LEPTOGENESIS:
IMPROVING PREDICTIONS FOR EXPERIMENTAL SEARCHES

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tu münchen

6. 8. 2016, ICHEP, Chicago, USA
Neutrinos have masses.

There is (almost) no antimatter in the observable universe.

There are $\sim 10^{10}$ times more photons in the observable universe than nuclei.
Neutrinos have masses.

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We need New Physics!
Could the same New Physics solve these puzzles?
Can we probe it in the lab?
### Three Generations of Matter (Fermions) spin $\frac{1}{2}$

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>2.4 MeV</td>
<td>1.27 GeV</td>
<td>171.2 GeV</td>
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<tr>
<td>Charge</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
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<tr>
<td>Name</td>
<td>up</td>
<td>charm</td>
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#### Quarks
- **d**: down, $\frac{-1}{3}$
- **s**: strange, $\frac{-1}{3}$
- **b**: bottom, $\frac{-1}{3}$

#### Bosons (Forces) spin 1
- **Z**: weak force, 91.2 GeV
- **W**: weak force, $W^+$, $W^-$, 80.4 GeV

#### Leptons
- **e**: electron, $-1$
- **μ**: muon, $-1$
- **τ**: tau, $-1$

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Figure by M. Shaposhnikov

**Leptogenesis**: Improving predictions for experimental searches
Neutrino masses: Seesaw mechanism

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


\[ \Rightarrow \frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \nu^c_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix} \]

two sets of Majorana mass states with mixing \( \theta = m_D M_M^{-1} = \nu FM_M^{-1} \)
Neutrino masses: Seesaw mechanism

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

two sets of Majorana mass states with mixing \( \theta = m_D M_M^{-1} = v F M_M^{-1} \)

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

- 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 \( U_{ai}^2 = |\theta_{ai}|^2 \ll 1 \)

LEPTOGENESIS: improving predictions for experimental searches
Neutrino oscillations

Leptogenesis

Low scale leptogenesis

Majorana neutrinos

Seesaw Mechanism (type I)

Low scale seesaw

GUT seesaw

\(M_M\)

Leptogenesis

\textit{from heavy neutrino oscillations}

\textit{from heavy neutrino decay}

electroweak precision data

CKM unitarity

neutrinoless double beta decay

LFV lepton decays

lepton universality in meson decays

Dirac Neutrinos

disfavoured by solar data

Leptogenesis

disfavoured by solar data

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

Dark Matter

Dirac Neutrinos

disfavoured by solar data

Leptogenesis

disfavoured by solar data

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

MaD/Garbrecht 1502.00477
Leptogenesis: Sakharov conditions

- baryon number violation
- C and CP violation
- nonequilibrium
Leptogenesis: Sakharov conditions

- baryon number violation
  - SM: sphalerons violate $B$, but conserve $B - L$ at $T > 140$ GeV

- C and CP violation
  - SM: weak interaction violates P and CP, but CP-violation insufficient

- nonequilibrium
  - SM: Hubble expansion insufficient, no EW phase transition
**Leptogenesis: Sakharov conditions**

- **baryon number violation**
  - SM: sphalerons violate $B$, but conserve $B - L$ at $T > 140$ GeV
  - Yukawa couplings $F$ violate individual lepton flavour numbers
  - in addition $M_M$ violates total lepton number

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Leptogenesis: Sakharov conditions

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  - $N_l$ production
    - "freeze in leptogenesis"
    - Akhmedov/Rubakov/Smirnov
  - $N_l$ freezeout and decay
    - "freeze out leptogenesis"
    - Fukugita/Yanagida

\[ \text{LEPTOGENESIS: improving predictions for experimental searches} \]
Vanilla Leptogenesis (freeze out)\textsuperscript{Fukugita/Yanagida}

- $N_i$ are produced thermally very early at $T > M$
- freeze out and decay at $T \lesssim M$
- CP-violating decay produces $L \neq 0$

$L \neq 0$ is partly transferred into $B \neq 0$ by sphalerons

Boltzmann equations ($x = M / T$) see e.g. Buchmüller/Plümacher

\[
\begin{align*}
    xH \frac{dY_N}{dx} &= -\Gamma_N (Y_N - Y_N^{\text{eq}}) \\
    xH \frac{dY_{B-L}}{dx} &= \epsilon \Gamma_N (Y_N - Y_N^{\text{eq}}) - c_W \Gamma_N Y_{B-L}
\end{align*}
\]
**first principles derivation of kinetic equations**
Anisimov/Buchmuller/MaD/Mendizabal, Beneke/Garbrecht/Herranen/Schwaller, Garny/Hohenegger/Kartavtsev, Dev/Millington/Pilaftsis/Teresi

**quasiparticle dispersion relations** Giudice/Notari/Raidal/Riotto 04, Plumacher/Kiessig 12

**momentum dependency** Hahn-Woernle/Plumacher/Wong 09, Asaks/Eijima/Ishida 12, Bodeker/Wormann 14

**production rate** $\Gamma_N$ Salvio/Lodone/Strumia 11, Laine 12, Besak/Bodeker 12, Biondini/Brambilla/Escobedo/Vairo 13, Garbrecht/Glowna/Herranen 13, Garbrecht/Glowna/Schwaller 13, Ghisoiu/Laine 14, Ghiglieri/Laine 15, Ghiglieri/Laine 16

**washout rates** $c_W \Gamma_N$ Bodeker/Laine 14, Ghisoiu/Laine 14, Ghiglieri/Laine 16

**CP violating parameter** $\epsilon$ Biondini/Brambilla/Escobedo/Vairo 15

**behaviour near resonance** Garny/Hohenegger/Kartavtsev 11, Garbrecht/Herranen 11, Dev/Millington/Pilaftsis/Teresi 11

**flavour effects** Abada/Davidson/Ibarra/Josse-Michaux/Losada/Riotto 06, Nardi/Nir/Roulet/Racker 06, Jose-Michaux/Abada 07, Aristazabal Sierra/Munoza/Nardi 09, Racker/Pena/Rius 12, Beneke/Fidler/Garbrecht/Herranen/Schwaller 11, ...

**low scale leptogenesis parameter space** this talk
Low scale leptogenesis

\begin{align*}
Y &= \frac{9}{12} \\
Y_{eq} &= \frac{M}{T}
\end{align*}

Leptogenesis: Improving Predictions for Experimental Searches
Leptogenesis from $\mathcal{N}$-oscillations (freeze-in)

Oscillating regime
Leptogenesis from $N$-oscillations (freeze-in)

Oscillating regime

Overdamped regime

LEPTOGENESIS: IMPROVING PREDICTIONS FOR EXPERIMENTAL SEARCHES
Introduction

Neutrino oscillations

Leptogenesis

Low scale leptogenesis

Leptogenesis with two heavy neutrinos

Requires mass degeneracy and small mixing. . .

but CP-violation may also be measurable

Cvetic/Kim/Zamora-Saa 1403.2555
allowed relative mixings $U_{\alpha}^2/U^2$ for given $U^2$ and $M = 1$ GeV and IH measuring Dirac phase $\delta$ would considerably reduce allowed regions
How to find the $N_I$?

- **Indirect searches** see e.g. MaD arXiv:1303.6912 [hep-ph]

- **Direct searches** see e.g. MaD/Garbrecht 1502.00477

- **Cosmology**: BBN and $N_{\text{eff}}$ see e.g. Hernandez/Kekic/Lopez-Pavon 1406.2961

- **Astrophysics**: X-ray, SN, pulsars, structure formation review 1602.04816
How to find the $N_f$?

**Indirect searches** see e.g. MaD/Garbrecht 1502.00477
- 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** see e.g. Antusch/Fischer 1502.05915, Deppisch/Dev 1502.06541

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**Direct searches** see e.g. Antusch/Fischer 1502.05915, Deppisch/Dev 1502.06541
- LNV and LFV in gauge boson or meson decays
  - displaced vertices, SHiP
  - peak searches, missing 4-momentum

**Cosmology**: BBN and $N_{\text{eff}}$ see e.g. Hernandez/Kekic/Lopez-Pavon 1406.2961

**Astrophysics**: X-ray, SN, pulsars, structure formation review 1602.04816
Direct searches

plot by Bhupal Dev

see talks by Bhupal Dev, Un-ki Yang, Eric van Herwijnen
Indirect searches

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

plot from MaD/Eijima 1606.06221

see also Lopez-Lavon/Pascoli/Wong 1209.5342, Lopez-Pavon/Molinaro/Pectov 1506.05296

see also: talk by Josu Hernandez
Summary

- Heavy right handed neutrinos can be the common origin of neutrino masses and baryons in the universe.

- Much progress has been made in the quantitative understanding of leptogenesis

- If the heavy neutrino masses are below the TeV scale, they can be found in experiments.

- The requirement to explain the neutrino masses and the baryon asymmetry impose strong constraints on the properties of the heavy neutrinos. If any heavy neutral leptons are found in experiments in the future, these can be used to assess whether the new particles are indeed the common origin of neutrino masses and matter in the universe.