How many new particles do we need after the Higgs boson?

Marco Drewes
TU München

12. 7. 2016
Werner Heisenberg Institut, Munich

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

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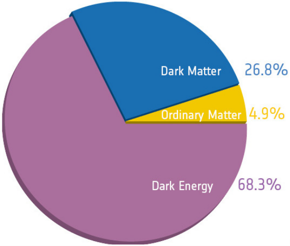
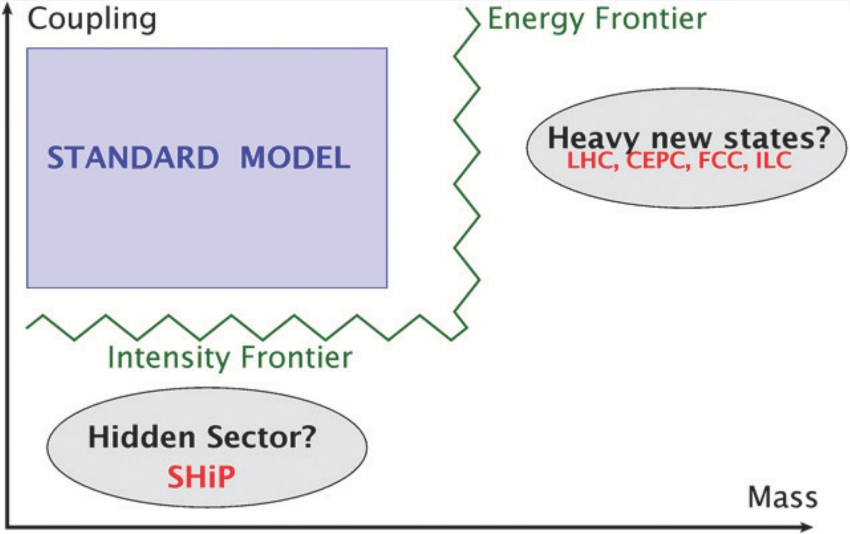
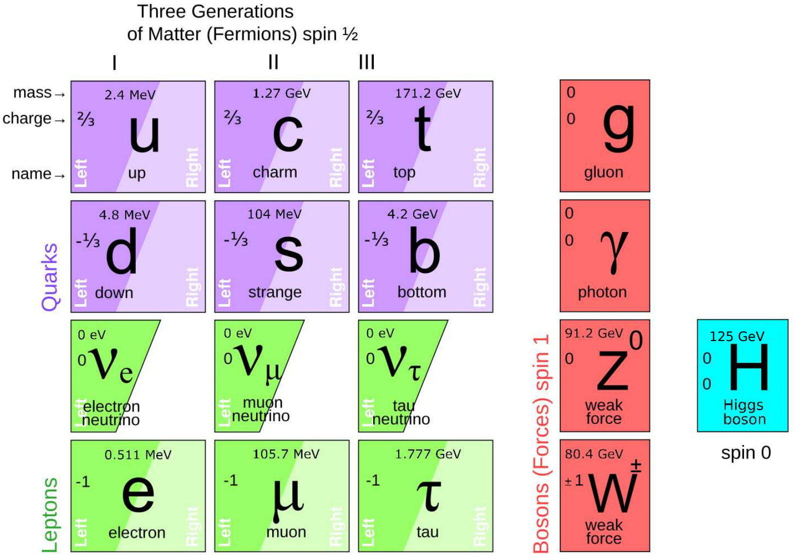
  - neutrino oscillations - the only signal found in the lab!
  - baryon asymmetry of the universe - leptogenesis?
  - dark matter - sterile neutrinos?
  - accelerated cosmic expansion
    (Higgs inflation + Cosmological Constant?)



planck.cf.ac.uk

Where is the New Physics hiding?




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
0
Z
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

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

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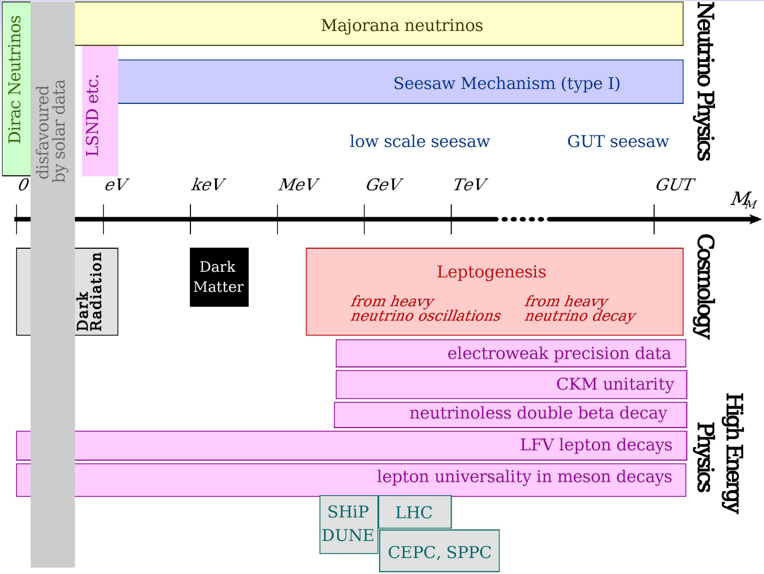
- three light neutrinos $\mathrm{v} \simeq U_\nu(\nu_L + \theta\nu_R^c)$
  - mostly "active" SU(2) doublet
  - light masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$
- three heavy neutrinos $N \simeq \nu_R + \theta^T \nu_L^c$
  - mostly "sterile" singlets
  - heavy masses $\boldsymbol{M_N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


Dirac Neutrinos
disfavoured
by solar data
Majorana neutrinos
LSND etc.
Seesaw Mechanism (type I)
low scale seesaw
GUT seesaw
Neutrino Physics
0
eV
keV
MeV
GeV
TeV
GUT
M_M
Dark
Radiation
Dark
Matter
Leptogenesis
from heavy
neutrino oscillations
from heavy
neutrino decay
Cosmology
electroweak precision data
CKM unitarity
neutrinoless double beta decay
LFV lepton decays
lepton universality in meson decays
High Energy
Physics
SHiP
DUNE
LHC
CEPC, SPPC

Where to see the N_I? see e.g. MaD arXiv:1303.6912 [hep-ph]

- **Indirect searches** see e.g. MaD/Garbrecht 1502.00477
- **Direct searches** see e.g. Antusch/Fischer 1502.05915
- **Cosmology**: BBN and $N_{\rm eff}$ see e.g. Hernandez/Kekic/Lopez-Pavon 1406.2961
- **Astrophysics**: X-ray, SN, pulsars, structure formation review 1602.04816

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  - neutrino oscillation data
  - 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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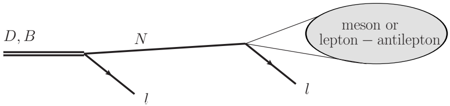
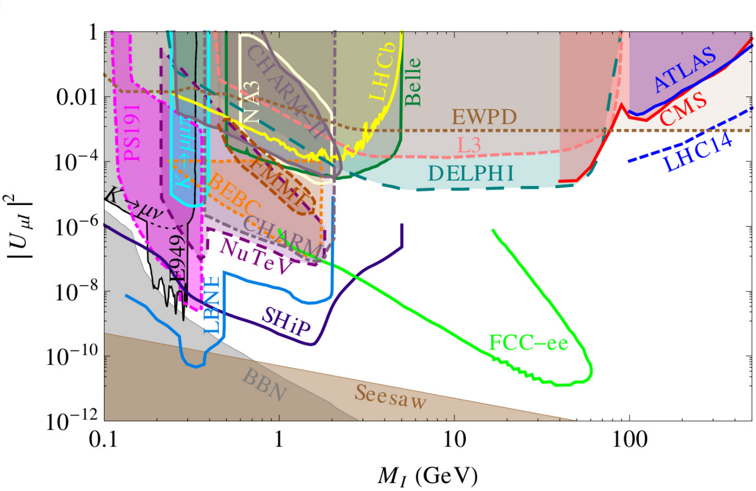
- **Direct searches** see e.g. Antusch/Fischer 1502.05915
  - LNV and LFV in gauge boson or meson decays



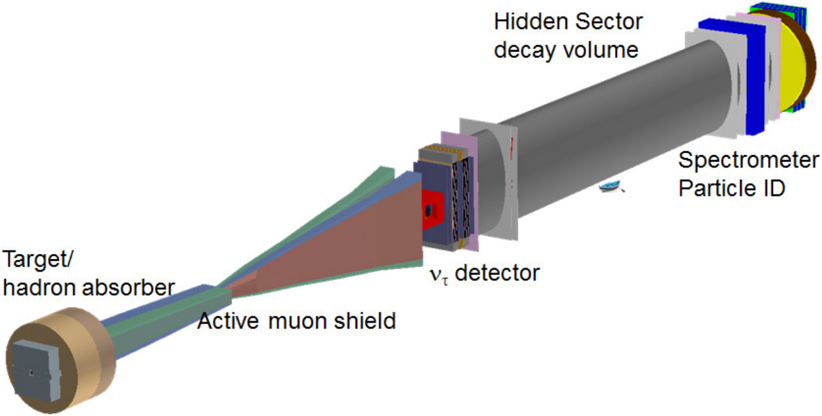
  - displaced vertices, SHiP
  - peak searches, missing 4-momentum
- **Cosmology**: BBN and N_{eff} see e.g. Hernandez/Kekic/Lopez-Pavon 1406.2961
- **Astrophysics**: X-ray, SN, pulsars, structure formation review 1602.04816

Bounds from colliders



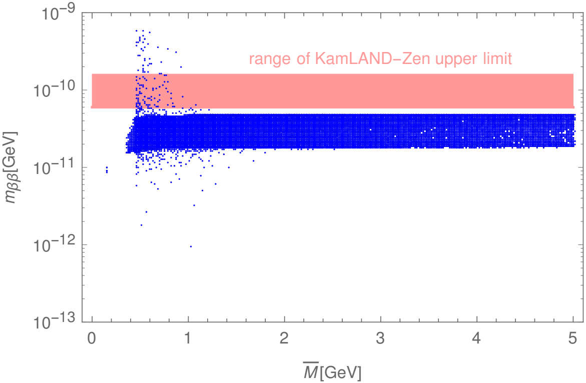
Plot from arXiv:1504.04855 [hep-ph]

The SHiP experiment



arXiv:1504.04956 [physics.ins-det]

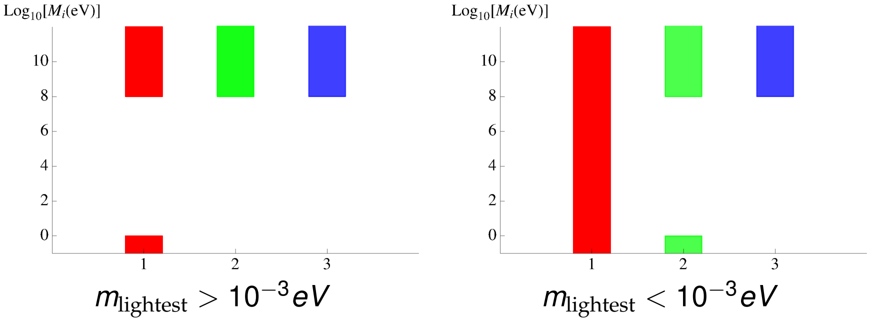
Neutrinoless Double β Decay and Leptogenesis



plot from MaD/Eijima 1606.06221

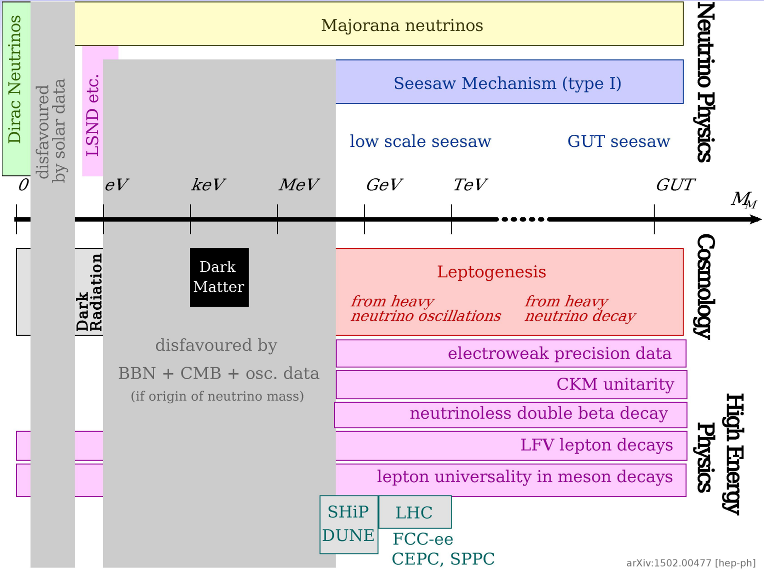
see also Lopez-Lavon/Pascoli/Wong 1209.5342, Lopez-Pavon/Molinaro/Pectov 1506.05296

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



from Hernandez/Kevic/Lopez-Pavon 1406.2961

Minimal seesaw model:
If one RH neutrino is DM, then $m_{\rm lightest} < 10^{-3}$ eV!



MaD/Garbrecht 1502.00477

So far we only asked the N_I to explain neutrino masses. . .

Given all these bounds, can they simultaneously explain the observed DM and the baryon asymmetry of the Universe (BAU)?

And which additional constraints would that imply?

$\Rightarrow$ The Neutrino Minimal Standard Model (νMSM) Asaka/Shaposhnikov 2005

Seesaw Partners N_2 and N_3

- have quasi-degenerate GeV masses $M_{2,3} = M \pm \delta M$
- couple strongly enough to be produced thermally in the early universe
- have decayed before BBN
- can be seen at colliders
- are responsible for lepton/baryon asymmetries
- generate active neutrino masses via seesaw mechanism

Dark Matter candidate N_1

- has a keV mass M_1
- never reach thermal equilibrium in the early universe due to small coupling
- are present today as dark matter
- cannot be seen in colliders, but in X-ray observatories (DM decays)
- require a resonant production mechanism to be DM
- effect on neutrino masses negligible

Leptogenesis: Sakharov conditions

- baryon number violation
- C and CP violation
- nonequilibrium

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  - 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 unsufficient, no EW phase transition

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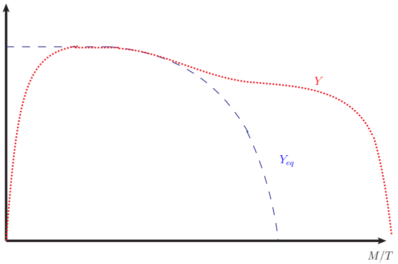
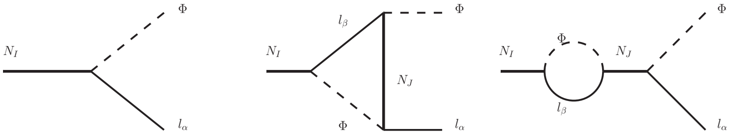
  - N_I production ("freeze in leptogenesis") Akhmedov/Rubakov/Smirnov
  - N_I freezeout and decay ("freeze out leptogenesis") Fukugita/Yanagida



Vanilla Leptogenesis (freeze out)

If N_I are superheavy $M_I \gg$ TeV, then

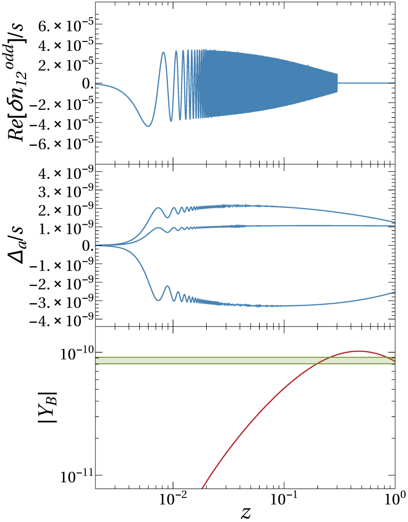
- N_I are produced thermally very early at $T > M_I$
- freeze out and decay at $T \lesssim M_I$
- CP-violating decay produces $L \neq 0$



- $L \neq 0$ is partly transferred into $B \neq 0$ by sphalerons
- requires $M_I > 10^8$ GeV Davidson/Ibarra
  ...but may still be ruled out? Deppisch/Harz/Hirsch/Päs 1503.04825
- can work with $M_I \gtrsim$ TeV with mass degeneracy ("resonant leptogenesis") Pilaftsis/Underwood

Leptogenesis from N-oscillations (freeze-in)

Oscillating regime



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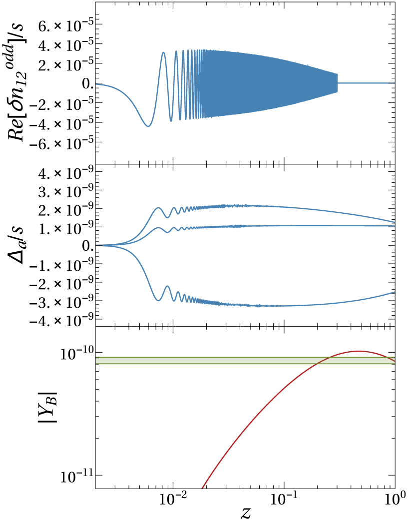
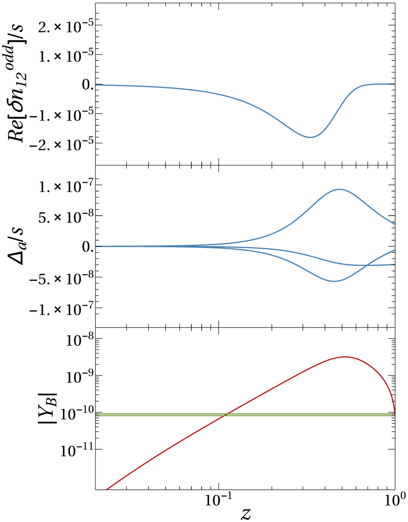
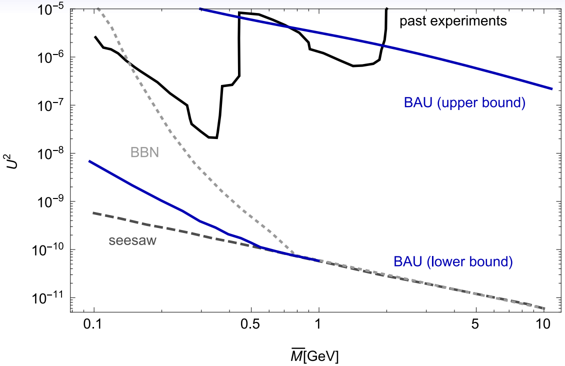


Overdamped regime



Leptogenesis with two heavy neutrinos



plot from MaD/Garbrecht/Gueter/Klaric 1606.06690

see also Canetti/MaD/Frossard/Shaposhnikov 1208.4607, Hernandez/Kekic/Lopez-Pavon/Salvado 1606.06719 and Abada/Arcadi/Domcke/Lucente 1507.06215

Requires mass degeneracy and small mixing. . .

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

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?

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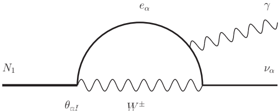
  - radiative decay $N \rightarrow \nu_L \gamma$
  - Search for X-ray line!



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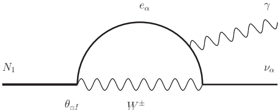
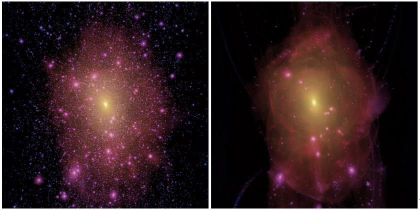


- How were they produced?
- Are they consistent with structure formation?
  - DM is absolutely essential to form structures in the universe
  - DM is "cold" , i.e. $\langle \mathbf{k} \rangle < M$ at freezeout


1104.2929

How to make sterile neutrino DM?

- **Thermal production via their mixing θ**
  - happens unavoidably for $\theta \neq 0$ Dodelson/Widrow
  - never reach equilibrium for realistic θ ("freeze in DM", "FIMP DM") $\Rightarrow$ non-thermal spectrum!
  - can be resonantly enhanced by MSW effect Shi/Fuller

  [This is realised in the νMSM]

- **Non-thermal production in the decay of heavy particles**
  - inflaton or other scalar
  - can occur when scalar is in equilibrium or during scalar production ("freeze in") Merle/Totzauer 1502.01011
  - scatterings can also contribute MaD/Kang 1510.05646

  [I will not talk about this. Alex really is the person to ask]

- **Thermal production via (gauge) interactions at high energies**

  [I won't talk about this]

Quantum mechanical picture

$$
\begin{aligned}
|\nu_\alpha\rangle &= \cos\theta_m(t)\,|\nu_1(t)\rangle + \sin\theta_m(t)\,|\nu_2(t)\rangle,\\
|\nu_s\rangle &= -\sin\theta_m(t)\,|\nu_1(t)\rangle + \cos\theta_m(t)\,|\nu_2(t)\rangle,
\end{aligned}
$$

Effective mixing leads to both, coherent oscillations and decoherent scatterings .

With $\Delta(p) = \Delta m^2/(2p)$ one finds:

$$
\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2},
$$

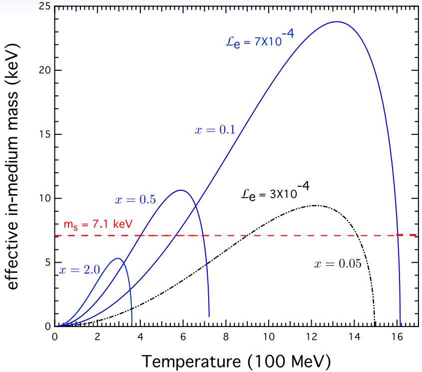
Heavy neutrino production rate $\Gamma_N \sim \theta_m^2 \Gamma_\nu$

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2},$$

$V_T \simeq -G_F^2\, p\, T^4$ suppresses Γ_N/T at large T
At low T, vacuum term dominates
$\Rightarrow$ maximum around $T \sim 0.1 - 1$ GeV Dodelson/Widrow

V_D can give MSW resonance at $\Delta m^2 \cos(2\theta) = 2p\,(V_D + V_T)$
$\Rightarrow$ enhanced DM abundance and complicated non-thermal spectrum! Shi/Fuller

Dispersion relation and MSW resonance

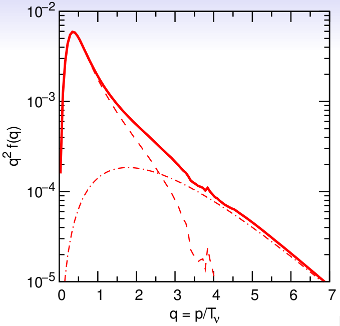


⇒ requires lepton asymmetries that are much larger than baryon asymmetry!

This can be achieved in the decay of heavier sterile neutrinos

Canetti/MaD/Frossard/Shaposhnikov 1208.4607

Schematically, the resulting spectrum looks like this:



plot from Boyarsky/Ruchayskiy/Shaposhnikov 2009

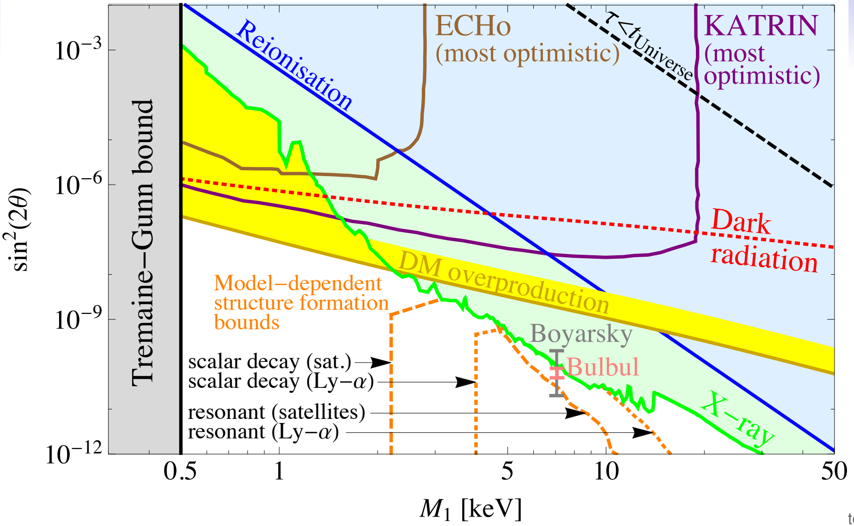
But it is rather complicated to get it quantitatively right:

- change of g_* during QCD crossover
- hadronic corrections to neutrino propagators
- back-reaction due to depletion of asymmetries

Two groups have recently made impressive progress

Venumadhav/Cyr-Racine/Abazajian/Hirata 1507.06655, Ghiglieri/Laine 1506.06752

- non-thermal spectra tend to be "colder"
- bounds on DM mass from structure formation usually assume a thermal spectrum or quote a bound on the "effective thermal mass", e.g. $M > 3.3$ keV Viel/Becker/Bolton/Haehnelt 1306.2314
- conversion of these into a bound on the physical DM-mass is non-trivial e.g. Schneider 1601.07553



to

appear in updated version of 1602.04816

How many new particles do we need after the Higgs boson?

Three.

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Three.

Frustra fit per plura
quod potest fieri per pauciora.

[It is futile to do with more things that which can be done with fewer]

William of Ockham, Summa Totius Logicae