TESTING THE SEEWSAW MECHANISM

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But what generates them? And may the same new physics solve cosmological puzzles?
Neutrino masses: Seesaw mechanism

\[ L = L_{\text{SM}} + i \bar{\nu}_R \partial \nu_R - \bar{\nu}_L \nu_L F_{\nu_R} - \bar{\nu}_R F_{\nu_L}^\dagger - \frac{1}{2} (\bar{\nu}_c R M \nu_R + \bar{\nu}_R M \nu_c R) \]

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

\[ \frac{1}{2} (\nu_L \nu_c R) (0_{\text{DM}} D_{\text{DM}} M M) (\nu_c L \nu_R) \]

125 GeV

\[ \text{three light neutrinos} \nu \simeq U_{\nu} (\nu_L + \theta \nu_c R) \]

mostly "active" SU(2) doublet

\[ m_{\nu} \simeq \theta M M \theta T = v^2 F M - \frac{1}{2} M_F T \]

\[ \text{three heavy neutrinos} \nu \simeq \nu_R + \theta T \nu_c L \]

mostly "sterile" singlets

\[ M_N \simeq M_M M \]

Majorana masses introduce new mass scale(s)

\[ \text{new heavy states only interact via small mixing} \]

\[ U_{2a} \sim |\theta_{aI}|^2 \ll \frac{1}{3} \]
Neutrino masses: Seesaw mechanism

\[ \mathcal{L} = \mathcal{L}_{SM} + i \bar{\nu}_R \phi \nu_R - \bar{L}_L F \nu_R \tilde{H} - \bar{\nu}_R F^\dagger \tilde{L}_L \]

\[ \text{Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80} \]

\[ \frac{1}{2} \left( \bar{\nu}_c R M M \nu_R + \bar{\nu}_R M^\dagger M \nu_c R \right) \]

\[ \text{three light neutrinos} \]

\[ \nu \approx U \nu_L (\nu_L + \theta \nu_c R) \]

\[ \text{mostly "active" SU(2) doublet} \]

\[ m_\nu \approx \theta M \]

\[ \text{mostly "sterile" singlets} \]

\[ M_N \approx \bar{M}_F T \]

\[ \text{heavy masses} \]

\[ U_{2aI} = |\theta_{aI}|^2 \ll 1/16 \]

\[ \text{new heavy states only interact via small mixing} \]
Neutrino masses: Seesaw mechanism

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Neutrino masses: Seesaw mechanism

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Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

\[ \Rightarrow \frac{1}{2} (\bar{\nu}_L \nu_R^c) \begin{pmatrix} 0 & m_D^T \\ m_D & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} \]
Neutrino masses: Seesaw mechanism

\[ \mathcal{L} = \mathcal{L}_{SM} + i \bar{\nu}_R \phi \nu_R - \bar{L}_L F \nu_R \tilde{H} - \bar{\nu}_R F^\dagger L \tilde{H}^\dagger - \frac{1}{2}(\bar{\nu}^c_R M M \nu_R + \bar{\nu}_R M_M^\dagger \nu^c_R) \]

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

\[ \Rightarrow \frac{1}{2}(\nu_L \nu_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} \]

two sets of Majorana mass states with mixing \( \theta = m_DM_M^{-1} = \nu FM_M^{-1} \)

- three light neutrinos \( \nu \simeq U_\nu (\nu_L + \theta \nu_R^c) \)
  - mostly "active" SU(2) doublet
  - light masses \( m_\nu \simeq \theta MM \theta^T = \nu^2 FM_M^{-1} F^T \)

- three heavy neutrinos \( N \simeq \nu_R + \theta^T \nu_L^c \)
  - mostly "sterile" singlets
  - heavy masses \( M_N \simeq M_M \)

- Majorana masses \( M_M \) introduce new mass scale(s) \( M_I \)

- new heavy states only interact via small mixing \( U_{al}^2 = |\theta_{al}|^2 \ll 1 \)
Testing the Seesaw Mechanism

The low scale seesaw

Cosmology connection

Conclusions

Majorana neutrinos

Seesaw Mechanism (type I)

low scale seesaw

GUT seesaw

\( M_M \)

Neutrino Physics

Cosmology

High Energy Physics

Dirac Neutrinos

\( eV \) \( keV \) \( MeV \) \( GeV \) \( TeV \) \( GUT \)

disfavoured by solar data


disfavoured by

BBN + CMB + osc. data
(if origin of neutrino mass)

Dark Matter

Leptogenesis

from heavy neutrino oscillations

from heavy neutrino decay

-electroweak precision data

-CKM unitarity

-neutrinoless double beta decay

-LFV lepton decays

-lepton universality in meson decays

SHiP

DUNE

LHC

FCC-ee

CEPC, SPPC

Drewes/Garbrecht 1502.00477
Combining constraints on heavy neutrinos

Combined analyses:

Atre/Han/Pascoli/Zhang 0901.3589  collection of direct and indirect constraints
Asaka/Eijima/Ishida 1101.1382 + later work by Asaka et al  indirect constraints
Ruchayskiy/Ivashko 1112.3319, 1202.2841  direct constraints, BBN
Abada, De Romeri, Teixeira, Vicente, Weiland (various works)  indirect and direct constraints
Hernandez/Kekic/Lopez-Pavon 1406.2961  combined cosmological constraints
Antusch/Fischer 1407.6607 + later work  global fits of indirect constraints
Gorbunov/Timiryasov 1412.7751  indirect constraints
MaD/Garbrecht 1502.00477  combined analysis of direct, indirect and cosmological constraints
Fernandez-Martinez/Hernandez-Garcia/Lopez-Pavon/Lucente 1508.03051  indirect constraints at loop level
Gouvea/Kobach 1511.00683  global fits of direct and indirect constraints
Enrique Fernandez-Martinez/Hernandez-Garcia/Lopez-Pavon 1605.08774  global fits of indirect constraints

recent reviews:

Boyarsky/Ruchayskiy/Shaposhnikov 0901.0011, Abazajian et al 1204.5379 , MaD 1303.6912,
Gninenko/Gorbunov/Shaposhnikov 1301.5516, Dev/Deppisch 1502.06541, [Adhikari et al 1602.04816]
Combining constraints

- **Indirect searches**

- **Direct searches**

- **Cosmology:** BBN
Combining constraints

- **Indirect searches**
  - neutrino oscillation data
  - LFV in rare lepton decays
  - violation of lepton universality
  - (apparent) violation of CKM unitarity
  - neutrinoless double $\beta$-decay
  - EW precision data

- **Direct searches**

- **Cosmology**: BBN
Combining constraints

- **Indirect searches**
  - neutrino oscillation data
  - LFV in rare lepton decays
  - violation of lepton universality,
  - (apparent) violation of CKM unitarity
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  - EW precision data

- **Direct searches**
  - LNV and LFV in gauge boson or meson decays
  - displaced vertices, peak searches, missing 4-momentum
  - SHiP see SHiP physics case paper 1504.04855

- **Cosmology**: BBN
The low scale seesaw

Conclusions

inverted hierarchy, $m_{\text{lightest}} = 0.23$ eV, $n = 3$
inverted hierarchy, $m_{\text{lightest}} = 0$, $n = 3$
Inverted hierarchy, \( m_{\text{lightest}} = 0, n = 3 \)
The low scale seesaw

Conclusions

inverted hierarchy, $m_{\text{lightest}} = 0$, $n = 3$
inverted hierarchy, \( m_{\text{lightest}} = 0, \ n = 2 \)

A measurement of the Dirac phase will lead to rather precise predictions for the flavour mixing pattern!

⇒ If a heavy neutral lepton discovered in experiment, we can decide if it is part of the seesaw mechanism
For $U_{eI}^2$ and $U_{\mu I}^2$, the global constraints are only mildly stronger than the direct search bound alone. But:

- Not every combination of $U_{\alpha I}^2$ is allowed
- This is a two dimensional projection of a twelve dimensional parameter space.
- Large $U_{eI}^2$ are only possible in very specific properties (approximate B-L conservation)

⇒ Any external constraint could drastically change the picture (model building, cosmology...)

For $U_{\tau I}^2$ and $M_I < 2$ GeV, the combined constraints are much stronger than the direct search bound.
Future sensitivities

plot by Bhupal Dev
Leptogenesis with two heavy neutrinos

Akhmedov/Rubakov/Smirnov 98, Asaka/Shaposhnikov 05

The common origin of matter and neutrino masses can be discovered in the lab!

**see also talks by Juraj Klaric and Jacobo Lopez-Pavon**

as well as Canetti/MaD/Frossard/Shaposhnikov 1208.4607, Hernandez/Kekic/Lopez-Pavon/Salvado 1508.03676 and Abada/Arcadi/Domcke/Lucente 15
Indirect searches

Example: leptogenesis and neutrinoless double $\beta$-decay

plot from MaD/Eijima 1606.06221
see also Hernandez/Kekic/Lopez-Pavon/Racker/Salvado 1606.06719, Asaka/Eijima/Ishida 1606.06686

see also: talk by Jacobo Lopez-Pavon
Conclusions

- The seesaw mechanism (still) provides an elegant explanation for the observed neutrino masses.

- Any value of the seesaw scale between 100 MeV and the GUT scale is consistent with experiment at observation.

- However, for Majorana masses below the TeV scale,
  - strong constraints on the heavy neutrino properties can be imposed by combining various data sets and
  - many experiments can discover the heavy neutrinos (ATLAS, CMS, NA62, LHCb, BELLE II, SHiP, FCC-ee, CEPC...).

- The low scale seesaw also allows to address cosmological problems (leptogenesis, sterile neutrino Dark Matter, ...) within the experimentally accessible parameter space.

- The future? Stay tuned!
  - Not all existing data has been exploited
  - New data is coming
  - Theory studies need improvement