Heavy sterile ν's

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

VIII International Pontecorvo

Neutrino Physics School

Sinaia, Romania

Outline

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Standard Model: Major Problems

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

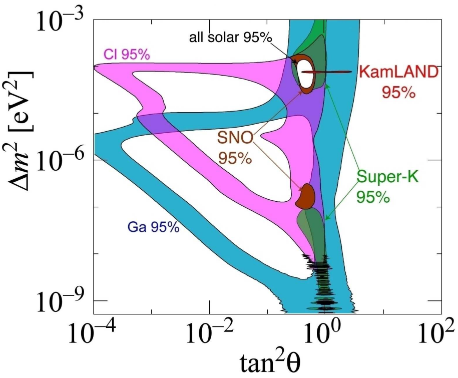
Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

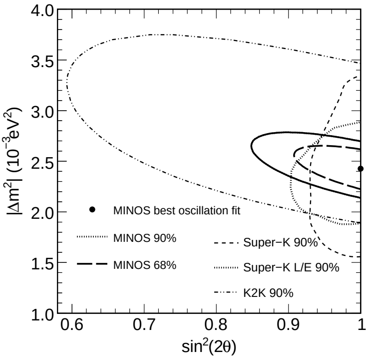
- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

Only direct evidence for New Physics ???

Neutrino oscillations: masses and mixing angles

Solar 2×2 "subsector" | Atmospheric 2×2 "subsector"





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

arXiv:0806.2237

$m_1 > 0.008\,\text{eV}$

$m_2 > 0.05\,\text{eV}$

DAYA-BAY, RENO, T2K: $\sin^2 2\theta_{13} \approx 0.08$

Physics behind the neutrino oscillations is still elusive

- nature of neutrino mass (Dirac vs Majorana)
- neutrino mass hierarchy
- *CP*-violation
- relevance for the matter-antimatter asymmetry
- neutrino anomalies — do not fit to 3ν
  - LSND $\rightarrow$ MiniBooNE
  - SAGE & GALLEX (gallium anomaly)
  - reactor antineutrinos $\rightarrow$ DANSS, NEUTRINO-4

These issues must be fixed before suggesting ν as a tool

- Explore entire structures of Earth and Sun
- Investigate the SN explosion mechanism
- Monitor nuclear reactors (nuclear power plants, etc)
- …

see Lecture by A.Hayes

New Physics can interfere if its scale is low

Phenomenological problems of the Standard Model

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

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  - Dark matter (Ω_{DM}) : sterile neutrino as DM
  - Baryon asymmetry : leptogenesis via sterile neutrino decays or oscillations

- Sterile neutrinos explain the oscillations
- and (add to) the cosmological problems

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Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

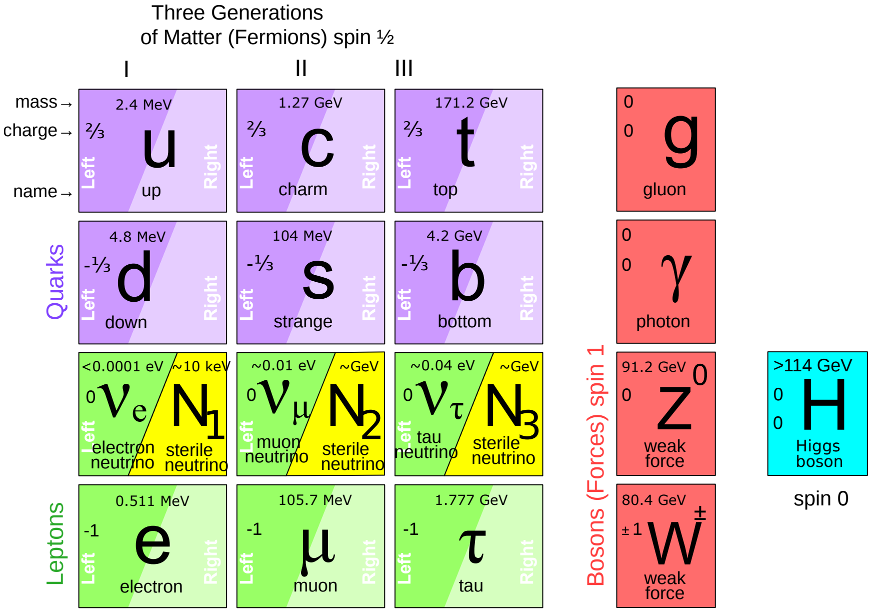
sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

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


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
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
<0.0001 eV
~10 keV
0
νe
N1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
νμ
N2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ντ
N3
tau neutrino
sterile neutrino
91.2 GeV
0
0
Z
weak force
>114 GeV
0
0
H
Higgs boson
spin 0
Leptons
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
Bosons (Forces) spin 1
Left
Right

Seesaw mechanism: $M_N \gg 1$ eV

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

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

Higgs gains $\langle H \rangle = v/\sqrt{2}$ and then

see Lecture by S.Bilenky and Lectures by A.Smirnov

$$\mathscr{V}_N = \frac{1}{2} \left(\overline{\nu}_e \, , \overline{N}^c \right) \begin{pmatrix} 0 & v \frac{f}{\sqrt{2}} \\ v \frac{f}{\sqrt{2}} & M_N \end{pmatrix} \begin{pmatrix} \nu_e \\ N \end{pmatrix} + \text{h.c.}$$

For a hierarchy $M_N \gg M^D \equiv v \frac{f}{\sqrt{2}}$ we have

flavor state $\nu_e = U \nu_1 + \theta \, N$ with $U \approx 1$ and

active-sterile mixing: $$\theta = \frac{M^D}{M_N} = \frac{v f}{2 M_N} \ll 1$$

and mass eigenvalues

$$\approx M_N \quad \text{and} \quad -m_{active} = \theta^2 M_N \lll M_N$$

Violation of L, C and CP symmetries

$$\mathscr{L}_N = \overline{N} i \partial\!\!\!/ N - f \overline{L}_e^c \tilde{H} N - \frac{M_N}{2} \overline{N}^c N + \text{h.c.}$$

- $f = 0 \quad \longrightarrow \quad$ free fermion, no need to call 'sterile'
- $M_N = 0 \quad \longrightarrow \quad N$ and ν form pure Dirac neutrino,
  the most boring case, worth than we have with the Higgs boson
  one may refuse to call it 'new physics'
- $f \neq 0, \quad M_N \neq 0 \quad \longrightarrow \quad$ introduces new massive parameter,
  violates lepton symmetry L see Lecture by G.Mitselmakher
  (and C- and CP-symmetry with several N's)

Seesaw mechanism: $M_N \gg 1$ eV

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

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

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

$$\mathscr{V}_N = \frac{1}{2}\left(\overline{\nu}_1, \ldots \overline{N}^c_1 \ldots\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_1, \ldots N_1 \ldots\right)^{\text{T}} + \text{h.c.}$$

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

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

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$ neither $U_{\alpha i}$ nor $\theta_{\alpha I}$ is unitary

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

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

Outline

Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$ appeared at energy scale Λ

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

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; see Lecture by S.Bilenky

in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{v^2 F_{\alpha\beta}}{4\Lambda} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.} = m_{\alpha\beta} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

where

Λ is the scale of new dynamics — only their ratio is fixed

$F_{\alpha\beta}$ is the strength of new dynamics — by the scale of active neutrino masses

Perturbative regime for model parameters

$$\frac{v^2 F_{\alpha\beta}}{4\Lambda} = m_{\alpha\beta}$$

$$F_{\alpha\beta} \lesssim 1 \qquad \Longrightarrow \qquad \Lambda \lesssim 3 \times 10^{14}\,\mathrm{GeV} \times \left(\frac{3 \times 10^{-3}\,\mathrm{eV}^2}{\Delta m^2_{\mathrm{atm}}}\right)^{1/2}$$

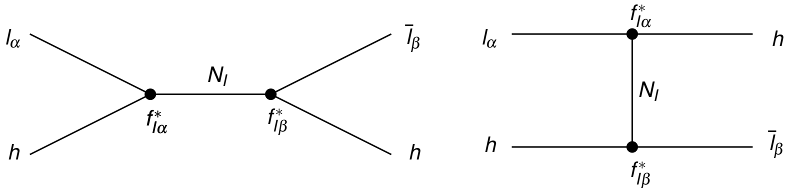
The model has to be UV-completed at the scale Λ $\rightarrow$ New physics

What is above Λ ?

Producing the effective dim-5 operator below M_N

integrating out the Heavy sterile neutrinos

see Lecture by S.Bilenky



thus we obtain

$$\propto \frac{f^2}{M_N} lhlh \quad \to \quad \frac{F(LH)(LH)}{\Lambda}$$

Seesaw mechanism: sterile neutrino scale

For $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we found the eigenvalues: see Lectures by A.Smirnov

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

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 $(LH)^2/\Lambda$

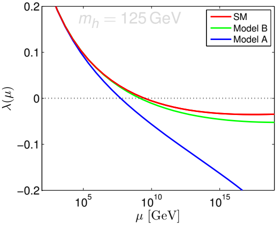
At given M_N without fine tuning the scale of Yukawas $\hat{f}$ and strength of active-sterile mixing $\theta_{\alpha I} = \frac{(M^D)^T_{\alpha I}}{M_I} \propto \hat{f}^T \frac{v}{M_N} \ll 1$ are fixed see Lecture by G.Mitselmakher 1203.3825

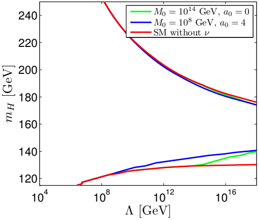
With fine tuning in $\hat{f}^T \hat{M}^{-1} \hat{f}$ can have larger f:

and change the Higgs mass window

$$\frac{d\lambda}{d\log\mu} \propto \lambda^2 + \lambda\, tr(\hat{f}^\dagger \hat{f}) - tr(\hat{f}^\dagger \hat{f} \hat{f}^\dagger \hat{f})$$

$$m_h^2 = 2\lambda v^2$$





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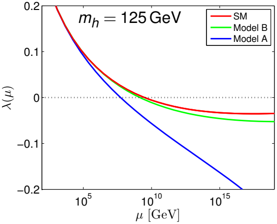

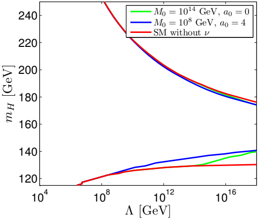

Where is sterile neutrino scale?

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

SEESAW says nothing about the sterile neutrino scale M_N !

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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 $\delta m_h^2 \propto f^2\Lambda^2$
- 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

$\delta m_h^2 \lesssim m_h^2$ then $M_N \lesssim 10^7$ GeV

see Lectures by A.Smirnov

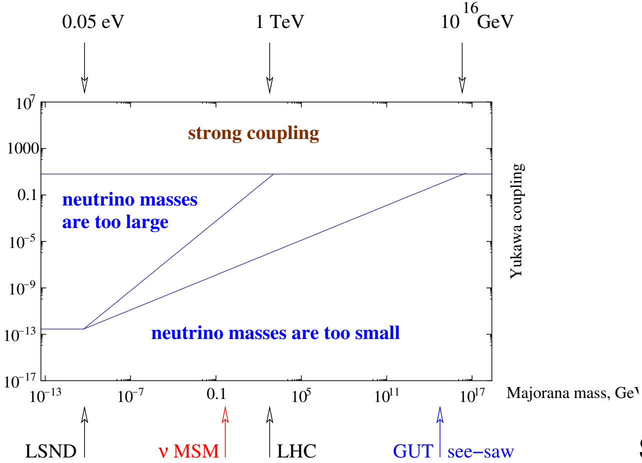
W.Bardeen (1995)

Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ 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



Seesaw diagram

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 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

18: $N = 3$ sterile neutrinos:

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

9 new parameters in total

Profit: can suggest why neutrinos are so light, $m_\nu \sim 0.1 - 0.01$ eV

Outline

Baryogenesis

– Need BAU $\eta_B \equiv n_B/n_\gamma \approx 6 \times 10^{-10}$ starting from BBN epoch, $T \lesssim 1$ MeV
– The same number at recombination and later

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)\ XY \dots \to X'Y' \dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}$
- processes above are out of equilibrium $X'Y' \dots B \to XY \dots$

At 100 GeV$\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

$$B - L\ , \quad L_e - L_\mu\ , \quad L_e - L_\tau$$

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe ... due to sterile neutrinos

Bonus: depends on the sterile neutrino mass range

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ 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
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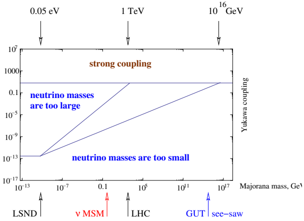
Extended seesaw



There are different regions:

$M_N \sim 1$ eV-100 GeV

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

direct searches!

$M_N \sim 100$ 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 colliders

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

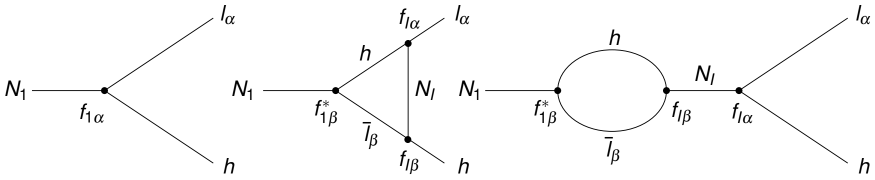
- BAU via leptogenesis

$f \simeq 0.01 - 1$

Untestable. . . ?
or already confirmed?

prefered by many, see Lectures by S.Bilenky, A.Smirnov

Lepton asymmetry δ at 1-loop level $\qquad f_{I\alpha}\bar{L}_\alpha N_I \widetilde{H}$



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

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

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

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)

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

  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 Δ_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)

Very heavy sterile neutrinos: $M_N \simeq 100$ GeV-5 TeV

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  No hierarchy between Λ_ν and Λ_{EW}
- Bad fact: Without extra symmetries, fine tuning or new interactions 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: as small as $f \sim 10^{-6}$!
- Conclusion: Seesaw type I is generally untestable in direct searches:
  Yuakawa couplings are too small, while sterile neutrinos are quite heavy.

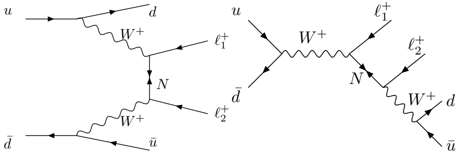
  To make interesting either NEW fields or fine tuning (larger f)
  or symmetries, e.g. $SU(2)_L \times SU(2)_R$ are required!!!

Very heavy sterile neutrinos: $M_N \simeq 50\,\text{GeV-}5\,\text{TeV}$

- Without fine tuning or extra symmetries:
  can be directly produced but @ tiny amount: $f \sim 10^{-6}$!
- With extra symmetries and/or interactions, e.g. $SU(2)_L \times SU(2)_R$
  can be studied at LHC $\quad pp \to W_R \to \mu N$
- Indirect searches ... $\Delta L = 2$ processes $\quad pp \to \ldots \mu^+\mu^+ \ldots,\ t \to b\mu^+\mu^+W^-$

$$D^+ \to \mu^+\mu^+K^-\,,\quad K^+ \to \mu^+\mu^+\pi^-$$

see Lectures by B.Kayser



$$\sigma\left(pp \to W^{\pm *}W^{\pm *} \to \ell_1^\pm \ell_2^\pm X\right) = \left(2-\delta_{\ell_1\ell_2}\right)\left|\theta_{\ell_1 N}\theta_{\ell_2 N}\right|^2 \sigma_0(WW)$$

$$\sigma(pp \to W^{+*} \to \ell_1^\pm\ \ell_2^\pm\ W^\mp) \approx \left(2-\delta_{\ell_1\ell_2}\right)\sigma(pp \to \ell_1^\pm N)Br(N \to \ell_2^\pm W^\mp)$$

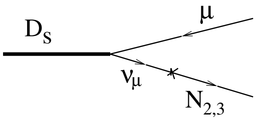
- Conclusion: Seesaw type I is testable only indirectly for this range of masses. To make interesting NEW fields (symmetries) are required!!!

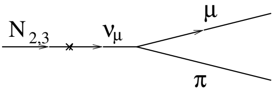
Outline

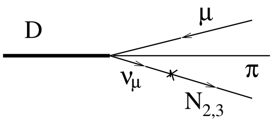
Heavy sterile neutrinos: $M_N \simeq 1\,\text{keV}$-$100\,\text{GeV}$

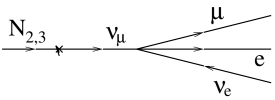
- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  True low-energy scale modification of the SM
- Good fact: At $T > 100\,\text{GeV}$ active-sterile neutrino oscillations produce lepton asymmetry in the early Universe, if $\Delta M_N \ll M_N$ E.Akhmedov, V.Rubakov, A.Smirnov (1998)
- can be directly produced !!

Weak decays due to mixing



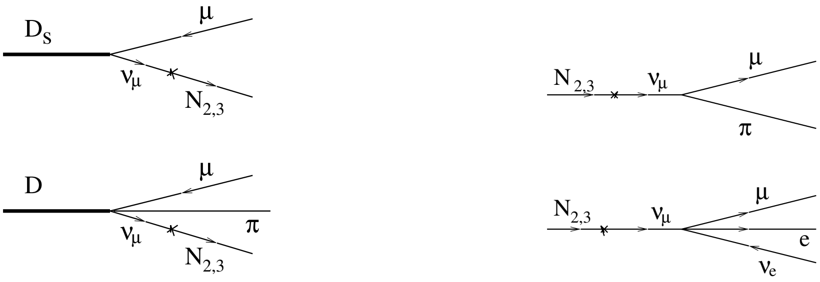






More on direct searches

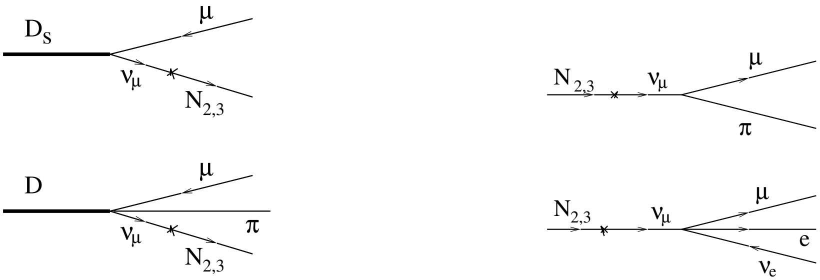
Weak decays due to mixing



$$\Gamma(A \to N + \ldots) \propto \theta^2 \qquad \Gamma(N \to B + \ldots) \propto \theta^2$$

- Searches for production of N: $S \propto \theta^2$ — e.g. peaks in p_μ
- Searches for decays of N:
  If the decay length is shorter than the detector size, $S \propto \theta^2$
  but with $\theta^2 \to 0$ arrive at $S \propto \theta^2 \times \theta^2$

And More. . .



- Amplification of production ini $1 \to 2$ (chirality)

$$\Gamma(M \to N + l) \propto \theta^2 M_N^2$$

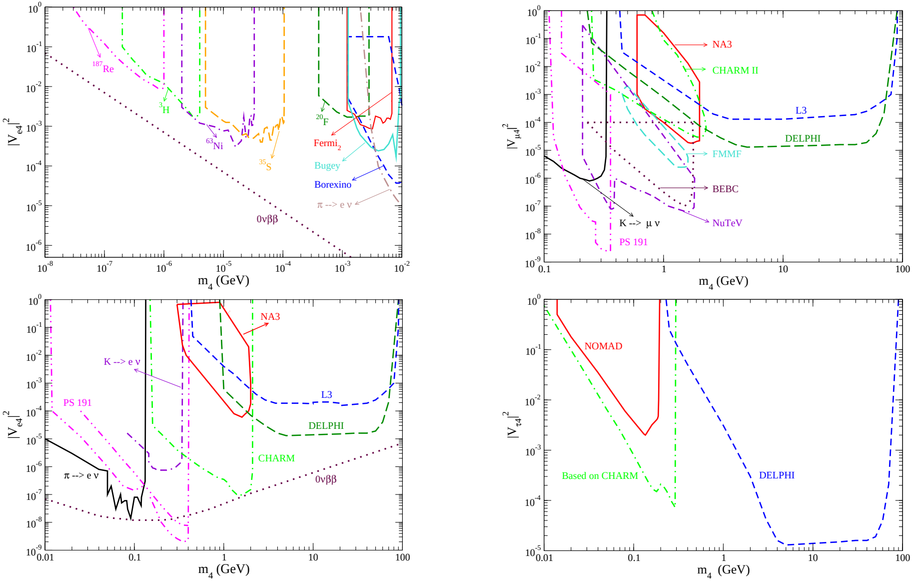
- heavy N decay is fast

$$\tau = \frac{\tau_\mu}{\theta^2} \times \left(\frac{m_\mu}{M_N}\right)^5 = 10^{-10}\,\text{s} \times \frac{10^{-6}}{\theta^2} \times \left(\frac{10\,\text{GeV}}{M_N}\right)^5$$

tends to decay inside the detector

Limits 10 years ago. . .

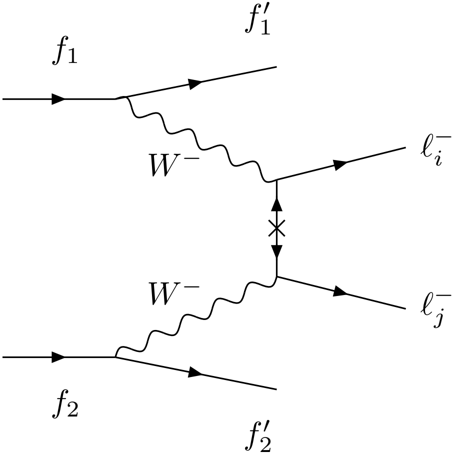
0901.3589



Indirect searches: $\Delta L = 2$ processes

$0\nu\beta\beta$

limits are only for one sterile neutrino...



for light sterile neutrinos

$$\langle m\rangle^2_{\ell_i\ell_j} = \left|\sum_I U_{\ell_i I} U_{\ell_j I} M_{N_I}\right|^2$$

for heavy sterile neutrinos

$$\left|\sum_I \frac{V_{\ell_i I} V_{\ell_j I}}{M_{N_I}}\right|^2,$$

How far we should go? νMSM

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

see Lectures by A.Smirnov

- Seesaw mechanism is provided mostly by two 'heavy' sterile neutrinos lightest active is almost massless
- They are (highly) degenerate in mass, $\Delta M_N \ll M_N$ producing matter-antimatter asymmetry of the Universe via leptogenesis in primordial plasma at $T > 100\,\text{GeV}$ E.Akhmedov, V.Rubakov, A.Smirnov (1998)

  mixing is constrained from above and from below !!
- The third 'light' sterile neutrino, $M_N \simeq$ 1-10 keV, is almost decoupled and serve as dark matter

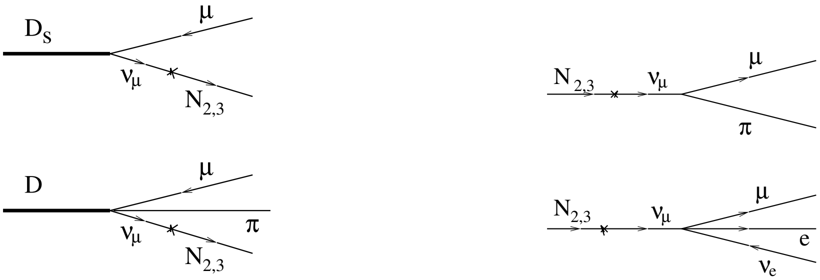
  mixing is constrained from above and from below !!

the model explain while the previous experiments fail...

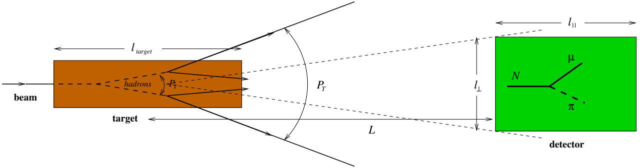
the model can be fully explored

Heavy sterile neutrinos: direct searches

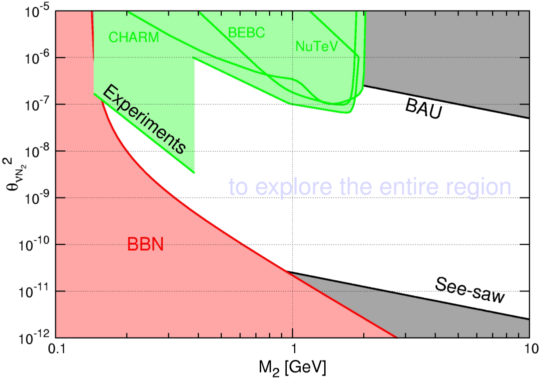
Weak decays due to mixing



Production in beam-dump experiments



Heavy sterile neutrinos on example of νMSM



D.G, M.Shaposhnikov (2007)

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

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

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

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

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

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

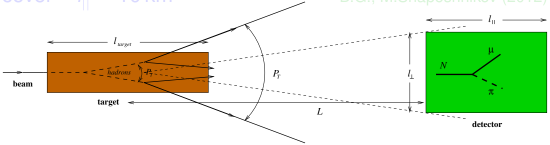
$Br(B \to DlN) \lesssim 7 \cdot 10^{-8}$

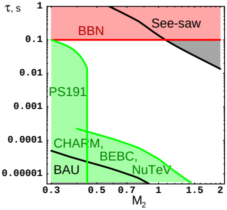
$Br(B \to D^* lN) \lesssim 4 \cdot 10^{-7}$

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

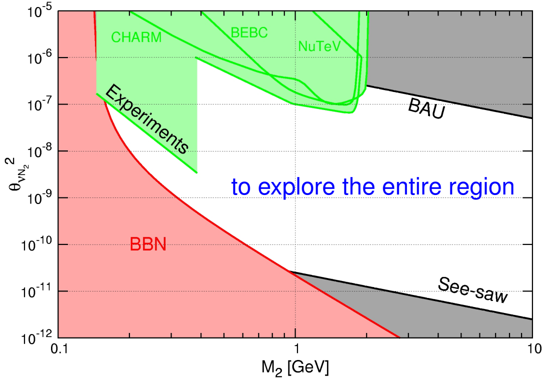
For 10^{20} PoT at 450 GeV (SPS) detectors have to cover $l_{||} \sim 10$ km

D.G., M.Shaposhnikov (2012)





Heavy sterile neutrinos on example of νMSM



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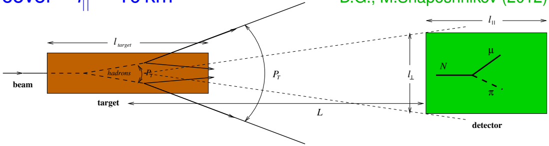
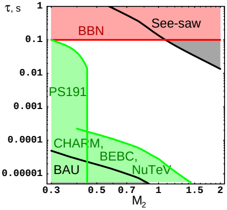
For 10^{20} PoT at 450 GeV (SPS) detectors have to cover $l_{||} \sim 10$ km

D.G., M.Shaposhnikov (2012)

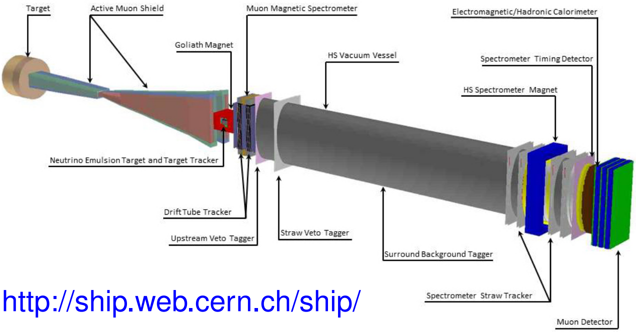




Towards a dedicated experiment

- νMSM: T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005),
- direct tests of νMSM: D.G., M.Shaposhnikov (2007)
- proposal for direct searches, to European Strategy Group, 2012 D.G., M.Shaposhnikov
- sketch of realistic experiment S.Gninenko, D.G., M.Shaposhnikov (2013)
- Expression Of Interests: Proposal to Search for Heavy Neutral Leptons at the SPS
  W. Bonivento, . . . D.G., et al, 1310.1762
- Technical Proposal and Physics Paper 1504.04956, 1504.04855
- included in the CERN GreyBook (2016) → 2028 46 institutes from 16 countries

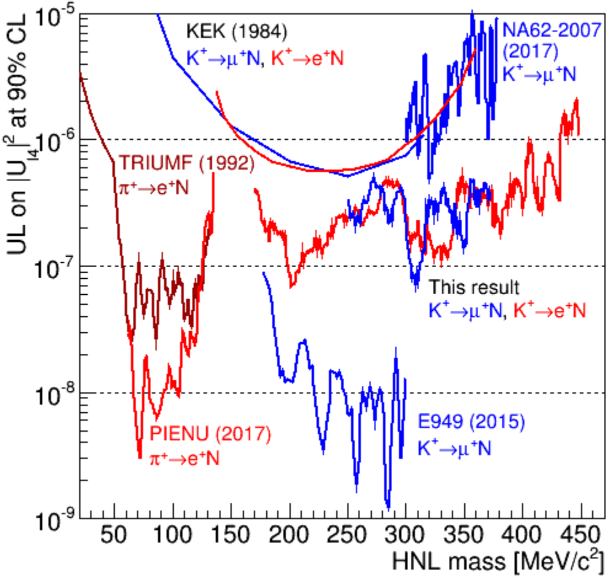
SHiP
Search for Hidden Particles



http://ship.web.cern.ch/ship/

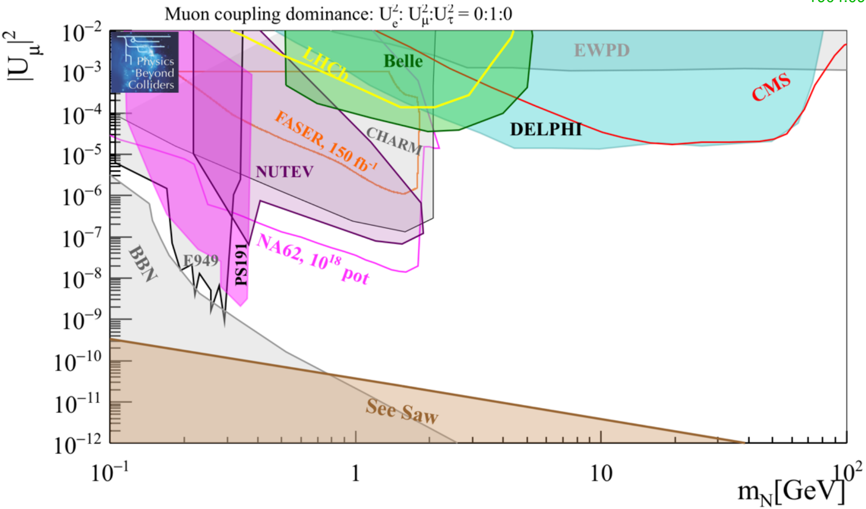
Present limits from production

1904.09124



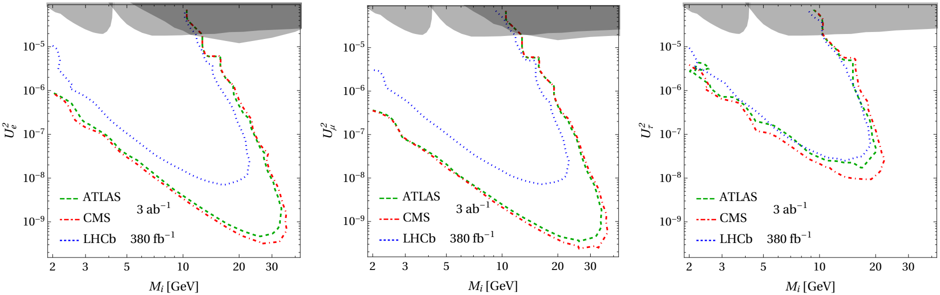
Present limits and expectations

1904.09124



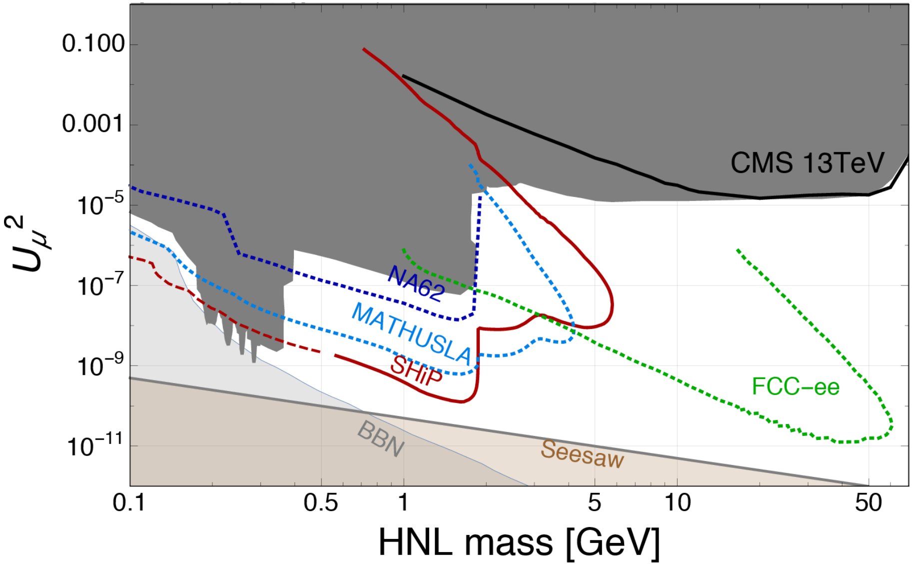
LHC-HL: expectations for a displaced vertex

1903.06100



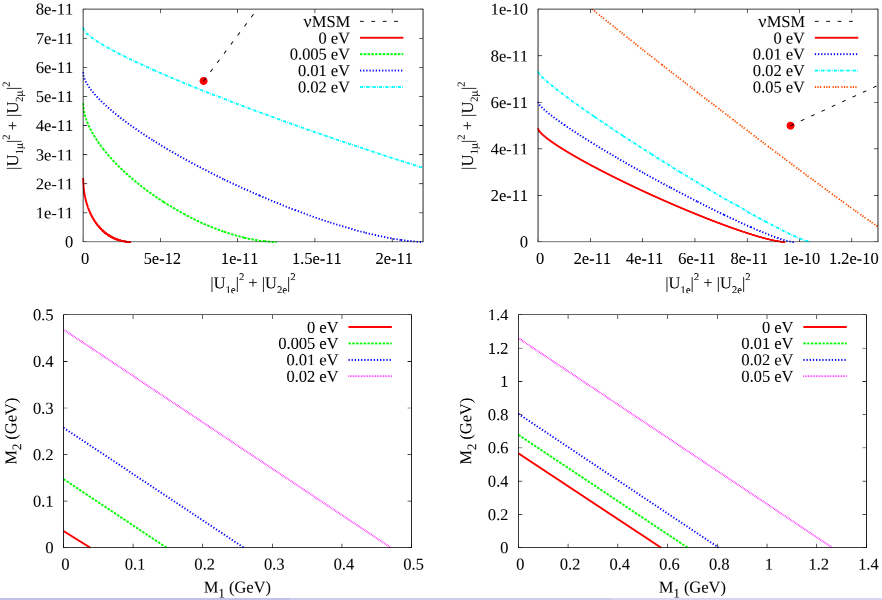
New projects. . .

1904.09124



Lowest mixing to falsify Seesaw type I

D.G., A.Panin (2013)



Outline

Sterile neutrino: a vast region of mass

Within the seesaw paradigm, as far as

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

Any set

(mass scale M_N, Yukawa coupling f)

is viable

And with special tunning or symmetry larger (but not smaller) mixing

is viable

$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f}\, v^2$$

Dark Matter properties from cosmology: $p = 0$

(If) particles:

1. stable on cosmological time-scale
   requires new (almost) conserved quantum number
2. produced in the early Universe at $T > 100\,\text{eV}$
3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\text{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies:
   smoothed out by free streaming
   If were in thermal equilibrium: $M_X \gtrsim 1$ keV
4. (almost) collisionless $p = 0$, $v_{\text{sound}} = 0$
5. (almost) electrically neutral CMB distortion
6. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

Sterile neutrino: well-motivated keV-mass Dark Matter

- massive fermions giving mass to active neutrino through mixing (seesaw)

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, $N \to \nu\nu\nu$ is always open
  but exceeding the age of the Universe if

(applicable for $M_N < M_W$)

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \quad \Longrightarrow \quad \theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\text{keV}}{M_N}\right)^5$$

- with seesaw constraint $m_a \sim \theta^2 M_N$

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

Sterile neutrino: indirect searches

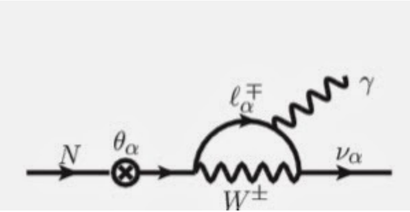
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe if

$$\frac{\theta^2}{3\times 10^{-3}} < \left(\frac{10\,\text{keV}}{M_N}\right)^5$$

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay

give limits in absence of the feature



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

$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\text{ keV}}{M_N}\right)^4$$

$F_\gamma \propto \Gamma_N \rho_N / M_N ...$

Can seesaw neutrino serve as DM ?

$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\ \text{keV}}{M_N}\right)^4 \qquad \frac{\theta^2}{10^{-5}} \sim \left(\frac{m_a}{0.1\,\text{eV}}\right)\left(\frac{10\,\text{keV}}{M_N}\right)$$

one order down

$$\frac{\theta^2}{10^{-7}} \lesssim \left(\frac{1\ \text{keV}}{M_N}\right)^4 \qquad \frac{\theta^2}{10^{-4}} \sim \left(\frac{m_a}{0.1\,\text{eV}}\right)\left(\frac{1\,\text{keV}}{M_N}\right)$$

...

How light can be this dark matter ?

Dark Matter Particle Properties $p=0$

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$, $\to M_X \gtrsim 1\text{keV}$ for thermal production)
3. (almost) collisionless
4. (almost) electrically neutral

Pauli blocking for fermions in a galaxy: $M_X \gtrsim 750$ eV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}} \Big|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Decoupling of relativistic Dark Matter

Assumptions

1. DM particles are in equlibrium in plasma
2. DM decouple from plasma at temperature $T_d \gtrsim M_X$,
   so they are relativistic (e.g. neutrino)

$$n_X(T_d) = g_X \cdot \binom{1}{\frac{3}{4}} \cdot \frac{\zeta(3)}{\pi^2} T_d^3$$

Later on useful

$$n_X a^3 = \text{const}, \qquad s a^3 = \text{const} \qquad \Longrightarrow \qquad \frac{n_X}{s} = \text{const} = \# \frac{g_X}{g_*(T_d)}$$

DM particle mass M_X fixes Ω_X:

$$\Omega_X = \frac{M_X \cdot n_{X,0}}{\rho_c} = \frac{M_X \cdot s_0}{\rho_c} \frac{n}{s} \approx 0.2 \times \frac{M_X}{100\ \text{eV}} \left(\frac{g_X}{2}\right) \cdot \left(\frac{100}{g_*(T_d)}\right)$$

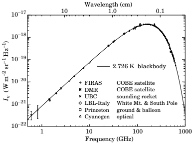
– NO thermal sterile neutrino DM !!

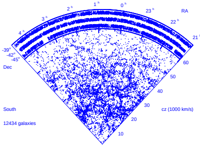
Pauli blocking prevents fermionic DM

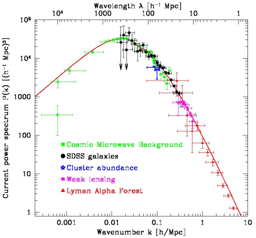
Matter perturbations

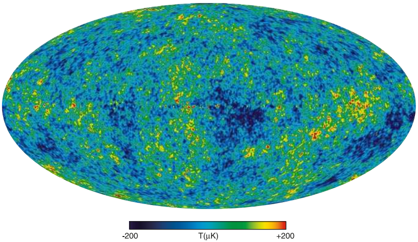
- CMB is isotropic, but “up to corrections, of course...”
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy: $\frac{\Delta T}{T} \sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination $(e + p \to \gamma + H^*)$ $\Longrightarrow$

  Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ galaxies (CDM halos)
- $\Delta\rho_{DM}/\rho_{DM} \propto a \propto 1/T$ from $T = 0.8\,\text{eV}$,
  while $\Delta\rho_B/\rho_B \propto a \propto 1/T$ only after recombination
  $T = 0.25\,\text{eV}$
  without DM total growth factor would be 1100
  not enough to explain structures!









Sterile neutrinos produced in plasma...

$$\Omega_N < \Omega_X = \frac{M_X \cdot n_{X,0}}{\rho_c} = \frac{M_X \cdot s_0}{\rho_c}\frac{n}{s} \approx 0.2 \times \frac{M_X}{100\text{ eV}}\left(\frac{g_X}{2}\right)\cdot\left(\frac{100}{g_*(T_d)}\right)$$

typical momenta are

$$\frac{p_X}{M_X} \propto \frac{a_d}{a} \sim \frac{3T}{M_X}\left(\frac{g_*(T)}{g_*(T_d)}\right)^{1/3}$$

at RD/MD transition (equality) their velocities are

$$v \sim \frac{T}{1\,\text{eV}}\frac{1\,\text{keV}}{M_X} \sim 10^{-3}$$

Warm Dark Matter:

all inhomogeneities of sizes smaller than (roughly)

$$l = v \times t_{Universe}$$

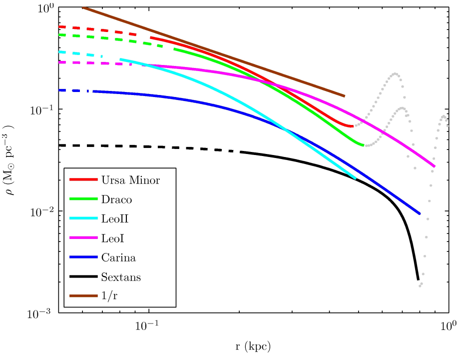
are smoothed out due to free streaming

it allows to test the model, but also...

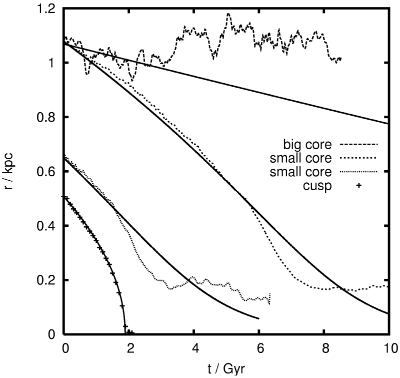
CDM Problems at small-scales . . . ?

- NFW profile fits nicely DM in galaxy clusters $\rho \propto r^{-1}(r + r_c)^{-2}$
- Dwarf galaxy density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
  most DM-dominated objects

Cores observed (?)

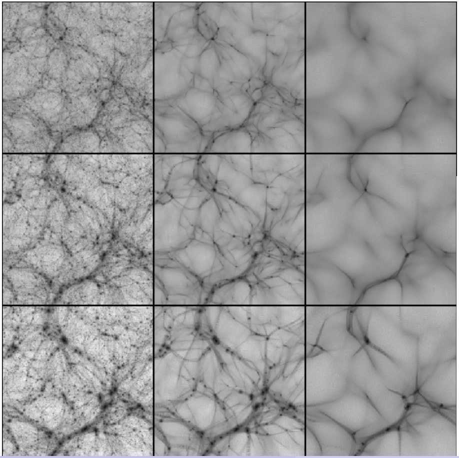


5 Clusters in the Fornax dSph

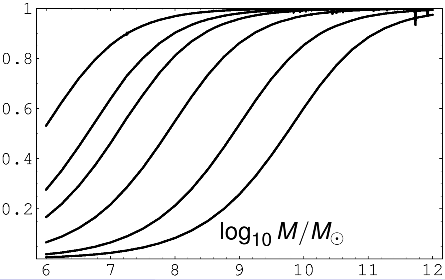


CDM Problems with small structures . . . ?

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 100 instead of 1000
- "Too big to fail" problem
- Solved (?) by Warm Dark Matter (sterile neutrino, gravitino) free-streaming



$\left(\frac{dN_{obj}}{d\ln M}\right)_{WDM} / \left(\frac{dN_{obj}}{d\ln M}\right)_{CDM}$



Refined constraint for DM: phase space density

after decoupling $f_i = f_i(\kappa)$ =const and defines psd, which remains intact due to the Liouville theorem even in galaxies with inhomogeneous distribution in space
coarse grained phase space density:

$$f(\kappa, \mathbf{x}, t) \leq \max_\kappa f_i(\kappa)$$

observation:

$$Q = \frac{\rho}{\langle v_{||}^2 \rangle^{3/2}} \equiv \mathscr{Q} \cdot 1 \frac{M_\odot/\mathrm{pc}^3}{(\mathrm{km/s})^3} = \left(5 \cdot 10^{-3} - 2 \cdot 10^{-2}\right) \frac{M_\odot/\mathrm{pc}^3}{(\mathrm{km/s})^3}.$$

$$Q \simeq 3^{3/2} \frac{\rho_{DM}}{\langle v_{DM}^2 \rangle^{3/2}} = 3^{3/2} m^4 \frac{n}{\langle P^2 \rangle^{3/2}} = 3^{3/2} m^4 f(\mathbf{P}, \mathbf{x}).$$

$$m^4 \gtrsim \frac{Q}{3^{3/2} \max f_i}$$

Sterile neutrino production in the early Universe

- before the EW transition, $T > T_{EW}$

$$H \to L + N\,, \qquad \frac{\Gamma_{H\to\nu_a N}}{H} \simeq \frac{f_\nu^2}{16\pi}\frac{T}{H} \ll 1,$$

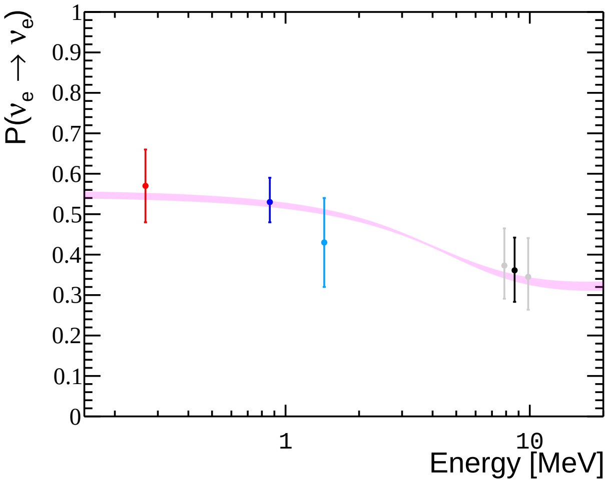
- after the EW transition, $T < T_{EW}$
  1. r.h. neutrino production in scatterings

$$\nu_L + X \to N_R + Y\,, \qquad \Gamma \propto \frac{M_D^2}{T^2}$$

  2. sterile neutrino production in oscillations

Neutrino matter effect: asymmetry

Mikheev–Smirnov–Wolfenstein effect



(BOREXINO)

Fermi charged currents

$$\mathscr{L} = -2\sqrt{2}G_F \bar{\nu}_e \gamma^\mu e \cdot \bar{e}\gamma_\mu \nu_e$$

only matter, no currents

$$\langle\langle \bar{e}_k \gamma^0_{kl} e_l \rangle\rangle = \langle\langle e^\dagger e \rangle\rangle = n_e,$$

$$\langle\langle \bar{e}_k \gamma^i_{kl} e_l \rangle\rangle = 0.$$

$$\langle\langle e_k \bar{e}_l \rangle\rangle = -\frac{1}{4}\gamma^0_{kl} \cdot n_e$$

Fermi interaction gives

$$\mathscr{L}_{eff} = -\sqrt{2}G_F n_e \bar{\nu}_e \gamma^0 \nu_e.$$

$$i\gamma^0 \partial_0 \to i\gamma^0 \partial_0 - \sqrt{2}G_F n_e \gamma^0,$$

effective potential

$i\partial_0 - V$, with $V = \sqrt{2}G_F n_e$

competes with

$$H_{eff} = \Delta m^2/2E$$

see Lectures by B.Kayser

Production in oscillations

$$\frac{\partial}{\partial t} f_s(t,\mathbf{p}) - H\mathbf{p}\frac{\partial}{\partial \mathbf{p}} f_s(t,\mathbf{p}) = \frac{1}{2}\Gamma_\alpha P(\nu_\alpha \to \nu_s)\, f_\alpha(t,\mathbf{p}).$$

$\Gamma_\alpha \propto G_F^2 T^4 E$ is the weak interaction rate in plasma

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha^{\text{mat}} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\text{mat}}}\right),$$

$$t_\alpha^{\text{mat}} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha}\cdot t_\alpha^{vac})^2}},$$

$$\sin 2\theta_\alpha^{\text{mat}} = \frac{t_\alpha^{\text{mat}}}{t_\alpha^{vac}} \cdot \sin 2\theta_\alpha, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

sign of the effective plasma potential matters:

$V_{\alpha\alpha} < 0 \implies$ mixing gets suppressed

$V_{\alpha\alpha} > 0 \implies$ amplification via resonance

DM from oscillations: (DW & ShF)

$$\left(\cos 2\theta_\alpha - V_{\alpha\alpha} \cdot t_\alpha^{vac}\right)^2$$

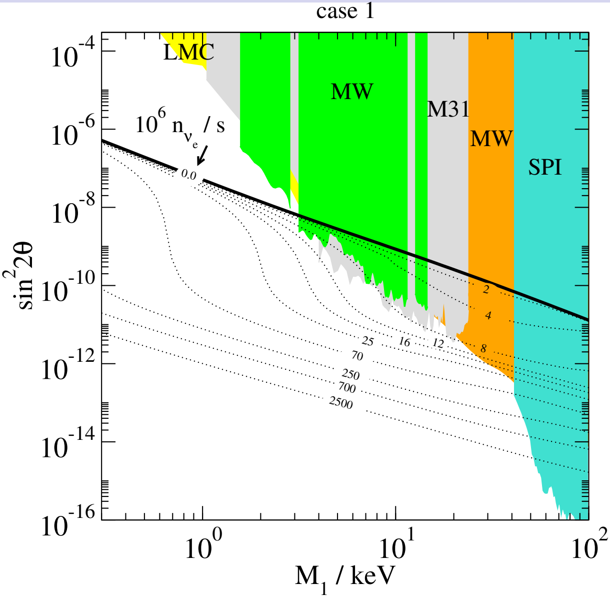
non-resonant:

$$V_{\alpha\alpha} \sim -\# G_F^2 T^4 E$$

resonant production in the lepton asymmetric plasma

$$V_{\alpha\alpha} \sim +\# G_F T^2 \mu_{L_\alpha}$$

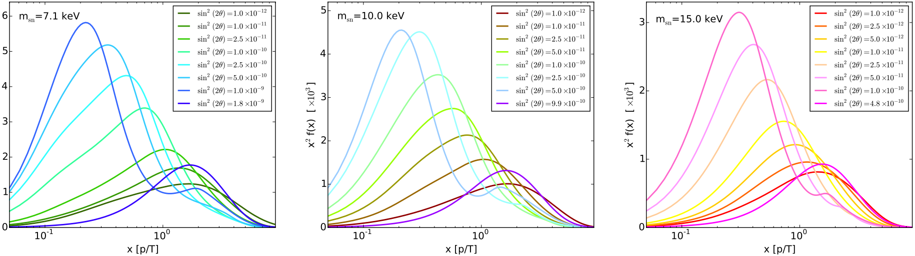
1601.07553

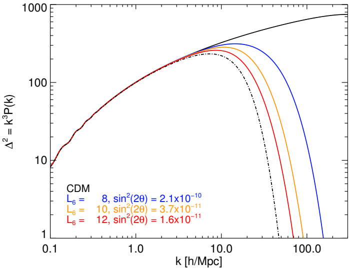


BAU-DM relation?

$\ldots \Omega_B \sim \Omega_{DM}$

Sterile neutrino spectra from oscillations





1601.07553

non-resonant production:

thermal-shape spectrum

both models imply Warm DM, $v_{EQ} \sim 10^{-3}$,
Free Streaming at scales $L \lesssim v_{EQ}/H_{EQ} \to$

no such structures

1611.00005

$$v = \frac{\langle p \rangle}{m} = 3.15\,\frac{T}{m}\left(\frac{g_{*,0}}{g_*}\right)^{1/3}$$

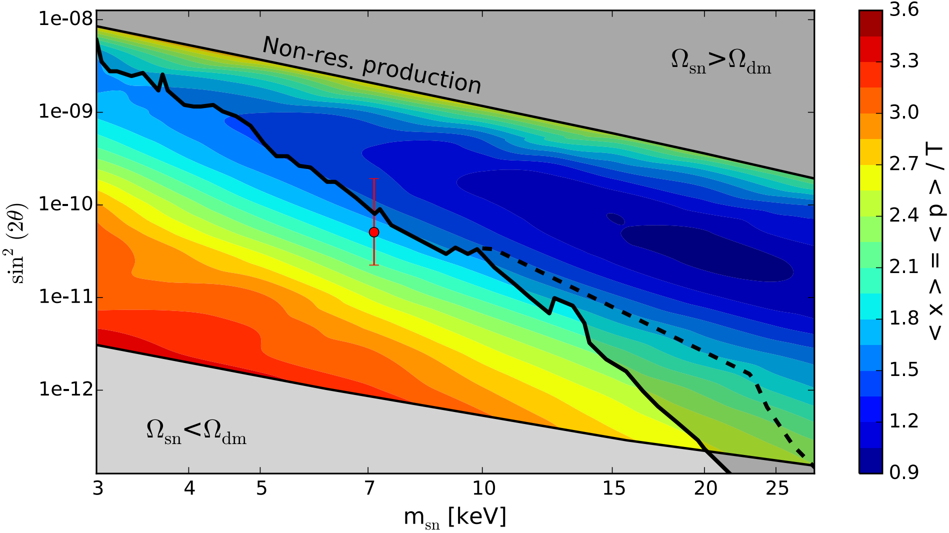
Refined constraint for DM: phase space density

for non-resonance production D.G., A.Khmelnitsky, V.Rubakov (2008)

$$m \gtrsim 6\,\text{keV} \cdot \left(\frac{0.2}{\Omega_{DM}}\right)^{1/3} \left(\frac{\mathcal{Q}}{5 \cdot 10^{-3}}\right)^{1/3} \left(\frac{g_*(T_d)}{43/4}\right)^{1/3},$$

and about 3-6 keV for resonant one F.Bezrukov, D.G. (work in progress)

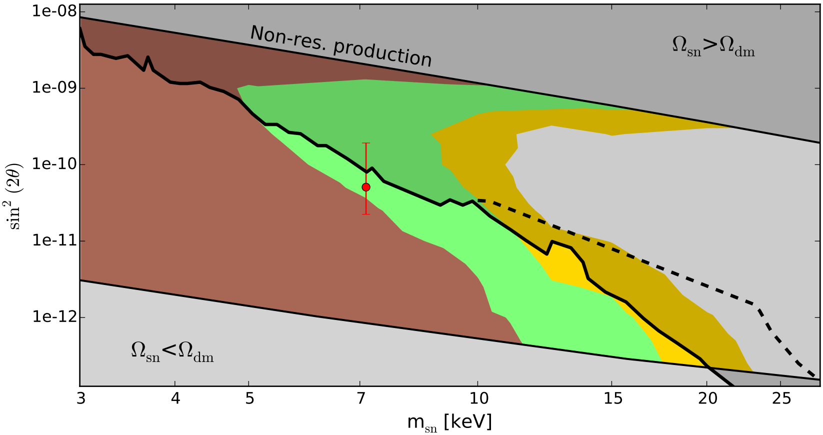
Sterile neutrino Dark Matter



A.Schneider (2016)

Sterile neutrino Dark Matter: ... gone?

A.Schneider (2016)



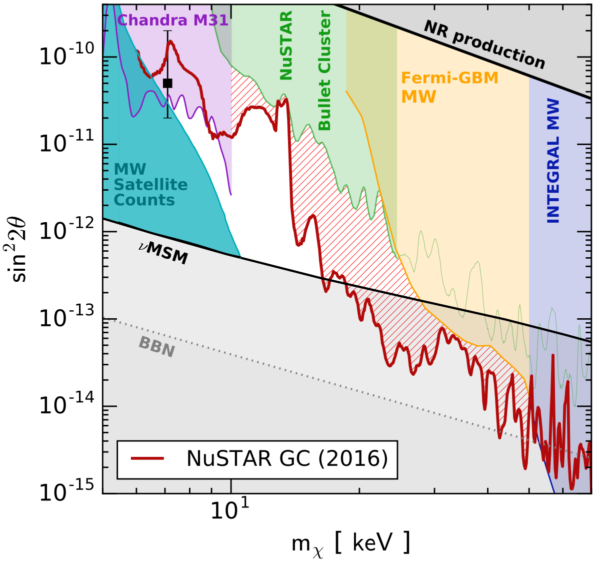
brown: MW satellite counts

green and yellow: Lyman-α

production by inflaton

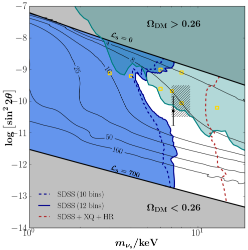
. . . present searches

1609.00667, 1706.03118



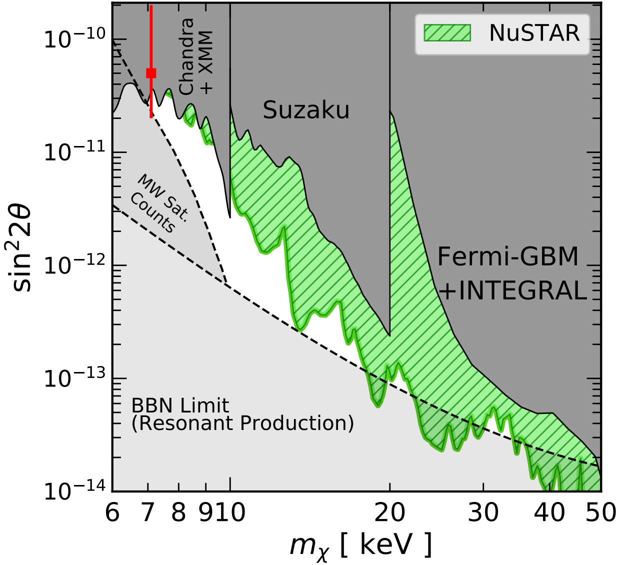
- (not a seesaw $\theta^2 \sim 10^{-5}(10\,\mathrm{keV}/M_N)$)
- upper limits on mixing: from X-ray searches
- lower limits on mass: from structure formation

$$\lambda_{FS} \sim 1\,\mathrm{Mpc} \times \frac{\mathrm{keV}}{M_N}\frac{\langle p_N\rangle}{\langle p_\nu\rangle}$$



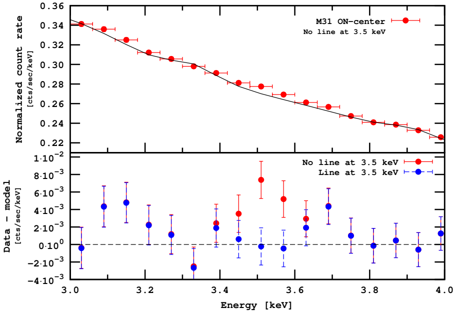
Most recent result of NuSTAR

1908.09037, see Lectures by A.Smirnov



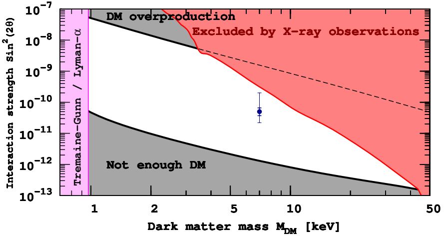
. . . 5 years ago: Dark Matter decay observed in X-ray?

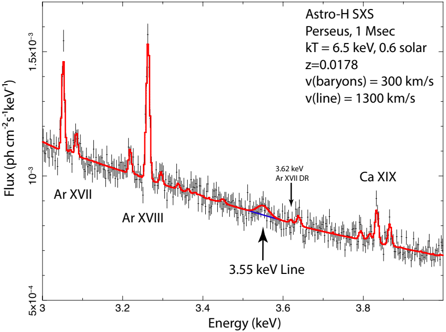
see Lecture by S.Kulkarni



Stacking signals from many galaxies, especially Perseus cluster, then Andromeda

1402.2301, 1402.4119





Closing sterile neutrino DM? . . . in a minimal variant

situation changes with just 1 new d.o.f. $\phi \bar{N}^c N$

- reopen large mixings with $\Omega_N < \Omega_{DM}$ (part of DM)

  to avoid X-ray bounds:

  $$\theta^2_{X-ray} = \theta^2_{\alpha I} \frac{\Omega_N}{\Omega_{DM}}$$

  direct searches: Troitsk, KATRIN

  can be seesaw neutrino

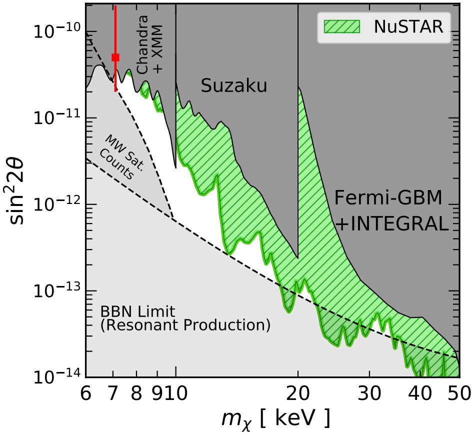
- small mixing: dominant DM

  testing with future telescopes

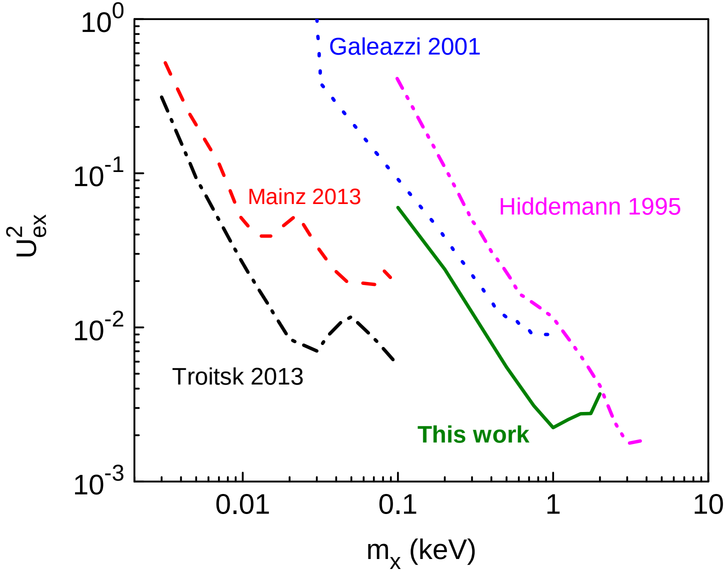
- reopen small masses with

  $v_N \ll v_{WDM}$,

  e.g. cold sterile neutrino



Searches for DM are deep inside the forbidden region



1703.10779

Larger mixing: Suppression of production

Form only a fraction of DM !!

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha^{\text{mat}} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\text{mat}}}\right), \quad \sin 2\theta_\alpha^{\text{mat}} = \frac{t_\alpha^{\text{mat}}}{t_\alpha^{vac}} \cdot \sin 2\theta_\alpha,$$

$$t_\alpha^{\text{mat}} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha} \cdot t_\alpha^{vac})^2}}, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

Most efficient production occurs at (DW)

$$T_{max} \approx 133\,\text{MeV}\left(\frac{1\,\text{keV}}{M_N}\right)^{1/3}$$

It is suppressed if $T_{reh} \ll T_{max}$

G.Gelmini, S.Palomares-Ruiz, S.Pascoli (2004)

Suppression of cosmological production

Add more ingredients e.g. Scalar? Majoron?

$\bar{L}\tilde{H}N + M_N \bar{N}^c N \to \bar{L}\tilde{H}N + \phi \bar{N}^c N$ (lepton symmetry)

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha^{\rm mat} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\rm mat}}\right), \quad \sin 2\theta_\alpha^{\rm mat} = \frac{t_\alpha^{\rm mat}}{t_\alpha^{vac}} \cdot \sin 2\theta_\alpha,$$

$$t_\alpha^{\rm mat} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha} \cdot t_\alpha^{vac})^2}}, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

Coupling to scalar can change
the effective neutrino Hamiltonian in the primordial plasma

$$\begin{pmatrix} V_{\alpha\alpha} & M_D \\ M_D & V_{NN} + M_N \end{pmatrix}$$

Suppression of production with $\phi \bar{N}^c N$

- strong coupling to scalar or Majoron,
  which decreases the active-sterile mixing in primordial plasma

  e.g. L.Bento, Z.Berezhiani (2001)

$$\phi NN \to G\bar{N}N\bar{N}N \to V_{NN}$$

- homogeneous $\phi = \phi(t)$
  makes sterile neutrino mass changing in cosmology,
  which suppresses the early-time oscillations

  F.Bezrukov, A.Chudaykin, D.G. (2017)

$$\phi(t)NN \to M_N = M_N(t) = M_N(T)$$

  - sterile neutrinos are massless in the early Universe
  - sterile neutrinos are superheavy in the early Universe

Massless in the early Universe

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\mu \phi - V(\phi) + \frac{f}{2} \phi \bar{N}^c N + \text{h.c.}$$

with a hidden sector. . . to make the phase transition:

$$T > T_c \quad \Longrightarrow \quad \langle\phi\rangle = 0\,, \quad M_N = 0$$
$$T < T_c \quad \Longrightarrow \quad \langle\phi\rangle = v_\phi\,, \quad M_N = f\, v_\phi$$

So the neutrino is pure Dirac fermion at the beginning. . .

The production in oscillations will be suppressed, if

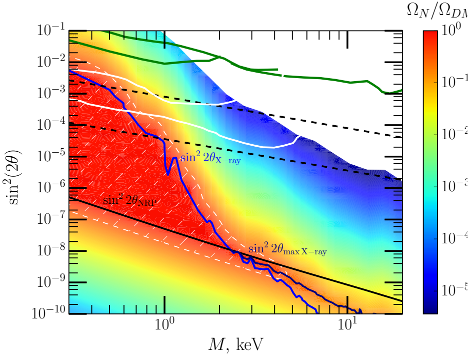
$$T_c < T_{max} \approx 133\,\text{MeV} \left(\frac{1\,\text{keV}}{M_N}\right)^{1/3}$$

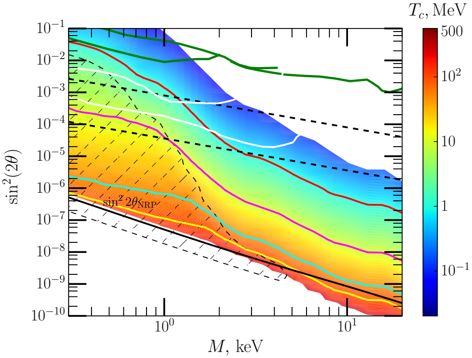
there is always a chirality flip contribution $\propto M_D^2/E^2$

similar for $\langle\phi\rangle \neq 0$ disappearing later. . .

Results: large mixing is allowed

for details see 1705.02184





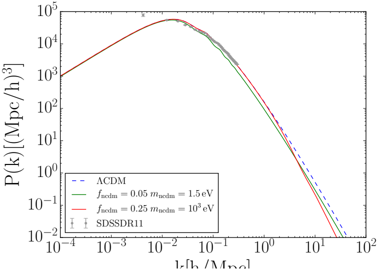
Important:

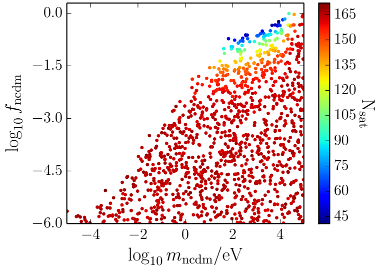
$m_a \sim \theta^2 M_N$

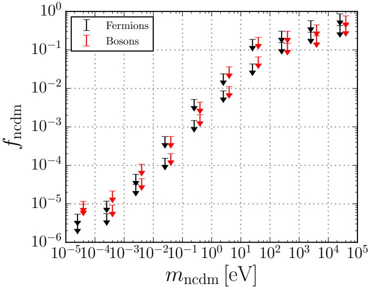
1. seesaw light sterile neutrino (dashed lines: $m_a \sim 0.008 - 0.2\,$eV)
2. can be directly tested !! (between green and white lines)
3. Warm, so most probably only a part of DM

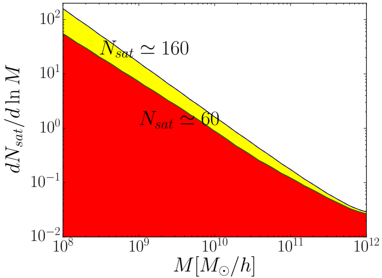
Sterile neutrinos: a part of dark matter

1701.03128









The oscillating scalar field

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 + \frac{f}{2} \phi \bar{N}^c N + \text{h.c.}$$

homogeneous scalar field in FLRW expanding Universe

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

two-stage evolution:

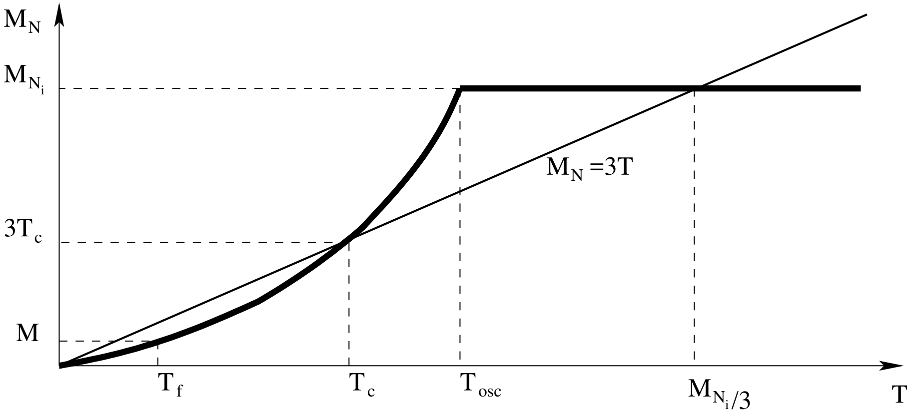
$$m_\phi < H(t) \implies \phi = \phi_i = \text{const}$$

$$m_\phi > H(t) \implies p = \langle E_k \rangle - \langle E_p \rangle = 0 , \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

- At $m_\phi < H(t)$ sterile neutrino mass is $M = M_N + f\phi_i \gg M_N$
- At present sterile neutrino mass is $M_N \sim 1\,\text{keV}$
- If at $m_\phi > H(t)$ sterile neutrinos are nonrelativistic most time, $m_\phi = H_{osc} = \frac{T_{osc}^2}{M_{Pl}^*}$

$$M(t) = M_N + f\phi_i \frac{T^3}{T_{osc}^3} > T$$

Subtleties with Effective neutrino mass



– $\rho_\phi > \rho_N$, so the scalar is DM

or, in case of rapid production, must account for the backreaction

– Yukawas induce $\lambda\phi^4 \sim f^4/(16\pi^2)\phi^4$ which may dominate instead

– Both L_{osc} and θ_{eff} change with $M(t)$, which oscillates !!

very complicated system: three oscillators with time-dependent couplings

Cool and Cold sterile neutrinos

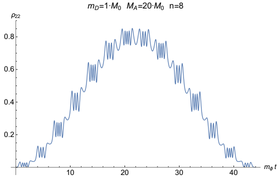
F.Bezrukov, A.Chudaykin, D.G. (2018)

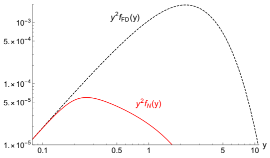
sterile neutrino mass

$$M(t) = M_N + f\phi(t) = M_N + f\,\phi_i \frac{T^3}{T_{osc}^3} \cos(m_\phi t)$$

1) sometimes crosses zero, which allows for sterile neutrino production
by a 'slow' oscillator $m_\phi \ll M_N$ with large amplitude
the produced sterile neutrinos are almost at rest — Cold Dark Matter
avoiding limits from structure formation
avoiding X-ray limits with tiny mixing angle

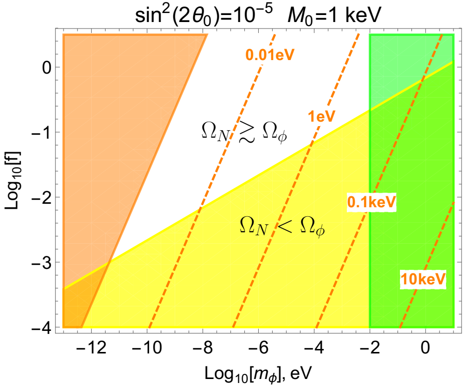
2) Both L_{osc} and θ_{eff} change with $M(t)$, which oscillates !! — resonance
very complicated system: three oscillators with time-dependent couplings — cool

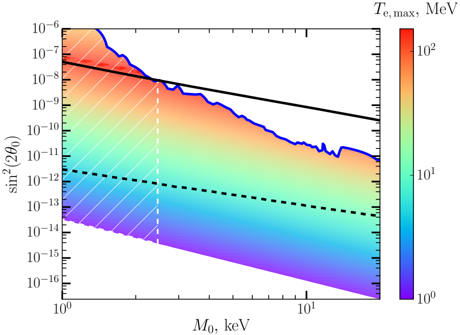




Allowed regions for each mechanism

F.Bezrukov, A.Chudaykin, D.G. (2018)





– $m_\phi < 2M_N$

– $\Gamma_{\phi\to\nu\nu} < \dots$

– $\rho_\phi + \rho_N \leq \rho_{DM}$

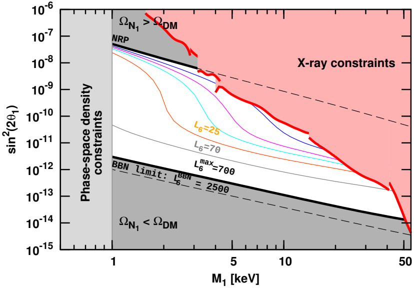
–

Another option: coupling to light inflaton

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 ($250\,\mathrm{MeV} < m_\chi < 1.8\,\mathrm{GeV}$)

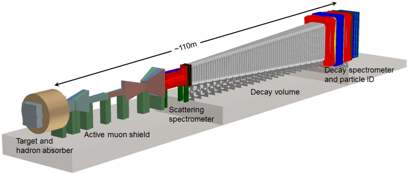
F.Bezrukov, D.G. (2009)

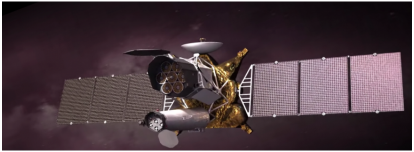
$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\ \mathrm{MeV}} \right) \mathrm{keV}$$

Outline

Summary on sterile neutrinos

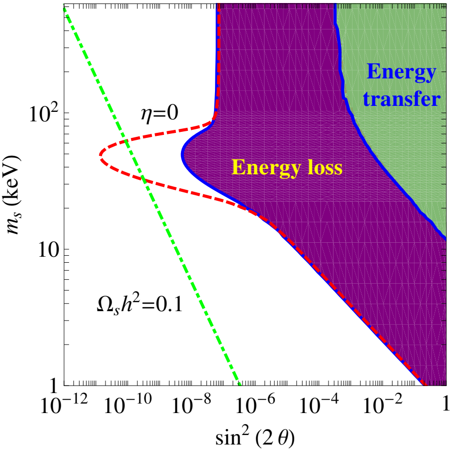
- Most economic explanation of neutrino oscillations within renormalizable approach: 2-3 Majorana neutrinos enough
- Capable of explaining baryon asymmetry of the Universe even at $\theta_{13} = \delta_{CP} = 0$
- One more neutrino can serve as (naturally Warm) dark matter
  this specia does not explain oscillations!
  there are allowed mechanisms of DM sterile neutrino productions
- 1 eV- sterile neutrino: cosmology vs anomalies (LSND, . . .) ...? dark radiation
- The seesaw can be tested, and in some cases (νMSM) fully explored:
  NA62, BelleII, LHCb, ND of HyperK, DUNE, . . . SHiP, MATHUSLA, etc
  DM searches with X-ray telescopes: ART-X, eROSITA of SRG



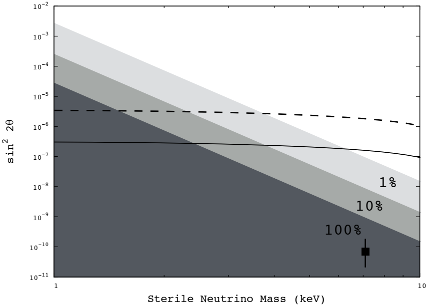


Backup slides

Limits form SN

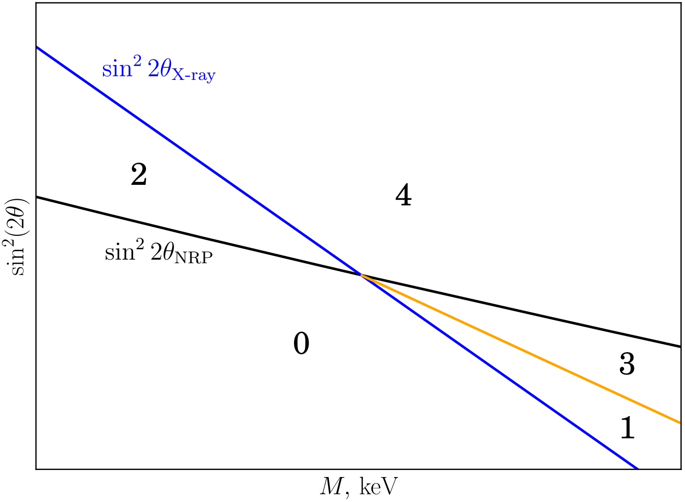


1102.5124



1603.05503

A sketch of model parameter space

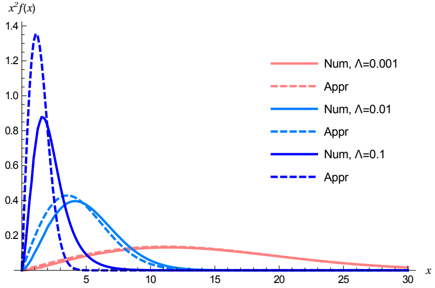


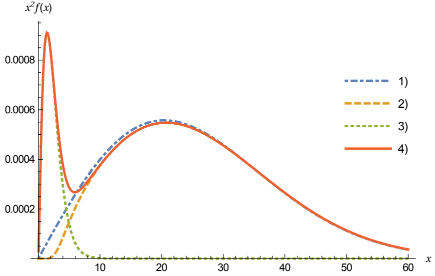
0,1: allowed even w/o scalar field

2: scalar helps to avoid X-ray bound and make $\Omega_N = \Omega_{DM}$, but free-streaming...

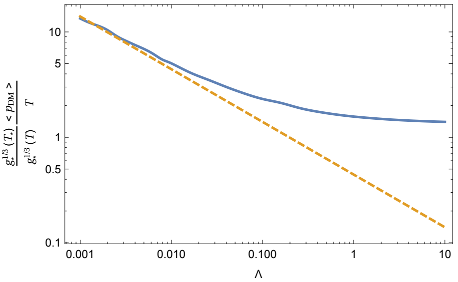
3,4: Ω_N is determined by X-ray bound

DM from Heavy scalar (Majoron?) decay





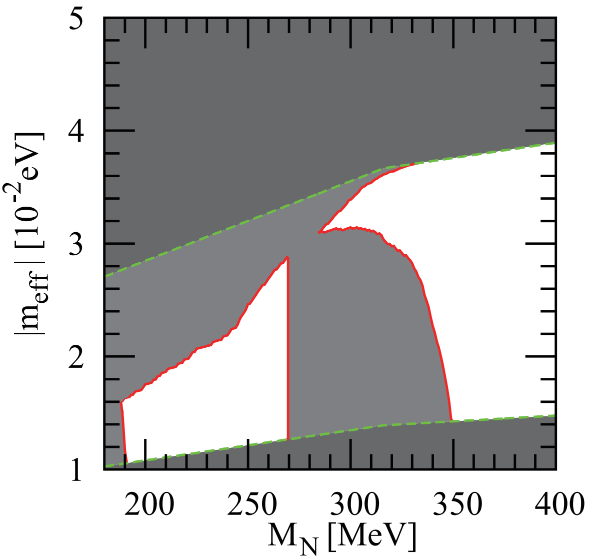
F.Bezrukov, D.G., 2014



$$\tau H(T = M/3) \equiv \frac{1}{18} \frac{1}{\Lambda}$$

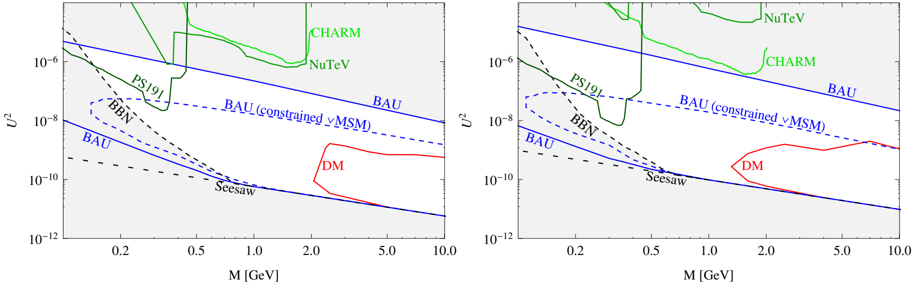
$$x = \frac{p}{T} \left(\frac{g_*(T_*)}{g_*(T)} \right)^{1/3}$$

Leptogenesis in $2+1$ scheme: $0\nu 2\beta$ decay region



Inverse hierarchy 1308.3550

νMSM parameter space with resonant DM



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