HEAVY NEUTRINOS IN PARTICLE PHYSICS AND COSMOLOGY

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March 16th 2016
UZH, Zürich, Switzerland

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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  - baryon asymmetry of the universe - leptogenesis?
  - dark matter - sterile neutrinos?
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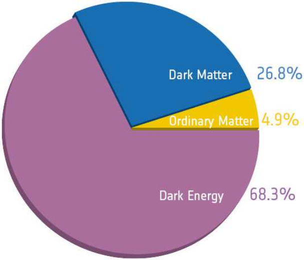
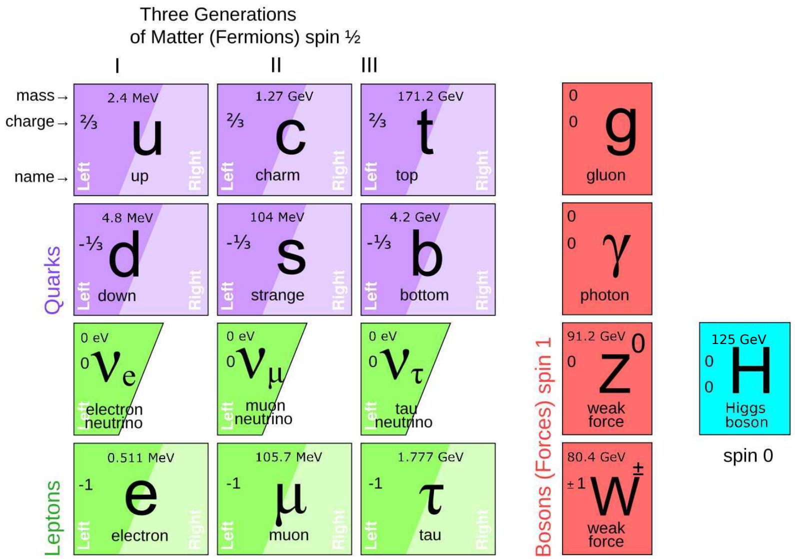
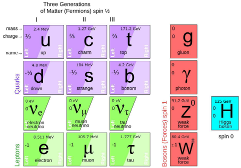


planck.cf.ac.uk


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
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
Left
Right
Quarks
Leptons
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

My Proposal

- **Assumption I**: seesaw mechanism generates neutrino masses



- **Assumption II**: The scale of the new physics is within reach or around the corner (TeV scale or below)

What are the implications for particle physics?
What happens in the early universe?
Can we solve cosmological puzzles (BAU, DM)?

$\Rightarrow$ Complete understanding of the low scale seesaw parameter space and implications

Neutrino masses: Seesaw mechanism

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

Minkowski 1979, Gell-Mann/Ramond/Slansky 1979, Mohapatra/Senjanovic 1979, Yanagida 1980, Schechter/Valle 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 $\theta = m_D M_M^{-1} = vFM_M^{-1}$

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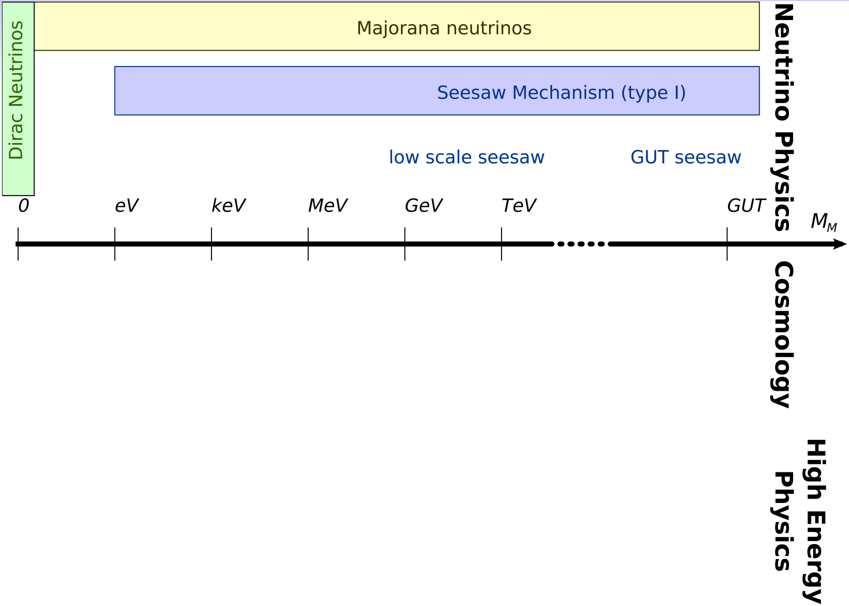
- three light neutrinos $\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
  - mostly "active" SU(2) doublet
  - light masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$
- three heavy neutrinos $N \simeq \nu_R + \theta^T \nu_L^c$
  - mostly "sterile" singlets
  - heavy masses $\boldsymbol{M_N \simeq M_M}$
- Majorana masses M_M introduce new mass scale(s)
- new heavy states only interact via small mixing $U_{\alpha I}^2 \equiv |\theta_{\alpha I}|^2 \ll 1$


Dirac Neutrinos
Majorana neutrinos
Seesaw Mechanism (type I)
low scale seesaw
GUT seesaw
0
eV
keV
MeV
GeV
TeV
GUT
M_M
Neutrino Physics
Cosmology
High Energy Physics

Where to see the N_I?

review: MaD arXiv:1303.6912 [hep-ph]

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

- **Direct searches** see e.g. Antusch/Fischer 1502.05915, Deppisch/Dev/Pilaftsis 1502.06541

- **Cosmology**: BBN and $N_{\rm eff}$ see e.g. Hernandz/Kekic/Lopez-Pavon 1406.2961
- **Astro**: X-ray, SN, pulsars, structure formation review 1602.04816

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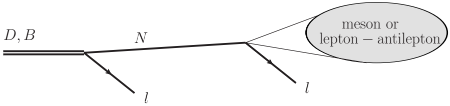
  - LNV and LFV in gauge boson or meson decays



  - displaced vertices, SHiP
  - peak searches, missing 4-momentum
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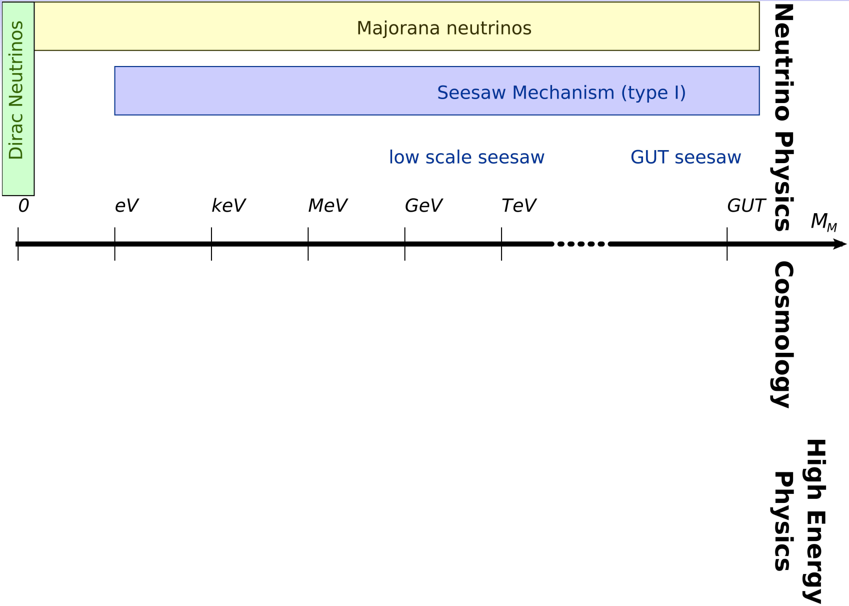
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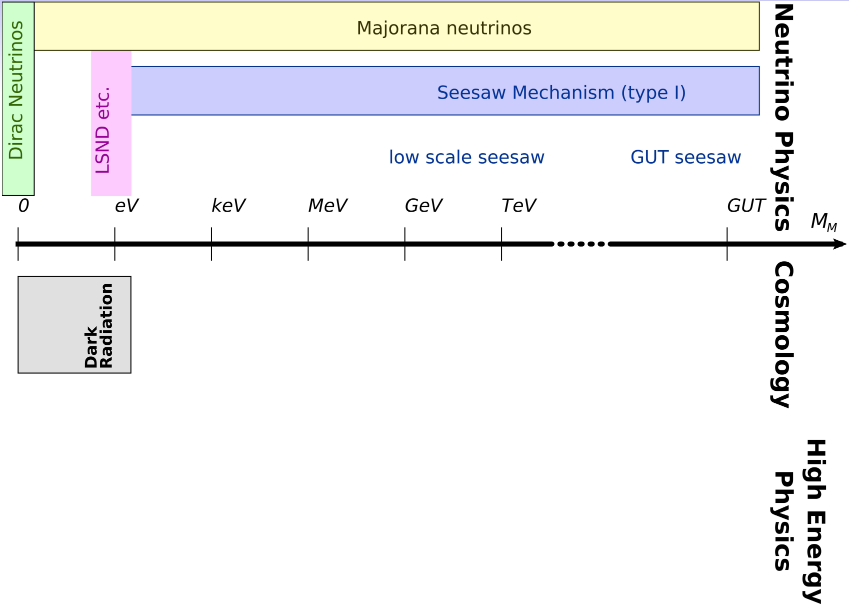
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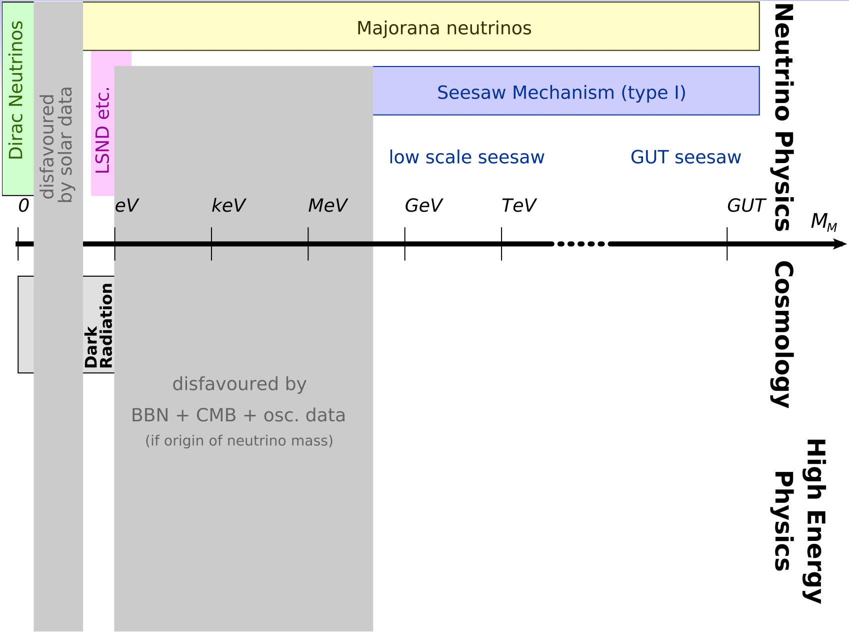
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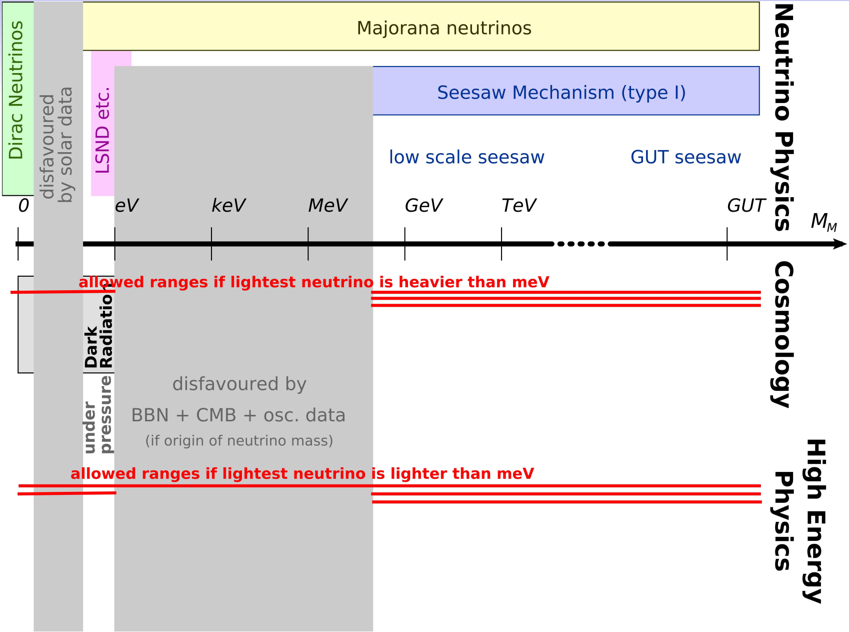

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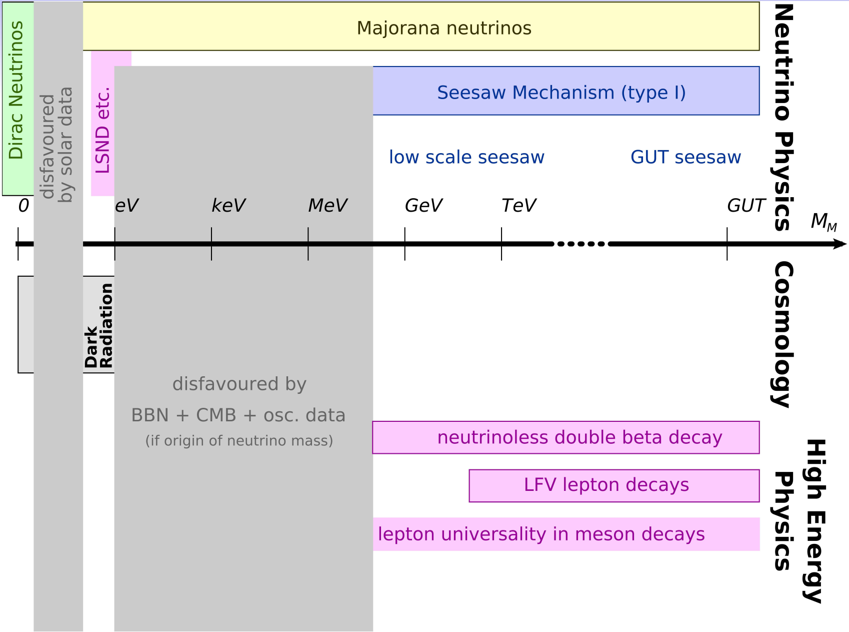
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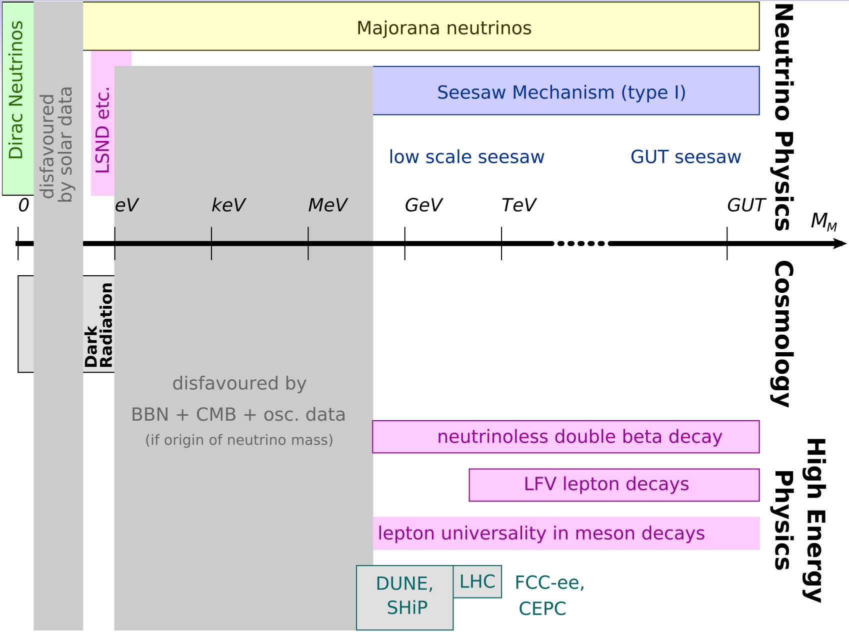
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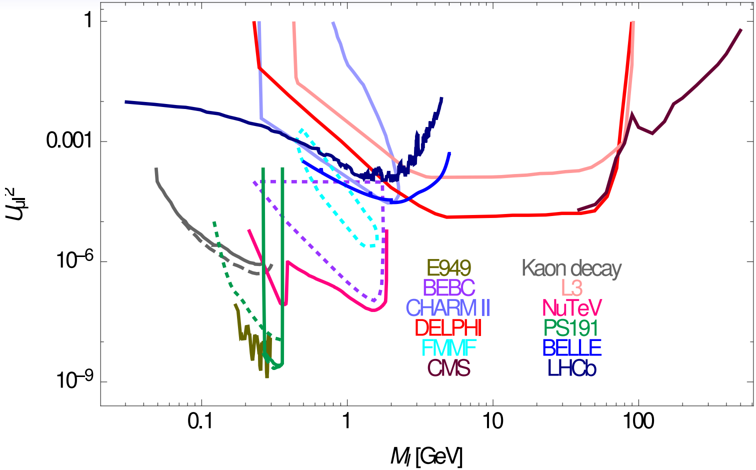
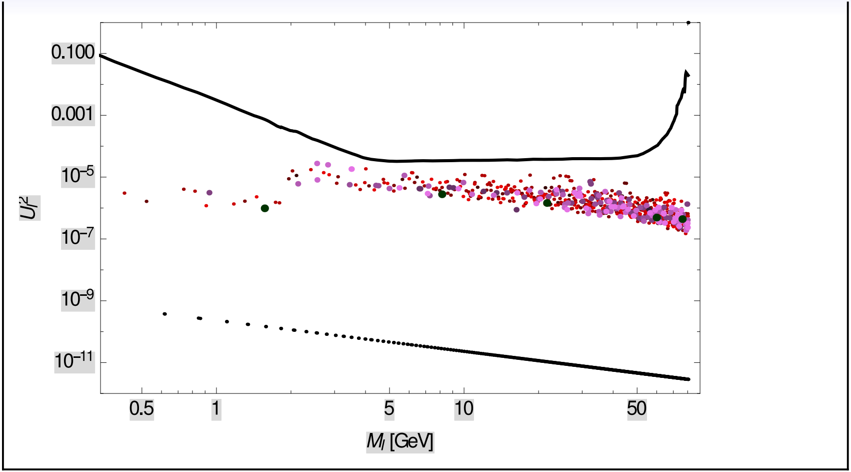
Bounds from Colliders



plot from MaD/Garbrecht 1502.00477

Combining direct and indirect bounds



to be updated in MaD/Garbrecht arXiv:1502.00477 [hep-ph]

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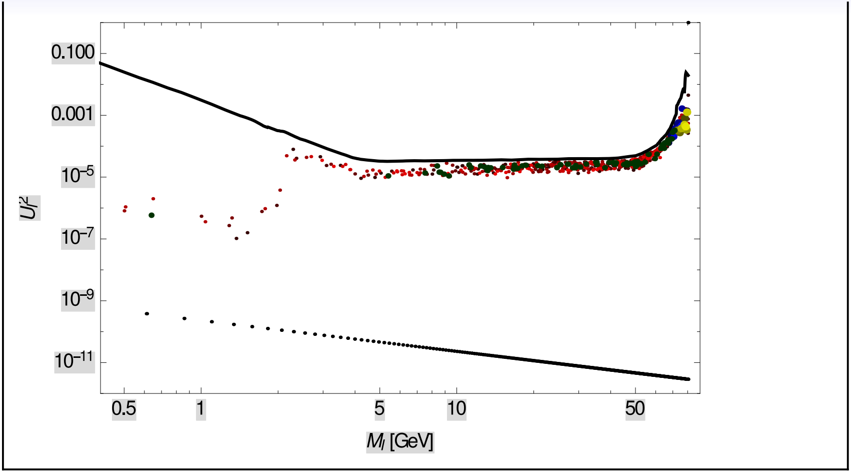

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Leptogenesis: Sakharov conditions

- baryon number violation
  - sphalerons violate B, but conserve $B-L$ at $T > 140$ GeV
  - Yukawa couplings F violate individual lepton flavour numbers
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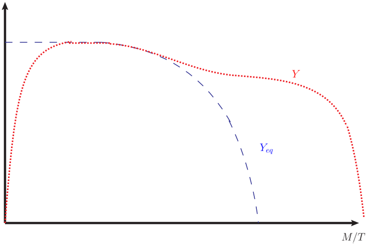
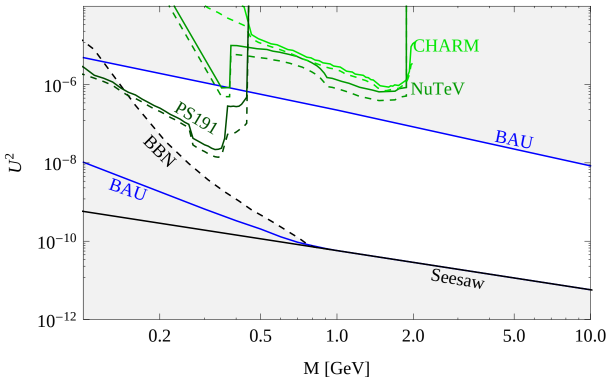
- C and CP violation
  - weak interaction violates P
  - additional complex phases in F violate CP
- nonequilibrium
  - N_I production ("freeze-in mechanism")
    Akhmedov/Rubakov/Smirnov
  - N_I decay ("freeze-out mechanism")
    Fukugita/Yanagida



Leptogenesis with 2 GeV scale RH neutrinos



Plot: Canetto/MaD/Frossard/Shaposhnikov 1208.4607

Requires mass degeneracy and small mixing
CP-violation in sterile sector may be measurable!

Cvetic/Kim/Zamora-Saa 1403.2555

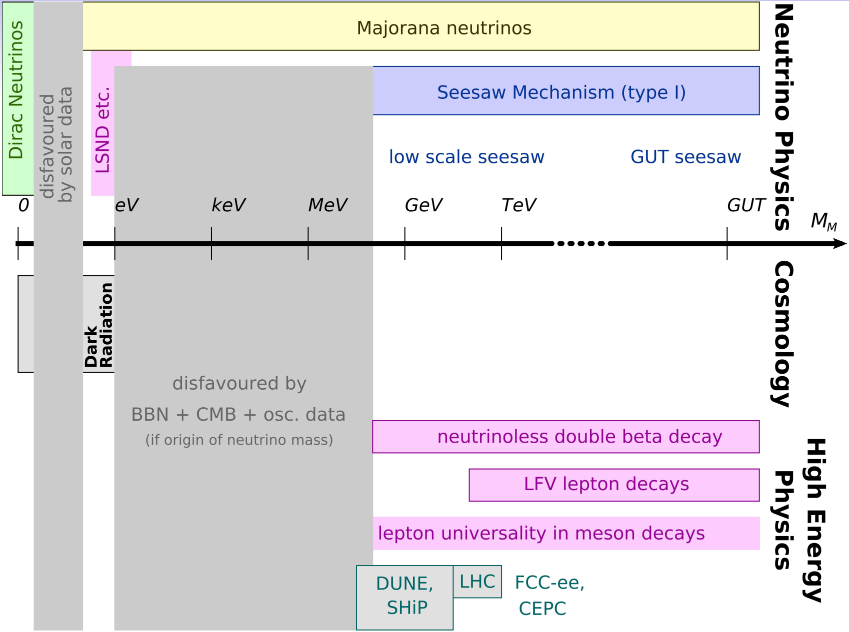
Two heavy neutrinos are the minimal scenario (if $m_{\mathrm{lightest}} = 0$).
What can a third one do for you?

Either Asaka/Shaposhnikov 2005

- a Dark Matter candidate Dodelson/Widrow 1994, Shi/Fuller 1999

or

- a non-zero absolute mass scale and
- low scale leptogenesis without mass degeneracy MaD/Garbrecht 1206.5537
- low scale leptogenesis with large mixings
  $\Rightarrow$ search at LHCb / Belle II can be possible! Canetti/MaD/Garbrecht 1404.7114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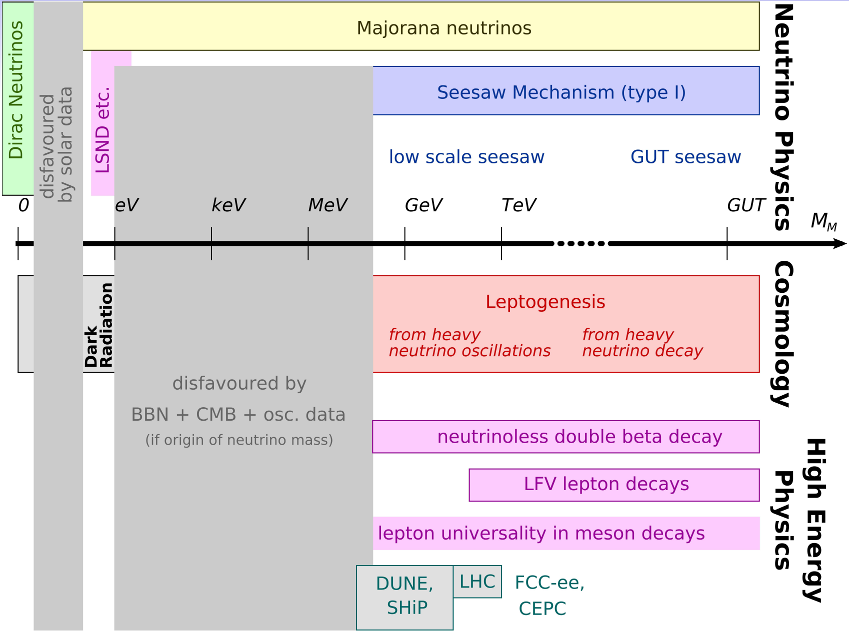

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Sterile neutrino Dark Matter

Sterile neutrinos are

- neutral
- collisionless
- massive
- potentially long lived

$\Rightarrow$ Obvious DM candidates

- Where is the decay line? Very active discussion of 3.5 keV excess...

- How were they produced?
- Are they consistent with structure formation?

White Paper: 1602.04816

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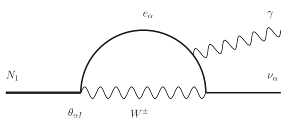
  - radiative decay $N \to \nu\gamma$
  - Search for X-ray line!



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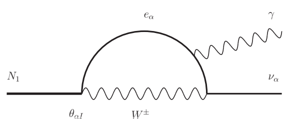
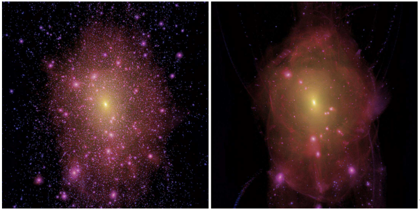


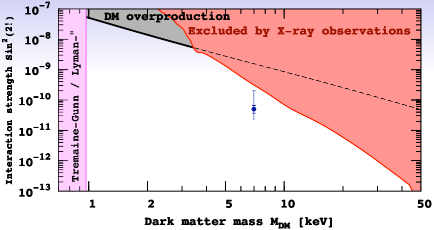
- How were they produced?
- Are they consistent with structure formation?
  - DM is absolutely essential to form structures in the universe
  - free streaming affects small scale structures



1104.2929

White Paper: 1602.04816

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



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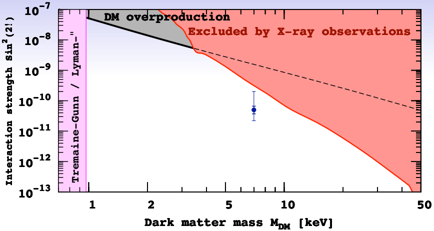

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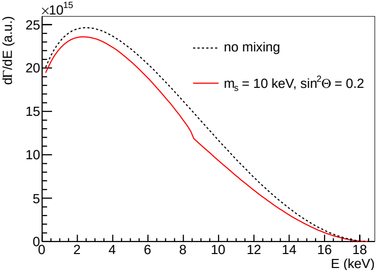
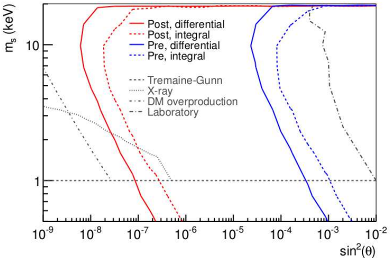
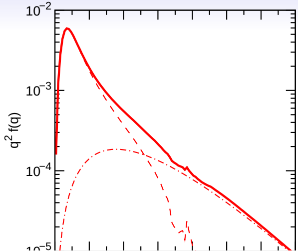
Potential of KATRIN 1409.0920, see also 1404.5955

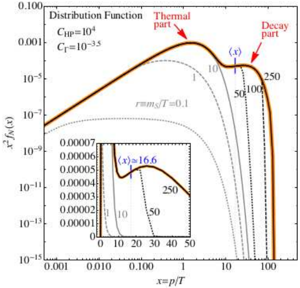


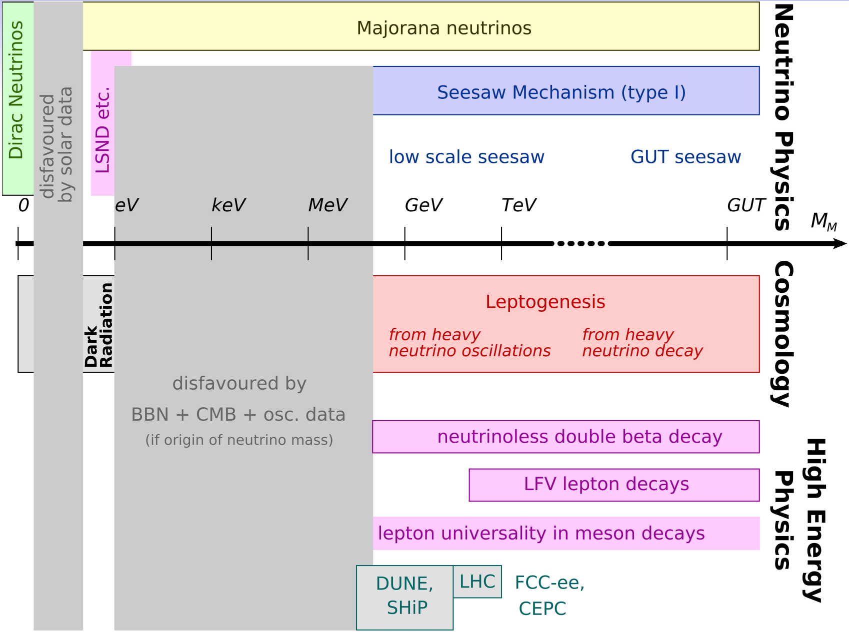


- **DM production via mixing**
  - efficient at $T \sim 100$ MeV
    $\Rightarrow$ hadronic corrections near QCD crossover
  - affected by MSW effect
    $\Rightarrow$ resonant production Shi/Fuller
  - recent updates: Ghiglieri/Laine 1506.06752, Venumadhav/Cyr-Racine/Abazajian/Hirata 1507.06655



- **DM production in decays**
  - spectrum tends to be colder Merle/Schneider 1409.6311, Merle/Totzauer 1502.01011
  - thermal corrections can affect spectrum MaD/Kang 1510.05646





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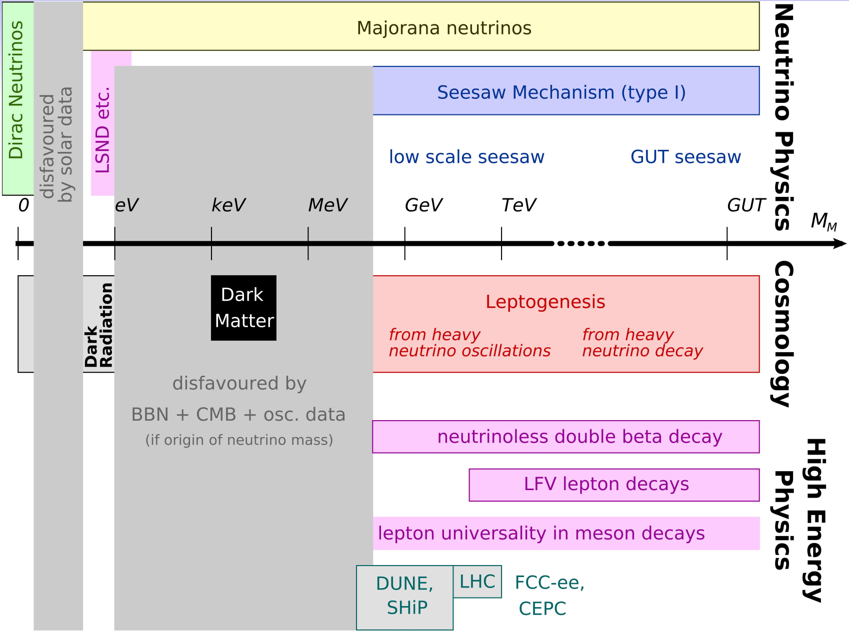
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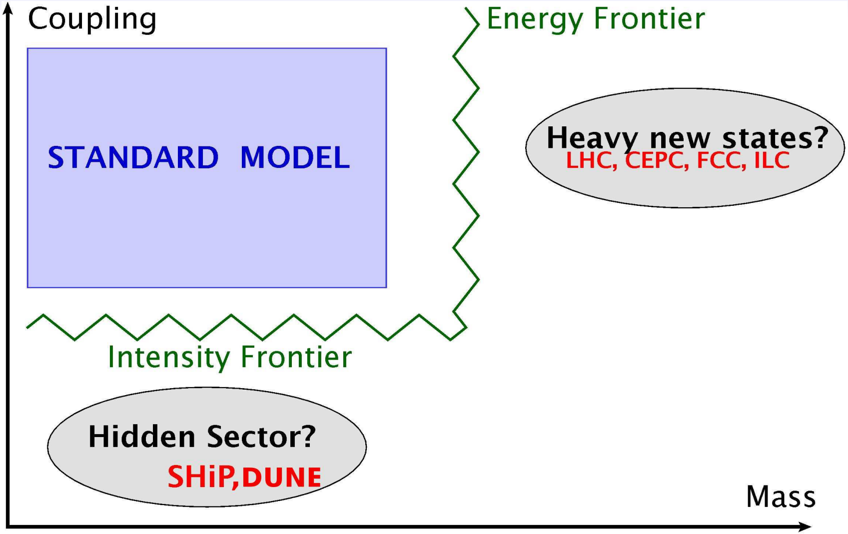
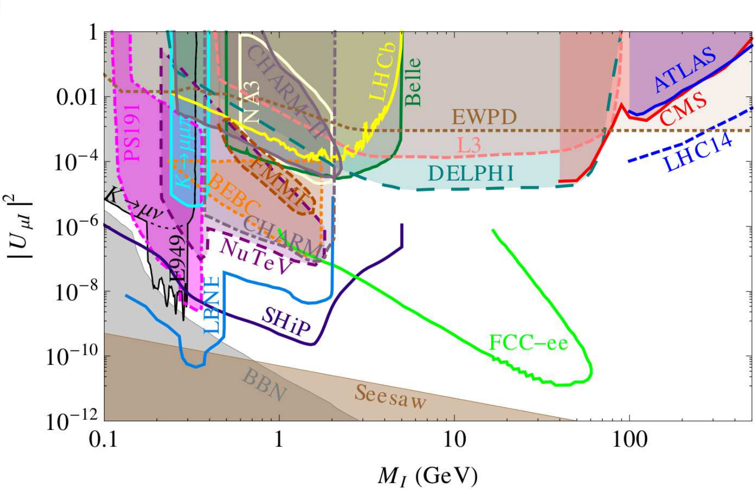
Open questions - my proposal

- **Experiments**
  - consistently combine constraints from all past experiments (rather than just superimpose)
  - systematically identify promising signals at future experiments
- **Cosmology**
  - derive suitable transport equations from nonequilibrium QFT and calculate coefficients in all regimes
  - study the viable parameter space in the entire experimentally accessible mass range
  - study both leptogenesis mechanisms (freeze-in and freeze-out)
  - in particular: study behaviour near EW transition
  - consider possible extensions of the minimal model (in particular in the scalar sector)
- **possible spin-offs**
  - improved understanding of nonequilibrium quantum systems
  - improving sterile neutrino DM production calculations
  - transport in other testable baryogenesis scenarios

Where is the New Physics hiding?



Future collider searches



Plot from arXiv:1504.04855 [hep-ph]

Neutrino Experiments

- **CP-violation**
  - CP-violation in PMNS matrix U_ν can drive low scale leptogenesis
  - Dirac-phase may be measured (NOvA, DUNE)
- **absolute neutrino mass scale**
  - if non-zero: at least three N_I needed in seesaw
  - crucial for heavy neutrino properties (minimal mixing, mass range)
  - affects leptogenesis parameter space
  - constraints from cosmology and KATRIN
- **hierarchy of light masses**
  - directly constraints heavy neutrino properties
  - can be measured (NOvA, DUNE, JUNO)
- **light sterile neutrino** searches (MicroBooNE, DUNE, etc.)

Other Indirect Searches

- **neutrinoless double β-decay**
  - can confirm Majorana nature, as predicted by seesaw
  - MAJORANA DEMONSTRATOR can access relevant L-violation in low scale leptogenesis work in progress
- **lepton flavour violation**
  - $\mu \to e\gamma$ can be observable if $M_I \gtrsim m_W$
  - contains information about active-sterile mixing
  - in the future also $\mu - e$ conversion in nuclei (Mu2e, COMET)
- **lepton universality**
  - contains information about active-sterile mixing for wide range of M_I
  - NA62 can reach leptogenesis parameter space
- **astrophysics**
  - if DM: X-ray (Astro-H), structure formation
  - super novae (SNO, DUNE)

Propagation in a dense medium

Need accurate early universe calculations to relate to new data

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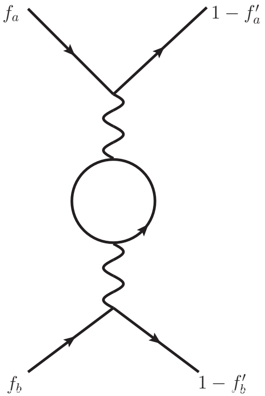
Some issues

- no asymptotic states
- quantum coherences
- quasiparticle dispersion relations
- quantum statistics for virtual particles
- resummation, IR ad collinear issues
- avoid double-counting



$\Rightarrow$ Systematic approach:
Closed Time Path Formalism, thermal field theory

A Ladder of Controlled Approximations

Nonequilibrium n-PI Effective Action Calzetta/Hu

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Anisimov Beneke, Buchmuller, Cirigliano, Dev, MaD, Fuller, Garbrecht, Garny, Hohenegger, Kartavtsev, Konstandin, Lee, Mendizabal, Millington, Pilaftsis, Prokopec, Raffelt, Ramsey-Musolf, Schmidt, Sigl, Teresi, Tulin, Vlasenko, Weinstock etc.

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$\Downarrow$ momentum averaging

Rate Equations for number densities

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Applications

- resonant and flavoured leptogenesis
- low scale leptogenesis
- sterile neutrino Dark Matter production
- neutrinos in the early universe
- neutrino transport in super novae
- transport in electroweak baryogenesis
- the very early universe

Summary

- Additional neutrino states can explain
    - neutrino masses (seesaw)
    - Dark Matter
    - Baryon Asymmetry of the Universe
    - oscillation anomalies, Dark Radiation

  $\Rightarrow$ Implications for **particle physics, cosmology, astrophysics**!
- Many **upcoming experiments** and observations may find heavy neutrinos (or traces of them)
  $\Rightarrow$ strongly motivates **accurate theoretical predictions**
    - for experimental signatures
    - in the early universe
    - in astrophysical environments / super novae
- The **computational methods** used to address these problems can be applied to describe many important transport phenomena.