# Sterile neutrinos in cosmology

**Dmitry Gorbunov**

**Institute for Nuclear Research of RAS, Moscow**

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# Phenomenological problems of the Standard Model

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

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 ($\Omega_{DM}$) : 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

# Sterile neutrinos: state of the art

- Mass scale $M_N$ is unclear: from $m_\nu$ to $10^{14}$ GeV
  Quantum corrections to Higgs: it is either below 10 TeV or . . . SUSY?
- BAU can be generally explained with $m_N \gtrsim 10^9$ GeV;
  Degeneracy in sterile neutrinos allows for leptogenesis even for $m_N \gtrsim 100$ MeV
- Dark matter sterile neutrino IS NOT see-saw neutrino:
  it contributes little to $m_\nu$
  however it may form Warm dark matter, from PhSD (Fermi principle) $M_N \gtrsim 1$ keV
- Presently 1 eV-neutrinos contribute little to Dark Matter but earlier to Dark radiation, as active neutrinos do
  Generally, 1 eV-neutrinos with mixing $\sim 0.01$ can be tested only with cosmological data, however $f(R)$ screens it
  At present 1 eV-neutrino is (still?) OK with cosmology

# Outline

1. Scheme: seesaw type I
2. Bonus: What else they can be responsible for?
3. Neutrino role in cosmology: present limits and future searches
4. Conclusion

# Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

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

$L_\alpha$ 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 $\Lambda_\nu$ ?

# Outline

# Sterile neutrino lagrangian

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 $\Delta m_{ij}^2$: | oscillation experiments |
| 3 $\theta_{ij}$: | oscillation experiments |
| 1 CP-phase: | oscillation experiments |
| 2(1) Majorana phases: | $0\nu ee$, $0\nu\mu\mu$ |
| 1(0) $m_\nu$: | $^3\text{H} \to ^3\text{He} + e + \bar{\nu}_e$, 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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# Seesaw mechanism: $M_N \gg 1$ eV

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:

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

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

# Seesaw mechanism: sterile neutrino scale

For $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we found the eigenvalues:

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

SEESAW says nothing about the sterile neutrino scale $M_I$ !

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 $(LH)^2/\Lambda$

At given $M_N$ without fine tuning the scale of Yukawas $\hat{f}$ and strength of active-sterile mixing $\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$ are fixed

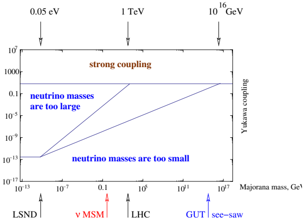
1203.3825

# Outline

# Bonus: depends on the sterile neutrino mass range

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}^\dagger \hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism
Extended seesaw




There are different regions:

$M_N \sim$ 1 eV-5 GeV

- keV-scale dark matter
- BAU via leptogenesis
- Neutrino anomalies (1 eV sterile neutrinos?)

direct searches!

$M_N \sim$ 50 GeV-5 TeV

- BAU via leptogenesis

$f \sim 10^{-6} \simeq Y_e$

but with fine tuning or new global or gauge symmetries (e.g. $SU(2)_L \times SU(2)_R$)

direct searches at LHC

$M_N \sim 10^{12}$-$10^{14}$ GeV

- BAU via leptogenesis

$f \simeq 0.01 - 1$

Untestable. . . ?

# Superheavy sterile neutrinos: $M_N \simeq 10^{12}$-$10^{14}$ GeV

- Motivation: close to GUT scales, e.g. $SO(10)$
- Bad fact: huge finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \gg m_H^2 (\Rightarrow M_N < 10^7$ GeV)
  SUSY solution? (New fileds...new problems: e.g. gravitino overproduction with high $T_{reh}$ for leptogenesis)
- Good fact: If $T > M_N$ decays of thermal sterile neutrino yield the lepton asymmetry in the early Universe: M.Fukugita, T.Yanagita (1986)

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{l=2,3} f\left(\frac{M_{N_1}}{M_{N_l}}\right) \cdot \frac{\mathrm{Im}\left(\sum_\alpha f_{1\alpha} f_{l\alpha}^*\right)^2}{\sum_\gamma |f_{1\gamma}|^2} .$$

  Needs $M_{N_1} \gtrsim 10^9$ GeV or $M_{N_1} \gtrsim 10^{12}$ GeV without fine tuning in $\hat{f}$
- Exciting fact: to avoid washing out of $\Delta_L$ in $hl_\alpha \leftrightarrow h\bar{l}_\beta$ we need ...
  $M^\nu < 0.1 - 0.3$ eV !!!
- Cooling down: No way to test further. Can get $\Delta_B \sim 10^{-10}$ even with
  $\theta_{13} = \delta_{CP} = 0$!

NB: can work for nonthermal case as well

production by inflaton decay G.Lazaridies, Q.Shafi (1991) e.g. in $R^2$-inflation D.G., A.Panin (2010)

# Lepton asymmetry from sterile neutrino decays

Most general renormalizable lagrangian with Majorana neutrinos $N_I$, $I,\alpha = 1,2,3$.

$$\mathscr{L}_{SM} + \overline{N}_I i\partial\!\!\!/ N_I - y_{I\alpha}\bar{L}_\alpha \widetilde{H} N_I - \frac{M_I}{2}\overline{N}_I^c N_I + \text{h.c.}$$

where $\widetilde{H}_i = \varepsilon_{ij} H_j^*$, $i,j = 1,2$; complex Yukawas, Majorana mass: $\Delta L \neq 0$ lepton number violating processes ($N = N^c$ !):

$$N_I \to h l_\alpha \;, \quad N_I \to h \bar{l}_\alpha \;,$$

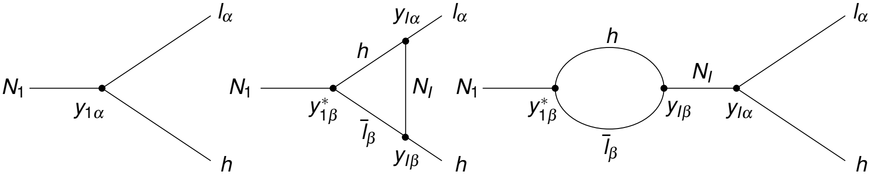
$$h l_\alpha \to h \bar{l}_\beta$$

At tree level one obtains ZERO

$$\Gamma^{tree}_{N_I} = \sum_\beta \frac{\left|y_{I\beta}\right|^2}{8\pi} M_I \;.$$

$$\Gamma^{tree}(N_I \to h l_\alpha) = \Gamma^{tree}(N_I \to h \bar{l}_\alpha) \;.$$

# Lepton asymmetry $\delta$ at 1-loop level $\quad y_{I\alpha}\bar{L}_\alpha N_I \widetilde{H}$




$$\Gamma(N_1 \to lh) = \frac{M_1}{8\pi} \cdot \sum_\alpha \left| y_{1\alpha} + \frac{1}{8\pi} \sum_{\beta,I} f\left(\frac{M_1}{M_I}\right) \cdot y^*_{1\beta} y_{I\alpha} y_{I\beta} \right|^2 , \quad m_\nu \ll M_I$$

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{I=2,3} f\left(\frac{M_1}{M_I}\right) \cdot \frac{\mathrm{Im}\left(\sum_\alpha y_{1\alpha} y^*_{I\alpha}\right)^2}{\sum_\gamma |y_{1\gamma}|^2} .$$

$$M_{2,3} \gg M_1 , f\left(\frac{M_1}{M_I}\right) = -\frac{3}{2}\frac{M_1}{M_I} , \quad \delta = -\frac{3M_1}{16\pi} \frac{1}{\sum_\gamma |y_{1\gamma}|^2} \sum_{\alpha\beta I} \mathrm{Im}\left[ y_{1\alpha} y_{1\beta} \left( y^*_{I\alpha} \frac{1}{M_I} y^*_{I\beta} \right) \right] .$$

# For the seesaw-neutrino $y_{I\alpha}\bar{L}_\alpha N_I \widetilde{H}$

$$m_{\alpha\beta} = -\frac{v^2}{2}\sum_I y_{I\alpha}\frac{1}{M_I}y_{I\beta}\,, \quad \delta = -\frac{3\,M_1}{16\pi}\frac{1}{\sum_\gamma |y_{1\gamma}|^2}\sum_{\alpha\beta I}\mathrm{Im}\left[y_{1\alpha}y_{1\beta}\left(y^*_{I\alpha}\frac{1}{M_I}y^*_{I\beta}\right)\right]\,.$$

get an estimate for the microscopic asymmetry

$$\delta \lesssim \frac{3\,M_1}{8\,\pi\,v^2}m_{atm} \simeq 10^{-8}\times\frac{M_1}{10^8\ \mathrm{GeV}}\,.$$

# Production of macroscopic asymmetry

Let sterile neutrinos be in equlibrium at $T > M_1$

$$\Gamma^{tot}_{N_1} = \frac{M_1}{8\pi} \sum_\alpha |y_{1\alpha}|^2 \,,$$

$$m_{\alpha\beta} = -\frac{v^2}{2} \sum_I y_{I\alpha} \frac{1}{M_I} y_{I\beta} \,,$$

$$\Gamma^{tot}_{N_1} \lesssim H(T \sim M_1) \simeq M_1^2 / M^*_{Pl}$$

- Need strong hierarchy in $y_{I\alpha}$
- At $T \gtrsim H(T = M_1)$ other interactions are responsible for sterile neutrino production in plasma
- For the final lepton asymmetry (at $T \ll M_1$)

$$\Delta_L \sim \delta \cdot \frac{n_{N_1}(M_1)}{s(M_1)} \sim \frac{\delta}{g_*(M_1)} \sim 10^{-2} \times \delta$$

- So, $M_1 \gtrsim 10^9$ GeV

$$\Gamma^{tot}_{N_1} \gtrsim H(T \sim M_1) = M_1^2 / M^*_{Pl}$$

- Without any hierarchy [inverse decay]

$$K \equiv \frac{\Gamma^{tot}_N}{H(T \sim M_1)} = \frac{m_{atm} M^*_{Pl}}{4\pi v^2} \sim 10^2$$

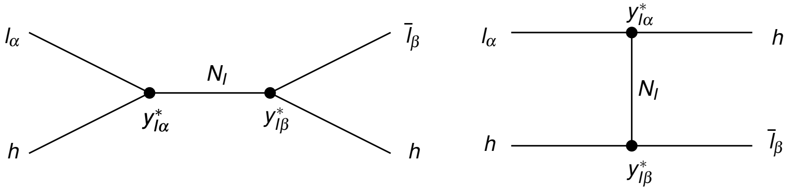
- For the final lepton asymmetry (at $T \ll M_1$)

$$\Delta_L \sim \frac{\delta}{g_*(M_1) \cdot K \cdot \log K} \sim 10^{-5} \times \delta$$

- So, $M_1 \gtrsim 10^{12}$ GeV

# Saving macroscopic asymmetry from "washing out"

e.g., due to scatterings $hl_\alpha \to h\bar{l}_\beta$ with exchange of virtual neutrino




at the interesting stage $T \ll M_1$ we estimate cross section for seesaw neutrino

$$\sigma_{lh}^{tot} \propto \sum_{\alpha\beta I} \left| \frac{y_{I\alpha} y_{I\beta}}{M_\gamma} \right|^2 \propto \frac{\mathrm{Tr}\left(mm^\dagger\right)}{v^4} \propto \frac{1}{v^4} \sum m_\nu^2$$

The asymmetry is safe if:

$\Gamma_{lh} = \text{const} \cdot \sigma_{lh}^{tot} \cdot T^3 \lesssim H(T)$ for $T = M_1\,, M_1/\log K$ one has $m_\nu < 0.1 - 0.3$ eV coincidence?

Certainly, everything can be obtained by numerical solution of the Boltzmann equation for the plasma components in the expanding Universe

# Superheavy sterile neutrinos: $M_N \simeq 10^{12}$-$10^{14}$ GeV

- Motivation: close to GUT scales, e.g. $SO(10)$
- Bad fact: huge finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \gg m_H^2 (\Rightarrow M_N < 10^7\,\text{GeV})$
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# Very heavy sterile neutrinos: $M_N \simeq 50\,\text{GeV-}5\,\text{TeV}$

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  No hierarchy between $\Lambda_\nu$ and $\Lambda_{EW}$
- Bad fact: Without extra symmetries, fine tuning or new interactions No generation of lepton asymmetry and hence No BAU
- Way out: fine tunning can help: e.g. resonant enhancement of CP-violation in out-of-equilibrium sterile neutrino decays:
  leptogenesis for $M_N \gtrsim 1$ TeV if $\Delta M_N \sim \Gamma_N$ Pilaftsis (1997,...)
- Further cooling down:
  can be directly produced but at a tiny amount only: $f \sim 10^{-6}$!
- Conclusion: Seesaw type I is generally untestable in direct searches:
  Yuakawa couplings are too small, while sterile neutrinos are quite heavy.

  To make interesting either NEW fields or fine tuning (or symmetries, e.g. $SU(2)_L \times SU(2)_R$) are required!!!

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

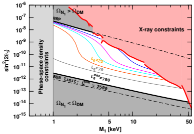
T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

- 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 $\Delta M_N \ll M_N$ 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

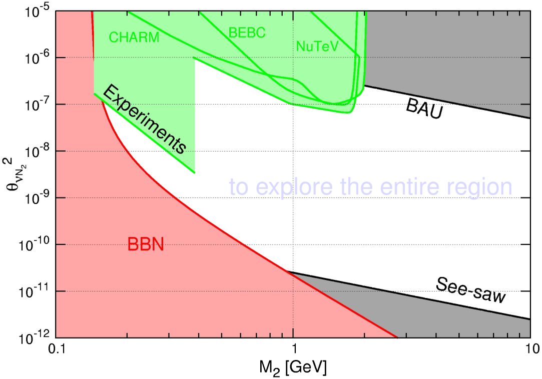
M.Shaposhnikov, I.Tkachev (2006), F.Bezrukov, D.G. (2009)

# Light sterile neutrinos: $M_N \lesssim 1$ eV

- For $M_N \sim m_\nu$ generally the active-sterile mixing is not small, $\theta_{se} \sim 1 \ldots$
  Is it dangerous? acceptable? preferable?
- We certainly change cosmology... Dark radiation, Hot Dark matter
  (BBN, CMB, structure formation, etc.)
  It can be found on top of quintessence (but cancel by $f(R)$) A.Starobinsky (2012)
- And they contribute to the active neutrino oscillations...
  (Neutrino anomalies at:
  LSND, gallium experiments, MiniBooNE, reactor experiments)
- Today It looks preferable! Though why not PQ-axion or dilaton?
- Impact on astrophysics (say, SN explosion, if needed) e.g., G.Raffelt (2010)
- Either special symmetry or not a seesaw: 1 eV by hand
  possible motivation: Mirror World?

# Outline

# Probing leptogenesis... on example of $\nu$MSM




D.G, M.Shaposhnikov (2007)

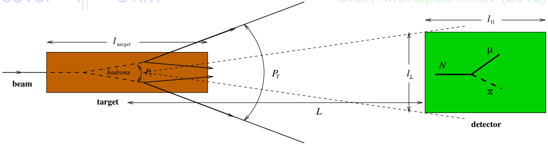
lower bound at $\times 10^{-4}$

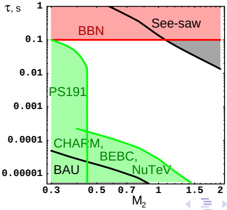
to explore the entire region

$$\mathrm{Br}\,(D \to lN) \lesssim 2\cdot 10^{-8}$$
$$\mathrm{Br}\,(D_s \to lN) \lesssim 3\cdot 10^{-7}$$
$$\mathrm{Br}\,(D \to KlN) \lesssim 2\cdot 10^{-7}$$
$$\mathrm{Br}\,(D_s \to \eta\, lN) \lesssim 5\cdot 10^{-8}$$
$$\mathrm{Br}\,(D \to K^* lN) \lesssim 7\cdot 10^{-8}$$
$$\mathrm{Br}\,(B \to DlN) \lesssim 7\cdot 10^{-8}$$
$$\mathrm{Br}\,(B \to D^* lN) \lesssim 4\cdot 10^{-7}$$
$$\mathrm{Br}\,(B_s \to D_s^* lN) \lesssim 3\cdot 10^{-7}$$

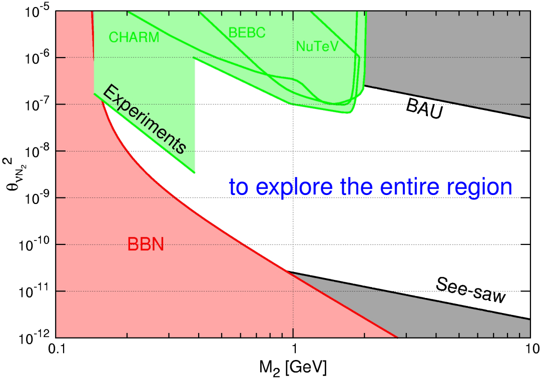
For $10^{20}$ PoT at 400 GeV (SPS) detectors have to cover $l_{||} \sim 3$ km

D.G., M.Shaposhnikov (2012)



# Probing leptogenesis... on example of $\nu$MSM




D.G, M.Shaposhnikov (2007)

lower bound at $\times 10^{-4}$

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

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

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

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

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

$Br(B \to DlN) \lesssim 7 \cdot 10^{-8}$

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

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

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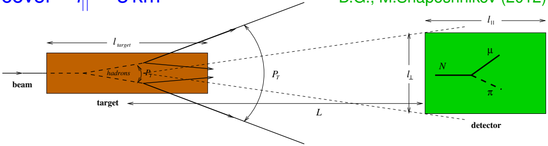
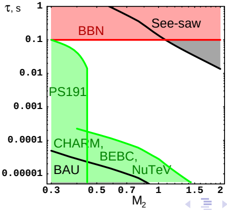
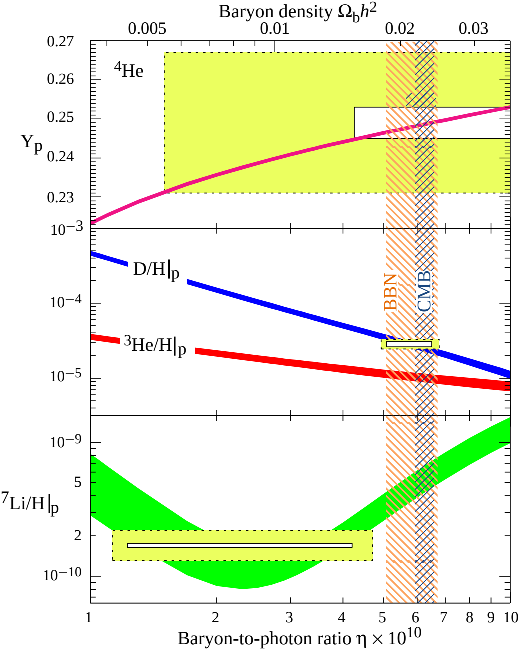


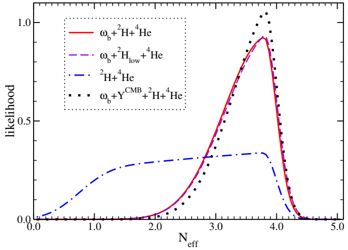






$$Y_p = 0.2581 \pm 0.025\,,$$

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

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

# Light sterile neutrinos at recombination and later

With larger $N_\nu$ and fixed $\Omega_M$ we get later RD/MD transition, hence:

- DM perturbations start to grow $\delta\rho_{DM}/\rho_{DM} \propto a$ later
- gravity potential evolution changes later
- oscillations in baryon-photon plasma change

CMB is sensitive to $(T_{eq} - T_{rec})$ !

LSS is sensitive to $T_{eq}$
if initial $\delta\rho_{DM}/\rho_{DM}$ is fixed

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma$$

Sterile neutrinos become nonrelativistic at $T \sim M_{\nu_s}/3 \sim 0.1 - 0.3$ eV ...

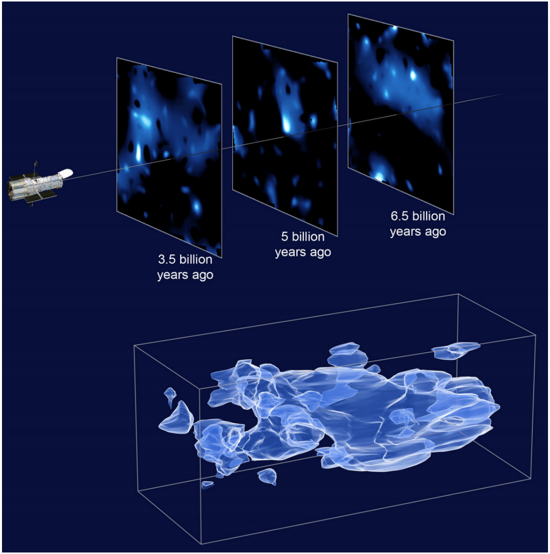
- neutrinos start to contribute to $\rho_M \propto 1/a^3$
- neutrino perturbations of large lengths contribute to DM perturbations $\delta\rho_M$
- neutrino perturbations of small scales disappear because of free streaming (Landau damping)
- oscillations in baryon-photon plasma: change ratio of acoustic and damping angular scales, thus smoothing the CMB damping tail

LSS is sensitive to both $N_\nu$ and $M_{\nu_s}$...
Not to forget about active neutrino masses!

$$\Omega_\nu = \frac{M_\nu}{93\, h^2\, \text{eV}}$$

1 eV neutrino contributes to dark matter but only a tiny amount!

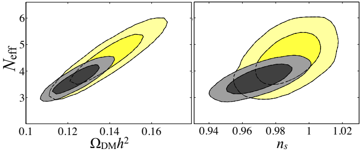
# LSS: SZ-clusters, Weak lensing of CMB



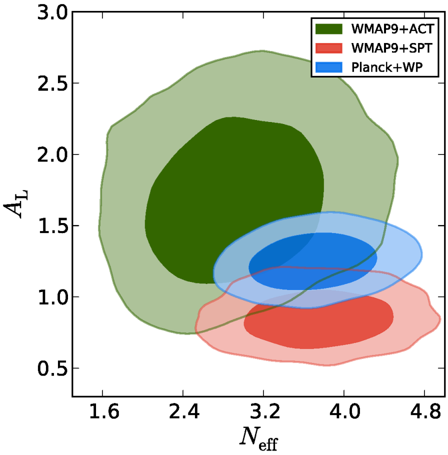

- $\Delta N_\nu$ amplifies shear power: cancel with quintessence contribution and flattening of spectrum, $n_s \to 1$
- $M_N$ reduces power

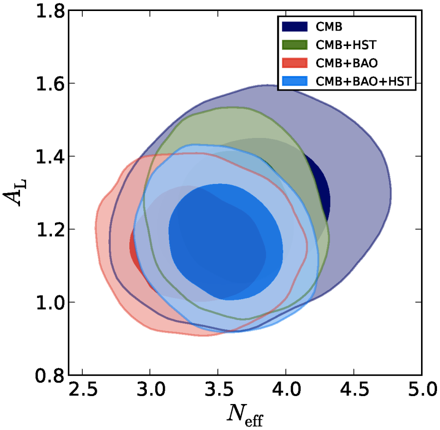
$$N_{eff} = 3 \;\to\; M_\nu < 0.46\,\text{eV}$$
$$M_\nu = 0 \;\to\; N_{eff} = 3.8 \pm 0.4$$
$$M_\nu < 0.62\,\text{eV} \;\to\; N_{eff} = 3.9 \pm 0.4$$

1212.3608



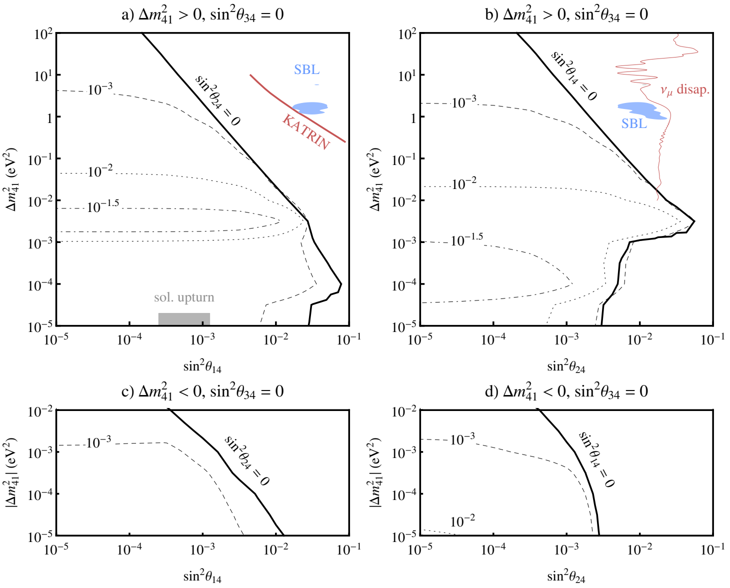
# However lensing is far from canonical




1304.6217

# Nevertheless, taking Planck $N_{eff} = 3.30 \pm 0.27$



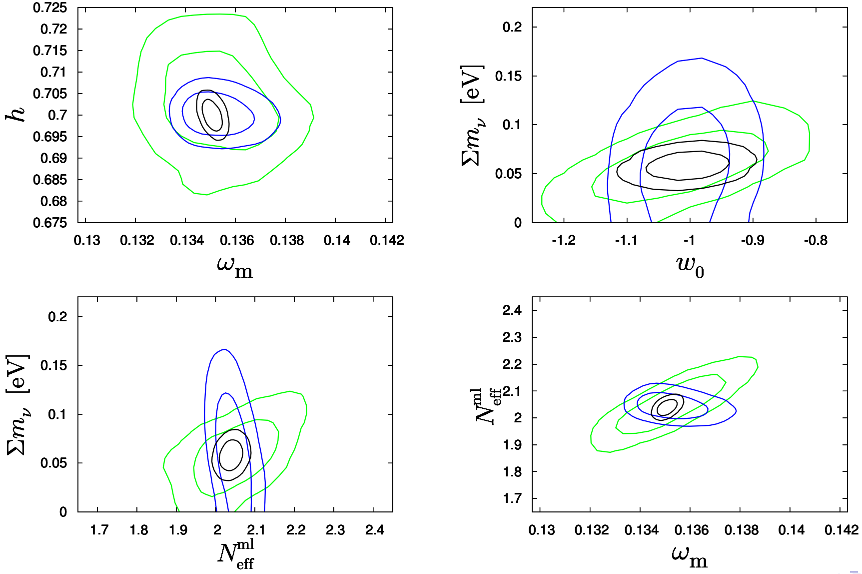

$\Delta m^2 =$

$10^{-5} - 10^{-2}$ eV$^2$

1303.5368

# Future: EUCLID-like survey of galaxies

1304.2321



# Outline

# Summary on sterile neutrinos

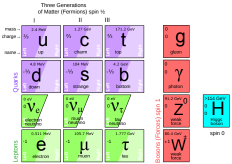
- Most economic explanation of neutrino oscillations within renormalizable approach:
  $N = 2$ Majorana neutrinos
- Capable of explaining baryon asymmetry of the Universe
  easily even with $\theta_{13} = \delta_{CP} = 0$
- One more neutrino can serve as (naturally Warm) dark matter
  this specia does not explain oscillations!
- Light sterile neutrino may be welcome in cosmology or to explain anomalies (LSND, . . . )
  but can not serve everywhere!
- If kinematically allowed: direct searches are feasible
- In the nearest future: CMB (Planck, $^4$He), LSS, reactor/gallium experiments;
  $N$ in atmospheric $\nu$ (IceCube, talk by C.Spiering) LSND/MiniBooNE: SPS beam with Li-Ar detectors

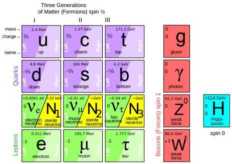
# Sterile neutrinos: the only unknown part of particle physics?!

- SM does not describe
  - Neutrino oscillations
  - Dark matter: sterile neutrino as DM
  - Baryon asymmetry: leptogenesis via sterile neutrino oscillations
  - Dark energy ($\Omega_\Lambda$)
  - Inflation: $R^2$, $RH^\dagger H$, ...
  - Strong CP: changing topology, ...
  - Gauge hierarchy: No scales!
  - Quantum gravity

$\nu$MSM explains these

explained by Plank-scale physics ?

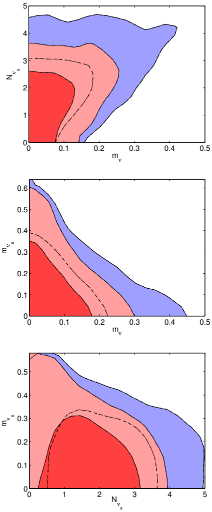


# Backup slides

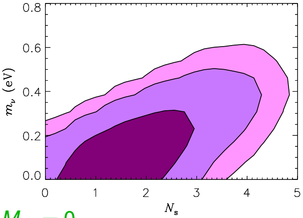
# Combined analysis for sterile and active neutrinos

WMAP7+LRG+HST

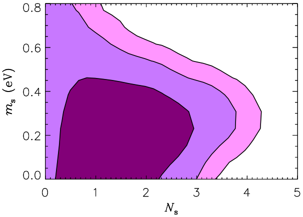



flat ΛCDM 1102.4774

CMB+SDSS+HST



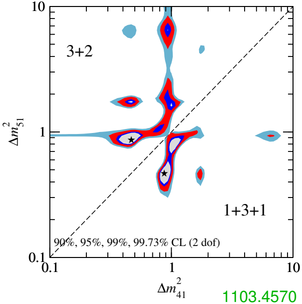

$M_{\nu s} = 0$




$m_\nu = 0$

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" :

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

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

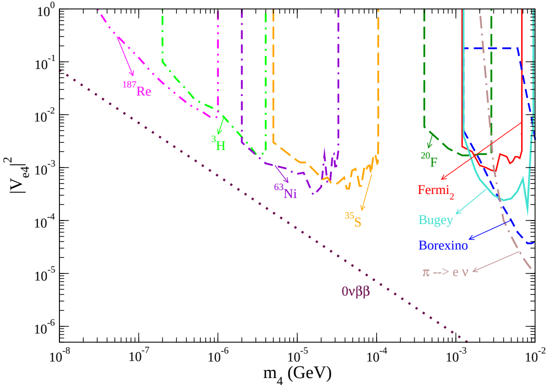
BBN rules out "3+2"

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

talk by A.Starobinsky

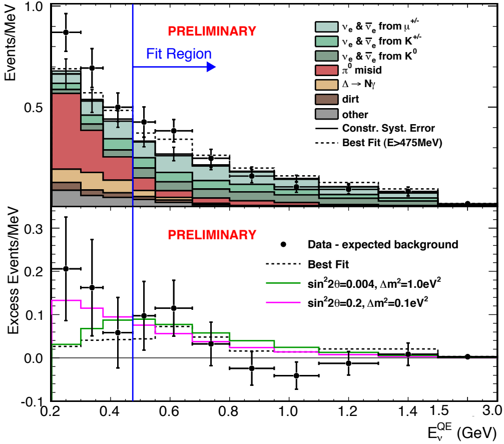
# Light sterile neutrinos: $M_N \lesssim 1$ eV

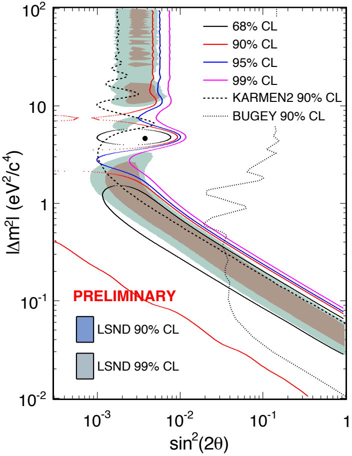
Essentially no bounds from kink searches, and even from $0\nu\beta\beta$




0901.3589: $0\nu\beta\beta$-bound is stronger by 10, 1205.3867

# LSND & MiniBooNE anomalies in $\bar{\nu}_\mu \to \bar{\nu}_e$

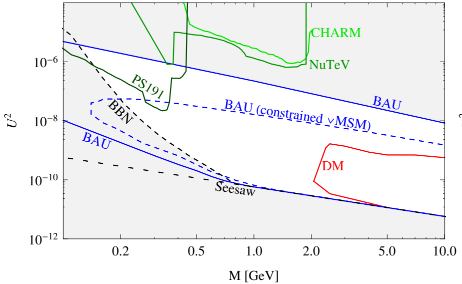


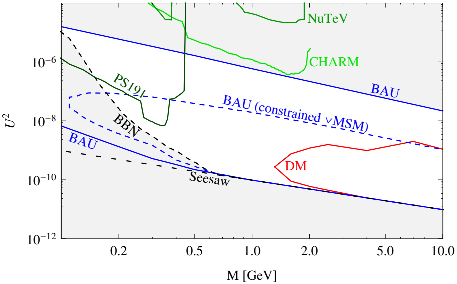




$\nu_e$ for $\nu_\mu$ mode at MiniBooNE: no LSND-like effects,
However Low energy excess of $\nu_e$
Explanation by $\nu_\mu \to N$, $N \to \gamma\nu$, S.Gninenko (2007,2010)

NuFuct2011, 1201.1519
LSND-like oscillations are preferable only at 90%CL

# $\nu$MSM parameter space with resonant DM



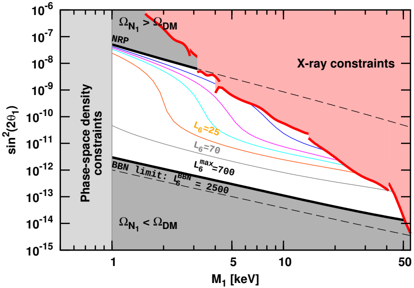

L.Canetti, M.Drewes, M.Shaposhnikov 1204.3902

# 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)

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