KSETA topical courses

Neutrino physics IV: Neutrinos and beyond Standard Model

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Karlsruhe, 7-8 Oct 2020
Neutrinos oscillate...

... and have mass $\Rightarrow$ physics beyond the Standard Model

- Lecture I: Neutrino Oscillations
- Lecture II: Neutrinos in Cosmology
- Lecture III: Neutrino mass - Dirac versus Majorana
- Lecture IV: Neutrinos and physics beyond the Standard Model
Neutrinos oscillate...

... and have mass \Rightarrow \text{physics beyond the Standard Model}

- Lecture I: Neutrino Oscillations
- Lecture II: Neutrinos in Cosmology
- Lecture III: Neutrino mass - Dirac versus Majorana
- Lecture IV: Neutrinos and physics beyond the Standard Model
Outline - Neutrinos and physics beyond the SM

Giving mass to neutrinos
   Weinberg operator

Right-handed neutrinos
   Dirac vs Majorana neutrinos
   Type-I Seesaw

Extending the scalar sector of the SM
   Higgs-triplet / Type-II Seesaw
   Radiative neutrino mass models

Leptogenesis

Lepton flavour violation

Conclusions
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
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Famous historical example:

Assume there is new physics at a high scale $\Lambda$. It will manifest itself by non-renormalizable operators suppressed by powers of $\Lambda$. 
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In the 1930’s Fermi did not know about $W$ and $Z$ bosons, but he could write down a non-renormalizable dimension-6 operator to describe beta decay:

$$\frac{g^2}{\Lambda^2}(\bar{e}\gamma_{\mu}\nu)(\bar{n}\gamma^{\mu}p)$$

- Fermi knew about charge conservation $\rightarrow$ his operator is invariant under $U(1)_{em}$
- Today we know that $\Lambda \simeq m_W$, and we know the UV completion of Fermi’s operator, i.e. the electro-weak theory of the SM.
The Weinberg operator

Assume there is new physics at a high scale $\Lambda$. It will manifest itself by non-renormalizable operators suppressed by powers of $\Lambda$.

Weinberg 1979: there is only one dim-5 operator consistent with the gauge symmetry of the SM, and this operator will lead to a Majorana mass term for neutrinos after EWSB:

$$Y^2 \frac{\bar{L}^c \tilde{\phi}^* \tilde{\phi}^\dagger L}{\Lambda} \longrightarrow m_\nu \sim Y^2 \frac{\langle \phi \rangle^2}{\Lambda}$$

at dim-5 lepton number can be broken
(above operator not invariant under $L \rightarrow e^{i\alpha} L$)
The Weinberg operator

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$$ Y^2 \frac{\overline{L}^c \tilde{\phi}^* \tilde{\phi}^\dagger L}{\Lambda} \quad \rightarrow \quad m_\nu \sim Y^2 \frac{\langle \phi \rangle^2}{\Lambda} $$

Seesaw:

neutrinos are light because of the presence of the large energy scale $\Lambda \gg \langle \phi \rangle$
High-scale versus low-scale seesaw

\[ m_\nu \sim Y^2 \frac{\langle \phi \rangle^2}{\Lambda} \approx Y^2 \frac{(178 \text{ GeV})^2}{\Lambda} \]

can obtain small neutrino masses by making \( \Lambda \) very large or \( Y \) very small (or both)

- **High scale seesaw**: \( \Lambda \sim 10^{14} \text{ GeV}, \ Y \sim 1 \)
  - "natural" explanation of small neutrino masses
  - Leptogenesis
  - very hard to test experimentally

- **Low scale seesaw**: \( \Lambda \sim \text{TeV}, \ Y \sim 10^{-6} \)
  - link neutrino mass generation to new physics testable at colliders
  - observable signatures in searches for LFV
    - \( \mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \mu \rightarrow eee, \ldots \)
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The Weinberg operator

\[ Y^2 \bar{L}^c \tilde{\phi}^* \tilde{\phi}^\dagger L \]  

What is the new physics responsible for neutrino mass?

many realisations (too many?) are known:

at tree-level:

- Type I: fermionic singlet (right-handed neutrinos)
- Type II: scalar triplet
- Type III: fermionic triplet

many extended scenarios:

- extended Higgs sector
- realisations due to quantum effects (loop-induced)
- ...

T. Schwetz (KIT)
The Weinberg operator

\[ Y^2 \frac{L^c \phi^* \tilde{\phi}^\dagger L}{\Lambda} \]

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What do we mean by “right-handed neutrino”?

A Majorana fermion field (2 dof) which is a singlet under the SM gauge group

- does not feel any of the gauge interactions of the SM, in particular also not the weak interaction (“sterile neutrino”)

- note that a so-called “right-handed neutrino” contains a right-handed ($N_R$) and a left-handed ($N_R^c$) component
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Let’s add right-handed neutrinos to the SM

quarks: \( Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \)

leptons: \( L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R, N_R \)
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\[
\mathcal{L}_Y = -\lambda_e \bar{L}_L \phi e_R - \lambda_\nu \bar{L}_L \tilde{\phi} N_R + \text{h.c.}
\]

\[
\text{EWSB} \rightarrow \quad -m_e \bar{e}_L e_R - m_D \bar{\nu}_L N_R + \text{h.c.}
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\[
\tilde{\phi} \equiv i \sigma_2 \phi^*, \ m_e = \lambda_e \frac{v}{\sqrt{2}}, \ m_D = \lambda_\nu \frac{v}{\sqrt{2}}, \ \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \ v = 246 \text{ GeV}
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\]

SM + Dirac neutrinos:

- \( \lambda_{\nu} \lesssim 10^{-11} \) for \( m_D \lesssim 1 \text{ eV} \) (\( \lambda_e \sim 10^{-6} \))
- why is there no Majorana mass term for \( N_R \)?
  \( \Rightarrow \) have to impose lepton number conservation as additional ingredient of the theory to forbid Majorana mass
Dirac neutrinos in the SM

- Majorana mass term $\frac{M_R}{2} N_R^T C^{-1} N_R$ is allowed by gauge symmetry

- However, $M_R = 0$ is technically natural (protected by Lepton number)
  - the symmetry of the Lagrangian is increased by setting $M_R = 0$
  - $M_R$ will remain zero to all loop order

- Also the Yukawas $\lambda_\nu$ are protected (chiral symmetry)
  tiny values are technically natural

- The values $M_R = 0$ and $\lambda_\nu \sim 10^{-11}$ are considered “special” and/or “unaesthetic” by many theorists...
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Charge quantization in the SM

Babu, Mohapatra, 89,90; Foot, Lew, Volkas, hep-ph/9209259

charge in the SM: $Q = (I_3 + Y/2)$ (for $y_\phi = 1$)

how to chose hyper-charges of fermions (SM, 1 gen): $y_{Q_L}, y_{u_R}, y_{d_R}, y_L, y_{e_R}$?

▶ gauge invariance of Yukawa terms:

\[ y_{Q_L} = 1 + y_{d_R}, \quad y_{Q_L} = -1 + y_{u_R}, \quad y_L = 1 + y_{e_R} \]

▶ gauge anomaly cancellations:

\[ SU(2)^2U(1) : Y_{Q_L} = -y_L/3, \quad U(1)^3 : Y_L = -1 \]

⇒ 5 constraints for 5 unknowns ⇒ unique solution

“charge quantization” in the SM (1 gen. no $N_R$)
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Right-handed neutrinos

Charge quantization in the SM  

Foot, Lew, Volkas, hep-ph/9209259

\begin{align*}
y_{Q_L} &= 1/3 \\
y_{u_R} &= 4/3 \\
y_{d_R} &= 2/3 \\
y_L &= -1 \\
y_{e_R} &= -2
\end{align*}
Charge quantization in the SM  
Foot, Lew, Volkas, hep-ph/9209259

\[ y_{Q_L} = \frac{1}{3} - \frac{y_N}{3} \]
\[ y_{u_R} = \frac{4}{3} - \frac{y_N}{3} \]
\[ y_{d_R} = \frac{2}{3} - \frac{y_N}{3} \]
\[ y_L = -1 + y_N \]
\[ y_{e_R} = -2 + y_N \]

- **SM + Dirac** \( N_R \): Yukawa and \( U(3)^3 \) same cond.: \( y_L = -1 + y_N \)
  - no additional constraint: 5 constraints for 6 unknowns \( \Rightarrow \)
  - \( y_N \) arbitr.: “charge dequantization”
  - reason: \( U(B - L) \) is anomaly free symmetry
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\begin{align*}
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\end{aligned}
\end{align*}

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\begin{itemize}
\item SM + Dirac $N_R$: Yukawa and $U(3)^3$ same cond.: $y_L = -1 + y_N$
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\end{itemize}

\begin{itemize}
\item SM + Maj. $N_R$: $U(B - L)$ broken by mass term
\item $m_N N_R^T C^{-1} N_R \rightarrow y_N = 0$ $\Rightarrow$ charge quantized
\end{itemize}
Charge quantization in the SM  Foot, Lew, Volkas, hep-ph/9209259

\[
\begin{align*}
y_{Q_L} &= 1/3 - y_N/3 \\
y_{u_R} &= 4/3 - y_N/3 \\
y_{d_R} &= 2/3 - y_N/3 \\
y_L &= -1 + y_N \\
y_e &= -2 + y_N \\
y_N &= \text{arbitr.: “charge dequantization”}
\end{align*}
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- **SM + Dirac \( N_R \):** Yukawa and \( U(3)^3 \) same cond.: \( y_L = -1 + y_N \)
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- **SM + Maj. \( N_R \):** \( U(B - L) \) broken by mass term
  \( m_N N_R^T C^{-1} N_R \rightarrow y_N = 0 \Rightarrow \) charge quantized

- **SM (3 gen, no \( N_R \) + gravitational anomaly):**
  \( (L_e - L_\mu), (L_\mu - L_\tau), (L_e - L_\tau) \) anomaly free \( \Rightarrow \) dequantization

- **SM (3 gen, Maj. \( N_R \)):**
  Majorana mass breaks all \( U(1) \)'s \( \Rightarrow \) charge quantization
Neutrinoless double beta decay

search for lepton-number violation via $(A, Z) \rightarrow (A, Z + 2) + 2e^-$

- absent for Dirac neutrinos
- rate of the process is proportional to
  \[ m_{ee} = |\sum_i U_{ei}^2 m_i| \]
Neutrinoless double beta decay

BUT: the process $\left(A, Z\right) \rightarrow (A, Z + 2) + 2e^-$ can be mediated by other mechanisms than neutrino mass:
Neutrinoless double beta decay

BUT: the process \((A, Z) \rightarrow (A, Z + 2) + 2e^-\) can be mediated by other mechanisms than neutrino mass:

Higgs triplet

\[
\begin{array}{c}
d_L \\
\end{array} \quad \begin{array}{c}
\Delta^- \\
W \\
\sqrt{2}g^0v_L \\
W \\
d_L \\
\end{array} \quad \begin{array}{c}
h_{ee} \\
e_L \\
e_L \\
u_L \\
\end{array} \quad \begin{array}{c}
u_L \\
\end{array}
\]

Neutrinoless double beta decay

BUT: the process \((A, Z) \rightarrow (A, Z + 2) + 2e^-\) can be mediated by other mechanisms than neutrino mass:

\(N_R\) and \(W_R\) in left-right symmetric models

\[
\begin{align*}
&d_L &\rightarrow &u_L \\
&d_R &\rightarrow &u_R \\
&\nu_L &\rightarrow &e_L^- \\
&N_R &\rightarrow &e_R^- \\
&W &\rightarrow &W_R \\
\end{align*}
\]

Neutrinoless double beta decay

BUT: the process \((A, Z) \rightarrow (A, Z + 2) + 2e^-\) can be mediated by other mechanisms than neutrino mass:

SUSY with R-parity violation

\[
\begin{align*}
\tilde{d} & \rightarrow \tilde{e} \rightarrow d e^- \\
\tilde{u} & \rightarrow \tilde{e} \rightarrow u e^- \\
\tilde{e} & \rightarrow \tilde{d} \rightarrow u e^- \\
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\tilde{d} & \rightarrow \tilde{d} \rightarrow d e^- \\
\end{align*}
\]

Schechter-Valle theorem

▶ an observation of neutrinoless DBD \((A, Z) \rightarrow (A, Z + 2) + 2e^-\) proves that L-number is violated

▶ this implies “Majorana nature” of neutrinos
Schechter, Valle, 1982; Takasugi, 1984

If neutrinoless DBD is observed, it is not possible to find a symmetry which forbids a Majorana mass term for neutrinos ⇒ in a "natural" theory a Majorana mass will be induced at some level.

▶ in practice, however, the Majorana mass may still be tiny
 e.g., Duerr, Lindner, Merle, 2011
Let’s add $N_R$ and allow for lepton number violation

$$\mathcal{L}_Y = -\lambda_e \bar{L}_L \phi e_R - \lambda_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.}$$
Let’s add $N_R$ and allow for lepton number violation

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What is the value of $M_R$?
Let’s add $N_R$ and allow for lepton number violation

$$\mathcal{L}_Y = -\lambda_e \bar{L}_L \phi e_R - \lambda_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.}$$

What is the value of $M_R$?

We do not know!

There is no guidance from the SM itself because $N_R$ is a gauge singlet. $M_R$ is a new scale in the theory, the scale of BSM physics.
Right-handed neutrinos at which scale?

- $\Delta m^2 \approx 10^{-5} \text{ eV}^2$ to fit better solar neutrino spectrum
- TeV scale L-R models, radiative neutrino mass, inverse seesaw, ...
- $10^{-3}$ eV to keV
- $10^3$ eV to TeV
- $10^{10}$ GeV to $10^{15}$ GeV
- sterile neutrino dark matter
- seesaw / GUT motivation
- short-baseline anomalies
- Leptogenesis via oscillations
- Leptogenesis
The Dirac+Majorana mass matrix

\[ \mathcal{L}_Y = -\lambda^\nu_L \bar{\nu} N_R + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.} \]

EWSB \rightarrow \quad \mathcal{L}_M = -m_D \bar{N}_R \nu_L + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.} \]

using \quad \psi^T C^{-1} = -\overline{\psi^c}, \quad \psi^c \equiv C^{-1} \psi^T

\Rightarrow \quad \mathcal{L}_M = \frac{1}{2} n^T C^{-1} \begin{pmatrix} 0 & m_D^T M_R \\ m_D & M_R \end{pmatrix} n + \text{h.c.} \quad \text{with} \quad n \equiv \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} \]
The Dirac+Majorana mass matrix

\[ \mathcal{L}_Y = -\lambda_\nu \bar{L}_L \phi N_R + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.} \]

EWSB \[ \rightarrow \mathcal{L}_M = -m_D \bar{N}_R \nu_L + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.} \]

using \[ \psi^T C^{-1} = -\overline{\psi}^c, \quad \psi^c \equiv C \overline{\psi}^T \]

\[ \Rightarrow \mathcal{L}_M = \frac{1}{2} n^T C^{-1} \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} n + \text{h.c.} \quad \text{with} \quad n \equiv \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} \]

\(\nu_L\) contains 3 SM neutrino fields, \(N_R\) can contain any number \(r\) of fields \((r \geq 2\) if this is the only source for neutrino mass, often \(r = 3\))

\(m_D\) is a general \(3 \times r\) complex matrix, \(M_R\) is a symmetric \(r \times r\) matrix
The Seesaw mechanism

let’s assume \( m_D \ll M_R \), then the mass matrix
\[
\begin{pmatrix}
0 & m_D^T \\
m_D & M_R
\end{pmatrix}
\]
can be approximately block-diagonalized to
\[
\begin{pmatrix}
m_\nu & 0 \\
0 & M_R
\end{pmatrix}
\]
with
\[
m_\nu = -m_D^T M_R^{-1} m_D \sim -\frac{m_D^2}{M_R}
\]
where \( m_\nu \) is the induced Majorana mass matrix for the 3 SM neutrinos.
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**Seesaw:**

$\nu_L$ are light because $N_R$ are heavy
The Seesaw mechanism

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with \( m_\nu = -m_D^T M_R^{-1} m_D \sim -\frac{m_D^2}{M_R} \)

where \( m_\nu \) is the induced Majorana mass matrix for the 3 SM neutrinos.

\( m_D = \lambda v / \sqrt{2} \)

- assuming \( \lambda \sim 1 \) we need \( M_R \sim 10^{14} \) GeV for \( m_\nu \lesssim 1 \) eV
  - very high scale - close to \( \Lambda_{\text{GUT}} \sim 10^{16} \) GeV
  - GUT origin of neutrino mass?
The Seesaw mechanism

let’s assume \( m_D \ll M_R \), then the mass matrix \( \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \) can be approximately block-diagonalized to

\[
\begin{pmatrix} m_\nu & 0 \\ 0 & M_R \end{pmatrix}
\]

with \( m_\nu = -m_D^T M_R^{-1} m_D \sim -\frac{m_D^2}{M_R} \)

where \( m_\nu \) is the induced Majorana mass matrix for the 3 SM neutrinos.

\( m_D = \lambda v / \sqrt{2} \)

- assuming \( \lambda \sim 1 \) we need \( M_R \sim 10^{14} \text{ GeV} \) for \( m_\nu \lesssim 1 \text{ eV} \)
  - very high scale - close to \( \Lambda_{\text{GUT}} \sim 10^{16} \text{ GeV} \)
  - GUT origin of neutrino mass?

- \( m_D \) could be lower, e.g., \( m_D \sim m_e \Rightarrow M_R \sim \text{TeV} \)
  - potentially testable at collider experiments like LHC
Type-I seesaw at LHC?

dilepton (or multi-lepton) events, e.g.:

- lepton number violating: $\ell^\pm \ell^\pm + \text{jets}$
- lepton flavour violating: $\ell^\pm_{\alpha} \ell^\mp_{\beta} + \text{jets}$
Type-I seesaw at LHC?

- In type-I seesaw, $N$ production is proportional to $Y^2$. $Y \sim 10^{-6}$ for $M_N \sim \text{TeV} \rightarrow$ negligible.

- Invoke cancellations in $m_{\alpha\beta} \propto \sum_i Y_{\alpha i} Y_{\beta i}/M_i$ to obtain large $Y$ cancellations motivated by symmetry (lepton number) $\rightarrow$ decouple LHC signature from light neutrino mass. Kersten, Smirnov, 07

- Give $N_R$ new interactions beyond the SM gauge interactions. Ex.: $W_R$ in L-R symmetric models. Keung, Senjanovic, 83
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Type-I seesaw

Type-I seesaw with 2 or 3 heavy right-handed neutrinos ($M_R \gtrsim 10^{10}$ GeV) is considered as “standard paradigm”

(+) “simple” extension of the SM field content

(+) “natural” explanation of smallness of neutrino mass

(+) “simple” implementation of Leptogenesis

(−) hard to “prove” - no specific experimental signatures
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\( \nu \text{MSM} \) Shaposhnikov,...

variant of type-I seesaw

(+) one \( N_R \) with \( M_R \sim 1 \text{ kev} \rightarrow \) provides Dark Matter (warm DM)

(+) two \( N_R \) with \( M_R \sim 1 \text{ GeV} \rightarrow \) provide neutrino mass and Leptogenesis

(+) does not require new physics up to the Planck scale

(−) requires tuning parameters to special values  
(e.g., tiny Yukawas, highly degenerate \( N_R \))

(−) invokes “intricate” mechanism for DM generation and Leptogenesis
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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\(^3\) 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

\(^3\)B-L at the quantum level
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3. restriction to renormalizable terms in the Lagrangian

We do not need right-handed neutrinos to give mass to \(\nu_L\)!

\(^3\)B-L at the quantum level
Outline

Giving mass to neutrinos
  Weinberg operator

Right-handed neutrinos
  Dirac vs Majorana neutrinos
  Type-I Seesaw

Extending the scalar sector of the SM
  Higgs-triplet / Type-II Seesaw
  Radiative neutrino mass models

Leptogenesis

Lepton flavour violation

Conclusions
Extending the scalar sector of the SM

fermionic bilinears from SM leptons considering SU(2)$_L$ quantum numbers

\[
\begin{align*}
L : & \quad 2 \\
e_R : & \quad 1 \\
\end{align*}
\] \Rightarrow \begin{cases} 
2 \times 1 = 2 & \bar{L}\phi e_R \quad \text{(SM doublet)} \\
2 \times 2 = 3 + 1 & \begin{align*}
L^T \Delta L \\
L^T i\sigma_2 L h^+ \\
\end{align*} \quad \text{(triplet)} \\
1 \times 1 = 1 & \bar{e}_R e_R k^{++} \quad \text{(singlet)} \\
\end{cases}
\]

Konetschny, Kummer, 1977; Cheng, Li, 1980
Extending the scalar sector of the SM

fermionic bilinears from SM leptons considering SU(2)_L quantum numbers

\[
\begin{align*}
L & : \begin{cases} 2 \cr e_R : 1 \end{cases} \quad \Rightarrow \quad \begin{cases} 2 \times 1 = 2 \quad \bar{L} \phi e_R & \text{(SM doublet)} \\
2 \times 2 = 3 + 1 \quad L^T \Delta L & \text{(triplet)} \\
1 \times 1 = 1 \quad \bar{e}_R e_R k^{++} & \text{(singlet)} 
\end{cases}
\end{align*}
\]

Konetschny, Kummer, 1977; Cheng, Li, 1980

- SU(2) triplet Higgs: $\Delta \to m_\nu$ at tree level ("type-II seesaw")
- one SU(2) singlet scalar with charge 1 and a second Higgs doublet $h^+, \phi' \to m_\nu$ at 1-loop level ("Zee model")
- two SU(2) singlet scalars with charge 1 and charge 2 $h^+, k^{++} \to m_\nu$ at 2-loop level ("Zee–Babu model")
Higgs-triplet / Type-II Seesaw

Let’s add a triplet $\Delta$ under $SU(2)_L$ to the SM:

\[ \mathcal{L}_\Delta = f_{ab} L_a^T C^{-1} i \tau_2 \Delta \ L_b + \text{h.c.}, \]

\[ \Delta = \begin{pmatrix} H^+/\sqrt{2} & H^{++} \\ H^0 & -H^+/\sqrt{2} \end{pmatrix} \]

The VEV of the neutral component $\langle H^0 \rangle \equiv v_T/\sqrt{2}$ induces a Majorana mass term for the neutrinos:

\[ \frac{1}{2} \nu^T \nu \ C^{-1} \ m_{ab}^\nu \ \nu L_b + \text{h.c.} \quad \text{with} \quad m_{ab}^\nu = \sqrt{2} \ v_T \ f_{ab} \]
Type-II Seesaw

\[ m_{\nu_{ab}} = \sqrt{2} \nu_T f_{ab} \lesssim 10^{-10} \text{GeV} \]

scalar potential: \[ \mathcal{L}_{\text{scalar}}(\phi, \Delta) = -\frac{1}{2} M_{\Delta}^2 \text{Tr}\Delta^\dagger \Delta + \mu \phi^\dagger \Delta \bar{\phi} + \ldots \]

\( \mu \)-term violates lepton number (\( \Delta \) has \( L = -2 \))

minimisation of potential: \[ v_T \simeq \mu \frac{\nu^2}{M_{\Delta}^2} \]
Type-II Seesaw

\[ m^\nu_{ab} = \sqrt{2} \nu_T f_{ab} \lesssim 10^{-10} \text{ GeV} \]

scalar potential:
\[ \mathcal{L}_{\text{scalar}}(\phi, \Delta) = -\frac{1}{2} M^2_\Delta \text{Tr} \Delta^\dagger \Delta + \mu \phi^\dagger \Delta \phi + \ldots \]

\( \mu \)-term violates lepton number (\( \Delta \) has \( L = -2 \))

minimisation of potential:
\[ \nu_T \simeq \mu \frac{\nu^2}{M^2_\Delta} \]

Type-II seesaw: heavy triplet

\[ \mu \sim M_\Delta \sim 10^{14} \text{ GeV} \quad \Rightarrow \quad \nu_T \sim \frac{\nu^2}{M_\Delta} \sim m^\nu, \; f_{ab} \sim \mathcal{O}(1) \]
Type-II Seesaw

\[ m_{\nu}^{ab} = \sqrt{2} \nu_T f_{ab} \lesssim 10^{-10} \text{GeV} \]

scalar potential:

\[ \mathcal{L}_{\text{scalar}}(\phi, \Delta) = -\frac{1}{2} M_{\Delta}^2 \text{Tr} \Delta^\dagger \Delta + \mu \phi^\dagger \Delta \tilde{\phi} + \ldots \]

\( \mu \)-term violates lepton number (\( \Delta \) has \( L = -2 \))

minimisation of potential:

\[ \nu_T \simeq \mu \frac{\nu^2}{M_{\Delta}^2} \]

triplet at the EW scale \( \mathcal{O}(100 \text{ GeV}) \): \( M_{\Delta} \sim \nu \implies \nu_T \sim \mu \)

need combination of "small" \( \mu \) and "small" \( f_{ab} \)
The triplet at LHC

\[ pp \rightarrow Z^*(\gamma^*) \rightarrow H^{++} H^{--} \rightarrow \ell^+ \ell^+ \ell^- \ell^- \]

doubly charged component of the triplet:

\[ \Delta = \begin{pmatrix} H^+/\sqrt{2} & H^{++} \\ H^0 & -H^+/\sqrt{2} \end{pmatrix} \]

very clean signature: two like-sign lepton paris with the same invariant mass and no missing transverse momentum; practically no SM background

Decays of the triplet:

\[ \Gamma(H^{++} \rightarrow \ell^+_a \ell^+_b) = \frac{1}{4\pi(1 + \delta_{ab})} |f_{ab}|^2 M_\Delta, \]

⇒ proportional to the elements of the neutrino mass matrix!
$L - R$ symmetric theories

Type I+II seesaw:

Assume $N_R, \Delta_L, \Delta_R$

$\langle \Delta_L \rangle$ gives Majorana mass term for $\nu_L$
$\langle \Delta_R \rangle$ gives Majorana mass term for $N_R$

Yukawa with Higgs gives Dirac mass term

\[
\begin{pmatrix}
M_L & m_D^T \\
m_D & M_R
\end{pmatrix}
\Rightarrow
m_\nu = M_L - m_D^T M_R^{-1} m_D
\]

Assuming $M_L \ll m_D \ll M_R$
SO(10) grand unified theory

- 16-dim representation contains all SM fermions + $N_R$

\[ \begin{pmatrix} q_L & u_R & d_R & L_L & \ell_R & N_R \end{pmatrix} \]
\[
\begin{array}{cccccc}
6 & 3 & 3 & 2 & 1 & 1
\end{array}
\]

- 126-dim scalar representation
  - needed to break SO(10) down to the SM gauge group
  - contains triplets under SU(2)$_L$ and SU(2)$_R$
    → natural framework for type-I and type-II seesaw

- seesaw scale $M_\Delta, M_R \sim M_{\text{GUT}} \sim 10^{16}$ GeV

Mohapatra, Senjanovic,...
Radiative neutrino mass models

- neutrino mass vanishes at tree level, generated radiatively at $n$-loop order
- suppression by coupling constants and loop factors
- new physics cannot be too heavy, typically around TeV
- testable at colliders, charged lepton flavour violation

review: Cai, Herrero-Garcia, Schmidt, Vicente, Volkas, 1706.08524
Zee model (1-loop) Zee, 1980

introduce singly charged scalar $h^+$ and second Higgs doublet $\phi'$

$$\mathcal{L}_\nu = f_{\alpha\beta} L_\alpha^T C \sigma_2 L_\beta h^+ + \mu h^+ \phi'^\dagger \bar{\phi}' + \text{h.c.}$$

$$m_\nu \sim \frac{\mu}{(4\pi)^2} f \frac{m_\ell^2}{m_h^2}$$

simplest version excluded, more complicated versions OK
Balaji, Grimus, Schwetz, 01; Herrero-Garcia, Ohlsson, Riad, Wiren, 17
rich phenomenology for LHC, FCNC, LFV $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \mu \rightarrow eee, ...$
Zee-Babu model (2-loop) Zee, 85, 86; Babu 88

introduce $SU(2)$-singlet scalars: $h^+, k^{++}$

\[
\mathcal{L}_\nu = f_{\alpha\beta} L^T_{\alpha} C^{-1} i\sigma_2 L_\beta h^+ + g_{\alpha\beta} \bar{e} e_R \epsilon_{R\alpha} e_R k^{++} + \mu h^- h^- k^{++} + \text{h.c.}
\]

\[
m_\nu \approx \frac{\mu}{48\pi^2 m_k^2} f m_\ell g^* m_\ell f^T
\]

good prospects to see doubly-charged scalar at LHC $\rightarrow$ like-sign lepton events if $k^{++}$ is within reach for LHC, tight constrains by perturbativity requirements and bounds from LFV Babu, Macesanu, 02; Aristizabal, Hirsch, 06; Nebot et al., 07; Schmidt, TS, Zhang, 14; Herrero-Garcia, Nebot, Rius, Santamaria, 14
Combining neutrino mass with Dark Matter

“scotogenic” model E. Ma, hep-ph/0601225

- version of inert Higgs doublet model
- SM + 2nd Higgs doublet $\eta +$ right-handed neutrinos $N$
- $\eta$ and $N$ are odd under a discrete $Z_2$ symmetry
  $\Rightarrow$ the lightest of them is a DM candidate
- neutrino masses generated at 1-loop:

$$
(1) \quad (M_{\nu})_{ij} = \sum_k h_{ik} h_{jk} M_k \pi^2 \left[ m_R^2 m_I^2 - M_k^2 \ln \frac{m_R^2}{M_k^2} - M_k^2 \ln \frac{m_I^2}{M_k^2} \right].
$$

many many variants discussed in literature
TeV scale neutrino mass

(+): potentially test neutrino mass mechanism at LHC

(+): typically signatures in LFV $\mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \mu \rightarrow eee, ...$

(+): radiative models explain smallness of neutrino mass by loop-factors

(+): in general, for mass generation at $n$-loop order one needs to explain the absence of all terms at order $< n \rightarrow$ invoke symmetry (can be used for stabilizing a DM candidate, e.g., Ma, 06)

(−): often TeV models appear ad-hoc and somewhat unmotivated
TeV scale neutrino mass

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(−) often TeV models appear ad-hoc and somewhat unmotivated
Automatized neutrino mass model building

Gargalionis, Volkas, 2009.13537; refs therein

- write down complete list of $\Delta L = 2$ operators
- systematically search for all possible UV completions (models)

```
<table>
<thead>
<tr>
<th>Dimension</th>
<th>Democratic</th>
<th>Unfiltered</th>
</tr>
</thead>
<tbody>
<tr>
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<td>10^1</td>
<td>10^1</td>
</tr>
<tr>
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<td>10^2</td>
<td>10^2</td>
</tr>
<tr>
<td>9</td>
<td>10^3</td>
<td>10^3</td>
</tr>
<tr>
<td>11</td>
<td>10^5</td>
<td>10^5</td>
</tr>
</tbody>
</table>
```

![Diagram of connectivity between exotic fields in neutrino-mass models. Each node represents an exotic field and edges connect fields with representations that cover those of the exotic fields featuring in our database. The weight of the edges indicates the number of times the two nodes appear in models together. The graph is clustered into roughly five communities within which there are many mutual connections. The additional interaction Lagrangian necessary to imprint neutrino masses suppressed by more than one loop factor, since the models presented all predict new physics below 15 TeV. In the representation, $\Delta L = 2$ operators are especially simple since they are SU(3) representations that cover those of the exotic fields featuring in our library. Only a handful of node labels are shown. The figure visualises the number of models with democratic and no filtering in Fig. 12: The bar chart shows the number of distinct Lagrangians derived from operators of different mass dimension in a way consistent with our neutrino-mass filtering criterion. The number of models grows with operator dimension, as shown in the table. At dimension five, 10^3 models are filtered out, and at dimension eleven, 10^6 models are filtered out.
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  Weinberg operator

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Conclusions
The baryon asymmetry

the asymmetry between baryons and antibaryons in the Universe is

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10} \text{ CMB+BAO, BBN}$$

<table>
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<td>Antibaryons:</td>
<td>− 10 000 000 000</td>
</tr>
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</table>

But in the SM this is a HUGE number.

Sacharow conditions:

1. Out of equilibrium processes [SC1]
2. CP violation [SC2]
3. Violation of Baryon number [SC3]

Are fulfilled in the SM, but

$$\eta_{\text{SM}} \approx 10^{-36}$$

which is many orders of magnitude too small!

⇒ requires physics beyond the SM
The baryon asymmetry

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Are fulfilled in the SM, but \( \eta_B^{\text{SM}} \) is many orders of magnitude too small!

\[ \Rightarrow \text{requires physics beyond the SM} \]
Leptogenesis

assume type-I seesaw with heavy ($\sim 10^{10}$ GeV) right-handed neutrinos $N$

- out of equilibrium decay of $N \rightarrow \phi \ell$ [SC1]

- CP asymmetry in $N$ decays: $\Gamma(N \rightarrow \phi^{+} \ell^{-}) \neq \Gamma(N \rightarrow \phi^{-} \ell^{+})$ [SC2]
due to tree- and loop-level interference

net-lepton number $L$ is generated

- $L$ is transformed to baryon number by non-perturbative $B - L$
  conserving (but $B + L$ violating) sphaleron processes in the SM [SC3]
Connection between low E CPV and Leptogenesis

Seesaw Lagrangian (3 $N_R$):

$$\mathcal{L}_{\text{seesaw}} = -\bar{L}\lambda_e\phi e_R - \bar{L}\lambda_\nu\phi N_R + \frac{1}{2}N_R^T C^{-1} M_R^* N_R + \text{h.c.}$$

contains 21 physical parameters: 15 moduli and 6 phases

- make $M_R$ and $\lambda_e$ diagonal and positive $\rightarrow$ 6
- left with complex $\lambda_\nu = V^\dagger \hat{\lambda} U$
  - $V$ and $U$ three complex angles each $\rightarrow 3 \times 3$ moduli + 6 phases

Branco, Lavoura, Rebelo, PLB 180 (1986) 264
Connection between low E CPV and Leptogenesis

Seesaw Lagrangian (3 $N_R$):

$$L_{\text{seesaw}} = -\bar{L}\lambda_e \phi e_R - \bar{L}\lambda_\nu \phi N_R + \frac{1}{2} N_R^T C^{-1} M^*_R N_R + \text{h.c.}$$

contains 21 physical parameters: 15 moduli and 6 phases

observable quantities at low energy:

- 3 charged lepton masses
- neutrino oscillations: 2 $\Delta m^2$, 3 angles, 1 phase
- absolute neutrino mass: 1
- Majorana phase in neutrinoless DBD: 1 (2) phase

→ 6 masses, 3 angles, 2 (3) phases

→ 3 masses ($N_R$), 3 angles and 4 (3) phases remain unmeasurable
Connection between low E CPV and Leptogenesis

Seesaw Lagrangian (3 $N_R$):

$$\mathcal{L}_{\text{seesaw}} = -\bar{L}\lambda_e \phi e_R - \bar{L}\lambda_\nu \tilde{\phi} N_R + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.}$$

contains 21 physical parameters: 15 moduli and 6 phases

- the CP asymmetry in Leptogenesis depends in general on a complicated combination of parameters involving both, low and high energy parameters

- no direct connection between CPV in oscillations and Leptogenesis can be established in general (may be possible in certain models, including models different from type-I with 3 $N_R$)
Connection between low E CPV and Leptogenesis

BUT: low energy Dirac and/or Majorana CPV can be \textit{sufficient} to generate the required CP asymmetry

- “classic” mass range $10^9 \text{ GeV} \lesssim M_N \lesssim 10^{12} \text{ GeV}$: successful LG possible from only Dirac or Majorana LE CPV phases
- outside this mass range fine tuning is needed

Leptogenesis – summary

(+) elegant mechanism to explain baryon asymmetry

(+) links neutrino physics to existence of matter

(+ ) many versions (with or without lepton number violation, for all types of seesaw, Dirac Leptogenesis, TeV-scale Leptogenesis, ...)

(−) in general can neither be tested nor excluded by low-energy experiments at best we can obtain “circumstantial evidence”:
   ▶ observe neutrinoless double beta decay (Majorana nature),
   ▶ observe CP violation in oscillations,
   ▶ none is necessary for successful Leptogenesis, but they can be sufficient!

Review articles on Leptogenesis:
Leptogenesis – summary

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Lepton flavour violation

- Neutrino oscillations imply violation of lepton flavour, e.g.: $\nu_\mu \rightarrow \nu_e$

- Can we see also LFV in charged leptons?

\[
\begin{align*}
\mu^\pm & \rightarrow e^\pm \gamma \\
\tau^\pm & \rightarrow \mu^\pm \gamma \\
\mu^+ & \rightarrow e^+ e^+ e^- \\
\mu^- + N & \rightarrow e^- + N
\end{align*}
\]

rich experimental program with sensitivities in the $10^{-13}$ to $10^{-18}$ range
Can we see also LFV in charged leptons?

Yes, BUT: $\mu^\pm \rightarrow e^\pm \gamma$ in the SM $+$ $\nu$ mass:

- $\text{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu i}^2}{m_W^2} \right|^2 \lesssim 10^{-54}$

- unobservably small (present limits: $\sim 10^{-13}$)
- observation of $\mu \rightarrow e\gamma$ implies new physics beyond neutrino mass

\[ \text{Br}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu i}^2}{m_W^2} \right|^2 \lesssim 10^{-54} \]
**μ → eγ and new physics**

generically one expects

\[
\text{Br}(\mu \rightarrow e\gamma) \sim 10^{-10} \left( \frac{\text{TeV}}{\Lambda_{\text{LFV}}} \right)^4 \left( \frac{\theta_{e\mu}}{10^{-2}} \right)^2
\]

- we are sensitive to new physics in the range 1 to 1000 TeV (TeV scale SUSY, TeV scale neutrino masses,...)

- cLFV does NOT probe neutrino Majorana mass (conserves lepton number)

  Majorana mass: dim-5 operator, LFV: dim-6 operators, e.g.

  \[
  \mathcal{L}_{\text{LFV}} = \frac{1}{\Lambda_{\text{LFV}}^2} (\bar{\mu}e)(\bar{e}e) + \frac{1}{\Lambda_{\text{LFV}}^2} (\bar{\mu}e)(\bar{q}q)
  \]

- cLFV is sensitive to new physics which may or may not be related to the mechanism for neutrino mass → extremely valuable information on BSM
Outline

Giving mass to neutrinos
  Weinberg operator

Right-handed neutrinos
  Dirac vs Majorana neutrinos
  Type-I Seesaw

Extending the scalar sector of the SM
  Higgs-triplet / Type-II Seesaw
  Radiative neutrino mass models

Leptogenesis

Lepton flavour violation

Conclusions
Conclusions - neutrinos and BSM

- neutrino mass established by oscillations
- identifying the mechanism for neutrino mass is one of the most important open questions in particle physics
- ... this may be a difficult task (the answer could be elusive forever)
- does not point to a specific energy scale of new physics
- hope for some signatures (neutrinoless double-beta decay, charged-lepton flavour violation, lepton-number violation at LHC)!