Searches for GeV-scale sterile neutrinos with CERN SPS proton beam

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Phenomenological problems of the Standard Model

Gauge fields (interactions) – γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations : active neutrino masses via mixing
  - Dark matter (Ω_{DM}) : sterile neutrino as DM
  - Baryon asymmetry : leptogenesis via sterile neutrino decays or oscillations

- Sterile neutrinos explain the oscillations
- and the cosmological problems

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Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- light(?) sterile neutrinos might be responsible for neutrino anomalies. . . ?

Disappointing feature:

Major part of parameter space is UNTESTABLE

Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

$$\mathscr{L}^{(5)} = \frac{\beta_L}{4\Lambda} F_{\alpha\beta} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{\beta_L v^2}{4\Lambda} \frac{F_{\alpha\beta}}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

hence

$$\Lambda \sim 3 \times 10^{14}\,\text{GeV} \times \beta_L \times \left(\frac{3 \times 10^{-3}\,\text{eV}^2}{\Delta m^2_{\text{atm}}}\right)^{1/2}$$

The model has to be UV-completed at the neutrino scale $\Lambda_\nu < \Lambda$ ...

What is beyond the neutrino scale Λ_ν ?

Why neutrino scale, 1 eV, is so low ?

Seesaw mechanism: $M_N \gg 1$ eV (Type I)

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

$$\mathscr{L}_N = \overline{N}_I i \partial\!\!\!/ N_I - f_{\alpha I} \overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2} \overline{N}_I^c N_I + \text{h.c.}$$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = v \frac{f_{\alpha I}}{\sqrt{2}} \overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2} \overline{N}_I^c N_I + \text{h.c.} = \left(\overline{\nu}_1, \ldots \overline{N}_1^c \ldots\right) \begin{pmatrix} 0 & v\frac{\hat{f}}{\sqrt{2}} \\ v\frac{\hat{f}^\dagger}{\sqrt{2}} & \hat{M}_N \end{pmatrix} \left(\nu_1, \ldots N_1 \ldots\right)^T$$

Then for $M_N \gg \hat{M}^D = v\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues: seesaw at work

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = -\hat{M}^{D\dagger} \frac{1}{\hat{M}_N} \hat{M}^D \propto f^2 \frac{v^2}{M_N} \propto \theta^2 M_N \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i} \nu_i + \theta_{\alpha I} N_I$

active-active mixing: $U^\dagger \hat{M}^\nu U = diag(m_1, m_2, m_3)$

active-sterile mixing: $\theta_{\alpha I} \propto \frac{(M^D)^\dagger_{\alpha I}}{M_N} = \hat{f}^\dagger \frac{v}{M_N} \ll 1$

Where is sterile neutrino scale?

eigenvalues: $\simeq \hat{M}_N$ and $\hat{M}^\nu = -\hat{M}^{D\dagger}\frac{1}{\hat{M}_N}\hat{M}^D \propto f^2\frac{v^2}{M_N} \lll M_N$

SEESAW says nothing about the sterile neutrino scale M_N !

Unitarity: $f \lesssim 1 \quad \Longrightarrow \quad M_N \lesssim 3\times 10^{14}\ \text{GeV} \times \left(\frac{3\cdot 10^{-3}\ \text{eV}^2}{\Delta m^2_{atm}}\right)^{1/2} \longrightarrow \Lambda$ in $(LH)^2/\Lambda$

Integrating out sterile neutrinos get dim-5 operator $-f_{\alpha I}\bar{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\bar{N}_I^c N_I \to f^2(LH)^2/M_N$

SM Higgs without NP at EW-scale favors sterile neutrinos at EW-scale (or below) !

- Majorana mass violates scale-invarinace $\Longrightarrow$ finite corrections $\delta m_h^2 \propto f^2 M_N^2$
- Scale invariance helps to abandon infinite corrections $\delta m_h^2 \propto f^2\Lambda^2 M_N^2$
- In SM scale invariance is broken by the Higgs mass and running of coupling constants
  $T^\mu_\mu \propto \beta(\alpha)\times\hat{O} + \left(m_h^2 + \alpha\Lambda^2\right)\times h^2 \quad \Longrightarrow$ quadratic divergences are irrelevant

W.Bardeen (1995)

Sterile neutrinos: M_{N_I} violate lepton symmetry

Most general renormalizable with 2(3...) right-handed neutrinos N_I ?

$$\mathscr{L}_N = \overline{N}_I i \partial\!\!\!/ N_I - f_{\alpha I} \overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2} \overline{N}_I^c N_I + \text{h.c.}$$

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: $^3\text{H} \to ^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H\rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total
help with leptogenesis

18: $N = 3$ sterile neutrinos:

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9 new parameters in total
both BAU and DM are possible

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νMSM: 2 GeV-scale & 1 keV-scale neutrinos

T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

2 GeV-scale seesaw neutrinos

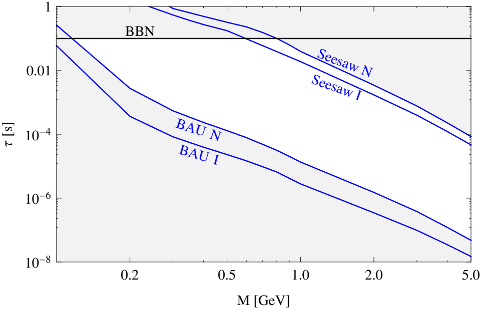
- give masses and mixing to active neutrinos — need two!
- violate CP — need two!

  out-of-equilibrium oscillations $\nu_a \leftrightarrow N_{2,3}$

  need very small mixing $\theta^2_{\alpha I} \lll 1$

  in the early Universe redistribute lepton charge

  need degeneracy: $\Delta M_{N_{2,3}} \ll M_{N_2}, M_{N_3}$

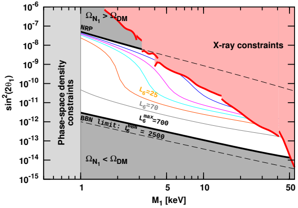


DM: 1-50 keV

mixing with active neutrinos:

- $\tau_{N_1} > \tau_U \rightarrow$ little contribution to m_ν
- signature in X-rays $N_1 \rightarrow \gamma\nu_a$
- produced in early Universe in plasma

  needs strong fine-tuning



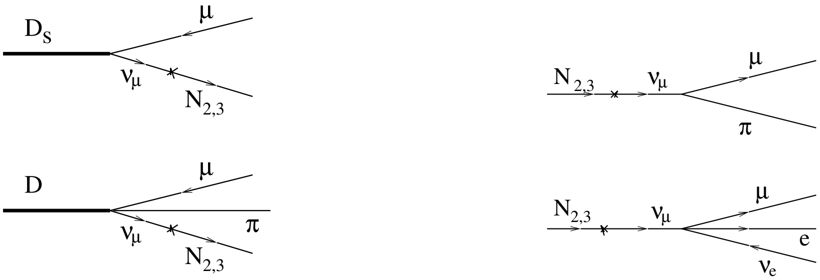
easily produced by inflaton XNN

M.Shaposhnikov, I.Tkachev (2006),

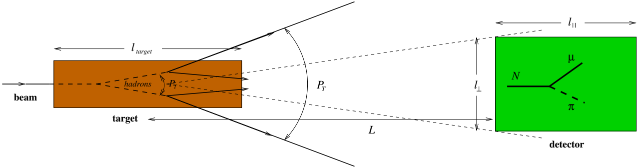
F.Bezrukov, D.G. (2009)

Direct searches for sterile neutrinos: 2 approaches

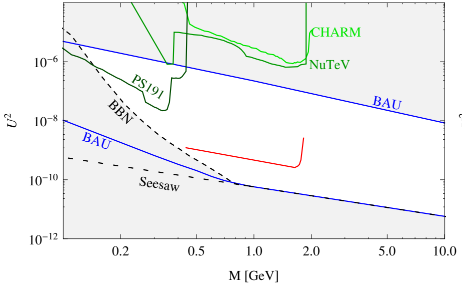
Weak decays due to mixing



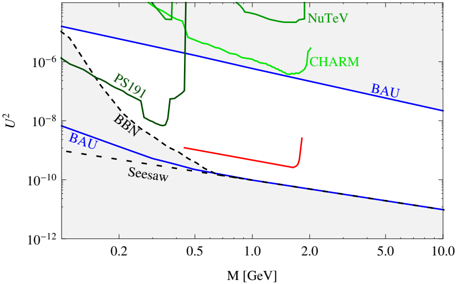
Production in beam-dump experiments



νMSM parameter space $\quad \theta^2_{\nu N} \propto U^2$



D.G, M.Shaposhnikov (2007)



L.Canetti, M.Drewes, M.Shaposhnikov (2012)

$$\mathrm{Br}\,(D \to lN) \lesssim 2 \cdot 10^{-8}$$

$$\mathrm{Br}\,(D_s \to lN) \lesssim 3 \cdot 10^{-7}$$

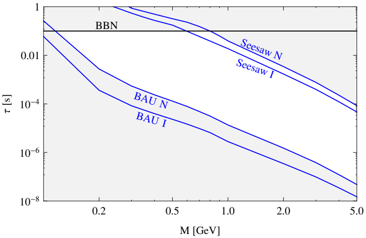
$$\mathrm{Br}\,(D \to KlN) \lesssim 2 \cdot 10^{-7}$$

$$\mathrm{Br}\,(D_s \to \eta lN) \lesssim 5 \cdot 10^{-8}$$

$$\mathrm{Br}\,(D \to K^* lN) \lesssim 7 \cdot 10^{-8}$$

$$\mathrm{Br}\,(B \to D^* lN) \lesssim 4 \cdot 10^{-7}$$

$$\mathrm{Br}\,(B_s \to D_s^* lN) \lesssim 3 \cdot 10^{-7}$$



Neutrino production in *pp*-collisions: meson decays

Experiment	E, GeV	N_{POT}, 10^{19}	$\sigma_c/\sigma_{\rm tot}$	$\sigma_b/\sigma_{\rm tot}$
CNGS	400	4.5	0.45×10^{-3}	3×10^{-8}
NuMi	120	5	1×10^{-4}	10^{-10}
T2K	30	100	0.5×10^{-5}	10^{-12}
NuTeV	800	1	1×10^{-3}	2×10^{-7}

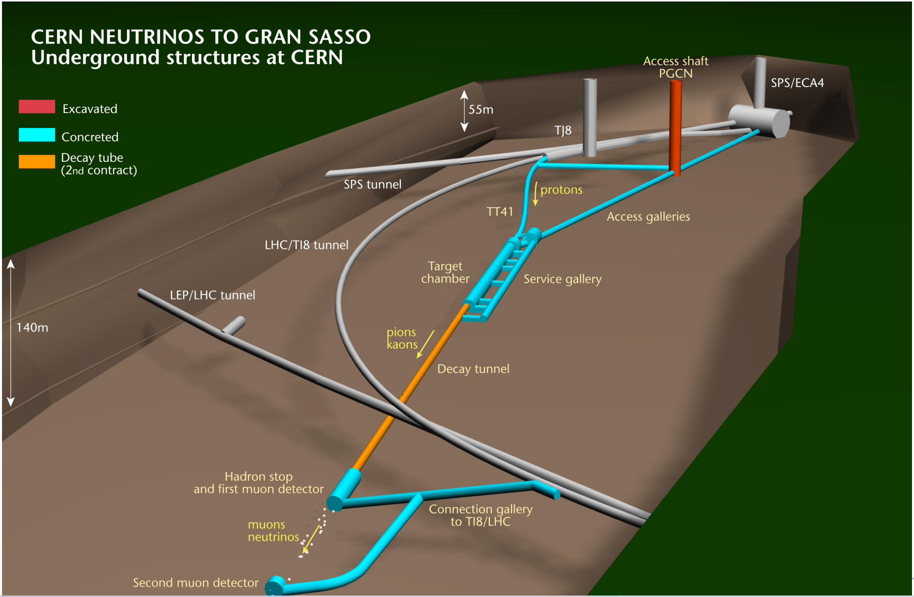
Pure geometrical factor as compared to CHARM

LBNE	PoT	detector length	distance to target	beam energy	detector area	charm production
HiResM$_\nu$	1.0×10^{22}	35 m	500 m	120 GeV	4×4 m^2	1.0×10^{-4}
CHARM	2.5×10^{18}	34 m	480 m	400 GeV	3×3 m^2	4.5×10^{-4}

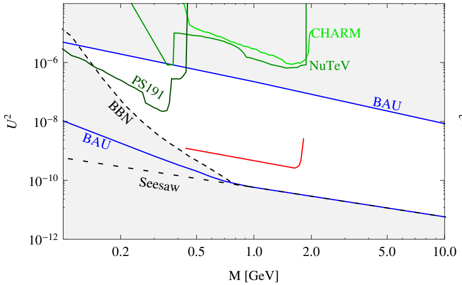
$$\frac{N_{signal}^{HiResM_\nu}}{N_{signal}^{CHARM}} = \frac{1.0\times10^{22}}{2.5\times10^{18}}\times\frac{35}{34}\times\left(\frac{480}{500}\right)^2\times\left(\frac{120}{400}\right)^2\times\frac{4\times4}{3\times3}\times\frac{1.0\times10^{-4}}{4.5\times10^{-4}}\approx 130$$

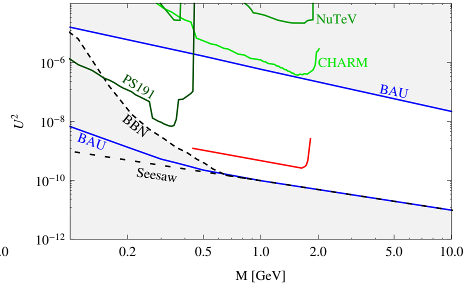
$N_{signal}\propto\theta^2_{\nu N_2}\times\theta^2_{\nu N_2}$ order of magnitude improvement in $\theta^2_{\nu N_2}$

CNGS site is free after OPERA



νMSM parameter space for $M_N < 2\,\text{GeV}$



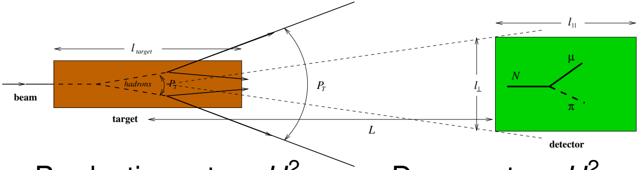


D.G, M.Shaposhnikov (2012)

L.Canetti, M.Drewes, M.Shaposhnikov (2012)

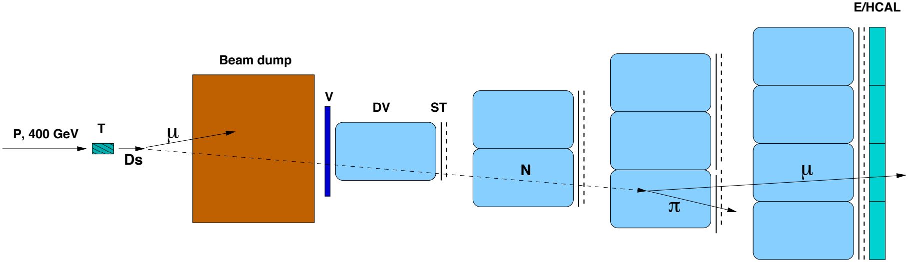
S.Gninenko, D.G, M.Shaposhnikov (2012)

L=100 m $\quad l_\perp \sim 5\,\text{m} \quad l_{||} \sim 100\,\text{m}$



Production rate $\propto U^2$, $\quad$ Decay rate $\propto U^2$

To fully explore the region $M_N < 2\,\text{GeV}$



$$N_{\text{PoT}} \simeq 10^{20}\,, \qquad l_{\text{total}} \simeq 3\,\text{km}$$

multisectional detector (presumably on surface)

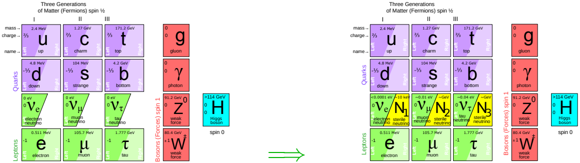
Sterile neutrinos: dedicated experiment is needed

- Most economic explanation of neutrino oscillations within renormalizable approach: $N = 2$ Majorana neutrinos
- Capable of explaining baryon asymmetry of the Universe even with $\delta_{CP} = 0$
- One more neutrino can serve as (naturally Warm) dark matter

νMSM

direct searches are feasible for $M_N < 2\,\text{GeV}$ ($5\,\text{GeV}$)

- 100-m length detector at SNGS site operated on upgraded SPS beam allows to cover major part of paramater space
- 3-km scale detector is needed to fully explore the model



Backup slides

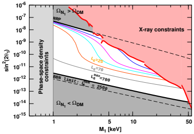
Heavy sterile neutrinos: $M_N \simeq 1\,\text{keV-}5\,\text{GeV}$ νMSM

T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  True low-energy scale modification of the SM
- Good fact: At $T > 100\,\text{GeV}$ active-sterile neutrino oscillations produce lepton asymmetry in the early Universe, if $\Delta M_{N_{2,3}} \ll M_{N_2}, M_{N_3}$ E.Akhmedov, V.Rubakov, A.Smirnov (1998)
- To make phenomenologically complete: Dark Matter?
  - NOT a seesaw neutrino! $m_\nu \ll m_{atm,sol}$ general statement

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

  either decay or equilibrate and then contribute to hot dark matter
  - production in primordial plasma due to mixing with active neutrinos is ruled out from searches at X-ray telescopes



$$\Gamma_{N\to\nu\gamma} \simeq 5.5\times 10^{-22}\,\theta_1^2 \left(\frac{M_1}{1\,\text{keV}}\right)^5 \text{s}^{-1}$$

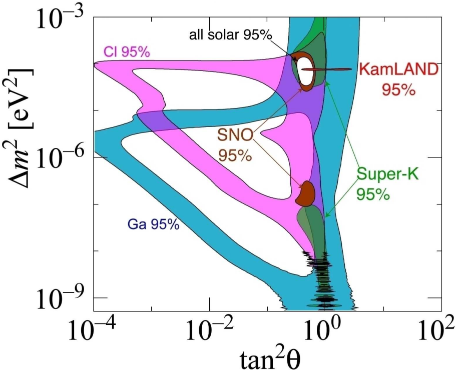
a narrow line ($\delta E_\gamma/E_\gamma \sim v \sim 10^{-3}$) at $E_\gamma = M_N/2$

  - Possible for 1-50 keV (WDM-CDM range) either with further unbelievable fine-tuning in M_{N_I} ($\Delta M_N \sim 10^{-7}$ eV) to get $L \gg B$ and use the resonant production or with ANOTHER source of production, e.g. inflaton decays.. then untestable

M.Shaposhnikov, I.Tkachev (2006), F.Bezrukov, D.G. (2009)

Neutrino oscillations: masses and mixing angles

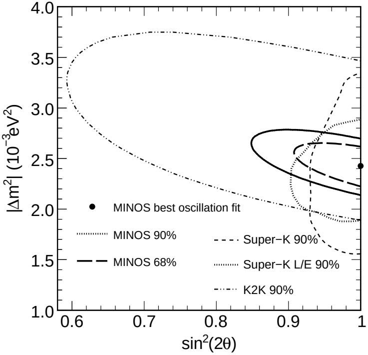
Solar 2×2 "subsector"



http://hitoshi.berkeley.edu/neutrino/

$m_1 > 0.008$ eV

Atmospheric 2×2 "subsector"



arXiv:0806.2237

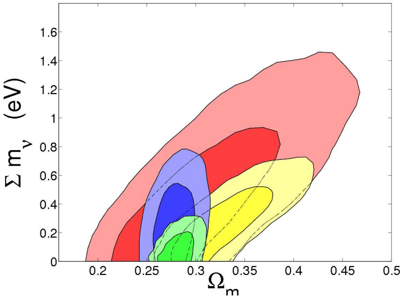
$m_2 > 0.05$ eV

DAYA-BAY, RENO: $\sin^2 2\theta_{13} \approx 0.1$

also T2K (talk by M.Khabibullin)

Cosmological limits on active neutrino masses

Neutrino contributions:
Start of structure formation
Gravity potentials at recombination
Late-time structure formation
Universe expansion

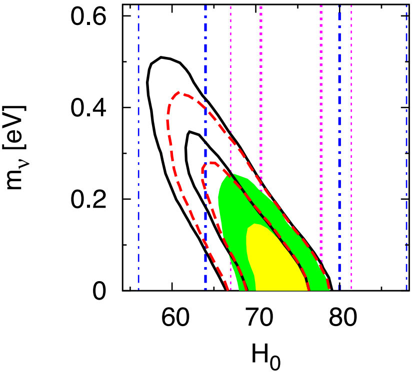


LRG+BAO+WMAP5+SNe

$\sum m_\nu < 0.28$ eV (95% CL)

0911.5291, see also 1112.4940

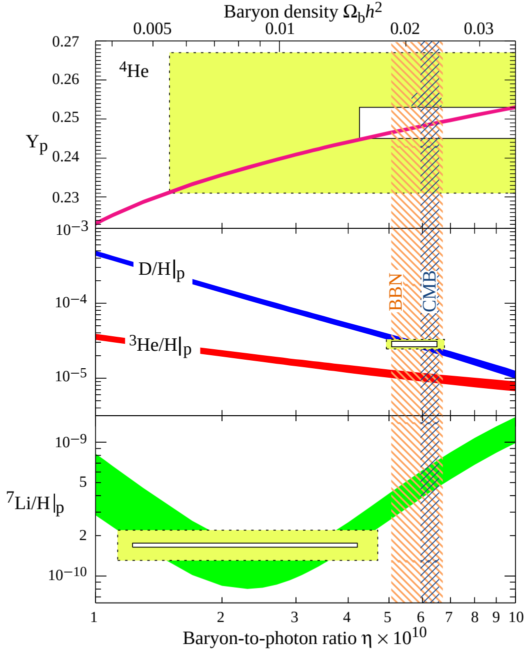
For $N_\nu = 3$ light neutrinos



CMB+Hubble measurements

$\sum m_\nu < 0.20$ eV (95% CL)

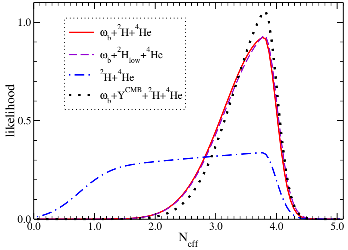
0911.0976, see also 1202.2889



$$Y_p = 0.2581 \pm 0.025\,,$$

$$D/H|_p = (2.87 \pm 0.21) \times 10^{-5}$$

1103.1261



similar results from other recent studies including structure formation

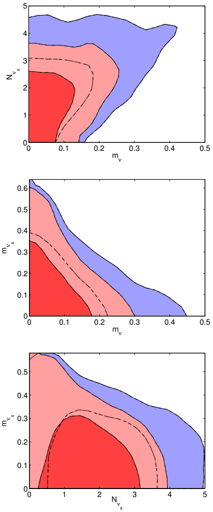
1001.4440, 1001.5218, 1202.2889

$N_\nu < 4.2$ @ 95%CL

$N_\nu < 3.6$ from D/H, 1205.3785

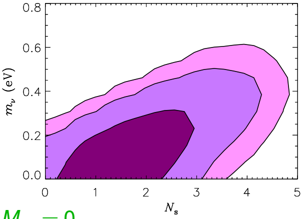
Combined analysis for sterile and active neutrinos

WMAP7+LRG+HST

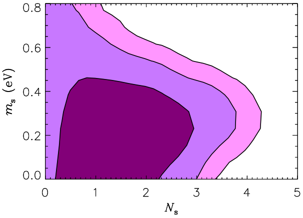


flat ΛCDM 1102.4774

CMB+SDSS+HST



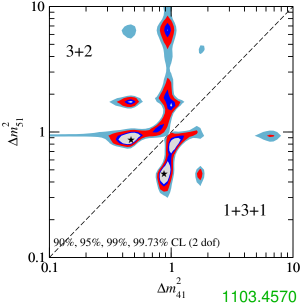
$M_{\nu_s} = 0$



$m_\nu = 0$

flat ΛCDM 1006.5276

LSND+MiniBooNE



1103.4570

"3+1" :

$\Delta m^2_{41} = 1.76\,\text{eV}^2\,, |U_{e4}| = 0.151$

"3+2" :

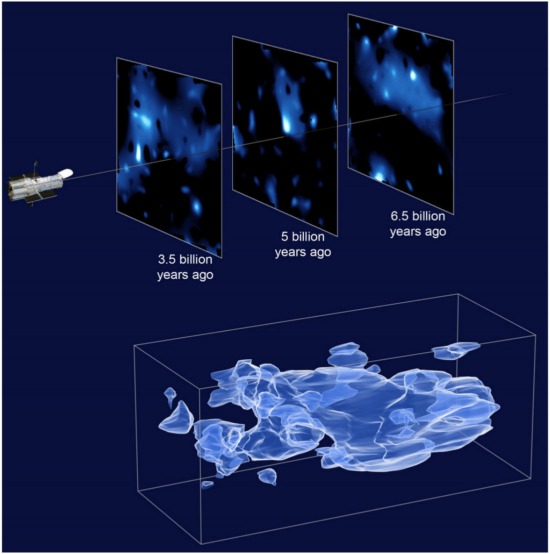
$\Delta m^2_{41} = 0.46\,\text{eV}^2\,, |U_{e4}| = 0.108$

$\Delta m^2_{51} = 0.89\,\text{eV}^2\,, |U_{e5}| = 0.124$

BBN rules out "3+2"

For "3+1" to allow $M_N \gtrsim 1$ eV for CMB and LSS we need a new ingredient

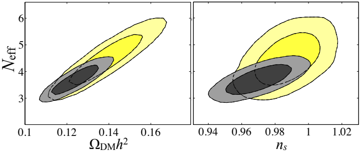
LSS: SZ-clusters, Weak lensing of CMB



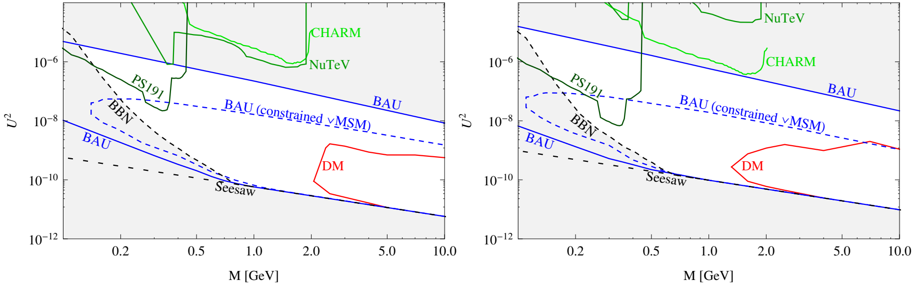
- ΔN_ν amplifies shear power: cancel with quintessence contribution and flattening of spectrum, $n_s \to 1$
- M_N reduces power

$$N_{eff} = 3 \;\to\; M_\nu < 0.46\,\text{eV}$$
$$M_\nu = 0 \;\to\; N_{eff} = 3.8 \pm 0.4$$
$$M_\nu < 0.62\,\text{eV} \;\to\; N_{eff} = 3.9 \pm 0.4$$

1212.3608



νMSM parameter space with resonant DM



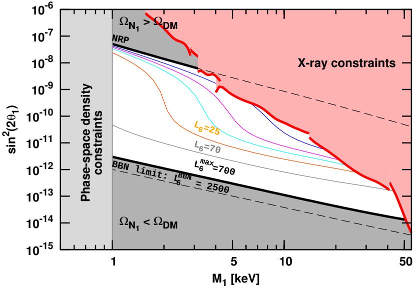
L.Canetti, M.Drewes, M.Shaposhnikov 1204.3902

Lightest sterile neutrino N_1 as Dark Matter

Non-resonant production (active-sterile mixing) is ruled out

Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16}$ GeV

arXiv:0804.4542, 0901.0011, 1006.4008



Dark Matter production from inflaton decays in plasma at $T \sim m_\chi$

Not seesaw neutrino!

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I}\bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be "naturally" Warm ($250\,\text{MeV} < m_\chi < 1.8\,\text{GeV}$)

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\text{ MeV}}\right) \text{keV}$$