A view on the
THEORETICAL STATUS OF NEUTRINO PHYSICS

Marco Drewes
TU München

(loosely following **arXiv:1303.6912 [hep-ph]**)

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NuFact 2014 conference
University of Glasgow, Scotland, UK(?)

Part I

Why are neutrinos so interesting?

The **Standard Model** and **General Relativity** together explain *almost* all phenomena observed in nature, but. . .

- gravity is not quantised
- a handful of observations remain unexplained
  - neutrino oscillations
  - baryon asymmetry of the universe
  - dark matter
  - accelerated cosmic expansion (Dark Energy, inflation)

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  - dark matter - sterile neutrinos?
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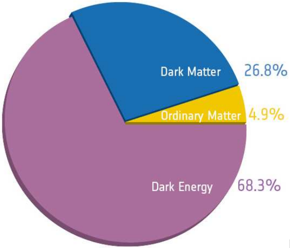

planck.cf.ac.uk

Neutrino masses and New Physics I

Dirac mass

- electron mass term is $\overline{e_L} m_e e_R + h.c.$
- neutrinos: $\overline{\nu_L} m_D \nu_R \qquad + h.c.$

Dirac mass requires existence of RH neutrinos ν_R.

$\Rightarrow$ **new neutrino states!**

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- for $M_M = 0$ neutrinos are Dirac particles and ν_R only act as new spin/helicity states
- in general neutrinos are Majorana particles and M_M introduces a new mass scale in nature
- for $M_M \gg 1$ eV: seesaw mechanism at work
  $\Rightarrow$ light active and heavy sterile neutrinos

Majorana mass

- Majorana mass term $\overline{\nu_L} m_\nu \nu_L^c + h.c.$
  is not gauge invariant.
- Weinberg operator $\frac{1}{2}\bar{L_L}\tilde{H}\frac{c_5}{M}\tilde{H}^T L_L^c + h.c.$
  can generate it via Higgs mechanism $\Rightarrow$ $m_\nu \sim c_5 \frac{v^2}{M}$
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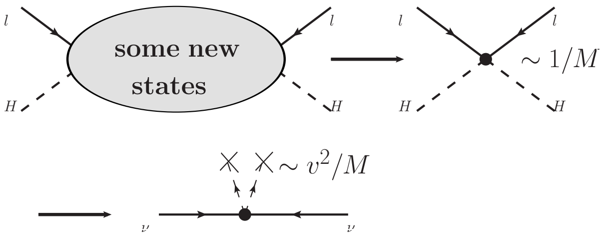
$\Rightarrow$ Must be interpreted as low energy effective field theory.

There must be some new states!



- **What are the new states?** $\Rightarrow$ models of neutrino mass
- **Why have we not seen them?**
  - weak coupling ($c_5 \ll 1$)?
  - too heavy ($M \gg 1$ TeV)?
- **Are they related to other phenomena?**
  - baryogenesis via leptogenesis?
  - Dark Matter?
  - anomalies : Dark Radiation? LSND/reactor/gallium?
- **How can we find them?**
  - heavy: energy frontier
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Neutrino experiments are crucial because they probe c_5/M.
$\Rightarrow$ constrain parameter space

To unveil the origin of neutrino mass we need to find the new states.

Models of neutrino masses

Why are neutrinos so light? see WG1 talks this afternoon

- **new states are heavy**
- **new states are very weakly coupled**
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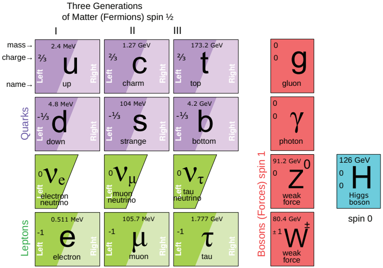
- **radiative mass generation**
  - classically massless neutrinos (loop suppression)
  - examples: Ma, Zee, Babu models

Assumption: It's RH neutrinos and the seesaw mechanism.

- all other fermions come in both chiralities
- "naturally" appears in models involving $U_{B-L}(1)$, e.g. left-right symmetric, SO(10) GUT...
- can solve cosmological problems (leptogenesis, Dark Matter,...)
- simplicity, predictivity (few parameters!)



Part II

Right Handed Neutrinos
in cosmology and particle physics

Neutrino masses: Seesaw mechanism

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L y \nu_R \tilde{H} - \bar{\nu}_R y^\dagger L \tilde{H}^\dagger - \frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

Minkowski 1979, Gell-Mann/Ramond/Slansky 1979, Mohapatra/Senjanovic 1979, Yanagida 1980

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

- Majorana masses M_M introduce new mass scale(s)
- two sets of Majorana mass states with small mixing $\theta \ll 1$
  here $\theta = m_D M_M^{-1} = vyM_M^{-1}$

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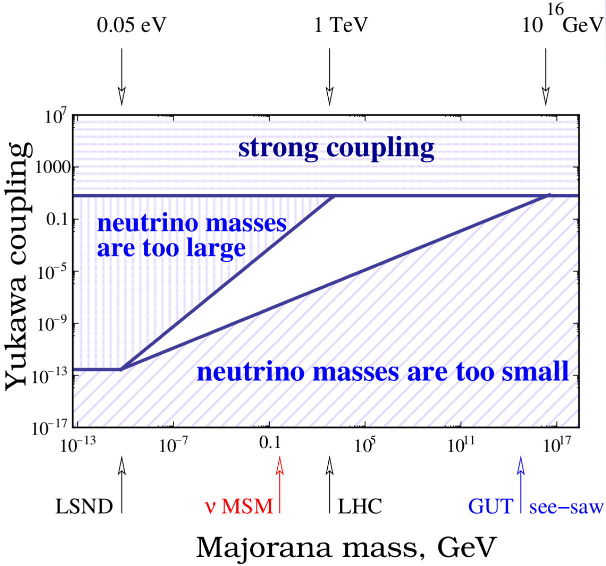
  here $\theta = m_D M_M^{-1} = vyM_M^{-1}$
- three light neutrinos $\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
  - mostly "active" SU(2) doublet
  - masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 y M_M^{-1} y^T}$
- three heavy neutrinos $N \simeq \nu_R + \theta^T \nu_L^c$
  - mostly "sterile" singlets
  - heavy masses $\boldsymbol{M_N \simeq M_M}$



plot from 1204.5379

The GUT seesaw

Pros:

- theoretically well-motivatedin GUTs, e.g. SO(10)
- “naturally” explains small neutrino masses
- “naturally” leads to leptogenesis Fukugita/Yanagida
- indirect experimental access to very high scales

Cons:

- new states experimentally inaccessible
- adds to hierarchy problem

What could we still observe?

- Decompose Yukawa matrix $y = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M_M}$ Casas/Ibarra
  $\Rightarrow$ **oscillation experiments** constrain some parameters

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- **absolute mass scale**: $\#\ \nu_R$-flavours $\geq \#$ non-zero m_i
- **lepton flavour violation**
  - if lepton number is approx. conserved, m_ν is protected by symmetry
    Wyler/Wolfenstein, Mohapatra/Valle, Branco/Grimus/Lavoura,. . .
  - $\mu \to e\gamma$ may be observable Smirnov/Kersten, Abada/Biggio/Bonnet/Gavela/Hambye, Gavela/Hambye/D.Hernandez/ P.Hernandez, Blanchet/Hambye/Josse-Michaux

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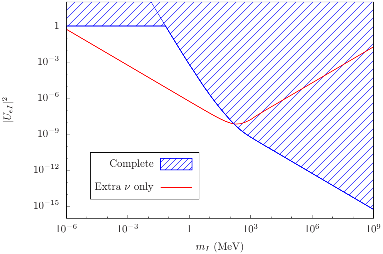
- **neutrinoless double β-decay**
  constrains $m_{ee} \sim -\sum_I M_I \theta_{eI}^2$



Blennow/Fernandez-Martinez/Lopez-Pavon/Menendez 1005.3240

The electroweak / TeV seesaw

Pros:

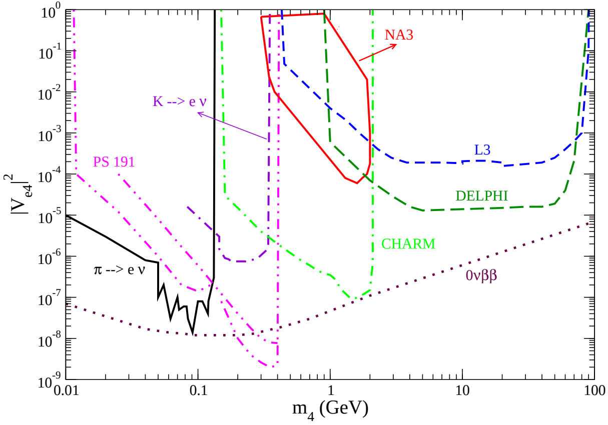
- some theoretical arguments
  - no new scale Asaka/Shaposhnikov
  - classical scale invariance Khoze/Ro,. . .
- allows for leptogenesis
  - during ν_R decay Pilaftsis 9707235
  - during ν_R production Akhmedov/Rubakov/Smirnov 9803255, Garbrecht 1401.3278
- new states can be found at LHC Smirnov/Kersten 0705.3221
- hints in EW data? Akhmedov/Kartavtsev/Lindner/Michaels/Smirnov 1302.1872

Cons:

- small Yukawa couplings y
- accessible regime constrained from low energy observations, in particular $\nu \to e\gamma$, $0\nu\beta\beta$-decay, PMNS-unitarity

  Ibarra/Molinaro/Petcov 1103.6217, Abada/Das/Teixeira/Vicente/Weiland 1211.3052 and 1311.2830,

  Basso/Fischer/van der Bij 1310.2057, Endo/Yoshinaga 1404.4498



Atre/Han/Pascoli/Zhang 0901.3589

See also talk by A. Golutvin on Thursday!

The GeV seesaw

Pros:

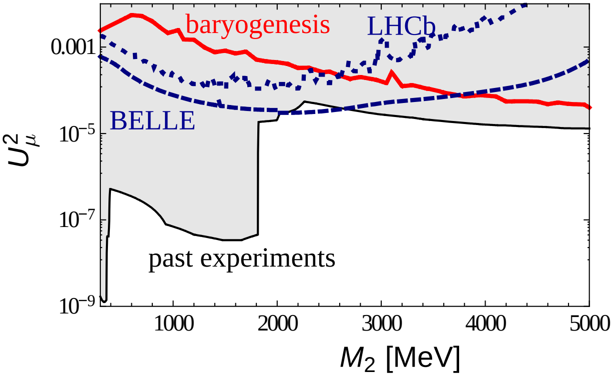
- some theoretical arguments
  - no new scale Asaka/Shaposhnikov
  - classical scale invariance Khoze/Ro,. . .
- allows for leptogenesis Akhmedov/Rubakov/Smirnov 9803255, Asaka/Shaposhnikov 0505013 even without mass degeneracy

  MaD/Garbrecht 1206.5537, Canetti/MaD/Garbrecht 1404.7114
- new states can be found in meson decays at BELLE II, LHCb or SHIP Canetti/MaD/Frossard/Shaposhnikov 1208.4607, Canetti/MaD/Garbrecht 1404.7114
- CP-violation in the sterile sector may be measurable Cvetic/Kim/Zamora-Saa 1403.2555

Cons:

- very small Yukawa couplings y, cancellations

Leptogenesis with GeV scale RH neutrinos



$M_1 = 1$ GeV, $M_3 = 3$ GeV plot updated from Canetti/MaD/Garbrecht 1404.7114

CP-violation may also be measurable Cvetic/Kim/Zamora-Saa 1403.2555

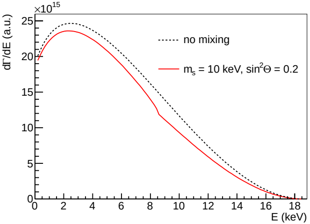
$\Rightarrow$ **LHCb, BELLE, SHIP may unveil the origin of matter!**

The keV seesaw

Pros:

- can in principle explain neutrino masses
- can be Dark Matter (cold, warm, non-thermal. . .)

- can be tested
  - KATRIN type experiments
  - astrophysics / cosmology



courtesy S. Mertens

Cons:

- very tiny Yukawa couplings y, cancellations
- a state can only **either** be DM **or** contribute to neutrino mass
- simplest scenario (Dodelson/Widrow) disfavoured by data

If RH neutrinos are DM, then there are three basic questions

- They are decaying DM. Where is the decay line?
- How were they produced?
- Are they consistent with structure formation?

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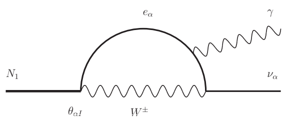
  - Search for X-ray line!



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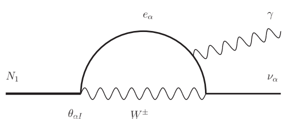
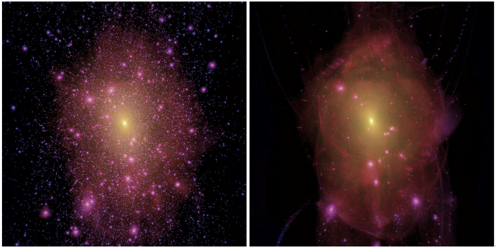
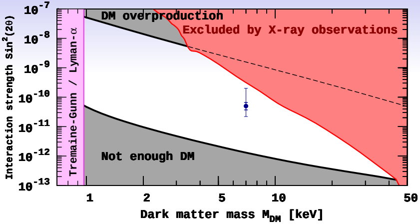


- How were they produced?
- Are they consistent with structure formation?
  - DM is absolutely essential to form structures in the universe
  - DM is "cold" , i.e. $\langle \mathbf{k} \rangle < M$ at freezeout



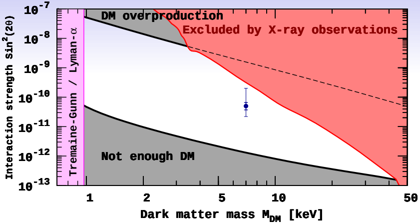
1104.2929

astro/cosmology status early 2014 plot from 1402.4119, see also 1402.2301



Now: very active discussion 1405.7943,1408.1699,1408.3531,1408.4388

astro/cosmology status early 2014 plot from 1402.4119, see also 1402.2301



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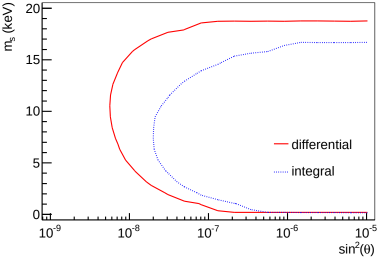
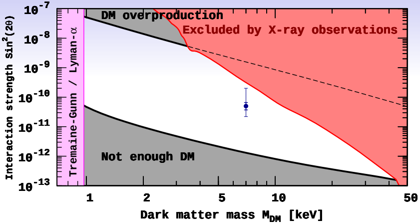
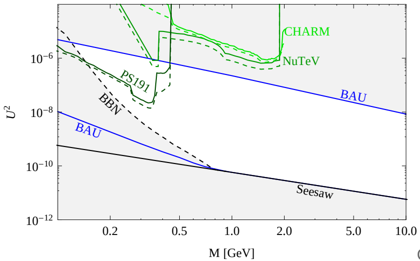
Potential of KATRIN courtesy S. Mertens, see also 1404.5955



The νMSM: neutrinos solve it all!



Boyarsky/Ruchayskiy/Iakubovskyi/Franse 1402.4119



Canetti/MaD/Frossard/Shaposhnikov 1208.4607

DM, Baryogenesis and neutrino masses from RH neutrinos!

See also talk by A.Golutvin on Thursday

Light sterile neutrinos

Pros:

- can in principle explain neutrino masses Gouvea 0501039
- may fit oscillation anomalies (LSND, reactor, gallium)
- light sterile neutrinos are preferred by some cosmological data

Cons:

- if origin of neutrino mass:
  extremely tiny Yukawa couplings y, cancellations
- pheno models ($3+1, 3+2$ etc.) do not explain neutrino mass
  $\Rightarrow$ implicitly assume existence of heavier states
- anomalies not consistent see talk by T. Schwetz-Mangold
  - oscillation anomalies amongst each other
  - different cosmological data sets
  - cosmology vs oscillation data

$\Rightarrow$ **New data is needed!**

Summary

- ν-oscillations are the only BSM signal seen in the lab **definitely** require new BSM degrees of freedom!
- the new particles may be related to cosmological puzzles (Dark Matter, baryogenesis, Dark Radiation)
- if new particles are below the electroweak scale, they can be found experimentally $\Rightarrow$ search for exciting New Physics!
- even if they are heavier, indirect probes involve
  - neutrino oscillation experiments
  - neutrinoless double β-decay
  - lepton flavour violation
  - lepton universality violation
  - unitarity of the PMNS matrix

We are looking forward to exciting new data. . .

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. . .**so let's get started here!**