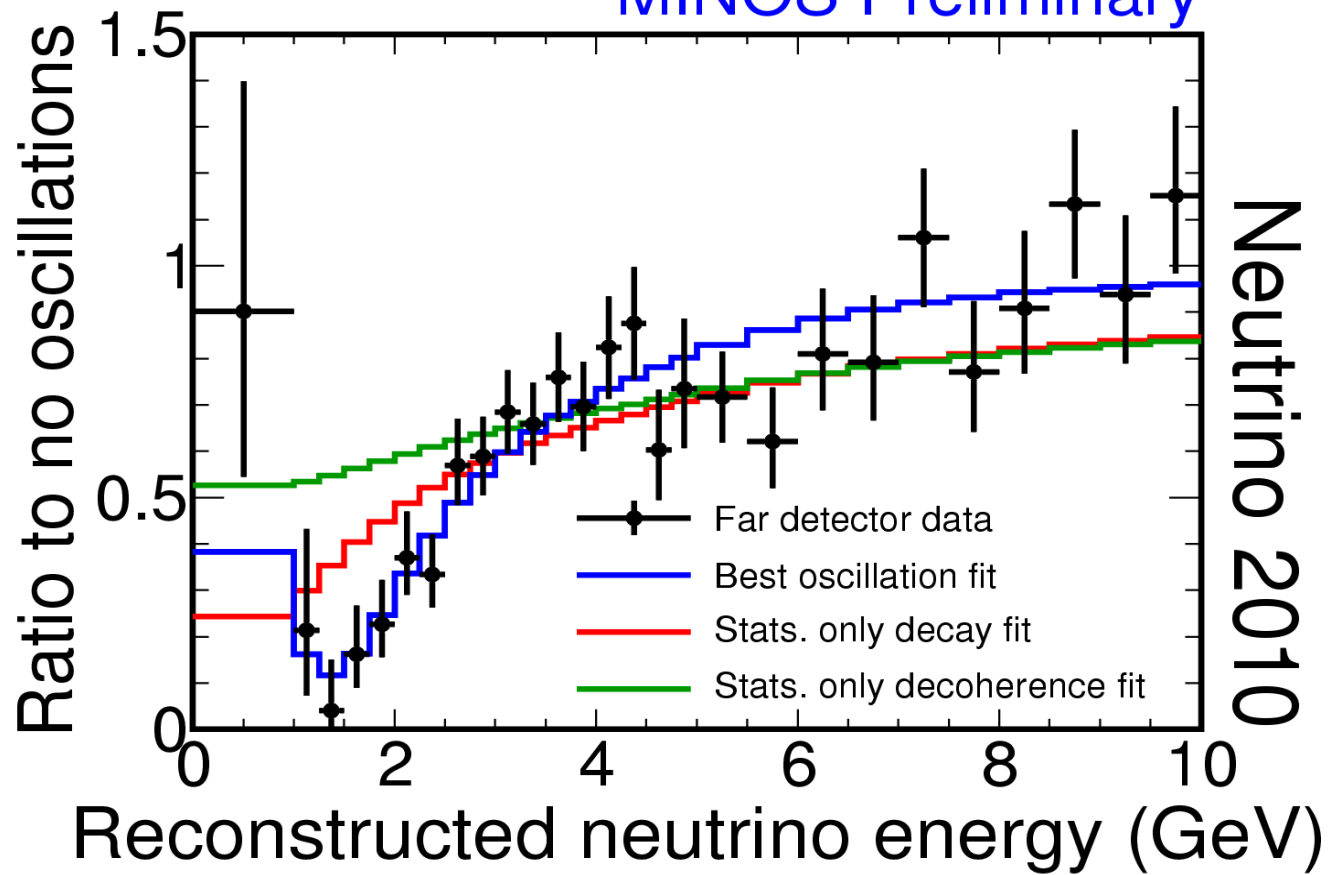
$$\Delta m_{31}^2 = (1.9 - 2.9) \times 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{23} \geq 0.92, \quad 99\% \text{ C.L.}$$

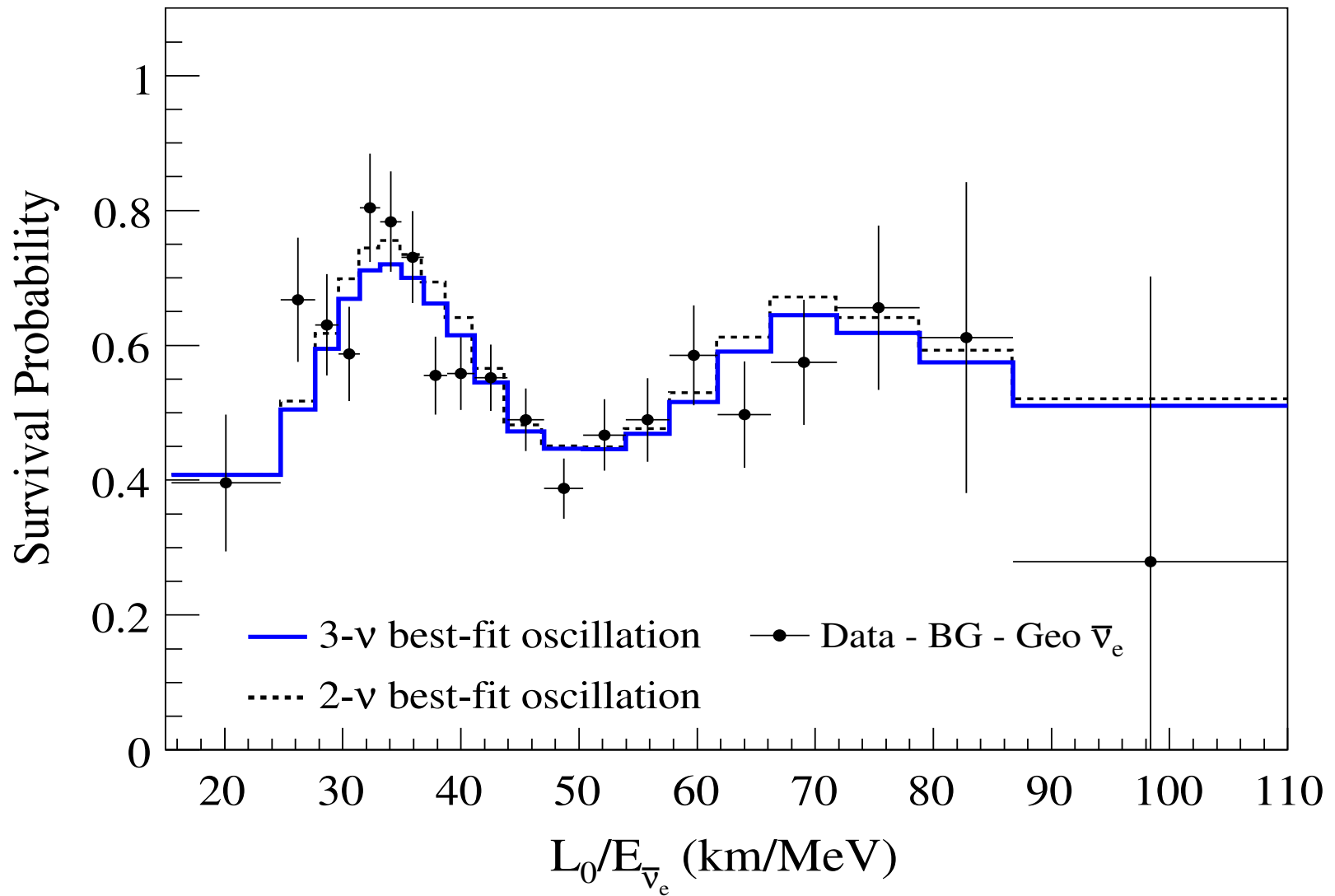
- sign of  $\Delta m_{\text{atm}}^2$  not determined. If  $\theta_{23} \neq \frac{\pi}{4}$ :  $\theta_{23}, (\frac{\pi}{4} - \theta_{23})$  ambiguity.

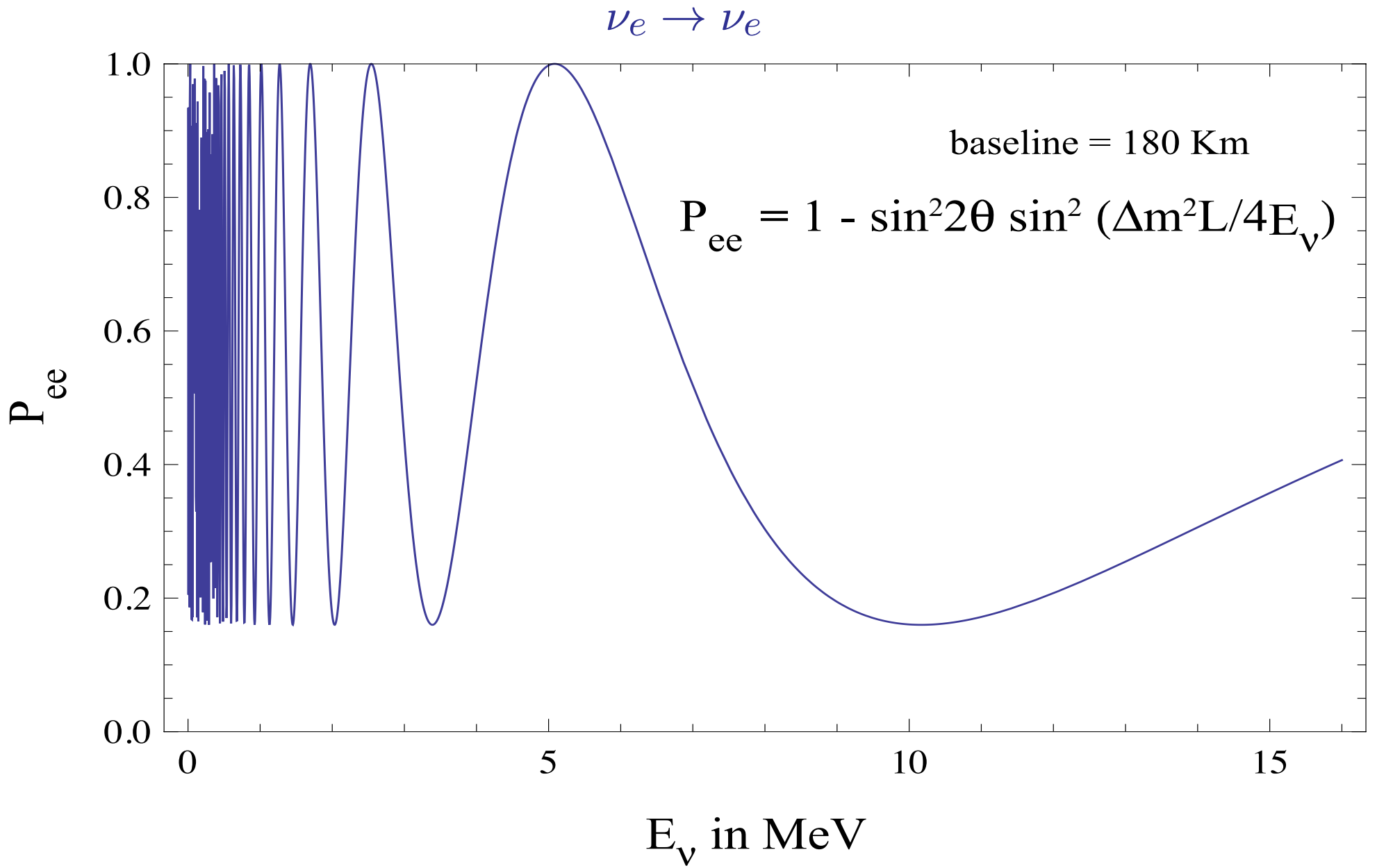
3- $\nu$  mixing:  $\Delta m_{31}^2 > 0, m_1 < m_2 < m_3$  (NH);  $\Delta m_{31}^2 < 0, m_3 < m_1 < m_2$  (IH).

# MINOS: $\nu_\mu$ Spectrum ( $\nu_\mu$ "disappearance")

MINOS Preliminary







## Reference Model: 3- $\nu$ mixing

$$\nu_{lL} = \sum_{j=1}^3 U_{lj} \nu_{jL} \quad l = e, \mu, \tau.$$

The PMNS matrix  $U$  -  $3 \times 3$  unitary matrix.

$\nu_j, m_j \neq 0$ : Dirac or Majorana particles.

3- $\nu$  mixing: 3-flavour neutrino oscillations possible.

$\nu_\mu, E$ ; at distance  $L$ :  $P(\nu_\mu \rightarrow \nu_{\tau(e)}) \neq 0, P(\nu_\mu \rightarrow \nu_\mu) < 1$

$$P(\nu_l \rightarrow \nu_{l'}) = P(\nu_l \rightarrow \nu_{l'}; E, L; U; m_2^2 - m_1^2, m_3^2 - m_1^2)$$

$$m_2^2 - m_1^2 \equiv \Delta m_{21}^2, \quad m_3^2 - m_1^2 \equiv \Delta m_{31}^2$$

# Three Neutrino Mixing

$$\nu_{lL} = \sum_{j=1}^3 U_{lj} \nu_{jL} .$$

$U$  is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

- $U$  -  $n \times n$  unitary:

	$n$	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6

CP-violating phases:

• $\nu_j$ - Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• $\nu_j$ - Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$ : 1 Dirac and  
2 additional CP-violating phases, Majorana phases

S.M. Bilenky, J. Hosek, S.T.P., 1980

# PMNS Matrix: Standard Parametrization

$$U = V P, \quad P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix},$$

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

- $s_{ij} \equiv \sin \theta_{ij}$ ,  $c_{ij} \equiv \cos \theta_{ij}$ ,  $\theta_{ij} = [0, \frac{\pi}{2}]$ ,
- $\delta$  - Dirac CPV phase,  $\delta = [0, 2\pi]$ ; CP inv.:  $\delta = 0, \pi, 2\pi$ ;
- $\alpha_{21}, \alpha_{31}$  - Majorana CPV phases; CP inv.:  $\alpha_{21(31)} = k(k')\pi$ ,  $k(k') = 0, 1, 2, \dots$   
S.M. Bilenky et al., 1980
- $\Delta m_{\odot}^2 \equiv \Delta m_{21}^2 \cong 7.34 \times 10^{-5} \text{ eV}^2 > 0$ ,  $\sin^2 \theta_{12} \cong 0.305$ ,  $\cos 2\theta_{12} \gtrsim 0.306$  ( $3\sigma$ ),
- $|\Delta m_{31(32)}^2| \cong 2.448$  (2.502)  $\times 10^{-3} \text{ eV}^2$ ,  $\sin^2 \theta_{23} \cong 0.545$  (0.551), NO (IO) ,
- $\theta_{13}$  - the CHOOZ angle:  $\sin^2 \theta_{13} = 0.0222$  (0.0223)  
F. Capozzi et al. (Bari Group), arXiv:2003.08511.

- $\text{sgn}(\Delta m_{\text{atm}}^2) = \text{sgn}(\Delta m_{31(32)}^2)$  not determined

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 > 0, \quad \text{normal mass ordering (NO)}$$

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{32}^2 < 0, \quad \text{inverted mass ordering (IO)}$$

Convention:  $m_1 < m_2 < m_3$  - NO,  $m_3 < m_1 < m_2$  - IO

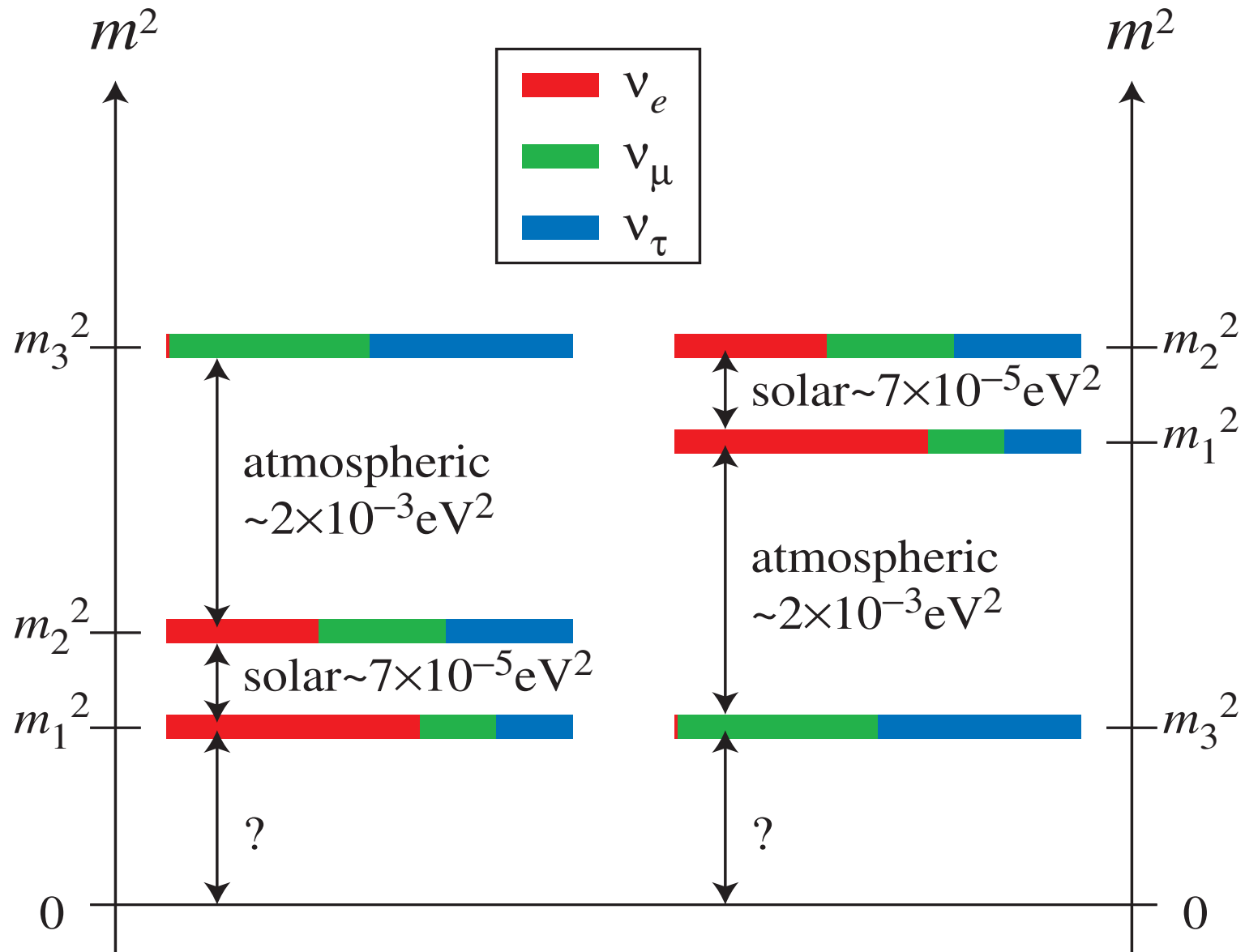
$$m_1 \ll m_2 < m_3, \quad \text{NH,}$$

$$m_3 \ll m_1 < m_2, \quad \text{IH,}$$

$$m_1 \cong m_2 \cong m_3, \quad m_{1,2,3}^2 \gg |\Delta m_{31(32)}^2|, \quad \text{QD; } m_j \gtrsim 0.10 \text{ eV.}$$

- $m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$  - NO;

- $m_1 = \sqrt{m_3^2 + \Delta m_{23}^2 - \Delta m_{21}^2}, \quad m_2 = \sqrt{m_3^2 + \Delta m_{23}^2}$  - IO;



# Neutrino Oscillations in Matter

## Neutrino Oscillations in Matter

When neutrinos propagate in matter, they interact with the background of electrons, protons and neutrons, which generates an effective potential in the neutrino Hamiltonian:  $H = H_{vac} + V_{eff}$ .

This modifies the neutrino mixing since the eigenstates and the eigenvalues of  $H_{vac}$  and of  $H = H_{vac} + V_{eff}$  are different, leading to a different oscillation probability w.r.t to that in vacuum.

Typically the matter background is not CP and CPT symmetric, e.g., the Earth and the Sun contain only electrons, protons and neutrons, and **the resulting oscillations violate CP and CPT symmetries.**

## Matter Effects in Neutrino Oscillations (Supp. S.)

Matter can affect strongly  $\nu$ -oscillations:

Mean free path in matter with  $\bar{\rho} = \bar{\rho}(Earth) \cong 8 \text{ gcm}^{-3}$  ( $N \cong 4N_A \text{cm}^{-3}$ ),

$E \sim 1 \text{ MeV}$ ,  $L_f \sim 2.5 \times 10^{14} \text{ km}$ ;  $R_E = 6371 \text{ km}$

$E \sim 1 \text{ GeV}$ ,  $L_f \sim 2.5 \times 10^8 \text{ km}$

For  $\bar{\rho} = \rho(\text{center of the Sun})$ :  $N \cong 50 N_A \text{cm}^{-3}$ ,

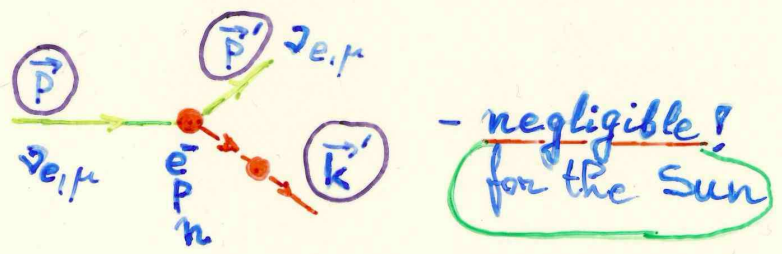
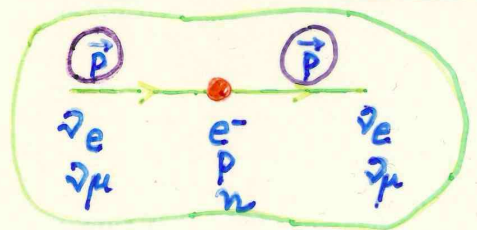
$E \sim 1 \text{ MeV}$ ,  $L_f \sim 10^{13} \text{ km}$ ;  $R_{Sun} = 6.96 \times 10^5 \text{ km}$

$\nu_e$  **incoherent** scattering - no relevant.

$\nu_e$  **coherent** scattering on  $e^-$ ,  $p$ ,  $n$  - effective potential (index of refraction)

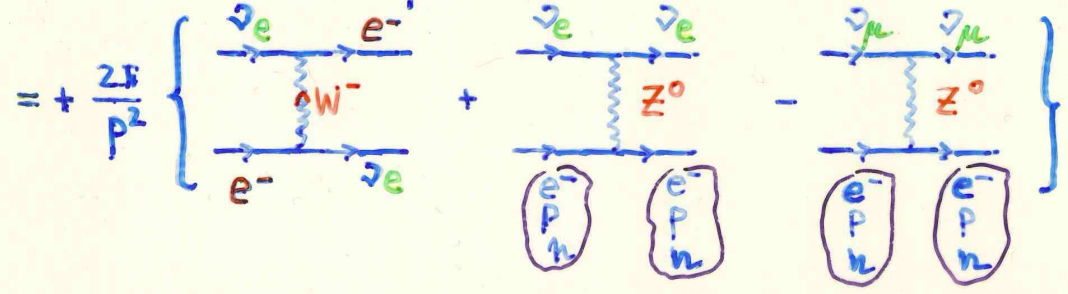
The presence of matter can change drastically the pattern of  $\nu$ -oscillations

$$H_m = H_{vac} + H_{int}$$



$$n(\nu_e) \neq 1, n(\nu_\mu) \neq 1$$

$$n(\nu_e) - n(\nu_\mu) = \frac{2\pi}{p^2} [F_{\nu_e}^{\nu_e}(0) - F_{\nu_e}^{\nu_\mu}(0)] =$$



$$= -\frac{1}{p} \sqrt{2} G_F N_e$$

$\nu$  coherent scattering on  $e^-$ ,  $p$ ,  $n$  - effective potential (index of refraction)

$$V_{e\mu} = V(\nu_e) - V(\nu_\mu) = \sqrt{2}G_F N_e$$

$$\bar{V}_{e\mu} = V(\bar{\nu}_e) - V(\bar{\nu}_\mu) = -\sqrt{2}G_F N_e$$

$$V_{\mu\tau} = V(\nu_\mu) - V(\nu_\tau) = 0 \text{ (leading order)}$$

L. Wolfenstein, 1978; V. Barger et al., 1980; P. Langacker et al., 1983

$$V_{es} = V(\nu_e) - V(\nu_s) = \sqrt{2}G_F(N_e - \frac{1}{2}N_n)$$

$$\bar{V}_{es} = V(\bar{\nu}_e) - V(\bar{\nu}_s) = -\sqrt{2}G_F(N_e - \frac{1}{2}N_n) = -V_{es}$$

$$V_{\mu s} = V(\nu_\mu) - V(\nu_s) = \sqrt{2}G_F(-\frac{1}{2}N_n)$$

$$\bar{V}_{\mu s} = V(\bar{\nu}_\mu) - V(\bar{\nu}_s) = -\sqrt{2}G_F(-\frac{1}{2}N_n) = -V_{\mu s}$$

$V_{e\mu} \neq \bar{V}_{e\mu}$ : CP, CPT violated

P. Langacker, S.T.P. et al., 1987

$E_\nu \gtrsim 2$  GeV, constant density,  $L > 10660$  km ( $\theta_n > 33.17^\circ$ ) Earth mantle crossing,

$$P_{3\nu}(\nu_\mu \rightarrow \nu_e) \cong \sin^2 \theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta M_{31}^2 L}{4E}$$

$\sin^2 2\theta_{13}^m$ ,  $\Delta M_{31}^2$  depend on the matter potential  
 $V_{eff} = \sqrt{2} G_F N_e$  (modified  $\theta_{13}$  and  $\Delta m_{31}^2$ )

For antineutrinos  $V_{eff}$  has the opposite sign:

$$V_{eff} = -\sqrt{2} G_F N_e.$$

$\Delta m_{31}^2 > 0$  (NO):  $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$  matter enhanced,  
 $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$  - suppressed

$\Delta m_{31}^2 < 0$  (IO):  $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$  matter enhanced,  
 $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$  - suppressed

## Supporting Slides

$$i \frac{d}{dt} \begin{pmatrix} A_\alpha(t, t_0) \\ A_\beta(t, t_0) \end{pmatrix} = \begin{pmatrix} -\epsilon(t) & \epsilon'(t) \\ \epsilon'(t) & \epsilon(t) \end{pmatrix} \begin{pmatrix} A_\alpha(t, t_0) \\ A_\beta(t, t_0) \end{pmatrix}$$

where  $\alpha = \nu_e$ ,  $\beta = \nu_{\mu(\tau)}$ ;  $A_{\nu_e(\nu_\mu)}(t_0, t_0) = 1$ ,  $A_{\nu_\mu(\nu_e)}(t_0, t_0) = 0$ .

$$\epsilon(t) = \frac{1}{2} \left[ -\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2} G_F N_e(t) \right],$$

$$\epsilon'(t) = \frac{\Delta m^2}{4E} \sin 2\theta, \text{ with } \Delta m^2 = m_2^2 - m_1^2.$$

In matter,  $H_m = H_0 + H_{int}$ .

$H_0 |\nu_{1,2}\rangle = E_{1,2} |\nu_{1,2}\rangle$ , not eigenstates of  $H_m$ .

Consider first  $N_e = const.$  (e.g., Earth mantle)

$$H_m |\nu_{1,2}^m\rangle = E_{1,2}^m |\nu_{1,2}^m\rangle.$$

Then at  $t = 0$  in matter

$$|\nu_e\rangle = |\nu_1^m\rangle \cos \theta_m + |\nu_2^m\rangle \sin \theta_m,$$

$$|\nu_{\mu(\tau)}\rangle = -|\nu_1^m\rangle \sin \theta_m + |\nu_2^m\rangle \cos \theta_m;$$

$$\sin 2\theta_m = \frac{\epsilon'}{\sqrt{\epsilon^2 + \epsilon'^2}} = \frac{\tan 2\theta}{\sqrt{\left(1 - \frac{N_e}{N_e^{\text{res}}}\right)^2 + \tan^2 2\theta}},$$

$$\cos 2\theta_m = \frac{1 - N_e/N_e^{\text{res}}}{\sqrt{\left(1 - \frac{N_e}{N_e^{\text{res}}}\right)^2 + \tan^2 2\theta}},$$

$$N_e^{\text{res}} = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2}G_F} \cong 6.56 \times 10^6 \frac{\Delta m^2 [\text{eV}^2]}{E [\text{MeV}]} \cos 2\theta \text{ cm}^{-3} N_A,$$

$$E_2^m - E_1^m = \frac{\Delta m^2}{2E} \left( \left(1 - \frac{N_e}{N_e^{\text{res}}}\right)^2 \cos^2 2\theta + \sin^2 2\theta \right)^{\frac{1}{2}}$$

$$P_m^{2\nu}(\nu_e \rightarrow \nu_\mu) = |A_\mu(t)|^2 = \frac{1}{2} \sin^2 2\theta_m \left[ 1 - \cos 2\pi \frac{L}{L_m} \right],$$

$$L_m = \frac{E_2^m - E_1^m}{2\pi} = L^v \left( \left( 1 - \frac{N_e}{N_e^{res}} \right)^2 \cos^2 2\theta + \sin^2 2\theta \right)^{-\frac{1}{2}}.$$

The resonance condition:  $N_e = N_e^{res} = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2}G_F}$

At the resonance:

$\sin^2 2\theta_m = 1$ , even if  $\sin 2\theta \ll 1$ ;  $\min(E_2^m - E_1^m)$ ,  $L_m^{res} = L^v / \sin 2\theta$ .

Limiting cases:

$N_e \ll N_e^{res}$ :  $\theta_m \cong \theta$ ,  $E_{1,2}^m \cong E_{1,2}$ ,  $L_m \cong L^v$ .

$N_e \gg N_e^{res}$ :  $\theta_m \cong \frac{\pi}{2}$ ,  $\nu_e \rightarrow \nu_\mu$  suppressed.

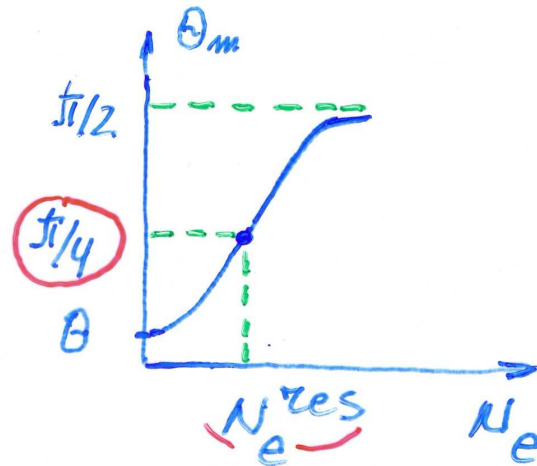
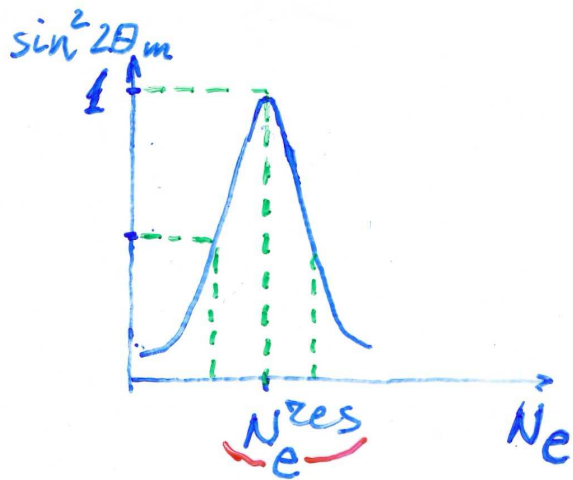
In this case:  $|\nu_e\rangle \cong |\nu_2^m\rangle$ ,  $|\nu_\mu\rangle = -|\nu_1^m\rangle$ .

$$N_e^{\text{res}} = \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2}G_F}$$

$$N_e \gg N_e^{\text{res}}, \theta_m \approx \pi/2$$

$$N_e \ll N_e^{\text{res}}, \theta_m \approx 0$$

$$N_e = N_e^{\text{res}}, \theta_m \approx \pi/4$$



$$\Delta N_e^{\text{res}} = 2N_e^{\text{res}} \tan 2\theta$$

$$E_2^m - E_1^m \Big|_{\text{res}} = \min(E_2^m - E_1^m)$$

Antineutrinos:  $N_e \rightarrow (-N_e)$

$\Delta m^2 \cos 2\theta > 0$ :  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$  suppressed by matter;  $\nu_e \rightarrow \nu_\mu$  can be enhanced.

$\Delta m^2 \cos 2\theta < 0$ :  $\nu_e \rightarrow \nu_\mu$  suppressed by matter;  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$  can be enhanced.

V. Barger et al., 1980; S.P. Mikheyev, A.Yu. Smirnov, 1985

Oscillations in matter (Earth, Sun) are neither CP- nor CPT- invariant.

P. Langacker, S.T.P., S. Toshev, G. Steigman, 1987

Earth:  $\bar{N}_e^{mant} \sim 2.3 N_A \text{ cm}^{-3}$ ,  $\bar{N}_e^{core} \sim 6.0 N_A \text{ cm}^{-3}$

$$P^m(\nu_e \rightarrow \nu_\mu; t) = \frac{1}{2} \sin^2 2\theta_m \left(1 - \cos 2\pi \frac{L}{L_{osc}^m}\right), \quad L_{osc}^m \sim L_{osc}^{vac}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\left(1 - \frac{N_e}{N_e^{res}}\right)^2 \cos^2 2\theta + \sin^2 2\theta}, \quad N_e^{res} \equiv \frac{\Delta m^2 \cos 2\theta}{2E\sqrt{2}G_F}$$

$N_e = N_e^{res}$ : MSW (Mikheyev, Smirnov, Wolfenstein) resonance

$\Delta m^2 \cos 2\theta > 0$ :  $\nu_e \rightarrow \nu_\mu$

$\Delta m^2 \cos 2\theta < 0$ :  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

$$\sin^2 2\theta_{13}^m = \frac{\tan^2 2\theta_{13}}{\left(1 - \frac{N_e}{N_e^{res}}\right)^2 + \tan^2 2\theta_{13}},$$

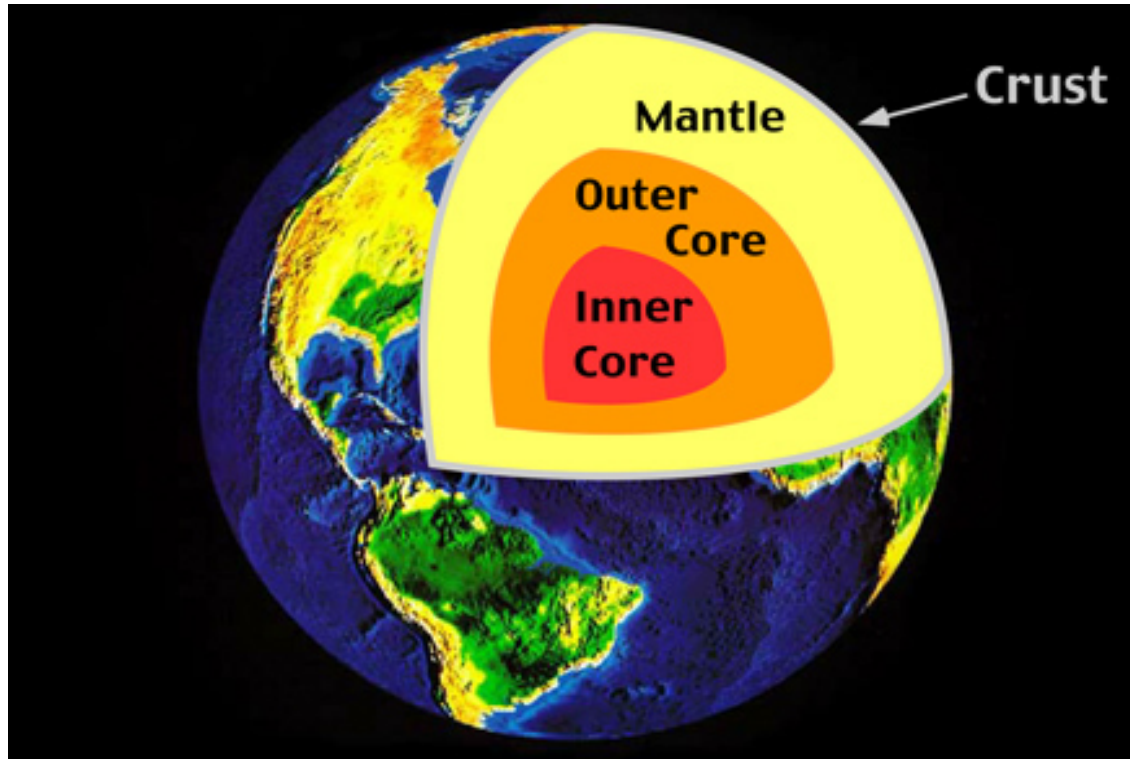
$$\cos 2\theta_{13}^m = \frac{1 - N_e/N_e^{res}}{\sqrt{\left(1 - \frac{N_e}{N_e^{res}}\right)^2 + \tan^2 2\theta_{13}}},$$

$$N_e^{res} = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2E\sqrt{2}G_F},$$

$$N_e^{res} \cong 6.56 \times 10^6 \frac{\Delta m^2 [\text{eV}^2]}{E [\text{MeV}]} \cos 2\theta_{13} \text{ cm}^{-3} N_A,$$

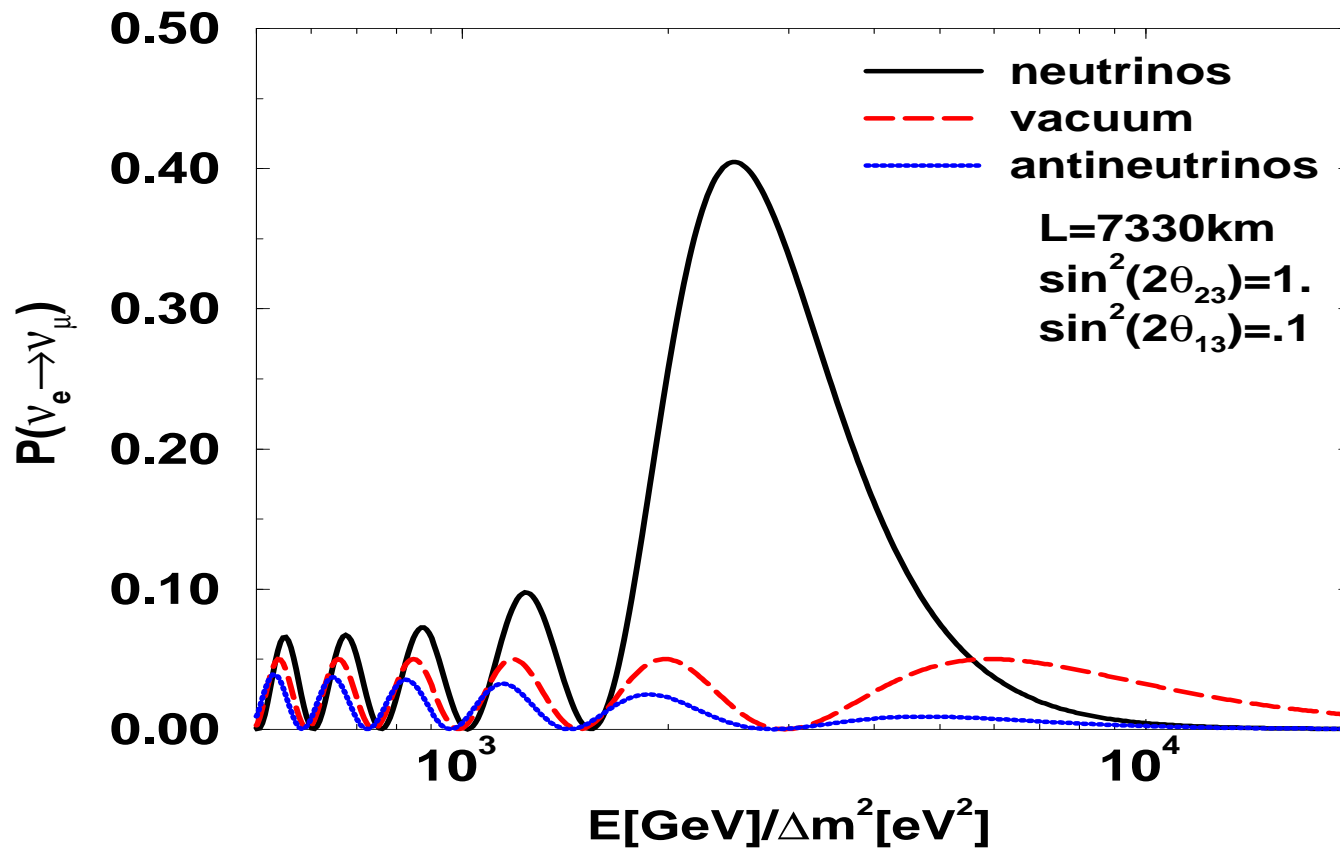
$$\frac{\Delta M_{31}^2}{2E} \equiv \frac{\Delta m_{31}^2}{2E} \left( \left(1 - \frac{N_e}{N_e^{res}}\right)^2 \cos^2 2\theta_{13} + \sin^2 2\theta_{13} \right)^{\frac{1}{2}}$$

For  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ :  $N_e \rightarrow (-N_e)$ .



$R_{\oplus} = 6371$  km;  $R_{IC} = 1221.5$  km;  $R_C = 3480$  km;  $D_{\text{man}} = 2891$  km;  
 $\bar{\rho}_{\text{man}} = 4.45$  g/cm<sup>3</sup>;  $\bar{\rho}_C = 10.99$  g/cm<sup>3</sup>;  $\bar{\rho}_{IC} = 12.89$  g/cm<sup>3</sup>;  $\bar{\rho}_{OC} = 10.90$  g/cm<sup>3</sup>.  
PREM: the density distribution in the Earth is spherically symmetric. The  $\nu$   
trajectory determined by the nadir (zenith) angle.  
For  $L < 10660$  km ( $\theta_n > 33.17^\circ$ ),  $\nu$ s cross only the mantle.

# Earth matter effect in $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ in the mantle (MSW)



$$\Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2, E^{res} = 6.25 \text{ GeV}; P^{3\nu} = \sin^2 \theta_{23} P_m^{2\nu} = 0.5 P_m^{2\nu};$$

$$N_e^{res} \cong 2.3 \text{ cm}^{-3} N_A; L_m^{res} = L^\nu / \sin 2\theta_{13} \cong 6250 / 0.32 \text{ km}; 2\pi L / L_m \cong 0.75\pi (\neq \pi).$$

I. Mocioiu, R. Shrock, 2000

**Sensitivity to  $\bar{\rho}_{\text{man}}$  along the  $\nu$  path in the mantle.**

# Resonance-like Amplification of Oscillations of Neutrinos Crossing the Earth Core

# The Earth (PREM)

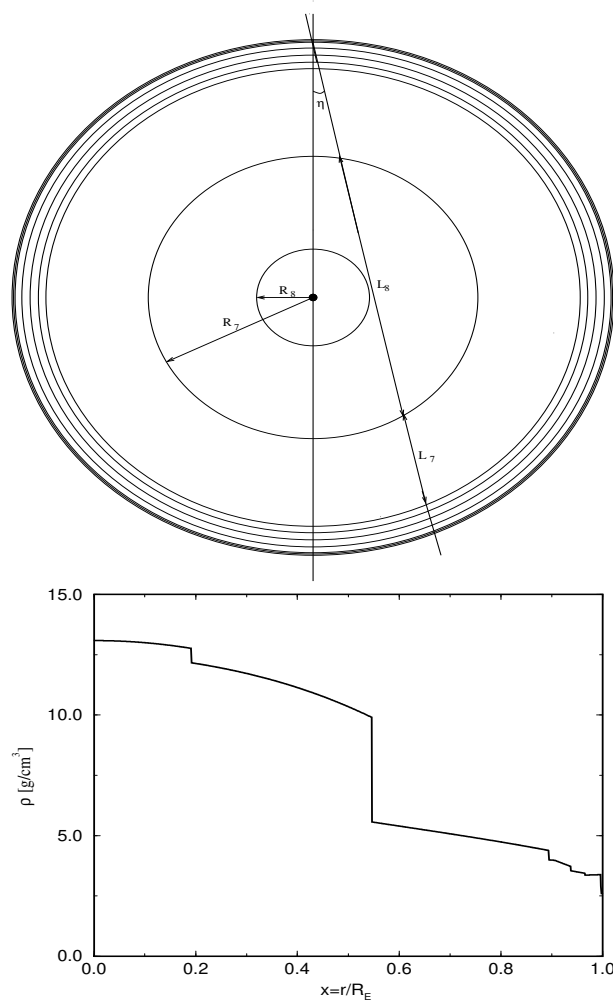
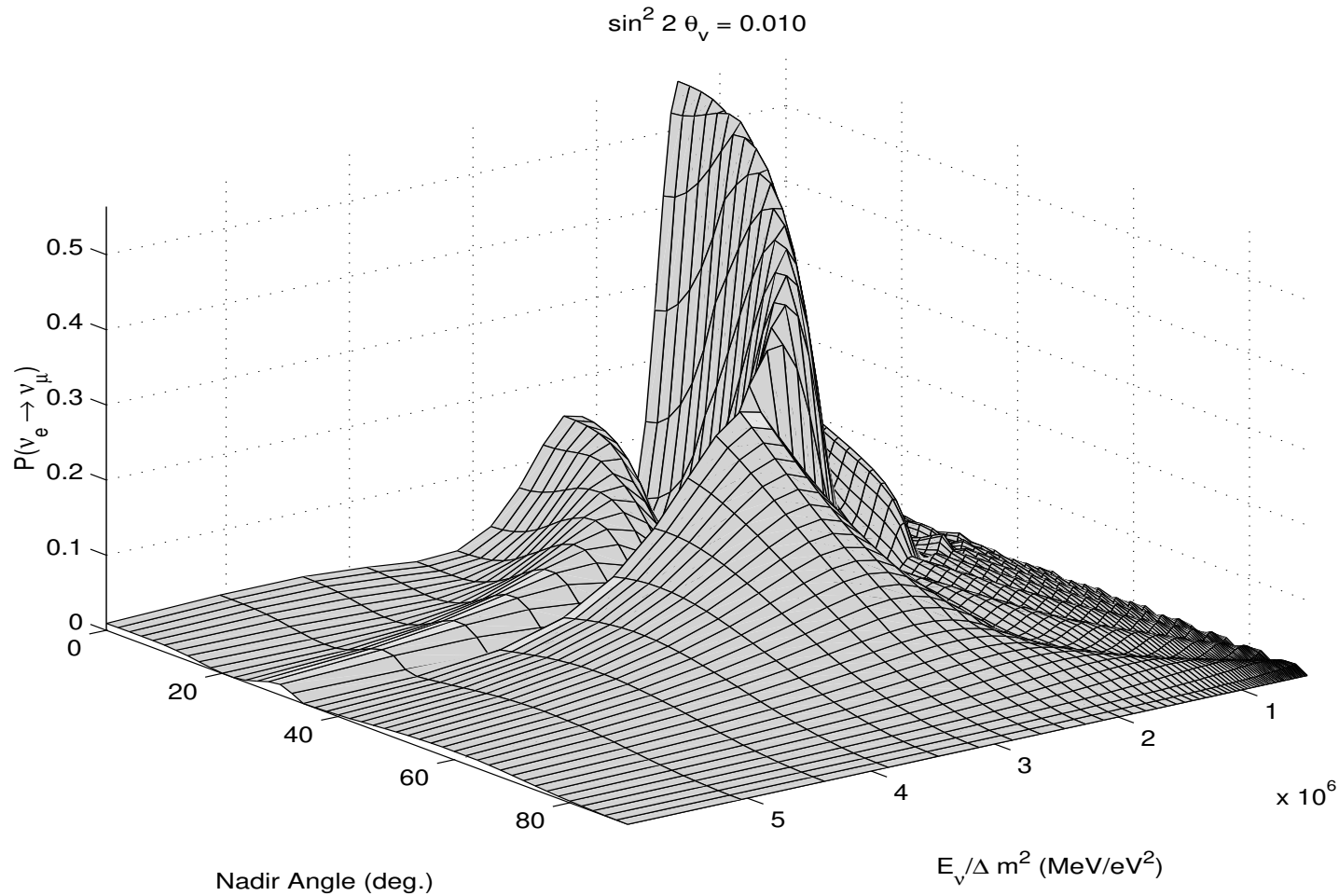


FIG. 1. Density profile of the Earth.

$$R_{\oplus} = 6371 \text{ km}; R_{\text{IC}} = 1221.5 \text{ km}; R_{\text{C}} = 3480 \text{ km}; D_{\text{man}} = 2891 \text{ km};$$
$$\bar{\rho}_{\text{man}} = 4.45 \text{ g/cm}^3; \bar{\rho}_{\text{C}} = 10.99 \text{ g/cm}^3; \bar{\rho}_{\text{IC}}^{16} = 12.89 \text{ g/cm}^3; \bar{\rho}_{\text{OC}} = 10.90 \text{ g/cm}^3.$$

# Earth matter effects in $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (NOLR)



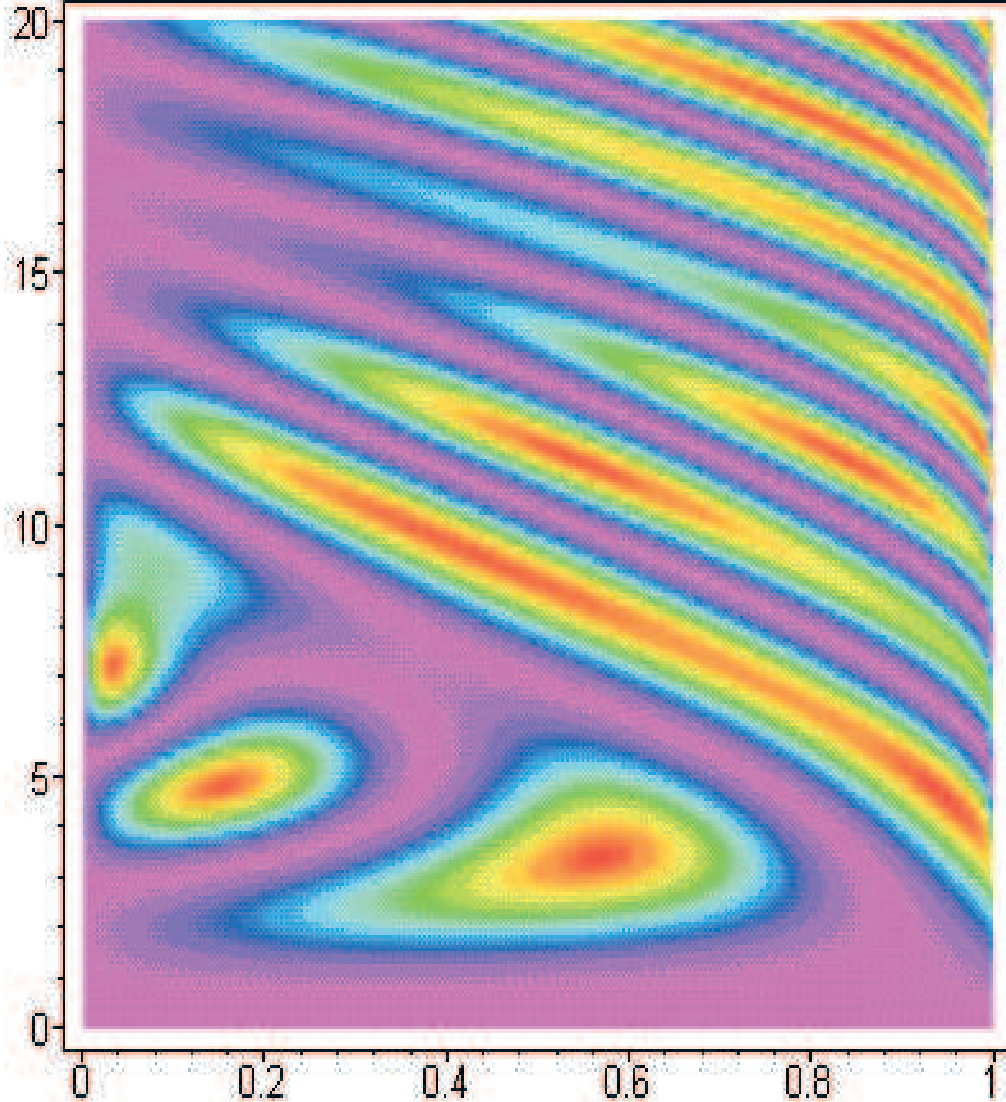
S.T.P., 1998;

M. Chizhov, M. Maris, S.T.P., 1998; M. Chizhov, S.T.P., 1999

$P(\nu_e \rightarrow \nu_\mu) \equiv P_{2\nu} \equiv (s_{23})^{-2} P_{3\nu}(\nu_{e(\mu)} \rightarrow \nu_{\mu(e)})$ ,  $\theta_v \equiv \theta_{13}$ ,  $\Delta m^2 \equiv \Delta m_{\text{atm}}^2$ ;

**Absolute maximum: Neutrino Oscillation Length Resonance (NOLR);**

**Local maxima: MSW effect in the Earth mantle or core.**

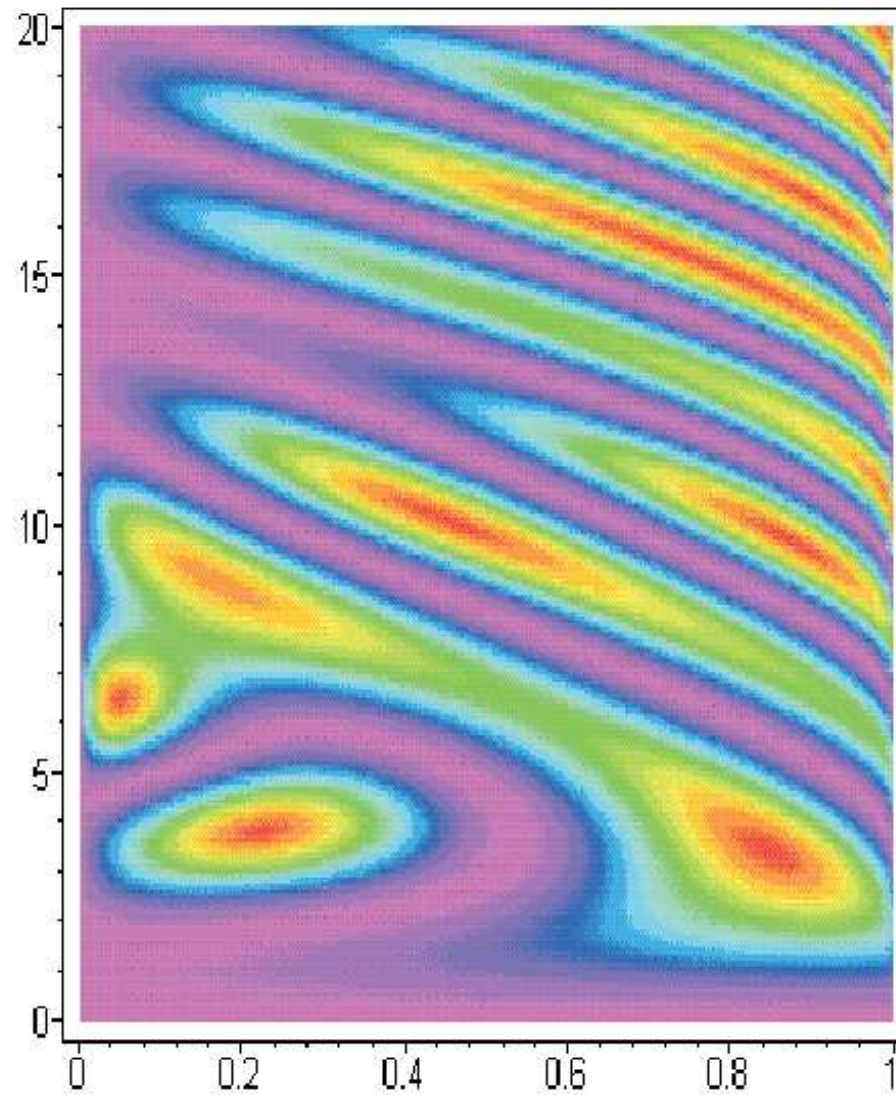


$(s_{23})^{-2} P_{3\nu}(\nu_{e(\mu)} \rightarrow \nu_{\mu(e)}) \equiv P_{2\nu}$ ; **NOLR: “Dark Red Spots”,  $P_{2\nu} = 1$ ;**  
**Vertical axis:  $\Delta m^2/E$  [ $10^{-7} eV^2/MeV$ ]; horizontal axis:  $\sin^2 2\theta_{13}$ ;  $\theta_n = 0$**

M. Chizhov, S.T.P., 1999 (hep-ph/9903399,9903424)

**Sensitivity to  $\bar{\rho}_{\text{man}}$ ,  $\bar{\rho}_{\text{Core}}$ , and to  $(\bar{\rho}_{\text{Core}}/\bar{\rho}_{\text{man}})_{mcb}$  at mantle-core boundary.**

S.T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026



The same for  $\theta_n = 23^\circ$ .

**Vertical axis:**  $\Delta m^2/E$  [ $10^{-7} eV^2/MeV$ ]; **horizontal axis:**  $\sin^2 2\theta_{13}$ .

M. Chizhov, S.T.P., 1999 (hep-ph/9903399,9903424)

- For Earth center crossing  $\nu$ 's ( $\theta_n = 0$ ) and, e.g.  $\sin^2 2\theta_{13} = 0.01$ , **NOLR** occurs at  $E \cong 4$  **GeV** ( $\Delta m^2(atm) = 2.5 \times 10^{-3} \text{ eV}^2$ ).

S.T.P., hep-ph/9805262

- For the Earth core crossing  $\nu$ 's:  $P_{2\nu} = 1$  **due to NOLR** when

$$\tan \Phi^{\text{man}}/2 \equiv \tan \phi' = \pm \sqrt{\frac{-\cos 2\theta''_m}{\cos(2\theta''_m - 4\theta'_m)}},$$

$$\tan \Phi^{\text{core}}/2 \equiv \tan \phi'' = \pm \frac{\cos 2\theta'_m}{\sqrt{-\cos(2\theta''_m) \cos(2\theta''_m - 4\theta'_m)}}$$

$\Phi^{\text{man}}$  ( $\Phi^{\text{core}}$ ) - phase accumulated in the Earth mantle (core),  
 $\theta'_m$  ( $\theta''_m$ ) - the mixing angle ( $\theta_{13}$ ) in the Earth mantle (core).

$P_{2\nu} = 1$  **due to NOLR** for  $\theta_n = 0$  (Earth center crossing  $\nu$ 's) at,  
 e.g.  $\sin^2 2\theta_{13} = 0.034; 0.154$ ,  $E \cong 3.5; 5.2$  **GeV** ( $\Delta m^2(atm) = 2.5 \times 10^{-3} \text{ eV}^2$ ).

For  $E = 3.5$  **GeV**, the probability  $P_{2\nu} \gtrsim 0.5$  for the values of  $\sin^2 2\theta_{13}$  from the interval  $0.02 \lesssim \sin^2 2\theta_{13} \lesssim 0.10$ .

The current b.f.v. of  $\sin^2 2\theta_{13} = 0.084$ .

M. Chizhov, S.T.P., Phys. Rev. Lett. 83 (1999) 1096 (hep-ph/9903399); Phys. Rev. Lett. 85 (2000) 3979 (hep-ph/0504247); Phys. Rev. D63 (2001) 073003 (hep-ph/9903424).

- The first “oscillogram of the Earth” type figures appeared in M. Chizhov, M. Maris, S.T.P., hep-ph/9810501.

The Earth matter effects in  $\nu_{e(\mu)} \rightarrow \nu_{\mu(e)}$ ,  $\bar{\nu}_{e(\mu)} \rightarrow \bar{\nu}_{\mu(e)}$ ,  $\nu_e \rightarrow \nu_\tau$  and  $\bar{\nu}_e \rightarrow \bar{\nu}_\tau$  oscillations are significant for  $E_\nu \sim (2 - 10)$  GeV.

MSW in the Mantle:  $E_\nu \sim (6-7)$  GeV ( $|\Delta m_{31}^2| \equiv \Delta m^2(atm) = 2.5 \times 10^{-3}$  eV<sup>2</sup>).

The mantle-core (NOLR) enhancement of  $P_m^{2\nu}$  (or  $\bar{P}_m^{2\nu}$ ):

$P_{2\nu} = 1$  due to NOLR for  $\theta_n = 0$  (Earth center crossing  $\nu$ 's) at,  
e.g.  $\sin^2 2\theta_{13} = 0.034; 0.154$ ,  $E \cong 3.5; 5.2$  GeV ( $|\Delta m_{31}^2| = 2.5 \times 10^{-3}$  eV<sup>2</sup>).

For  $E = 3.5$  GeV, the probability  $P_{2\nu} \gtrsim 0.5$  for the values of  $\sin^2 2\theta_{13}$  from the interval  $0.02 \lesssim \sin^2 2\theta_{13} \lesssim 0.10$ .

The current b.f.v. of  $\sin^2 2\theta_{13} = 0.084$ .

The effects of Earth matter on the oscillations of atmospheric (and accelerator) neutrinos have not been observed so far; can be used for performing  $\nu$  oscillation tomography of the Earth with neutrinos having  $E_\nu \sim (2 - 10)$  GeV (ORCA experiment withing the KM3Net project in the Mediterranean sea in Europe, HK experiment (see, e.g., F. Capozzi, S.T.P., 2111.13048; C. Jesus-Valls et al., 2411.12344); DUNE:  $E_\nu \sim 0.2$  GeV, K.J. Kelly et al., 2110.00003).

The fluxes of atmospheric  $\nu_{e,\mu}$  of energy  $E$  which reach the detector after crossing the Earth along a given trajectory specified by the value of  $\theta_n$ ,  $\Phi_{\nu_{e,\mu}}(E, \theta_n)$ , are given by the following expressions in the case of the 3-neutrino oscillations under discussion and  $E_\nu \gtrsim 2$  GeV:

$$\Phi_{\nu_e}(E, \theta_n) \cong \Phi_{\nu_e}^0 (1 + [s_{23}^2 r - 1] P_m^{2\nu}),$$

$$\Phi_{\nu_\mu}(E, \theta_n) \cong \Phi_{\nu_\mu}^0 (1 + s_{23}^4 [(s_{23}^2 r)^{-1} - 1] P_m^{2\nu} - 2c_{23}^2 s_{23}^2 [1 - \text{Re} (e^{-i\kappa} A_m^{2\nu}(\nu_\tau \rightarrow \nu_\tau))]) ,$$

where  $\Phi_{\nu_{e(\mu)}}^0 = \Phi_{\nu_{e(\mu)}}^0(E, \theta_n)$  is the  $\nu_{e(\mu)}$  flux in the absence of neutrino oscillations and

$$r \equiv r(E, \theta_n) \equiv \frac{\Phi_{\nu_\mu}^0(E, \theta_n)}{\Phi_{\nu_e}^0(E, \theta_n)} .$$

$$r = 2, s_{23}^2 = 0.5: [s_{23}^2 r - 1] = 0$$

$$s_{23}^2: \text{b.f.v. } 0.455 (0.569) \text{ NO (IO); } 3\sigma \text{ CL: } (0.416 (0.417)\text{-}0.599 (0.606) .$$

F. Capozzi et al., 2107.00532; M.C. Gonzalez-Garcia et al., 2111.03086

$r(E, \theta_n) \cong (2.6 \div 4.5)$  for neutrinos giving the main contribution to the multi-GeV samples,  $E \cong (2 \div 10)$  GeV.

M. Honda, 1995.

$E_\nu \sim 0.2$  GeV,  $r = 2$ :

$$\Phi_{\nu_e}(E, \theta_n) \cong \Phi_{\nu_e}^0 (1 + [c_{23}^2 r - 1] P_m^{2\nu}) \cong \Phi_{\nu_e}^0, \text{ if } c_{23}^2 = 0.5.$$

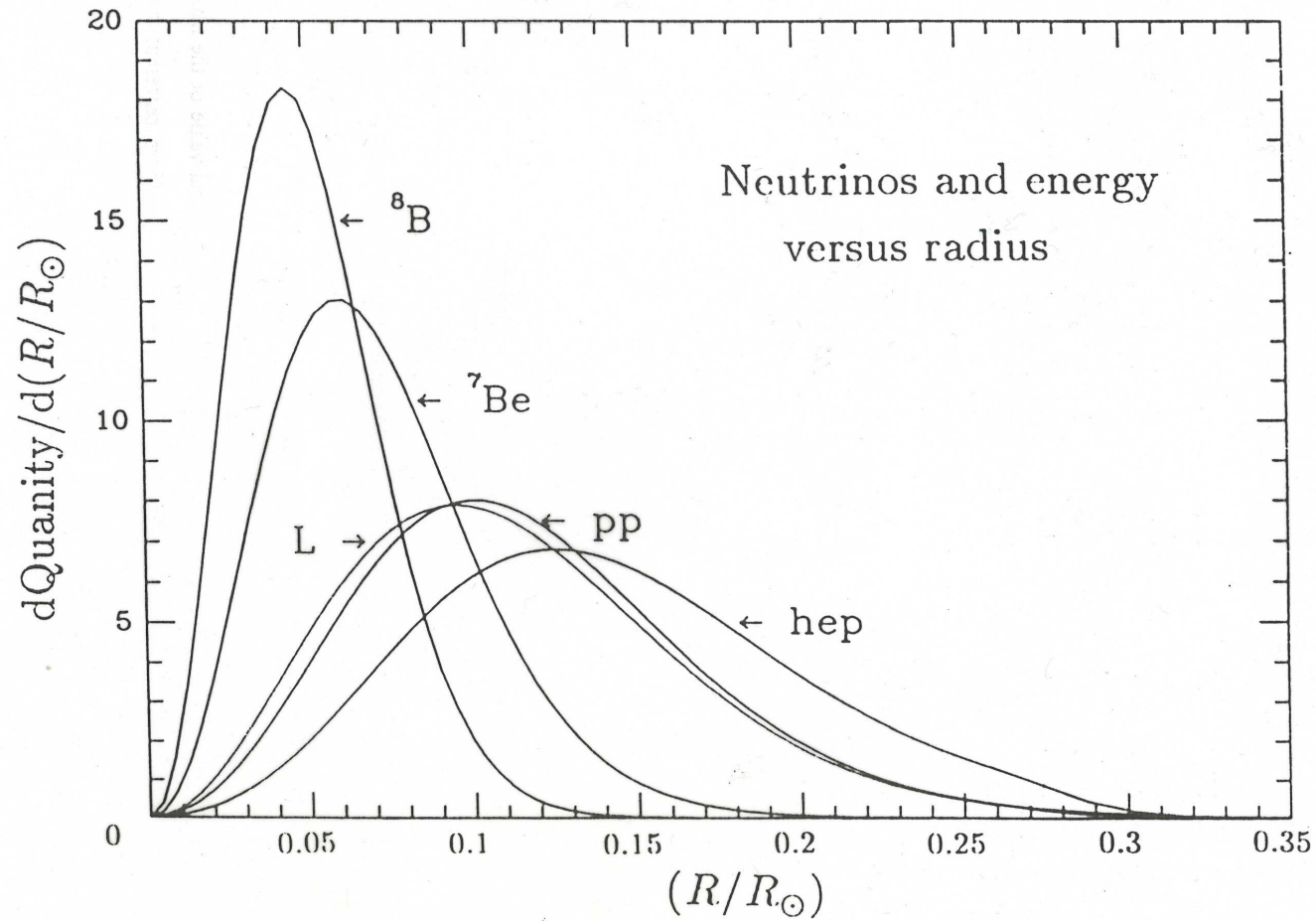
# Solar Neutrinos

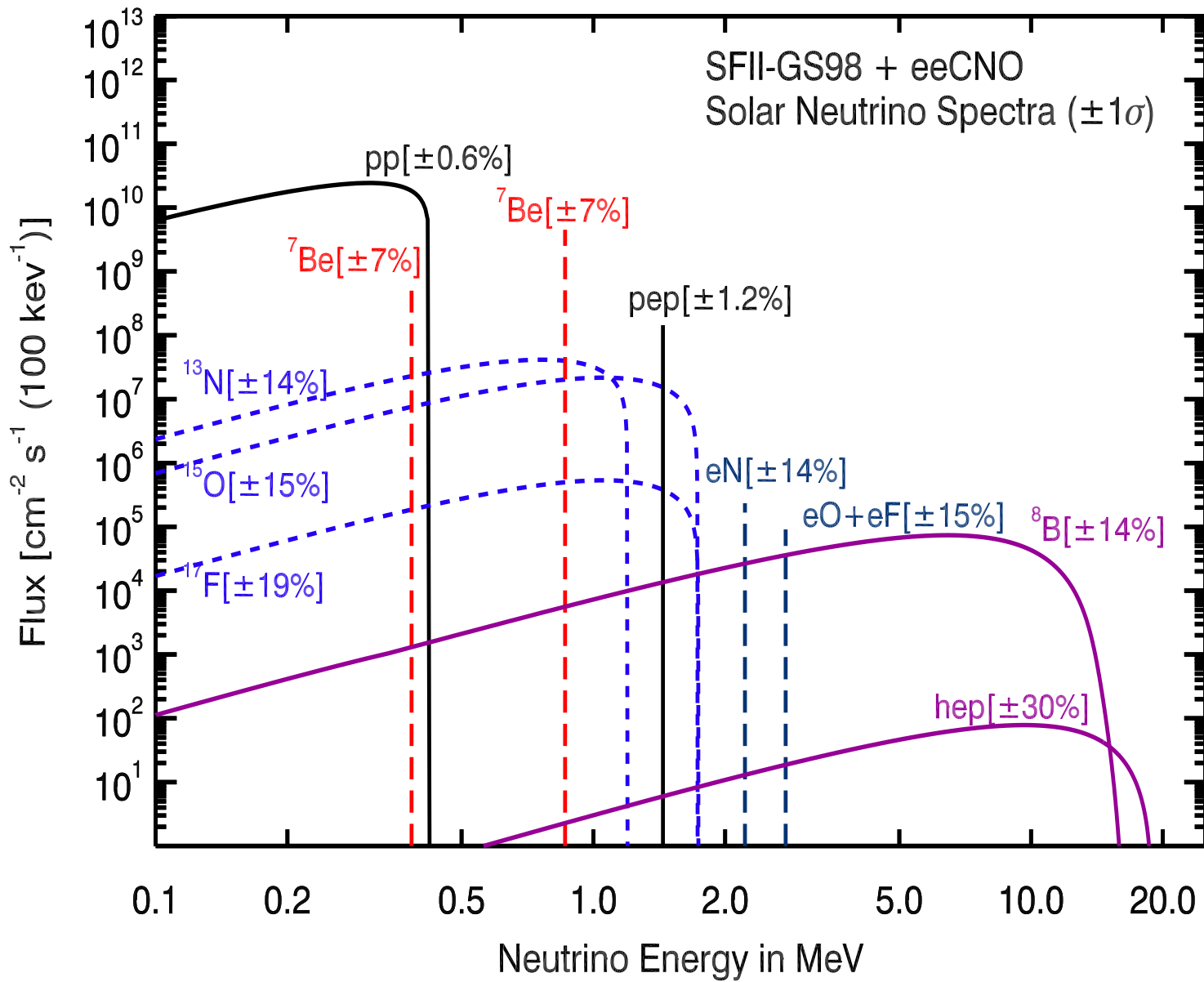


- $pp$  neutrinos,  $E \leq 0.420$  MeV,  $\bar{E} = 0.265$  MeV,
- ${}^7\text{Be}$  neutrinos,  $E=0.862$  MeV (89.7% of the flux),  $0.384$  MeV (10.3%) ,
- ${}^8\text{B}$  neutrinos,  $E \leq 14.40$  MeV,  $\bar{E} = 6.71$  MeV,
- $pep$  neutrinos,  $E=1.442$  MeV,
- of  ${}^{13}\text{N}$ ,  $E \leq 1.199$  MeV,  $\bar{E} = 0.707$  MeV,
- of  ${}^{15}\text{O}$ ,  $E \leq 1.732$  MeV,  $\bar{E} = 0.997$  MeV.

## The neutrinos

147





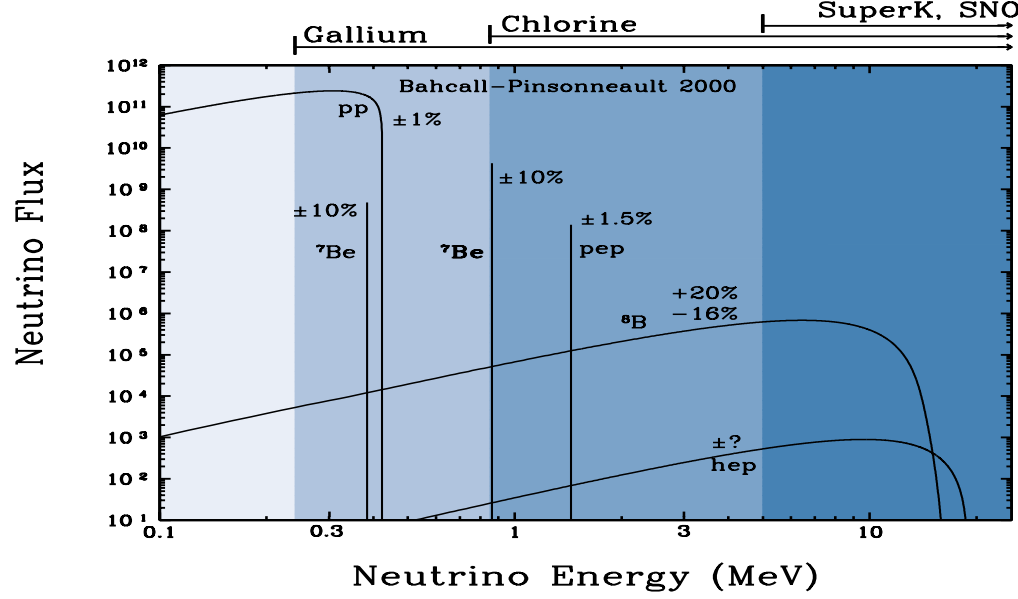


Figure 2: Differential Standard Solar Model neutrino fluxes [14].

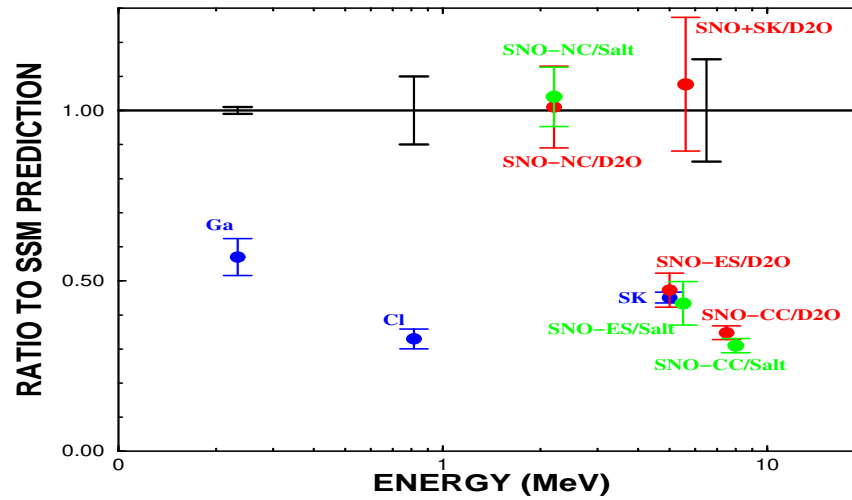
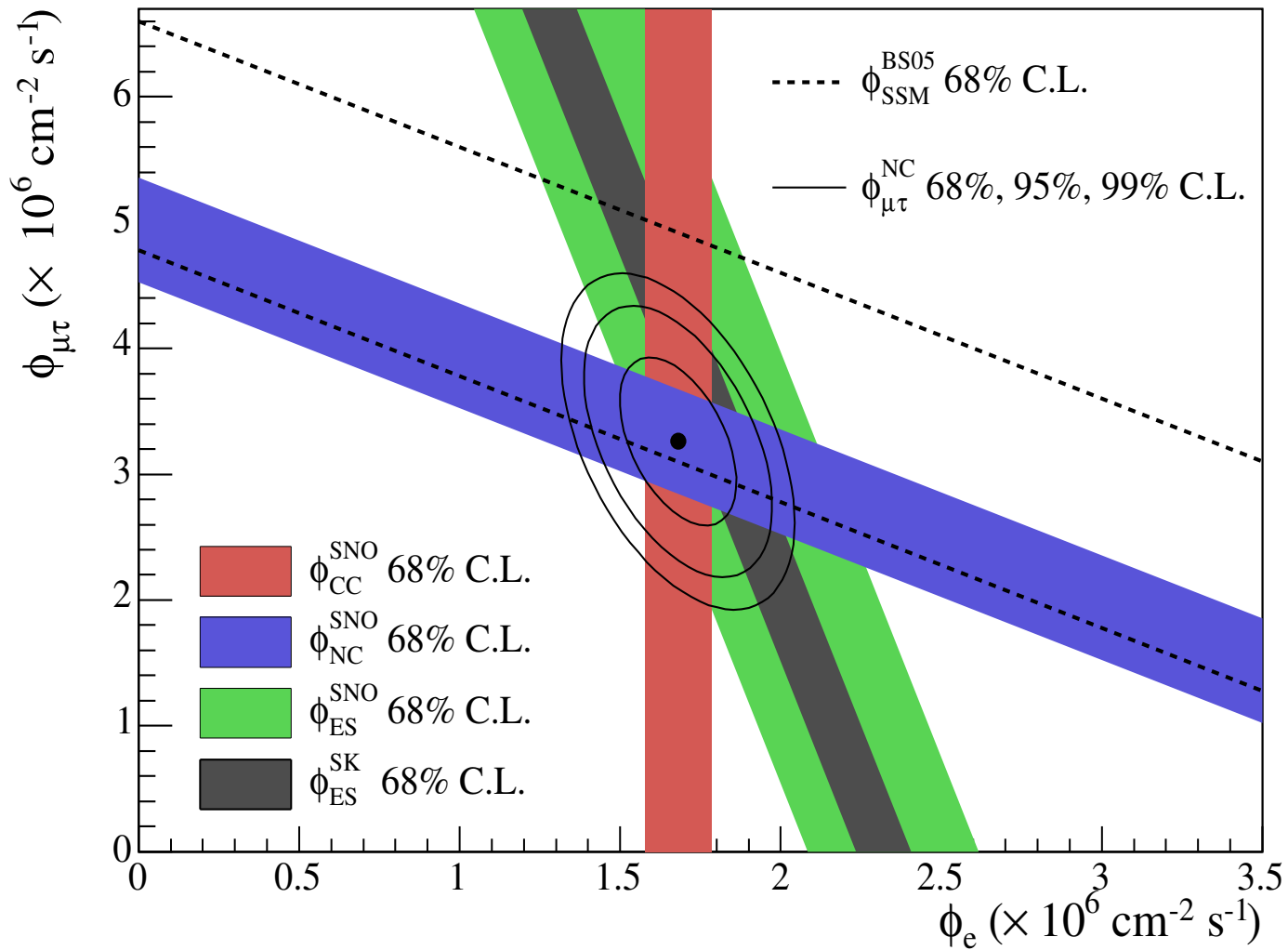


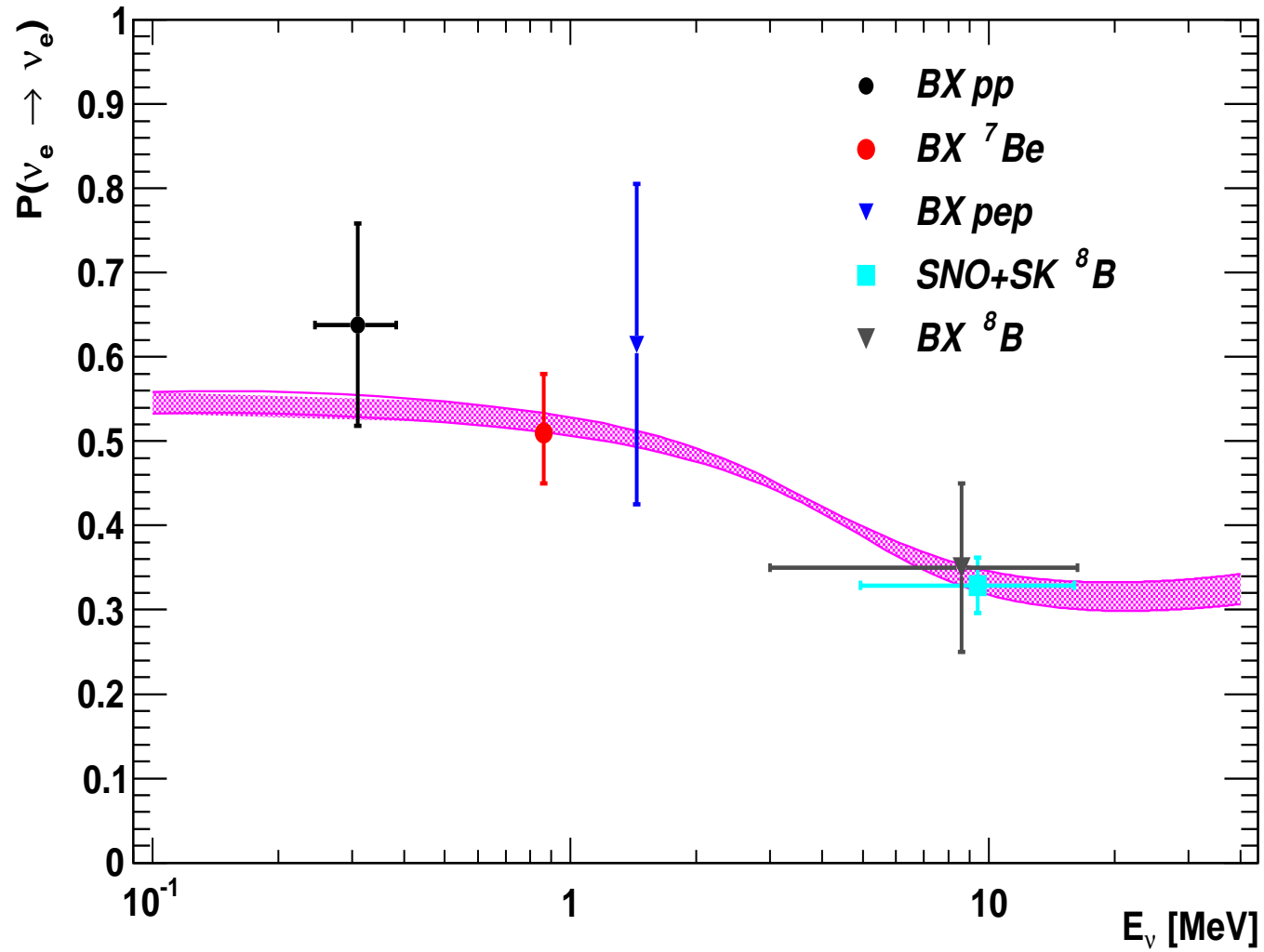
Figure 3: Comparison of measurements to Standard Solar Model predictions.

Experiment	Observed rate/BP04 prediction	Predicted Rate at global best-fit	Predicted Rate at solar best-fit
Ga	$0.52 \pm 0.029$	0.555	0.540
Cl	$0.301 \pm 0.027$	0.356	0.345
SK(ES)	$0.406 \pm 0.014$	0.394	0.395
SNO(CC)	$0.274 \pm 0.019$	0.289	0.289
SNO(ES)	$0.38 \pm 0.052$	0.386	0.386
SNO(NC)	$0.895 \pm 0.08$	0.889	0.908

The observed rates w.r.t predictions from the Standard Solar Model BP04. Shown are also the predicted rates for the best fit values of  $\Delta m_{21}^2$  and  $\sin^2 \theta_{12}$ , obtained in the analysis of the i) global solar neutrino data, and ii) global solar neutrino +KamLAND data.



# Results from BOREXINO



# MSW Transitions of Solar Neutrinos in the Sun and the Hydrogen Atom

$$i \frac{d}{dt} \begin{pmatrix} A_\alpha(t, t_0) \\ A_\beta(t, t_0) \end{pmatrix} = \begin{pmatrix} -\epsilon(t) & \epsilon'(t) \\ \epsilon'(t) & \epsilon(t) \end{pmatrix} \begin{pmatrix} A_\alpha(t, t_0) \\ A_\beta(t, t_0) \end{pmatrix}$$

where  $\alpha = \nu_e$ ,  $\beta = \nu_{\mu(\tau)}$ ,

$$\epsilon(t) = \frac{1}{2} \left[ -\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2} G_F N_e(t) \right],$$

$$\epsilon'(t) = \frac{\Delta m^2}{4E} \sin 2\theta, \text{ with } \Delta m^2 = m_2^2 - m_1^2.$$

- Standard Solar Models

$$N_e(t) = N_e(t_0) \exp \left\{ -\frac{t-t_0}{r_0} \right\}, \quad r_0 \sim 0.1 R_\odot, \quad R_\odot = 6.96 \times 10^5 \text{ km}$$

The region of  $\nu_{\odot}$  production:  $r \lesssim 0.2R_{\odot}$

$$20 N_A \text{ cm}^{-3} \lesssim N_e(x_0) \lesssim 100 N_A \text{ cm}^{-3}$$

Suppose  $N_e(x_0) \gg N_e^{res}$ :  $|\nu_e\rangle \cong |\nu_2^m\rangle$ .

Possible evolution:

The system stays at this level; at the surface:  $|\nu_2^m\rangle = |\nu_2\rangle$

$$P(\nu_e \rightarrow \nu_e) \cong |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2 \theta, \quad \text{Adiabatic}$$

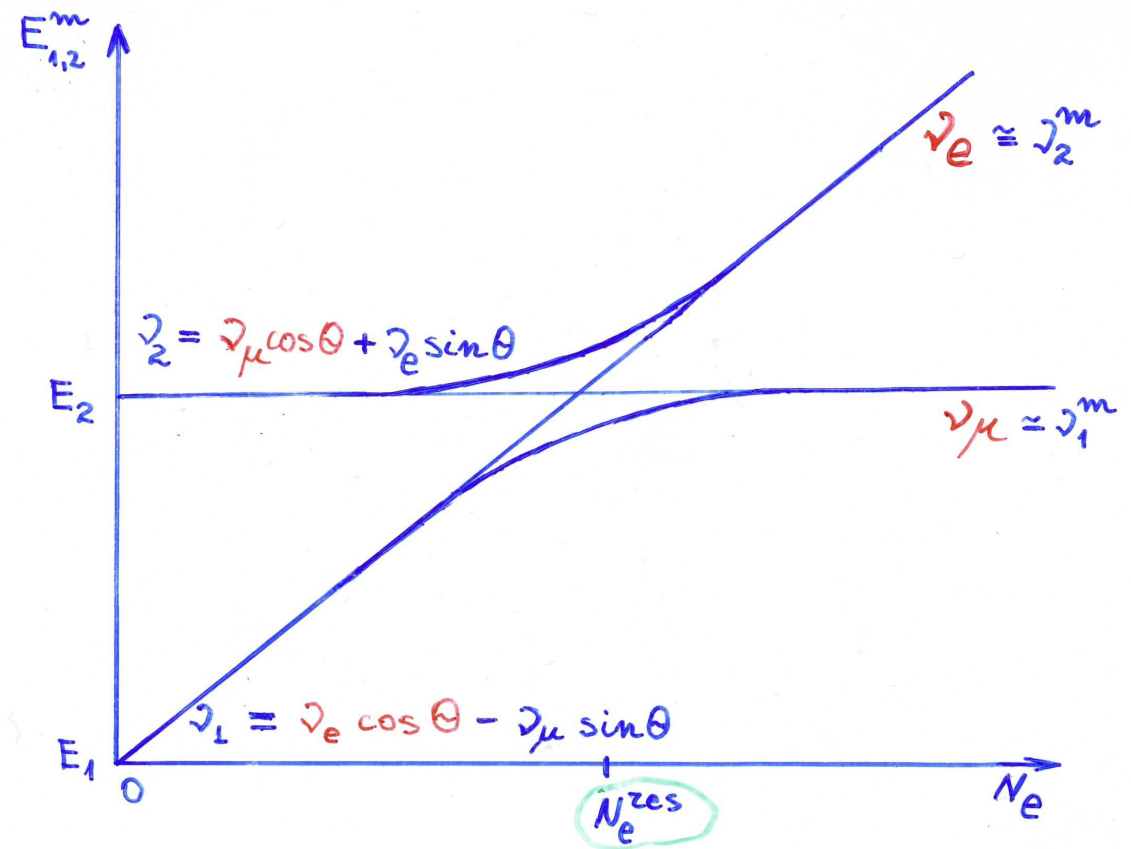
At  $N_e = N_e^{res}$ , where  $E_2^m - E_1^m$  is minimal, the system jumps to lower level  $|\nu_1^m\rangle$ ; at the surface:  $|\nu_1^m\rangle = |\nu_1\rangle$

$$P(\nu_e \rightarrow \nu_e) \cong |\langle \nu_e | \nu_1 \rangle|^2 = \cos^2 \theta, \quad \text{Nonadiabatic}$$

Type of transition:  $P' \equiv P(\nu_2^m(t_0) \rightarrow \nu_1)$ , **jump probability**

4.

$\sin \theta \ll 1.$



- ①.  $P(\nu_2^m \rightarrow \nu_1; t_0, t_0) \equiv P'$  - negligible: adiabatic transition
- ②.  $P'$  - nonnegligible: nonadiabatic

Introducing the dimensionless variable

$$Z = ir_0 \sqrt{2} G_F N_e(t_0) e^{-\frac{t-t_0}{\tau_0}}, \quad Z_0 = Z(t = t_0),$$

and making the substitution

$$A_e(t, t_0) = (Z/Z_0)^{c-a} e^{-(Z-Z_0) + i \int_{t_0}^t \epsilon(t') dt'} A'_e(t, t_0),$$

$A'_e(t, t_0)$  satisfies the confluent hypergeometric equation (CHE):

$$\left\{ Z \frac{d^2}{dZ^2} + (c - Z) \frac{d}{dZ} - a \right\} A'_e(t, t_0) = 0,$$

where

$$a = 1 + ir_0 \frac{\Delta m^2}{2E} \sin^2 \theta, \quad c = 1 + ir_0 \frac{\Delta m^2}{2E}.$$

The confluent hypergeometric equation describing the  $\nu_e$  oscillations in the Sun, coincides in form with the **Schroedinger (energy eigenvalue) equation obeyed by the radial part,  $\psi_{kl}(r)$ , of the non-relativistic wave function of the hydrogen atom,**

$$\Psi(\vec{r}) = \frac{1}{r} \psi_{kl}(r) Y_{lm}(\theta', \phi'),$$

$r$ ,  $\theta'$  and  $\phi'$  are the spherical coordinates of the electron in the proton's rest frame,  $l$  and  $m$  are the orbital momentum quantum numbers ( $m = -l, \dots, l$ ),  $k$  is the quantum number labeling (together with  $l$ ) the electron energy (the principal quantum number is equal to  $(k + l)$ ),  $E_{kl}$  ( $E_{kl} < 0$ ), and  $Y_{lm}(\theta', \phi')$  are the spherical harmonics. The function

$$\psi'_{kl}(Z) = Z^{-c/2} e^{Z/2} \psi_{kl}(r)$$

satisfies the confluent hypergeometric equation in which the variable  $Z$  and the parameters  $a$  and  $c$  are in this case related to the physical quantities characterizing the hydrogen atom:

$$Z = 2 \frac{r}{a_0} \sqrt{-E_{kl}/E_I}, \quad a \equiv a_{kl} = l + 1 - \sqrt{-E_I/E_{kl}}, \quad c \equiv c_l = 2(l + 1)$$

$a_0 = \hbar/(m_e e^2)$  is the Bohr radius and  $E_I = m_e e^4/(2\hbar^2) \cong 13.6 \text{ eV}$  is the ionization energy of the hydrogen atom.

Quite remarkably, the behavior of such different physical systems as solar neutrinos undergoing MSW transitions in the Sun and the non-relativistic hydrogen atom are governed by one and the same differential equation.

**Any solution - linear combination of two linearly independent solutions:**

$$\Phi(a, c; Z), Z^{1-c} \Phi(a - c + 1, 2 - c; Z); \Phi(a', c'; Z = 0) = 1, a', c' \neq 0, -1, -2, \dots$$

$$A(\nu_e \rightarrow \nu_{\mu(\tau)}) = \frac{1}{2} \sin 2\theta \left\{ \Phi(a - c, 2 - c; Z_0) - e^{i(t-t_0)\frac{\Delta m^2}{2E}} \Phi(a - 1, c; Z_0) \right\}.$$

**Sun:**  $N_e(x) \cong N_e(x_0)e^{-\frac{x}{r_0}}$ ,  $r_0 \cong 0.1R_{\odot}$ ,  $R_{\odot} \cong 7 \times 10^5$  km

**The region of  $\nu_{\odot}$  production:**

$$20 N_A \text{ cm}^{-3} \lesssim N_e(x_0) \lesssim 100 N_A \text{ cm}^{-3}: |Z_0| > 500 \text{ (!)}$$

**The solar  $\nu_e$  survival probability:**

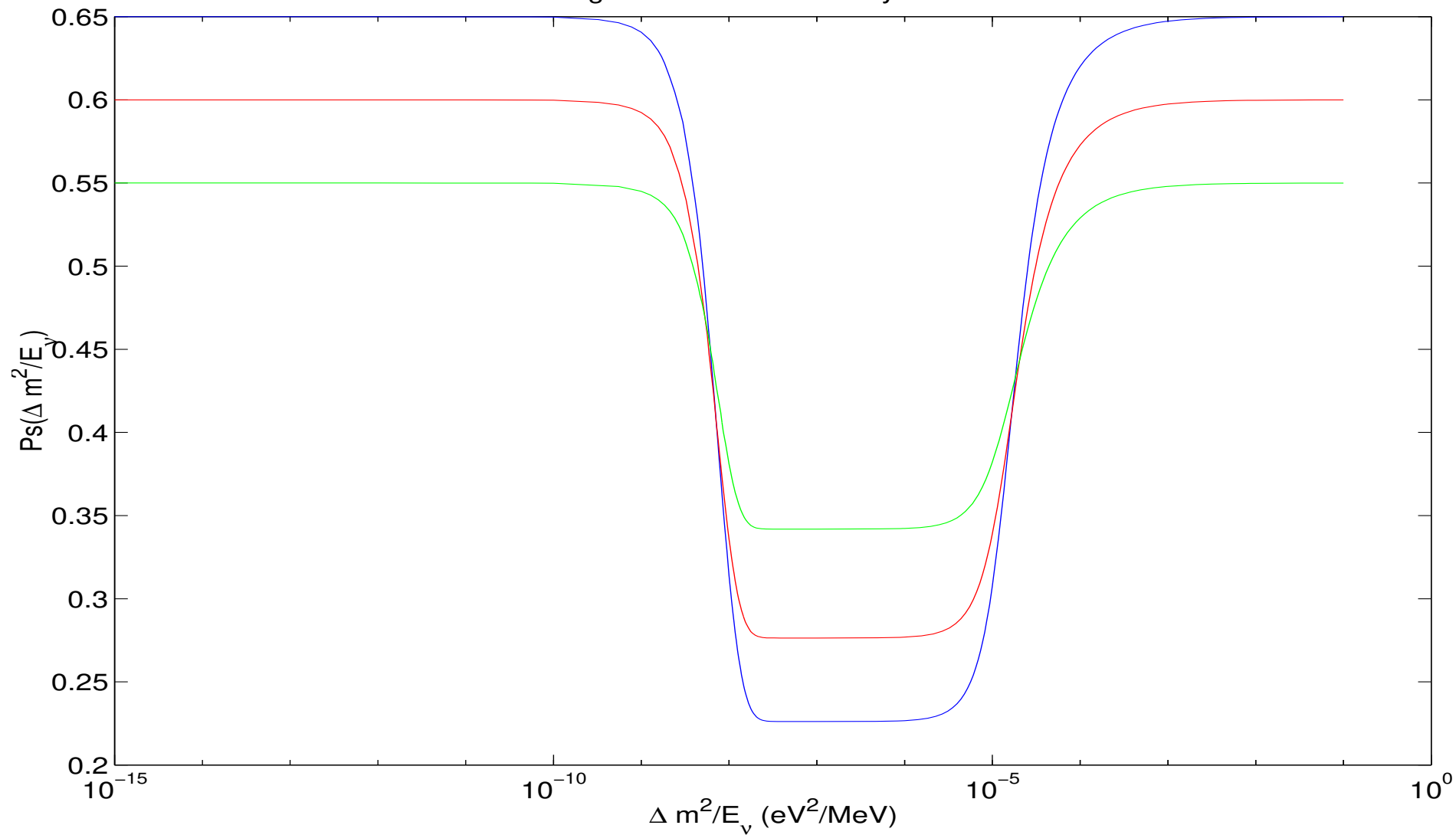
$$\bar{P}(\nu_e \rightarrow \nu_e) = \frac{1}{2} + \left(\frac{1}{2} - P'\right) \cos 2\theta_m^0 \cos 2\theta, \theta = \theta_{12}, \Delta m^2 = \Delta m_{21}^2,$$

$$P' = \frac{e^{-2\pi r_0 \frac{\Delta m^2}{2E}} \sin^2 \theta - e^{-2\pi r_0 \frac{\Delta m^2}{2E}}}{1 - e^{-2\pi r_0 \frac{\Delta m^2}{2E}}}$$

S.T.P., 1988

$$\nu_e \rightarrow \nu_e$$

Averaged Survival Probability in the Sun



$\sin^2 2\theta = 0.7, 0.8, 0.9.$

The solar  $\nu_e$  survival probability:

$$\bar{P}(\nu_e \rightarrow \nu_e) = \frac{1}{2} + \left(\frac{1}{2} - P'\right) \cos 2\theta_m^0 \cos 2\theta,$$

$$P' = \frac{e^{-2\pi r_0 \frac{\Delta m^2}{2E}} \sin^2 \theta - e^{-2\pi r_0 \frac{\Delta m^2}{2E}}}{1 - e^{-2\pi r_0 \frac{\Delta m^2}{2E}}}$$

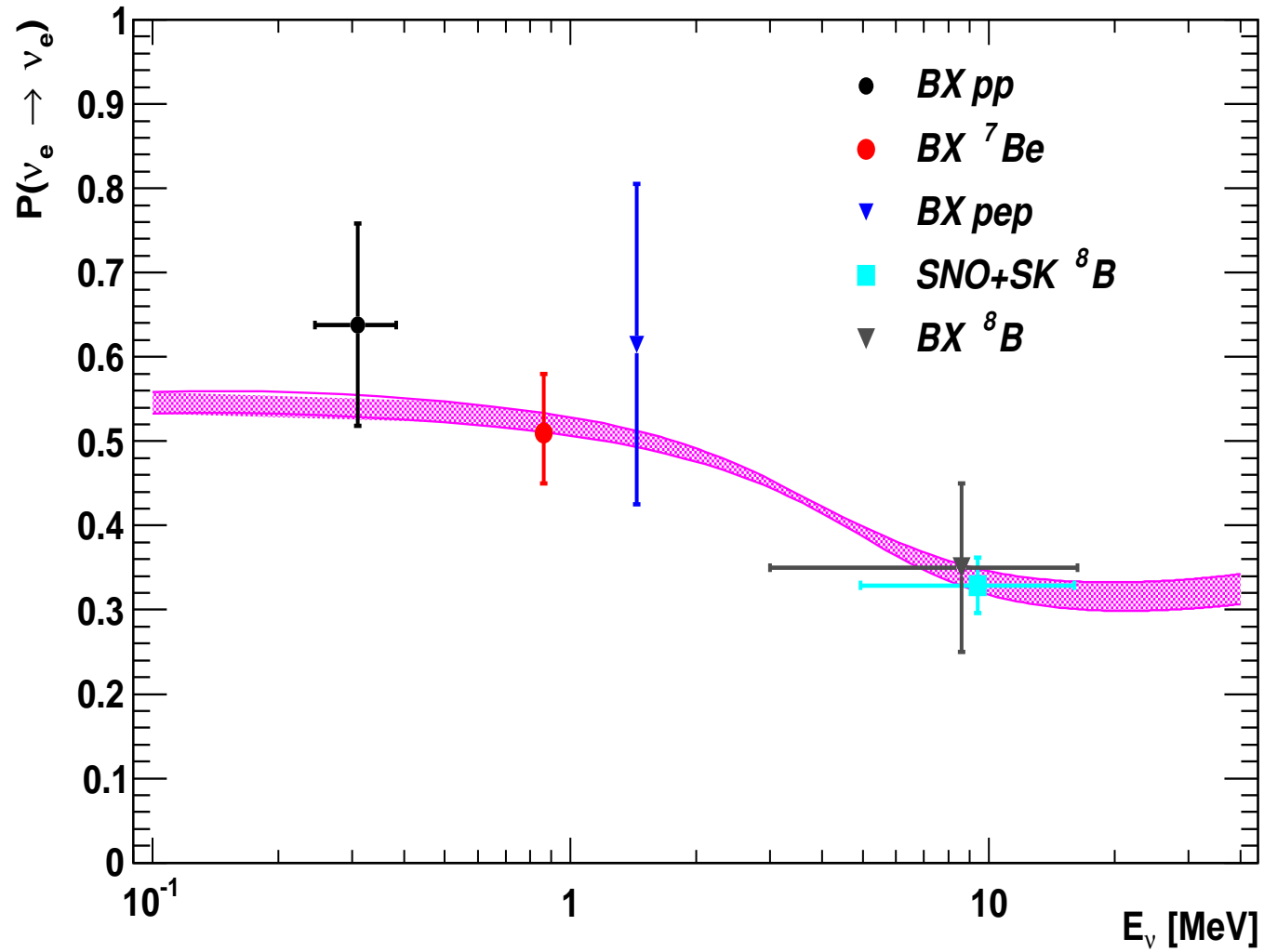
Case 1:  $\cos 2\theta_m^0 = -1$ ,  $P' = 0$ ,  $\bar{P} = \frac{1}{2}(1 - \cos 2\theta)$ .

Case 2:  $\theta_m^0 = \theta$ ,  $P' = 0$ ,  $\bar{P}(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2} \sin^2 2\theta$

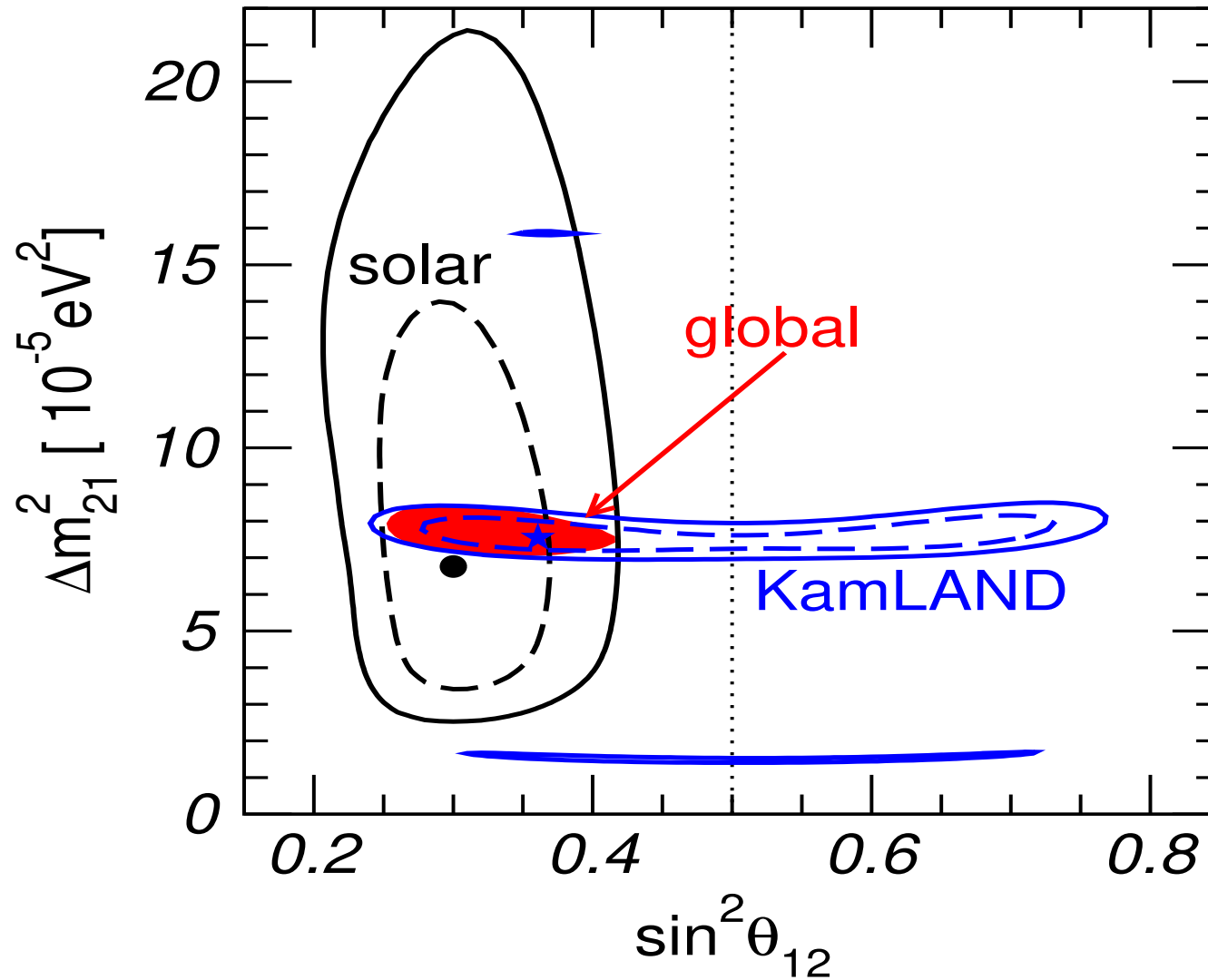
Case 1: SNO, Super Kamiokande;  $\bar{P} \cong 0.3$ :  $\cos 2\theta > 0$ !

Case 2: *pp* neutrinos.

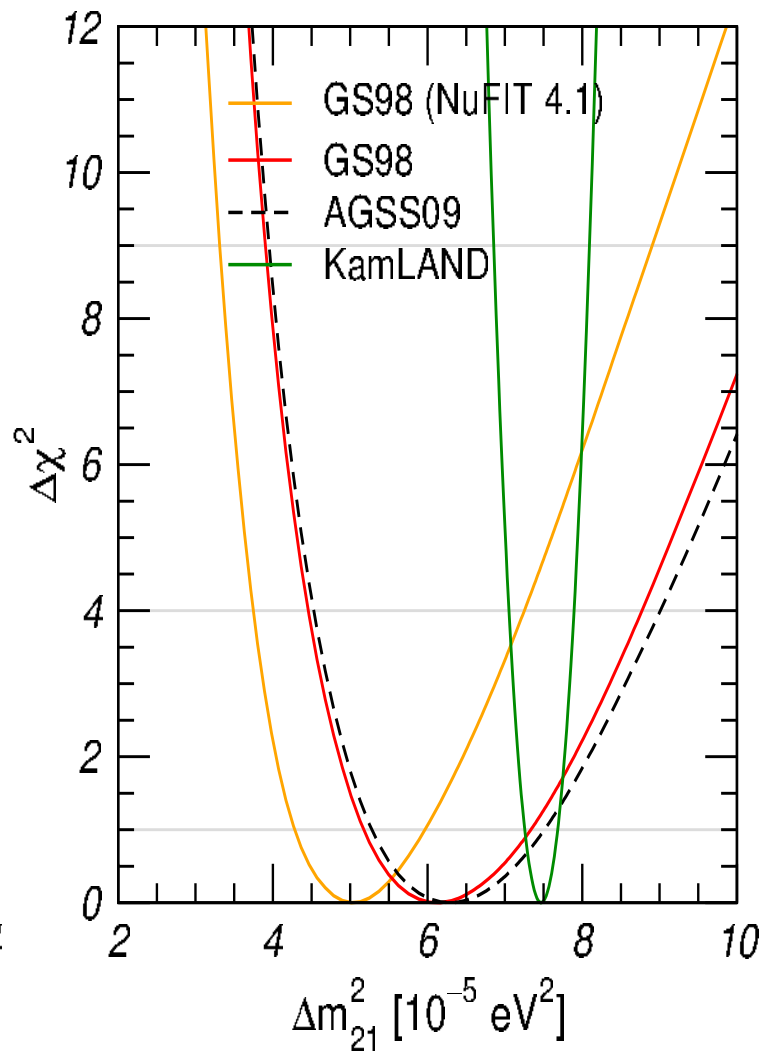
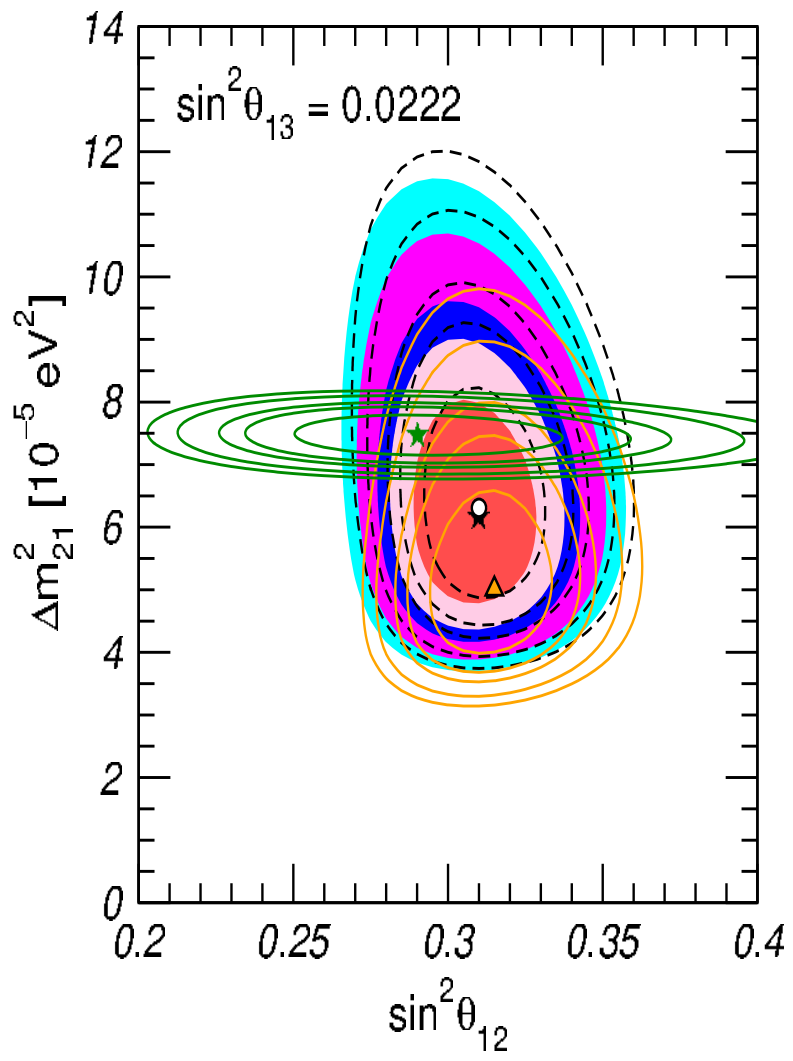
# Results from BOREXINO



# "solar" parameters



T. Schwetz, arXiv:0710.5027[hep-ph]



I. Esteban et al., arXiv:2007.14792 [hep-ph]

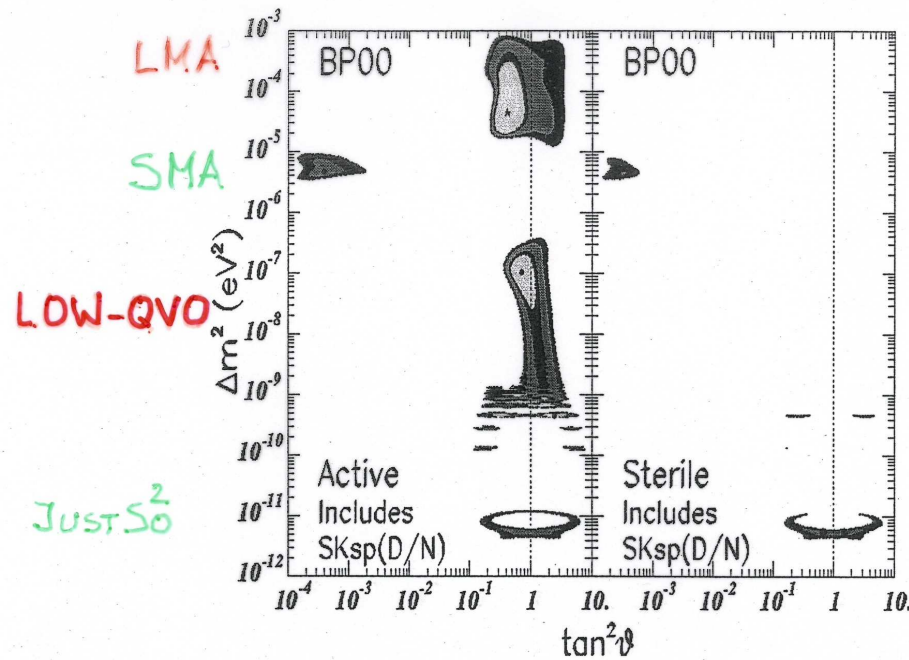


Figure 1: Global solutions including all available solar neutrino data. The input data include the total rates from the Chlorine [2], Gallium (averaged) [3, 5, 4], Super-Kamiokande [6], and SNO [1] experiments, as well as the recoil electron energy spectrum measured by Super-Kamiokande during the day and separately the energy spectrum measured at night. The C.L. contours shown in the figure are 90%, 95%, 99%, and 99.73% ( $3\sigma$ ). The allowed regions are cutoff below  $10^{-3}\text{eV}^2$  by the Chooz reactor measurements [22]. The local best-fit points are marked by dark circles. The theoretical errors for the BP2000 neutrino fluxes are included in the analysis

# Three Neutrino Mixing

$$\nu_{lL} = \sum_{j=1}^3 U_{lj} \nu_{jL} .$$

$U$  is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

- $U$  -  $n \times n$  unitary:

	$n$	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6

CP-violating phases:

• $\nu_j$ - Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• $\nu_j$ - Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$ : 1 Dirac and  
2 additional CP-violating phases, Majorana phases

S.M. Bilenky, J. Hosek, S.T.P., 1980

# Majorana versus Dirac Massive Neutrinos

## Majorana Neutrinos (Fermions)

Can be defined in QFT using fields or states.

Fields:  $\chi_k(x)$  - 4 component (spin 1/2), complex,  $m_k$

**Majorana condition:**

$$C (\bar{\chi}_k(x))^T = \xi_k \chi_k(x), \quad |\xi_k|^2 = 1, \quad C^{-1} \gamma_\mu C = -\gamma_\mu^T \quad (C^T = -C)$$

- Invariant under proper Lorentz transformations.
- Reduces by 2 the number of components in  $\chi_k(x)$ .

**Implications:**

$$U(1) : \chi_k(x) \rightarrow e^{i\alpha} \chi_k(x) - \text{impossible}$$

- $\chi_k(x)$  cannot absorb phases.
- $Q_{U(1)} = 0 : Q_{\text{el}} = 0, L_l = 0, L = 0, \dots$
- $\chi_k(x)$ : 2 spin states of a spin 1/2 absolutely neutral particle
- $\chi_k \equiv \bar{\chi}_k$

## Propagators: $\Psi(x)$ –Dirac, $\chi(x)$ –Majorana

$$\langle 0|T(\Psi_\alpha(x)\bar{\Psi}_\beta(y))|0\rangle = S_{\alpha\beta}^F(x-y) ,$$

$$\langle 0|T(\Psi_\alpha(x)\Psi_\beta(y))|0\rangle = 0 , \quad \langle 0|T(\bar{\Psi}_\alpha(x)\bar{\Psi}_\beta(y))|0\rangle = 0 .$$

$$\langle 0|T(\chi_\alpha(x)\bar{\chi}_\beta(y))|0\rangle = S_{\alpha\beta}^F(x-y) ,$$

$$\langle 0|T(\chi_\alpha(x)\chi_\beta(y))|0\rangle = -\xi^* S_{\alpha\kappa}^F(x-y) C_{\kappa\beta} ,$$

$$\langle 0|T(\bar{\chi}_\alpha(x)\bar{\chi}_\beta(y))|0\rangle = \xi C_{\alpha\kappa}^{-1} S_{\kappa\beta}^F(x-y)$$

$$U_{CP} \chi(x) U_{CP}^{-1} = \eta_{CP} \gamma_0 \chi(x'), \quad \eta_{CP} = \pm i .$$

## Special Properties of the Currents of $\chi(x)$ –Majorana:

$$\bar{\chi}(x)\gamma_\alpha\chi(x) = 0 : \quad Q_{U(1)} = 0 \quad (Q_{U(1)}(\Psi) \neq 0);$$

Has important implications, e.g. for SUSY DM (neutralino) abundance determination (calculation).

$$\bar{\chi}(x)\sigma_{\alpha\beta}\chi(x) = 0 : \quad \mu_\chi = 0 \quad (\mu_\Psi \neq 0)$$

$$\bar{\chi}(x)\sigma_{\alpha\beta}\gamma_5\chi(x) = 0 : \quad d_\chi = 0 \quad (d_\Psi \neq 0, \text{ if } CP \text{ is not conserved})$$

$\chi(x)$  cannot couple to a real photon (field).

$\chi(x)$  couples to a virtual photon through an anapole moment :

$$(g_{\alpha\beta} q^2 - q_\alpha q_\beta)\gamma_\beta\gamma_5 F_a(q^2).$$

**Properties of Currents Formed by  $\chi_1(x)$ ,  $\chi_2(x)$ :**  $\chi_2 \rightarrow \chi_1 + \gamma$ ,  $\chi_2 \rightarrow \chi_1 \chi_1 \chi_1$ , etc.

$$\bar{\chi}_1(x) \gamma_\alpha (v - a \gamma_5) \chi_2(x) \quad (\bar{\chi}_1(x) \gamma^\alpha (1 - \gamma_5) \chi_1(x), \dots) :$$

- **CP is conserved:**  $v = 0$  ( $a = 0$ ) **if**  $\eta_{1CP} = \eta_{2CP}$  ( $\eta_{1CP} = -\eta_{2CP}$ )
- **CP is not conserved:**  $v \neq 0$ ,  $a \neq 0$

(Has important implications also, e.g. for **SUSY** neutralino phenomenology:  $e^+ + e^- \rightarrow \chi_1 + \chi_2$ ,  $\chi_2 \rightarrow \chi_1 + l^+ + l^-$ , etc.)

$$\bar{\chi}_1(x) \sigma_{\alpha\beta} (\mu_{12} - d_{12} \gamma_5) \chi_2(x) \quad (F^{\alpha\beta}(x)) :$$

- **CP is conserved:**  $\mu_{12} = 0$  ( $d_{12} = 0$ ) **if**  $\eta_{1CP} = \eta_{2CP}$  ( $\eta_{1CP} = -\eta_{2CP}$ )
- **CP is not conserved:**  $\mu_{12} \neq 0$ ,  $d_{12} \neq 0$

## PMNS Matrix: CPV Phases

$$\mathcal{L}^{CC}(x) = -\frac{g}{2\sqrt{2}} \sum_l \bar{l}(x) \gamma_\alpha (1 - \gamma_5) U_{lj} \nu_j(x) W^\alpha(x) + \text{h.c.}$$

Assume  $n$  families.

$\nu_j$ : Dirac particles (fields); phases of  $l(x)$ ,  $\nu_j(x)$  - unphysical.

CPV phases:  $\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$ : no CPV if  $n = 1, 2$ ;

$n = 3$ : 1 physical CPV phases, Dirac phase (similar to the quark case).

$\nu_j$ : Majorana particles (fields); phases of  $l(x)$  - unphysical;  $\nu_j(x)$  cannot "absorb" phases.

CPV phases:  $\frac{n(n+1)}{2} - n = \frac{n(n-1)}{2}$ : no CPV if  $n = 1$ ;

$n = 2$ : 1 physical CPV phase, Majorana phase (used, e.g., in LG);

$n = 3$ : 3 physical CPV phases, 1 Dirac + 2 Majorana.

S.M. Bilenky, J. Hosek, S.T.P., 1980

## CP Invariance

$$U_{CP} l(x) U_{CP}^\dagger = \eta_l \gamma_0 C (\bar{l}(x_p))^T,$$

$$U_{CP} W_\alpha(x) U_{CP}^\dagger = \eta_W \eta_\alpha W_\alpha^\dagger(x_p),$$

$\eta_l, \eta_w$  - **unphysical phases**,  $|\eta_{l(w)}|^2 = 1$ ,  $\eta_\alpha = \text{diag}(-1, 1, 1, 1)$ .

$$U_{CP} \nu_i(x) U_{CP}^\dagger = \eta_i \gamma_0 C (\bar{\nu}_i(x_p))^T, \text{ Dirac } \nu_i,$$

$$U_{CP} \nu_k(x) U_{CP}^\dagger = \eta_k^{\text{CP}} \gamma_0 \nu_k(x_p), \text{ Majorana } \nu_k : \eta_k^{\text{CP}} = \pm i .$$

$\eta_i$  - **unphysical phase**,  $|\eta_i|^2 = 1$ ;

$\eta_k^{\text{CP}} = \pm i = i \rho_k$  - **CP parity of Majorana neutrino**  $\nu_k$  .

**CP Invariance:**  $U_{CP} \mathcal{L}^{CC}(x) U_{CP}^\dagger = \mathcal{L}^{CC}(x_p)$

$$(U_{PMNS})_{li}^* = \eta_w \eta_l^* \eta_i (U_{PMNS})_{li}, \quad \text{Dirac } \nu_i$$

**Convenient choice**  $\eta_w \eta_l^* \eta_i = 1$ :  $(U_{PMNS})_{li}^* = (U_{PMNS})_{li}$ .

$$(U_{PMNS})_{lk}^* = i \rho_k \eta_w^* \eta_l^* (U_{PMNS})_{lk}, \quad \text{Majorana } \nu_k.$$

**Convenient choice:**  $\eta_w = 1, \eta_l = i$ :  $(U_{PMNS})_{lk}^* = \rho_k (U_{PMNS})_{lk}, \rho_k = \pm 1$ .

# PMNS Matrix: Standard Parametrization

$$U = V P, \quad P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix},$$

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

- $s_{ij} \equiv \sin \theta_{ij}$ ,  $c_{ij} \equiv \cos \theta_{ij}$ ,  $\theta_{ij} = [0, \frac{\pi}{2}]$ ,
- $\delta$  - Dirac CPV phase,  $\delta = [0, 2\pi]$ ; CP inv.:  $\delta = 0, \pi, 2\pi$ ;
- $\alpha_{21}, \alpha_{31}$  - Majorana CPV phases; CP inv.:  $\alpha_{21(31)} = k(k')\pi$ ,  $k(k') = 0, 1, 2, \dots$   
S.M. Bilenky et al., 1980
- $\Delta m_{\odot}^2 \equiv \Delta m_{21}^2 \cong 7.34 \times 10^{-5} \text{ eV}^2 > 0$ ,  $\sin^2 \theta_{12} \cong 0.305$ ,  $\cos 2\theta_{12} \gtrsim 0.306$  ( $3\sigma$ ),
- $|\Delta m_{31(32)}^2| \cong 2.448$  (2.502)  $\times 10^{-3} \text{ eV}^2$ ,  $\sin^2 \theta_{23} \cong 0.545$  (0.551), NO (IO) ,
- $\theta_{13}$  - the CHOOZ angle:  $\sin^2 \theta_{13} = 0.0222$  (0.0223)  
F. Capozzi et al. (Bari Group), arXiv:2003.08511.

- $\text{sgn}(\Delta m_{\text{atm}}^2) = \text{sgn}(\Delta m_{31(32)}^2)$  not determined

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 > 0, \quad \text{normal mass ordering (NO)}$$

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{32}^2 < 0, \quad \text{inverted mass ordering (IO)}$$

Convention:  $m_1 < m_2 < m_3$  - NO,  $m_3 < m_1 < m_2$  - IO

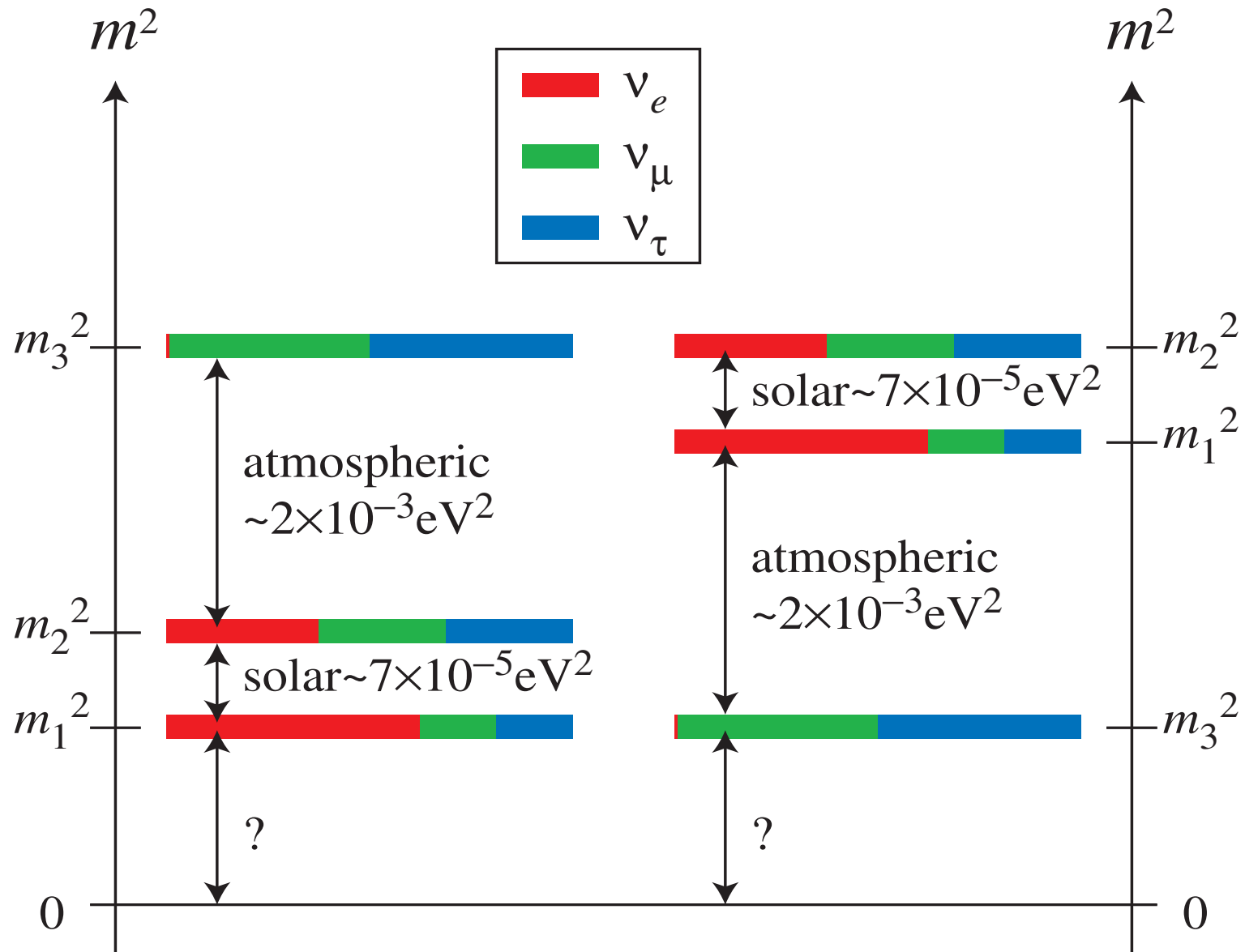
$$m_1 \ll m_2 < m_3, \quad \text{NH,}$$

$$m_3 \ll m_1 < m_2, \quad \text{IH,}$$

$$m_1 \cong m_2 \cong m_3, \quad m_{1,2,3}^2 \gg |\Delta m_{31(32)}^2|, \quad \text{QD; } m_j \gtrsim 0.10 \text{ eV.}$$

- $m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$  - NO;

- $m_1 = \sqrt{m_3^2 + \Delta m_{23}^2 - \Delta m_{21}^2}, \quad m_2 = \sqrt{m_3^2 + \Delta m_{23}^2}$  - IO;



• **Dirac phase**  $\delta$ :  $\nu_l \leftrightarrow \nu_{l'}, \bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}, l \neq l'$ ;  $A_{\text{CP}}^{(l,l')} \propto J_{\text{CP}} \propto \sin \theta_{13} \sin \delta$ :

$3\nu$ —mixing:

P.I. Krastev, S.T.P., 1988

$$A_{\text{CP}}^{(l,l')} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) , \quad l \neq l' = e, \mu, \tau$$

$$A_{\text{T}}^{(l,l')} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

$$A_{\text{CP(T)}}^{(e,\mu)} = A_{\text{CP(T)}}^{(\mu,\tau)} = -A_{\text{CP(T)}}^{(e,\tau)}$$

**In vacuum:**  $A_{CP(T)}^{(e,\mu)} = 4 J_{CP} F_{osc}^{vac}$  ( $A_{CP(T)}^{(e,\mu)} = A_{CP(T)}^{(\mu,\tau)} = -A_{CP(T)}^{(e,\tau)}$ )

$$J_{CP} = \text{Im} \{ U_{e1} U_{\mu 2} U_{e2}^* U_{\mu 1}^* \} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

$$F_{osc}^{vac} = \sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{32}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{13}^2 L}{2E}\right)$$

P.I. Krastev, S.T.P., 1988

**In matter: Matter effects (Earth, Sun) violate**

**CP :**  $P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$

**CPT :**  $P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_{l'} \rightarrow \bar{\nu}_l)$

P. Langacker et al., 1987

Can conserve the T-invariance (constant density or density profile symmetric relative to the middle point, e.g., **Earth**)

$$P(\nu_l \rightarrow \nu_{l'}) = P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

**In matter with constant density (T2K, NO $\nu$ A, T2HK, DUNE):**

$$J_{CP}^{mat} = J_{CP}^{vac} R_{CP}, \quad A_T^{(e,\mu)} = J_{CP}^{mat} F_{osc}^{mat}$$

$R_{CP}$ - real, does not depend on  $\theta_{23}$  and  $\delta$ ;  $|R_{CP}| \lesssim 2.5$

P.I. Krastev, S.T.P., 1988

**2018:  $R_{CP} > 0$ ,  $R_{CP} \leq 1.2$ ; numerically  $R_{CP}$ =Naumov-HS factor (from 1991).**

S.T.P., Y.-L. Zhou, 1806.09112

Current data:  $|J_{CP}| \lesssim 0.040$  (can be relatively large!); b.f.v. with  $\delta = 3\pi/2$ :  
 $J_{CP} \cong -0.035$ .

• Majorana phases  $\alpha_{21}, \alpha_{31}$ :

–  $\nu_l \leftrightarrow \nu_{l'}, \bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$  not sensitive;

S.M. Bilenky, J. Hosek, S.T.P., 1980;  
P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

–  $|\langle m \rangle|$  in  $(\beta\beta)_{0\nu}$ -decay depends on  $\alpha_{21}, \alpha_{31}$ ;

–  $\Gamma(\mu \rightarrow e + \gamma)$  etc. in SUSY theories depend on  $\alpha_{21,31}$ ;

– BAU, leptogenesis scenario:  $\delta, \alpha_{21,31}$  !

Parameter	Ordering	Best fit	$1\sigma$ range	$2\sigma$ range	$3\sigma$ range	" $1\sigma$ " (%)
$\Delta m_{21}^2/10^{-5} \text{ eV}^2$	NO, IO	$7.49^{+0.19}_{-0.19}$	–	–	6.92 – 8.05	2.5
$\sin^2 \theta_{12}/10^{-1}$	NO, IO	$3.08^{+0.012}_{-0.011}$	–	–	2.75 – 3.45	4.5
$\Delta m_{31}^2/10^{-3} \text{ eV}^2$	NO	$2.513^{+0.021}_{-0.019}$	–	–	2.451 – 2.578	1.1
$\Delta m_{32}^2/10^{-3} \text{ eV}^2$	IO	$-2.484 \pm 0.020$	–	–	-2.547 – (-2.421)	1.1
$\sin^2 \theta_{13}/10^{-2}$	NO	$2.215^{+0.056}_{-0.058}$	–	–	2.0300 – 2.388	3.0
	IO	$2.231 \pm 0.056$	–	–	2.060 – 2.409	3.1
$\sin^2 \theta_{23}/10^{-1}$	NO	$4.70^{+0.017}_{-0.013}$	–	–	<b>4.35 – 5.85</b>	5.5
	IO	$5.50^{+0.012}_{-0.015}$	–	–	<b>4.40 – 5.84</b>	4.4
$\delta$	NO	$212^{+26}_{-41}$	–	–	124 – 364	19
	IO	$274^{+22}_{-25}$	–	–	<b>201 – 335</b>	8

$$\Delta\chi_{\text{IO-NO}}^2 \quad \text{IO-NO} \quad +6.1 (2.45\sigma)$$

Global  $3\nu$  analysis of oscillation parameters: best-fit values and allowed ranges at  $N_\sigma = 3$  for either NO or IO, including all data (also the SK atmospheric neutrino data). The latter column shows the formal " $1\sigma$  fractional accuracy" for each parameter, defined as  $1/6$  of the  $3\sigma$  range, divided by the best-fit value and expressed in percent. The last row reports the difference between the  $\chi^2$  minima in IO and NO. The results on the NO and CPV due to  $\delta$  are inconclusive.

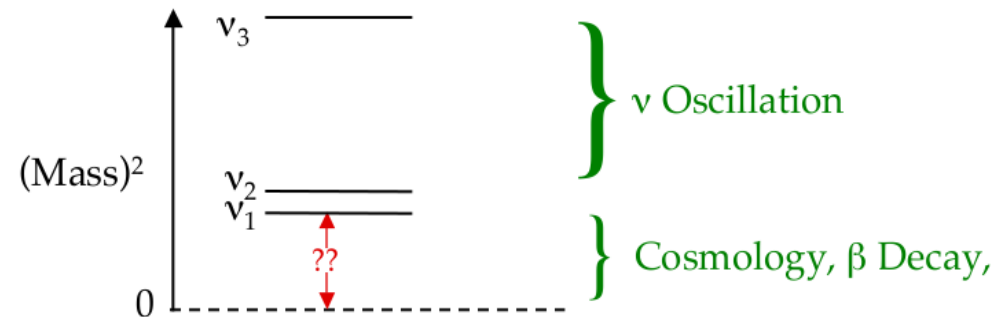
I. Esteban et al., arXiv:2410.05380 (NuFit-6.0 results).

$\sin^2 \theta_{23}$  - relatively large uncertainty.

$$\Delta m_{21}^2 / |\Delta m_{31}^2| \cong 1/30.$$

# Absolute Neutrino Mass Scale

## The Absolute Scale of Neutrino Mass



How far above zero  
is the whole pattern?

$$\text{Oscillation Data} \Rightarrow \sqrt{\Delta m_{\text{atm}}^2} < \text{Mass}[\text{Heaviest } \nu_i]$$

4

Due to B. Kayser

# Absolute Neutrino Mass Measurements

Experiments on  $e^-$ -spectrum in  ${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}_e$   
(super-allowed  ${}^3\text{H} \rightarrow {}^3\text{He}$  transition, NME - constant,  $E_0 \simeq 18574.3 \pm 1.7$  eV,  
half-life 12.3 years)

$$m_{\bar{\nu}_e} < 2.2 \text{ eV} \quad (95\% \text{ C.L.}) \text{ Troitzk, Mainz.}$$

We have  $m_{\bar{\nu}_e} \simeq m_{1,2,3}$  in the case of QD spectrum.

The **KATRIN** experiment (11/06/2018) is planned to reach sensitivity

$$\text{KATRIN: } m_{\bar{\nu}_e} \sim 0.2 \text{ eV}$$

i.e., it will probe the region of the QD spectrum.

**KATRIN data (2022):**

$$m_{\bar{\nu}_e} < 0.81 \text{ eV} \quad (90\% \text{ C.L.})$$

**Latest KATRIN data (2024):**

$$m_{\bar{\nu}_e} < 0.45 \text{ eV} \quad (90\% \text{ C.L.})$$

E. Lokhov et al., talk at Neutrino 2024 (June 17-22, 2024, Milano)

$$\frac{d\Gamma(^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e)}{dE_e} = \sum_i |U_{ei}|^2 \frac{d\Gamma(m_i)}{dE_e},$$

$$\frac{d\Gamma(m_i)}{dE_e} = C p_e (E_e + m_e) (E_0 - E_e) \sqrt{(E_0 - E_e)^2 - m_i^2} F(E_e) \theta(E_0 - E_e - m_i).$$

Here  $E_e \leq E_0 - m_i$  is the kinetic energy of the electron,  $E_0$  is the energy released in the decay,  $p_e$  is the electron momentum,  $m_e$  is the mass of the electron,  $F(E_e)$  is the Fermi function which takes into account the Coulomb interaction of the final state particles, and  $C$  is a constant.  $(E_0 - E_e)$  is the neutrino energy and  $p_i = \sqrt{(E_0 - E_e)^2 - m_i^2}$  is the momentum of neutrino with mass  $m_i$ .

Usually

$$m_\beta \equiv m_{\bar{\nu}_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \quad (\simeq m_{1,2,3}, \quad \text{QD spectrum})$$

is considered as the neutrino mass related observable in  $\beta$ -decay experiments.

Improved  $\beta$  energy resolution requires a **BIG**  $\beta$  spectrometer.





Future plans ( $\gtrsim$  2027): **KATRIN++**, 50 g of  $^3\text{H}$  (use of atomic  $^3\text{H}$ ); goal: reach sensitivity to  $m_\beta < 0.04$  eV.

In development: **PROJECT 8** (CRES technique, B. Monreal, J. A. Formaggio, Phys.Rev.D 80(2009) 051301):

$$2\pi f(E_\beta) = \frac{eB}{E_\beta + m_e}; \text{ Energy resolution: } \frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$

CRES technique demonstrated by Project 8 for  $e^-$  magnetically trapped inside a wave guide; best E-resolution  $\Delta E_{FWHM} = 1.7$  eV at 18 keV.

**Limit obtained**  $m_\beta < 152$  eV; **goal:**  $m_\beta < 0.04$  eV.

In development: **HOLMES** and **ECHO**  $e^-$  capture calorimetric experiments,



$H_i = \text{M1, M2, N1, N2, O1, O2, P1}$ ; EC from shell  $\geq$  M1.

$Q = 2863.2 \pm 0.6$  eV;  $\tau_{1/2} \cong 4570$  years;  $2 \times 10^{11}$   $^{163}\text{Ho}$  nuclei  $\leftrightarrow$  1 Bq.

End-point rate and  $m_\beta$  sensitivity depend on  $Q - E_b(M1)$ .

**Current limits**  $m_{\nu_e} < 28$  eV (**HOLMES**), 19 eV (**ECHO**) (90% C.L.)

A. Nicciotti, talk at Neutrino 2024

# Mass and Hierarchy from Cosmology

Cosmological and astrophysical data on  $\sum_j m_j$  - the current most stringent constraints (Planck CMB + BAO data + lensing data + the Hubble constant datum [H0(R19)] +  $\Lambda$ CDM (6 parameter) model + assuming 3 light massive neutrinos):

$$\sum_j m_j \equiv \Sigma < 0.12 \text{ eV} \quad (95\% \text{ C.L.})$$

The upper limit depends on the data set and assumptions used. According to F. Capozzi et al., arXiv:2503.07752, it reads:

$$\sum_j m_j \equiv \Sigma < 0.064 - 0.616 \text{ eV} \quad (95\% \text{ C.L.})$$

where 0.616 eV corresponds to the data set used which leads to one of the most conservative result ( $\Lambda$  CDM +  $\Sigma$  +  $A_{lens}$  + Planck + lensing data;  $A_{lens}$  - empirical parameter added to marginalise over the excess amount of gravitational lensing emerging in the fits of the Planck data (arXiv:1807.06209); see also arXiv:1903.07603).

A.G. Adama et al. (DESI Collaboration), arXiv:2411.12022:

$$\sum_j m_j \equiv \Sigma < 0.071 (0.196) \text{ eV} \quad (95\% \text{ C.L.})$$

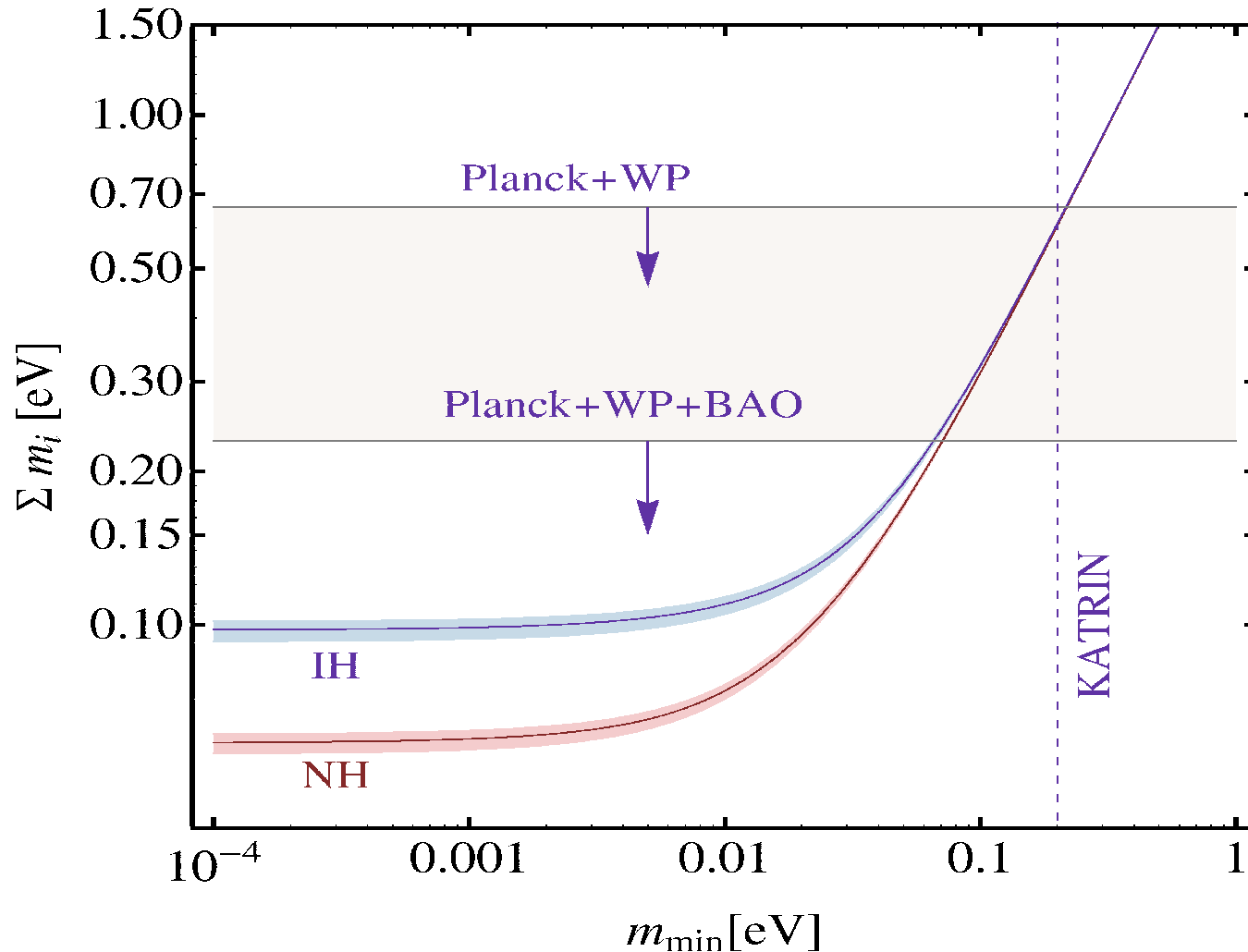
Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP, Planck and currently taking data EUCLID experiments might allow to determine

$$\sum_j m_j : \quad \delta \cong (0.01 - 0.04) \text{ eV}.$$

Similar sensitivity ( $\delta \cong 0.03 \text{ eV}$ ) is planned to be reached in CMB-S4 and DESI experiments; combining data from DESI and CMB-S4 experiments ( $\delta \cong 0.012 - 0.020 \text{ eV}$ ).

Talks by M. Archidiacono and W. Elbers at Neutrino 2024, June 17-22, Milano

# Mass and Hierarchy from Cosmology



**NH** ( $m_1 \cong 0$ ):  $\sum_j m_j \cong m_2 + m_3 = \sqrt{\Delta m_{21}^2} + \sqrt{\Delta m_{31}^2} \cong 0.061 \text{ eV}$  ( $3\sigma$  max);

**IH** ( $m_3 \cong 0$ ):  $\sum_j m_j \cong m_1 + m_2 \cong 2\sqrt{\Delta m_{23}^2} \cong 0.098 \text{ eV}$  ( $3\sigma$  min);  $\sum_j m_j \gtrsim 0.098 \text{ eV}$ .

## Determining the Nature of Massive Neutrinos.

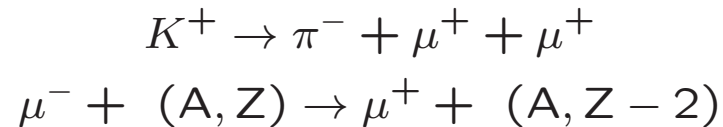
Determining the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos is one of the most challenging and pressing problems in present day elementary particle physics.

Establishing that the total lepton charge  $L = L_e + L_\mu + L_\tau$  is not conserved in particle interactions by observing the  $(\beta\beta)_{0\nu}$ -decay would be a fundamental discovery (similar to establishing baryon number nonconservation (e.g., by observing proton decay)).

Establishing that  $\nu_j$  are Majorana particles would be of fundamental importance, as important as the discovery of  $\nu$ -oscillations, and would have far reaching implications.

$\nu_l$  oscillations are not sensitive to the nature of  $\nu_j$ .

The Majorana nature of  $\nu_j$  can manifest itself in the existence of  $\Delta L = \pm 2$  processes:



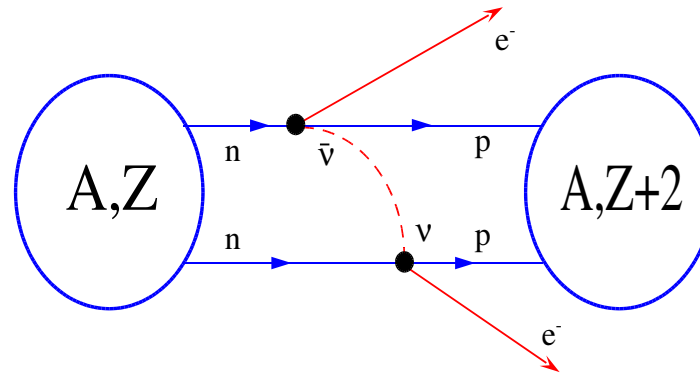
The process most sensitive to the possible Majorana nature of  $\nu_j$  -  $(\beta\beta)_{0\nu}$ -decay



of even-even nuclei,  $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$ .

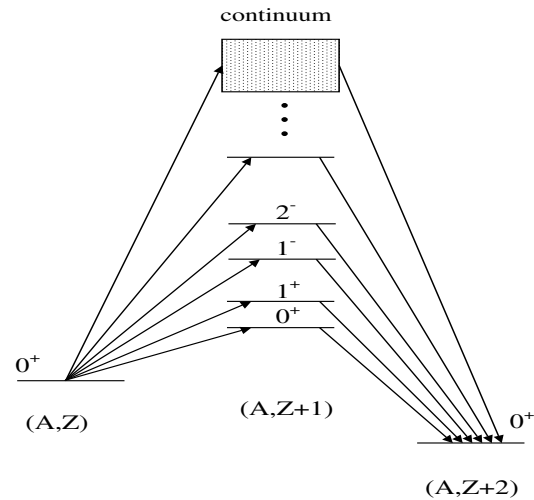
$2n$  from  $(A, Z)$  exchange a virtual Majorana  $\nu_j$  (via the CC weak interaction) and transform into  $2p$  of  $(A, Z+2)$  and two free  $e^-$ .

# Nuclear $0\nu\beta\beta$ -decay



strong in-medium modification of the basic process

$$dd \rightarrow uue^-e^-(\bar{\nu}_e\nu_e)$$



virtual excitation  
of states of all multiplicities  
in  $(A, Z+1)$  nucleus

Figure due to V. Rodin

## $(\beta\beta)_{0\nu}$ –Decay Experiments:

- $L$ –nonconservation, Majorana nature of  $\nu_j$ .
- Type of  $\nu$ –mass spectrum (NH, IH, QD)
- Absolute neutrino mass scale

$^3\text{H}$   $\beta$ -decay, cosmology:  $\min(m_i)$  (QD, IH)

- CPV due to Majorana CPV phases

$$A(\beta\beta)_{0\nu} \sim G_F^2 \langle m \rangle \mathbf{M}(\mathbf{A}, \mathbf{Z}), \quad \mathbf{M}(\mathbf{A}, \mathbf{Z}) - \text{NME},$$

$$\begin{aligned} |\langle m \rangle| &= \left| \sum_k U_{ek}^2 m_k \right| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \right| \\ &= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i\alpha_{31}} \right|, \quad \theta_{12} \equiv \theta_{\odot}, \theta_{13} - \text{CHOOZ} \end{aligned}$$

$\alpha_{21}, \alpha_{31}$  ( $(\alpha_{31} - 2\delta) \rightarrow \alpha_{31}$ ) - the two Majorana CPVP of the PMNS matrix.

$$|\langle m \rangle| = |\langle m \rangle| (\min(m_j), \alpha_{21,31}, \text{MO})$$

**CP-invariance:**  $\alpha_{21} = 0, \pm\pi, \alpha_{31} = 0, \pm\pi;$

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

relative CP-parities of  $\nu_1$  and  $\nu_2$ , and of  $\nu_1$  and  $\nu_3$  .

L. Wolfenstein, 1981;

S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;

B. Kayser, 1984.

$$A(\beta\beta)_{0\nu} \sim G_{\text{F}}^2 \langle m \rangle M(A,Z), \quad M(A,Z) - \text{NME},$$

$$|\langle m \rangle| \cong \left| \sqrt{\Delta m_{21}^2} \sin^2 \theta_{12} e^{i\alpha_{21}} + \sqrt{\Delta m_{31}^2} \sin^2 \theta_{13} e^{i\alpha_{31}} \right|, \quad m_1 \ll m_2 \ll m_3 \text{ (NH)},$$

$$|\langle m \rangle| \cong \sqrt{m_3^2 + \Delta m_{23}^2} |\cos^2 \theta_{12} + e^{i\alpha_{21}} \sin^2 \theta_{12}|, \quad m_3 < (\ll) m_1 < m_2 \text{ (IH)},$$

$$|\langle m \rangle| \cong m |\cos^2 \theta_{12} + e^{i\alpha_{21}} \sin^2 \theta_{12} + \sin^2 \theta_{13} e^{i\alpha_{31}}|, \\ m_{1,2,3} \cong m \gtrsim 0.10 \text{ eV (QD)}.$$

**CP-invariance:**  $\alpha_{21} = 0, \pm\pi, \alpha_{31} = 0, \pm\pi;$

$$1.2 \times 10^{-3} \lesssim |\langle m \rangle| \lesssim 4.1 \times 10^{-3} \text{ eV, NH (3}\sigma\text{);}$$

$$\sqrt{\Delta m_{23}^2} \cos 2\theta_{12} \cong 0.016 \text{ eV} \lesssim |\langle m \rangle| \lesssim \sqrt{\Delta m_{23}^2} \cong \\ 0.049 \text{ eV IH (3}\sigma\text{);}$$

J.Penedo, S.T.P., 2603.07787; S.-F. Ge et al., 2511.15391

$$m \cos 2\theta_{12} \lesssim |\langle m \rangle| \lesssim m, \quad m \gtrsim 0.03 \text{ eV, QD (3}\sigma\text{)}.$$

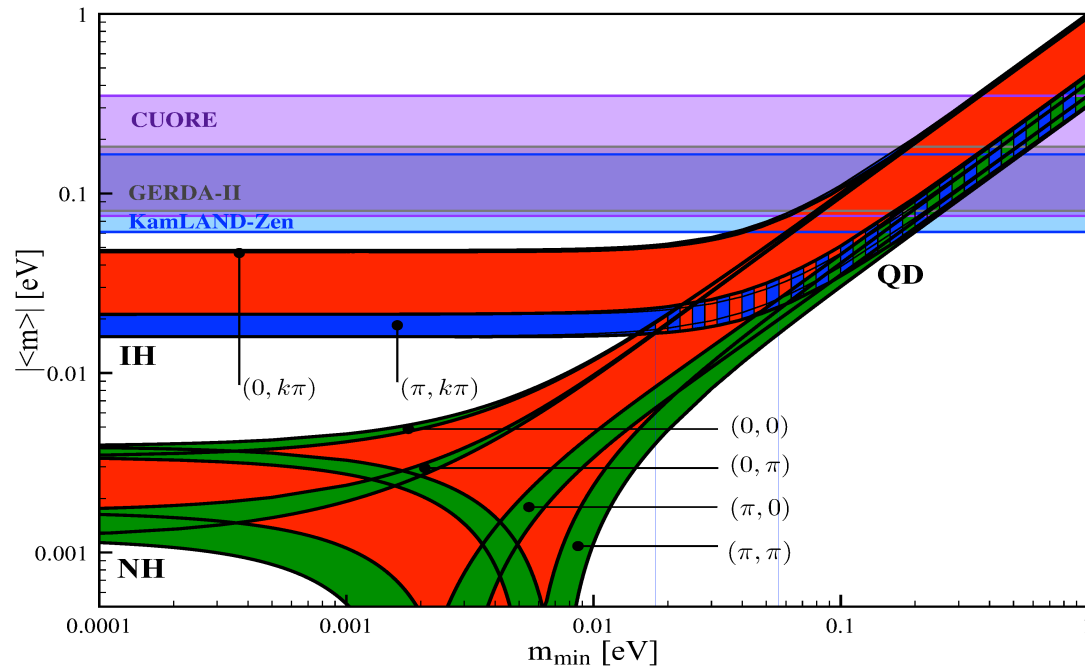
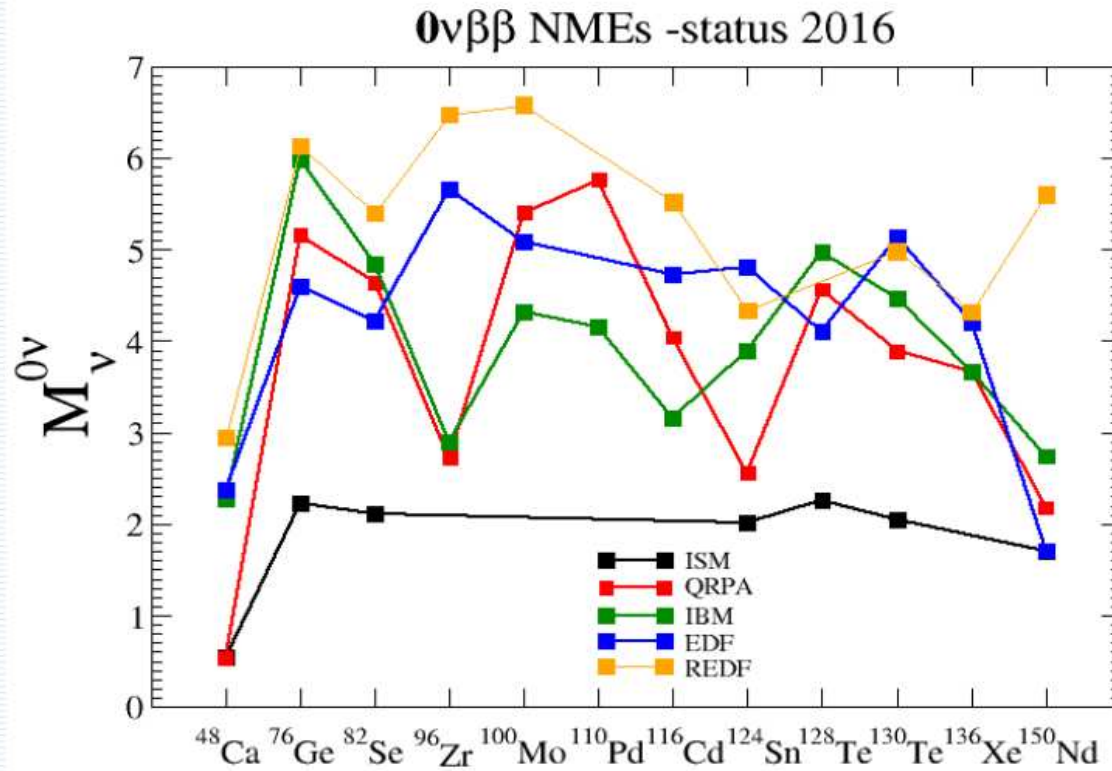


Figure by S. Pascoli, 2020

The figure is obtained using the b.f.v. and the  $1\sigma$  ranges of allowed values of  $\Delta m_{21}^2$ ,  $\sin^2 \theta_{12}$ ,  $\sin^2 \theta_{13}$  and  $|\Delta m_{31(32)}^2|$  from F. Capozzi et al., arXiv:2003.08511, propagated to  $\langle m \rangle$  and then taking a  $2\sigma$  uncertainty.  $\alpha_{21}$  and  $(\alpha_{31} - 2\delta)$  are varied in the interval  $[0, 2\pi]$ . The predictions for the NH, IH and QD spectra as well as the CUORE, GERDA-II and KamLAND-Zen limits are indicated. The black lines determine the ranges of values of  $|\langle m \rangle|$  for the CP conserving values  $(\alpha_{21}, \alpha_{31} - 2\delta) = (0, 0), (0, \pi), (\pi, 0)$  and  $(\pi, \pi)$ . The red regions correspond to  $\alpha_{21}$  and/or  $(\alpha_{31} - 2\delta)$  having a CP violating value. (Update by S. Pascoli of a figure from S. Pascoli, STP, Phys. Rev. D77 (2008) 113003.)

# NMEs for Light $\nu$ Exchange



	<b>mean field meth.</b>	<b>ISM</b>	<b>IBM</b>	<b>QRPA</b>
<b>Large model space</b>	yes	no	yes	yes
<b>Constr. Interm. States</b>	no	yes	no	yes
<b>Nucl. Correlations</b>	limited	all	restricted	restricted

F. Simkovic, 2017

**Table 1:** Compilation of  $M_{\alpha i}^{\text{long}}$  values for light Majorana neutrino exchange calculated with different nuclear models from [2]. These results have been obtained by assuming the bare value of the axial coupling constant  $g_A^{\text{free}} = 1.27$ . Each model is identified through an index, given in the second column.

Nuclear Model	Index [Ref.]	$^{76}\text{Ge}$	$^{82}\text{Se}$	$^{100}\text{Mo}$	$^{130}\text{Te}$	$^{136}\text{Xe}$
NSM	N1 [25]	2.89	2.73	-	2.76	2.28
	N2 [25]	3.07	2.90	-	2.96	2.45
	N3 [26]	3.37	3.19	-	1.79	1.63
	N4 [26]	3.57	3.39	-	1.93	1.76
	N5 [27, 28]	2.66	2.72	2.24	3.16	2.39
QRPA	Q1 [29]	5.09	-	-	1.37	1.55
	Q2 [30]	5.26	3.73	3.90	4.00	2.91
	Q3 [31]	4.85	4.61	5.87	4.67	2.72
	Q4 [32]	3.12	2.86	-	2.90	1.11
	Q5 [32]	3.40	3.13	-	3.22	1.18
	Q6 [33]	-	-	-	4.05	3.38
EDF	E1 [34]	4.60	4.22	5.08	5.13	4.20
	E2 [35]	5.55	4.67	6.59	6.41	4.77
	E3 [36]	6.04	5.30	6.48	4.89	4.24
IBM	I1 [37]	5.14	4.19	3.84	3.96	3.25
	I2 [13]	6.34	5.21	5.08	4.15	3.40

M. Agostini et al., arXiv:2202.01787

**The searches for  $(\beta\beta)_{0\nu}$ - decay have a long history.**

See, e.g., S.T.P., arXiv:1910.09331 and A. Barabash, arXiv:1104.2714

**Results from IGEX ( $^{76}\text{Ge}$ ), NEMO3 ( $^{100}\text{Mo}$ ), CUORICINO+CUORE-0 ( $^{130}\text{Te}$ ):**

**IGEX  $^{76}\text{Ge}$ :  $|\langle m \rangle| < (0.33 - 1.35) \text{ eV (90\% C.L.)}$ .**

**Data from NEMO3 ( $^{100}\text{Mo}$ ):**

**$T(^{100}\text{Mo}) > 1.1 \times 10^{24} \text{ yr}$ ,  $|\langle m \rangle| < (0.3-0.6) \text{ eV}$ ;**

## Best Sensitivity Results

$$T(^{136}\mathbf{Xe}) > 1.6 \times 10^{25} \text{yr at 90\% C.L., EXO}$$

$$T(^{136}\mathbf{Xe}) > 3.8 \times 10^{26} \text{y at 90\% C.L., KamLAND – Zen}$$

$$|\langle m \rangle| < (0.028 - 0.122) \text{ eV} .$$

H. Shimizu, talk at Neutrino 2024, June 17-22, Milano

$$T(^{76}\mathbf{Ge}) > 1.8 \times 10^{26} \text{yr at 90\% C.L., GERDA II.}$$

$$|\langle m \rangle| < (0.079 - 0.182) \text{ eV} .$$

S. Calgola, Talk at NuTel, October 2023

$$T(^{76}\mathbf{Ge}) > 1.9 \times 10^{26} \text{yr at 90\% C.L., LEGEND – 200 .}$$

L. Pertoldi, talk at Neutrino 2024, June 17-22, Milano

(GERDA + MAJORANA → LEGEND)

$$T(^{130}\text{Te}) > 4.4 \times 10^{25} \text{yr at 90\% C.L.},$$

$$|\langle m \rangle| < (0.070 - 0.240) \text{ eV}, \text{ CUORE}$$

C. Bucci, talk at Neutrino 2024, June 17-22, Milano

## Constraints on $\min(m_j)$

$$T(^{136}\text{Xe}) > 3.8 \times 10^{26} \text{yr at 90\% C.L.}, \text{ KamLAND - Zen}$$

$$|\langle m \rangle| < (0.028 - 0.122) \text{ eV}.$$

$$|\langle m \rangle| < 0.122 \text{ eV}, \text{ QD region:}$$

$$m_{1,2,3} < \frac{0.122 \text{ eV}}{\cos 2\theta_{12}} \cong 0.384 \text{ eV} (\cos 2\theta_{12} \gtrsim 0.318, 3\sigma)$$

**Large number of experiments:  $|\langle m \rangle| \sim (0.01-0.05) \text{ eV}$**

**CUORE -  $^{130}\text{Te}$ ;**

**\*CUPID -  $^{100}\text{Mo}$  (250 kg; CUPID-IT: 1000 kg ( $8 \times 10^{27}$  yr));**

**LEGEND -  $^{76}\text{Ge}$  (LEGEND-200; LEGEND-1000);**

**KamLAND-ZEN -  $^{136}\text{Xe}$  (750 kg,  $4.6 \times 10^{26}$  yr);**

**NEXT-100 -  $^{136}\text{Xe}$  (NEXT-HD ( $10^{27}$  yr); NEXT-BOLD ( $10^{28}$  yr));**

**SNO+ -  $^{130}\text{Te}$  (800 tons of LS loaded with (0.5%) Te, 33.8%  $^{130}\text{Te}$ );**

**AMoRE -  $^{100}\text{Mo}$  (200 kg of XMoO<sub>4</sub> crystals);**

**PANDAX-III -  $^{136}\text{Xe}$  (200 kg of Xe enriched at 90% in  $^{136}\text{Xe}$ );**

**CANDLES -  $^{48}\text{Ca}$ ;**

**\*SuperNEMO -  $^{82}\text{Se}$  (100 kg of  $^{82}\text{S}$ , 20 modules);**

**DCBA -  $^{82}\text{Se}$ ,  $^{150}\text{Nd}$ ;**

**XMASS -  $^{136}\text{Xe}$ ;**

**ZICOS -  $^{96}\text{Zr}$ ;**

**MOON -  $^{100}\text{Mo}$ ;**

...

See, e.g., A. Giuliani et al., 1910.04688; M. Agostini et al., 2202.01787

# And many more ideas

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	$^{48}\text{Ca}$	305 kg	$^{nat}\text{CaF}_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	$^{76}\text{Ge}$	1 kg	$^{enr}\text{Ge}$ semicond. det.	Prototype	CJPL
CDEX-300 $\nu$ [125]	$^{76}\text{Ge}$	225 kg	$^{enr}\text{Ge}$ semicond. det.	Construction	CJPL
LEGEND-200 [16]	$^{76}\text{Ge}$	200 kg	$^{enr}\text{Ge}$ semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	$^{76}\text{Ge}$	1 ton	$^{enr}\text{Ge}$ semicond. det.	Proposal	
CUPID-0 [19]	$^{82}\text{Se}$	10 kg	$\text{Zn}^{enr}\text{Se}$ scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	$^{82}\text{Se}$	7 kg	$^{enr}\text{Se}$ foils/tracking	Operation	Modane
SuperNEMO [126]	$^{82}\text{Se}$	100 kg	$^{enr}\text{Se}$ foils/tracking	Proposal	Modane
Selena [127]	$^{82}\text{Se}$		$^{enr}\text{Se}$ . CMOS	Development	
IFC [128]	$^{82}\text{Se}$		ion drift $\text{SeF}_6$ TPC	Development	
CUPID-Mo [17]	$^{100}\text{Mo}$	4 kg	$\text{Li}^{enr}\text{MoO}_4$ scint. bolom.	Prototype	LNGS
AMoRE-I [129]	$^{100}\text{Mo}$	6 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Operation	YangYang
AMoRE-II [129]	$^{100}\text{Mo}$	200 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Construction	Yemilab
CROSS [130]	$^{100}\text{Mo}$	5 kg	$\text{Li}_2^{100}\text{MoO}_4$ , surf. coat bolom.	Prototype	Canfranc
BINGO [131]	$^{100}\text{Mo}$		$\text{Li}^{enr}\text{MoO}_4$	Development	LNGS
CUPID [28]	$^{100}\text{Mo}$	450 kg	$\text{Li}^{enr}\text{MoO}_4$ scint. bolom.	Proposal	LNGS
China-Europe [132]	$^{116}\text{Cd}$		$^{enr}\text{CdWO}_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	$^{116}\text{Cd}$	0.32 kg	$^{nat}\text{Cd}$ CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	$^{116}\text{Cd}$		$^{nat}\text{CdTe}$ det.	Development	
TIN.TIN [135]	$^{124}\text{Sn}$		Tin bolometers	Development	INO
CUORE [10]	$^{130}\text{Te}$	1 ton	$\text{TeO}_2$ bolometers	Operating	LNGS
SNO+ [136]	$^{130}\text{Te}$	3.9 t	0.5-3% $^{nat}\text{Te}$ loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	$^{136}\text{Xe}$	5 t	Liq. $^{enr}\text{Xe}$ TPC/scint.	Proposal	
NEXT-100 [137]	$^{136}\text{Xe}$	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	$^{136}\text{Xe}$	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	$^{136}\text{Xe}$		gas TPC	Prototype	
KamLAND-Zen-800 [13]	$^{136}\text{Xe}$	745 kg	$^{enr}\text{Xe}$ dissolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	$^{136}\text{Xe}$		$^{enr}\text{Xe}$ dissolved in liq. scint.	Development	Kamioka
LZ [139]	$^{136}\text{Xe}$	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	$^{136}\text{Xe}$	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	$^{136}\text{Xe}$	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	$^{136}\text{Xe}$	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	$^{136}\text{Xe}$		Spherical Xe TPC	Development	
LAr TPC [143]	$^{136}\text{Xe}$	kton	Xe-doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA [145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	

I did not have time to discuss these, but they all have unique features....

Opportunistic searches with Dark Matter experiments: L. Baudis' talk on Friday

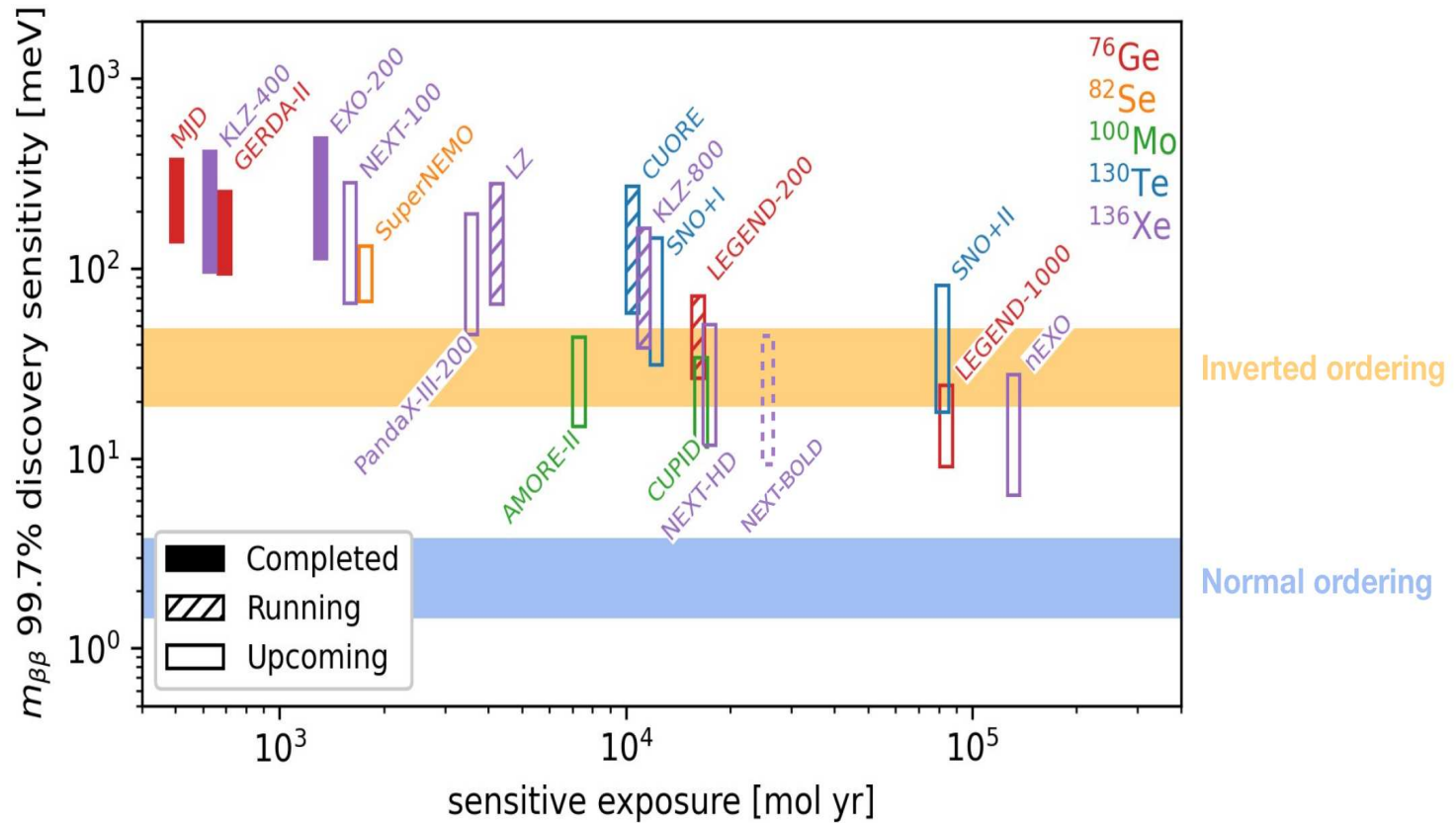
arXiv:2212.11099

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R. Guinette, talk at Neutrino 2024

# Conquering the inverted ordering

- Next generation will *cover* the inverted ordering

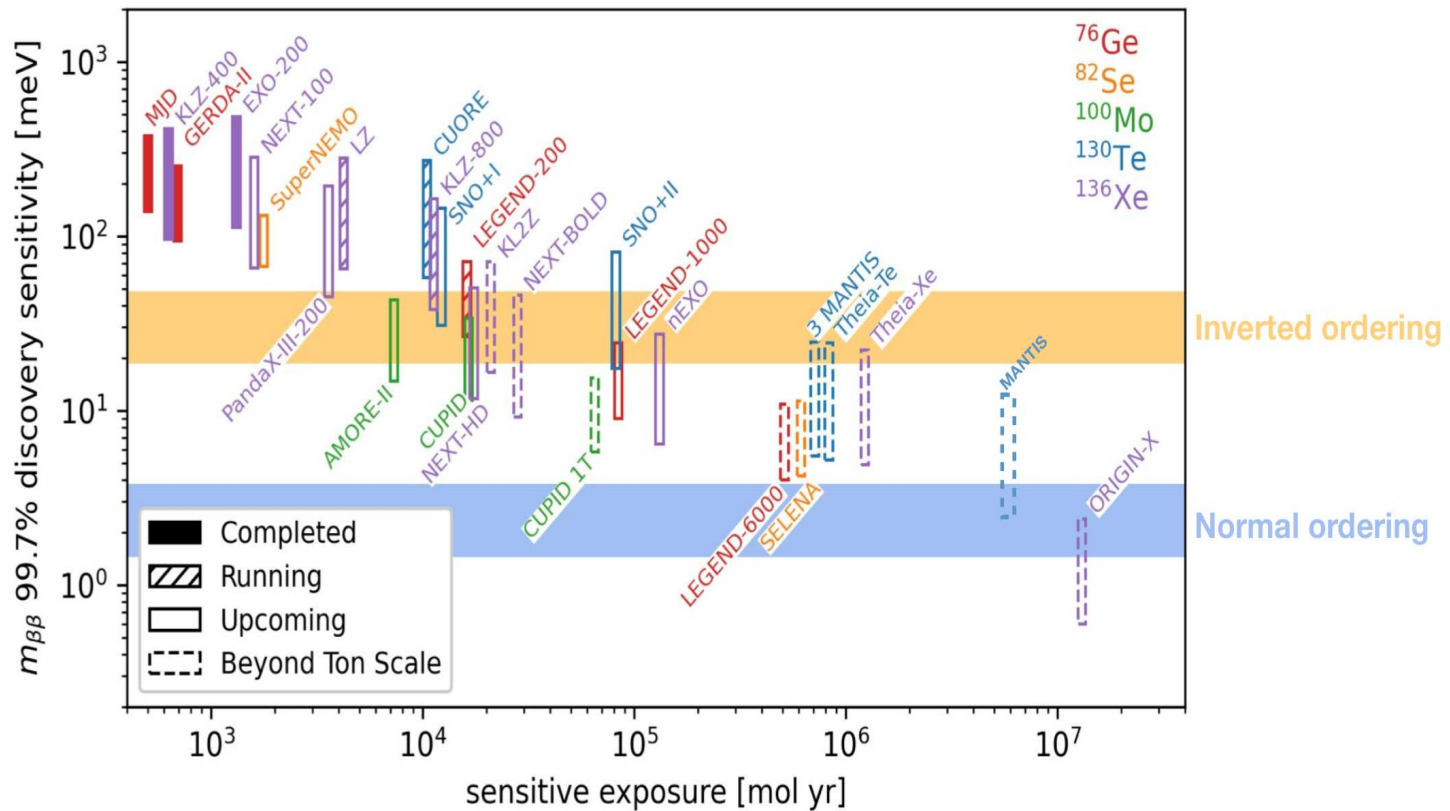


Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

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R. Guinette, talk at Neutrino 2024

# Next next step: Attempt the Normal Ordering

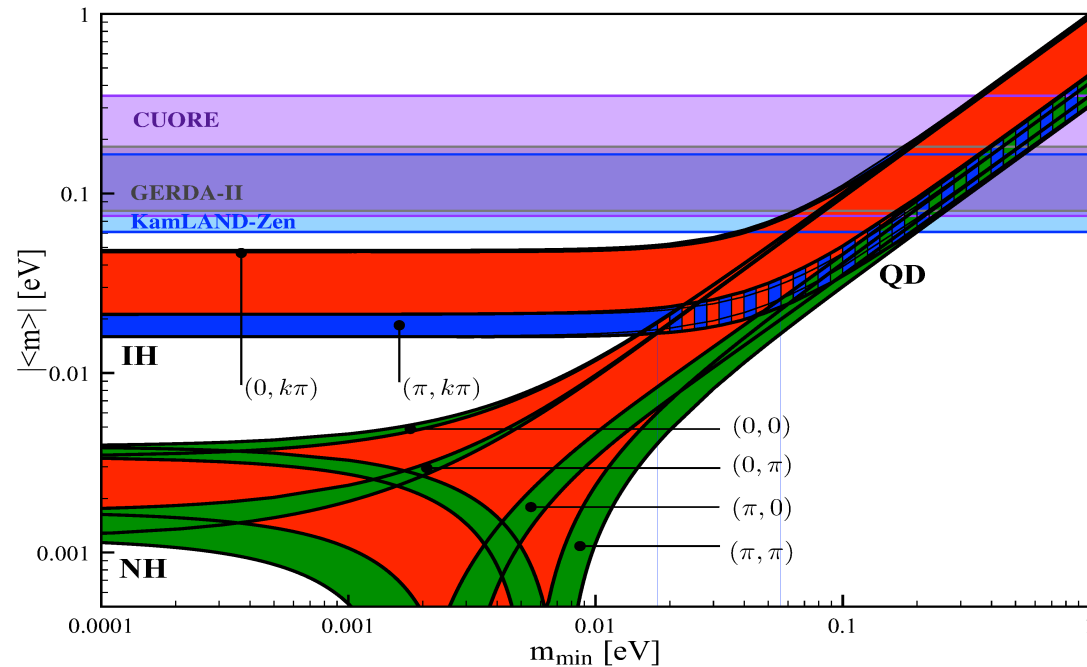


Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

R. Guinette, talk at Neutrino 2024

If  $|\langle m \rangle| < 0.01$  eV, the next frontier will be  $|\langle m \rangle| \sim (1.0 - 5.0) \times 10^{-3}$  eV

Experiments: LEGEND-1000 (6000), CUPID (CUPID-1T), NEXT-BOLD, KamLAND-2ZEN,...



Under what conditions  $|\langle m \rangle| \geq 1.0$  ( $5.0$ )  $\times 10^{-3}$  eV, or how not to "fall" in the "well of non-observability".

S. Pascoli, STP, arXiv:0711.4993; J. Penedo, STP, PL B786 (2018) 410

If it is experimentally established that

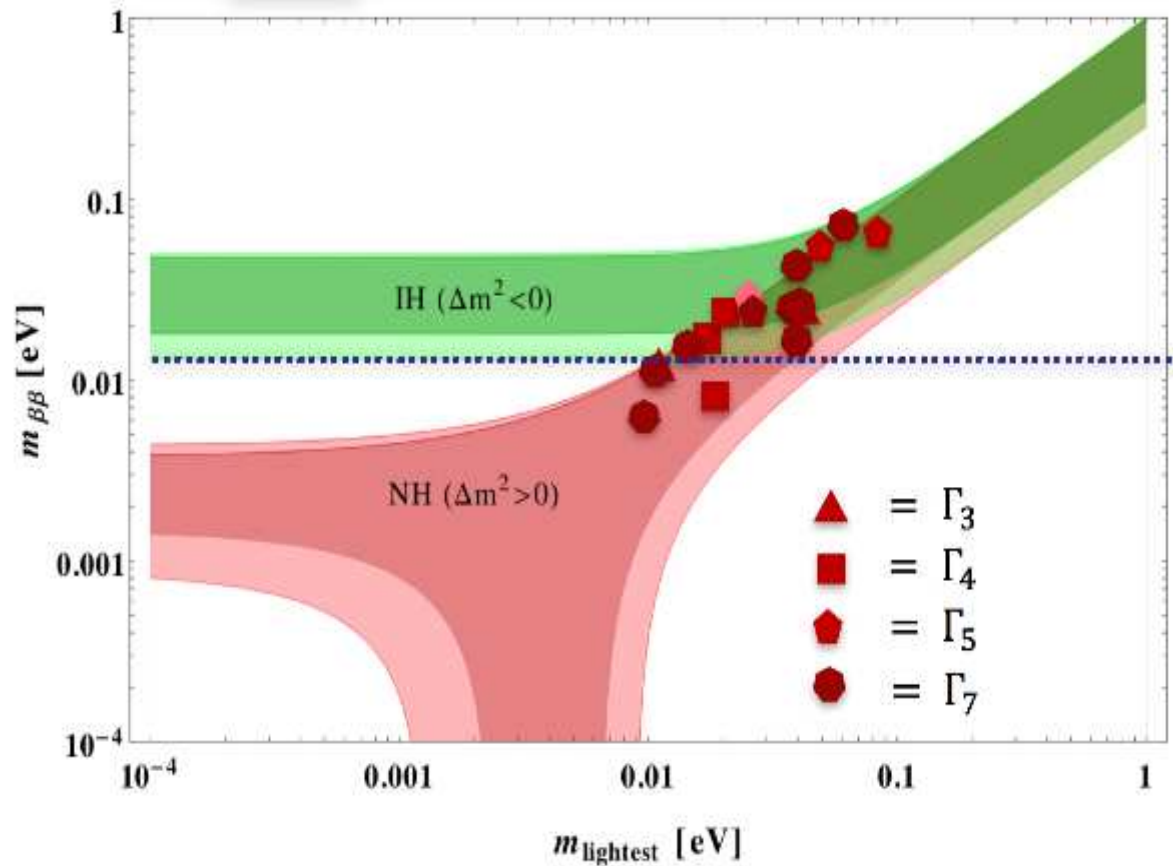
$$\sum_j m_j \gtrsim 0.10 \text{ (0.08) eV,}$$

this would imply for NO  $\nu$  mass spectrum that

$$|\langle m \rangle| \geq 5 \times 10^{-3} \text{ (} 10^{-3} \text{) eV} \quad (3\sigma \text{ C.L.)}$$

J.T. Penedo, STP, arxiv:1806.03203; 2603.08787

# Predictions of modular invariant theories of lepton flavour



F. Feruglio, talk at Bethe Colloquium, 18/06/2020

New approach to neutrino and charged lepton masses, lepton (neutrino) mixing and leptonic CP violation (for a review see, e.g., F. Feruglio and A. Romanino, arXiv:1912.06028). Has been intensively developed in the last two years. Models typically predict  $m_1 > 0.01$  eV for NO spectrum (see, e.g., J. Penedo, STP, arXiv:1806.1040, P. Novichkov et al., arXiv:1811.04933).

**The existing data imply that**

$$m_{\nu_j} \lll m_{e,\mu,\tau}, m_q, \quad q = u, c, t, d, s, b$$

**For  $m_{\nu_j} \lesssim 1$  eV:**  $m_{\nu_j}/m_{l,q} \lesssim 10^{-6}$

**For a given family:**  $10^{-2} \lesssim m_{l,q}/m_{q'} \lesssim 10^2$

# This suggests that

- $\nu_j$  get their masses from a mechanism which differs from that generating the masses of  $m_{e,\mu,\tau}, m_q$  in the SM;
- the smallness of  $m_{\nu_j}$  is related to the existence of a new fundamental mass scale in particle physics, i.e., to the existence of New Physics beyond the SM.

**Natural to assume  $\nu_j$  "differ" from  $m_{e,\mu,\tau}, m_q$  because they are Majorana particles ( $e, \mu, \tau$ , quarks are Dirac particles).**

The observation of, e.g.,  $(\beta\beta)_{0\nu}$ – decay would be a proof.

These ideas are realised in many theoretical models which predict massive Majorana  $\nu_j$ : seesaw ( $N_j, H, T$ ), HTP ( $H^{--}, H^-$ ), models of lepton flavour.

The observed patterns of  $\nu$ –mixing and of  $\Delta m_{\text{atm}}^2$  and  $\Delta m_{\odot}^2$  can be related to Majorana  $\nu_j$  and a **new fundamental (approximate flavour) symmetry**, e.g.,

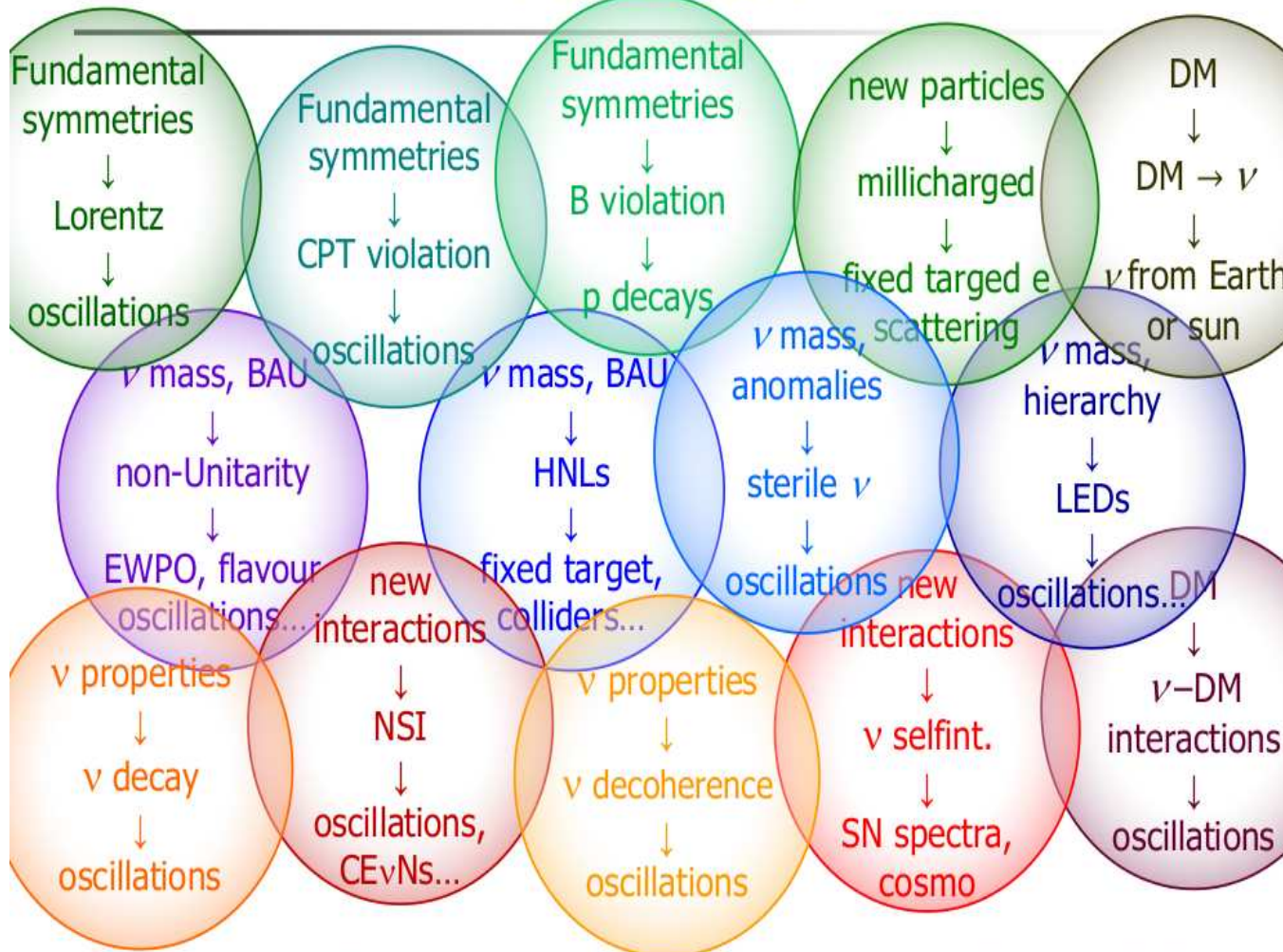
$$A_4 (\sim \Gamma_3), S_4 (\sim \Gamma_4), \dots, U(1)_{L'} (L' = L_e - L_\mu - L_\tau), \dots$$

**These discoveries suggest the existence of  
New Physics beyond that of the ST.**

## The New Physics can manifest itself (can have a variety of different “flavours”):

- In the existence of more than 3 massive neutrinos:  $n > 3$  ( $n = 4$ , or  $n = 5$ , or  $n = 6, \dots$ ).
- In the observed pattern of neutrino mixing and in the values of the CPV phases in the PMNS matrix.
- In the Majorana nature of massive neutrinos.
- In the existence of LFV processes:  $\mu \rightarrow e + \gamma$ ,  $\mu \rightarrow 3e$ ,  $\mu - e$  conversion, etc., which proceed with rates close to the existing upper limits.
- In the existence of new particles, e.g., at the TeV scale: heavy Majorana Neutrinos  $N_j$ , doubly charged scalars,...
- In the existence of new (FChNC, FCFNSNC) neutrino interactions.
- In the existence of “unknown unknowns” ...

# $\nu$ and BSM



See posters by Natsumi Taniuchi, Joshua Barrow, Daisy Kalra, Roxanne Guenette, Cailian Jiang

E. Fernandez-Martinez, talk at Neutrino 2024, June 17-22, Milano

We can have  $n > 3$  ( $n = 4$ , or  $n = 5$ , or  $n = 6, \dots$ ) if, e.g., sterile ( $SU(2)_L$  singlet states)  $\nu_R, \tilde{\nu}_L$  exist and they mix with the active flavour neutrinos  $\nu_l$  ( $\tilde{\nu}_l$ ),  $l = e, \mu, \tau$ .

Two (extreme) possibilities:

i)  $m_{4,5,\dots} \sim 1$  eV;

in this case  $\nu_{e(\mu)} \rightarrow \nu_S$  oscillations are possible (hints from LSND and MiniBooNE experiments, re-analyses of SBL reactor  $\bar{\nu}_e$  oscillation data with “new” fluxes of  $\bar{\nu}_e$  (“RAA”), data of radioactive source calibration of the solar neutrino SAGE and GALLEX experiments (“Galium anomaly”); Neutrino-4 claim; tests (SBNP (Fermilab, ICARUS + 2 detectors), JSNS2 (at KEK), DANSS, NEOS, PROSPECT, STEREO, ...).

ii)  $M_{4,5,\dots} \sim (1 - 10^3)$  GeV, low-scale seesaw models;

$M_{4,5,\dots} \sim (10^6 - 10^{14})$  GeV, high-scale seesaw models.

We can also have, in principle:

$m_4 \sim 3$  keV (DM),  $M_{5,6} \sim (1 - 10^3)$  GeV (seesaw).

## Of fundamental importance are:

- determining the status of CP symmetry in the lepton sector and high precision measurement of  $\delta$  (T2K, NO $\nu$ A, T2HK, DUNE); leptonic CPV might be at the origin of matter-antimatter (or baryon) asymmetry of the Universe; critical test of symmetry origin of the  $\nu$ -mixing pattern.
- the determination of the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos (which is one of the most challenging and pressing problems in present day elementary particle physics) (LEGEND (GERDA, MJORANA), KamLAND-Zen II, CUORE (CUPID), nEXO (EXO), SNO+, NEXT, ...);
- determination of the type of spectrum neutrino masses possess, or the “neutrino mass ordering” (T2K + NO $\nu$ A; JUNO; ORCA; T2HK+HK(atm.data); DUNE; INO);
- determination of the absolute neutrino mass scale, or  $\min(m_j)$  (KATRIN, new ideas; cosmology).
- High precision determination of  $\sin^2 \theta_{23}$  (T2HK+HK(atm.data); DUNE) - relevant, e.g., for  $\nu$ -osc. tomography of the Earth (ORCA), and  $\sin^2 \theta_{12}$  (JUNO); both crucial for tests of ideas on origin of the  $\nu$ -mixing pattern.

The program of research extends beyond 2035.

- Understanding at fundamental level the mechanism giving rise to the  $\nu$ -masses and mixing and to the  $L_l$ -non-conservation. Includes understanding
  - the origin of the observed patterns of  $\nu$ -mixing and  $\nu$ -masses ;
  - the physical origin of  $CPV$  phases in  $U_{PMNS}$  ;
  - Are the observed patterns of  $\nu$ -mixing and of  $\Delta m_{21,31}^2$  related to the existence of a new symmetry?
  - Is there any relations between  $q$ -mixing and  $\nu$ - mixing? Is  $\theta_{12} + \theta_c = \pi/4$  ?
  - Is  $\theta_{23} = \pi/4$ , or  $\theta_{23} > \pi/4$  or else  $\theta_{23} < \pi/4$ ?
  - Is there any correlation between the values of  $CPV$  phases and of mixing angles in  $U_{PMNS}$ ?
- Progress in the theory of  $\nu$ -mixing might lead to a better understanding of the origin of the BAU.
  - Can the Majorana and/or Dirac  $CPVP$  in  $U_{PMNS}$  be the leptogenesis  $CPV$  parameters at the origin of BAU?

**BS3 $\nu$ RM: eV scale sterile  $\nu$ 's; NSIs; ChLFV processes ( $\mu \rightarrow e + \gamma$ ,  $\mu \rightarrow 3e$ ,  $\mu^- - e^-$  conversion on  $(A, Z)$ );  $\nu$ -related BSM physics at the TeV scale ( $N_{jR}$ ,  $H^{--}$ ,  $H^-$ , etc.).**

## Future Developments

Three major new detectors (experiments):

**JUNO, DUNE, Hyper-Kamiokande**

# JUNO

20 kt LS detector of reactor  $\bar{\nu}_e$  via IBD

$\bar{\nu}_e + p \rightarrow n + e^+$ ;  $E_{res} = 3\%/\sqrt{E}$ ;  $L \cong 53$  km;

thermal power of the used reactors: 26.6 GW;

Sphere with a diameter of 35 m.

Cost:  $300 \times 10^6$  US Dollars.

Built in China by international collaboration of more than 700 scientists from 74 Institutions in 17 countries/regions. Expected to start data-taking in the second half of 2025.

After 6 years of operation: NMO at  $3\sigma$  (using reactor  $\nu$  data only). Adding  $\nu_{atm}$  data can improve the sensitivity by  $(0.8 - 1.4)\sigma$ .

The idea put forward in S.T.P., M. Piai, PLB 553 (2002) 94 (hep-ph/0112074).

**Based on:**  $P_{NO}(\bar{\nu}_e \rightarrow \bar{\nu}_e) \neq P_{IO}(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

$$P^{NO}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left(1 - \cos \frac{\Delta m_{atm}^2 L}{2E_\nu}\right) - \frac{1}{2} \cos^4 \theta_{13} \sin^2 2\theta_{12} \left(1 - \cos \frac{\Delta m_{\odot}^2 L}{2E_\nu}\right) \\ + \frac{1}{2} \sin^2 2\theta_{13} \sin^2 \theta_{12} \left(\cos \left(\frac{\Delta m_{atm}^2 L}{2E_\nu} - \frac{\Delta m_{\odot}^2 L}{2E_\nu}\right) - \cos \frac{\Delta m_{atm}^2 L}{2E_\nu}\right), \quad \Delta m_{\odot}^2 \equiv \Delta m_{21}^2,$$

$$P^{IO}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left(1 - \cos \frac{\Delta m_{atm}^2 L}{2E_\nu}\right) - \frac{1}{2} \cos^4 \theta_{13} \sin^2 2\theta_{12} \left(1 - \cos \frac{\Delta m_{\odot}^2 L}{2E_\nu}\right) \\ + \frac{1}{2} \sin^2 2\theta_{13} \cos^2 \theta_{12} \left(\cos \left(\frac{\Delta m_{atm}^2 L}{2E_\nu} - \frac{\Delta m_{\odot}^2 L}{2E_\nu}\right) - \cos \frac{\Delta m_{atm}^2 L}{2E_\nu}\right).$$

$$\Delta m_{atm}^2 = \Delta m_{31(32)}^2 (NO), \quad \Delta m_{atm}^2 = \Delta m_{32(31)}^2 (IO),$$

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

**Spectrum of  $e^+$  - sensitive to the difference between  $P^{NO}(\bar{\nu}_e \rightarrow \bar{\nu}_e)$  and  $P^{IO}(\bar{\nu}_e \rightarrow \bar{\nu}_e)$  - can be used to determine neutrino mass ordering. Optimal  $L$  exists;  $E_{res} \sim 3\%/\sqrt{E}$  required.**

S.T.P., M. Piai, 2001

**JUNO** (China, International collaboration)

S. Choubey, S.T.P., M. Piai, PRD 68 (2003) 113006 ((hep-ph/0306017):  
can measure  $\sin^2 \theta_{12}$ ,  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$  with excep-  
tionally high precision.

**After 6 years of dataking:**

$\sin^2 \theta_{12}$ : 0.5%;  $\Delta m_{21}^2$ : 0.3%;  $\Delta m_{31}^2$ : 0.2% ( $1\sigma$ )

(Y. Wang, talk given at CERN on March 20, 2024).

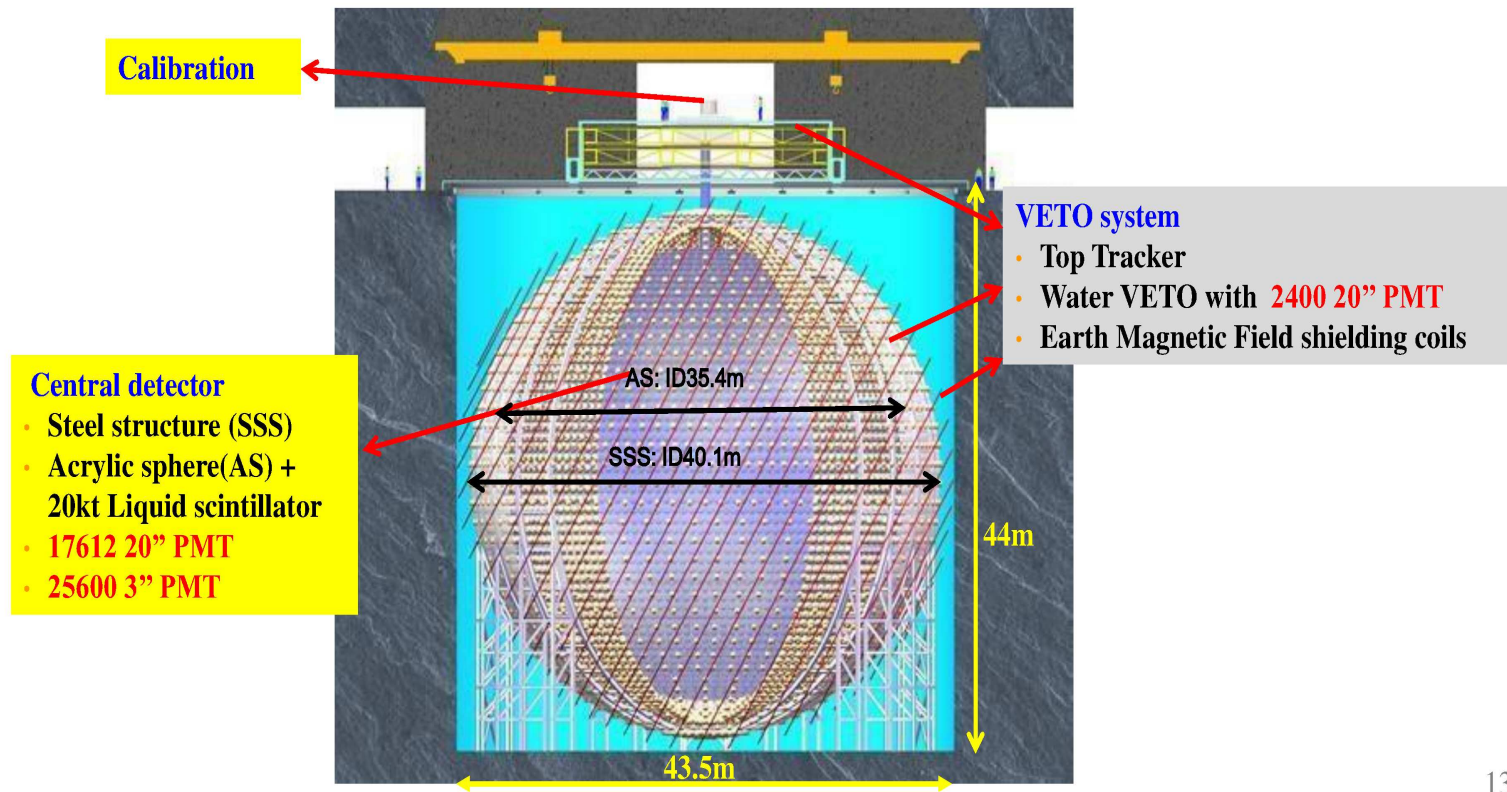
Wide program of research: atmospheric  $\nu$  oscilla-  
tions, solar neutrinos, SN neutrinos, geo-neutrinos,  
nucleon decay; distant future:  $(\beta\beta)_{0\nu}$  decay.

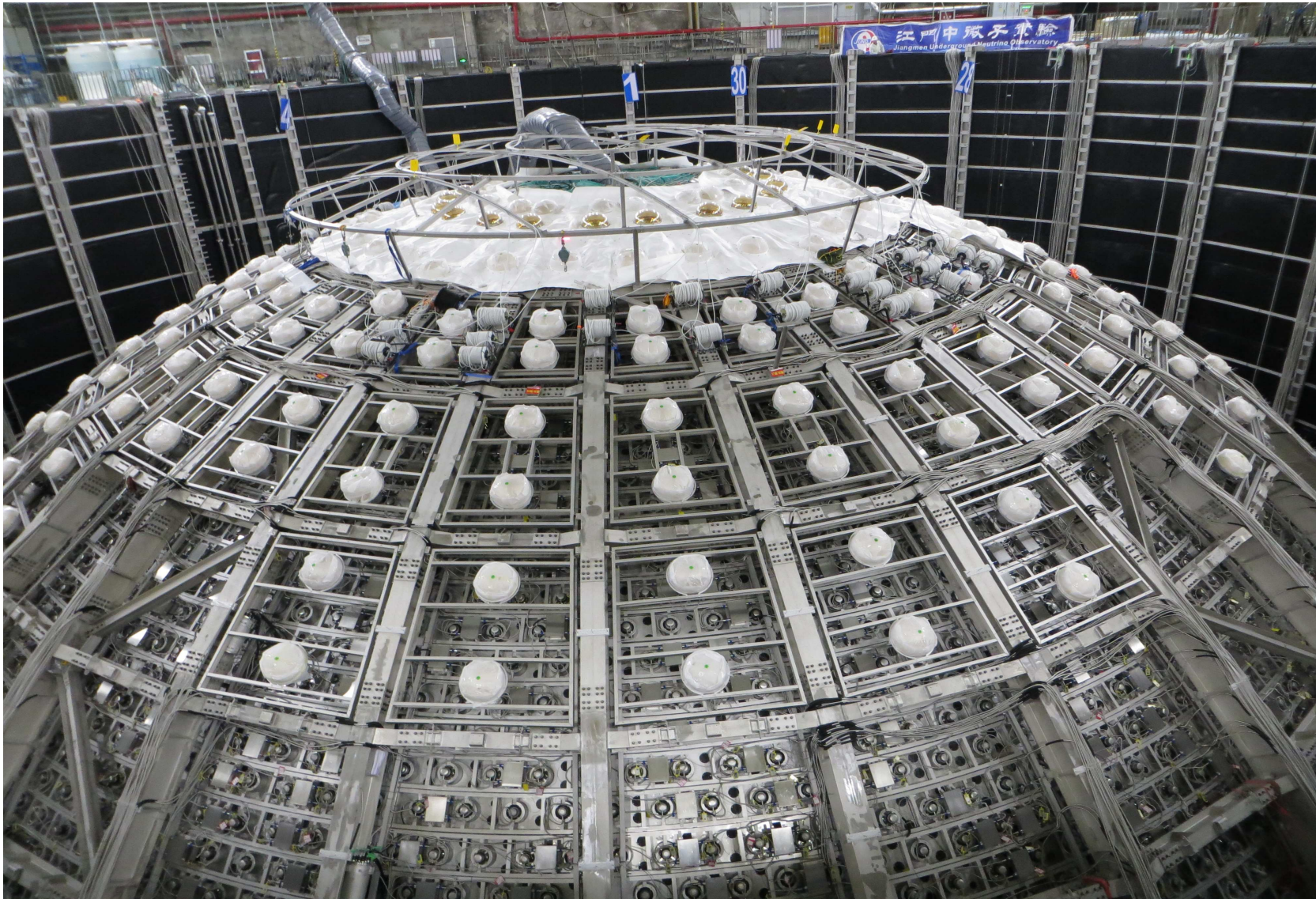


# Concept of JUNO for Mass Ordering



- Two-layer structure for simplicity and cost: stainless steel frame + Acrylic tank
- Water as VETO and Buffer → radiopurity control of water





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S.T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026



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S.T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026

# DUNE

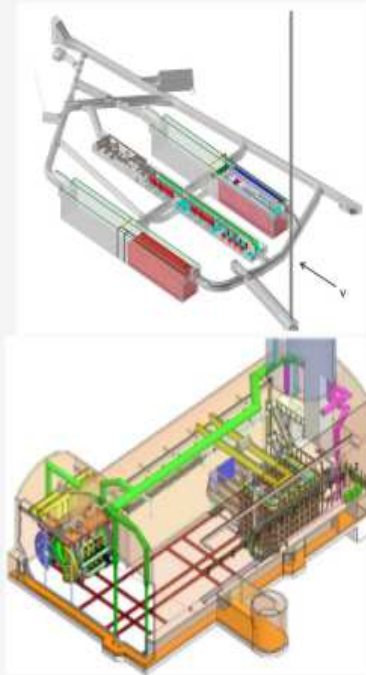
**DUNE (LBNE):** Fermilab-DUSEL,  $L = 1290$  km, 1.2 MW (2.3 MW) proton beam, wide band  $\nu$  beam (first and second osc. maxima at  $E = 2.4$  GeV and 0.8 GeV); 34 kt fiducial volume LAr detectors; plans to run 5 years with  $\nu_\mu$  and 5 years with  $\bar{\nu}_\mu$ ; 2028-2029

**DUNE could have very good sensitivity to CP-violation with a 75% coverage at  $3\sigma$  in the allowed range of values of  $\sin^2 \theta_{13}$  (assuming it will run for 5 years in neutrinos and 5 years in antineutrinos), with  $\delta(\delta) = 6^\circ - 16^\circ$  depending on b.f.v. of  $\delta$ .**

**DUNE could achieve the determination of the NMO at  $5\sigma$  in 1 year (3 years) in the best-case (worst-case) oscillation scenario (value of  $\sin^2 \theta_{23}$ ).**

**The next slides on DUNE are from the talk by Ch. Marshall at Neutrino 2024.**

# DUNE construction: Phase I



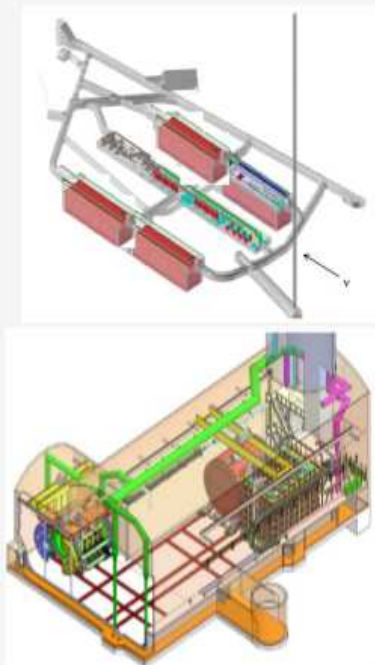
- Full Near and Far Site facility
- Two LArTPC modules (VD & HD), each 17 kt Ar
- 1.2 MW upgradeable neutrino beamline
- Movable LArTPC ND+muon catcher, SAND

Completing Phase I is highest priority in P5 report:

**Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.**

- b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos.

# DUNE construction: Phase II



- Two additional FD modules
- Beamline upgrade to >2MW (ACE-MIRT)
- More capable Near Detector (ND-GAr)

P5 report endorses FD3, ACE-MIRT, and MCND in the next decade, and R&D toward FD4

**Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.**

- b. A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind

**Recommendation 4: Invest in a comprehensive initiative to develop the resources—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an aggressive R&D program that, while**

- e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an  $e^+e^-$  Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping

# Building DUNE: construction schedule



- Far site excavation is complete
- Next: Building & Site Infrastructure work until mid-2025
- Cryostat warm structure is on its way to US from CERN to be installed in 2025-26
- Far Detector installation in 2026-27
- Purge and fill with argon in 2028
- Physics in 2028 or early 2029
- Beam physics with Near Detector 2031



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DUNE - Neutrino24 - Chris Marshall



# Hyper-Kamiokande and T2HK

# Hyper-Kamiokande: water-Cherenkov, $\sim 0.25$ Mton, fiducial $\sim 0.2$ Mton; 2027; T2HK.





## Summary

- Hyper-K will play a central role in exploring the future of particle physics and contribute to the future of astronomy. Expectations in 10 yrs HK:
  - Mass ordering:  $3.8-6.2\sigma$  depending on  $\sin^2\theta_{23}$
  - CP violation:  $5\sigma$  discovery,  $> 60\%$
  - Proton decay:  $p \rightarrow e^+\pi^0$ :  $\sim 6 \times 10^{34}$  yrs etc.
  - $> 3\sigma$  sensitivity for the solar  $\nu$  spectrum up-turn
  - $\sim 70k$  events @10 kpc supernova
  - $\sim 4$  events/yr diffuse supernova neutrino background
- The highlight of the civil construction, the dome excavation, was completed. Detailed design of tank lining and photosensor support structure completed.
- 50 cm PMT delivery is ongoing and on schedule.
- Beam intensity increase/IWCD construction is on the way.
- Data-taking is expected to start in 2027!

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**Data-taking is planned to start in 2028.**

**Research in Neutrino Physics:** we strive to understand at deepest level what are the origins of neutrino masses and mixing and what determines the pattern of neutrino mixing and of neutrino mass squared differences that emerged from the neutrino oscillation data in the recent years. And we try to understand what are the implications of the remarkable discovery that neutrinos have mass, mix and oscillate for elementary particle physics, cosmology and for better understanding of the Earth, the Sun, the stars, formation of Galaxies, the Early Universe, i.e., for better deeper understanding of Nature in general.

# Conclusions

We are heading to a period in which some of the fundamental questions in neutrino physics, and more generally, in particle and astroparticle physics - the status of CP symmetry in the lepton sector and its possible implications for the generation of BAU, the type of spectrum neutrino masses obey, the origin of the patterns of neutrino masses and mixing (symmetry?), the value of the absolute neutrino mass scale, and possibly the nature - Dirac or Majorana - of massive neutrinos, will be answered. This will have profound implications not only for particle and astroparticle physics, for astrophysics and cosmology, but also for our quest for understanding the origins of the patterns of neutrino and charged lepton masses, neutrino mixing and leptonic CP violation.

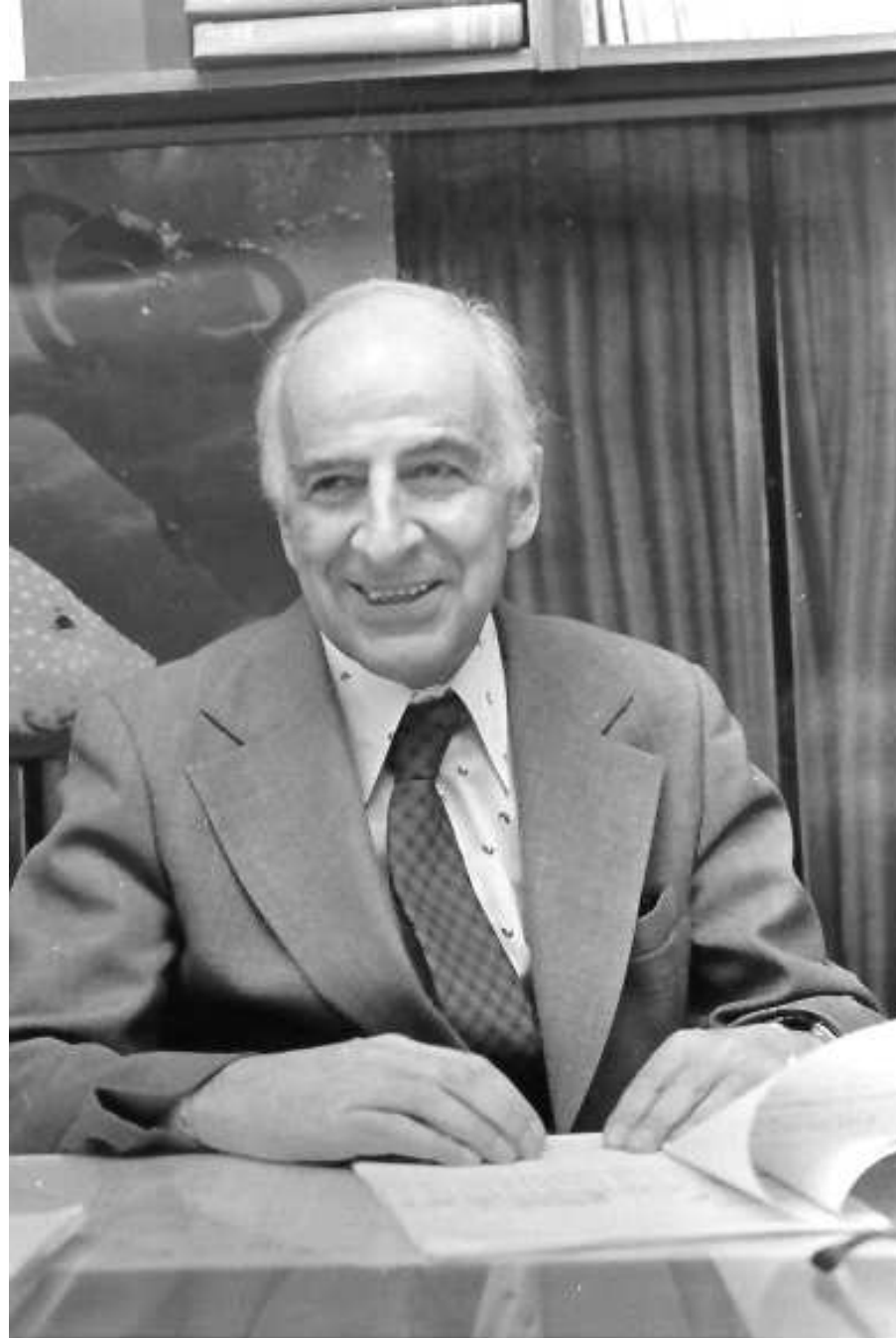
The program of research in neutrino physics extends beyond 2040.

**The future of neutrino physics is bright.**

# Supporting Slides

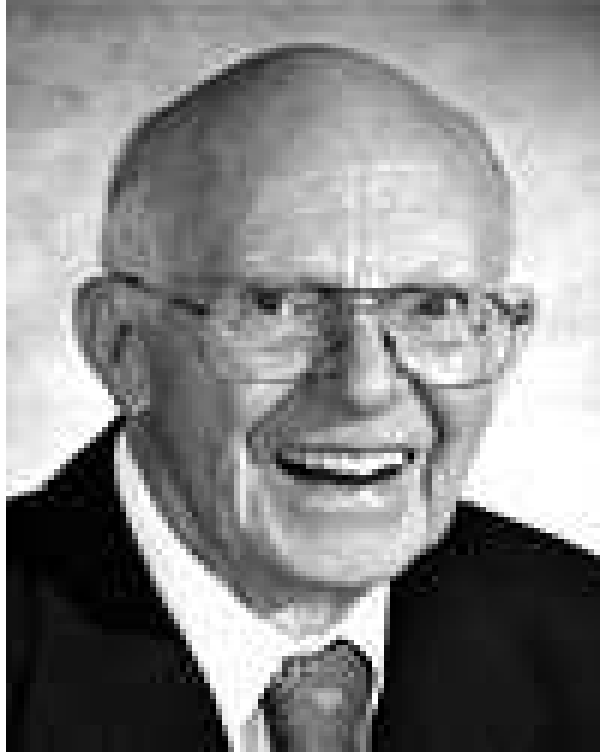
## Neutrini: i Protagonisti...





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S.T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026



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S.T. Petcov, PPP16, Hsinchu, Taiwan, 15-18/06/2026



Offener Brief an die Gruppe der Radioaktiven bei der  
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut  
der Eidg. Technischen Hochschule  
Zürich

Zürich, 4. Des. 1930  
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich baldvollst  
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich  
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie  
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg  
verfallen um den "Wechselstz" (1) der Statistik und den Energiesatz  
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale  
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,  
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und  
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie  
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen  
müsste von derselben Grössenordnung wie die Elektronenmasse sein und  
jedemfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche  
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim  
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert  
wird, derart, dass die Summe der Energien von Neutron und Elektron  
konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die  
Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint  
mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer  
dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein  
magnetischer Dipol von einem gewissen Moment  $\mu$  ist. Die Experimente  
verleihen wohl, dass die ionisierende Wirkung eines solchen Neutrons  
nicht grösser sein kann, als die eines gamma-Strahls und darf dann  
 $\mu$  wohl nicht grösser sein als  $e \cdot (10^{-13} \text{ cm})$ .

Ich traue mich vorläufig aber nicht, etwas über diese Idee  
zu publizieren und wende mich erst vertrauensvoll an Euch, liebe  
Radioaktive, mit der Frage, wie es um den experimentellen Nachweis  
eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa  
10mal grösseres Durchdringungsvermögen besitzen würde, wie ein  
gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein  
wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn  
sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt,  
gesteht und der Ernst der Situation beim kontinuierliche beta-Spektrum  
wird durch einen Ausspruch meines verehrten Vorgängers im Amte,  
Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat:  
"0, daran soll man am besten gar nicht denken, sowie an die neuen  
Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.-  
Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht  
persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht  
vom 6. zum 7. Des. in Zürich stattfindenden Balles hier unabkömmlich  
bin.- Mit vielen Grüssen an Euch, sowie an Herrn Baek, Euer  
untertänigster Diener

ges. W. Pauli

[This is a translation of a machine-typed copy of a letter that Wolfgang Pauli sent to a group of physicists meeting in Tübingen in December 1930. Pauli asked a colleague to take the letter to the meeting, and the bearer was to provide more information as needed.]

Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the Gauverein meeting in Tübingen.

Copy

Physics Institute  
of the ETH  
Zürich

Zürich, Dec. 4, 1930  
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment  $\mu$ . The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then  $\mu$  is probably not allowed to be larger than  $e \cdot (10^{-13} \text{ cm})$ .

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

[Translation: Kurt Riesselmann]

I neutrini sono messaggeri... Viaggiano nell'Universo senza sosta e portano con loro preziose informazioni sugli eventi cosmici...Non hanno una destinazione precisa... Quando attraversano la Terra possono cambiare la loro identità...Non si fermano mai... E solo chi riesce a “catturarli” potrà leggere i segreti che loro portano...