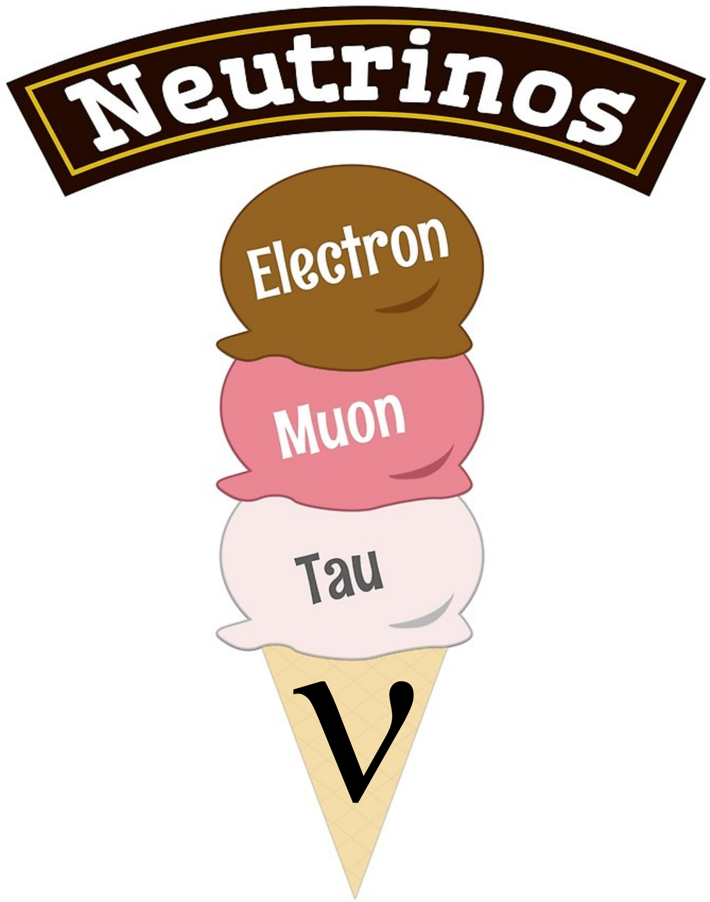


PILAR HERNÁNDEZ

(IFIC, UNIVERSIDAD DE VALENCIA & CSIC)

Neutrino

Neutrinos are the most elusive particles in the Standard Model

Can keep quantum coherence at 1000km distances

Could be their own antiparticle

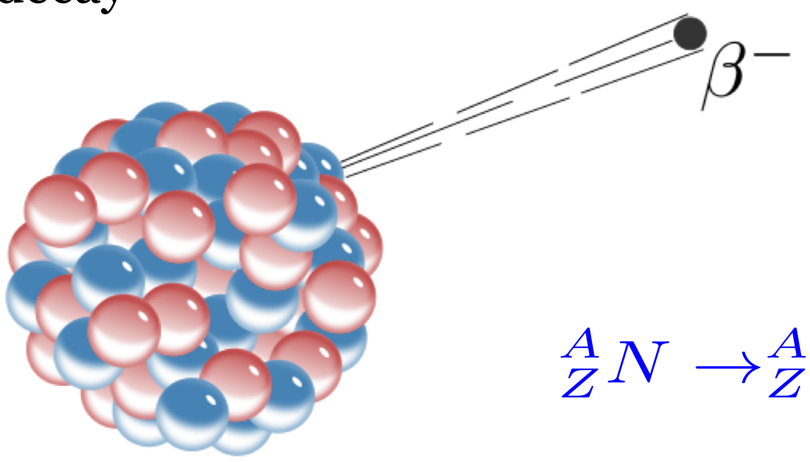
The older relics from the Big Bang …

The first portal to new physics… ?

The explanation of why there is something rather than nothing in the Universe ?

Neutrino: the archetype dark particle

β decay



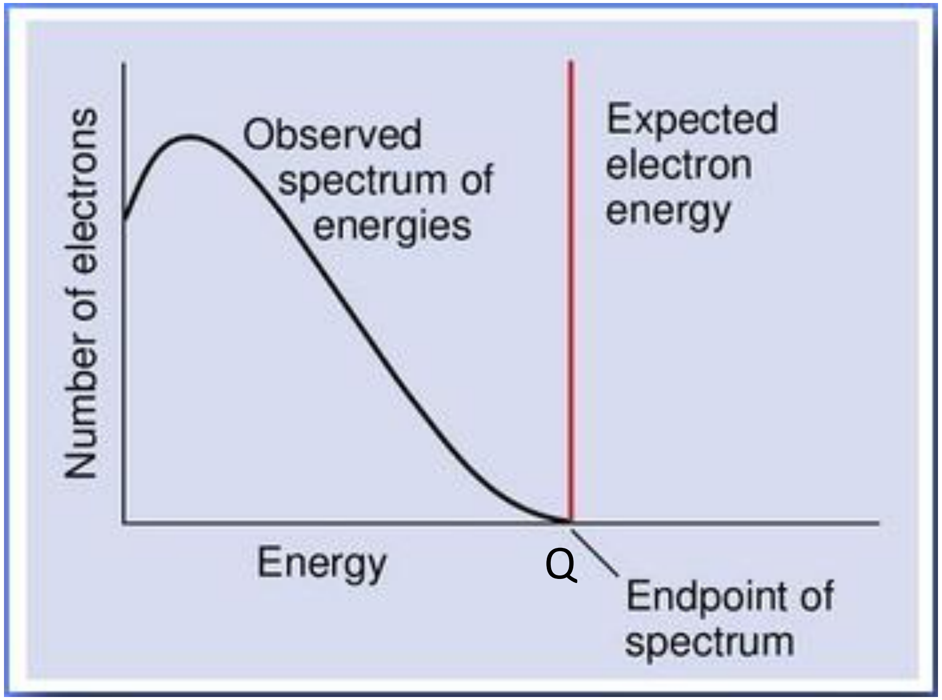
$${}^A_Z N \rightarrow {}^A_{Z+1} N' + e^-$$

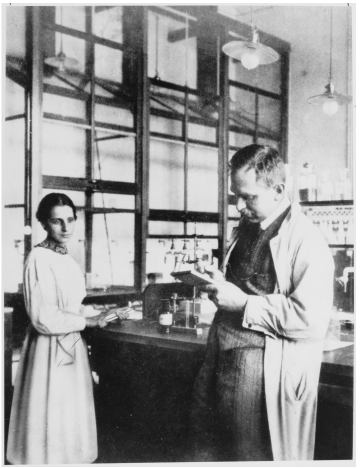
Energy-momentum conservation:

$$E_{\text{electron}} \simeq (M_N - M_{N'})c^2 = Q = \text{constante}$$

1911/1914

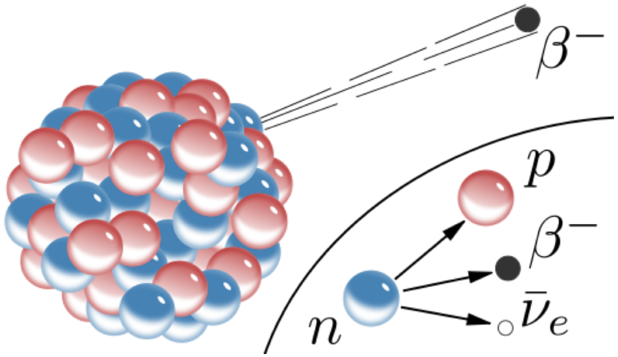
Electron spectrum:





Meitner, Hahn
(Nobel 1944 only him!)

Chadwick (Nobel 1935)



1930

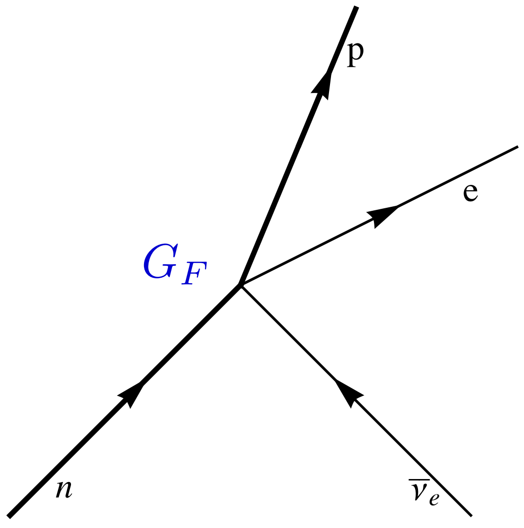
Pauli (Nobel 1945)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

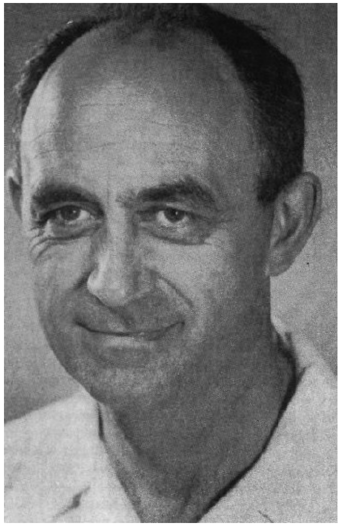
Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7….

1934: Theory of beta decay



$$n + \nu \rightarrow p + e^-$$

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



E. Fermi
(Nobel 1938)

Nature did not publish his article: "contained speculations too remote from reality to be of interest to the reader…"

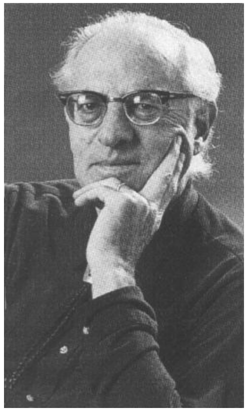
Bethe-Peierls (1934): compute the neutrino cross section using this theory

$$\sigma \simeq 10^{-44} cm^2, \; E(\bar{\nu}) = 2 \text{ MeV}$$

"there is not practically possible way of detecting a neutrino"

1956 (anti-) neutrino detection

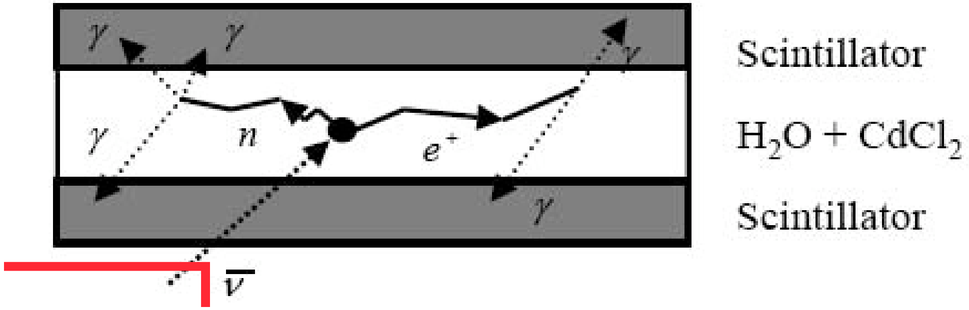
In a 1000kg detector, a 10^{11} $\nu/cm^2/s$
a few events per day



Reines

Cowan

Golden signal



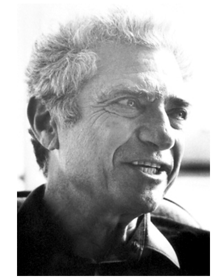
Modern versions of Reines&Cowan experiment: Chooz, KamLAND, DChooz, Daya Bay, RENO… still making discoveries today

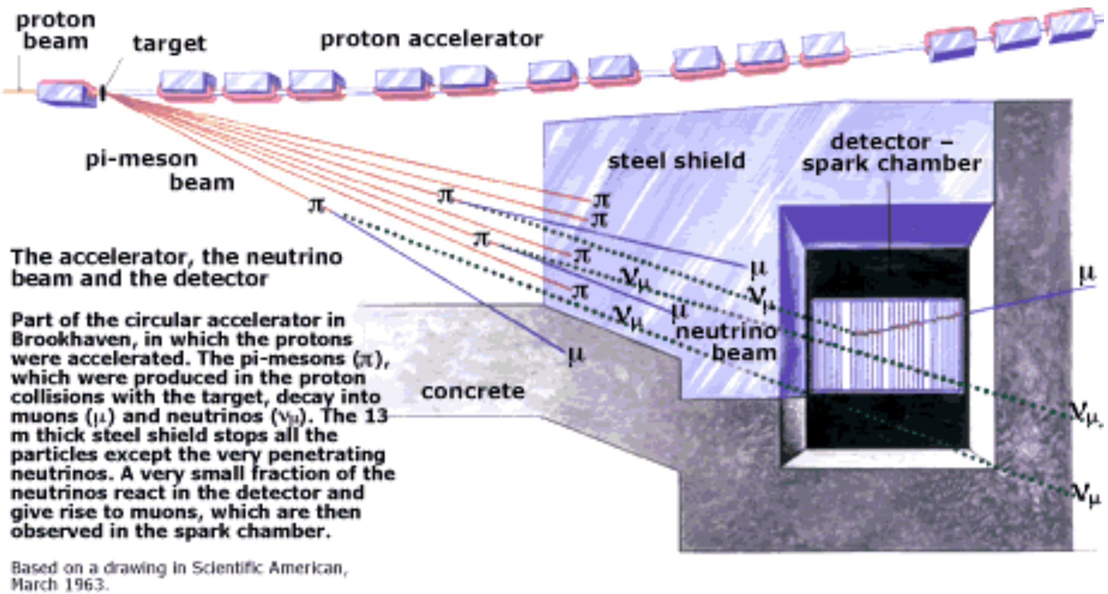
Neutrino Flavour & SM families

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$


Lederman


Schwartz


Steinberger



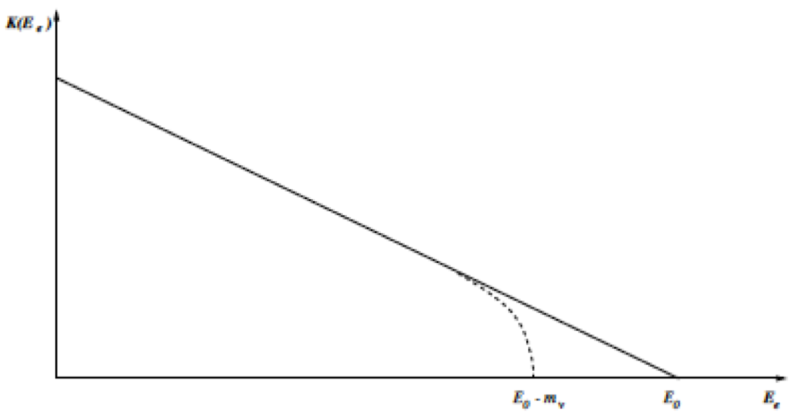
$$\pi \to \mu \; \bar{\nu}_\mu$$

Modern versions of Lederman, Schwartz, Steinberger experiment are accelerator neutrino experiments: MINOS, OPERA, T2K, NoVA,...

Kinematical effects of neutrino mass

Most stringent from tritium beta-decay

$$H^3 \to^3 He + e^- + \bar{\nu}_e$$



$m_{\nu_e} < 2.2\text{eV}$ (Mainz-Troitsk)

$m_{\nu_\mu} < 170\text{keV}$ (PSI: $\pi^+ \to \mu^+ \nu_\mu$)

$m_{\nu_\tau} < 18.2\text{MeV}$ (LEP: $\tau^- \to 5\pi\nu_\tau$)

Standard Model neutrinos assumed massless

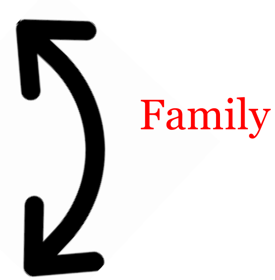
The most elusive & lightest particles have been key in the discovery of the weak interactions and in establishing the two most intringuing features of the baroque SM:

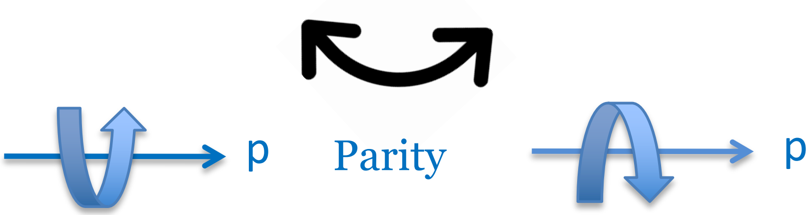
chiral nature of the weak interactions

3-fold repetition of family structures

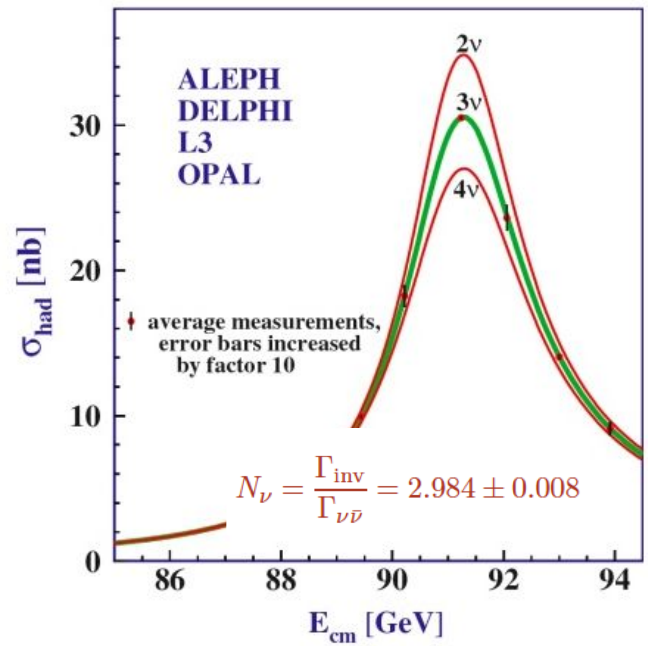
$SU(3) \times SU(2) \times U(1)_Y$

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



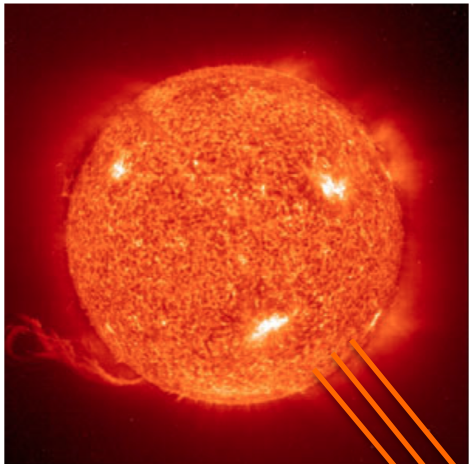


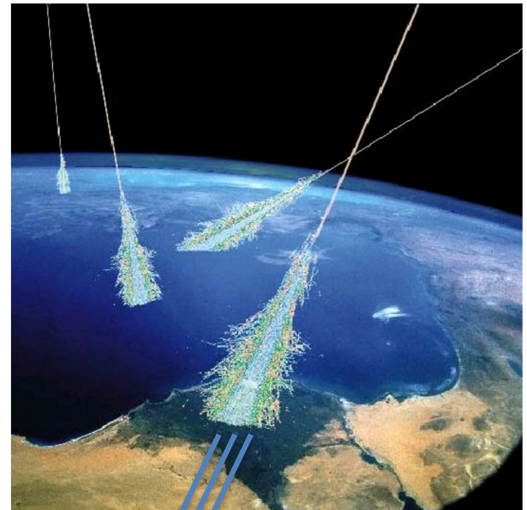
$e^+e^- \to Z^0 \to f\bar{f}$



Ubiquitous Neutrinos

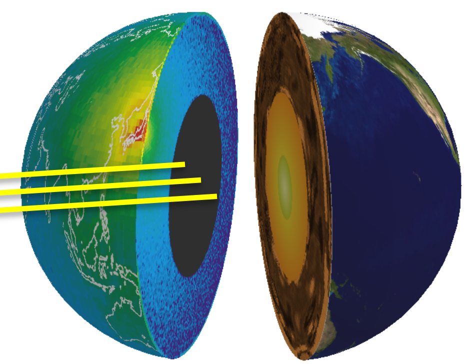
They are everywhere…





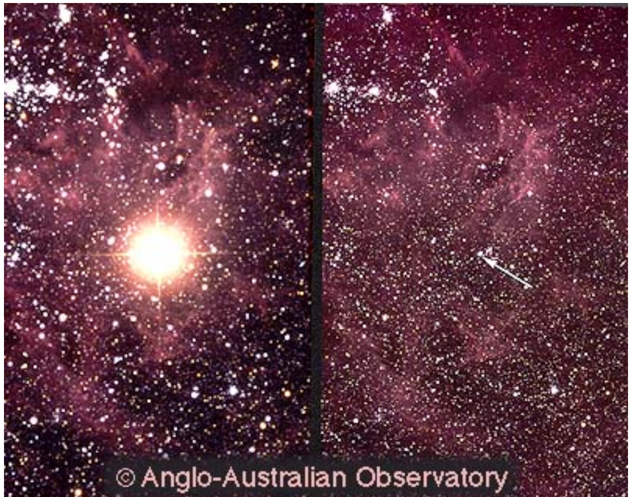
Sun: 5 x 10^{12}/second

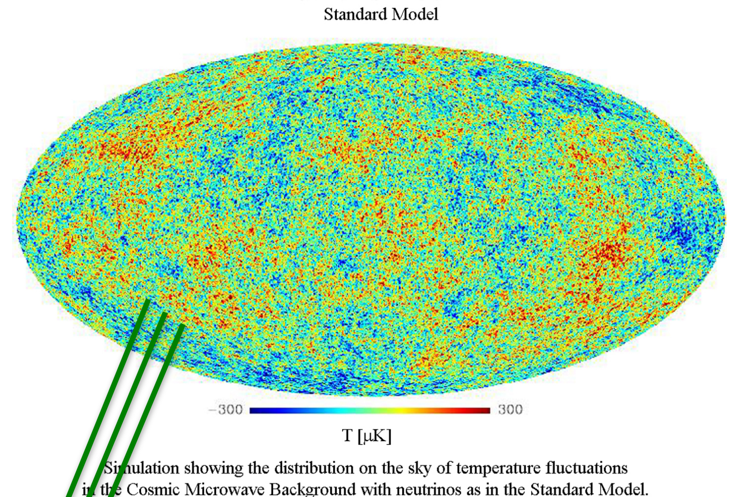
Atmosphere: ~20/second



Earth: ~10^9/second

Ubiquitous Neutrinos





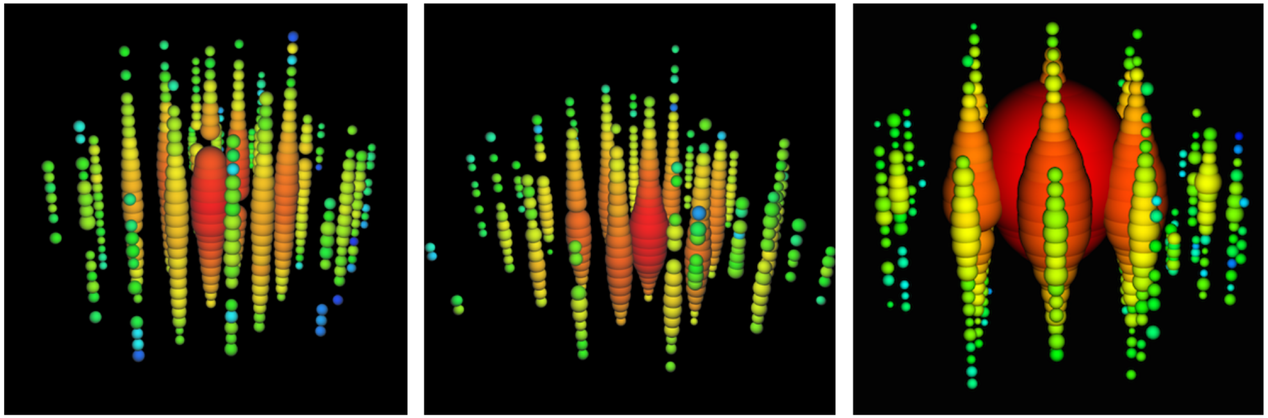
Big Bang: ~2 x 10^{12}/second

Supernova 1987: ~10^{12}/second

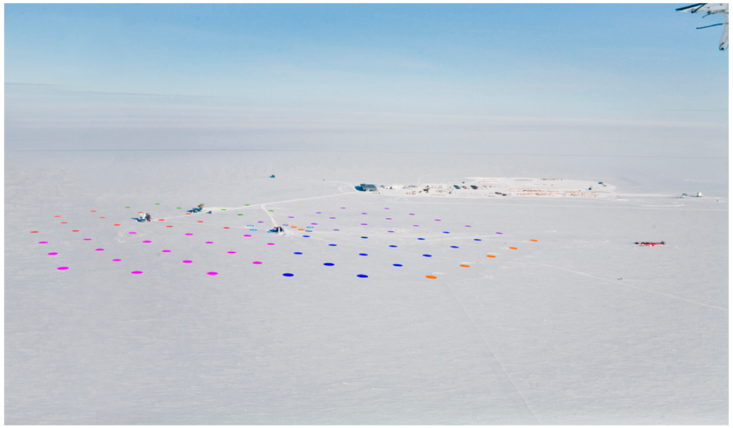
@168000 Light years!
10^8 farther from Earth

Ubiquitous Neutrinos

Recently discovered PeV neutrino flux from still unknown sources…



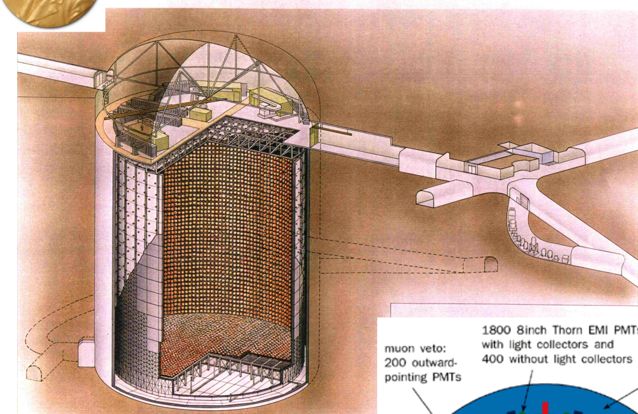
Barbano's talk



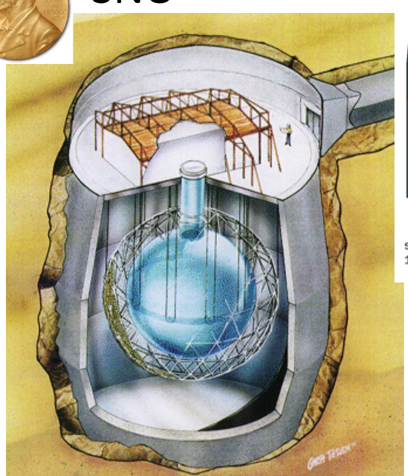
Icecube

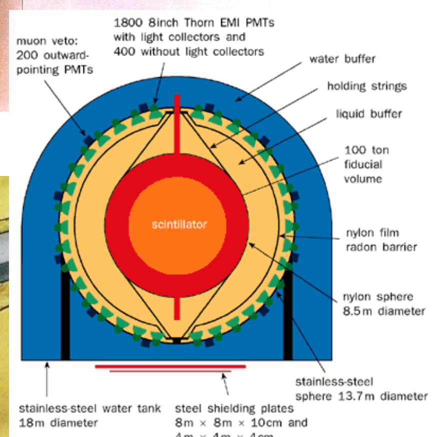
Using many of these sources, and others man-made, two decades of revolutionary neutrino experiments have demonstrated that neutrinos are not quite standard, because they have a tiny mass & massive neutrinos require to extend the SM!

SuperKamiokande



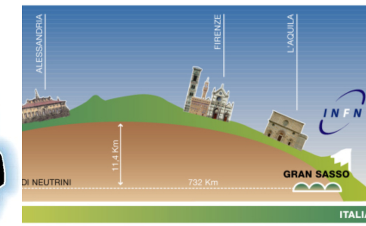
SNO





Borexino

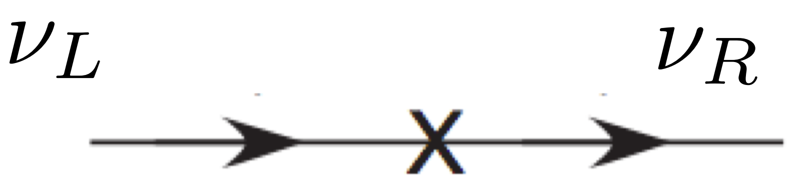
MINOS, Opera



...and more

Massive Dirac fermions

$$-\mathcal{L}_m^{\rm Dirac} = m\bar{\psi}\psi = m(\overline{\psi_L + \psi_R})(\psi_L + \psi_R) = m(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$



A massive particle must have both helicities…

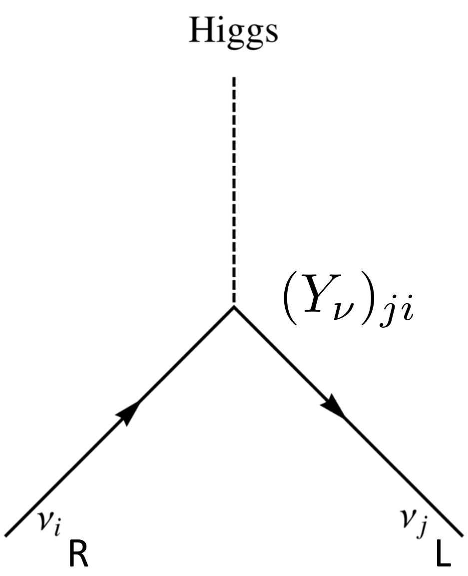
$$\nu_{\rm D} = \nu_L + \nu_R$$

Since left/right carry different SU(2) x U(1) charges: we need the higgs!

Massive Dirac neutrinos via SSB

Massive Dirac neutrinos require an extension of the SM table: eg. ν_R

$$-\mathcal{L}_{\rm SM} \supset Y_{\nu ij} \bar{L}_i \tilde{\phi}\, \nu_{Rj}$$



$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

A lepton flavour sector analogous to the quark one

Neutrino masses & lepton mixing

Yukawa couplings are generic complex matrices in flavour space:

$$-\mathcal{L}_m^{lepton} = \bar{\nu}_{Li} \underbrace{(M_\nu)_{ij}}_{3\times n_R} \nu_{Rj} + \bar{l}_{Li} \underbrace{(M_l)_{ij}}_{3\times 3} l_{Rj} + h.c.$$

$$M_\nu = U_\nu^\dagger \ \mathrm{Diag}(m_1, m_2, m_3)\ V_\nu, \ \ M_l = U_l^\dagger \ \mathrm{Diag}(m_e, m_\mu, m_\tau)\ V_l$$

In the mass eigenbasis

$$\mathcal{L}_{\mathrm{gauge-lepton}} \supset -\frac{g}{\sqrt{2}} \bar{l}'_{Li} \underbrace{(U_l^\dagger U_\nu)_{ij}}_{U_{PMNS}} \gamma_\mu W_\mu^- \nu'_{Lj} + h.c.$$

Pontecorvo-Maki-Nakagawa-Sakata

$U_{\mathrm{PMNS}}(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ unitary matrix analogous to CKM

Neutrino oscillations

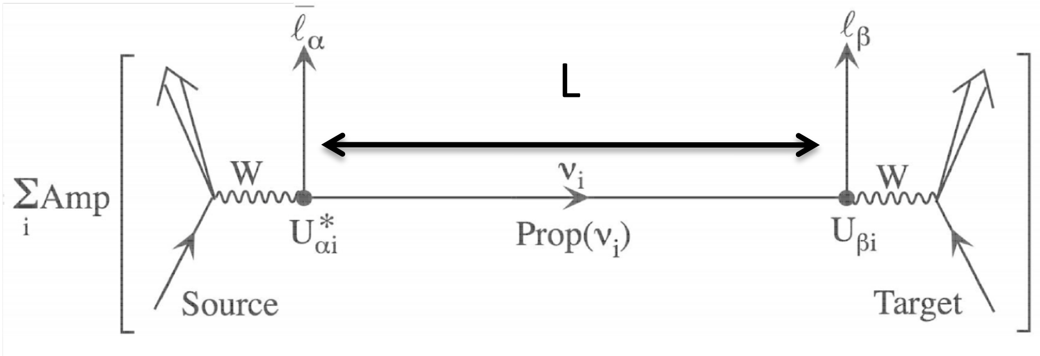
Neutrinos are produced/detected in flavour basis (via CC):

States produced in a CC interaction in combination with e, μ, τ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Eigenstates of the free Hamiltonian

A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances !



Neutrino Oscillation

$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{(m_i^2 - m_j^2)L}{2E}}$$

$\alpha \neq \beta$ appearance probability: $\alpha = \beta$ disappearance or survival prob.

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \underbrace{2\sum_{i<j} Re[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] + \sum_{i=j} |U_{\alpha i}|^2 |U_{\beta i}|^2}_{\delta_{\alpha\beta}}$$

CP-even

$$- 4\sum_{i<j} \mathrm{Re}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin^2\left[\frac{\Delta m^2_{ji} L}{4E}\right]$$

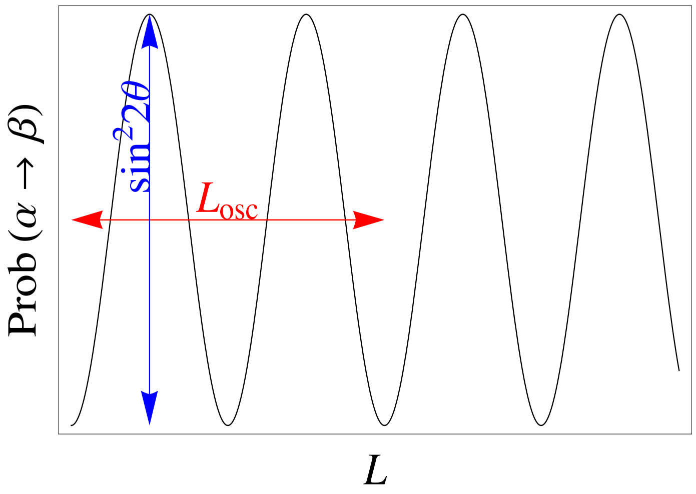
CP-odd

$$\mp 2\sum_{i<j} \mathrm{Im}[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}] \sin\left[\frac{\Delta m^2_{ji} L}{2E}\right]$$

Neutrino Oscillation: 2ν

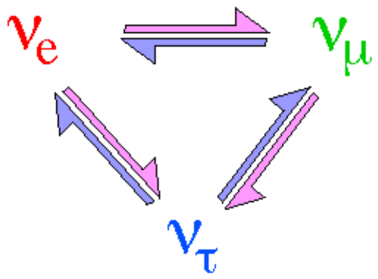
Two families: $U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

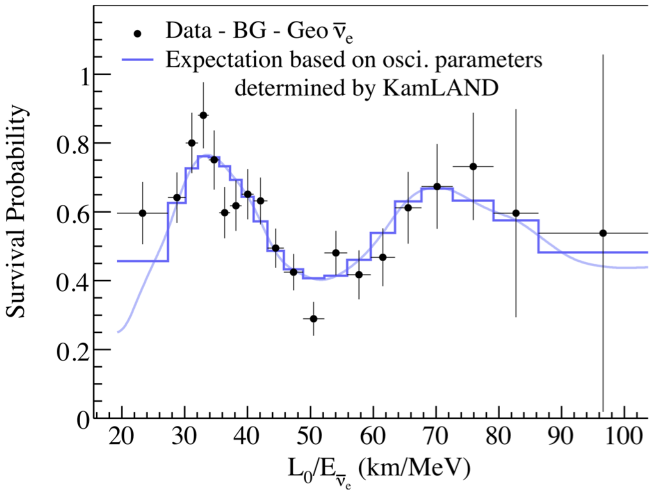


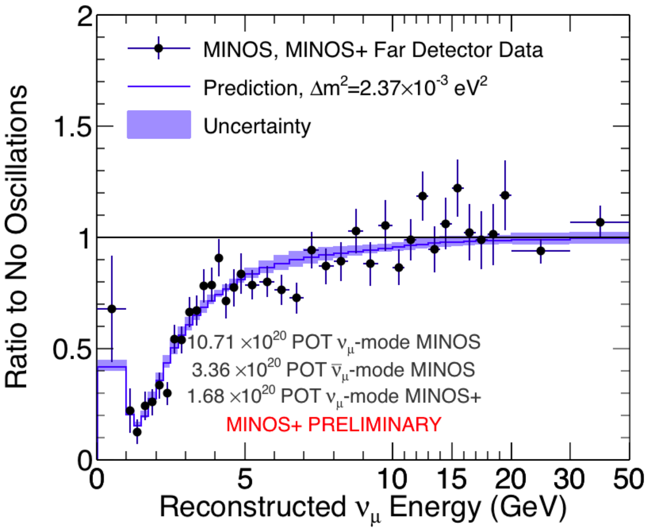
$$L_{osc}(km) = \frac{\pi}{1.27}\frac{E(GeV)}{\Delta m^2(eV^2)}$$

Two distinct oscillations precisely measured



$$\Delta m^2_{\text{sol}} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(100km)}$$

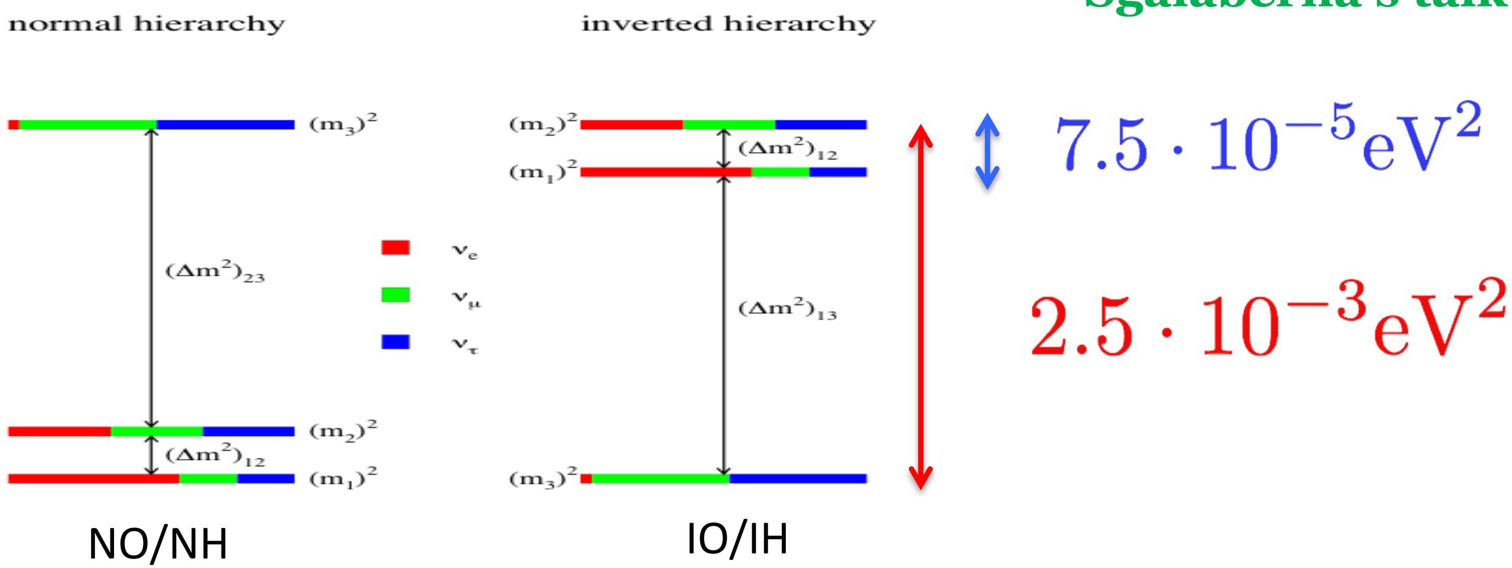




$$|\Delta m^2_{\text{atm}}| \sim \frac{\mathcal{O}(GeV)}{\mathcal{O}(1000km)} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1km)}$$

Standard 3ν scenario

Sgalaberna's talk



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

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

$\theta_{23} \sim 42^\circ$ o 48°

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

$\delta \sim\ ?$

Caveat: O(eV) neutrinos…reactor/accelerator short baseline anomalies still unresolved

Sanchez's talk

The known unknowns

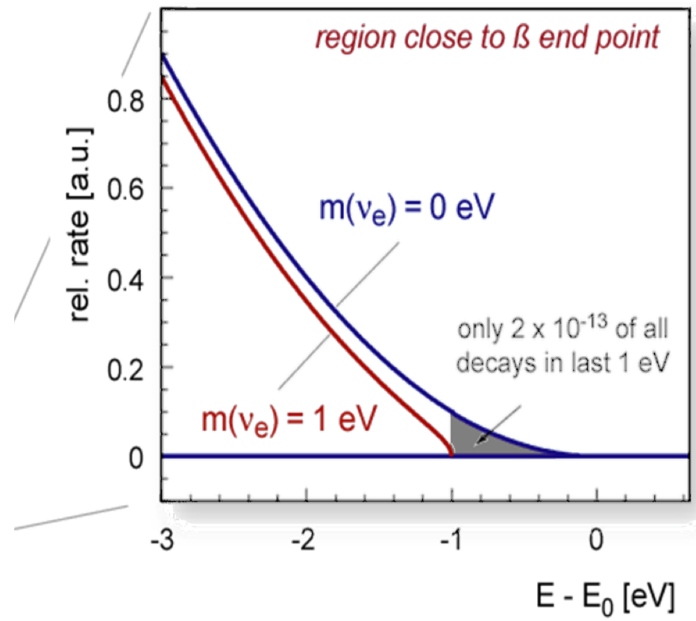
What is the neutrino ordering normal or inverted ? Is there leptonic CP violation ? $\delta \neq 0, \pi$

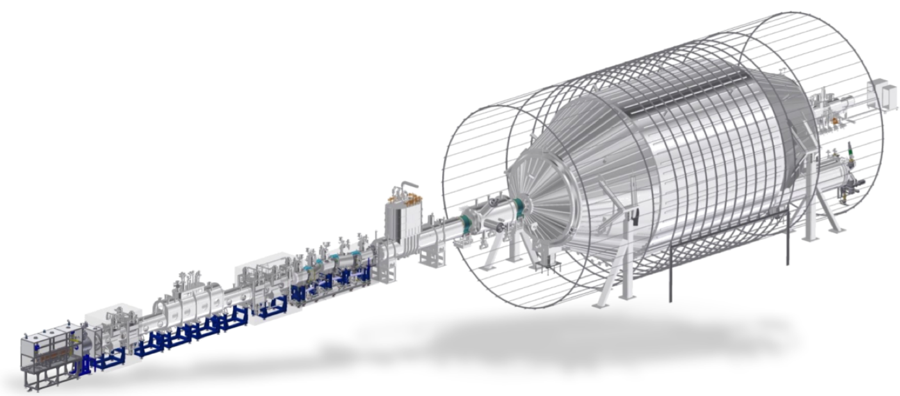
-> neutrino oscillation experiments **Sgalaberna's talk**

Absolute mass scale ?

-> tritium beta decay + cosmology

State-of-the-art tritium beta decay experiment: Katrin



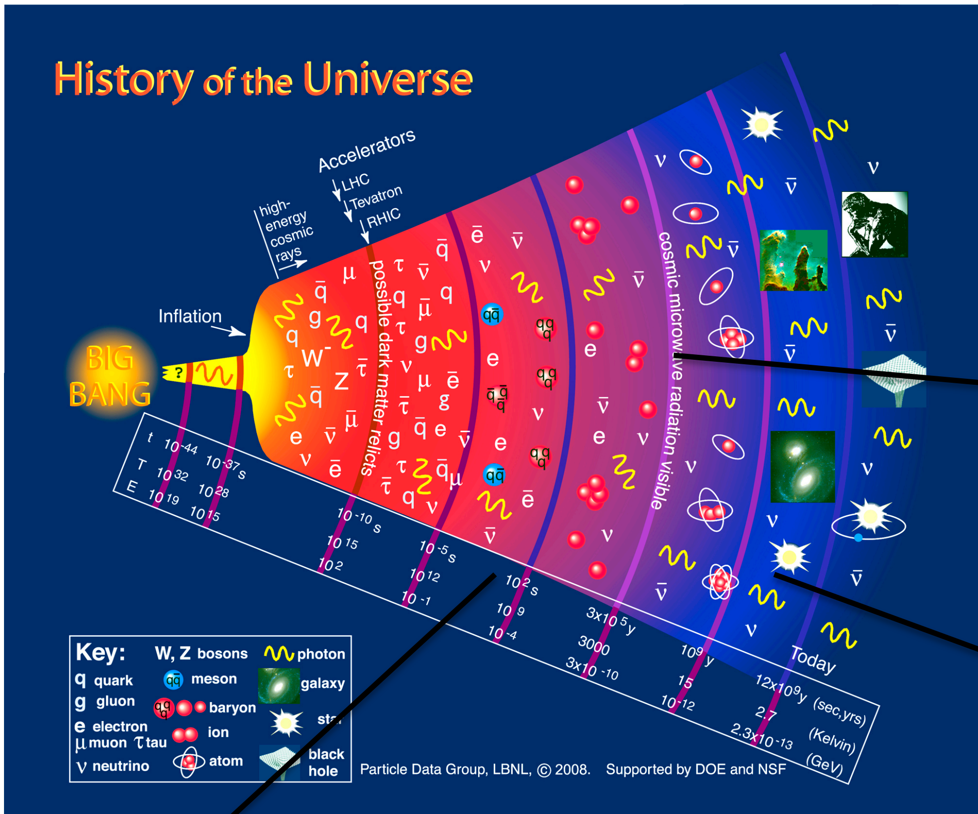


Goal:

“$m_{\nu e}$ "< 0.2 eV

Neutrinos in cosmology

Neutrinos have left many traces in the history of the Universe: contribution to radiation and to matter



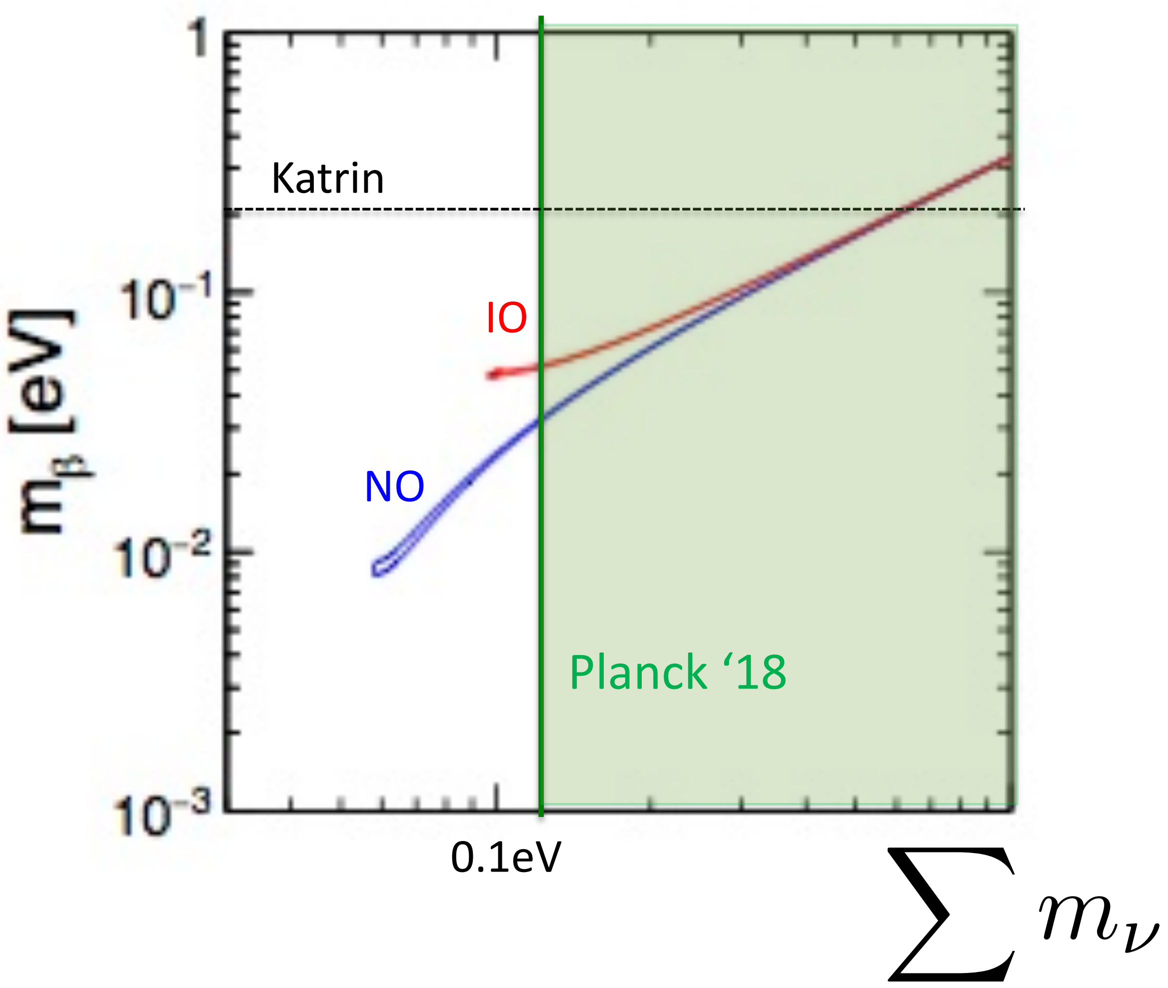
CMB

Galaxy distribution (LSS)

Nucleosynthesis

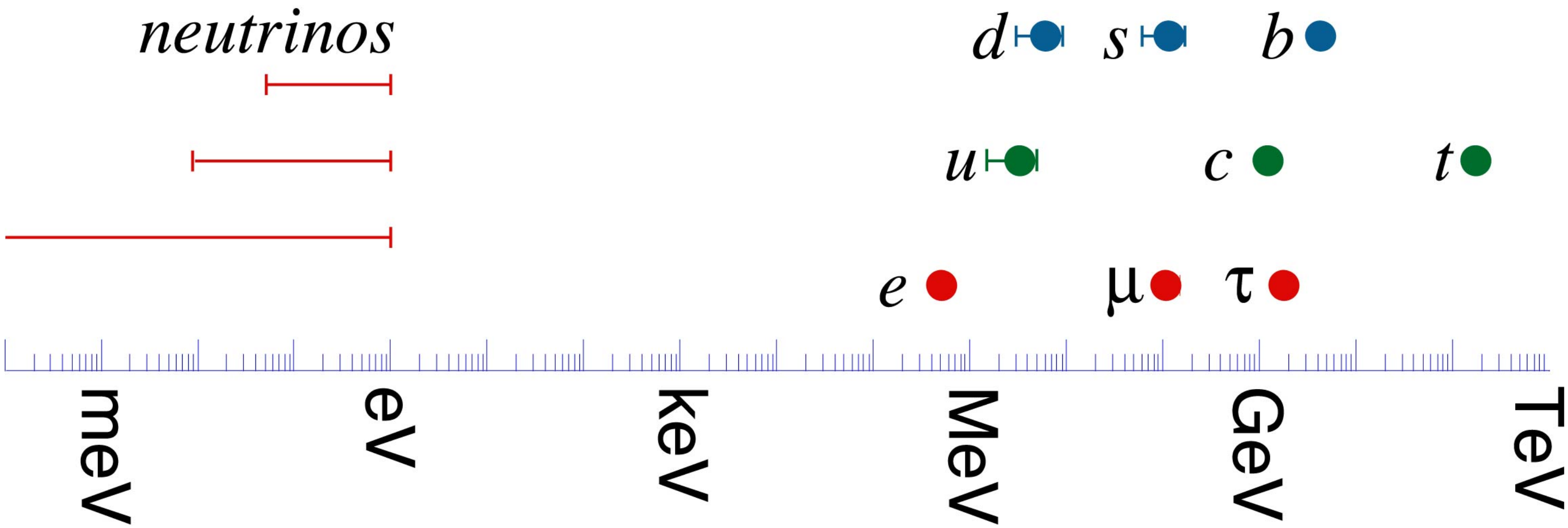
Planck ‘18 $\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

Absolute ν mass scale



Massive neutrinos: a new flavour perspective

Why are neutrinos so much lighter ?



Massive neutrinos: a new flavour perspective

Why do they mix so differently ?

CKM

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

PMNS

3σ

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

Massive neutrinos: a new flavour perspective

Why do they mix so differently ?

CKM

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

PMNS

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

Harrison, Perkins, Scott

Majorana fermion

Majorana fermion of mass m:

$$-\mathcal{L}_m^{Majorana} = \frac{m}{2}\overline{\psi^c_L}\psi_L + \frac{m}{2}\overline{\psi_L}\psi^c_L \equiv \frac{m}{2}\psi_L^T C\psi_L + \frac{m}{2}\bar{\psi}_L C\bar{\psi}_L^T,$$

$C = i\gamma_2\gamma_0$

ν_L $\qquad$ $\nu_L^c = C\overline{\nu_L}^T$

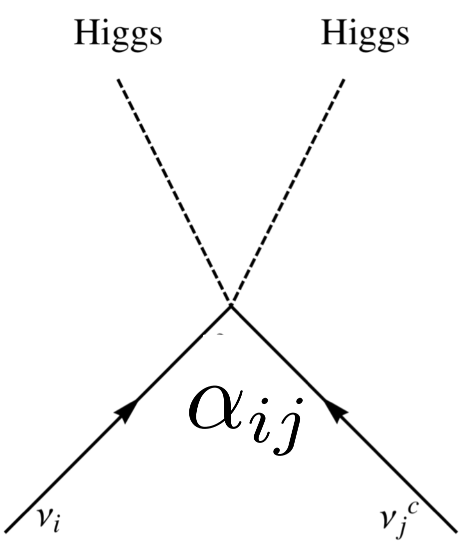
Massive field is both particle and antiparticle $\qquad \nu_M = \nu_L + \nu_L^c$

No conserved charge global or gauge !

Massive Majorana neutrinos via SSB ?

Weinberg's coupling

$$-\mathcal{L}^{\text{Majorana}} = \alpha \bar{L}\ \widetilde{\phi}\ C \widetilde{\phi}^T \bar{L}^T + h.c. \rightarrow SSB \rightarrow \alpha \frac{v^2}{2} \bar{\nu}_L C \bar{\nu}_L^T + h.c.$$



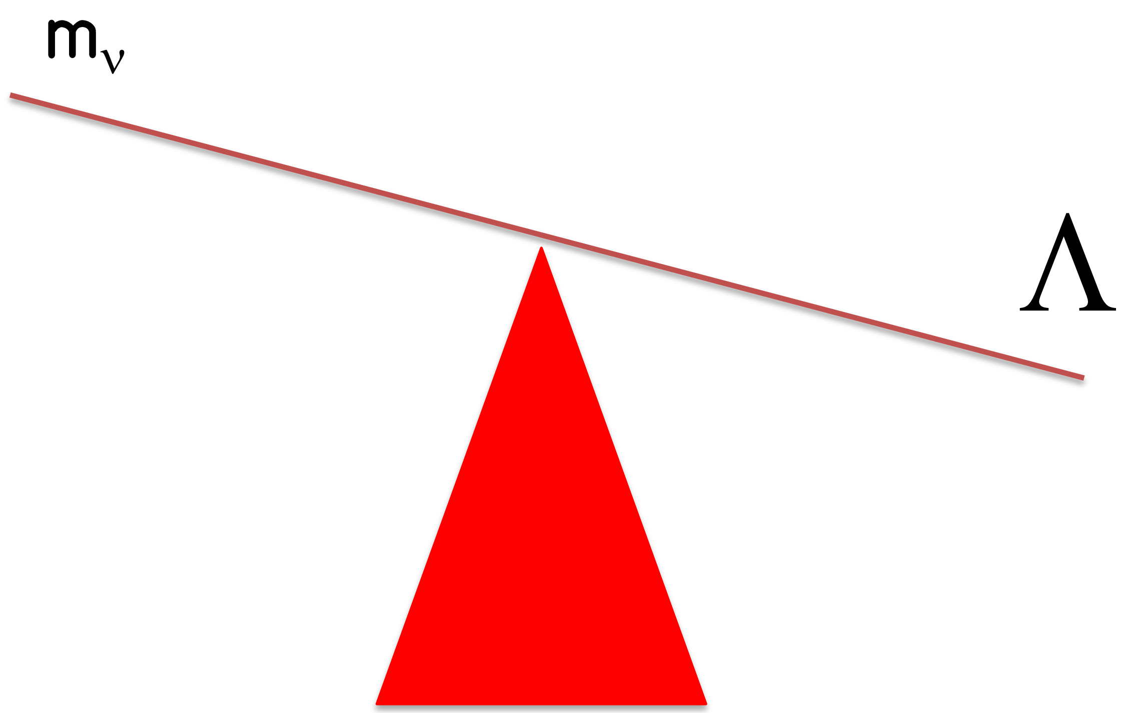
$$m_\nu = \alpha \frac{v^2}{2}$$

$$[\alpha] = -1 \qquad \alpha \equiv \frac{c}{\Lambda}$$

Implies the existence of a new physics scale possibly unrelated to v !

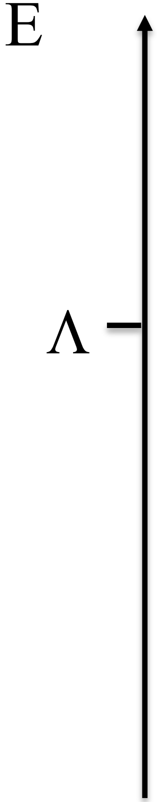
Seesaw mechanism:

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



SM + New Physics = SMEFT

What if there is new physics (ie. new fields with mass Λ) ?



$$\mathcal{L}_{\rm SM}[\phi] + \mathcal{L}_{\rm BSM}[\phi, \Phi]$$

Φ : new particles of mass Λ

$$\mathcal{L}'_{\rm SM}[\phi] + \mathcal{L}_{\rm SMEFT}[\phi]$$

$$\mathcal{L}_{\rm SMEFT} = \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

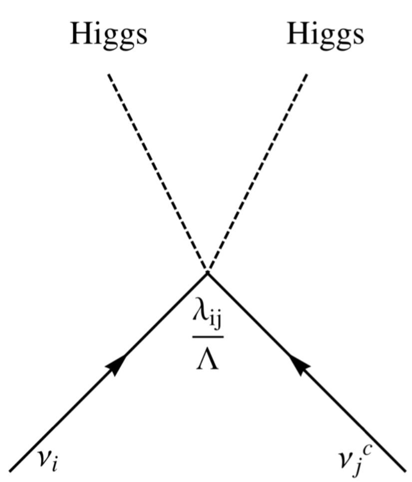
Hierarchy problem !

$$\mu'^2 = \mu^2 + \mathcal{O}(\Lambda^2)$$

Violation of unitarity at E ≥ Λ !

SMEFT

$$\mathcal{L}_{\rm SMEFT} = \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)}}_{1\ \text{operator}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}}_{2499\ \text{operators(59 B,L,FC)}} + \ldots$$



$$\mathcal{O}^{(5)} = \frac{c_{ij}^{(5)}}{\Lambda}\bar{L}_i H (H L_j)^c + h.c. \rightarrow \overline{\nu}_L \frac{m_\nu}{2}\nu_L^c + h.c.$$

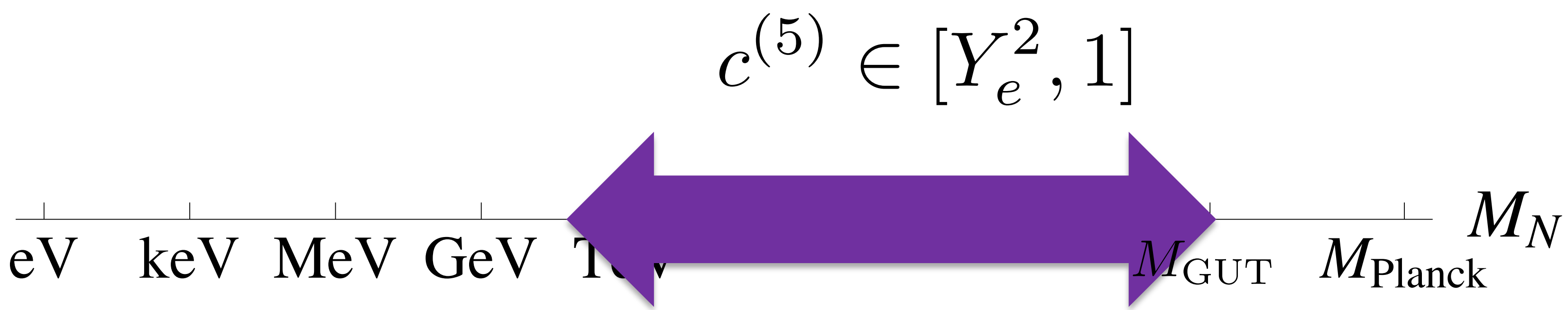
Scale at which new particle(s) will show up !

$$c_i^{(d)} \propto (\text{couplings})^{\#}$$

$$\frac{c^{(5)}}{\Lambda} = \frac{m_\nu}{v^2} \sim \mathcal{O}\left(\frac{1}{10^{15}\ \text{GeV}}\right)$$

Neutrino mass mediator scale ?

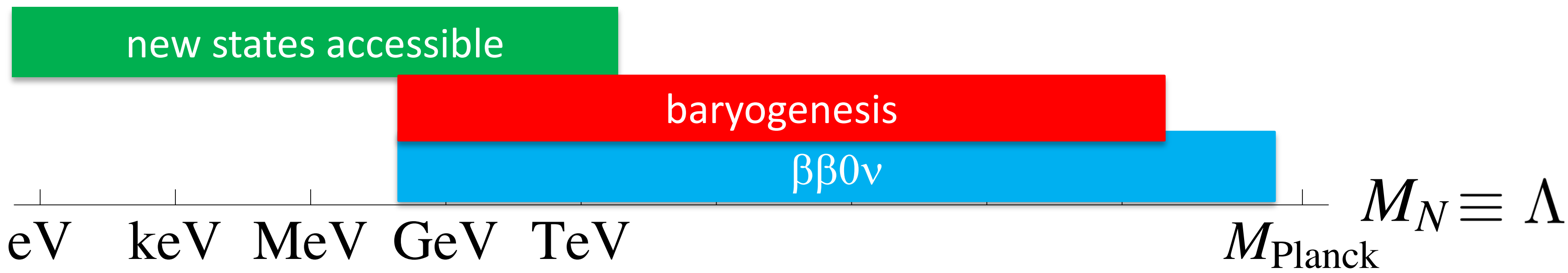
12 order of magnitude of possibilities that can explain naturally why neutrinos are special



The million dollar open question:

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

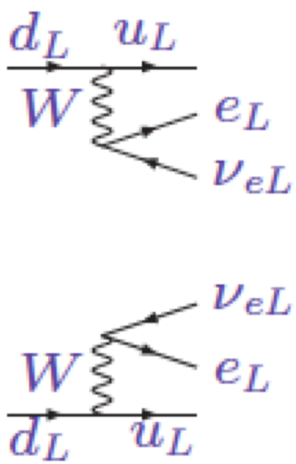
Neutrino mass mediator scale ?

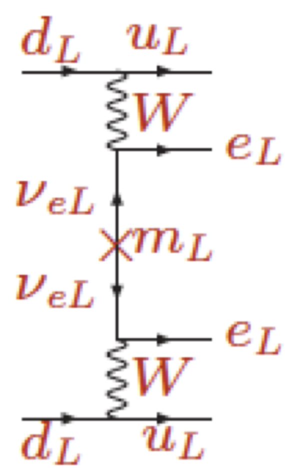


- Model independent prediction: neutrinoless double beta decay if $\Lambda \geq 100$ MeV
- Generic but details model dependent: new states accessible, baryogenesis

The EW scale is an interesting region: new physics underlying neutrino mass and baryogenesis could be testable !

Majorana nature: ββ0ν





$T_{2\beta 2\nu} \sim 10^{18} - 10^{21}$ years

$$T^{-1}_{2\beta 0\nu} \sim \left(\frac{m_\nu}{E}\right)^2 10^9\, T^{-1}_{2\beta 2\nu}$$

If neutrinos are Majorana this process must be there at some level $\Lambda \geq 100$ MeV

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

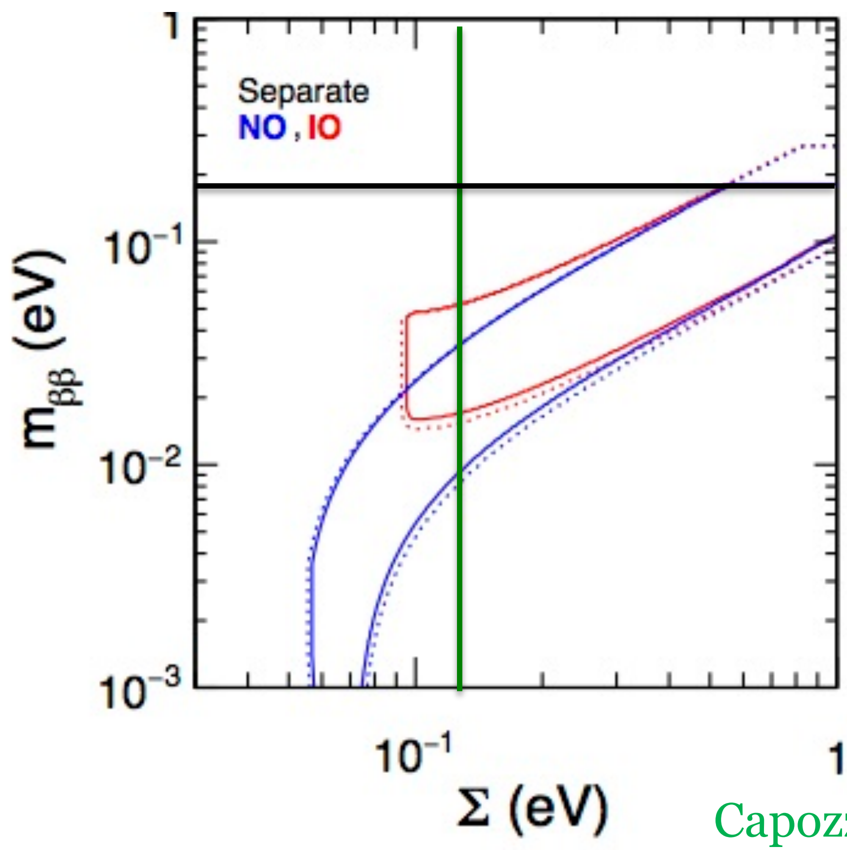
$$U_{\text{PMNS}}(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \underbrace{\alpha_1, \alpha_2}_{\text{Majorana CP phases}})$$

Majorana nature: ββ0ν

Plethora of experiments with different isotopes/techniques: EXO, KamLAND-Zen, SNO+, GERDA, Cuore, NEXT, CUPID, LEGEND, DARWIN ...

$$m_{\beta\beta} = \underbrace{\sum_{i=1}^{3} \left[(U_{PMNS})_{ei} \right]^2 m_i}$$

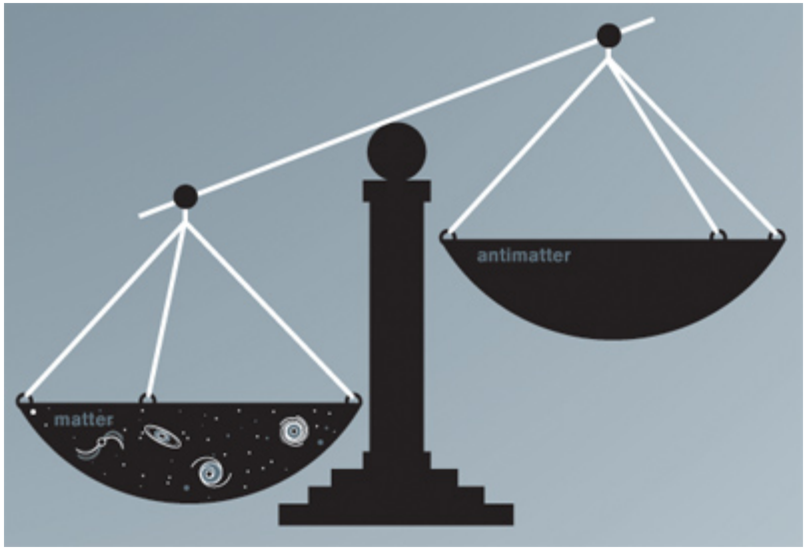
$$\Sigma \equiv \sum_i m_i$$



Capozzi et al ‘17

Baryon asymmetry

The Universe seems to be made of matter $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}$



Can it arise from a symmetric initial condition with same matter & antimatter: baryogenesis ?

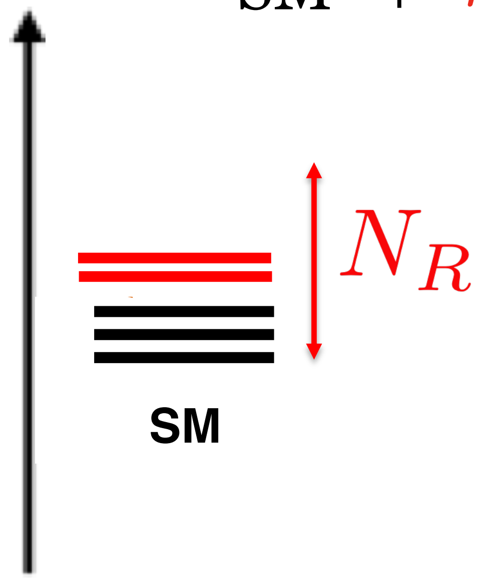
Sakharov's necessary conditions:
1) C, CP violation
2) B violation
3) out-of-equilibrium

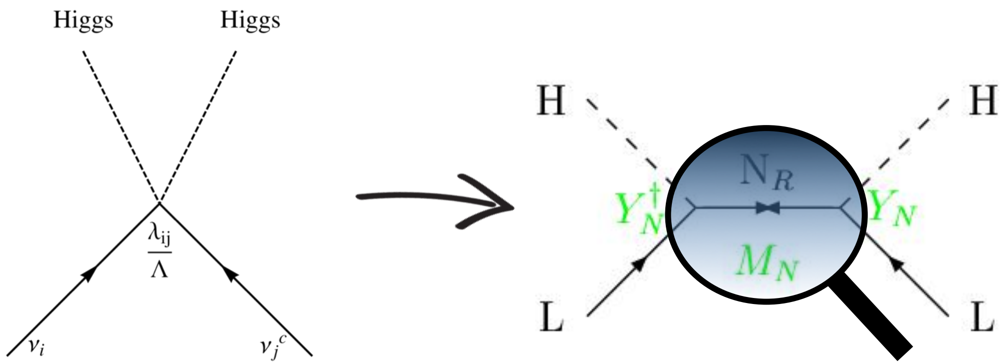
All present in SM but not enough...

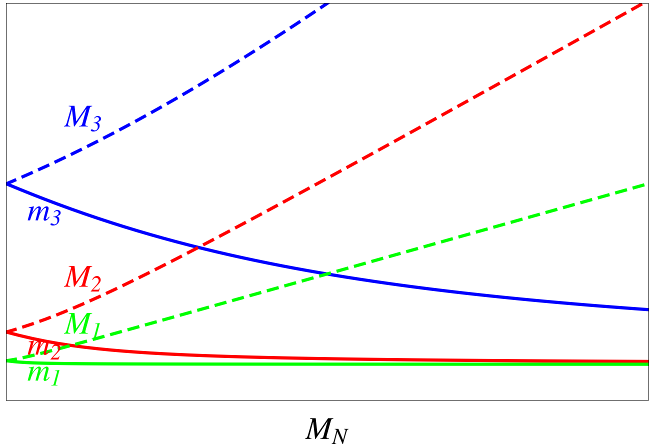
Minimal model of neutrino masses: Type I seesaw

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

SM + $n_R \geq 2$ massive Majorana singlets







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

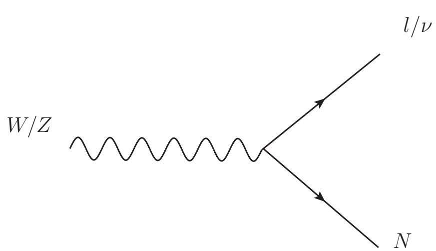
$n_R = 2$: 11 free parameters (4 masses+4 angles+3 phases)

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

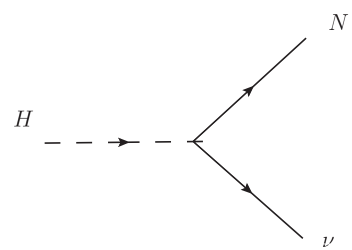
Type I seesaw models

Phenomenology (beyond neutrino masses) of these models depends on the spectrum and the size of active-heavy mixing:

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



U_{lh}



$U_{lh} \frac{\sqrt{2} M_h}{v}$

Strong correlation between active-heavy mixing and neutrino masses:

$|U_{lh}|^2 \sim \frac{m_l}{M_N}$ (but not true for $n_R > 1$...)

Baryogenesis via Leptogenesis

Sakharov's necessary conditions

C & CP violation (3 or more new CP phases in the lepton sector)

B+L violation from sphalerons $T > T_{EW}$ and L violation from Majorana masses

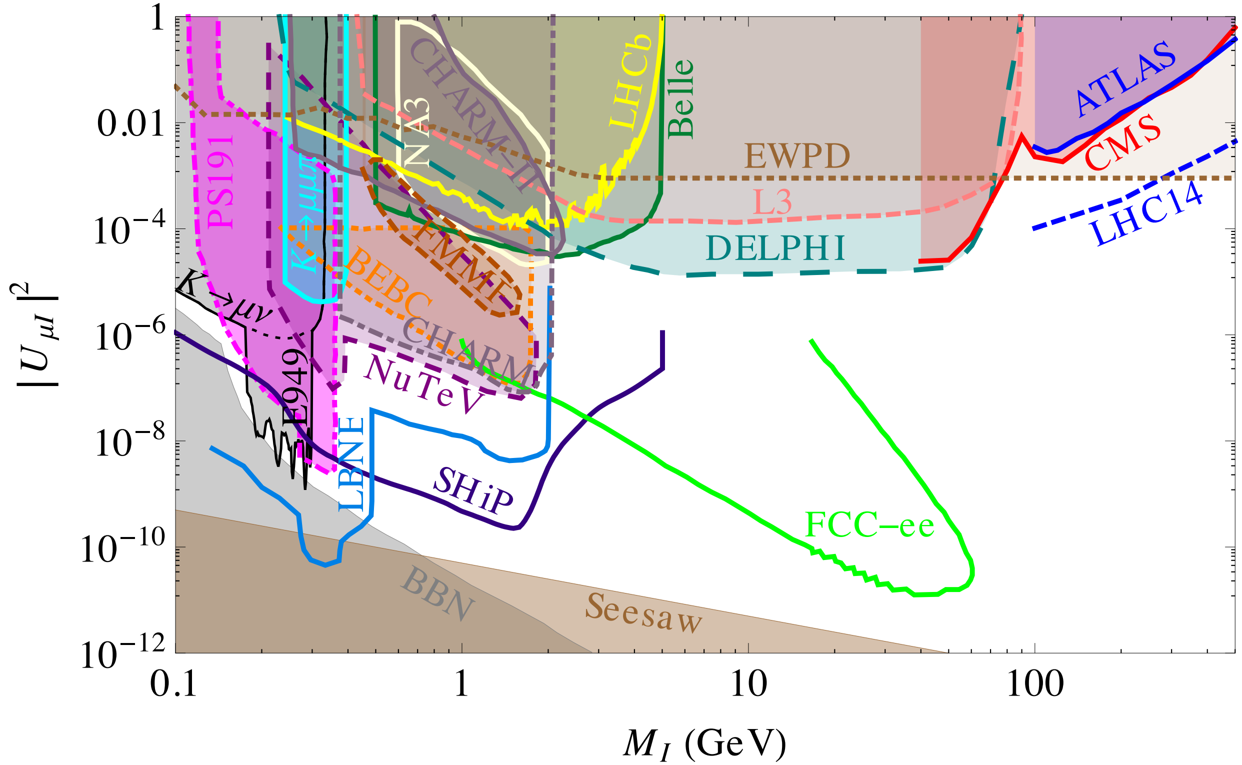
Out of equilibrium: N_R fall out of equilibrium early or never reach equilibrium

Testability ?

Y_B cannot be predicted from light neutrino masses and mixings only, need more information from the heavy sector

Searching for a neutrino mass mediator

Beam dump and collider searches of neutral heavy leptons



Reviews Atre, Han, Pascoli, Zhang; Gorbunov, Shaposhnikov; Ruchayskiy, Ivashko; Deppisch, Dev, Pilaftsis

Searching for a neutrino mass mediator

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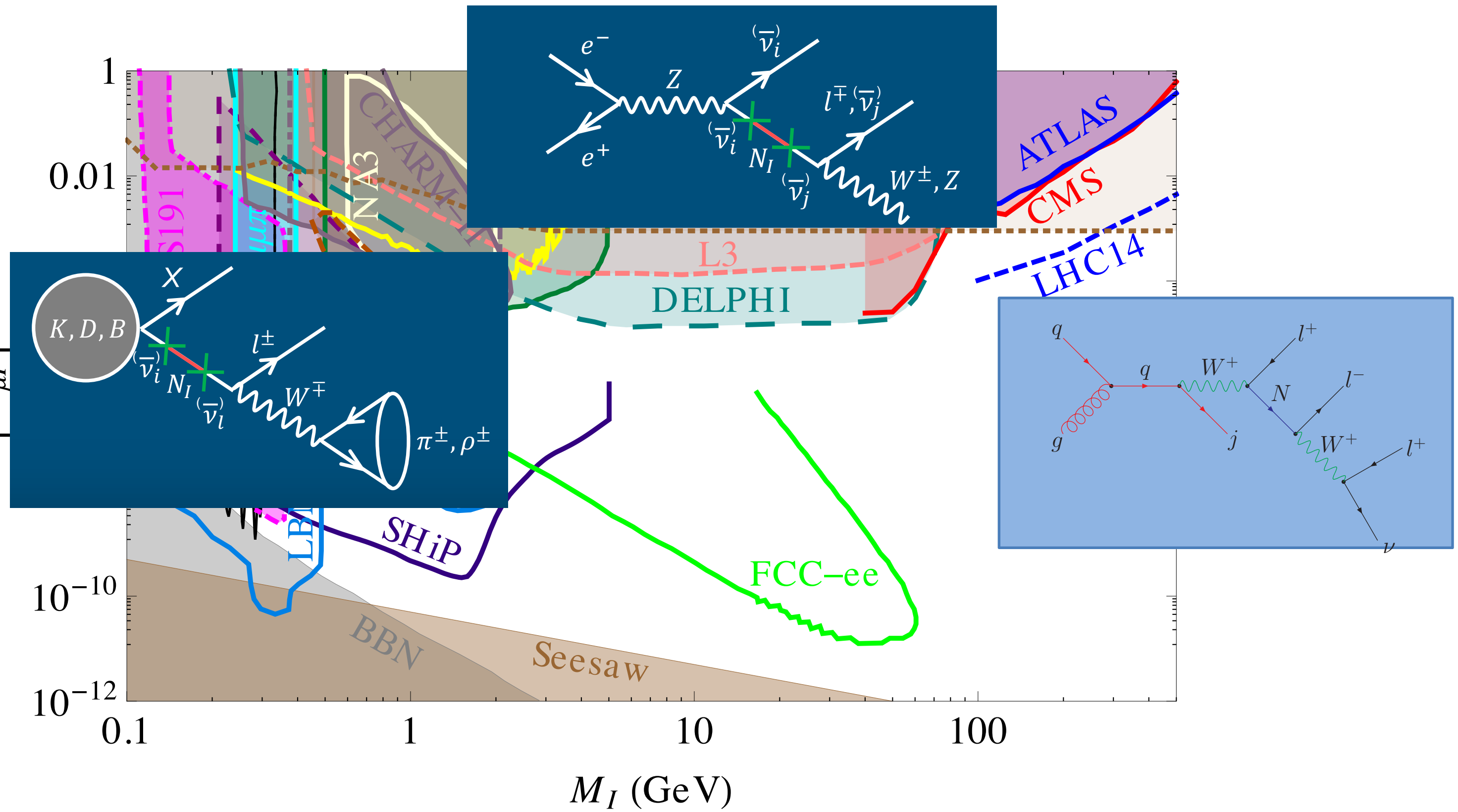
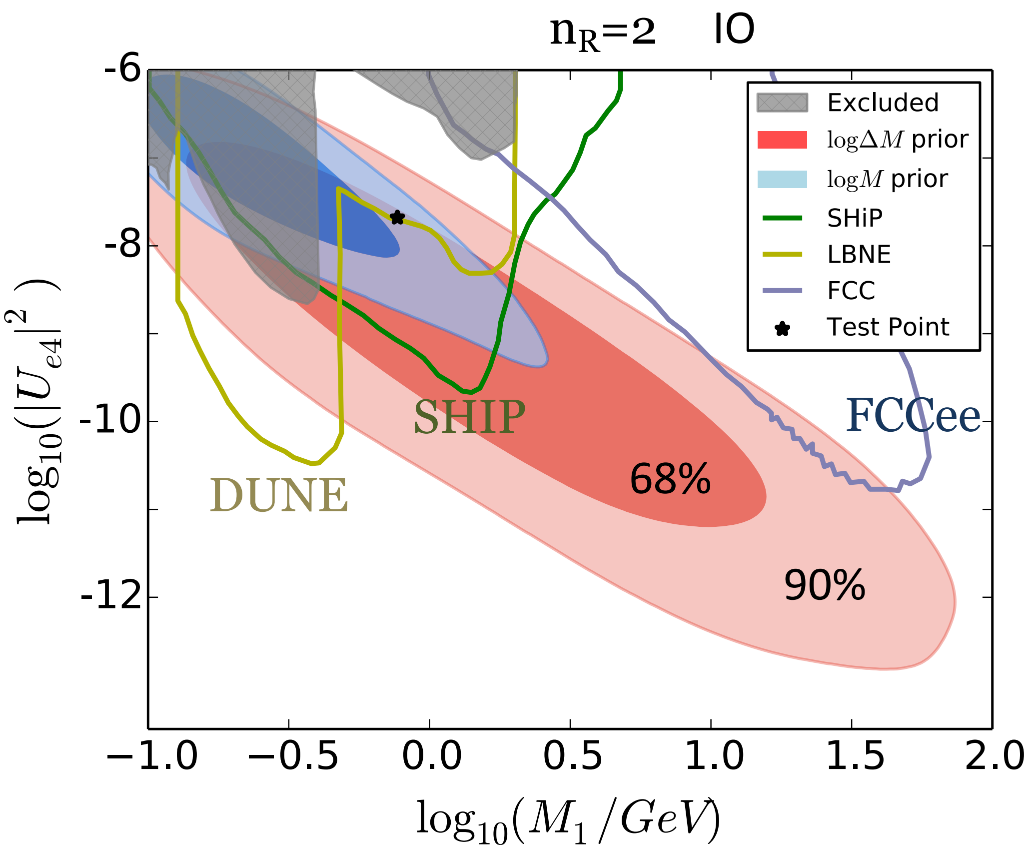


Reviews Atre, Han, Pascoli, Zhang; Gorbunov, Shaposhnikov; Ruchayskiy, Ivashko; Deppisch, Dev, Pilaftsis

Testing neutrino mass + low-scale leptogenesis

Posterior of successful baryon asymmetry $$\mathcal{L} = -\left(\frac{Y_B(\text{param}) - Y_B^{\text{obs}}}{\sigma_{Y_B}}\right)^2$$



PH, Kekic, Lopez-Pavon, Racker, Salvado arxiv:1606.06719

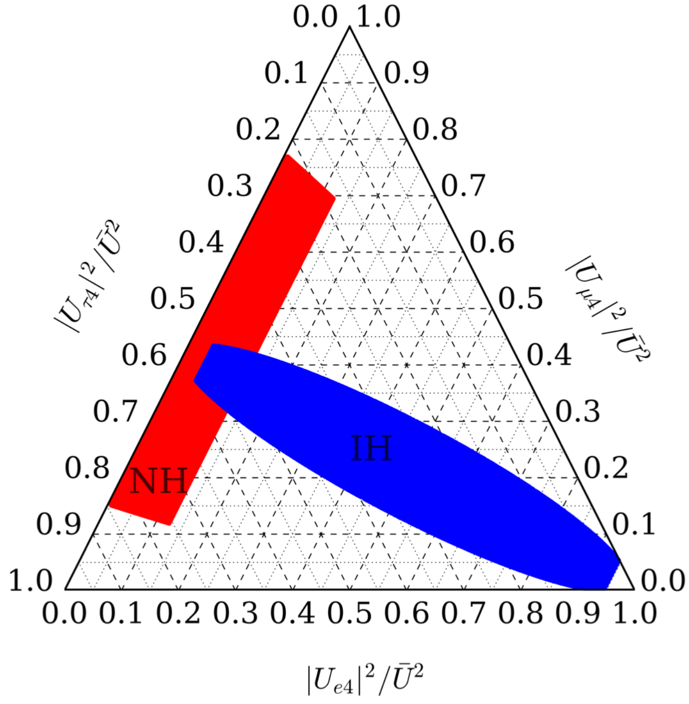
The measurement of the mixing to e/μ of the heavy states, ββ0ν and δ in neutrino oscillations have a chance to give a prediction for Y_B

Can we tell if they are neutrino mass mediators ?

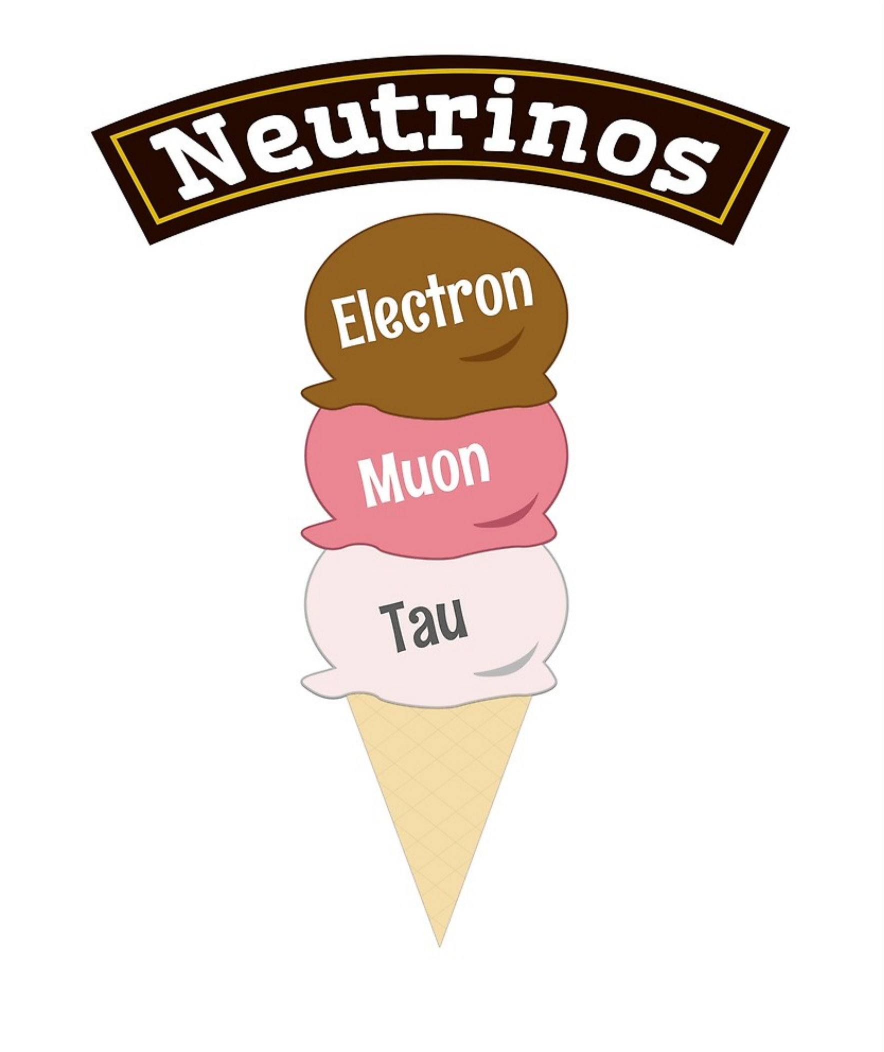
Seesaw correlations:

flavour ratios of heavy lepton mixings strongly correlated with ordering, U_{PMNS} matrix: δ, ϕ_1

n_R=2:



Caputo, PH, Lopez-Pavon, Salvado arxiv:1704.08721



TASTY ICECREAM FULL OF SURPRISES !