Theoretical Aspects of Astroparticle Physics, Cosmology and Gravitation

Firenze, 18-22 March 2019

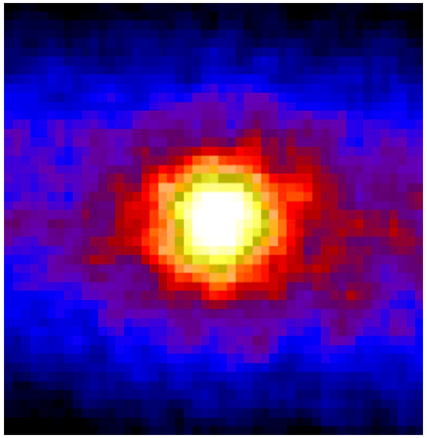
Aspects of neutrino physics (I)
Neutrino Masses, Mixing and Oscillations: the data

Ferruccio Feruglio
Universita' di Padova

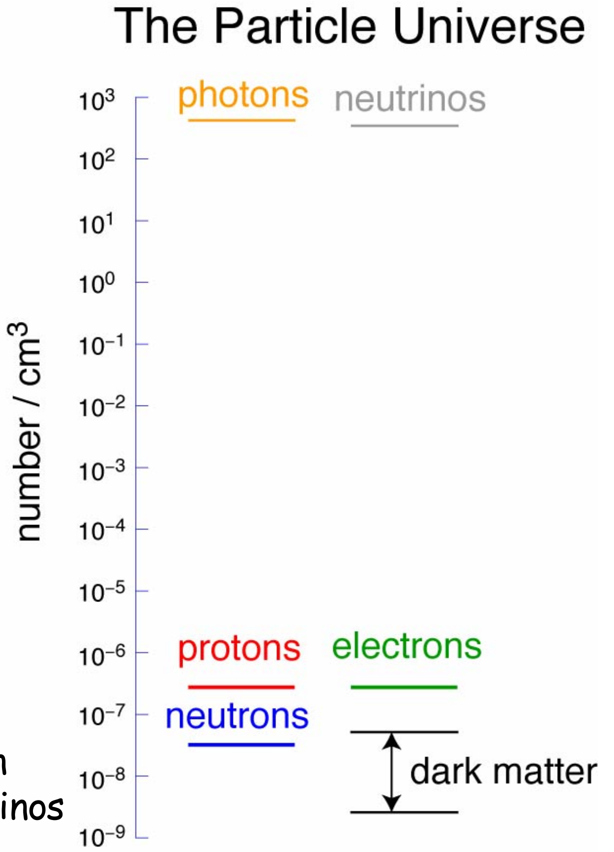
General remarks on neutrinos

the more abundant particles in the universe after the photons: about 300 neutrinos per cm^3

produced by stars: most of the sun energy emitted in neutrinos. As I speak more than 1 000 000 000 000 000 solar neutrinos go through your bodies each second.



this is a picture of the sun reconstructed from neutrinos

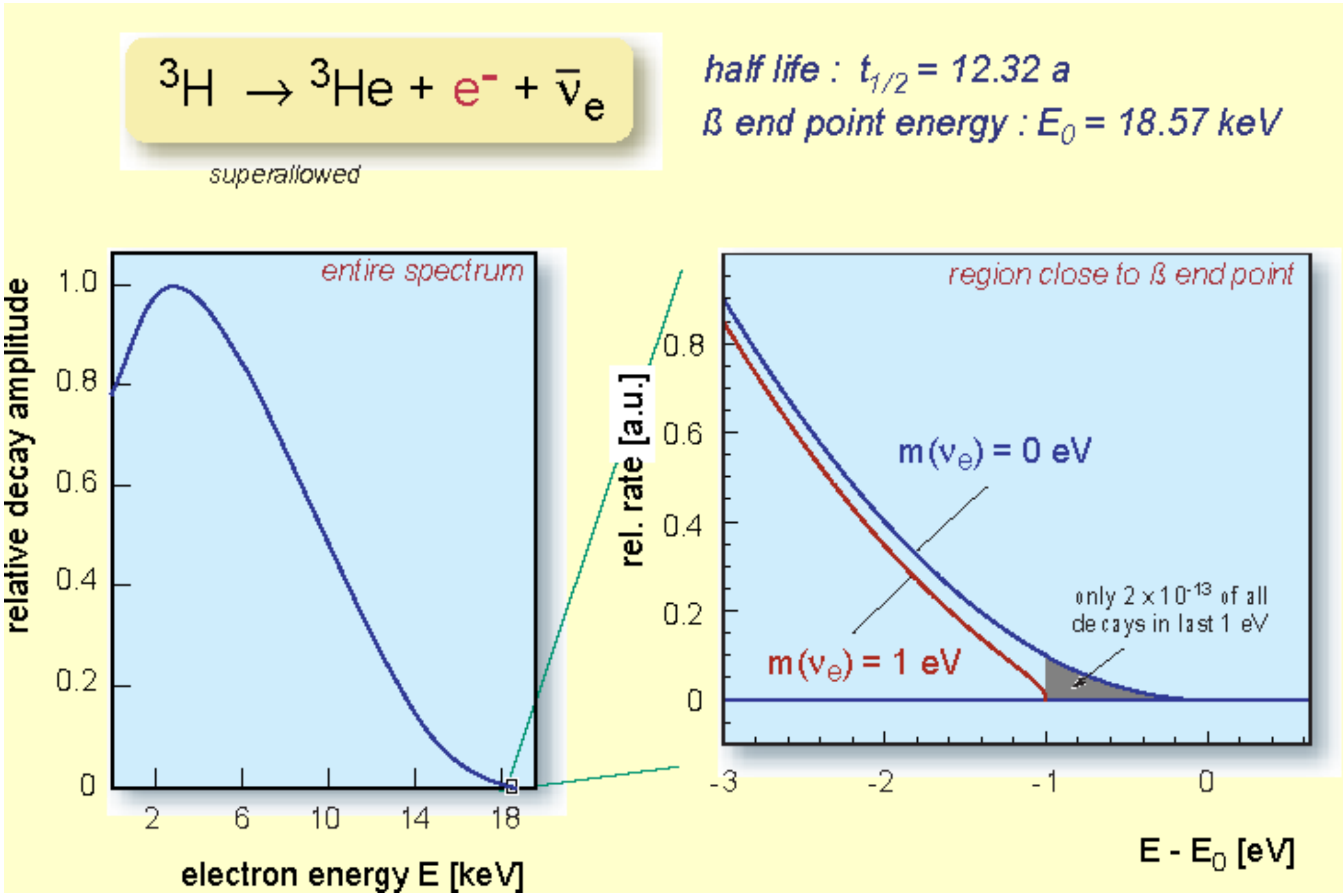


from Murayama talk Aspen 2007

electrically neutral and extremely light:
they can carry information about extremely large length scales
e.g. a probe of supernovae dynamics: neutrino events from a supernova explosion first observed 27 years ago

in particle physics:
they have a tiny mass (1 000 000 times smaller than the electron's mass)
the discovery that they are massive allows us to explore, at least in principle, extremely high energy scales, otherwise inaccessible to present laboratory experiments

Upper limit on neutrino mass (laboratory)



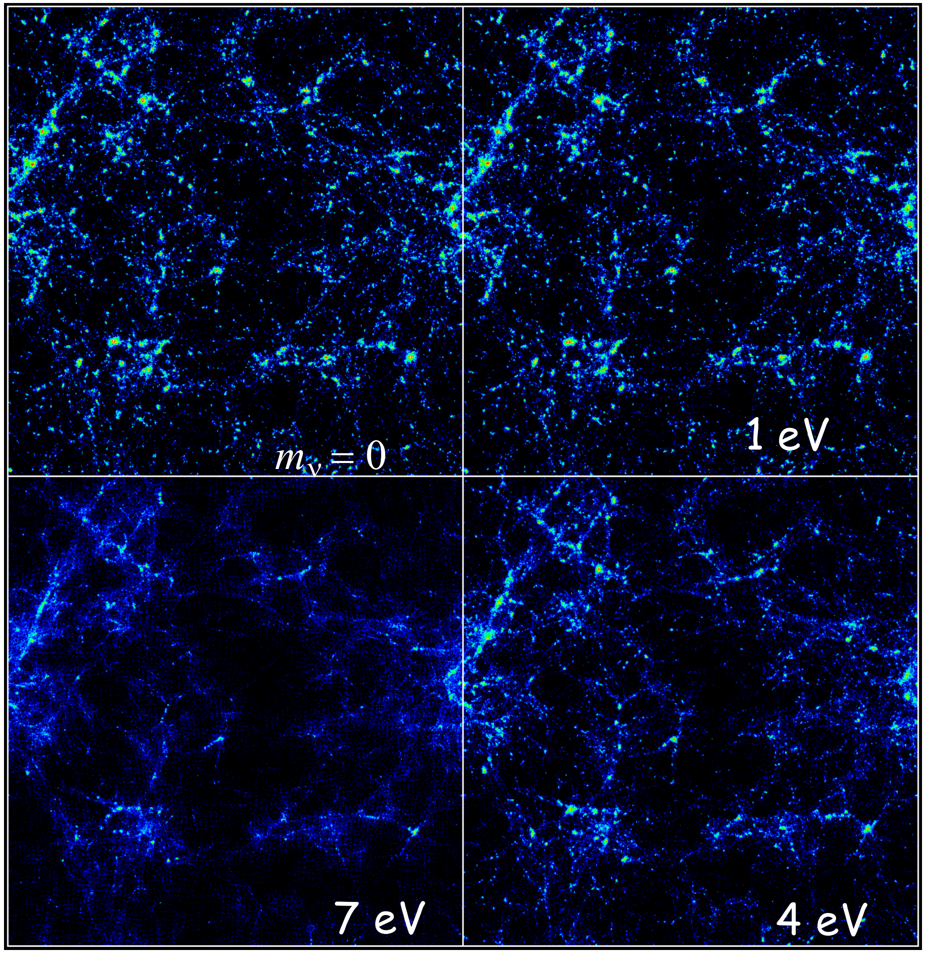
$$m_\nu < 2.2\ eV \quad (95\%\ CL)$$

Upper limit on neutrino mass (cosmology)

massive ν suppress the formation of small scale structures

$$\sum_i m_i < 0.2 \div 1 \quad eV$$

depending on
- assumed cosmological model
- set of data included
- how data are analyzed



$$k_{\rm nr} \approx 0.026 \left(\frac{m_\nu}{1\,{\rm eV}}\right)^{1/2} \Omega_m^{1/2} h\,{\rm Mpc}^{-1}.$$

The small-scale suppression is given by

$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,{\rm eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2)\rangle = \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\cdot(\vec{x}_1-\vec{x}_2)} P(\vec{k})$$

Two-flavour neutrino oscillations (ν_e,ν_μ)

here ν_e are produced with average energy E

source ←———— L ————→ detector

here we measure

$$P_{ee} \equiv P(\nu_e \to \nu_e)$$

neutrino interaction eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\alpha} \end{pmatrix}}_{U} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$-\frac{g}{\sqrt{2}} W_\mu^- \bar{l}_L \gamma^\mu \nu_l$$

as before, but

$$\gamma/2 = \vartheta$$

$$t \approx L$$

$$E_2 - E_1 = \sqrt{p^2 + m_2^2} - \sqrt{p^2 + m_2^2} \approx \frac{m_2^2}{2E} - \frac{m_1^2}{2E} \equiv \frac{\Delta m_{21}^2}{2E}$$

$$P_{ee} = \left|\langle \nu_e | \psi(L) \rangle\right|^2 = 1 - \underbrace{4|U_{e1}|^2 |U_{e2}|^2}_{\sin^2 2\vartheta} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

no dependence on the phase α more on this later on ….

to see any effect, if Δm^2 is tiny, we need both θ and L large

regimes

$$P_{ee} = |\langle \nu_e | \psi(L) \rangle|^2 = 1 - \underbrace{4|U_{e1}|^2|U_{e2}|^2}_{\sin^2 2\vartheta} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\frac{\Delta m^2 L}{4E} << 1 \qquad\qquad P_{ee} \approx 1$$

$$\frac{\Delta m^2 L}{4E} >> 1 \qquad \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \approx \frac{1}{2} \qquad P_{ee} \approx 1 - \frac{\sin^2 2\vartheta}{2}$$

by averaging over ν_e energy at the source

$$\frac{\Delta m^2 L}{4E} \approx 1 \qquad\qquad P_{ee} = P_{ee}(E)$$

useful relation $\frac{\Delta m^2 L}{4E} \approx 1.27 \left(\frac{\Delta m^2}{1\, eV^2}\right)\left(\frac{L}{1\, Km}\right)\left(\frac{E}{1\, GeV}\right)^{-1}$

source	L(km)	E(GeV)	$\Delta m^2 (eV^2)$
ν_e, ν_μ (atmosphere)	10^4 (Earth diameter)	1-10	10^{-4} - 10^{-3}
anti- ν_e (reactor)	1	10^{-3}	10^{-3}
anti- ν_e (reactor)	100	10^{-3}	10^{-5}
ν_e (sun)	10^8	10^{-3} - 10^{-2}	10^{-11} - 10^{-10}

neglecting matter effects

Three-flavour neutrino oscillations $(\nu_e, \nu_\mu, \nu_\tau)$

survival probability as before, with more terms

$$P_{ff} = P(\nu_f \to \nu_f) = \left|\langle \nu_f | \psi(L) \rangle\right|^2 = 1 - 4\sum_{k<j} |U_{fk}|^2 |U_{fj}|^2 \sin^2\left(\frac{\Delta m_{jk}^2 L}{4E}\right)$$

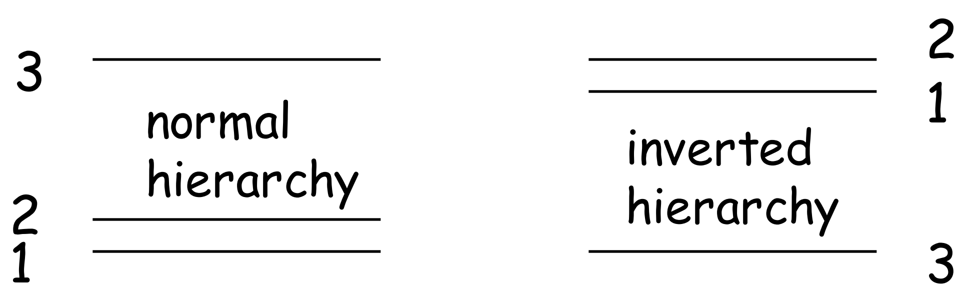
similarly, we can derive the disappearance probabilities $P_{ff'} = P(\nu_f \to \nu_{f'})$

conventions: $[\Delta m_{ij}^2 \equiv m_i^2 - m_j^2]$

$$m_1 < m_2$$

$$\Delta m_{21}^2 < |\Delta m_{32}^2|, |\Delta m_{31}^2|$$ i.e. 1 and 2 are, by definition, the closest levels

two possibilities:



Mixing matrix U=U$_{PMNS}$ (Pontecorvo,Maki,Nakagawa,Sakata)

neutrino interaction eigenstates

$$\nu_f = \sum_{i=1}^{3} U_{fi} \nu_i$$

$$(f = e, \mu, \tau)$$

neutrino mass eigenstates

U is a 3 x 3 unitary matrix
standard parametrization

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ -c_{12}s_{13}c_{23}e^{-i\delta} + s_{12}s_{23} & -s_{12}s_{13}c_{23}e^{-i\delta} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$$c_{12} \equiv \cos\vartheta_{12}, \ldots$$

three mixing angles $\vartheta_{12}, \quad \vartheta_{13}, \quad \vartheta_{23}$

three phases (in the most general case) δ $\qquad \underbrace{\alpha, \quad \beta}_{\text{do not enter}}$ $P_{ff'} = P(\nu_f \to \nu_{f'})$

oscillations can only test 5 combinations

$\Delta m^2_{21}, \Delta m^2_{32}, \quad \vartheta_{12}, \quad \vartheta_{13}, \quad \vartheta_{23} \quad \delta$

structure of the mixing matrix

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

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Analysis of Oscillations Data

we anticipate that there are two small parameters

$$|\alpha| \equiv \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \approx 0.03$$

$$|U_{e3}|^2 \approx \sin^2\vartheta_{13} \approx 0.02$$

$$\Delta m^2_{21} << |\Delta m^2_{32}|, |\Delta m^2_{31}|$$

we first consider experiments not sensitive to Δm^2_{21} (L not very large, E not very small) and we set $\Delta m^2_{21} = 0$

EXERCISE
derive $P_{ee}, P_{\mu\mu}, P_{\mu e}$ in the limit $\Delta m^2_{21} = 0$ (vacuum osc., no matter effects)

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E} \qquad \Delta \equiv \frac{\Delta m^2_{13} L}{4E} \quad [\Delta m^2_{21} = 0]$$

$$P_{ee} = 1 - 4|U_{e3}|^2 (1 - |U_{e3}|^2) \sin^2\Delta$$

$$P_{\mu\mu} = 1 - 4|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) \sin^2\Delta$$

$$P_{\mu e} = P_{e\mu} = 4|U_{\mu 3}|^2 |U_{e3}|^2 \sin^2\Delta$$

similarly, $P_{\tau\tau}, P_{\tau\mu}, P_{\mu\tau}, P_{\tau e}, P_{e\tau}$ only depend on U_{f3} and Δ for $\Delta m^2_{21} = 0$

we are testing the third column

$$U_{PMNS} = \begin{pmatrix} \cdot & \cdot & U_{e3} \\ \cdot & \cdot & U_{\mu 3} \\ \cdot & \cdot & U_{\tau 3} \end{pmatrix}$$

we also consider the limit $\vartheta_{13} = 0$
we are left with one frequency and one mixing angle

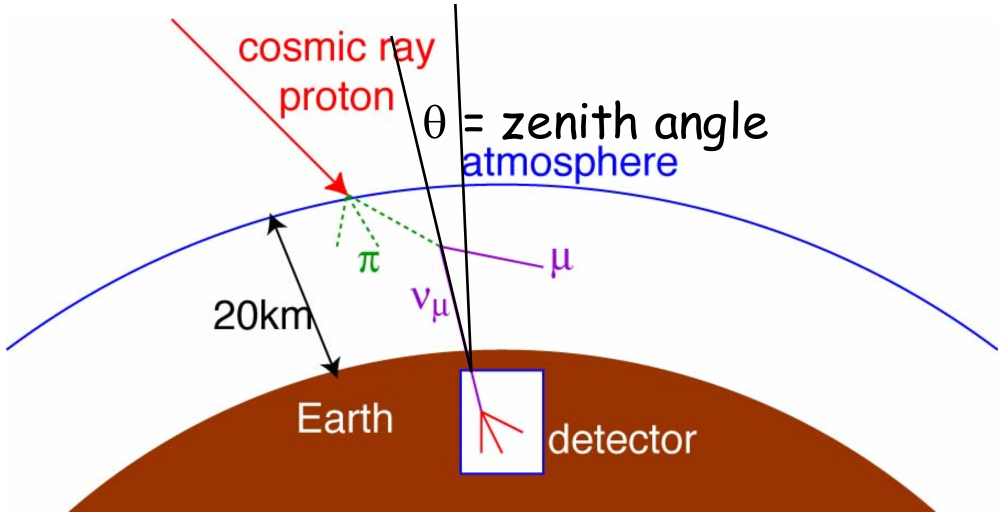
$$|U_{e3}|^2 \approx \sin^2 \vartheta_{13} \approx 0$$

$$P_{ee} = 1$$
$$P_{\mu\mu} = 1 - \sin^2 2\vartheta_{23} \sin^2 \Delta$$
$$P_{\mu e} = P_{e\mu} = 0$$

$$P_{\tau\tau} = P_{\mu\mu}$$
$$P_{\tau\mu} = P_{\mu\tau} = \sin^2 2\vartheta_{23} \sin^2 \Delta$$
$$P_{\tau e} = P_{e\tau} = 0$$

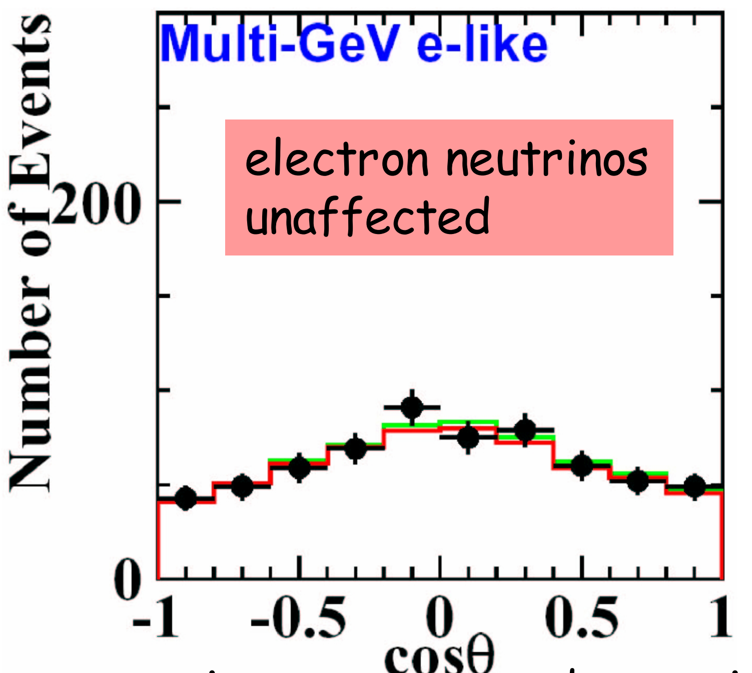
two-flavour oscillations

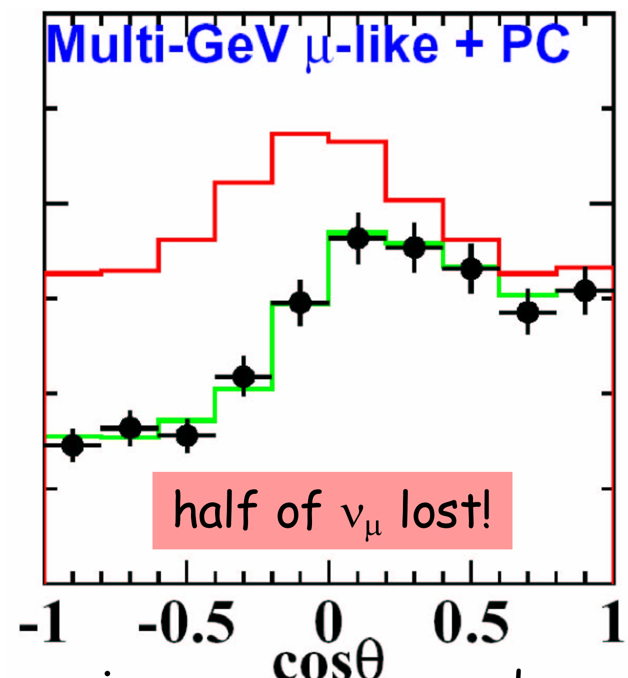
Atmospheric neutrino oscillations



Electron and muon neutrinos (and antineutrinos) produced by the collision of cosmic ray particles on the atmosphere

Experiment:
SuperKamiokande (Japan)





up-going down-going up-going down-going

electron neutrinos do not oscillate

by working in the approximation $\Delta m^2_{21} = 0$

$$P_{ee} = 1 - \underbrace{4|U_{e3}|^2(1-|U_{e3}|^2)}_{\sin^2 2\vartheta_{13}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \approx 1$$

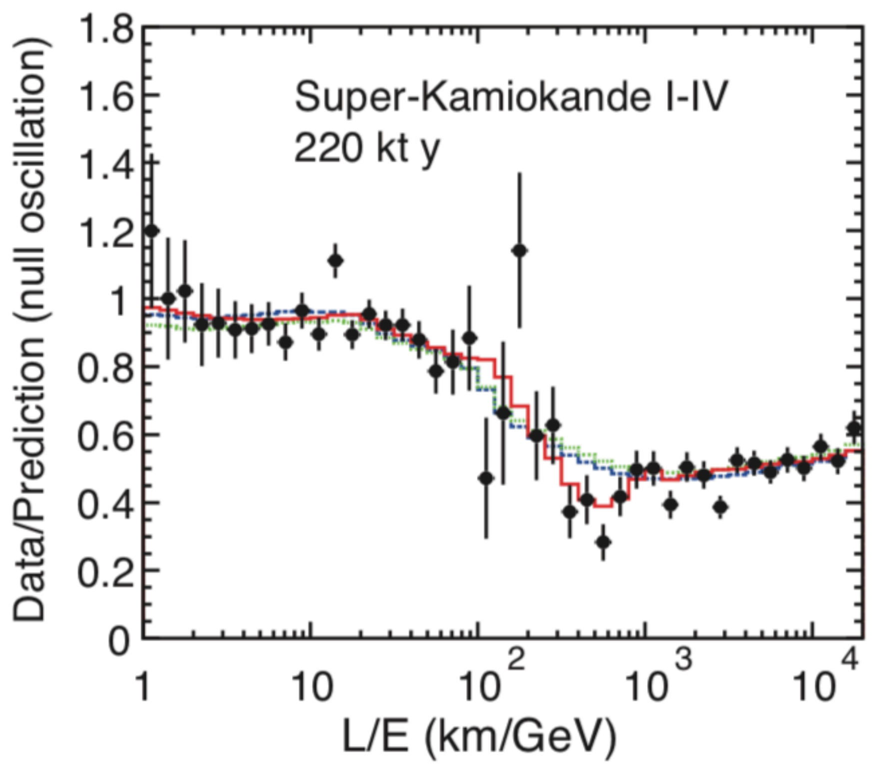
for $U_{e3} = \sin\vartheta_{13} \approx 0$

muon neutrinos oscillate

$$P_{\mu\mu} = 1 - \underbrace{4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)}_{\sin^2 2\vartheta_{23}} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$|\Delta m^2_{32}| \approx 2\cdot 10^{-3} \quad eV^2$$

$$\sin^2\vartheta_{23} \approx \frac{1}{2}$$



$$U_{PMNS} = \begin{pmatrix} \cdot & \cdot & 0 \\ \cdot & \cdot & -\frac{1}{\sqrt{2}} \\ \cdot & \cdot & \frac{1}{\sqrt{2}} \end{pmatrix} + (\text{small corrections})$$

maximal mixing!
not a replica of the quark mixing pattern

man made neutrino beams

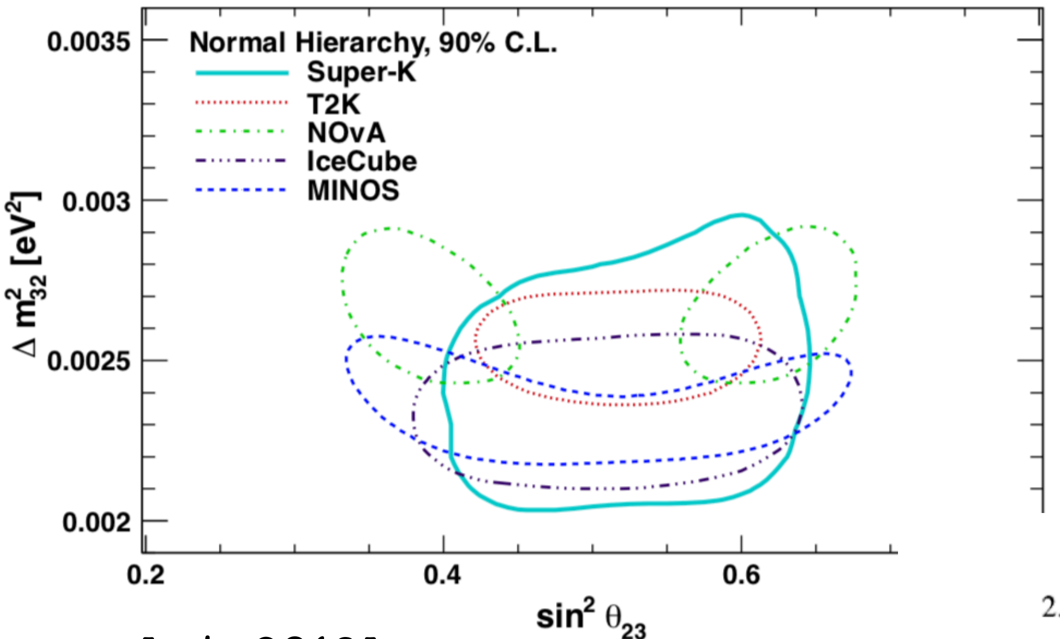
other terrestrial experiments measuring $P_{\mu\mu}$

K2K (Japan, from KEK to Kamioka mine $L \approx 250$ Km $E \approx 1.3$ GeV)
MINOS (USA, from Fermilab to Soudan mine $L \approx 735$ Km $E \approx 3$ GeV)
NOvA (USA, from Fermilab to Ash River $L \approx 810$ Km $E \approx 2$ GeV)
T2K (Japan, from Tokai,J-Park to Kamioka mine $L \approx 295$ Km $E \approx 0.6$ GeV)
OPERA (CERN-Italy, from CERN to LNGS $L \approx 732$ Km $E \approx 17$ GeV)

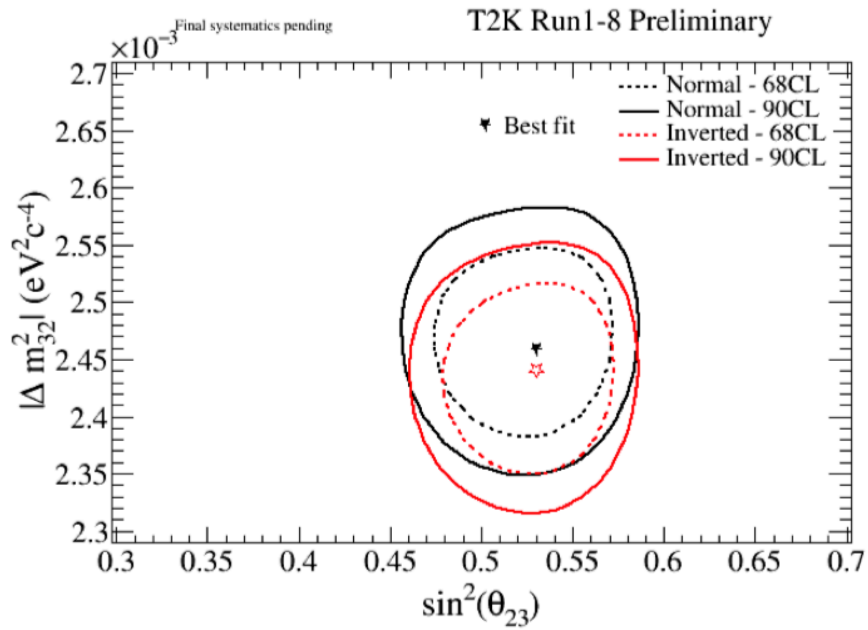
all sensitive to Δm_{32}^2 close to 10^{-3} eV^2

OPERA energy optimized to maximize τ production, via CC events
by 2018 about 10 τ events have been seen

recent results



[pdg 2018]



EPJ Web of Conferences **191**, 03001 (2018)

KamLAND

previous experiments were sensitive to Δm^2 close to 10^{-3} eV^2
to explore smaller Δm^2 we need larger L and/or smaller E

KamLAND experiment exploits the low-energy electron anti-neutrinos (E≈3 MeV) produced by Japanese and Korean reactors at an average distance of L≈180 Km from the detector and is potentially sensitive to Δm^2 down to 10^{-5} eV^2

by working in the approximation

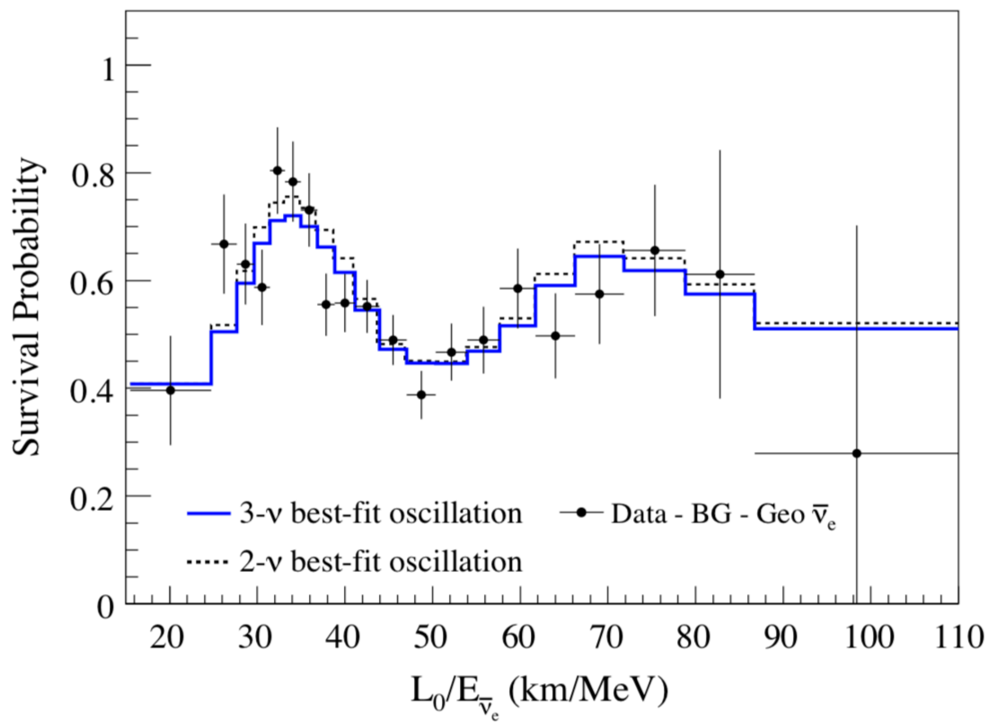
$U_{e3} = \sin\vartheta_{13} = 0$ we get

[Exercise]

$$P_{ee} = 1 - \underbrace{4|U_{e1}|^2 |U_{e2}|^2}_{\sin^2 2\vartheta_{12}} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\Delta m_{21}^2 \approx 8\cdot 10^{-5} \quad eV^2$$

$$\sin^2\vartheta_{12} \approx 1/3$$



EXERCISE

estimate Δm^2_{21} from position of second oscillation dip in previous plot

$$\Delta m^2_{21} = 6\pi \frac{E}{L}\bigg|_{dip} \approx 6\pi \times \frac{1}{50}\ MeV/Km = 7.5\times 10^{-5}\ eV^2$$

EXERCISE

work out P_{ee} by keeping U_{e3} non-vanishing

$$P_{ee} \approx |U_{e3}|^4 + (1-|U_{e3}|^2)^2\left(1-\sin^2 2\vartheta_{12}\sin^2\Delta_{21}\right)$$

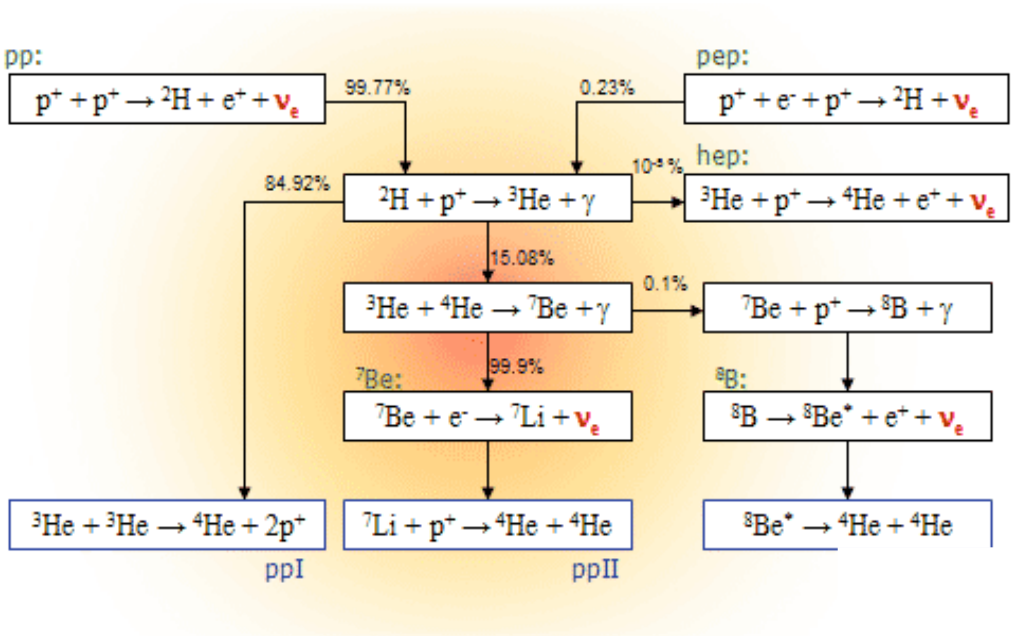
$$U_{PMNS} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} + (\text{small corrections})$$

this pattern is called tri-bimaximal completely different from the quark mixing pattern: two angles are large

by unitarity

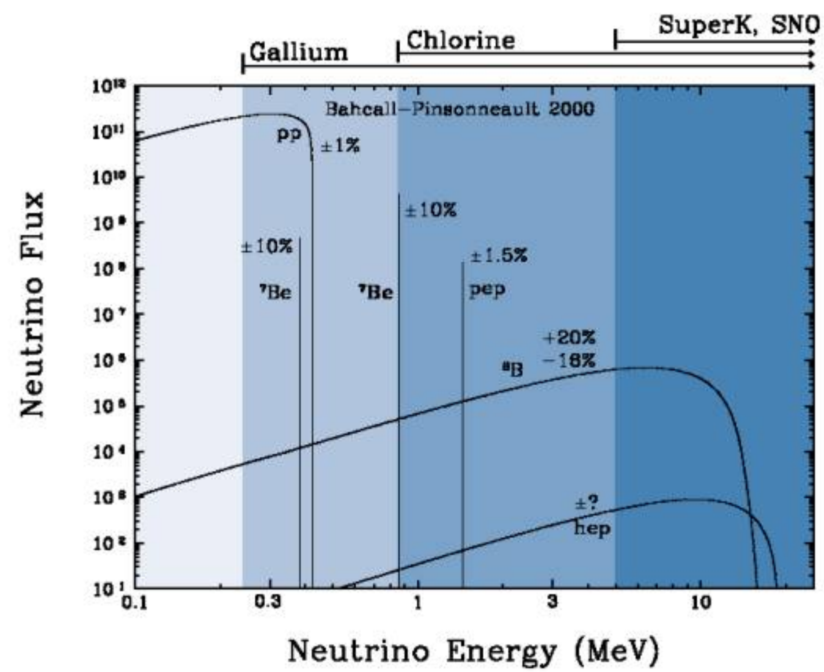
historically Δm_{21}^2 and $\sin^2 \theta_{12}$ were first determined by solving the solar neutrino problem, i.e. the disappearance of about one third of solar electron neutrino flux, for solar neutrinos above few MeV. The desire of detecting solar neutrinos, to confirm the thermodynamics of the sun, was the driving motivation for the whole field for more than 30 years. Electron solar neutrinos oscillate, but the formalism requires the introduction of matter effects, since the electron density in the sun is not negligible. Experiments: SuperKamiokande, SNO, Borexino

Solar Neutrinos



ν_e produced in the core of the sun through several chains/reactions

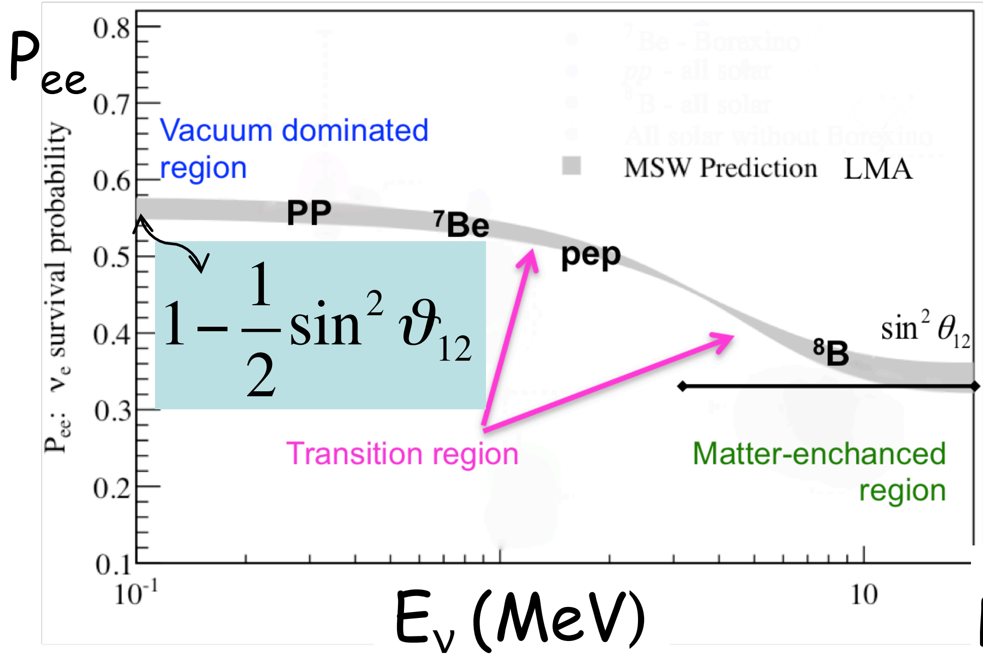
with different energy spectrum



most neutrinos come from pp fusion $E_{max} \approx 0.4$ MeV

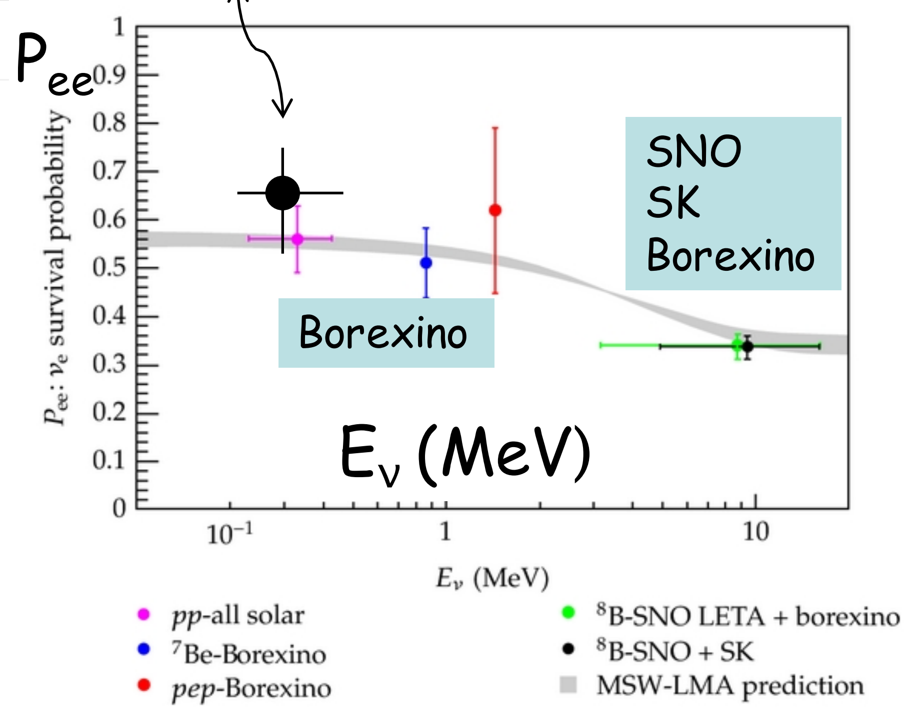
most energetic neutrinos come from ^{8}B decay $E_{max} \approx 15$ MeV

Theory prediction for P_{ee}



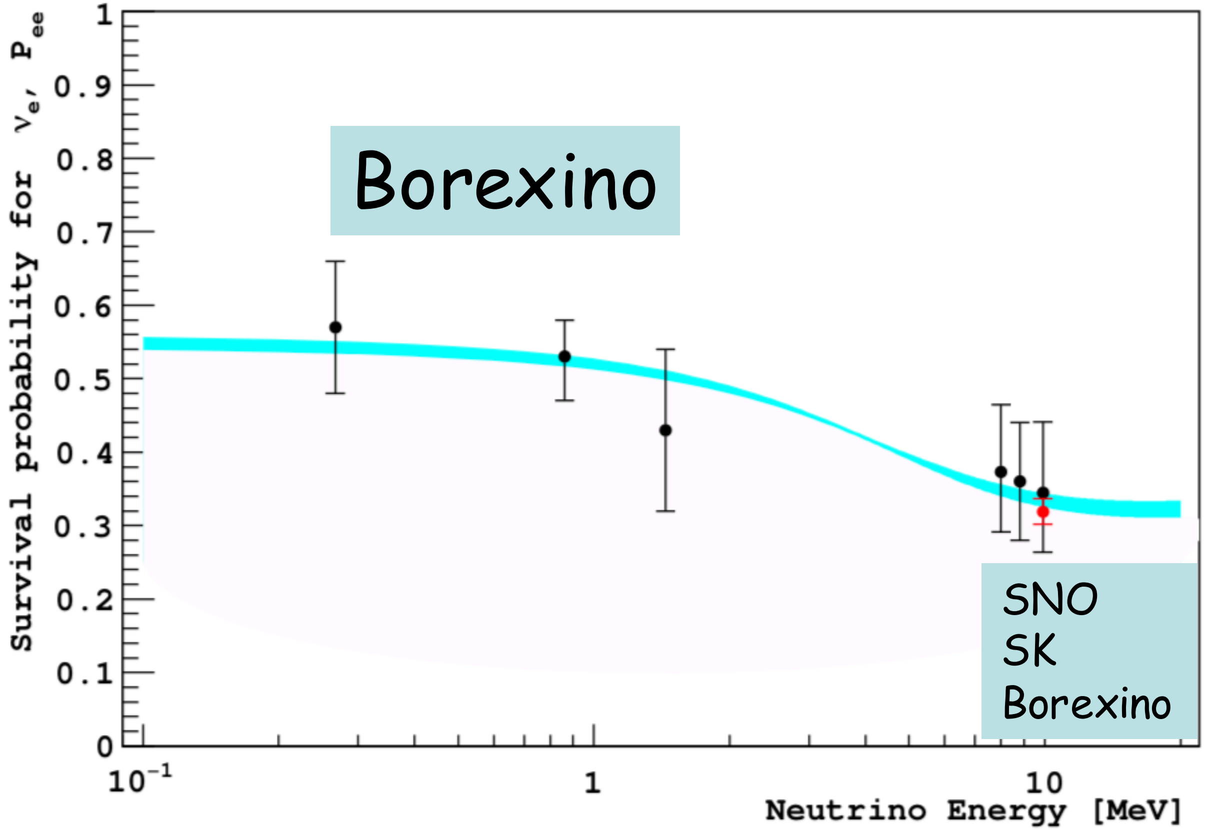
$\sin^2\vartheta_{12}$

[Borexino, Nature 512 (2014) 383]



experiments reveal solar neutrinos through different processes and have different energy thresholds

[pdg2018]


Borexino
SNO
SK
Borexino
Survival probability for ν_e, P_{ee}
Neutrino Energy [MeV]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-1}
1
10

ϑ_{13} from disappearance experiments

These experiments have been realized with reactors. Electron anti-neutrinos are produced by a reactor ($E \approx 3$ MeV, $L \approx 1$ Km) (by CPT the survival probability in vacuum is the same for neutrinos and antineutrinos and matter effects are negligible).
In this range of (L,E) oscillations driven by Δm^2_{21} are negligible and the survival probability P_{ee} only depends on $(|U_{e3}|, \Delta m^2_{31})$.

$$P_{ee} = 1 - \underbrace{4|U_{e3}|^2 (1-|U_{e3}|^2)}_{\sin^2 2\vartheta_{13}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$E \approx 3\ MeV \qquad L \approx 1\ Km$$

Experiment	Near Detectors	Far Detectors
CHOOZ (France)	–	(1) 1050m
Double CHOOZ	400 m	(1) 1050m
Reno (Korea)	(1) 290m	(1) 1380m
Daya Bay (China)	(4) (360-530)m	(4) (1600-2000)m

before 2012 there was only an upper bound on $|U_{e3}|$ by CHOOZ
today (2019) the value of ϑ_{13} is dominated by the Daya Bay result

$$sin^2 2\vartheta_{13} = 0.0841 \pm 0.0033 \qquad \vartheta_{13} = (8.4 \pm 0.2)^0$$

$$|U_{e3}|^2 = sin^2\vartheta_{13} = 0.0215 \pm 0.0009$$

$$|\Delta m^2_{32}| = \begin{cases} 2.45 \pm 0.09 (NO) \\ 2.56 \pm 0.09\ (IO) \end{cases}$$

ϑ_{13} from appearance experiments

These experiments use a muon-neutrino beam from an accelerator and look for conversion of muon-neutrinos into electron-neutrinos. The (L,E) range is such that they are mainly sensitive to Δm^2_{31}

Experiment	E(GeV)	L(Km)
T2K (Japan)	0.6	295
MINOS (USA)	3	735
NOvA (USA)	2	810

at the LO (neglecting Δm^2_{21} and matter effects)

$$P_{\mu e} = 4|U_{\mu 3}|^2 |U_{e3}|^2 \sin^2\Delta = \sin^2\vartheta_{23}\sin^2 2\vartheta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

however in this case corrections from Δm^2_{21} and matter effects are non-negligible

EXERCISE

by expanding $P_{\mu e}$ to first order in $\alpha = \Delta m^2_{21}/\Delta m^2_{13}$ show that

$$\begin{aligned} P_{\mu e} \;=\; & \sin^2\vartheta_{23}\sin^2 2\vartheta_{13}\sin^2\Delta_{13} \\ & -8\alpha J_{CP}\Delta_{13}\sin^2\Delta_{13} \\ & -8\alpha J_{CP}\frac{\cos\delta}{\sin\delta}\Delta_{13}\cos\Delta_{13}\sin\Delta_{13} \\ & +O(\alpha^2) + matter\ effects \end{aligned}$$

$$\Delta_{13} = \frac{\Delta m^2_{31} L}{4E}$$

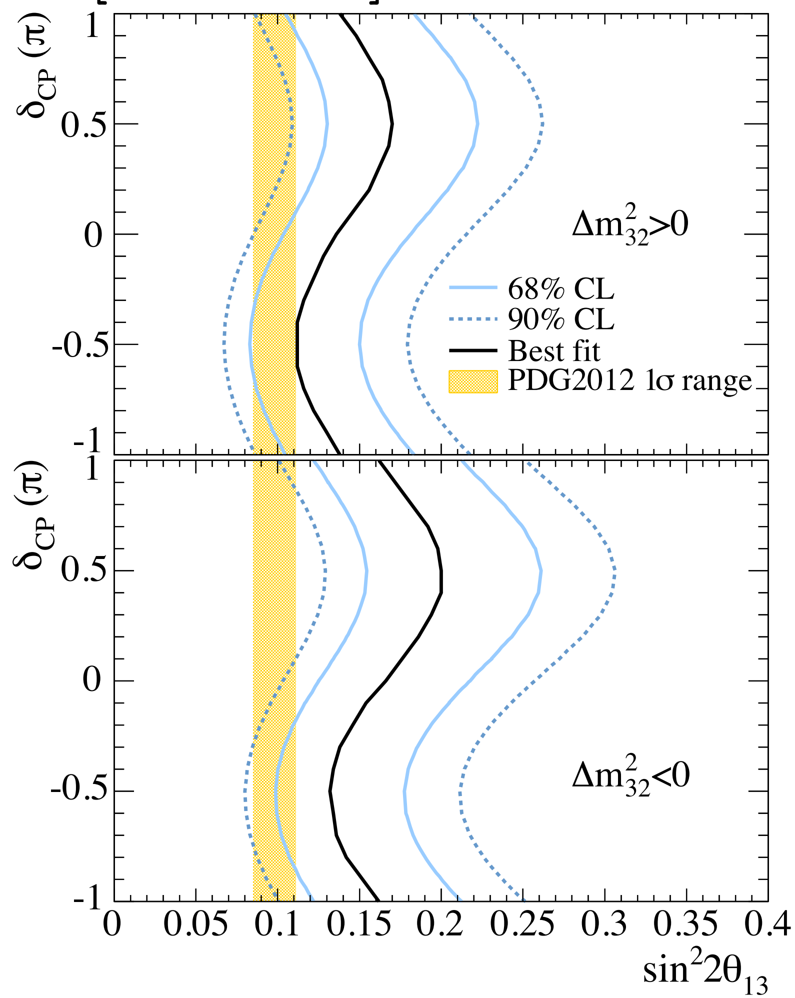
$$\begin{aligned} J_{CP} &= \mathrm{Im}\left(U_{\mu 3}U^*_{e3}U^*_{\mu 2}U_{e2}\right) \\ &= \frac{1}{8}\sin 2\vartheta_{12}\sin 2\vartheta_{23}\sin 2\vartheta_{13}\cos\vartheta_{13}\sin\delta \end{aligned}$$

T2K works near the first oscillation maximum where $|\Delta_{13}|=\pi/2$

$$P_{\mu e} = \sin^2\vartheta_{23}\sin^2 2\vartheta_{13} - 4\pi|\alpha| J_{CP} + O(\alpha^2) + \textit{matter effects}$$

the relative subleading corrections are O(20%) and are sensitive to $\sin\delta$

[T2K 1311.4750]



At present (2019) agreement with the value of ϑ_{13} determined by reactor disappearance experiments requires

$$\sin\delta \approx -1$$

$$\delta \approx \frac{3}{2}\pi$$

i.e. maximal CP violation in the lepton sector

main detection processes

Neutrinos	Experiment	Process
atmospheric ν	SK K2K, MINOS, T2K, Opera	$\nu N \to l X$
solar ν	SK, Borexino SNO	$\nu_X e \to \nu_X e$ $\nu_X D \to \nu_X pn, \nu_e D \to e pp$
reactor ν	KamLand, Chooz, DoubleChooz, Reno, Daya Bay	$\bar{\nu}_e p \to e^+ n \quad (e^+ D\gamma)$

Summary of data

$m_\nu < 2.2\ eV \quad (95\%\ CL)$ (lab)

$\sum_i m_i < 0.2 \div 1 \quad eV$ (cosmo)

Parameter	Ordering	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51
	IO	7.34	7.20 – 7.51
$\sin^2\theta_{12}$	NO	3.04	2.91 – 3.18
	IO	3.03	2.90 – 3.17
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23
	IO	2.18	2.11 – 2.26
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.455	2.423 – 2.490
	IO	2.441	2.406 – 2.474
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70
	IO	5.57	5.33 – 5.74
δ/π	NO	1.32	1.14 – 1.55
	IO	1.52	1.37 – 1.66

[Capozzi, Lisi, Marrone, Palazzo 1804.09678]

violation of individual lepton number
implied by neutrino oscillations

Summary of data

$m_\nu < 2.2\, eV \quad (95\%\, CL)$ (lab)

$\sum_i m_i < 0.2 \div 1 \quad eV$ (cosmo)

Parameter	Ordering	Best fit	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO	7.34	2.2
	IO	7.34	2.2
$\sin^2\theta_{12}$	NO	3.04	4.4
	IO	3.03	4.4
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	3.8
	IO	2.18	3.7
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.455	1.4
	IO	2.441	1.4
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	5.2
	IO	5.57	4.8
δ/π	NO	1.32	14.6
	IO	1.52	9.3

[Capozzi, Lisi, Marrone, Palazzo 1804.09678]

violation of individual lepton number implied by neutrino oscillations

Summary of unkowns

absolute neutrino mass scale is unknown [but well-constrained!]

sign $[\Delta m^2_{atm}]$ unknown

[complete ordering (either normal or inverted hierarchy) not known]

NO favored by global fits at ~ 3σ level

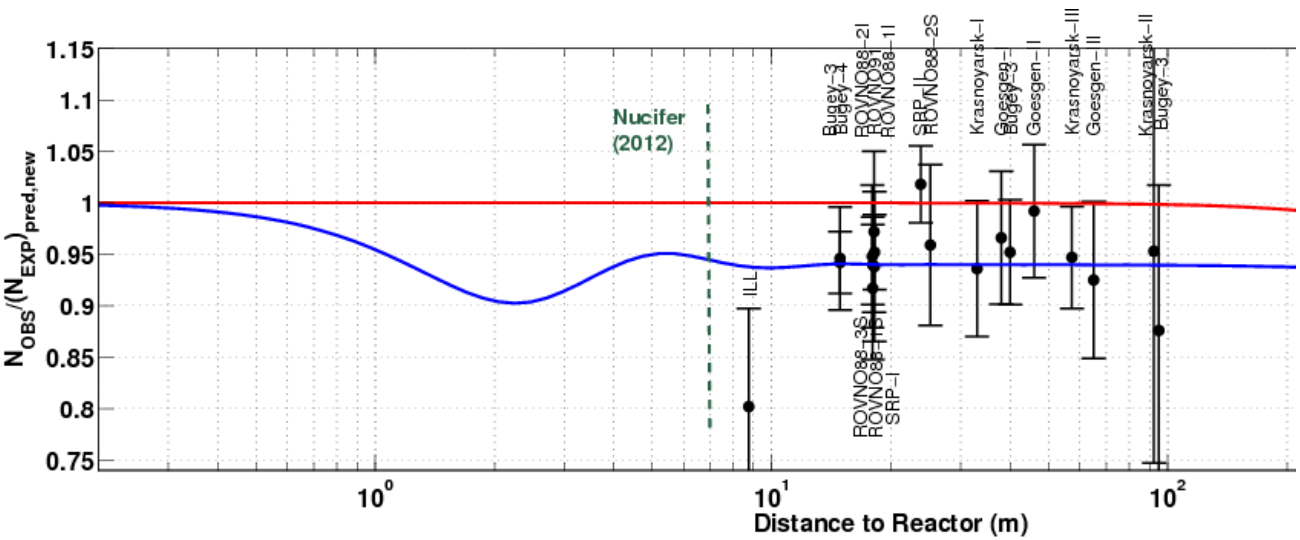
α, β unkown

[CP violation in lepton sector not yet established]

violation of total lepton number not yet established sterile neutrinos ?

1 reactor anomaly (anti-ν_e disappearance)

re-evaluation of reactor anti-ν_e flux: new estimate 3.5% higher than old one



$$(\Phi_{exp} - \Phi_{th}) / \Phi_{th} \approx -6\%$$

[th. uncertainty?]

very SBL L ≤ 100 m

$$\vartheta_{es} \approx 0.2$$

$$\Delta m^2 \approx m_s^2 \geq 1\, eV^2$$

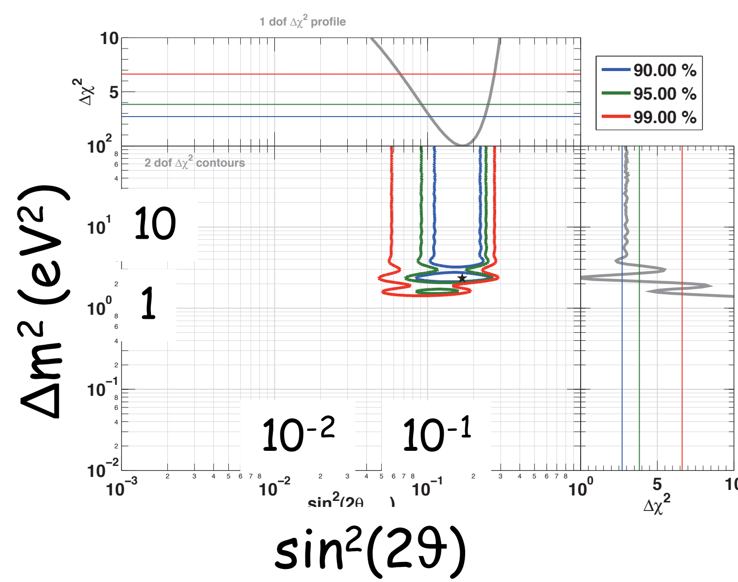
supported by the Gallium anomaly

ν_e flux measured from high intensity radioactive sources in Gallex, Sage exp

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

[error on σ or on Ge extraction efficiency]

... but disfavoured by cosmological limits



2 long-standing claim

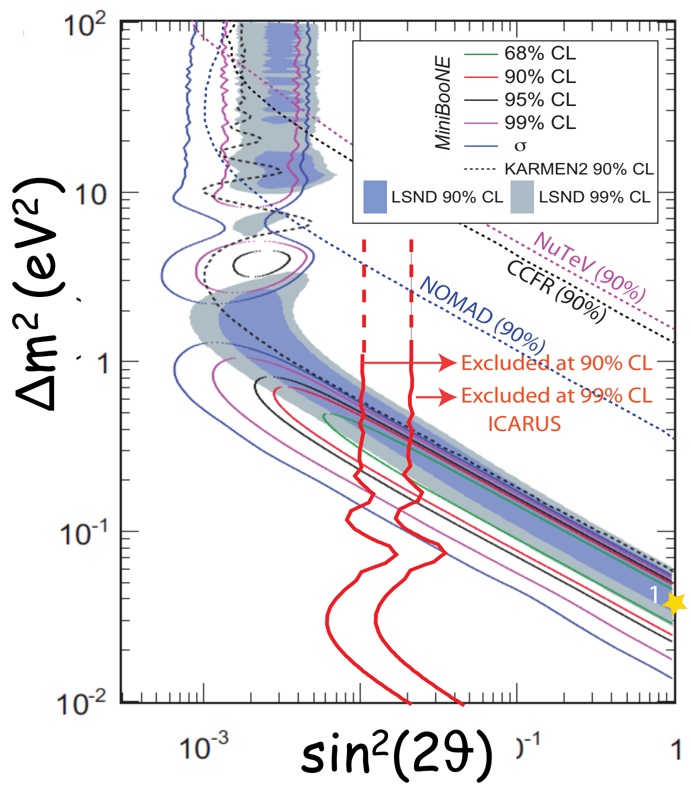
evidence for $\nu_\mu \to \nu_e$ appearance in accelerator experiments

exp		$E(MeV)$	$L(m)$	
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	$10 \div 50$	30	3.8σ
MiniBoone	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	$300 \div 3000$	541	3.8σ [signal from low-energy region]

parameter space limited by negative results from Karmen and ICARUS

$$\vartheta_{e\mu} \approx 0.035$$

$$\Delta m^2 \approx 0.5\, eV^2$$



3

interpretation in 3+1 scheme: inconsistent
(more than 1s disfavored by
cosmology)

$$\underbrace{\vartheta_{e\mu}}_{0.035} \approx \underbrace{\vartheta_{es}}_{0.2} \times \vartheta_{\mu s} \quad \Rightarrow \quad \vartheta_{\mu s} \approx 0.2$$

predicted suppression in ν_μ disappearance
experiments: undetected

by ignoring LSND/Miniboone data the
reactor anomaly can be accommodated
by $m_s \geq 1$ eV and $\vartheta_{es} \approx 0.2$
[not suitable for Warm DM]