Heavy Neutrinos in Particle Physics and Cosmology

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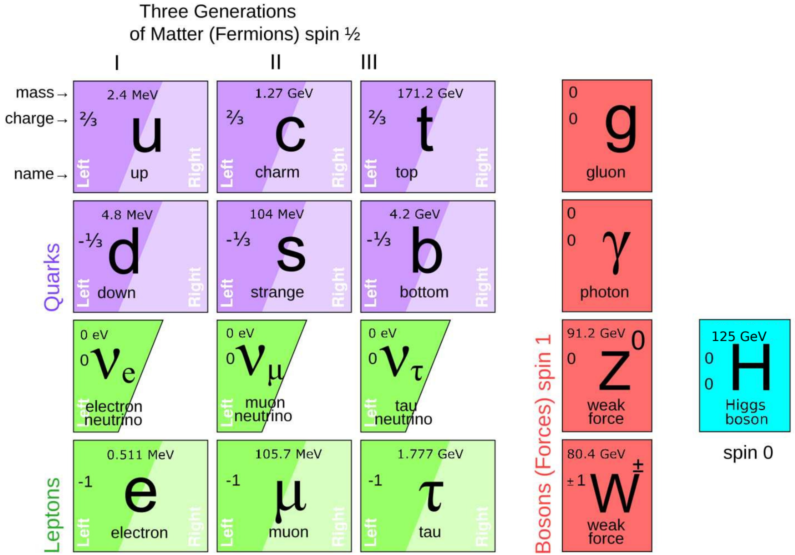
2013 review arXiv:1303.6912 [hep-ph]
update arXiv:1502.06891 [hep-ph]

23. 7. 2015
EPS-HEP meeting Vienna, Austria


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV ⅔ u up
1.27 GeV ⅔ c charm
171.2 GeV ⅔ t top
4.8 MeV -⅓ d down
104 MeV -⅓ s strange
4.2 GeV -⅓ b bottom
Quarks
0 eV 0 νe electron neutrino
0 eV 0 νμ muon neutrino
0 eV 0 ντ tau neutrino
0.511 MeV -1 e electron
105.7 MeV -1 μ muon
1.777 GeV -1 τ tau
Leptons
Left
Right
0 0 g gluon
0 0 γ photon
91.2 GeV 0 Z0 weak force
80.4 GeV ±1 W± weak force
Bosons (Forces) spin 1
125 GeV 0 0 H Higgs boson
spin 0

Neutrino masses: Seesaw mechanism

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

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

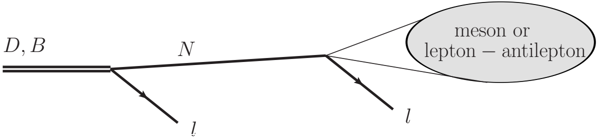
$$\Rightarrow \frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c}) \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

two sets of Majorana mass states with mixing $\theta = m_D M_M^{-1} = vFM_M^{-1}$

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

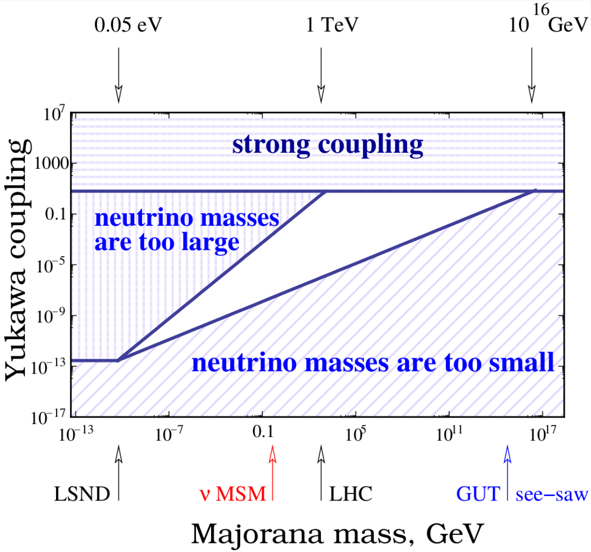
- **Indirect searches**
  - neutrino oscillation data
  - LFV in rare lepton decays
  - violation of lepton universality,
  - (apparent) violation of CKM unitarity
  - neutrinoless double β-decay
  - EW precision data
- **Direct searches**
  - LNV and LFV in gauge boson or meson decays



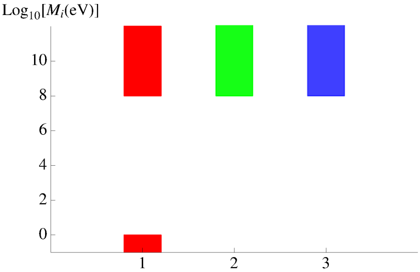
  - displaced vertices
  - peak searches, missing 4-momentum
- **Cosmology**: BBN and N_{eff}

ν-oscillation data and the seesaw scale

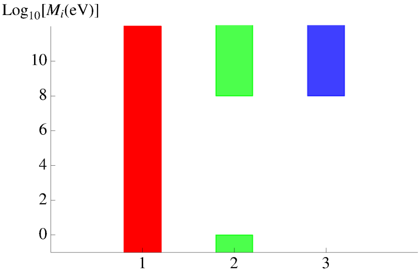
plot from 1204.5379



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



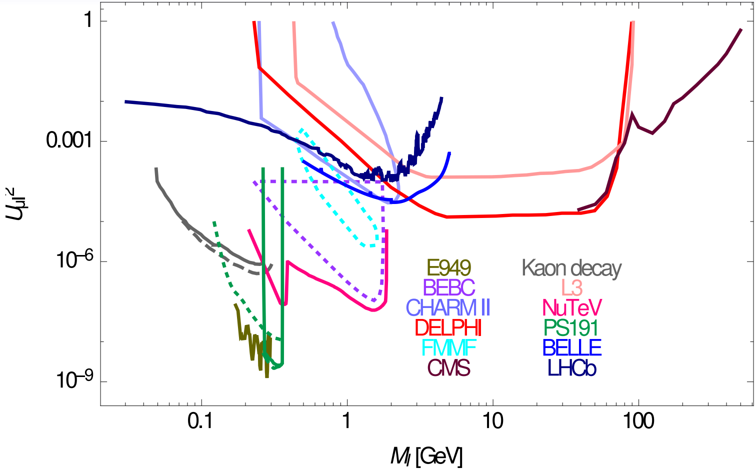
$m_{\rm lightest} > 10^{-3} eV$



$m_{\rm lightest} < 10^{-3} eV$

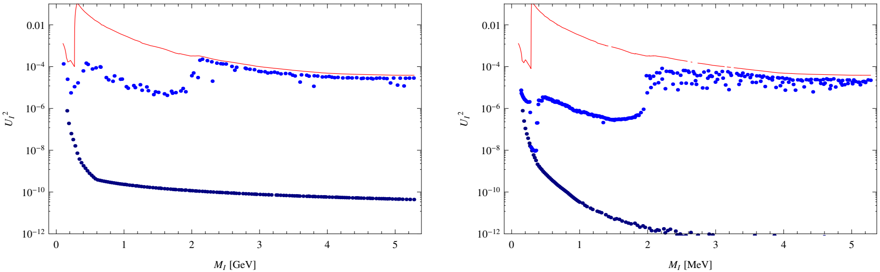
from Hernandez/Kevic/Lopez-Pavon 1406.2961

Bounds from Colliders



plot from MaD/Garbrecht 1502.00477

Combining direct and indirect constraints



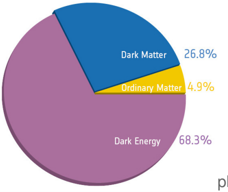
$m_{\text{lightest}} = 0.23\text{eV}$ $\qquad$ $m_{\text{lightest}} = 0\text{eV}$

plot from MaD/Garbrecht 1502.00477

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 θ 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 $N_{\rm eff}$ in the early univsere.

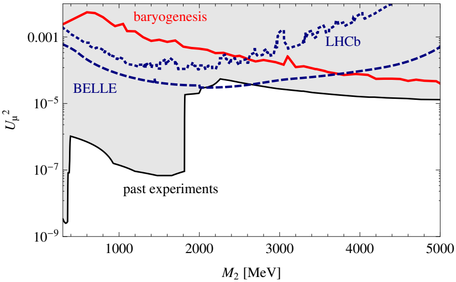


planck.cf.ac.uk

- **GUT seesaw**
  - naturally fits into GUTs
  - naturally gives neutrino masses
  - naturally does leptogenesis
  - not observable
  - adds to hierarchy problem
- **electroweak or TeV seesaw**
  - common origin with EW scale?
  - gives neutrinos masses
  - allows for leptogenesis
  - accessible to LHC
  - requires some "tuning" or an approximate *L*-conservation
  - not "natural"
- **GeV seesaw**
  - gives neutrino masses
  - does leptogenesis
  - accessible to LHC, BELLE, SHiP
  - part of minimal νMSM
  - requires some "tuning" or an approximate *L*-conservation
  - not "natural"
  - origin of this scale?
- **keV seesaw**
  - viable DM candidate
  - cannot give neutrino masses & be DM at the same time
  - origin of this scale & mixing?
- **eV seesaw**
  - LSND, gallium, reactor anomaly
  - "Dark Radiation" $N_{\rm eff}$
  - cannot explain neutrino masse anomalies at the same time
  - origin of this scale & mixing?

Low scale leptogenesis

- baryon asymmetry can be produced in the early universe
  - during N_I decay Fukugita/Yanagida 1986, Pilaftsis 2004
  - during N_I production Akhmedov/Rubakov/Smirnov 1998, Asaka/Shaposhnikov 2005
- 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:
http://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=3446

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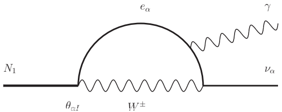
  - radiative decay $N \to \nu_L \gamma$
  - Search for X-ray line!



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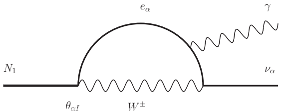
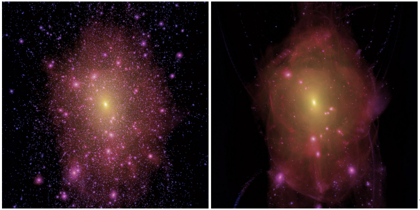


- How were they produced?
- Are they consistent with structure formation?
  - DM is absolutely essential to form structures in the universe
  - DM is "cold" , i.e. $\langle \mathbf{k} \rangle < M$ at freezeout



1104.2929

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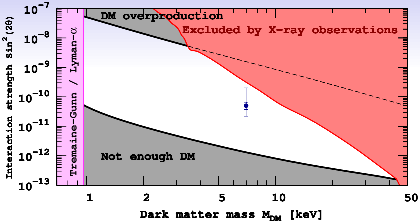
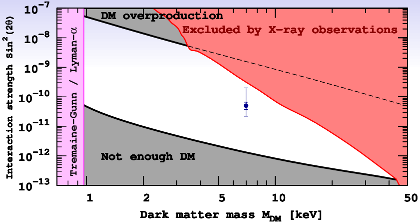
astro/cosmology status early 2014 plot from 1402.4119, see also 1402.2301



Now: very active discussion 1405.7943,1408.1699,1408.3531,1408.4388 and many more

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



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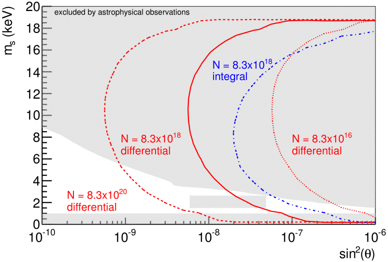
Potential of KATRIN 1409.0920, see also 1404.5955



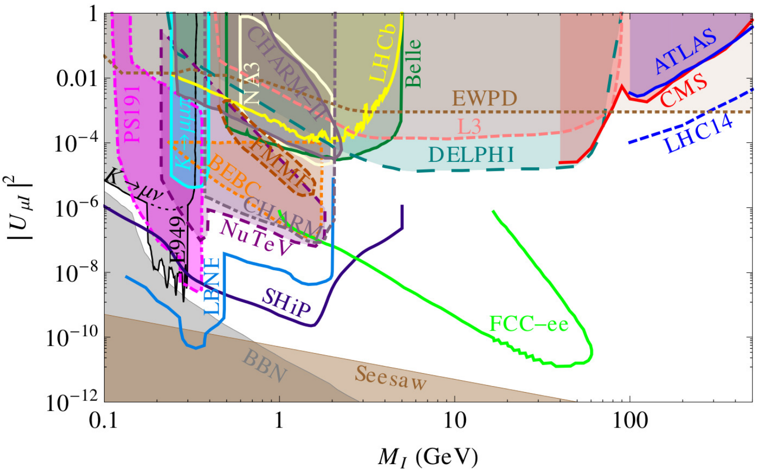
What's the most promising experiment?
. . . of course it depends on the mass scale. . .

Some selected comments:

- neutrinoless double β-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



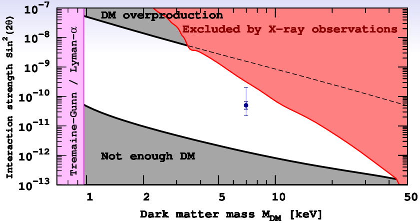
Plot from arXiv:1504.04855 [hep-ph]

Summary

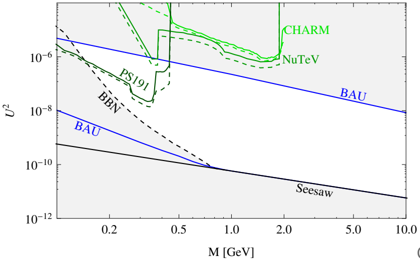
- ν-oscillations are the only BSM signal seen in the lab **definitely** require new BSM degrees of freedom!
- the new particles are RH neutrinos, they may be related to cosmological puzzles (Dark Matter, baryogenesis, Dark Radiation)
- if new particles are below the electroweak scale, they can be found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

We are looking forward to exciting new data. . .

The νMSM: heavy neutrinos solve all problems! Asaka/Shaposhnikov



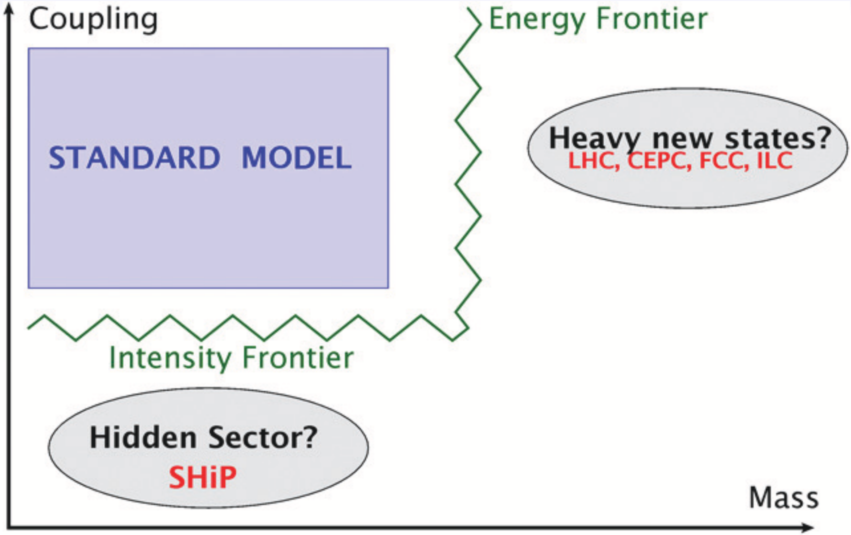
Boyarsky/Ruchayskiy/Iakubovskyi/Franse 1402.4119



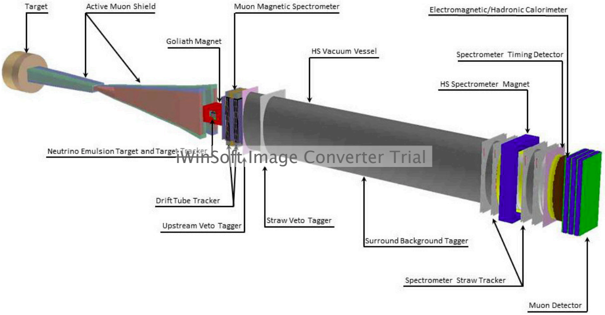
Canetti/MaD/Frossard/Shaposhnikov 1204.3902, 1208.4607

DM, Baryogenesis and neutrino masses from RH neutrinos!

Where is the New Physics hiding?



The SHiP Experiment



- intensity frontier experiment using CERN SPS beam
- fixed target experiment with strong shield
- technical report arXiv:1504.04956 [physics.ins-det]

The SHiP Experiment

Search for **Hi**dden **P**articles

- neutrino portal
- scalar portal
- vector portal
- axion-like particles
- ν_τ physics
- LFV in τ-decays
- very light neutralino?
- your proposal!

see arXiv:1504.04855 [hep-ph] for details

great opportunity at the intensity frontier - also for China