Neutrino physics: status and open questions

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and

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Aachen, Germany

Why are neutrinos so important ?

Neutrino oscillations – the only laboratory physics beyond the SM

Neutrino masses and mixing – origin of neutrino masses

Baryon asymmetry of the Universe – explained through leptogenesis ?

Dark matter – keV sterile neutrinos ?

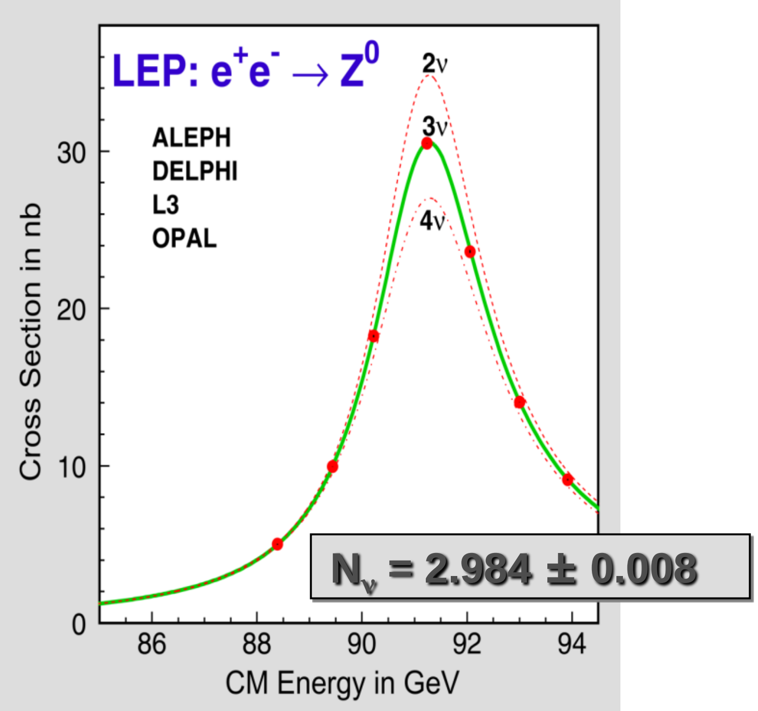
Standard Model

Three active neutrino flavors (types): ν_e ν_μ ν_τ
Neutrinos - partners of corresponding charged leptons: $W \to e\nu_e$ $W \to \mu\nu_\mu$ $W \to \tau\nu_\tau$
Neutrinos are massless particles

Conservation of lepton numbers L_e L_μ L_τ
Transitions between different flavors are forbidden
CP conserved in lepton sector

Experiments at LEP (ЦЕРН):
from Z width

three types of of light active neutrinos



We have also directly observed three types in reactor and accelerator experiments:

ν_e: **Reines and Cowan (Reactor) 1956**
ν_μ: **Lederman, Schwartz, & Steinberger (BNL) 1962**
ν_τ: **DONuT (FNAL) 2000**

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

***U* parameterization:**
three mixing angles θ_{12} θ_{23} θ_{13}
CP violating phase δ_{CP}

atmospheric — link between atmospheric and solar — solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \begin{matrix} m_1 \\ m_2 \\ m_3 \end{matrix}$$

SuperK, K2K, MINOS, T2K

$\theta_{23} \sim 45^0$

$$\Delta m^2_{32} \cong \Delta m^2_{31} = \Delta m^2_{atm} \approx 2.4\times10^{-3}\,\mathrm{eV}^2$$

T2K, MINOS — Daya Bay, RENO, Double Chooz

$\theta_{13} \approx 9^0$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

two independent Δm^2

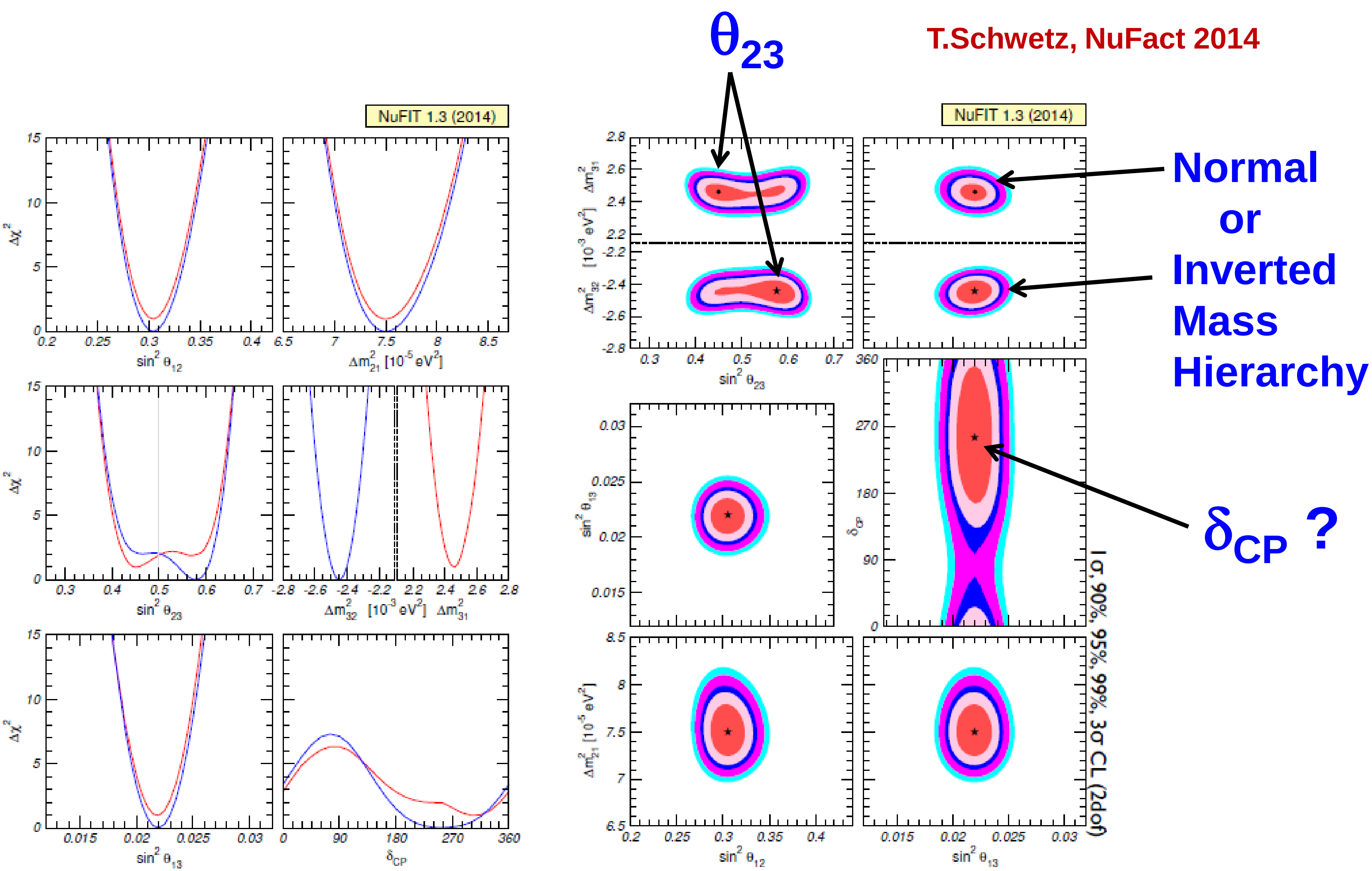
Solar experiments, SuperK, KamLAND

$\theta_{12} \approx 34^0$

$$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times10^{-5}\,\mathrm{eV}^2$$

3-ν global fit of oscillation data

T.Schwetz, NuFact 2014

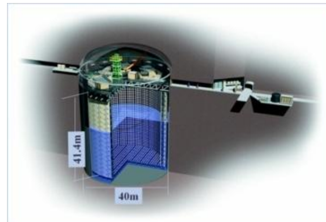


Current oscillation experiments

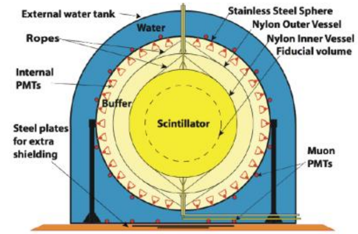
Solar neutrinos

Δm^2_{13}, θ_{12}, MSW

SuperKamiokande



Borexino

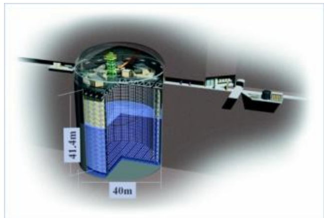


Sage

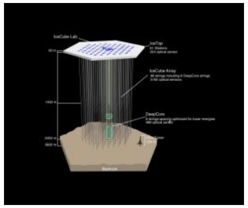
Atmospheric and Astophysical neutrinos

Δm^2_{23}, θ_{23}, high-energy ν astronomy

SuperKamiokande



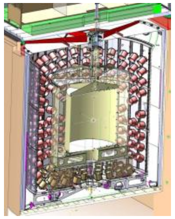
IceCube



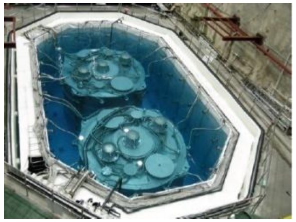
Reactor neutrinos

θ_{13}

DoubleChooz



Daya Bay



RENO

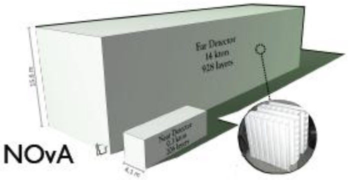
Accelerator neutrinos

Δm^2_{23}, θ_{23}, δ_{CP}, MH, sterile neutrinos

T2K

Minos+

NOVA

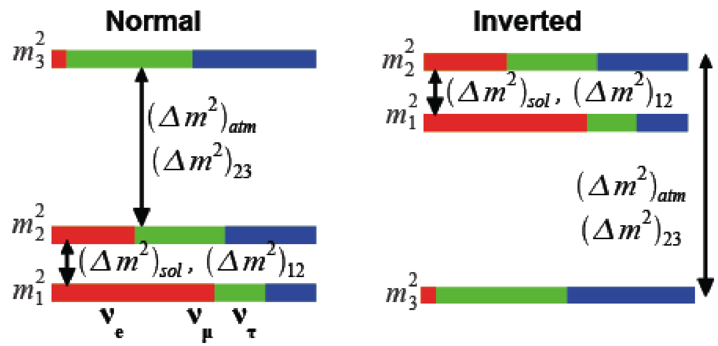


OPERA
ICARUS
MicroBooNE

Open questions

CP violation $P(\nu_\mu \to \nu_e) \neq P(\text{anti-}\nu_\mu \to \text{anti-}\nu_e)$ **??**

Mass hierarchy ??



$\theta_{23} = \pi/4$ or $> \pi/4$ or $< \pi/4$ maximal mixing **??**

Absolute mass scale
origin of mass/mixing ??

Dirac or Majorana $0\nu 2\beta$ decay **??**

Light and heavy sterile neutrinos ??

Talks
G.Barker
J.Coelho
M.Mezzetto
S.Jetter
K.Lang
W.Maneschg
A.Weber

Overview of the latest results

Neutrino oscillations: reactor and accelerator experiments

Reactor Based Experiments: Daya Bay, RENO, DoubleChooz

Anti-electron neutrino disappearance (anti-ν_e →anti-ν_e):

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} \longrightarrow$$

Sensitive to:
θ_{13}, $|\Delta m^2_{31}|$

Accelerator Based Experiments: T2K, MINOS, NOνA

Electron neutrino appearance ($\nu_\mu \to \nu_e$):

Appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta(1-A))}{(1-A)^2} + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A\Delta}{A^2}$$

Expanded under small θ_{13}, α

$$+\alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \frac{\sin((1-A)\Delta)}{1-A} \frac{\sin A\Delta}{A} \cos(\delta + \Delta) \longrightarrow$$

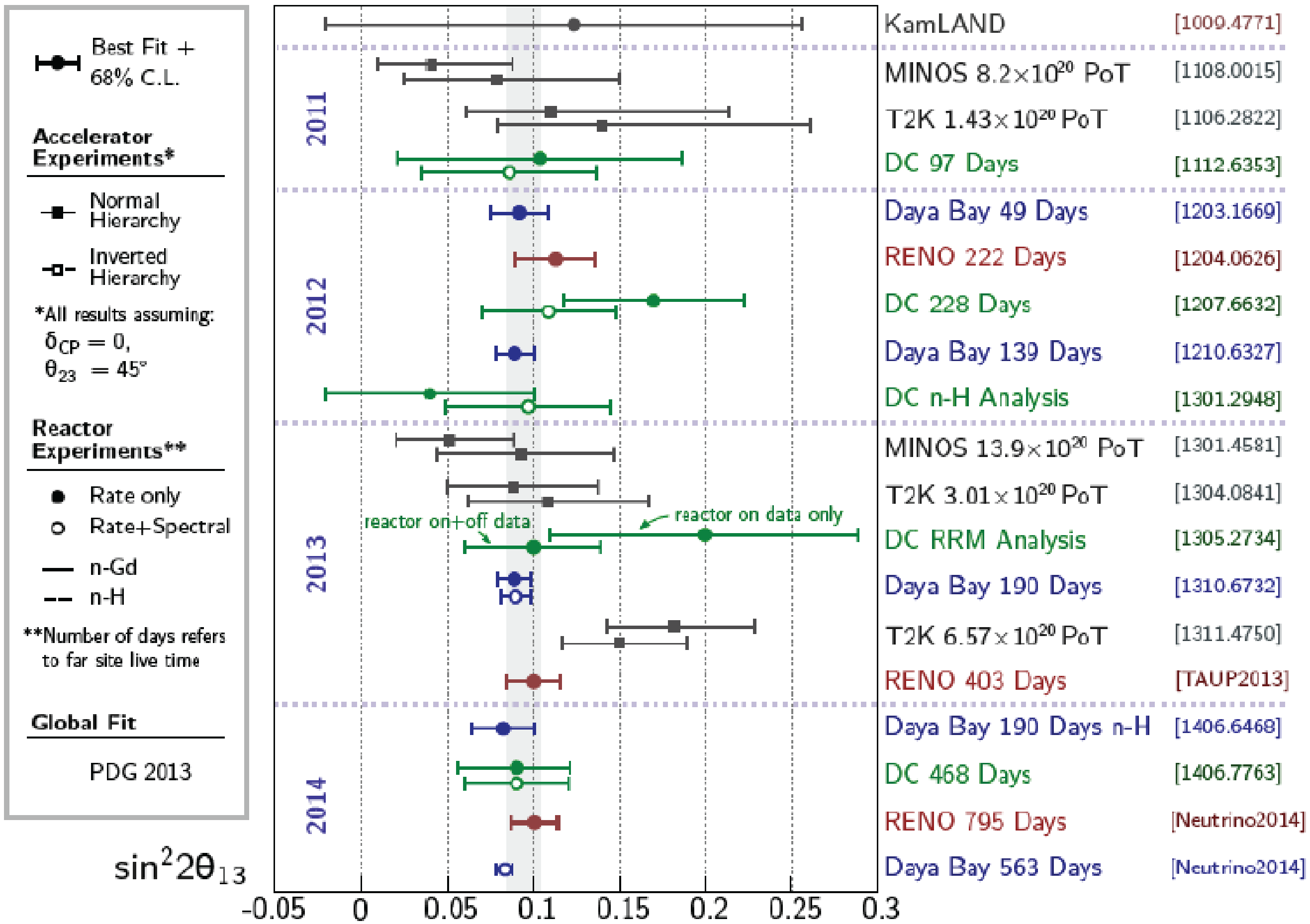
Sensitive to:
Θ_{13} δ_{CP}
Θ_{23} Δm^2_{31}

$$A = \pm 2\sqrt{2} G_F n_e E \Delta m^2_{31} \qquad \Delta = \frac{\Delta m^2_{31} L}{E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Hierarchy?

CP Violation!

θ_{13} history



$\theta_{13} \approx 9^o$

Search for CP violation?

$\theta_{13} \neq 0$ opens a door for CP violation search in neutrino oscillations

The strength of CP violation $\longrightarrow$ **Jarlskog invariant J_{CP}**

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = \mathrm{Im}(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2}) =$$

$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta$$

all mixing angles $\neq 0 \rightarrow J_{CP} \neq 0$ if $\delta_{CP} \neq 0$

Big difference between quark and neutrino mixings

Quark sector $J_{CP} \approx 3\times10^{-5}$

Lepton sector $J_{CP} \sim 0.02\times\sin\delta$

neutrinos

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Real chance to test CP violation in neutrino oscillations

Why is δ_{CP} important?

Baryon Asymmetry of Universe (BAU)

$$\eta = \frac{n_B - n_{\bar{B}}}{\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

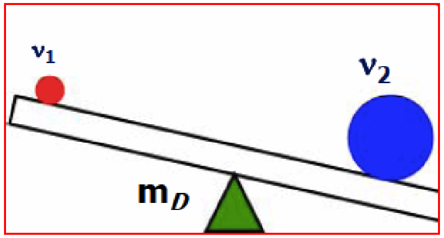
$$\frac{n_{\bar{B}}}{n_B} < 10^{-6}$$

Universe contains baryons, but no antibaryons

3 Sakharov's conditions:
- baryon number violation
- C and CP violation
- deviation from thermal equilibrium dynamics

CP violation in quark sector too small to generate BAU

See-saw model



$$m_\nu \approx \frac{m_D^2}{M_R}$$

$m_D \sim 100$ GeV $M_R \geq 10^{15}$ GeV

See-saw model naturally satisfies these requirements producing BAU by leptogenesis mechanism

Leptogenesis

Leptogenesis: is a class of scenarios where the Universe baryon asymmetry $(Y_{\Delta B})$ is produced from a lepton asymmetry $(Y_{\Delta L})$ generated in the decays of the heavy $SU(2)$ singlet *seesaw* Majorana neutrinos.

M. Fukugita and T. Yanagida, 1986

N_R decays → **lepton asymmetry ε_1** → **partially transformed into BAU**

lepton asymmetry from N_R decays ε_1 must be > 10^{-6}

Baryon Asymmetry ↔ Neutrino Physics

Observation of CP violation in neutrino oscillations would be an indication of leptogenesis as the explanation for BAU,
…but no direct relation between ε_1 and δ_{CP} established

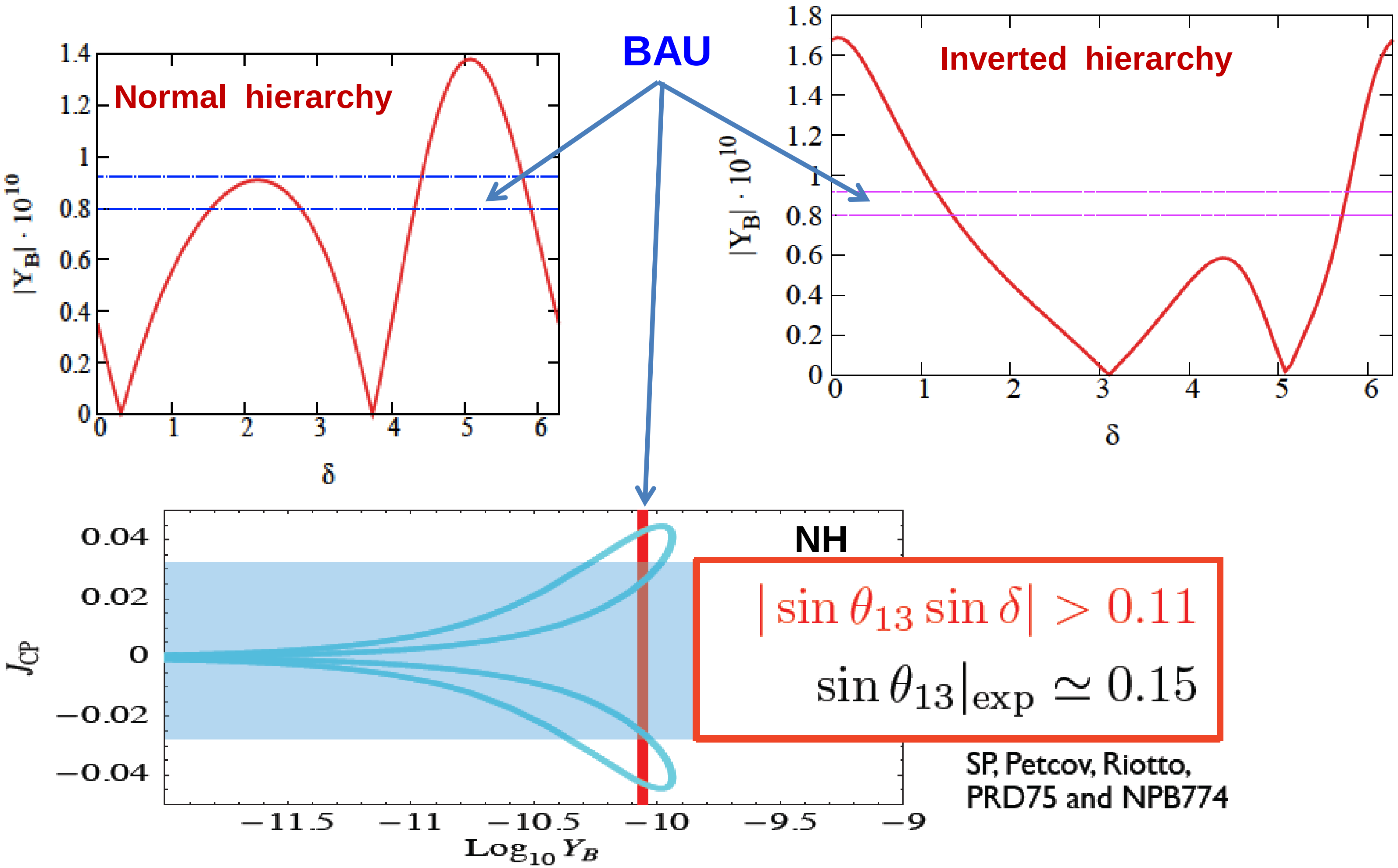
Examples: $\delta_{CP} \leftrightarrow Y_B$

Type I see-saw

three heavy right-handed Majorana neutrinos N_j (j=1,2,3)

masses $M_1 << M_{2,3}$

Molinaro, Petcov '09

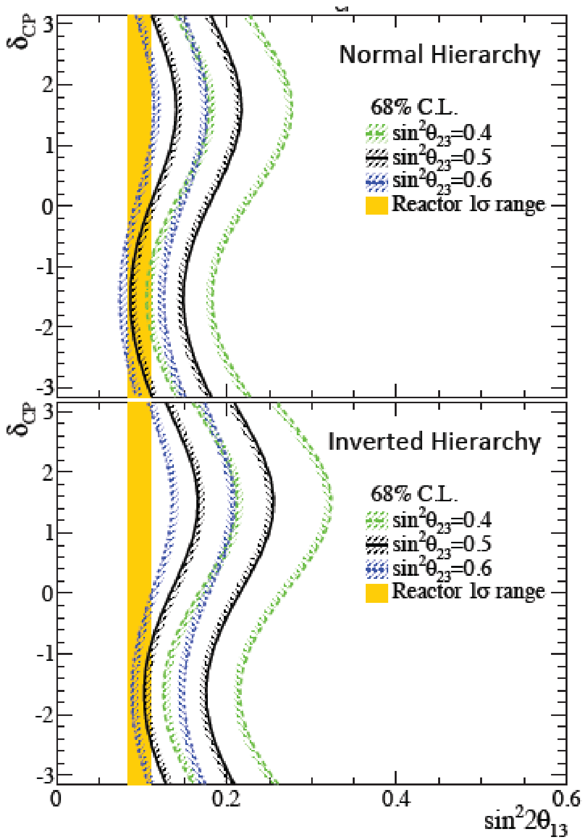


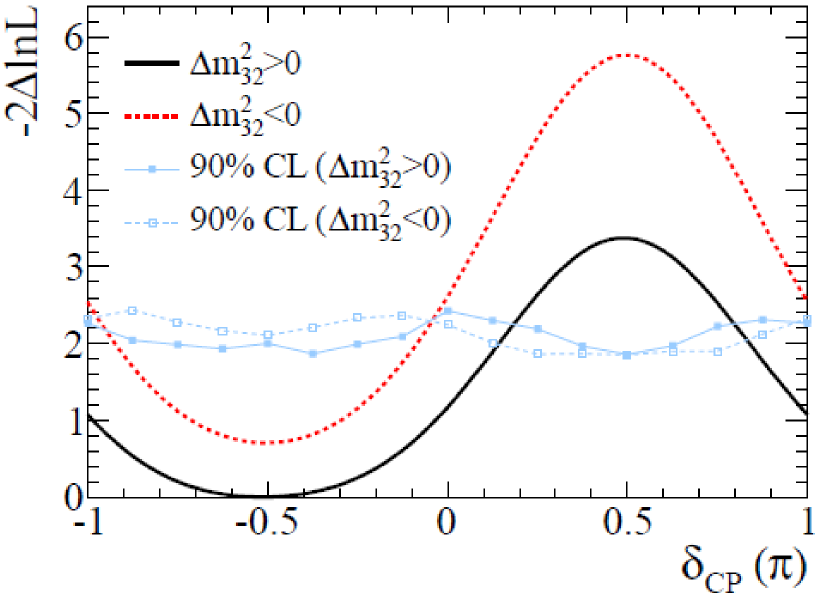
SP, Petcov, Riotto, PRD75 and NPB774

T2K: first CP violation search

Constraint on δ_{CP} with combination $\sin^2 2\theta_{13} = 0.095 \pm 0.010$ measured by reactor experiments Daya Bay, RENO, Double Chooz

T2K, PRL 112 (2014) 061802





90% inclusion regions for δ_{CP}

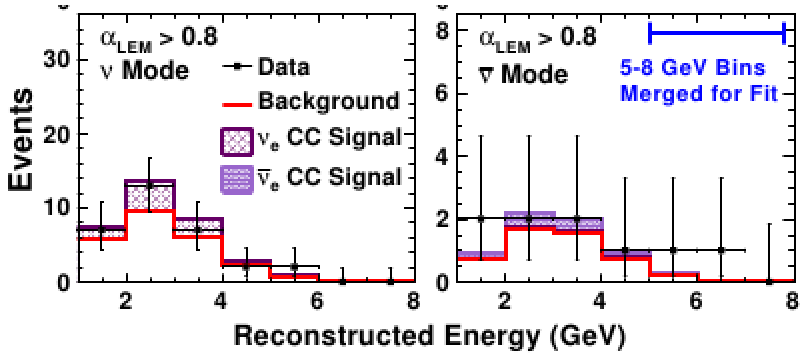
NH: $-1.18\pi < \delta_{CP} < 0.15\pi$

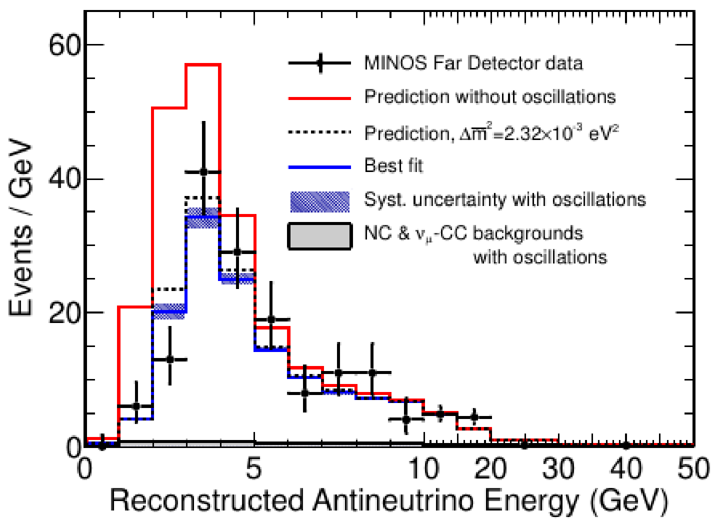
IN: $-0.91\pi < \delta_{CP} < -0.08\pi$

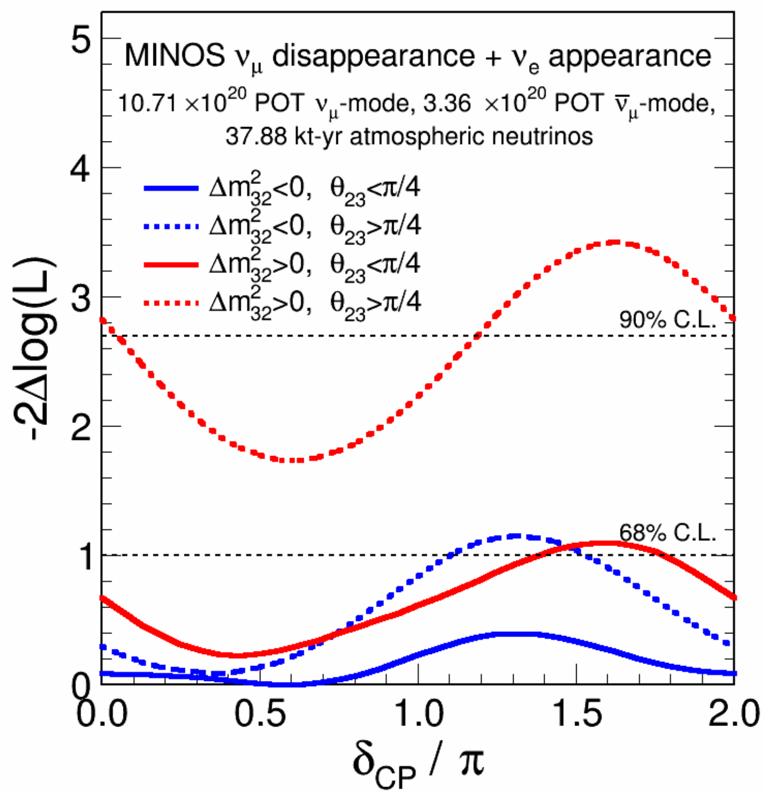
Preferable value $\delta_{CP} \approx -\pi/2$ and NH

MINOS: first CP violation search

MINOS, PRL 112 (2014) 191801



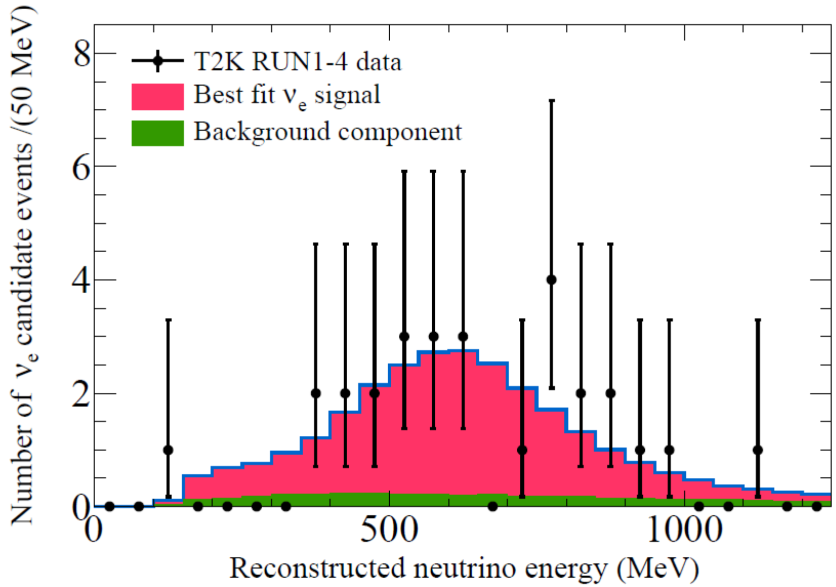




Preference for Inverted Hierarchy and a value of δ_{CP} around $\pi/2$

Observation of ν_e appearance

T2K
ν_e appearance result



PRL 112, 061802 (2014)

28 ν_e candidates detected

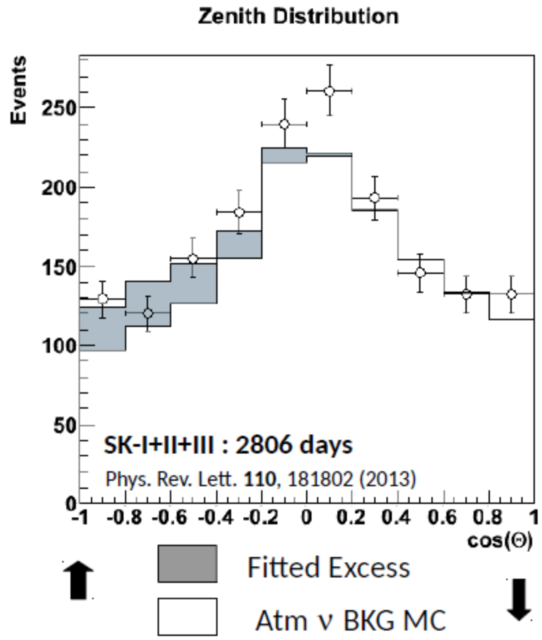
expected 4.92±0.55 events for $\sin^2 2\theta_{13} = 0.0$

expected 21.6 ± 0.8 events for $\sin^2 2\theta_{13} = 0.1$ and $\delta_{CP} = 0$

7.3σ significance for $\theta_{13} \neq 0$
First observation of neutrino appearance

ν_τ appearance

SuperKamiokande



R.Wendell, Neutrino2014

Result	Background	DIS (γ)	Signal
SK-I+II+III	0.94 ± 0.02	1.10 ± 0.05	**1.42 ± 0.35**

This corresponds to 180.1 ±44.3 (stat) +17.8-15.2 (sys) events, a **3.8 σ** excess (Expected 2.7 σ significance)

OPERA

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32\ meV^2$	Total background	Observed
$\tau \rightarrow h$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau \rightarrow 3h$	0.57 ± 0.11	0.155 ± 0.03	1
$\tau \rightarrow \mu$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau \rightarrow e$	0.61 ± 0.12	0.027 ± 0.005	0
Total	2.1 ± 0.42	0.23 ± 0.04	4

S.Dusini, Neutrino2014

no oscillation excluded at 4.2 σ CL

Neutrino mass measurements

H.Robertson, NOW2014

Troitsk experiment

- windowless gaseous tritium source

- 2011 re-analysis of selected data from 1994-2004: no evidence for Troitsk anomaly

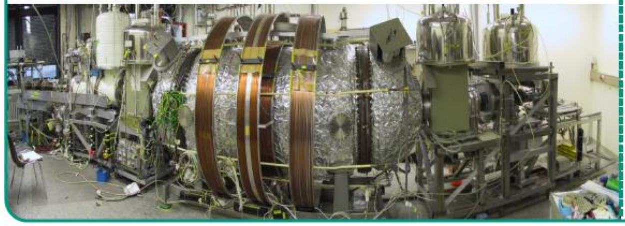
$$m^2(\nu_e) = (-0.67 \pm 1.89 \pm 1.68)\ eV^2$$

$$m(\nu_e) < 2.05\ eV$$

V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003

Mainz experiment

- quench condensed tritium source



- 2004 final analysis of Mainz phase II data from 1998-2001: analysis of last 70 eV

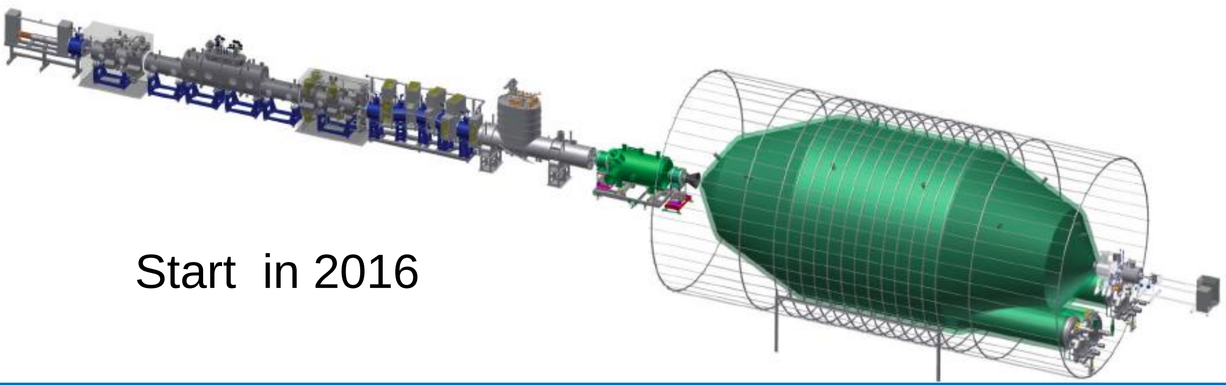
$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\ eV^2$$

$$m(\nu_e) < 2.3\ eV$$

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

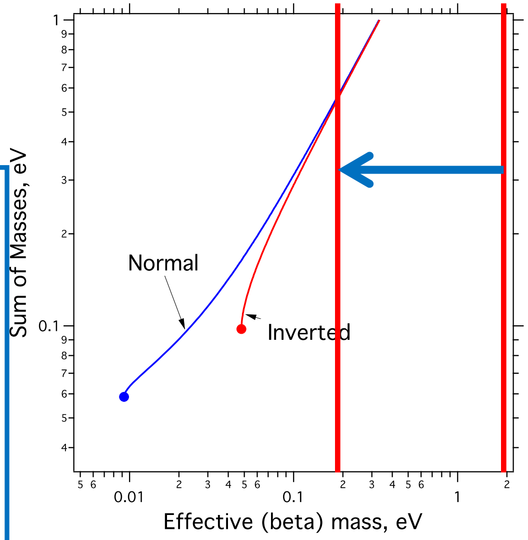
Together:…
$m_\nu < 1.8$ eV
(95% CL)

KATRIN



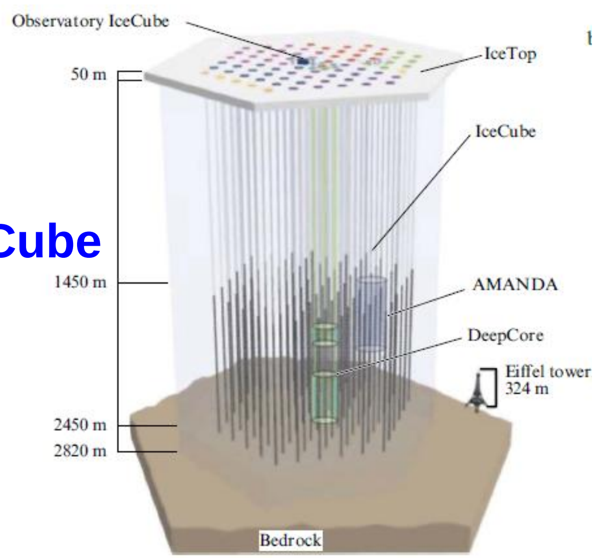
Start in 2016

KATRIN: mass range accessible



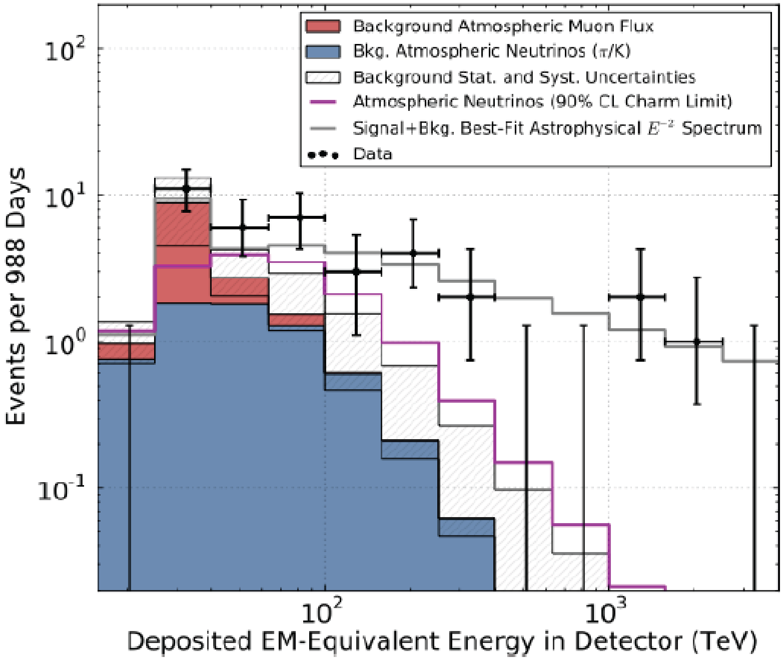
High energy astrophysical neutrinos

IceCube

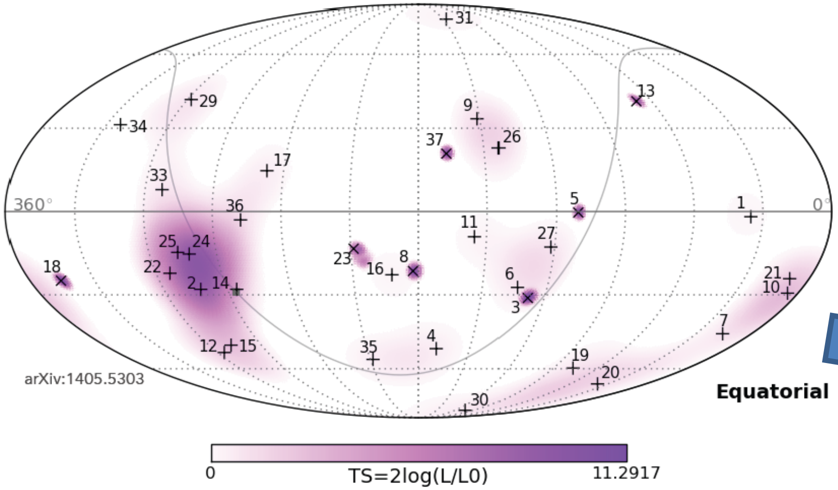


IceCube detected 37 events in energy range 30 – 2000 TeV

arXiv:1405.5303

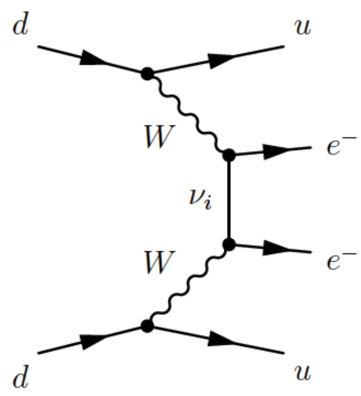


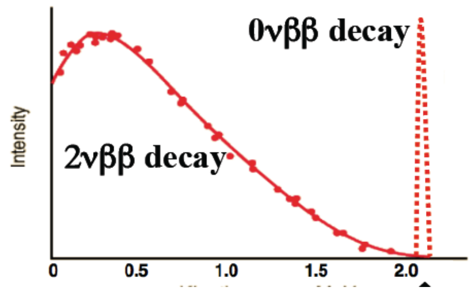
Purely atmospheric explanation rejected at 5.7σ.



Source is unknown and no significant clustering was observed.

Neutrinoless 2β decay





Majorana vs Dirac
Absolute mass scale
Neutrino mass hierarchy

0ν2β decay: Majorana masses, ΔL = 2

(A,Z) → (A,Z+2) + 2e$^-$

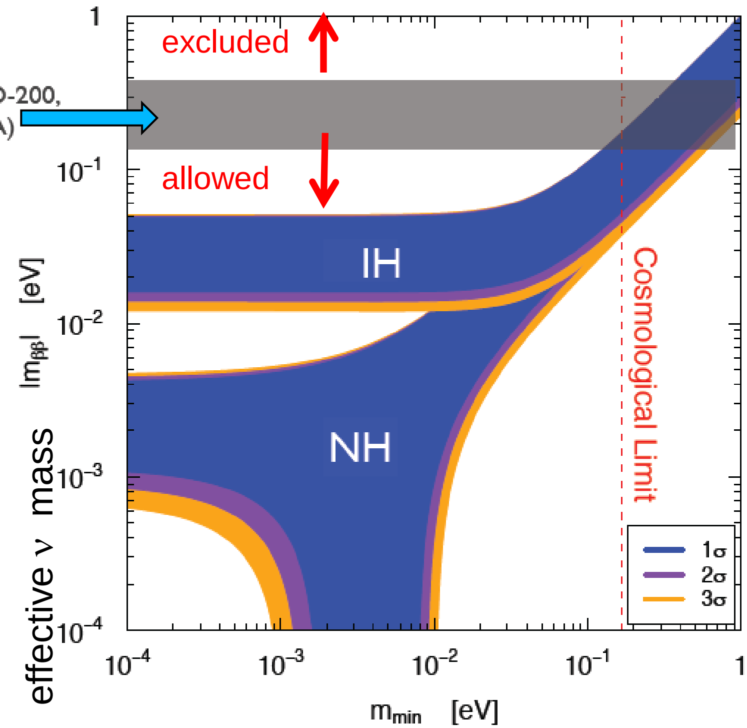
Expected decay rate

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

Phase space integral — Nuclear matrix element

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$ Effective neutrino mass

U_{ei} Elements of (complex) PMNS mixing matrix



S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

Next generation of experiments should probe mass range predicted for **IH:**

- ~10 meV
- **0νββ: $T_{1/2}$ ~ 10^{27} - 10^{28} years**

Broad experimental program: GERDA, NEMO-3, EXO, KamLAND-Zen, NEXT, SNO+, Cuore…

Discovery of 0ν2β decay → Majorana nature of neutrinos and L is violated

Neutrino anomalies

Reactor anomaly ($\overline{\nu}_e$ disappearance)

Gallium anomaly (ν_e disappearance)

LSND ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance)

MiniBooNE ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$, $\nu_\mu \rightarrow \nu_e$ appearance)

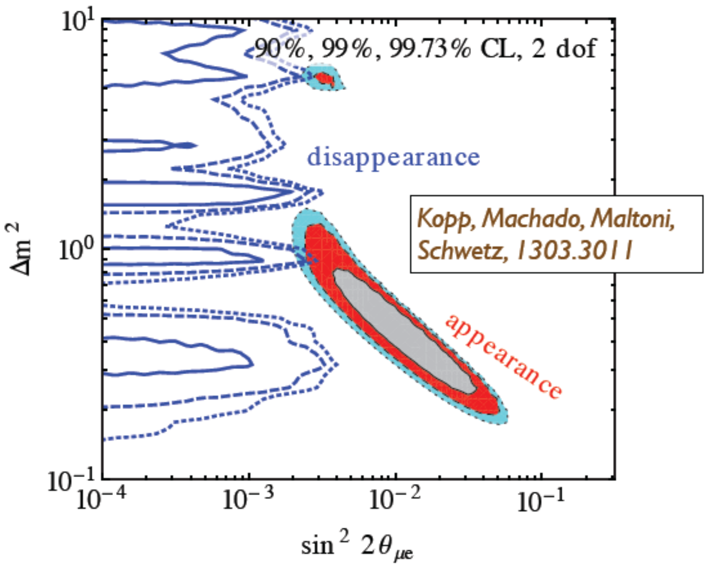
$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

However

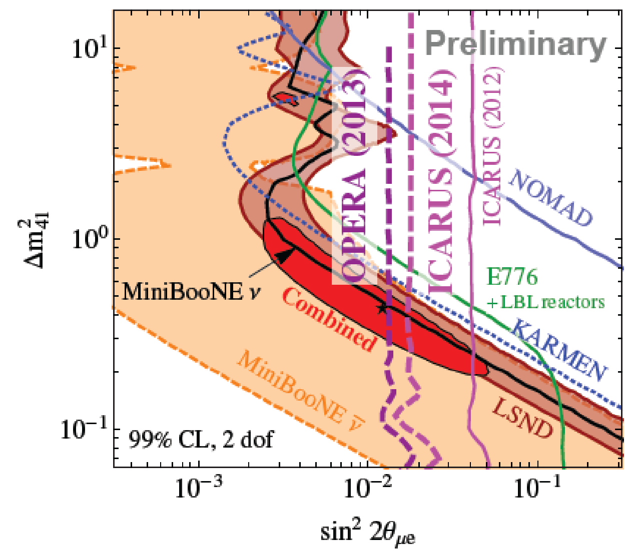
no hint for ν_μ disappearance

limits from SK, CDHS, MiniBooNE, MINOS

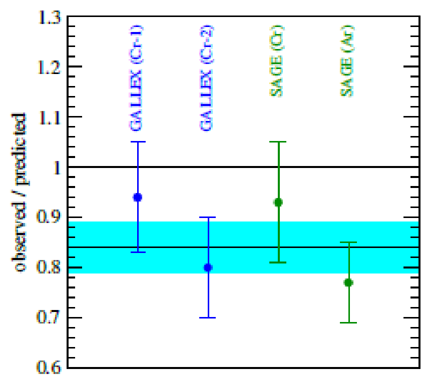
T.Schwetz, Nufact2014



Accelerator experiments

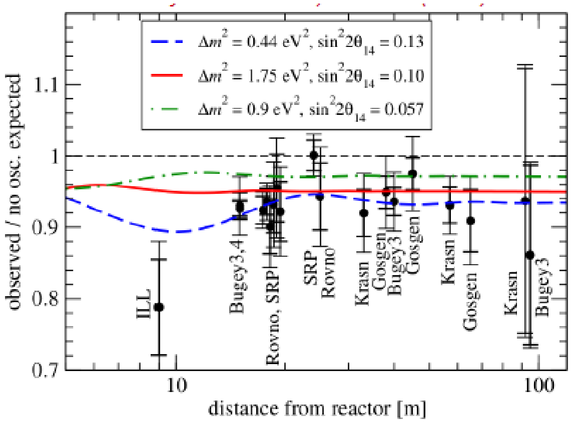


Ga experiments



$$R = 0.87 \pm 0.05$$

Reactor experiments

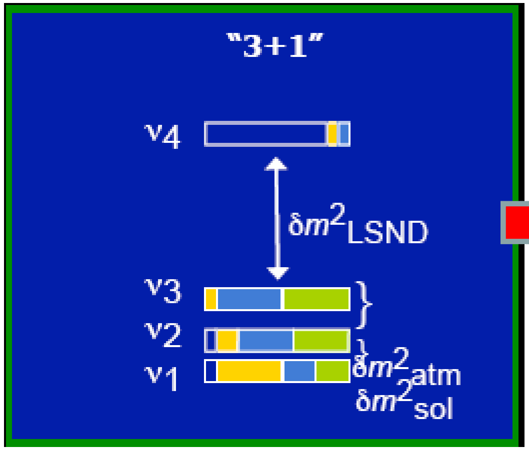


$$R = 0.927 \pm 0.023$$

Light sterile neutrinos ?

Combined analysis of anomalies:
- **reactors**
- **Ga experiments**
- **LSND и MiniBooNe,**

$|\Delta m^2| > 1.0$ эВ^2
$\sin^2 2\theta_{new} \simeq 0.17$



$\Delta m^2_{34} \sim 1$ eV^2 $\Rightarrow$ 4-th neutrino?
...but SM and LEP
$\Downarrow$
***3* light active neutrinos**

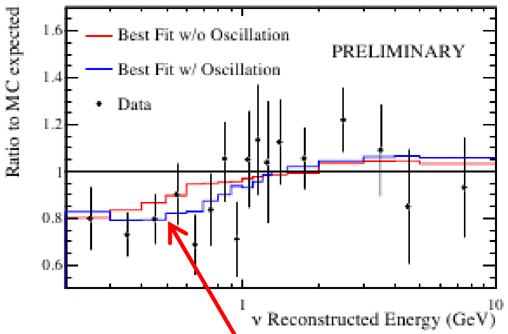
Hypothesis of sterile neutrino

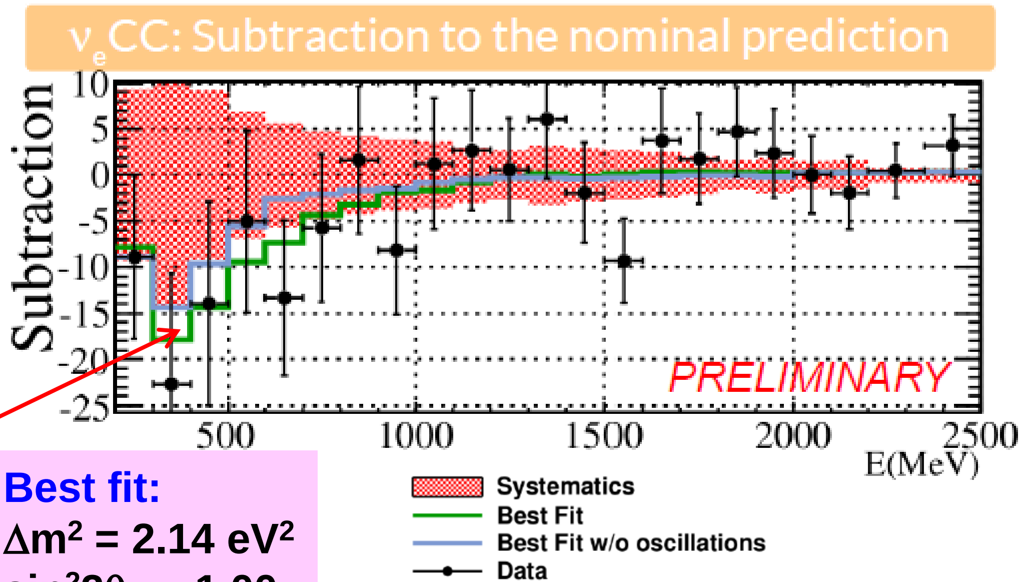
Sterile neutrino ν_s
- can be born in early Universe due to mixing with active neutrinos
- do not participate in weak interaction
- both left and right helicity are possible
- 4th mass eigenstate

T2K: search for sterile ν's

J.Caravaca, NuFact2014

T2K near detector measurements of ν_e disappearance

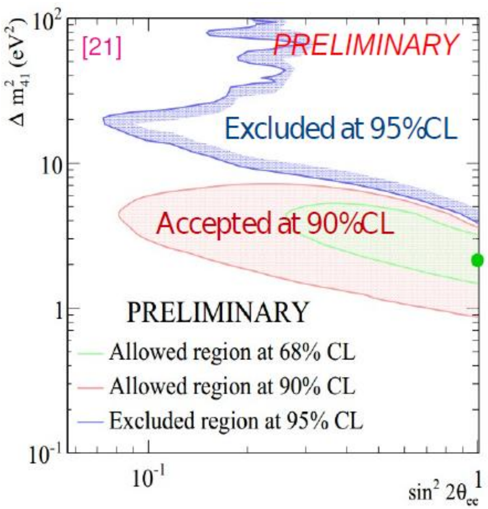


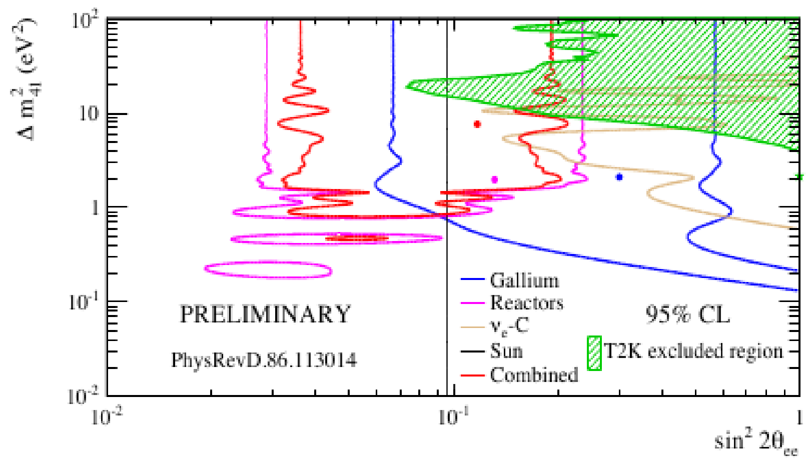


small deficit

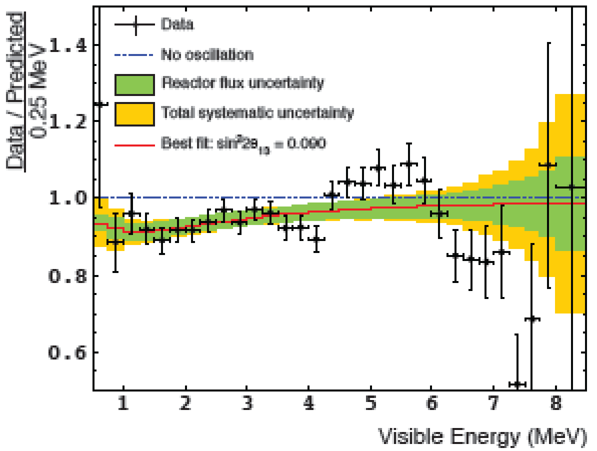
Best fit:
$\Delta m^2 = 2.14$ eV^2
$\sin^2 2\theta_{ee} = 1.00$

- **Oscillation with $\Delta m^2 > 1$ eV^2**
- **No oscillation hypothesis p-value = 0.06**

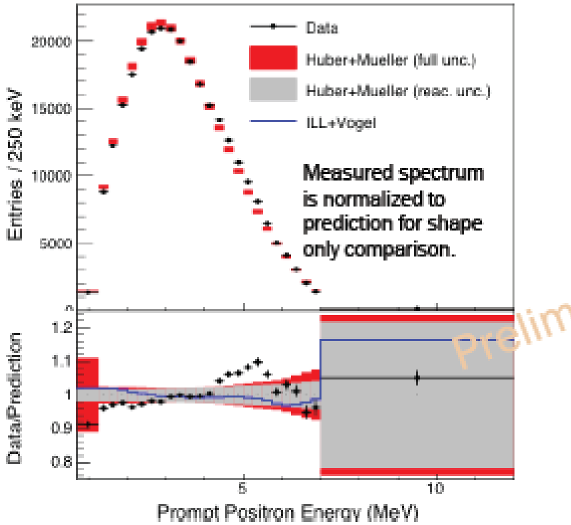




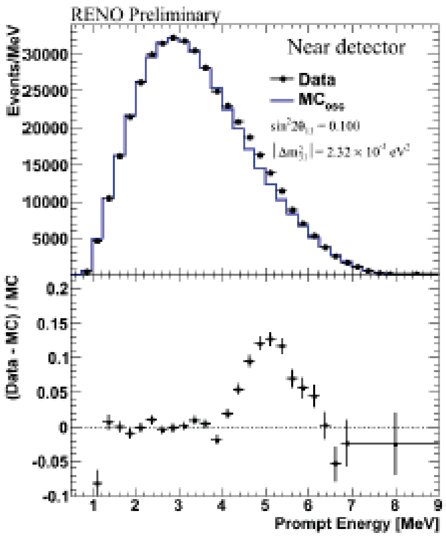
New reactor anomaly?



Double Chooz, arXiv:1406.7763



Daya Bay, ICHEP 2014



RENO, Neutrino 2014

This new anomaly unlikely connected to neutrino oscillations

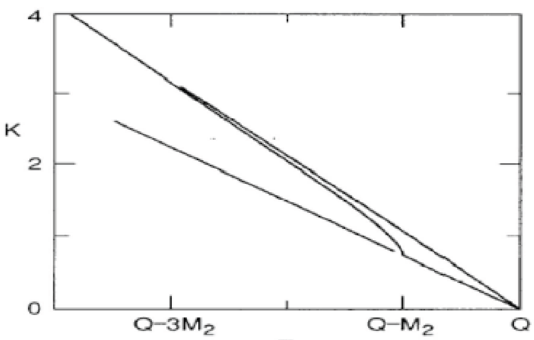
Heavy sterile neutrinos

T.Asaka, M.Shaposhnikov, PLB260 (2005) 17

Neutrino oscillations, BAU, DM can be explained in νMSM model with 3 heavy right handed Majorana neutrinos (heavy neutral leptons) N_1, N_2, N_3.
Mixing between active and heavy sterile ν's:
→ production of heavy ν's in weak decays of mesons.
The same mixing: → decay of heavy ν's to SM particles

N_1 with mass of a few keV
- a candidate for Dark Matter

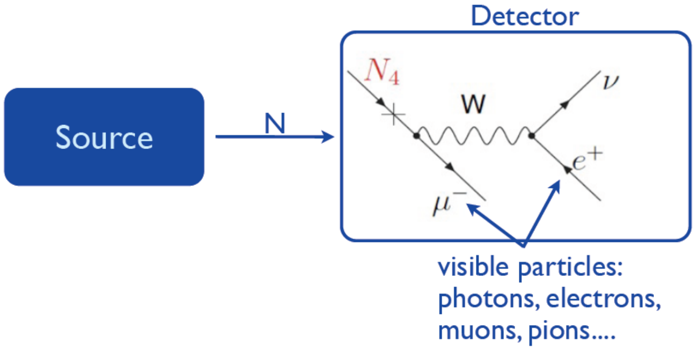
($N_1 \to 3\nu$ or $N_1 \to \nu\gamma$)



kink in β-decay

N_2 and N_3 with masses from 150 MeV to 100 GeV
→ neutrino masses using see-saw mechanism
→ BaU

$N_{2,3} \to \mu/e\,\pi$ or $N_{2,3} \to \mu\nu e$

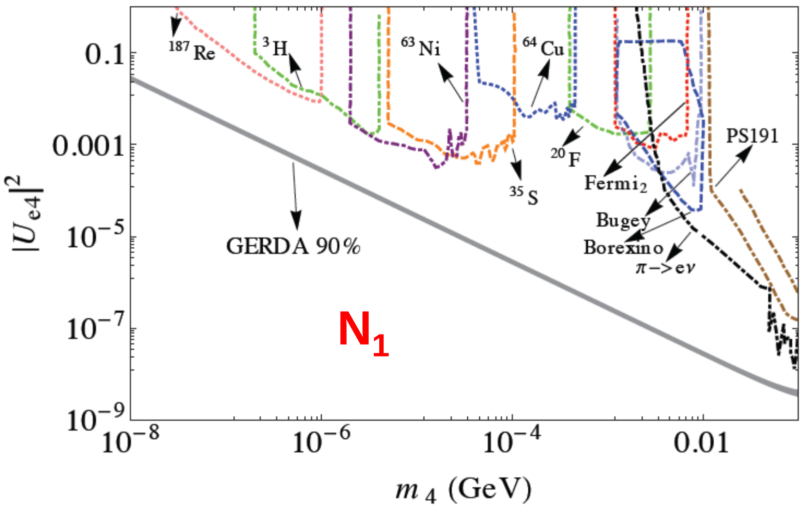


accelerator experiments

Search for heavy sterile neutrinos

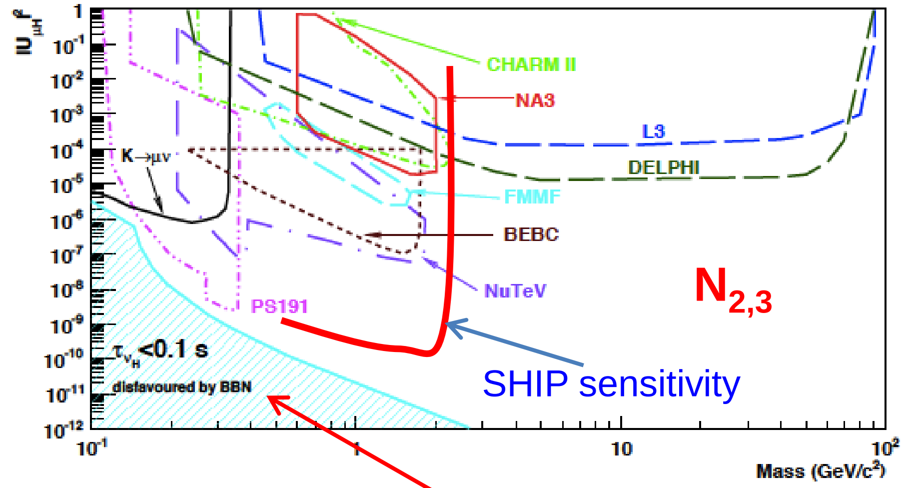
S.Pascoli et al. 1310.6218

Direct search



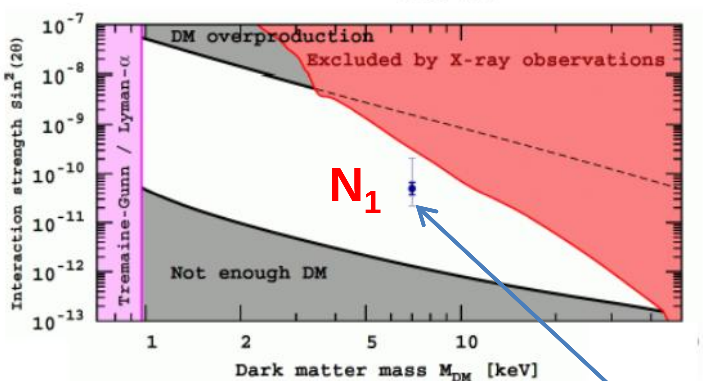
Direct search

Atre et al. 0901.3589

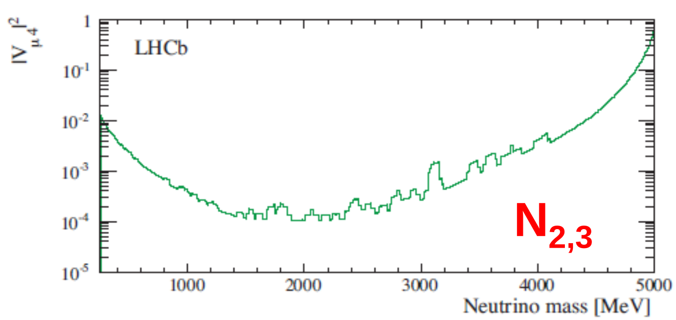


Cosmology

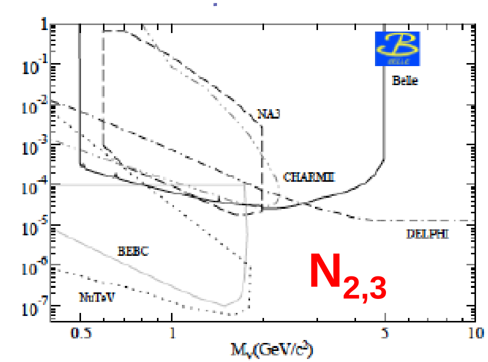
Cosmology



LHCb, PRL 112 (2014) 131802



BELLE, PRD 87 (2013) 071102



can be explained by decay of 7 keV ν_s and $\sin^2 2\theta$ ~5x10-11

Conclusion

- Neutrinos - an important laboratory to study physics beyond the Standard Model

- Large θ_{13} opens door to measure MH and δ_{CP} in neutrino oscillations

- If $\delta_{CP} \neq 0$ $\rightarrow$ an indication of leptogenesis ?

- $0\nu2\beta$ decay can be detected in case of inverted mass hierarchy in near future

- Sterile neutrinos: more dedicated measurements are needed

- An exiting new era of High Energy Neutrino Astrophysics has begun

- Presently Neutrino Physics is experimentally driven
- Long history of surprises may continue….