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Introduction on neutrino oscillations

Applications of Quantum Information in Astrophysics and Cosmology,
Cape Town (ZA), 25/04/2023

Outline

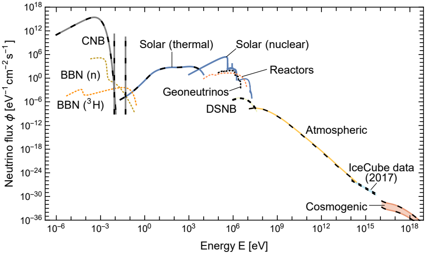
- ***Neutrinos***
- ***Neutrino oscillations in vacuum***
- ***Neutrino oscillations in matter***
- ***Phenomenology of neutrino oscillations***
- ***Status of three-neutrino parameters***
- ***Measurements of neutrino masses***
- ***Additional neutrinos***

N Neutrinos

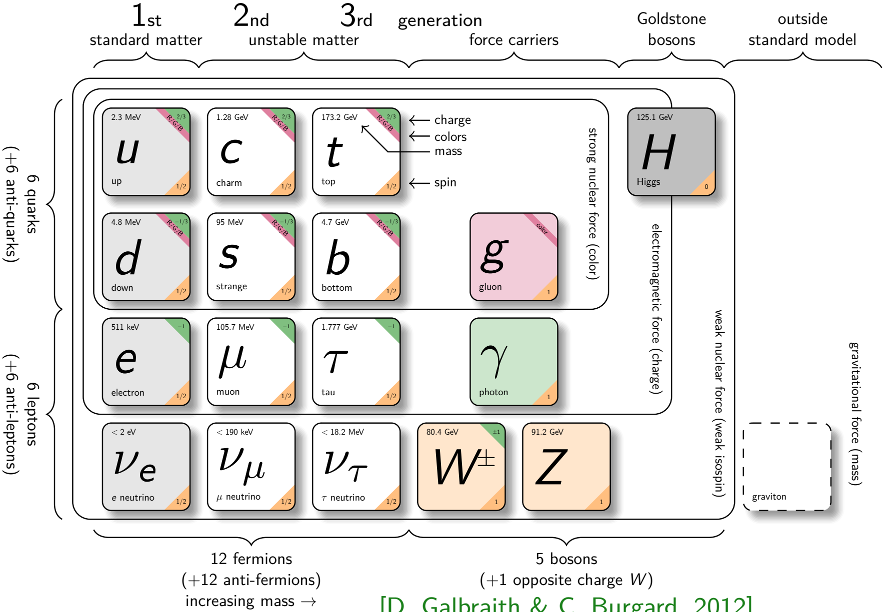
A short historical summary

Based on:

- https://neutrino-history.in2p3.fr/

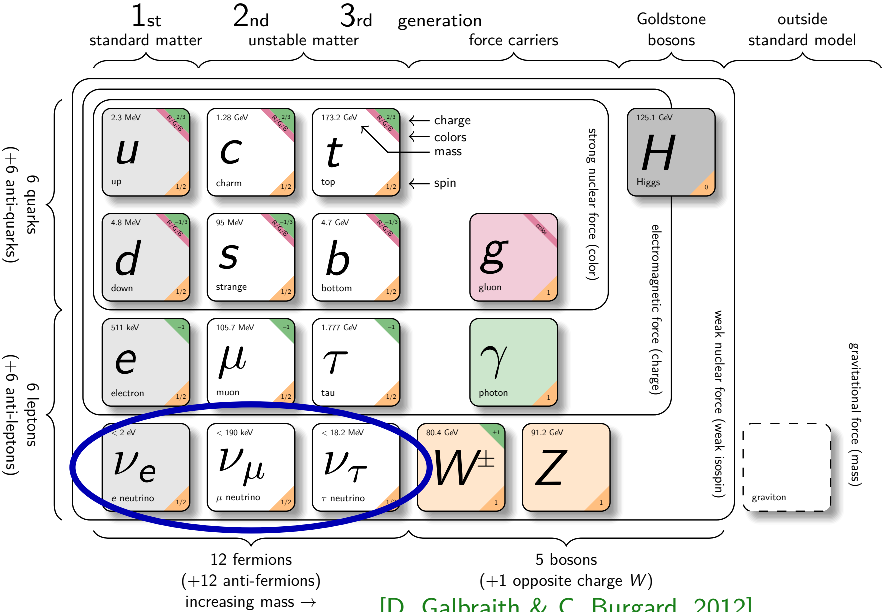


The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

Neutrino proposal and discovery

Milestones in neutrino history:
see `https://neutrino-history.in2p3.fr/`

1896	Bequerel [1][2]	discovery of radioactivity
1927	Ellis [1]	β decay spectrum ($n \to pe^-!$) is continuous

Bohr will desperately propose that energy is conserved "in the mean"

1930	Pauli [1]	proposal of new neutral particle, small mass
1932	Chadwick [1]	neutron discovery, too heavy to be it
1933	Fermi [1][2][3]	name "neutrino" as lighter than neutron
1937	Majorana [1]	neutrino is its own antiparticle?
1948	Pontecorvo [1]	proposal of experiment for detecting neutrinos
1956	Reines&Cowan [1]	first experimental evidence of neutrinos

$\sim$ 25 years from proposal to discovery,
$\sim$ 40 years from discovery to Nobel prize

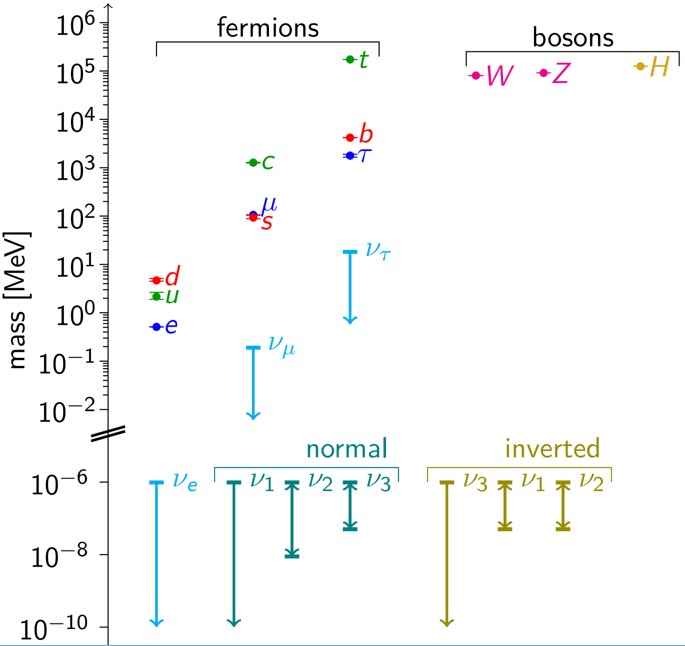
History of neutrino oscillations

After ν discovery: see `https://neutrino-history.in2p3.fr/`

1957		Pontecorvo [1]	first proposal of neutrino oscillations $(\nu - \bar{\nu})$
1959		Pontecorvo [1], Schwartz [1]	existence of second ν family?
1962		Maki-Nakagawa-Sakata [1]	flavor mixing of neutrinos
1962		Lederman, Schwartz, Steinberger [1]	discovery of **muon** ν
1964		Bahcall [1], Davis [1]	First prediction for solar ν
1968		Davis [1]	First observation of solar ν, 1st deficit
1985		Mikheyev, Smirnov [1][2], Wolfenstein [1]	MSW effect
1987		Kamiokande [1], IMB [1], Baksan [1]	Supernova neutrinos
1989		LEP [1][2][3]	There are only 3 neutrino families
1998		SuperKamiokande [1]	Atmospheric $\nu_\mu - \nu_\tau$ oscillations
2001		SNO [1]	Solar deficit explained by MSW+oscillations

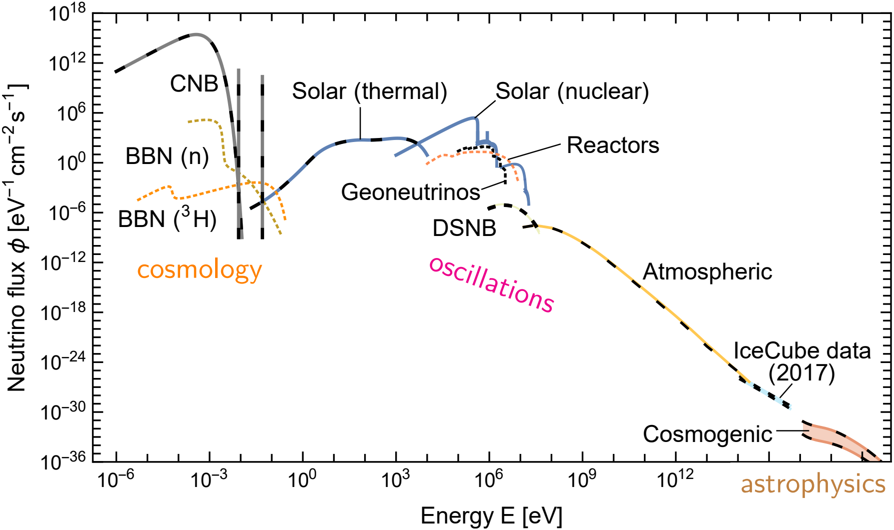
Masses in the Standard Model

[masses from PDG 2020]



Neutrino spectrum

[Vitagliano+, RMP 92 (2020)]



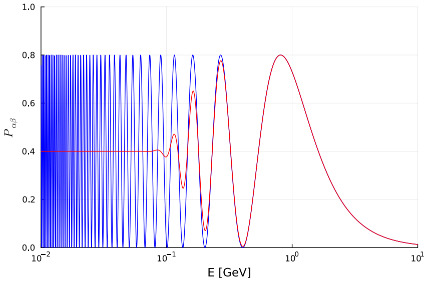
neutrinos at all energies provide valuable information!

V Neutrino oscillations in vacuum

Short theoretical introduction

Based on:

- Giunti&Kim book "Fundamentals of Neutrino Physics and Astrophysics" (2007)



Two neutrino bases

weak interactions

flavor neutrinos ν_α

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

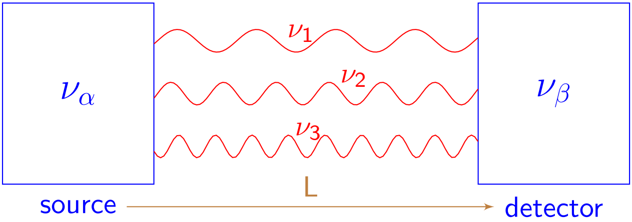
U mixing matrix

$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$

propagation

massive neutrinos ν_k

$k = 1, 2, 3$



neutrino energy $E_k^2 = p_k^2 + m_k^2$

Oscillation probability between source and detector?

$$P_{\nu_\alpha \to \nu_\beta}(L, E, U_{\alpha k}, m_j^2 - m_i^2)$$

Neutrino oscillations in vacuum

Interaction Lagrangian: $\mathcal{L}_{CC} \sim W_\rho \left(\bar{\nu}_{eL}\gamma^\rho e_L + \bar{\nu}_{\mu L}\gamma^\rho \mu_L + \bar{\nu}_{\tau L}\gamma^\rho \tau_L\right)$

Fields $\nu_{\alpha L} = \sum_k U_{\alpha k}\nu_{kL} \quad \Rightarrow \quad$ states $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle$, $|\nu_k\rangle = \sum_\beta U_{\beta k}|\nu_\beta\rangle$

$$|\nu_k(t,x)\rangle = e^{-iE_k t + i p_k x}|\nu_k\rangle \quad \Rightarrow \quad |\nu_\alpha(t,x)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t + i p_k x}|\nu_k\rangle$$

Combining, we get $|\nu_\alpha(t,x)\rangle = \sum_{\beta=e,\mu,\tau} \left(\sum_k U^*_{\alpha k} e^{-iE_k t + i p_k x} U_{\beta k}\right)|\nu_\beta\rangle$

$\equiv \mathcal{A}_{\nu_\alpha \to \nu_\beta}(t,x) \equiv \mathcal{A}_{\alpha\beta}$

$\mathcal{A}_{\alpha\beta}(0,0) = \sum_k U^*_{\alpha k} U_{\beta k} = \delta_{\alpha\beta}$

$\mathcal{A}_{\alpha\beta}(t>0, x>0) \neq \delta_{\alpha\beta}$

Neutrino oscillations in vacuum

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$\equiv \mathcal{A}_{\nu_\alpha\to\nu_\beta}(t,x) \equiv \mathcal{A}_{\alpha\beta}$

$$P_{\nu_\alpha\to\nu_\beta}(t,x) = P_{\alpha\beta} = |\mathcal{A}_{\alpha\beta}|^2 = \left|\sum_k U^*_{\alpha k} e^{-iE_k t + ip_k x} U_{\beta k}\right|^2$$

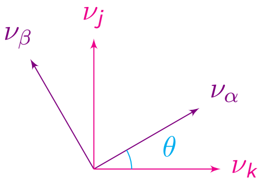
ultra-relativistic neutrinos: $t \simeq x = L$ $(c = 1)$

$$E_k t - p_k x \simeq (E_k - p_k)L = \frac{E_k^2 - p_k^2}{E_k + p_k}L \simeq \frac{m_k^2}{2E}L \qquad \Delta m^2_{kj} = m_k^2 - m_j^2$$

$$\boxed{P_{\alpha\beta}(L,E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)}$$

Two-neutrino oscillations

$$|\nu_\alpha\rangle = \cos\theta|\nu_k\rangle + \sin\theta|\nu_j\rangle$$
$$|\nu_\beta\rangle = -\sin\theta|\nu_k\rangle + \cos\theta|\nu_j\rangle$$



$$U = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}$$

$c_\theta \equiv \cos\theta$
$s_\theta \equiv \sin\theta$
$\Delta m^2 = m_k^2 - m_j^2$

Transition probability:
(appearance)
$$P_{\alpha\beta}(L,E) = P_{\beta\alpha}(L,E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

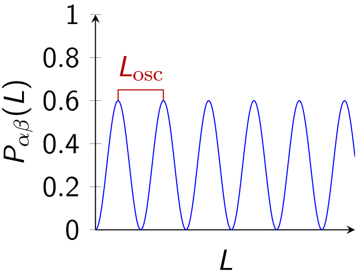
Survival probability:
(disappearance)
$$P_{\alpha\alpha}(L,E) = P_{\beta\beta}(L,E) = 1 - P_{\alpha\beta}(L,E)$$

Oscillation phase: $\frac{\Delta m^2 L}{4E} =$

$$1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{m}]}{E[\mathrm{MeV}]} = 1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

Oscillation length: $L_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2} =$

$$2.47\frac{E[\mathrm{MeV}]}{\Delta m^2[\mathrm{eV}^2]}\mathrm{m} = 2.47\frac{E[\mathrm{GeV}]}{\Delta m^2[\mathrm{eV}^2]}\mathrm{km}$$



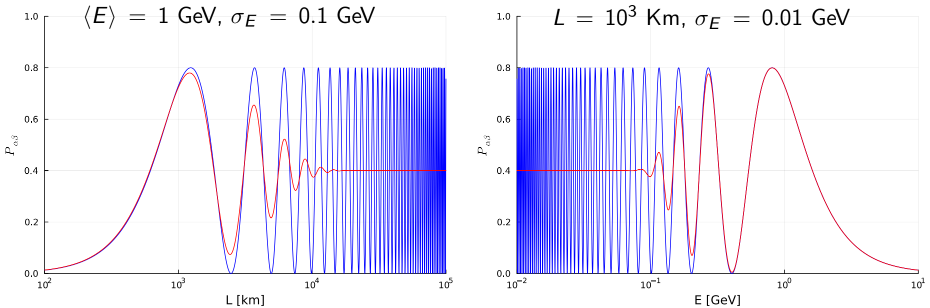
Measuring oscillations with finite energy resolution

$$P_{\alpha\beta}(L,E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \frac{1}{2}\sin^2 2\theta\left[1-\cos\left(\frac{\Delta m^2 L}{2E}\right)\right]$$

$$\langle P_{\alpha\beta}(L,E)\rangle = \frac{1}{2}\sin^2 2\theta\left[1-\int\cos\left(\frac{\Delta m^2 L}{2E}\right)\phi(E)\mathrm{d}E\right]$$

$\Delta m^2 = 10^{-3}$ eV^2, $\sin^2 2\theta = 0.8$

$\phi(E)$ Gaussian distribution



The three-neutrino mixing matrix

U can be parameterized using 3 angles (θ_{12}, θ_{13}, θ_{23}) and max 3 (1 Dirac δ, 2 Majorana [∃ only for Majorana ν]) phases

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{mainly atmospheric and LBL accelerator disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{mainly LBL reactors and LBL accelerator appearance}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{mainly solar and VLBL reactors}} M$$

Majorana phases irrelevant for oscillation experiments ←

Relevant for example in neutrinoless double-beta decay

$$s_{ij} \equiv \sin\theta_{ij};\ c_{ij} \equiv \cos\theta_{ij}$$

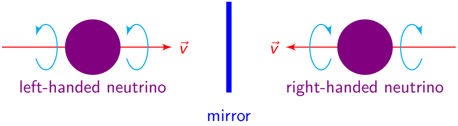
LBL = long baseline; VLBL = very long baseline;

Neutrinos and antineutrinos

Right-Handed antineutrinos are described by CP-conjugated fields:

$$\nu_{\alpha L}^{\mathrm{CP}} = \gamma^0 \mathcal{C} \overline{\nu_{\alpha L}}^T$$

C: Particle $\leftrightarrows$ Antiparticle
P: Left-Handed $\leftrightarrows$ Right-Handed



States: $|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle \xrightarrow{CP} |\bar{\nu}_\alpha\rangle = \sum_k U_{\alpha k} |\bar{\nu}_k\rangle$

Neutrinos $U \leftrightarrows U^*$ Antineutrinos (CP)

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right) \qquad P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} = \sum_{k,j} U_{\alpha k} U_{\beta k}^* U_{\alpha j}^* U_{\beta j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$$

$P_{\nu_\alpha \to \nu_\beta} = P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$ is invariant under CPT ($U \leftrightarrows U^*$, $\alpha \leftrightarrows \beta$)

(Local QFT is CPT symmetric)

$$P_{\nu_\alpha \to \nu_\alpha} = P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}$$

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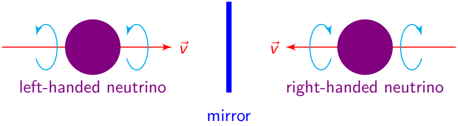

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(Local QFT is CPT symmetric)

$\to$ $P_{\nu_\alpha \to \nu_\alpha} = P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}$

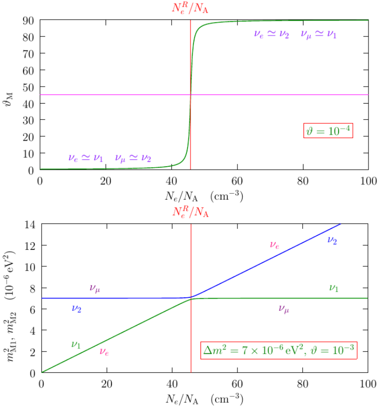
CP asymmetries: $A_{\alpha\beta}^{\mathrm{CP}} = P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} = 4 \sum_{k>j} \underbrace{\mathrm{Im}[U_{\alpha k} U_{\beta k}^* U_{\alpha j}^* U_{\beta j}]} \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$

$J = c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \sin\delta$ Jarlskog rephasing invariant

M Neutrino oscillations in matter

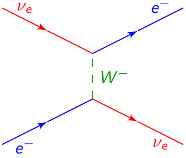
Based on:

- Giunti&Kim book "Fundamentals of Neutrino Physics and Astrophysics" (2007)



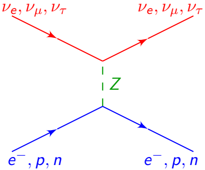
Flavor oscillations in matter

coherent interactions with medium: forward elastic CC and NC scattering



$V_{\rm CC} = \sqrt{2} G_{\rm F} N_e$

no μ, τ in medium



$V_{\rm NC} = \cancel{V_{\rm NC}^{(e^-)}} + \cancel{V_{\rm NC}^{(p)}} + V_{\rm NC}^{(n)} = -\sqrt{2}/2 G_{\rm F} N_n$

$V_{\rm NC}$ irrelevant for 3ν flavor oscillations (diagonal contribution in flavor)

antineutrinos: change sign, so that $\bar{V}_{\rm CC} = -V_{\rm CC}$ and $\bar{V}_{\rm NC} = -V_{\rm NC}$

Flavor oscillations in matter

coherent interactions with medium: forward elastic CC and NC scattering

Flavor evolution determined by Hamiltonian $\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_I$

$\mathcal{H}_0|\nu_k(p)\rangle = E_k|\nu_k(p)\rangle$ while $\mathcal{H}_I|\nu_\alpha(p)\rangle = V_\alpha|\nu_\alpha(p)\rangle$

flavor superposition at $t > 0$: $|\nu(p,t)\rangle = \sum_\beta \varphi_\beta(p,t)|\nu_\beta(p)\rangle$

$$P_{\nu_\alpha\to\nu_\beta} = |\varphi_\beta|^2 = |\psi_\beta|^2$$

states: $i\frac{d}{dt}|\nu(p,t)\rangle = \mathcal{H}|\nu(p,t)\rangle$ amplitudes: $\psi_\beta(p,t) = e^{iC}\varphi_\beta(p,t)$

$$i\frac{d}{dx}\Psi_\alpha = \frac{1}{2E}\left(U\mathbb{M}^2U^\dagger + \mathbb{A}\right)\Psi_\alpha$$

$\to A_{\rm CC} = 2EV_{\rm CC}$

$$\Psi_\alpha = \begin{pmatrix}\psi_e\\ \psi_\mu\\ \psi_\tau\end{pmatrix} \quad \mathbb{M}^2 = \begin{pmatrix} m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{pmatrix} \quad \mathbb{A} = \begin{pmatrix} A_{\rm CC} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$\mathbb{M}^2_{\rm vacuum} = U\mathbb{M}^2U^\dagger \xrightarrow{matter} U\mathbb{M}^2U^\dagger + 2E\mathbb{V} = \mathbb{M}^2_{\rm matter}$$

Two-neutrino mixing in matter

Consider $\nu_e \to \nu_\mu$ transitions, $U = (\cos\theta \quad \sin\theta; -\sin\theta \quad \cos\theta)$

$$U\mathbb{M}^2U^\dagger = \cancel{\frac{1}{2}\Sigma m^2} + \frac{1}{2}\begin{pmatrix} -\Delta m^2\cos 2\theta & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta \end{pmatrix}$$

$$\boxed{i\frac{d}{dx}\begin{pmatrix}\psi_e \\ \psi_\mu\end{pmatrix} = \frac{1}{4E}\begin{pmatrix} -\Delta m^2\cos 2\theta + 2A_{\rm CC} & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta \end{pmatrix}\begin{pmatrix}\psi_e \\ \psi_\mu\end{pmatrix}}$$

initial ν_e: $(\psi_e, \psi_\mu)(0) = (1, 0) \quad \Rightarrow \quad \begin{aligned} P_{e\mu}(x) &= |\psi_\mu(x)|^2 \\ P_{ee}(x) &= |\psi_e(x)|^2 = 1 - P_{e\mu} \end{aligned}$

Constant matter density: $dA_{\rm CC}/dx = 0$

$$\boxed{P_{e\mu} = \sin^2 2\theta_{\rm M} \sin^2\left(\frac{\Delta m^2_{\rm M} x}{4E}\right)}$$

$$\tan 2\theta_{\rm M} = \tan 2\theta / \left(1 - \frac{A_{\rm CC}}{\Delta m^2 \cos 2\theta}\right)$$

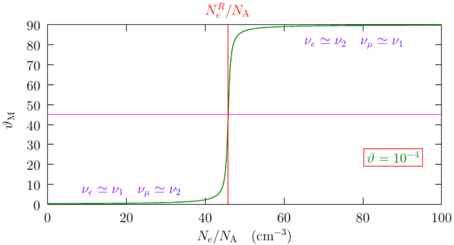
$$\Delta m^2_{\rm M} = \sqrt{(\Delta m^2 \cos 2\theta - A_{\rm CC})^2 + (\Delta m^2 \sin 2\theta)^2}$$

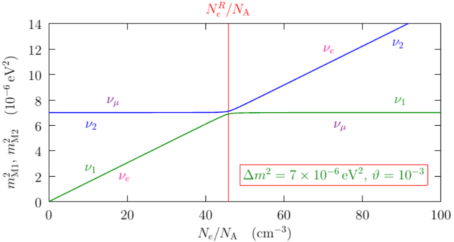
resonance ($\theta_{\rm M} = \pi/4$): $\Delta m^2 \cos 2\theta = A^{\rm R}_{\rm CC} \longrightarrow N^{\rm R}_e = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} E G_{\rm F}}$

Resonant transitions (MSW effect)

[Wolfenstein 1978]
[Mikheev, Smirnov, 1986]

What if the matter density is not constant?





Notice: $A_{CC} > 0$

↓

ν resonance only possible if $\theta < \pi/4$

$$\nu_e = \cos\theta_M \nu_1 + \sin\theta_M \nu_2$$
$$\nu_\mu = -\sin\theta_M \nu_1 + \sin\theta_M \nu_2$$

$$\tan 2\theta_M = \tan 2\theta \Big/ \left(1 - \frac{A_{CC}}{\Delta m^2 \cos 2\theta}\right)$$

$$\Delta m^2_M = \sqrt{(\Delta m^2 \cos 2\theta - A_{CC})^2 + (\Delta m^2 \sin 2\theta)^2}$$

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

if $N_e > N_e^R$, ν_e is produced as ν_2, while in vacuum it would be ν_1!

this happens for example in the Sun (adiabatic crossing of the resonance)

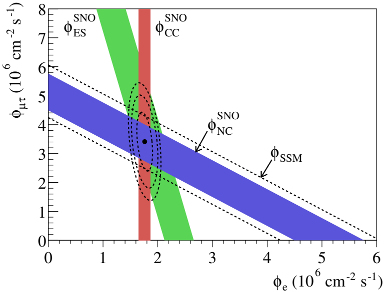
P

Phenomenology of neutrino oscillations

Using different neutrino sources

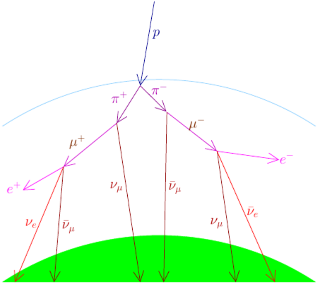
Based on:

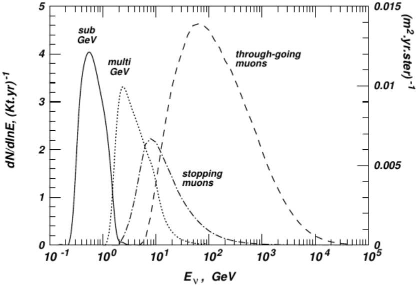
- Giunti&Kim book “Fundamentals of Neutrino Physics and Astrophysics” (2007)
- SuperKamiokande
- SNO



Atmospheric neutrinos

Produced in showers when cosmic rays hit the atmosphere





expected ratio of μ vs e (anti)neutrinos:

$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \simeq 2 \text{ at } E \lesssim 1 \text{ GeV}$$

uncertainty on ratios ($\sim$ 5%) smaller than uncertainty on fluxes ($\sim$ 30%)

better to measure ratios!

$$R \equiv \frac{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\rm data}}{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\rm MC}}$$

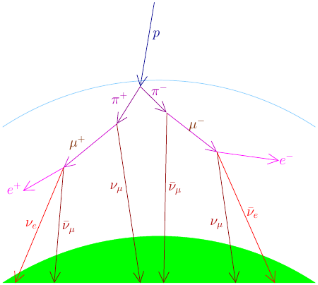
$$R^K_{E<1\text{ GeV}} = 0.60 \pm 0.07 \pm 0.05$$

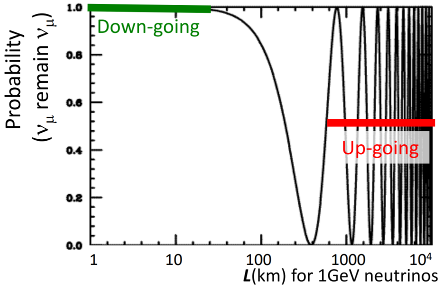
[Kamiokande, PLB 280 (1992)]

neutrinos are missing!

Atmospheric neutrinos

Produced in showers when cosmic rays hit the atmosphere





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uncertainty on ratios ($\sim$ 5%) smaller than uncertainty on fluxes ($\sim$ 30%)

better to measure ratios!

$$R \equiv \frac{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{data}}}{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{MC}}}$$

$$R^K_{E<1\text{ GeV}} = 0.60 \pm 0.07 \pm 0.05$$

[Kamiokande, PLB 280 (1992)]

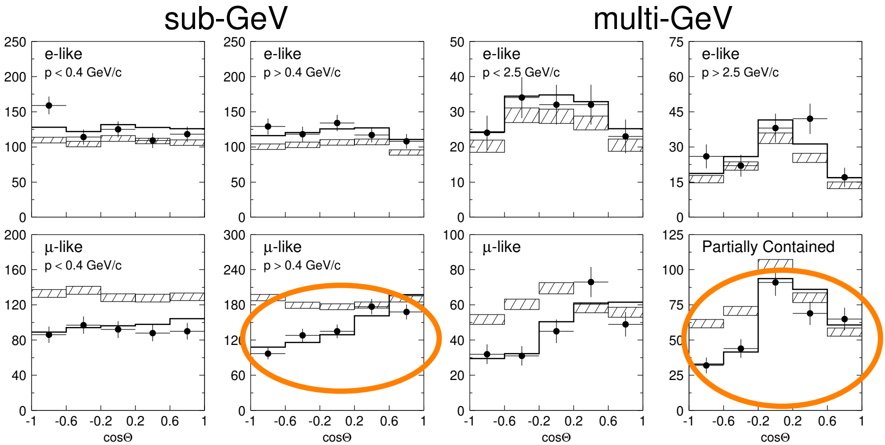
neutrinos are missing!

oscillations?

Atmospheric neutrinos from SuperKamiokande

SuperKamiokande: 50 kton water-Cherenkov detector, 1km undergound

Can distinguish ν_e and ν_μ, measure zenith dependence



[SuperKamiokande, PRL 81 (1998)]

$R^{\rm SK}_{>\rm GeV,e} = 0.93^{+0.13}_{-0.12}$ $\quad$ $R^{\rm SK}_{>\rm GeV,\mu} = 0.54^{+0.06}_{-0.05}$: 6.2σ!

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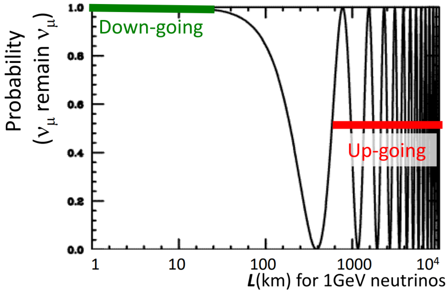

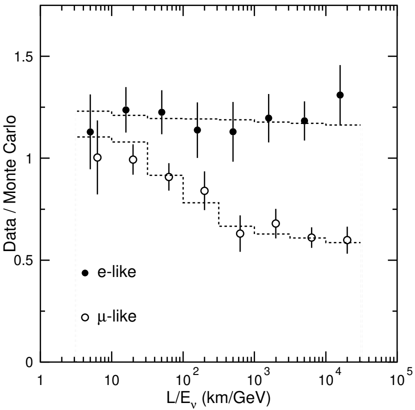

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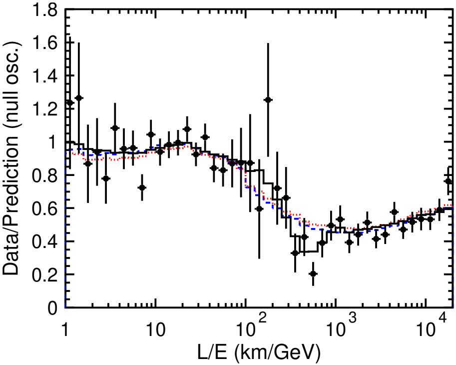
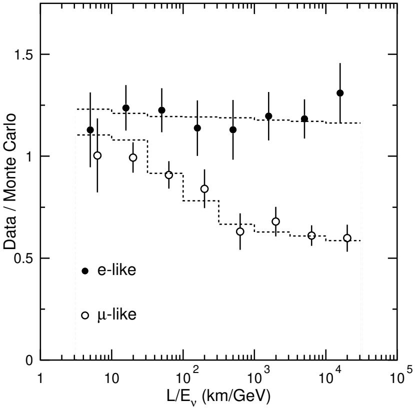


[SuperKamiokande, PRL 93 (2004)]



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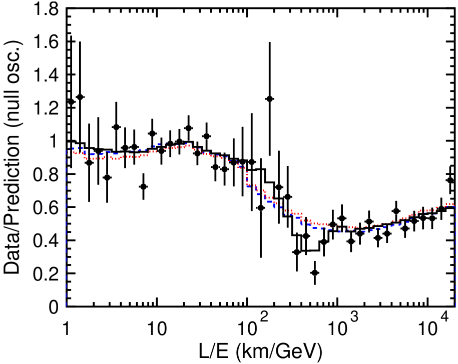

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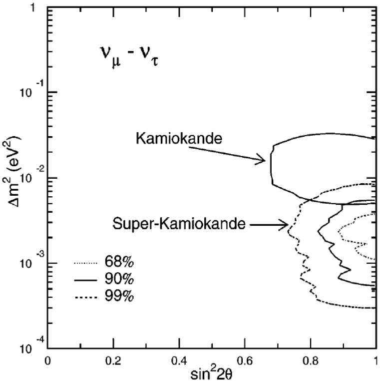


[SuperKamiokande, PRL 81 (1998)]

First observation of atmospheric ν_μ disappearence because of oscillations

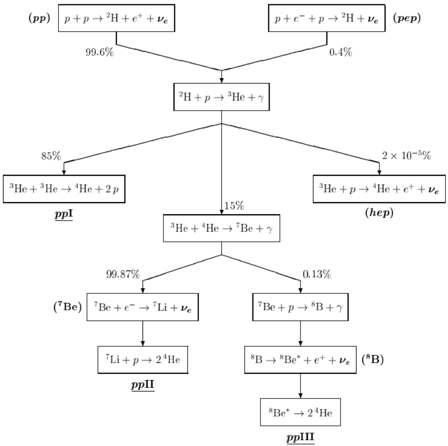
mixing angle θ_{23} is maximal

Solar neutrinos

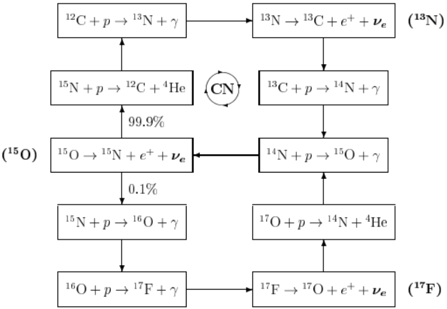
Neutrinos are produced in multiple nuclear reactions inside the Sun

Main production mechanisms:

pp chain



CNO cycle

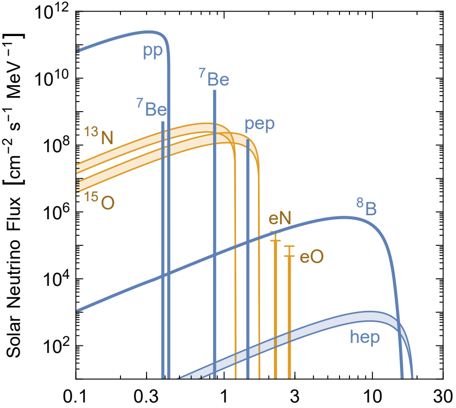


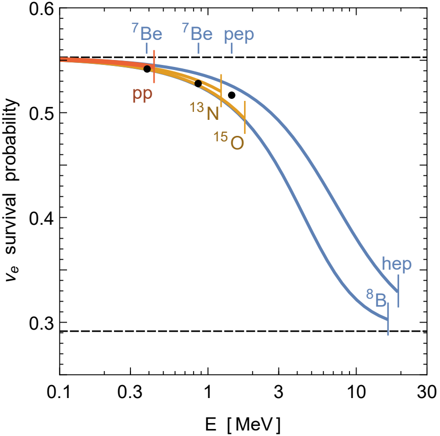
see e.g. [J.N. Bahcall, `http://www.sns.ias.edu/~jnb`]

Solar neutrinos

[Vitagliano+, RMP 92 (2020)]

Neutrinos are produced in multiple nuclear reactions inside the Sun



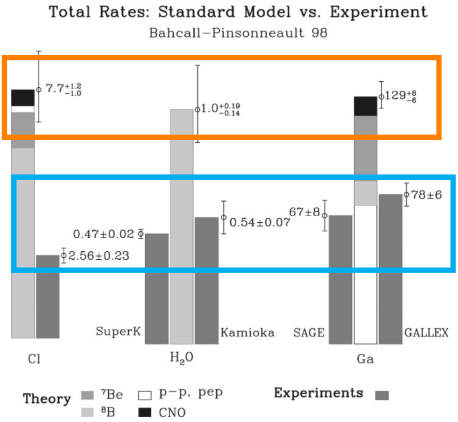


pp neutrinos are more abundant but fainter, more difficult to observe

Borexino first observed simultaneously *pp*, ^{7}Be and *pep* neutrinos [1] as well as ^{8}B [2] and CNO [3] neutrinos

Solar neutrinos

Neutrinos are produced in multiple nuclear reactions inside the Sun



[Bahcall, Phys.Rep. 2000]

early measurements
of solar neutrinos
only considered electron flavor

↓

Solar deficit:

Discrepancy between
expected
and measured
fluxes
(experiment dependent)

Disagreement lasted for >30 years!

Maybe the Sun has a problem?

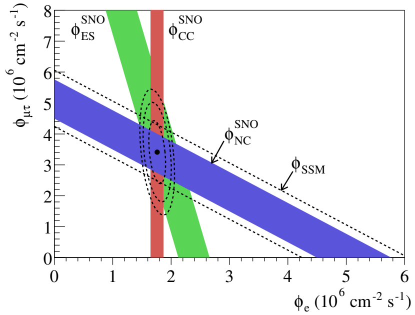
SNO: Sudbury Neutrino Observatory

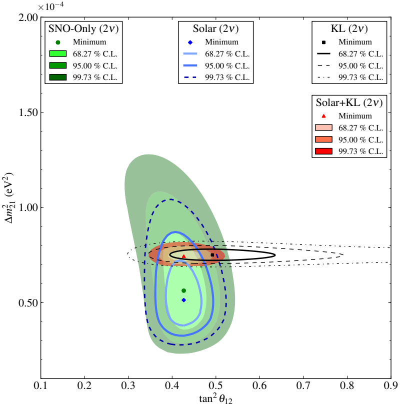
[e.g. Bellerive+, NPB 2016]

water Cherenkov detector, >2000 m underground

CC: $\nu_e + d \to p + p + e^-$, threshold $\simeq$ 8.2 MeV
NC: $\nu + d \to p + n + \nu$, threshold $\simeq$ 2.2 MeV
ES: $\nu + e^- \to \nu + e^-$, threshold $\simeq$ 7.0 MeV

$\Rightarrow$ ^{8}B, *hep*





$\phi_e \equiv \phi_{\nu_e}$ from CC, NC, ES
$\phi_{\mu\tau} \equiv \phi_{\nu_\mu+\nu_\tau}$ from NC, ES

SNO solved solar neutrino problem!

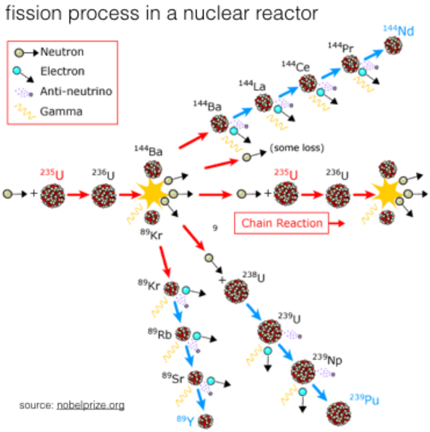
[PRL 89 (2002) 011301]

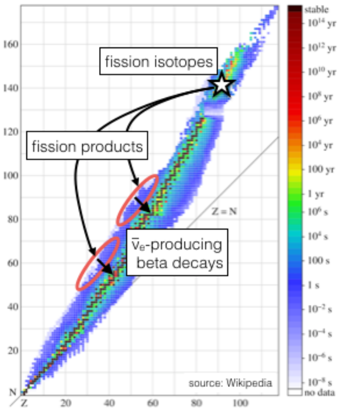
Reactor (anti)neutrinos

$\bar{\nu}_e$ produced in β decays of fission reaction products in the reactor core

decay chains of all isotopes produce multiple $\bar{\nu}_e$

a ~1 GW standard nuclear plant radiates $\sim 5 \times 10^{20}$ $\bar{\nu}_e$ per second!





[PROSPECT web page]

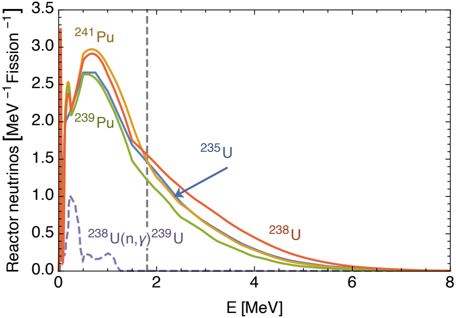
Reactor (anti)neutrinos

$\bar{\nu}_e$ produced in β decays of fission reaction products in the reactor core

decay chains of all isotopes produce multiple $\bar{\nu}_e$

a $\sim$1 GW standard nuclear plant radiates $\sim 5 \times 10^{20}$ $\bar{\nu}_e$ per second!

Main fissile isotopes: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



[Vitagliano+, Rev.Mod.Phys. 92 (2020)]

$\bar{\nu}_e$ energy $\sim$ 1 − 10 MeV

reactor $\bar{\nu}_e$ detected through inverse beta-decay:

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

(threshold $\sim$ 1.8 MeV)

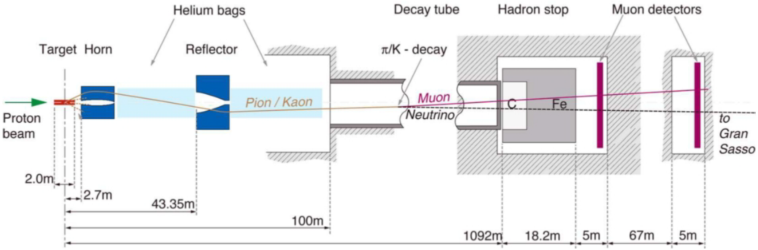
First measurement of θ_{13}:
[DayaBay, PRL 108 (2012)]

Reactor experiments play key role in light sterile neutrino searches!

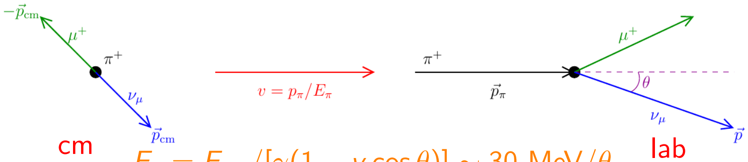
Accelerator neutrinos

Particle accelerators are artificial sources of (mainly muon) neutrinos

e.g. CERN Neutrinos to Gran Sasso (CNGS) setup, [Mezzetto+, 2020]:



Off-axis beam allows to select almost monochromatic neutrinos:



$$E_\nu = E_{cm}/[\gamma(1 - v\cos\theta)] \sim 30\ \text{MeV}/\theta$$

E_ν can be tuned on oscillation peak $\Delta m^2 L/2\pi$

Accelerator neutrinos

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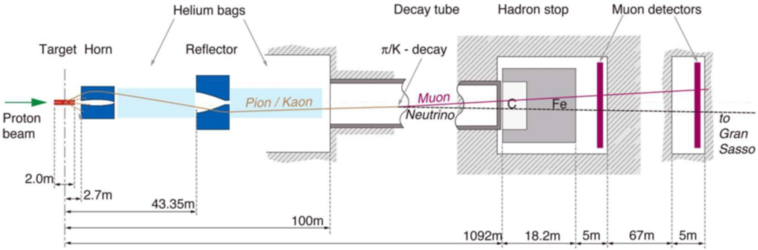
e.g. CERN Neutrinos to Gran Sasso (CNGS) setup, [Mezzetto+, 2020]:



Can generate flux of neutrinos and antineutrinos

Possibility to test asymmetries (e.g. $A^{\rm CP}_{\mu e} = P_{\nu_\mu\to\nu_e} - P_{\bar\nu_\mu\to\bar\nu_e}$)

$\Rightarrow$ test CP violation (measure $\delta_{\rm CP}$?)

future experiment DUNE will improve constraints on $\delta_{\rm CP}$ [EPJC 80 (2020)]

expected $\lesssim$ 5% resolution or 3σ sensitivity on 75% of the parameter space

Types of experiments

baseline

Transitions due to Δm^2 observable only if $\Delta m^2 \frac{L}{E} \gtrsim 1 \Leftrightarrow \Delta m^2 \gtrsim \left(\frac{L}{E}\right)^{-1}$

Types of experiments

Transitions due to Δm^2 observable only if $\Delta m^2 \frac{L}{E} \gtrsim 1 \Leftrightarrow \Delta m^2 \gtrsim \left(\frac{L}{E}\right)^{-1}$ (baseline: L)

Short BaseLine (SBL)

$L/E \lesssim 10 \text{ eV}^{-2} \Rightarrow \Delta m^2 \gtrsim 0.1 \text{ eV}^2$

Reactor: $L \sim 10$ m, $E \sim 1$ MeV

NEOS, DANSS, STEREO, Prospect, ...

Accelerator: $L \sim 1$ km, $E \gtrsim 0.1$ GeV

LSND, MiniBooNE, Karmen, ...

Long BaseLine (LBL)

$L/E \lesssim 10^4 \text{ eV}^{-2} \Rightarrow \Delta m^2 \gtrsim 10^{-4} \text{ eV}^2$

Reactor: $L \sim 1$ km, $E \sim 1$ MeV

DayaBay, RENO, Double Chooz, ...

Accelerator: $L \sim 10^3$ km, $E \gtrsim$ GeV

T2K, NOνA, OPERA, MINOS, ...

Atmospheric: $L \sim 10^2 - 10^4$ km, $E \gtrsim 0.1 - 10^2$ GeV

Kamiokande, SuperKamiokande, ANTARES, IceCube, ...

Very Long BaseLine (VLBL)

$L/E \lesssim 10^5 \text{ eV}^{-2} \Rightarrow \Delta m^2 \gtrsim 10^{-5} \text{ eV}^2$

Reactor: $L \sim 10^2$ km, $E \sim 1$ MeV

KamLAND

Types of experiments

Transitions due to Δm^2 observable only if $\Delta m^2 \frac{L}{E} \gtrsim 1 \Leftrightarrow \Delta m^2 \gtrsim \left(\frac{L}{E}\right)^{-1}$ (baseline → L)

Short BaseLine (SBL)

$L/E \lesssim 10\ \text{eV}^{-2} \Rightarrow \Delta m^2 \gtrsim 0.1\ \text{eV}^2$

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Atmospheric: $L \sim 10^2 - 10^4$ km, $E \gtrsim 0.1 - 10^2$ GeV

Kamiokande, SuperKamiokande, ANTARES, IceCube, ...

Solar

$L \sim 10^8$ km, $E \sim 0.1 - 10$ MeV

$L/E \lesssim 10^{11}\ \text{eV}^{-2} \Rightarrow \Delta m^2 \gtrsim 10^{-11}\ \text{eV}^2$

Homestake, SNO, Borexino, GALLEX, SAGE, ...

Very Long BaseLine (VLBL)

$L/E \lesssim 10^5\ \text{eV}^{-2} \Rightarrow \Delta m^2 \gtrsim 10^{-5}\ \text{eV}^2$

Reactor: $L \sim 10^2$ km, $E \sim 1$ MeV

KamLAND

Basically: LBL $\to \Delta m^2_{31}$, Solar/VLBL $\to \Delta m^2_{21}$

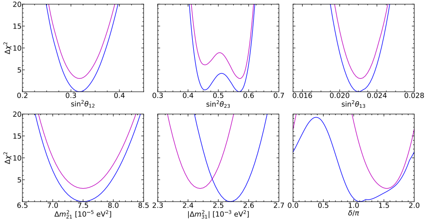
3 Status of three-neutrino parameters

State-of-the-art constraints

Based on:

- JHEP 02 (2021) 071

see also `http:`
- `//globalfit.astroparticles.es`



Three-neutrino oscillation data

Solar + VLBL reactors	
Experiments:	**Parameters:**
SuperK	θ_{12}
SNO	Δm^2_{21}
Borexino	(θ_{13})
KamLAND	
...	

baseline defined by $\Delta m^2_{kj} \cdot L/E$ LBL: long baseline ($E/L \gtrsim \Delta m^2_{31}$) VLBL: short baseline ($E/L \sim \Delta m^2_{21}$)

Three-neutrino oscillation data

Solar + VLBL reactors	
Experiments:	**Parameters:**
SuperK	θ_{12}
SNO	Δm^2_{21}
Borexino	(θ_{13})
KamLAND	
...	

LBL reactors	
Experiments:	**Parameters:**
DayaBay	θ_{13}
RENO	Δm^2_{31}
DoubleChooz	(θ_{12})
...	(Δm^2_{21})

baseline defined by $\Delta m^2_{kj} \cdot L/E$ LBL: long baseline ($E/L \gtrsim \Delta m^2_{31}$) VLBL: short baseline ($E/L \sim \Delta m^2_{21}$)

Three-neutrino oscillation data

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KamLAND	
...	

LBL reactors	
Experiments:	**Parameters:**
DayaBay	θ_{13}
RENO	Δm^2_{31}
DoubleChooz	(θ_{12})
...	(Δm^2_{21})

Atmospheric	
Experiments:	**Parameters:**
Antares	θ_{23}
IceCube	Δm^2_{31}
SuperK	(θ_{13})
...	$(\delta_{\rm CP})$

baseline defined by $\Delta m^2_{kj} \cdot L/E$ LBL: long baseline ($E/L \gtrsim \Delta m^2_{31}$) VLBL: short baseline ($E/L \sim \Delta m^2_{21}$)

Three-neutrino oscillation data

Solar + VLBL reactors

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KamLAND	
...	

LBL reactors

Experiments:	Parameters:
DayaBay	θ_{13}
RENO	Δm^2_{31}
DoubleChooz	(θ_{12})
...	(Δm^2_{21})

Atmospheric

Experiments:	Parameters:
Antares	θ_{23}
IceCube	Δm^2_{31}
SuperK	(θ_{13})
...	$(\delta_{\rm CP})$

LBL accelerators

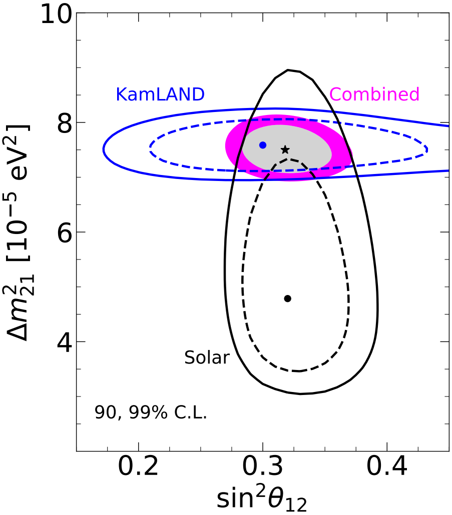
Experiments:	Parameters:
NOνA	θ_{13}
T2K	θ_{23}
MINOS	Δm^2_{31}
...	$\delta_{\rm CP}$

baseline defined by $\Delta m^2_{kj} \cdot L/E$ LBL: long baseline $(E/L \gtrsim \Delta m^2_{31})$ VLBL: short baseline $(E/L \sim \Delta m^2_{21})$

Solar experiments and KamLAND

[JHEP 02 (2021)]

Mainly test θ_{12} and Δm^2_{21}



Solar experiments:
(0.1 MeV$\lesssim E \lesssim$ 20 MeV)
Homestake [1]
GALLEX [2]
SAGE [3]
Borexino [4][5]
SuperK (day/night) [6][7][8]
SNO [9]

KamLAND [10]
(reactor $\bar{\nu}_e$s, avg. distance 180 km)

Residual sensitivity to θ_{13} not considered in this plot, only full analysis

Reactor experiments

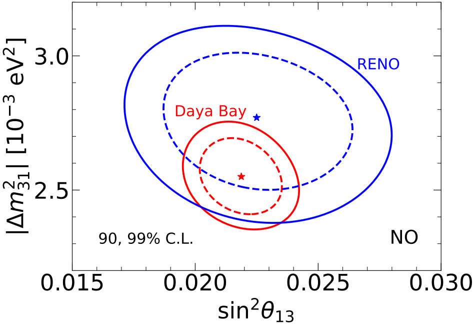
[JHEP 02 (2021)]

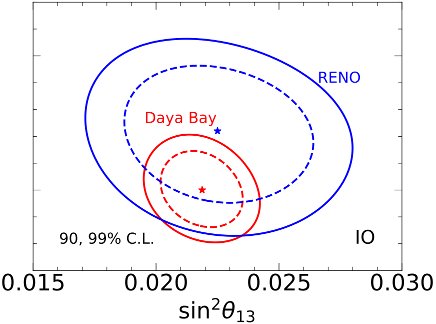
Mainly test θ_{13} and Δm^2_{31}

reactor $\bar{\nu}_e$s (~ 1.8 MeV$\lesssim E \lesssim 8$ MeV)

RENO [1][2][3]: 2 detectors, 294 m / 1383 m from the centerline of sources

DayaBay [4]: 8 detectors, 2 in near experimental halls ($\sim 0.3-1.3$ Km) and 4 far away ($\sim 1.5-1.9$ Km)





Atmospheric experiments

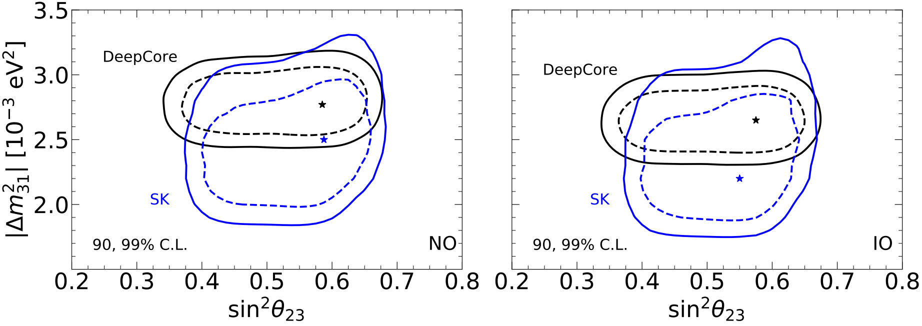
[JHEP 02 (2021)]

Mainly test θ_{23} and Δm^2_{31}

energies of interest: 0.1 GeV $\lesssim E \lesssim$ 100 GeV

SuperKamiokande [1] phases I-III plus public χ^2 grid from phase IV

IceCube DeepCore [2][3] 3yrs of data



Accelerator experiments

Measure $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\mu \Rightarrow$ test θ_{13}, θ_{23}, Δm^2_{31} and δ

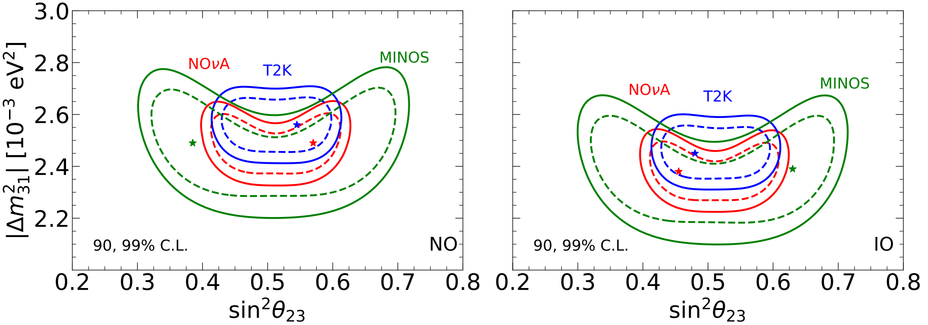
can select mostly pure beam of neutrinos or antineutrinos

always near (initial unoscillated flux) + far (oscillated flux) detector

NOνA [1]: 212 μ^- (105 μ^+) events + 82 e^- (33 e^+) events

T2K [2]: 318 μ^- (137 μ^+) events + 94 e^- (16 e^+) events

MINOS [3][4][5]: complete data set until 2013, no sensitivity on δ



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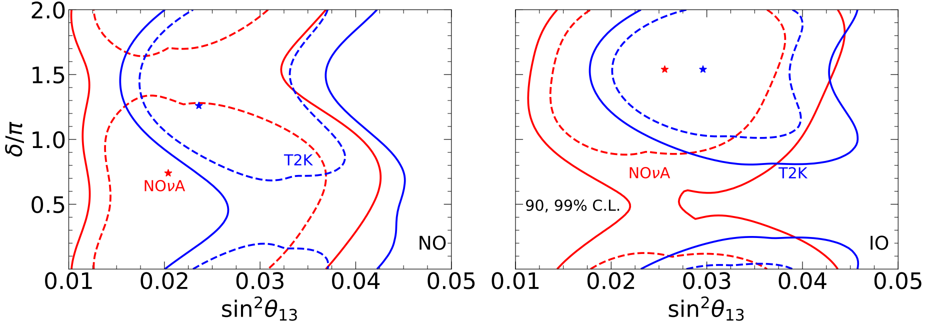
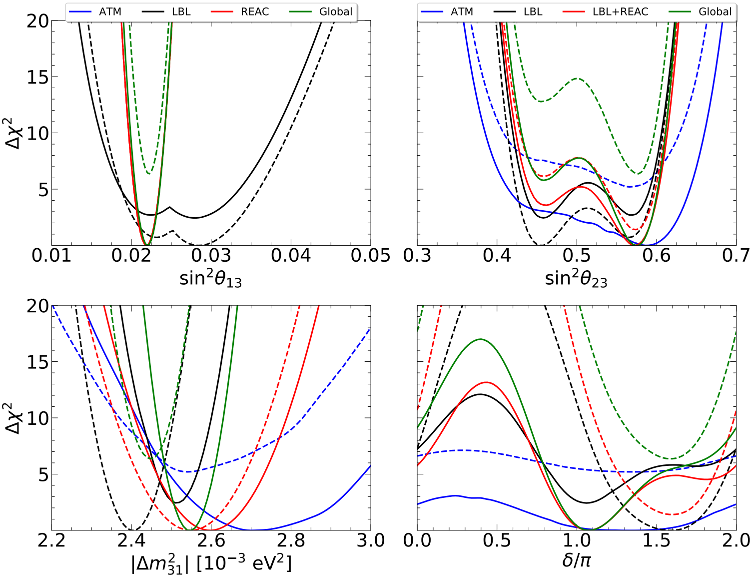


Global constraints - I

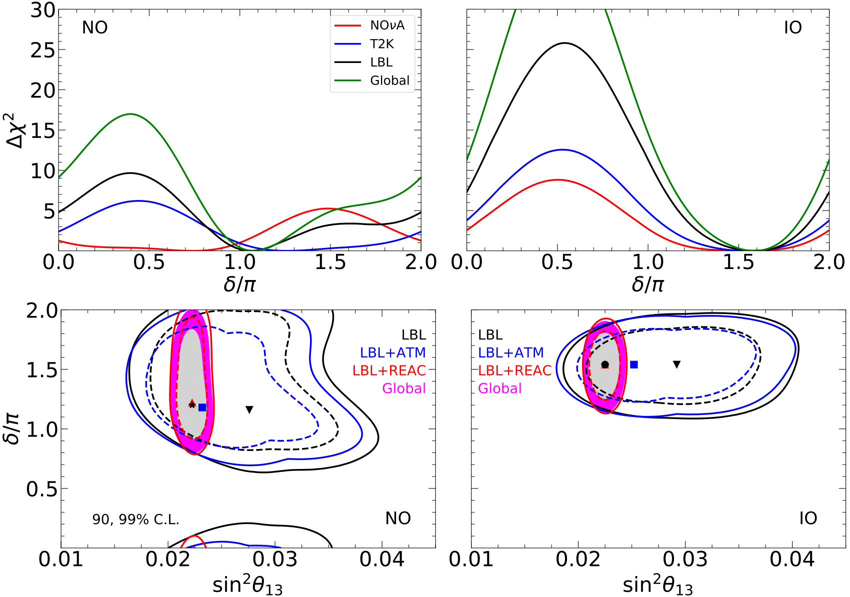
[JHEP 02 (2021)]

What do we get from the combination of all the datasets?



Global constraints - II

The situation for the CP phase δ is complicated



Three Neutrino Oscillations

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

$U_{\alpha k}$ described by 3 mixing angles θ_{12}, θ_{13}, θ_{23} and one CP phase δ

Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

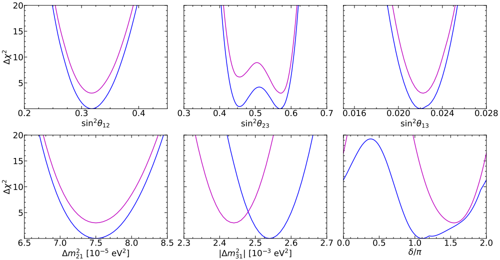
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.54 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.44 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

$$10 \sin^2(\theta_{12}) = 3.18 \pm 0.16$$
$$10^2 \sin^2(\theta_{13}) = 2.200^{+0.069}_{-0.062}\ (\mathrm{NO})$$
$$= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO})$$
$$10 \sin^2(\theta_{23}) = 4.55 \pm 0.13 U 5.71 \pm 0.12\ (\mathrm{NO})$$
$$= 5.71^{+0.14}_{-0.17}\ (\mathrm{IO})$$

$$\delta/\pi = 1.10^{+0.27}_{-0.12}\ (\mathrm{NO})$$
$$= 1.54 \pm 0.14\ (\mathrm{IO})$$



mass ordering still unknown

δ still unknown

see also: `http://globalfit.astroparticles.es`

Neutrinos and their masses

[de Salas+, Frontiers 5 (2018) 36]

Normal ordering (NO)

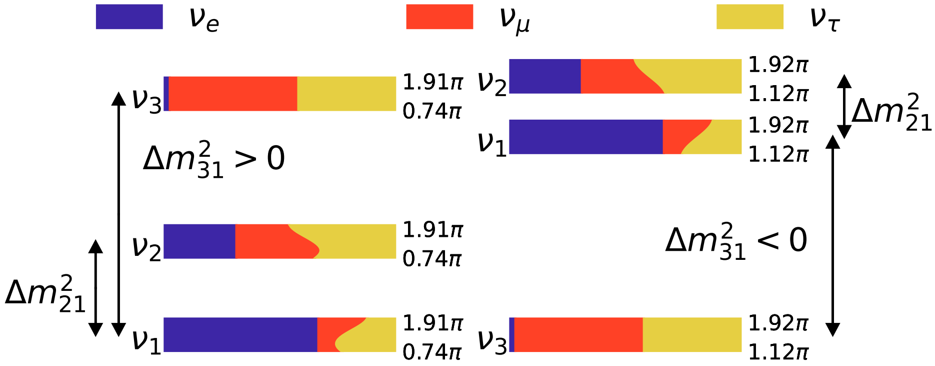
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV



Absolute scale unknown!

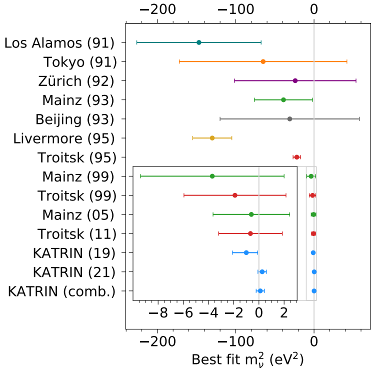
Can we constrain the mass ordering using bounds on $\sum m_\nu$?

M Measurements of neutrino masses

Kinematics of β decay

Based on:

- Giunti&Kim book “Fundamentals of Neutrino Physics and Astrophysics” (2007)
- KATRIN
- de Salas+, Frontiers 5 (2018) 36



β decay

$$\beta \text{ decay: } \mathcal{N}(A, Z) \longrightarrow \mathcal{N}(A, Z+1) + e^- + \bar{\nu}_e$$

$$Q_\beta = M_i - M_f - m_e$$

total available energy

$$E_\nu = Q_\beta - T = Q_\beta - (E_e - m_e)$$

neutrino energy

notice that max electron energy is:

$$T_{\rm max} = Q_\beta - m_{\bar{\nu}_e}$$

Kurie function: (degenerate ν masses)

$$K(T) = \left[(Q_\beta - T)\sqrt{(Q_\beta - T)^2 - m^2_{\bar{\nu}_e}}\right]^{1/2}$$

Useful to describe the e^- spectrum near the endpoint

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notice: flavor neutrinos have no definite mass!

$$m^2_{\bar{\nu}_e} = \sum |U_{ei}|^2 m_i^2$$

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$$m^2_{\bar{\nu}_e} = \sum |U_{ei}|^2 m_i^2$$

Full expression:

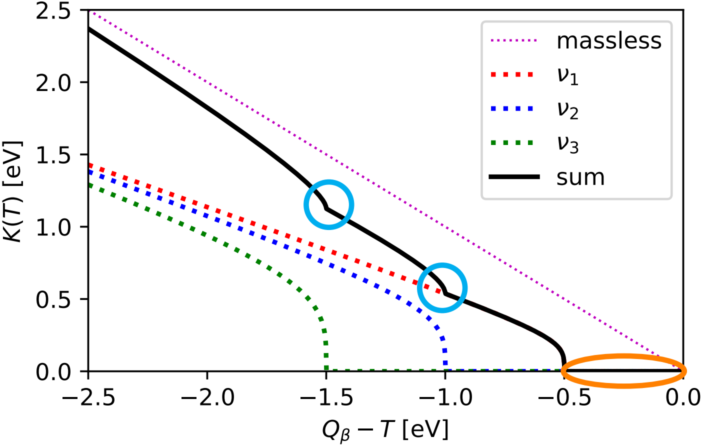
$$K(T) = \left[(Q_\beta - T)\sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2}\right]^{1/2}$$

N_ν neutrinos with different masses m_i

mixing angles enter ($|U_{ei}|^2$)

β decay

$$K(T) = \left[(Q_\beta - T)\sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2}\right]^{1/2}$$



Fake case:
3 neutrinos

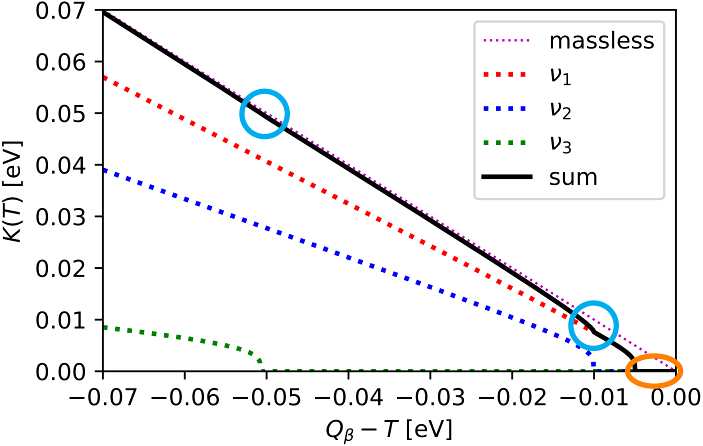
masses:
$m_i = i \cdot 0.5$ eV,

mixings:
$|U_{ei}|^2 = 1/3$

endpoint shifted + one kink for each mass eigenstate

β decay

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$



Realistic case:
3 neutrinos, normal ordering

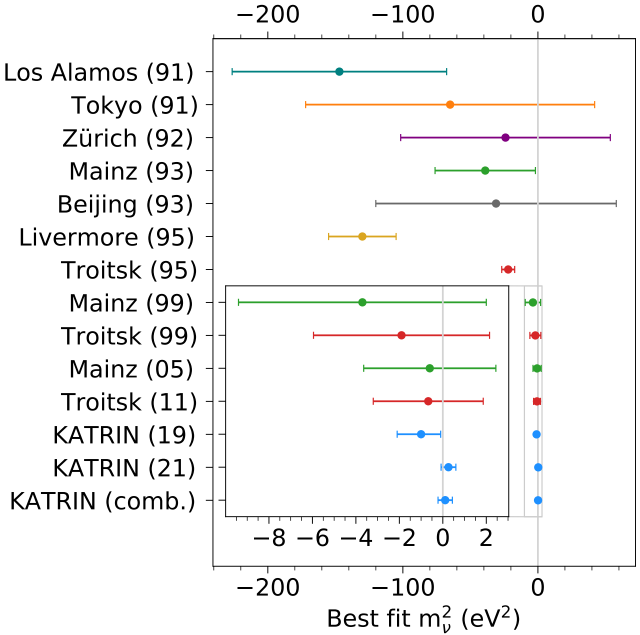
masses: $m_i = [5, 10, 51]$ meV,

mixings: $|U_{ei}|^2 = [0.67, 0.31, 0.02]$

Much harder to see the endpoint shift and kinks!

KATRIN results

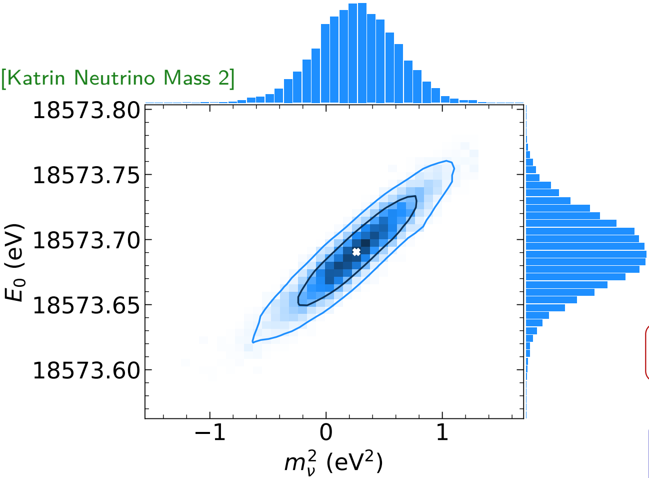
[KATRIN]



KATRIN results

strongest bound on $m_\nu (\equiv m_{\bar{\nu}_e})$ are from KATRIN

[Katrin Neutrino Mass 2]



KNM1+KNM2:
$m_\nu^2 = (0.1 \pm 0.3)\ eV^2$

Upper limit 90%:
$m_\nu < 0.8$ eV

Bayesian 90%:
$m_\nu < 0.7$ eV

statistics dominated!

expected final sensitivity (90%):
$m_\nu \lesssim 0.2$ eV

Neutrino masses from neutrinoless double β decay

(if neutrino is Majorana)

[Schechter&Valle, 1982]

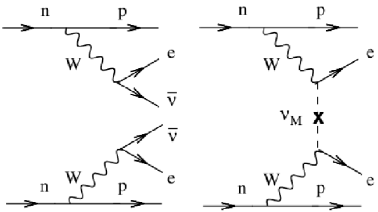
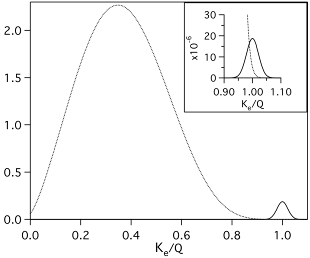
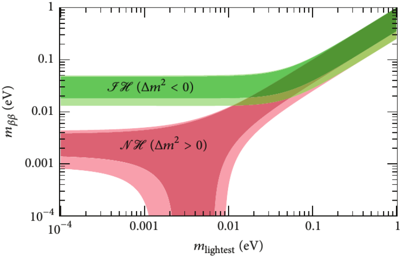


figure from [NEXT] webpage





[Dell'Oro+, 2016]

Measure $T^{0\nu}_{1/2}$

m_e electron mass,
$G_{0\nu}$ phase space,
$\mathcal{M}'^{\nu}$ matrix element

convert into $m_{\beta\beta} = \dfrac{m_e}{\mathcal{M}'^{\nu}\sqrt{G_{0\nu}\,T^{0\nu}_{1/2}}}$

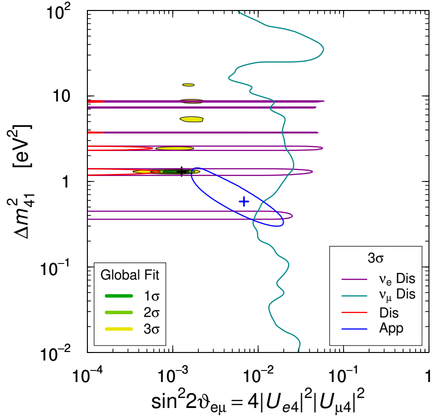
and then use $m_{\beta\beta} = \left|\sum_k e^{i\alpha_k}\,U^2_{ek}\,m_k\right|$ (α_k Majorana phases)

A Additional neutrinos

Particularly, the light sterile neutrino

Based on:

- SG+, JPG 43 (2016)
- SG+, JHEP 06 (2017) and updates
- several experiments



Active neutrinos

In principle, previous discussion is valid for N neutrinos

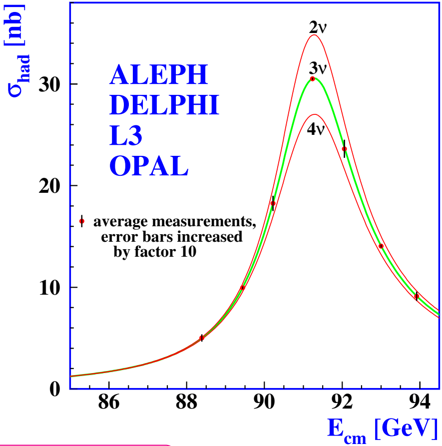
only constraint: there are exactly three flavor neutrinos in the SM

[LEP, Phys. Rept. 427 (2006) 257]
$N_\nu^{(Z)} = 2.9840 \pm 0.0082$

[Janot+, PLB 2020]
$N_\nu^{(Z)} = 2.9963 \pm 0.0074$

from measurement of Z resonance

$$e^+e^- \longrightarrow Z \longrightarrow \sum_{a=e,\mu,\tau} \nu_a \bar{\nu}_a$$

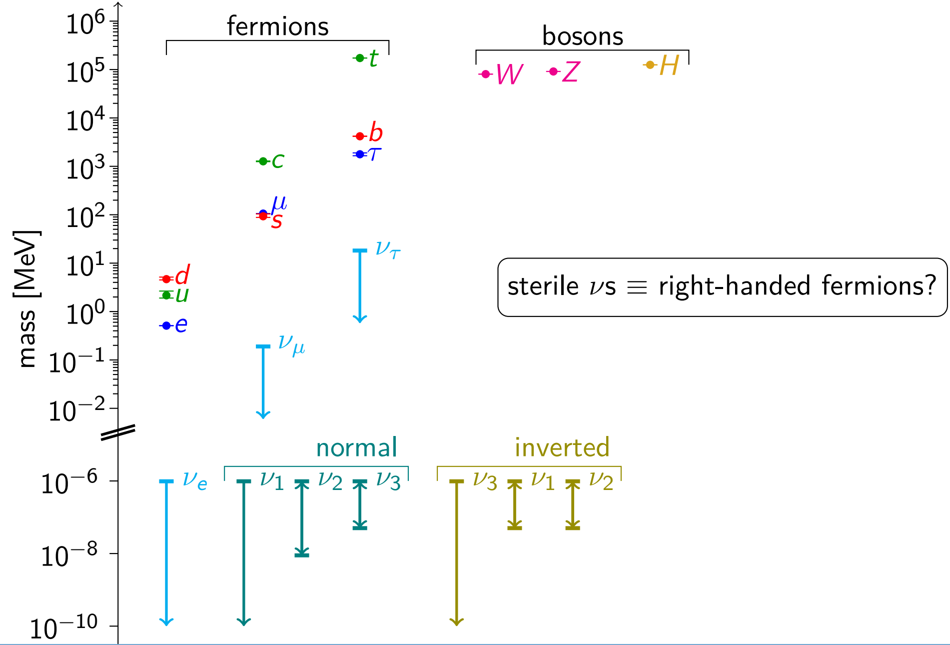


neutrinos $\alpha > 3$ must be sterile

sterile neutrino = SM singlet: no couplings with other SM particles

Masses in the Standard Model

[masses from PDG 2020]



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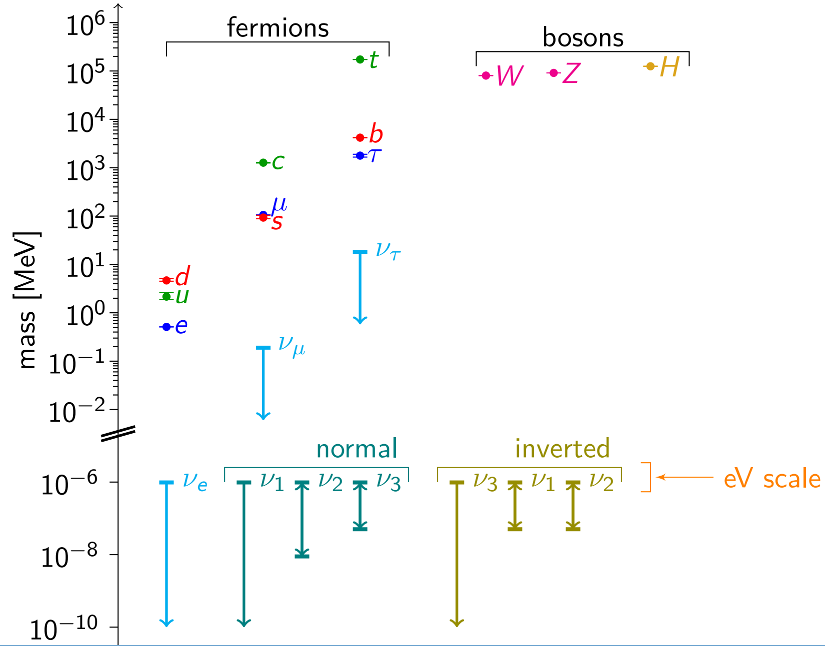

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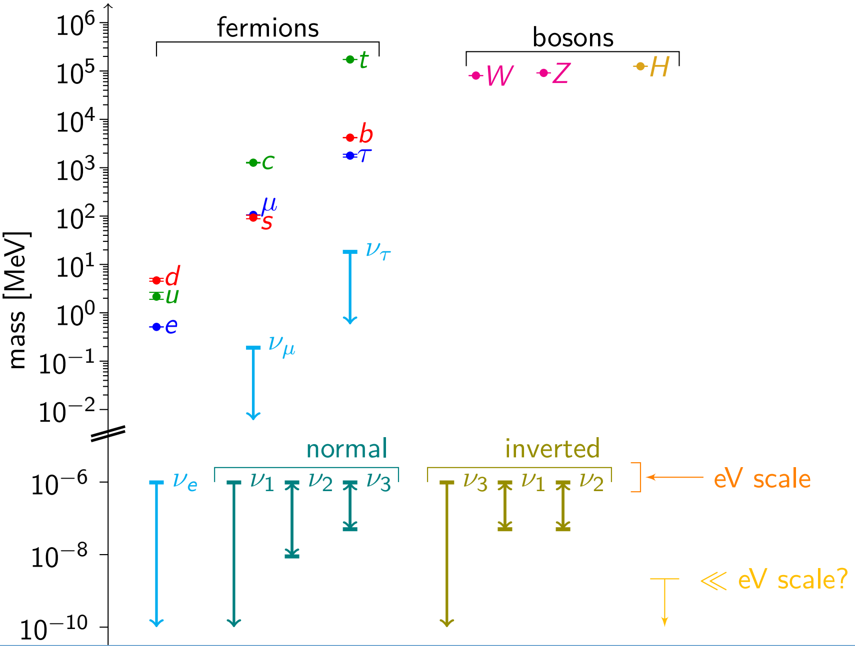

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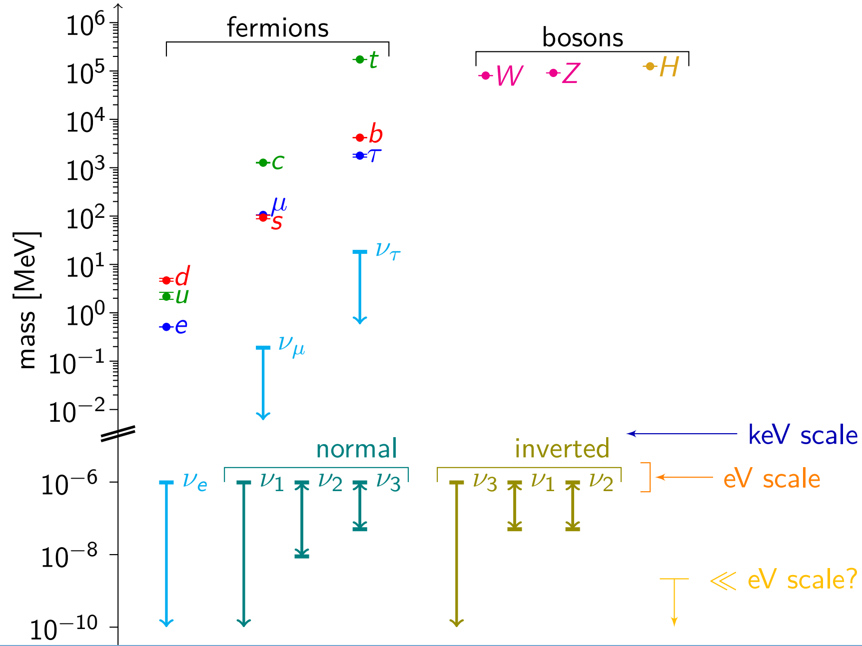

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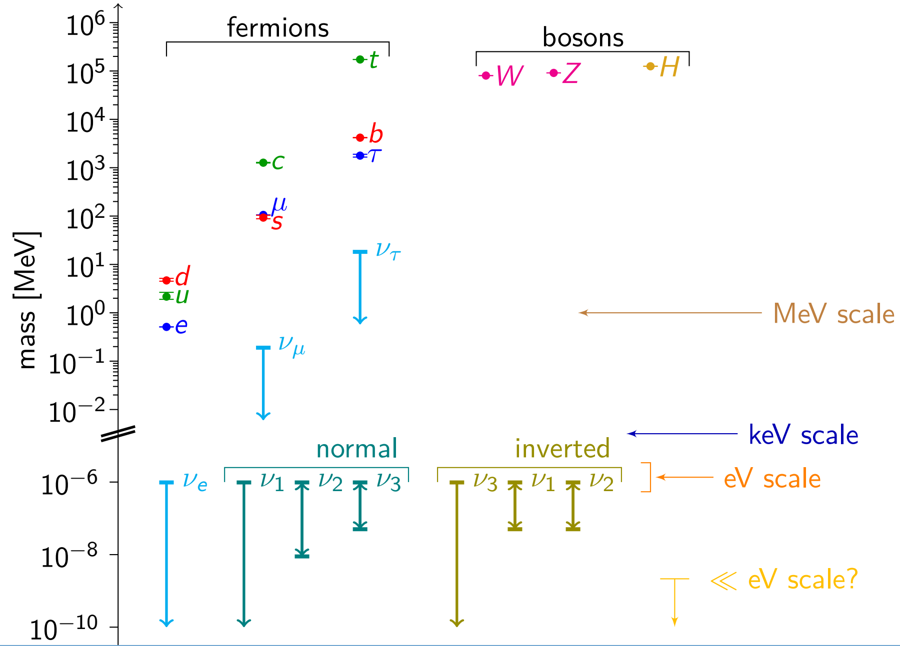

Masses in the Standard Model

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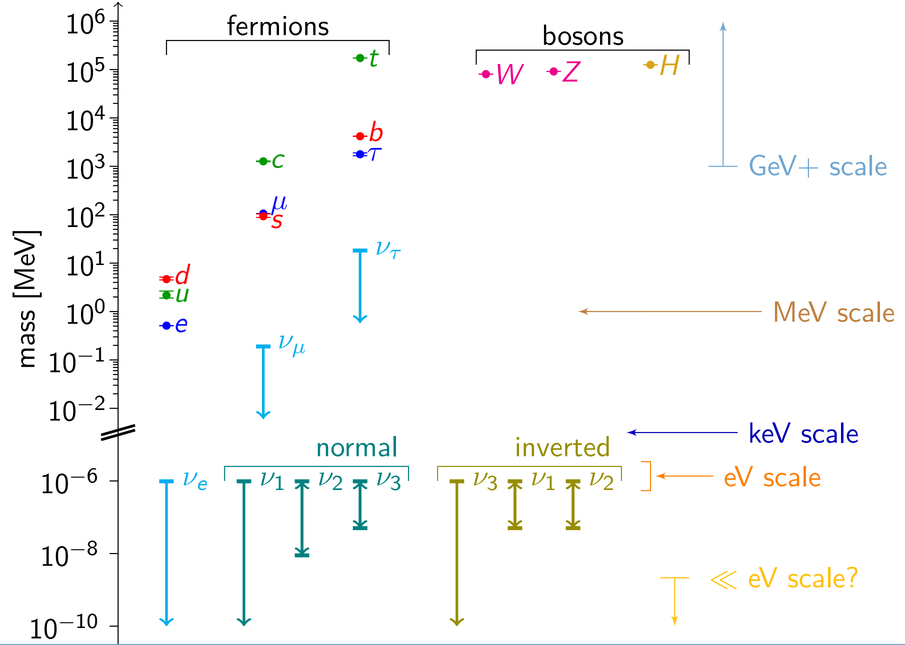


Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

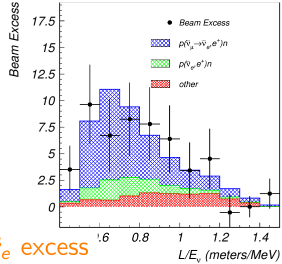
Do three-neutrino oscillations explain all experimental results?

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

LSND



[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

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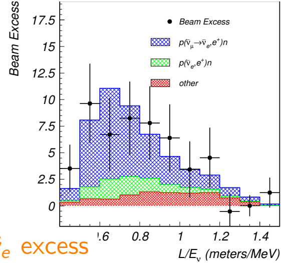

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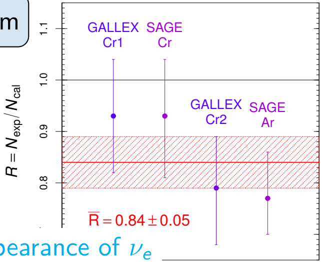
Gallium



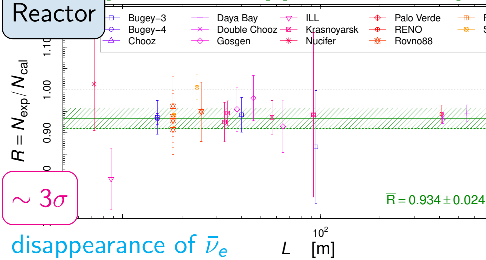
[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

[Mention+, 2011] [Azabajian+, 2012]

Reactor



$\sim 3\sigma$

disappearance of $\bar\nu_e$

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[SG+, JPG 43 (2016) 033001]

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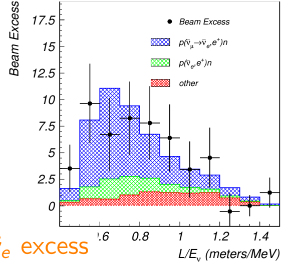
LSND



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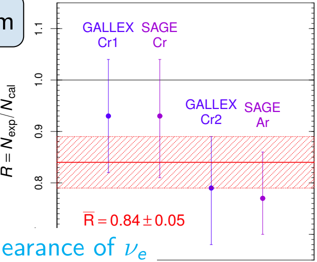

[Giunti, Laveder, 2011]

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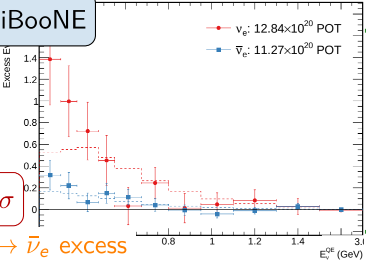
MiniBooNE



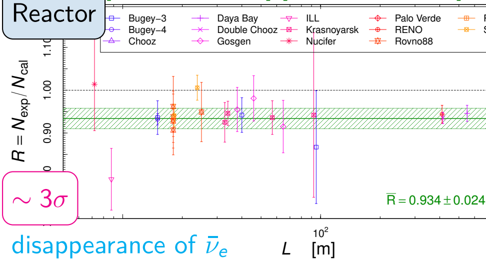
[Aguilar+, 2008-2018]

$\sim 5\sigma$

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

Reactor

[Mention+, 2011] [Azabajian+, 2012]



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

A large neutrino family

In principle, previous discussion is valid for N neutrinos

$N \times N$ mixing matrix, N flavor neutrinos, N massive neutrinos

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_{s_1}\rangle \\ \ldots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \vdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \\ \ldots & & & & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \ldots \end{pmatrix}$$

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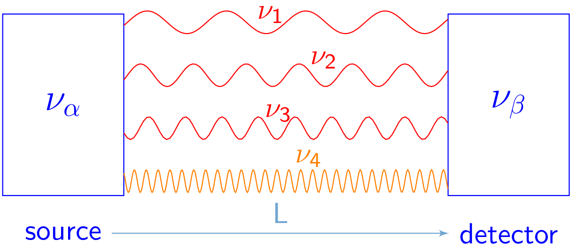
Our case will be 3 (active)+1 (sterile), a perturbation of 3 neutrinos case

$m_4 \gg m_\ell$
$\ell = 1, 2, 3$

$\Delta m^2_{41} \simeq 1\ \text{eV}^2$
$\simeq \Delta m^2_{42}$
$\simeq \Delta m^2_{43}$



6 angles

3 Dirac CP phases

3 Majorana CP phases

Short BaseLine (SBL)

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

If $m_4 \gg m_\ell$, faster oscillations

ν_4 oscillations are averaged in most neutrino oscillation experiments

Effect of 4th neutrino only visible as global normalization

Short BaseLine (SBL) oscillations: $\frac{\Delta m^2_{41} L}{E} \simeq 1$

At SBL, oscillations due to Δm^2_{21} and $|\Delta m^2_{31}|$ do not develop

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source of $\overset{(-)}{\nu}_\alpha$

detect different flavor $\overset{(-)}{\nu}_\beta$

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$\overset{(-)}{\nu}_s$ goes undetected

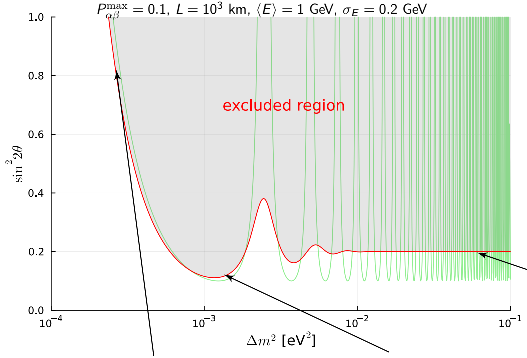
CP violation cannot be observed in SBL experiments!

Exclusion curves

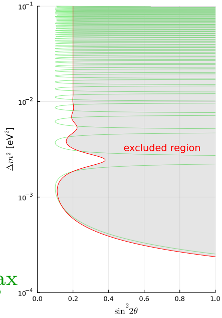
$$\langle P_{\alpha\beta}(L,E)\rangle = \frac{1}{2}\sin^2 2\theta \left[1 - \int \cos\left(\frac{\Delta m^2 L}{2E}\right)\phi(E)\mathrm{d}E\right] \leq P_{\alpha\beta}^{\max}$$

measured

$$\sin^2 2\theta \leq \frac{2P_{\alpha\beta}^{\max}}{1 - \int \cos\left(\frac{\Delta m^2 L}{2E}\right)\phi(E)\mathrm{d}E}$$



swap axes



$$\sin^2 2\theta \simeq 2P_{\alpha\beta}^{\max}$$

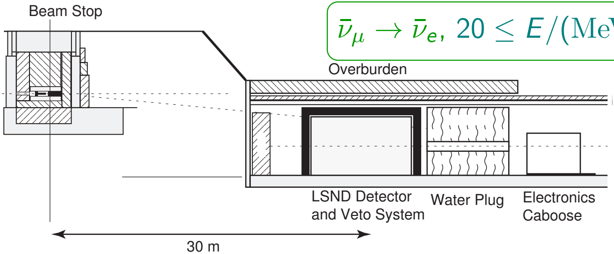
$$\Delta m^2 \simeq 4\left\langle\frac{E}{L}\right\rangle\sqrt{\frac{P_{\alpha\beta}^{\max}}{\sin^2 2\theta}}$$

$$\sin^2 2\theta > P_{\alpha\beta}^{\max}$$

$$\Delta m^2 \simeq 2\pi\left\langle\frac{E}{L}\right\rangle$$

LSND

[PRD 64 (2001) 112007]



$\bar{\nu}_\mu \to \bar{\nu}_e$, $20 \leq E/(\mathrm{MeV}) \leq 52.8$

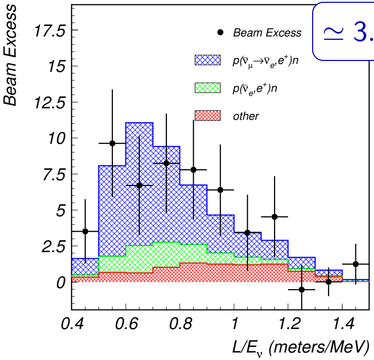
well known source of $\bar{\nu}_\mu$:

$$p + \mathrm{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow{\text{at rest}} e^+ + \nu_e + \bar{\nu}_\mu$$

$L \simeq 30$ m

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



$\simeq 3.8\sigma$

No signal seen in KARMEN ($L \simeq 18$ m)

[PRD 65 (2002) 112001]

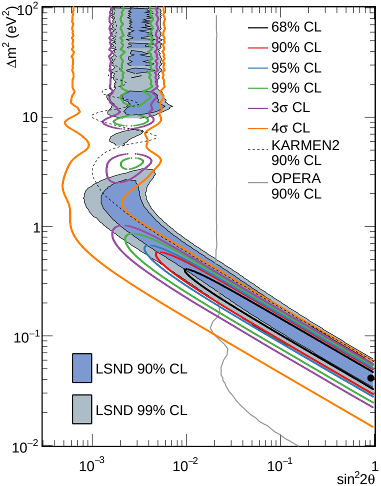
MiniBooNE

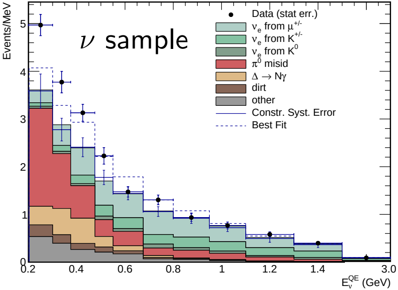
[PRL 121 (2018) 221801]

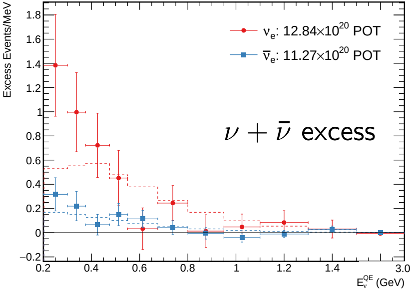
purpose: check LSND signal

$L \simeq 541$ m, 200 MeV $\leq E \lesssim 3$ GeV

no money, no near detector







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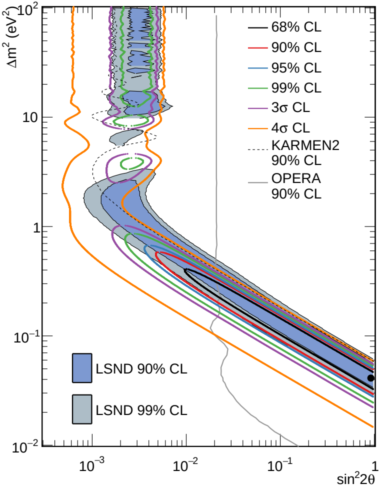
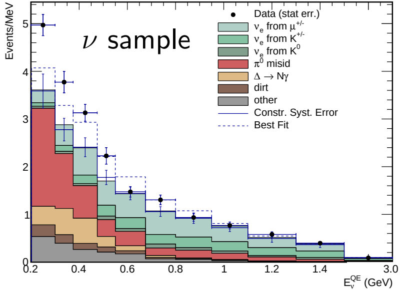
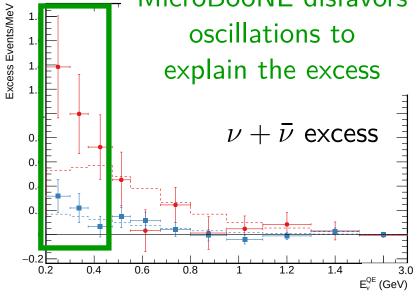




MicroBooNE disfavors oscillations to explain the excess



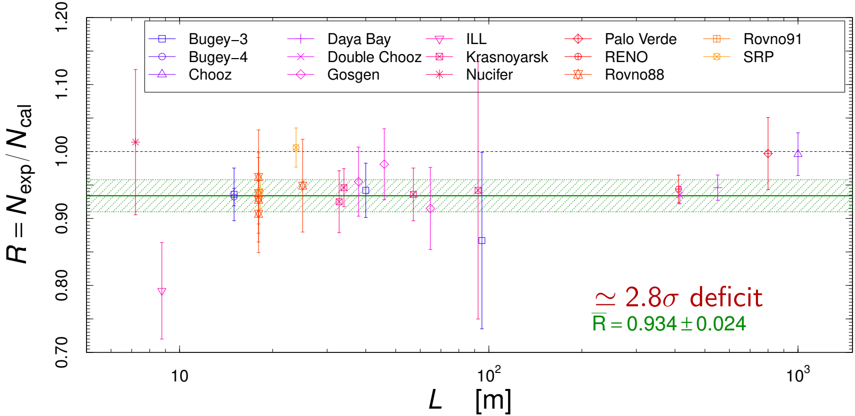
Reactor Antineutrino Anomaly (RAA)

[Mention+, PRD 83 (2011)]

2011: new reactor $\bar{\nu}_e$ fluxes by Huber and Mueller+ (HM)

[Huber, PRC 84 (2011) 024617] [Mueller+, PRC 83 (2011) 054615]

Previous reactor rates evaluated with new fluxes ⇒ deficit



Suppression at detector due to active-sterile oscillations?

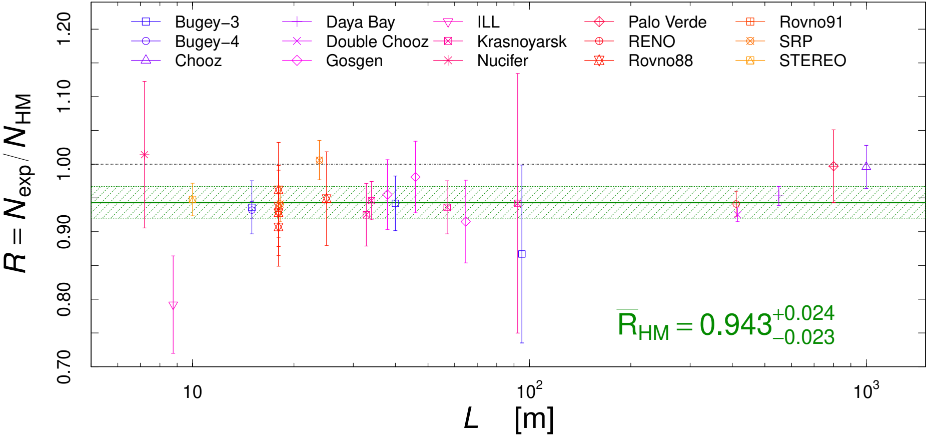
Reactor antineutrino spectrum and RAA

[Giunti+, PLB 2022]

When the RAA was discovered:

conversion method (ILL data) and *ab initio* calculations in agreement

[Huber, 2011], [Mueller+, 2011] spectra



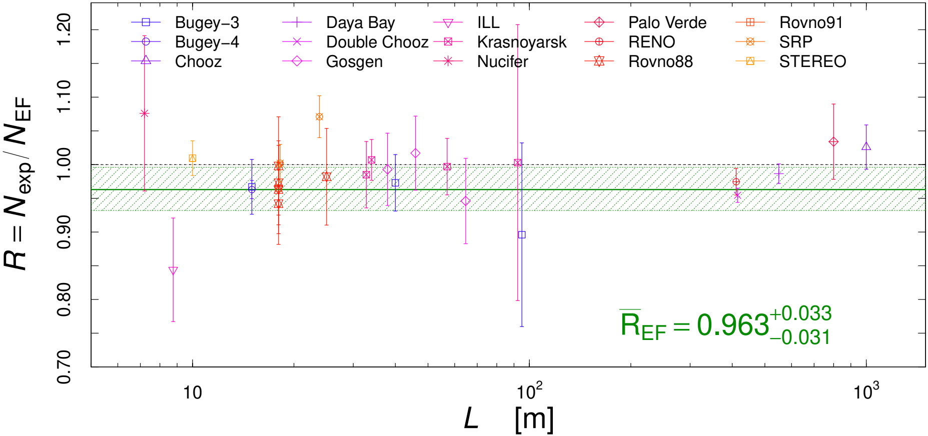
$\sim 2.4\sigma$ deficit $\Longrightarrow$ anomaly!

Reactor antineutrino spectrum and RAA

[Giunti+, PLB 2022]

Revised *ab initio* calculation:

[Estienne, Fallot+, PRL 123 (2019)]



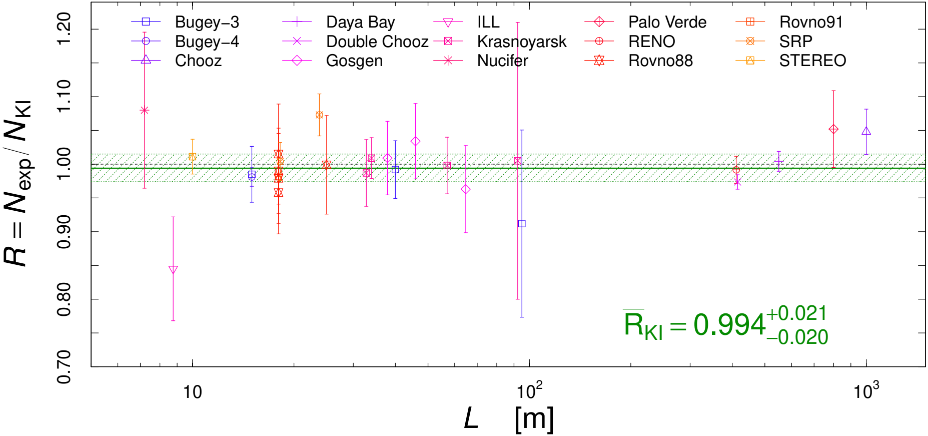
$\sim 1.2\sigma$ deficit $\Longrightarrow$ no anomaly!

Reactor antineutrino spectrum and RAA

[Giunti+, PLB 2022]

Conversion method on new measurements of electron spectrum at Kurchatov Institute (KI) (updates ILL measurements from the 80's):

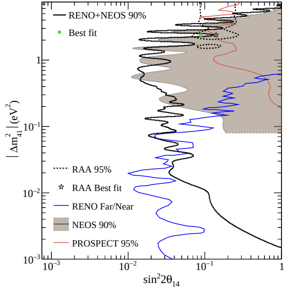
[Kopeikin+, PRD 2021]



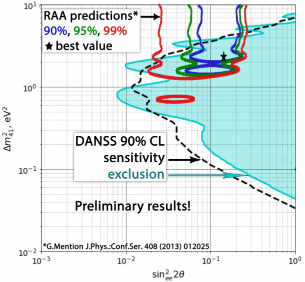
approximate agreement with EF fluxes, no anomaly!

ν_s at reactors in 2020

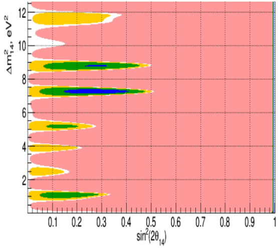
[RENO+NEOS, 2020]



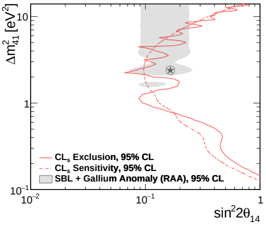
[DANSS, 2020]



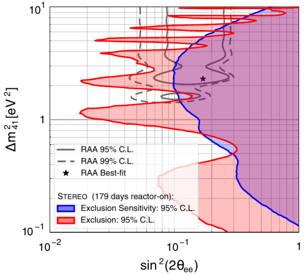
[Neutrino-4, PZETF 2020]



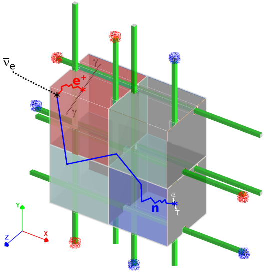
[PROSPECT, PRD 2020]



[STEREO, PRD 2020]

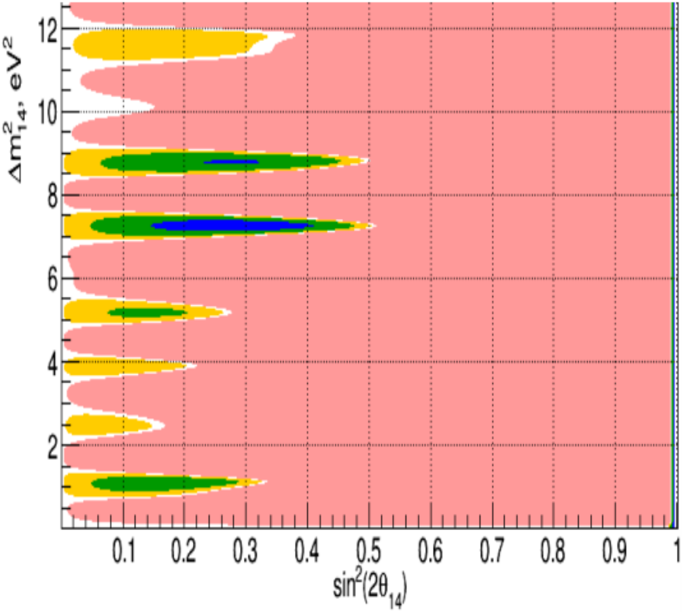


[SoLiD, JINST 2021]



Neutrino-4

[Neutrino-4 2020]

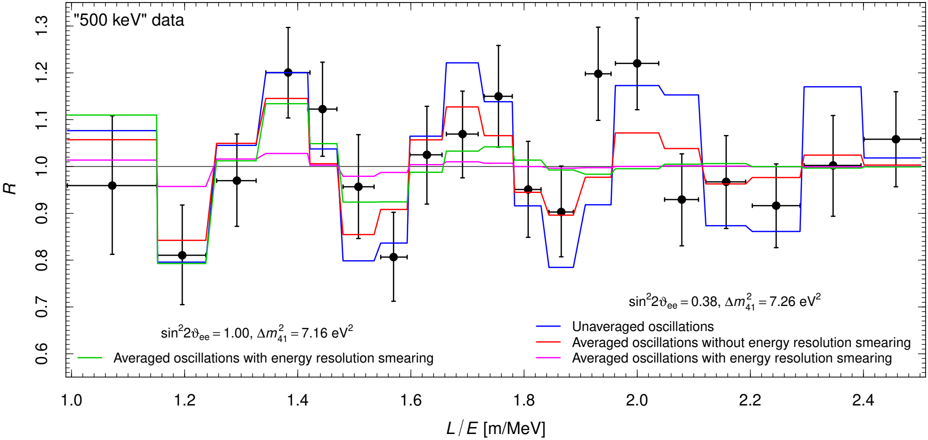


claimed $> 3\sigma$ preference for 3+1 over 3ν case

best fit incompatible with other reactor experiments

Neutrino-4

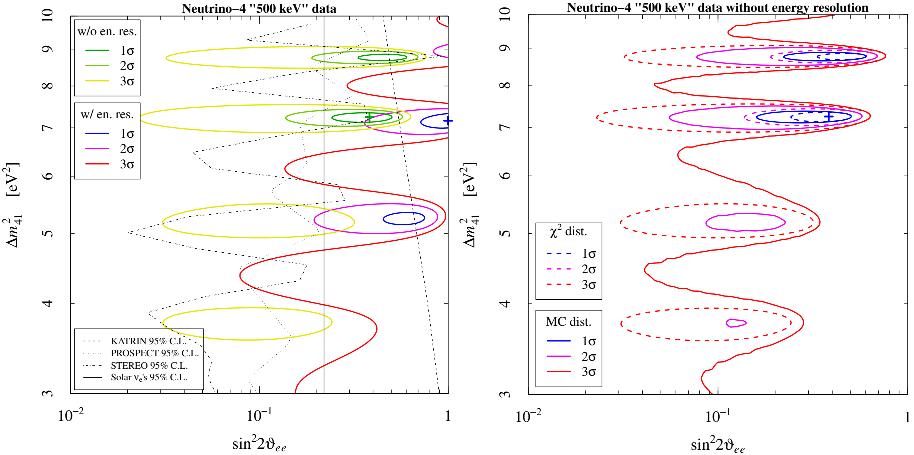
[Giunti+, PLB 2021]



energy resolution smearing not properly taken into account?

Neutrino-4

[Giunti+, PLB 2021]



proper energy resolution treatment moves best-fit $\rightarrow \sin^2 2\vartheta \simeq 1$

need to take into account violation of Wilk's theorem

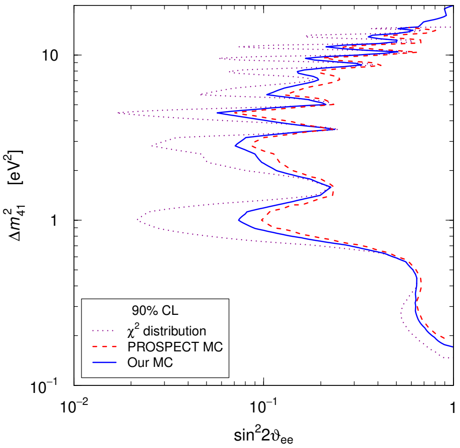
↓

relaxed constraints

Significance of the preference?

[Giunti, PRD 101 (2020)]

standard χ^2 distribution may be not appropriate to study the significance due to undercoverage at angles below the experiment sensitivity



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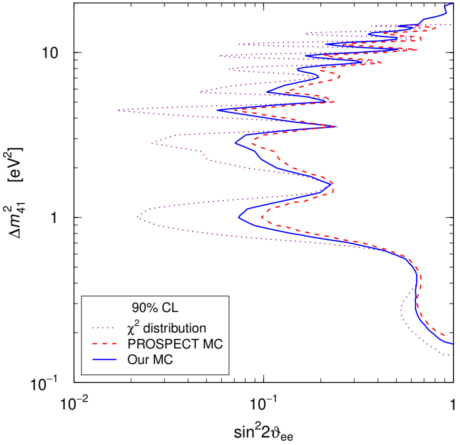
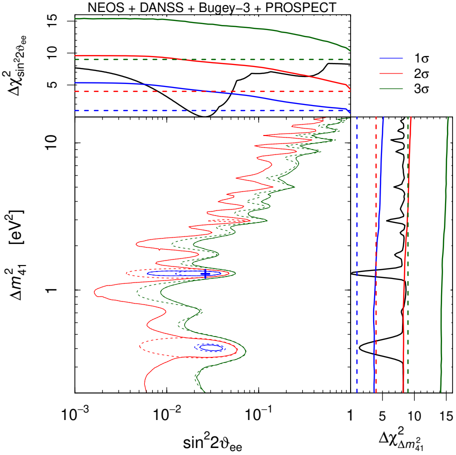




solid: MC, dashed: χ^2

True significance smaller than usually quoted (e.g. $2.4 \rightarrow 1.8\sigma$)

Gallium anomaly

[SAGE, 2006][Giunti&Laveder, 2011]

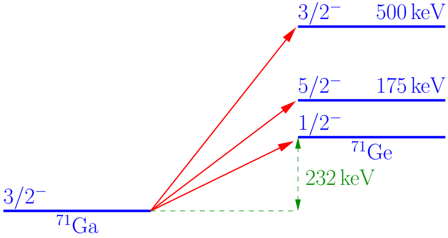
$L \simeq 1.9$ m $\quad L \simeq 0.6$ m

Gallium radioactive source experiments: GALLEX and SAGE

ν_e sources: $e^- + ^{51}\text{Cr} \to ^{51}\text{V} + \nu_e$ $\quad e^- + ^{37}\text{Ar} \to ^{37}\text{Cl} + \nu_e$

$E \simeq 0.75$ MeV $\quad E \simeq 0.81$ MeV

In the detector: $\nu_e + ^{71}\text{Ga} \to ^{71}\text{Ge} + e^-$



cross sections of
the transitions from

[Krofcheck+, PRL 55 (1985) 1051]

[Frekers+, PLB 706 (2011) 134]

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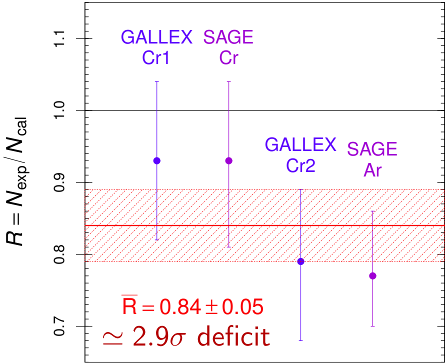
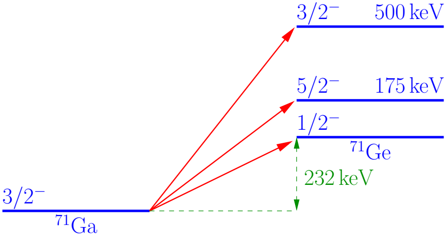
Test detection of solar ν_e





cross sections of
the transitions from

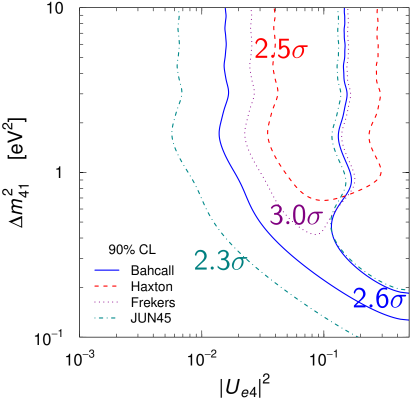
[Krofcheck+, PRL 55 (1985) 1051]

[Frekers+, PLB 706 (2011) 134]

Gallium anomaly revisited

[Kostensalo+, PLB 795 (2019) 542-547]

New cross section calculations:
(interacting nuclear shell model)



original Gallium anomaly: $\sim 2.9\sigma$

[SAGE, 2006]

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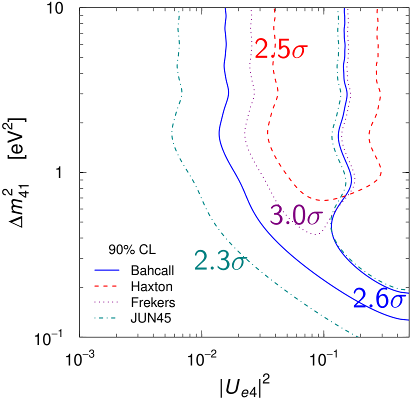
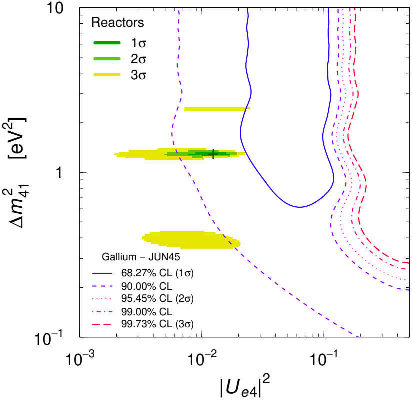


original Gallium anomaly: $\sim 2.9\sigma$

[SAGE, 2006]

[Giunti&Laveder, 2011]

Compare with DANSS+NEOS:

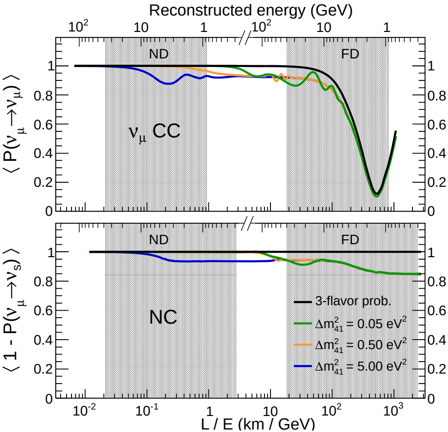


Better compatibility with reactors

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector

$1~\text{GeV} \lesssim E \lesssim 40~\text{GeV}$, peak at 3 GeV



[PRL 117 (2016) 151803]:

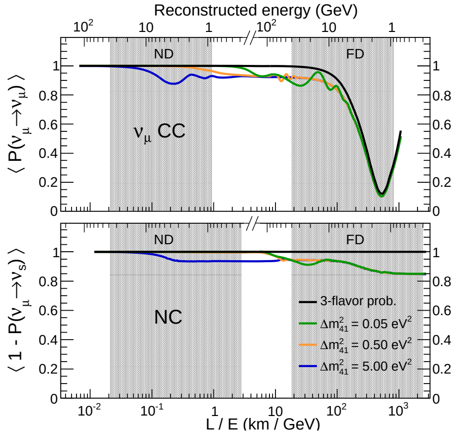
far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

MINOS & MINOS+

Near (ND, $\simeq$ 500 m) and far (FD, $\simeq$ 800 km) detector



[PRL 117 (2016) 151803]:

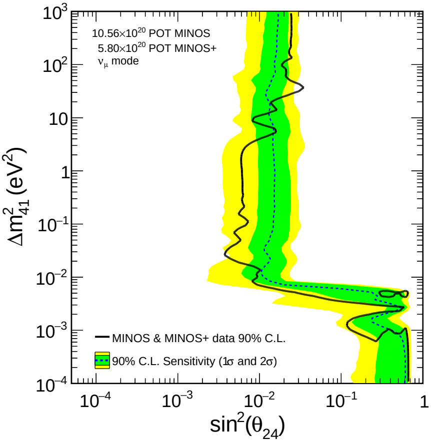
far-to-near ratio

[PRL 122 (2019) 091803]:

full two-detectors fit

1 GeV $\lesssim E \lesssim$ 40 GeV,
peak at 3 GeV

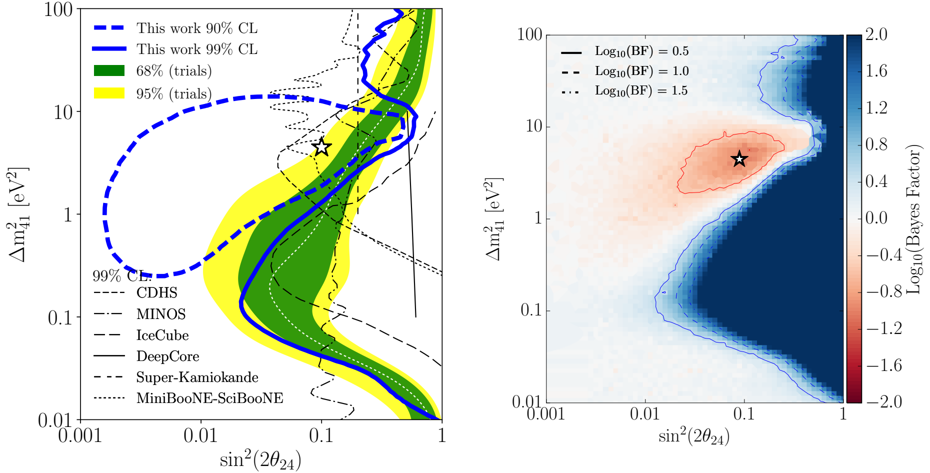
Sensitivity and exclusion limit:



[PRL 122 (2019) 091803]

IceCube 8 yr update

[IceCube, PRL 2020]



first indication in favor of sterile from ν_μ DIS!

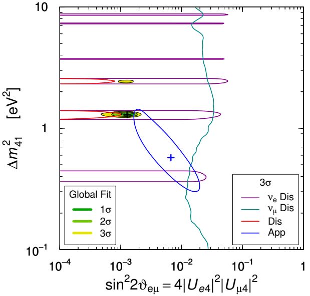
although rather weak: $\log_{10} BF \simeq 1$ (weak preference)

or compatible with no oscillations at p-value of 8%

APP – DIS tension in 2019

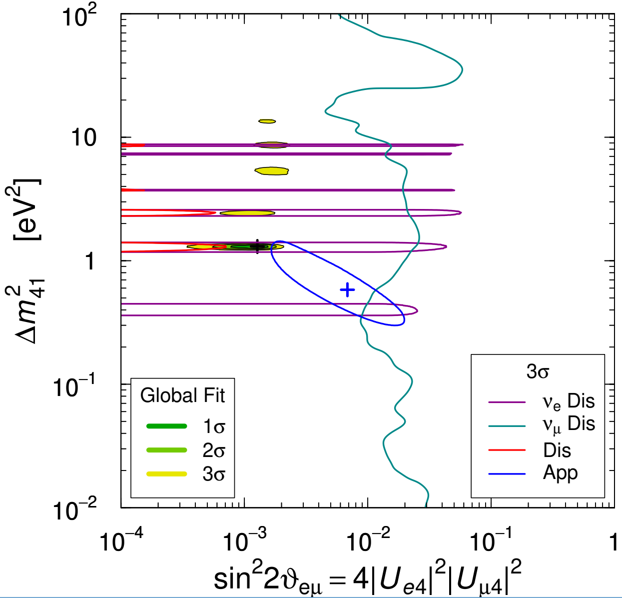
[SG+, in preparation]

Status just after Neutrino 2018:



MINOS+ update, new data including MiniBooNE (all bins)

Status in early 2019



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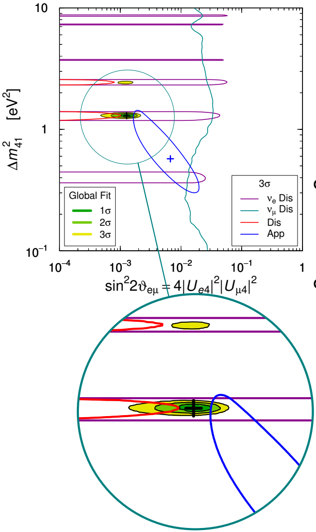
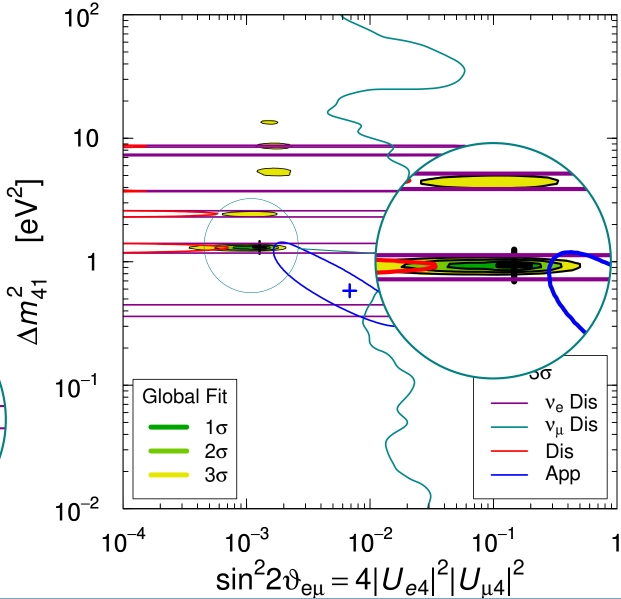


Status in early 2019



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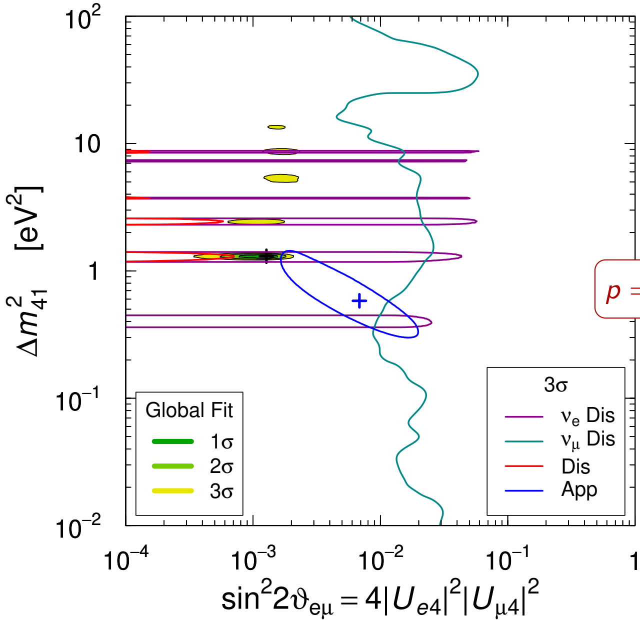
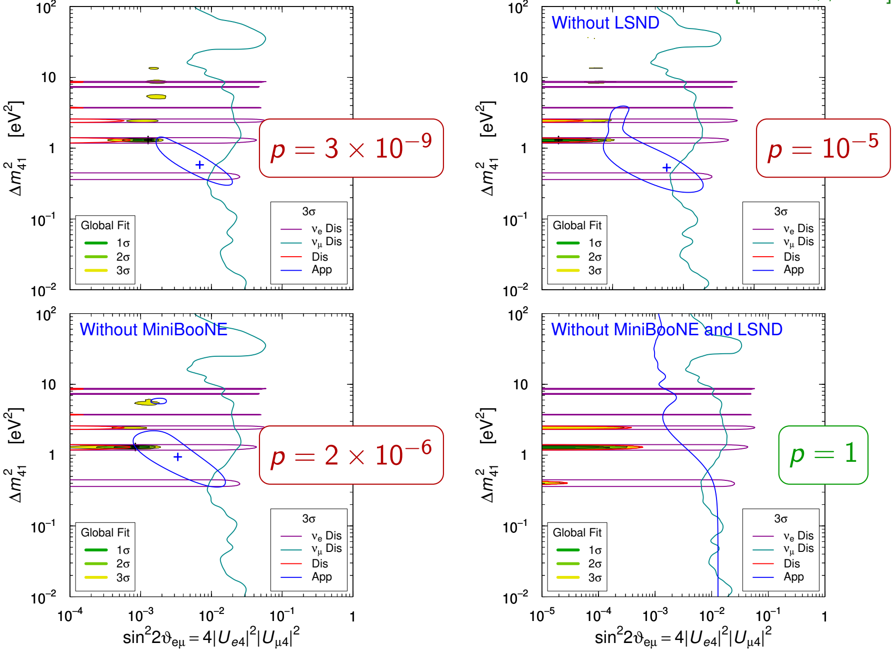


$p = 3 \times 10^{-9}$

APP – DIS tension in 2019

[SG+, in preparation]
see also [Dentler+, 2018]



Next...

let's take a break