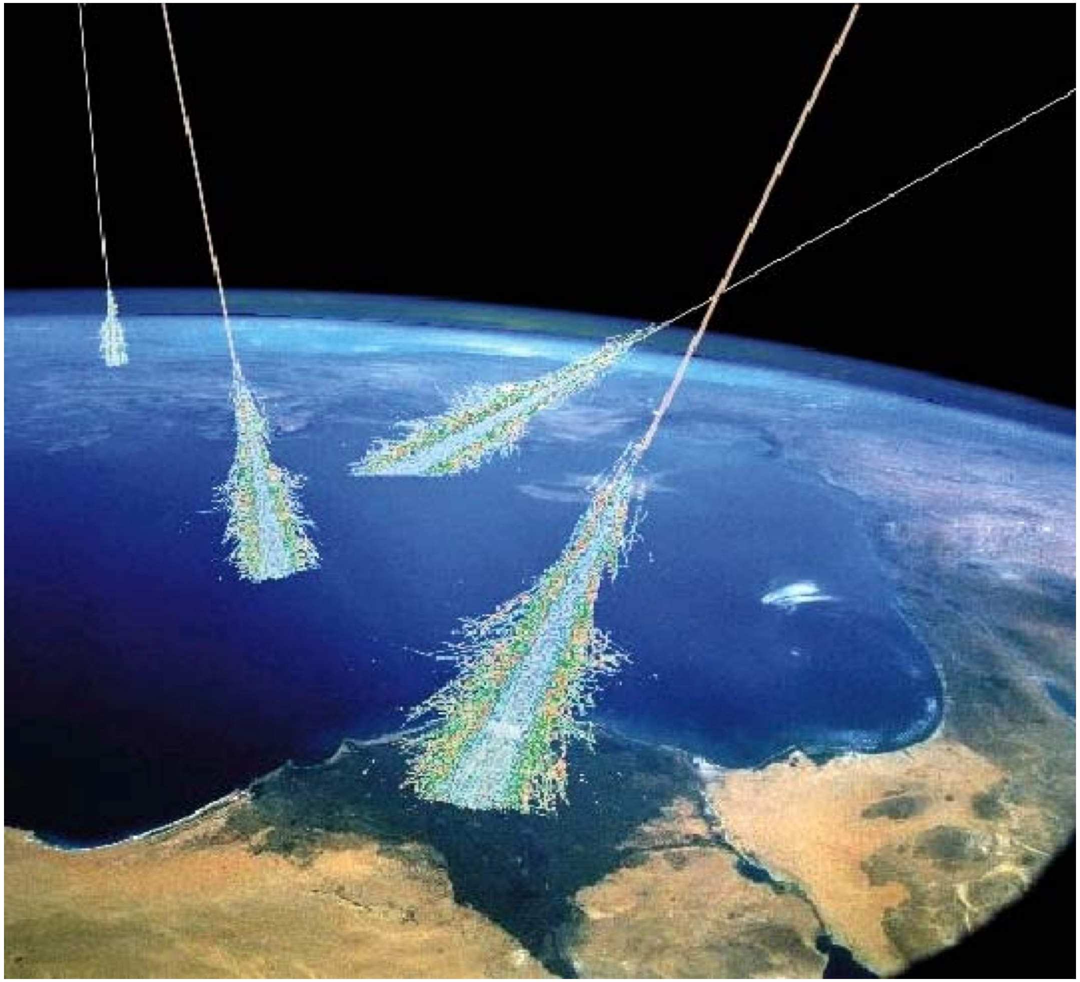
LECTURE II

- Evidence for neutrino masses

- The standard 3ν scenario and its unknowns: status and prospects

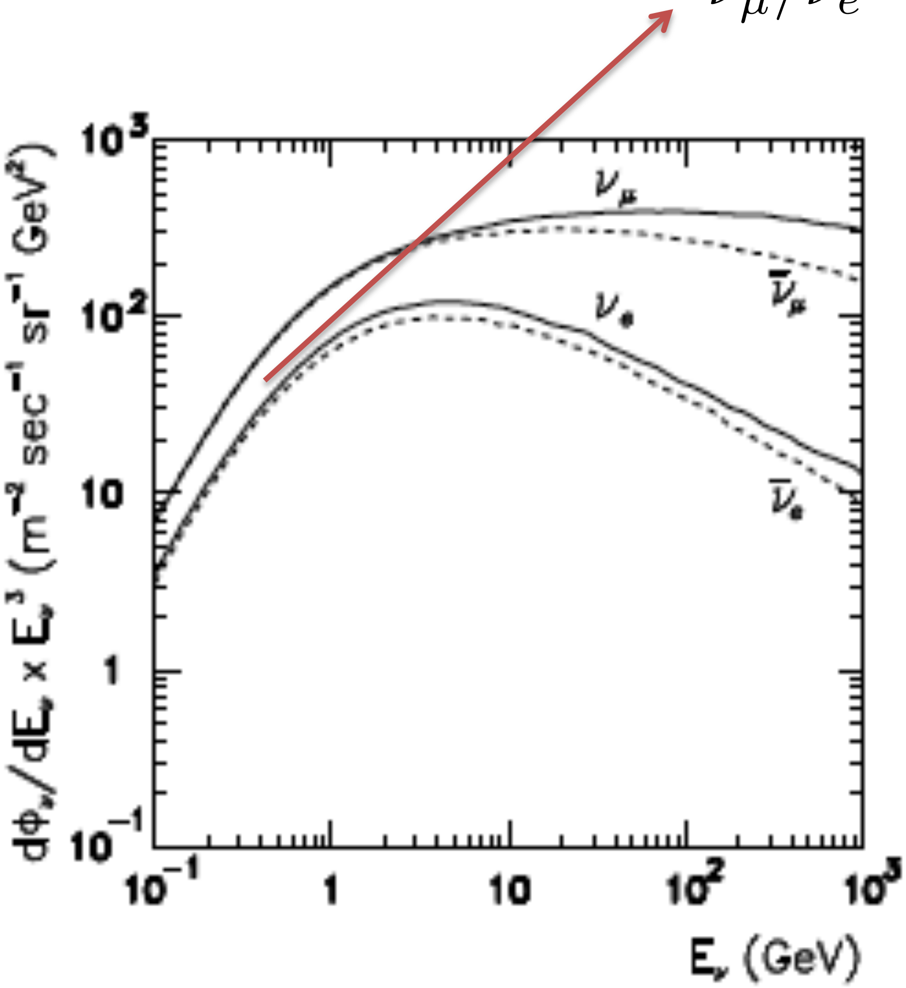
- Neutrinos and beyond the Standard Model physics

Atmospheric Neutrinos



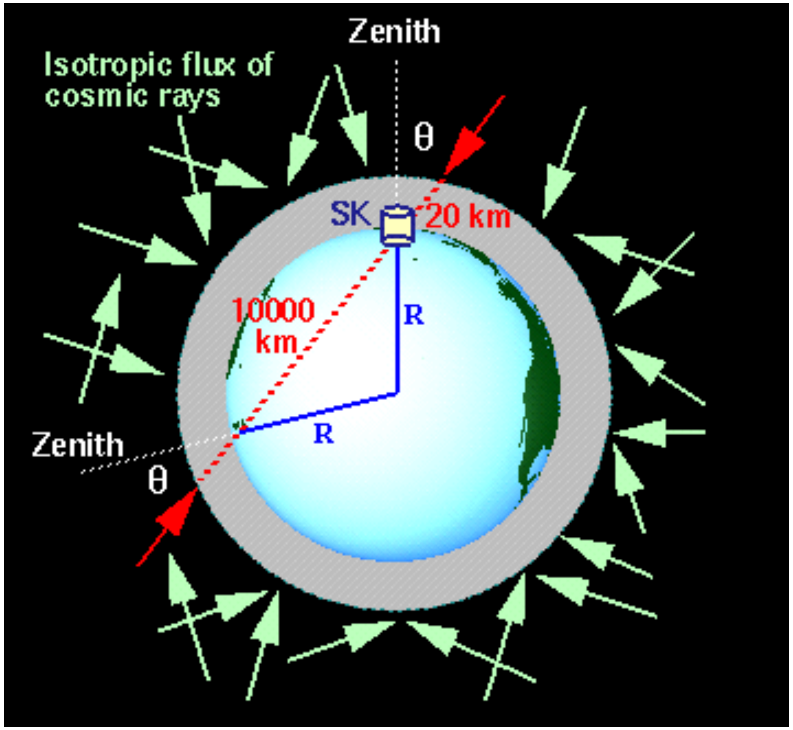
Atmospheric Neutrinos

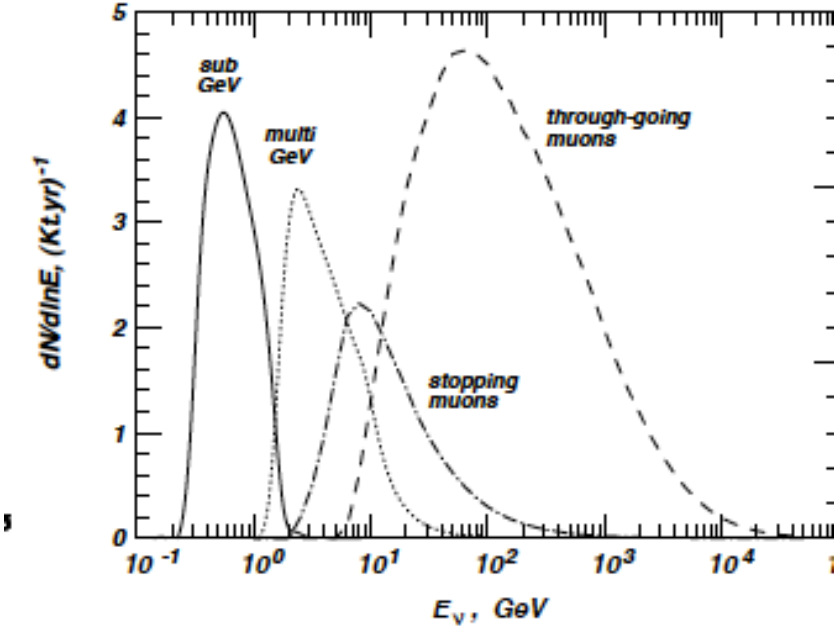
$\nu_\mu / \nu_e \sim 2$



Produced in the atmosphere when primary cosmic rays collide with it, producing π, K

Atmospheric Neutrinos

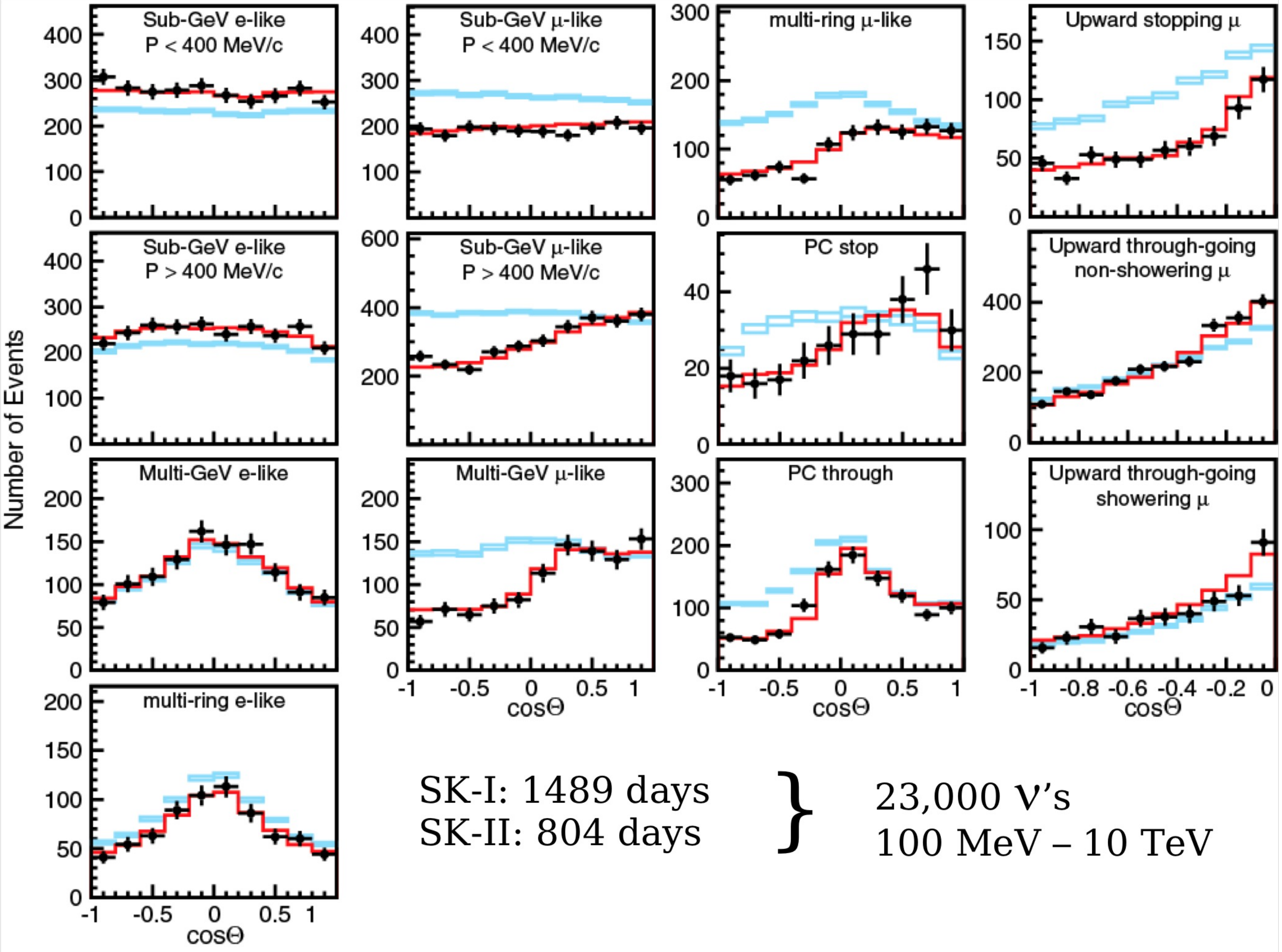




$$L = 10 - 10^4 \text{ Km}$$

Measuring the energy dependence and the zenith angle E/L spans many orders of magnitude

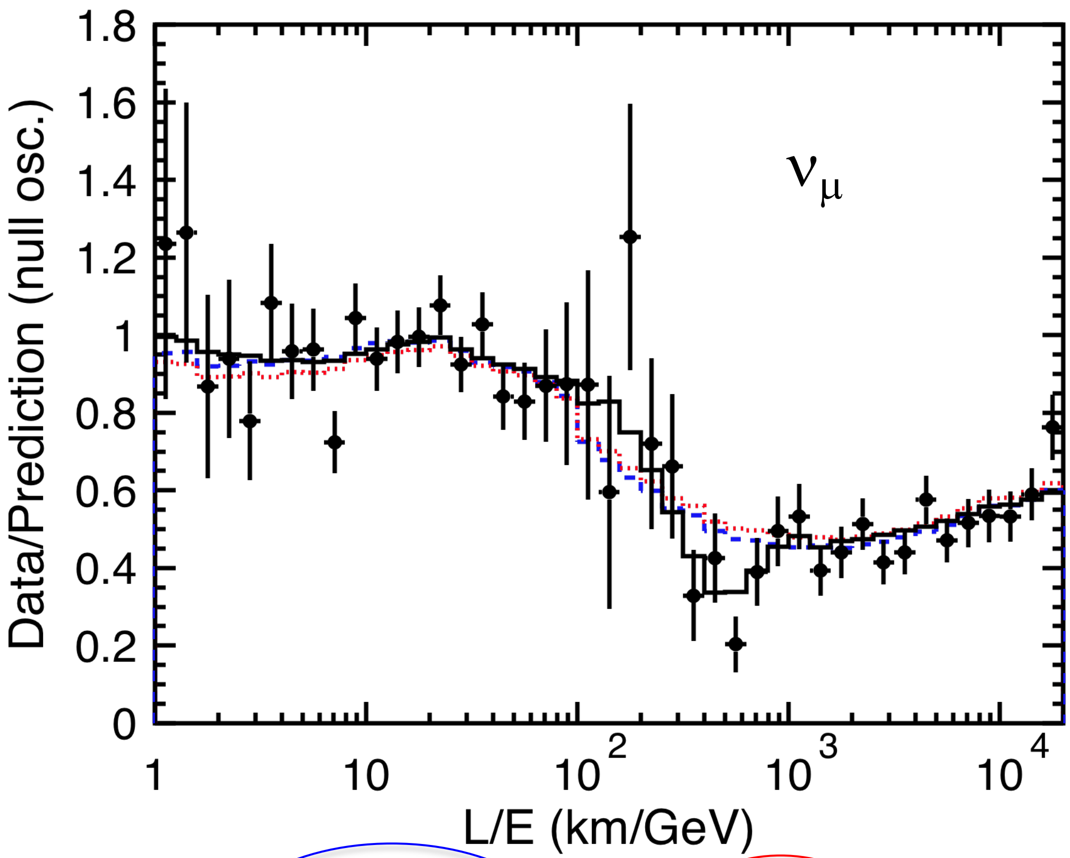
Oscillation of Atmospheric Neutrinos



SK-I: 1489 days
SK-II: 804 days

} 23,000 ν's
100 MeV – 10 TeV

Atmospheric Oscillation



$$\Delta m^2_{\text{atm}} = 2.5 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{\text{atmos}} \simeq 1$$

$$|\Delta m^2|^{-1} \sim \frac{O(1000Km)}{O(GeV)} \sim \frac{O(1km)}{O(MeV)}$$

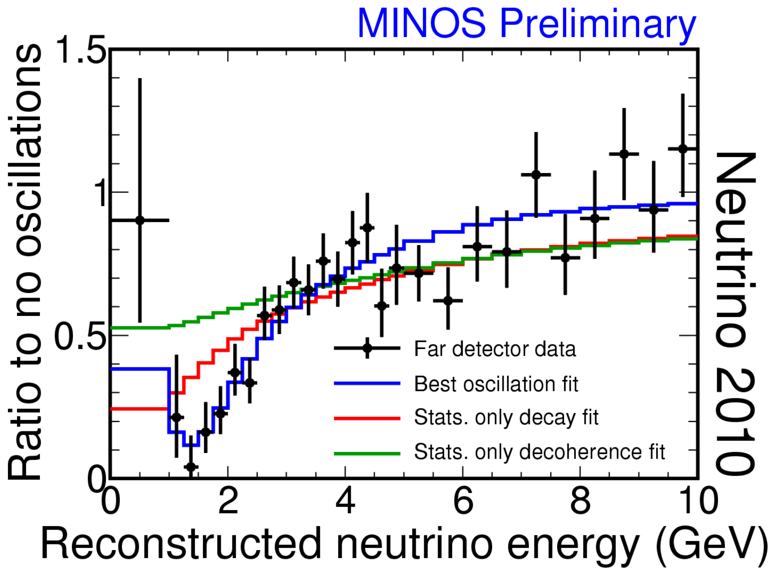
Reines&Cowan experiment at 1km!

Lederman&co experiment at 1000km!

Accelerator Neutrinos oscillate with the atmospheric wavelength

Pulsed neutrino beams to 700 km baselines $\nu_\mu \rightarrow \nu_\mu$

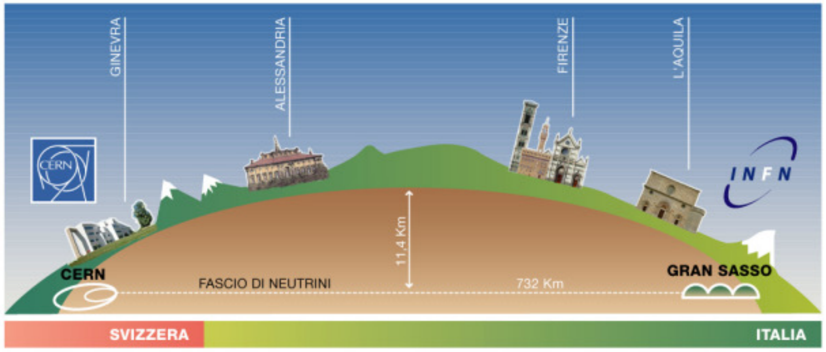
MINOS



$\nu_\mu \rightarrow \nu_\tau$ OPERA

$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3}\ eV^2$$

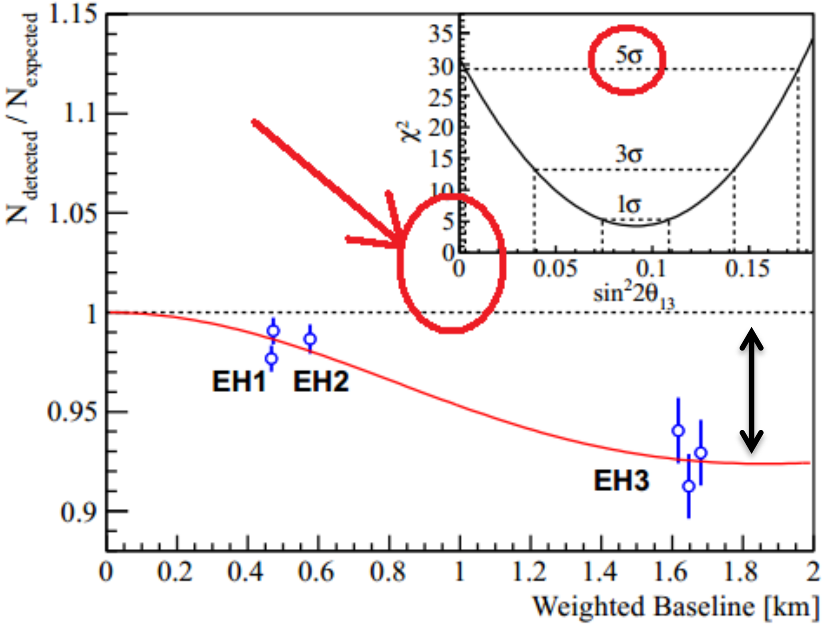
$$\sin^2 2\theta_{\rm atmos} \simeq 1$$



Reactor neutrinos oscillate with atmospheric wavelength

Double Chooz, Daya Bay, RENO

$$\bar{\nu}_e \to \bar{\nu}_e$$



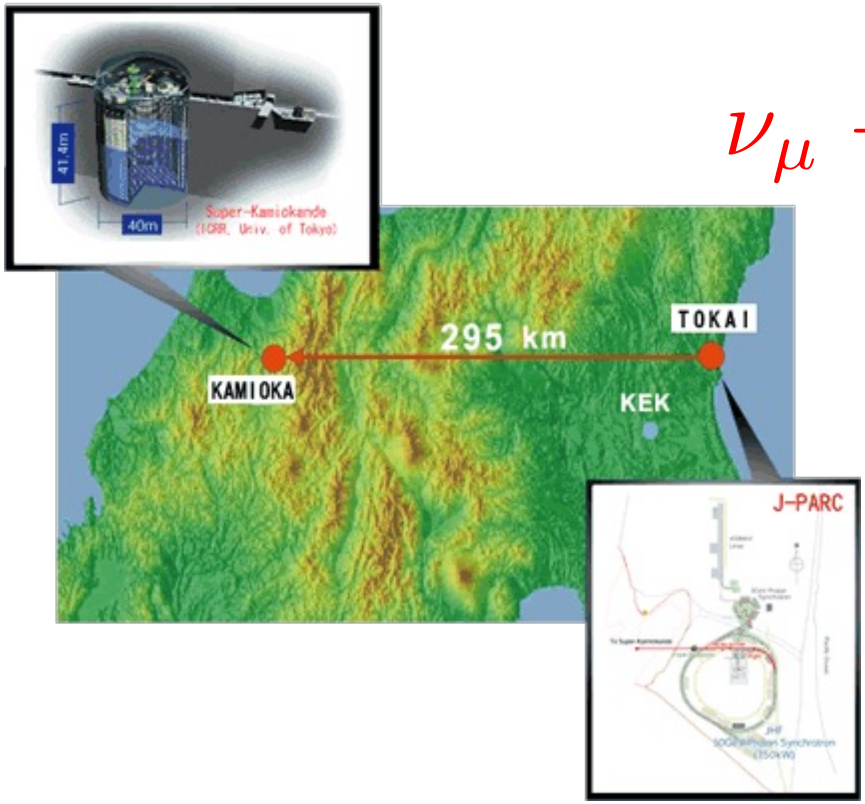
10% effect

$$|\Delta m^2_{\text{atmos}}| \simeq 2.5 \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta_r = 0.1 \Rightarrow \theta_r \sim 9^\circ$$

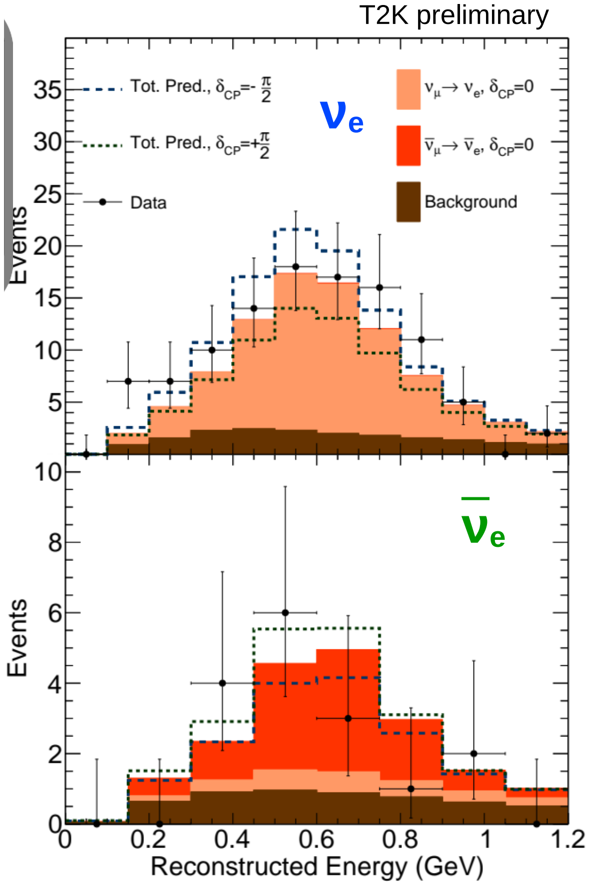
Accelerator Neutrinos :T2K

Using the SuperKamiokande detector!



$$\nu_\mu \to \nu_e \quad \text{vs.} \quad \bar{\nu}_\mu \to \bar{\nu}_e$$

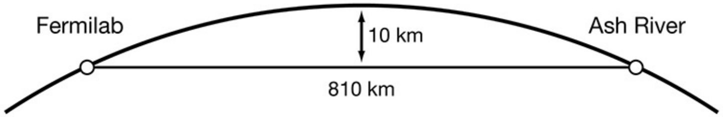
@L=300km

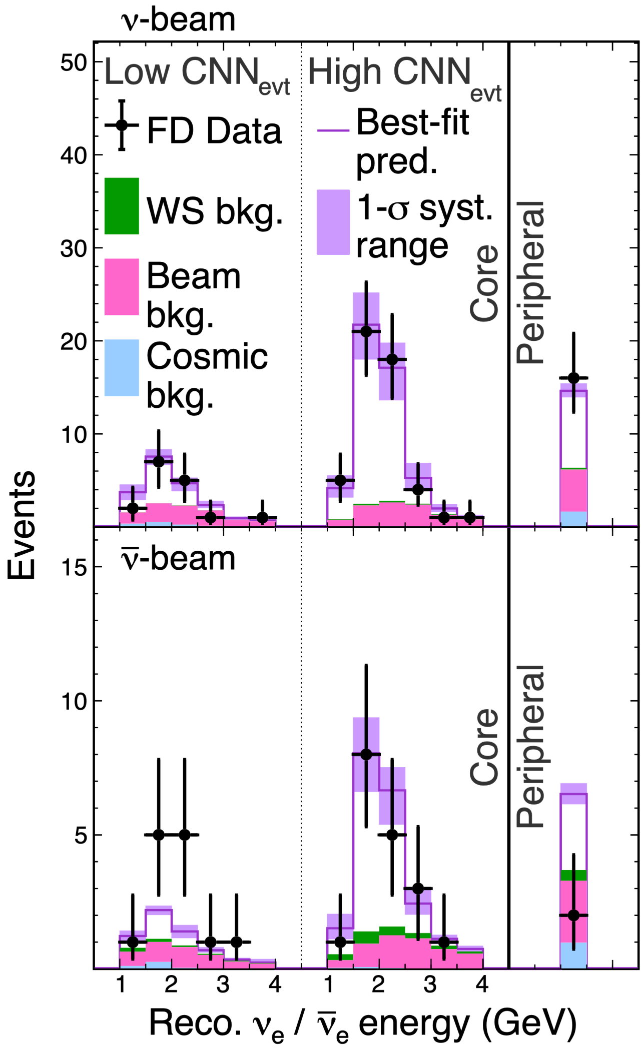


$$|\Delta m^2_{\rm atmos}| \simeq 2.5 \times 10^{-3} \ eV^2$$

Accelerator Neutrinos : NOνA

$\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ @ L=810km





$$|\Delta m^2_{\mathrm{atmos}}| \simeq 2.5 \times 10^{-3}\ eV^2$$

3ν scenario

$$\Delta m^2_{23} = m^2_3 - m^2_2 \equiv \Delta m^2_{atm}$$

$$\Delta m^2_{12} = m^2_2 - m^2_1 \equiv \Delta m^2_{sol}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{23}(\theta_{23}) U_{13}(\theta_{13}, \delta) U_{12}(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar and atmospheric osc. decouple as 2x2 mixing phenomena:

- hierarchy $\frac{|\Delta m^2_{atm}|}{|\Delta m^2_{sol}|} > 10$
- small θ_{13}

Tunning to the large splitting and neglecting the small one:

$$E_\nu/L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

Reactor Neutrinos

$$P(\bar{\nu}_e \to \bar{\nu}_e) \quad = \quad 1 - \sin^2 2\theta_{13}\, \sin^2\left(\frac{\Delta m^2_{23}}{4E}\, L\right)$$

$$\theta_r \leftrightarrow \theta_{13}$$

The <10% effect implies that one of the angles is small

Tunning to the large splitting and neglecting the small one:

$$E_\nu/L \sim \Delta m^2_{23} \gg \Delta m^2_{12}$$

Accelerator Neutrinos

$$\begin{aligned}
P(\nu_e \to \nu_\mu) &= s^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)\\
P(\nu_e \to \nu_\tau) &= c^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)\\
P(\nu_\mu \to \nu_\tau) &= c^4_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta m^2_{23}}{4E}\,L\right)
\end{aligned}$$

Tunning to the large splitting and neglecting the small one:

$$E_\nu / L \sim \Delta m^2_{23} \gg \Delta m^2_{12} \qquad \theta_{13} \rightarrow 0$$

Accelerator Neutrinos

$$\begin{aligned} P(\nu_e \rightarrow \nu_\mu) &= 0 \\ P(\nu_e \rightarrow \nu_\tau) &= 0 \\ P(\nu_\mu \rightarrow \nu_\tau) &= \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{23}}{4E} L \right) \end{aligned}$$

Experiments in the atmospheric range are described approximately by 2x2 mixing with

$$(\Delta m^2_{23}, \theta_{23}) = (\Delta m^2_{atm}, \theta_{atm})$$

Tunning to the small splitting and averaging large oscillations:

$$E_\nu/L \sim \Delta m^2_{12} \ll \Delta m^2_{23}$$

Reactor Neutrinos

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq c^4_{13} \left(1 - \sin^2 2\theta_{12}\, \sin^2 \left(\frac{\Delta m^2_{12}}{4E}\, L\right)\right) + s^4_{13}$$

Tunning to the small splitting and averaging large oscillations:

$$E_\nu/L \sim \Delta m^2_{12} \ll \Delta m^2_{23} \qquad \theta_{13} \to 0$$

Reactor Neutrinos

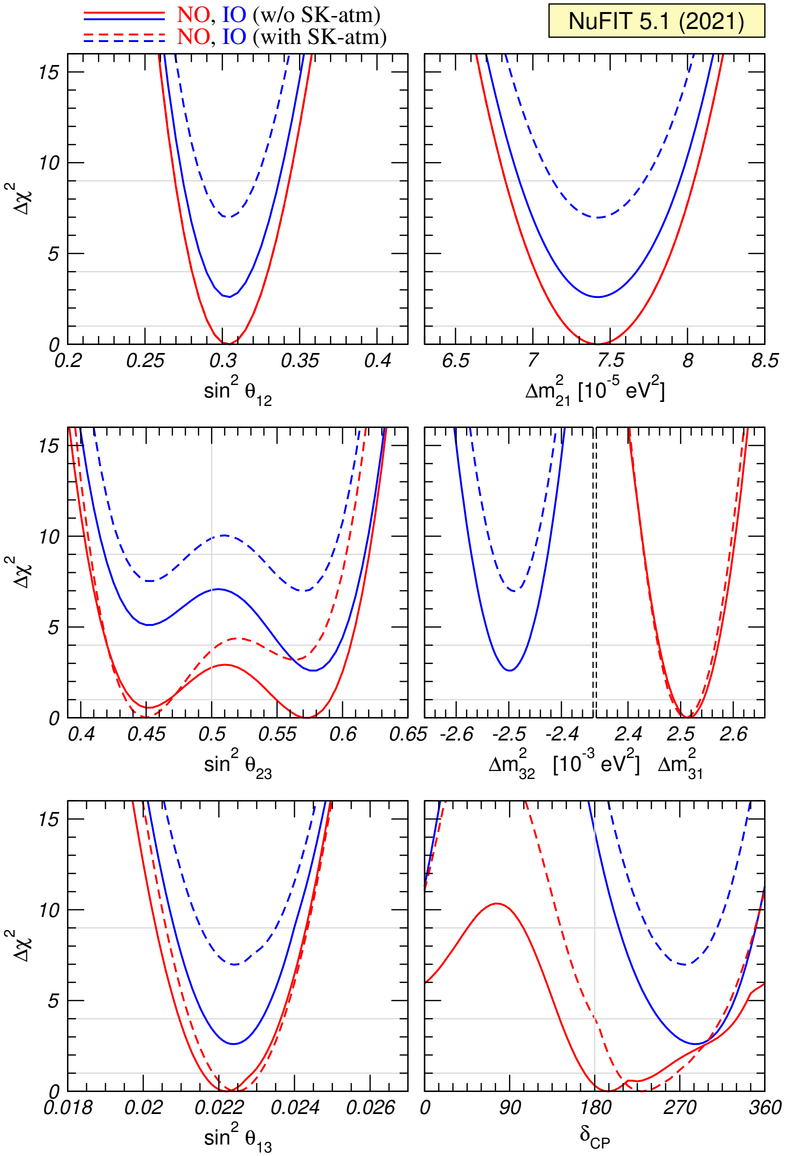
$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq \qquad 1 - \sin^2 2\theta_{12} \, \sin^2\left(\frac{\Delta m^2_{12}}{4E} L\right)$$

Experiments in the solar range are described approximately by 2x2 mixing with

$$(\Delta m^2_{12}, \theta_{12}) = (\Delta m^2_{\rm sol}, \theta_{\rm sol})$$

The measurement of $\theta_{13} \sim 9^\circ$ implies that corrections to these approximations are sizeable O(10%) and need to be included in all analyses

SM+3 massive neutrinos: Global Fits

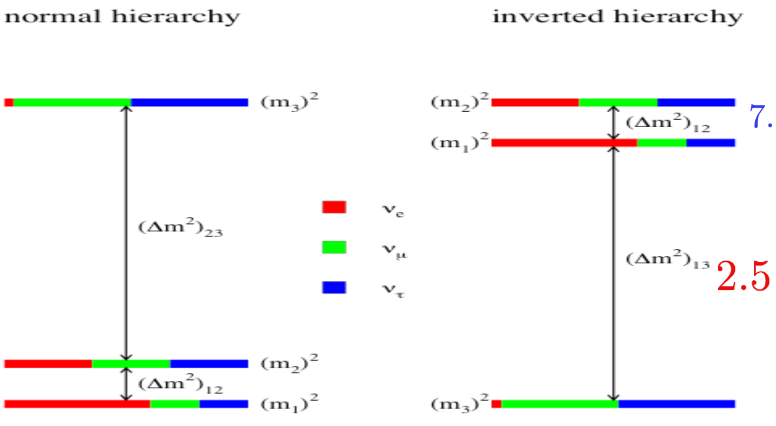


$\theta_{12} \sim 34^\circ$

$\theta_{23} \sim 42^\circ$ o 48°

$\theta_{13} \sim 8.5^\circ$

$\delta \sim\ ?$



$7.5 \cdot 10^{-5}\mathrm{eV}^2$

$2.5 \cdot 10^{-3}\mathrm{eV}^2$

$\Delta m^2_{13} > 0$

$\Delta m^2_{13} < 0$

Esteban et al '20; see also Salas et al, '20 and Capozzi et al '21

The big open questions

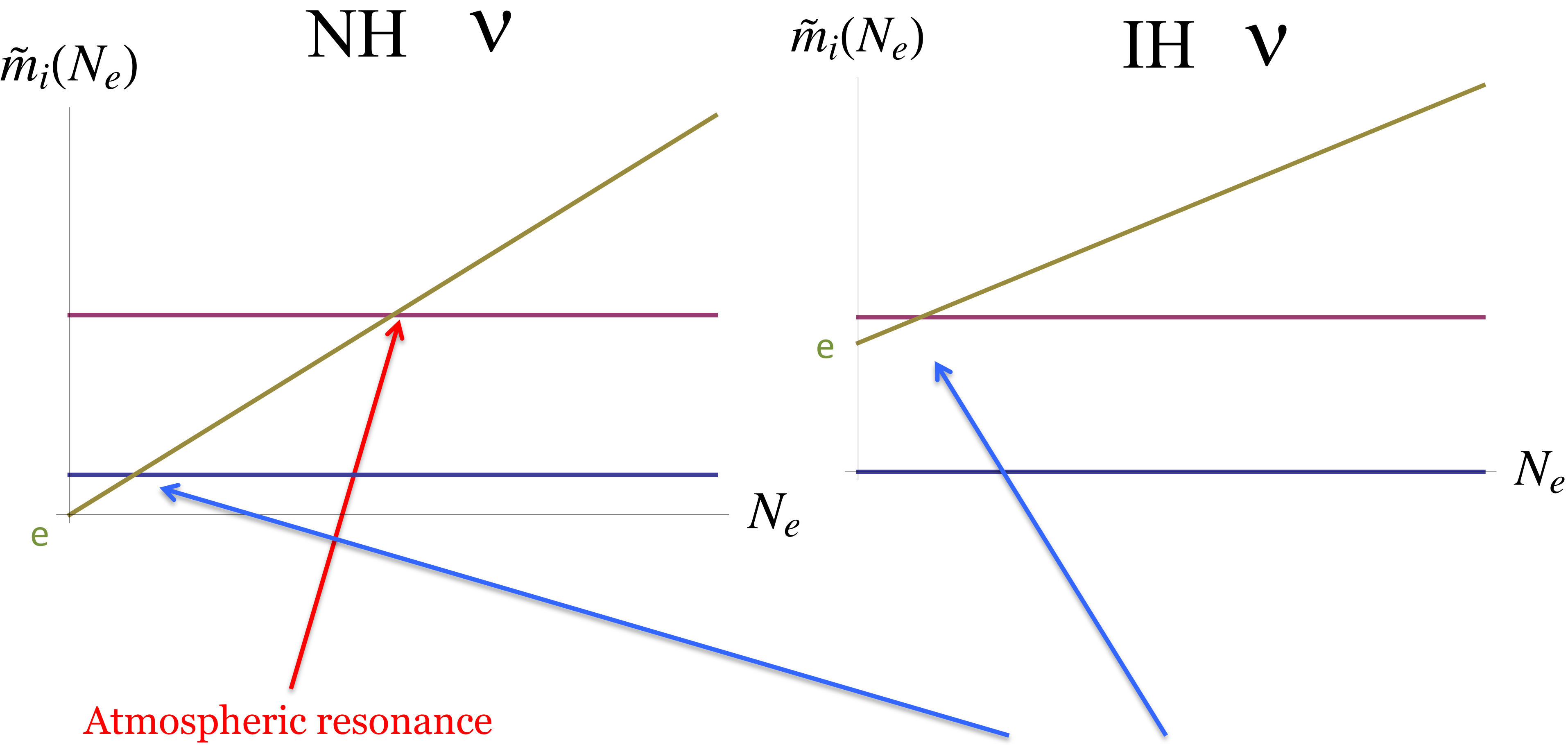
What is the neutrino ordering normal or inverted ?

Is there leptonic CP violation ?

Absolute mass scale: minimum m_ν

Are neutrinos Majorana and if so, what new physics lies behind this fact ?

Neutrino ordering from MSW



Atmospheric resonance

Solar resonance

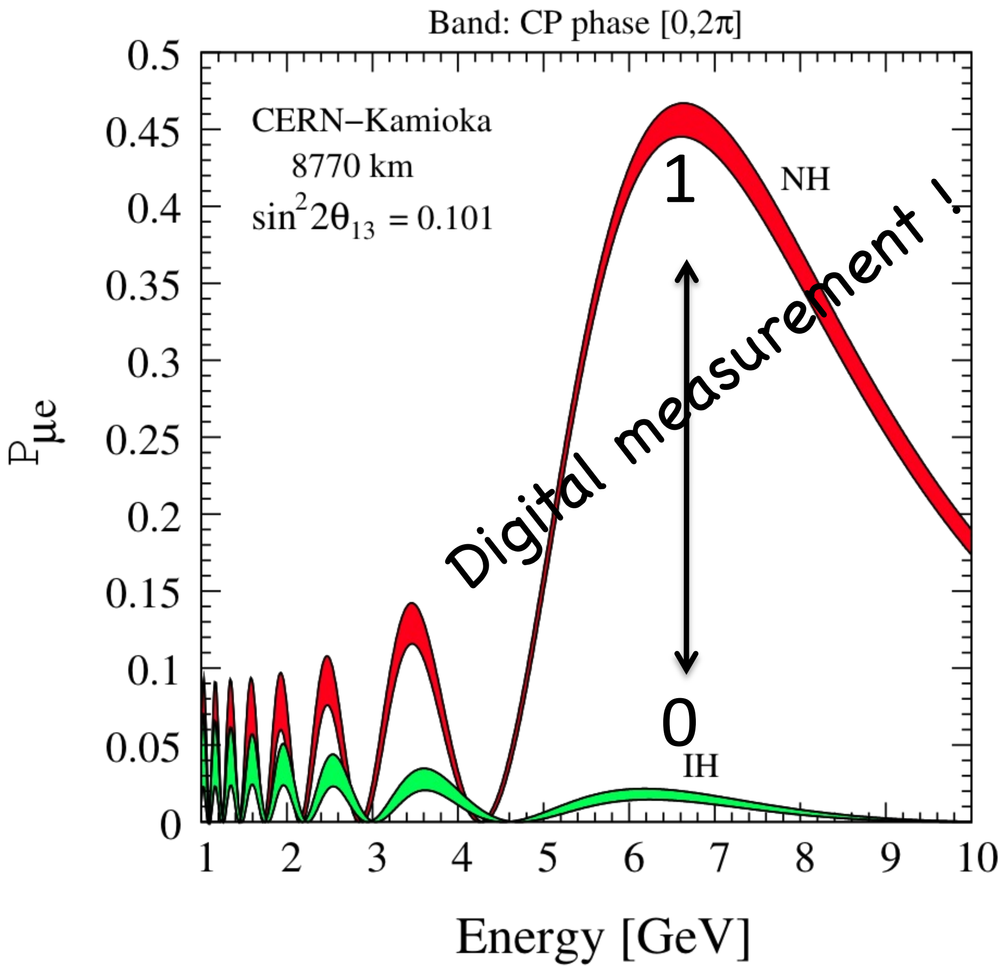
$$\Delta m^2_{23} \cos 2\theta_{13} = \pm 2\sqrt{2} G_F E N_e$$

Earth density, E_{res} ~ few GeV !

$$\Delta m^2_{12} \cos 2\theta_{12} = 2\sqrt{2} G_F E N_e$$

Solar density, E_{res} ~ few MeV !

Hierarchy through MSW @Earth



$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F n_e},$$

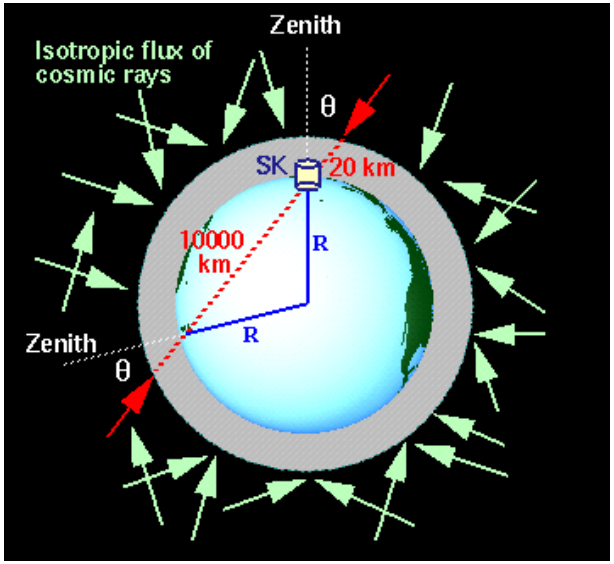
$$n_e(L)L|_{L_{\max}} = \frac{\pi}{\sqrt{2}G_F \tan 2\theta_{13}}$$

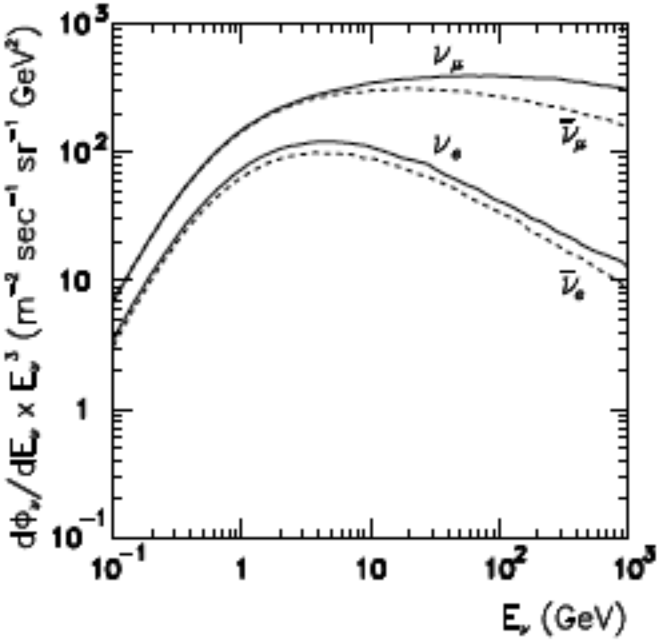
Spectacular MSW effect at O(6GeV) and very long baselines: no need for spectral info nor two channels

Even if we don't shoot so far away, relatively easy measurements for L >1000km

Hierarchy from atmospherics ? the hard way…

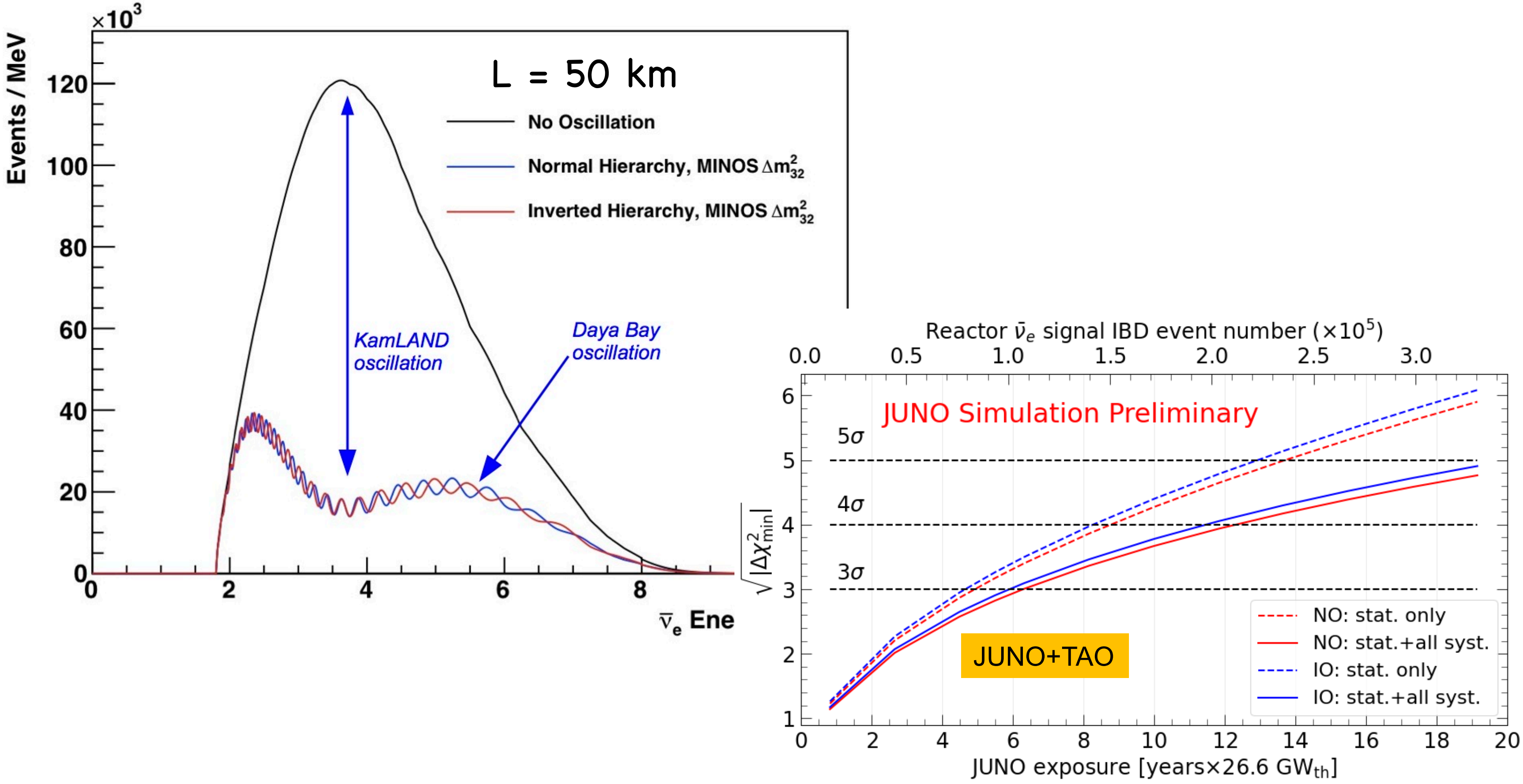
$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$





Atmospheric data contain the golden signal but hard to dig…
neutrino telescopes (ORCA, PINGU) or improved atmospheric detectors (HyperK, INO)

Hierarchy from reactor ν's



JUNO experiment is planning to do this measurement

Leptonic CP violation

CP violation shows up in a difference between

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \qquad \alpha \neq \beta$$

Golden channel: $\nu_\mu \leftrightarrow \nu_e$

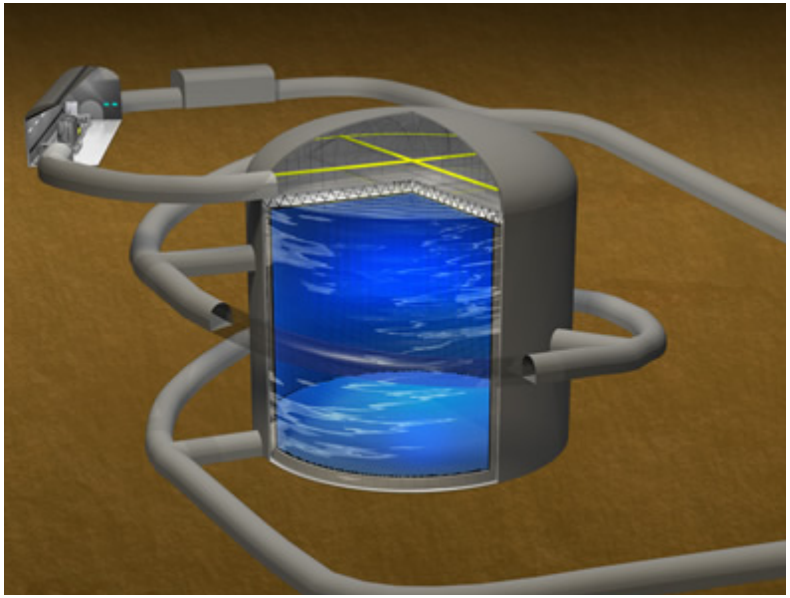
$$\begin{aligned} P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23} L}{2}\right) && \equiv P^{atmos} \\ &+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) && \equiv P^{solar} \\ +\tilde{J} \quad & \cos\left(\pm\delta - \frac{\Delta_{23} L}{2}\right) \frac{\Delta_{12} L}{2} \sin\left(\frac{\Delta_{23} L}{2}\right) && \equiv P^{inter} \end{aligned}$$

$$\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

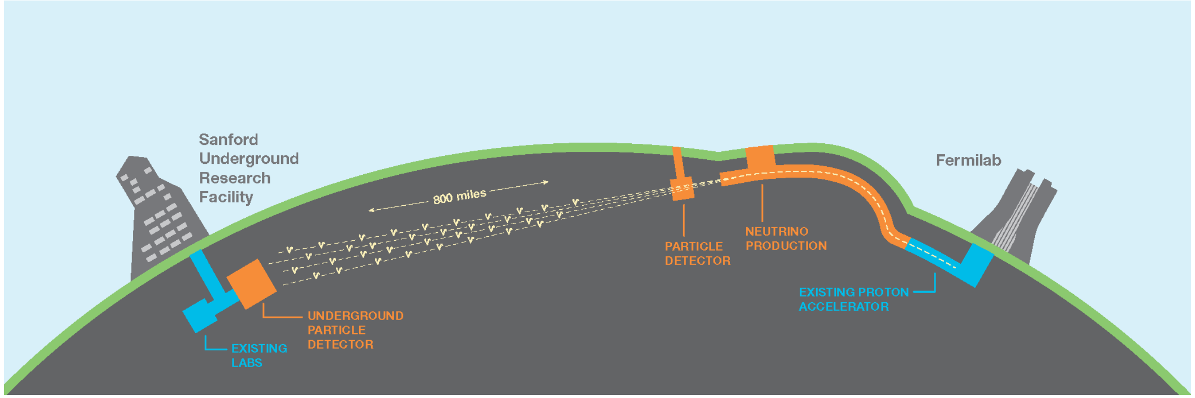
simultaneous sensitivity to both splittings is needed

Hierarchy + CP in one go…
superbeams+superdectectors

Japan Hyper-Kamiokande: 295km

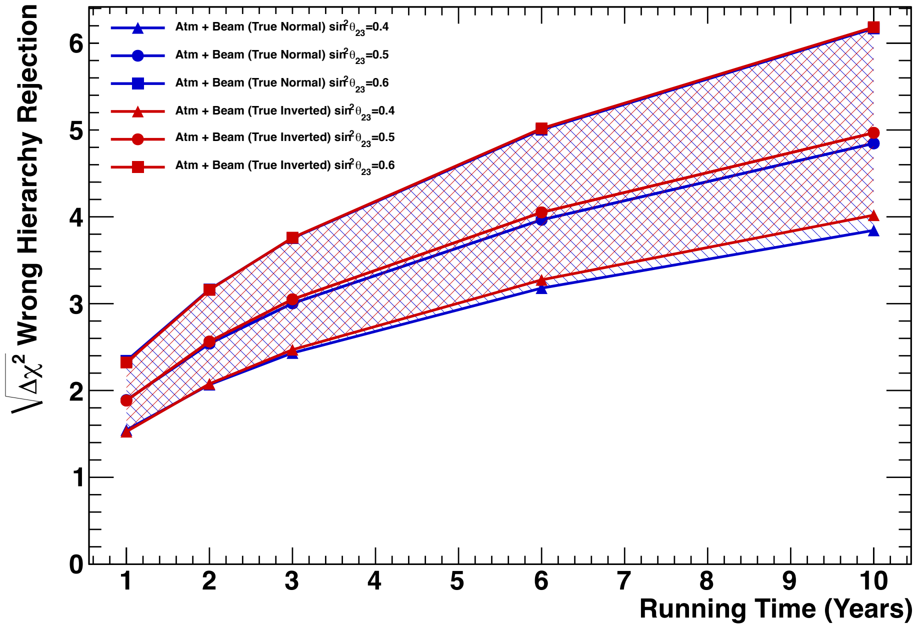


USA DUNE: 1300km



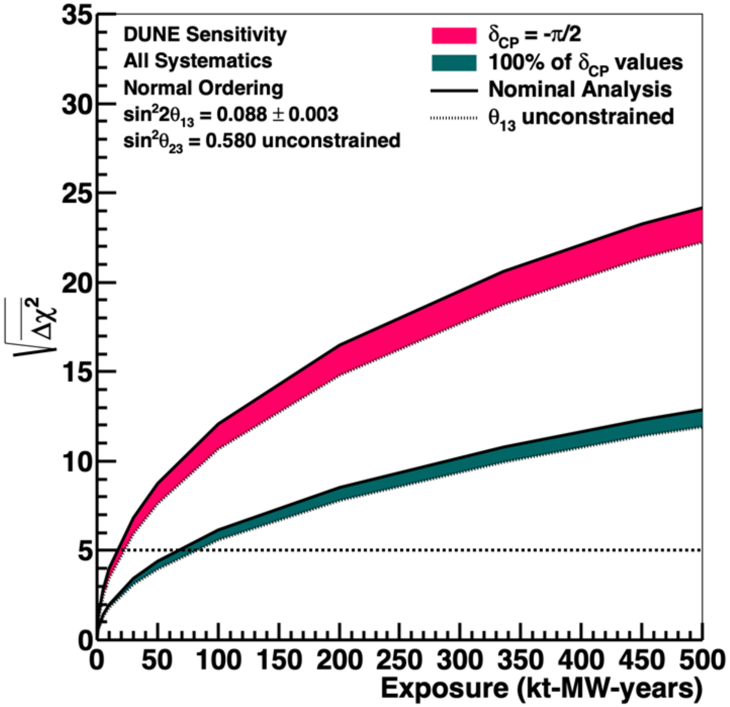
Hierarchy

Hyper Kamiokande



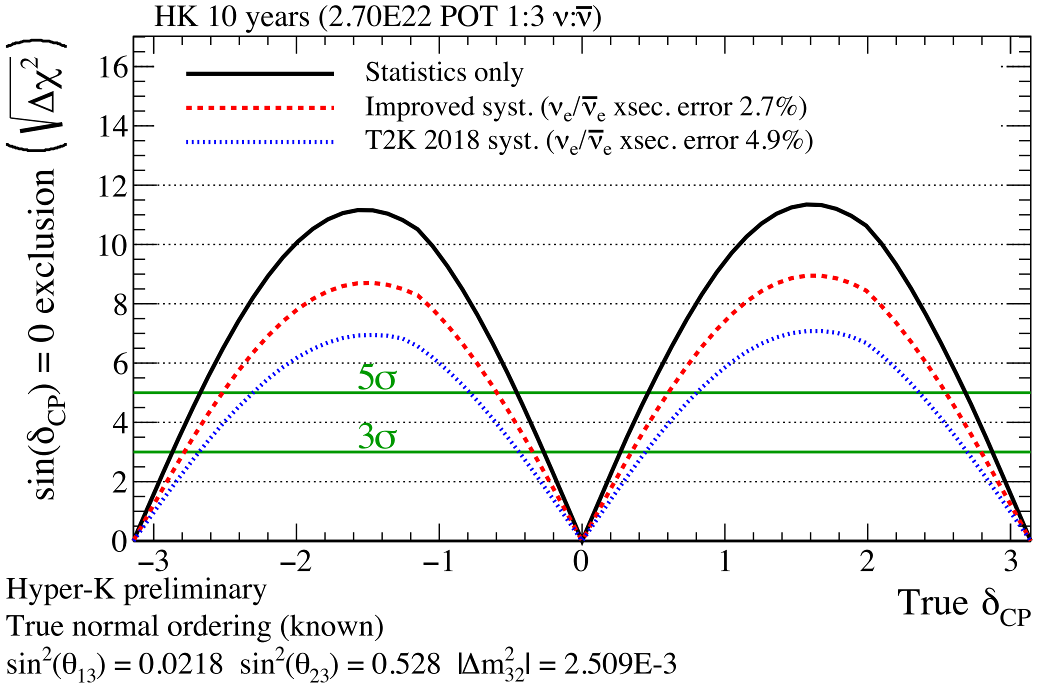
(Using atmospheric neutrinos)

DUNE

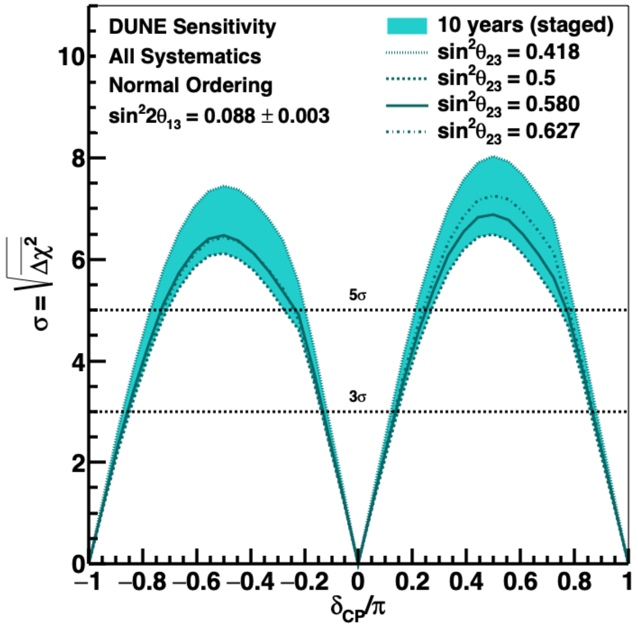


CP violation

Hyper Kamiokande (10y)



DUNE(10y)



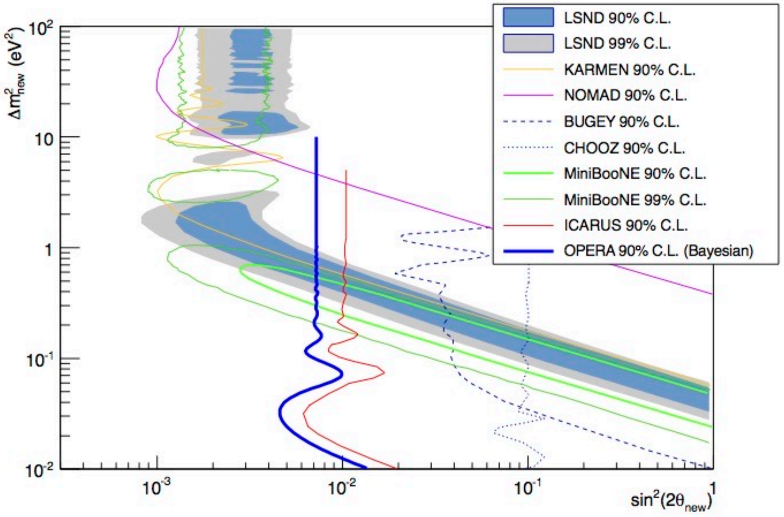
Neutrino Anomalies

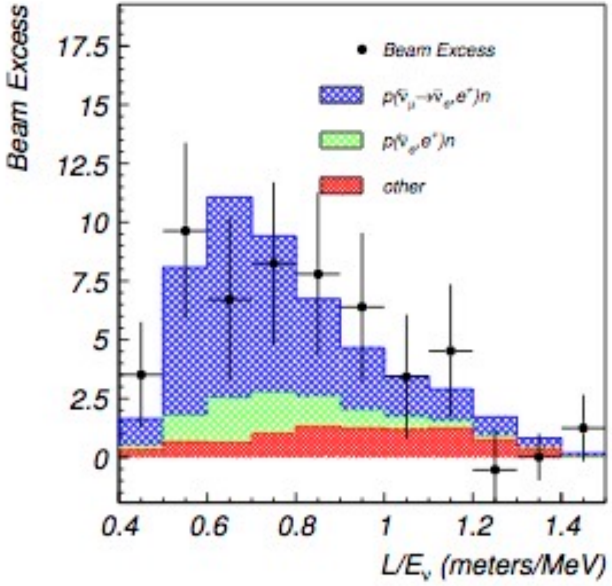
Outliers: LSND anomaly

$$\begin{aligned} \pi^+ \to \quad & \mu^+ \quad \nu_\mu \\ & \nu_\mu \quad \to \nu_e \ \text{DIF}\ (28 \pm 6/10 \pm 2) \end{aligned}$$

$$\begin{aligned} \mu^+ \to \quad & e^+ \quad \nu_e\ \bar{\nu}_\mu \\ & \bar{\nu}_\mu \quad \to \bar{\nu}_e \ \text{DAR}\ (64 \pm 18/12 \pm 3) \end{aligned}$$

$$P(\nu_\mu \to \nu_e)$$

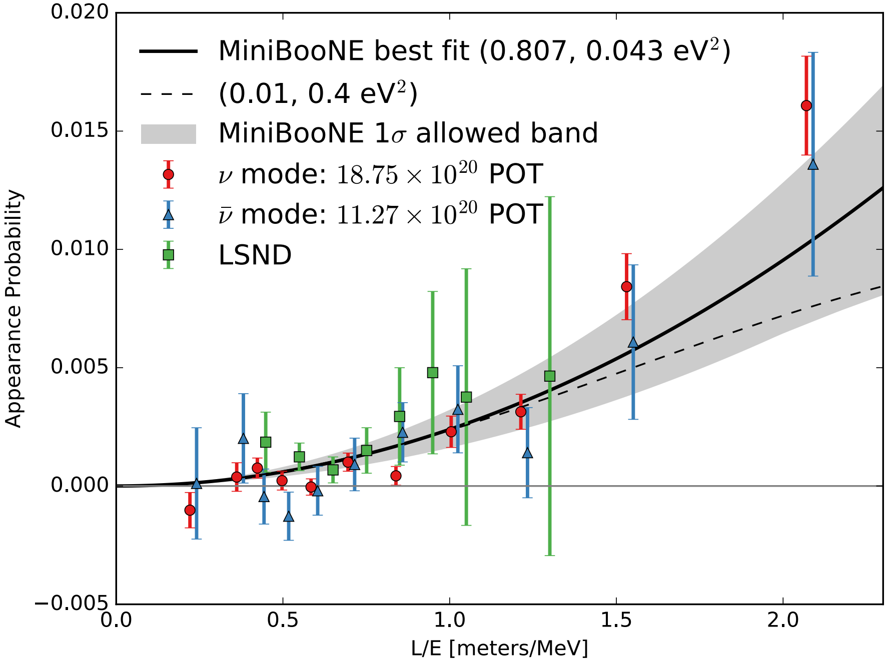


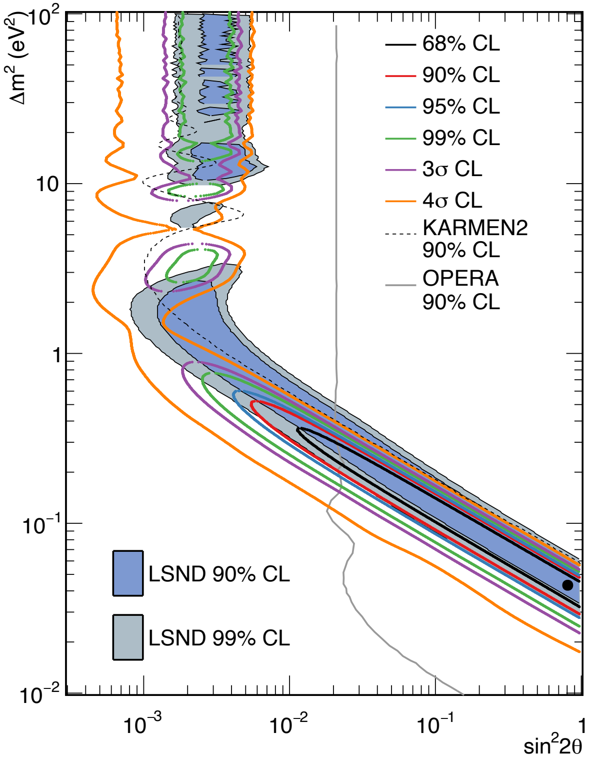


$$|\Delta m^2| \gg |\Delta m^2_{atm}|$$

Outliers: LSND anomaly

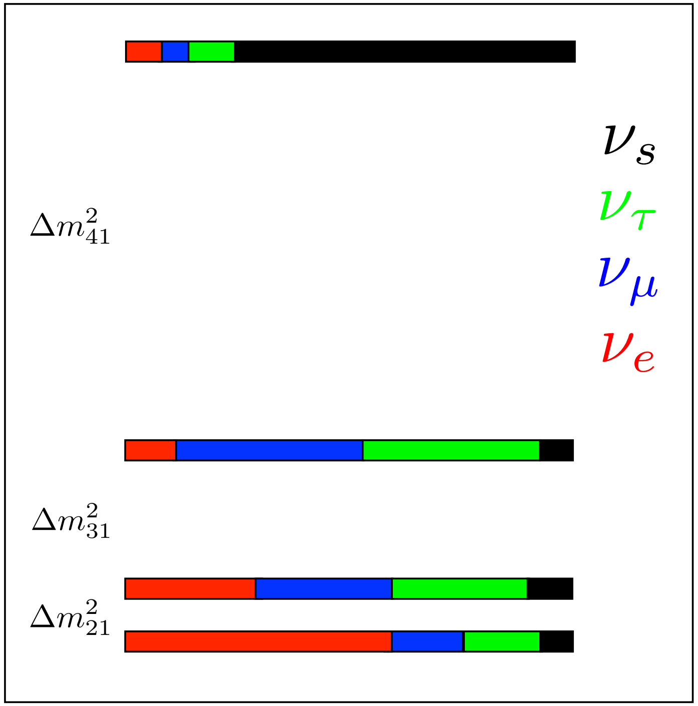
+ MiniBOONE





4.8σ discrepancy with SM !

SBL anomalies: 4th neutrino ?



$P(\nu_\mu \rightarrow \nu_e) = O(|U_{e4}|^2\ |U_{\mu4}|^2)$

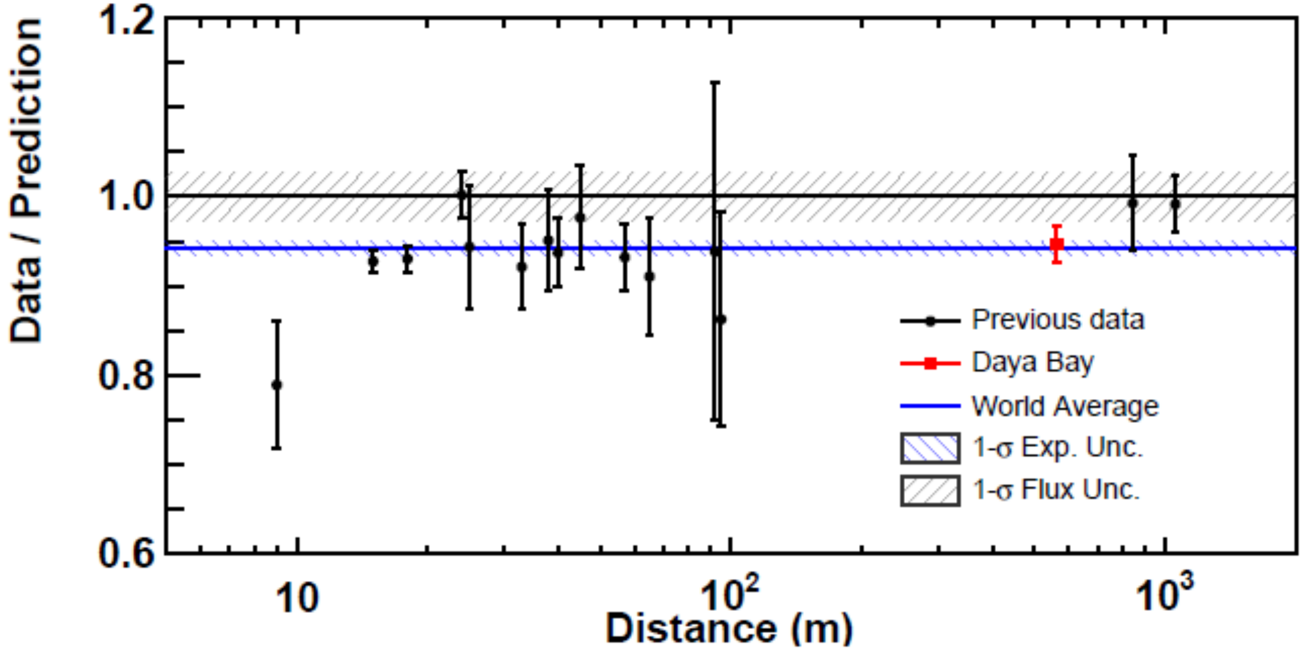
$P(\nu_e \rightarrow \nu_e) = O(|U_{e4}|^2)$

$P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu4}|^2)$

Oscillations at @meters for MeV neutrinos: short baseline reactor experiment

Outliers: SBL reactor anomalies

Reactor $P(\bar{\nu}_e \to \bar{\nu}_e)$

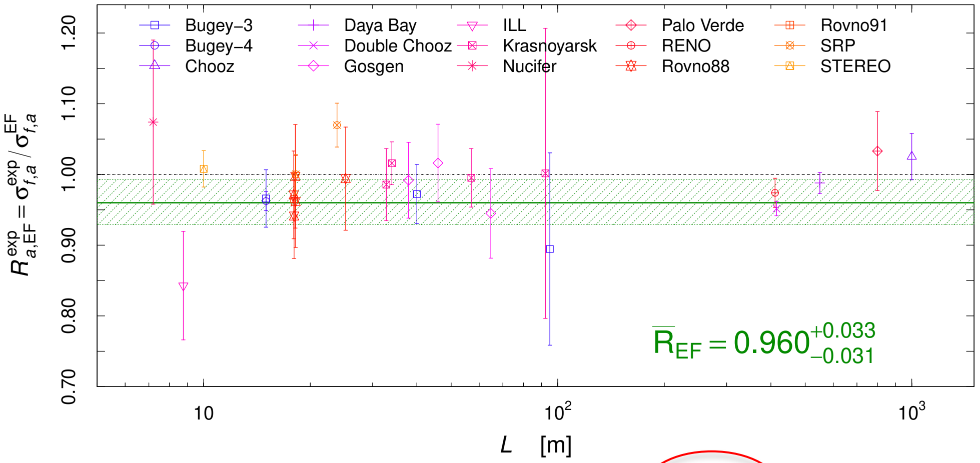


Mueller et al ‘11
Huber ‘11

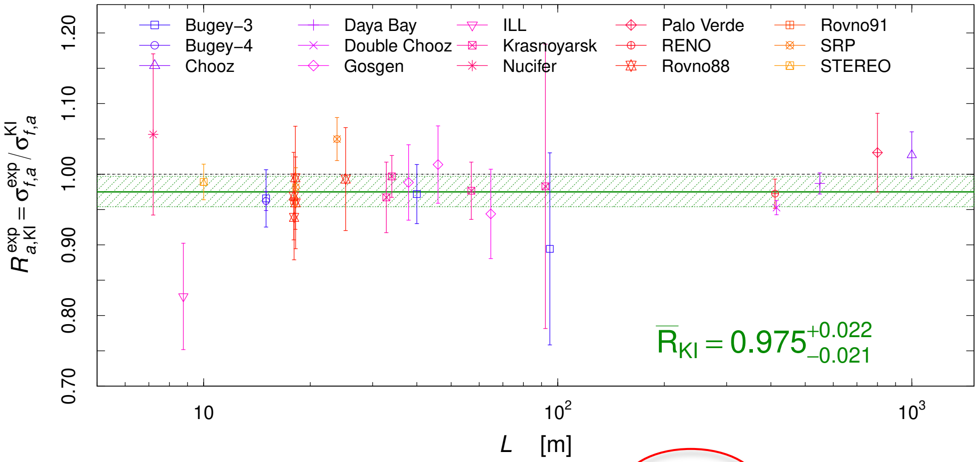
Re-evaluation of the predicted fluxes in ‘11 indicates an L-independent deficit (~2.5σ)

Outliers: SBL reactor anomalies

New re-evaluation… Estienne, Fallot et al, ‘19; Hayen et al ’19; Kopeikin et al ‘21



(a) EF model [18]: no RAA (1.2 σ).



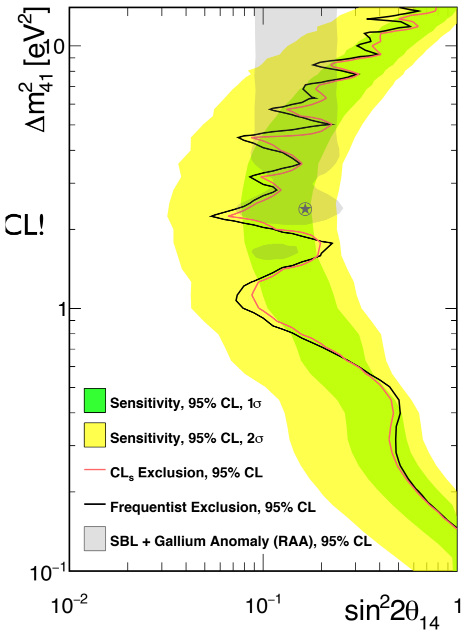
(c) KI model [24]: no RAA (1.1 σ).

Giunti et al, ‘21

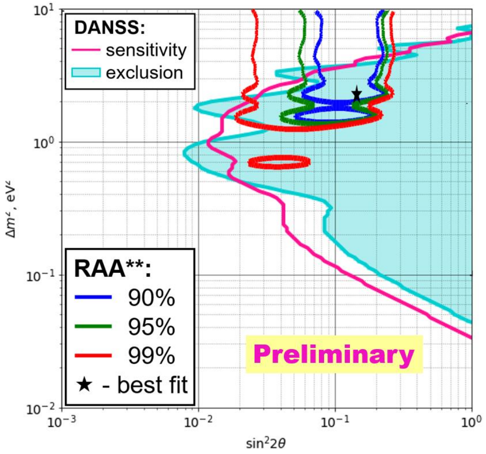
SBL reactor anomaly Vews

New SBL reactor strategies: L-dep of signal

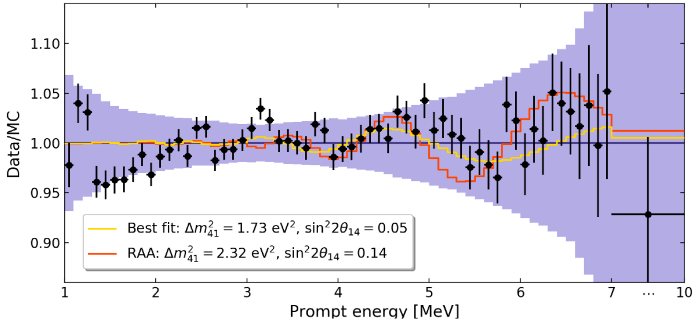
Prospect



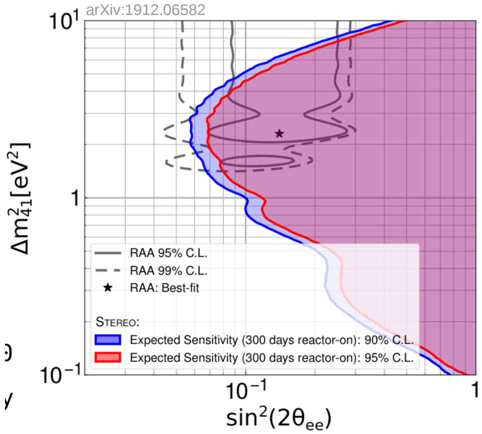
DANSS



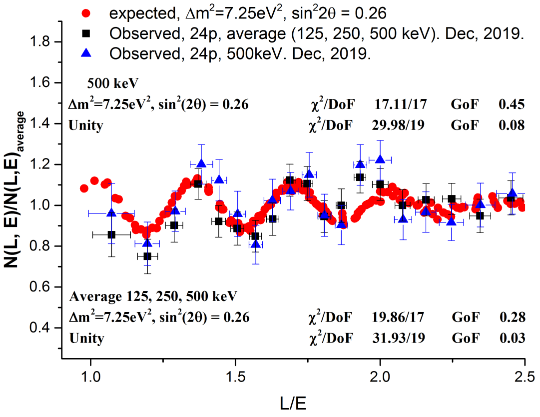
NEOS



Stereo

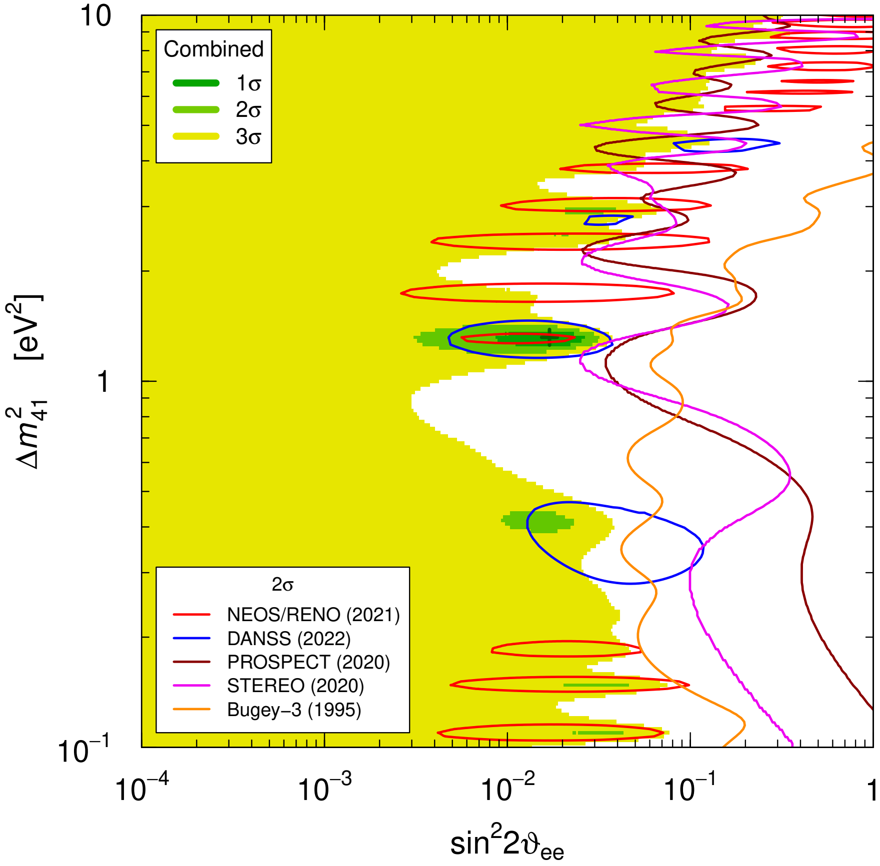


NEUTRINO-4



SBL reactor anomaly νews

New SBL reactor strategies: L-dep of signal

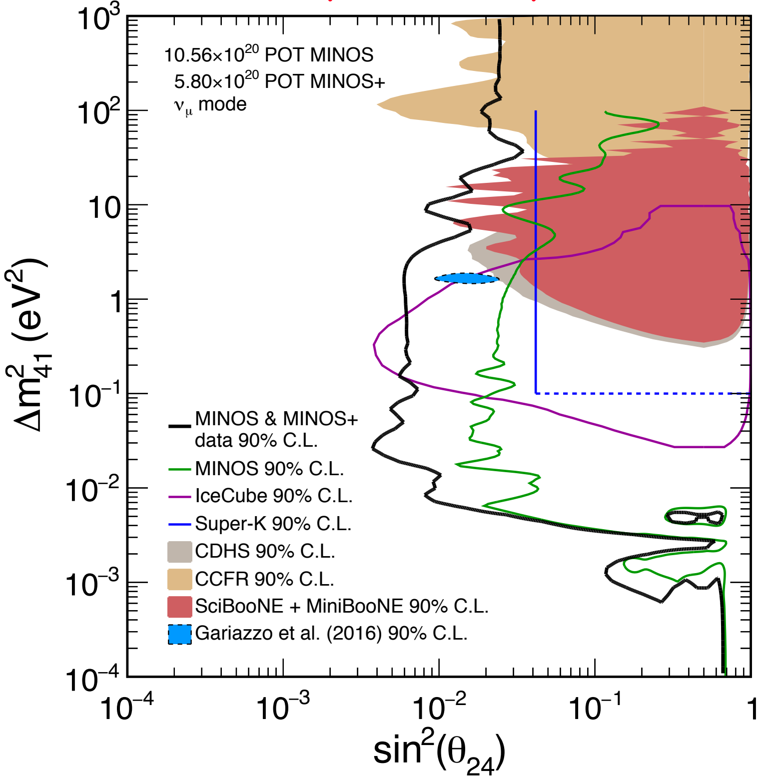


2.6σ effect

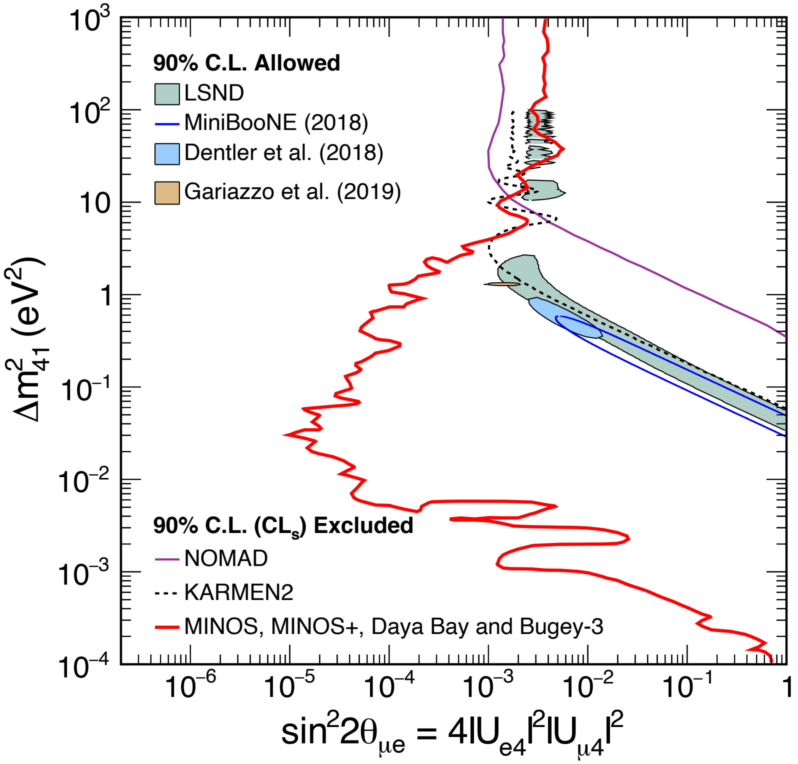
O(eV) sterile neutrinos ?

Neutrino muons must disappear also but they don't Minos, Minos+

$P(\nu_\mu \to \nu_\mu)$

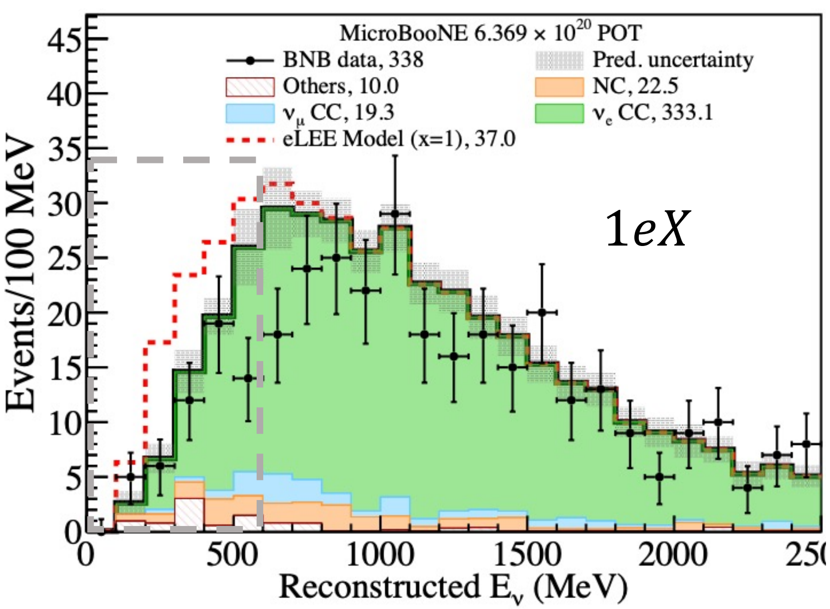


$P(\nu_\mu \to \nu_\mu)$ & $P(\bar{\nu}_e \to \bar{\nu}_e)$

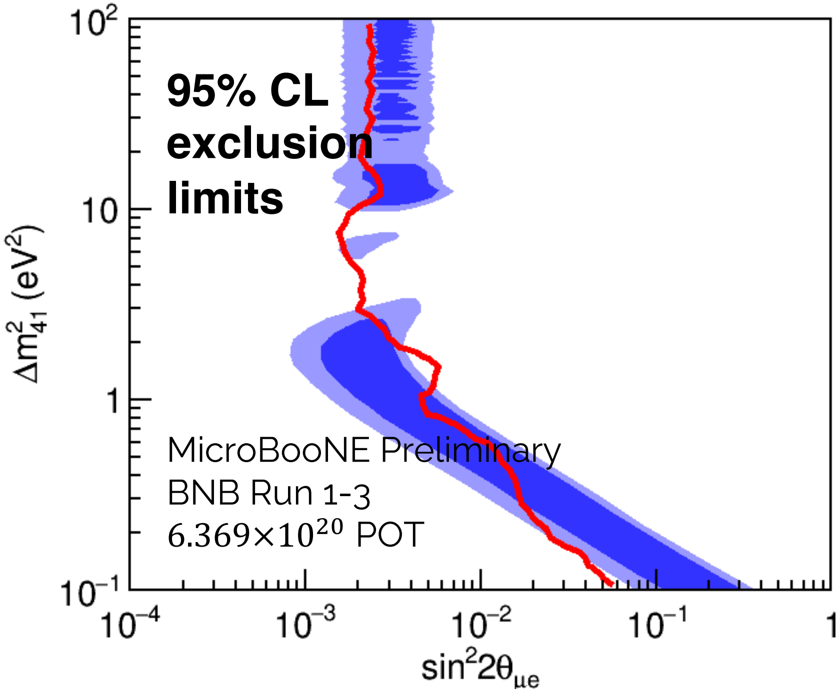


O(eV) 4th neutrino is not a good fit (all things considered…)

MicroBooNE



$1eX$



95% CL exclusion limits

MicroBooNE Preliminary
BNB Run 1-3
6.369×10^{20} POT

Does not confirm the MiniBooNE excess

All in all: significant hints of deviations with the SM remain, but non-understood systematics is possible and sterile hypothesis not a good fit to the data

Exercise: what about MSW resonances in the 4ν model ?
Can the steriles oscillation be resonantly enhanced ? Estimate the resonance energy for Earth density and think where to look for this effect.

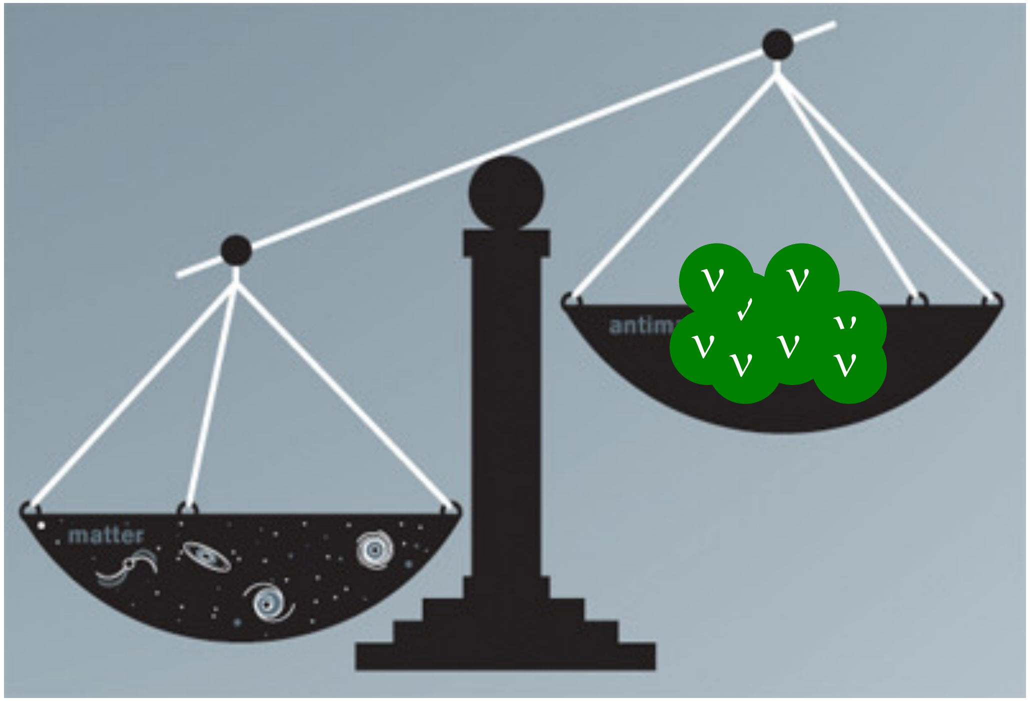
The other big open questions

Absolute mass scale: minimum m_ν

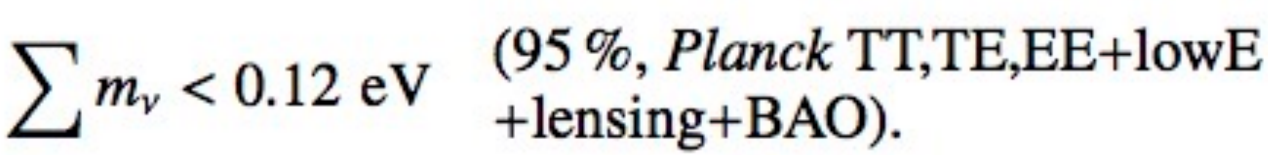
Are neutrinos Majorana and if so, what new physics lies behind this fact ?

Absolute ν mass scale

Best constraints at present from cosmology



Planck ‘18

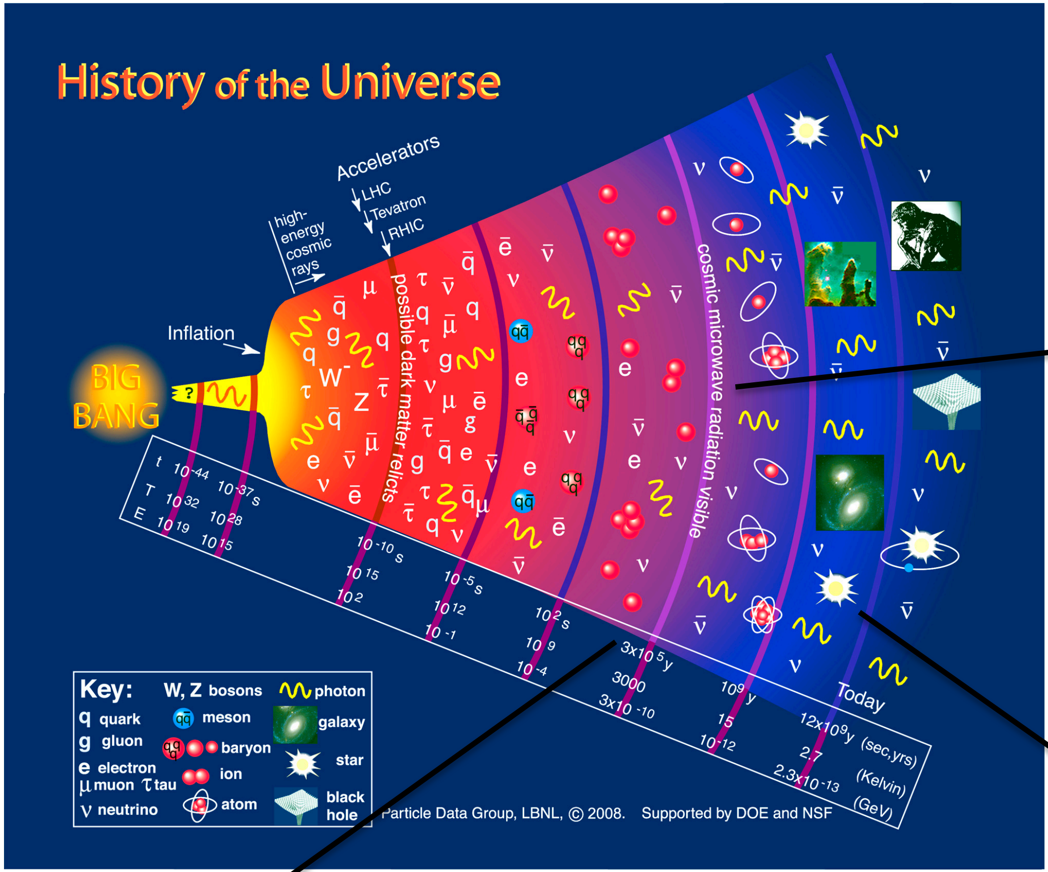


$\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

Cosmological neutrinos

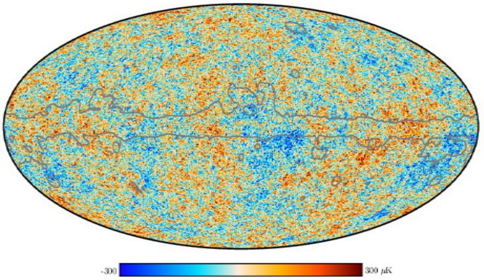
-> G. Servant's lectures

Neutrinos have left many traces in the history of the Universe

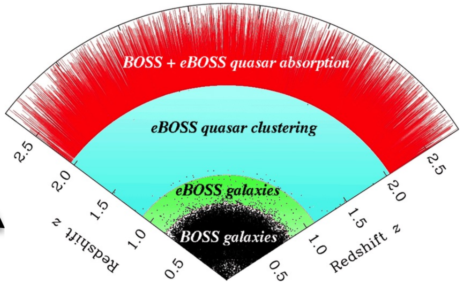


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

$$\sum m_\nu$$



CMB

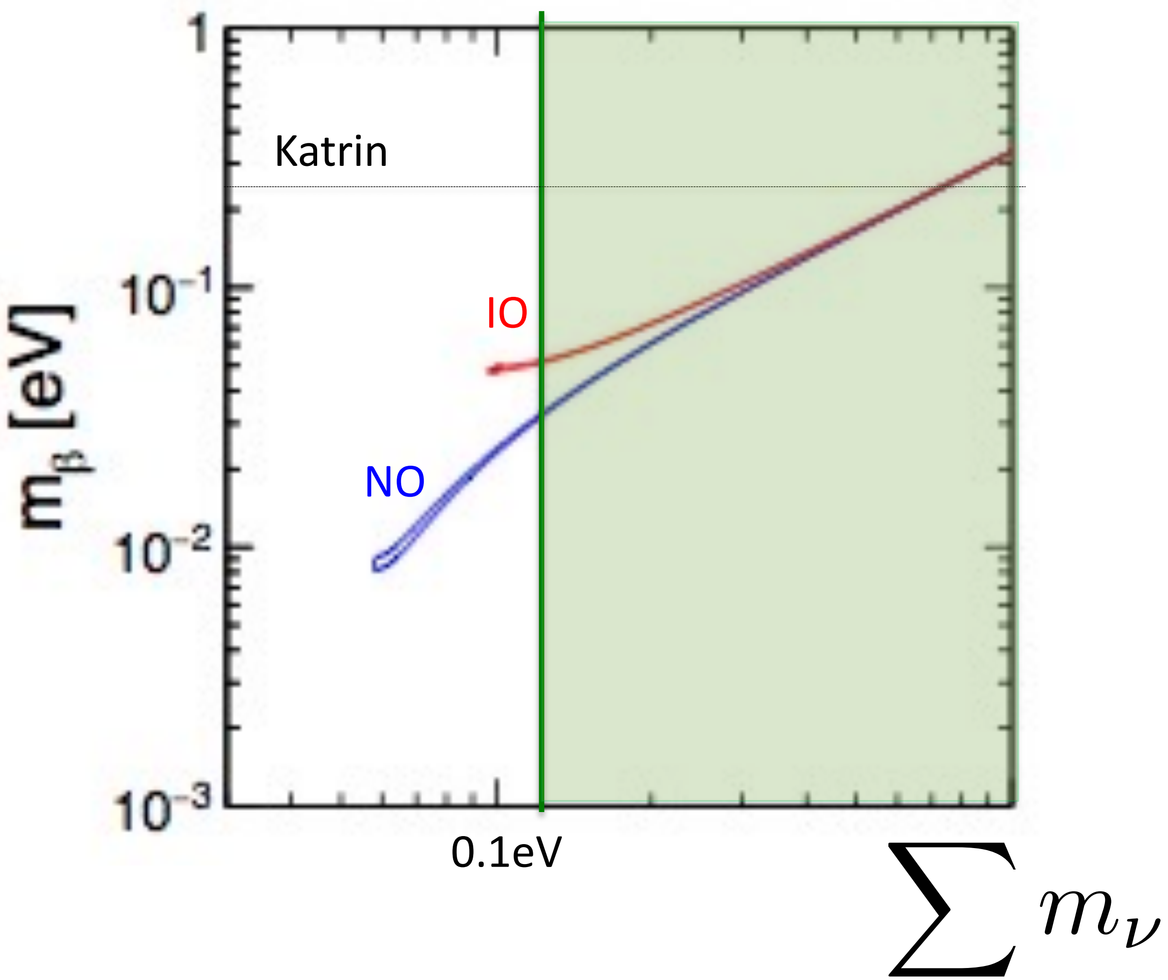


Galaxy distribution (LSS)

Nucleosynthesis N_ν

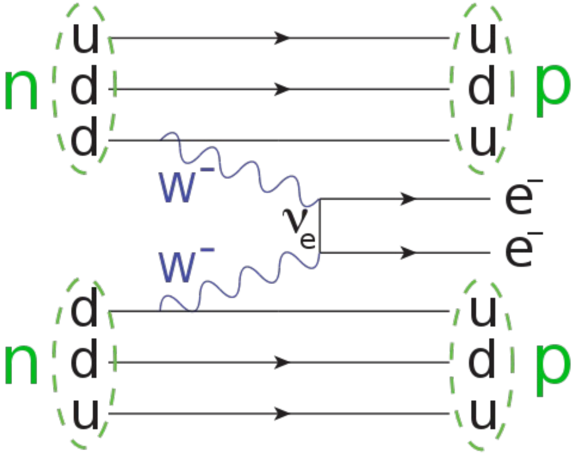
Absolute ν mass scale

Neutrinos as light as 0.1-1eV modify the large scale structure and CMB



Majorana nature: ββ0ν

Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT…

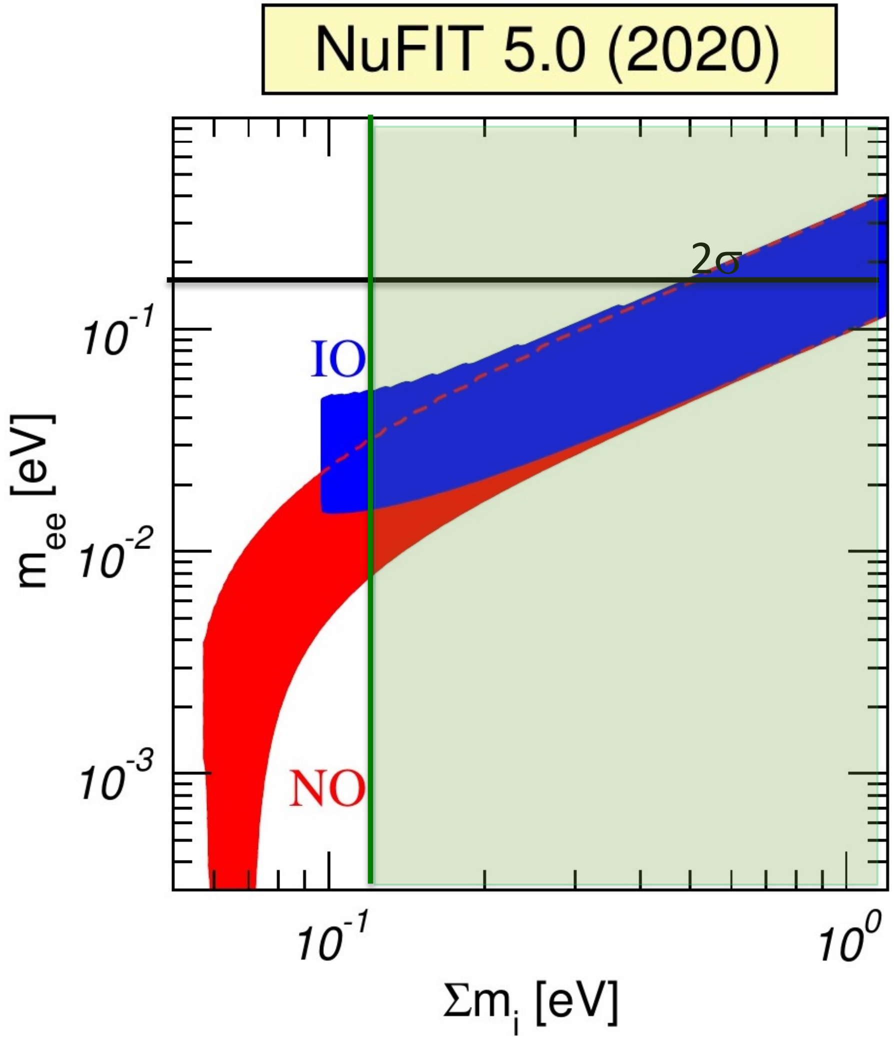


$$T^{-1}_{2\beta 0\nu} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear M.E.}} \underbrace{\left|\sum_i \left(V^{ei}_{MNS}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

$$|m_{ee}| = |c^2_{13}(m_1 c^2_{12} + m_2 e^{i\alpha} s^2_{12}) + m_3 e^{i\beta} s^2_{13}|$$

Majorana nature: $\beta\beta 0\nu$

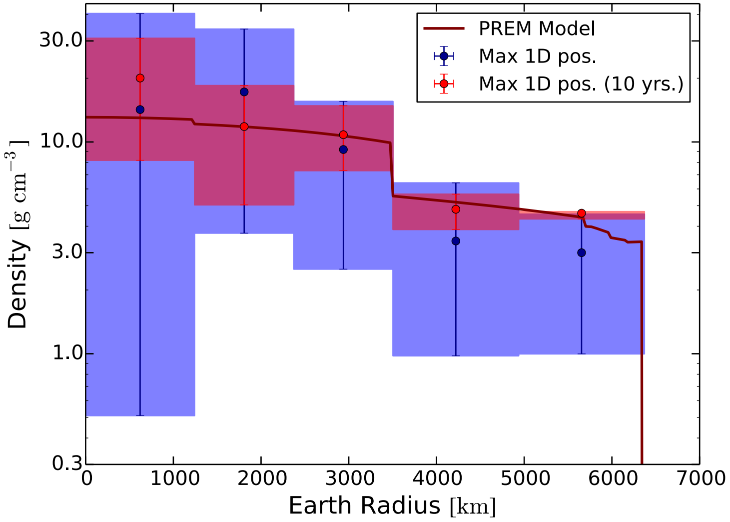
Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT …



Next generation of experiments @Ton scale to cover the IO region (eg. LEGEND)

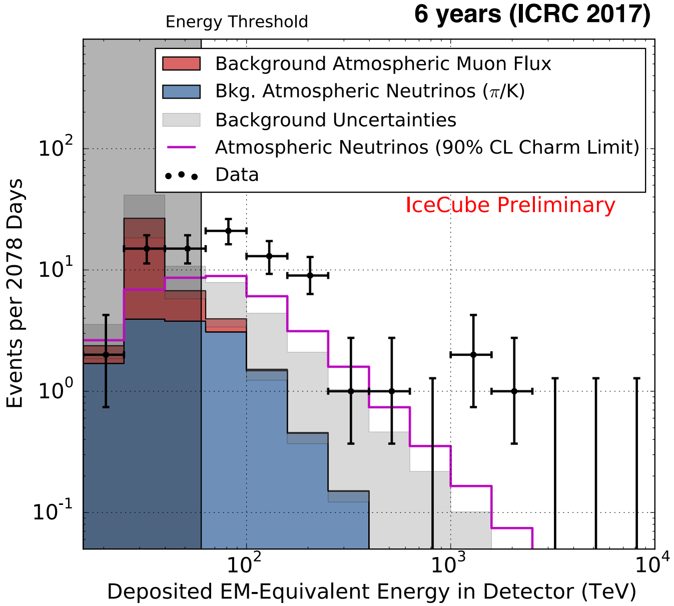
New era of ν physics:
neutrino astronomy, geology,…

Understand the Earth



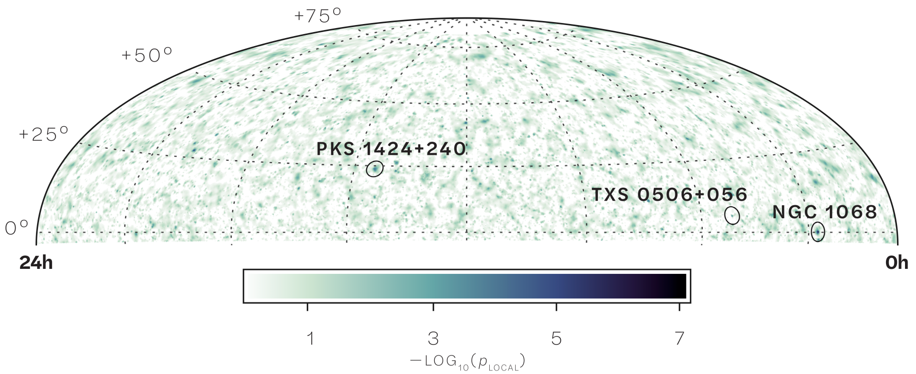
Donini, Palomares-Ruiz, Salvado '18

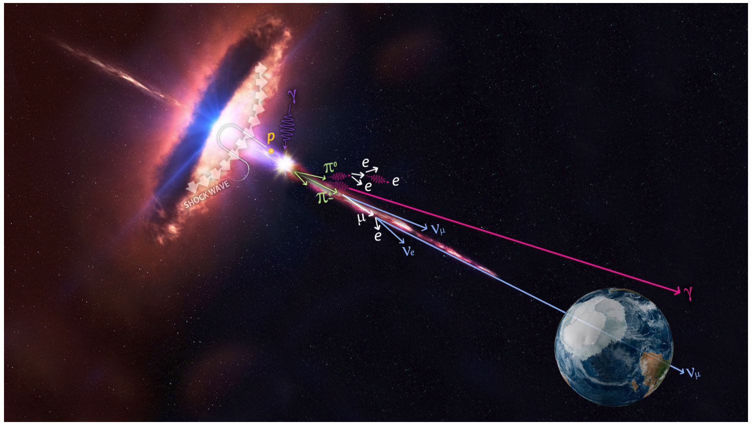
Understand Astrophysical sources

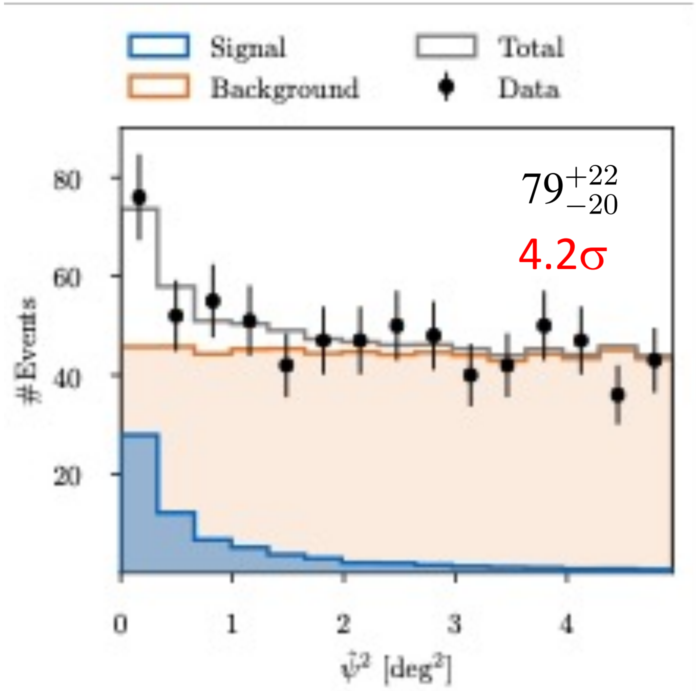


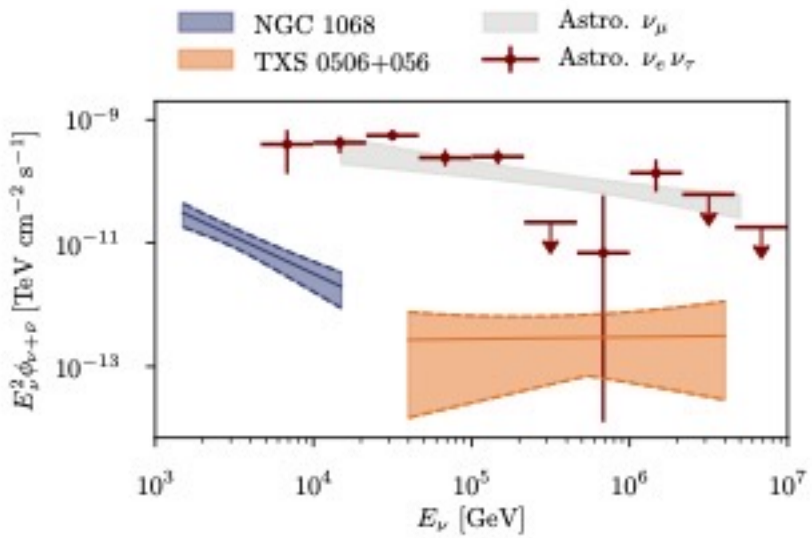
Icecube

Icecube started mapping the most powerful cosmic accelerators



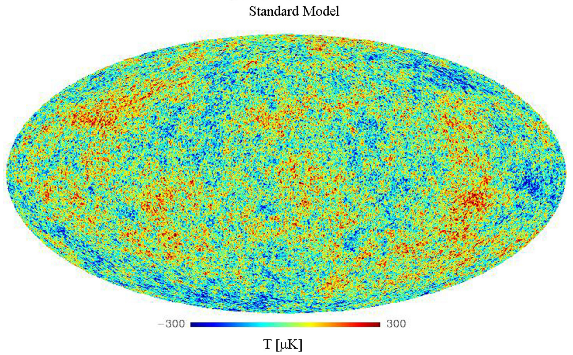






Icecube col. 2211.09972

New era of ν physics:CνB?



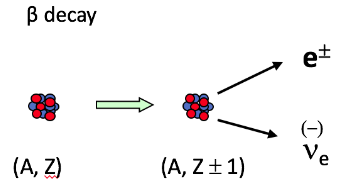
Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

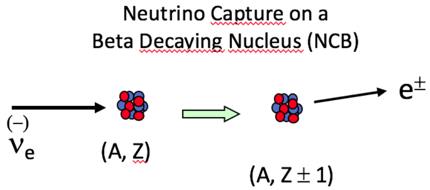
$$n_\nu = 336\nu/cm^3(1/6\ \nu_e)$$

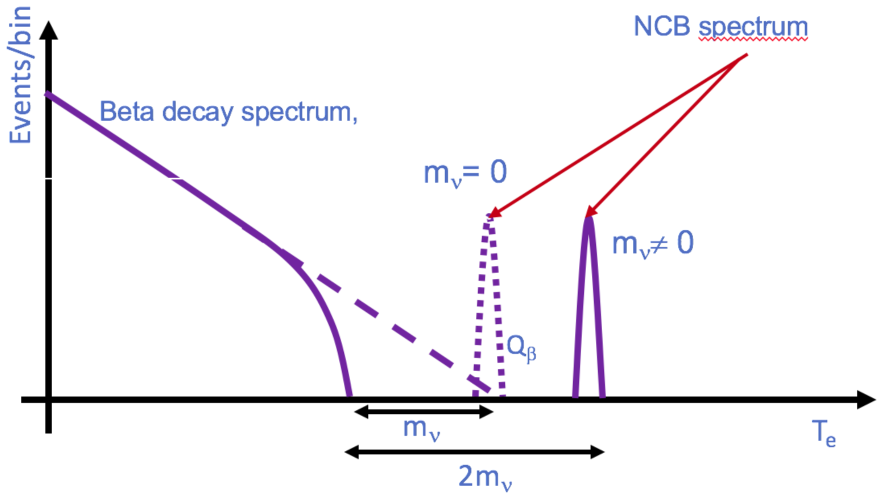
$$T_\nu = 1.95K \simeq 2\times 10^{-4}\mathrm{eV}$$

PTOLOMY experiment

Atomic Tritium on graphene


β decay


Neutrino Capture on a Beta Decaying Nucleus (NCB)

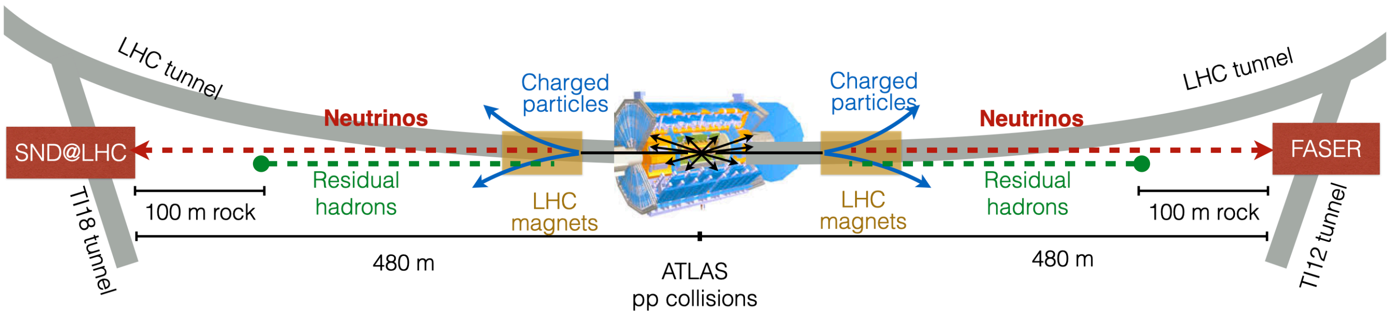


M. Messina '18

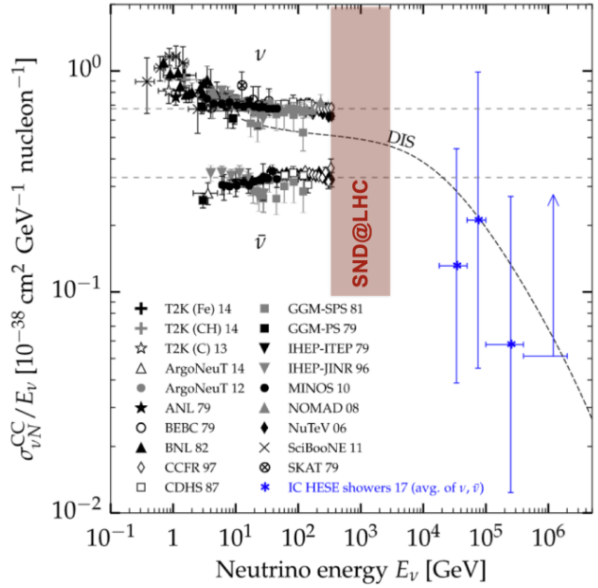
New era of ν physics:

Neutrino interactions in new regimes

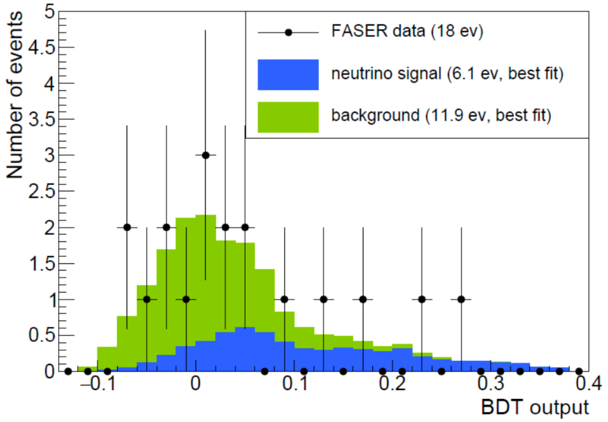
LHC is in intense source of TeV scale neutrinos !



PRL 122 (2019) 041101



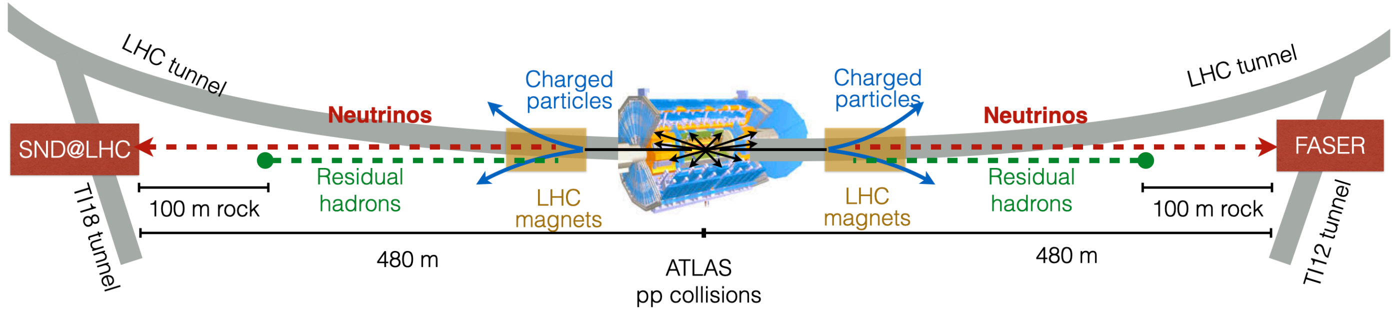
2.7σ evidence for LHC neutrinos

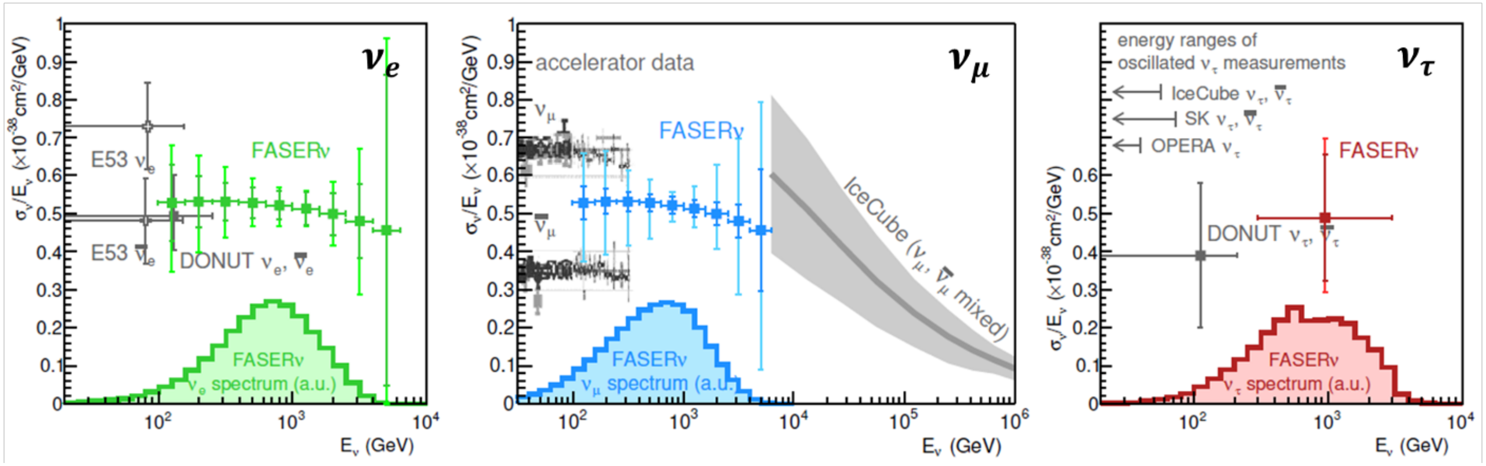

Best fit (no N_{BG} constraint)

New era of ν physics:

Neutrino interactions in new regimes

LHC is in intense source of TeV scale neutrinos !

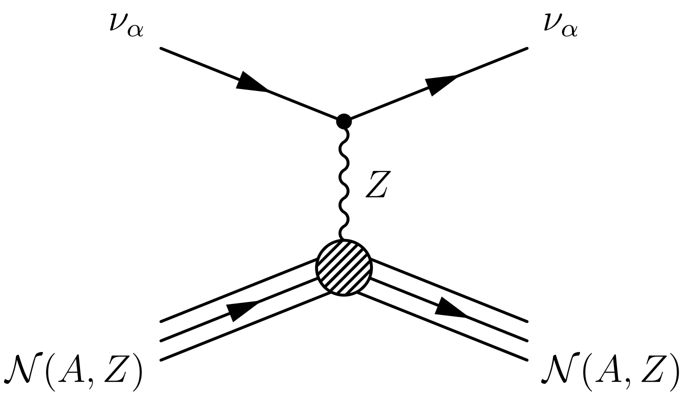




New era of ν physics:

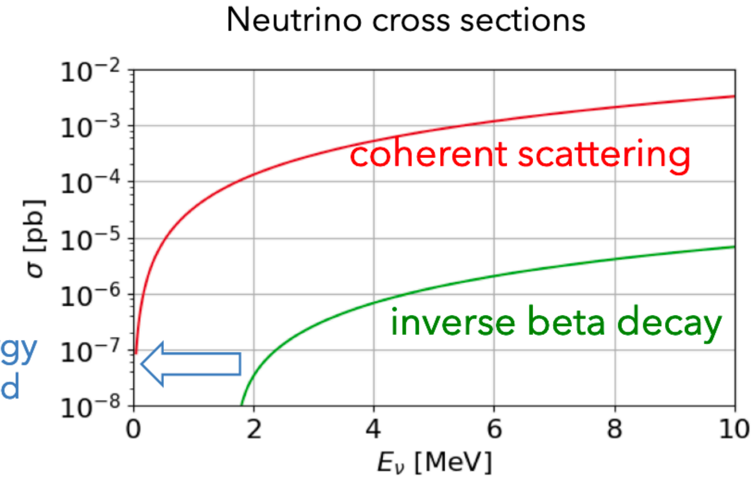
Neutrino interactions in new regimes

Coherent Neutrino Scattering



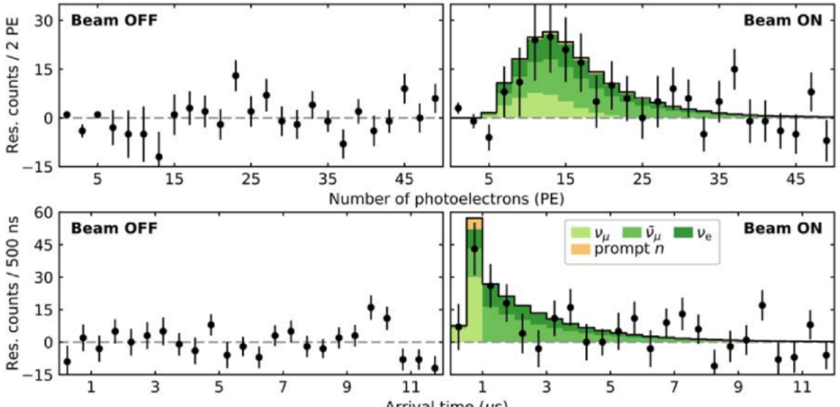
D. Freedman '74

No energy threshold



$$\sigma \approx \frac{G_F^2}{4\pi}(N-(1-4\sin^2\theta_W)Z)^2E_\nu^2$$

First measured in 2017 by COHERENT experiment!



New era of ν physics:

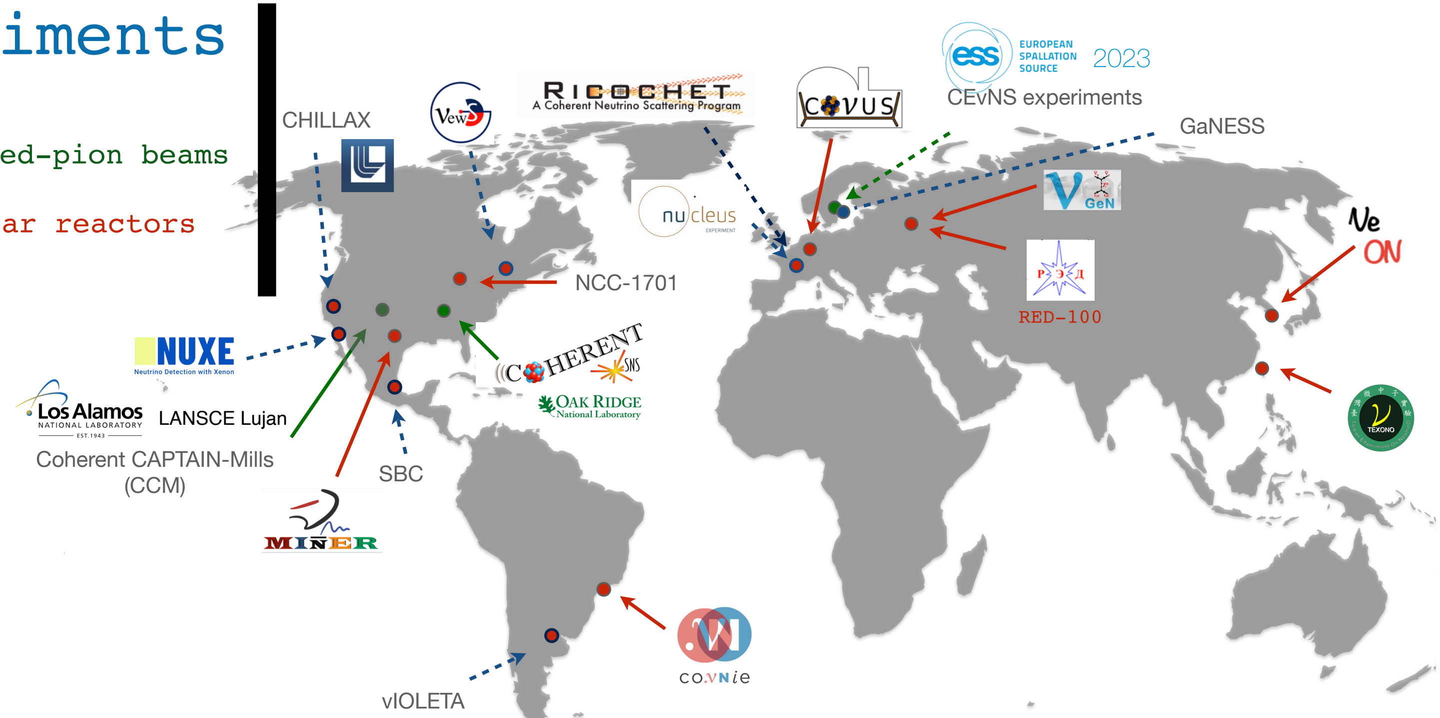
Neutrino interactions in new regimes

Coherent Neutrino Scattering

Experiments

● Stopped-pion beams

● Nuclear reactors



Bonifazi ‘22

New era of ν physics:

Neutrino interactions in new regimes

Coherent Neutrino Scattering

- Test neutrino properties and light BSM connected to neutrinos
- Understand background to DM searches (neutrino floor: CNS of solar neutrinos)
- Nuclear physics: new probe of nuclear properties
- Monitoring reactor fluxes (for physics and non proliferation)

Neutrinos and BSM

Massive neutrinos: a new flavour perspective

Why do they mix so differently ?

CKM

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

$$J = (3.18 \pm 0.15) \times 10^{-5}$$

PMNS

NuFIT 5.0 (2020)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.631 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}$$

$$J \simeq 0.033 \sin\delta$$

Why so different mixing ?

CKM

$$V_{CKM} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PMNS

$$|V_{PMNS}| \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Where the large mixing comes from ?

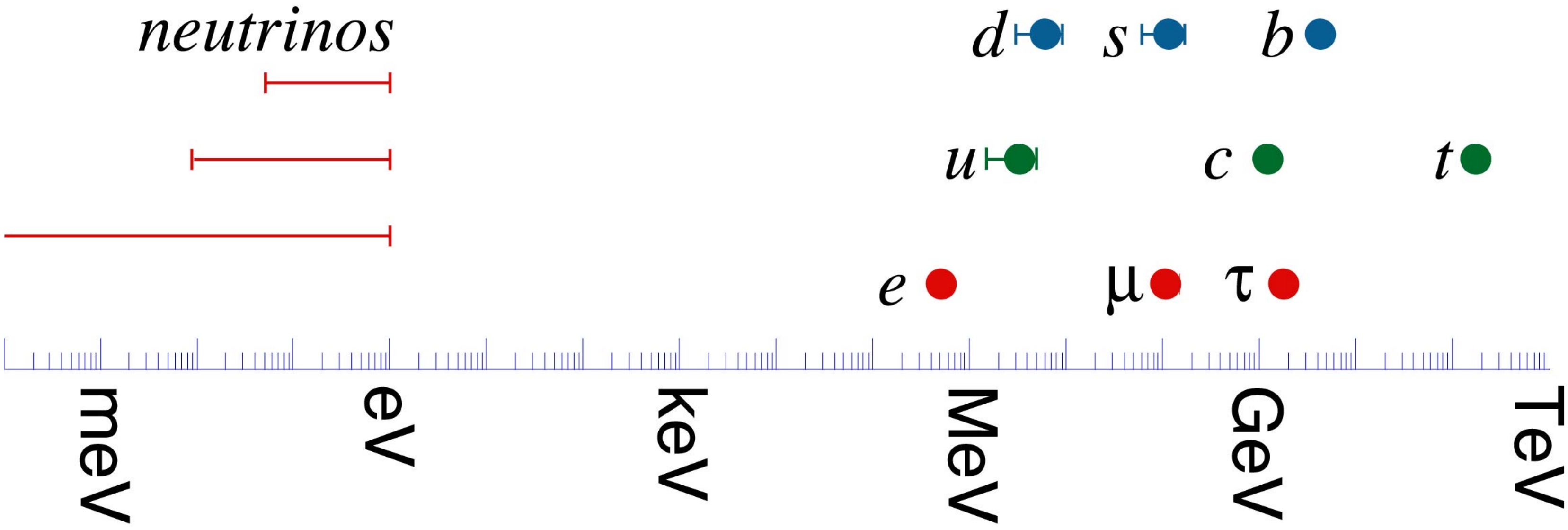
Anarchy for leptons

Discrete or continuous symmetries

Lepton-quark flavour connection in GUTs ?

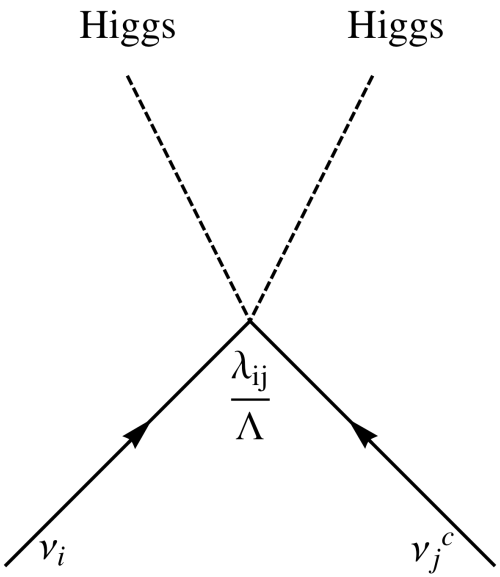
Massive neutrinos: a new flavour perspective

Why are neutrinos so much lighter ?



They get their masses differently!

Neutrinos have tiny masses -> a new physics scale, what ?



➡ νSM ?

$$m_\nu = \lambda \frac{v^2}{\Lambda}$$

Scale at which new particles will show up

What originates the neutrino mass ?

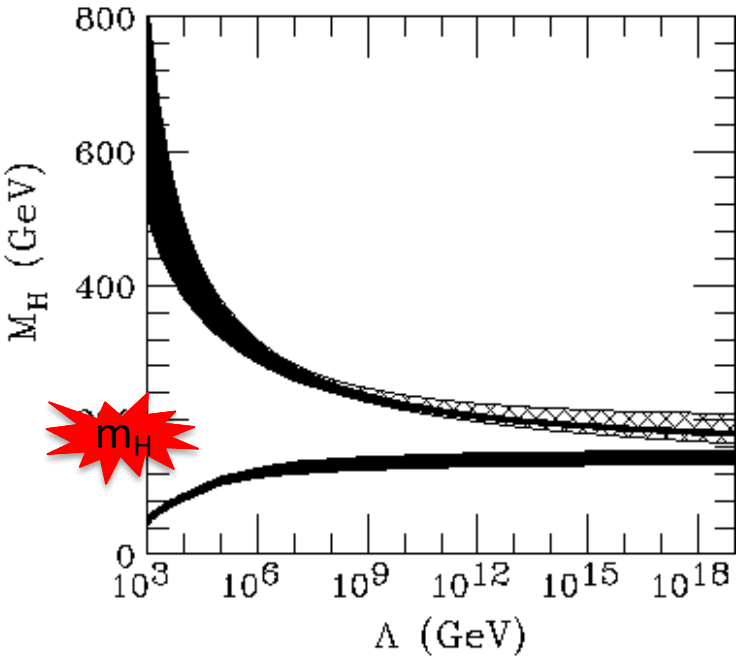
Could be $\Lambda >> v$… the standard lore (theoretical prejudice ?)

$$\left.\begin{array}{l} \Lambda = M_{\mathrm{GUT}} \\ \lambda \sim \mathcal{O}(1) \end{array}\right\} \quad m_\nu \quad \surd$$

Hierarchy problem $\quad m_H^2 \propto \Lambda^2 \quad$ Vissani

not natural in the absence of SUSY/other solution to the hierarchy problem

The Standard Model is healthy as far as we can see…



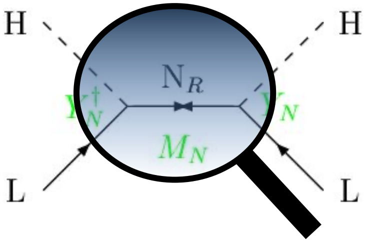
Could be naturally $\Lambda \sim v$?

Yes ! λ in front of neutrino mass operator must be small…

Resolving the neutrino mass operator at tree level

E. Ma

Type I see-saw:
a heavy singlet scalar

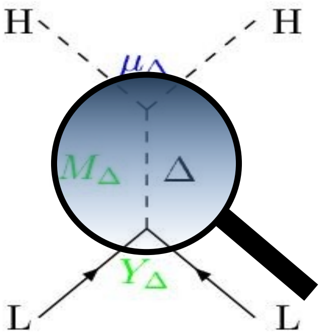


$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

Minkowski;
Yanagida; Glashow;
Gell-Mann, Ramond Slansky;
Mohapatra, Senjanovic...

$\lambda \sim O(Y^2)$

Type II see-saw:
a heavy triplet scalar

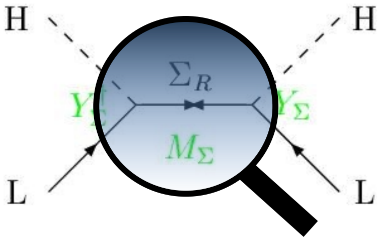


$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Konetschny, Kummer;
Cheng, Li;
Lazarides, Shafi, Wetterich ...

$\lambda \sim O(Y\, \mu/M_\Delta)$

Type III see-saw:
a heavy triplet fermion



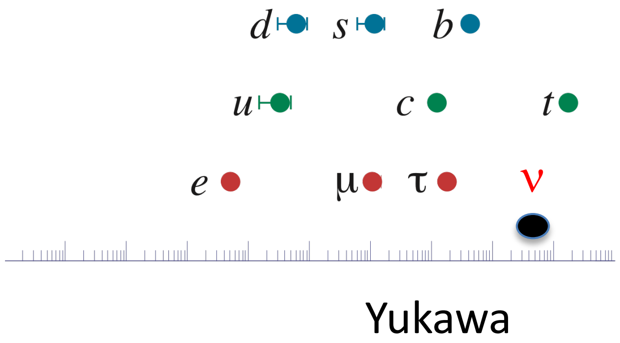
$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

Foot et al; Ma;
Bajc, Senjanovic...

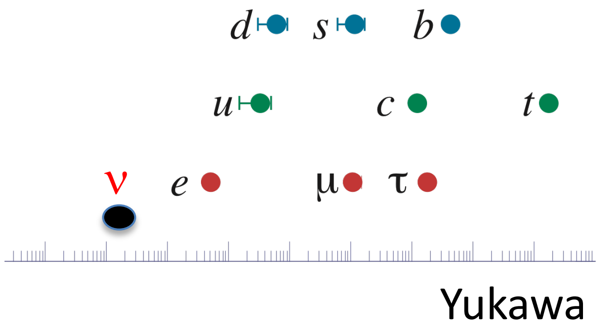
$\lambda \sim O(Y^2)$

Type I and III

$M_N \sim$ GUT



$M_N \sim \nu$



Where is the new scale ?

Generic predictions

- ➢ there is neutrinoless double beta decay at some level ($\Lambda > 100\text{MeV}$)

model independent contribution from the neutrino mass 😊

Where is the new scale ?


Leptogenesis

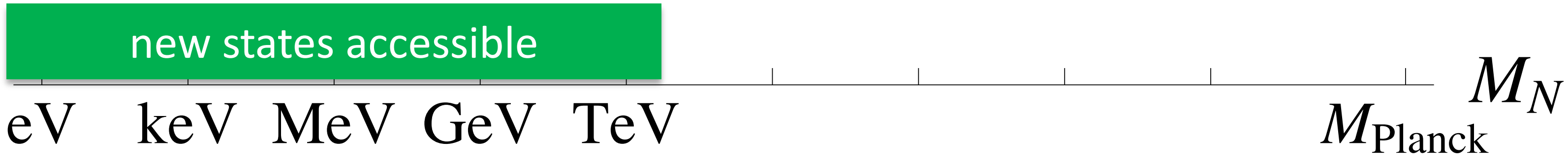
eV keV MeV GeV TeV M_{Planck} M_N

Generic predictions:

- a matter-antimatter asymmetry if there is CP violation in the lepton sector via leptogenesis

model dependent…

Where is the new scale ?



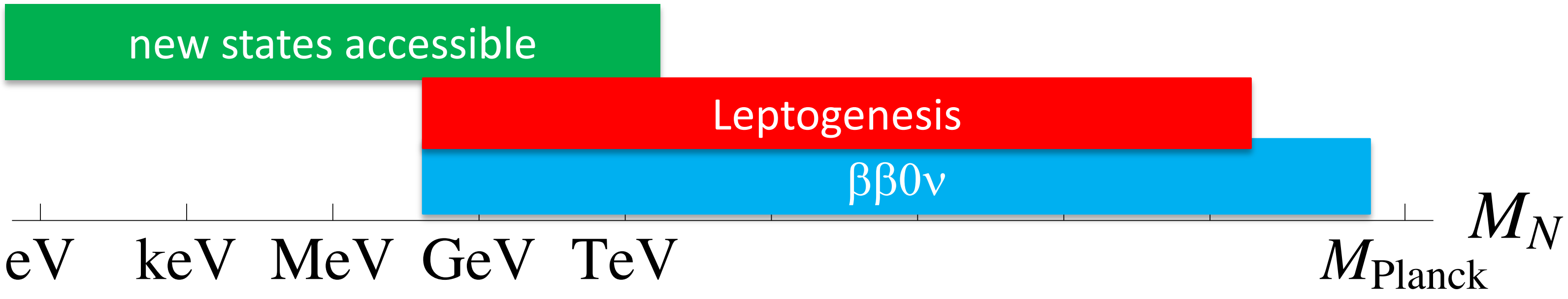
Generic predictions:

- there are other states out there at scale Λ: new physics beyond neutrino masses

potential impact in cosmology, EW precision tests, collider, rare searches, ββ0ν, ...

model dependent... 😪

Where is the new scale ?



The EW scale is an interesting region: new physics underlying the matter-antimatter asymmetry could be predicted & tested !

The Standard Model+massive ν

An extension of the SM table is mandatory

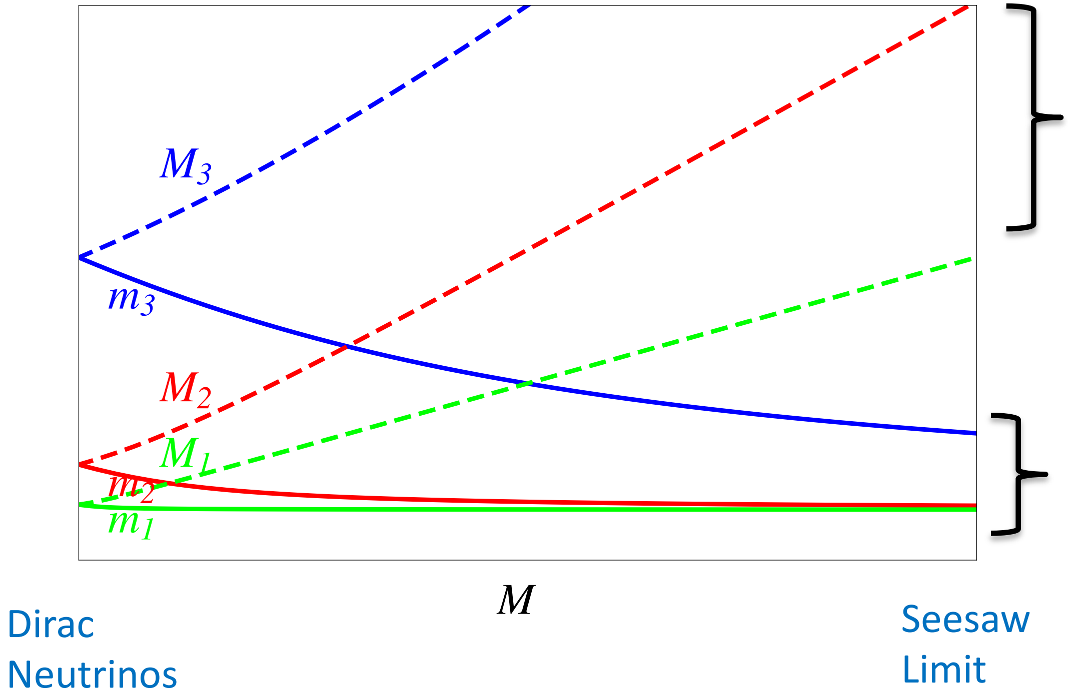
$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{3},\mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{1},\mathbf{1})_0$
$\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L$	$\begin{pmatrix}u^i \\ d^i\end{pmatrix}_L$	e_R	u^i_R	d^i_R	ν^1_R
$\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c^i \\ s^i\end{pmatrix}_L$	μ_R	c^i_R	s^i_R	ν^2_R
$\begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t^i \\ b^i\end{pmatrix}_L$	τ_R	t^i_R	b^i_R	ν^3_R

$$\mathcal{L}_{SM} \supset \bar{\nu}_{Li} Y_{ij} H \nu_{Rj} + \bar{\nu}_{Ri} M_{ij} \nu^c_{Rj}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...

The Standard Model+massive ν

M≠ 0 <-> 6 Majorana neutrinos (3 light, 3 heavy)



Heavy Neutral Leptons (N)

$$m_{\text{heavy}} \sim M$$

Light neutrinos (ν)

$$m_{\text{light}} \sim Y \frac{v^2}{M} Y^T$$

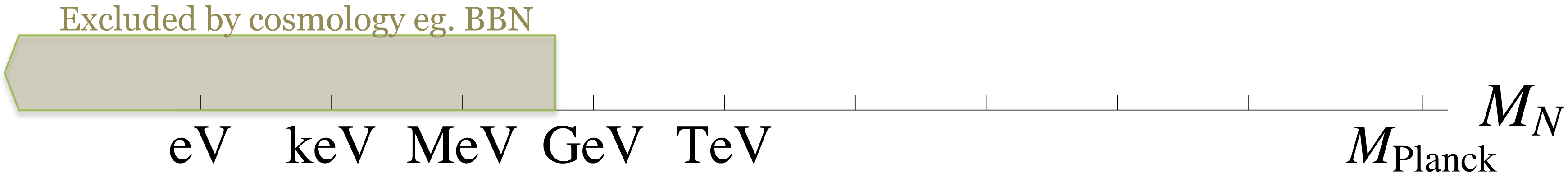
Fixing the light neutrino masses leaves us with a degeneracy

$$M \sim Y^2$$

The Standard Model+massive ν

Robust prediction: generation of a baryon asymmetry via leptogenesis for a wide range of M

Fukugita, Yanagida; Abada et al;..Pilaftsis…; Ahkmedov,Rubakov, Smirnov; Asaka, Shaposhnikov…



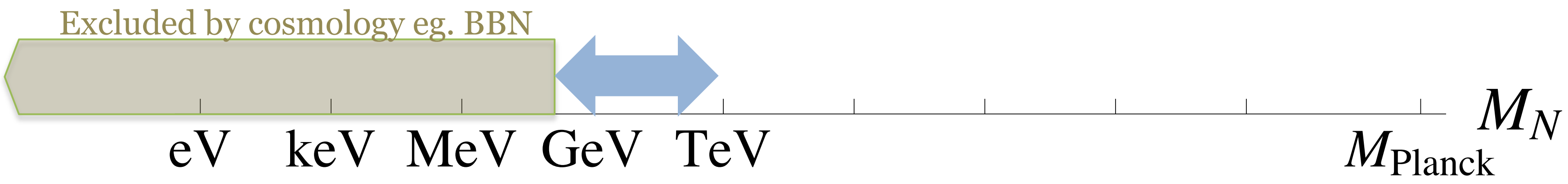
Excluded by cosmology eg. BBN

eV keV MeV GeV TeV M_{Planck} M_N

The Standard Model+massive ν

Robust prediction: generation of a baryon asymmetry via leptogenesis for a wide range of M

Fukugita, Yanagida; Abada et al;..Pilaftsis…; Ahkmedov,Rubakov, Smirnov; Asaka, Shaposhnikov…

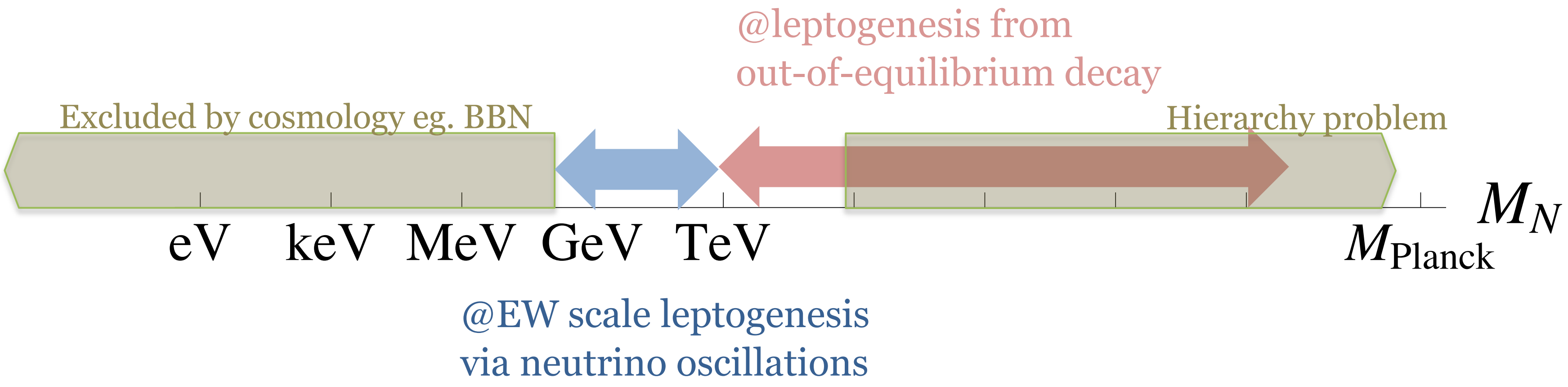


@EW scale leptogenesis via neutrino oscillations

The Standard Model+massive ν

Robust prediction: generation of a baryon asymmetry via leptogenesis for a wide range of M

Fukugita, Yanagida; Abada et al;..Pilaftsis…; Ahkmedov,Rubakov, Smirnov; Asaka, Shaposhnikov…



Heavy Neutral Leptons

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{ll} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} + U_{lh} \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

Light neutrino mixing
(~PMNS)

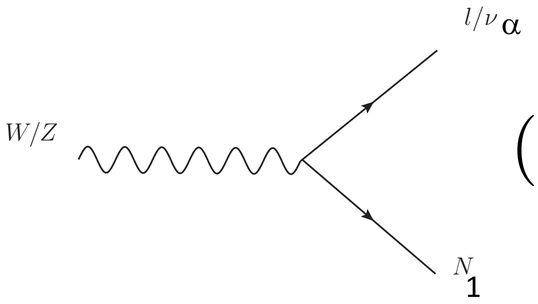
HNL mixing

Naïve seesaw scaling:

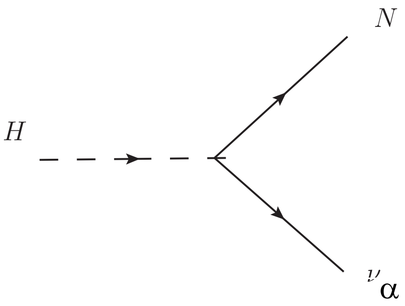
$$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$

For n ≥ 2, large naïve scaling not true !

Heavy Neutral Leptons

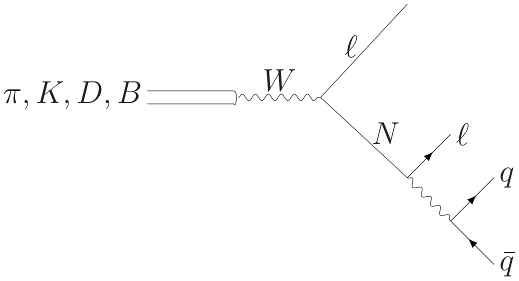


$$(U_{hl})_{\alpha 1}$$

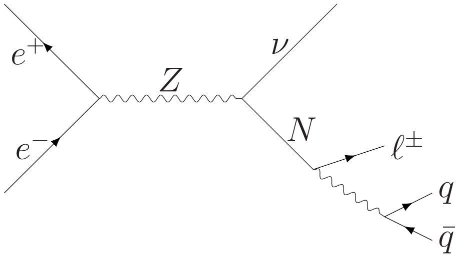


$$(U_{hl})_{\alpha 1}$$

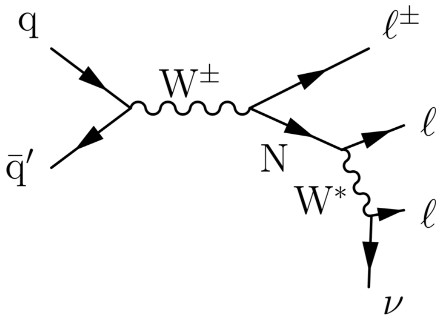
Meson decays



e+e-@Z peak



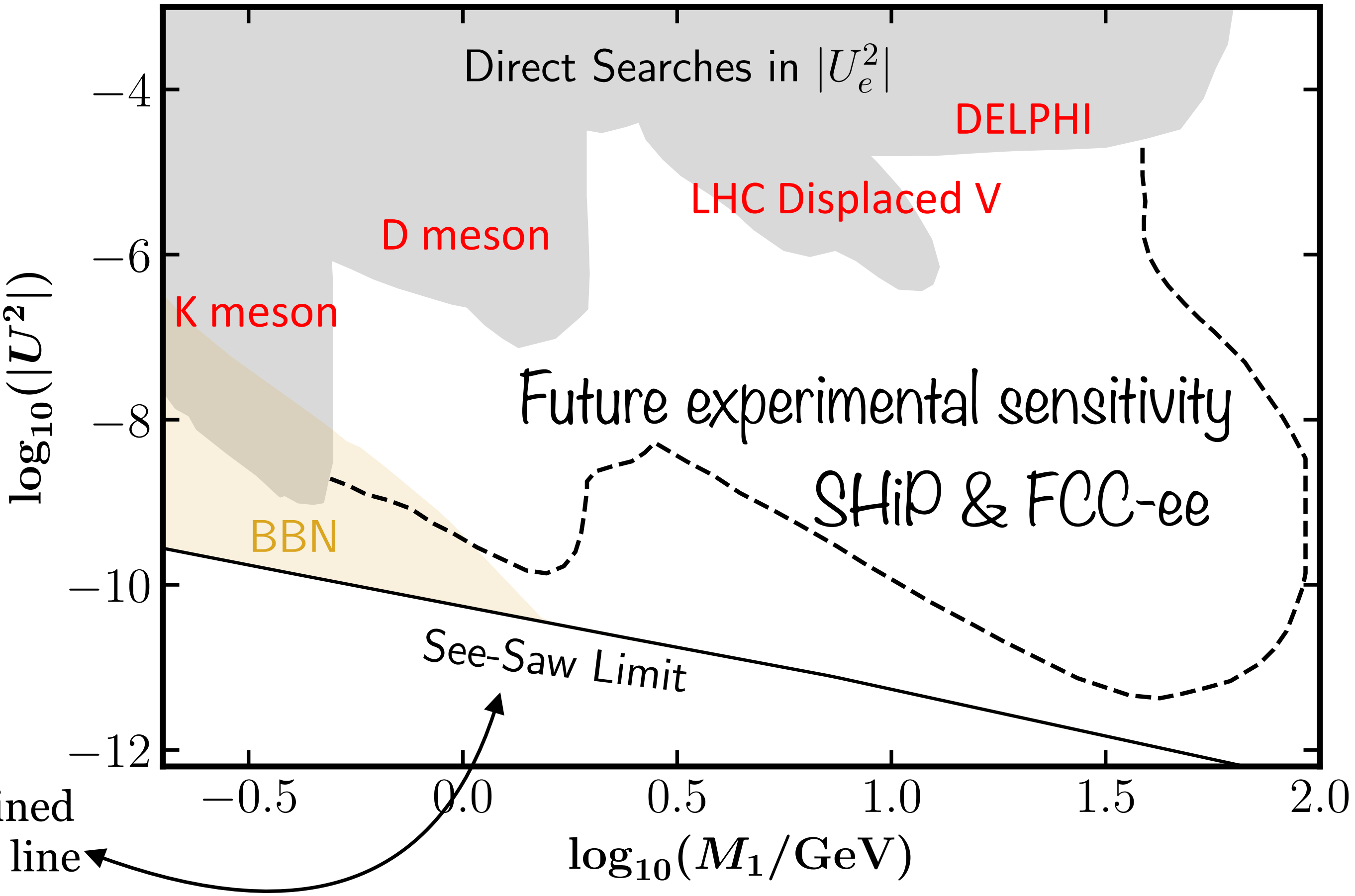
Hadron colliders



@Laboratory (fixed target, colliders) and cosmic rays

Heavy Neutral Leptons

$$U^2 = \sum_\alpha |(U_{hl})_{\alpha 1}|^2$$

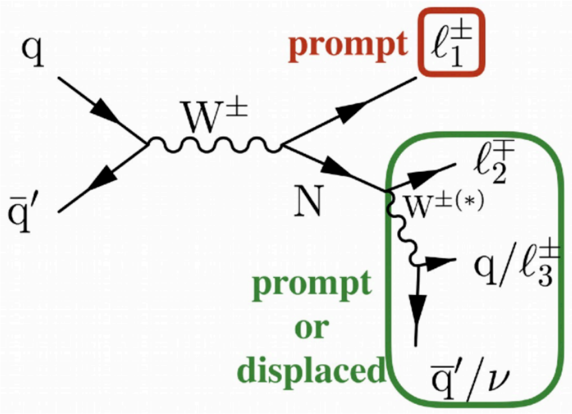


ν masses
not explained
below the line

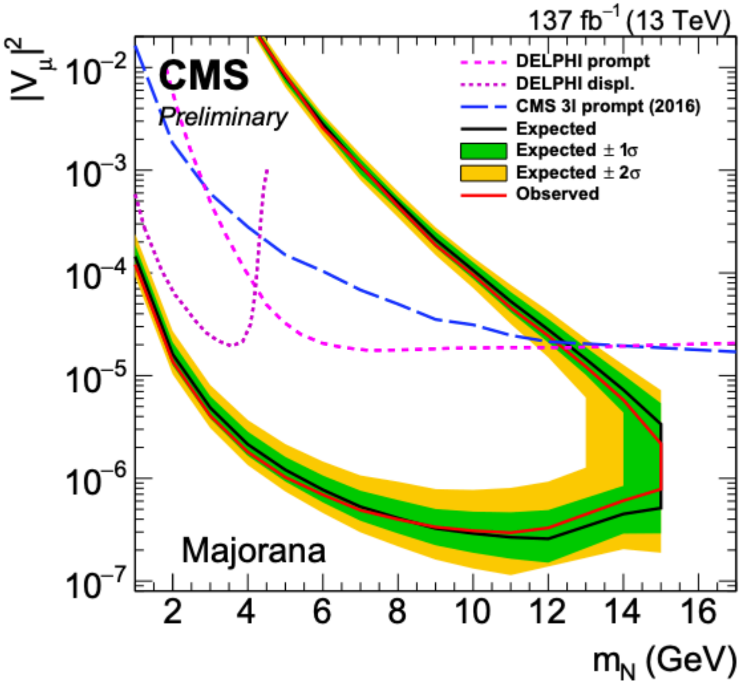
Most of the accessible region is quite far from the seesaw limit … $|U|^2 \gg \frac{m_l}{M}$

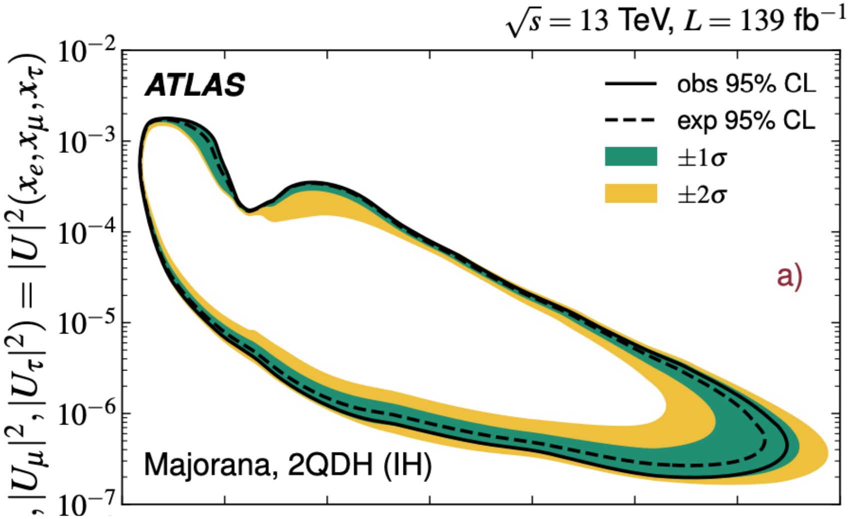
Is this natural ?

“Light” HNL searches at LHC



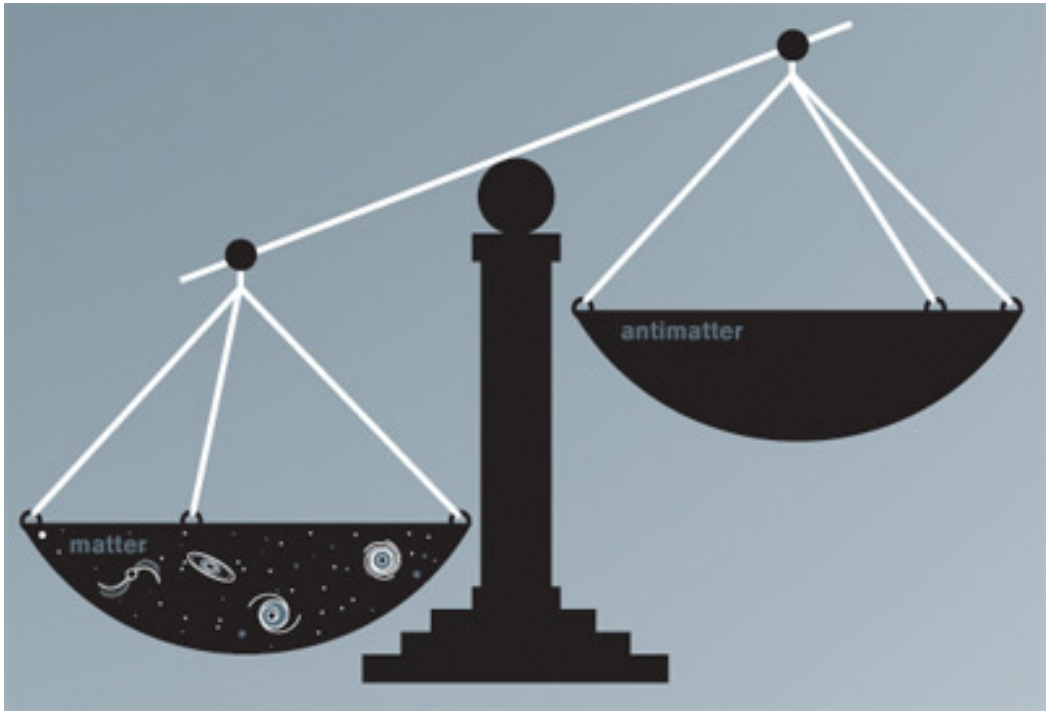
Displaced vertices is the golden signal !





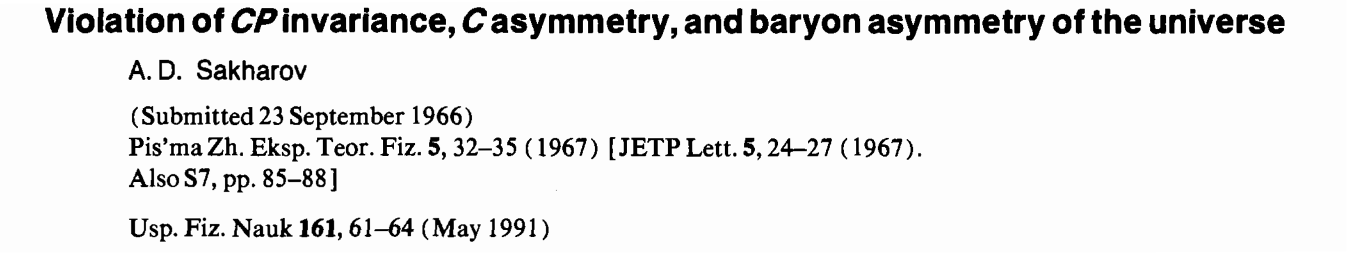
Baryon asymmetry

The Universe seems to be made of matter



$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}$$

A. Sakharov



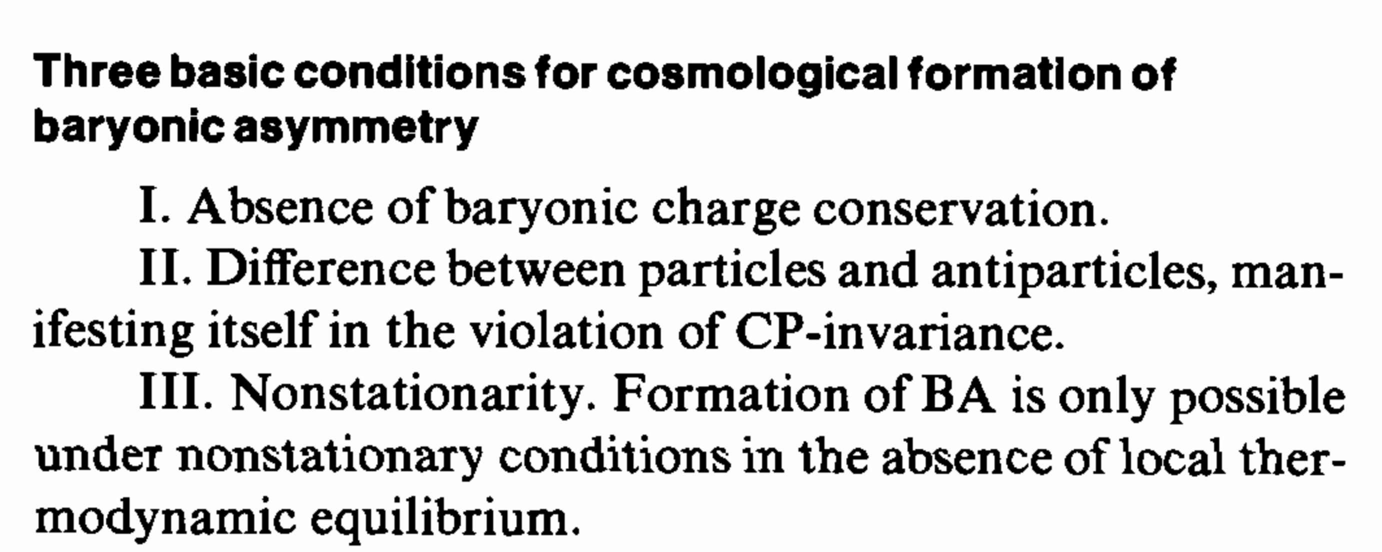
Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

-> G. Servant, Y. Nir lectures



Three basic conditions for cosmological formation of baryonic asymmetry

I. Absence of baryonic charge conservation.

II. Difference between particles and antiparticles, manifesting itself in the violation of CP-invariance.

III. Nonstationarity. Formation of BA is only possible under nonstationary conditions in the absence of local thermodynamic equilibrium.

$$n_b \sim n_{\bar{b}} \propto e^{-m_b/T}$$

The Standard Model (subtly) complies

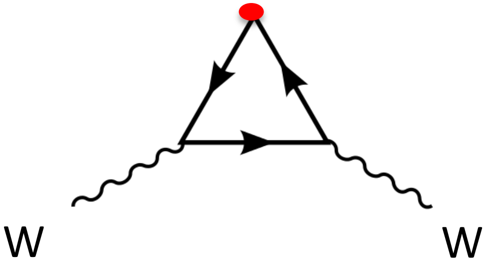
I Baryon Number

Symmetry is broken by quantum vacuum effects: anomaly

t'Hooft '76, Klinkhammer, Manton '84;

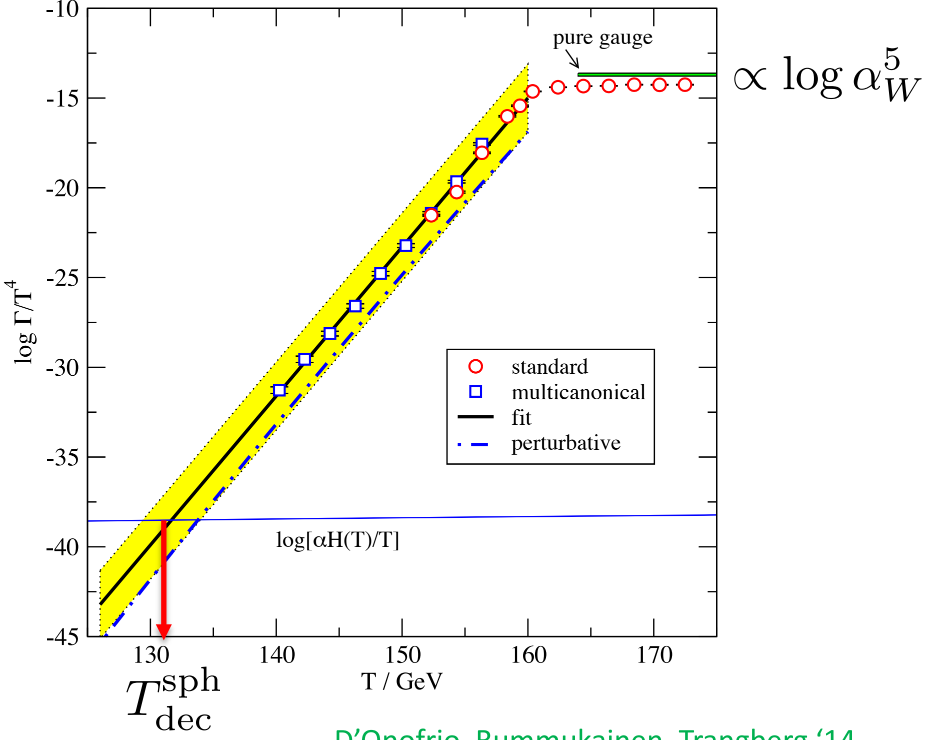
Only B-L is conserved in the SM !

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu$$



$$\Gamma \propto e^{-\frac{4\pi}{\alpha_W}}, T < T_{\mathrm{EW}}$$

Sphaleron rate in the SM



D'Onofrio, Rummukainen, Trangberg '14

But the Standard Model fails

II CP violation

It is a subtle phenomenon that depends on many flavour parameters

$$Y_B \propto \Delta_{\mathrm{CP}}$$

$$\Delta_{CP}^{\mathrm{quarks}} = \begin{cases} \bullet\ \text{Polynomial in } Y_u, Y_d \\ \bullet\ \text{Has an imaginary part} \\ \bullet\ \text{It is flavour-basis invariant} \end{cases}$$

But the Standard Model fails

II CP violation

It is a subtle phenomenon that depends on many flavour parameters

$$Y_B \propto \Delta_{\rm CP}$$

$$\Delta_{CP}^{\rm quarks} = {\rm Im}\left[\det\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]\right)\right] \propto J \prod_{i<j}(m_{d_i}^2 - m_{d_j}^2) \prod_{i<j}(m_{u_i}^2 - m_{u_j}^2)$$

$$J = {\rm Im}[V_{ij}^* V_{ii} V_{ji}^* V_{jj}] = c_{23} s_{23} c_{12} s_{12} c_{13}^2 s_{13} \sin\delta$$

Jarlskog '85

Three non-degenerate families of up and down quarks that mix are needed for there to be CP violation !

But the Standard Model fails

Too small CP violation in quark sector

Gavela, PH, Orloff, Pene ‘93

$$\frac{n_b}{n_\gamma} \propto \frac{\Delta^{\rm CP}}{(T_{\rm EW})^{12}} \sim 10^{-20}$$

New sources of CP violation are needed !

But the Standard Model fails

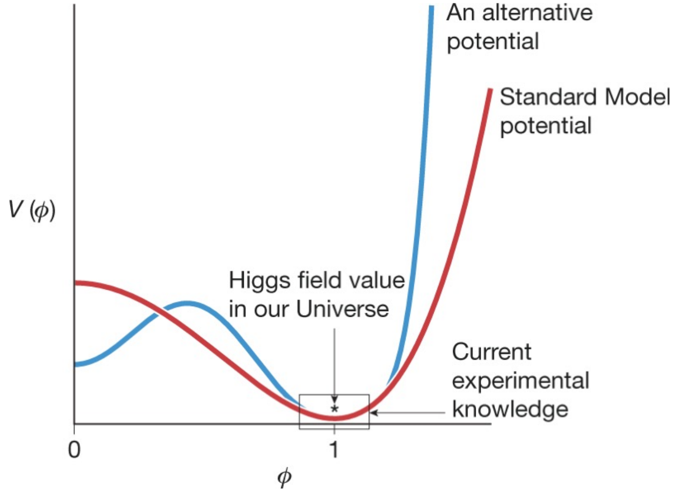
III Non-equilibrium

- First order phase transitions

It is a smooth crossover in the SM (too heavy higgs)

Kajantie, Laine, Rummukainen,Shaposhnikov ‘96

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$



$$\lambda_3^{SM} = \frac{m_H^2}{\sqrt{2}v}, \lambda_4^{SM} = \frac{m_H^2}{4v^2}$$

But the Standard Model fails

III Non-equilibrium

- Expansion of the Universe when $\Gamma(T) \leq H(T)$

scattering rate < Hubble expansion

All particles in the SM (even neutrinos) satisfy

$$\Gamma_{SM}(T) \geq H(T), \qquad T \geq T_{\mathrm{EW}}$$

The Standard Model+massive ν

New opportunities for baryogenesis!

- CP violation in the lepton sector potentially larger if M ≠ 0: new invariants

$$\Delta_{CP}^{\text{leptons}} = \text{Im}\left\{\text{Tr}[Y^\dagger Y M^\dagger M M^* (Y^\dagger Y)^* M]\right\}$$

Branco et al; Jenkins, Manohar;Wang, Yu Zhou…

- Heavy neutrino states might exit early/never reach thermal equilibrium at $T > T_{EW}$

Fukugita, Yanagida

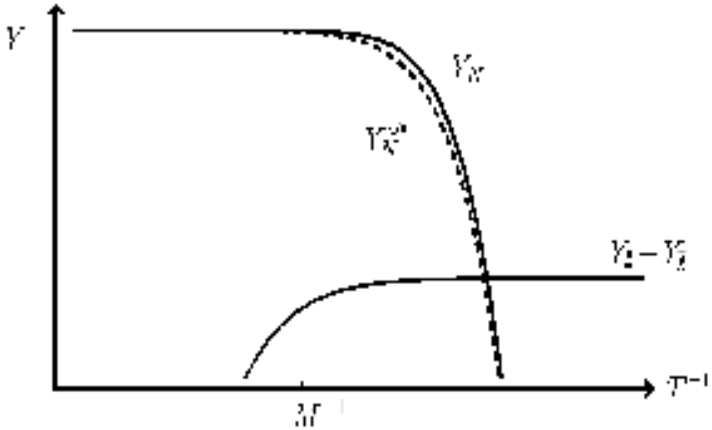
$$\Gamma_{N_i}(T) \leq H(T), T \geq T_{EW}$$

(Scattering rate < Hubble expansion rate)

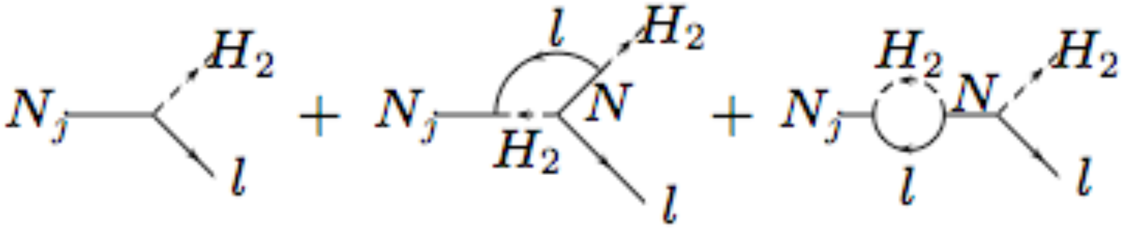
High–scale (vanilla) leptogenesis

Fukuyita, Yanagida

$$\Gamma_{N_i}(M_i) \leq H(M_i)$$



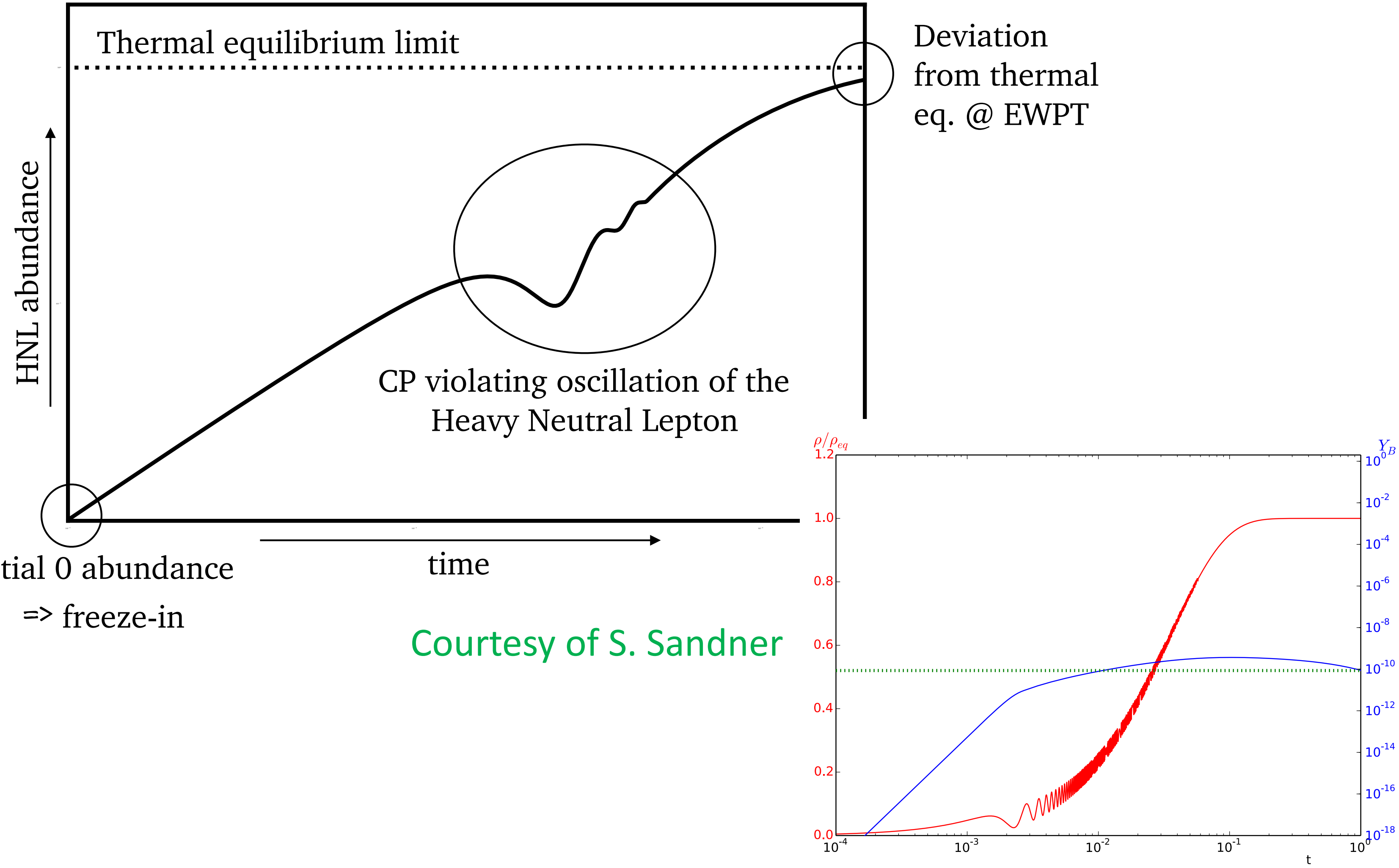
$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$



Works for large enough masses $M_N > 10^7$-10^9 GeV (unless an extreme degeneracy exits)

Low-scale (Freeze-in) Leptogenesis

Akhmedov, Rubakov, Smirnov



Thermal equilibrium limit

Deviation
from thermal
eq. @ EWPT

HNL abundance

CP violating oscillation of the
Heavy Neutral Lepton

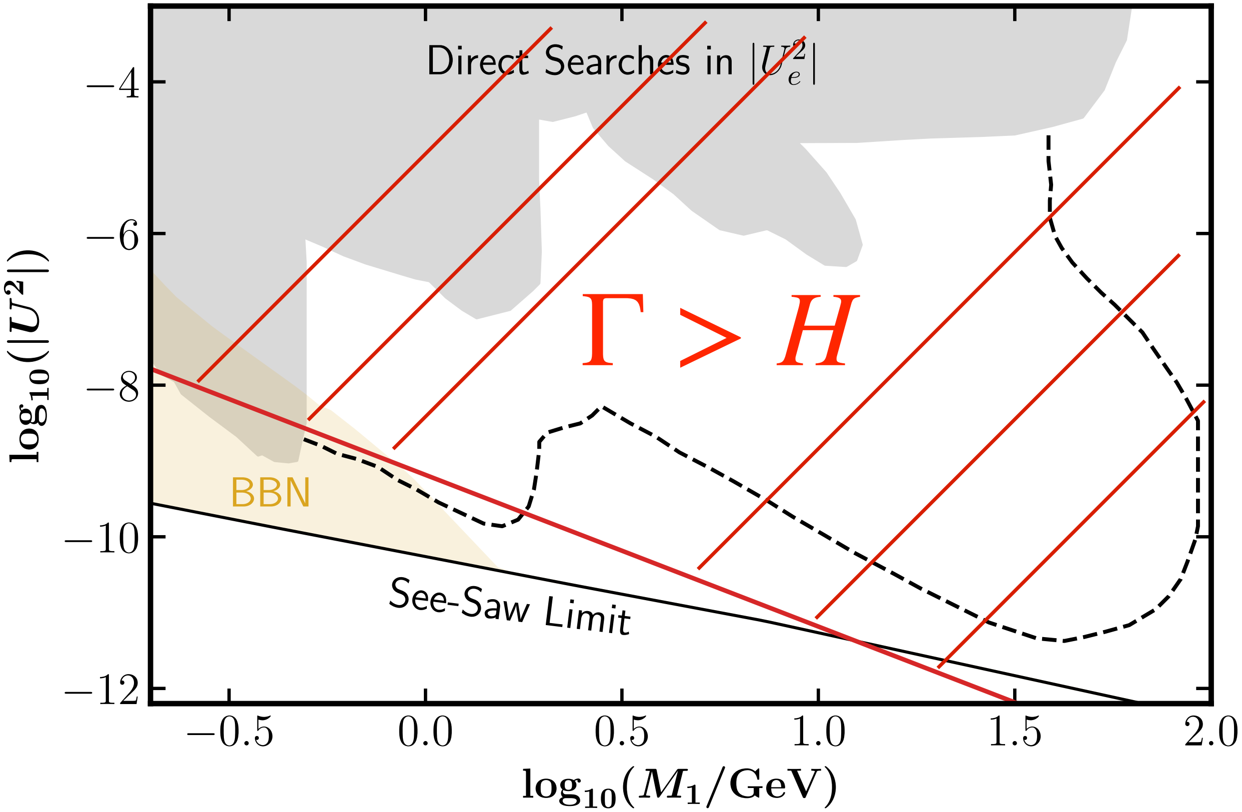
Initial 0 abundance
=> freeze-in

time

Courtesy of S. Sandner

Non thermal equilibration?

$\Gamma(T_{\mathrm{EW}}) \leq H(T_{\mathrm{EW}})$ is required $\Gamma \propto \mathrm{Tr}[Y^\dagger Y]T$



BUT approximate LN symmetry and flavour effects can lead to other slow modes

Heavy Neutral Leptons

Strongly mixed HNL that explain neutrino masses iff approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao;Kersten, Smirnov; Abada et al; Gavela et al….many others

Minimal Model two neutrinos: $L(N_1)= +1$, $L(N_2) = -1$

$$M = \begin{pmatrix} 0 & \Lambda \\ \Lambda & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} y_e & 0 \\ y_\mu & 0 \\ y_\tau & 0 \end{pmatrix}$$

Degenerate heavy neutrinos, massless light neutrinos, no CP violation…

Heavy Neutral Leptons

Strongly mixed HNL that explain neutrino masses iff approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao;Kersten, Smirnov; Abada et al; Gavela et al….many others

$$M = \begin{pmatrix} \mu_1 & \Lambda \\ \Lambda & \mu_2 \end{pmatrix} \qquad Y = \begin{pmatrix} y_e & y'_e e^{i\beta_e} \\ y_\mu & y'_\mu e^{i\beta_\mu} \\ y_\tau & y'_\tau e^{i\beta_\tau} \end{pmatrix}$$

Expansion parameters $\quad y' \ll y, \mu \ll \Lambda, \;\; \Delta M \propto \mu$

Neutrino masses suppressed:

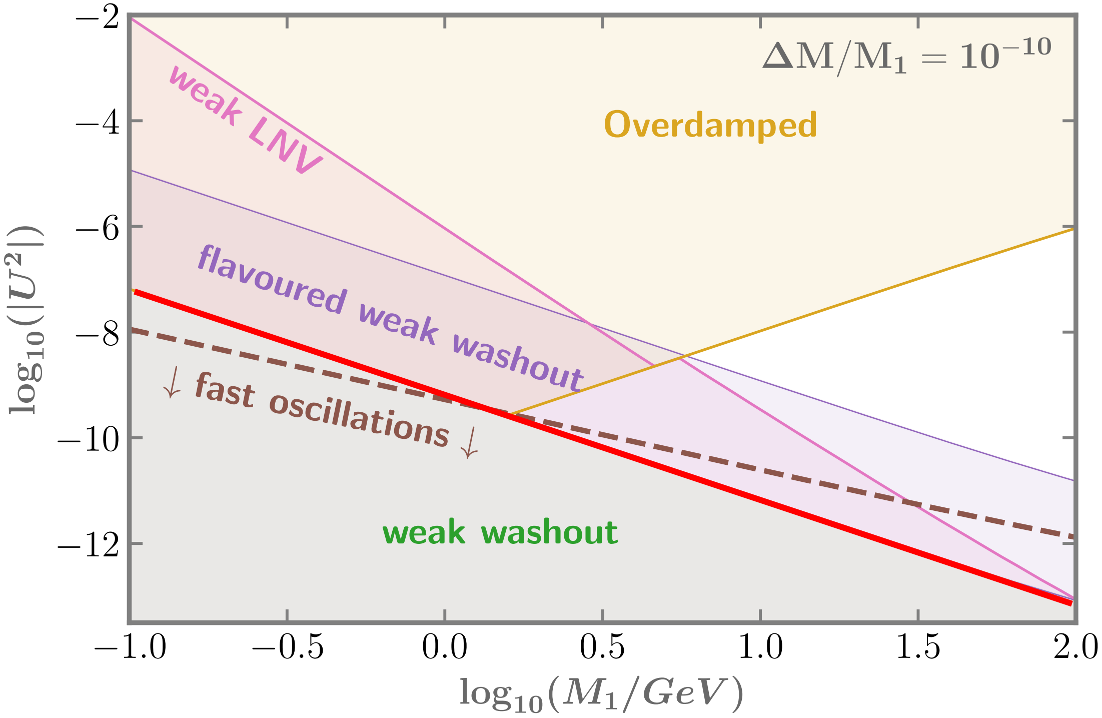
$$(m_\nu)_{\alpha\beta} \propto \frac{v^2}{\Lambda}\left(y_\alpha y'_\beta + y_\beta y'_\alpha - y_\alpha y_\beta \frac{\mu_2}{\Lambda}\right)$$

HNL Mixing unsuppressed:

$$U^2 \sim \frac{y^2 v^2}{2M^2}$$

Highly-degenerate regime

Shaded regions have slow thermalizing modes

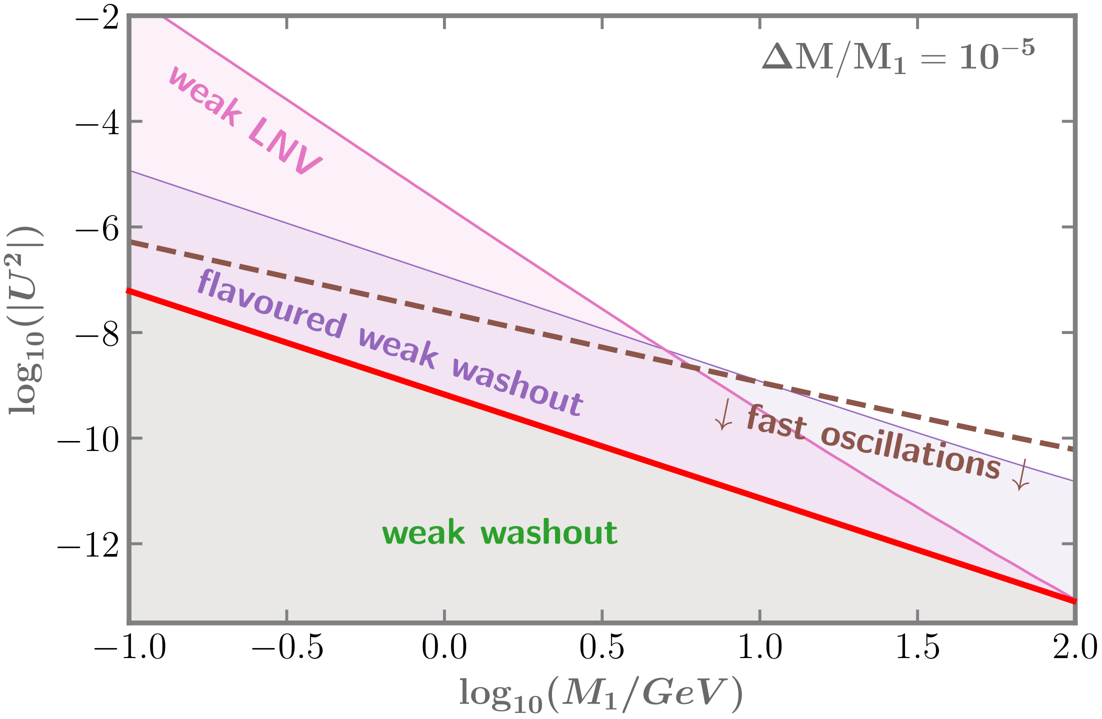


Overdamped: $\Delta M \ll M$

$$\Gamma_{\text{osc}}^{\text{slow}} = \epsilon^2 \Gamma \qquad \epsilon \equiv \frac{\Gamma_{osc}}{\Gamma} \qquad \Gamma_{\text{osc}}(T) \propto \frac{M_2^2 - M_1^2}{T}$$

Not-so-degenerate regime

Shaded regions have slow thermalizing modes



Flavoured: $y_\alpha \ll y_\beta$

wLNV: $M \ll T$

$$\Gamma_\alpha \propto (YY^\dagger)_{\alpha\alpha} T$$

$$\Gamma_M^{\text{slow}} \propto \left(\frac{M_i}{T}\right)^2 \Gamma$$

Towards an analytical understanding

- Identify the different non-thermal regimes and their characteristic time-scales

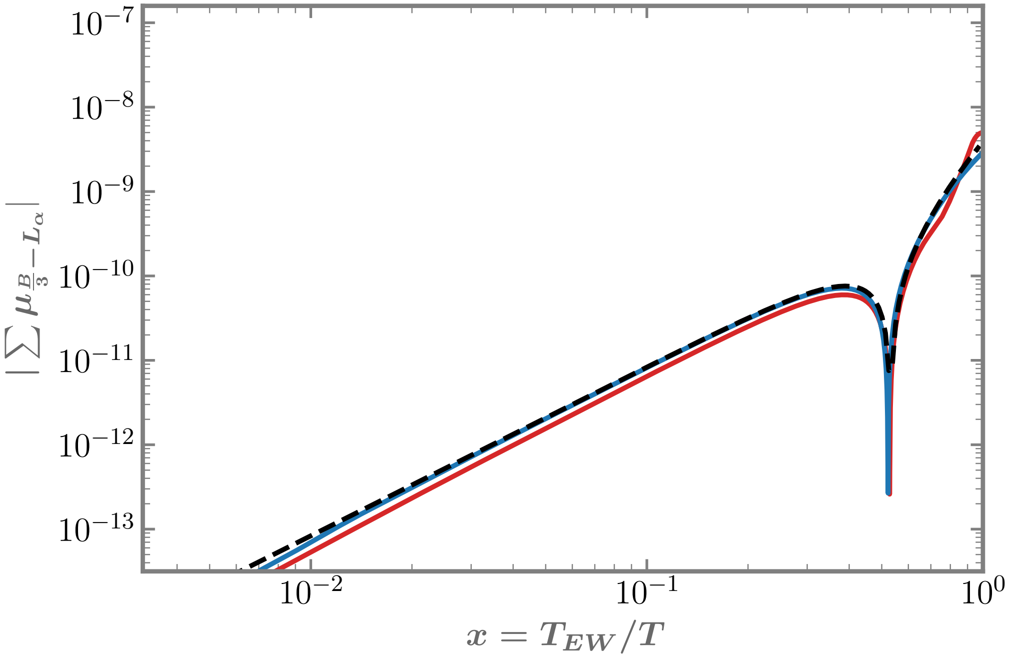
- Identify the CP invariants that control the parameter dependences of Y_B

$$I_0 = \mathrm{Im}\left(\mathrm{Tr}[Y^\dagger Y M^\dagger M Y^\dagger Y_l Y_l^\dagger Y]\right)$$

$$I_1 = \mathrm{Im}\left(\mathrm{Tr}[Y^\dagger Y M^\dagger M M^* (Y^\dagger Y)^* M]\right)$$

- Write the CP invariants in terms of observable parameters (neutrino masses, HNL properties, ββ0ν): find bounds and correlations implied by the matter-antimatter asymmetry

Analytical understanding



PH, Lopez-Pavon, Rius, Sandner '22

$$Y_B \simeq \alpha x^2 \Delta^{\rm ov}_{\rm LNC} + \beta x^5 \Delta^{\rm ov}_{\rm LNV}$$

I$_0$: $\Delta^{\rm ov}_{\rm LNC} = \frac{1}{\left[{\rm Tr}\left(Y^\dagger Y\right)\right]^2} \sum_\alpha \frac{1}{\left(Y Y^\dagger\right)_{\alpha\alpha}} \sum_{i<j} \left(M_j^2 - M_i^2\right) {\rm Im}\left[Y^*_{\alpha j} Y_{\alpha i} \left(Y^\dagger Y\right)_{ij}\right]$

I$_1$: $\Delta^{\rm ov}_{\rm LNV} = \frac{1}{\left[{\rm Tr}\left(Y^\dagger Y\right)\right]^2} \sum_\alpha \sum_{i<j} \left(M_j^2 - M_i^2\right) M_i M_j {\rm Im}\left[Y_{\alpha j} Y^*_{\alpha i} \left(Y^\dagger Y\right)_{ij}\right]$

Imprint of Y_B on other observables

For Inverted Ordering:

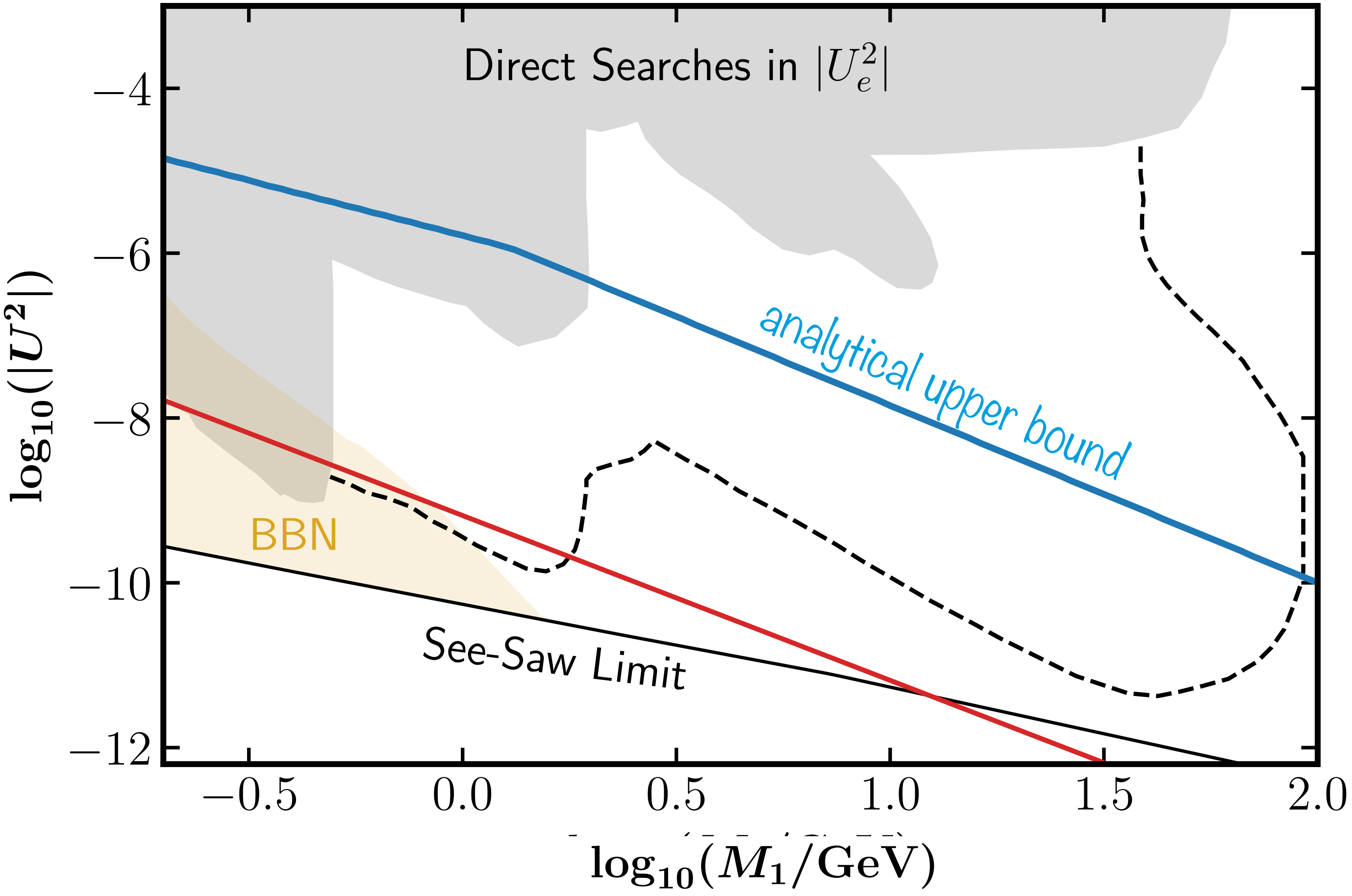
$$\frac{\Delta^{\rm ov}_{\rm LNC}}{M_2^2 - M_1^2} \approx \frac{v^2\sqrt{\Delta m^2_{\rm atm}}}{8M^3U^4}\frac{(1+3c_\phi \sin 2\theta_{12})\left(c_\theta s_\phi \sin 2\theta_{12} + s_\theta \cos 2\theta_{12}\right)}{-1+c_\phi^2 \sin^2 2\theta_{12}}$$

$$\frac{\Delta^{\rm ov}_{\rm LNV}}{M_1 M_2 (M_2^2 - M_1^2)} \approx -\frac{\sqrt{\Delta m^2_{\rm atm}}}{8MU^2} r^2 s_\theta$$

Depend on:

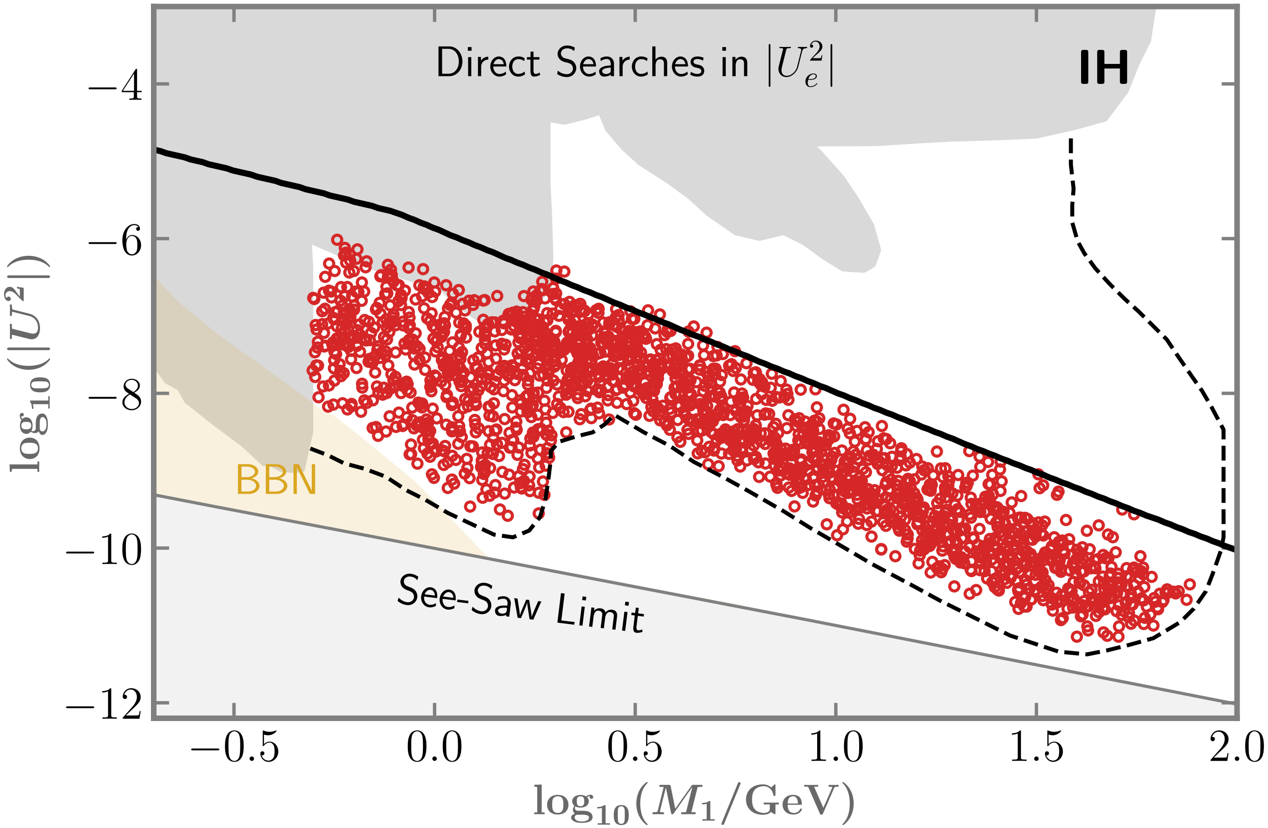
- HNL properties: M, U, θ not accessible at low energies
- Neutrino masses and PMNS parameters (eg Majorana phase ϕ)

Upper bound on the HNL mixing



PH, Lopez-Pavon, Rius, Sandner ‘22

Upper bound on the HNL mixing

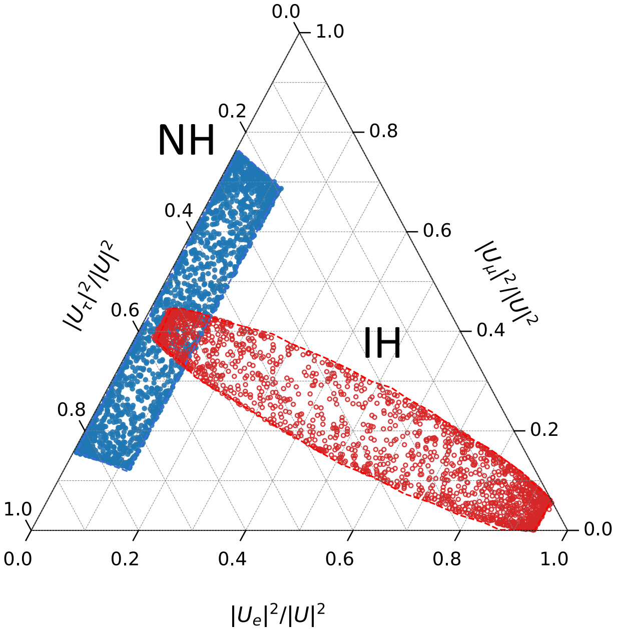


PH, Lopez-Pavon, Rius, Sandner '22

Numerical scan within the sensitivity region of SHIP and FCCee

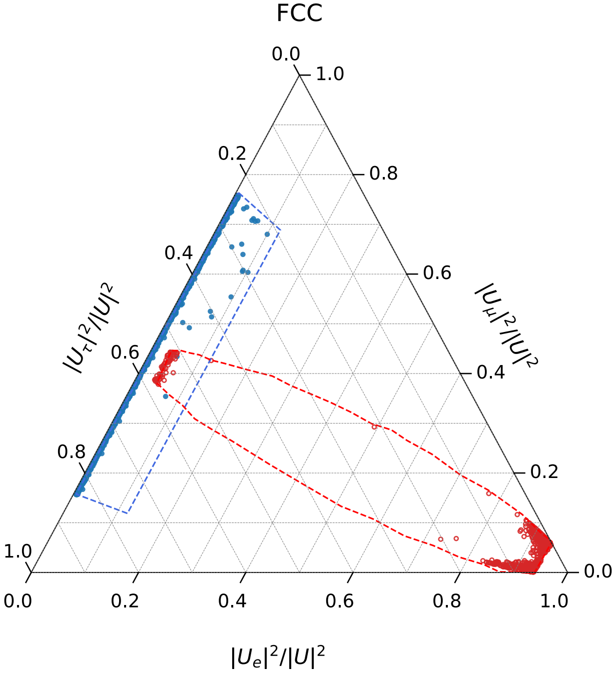
Implications for HNL mixings

In the not-so-degenerate case Y_B constrains significantly flavour ratios because flavour effects are necessary



Constrained by ν masses

$$\frac{\Delta M}{M} = 10^{-2}$$

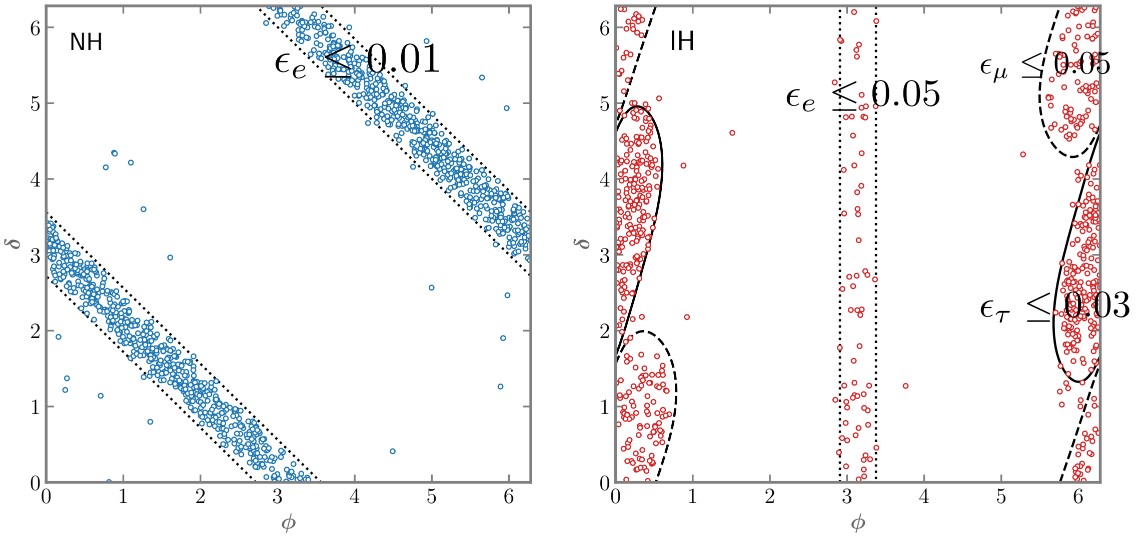


$$+ \ \frac{n_b}{n_\gamma} \checkmark$$

Implications for PMNS CP violation

In the not-so-degenerate case strong correlations with U_{PMNS} CP phases because flavour effects are necessary

$$\frac{\Delta M}{M} = 10^{-2} \qquad \frac{n_b}{n_\gamma} \surd$$



CP violation in
ν oscillations

Majorana phase

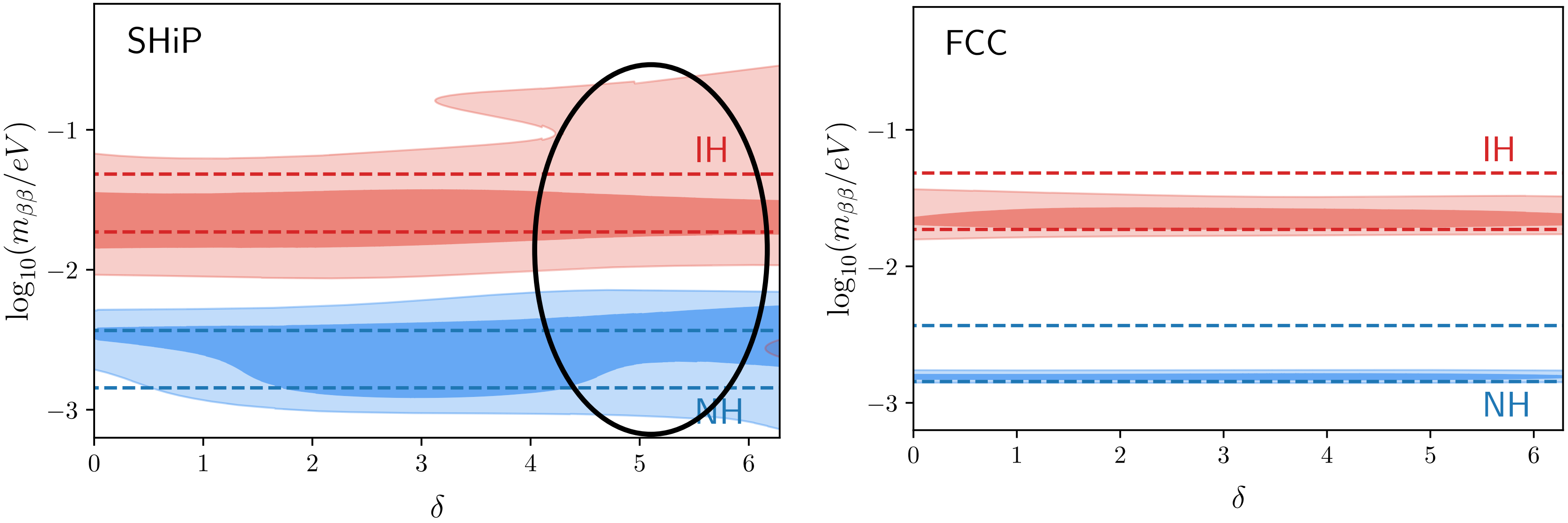
δ+ϕ in ββ0ν

Implications for ββ0ν

$$m_{\beta\beta} = \left| \sum_{i=\text{light}} U_{ei}^2 m_i + \sum_{I=\text{heavy}} \Theta_{eI}^2 M_I \mathcal{M}(M_I)/\mathcal{M}(0) \right|$$

$$\frac{\Delta M}{M} = 10^{-2}$$

$$\frac{n_b}{n_\gamma} \checkmark$$



- HNL effects on the amplitude within SHIP: no trivial dependence on phases
- Flavour effects needed for Y_B constrain the light contribution within FCC

Beyond the minimal model

Many possibilities:

Examples: type I + extra Z’,
type II, III
left-right symmetric models
GUTs, etc

Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic;
Ferrari et al + many recent refs … And many LHC analyses

- Generically new gauge interactions can enhance the production in colliders: richer phenomenology

- But also make leptogenesis more challenging (out-of-equilibrium condition harder to meet)

Conclusions

- The results of many beautiful experiments have demonstrated that ν are (for the time-being) the less standard of the SM particles

- Many fundamental questions remain to be answered however:
Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ?
Lepton vs quark flavour ?

- A new scale Λ could explain the smallness of neutrino and other mysteries such as the matter-antimatter asymmetry, DM, etc

- Complementarity of different experimental approaches: ββ0ν, CP violation in neutrino oscillations, direct searches in meson decays, collider searches of displaced vertices, etc…holds in well motivated models with a low scale Λ (GeV scale very interesting)

These tiny pieces of reality have brought many (lucky) surprises, maybe they will continue with their tradition…