HOW MANY NEW PARTICLES DO WE NEED AFTER THE HIGGS?

Marco Drewes
TU München

based on
arXiv:1404.7114 [hep-ph],
Phys.Rev.Lett. 110 (2013) 6, 061801 ,
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**

29th April 2014 | INFN Genova

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1. **describes all observed phenomena and**
2. **can be tested empirically?**

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Remarks...

- test = confirm existence of all particles and study their interactions
- Of course this need not be a complete theory of nature, as there may be phenomena beyond reach of our instruments.

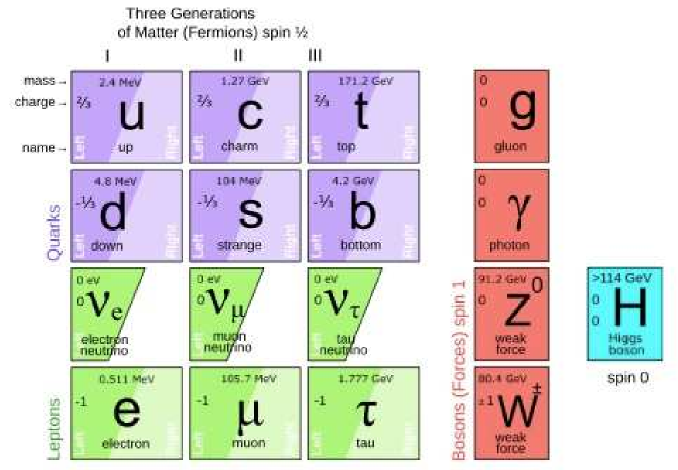
The **Standard Model** and **General Relativity** together *almost* fulfil both conditions, but. . .

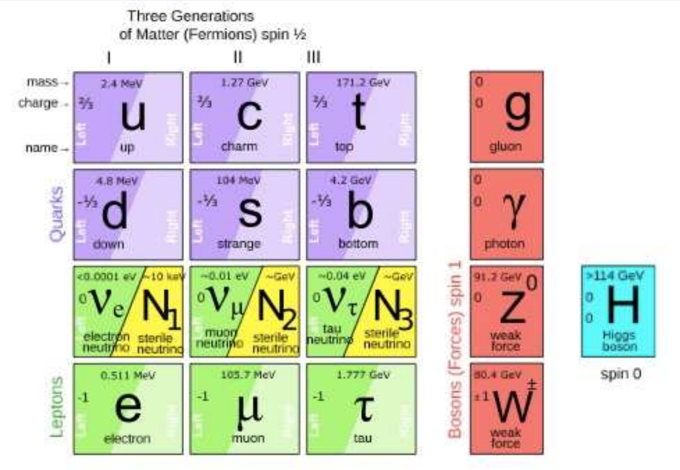
- gravity is not quantized
- a handful of observations remain unexplained
    - overall geometry of the observable universe
    - neutrino oscillations
    - baryon asymmetry of the universe
    - dark matter

In addition there are some *hints*. . .

- esthetic concerns
  - hierarchy problem(s)
  - strong CP-problem
  - parameter values, flavour structure, gauge group. . .
- inconclusive issues
  - vacuum stability
  - $g - 2$
  - neutrino oscillation anomalies
  - hints for dark radiation
  - varying α
  - . . .

. . . the meaning of which is unclear at this stage.


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
0 0 g gluon
4.8 MeV -⅓ d down
104 MeV -⅓ s strange
4.2 GeV -⅓ b bottom
0 0 γ photon
0 eV 0 νe electron neutrino
0 eV 0 νμ muon neutrino
0 eV 0 ντ tau neutrino
91.2 GeV 0 Z0 weak force
>114 GeV 0 0 H Higgs boson
spin 0
0.511 MeV -1 e electron
105.7 MeV -1 μ muon
1.777 GeV -1 τ tau
80.4 GeV ±1 W± weak force
Left
Right
Quarks
Leptons
Bosons (Forces) spin 1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photon
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0
ν_e
N_1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
ν_μ
N_2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ν_τ
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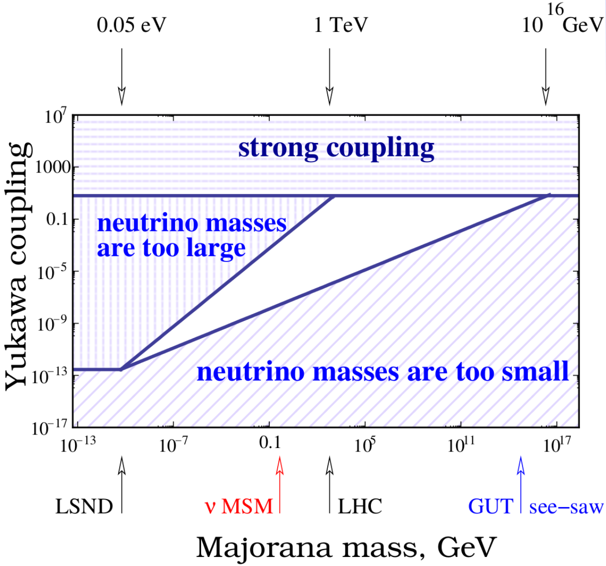
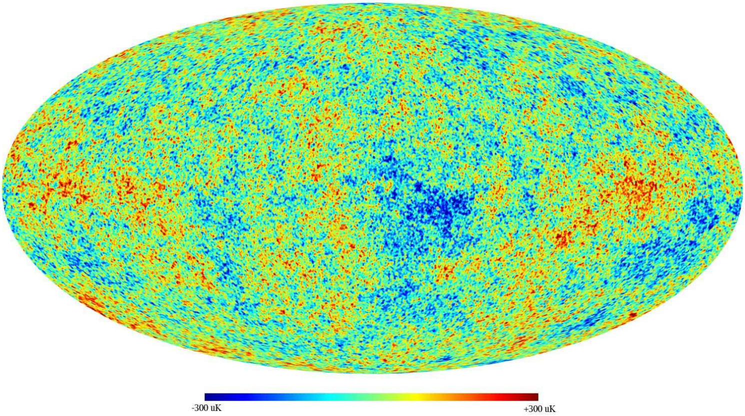
$$\mathcal{S} = \int d^4 \sqrt{-g}\Big[\mathcal{L}_{SM} - \frac{\tilde{M}_P^2}{2} R - \xi \Phi^\dagger \Phi R$$
$$+ \quad i\overline{\nu_R}\partial\!\!\!/\nu_R - \overline{l_L} F \nu_R \tilde{\Phi} - \overline{\nu_R} F^\dagger l_L \tilde{\Phi}^\dagger - \frac{1}{2}(\overline{\nu_R^c} M_M \nu_R + \overline{\nu_R} M_M^\dagger \nu_R^c)\Big].$$

- Majorana masses M_M introduce new mass scale(s)
- For different Majorana mass values they can explain
    - neutrino oscillations
    - baryogenesis
    - dark matter
    - dark radiation, oscillation anomalies



plot from 1204.5379

Geometry of the Universe



The CMB shows that the universe was remarkably simple at redshift $z \sim 1100$. But how did this happen?

- horizon problem
- flatness problem
- origin of temperature perturbations

Can be explained by a period of accelerated cosmic expansion
$\Rightarrow$ Cosmic Inflation

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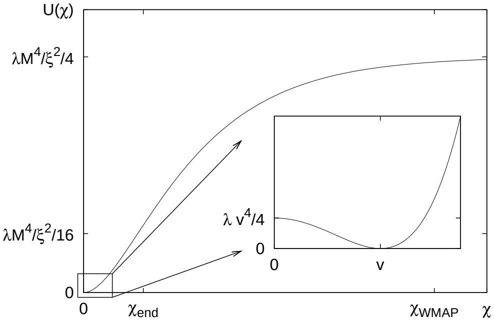
Can be explained by a period of accelerated cosmic expansion
$\Rightarrow$ Cosmic Inflation

- requires negative equation of state
- potential energy of scalar field
- scalar field in general can parameterise complicated new physics

Higgs inflation

Let χ be the Higgs field value $(\Phi^\dagger\Phi)^{(1/2)}$ in the Einstein frame.

- non-minimal coupling ξ can make the potential $U(\chi)$ flat at large χ $\Rightarrow \chi$ "rolls slowly" Bezrukov/Shaposhnikov
- inflation while $U(\chi)$ dominates the energy
- works if $m_H > m_{\text{crit}} = 129.6 + 2.0\frac{y_t - 0.9361}{0.0058} - 0.5\frac{\alpha_s - 0.1184}{0.0007}$

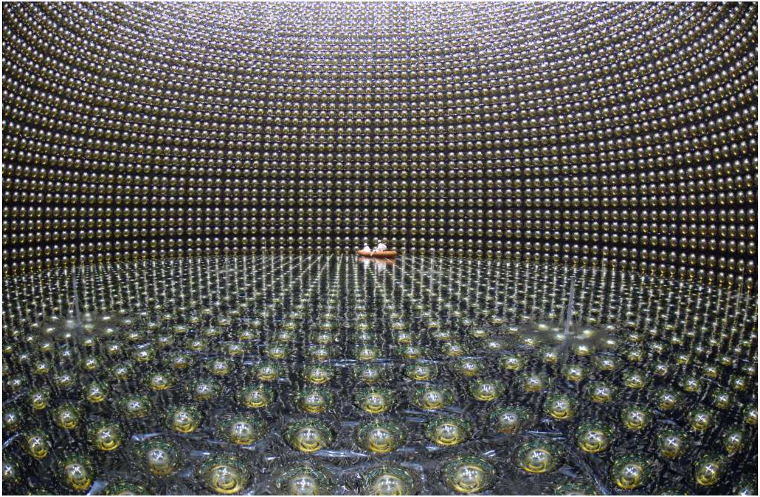


BICEP2 and the critical point

- If $m_H \gg m_{\mathrm{crit}}$
  - quantum corrections to $U(\chi)$ small
  - COBE normalisation implies $\xi \sim 47000\sqrt{\lambda}$
  - generic prediction $r \simeq 0.003$, $n_s \simeq 0.97$
- If $m_H \sim m_{\mathrm{crit}}$
  - sensitivity to quantum corrections
  - inflation seems to work for $\xi \sim 10$
  - $r = 0.1$, $n_s = 0.96$ implies $m_H \simeq 126.4$ GeV and $m_t \simeq 171.6$ GeV, close to observed values!

Bezrukov/Shaposhnikov 1403.6078

Neutrino Oscillations



Seesaw Mechanism

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

- the mass matrices $m_D = vF$ and M_M are not diagonal in the basis of weak interaction eigenstates
- The seesaw limit $m_D \ll M_M$ yields two sets of mass states,

$$\begin{aligned} \nu &\simeq U_\nu^\dagger(\nu_L - \theta\nu_R^c) + \text{conj.} \\ N &\simeq \nu_R + \theta^T\nu_L^c + \text{conj.} \end{aligned}$$

with $\theta = m_D M_M^{-1} \ll \mathbb{1}$ and mass matrices

$$m_\nu \simeq -\theta M_M \theta^T \quad , \quad M_N \simeq M_M$$

Mixing with sterile neutrinos

θ is the mixing with the sterile neutrinos

- at **energies $E \ll M_M$ the N are too heavy to be produced**,
    - N can be "integrated out" and leave only an indirect trace by generating the mass term

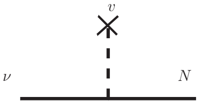
$$\frac{1}{2}\overline{\nu_L} m_\nu \nu_L^c + h.c.$$

    - it is constrained by the seesaw-relation $m_\nu \simeq -\theta M_M \theta^T = -m_D M_M^{-1} m_D^T = -F M_M^{-1} F^T \frac{1}{v^2}$
- **at energies $E \gtrsim M_M$ the N appear as new particles**

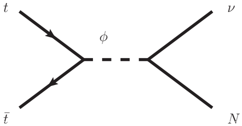
$\Rightarrow \nu_{e,\mu,\tau}$ mix with N

Neutrino Mixing

- at $T = 0$ the *N* only interact via their mixing with the SM
- they participate in all processes that the SM neutrinos take part in, but with an amplitude suppressed by $\theta \ll 1$



- at $T > T_{EW}$ there are Higgs particles in the primordial plasma
$\Rightarrow$ N_I can be produced in various scattering processes



Baryogenesis ($200\mathrm{MeV} \lesssim M < 10^{15}$ GeV)

Baryogenesis

- The baryons that our world is made of are the remnant of a small matter-antimatter asymmetry $\eta \sim \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$ in the early universe
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    by sphaleron processes OK.
  - C and CP violation
    by weak interaction and CKM phase TOO SMALL!
  - nonequilibrium
    by expansion of the universe TOO SMALL!

Baryogenesis via Leptogenesis

- baryon number (B) violation
  - again sphalerons violate B, but conserve $B - L$
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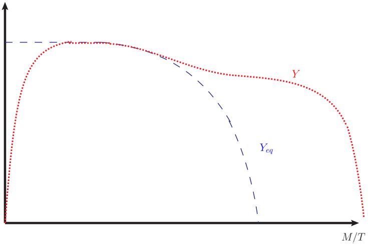
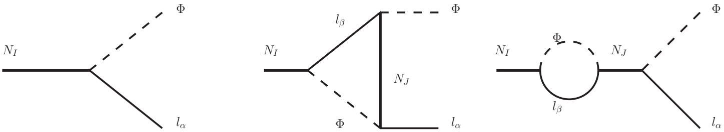
- nonequilibrium
  - N_I production
  - N_I freezeout
  - N_I decay



all conditions are fulfilled

Leptogenesis during N_I-freezeout/decay

- Majorana fermions N_I can decay into leptons or antileptons
- The probabilities for both decays are different due to the CP-violation in F
- decay violates total lepton number L
- sphalerons convert part of L into B



Fukugita/Yanagida 1986

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

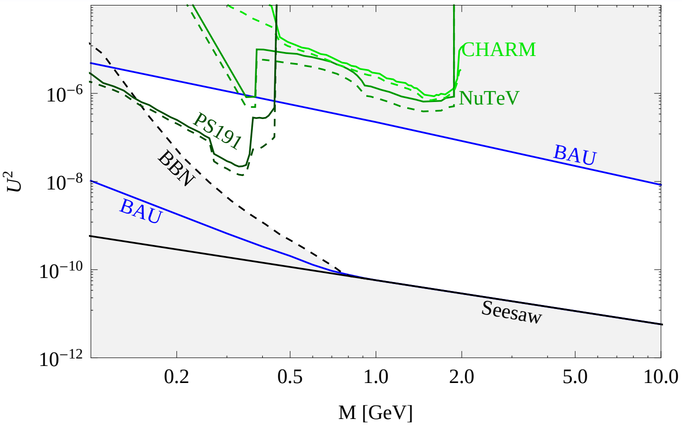
- With two RH neutrinos this requires a mass degeneracy $\sim 10^{-3}$

Canetti/MaD/Frossard/Shaposhnikov 1208.4607

- With three RH neutrinos no such degeneracy is needed!

MaD/Garbrecht 1206.5537

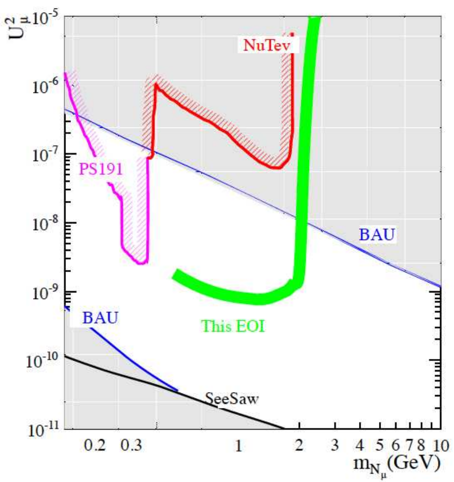
Minimal scenario: Two RH neutrinos



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

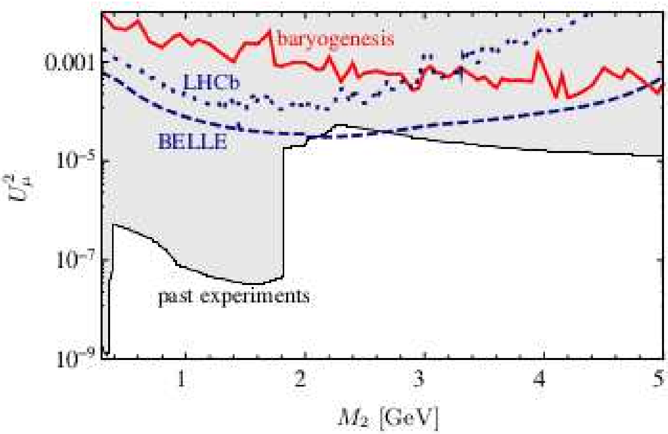
Canetti/MaD/Frossard/Shaposhnikov 1208.4607

SHIP proposal



arXiv:1310.1762 [hep-ex]

Leptogenesis with three RH Neutrinos



Canetti/MaD/Garbrecht 1404.7114

Probing the origin of matter in the laboratory

GeV range masses

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

TeV range masses

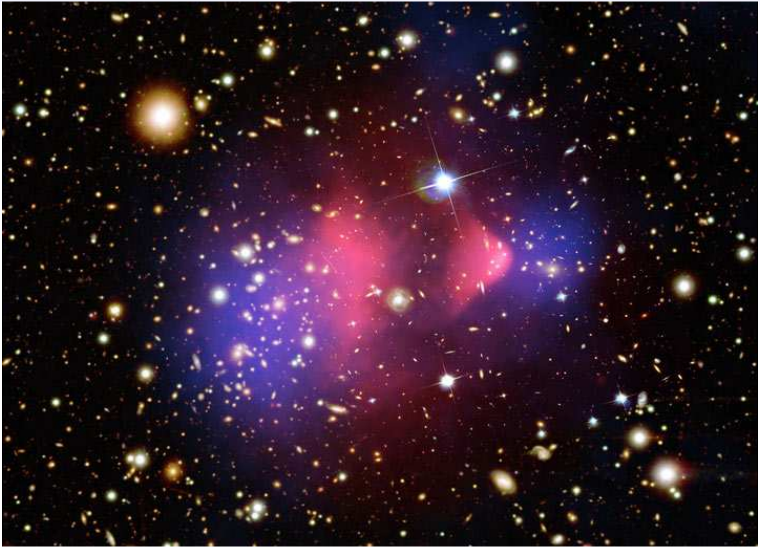
	two RH neutrinos	three RH neutrinos
baryogenesis	requires mass degeneracy	work in progress
lab searches	tiny branching ratio from $\mu \rightarrow e\gamma$	work in progress

MaD/Garbrecht 2013, Canetti/MaD/Frossard/Shaposhnikov 2013,

Canetti/MaD/Shaposhnikov 2013, Ibarra/Molinaro/Petcov 2011,

Atre/Han/Pascoli/Zhang 2009, Smirnov/Kersten 2007

Dark Matter ($M \sim$ keV)



If RH neutrinos are DM, then there are three basic questions

- They are decaying DM. Where is the decay line?

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

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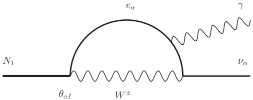

-
    - Search for X-ray line!
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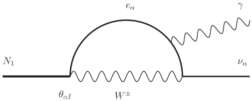
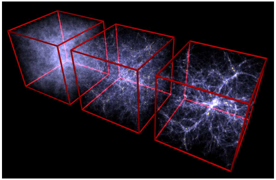
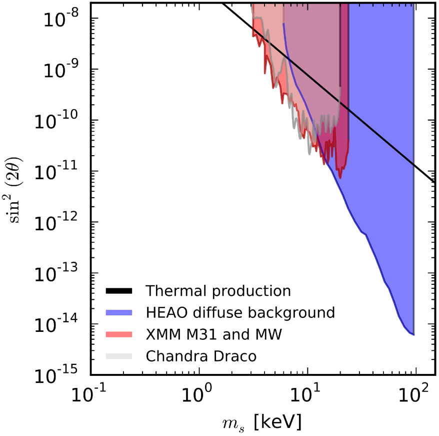


    - Search for X-ray line!
- How were they produced?
- Are they consistent with structure formation?
    - DM is absolutely essential to form structures in the universe
    - DM is “cold” , i.e. $\langle \mathbf{k} \rangle < M$ at freezeout



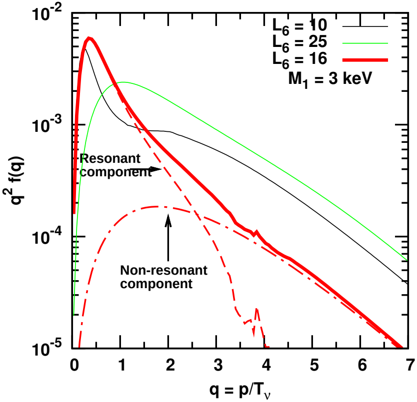
X-ray constraints



MaD 1303.6912, thanks to S. Riemer-Sørensen

Dark Matter Production

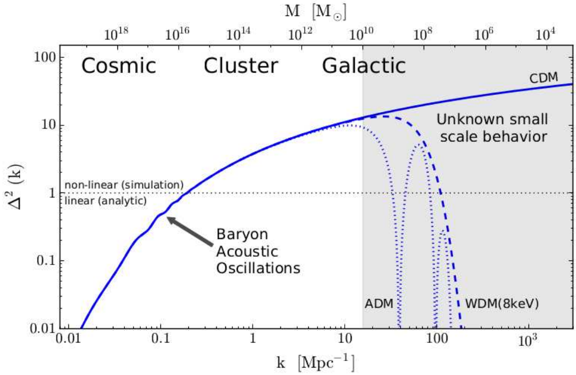
- produced via active-sterile neutrino mixing
- most efficient at $T \sim 100$ MeV
- affected by chemical potential Shi/Fuller, Laine/Shaposhnikov
- spectrum is non-thermal
- effectively a superposition of CDM and WDM (**CWDM**)



plot from Boyarsky/Ruchayskiy/Shaposhnikov 2009

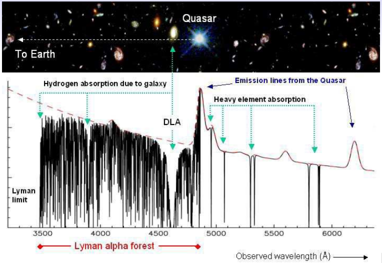
Structure Formation

- 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*α-forest) map structure in the universe



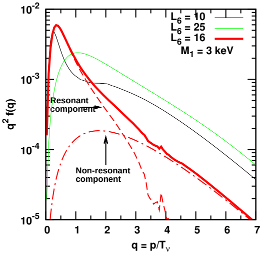
Murphy/Webb

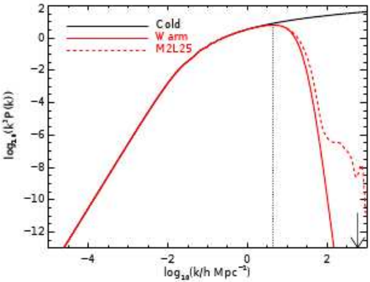
This is compared to structure formation simulations

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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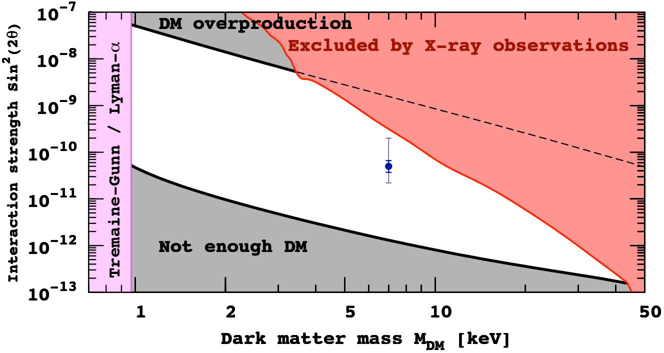
Dark Matter Bounds - Summary



Boyarsky/Ruchayskiy/Iakubovskyi/Franse 1402.4119

3.5 keV signal found in 1402.2301 and 1402.4119 fits predictions perfectly!

Summary

- Right handed neutrinos with different Majorana masses can explain
  - neutrino oscillations (almost any M)
  - Dark Matter ($M \sim$ keV)
  - baryon asymmetry of the universe ($M >$ 200 MeV)
  - Dark Radiation?, oscillation anomalies? ($M \lesssim$ eV)
- they can be searched for in the lab and in the sky

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  - Dark Radiation?, oscillation anomalies? ($M \lesssim$ eV)
- they can be searched for in the lab and in the sky
- But can they explain all of this *simultaneously*?

Can the SM+GR+ν_R be a valid effective field theory up to the Planck scale?

I want it all!

A theory of (almost) everything

Yes.

- let's assume that there are three RH neutrinos
- one has a keV mass
  - composes the observed Dark Matter
- two have masses > 200 MeV
  - give masses to SM neutrinos via seesaw mechanism
  - create the baryon asymmetry of the universe via leptgenesis
- if there were a fourth one with an $\lesssim$ eV mass it could be Dark Radiation or explain neutrino oscillation anomalies

Asaka/Shaposhnikov 2005, Canetti/MaD/Shaposhnikov 1204.3902

How many new particles do we need after the Higgs?

Three.

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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