HEAVY NEUTRINOS IN PARTICLE PHYSICS AND COSMOLOGY

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Three Generations of Matter (Fermions) spin $\frac{1}{2}$

- **Mass**
  - I: 2.4 MeV
  - II: 1.27 GeV
  - III: 171.2 GeV

- **Charge**
  - $\frac{2}{3}$
  - $\frac{1}{3}$

- **Name**
  - I: up, down
  - II: charm, strange
  - III: top, bottom

- **Bosons (Forces) spin 1**
  - $Z^0$ weak force (91.2 GeV)
  - $W^\pm$ weak force (80.4 GeV, $W^+$, $W^-$)

- **Leptons**
  - I: electron (e), electron neutrino ($\nu_e$)
  - II: muon ($\mu$), muon neutrino ($\nu_\mu$)
  - III: tau ($\tau$), tau neutrino ($\nu_\tau$)

- **Quarks**
  - I: 0 eV (left, right)
  - II: 0 eV (left, right)
  - III: 0 eV (left, right)

- **Bosons (Forces) spin 0**
  - $H$ Higgs boson (125 GeV)
Neutrino masses: Seesaw mechanism

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

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

\[ \Rightarrow \quad \frac{1}{2} (\bar{\nu}_L \nu^c_R) \left( \begin{array}{cc} 0 & m_D \\ m_D^T & M_M \end{array} \right) \left( \begin{array}{c} \nu^c_L \\ \nu_R \end{array} \right) \]

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

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

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

- Majorana masses \( M_M \) introduce new mass scale(s)
- new heavy states only interact via small mixing \( \theta \ll 1 \)
Where to see the $N_i$

- **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**
  - LNV and LFV in gauge boson or meson decays

  \[ D, B \rightarrow N, l, l \rightarrow \text{meson or lepton} - \text{antilepton} \]

  - displaced vertices
  - peak searches, missing 4-momentum

- **Cosmology**: BBN and $N_{\text{eff}}$
ν-oscillation data and the seesaw scale

plot from 1204.5379
Introduction

How to find heavy neutrinos?

What can they do for you?

Low scale seesaw

Outlook

Bounds from cosmology: $N_{\text{eff}}$ and BBN

from Hernandez/Kevic/Lopez-Pavon 1406.2961
Bounds from Colliders

plot from MaD/Garbrecht 1502.00477
Combining direct and indirect constraints

\[ m_{\text{lightest}} = 0.23 \text{eV} \]

plot from MaD/Garbrecht 1502.00477

\[ m_{\text{lightest}} = 0 \text{eV} \]
What can RH neutrinos do for you?

Neutrino masses and...

- $M > 100$ MeV: Leptogenesis
  CP-violating interactions of RH neutrinos can generate a matter-antimatter asymmetry in the early universe.

- $M \sim$ keV: sterile neutrino Dark Matter
  RH neutrinos with tiny mixing $\theta$ are long lived massive particles and obvious DM candidates.

- $M \lesssim$ eV: oscillation anomalies and Dark Radiation
  Light sterile neutrinos could explain oscillation anomalies (LSND, Galllium, reactor) and contribute to $N_{\text{eff}}$ in the early universe.
**GUT seesaw**
- Naturally fits into GUTs
- Naturally gives neutrino masses
- Naturally does leptogenesis

**Electroweak or TeV seesaw**
- Common origin with EW scale?
- Gives neutrino masses
- Allows for leptogenesis
- Accessible to LHC

**GeV seesaw**
- Gives neutrino masses
- Does leptogenesis
- Accessible to LHC, BELLE, SHiP
- Part of minimal $\nu$MSM

**KeV seesaw**
- Viable DM candidate

**eV seesaw**
- LSND, gallium, reactor anomaly
- "Dark Radiation" $N_{\text{eff}}$
Low scale leptogenesis

- baryon asymmetry can be produced in the early universe
  - during $N_i$ decay Fukugita/Yanagida 1986, Pilaftsis 2004
- $N_i$ can be found at LHC, BELLE II or SHiP plot: Canetti/MaD/Garbrecht 1404.7114

relevant CP-violation can be observable
  - can work with PMNS-phases alone 1208.4607
  - sterile sector CP-violation may also be observable 1403.2555
keV Masses: Sterile Neutrino Dark Matter?

- Where is the decay line? Very active discussion of 3.5 keV excess...
- How were they produced?
- Are they consistent with structure formation?

Upcoming White Paper:
keV Masses: Sterile Neutrino Dark Matter?

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  - radiative decay $N \rightarrow \nu_L \gamma$
  - Search for X-ray line!

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- Are they consistent with structure formation?
  - DM is absolutely essential to form structures in the universe
  - DM is “cold”, i.e. $\langle k \rangle < M$ at freezeout

Upcoming White Paper:
How to find heavy neutrinos? 
What can they do for you? 
Low scale seesaw 
Outlook

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 and many more
How to find heavy neutrinos?
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Interaction strength $\sin^2(2\theta)$

Dark matter mass $M_{DM}$ [keV]

$10^{-13}$
$10^{-12}$
$10^{-11}$
$10^{-10}$
$10^{-9}$
$10^{-8}$
$10^{-7}$

DM overproduction
Excluded by X-ray observations

Not enough DM

Tremaine-Gunn / Lyman-α Excluded by X-ray observations

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Potential of KATRIN 1409.0920, see also 1404.5955
What’s the most promising experiment?  
... of course it depends on the mass scale... 

Some selected comments: 

- **neutrinoless double $\beta$-decay**
  - very sensitive, clear BSM signal  
  - but can be hidden if approx. B-L conserving scenarios

- **lepton flavour violation**
  - may be observable in approx. B-L conserving scenario

- **lepton universality**
  - may be observable in approx. B-L conserving scenario

- **direct searches**
  - EW/TeV scale: LHC, FCC-ee
  - GeV scale: SHiP, LHCb, BELLE II

Also important: absolute mass scale, hierarchy, Dirac-phase
Future collider searches

Plot from arXiv:1504.04855 [hep-ph]
Summary

- $\nu$-oscillations are the only BSM signal seen in the lab *definitely* require new BSM degrees of freedom!

- the new particles are RH neutrinos, they may be related to *cosmological puzzles* (Dark Matter, baryogenesis, Dark Radiation)

- if new particles are below the electroweak scale, they can be found experimentally $\Rightarrow$ experimental search for exciting New Physics!

- even if they are heavier, indirect probes involve
  - neutrino oscillation experiments
  - neutrinoless double $\beta$-decay
  - lepton flavour violation
  - lepton universality violation
  - unitarity of the observed CKM matrix

We are looking forward to exciting new data...
The $\nu$ MSM: heavy neutrinos solve all problems!

Asaka/Shaposhnikov

Boyarsky/Ruchayskiy/Iakubovskyi/Franse 1402.4119

Canetti/MaD/Frossard/Shaposhnikov 1204.3902, 1208.4607

DM, Baryogenesis and neutrino masses from RH neutrinos!
Where is the New Physics hiding?

Coupling

Energy Frontier

STANDARD MODEL

Heavy new states?
LHC, CEPC, FCC, ILC

Hidden Sector?
SHiP

Mass

Intensity Frontier
The SHiP Experiment

- intensity frontier experiment using CERN SPS beam
- fixed target experiment with strong shield
The SHiP Experiment

Search for Hidden Particles

- neutrino portal
- scalar portal
- vector portal
- axion-like particles
- $\nu_\tau$ physics
- LFV in $\tau$-decays
- very light neutralino?
- your proposal!

see arXiv:1504.04855 [hep-ph] for details

great opportunity at the intensity frontier - also for China