Dark Matter, Baryogenesis and Neutrino oscillations from Right Handed neutrinos

Marco Drewes
TU München

based on
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JHEP 1303 (2013) 096 ,
Phys.Rev. D87 (2013) 093006
and work in progress

2013 review: **arXiv:1303.6912 [hep-ph] Int.J.Mod.Phys. E22 (2013) 1330019**

Rencontres de Moriond 2014, La Thuile

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

- gravity is not quantized
- a handful of observations remain unexplained
  - neutrino oscillations
  - baryon asymmetry of the universe
  - dark matter
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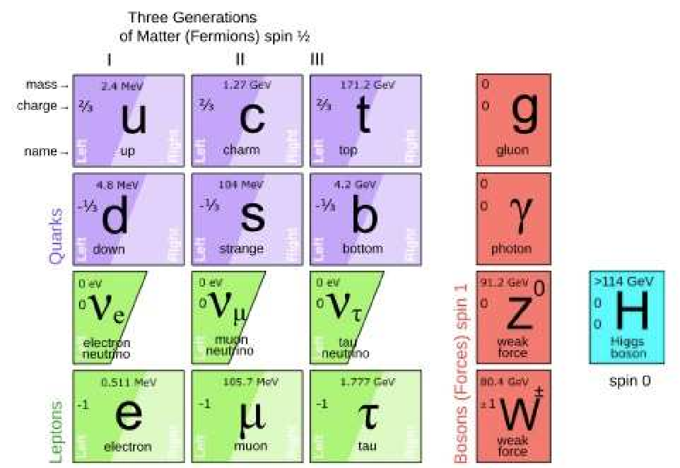
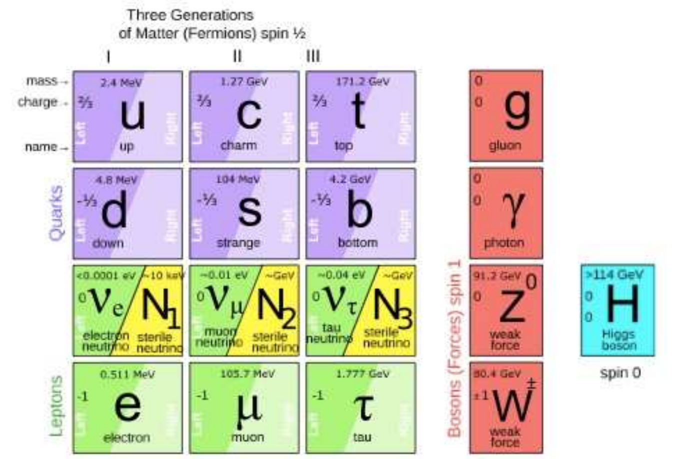
  - accelerated expansion of the universe (now and then)
- In addition there are esthetic issues (tuning/hierarchy, strong CP. . .) and some inconclusive observations ($g-2$, $N_{\rm eff}$,. . .).


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
ν_e
electron neutrino
0 eV
0
ν_μ
muon neutrino
0 eV
0
ν_τ
tau neutrino
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Quarks
Leptons
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
Z^0
weak force
80.4 GeV
±1
$W^\pm$
weak force
Bosons (Forces) spin 1
>114 GeV
0
0
H
Higgs boson
spin 0
Left
Right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N1
sterile neutrino
~0.01 eV
0
νμ
muon neutrino
~GeV
N2
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~0.04 eV
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ντ
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Neutrino minimal Standard Model (νMSM)

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

- Majorana masses M_M introduce new mass scale(s)
- six (Majorana) mass eigenstates
  - three light "active neutrinos" $\nu_i \simeq U_\nu(\nu_L + \theta\nu_R^c)_i$
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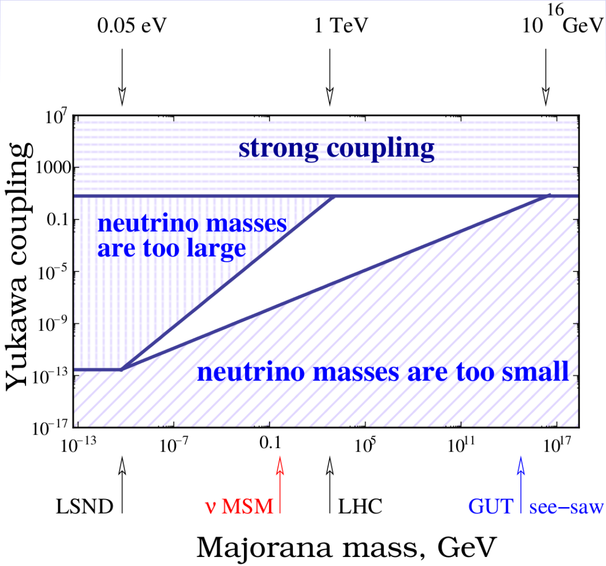
- mass of N_1 is in the keV range
  - decaying DM candidate
  - predicted properties match "observed" 3.5keV signal!
- masses of $N_{2,3}$ in the GeV range
  - generate neutrino masses via seesaw
  - do baryogenesis via leptogenesis in the early universe

Asaka/Shaposhnikov 2005



plot from 1204.5379

Leptogenesis

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  - Yukawa couplings F violate individual lepton flavour numbers
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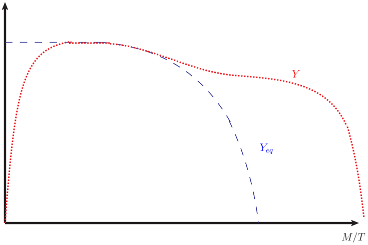
- nonequilibrium
  - N_I production
  - N_I freezeout
  - N_I decay



Leptogenesis during N_I production

- CP-violating oscillations amongst N_I generate L_α during their thermal production
- sphalerons convert part of them into B

Akhmedov/Rubakov/Smirnov 1998, Asaka/Shaposhnikov 2006

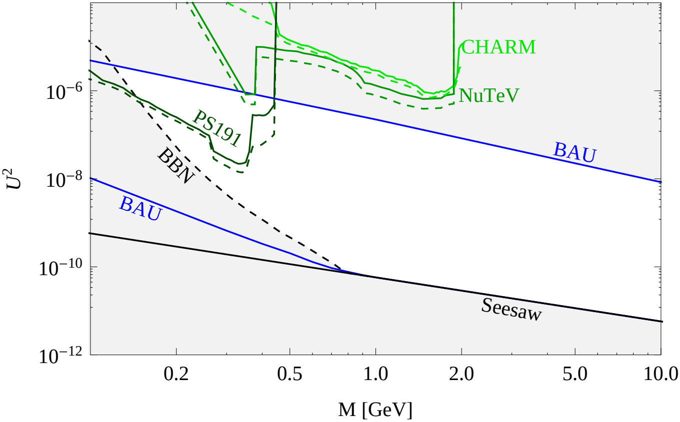
- With two RH neutrinos this requires a mass degeneracy $\sim 10^{-3}$

Canetti/MaD/Frossard/Shaposhnikov 1208.4607

- With three RH neutrinos no such degeneracy is needed!

MaD/Garbrecht 1206.5537

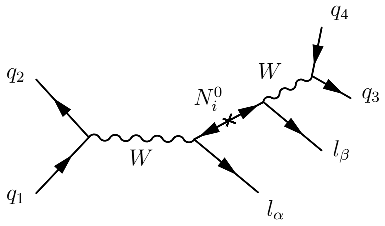
Minimal scenario: Two RH neutrinos

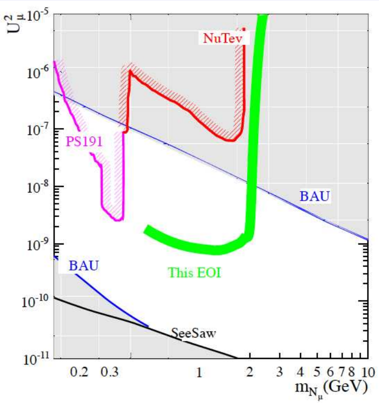


$$U^2 \equiv \mathrm{tr}\theta^\dagger\theta$$

Canetti/MaD/Frossard/Shaposhnikov 1208.4607

Probing the origin of matter in the laboratory





	two RH neutrinos	three RH neutrinos
baryogenesis	requires mass degeneracy	works without degeneracy
lab searches	SNOOPY 1310.1762	LHCb, BELLE, SNOOPY,. . .

Smirnov/Kersten, Atre/Han/Pascoli/Zhang, Canetti/MaD/Shaposhnikov, . . .

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

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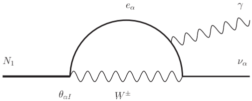

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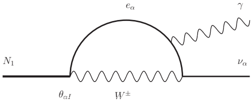
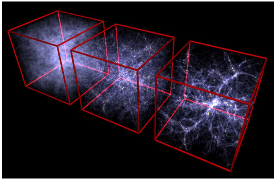
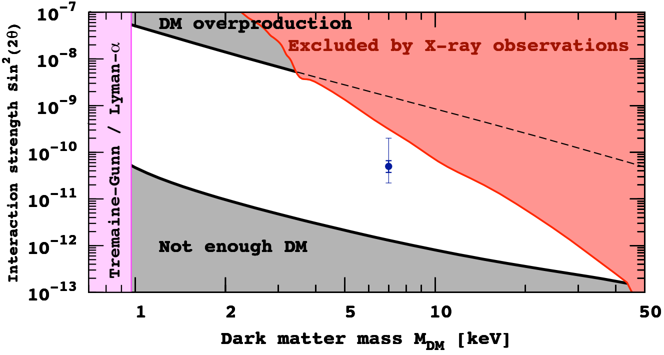


  - Has the X-ray line been found? 1402.2301,1402-4119
- How were they produced?
- Are they consistent with structure formation?
  - DM is absolutely essential to form structures in the universe
  - DM is "cold" , i.e. $\langle \mathbf{k} \rangle < M$ at freezeout



RH neutrino Dark Matter - observations



Boyarsky/Ruchayskiy/Iakubovskyi/Franse 1402.4119,

Canetti/MaD/Frossard/Shaposhnikov 1208.4607

How many new particles do we need after the Higgs?

Three.

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Three.

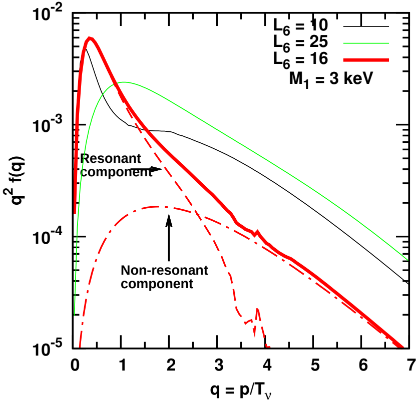
Frustra fit per plura
quod potest fieri per pauciora.

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

William of Ockham, Summa Totius Logicae

Dark Matter Production

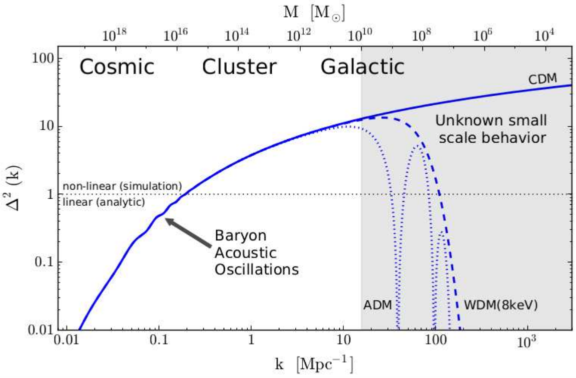
- produced via active-sterile neutrino mixing
- most efficient at $T \sim 100$ MeV
- affected by chemical potential Shi/Fuller, Laine/Shaposhnikov
- spectrum is non-thermal
- effectively a superposition of CDM and WDM (**CWDM**)



plot from Boyarsky/Ruchayskiy/Shaposhnikov 2009

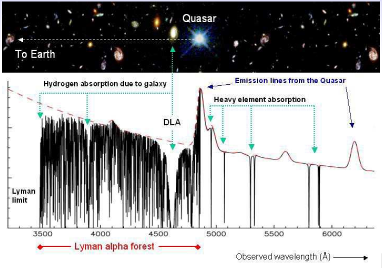
Structure Formation

- free streaming of DM erases small scale structures
  $\Rightarrow$ DM is "cold" , i.e. $\langle \mathbf{k} \rangle \lesssim M$ at freezeout
- for thermal spectrum this implies: DM particle is heavy
- but for non-thermal spectrum predictions are complicated. . .



from 1209.5745

Quasar absorption lines ($Ly\alpha$-forest) map structure in the universe



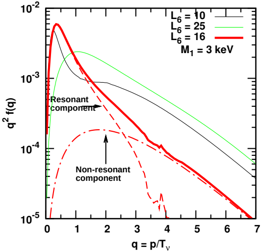
Murphy/Webb

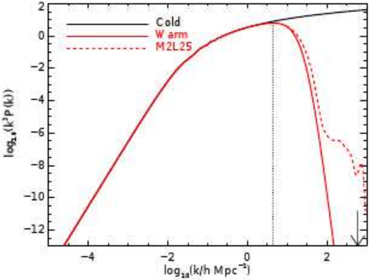
This is compared to structure formation simulations

1104.2929

Structure formation with CWDM

- CDM works very well on large scales
- WDM seems to work better on small scales (subhalos)
- few simulations exist for non-thermal spectra / CWDM
- the initial spectra were calculated under very simplifying assumptions about the chemical potentials





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