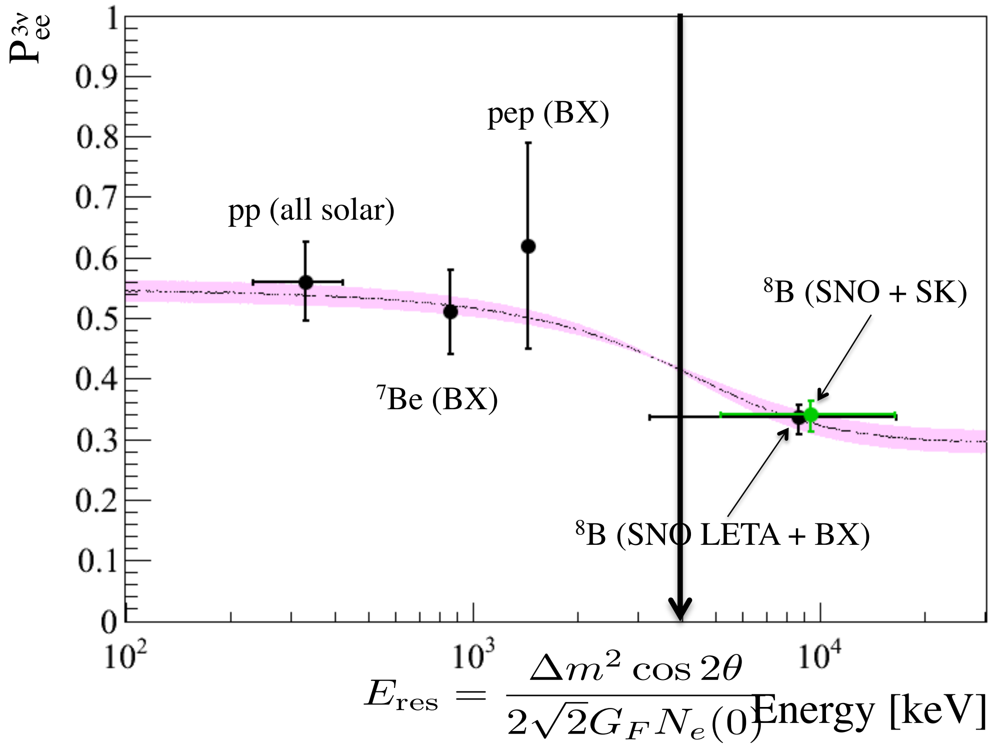
LECTURE II

- The standard 3ν scenario and its unknowns: status and prospects
- Neutrinos and beyond the Standard Model physics

Tunning to solar frequency



$$E_{\rm res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N_e(0)}$$

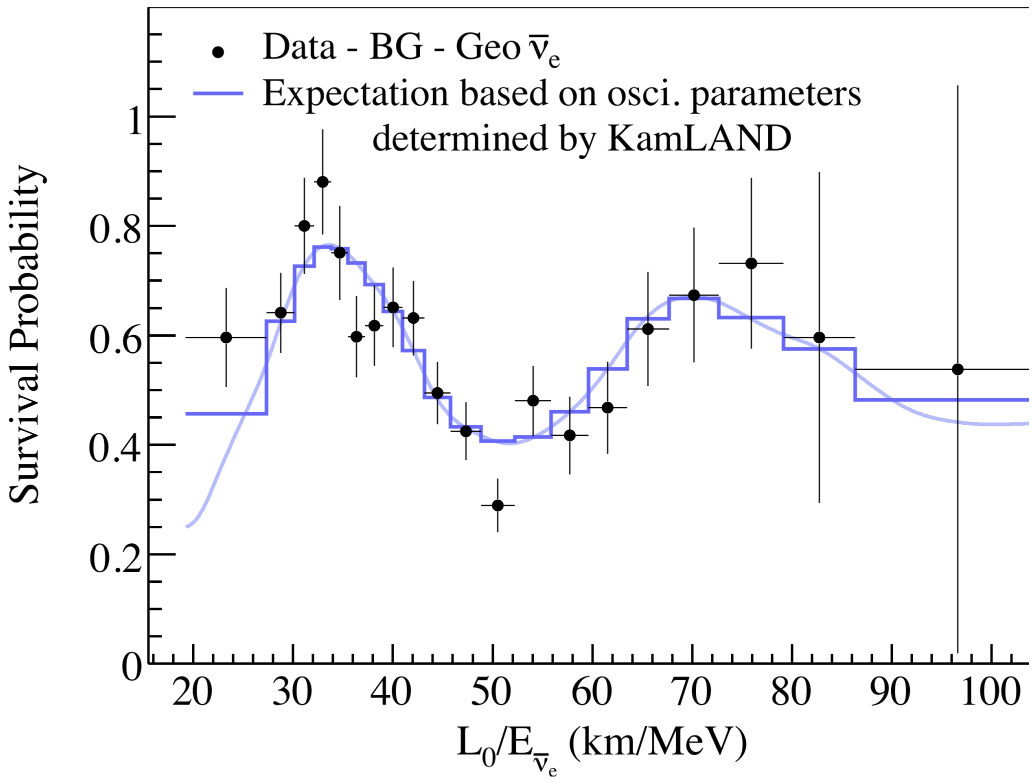
$$\sin^2\theta$$

$$|\Delta m^2| \overset{-1}{\sim} \frac{O(100Km)}{O(MeV)}$$

Only possible with reactor neutrinos!

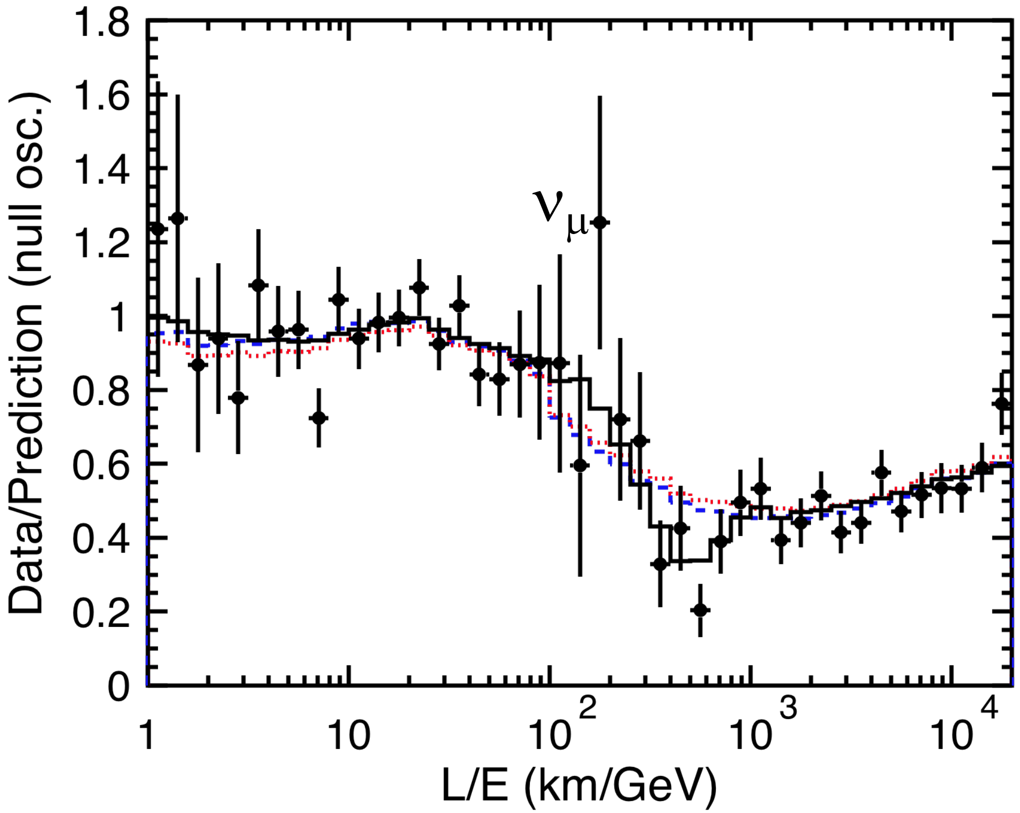
Tunning to solar frequency

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



$$|\Delta m^2|^{-1} \sim \frac{O(100Km)}{O(MeV)}$$

Tunning to atmospheric frequency

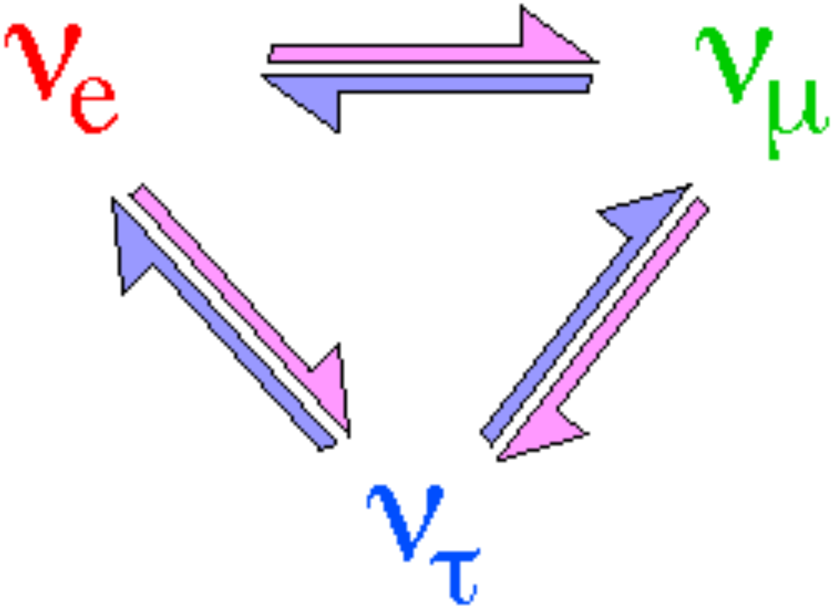


$$|\Delta m^2|^{-1} \sim \frac{O(1000Km)}{O(GeV)} \sim \frac{O(1km)}{O(MeV)}$$

Reines&Cowan experiment at 1km!

Lederman&co experiment at 1000km!

3ν scenario



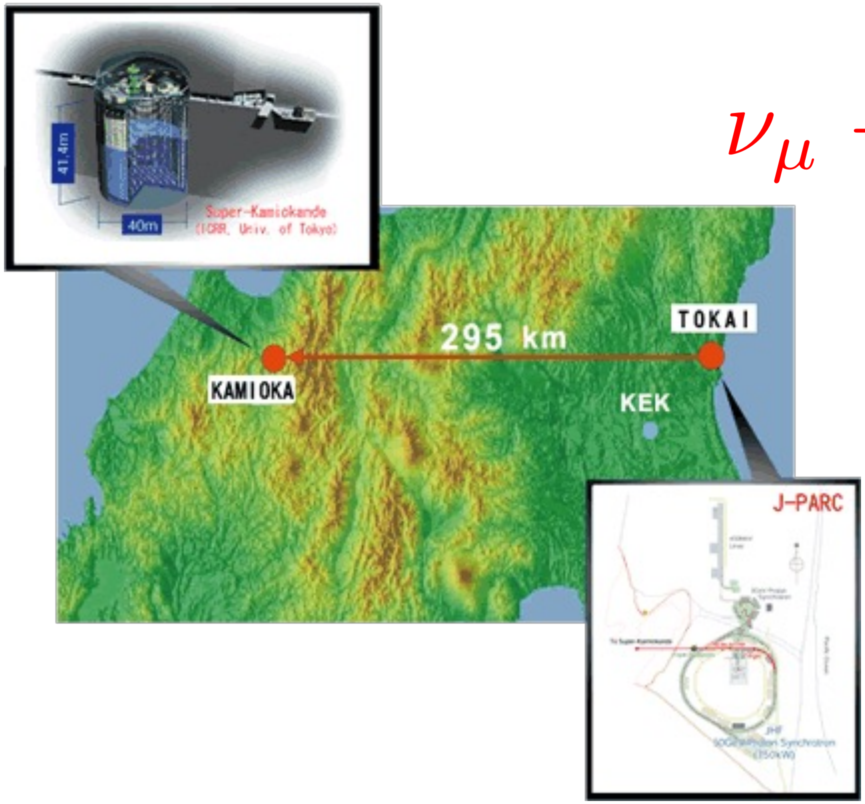
According to the master formula all flavour oscilate to all flavour with all possible wavelengths…

Tunning to atmospheric frequency

	E/L	
Accelerator ν		
$\nu_\mu \to \nu_\mu$	$\sim \mathrm{GeV}/700\mathrm{km}$	MINOS experiment (Fermilab-> Sudan)
$\nu_\mu \to \nu_\tau$	$\sim \mathrm{GeV}/700\mathrm{km}$	OPERA experiment (CERN -> Gran Sasso)
$\left.\begin{matrix} \nu_\mu \to \nu_e \\ \bar{\nu}_\mu \to \bar{\nu}_e \end{matrix}\right\}$	$\sim \mathrm{GeV}/300\mathrm{km}$ $\sim \mathrm{GeV}/800\mathrm{km}$	T2K (Tokai-Kamioka) NoVA (Fermilab->Ash River)
Reactor ν		
$\bar{\nu}_e \to \bar{\nu}_e$	$\sim \mathrm{MeV}/1\mathrm{km}$	DAYA-Bay, RENO, DChooz experiments (reactors in China, Korea, France)

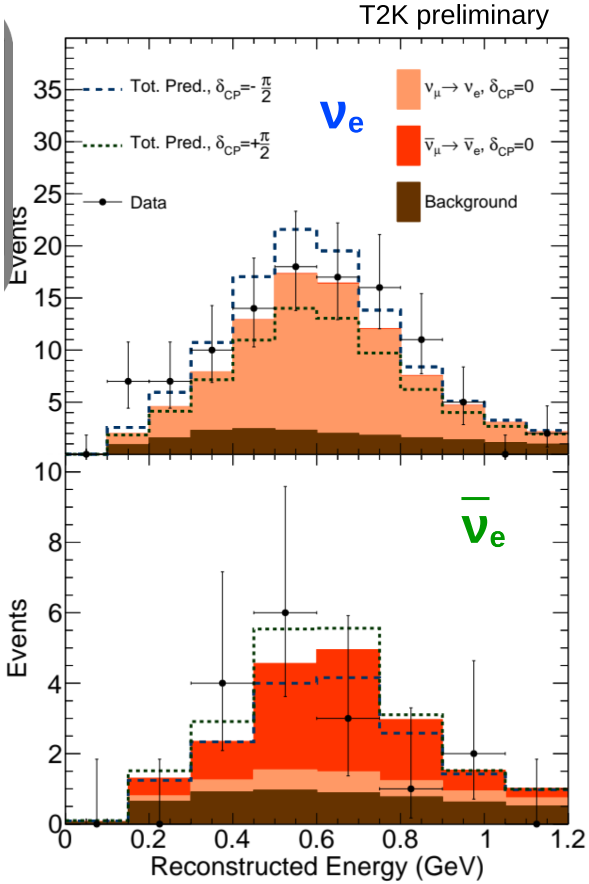
Accelerator Neutrinos :T2K

Using the SuperKamiokande detector!



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

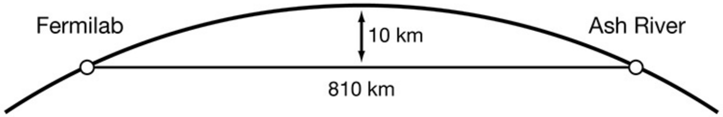
@L=300km

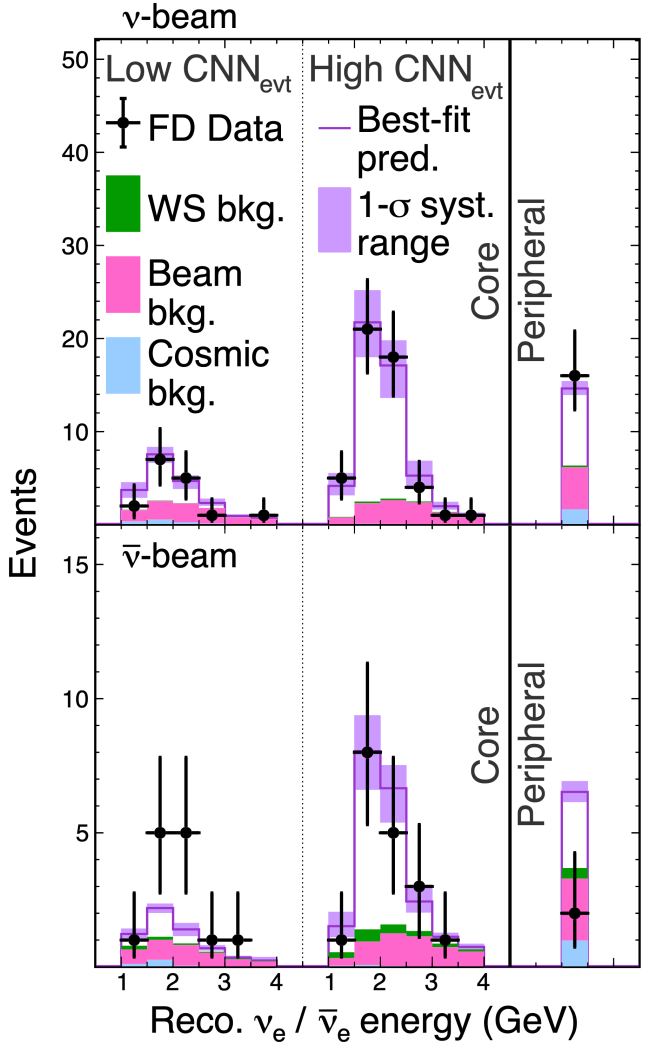


$$|\Delta m^2_{\text{atmos}}| \simeq 2.5 \times 10^{-3}\ eV^2$$

Accelerator Neutrinos : NOνA

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





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

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}

1) 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

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

1)Tunning to the large splitting and neglecting the small one:

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

Accelerator Neutrinos (MINOS, OPERA)

$$P(\nu_e \to \nu_\mu) = 0$$

$$P(\nu_e \to \nu_\tau) = 0$$

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

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

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

1) 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 (Daya Bay, Dchooz, RENO)

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

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

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

2) Tunning to the small splitting and averaging large oscillations:

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

Reactor Neutrinos

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

2)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

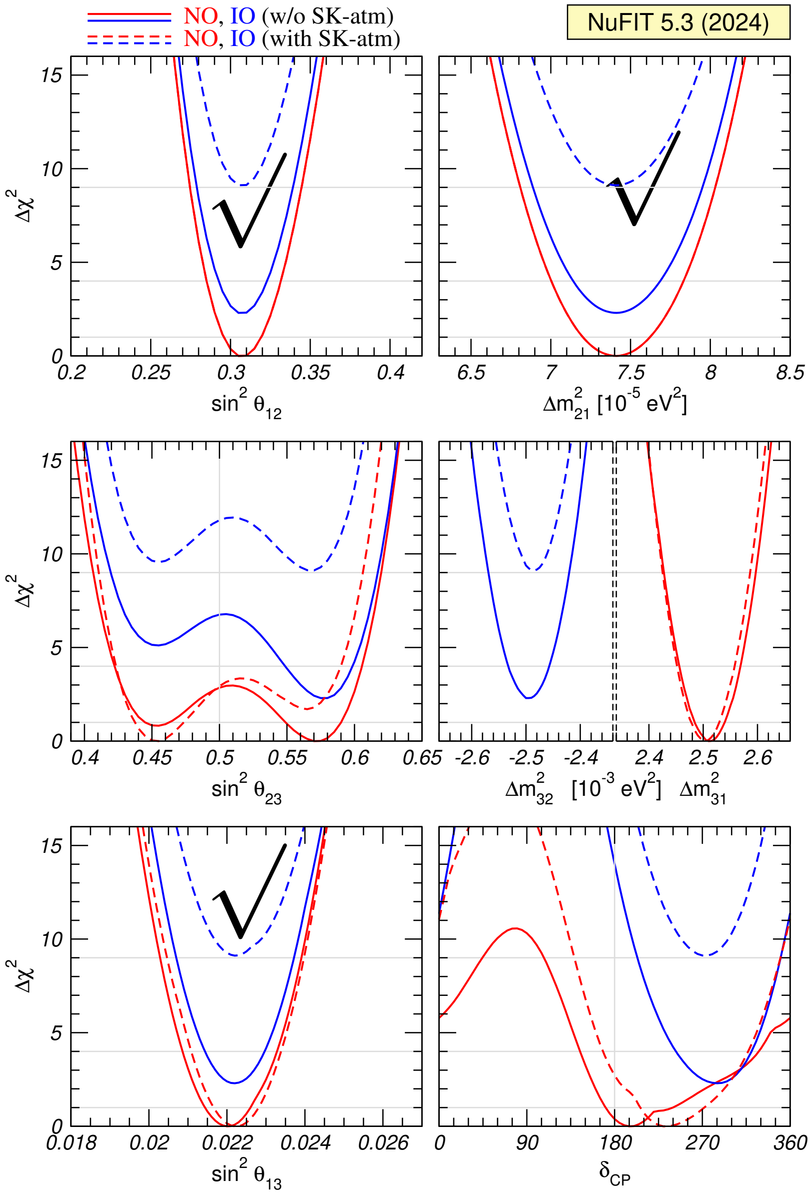
$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq \qquad 1 - \sin^2 2\theta_{12} \, \sin^2\left(\frac{\Delta m^2_{12}}{4E} L\right)$$

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

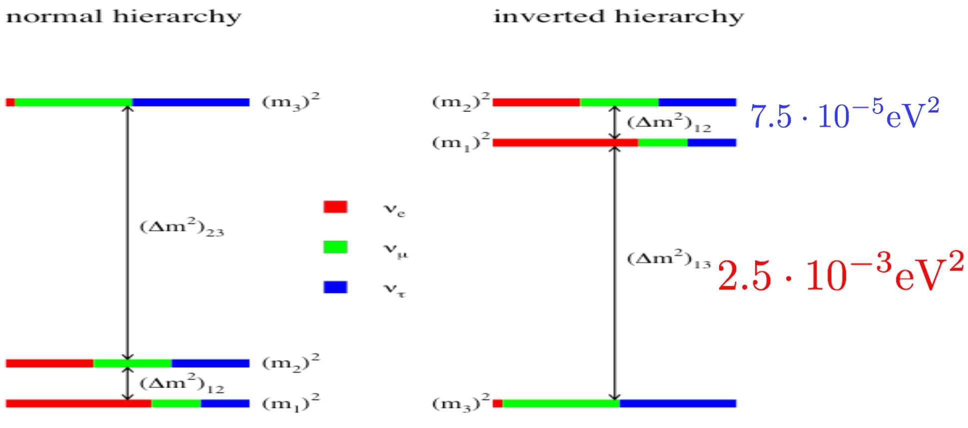


$\theta_{12} \sim 34°$

$\theta_{23} \sim 42°$ o $48°$

$\theta_{13} \sim 8.5°$

$\delta \sim\ ?$



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

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

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

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

Esteban et al ’20; de Salas et al, ’21 and Capozzi et al ‘21

The big open questions

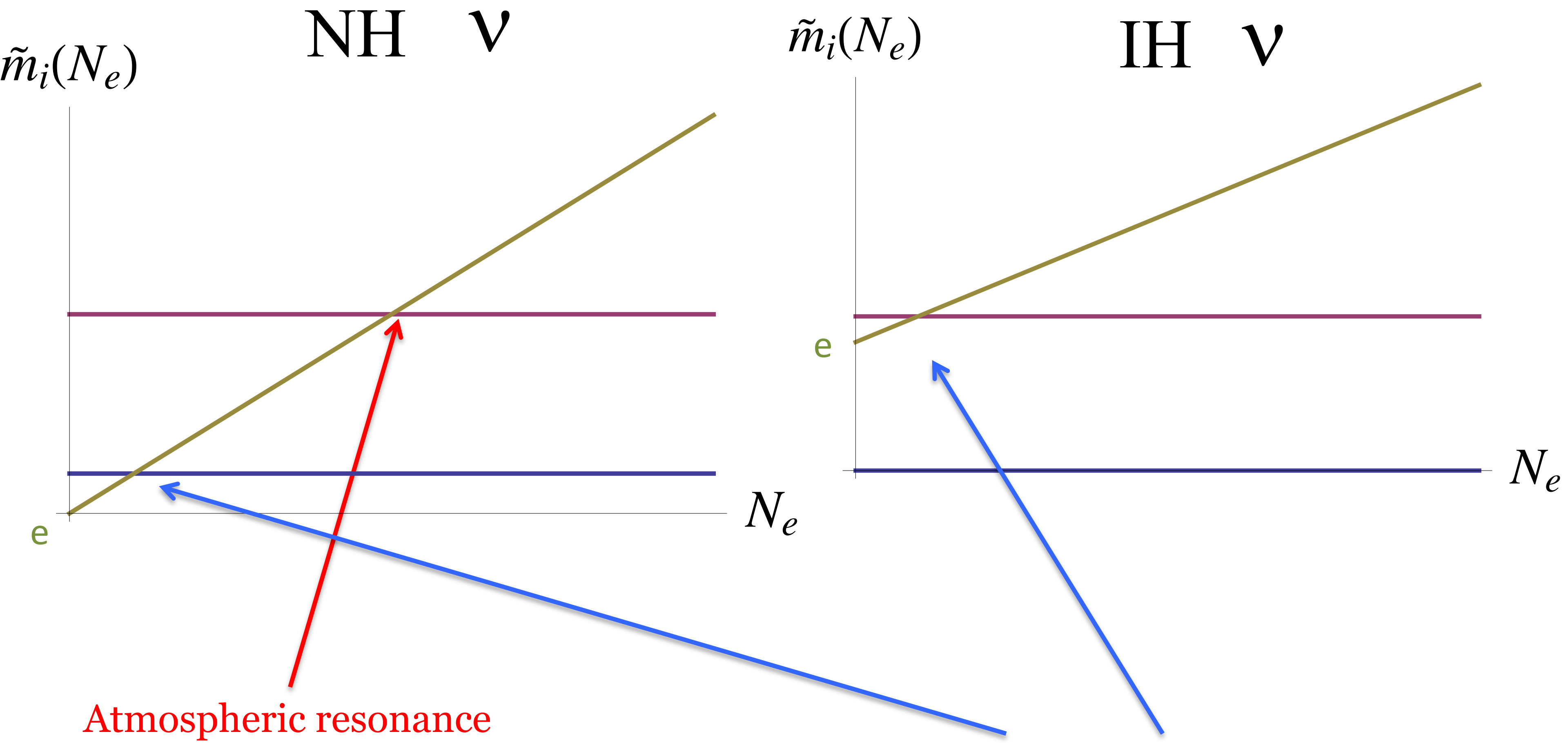
What is the neutrino ordering normal or inverted ?

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

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

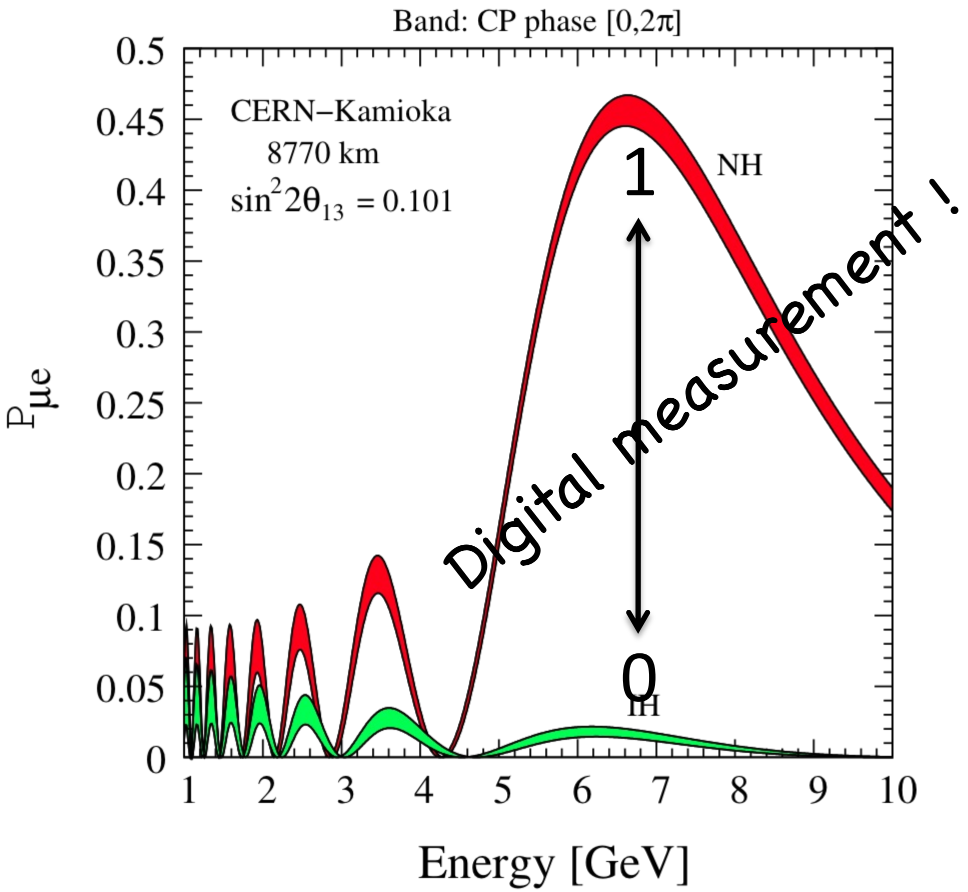
Earth density, E_{res} ~ few GeV !

Solar resonance

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

Solar density, E_{res} ~ few MeV !

Hierarchy through MSW @Earth



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

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

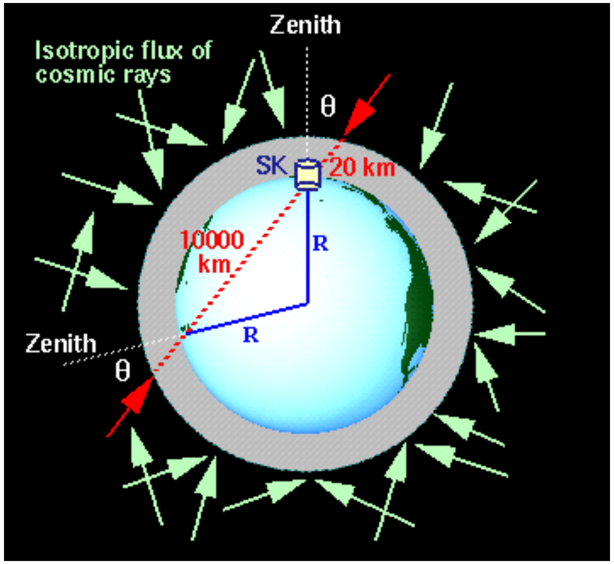
Spectacular MSW effect at O(6GeV) and very long baselines

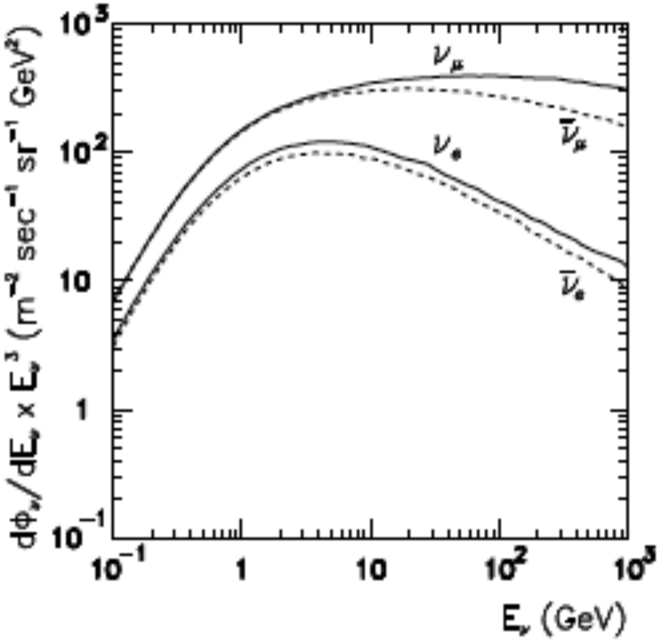
Even if we don’t shoot so far away, relatively easy measurements for L >1000km

Shorter distances degeneracy with δ

Hierarchy from atmospherics ? the hard way…

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

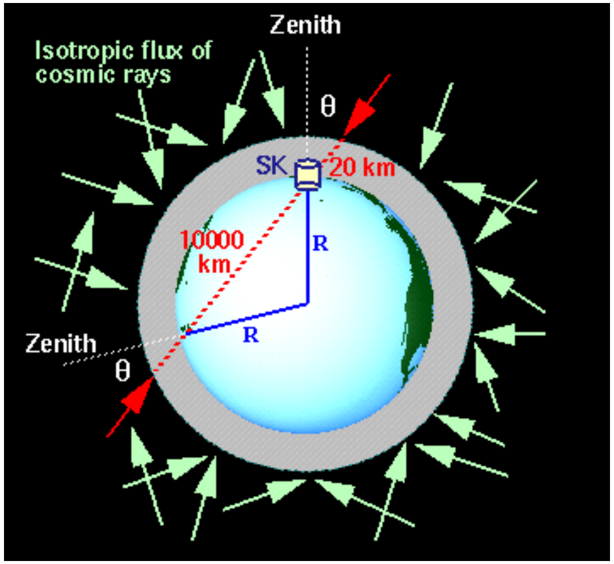


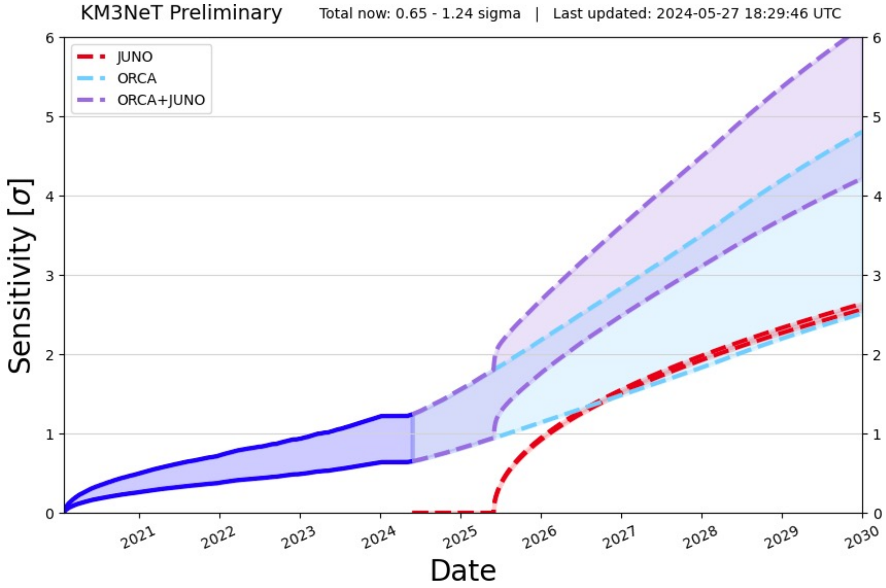


Atmospheric data contain the golden signal but hard to dig…
neutrino telescopes (ORCA/KM3NET, PINGU/ICECUBE) or improved atmospheric detectors (HyperK, INO)

Hierarchy from atmospherics ? the hard way…

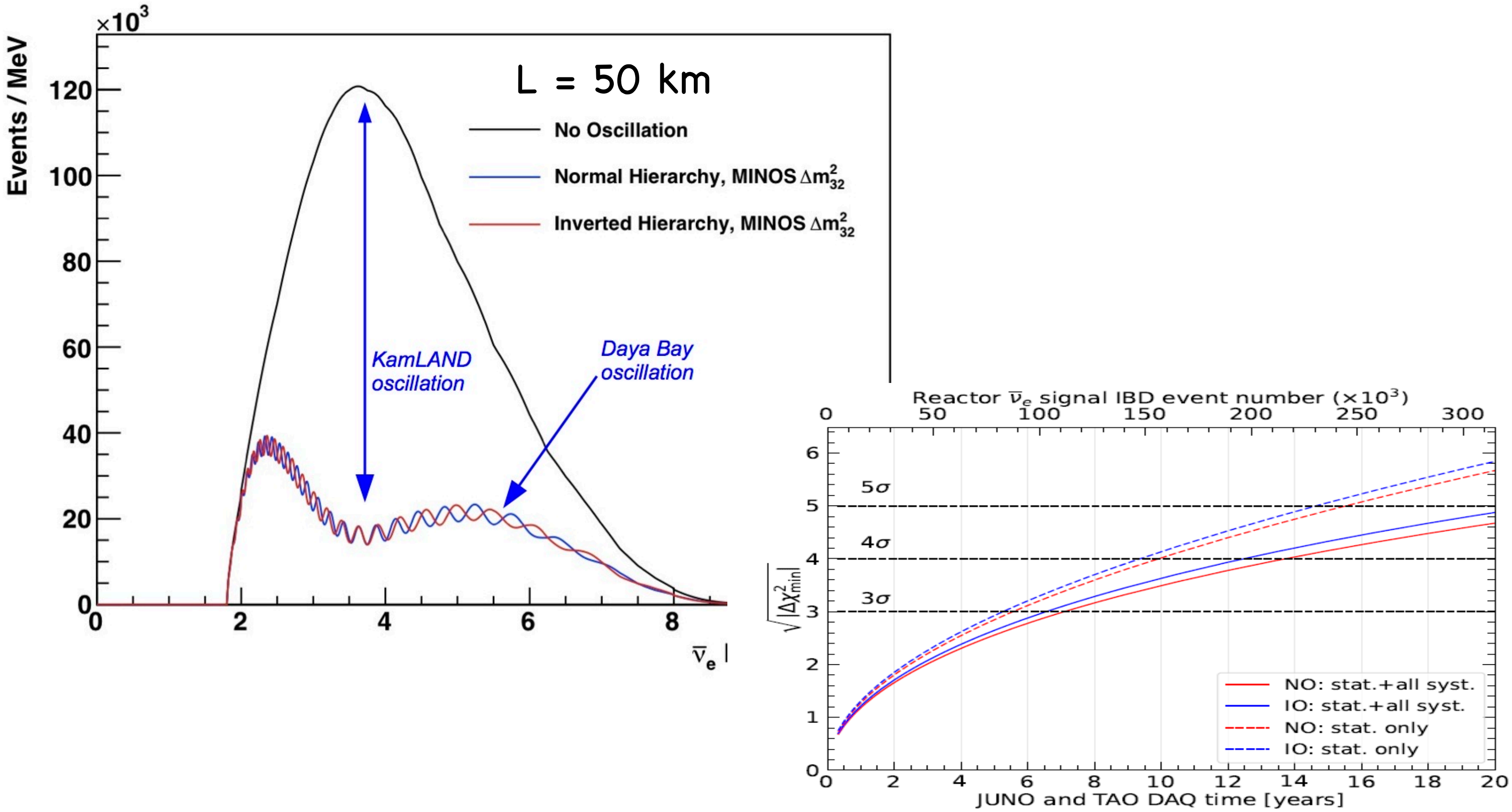
$$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$$





Atmospheric data contain the golden signal but hard to dig…
neutrino telescopes (ORCA/KM3NET, PINGU/ICECUBE) or improved atmospheric detectors (HyperK, INO)

Hierarchy from reactor ν's : the hard way?



JUNO experiment is planning to do this measurement

Leptonic CP violation

CP violation shows up in a difference between

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

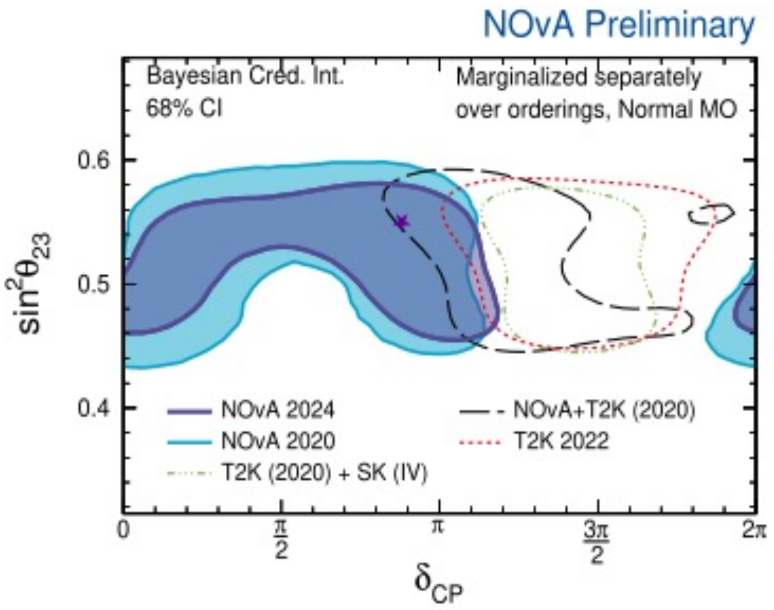
Golden channel: $\nu_\mu \leftrightarrow \nu_e$

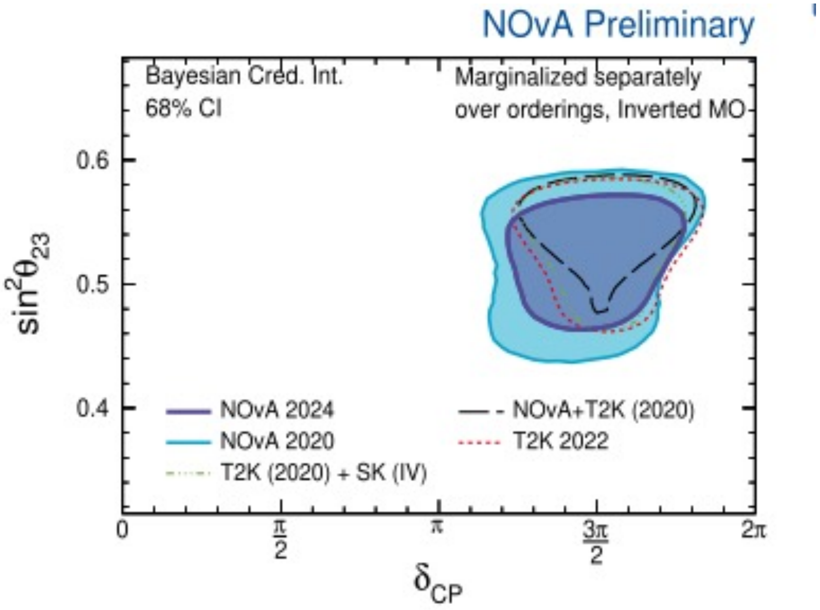
$$\begin{aligned} P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23} L}{2}\right) \equiv P^{atmos} \\ &+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) \equiv P^{solar} \\ +\tilde{J} & \cos\left(\pm\delta - \frac{\Delta_{23}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

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

simultaneous sensitivity to both splittings is needed

Nova vs T2K



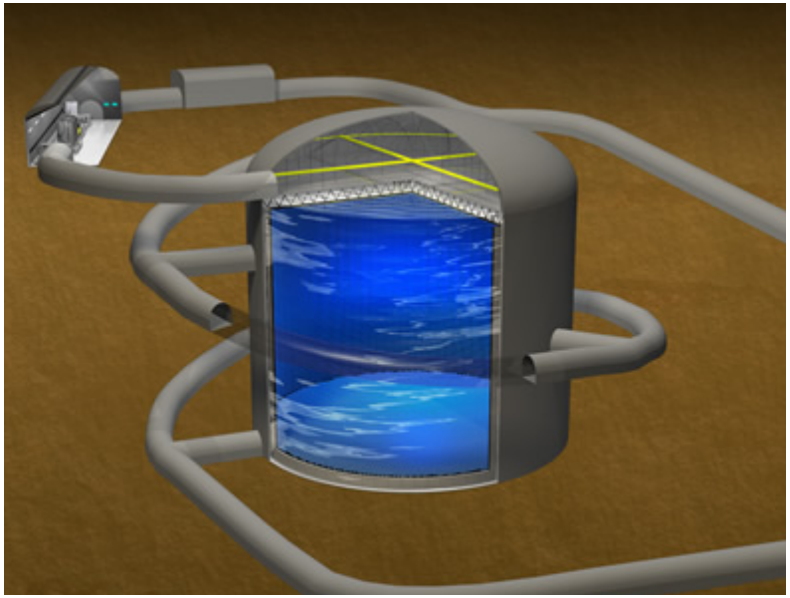


Neutrino 2024

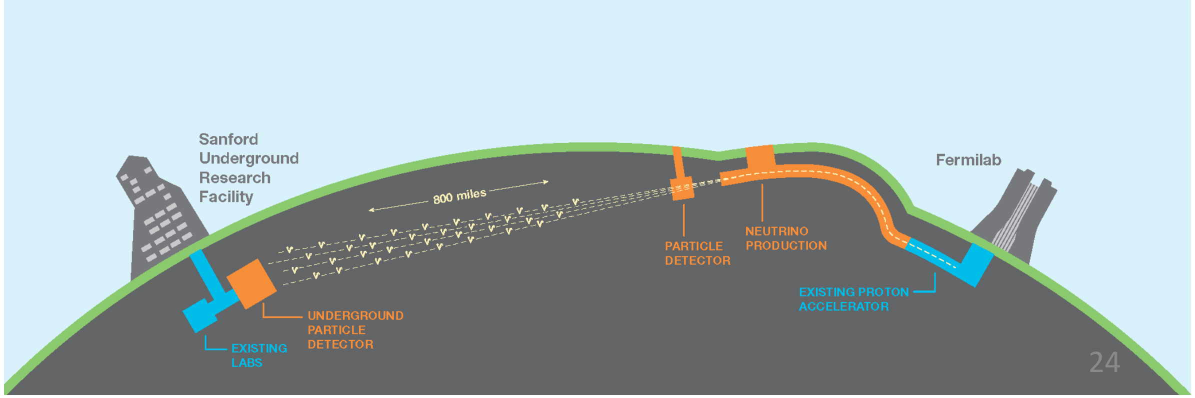
- NO: Tension between T2K and Nova data
- IO: preference for CP violation

Hierarchy + CP in one go…
superbeams+superdectectors

Japan Hyper-Kamiokande: 295km

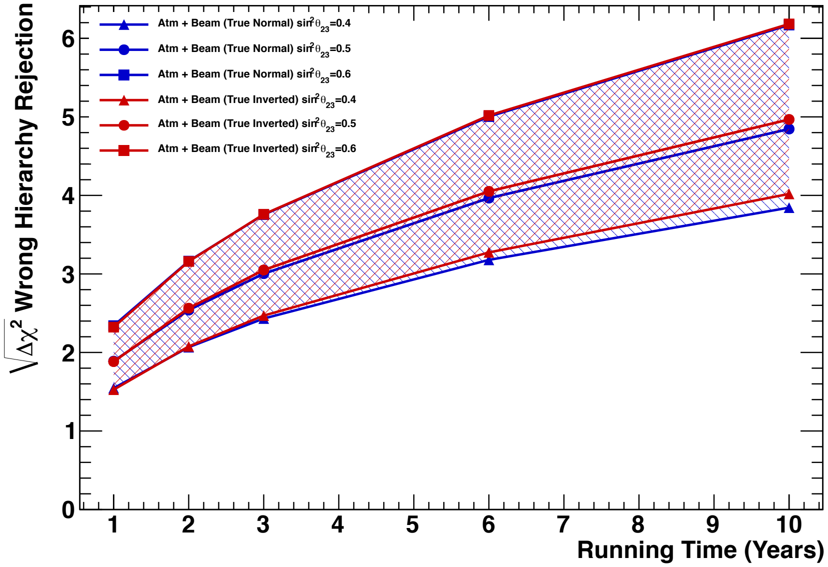


USA DUNE: 1300km



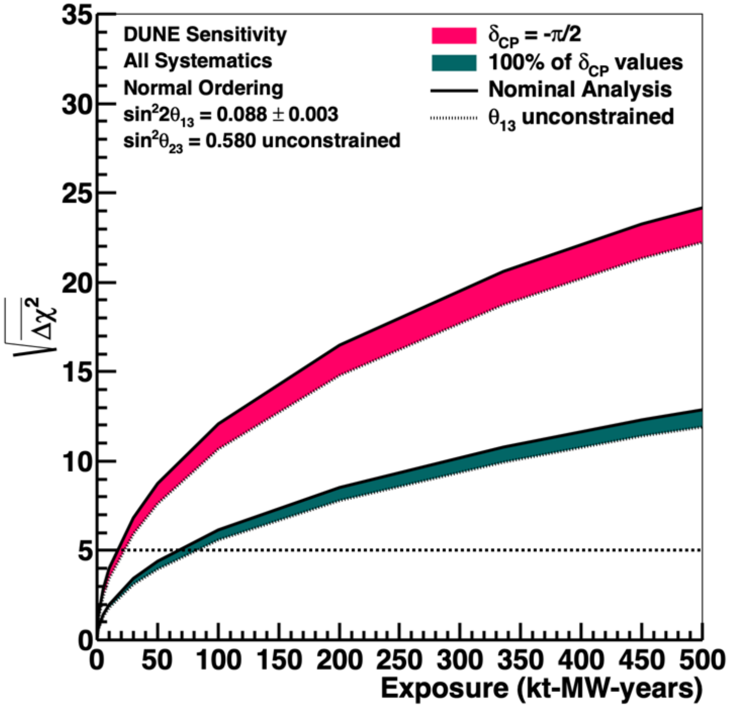
Hierarchy

Hyper Kamiokande



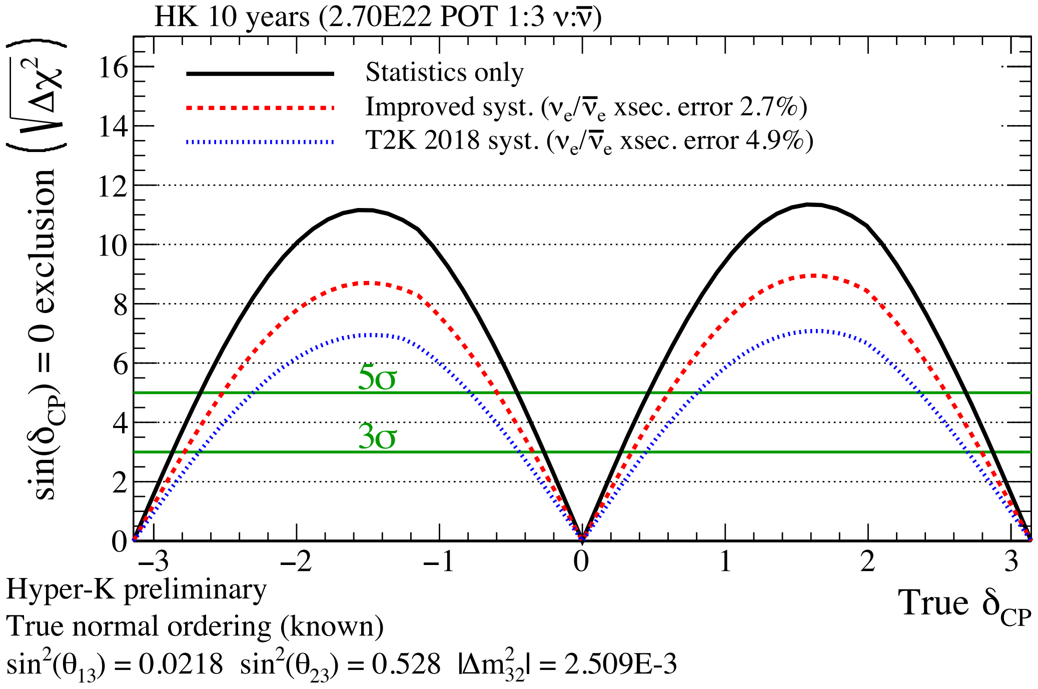
(Using atmospheric neutrinos)

DUNE

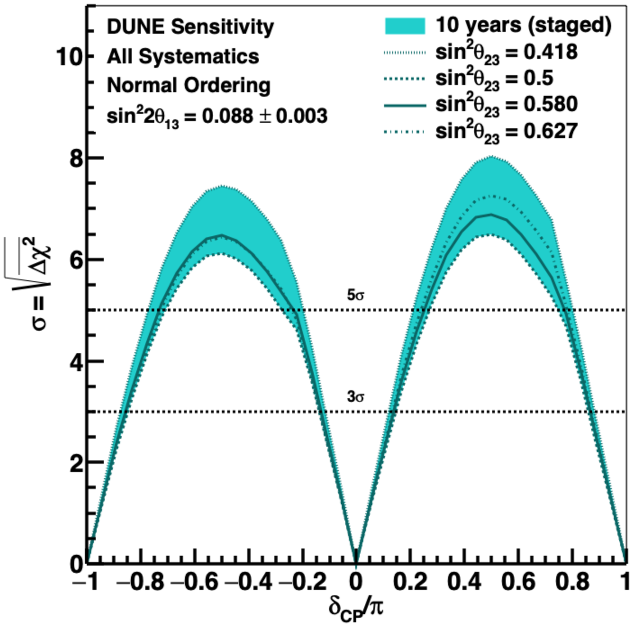


CP violation

Hyper Kamiokande (10y)



DUNE(10y)



Neutrino Anomalies

(LSND, MiniBOONE, Reactor,..)

Still there, likely non-under-full-control systematics, no BSM explanations provide good fits to data…

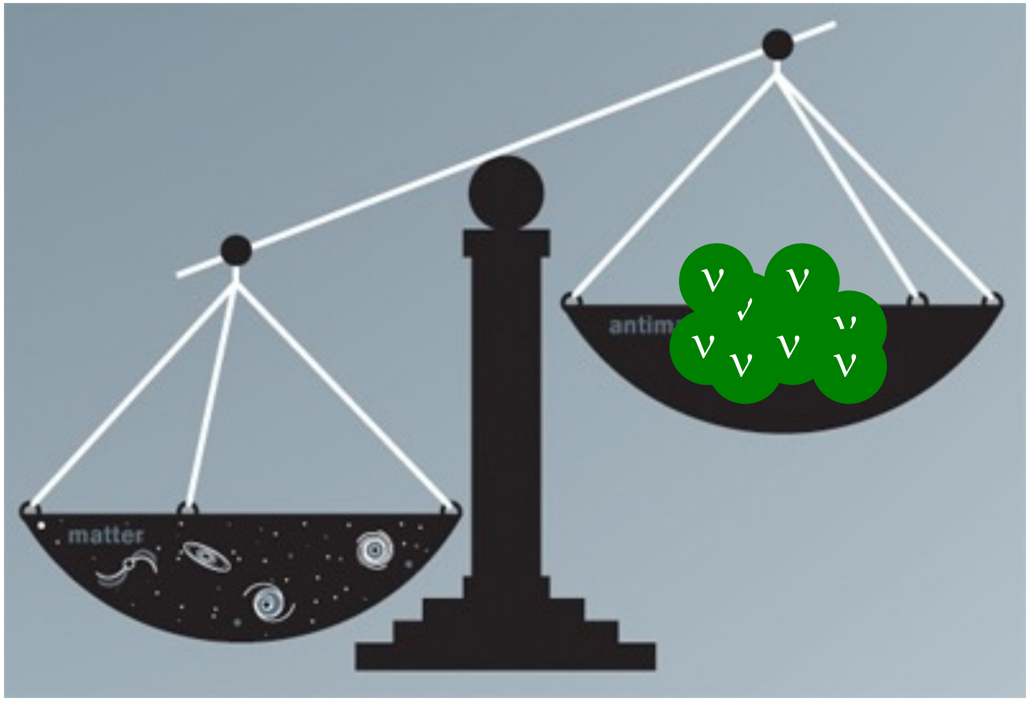
The other big open questions

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



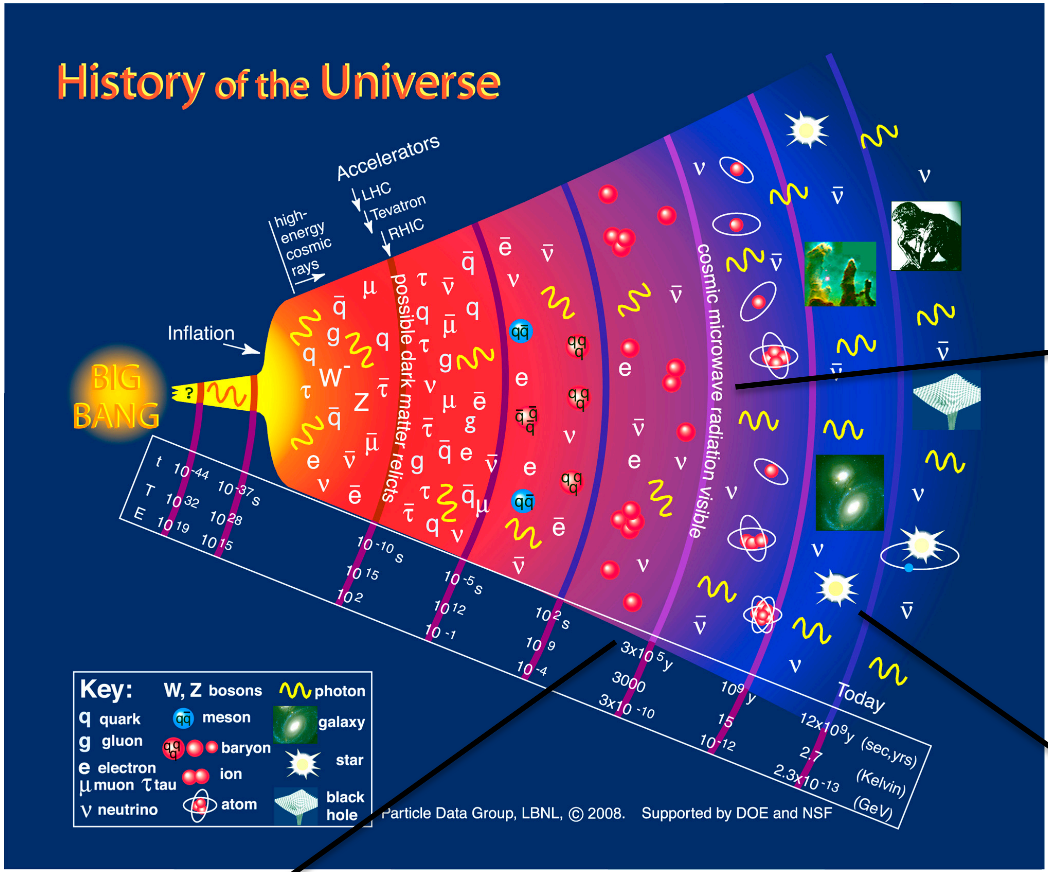
Planck '18 $\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

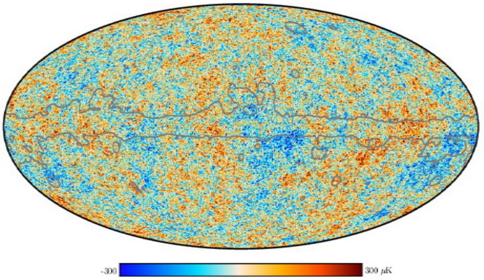
Cosmological neutrinos

-> Turok's lectures

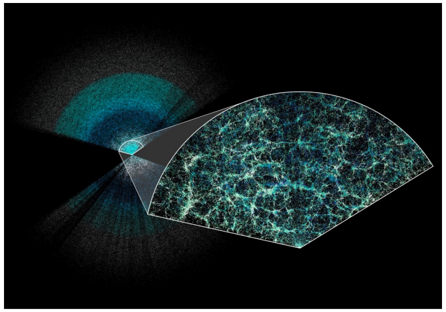
Neutrinos have left many traces in the history of the Universe

$$\sum m_\nu$$





CMB



Galaxy distribution (LSS)

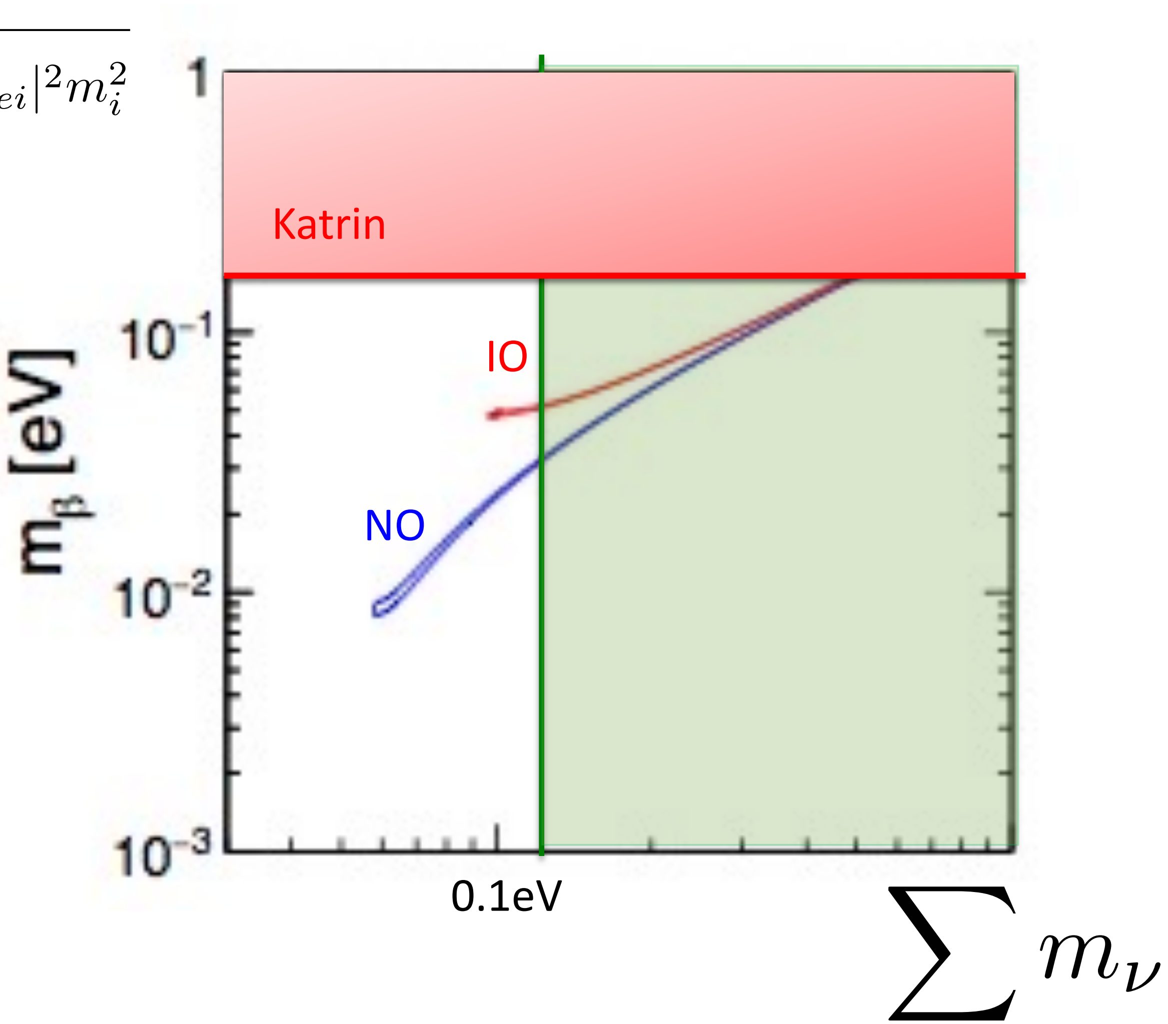
Nucleosynthesis N_ν

Absolute ν mass scale

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

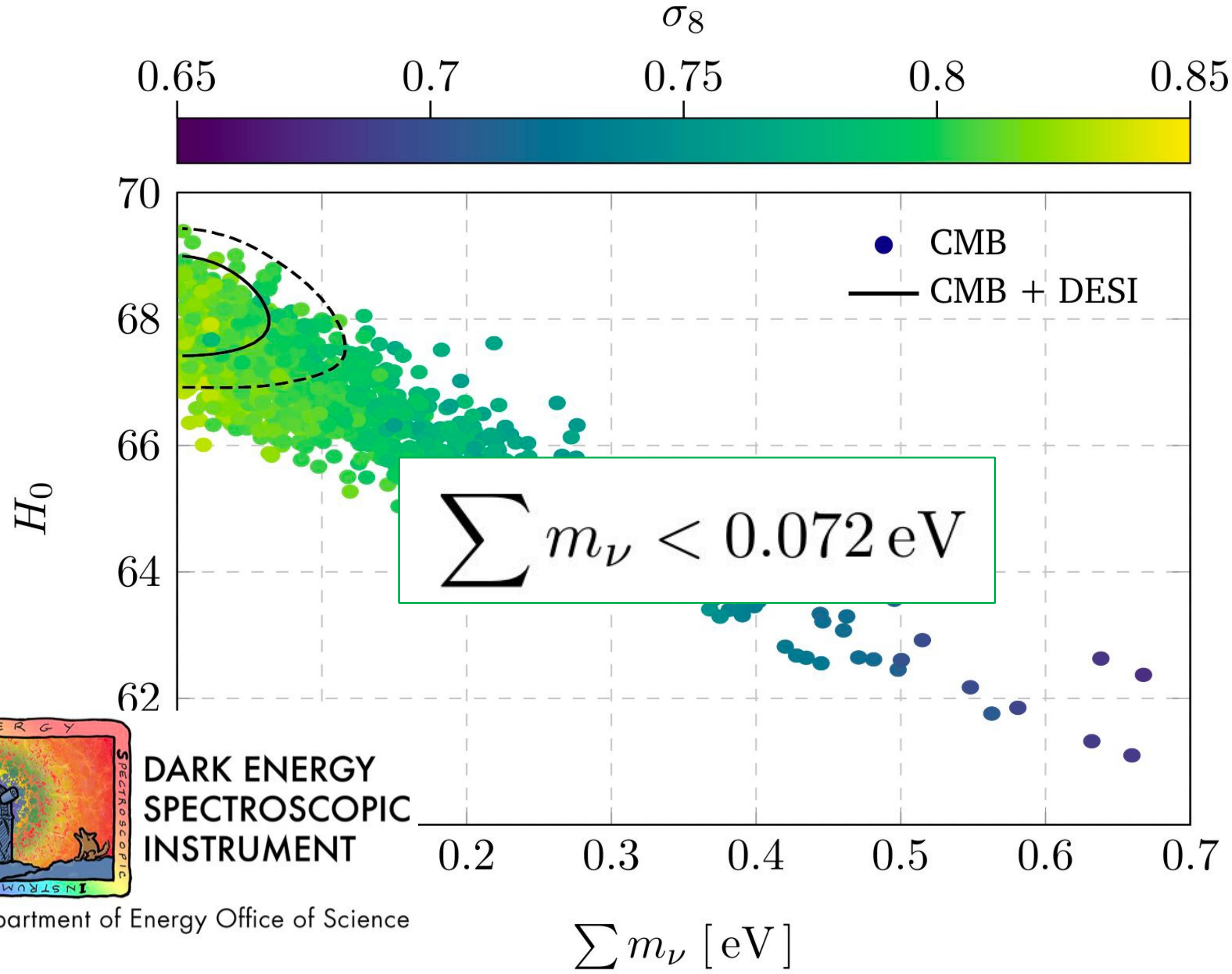
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium



Cosmo

Cosmological neutrinos



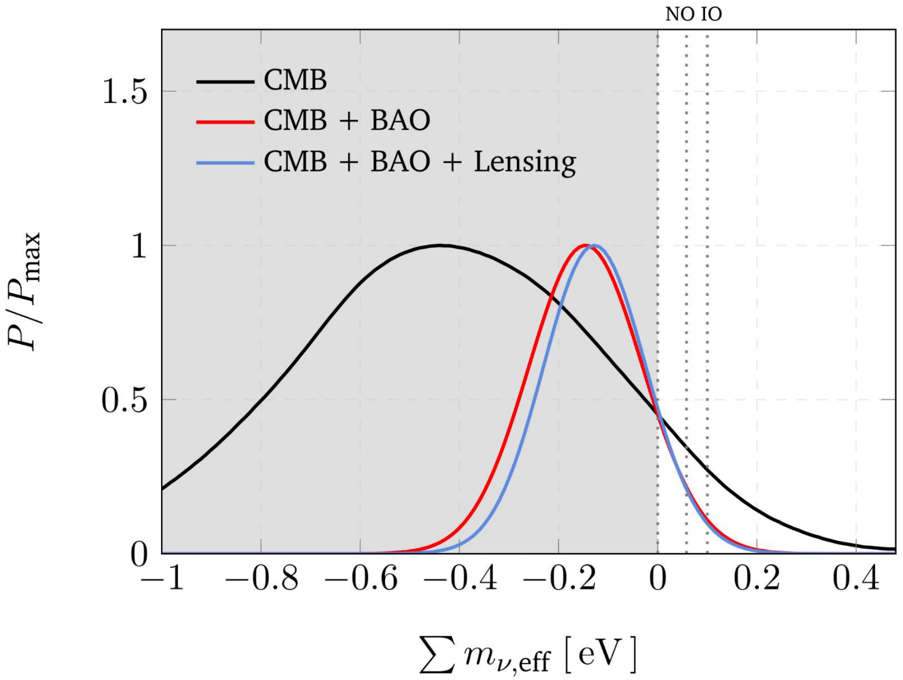
$$\sum m_\nu < 0.072\,\mathrm{eV}$$

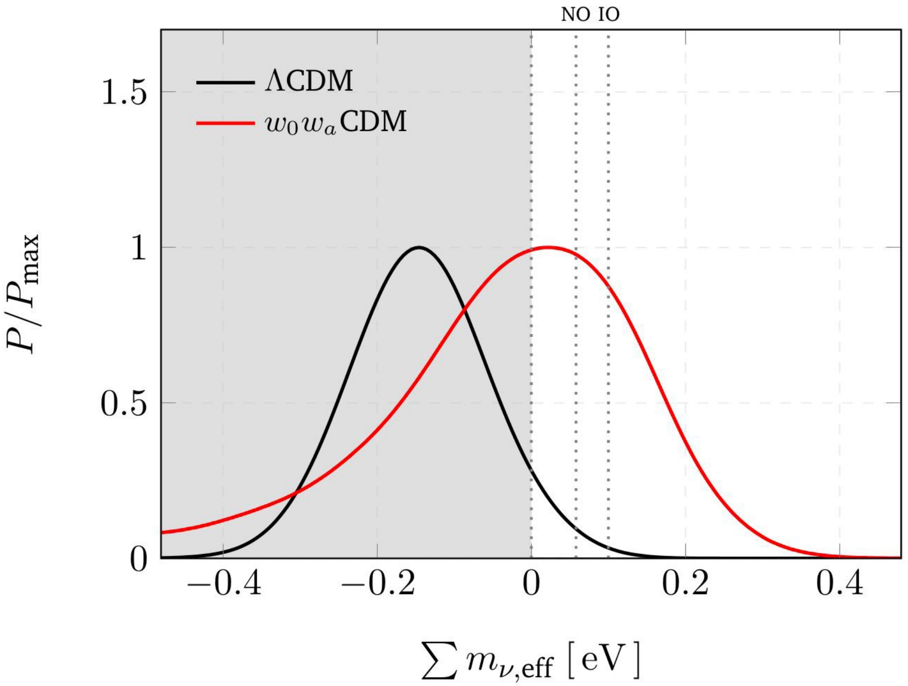
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Cosmological neutrinos

- 2-6-2.8σ tension between Λ CDM with physical neutrino masses



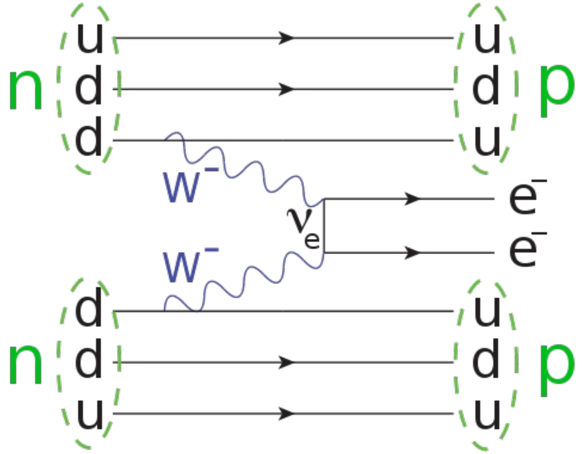


- No tension with physical neutrino masses time-evolving dark energy

$$\sum m_\nu < 0.195\,\text{eV}$$

Majorana nature: ββ0ν

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

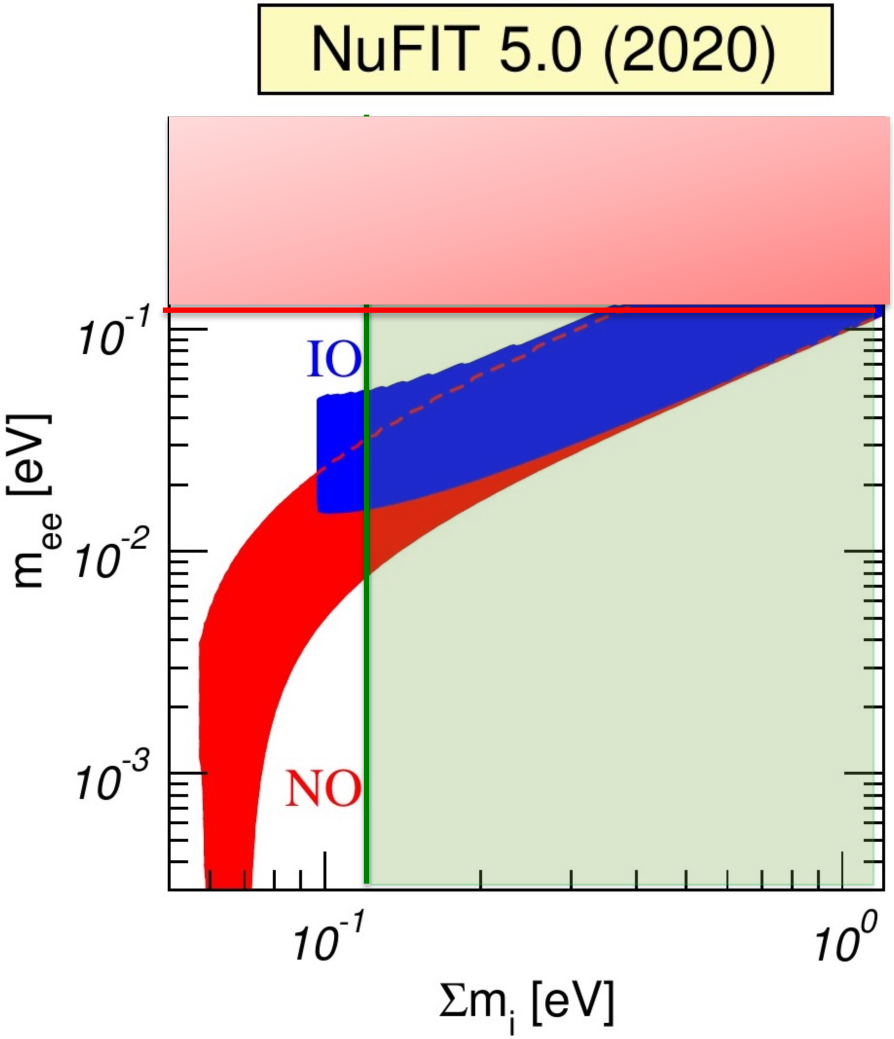


$$T^{-1}_{2\beta0\nu} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear M.E.}} \underbrace{\left|\sum_i \left(V^{ei}_{MNS}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

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

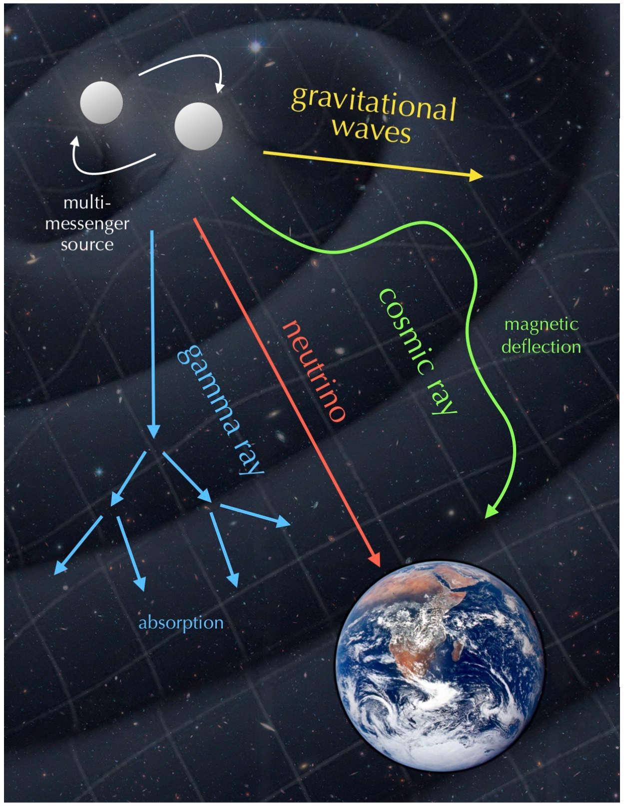
Majorana nature: ββ0ν

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

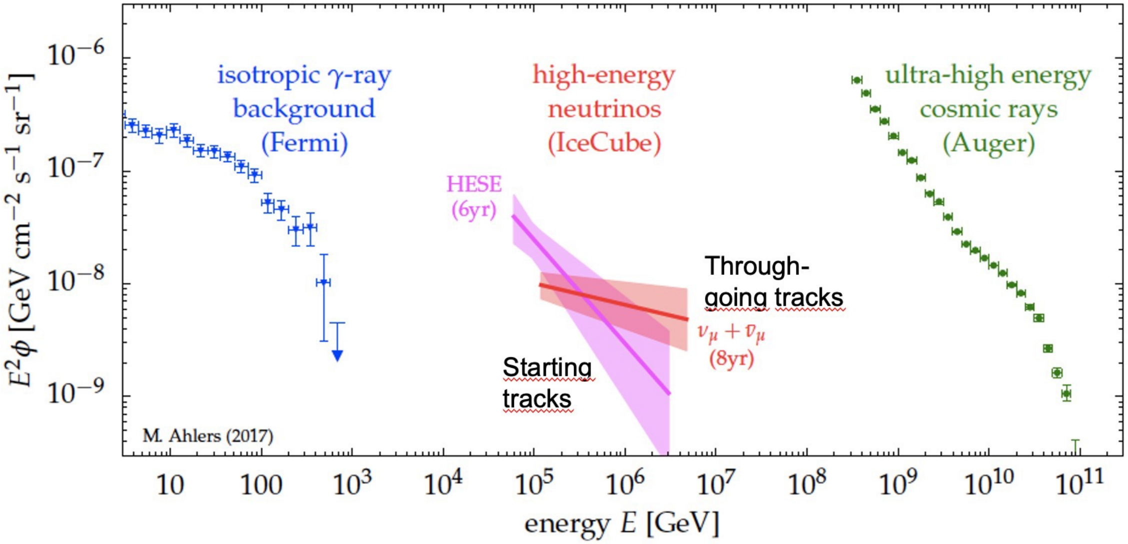


Next generation of experiments @Ton scale to cover the IO region (eg. LEGEND)

New era of ν physics:
neutrino astronomy…

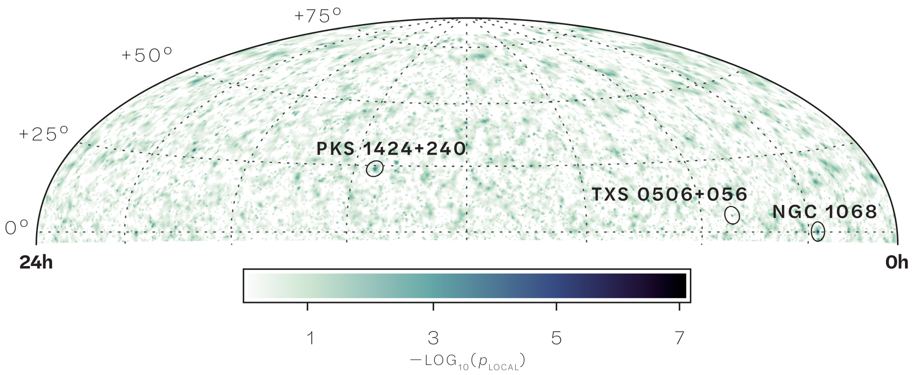


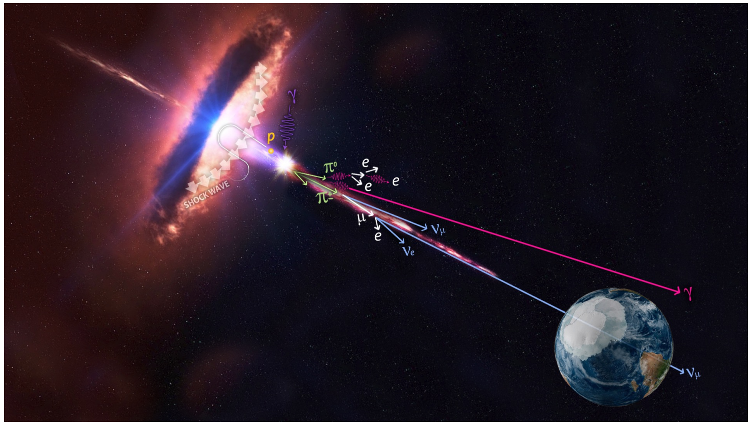
Understand Astrophysical sources

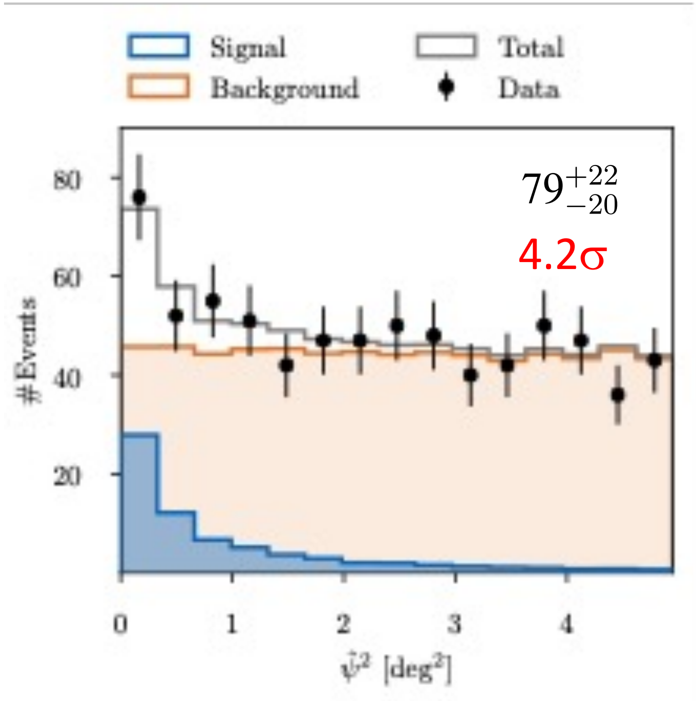


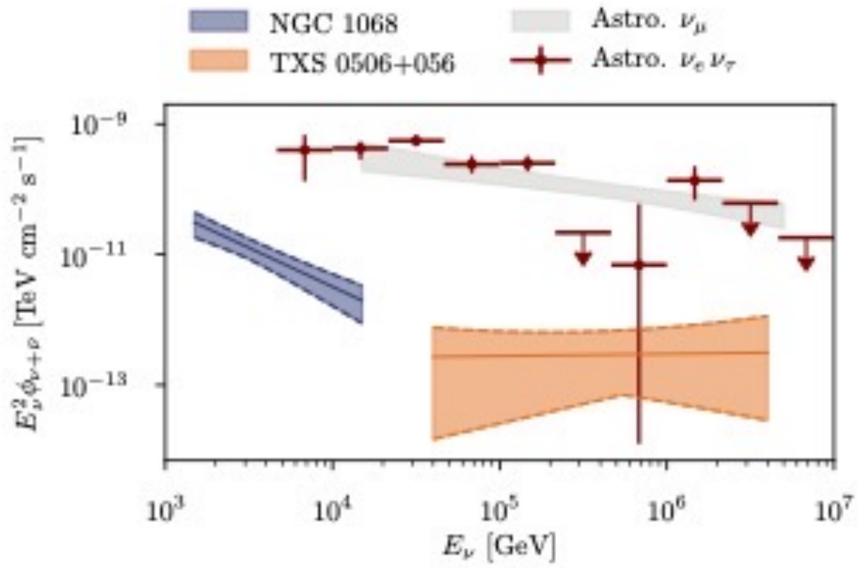
Just as neutrino allowed us to understand the processes in the stars, they might help us to understand the most powerful sources in the Universe

Icecube started mapping the most powerful cosmic accelerators



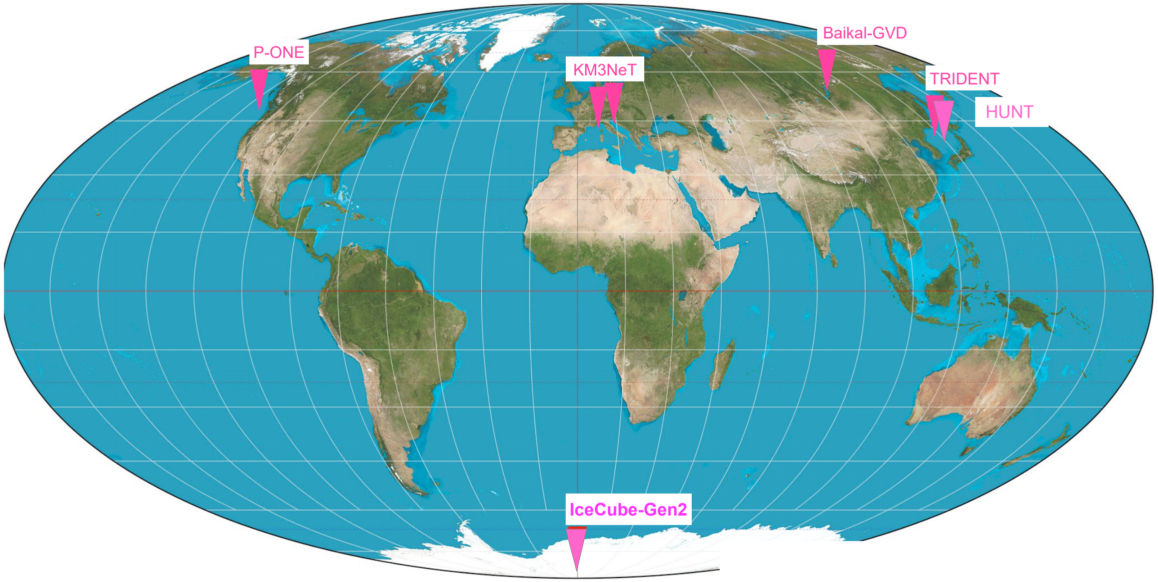


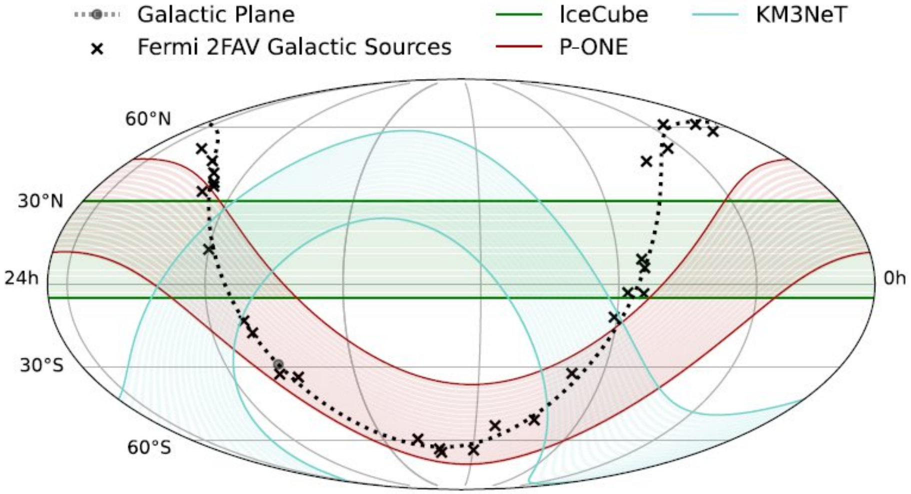




Icecube col. 2211.09972

Mapping the Universe with HE ν

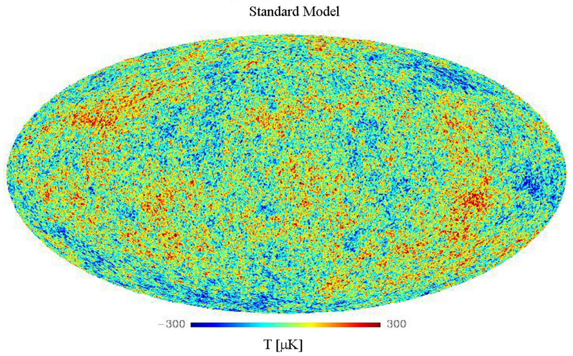




Courtesy: P-ONE, L. Schumacher (Erlangen), S. Sclafani (Univ of Maryland)

N. Kurahashi Neilson Neutrino '24

New era of ν physics:CνB?



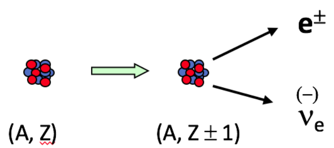
Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

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

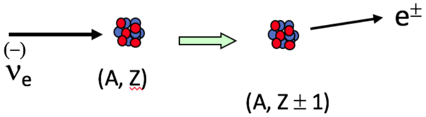
$$T_\nu = 1.95K \simeq 2\times 10^{-4}\text{eV}$$

PTOLEMY experiment

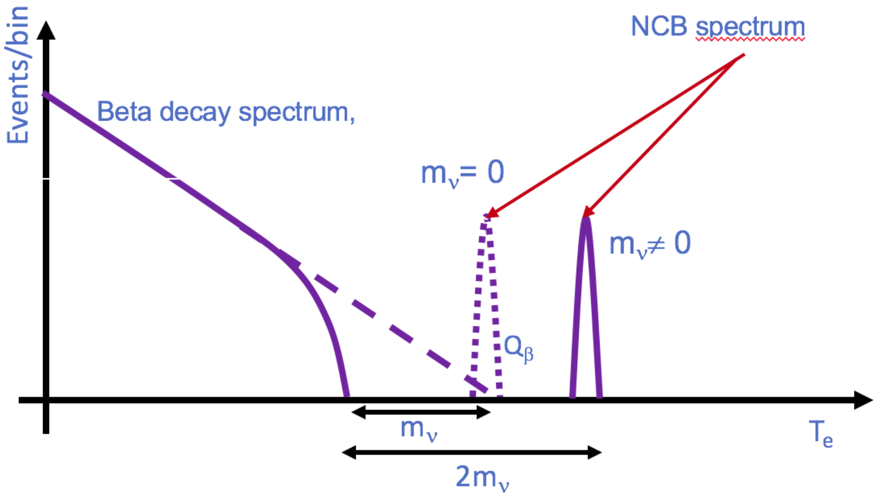
β decay



Neutrino Capture on a Beta Decaying Nucleus (NCB)



Atomic Tritium on graphene



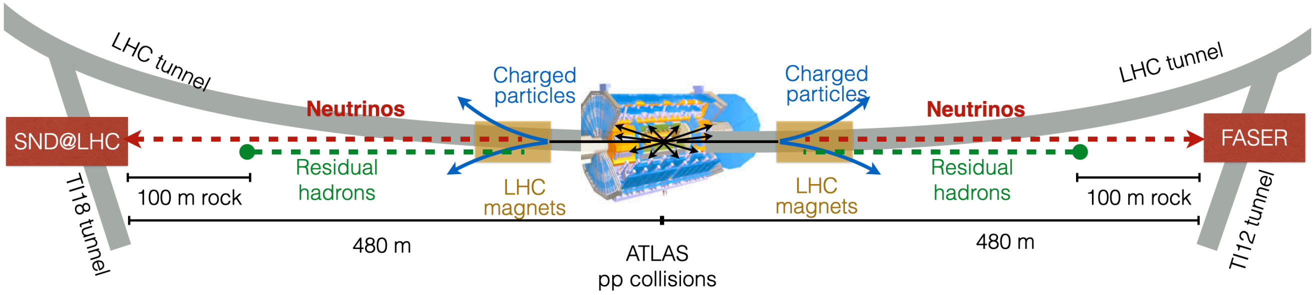
M. Messina ‘18

A picture of the Universe before nucleosynthesis!

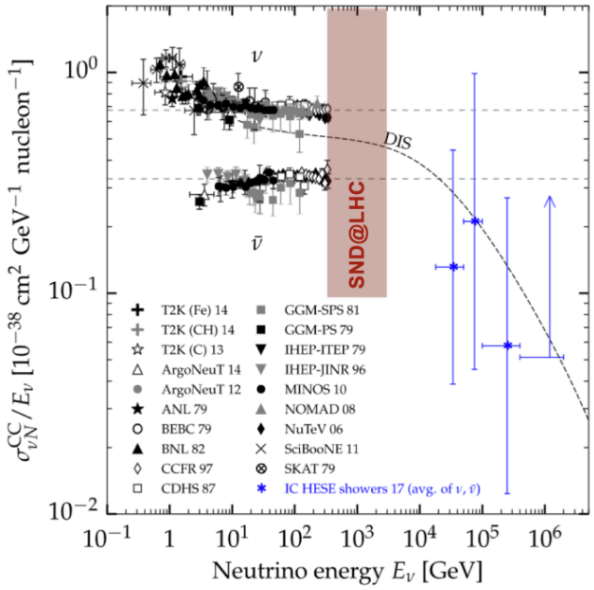
New era of ν physics:

Neutrino interactions in new regimes

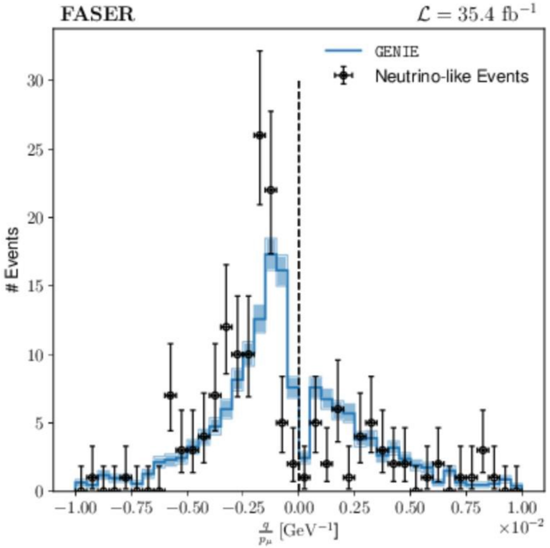
LHC is an intense source of TeV scale neutrinos !



PRL 122 (2019) 041101



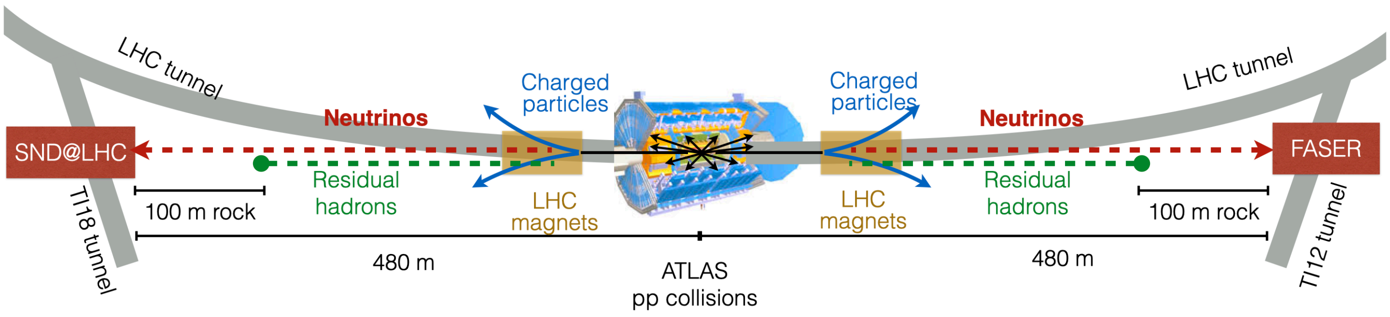
16σ evidence for LHC neutrinos

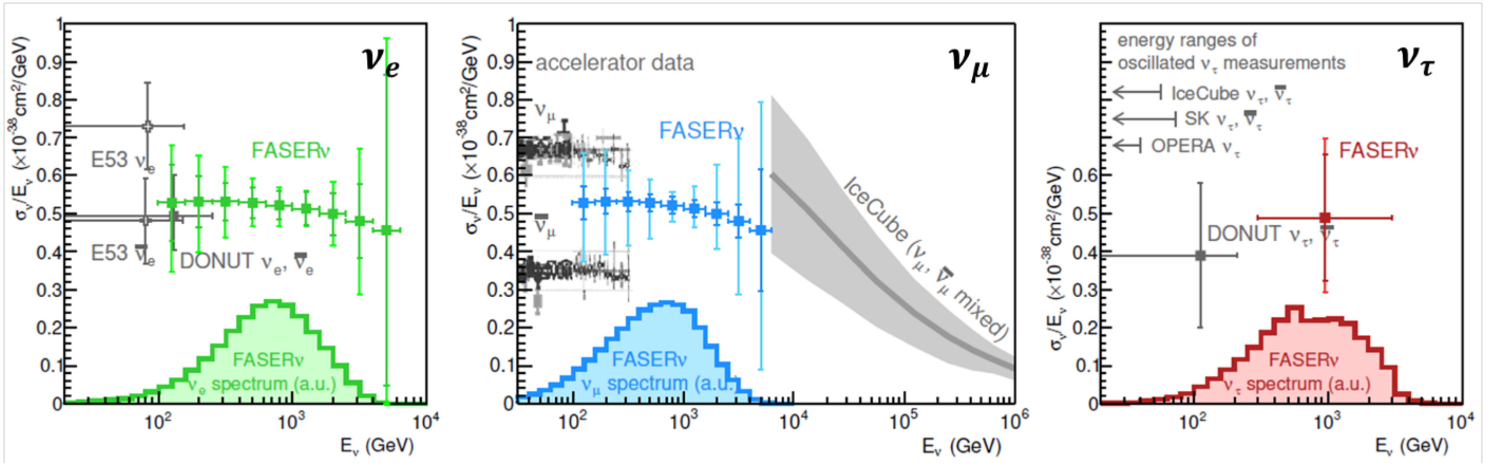


New era of ν physics:

Neutrino interactions in new regimes

LHC is in intense source of TeV scale neutrinos !

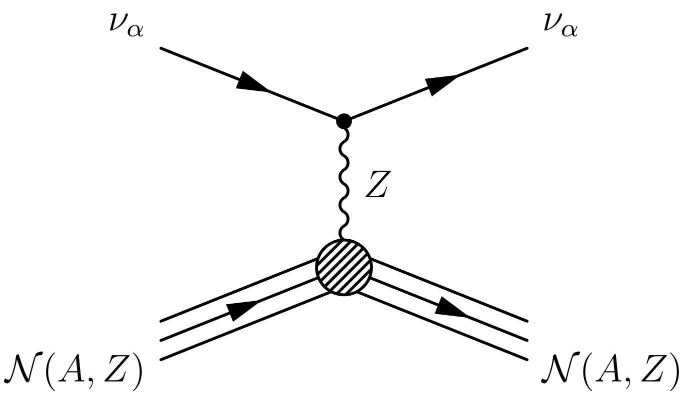




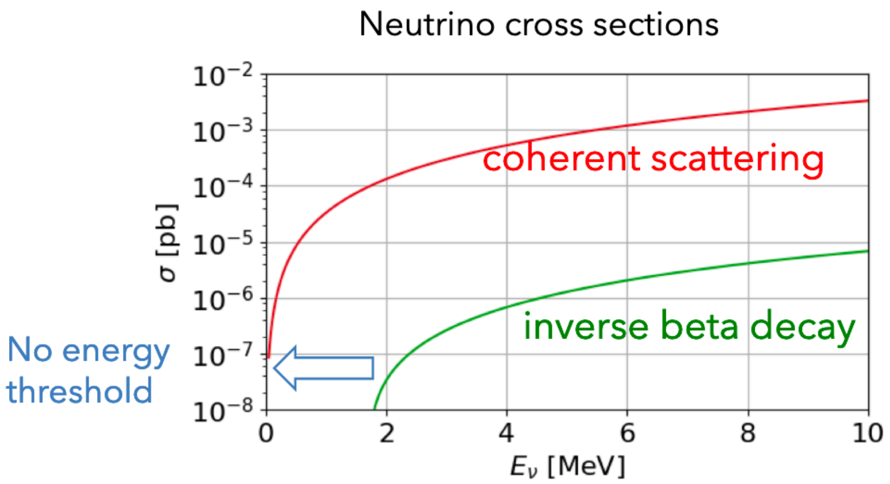
New era of ν physics:

Neutrino interactions in new regimes

Coherent Neutrino Scattering

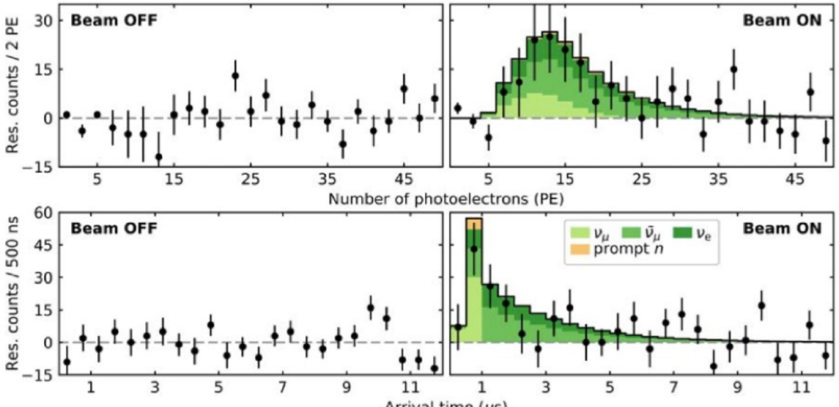


D. Freedman '74



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

First measured in 2017 by COHERENT experiment!



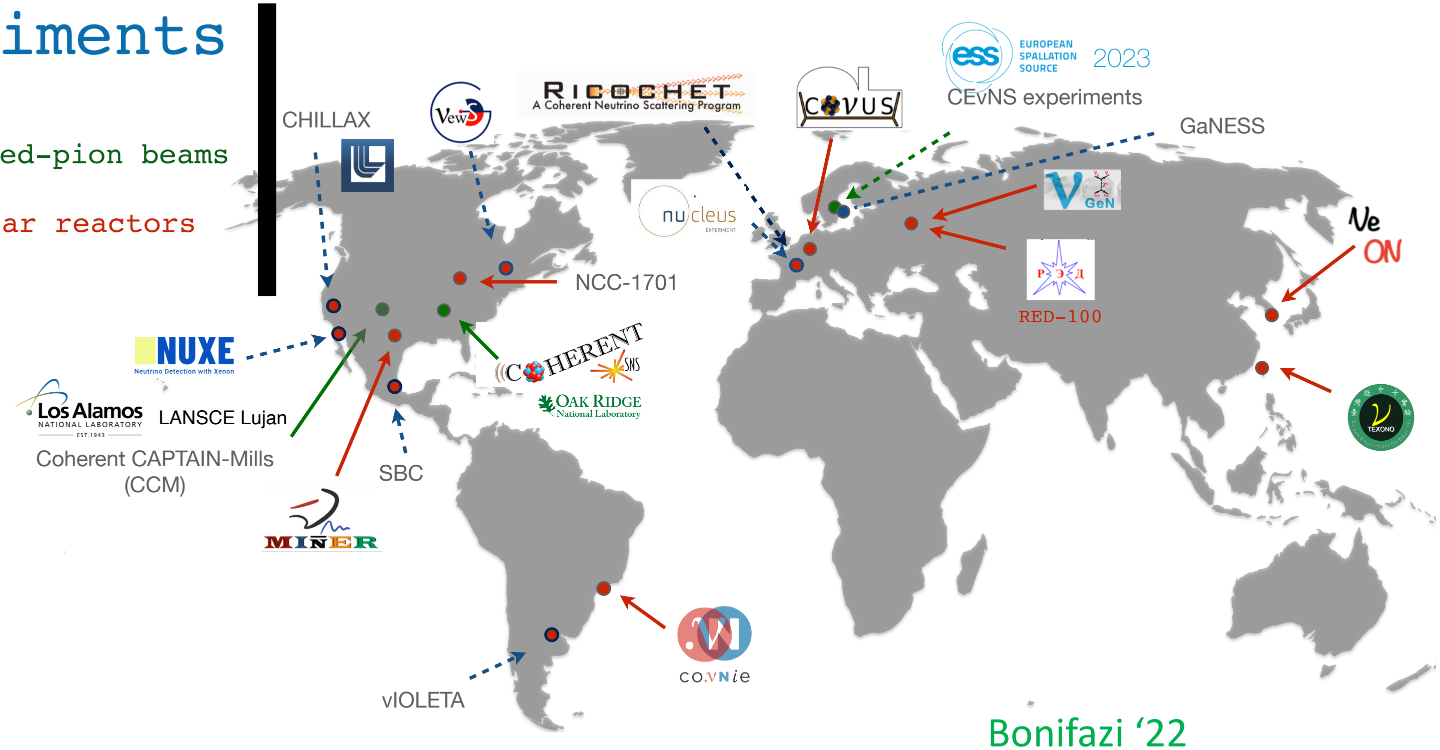
New era of ν physics:

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

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

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

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 ?

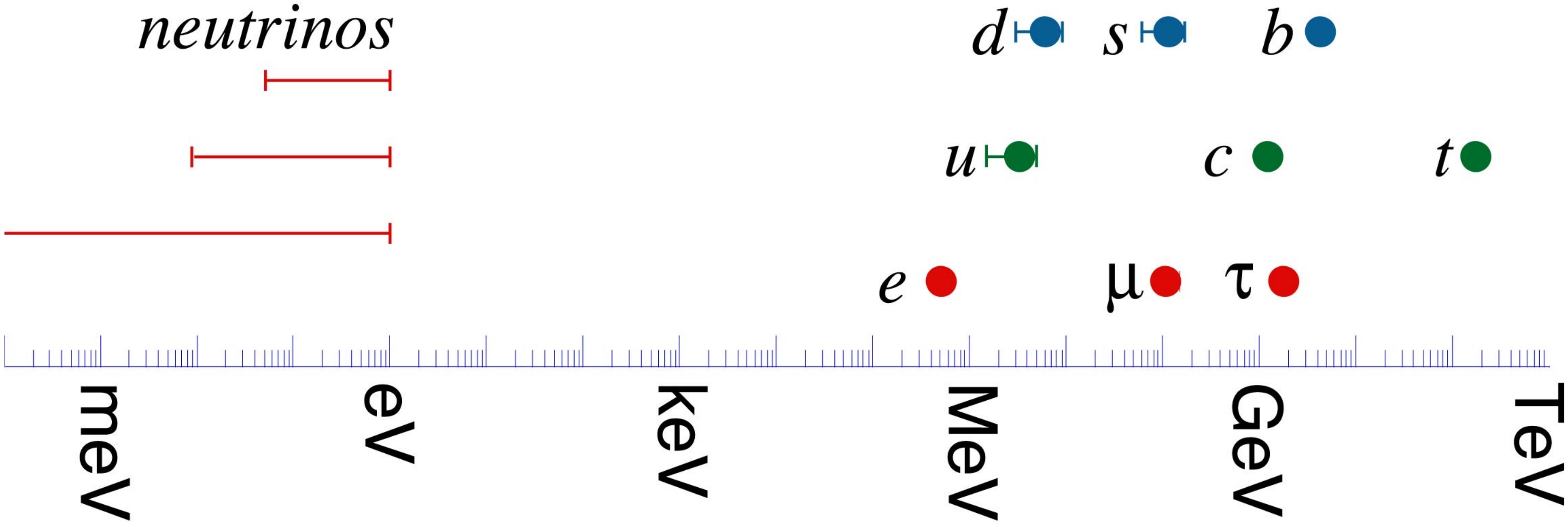
Anarchy for leptons

Discrete or continuous symmetries

Lepton-quark flavour connection in GUTs ?

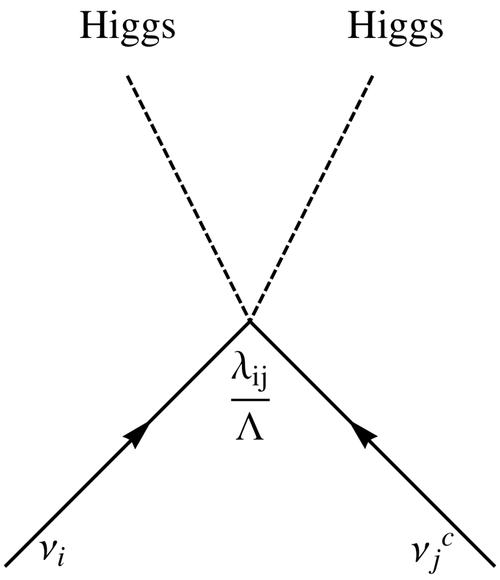
Massive neutrinos: a new flavour perspective

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 ?

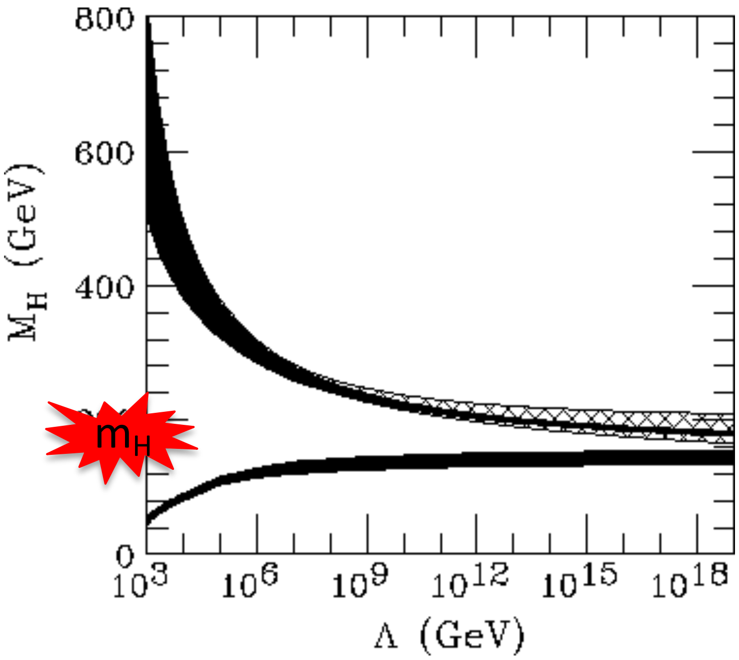
Could be $\Lambda >> v$… the standard lore (theoretical prejudice ?)

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

Hierarchy problem $m_H^2 \propto \Lambda^2$ 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…

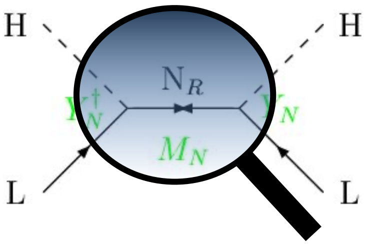


Could be naturally $\Lambda \sim v$?

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

Resolving the neutrino mass operator at tree level

Type I see-saw:
a heavy singlet scalar

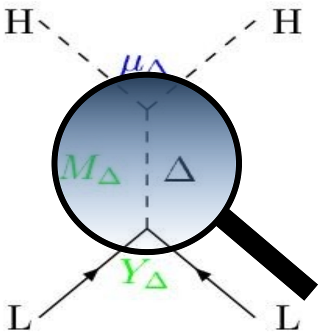


$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

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

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

Type II see-saw:
a heavy triplet scalar



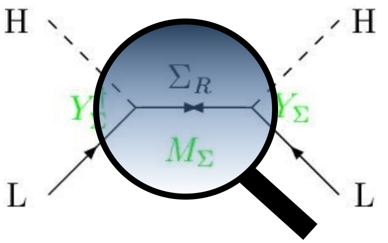
$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

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

E. Ma

Type III see-saw:
a heavy triplet fermion



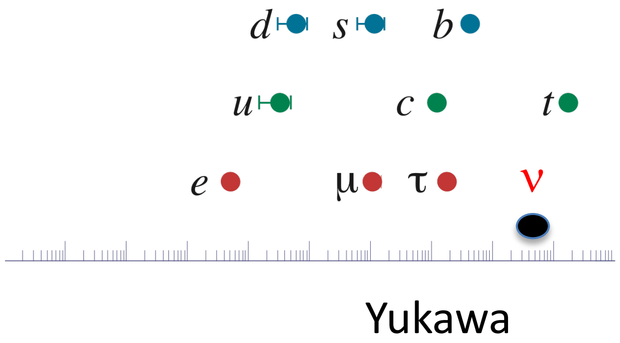
$$m_\nu = \frac{\lambda v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

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

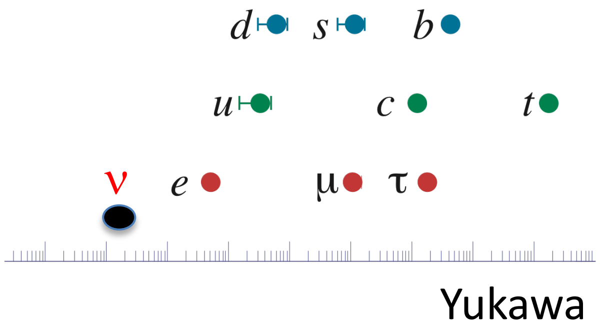
$\lambda \sim O(Y^2)$

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 (M > 100MeV)

model independent contribution from the neutrino mass 😊

Where is the new scale ?

Leptogenesis

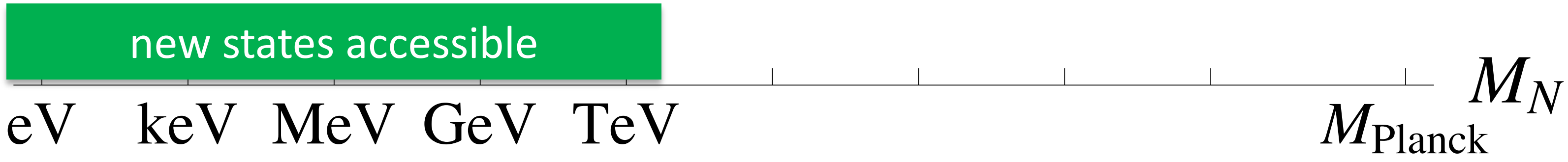
eV keV MeV GeV TeV M_{Planck} M_N

Generic predictions:

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

model dependent... 😪

Where is the new scale ?



new states accessible

eV keV MeV GeV TeV M_{Planck} M_N

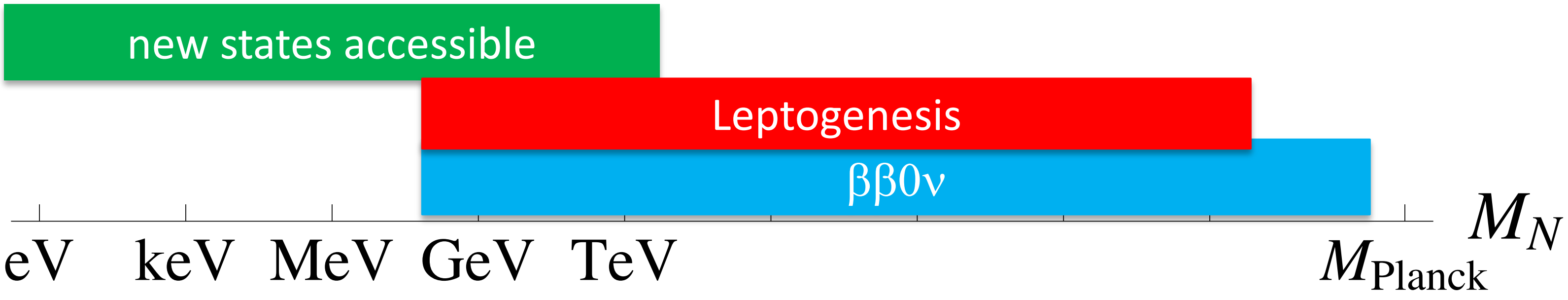
Generic predictions:

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

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

model dependent... 😪

Where is the new scale ?



new states accessible

Leptogenesis

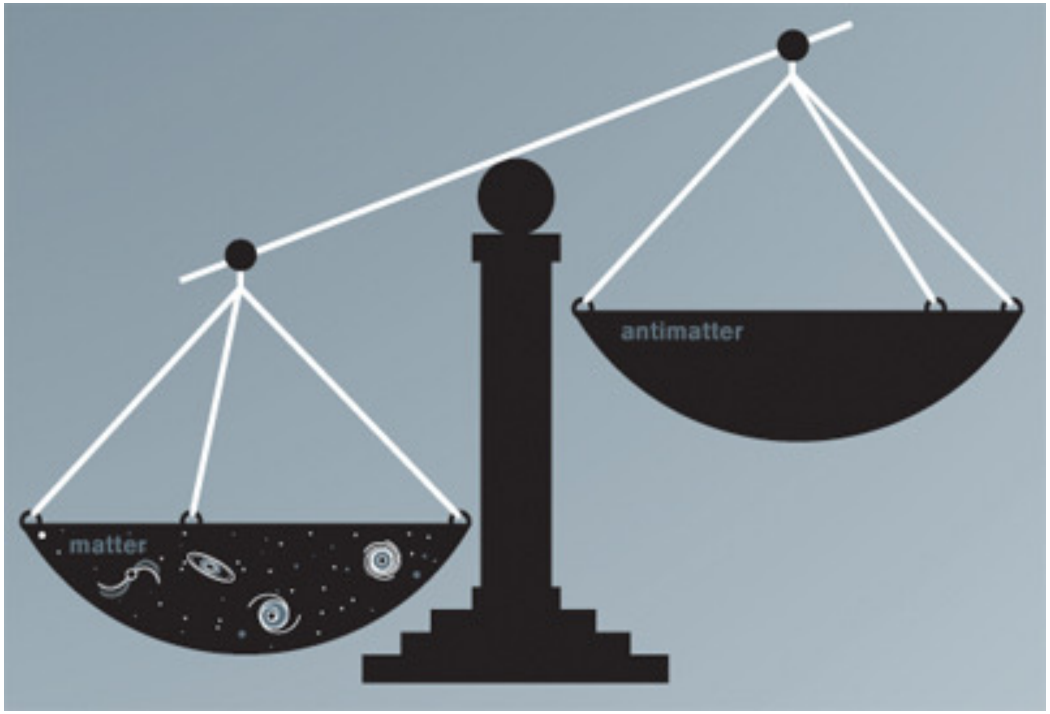
ββ0ν

eV keV MeV GeV TeV M_{Planck} M_N

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

The matter-antimatter asymmetry

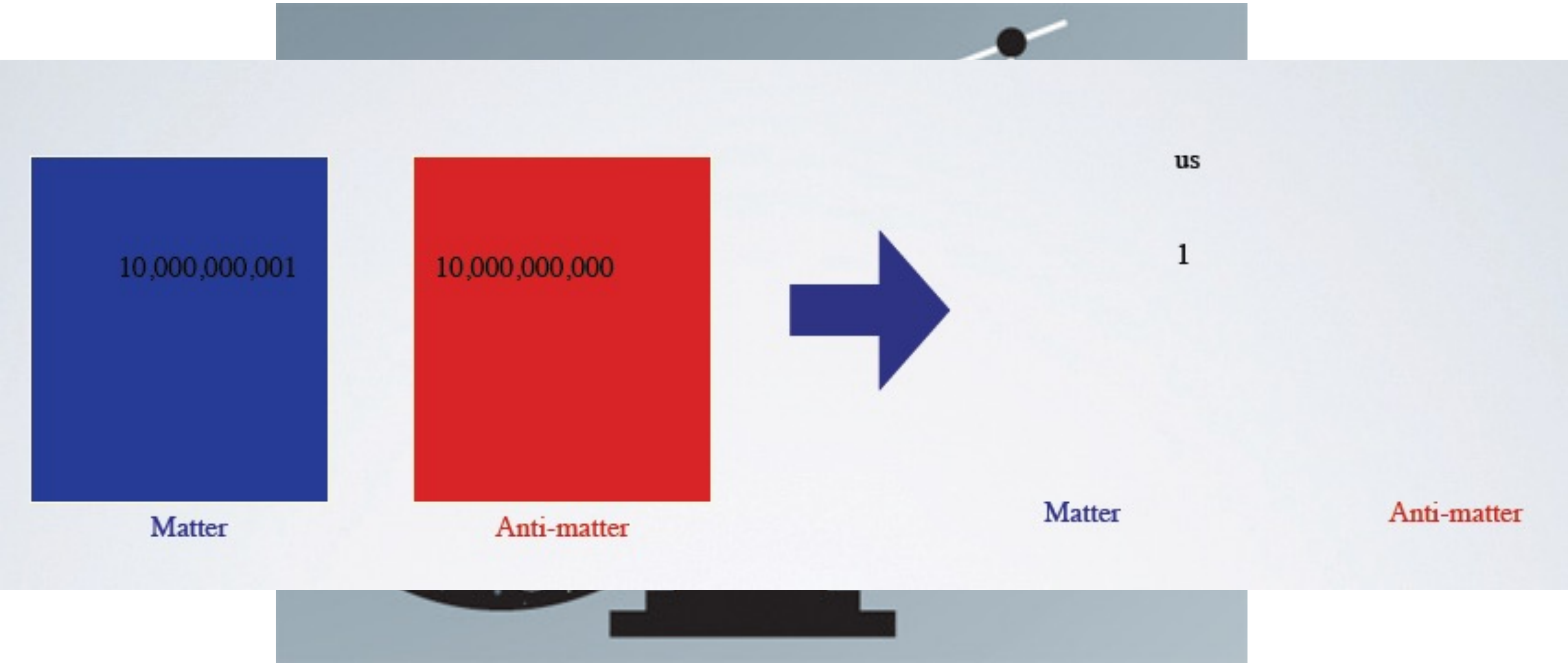
The Universe seems to be made of matter



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

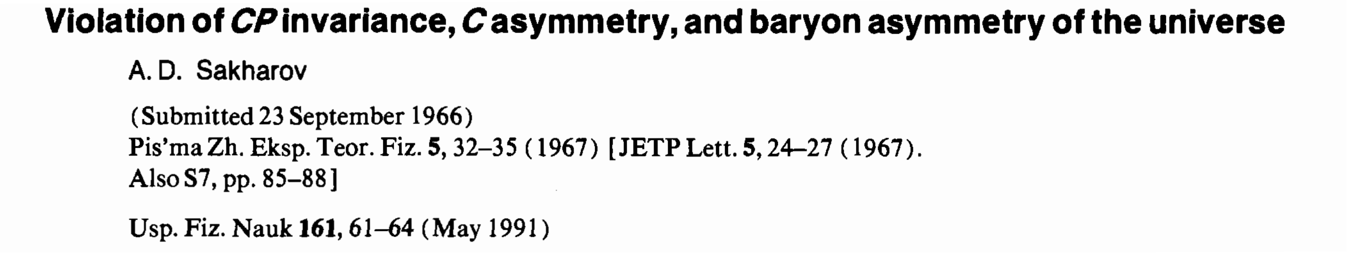
The matter-antimatter asymmetry

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

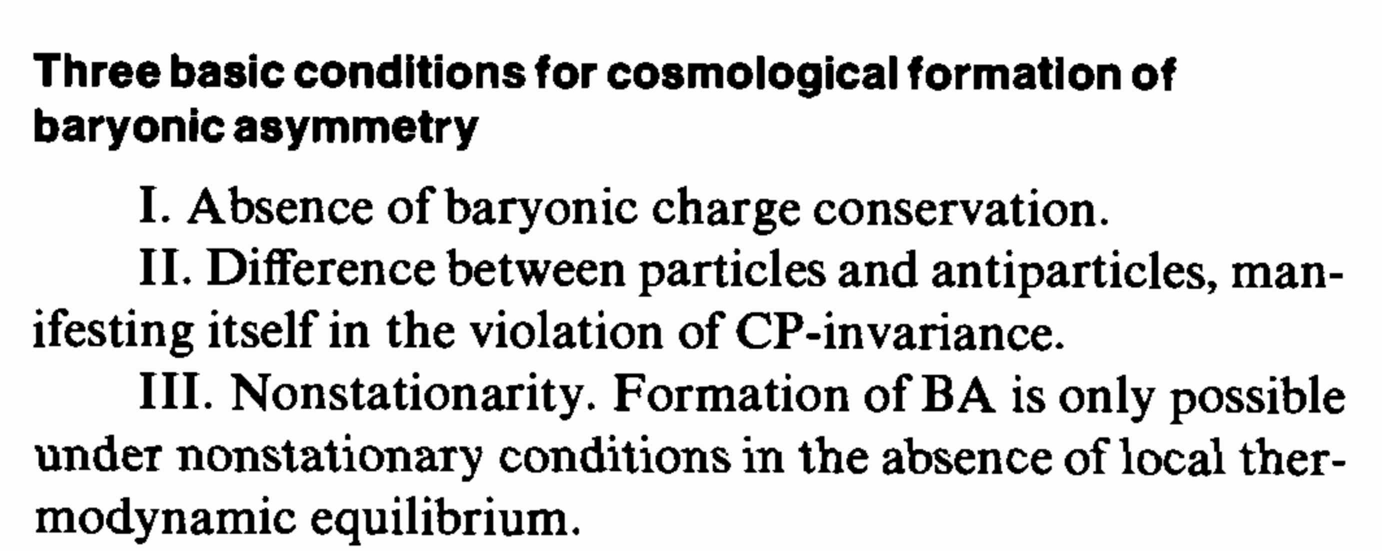


Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

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)



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

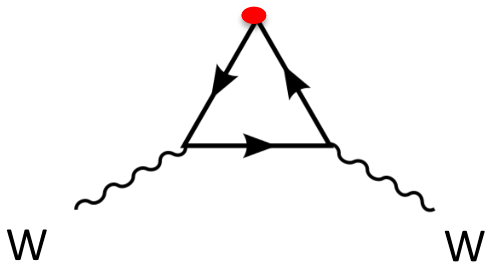
I. Baryon Number non-conservation

Symmetry is broken by quantum vacuum effects: anomaly

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

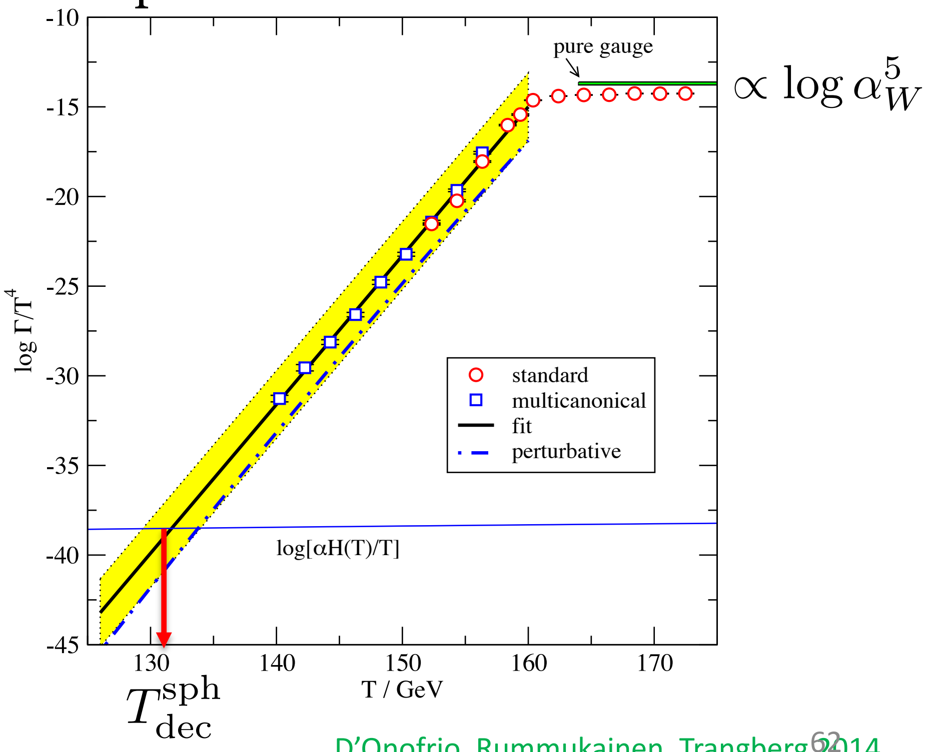
Only B-L is conserved in the SM !

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



$$\text{Rate}(\not{B}) \propto e^{-\frac{4\pi}{\alpha_W}}$$

Sphaleron rate in the SM



D'Onofrio, Rummukainen, Trangberg 2014

But the Standard Model fails

II. Difference between particles-antiparticles: CP violation

It is a subtle phenomenon that depends on many flavour parameters

$$Y_B \propto \Delta_{\rm CP} \qquad \delta_{\rm CKM} \simeq 65.5^\circ(1.5)$$

$$\Delta_{CP}^{\rm quarks} = \left\{ \right.$$

- Polynomial in Y_u, Y_d
- Has an imaginary part
- It is flavour-basis invariant

Cecilia Jarlskog '85

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

$$Y_B \propto \frac{\Delta_{CP}^{\rm quarks}}{T_{\rm EW}^{12}} \sim 10^{-20}$$

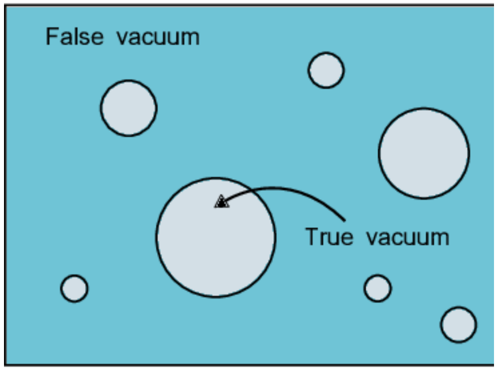
Gavela, PH et al '94

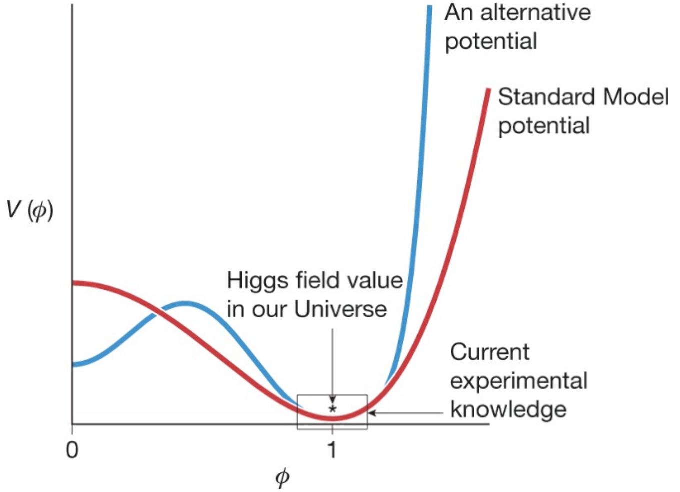
But the Standard Model fails

III Non stationarity (T> T_{EW})

First order phase transitions (EW symmetry is restored at high enough T)

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





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

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

Kajantie, Laine, Rummukainen,Shaposhnikov '96

But the Standard Model fails

III Non stationarity

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

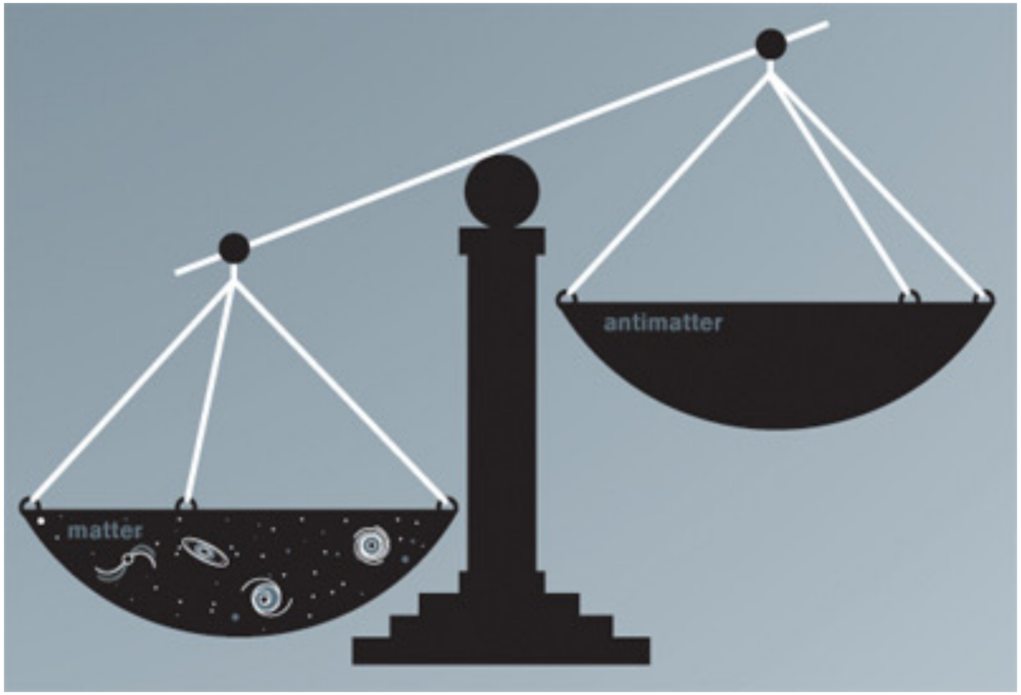
scattering rate < Hubble expansion

All particles in the SM (even neutrinos) satisfy

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

No out-of-equilibrium in the minimal SM when sphalerons are still active !

SM $+\mathcal{L}_\nu$ vs Baryon Asymmetry



Not a model independent answer …

Simplest neutrino mass mediator: Type I seesaw

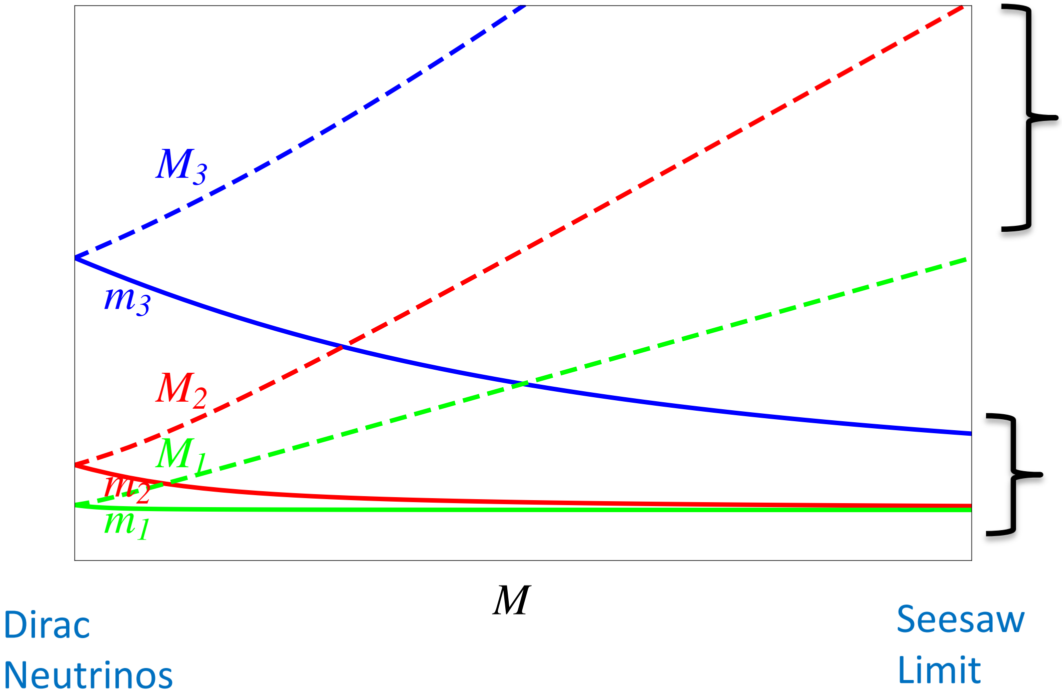
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow; Mohapatra, Senjanovic

$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{3},\mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{1},\mathbf{1})_0$
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}u^i\\ d^i\end{pmatrix}_L$	e_R	u_R^i	d_R^i	ν_R^1
$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c^i\\ s^i\end{pmatrix}_L$	μ_R	c_R^i	s_R^i	ν_R^2
$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t^i\\ b^i\end{pmatrix}_L$	τ_R	t_R^i	b_R^i	ν_R^3

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

Simplest neutrino mass mediator: Type I seesaw

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



Heavy Neutral Leptons (N)

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

Light neutrinos (ν)

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

$n_R = 3$: + 18 free parameters (6 masses+6 angles+6 phases)
$n_R = 2$: +11 free parameters (4 masses+4 angles+3 phases)

(out of which we have measured 2ν masses and 3 angles...)

Heavy Neutral Leptons

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

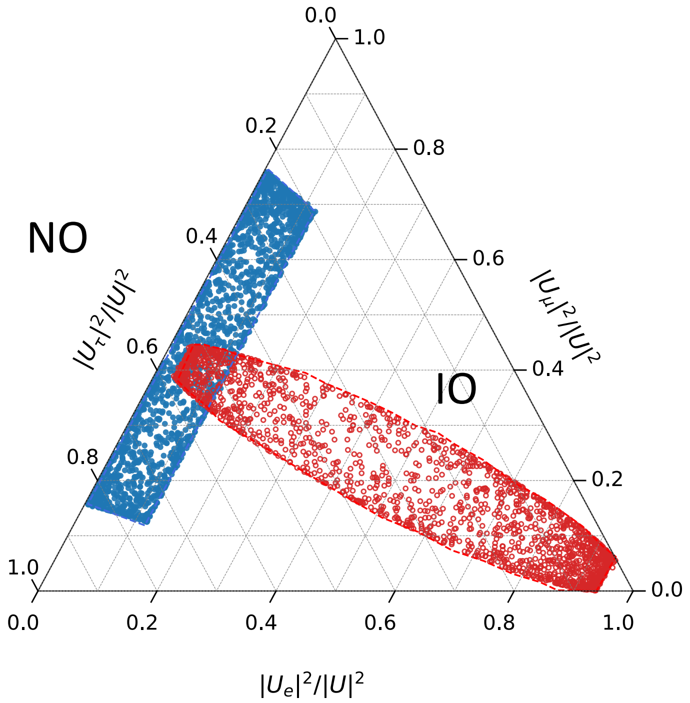
Light neutrino mixing
(~PMNS)

HNL mixing

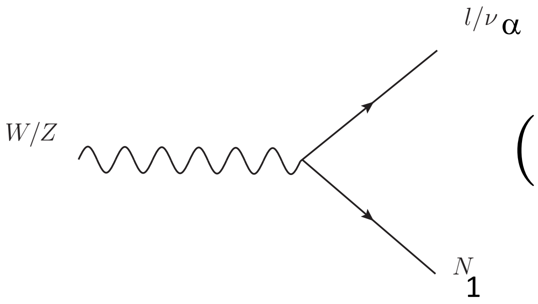
Seesaw scaling: $|U_{\mathrm{lh}}|^2 \propto \frac{m_{\mathrm{light}}}{m_{\mathrm{heavy}}}$

Heavy Neutral Leptons

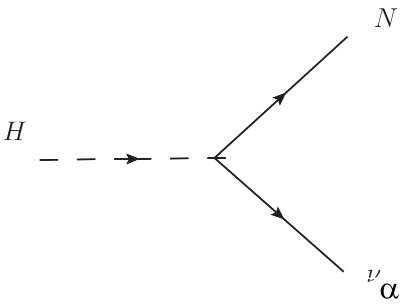
n_R=2: the flavour of HNL mixings fixed by $U_{PMNS}(\delta,\alpha)$ and hierarchy



Heavy Neutral Leptons

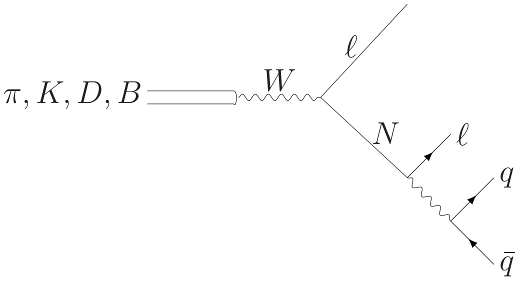


$$(U_{hl})_{\alpha 1}$$

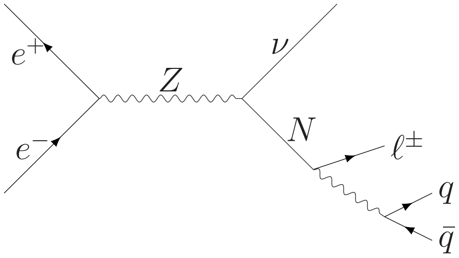


$$(U_{hl})_{\alpha 1}$$

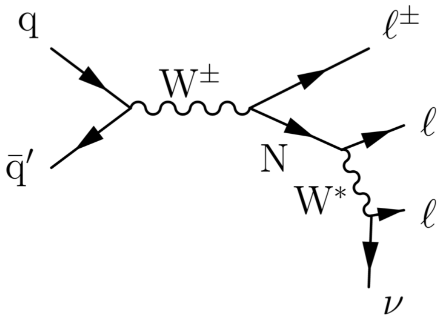
Meson decays



e+e-@Z peak

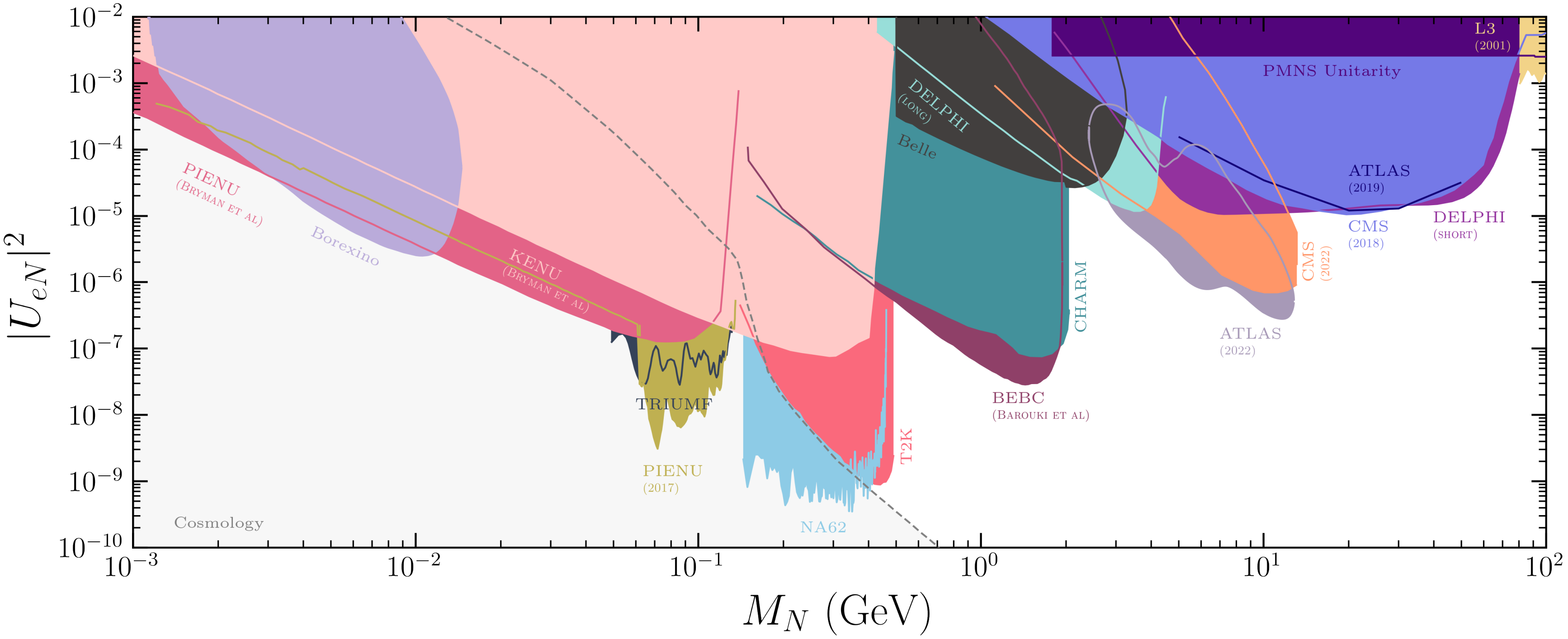


Hadron colliders



@Laboratory (fixed target, colliders) and cosmic rays

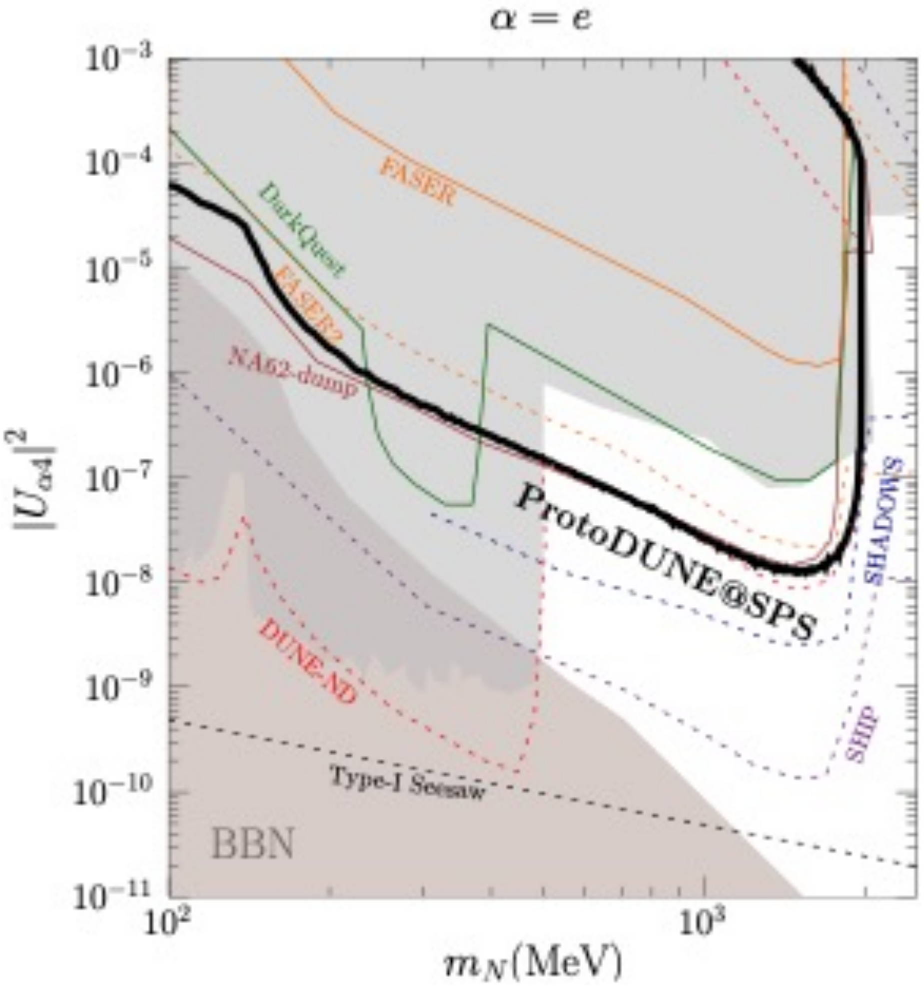
Heavy Neutral Leptons



Fernández-Martínez et al ‘23

Heavy Neutral Leptons

Good prospects in D, B meson decay searches: SHIP approved by CERN, ProtoDUNE can improve present bounds for free !

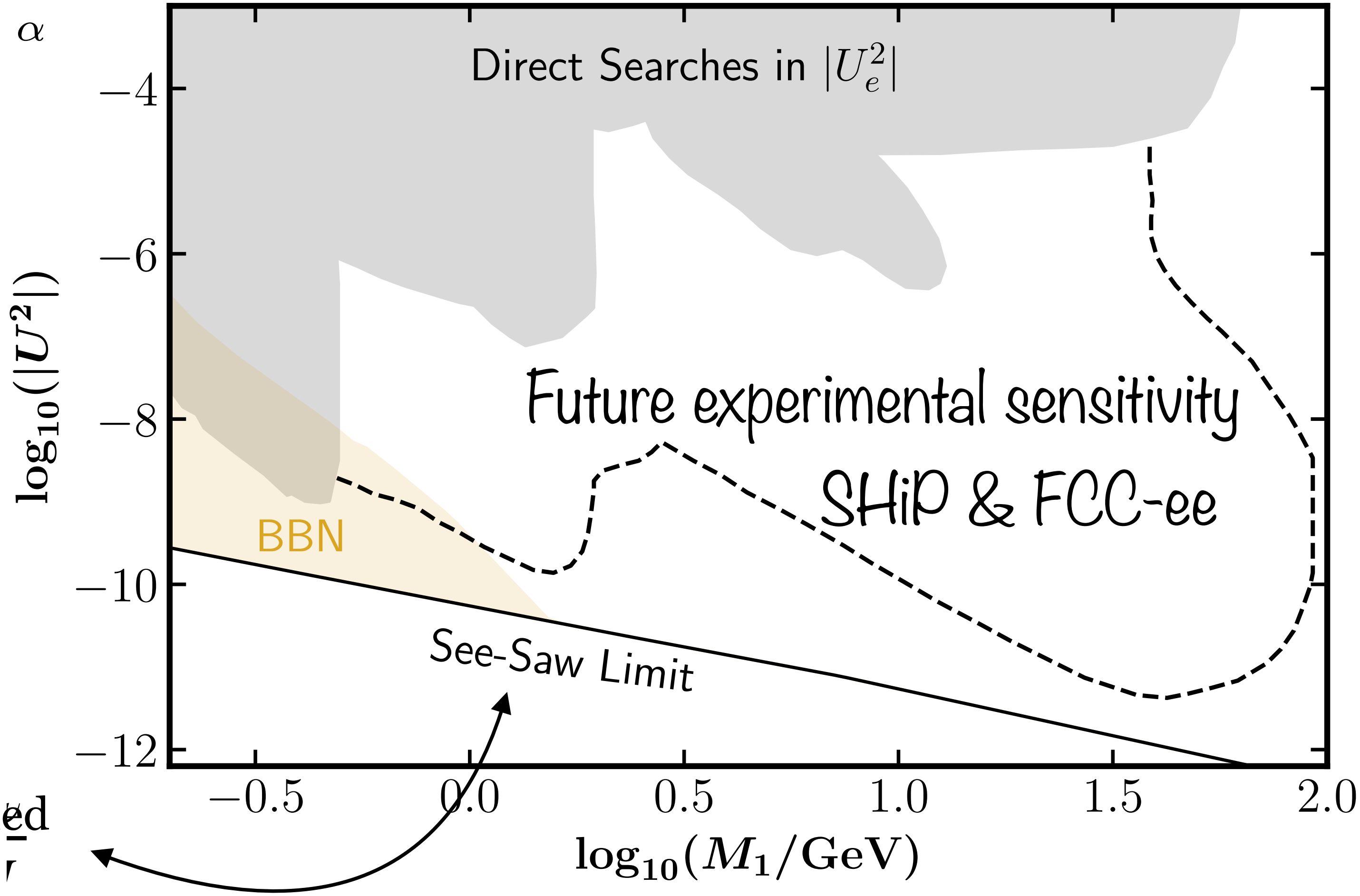


P. Coloma et al '23

Heavy Neutral Leptons

Impressive sensitivity from FCCee at the Z-pole !

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



ν masses
not explained

Sakharov conditions revisited

- 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…

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

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

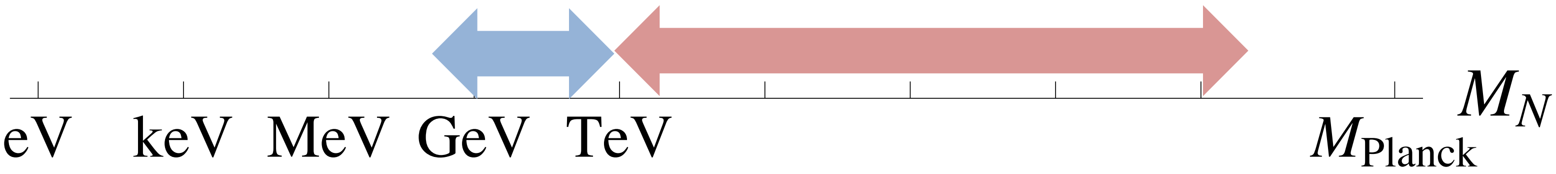
(Scattering rate < Hubble expansion rate)

The Standard Model+massive ν

Baryogenesis is a 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…

@leptogenesis from
out-of-equilibrium decay



@EW scale leptogenesis
via neutrino oscillations

Can we test this scenario ? Can we predict Y_B ?

SM $+\mathcal{L}_\nu$ & Baryon Asymmetry

Quantum kinetic equations describe the evolution of the N density matrix and the B/3-L_α chemical potentials

Raffelt-Sigl '93

$$\frac{d\rho_N(k)}{dt} = \underset{\text{Oscillations}}{\underset{\downarrow}{-i[H,\rho_N(k)]}} \underbrace{- \frac{1}{2}\{\Gamma^a_N,\rho_N\} + \frac{1}{2}\{\Gamma^p_N, 1-\rho_N\}}_{\text{Scattering}}$$

$$\bar{\rho}_N(H \to H^*)$$

...Ghiglieri,Laine '17

$$\frac{d\mu_{B/3-L_\alpha}}{dt} = f(\rho_N, \rho_{\bar{N}}, \mu_{B/3-L_\alpha})$$

Stiff differential equations, challenging to solve numerically

The wisdom of CP invariants

PH, Lopez-Pavon, Rius, Sandner, arxiv: 2207.01651

- Identify the different non-thermal modes and their characteristic time-scales
- Solve the equations perturbatively exploiting these weakly coupled modes
- Identify the CP invariants that control the flavour parameter dependencies of Y_B

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

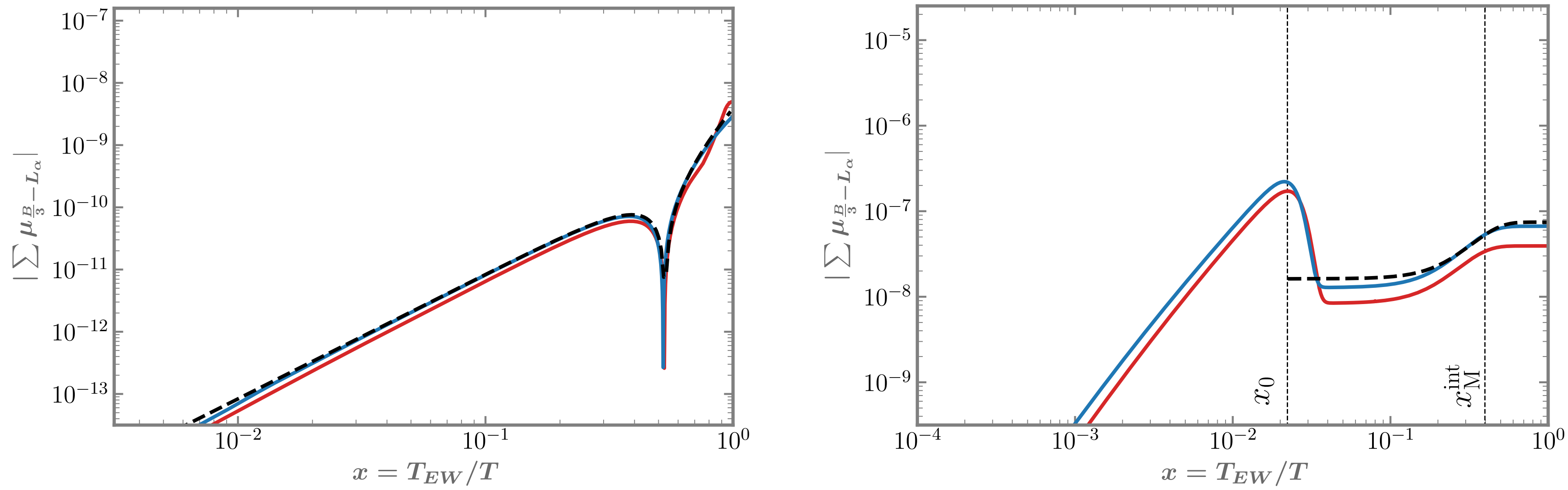
$$I_1 = \mathrm{Im}\left(\mathrm{Tr}[Y^\dagger Y M^\dagger M M^* (Y^\dagger Y)^* M]\right)$$

$$\tilde{I}_0 \equiv \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y M_R^* Y^T Y^* M_R Y^\dagger Y_l Y_l^\dagger Y\right]\right)$$

Analytical vs numerical solution

PH, Lopez-Pavon, Rius, Sandner, arxiv: 2207.01651

N=2

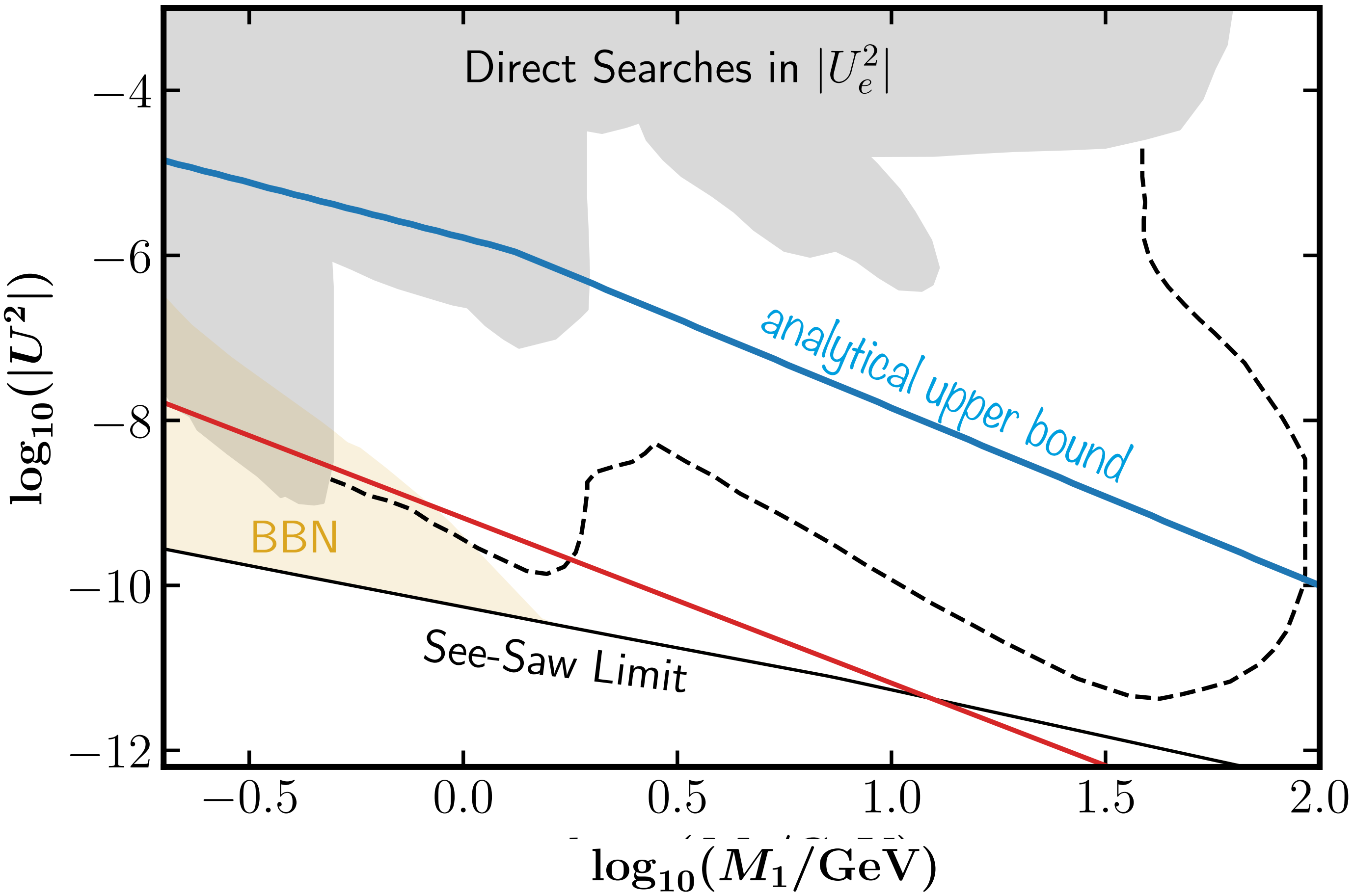


$$\left(\sum_\alpha \mu_{B/3-L_\alpha}\right)^{\rm ov-wLNV} \simeq \frac{\kappa x^2}{6\gamma_0+\kappa\gamma_1}\frac{\gamma_0^2}{\gamma_0^2+4\omega^2}\frac{c_H M_P^*}{T_{EW}^3}\left(\Delta_{\rm LNC}^{\rm ov}-\frac{24}{5}\frac{s_0 x^3}{T_{\rm EW}^2}\Delta_{\rm LNV}^{\rm ov}\right)$$

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

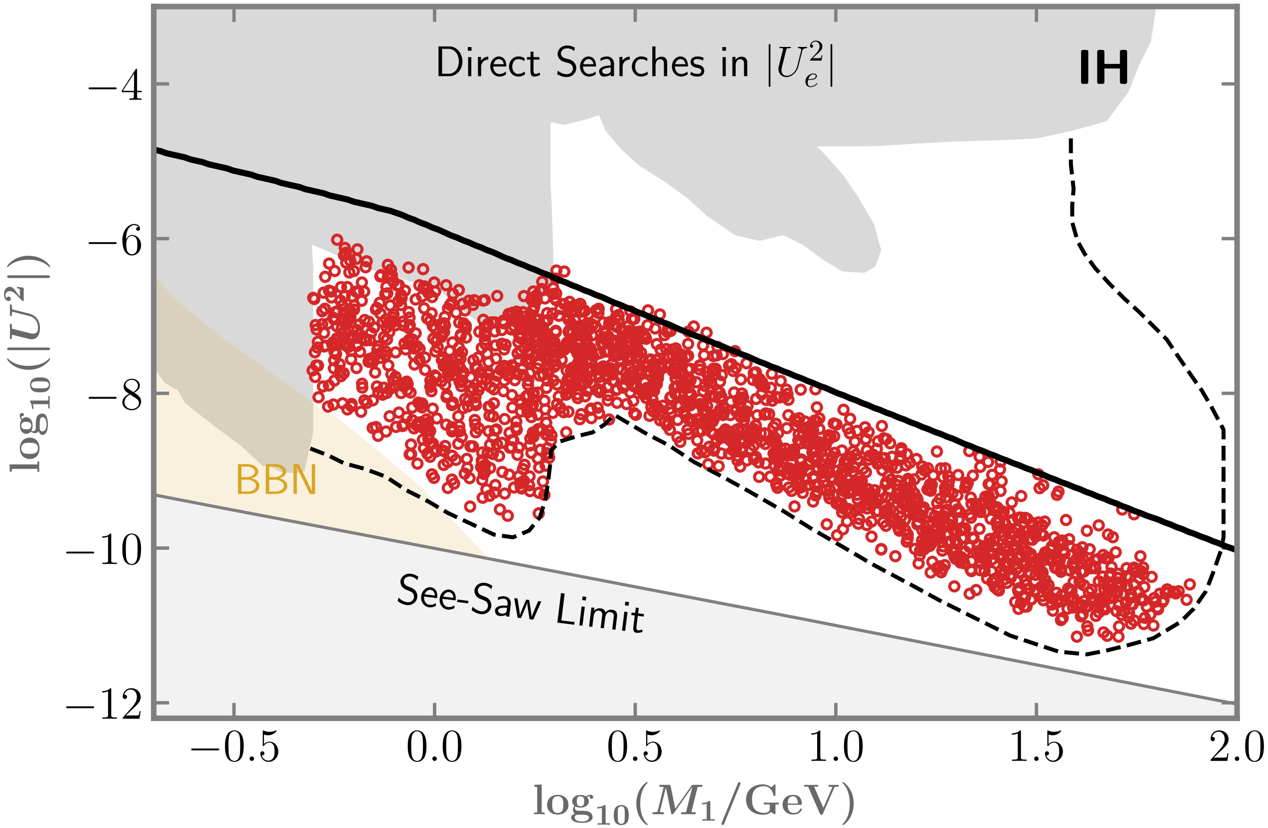
$$\Delta_{\rm LNV}^{\rm ov} = \frac{1}{\left[{\rm Tr}\left(Y^\dagger Y\right)\right]^2}\sum_\alpha\sum_{i<j}\left(M_j^2-M_i^2\right)M_i M_j{\rm Im}\left[Y_{\alpha j} Y_{\alpha i}^*\left(Y^\dagger Y\right)_{ij}\right]$$

Y_B: Upper bound on the HNL mixing



PH, Lopez-Pavon, Rius, Sandner, arxiv: 2207.01651

Y_B: Upper bound on the HNL mixing



PH, Lopez-Pavon, Rius, Sandner, arxiv: 2207.01651

Numerical scan within the sensitivity region of SHIP and FCCee

Predicting Y_B from lab measurements ?

In general very difficult, even for the simplest case n_R=2:

The measurement of the masses and mixings of the HNL and the CP phase in neutrino oscillations allows us to constrain in principle 10 out 11 parameters !

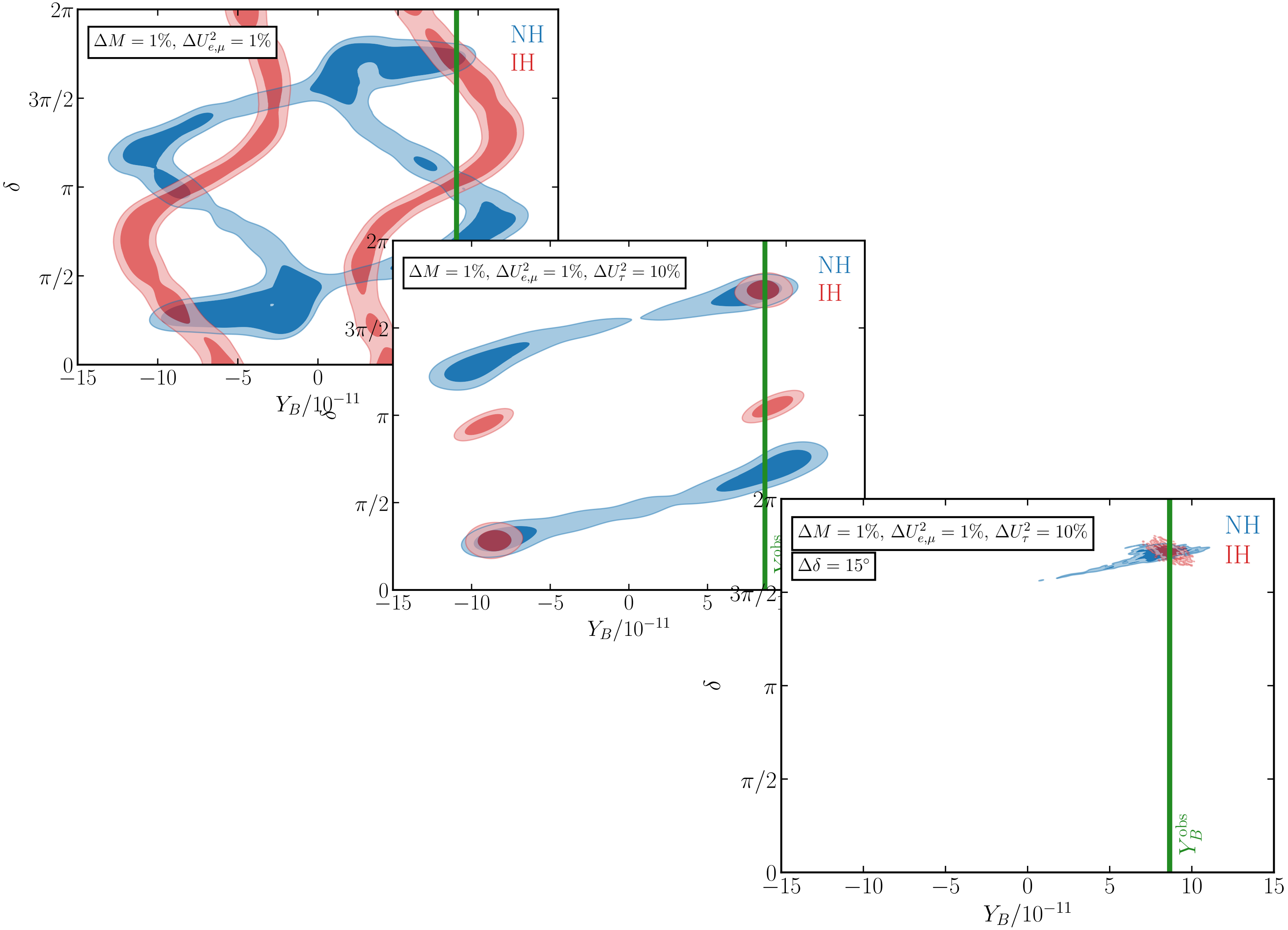
The remaining one can be tuned to set Y_B=0... 😪

Predicting Y_B from lab measurements

For n_R=2 and degenerate HNLs: $$\frac{\Delta M}{M} \to 0$$

The measurement of the masses and mixings of the HNL and the CP phase in neutrino oscillations we can predict the baryon asymmetry !

Predicting Y_B from lab measurements



Sandner, PH, Lopez-Pavón, Rius 2305.14427

Beyond the minimal model

Many possibilities:

Examples: type I + extra Z', extra scalars
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

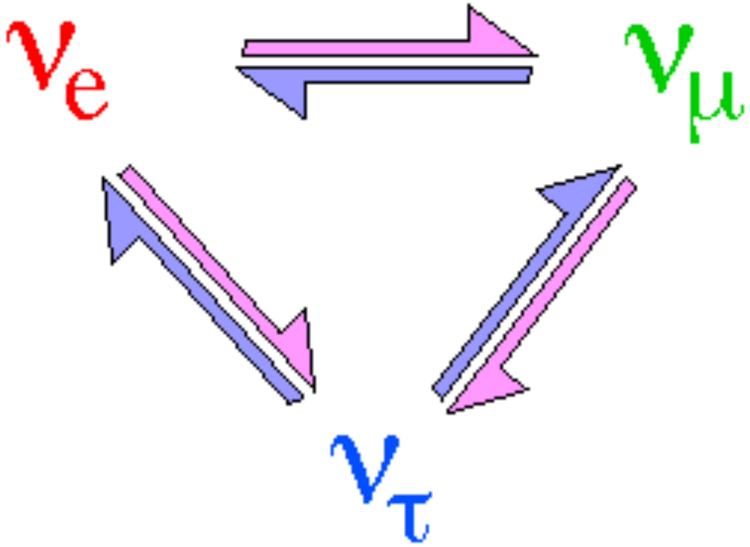
- The results of many beautiful experiments have demonstrated that ν are (for the time-being) the less standard of the SM particles

- 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…



Neutrino Anomalies

(LSND, MiniBOONE, Reactor,..)

Still there, likely non-under-full-control systematics, no BSM explanations provide good fits to data…

Outliers: LSND anomaly

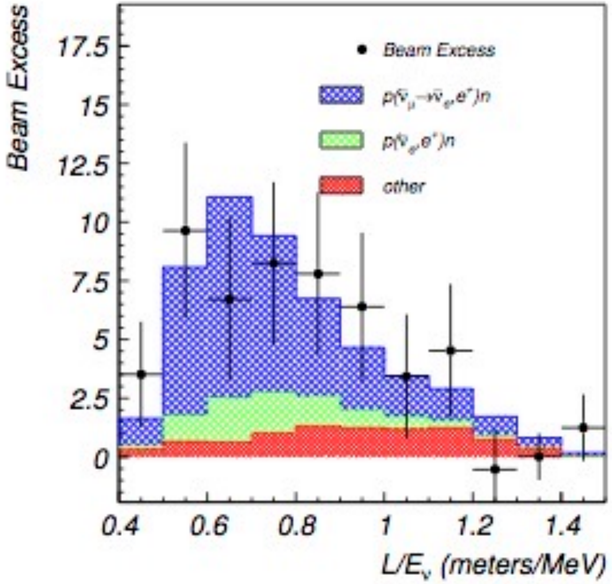
$$\pi^+ \to \quad \mu^+ \quad \nu_\mu$$

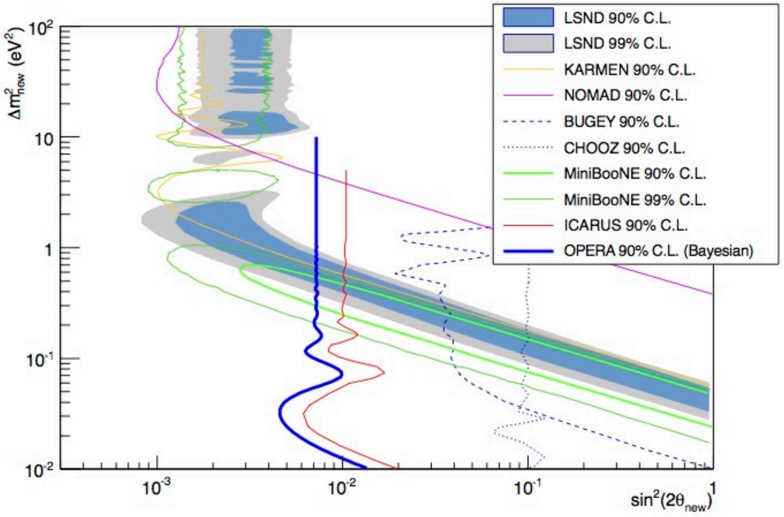
$$\nu_\mu \quad \to \nu_e \ \mathrm{DIF}\ (28 \pm 6/10 \pm 2)$$

$$\mu^+ \to \quad e^+ \quad \nu_e\ \bar{\nu}_\mu$$

$$\bar{\nu}_\mu \quad \to \bar{\nu}_e \ \mathrm{DAR}\ (64 \pm 18/12 \pm 3)$$

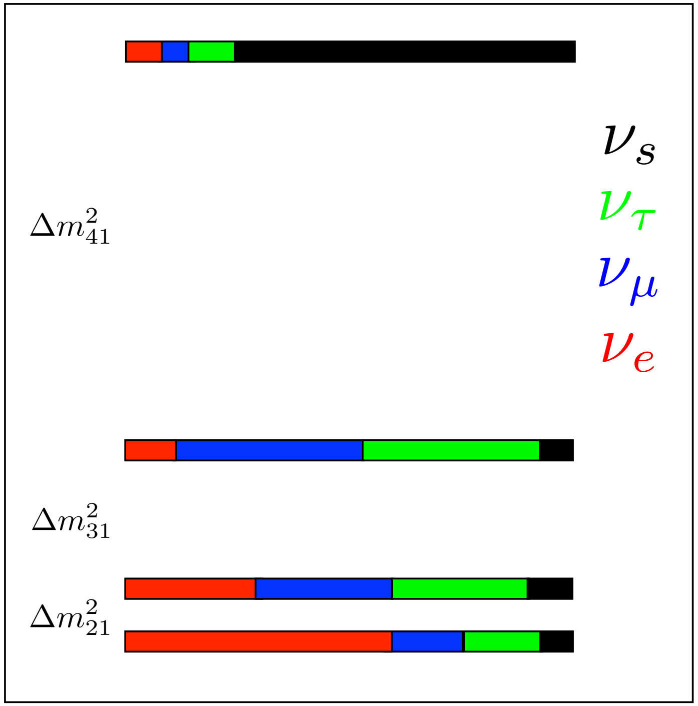
$$P(\nu_\mu \to \nu_e)$$





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

SBL anomalies: 4th neutrino ?



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

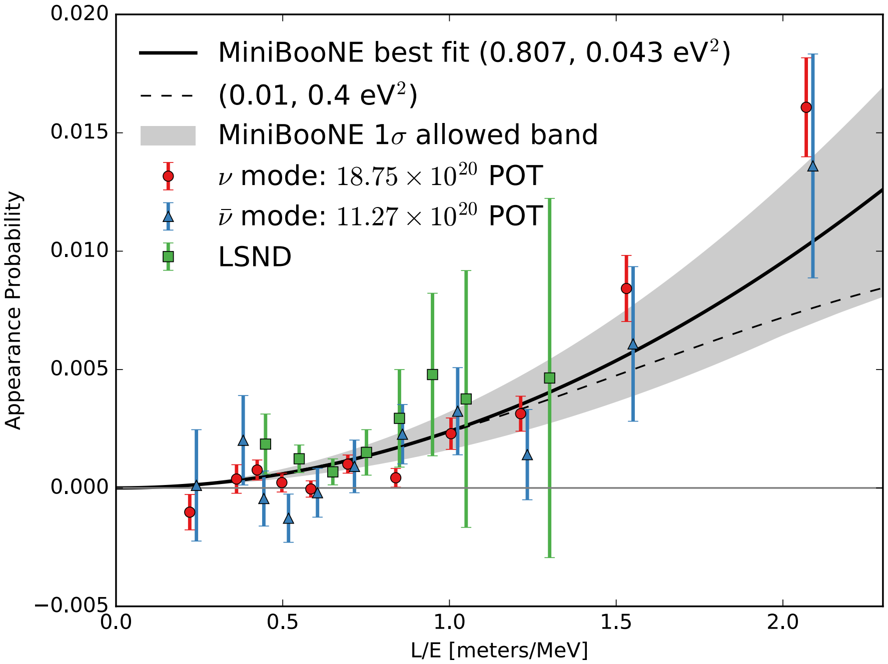
$P(\nu_e \rightarrow \nu_e) = O(|U_{e4}|^2)$

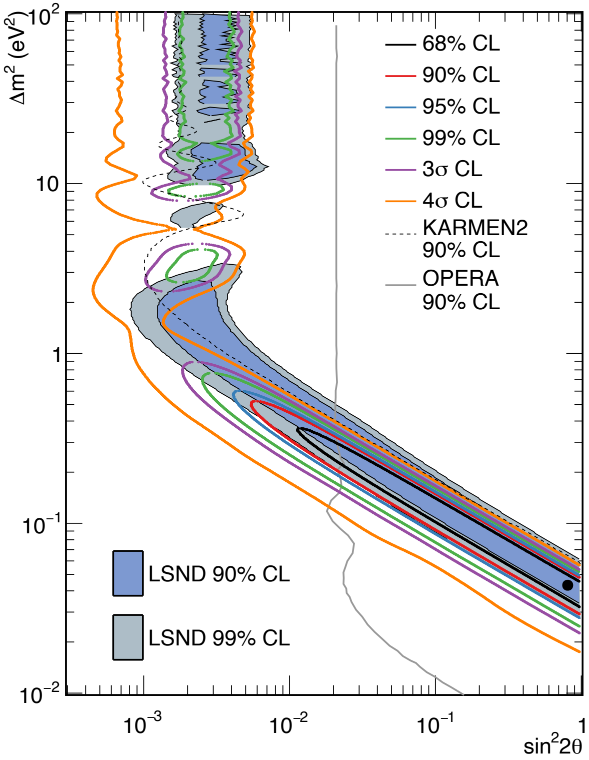
$P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu4}|^2)$

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

MiniBooNE

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

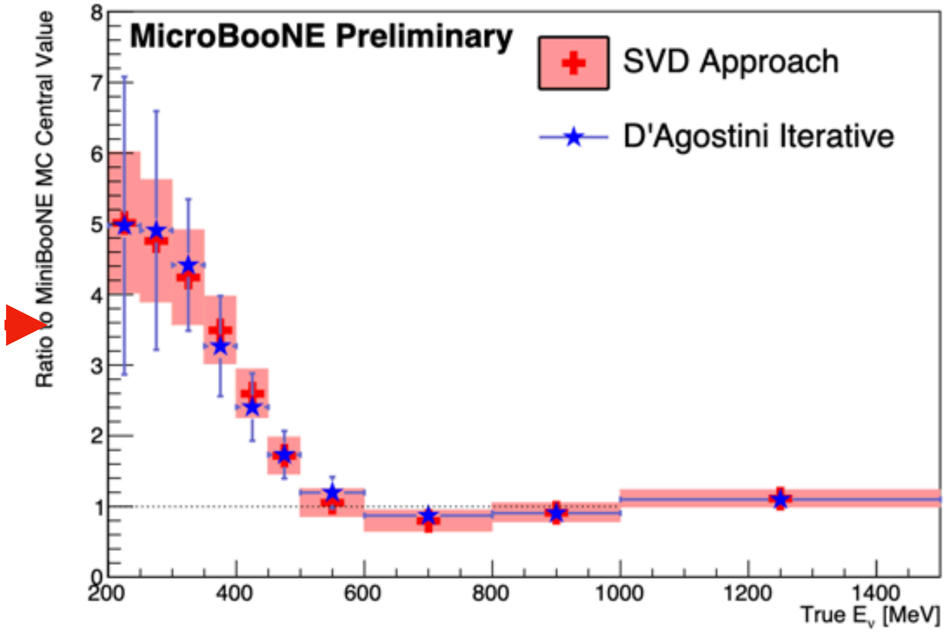


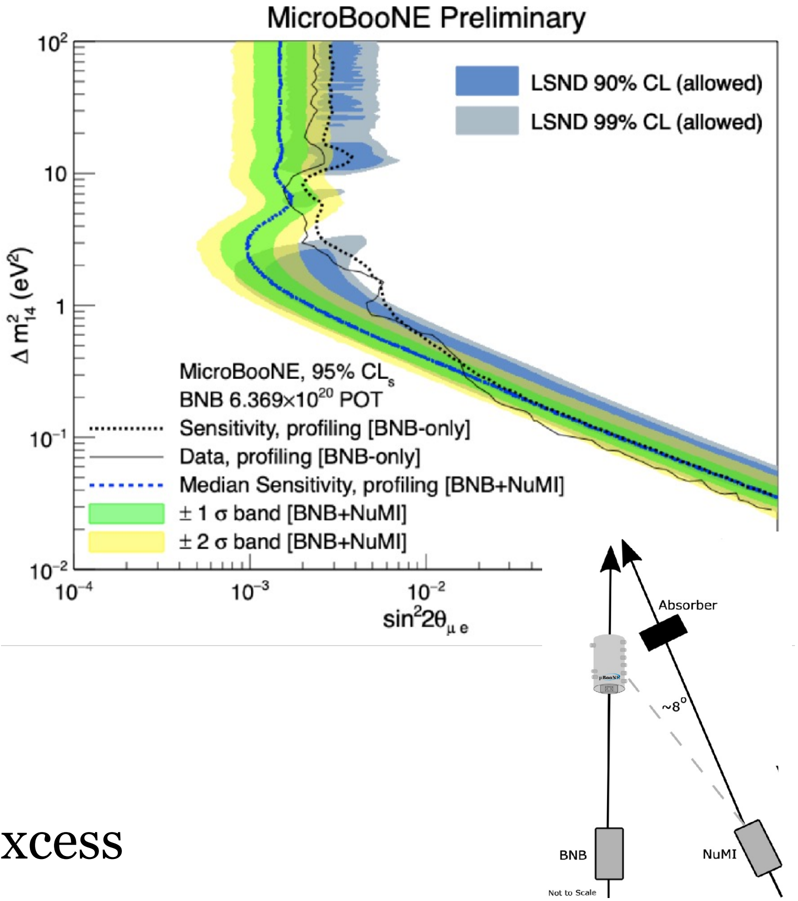


4.8σ discrepancy with SM !

MicroBooNE

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

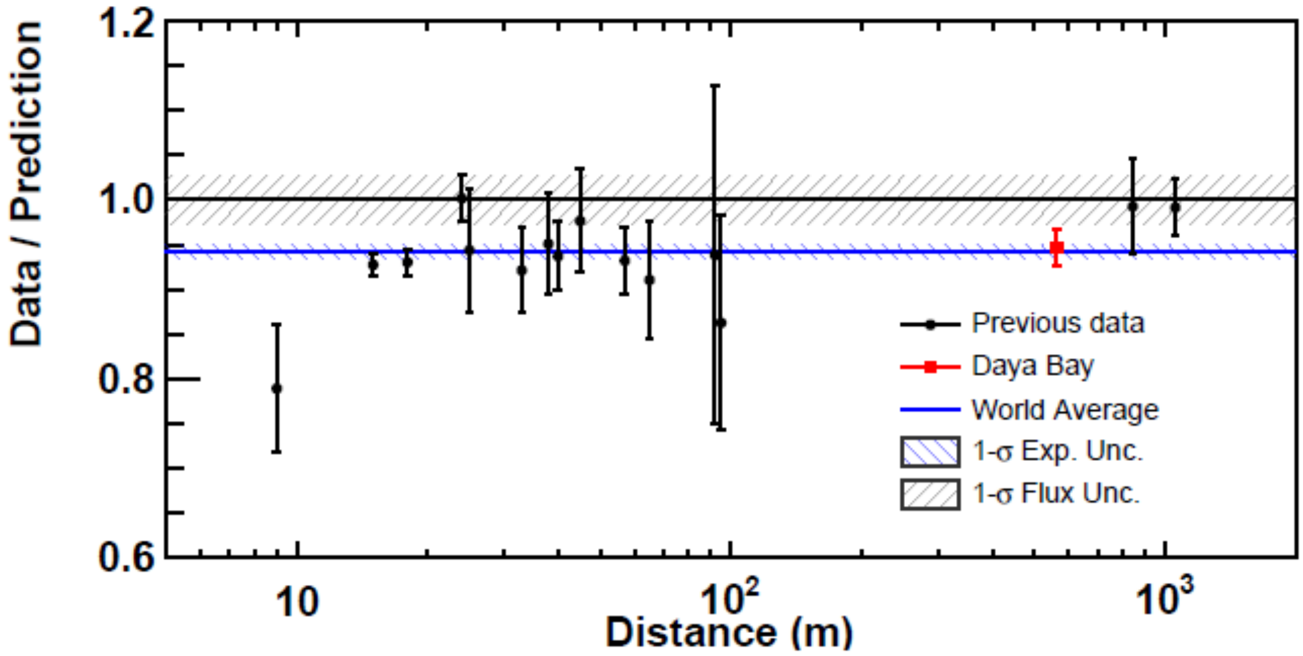




Does not confirm the MiniBooNE excess

Outliers: SBL reactor anomalies

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



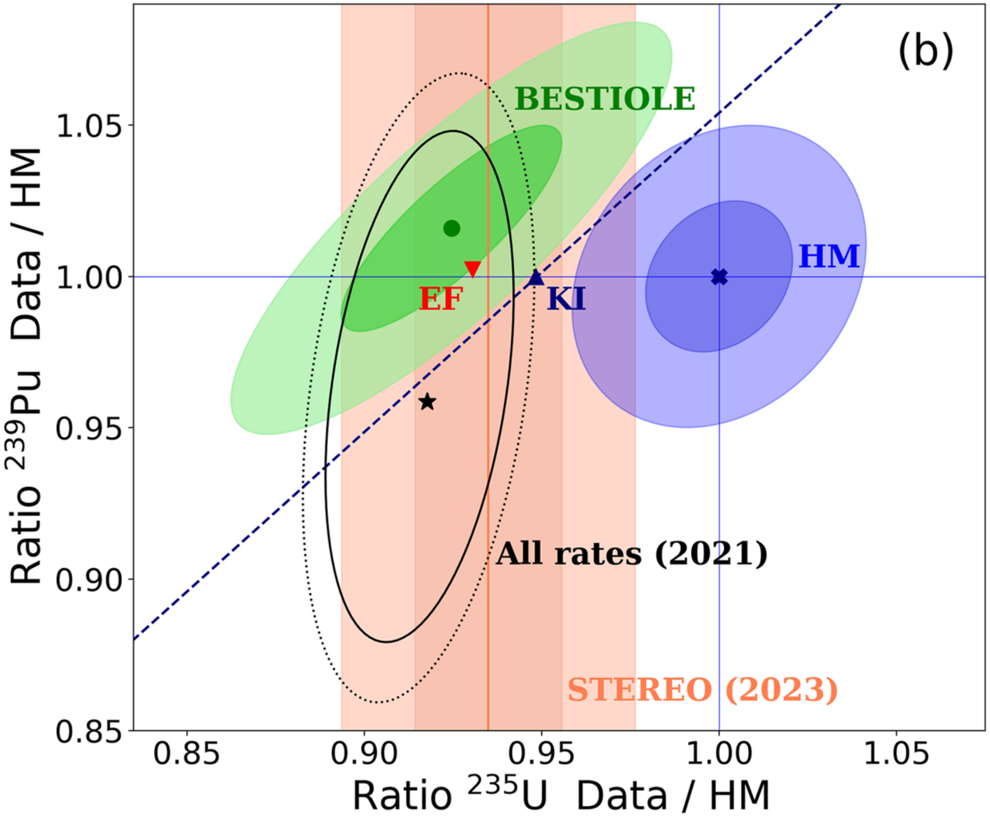
Mueller et al ‘11
Huber ‘11

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, Perisse et al '23

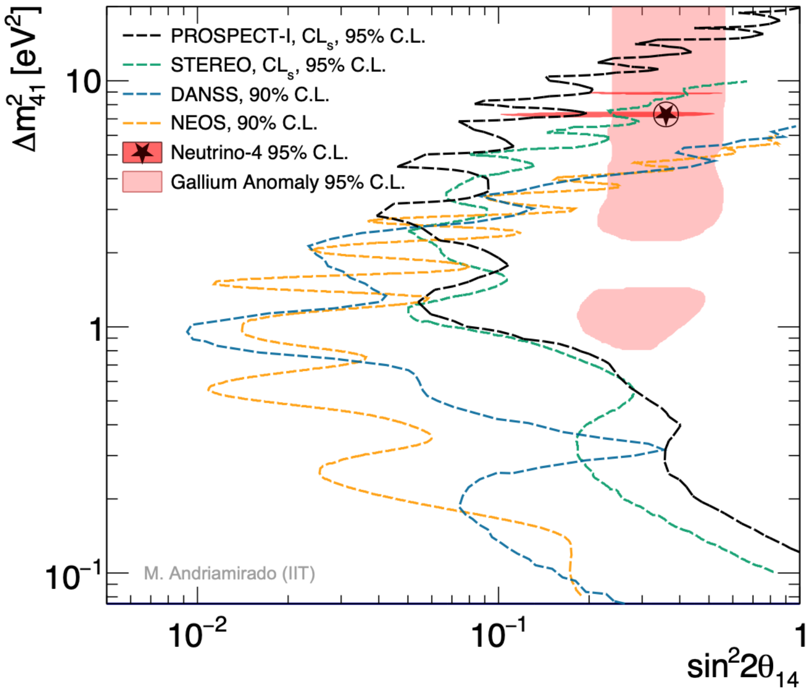


Perisse et al '23

SBL reactor anomaly νews

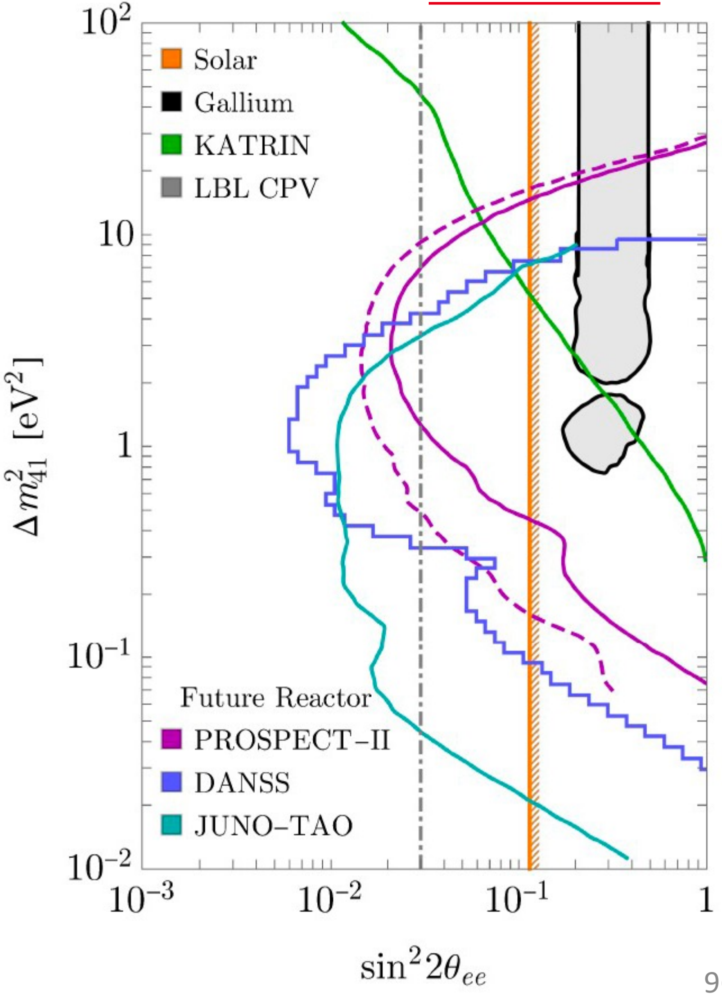
New SBL reactor strategies: L-dep of signal

Present



Future

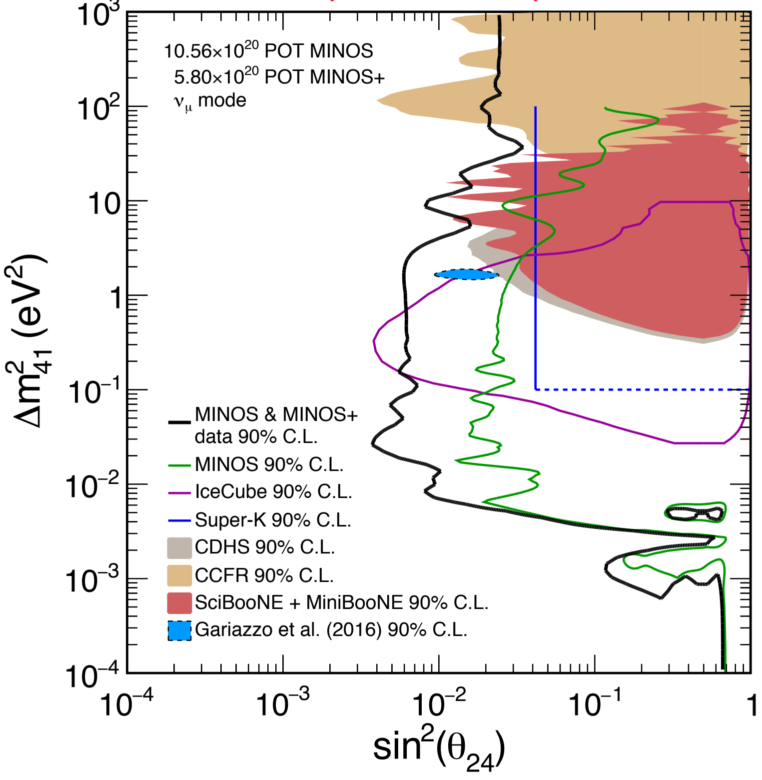
Snowmass 2021



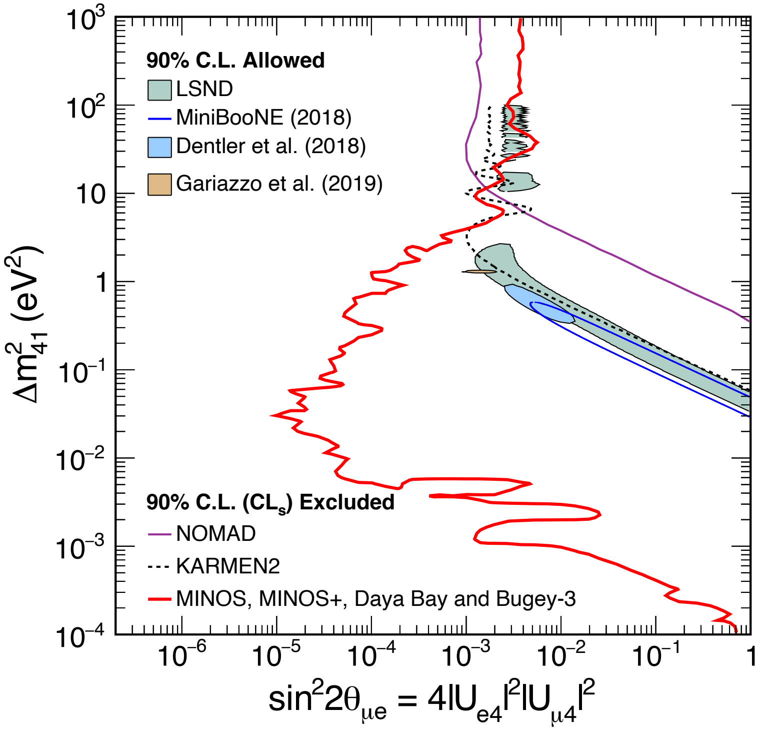
O(eV) sterile neutrinos ?

Neutrino muons must disappear also but they don't

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



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



Not everything is understood but a 4th neutrino is not a good fit to the data!