NORDITA Winter School 2024
in Particle Physics and Cosmology

Neutrino physics II: Neutrino Mass

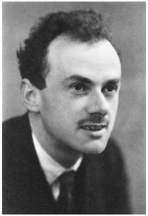
Thomas Schwetz-Mangold

Karlsruher Institut für Technologie

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Stockholm, 15-17 Jan 2024

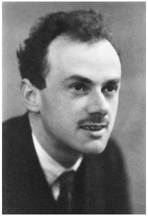
Neutrinos oscillate...



... and have mass ⇒ physics beyond the Standard Model

- Part I: Neutrino Oscillations
- Part II: Neutrino mass - Dirac versus Majorana
- Part III: Neutrinos and physics beyond the Standard Model

Neutrinos oscillate...



... and have mass ⇒ physics beyond the Standard Model

- Part I: Neutrino Oscillations
- Part II: Neutrino mass - Dirac versus Majorana
- Part III: Neutrinos and physics beyond the Standard Model

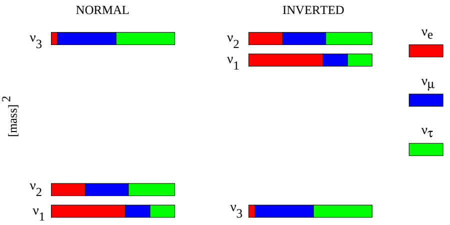
Outline

Outline

3-flavour neutrino parameters

- 3 masses: Δm^2_{21}, Δm^2_{31}, m_0
- 3 mixing angles: θ_{12}, θ_{13}, θ_{23}
- 3 phases: 1 Dirac (δ), 2 Majorana (α_1, α_2)

neutrino oscillations
absolute mass observables
lepton-number violation
(neutrinoless double-beta decay)



Absolute neutrino mass

Three ways to measure absolute neutrino mass:

- Cosmology
  (with caveats: cosmological model/data selection)

- Endpoint of beta spectrum: $^3\mathrm{H} \rightarrow ^3\mathrm{He} + e^- + \bar{\nu}_e$
  (experimentally challenging $\rightarrow$ KATRIN)

- Neutrinoless double beta-decay: $(A, Z) \rightarrow (A, Z+2) + 2e^-$
  (with caveats: lepton number violation)

Absolute neutrino mass

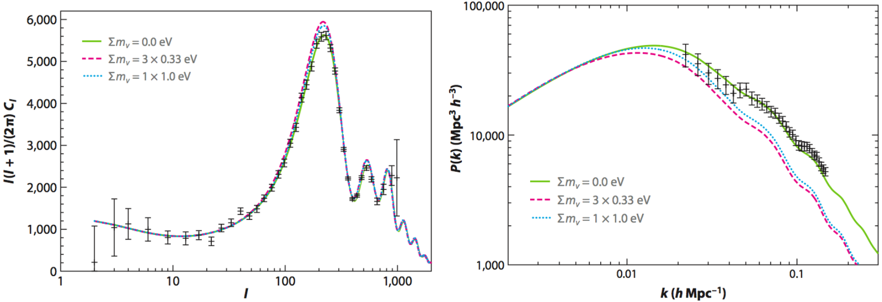
Three ways to measure absolute neutrino mass:
sensitive to different quantities

- Cosmology
  (with caveats: cosmological model/data selection)
  $\sum_i m_i$

- Endpoint of beta spectrum: $^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$
  (experimentally challenging $\rightarrow$ KATRIN)
  $m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$

- Neutrinoless double beta-decay: $(A, Z) \rightarrow (A, Z+2) + 2e^-$
  (with caveats: lepton number violation)
  $m_{ee} = |\sum_i U_{ei}^2 m_i|$

Effect of neutrino mass on CMB and LSS



data points: WMAP 3yr and 2dF '05 Y.Y.Y. Wong, 1111.1436

- CMB: mainly height of 1st peak
- LSS: suppression of structure at scales smaller than 1–10 Mpc
- effects correlated with other parameters of the ΛCDM model

see Lesgourgues, Pastor, astro-ph/06034494 for a review

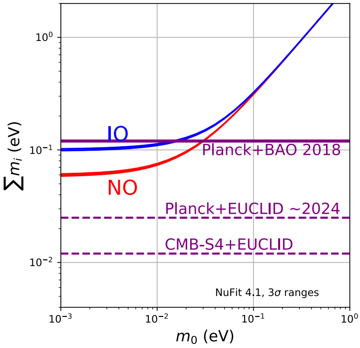
Neutrino mass from cosmology

$$\sum_i m_i \approx \begin{cases} m_0 + \sqrt{m_0 + \Delta m^2_{21}} + \sqrt{m_0 + \Delta m^2_{31}} & (NO) \\ m_0 + 2\sqrt{m_0 + |\Delta m^2_{31}|} & (IO) \end{cases}$$

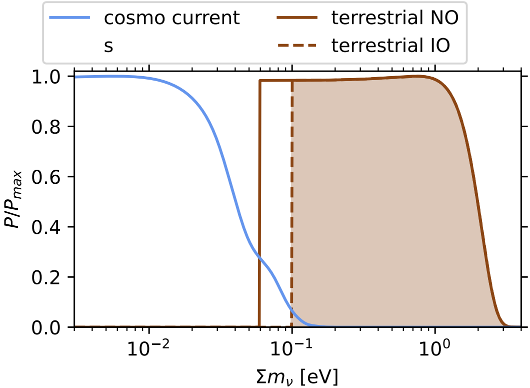
- minimal value predicted for $m_0 = 0$:

$$\sum m_i\Big|_{\min} \approx \begin{cases} 98.6 \pm 0.85\,\mathrm{meV} & (IO) \\ 58.5 \pm 0.48\,\mathrm{meV} & (NO) \end{cases}$$

- detection of non-zero neutrino mass expected soon!
- current limit close to IO minimum
  excluding IO with cosmology: ongoing discussion [Gariazzo et al., 2205.02195]

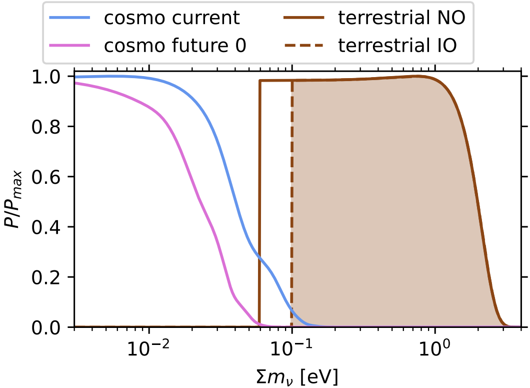


Neutrino mass from cosmology vs terrestrial



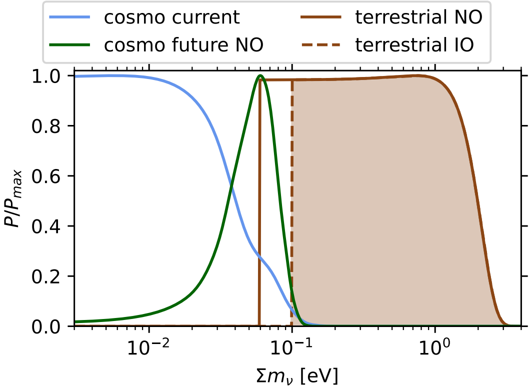
Gariazzo, Mena, TS, 2302.14159

Neutrino mass from cosmology vs terrestrial



Gariazzo, Mena, TS, 2302.14159

Neutrino mass from cosmology vs terrestrial



Gariazzo, Mena, TS, 2302.14159

Beta decay

$$N(A,Z) \to N(A,Z+1) + e^- + \bar{\nu}_e$$

$$\frac{d\Gamma}{dE_e} = \frac{G_F^2 m_e^5}{2\pi^2} \cos\theta_c |\mathcal{M}|^2 F(Z,E_e) \underbrace{E_e p_e E_\nu p_\nu}_{\text{phase space}}$$

Tritium decay: ${}^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$

$$\begin{aligned} M_{^3\text{H}} &= 2.808\,920\,8205 \times 10^6\,\text{keV} \\ M_{^3\text{He}} &= 2.808\,391\,2193 \times 10^6\,\text{keV} \\ m_e &= 510.9989\,\text{keV} \\ Q &\equiv M_{^3\text{H}} - M_{^3\text{He}} - m_e = 18.6023\,\text{keV} \ll M_{^3\text{H}}, M_{^3\text{He}} \\ \kappa &\equiv M_{^3\text{He}}/M_{^3\text{H}} = 1 - 1.89 \times 10^{-4} \end{aligned}$$

Beta decay

$$N(A,Z) \to N(A,Z+1) + e^- + \bar{\nu}_e$$

$$\frac{d\Gamma}{dE_e} = \frac{G_F^2 m_e^5}{2\pi^2} \cos\theta_c |\mathcal{M}|^2 F(Z,E_e) \underbrace{E_e p_e E_\nu p_\nu}_{\text{phase space}}$$

Tritium decay: $^3\mathrm{H} \to ^3\mathrm{He} + e^- + \bar{\nu}_e$

$$\begin{aligned} M_{^3\mathrm{H}} &= 2.808\,920\,8205 \times 10^6\,\mathrm{keV} \\ M_{^3\mathrm{He}} &= 2.808\,391\,2193 \times 10^6\,\mathrm{keV} \\ m_e &= 510.9989\,\mathrm{keV} \\ Q &\equiv M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.6023\,\mathrm{keV} \ll M_{^3\mathrm{H}}, M_{^3\mathrm{He}} \\ \kappa &\equiv M_{^3\mathrm{He}}/M_{^3\mathrm{H}} = 1 - 1.89 \times 10^{-4} \end{aligned}$$

Tritium beta decay

use E-momentum conservation, calculate electron kin. energy:

$$T \equiv E_e - m_e = \frac{1}{2M_{^3\mathrm{H}}}\left[(M_{^3\mathrm{H}} - m_e)^2 - M^2_{^3\mathrm{He}} - 2M_{^3\mathrm{He}}E_\nu\right]$$

T has a maximum when E_ν has a minimum:

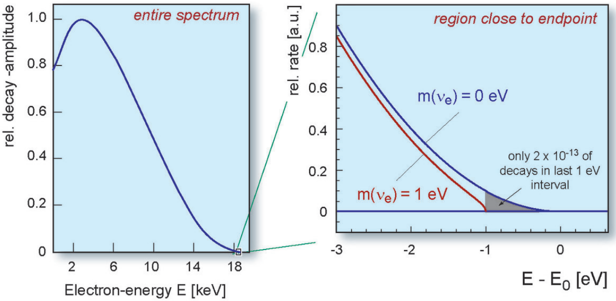
$$\begin{aligned} m_\nu = 0: \quad T_{max,0} &= \tfrac{1}{2M_{^3\mathrm{H}}}\left[(M_{^3\mathrm{H}} - m_e)^2 - M^2_{^3\mathrm{He}}\right] \\ &= Q - \tfrac{(M_{^3\mathrm{H}} - M_{^3\mathrm{He}})^2}{2M_{^3\mathrm{H}}} \approx Q - 3.4\,\mathrm{eV} \\ m_\nu > 0: \quad T_{max} &= T_{max,0} - \kappa m_\nu \end{aligned}$$

$\Rightarrow$ finite neutrino mass leads to a shift in electron spectrum endpoint

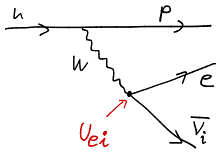
Tritium decay spectrum close to the endpoint

phase space factor: $E_\nu p_\nu = E_\nu \sqrt{E_\nu^2 - m_\nu^2}$, use $E_\nu \approx \frac{M_{^3\mathrm{H}}}{M_{^3\mathrm{He}}}(T_{max,0} - T)$:

$$\frac{d\Gamma}{dT} \propto (T_{max,0} - T)\sqrt{(T_{max,0} - T)^2 - \kappa^2 m_\nu^2}$$



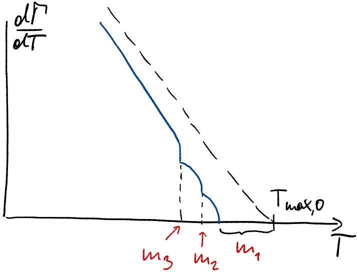
Take into account neutrino mixing



incoherent sum of individual mass states:

$$\frac{d\Gamma}{dT} = \sum_i |U_{ei}|^2 \frac{d\Gamma_i}{dT}$$

$$\propto (T_{max,0} - T) \sum_i |U_{ei}|^2 \sqrt{(T_{max,0} - T)^2 - \kappa^2 m_i^2}$$

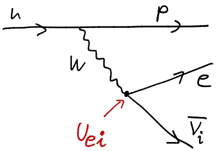


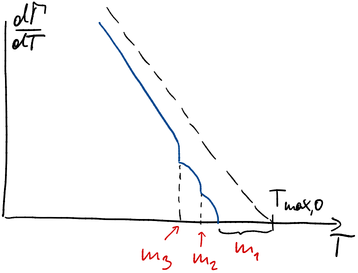
for $T_{max,0} - T \gg \Delta m$:

$$\frac{d\Gamma}{dT} \approx (T_{max,0} - T) \sqrt{(T_{max,0} - T)^2 - \kappa^2 m_\beta^2}$$

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

Take into account neutrino mixing





incoherent sum of individual mass states:

$$\frac{d\Gamma}{dT} = \sum_i |U_{ei}|^2 \frac{d\Gamma_i}{dT}$$

$$\propto (T_{max,0} - T) \sum_i |U_{ei}|^2 \sqrt{(T_{max,0} - T)^2 - \kappa^2 m_i^2}$$

for $T_{max,0} - T \gg \Delta m$:

$$\frac{d\Gamma}{dT} \approx (T_{max,0} - T) \sqrt{(T_{max,0} - T)^2 - \kappa^2 m_\beta^2}$$

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

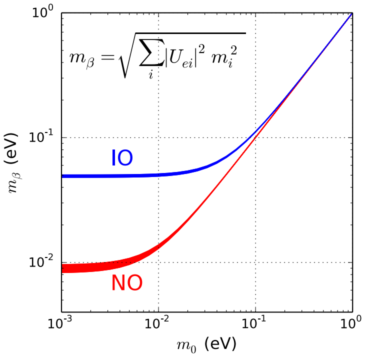
The effective mass

$$m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2 \approx \begin{cases} m_0^2 + |U_{e2}|^2 \Delta m_{21}^2 + |U_{e3}|^2 \Delta m_{31}^2 & \text{(NO)} \\ m_0^2 + (1 - |U_{e3}|^2)|\Delta m_{31}^2| & \text{(IO)} \end{cases}$$

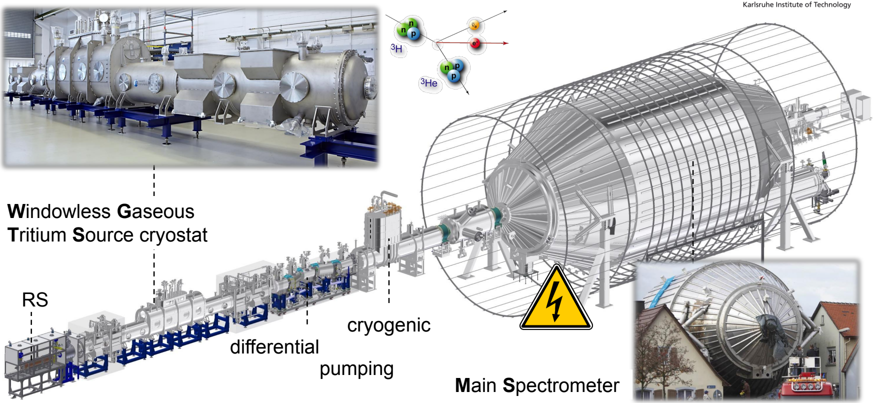
minimum values for $m_0 = 0$:

$$m_\beta^{\text{min}} \approx \begin{cases} 9\,\text{meV} & \text{(NO)} \\ 50\,\text{meV} & \text{(IO)} \end{cases}$$

for $m_0 \gg |\Delta m_{31}^2|$: $m_\beta \approx m_0$



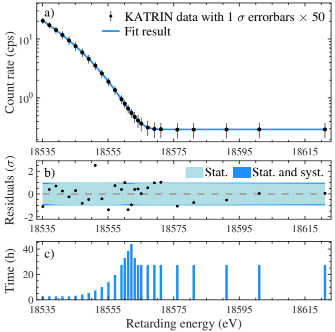
KATRIN overview: 70 m long beamline

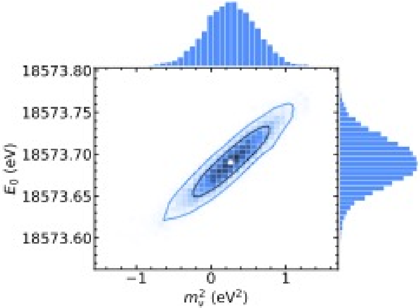


22 Sept. 13, 2019 G. Drexlin – direct neutrino mass measurement KIT-KCETA

KATRIN results

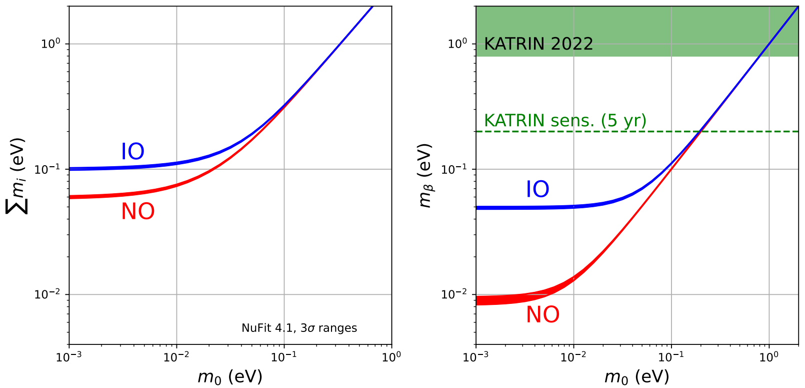
Aker et al., 1909.06048 (PRL19), 2105.08533 (Nature Phys. 22)



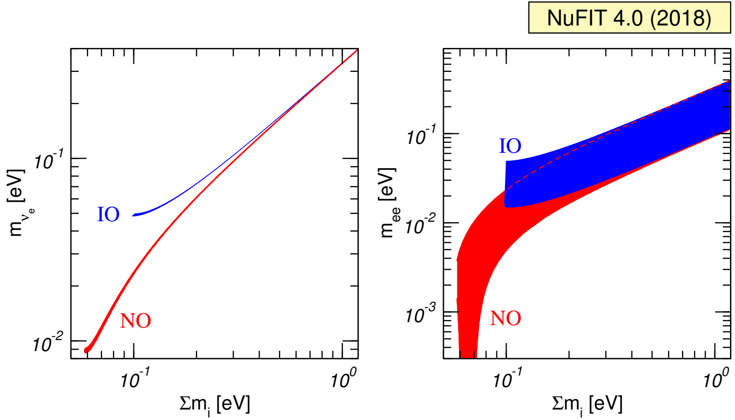


$$m_\beta^2 = 0.26 \pm 0.34\,\mathrm{eV}^2 \qquad m_\beta < 0.8\,\mathrm{eV}\,(90\%\,\mathrm{CL})$$

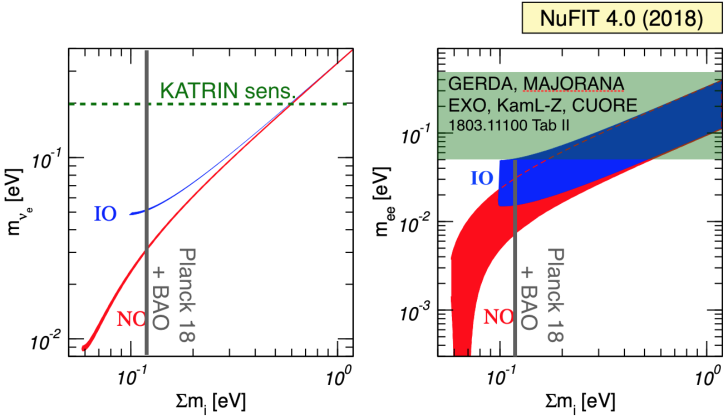
Cosmology and β decay observables



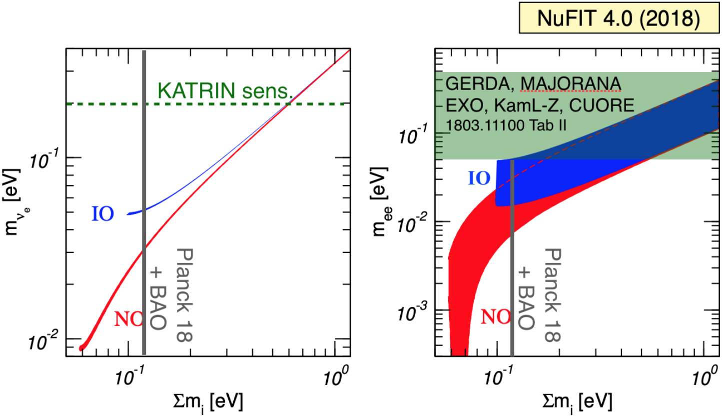
Absolute neutrino mass



Absolute neutrino mass



Absolute neutrino mass



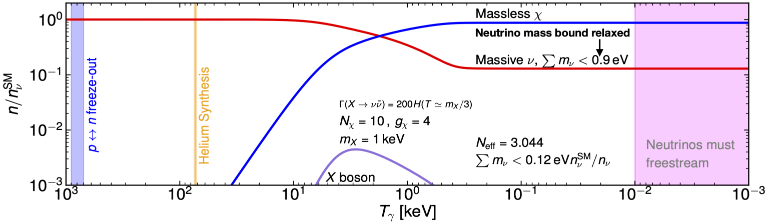
relies on standard three-flavour scenario and standard cosmology

Any inconsistency would indicate new physics beyond 3 flavour neutrino mass!

discussion of non-standard neutrino cosmology: Alvey et al., 2111.14870

One example how to relax the cosmological bound

Farzan, Hannestad, 1510.02201; Escudero, TS, Terol-Calvo, 2211.01729

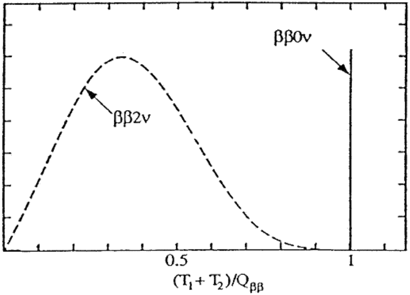


- introduce $N_\chi \gtrsim 10$ generations of massless sterile neutrinos with $\theta_{\nu_\chi} \sim 10^{-3}$
- a vector mediator X, $m_X \sim 10$ keV, $\mathrm{U}(1)_{\mathrm{dark}}$ breaking around ~ 1 GeV
- convert active neutrinos into sterile neutrinos between BBN and recombination
- mass bound gets relaxed: $\sum m_\nu < 0.12\,\mathrm{eV}(1 + 2N_\chi/3)$

Neutrinoless double-beta decay

2-neutrino double-beta decay: $(A, Z) \to (A, Z+2) + 2e^- + 2\bar{\nu}_e$

neutrinoless double-beta decay: $(A, Z) \to (A, Z+2) + 2e^-$



Example ^{76}Ge (GERDA experiment):

$$2\beta2\nu: \quad T_{1/2} = (1.8 \pm 0.1) \times 10^{21}\,\text{yr}$$
$$2\beta0\nu: \quad T_{1/2} > 2.1 \times 10^{25}\,\text{yr}$$

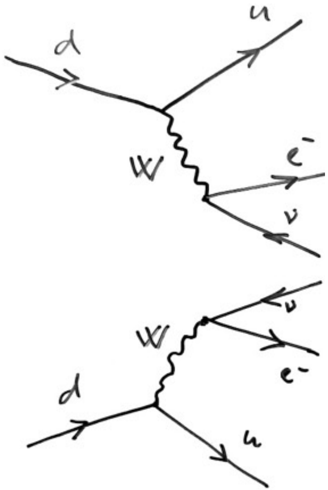
(importance of energy resolution and background suppression)

Neutrinoless double-beta decay

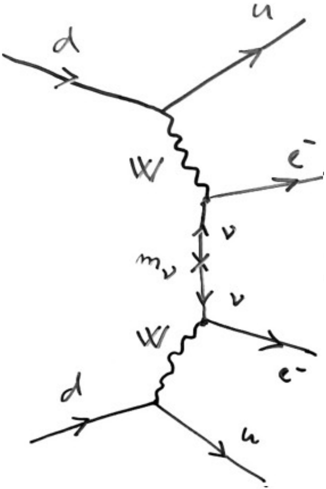
$$(A, Z) \to (A, Z + 2) + 2e^-$$

- an observation of this process would prove that lepton number is violated
- proves Majorana nature of neutrinos
- BUT no direct prove of neutrino mass (a different mechanism could be responsible)

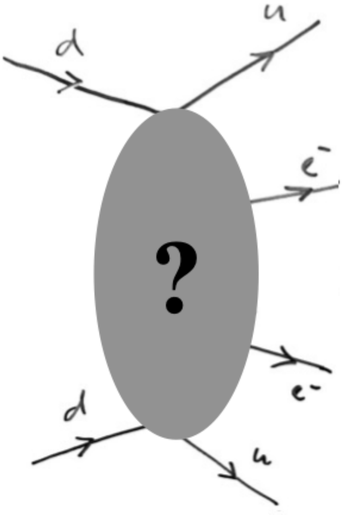
The neutrino-mass mechanism



The neutrino-mass mechanism



The neutrino-mass mechanism



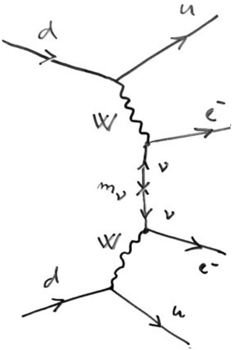
BUT: what we observe is just $\Delta L = 2$

The neutrino-mass mechanism

assuming that light neutrino exchange is responsible for the decay:

$$m_{\beta\beta} = |\mathcal{M}_{ee}| \qquad \text{(in basis where ch. lepton mass matrix is diag.)}$$

$$= \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3\right|$$



coherent sum of individual neutrino masses

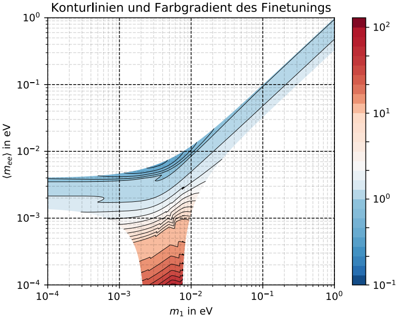
The neutrino-mass mechanism

assuming that light neutrino exchange is responsible for the decay:

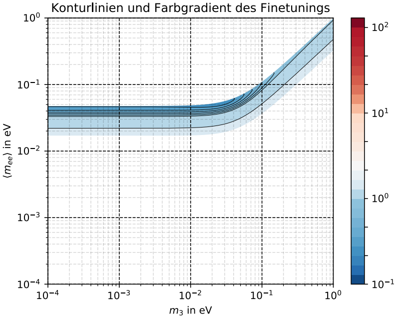
$$m_{\beta\beta} = |\mathcal{M}_{ee}| \qquad \text{(in basis where ch. lepton mass matrix is diag.)}$$

$$= \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3\right|$$

normal ordering

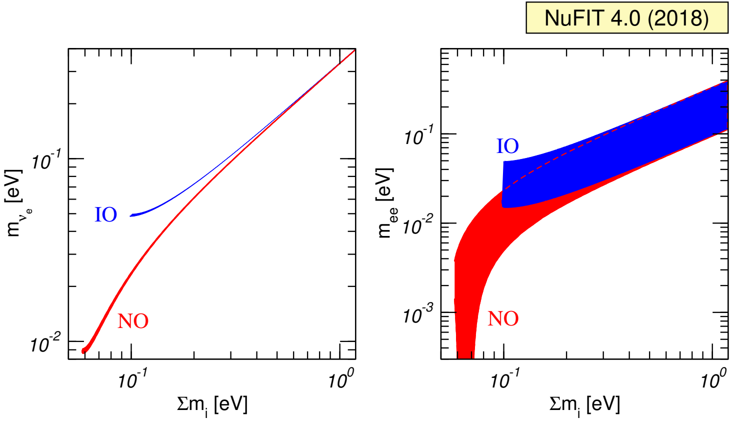


inverted ordering

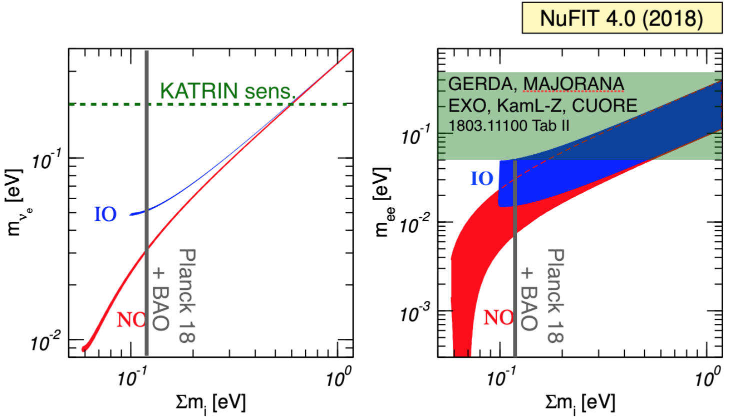


M. Eichhorn, BSc thesis, KIT 2018

Absolute neutrino mass



Absolute neutrino mass



uncertainties on $m_{\beta\beta}$ due to Majorana phases and
relating $T_{1/2}$ to $m_{\beta\beta}$ due to nuclear matrix elements
recent review: Agostini et al., 2202.01787

Outline

Dirac fermion

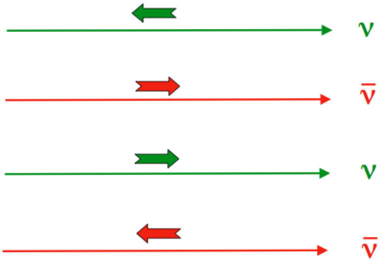
$$\mathcal{L}_D = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi$$

Dirac equation:

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

ψ is a 4-component object: 2 helicity states for particle and anti-particle

4 mass-degenerate states:



Representations of SM are chiral fields

left- and right-chirality projection operators:

$$P_L = \frac{1}{2}(1 - \gamma_5)\,, \qquad P_R = \frac{1}{2}(1 + \gamma_5)$$

left and right chiral flields (irreducible representations of Lorentz group):

$$P_L\psi_L = \psi_L\,, \qquad P_R\psi_R = \psi_R\,, \qquad \psi = \psi_L + \psi_R$$

Dirac Lagrangian:

$$\begin{aligned}\mathcal{L}_D &= i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \\ &= i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R - m\bar{\psi}_L\psi_R - m\bar{\psi}_R\psi_L\end{aligned}$$

Dirac equation (mass term mixes chiralities):

$$\begin{aligned}i\gamma^\mu\partial_\mu\psi_L - m\psi_R = 0 \\ i\gamma^\mu\partial_\mu\psi_R - m\psi_L = 0\end{aligned}$$

Representations of SM are chiral fields

left- and right-chirality projection operators:

$$P_L = \frac{1}{2}(1-\gamma_5)\,, \qquad P_R = \frac{1}{2}(1+\gamma_5)$$

left and right chiral flields (irreducible representations of Lorentz group):

$$P_L\psi_L = \psi_L\,, \qquad P_R\psi_R = \psi_R\,, \qquad \psi = \psi_L + \psi_R$$

Dirac Lagrangian:

$$\begin{aligned}\mathcal{L}_D &= i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \\ &= i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R - m\bar{\psi}_L\psi_R - m\bar{\psi}_R\psi_L\end{aligned}$$

Dirac equation (mass term mixes chiralities):

$$\begin{aligned}i\gamma^\mu\partial_\mu\psi_L - m\psi_R = 0 \\ i\gamma^\mu\partial_\mu\psi_R - m\psi_L = 0\end{aligned}$$

Dirac Lagrangian:

$$\begin{aligned}\mathcal{L}_D &= i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \\ &= i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R - m\bar{\psi}_L\psi_R - m\bar{\psi}_R\psi_L\end{aligned}$$

invariant under a $U(1)$ symmetry

$$\psi_L \to e^{i\alpha}\psi_L\,, \qquad \psi_R \to e^{i\alpha}\psi_R$$

conserved quantum number (charge, lepton number,...)

particle is different from anti-particle

$\Rightarrow$ any charged Fermion has to be a Dirac particle

Majorana field: replace ψ_R by ψ_L^c:

$$\psi = \psi_L + \psi_L^c$$

with particle- antiparticle conjugation $\hat{\mathcal{C}}$:

$$\hat{\mathcal{C}}: \qquad \psi \to \psi^c \equiv C\bar{\psi}^T \equiv C\gamma_0^T\psi^*$$

$$C^{-1}\gamma^\mu C = -\gamma^{\mu T}, \qquad C^\dagger = C^{-1} = -C^*$$

$\hat{\mathcal{C}}$ changes chirality:

$$\psi_L \to (\psi_L)^c \equiv \psi_L^c \quad \text{with} \quad P_R\psi_L^c = \psi_L^c, \quad P_L\psi_L^c = 0$$

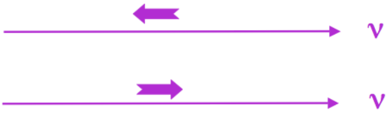
Majorana fermion

the Majorana field $\psi = \psi_L + \psi_L^c$ fulfills the Majorana condition

$$\psi = \psi^c$$

"is its own anti-partice"

only 2 independent
(mass-degenerate) states:



Majorana fermion

$$\mathcal{L}_M = i\overline{\psi_L}\gamma^\mu\partial_\mu\psi_L + \frac{m}{2}\left[\psi_L^T C^{-1}\psi_L + \mathrm{h.c.}\right]$$

- explicitly built out of only ψ_L (2 dof)
- this Lagrangian is not invariant under $\psi_L \to e^{i\alpha}\psi_L$
- Majorana mass term breaks all $U(1)$ charges by 2 units
- cannot define "particle" and "anti-particle"
- any (electrically) charged particle cannot be a Majorana particle

In weak interactions we speak about
"neutrinos" and "antineutrinos"

How can the neutrino be a Majorana particle,
being its own antiparticle?

In the SM neutrinos only left-chiral fields participate in weak interactions:

the left-handed field ν_L acts as “neutrino”
the right-handed field $\overline{\nu_L}$ acts as “antineutrino”

- we need a “L” and a “R” neutrino state for weak interactions (to describe “neutrino” and “antineutrino”)
- we need a “L” and a “R” neutrino state to form a mass term

Majorana:

- those states are identical (there are only two independent states, ν_L, ν_L^c)

Dirac:

- the R state to from the mass term is different than the one acting as “antineutrino” in weak interactions (4 independent states) $\rightarrow$ “right-handed neutrino”: does not participate in weak interactions

In the SM neutrinos only left-chiral fields participate in weak interactions:

the left-handed field ν_L acts as “neutrino”
the right-handed field $\overline{\nu_L}$ acts as “antineutrino”

- we need a “L” and a “R” neutrino state for weak interactions (to describe “neutrino” and “antineutrino”)
- we need a “L” and a “R” neutrino state to form a mass term

Majorana:

- those states are identical (there are only two independent states, ν_L, ν_L^c)

Dirac:

- the R state to from the mass term is different than the one acting as “antineutrino” in weak interactions (4 independent states) $\rightarrow$ “right-handed neutrino”: does not participate in weak interactions

In the SM neutrinos only left-chiral fields participate in weak interactions:

the left-handed field ν_L acts as “neutrino”
the right-handed field $\overline{\nu_L}$ acts as “antineutrino”

- we need a “L” and a “R” neutrino state for weak interactions (to describe “neutrino” and “antineutrino”)
- we need a “L” and a “R” neutrino state to form a mass term

Majorana:

- those states are identical (there are only two independent states, ν_L, ν_L^c)

Dirac:

- the R state to from the mass term is different than the one acting as “antineutrino” in weak interactions (4 independent states) $\rightarrow$ “right-handed neutrino”: does not participate in weak interactions

Chirality versus helicity

physical states are helicity eigenstates:

$$\frac{\vec{\sigma}\vec{p}}{|\vec{p}|}\psi_{\pm} = \pm\psi_{\pm}$$

for massless fermions helicity and chirality coincides:

$$\psi_- = \psi_L\,, \qquad \psi_+ = \psi_R \qquad \text{(massless)}$$

for relativistic massive fermions ($m \ll E$) we have:

$$\psi_- \approx \psi_L + \frac{m}{2E}\psi_R\,, \qquad \psi_+ \approx \psi_R + \frac{m}{2E}\psi_L$$

OBS: here "ψ_R" denotes the right-chiral field in the mass term, which corresponds to ψ^c in the Majorana case

Chirality versus helicity

physical states are helicity eigenstates:

$$\frac{\vec{\sigma}\vec{p}}{|\vec{p}|}\psi_\pm = \pm\psi_\pm$$

for massless fermions helicity and chirality coincides:

$$\psi_- = \psi_L\,, \qquad \psi_+ = \psi_R \qquad \text{(massless)}$$

for relativistic massive fermions ($m \ll E$) we have:

$$\psi_- \approx \psi_L + \frac{m}{2E}\psi_R\,, \qquad \psi_+ \approx \psi_R + \frac{m}{2E}\psi_L$$

OBS: here "ψ_R" denotes the right-chiral field in the mass term, which corresponds to ψ^c in the Majorana case

Chirality versus helicity

physical states are helicity eigenstates:

$$\frac{\vec{\sigma}\vec{p}}{|\vec{p}|}\psi_\pm = \pm\psi_\pm$$

for massless fermions helicity and chirality coincides:

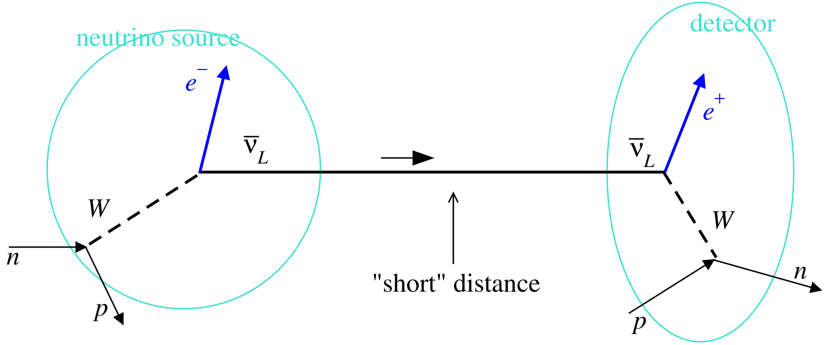
$$\psi_- = \psi_L\,, \qquad \psi_+ = \psi_R \qquad \text{(massless)}$$

for relativistic massive fermions ($m \ll E$) we have:

$$\psi_- \approx \psi_L + \frac{m}{2E}\psi_R\,, \qquad \psi_+ \approx \psi_R + \frac{m}{2E}\psi_L$$

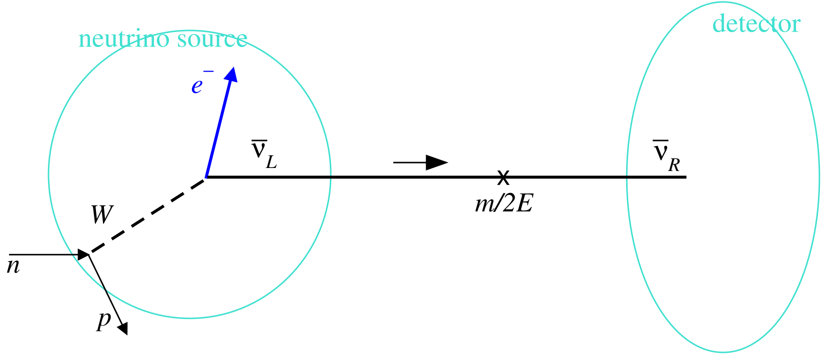
OBS: here "ψ_R" denotes the right-chiral field in the mass term, which corresponds to ψ^c in the Majorana case

A typical neutrino experiment (massless neutrinos)



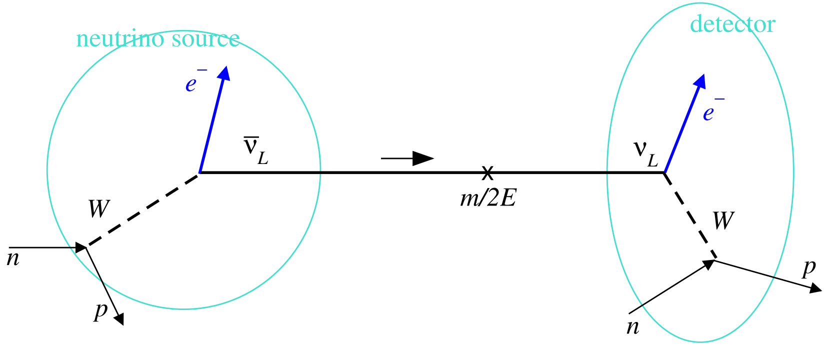
Mass induced chirality flip - Dirac

with a probability suppressed wrt leading diagram by $(m/2E)^2 \lesssim 10^{-12}$



Mass induced chirality flip - Majorana

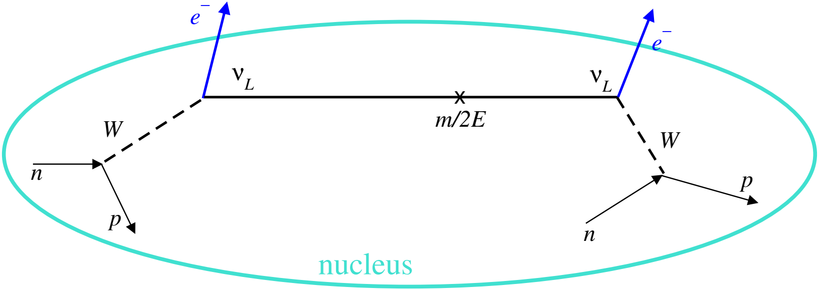
with a probability suppressed wrt leading diagram by $(m/2E)^2 \lesssim 10^{-12}$



Schechter, Valle, PRD 1981

Mass induced chirality flip - Majorana

Neutrinoless double-beta decay $(A, Z) \to (A, Z+2) + 2e^-$



Outline

Masses in the Standard Model

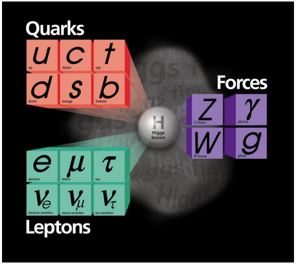
- The Standard Model has only one dimension full parameter: the vacuum expectation value of the Higgs:

$$\langle \phi \rangle \approx 174 \text{ GeV}$$

- All masses in the Standard Model are set by this single scale:

$$m_i = y_i \langle \phi \rangle$$

top quark: $y_t \approx 1$
electron: $y_e \approx 10^{-6}$



Fermion masses in the Standard Model

fermions of one generation:

$$\text{quarks: } Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix},\ u_R,\ d_R \qquad \text{leptons: } L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix},\ e_R$$

mass terms from Yukawa coupling to Higgs ϕ

$$\mathcal{L}_Y = -\lambda_d \bar{Q}_L \phi d_R - \lambda_u \bar{Q}_L \tilde{\phi} u_R + \text{h.c.} \qquad -\lambda_e \bar{L}_L \phi e_R + \text{h.c.}$$

$$\text{EWSB} \rightarrow \quad -m_d \bar{d}_L d_R - m_u \bar{u}_L u_R + \text{h.c.} \qquad -m_e \bar{e}_L e_R + \text{h.c.}$$

$$\tilde{\phi} \equiv i\sigma_2 \phi^*,\ m_d = \lambda_d \frac{v}{\sqrt{2}},\ m_u = \lambda_u \frac{v}{\sqrt{2}},\ m_e = \lambda_e \frac{v}{\sqrt{2}},\ \langle\phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Dirac mass terms for charged fermions

Fermion masses in the Standard Model

fermions of one generation:

$$\text{quarks: } Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \qquad \text{leptons: } L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R$$

mass terms from Yukawa coupling to Higgs ϕ

$$\mathcal{L}_Y = -\lambda_d \bar{Q}_L \phi d_R - \lambda_u \bar{Q}_L \tilde{\phi} u_R + \text{h.c.} \qquad -\lambda_e \bar{L}_L \phi e_R + \text{h.c.}$$

$$\text{EWSB} \rightarrow \quad -m_d \bar{d}_L d_R - m_u \bar{u}_L u_R + \text{h.c.} \qquad -m_e \bar{e}_L e_R + \text{h.c.}$$

$$\tilde{\phi} \equiv i\sigma_2 \phi^*, \; m_d = \lambda_d \frac{v}{\sqrt{2}}, m_u = \lambda_u \frac{v}{\sqrt{2}}, m_e = \lambda_e \frac{v}{\sqrt{2}}, \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Dirac mass terms for charged fermions

- “right-handed” neutrinos would be complete gauge singlets in the SM
- no gauge interactions
- left out in the original formulation of the SM
  $\Rightarrow$ no Dirac mass term for neutrinos

- Why is there no Majorana mass term?
- Lepton-number is an accidental symmetry in the SM $\rightarrow$ given the gauge symmetry and the field content of the SM we cannot construct a Majorana mass term for neutrinos (true at any loop order)

- “right-handed” neutrinos would be complete gauge singlets in the SM
- no gauge interactions
- left out in the original formulation of the SM
  $\Rightarrow$ no Dirac mass term for neutrinos

- Why is there no Majorana mass term?
- Lepton-number is an accidental symmetry in the SM $\rightarrow$ given the gauge symmetry and the field content of the SM we cannot construct a Majorana mass term for neutrinos (true at any loop order)

In the SM neutrinos are massless because...

1. there are no right-handed neutrinos to form a Dirac mass term
2. because of the field content (scalar sector) and gauge symmetry lepton number[1] is an accidental global symmetry of the SM and therefore no Majorana mass term can be induced.
3. restriction to renormalizable terms in the Lagrangian

[1] B-L at the quantum level

In the SM neutrinos are massless because. . .

1. there are no right-handed neutrinos to form a Dirac mass term
2. because of the field content (scalar sector) and gauge symmetry lepton number[1] is an accidental global symmetry of the SM and therefore no Majorana mass term can be induced.
3. restriction to renormalizable terms in the Lagrangian

Neutrino mass implies physics beyond the Standard Model

At least one of the above items needs to be violated

[1] B-L at the quantum level