More room for sterile neutrino dark matter

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

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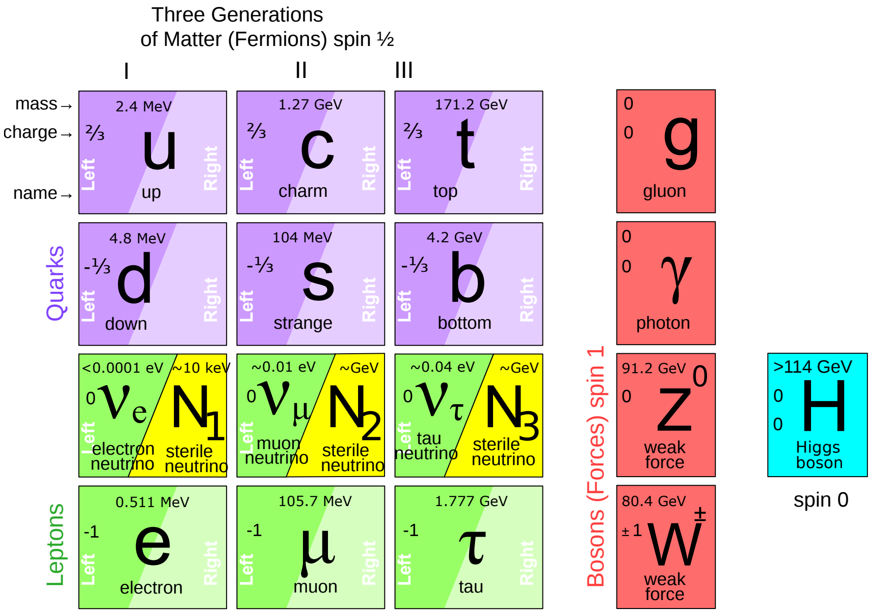
Department of Physics and Astronomy, University of Manchester, Manchester, UK


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
Quarks
Leptons
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
<0.0001 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
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Left
Right
Bosons (Forces) spin 1
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
0
Z
weak force
80.4 GeV
±1
±
W
weak force
>114 GeV
0
0
H
Higgs boson
spin 0

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

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

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

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

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

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

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

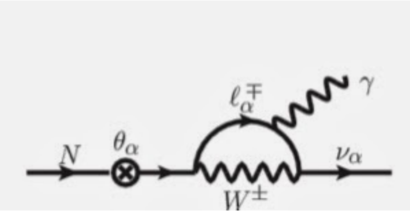
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- 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 $\qquad p=0$

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

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

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

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:

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

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

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

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

Production in oscillations

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

$\Gamma_\alpha \propto G_F^2 T^4 E$ 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:

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

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

DM from oscillations: (DW & ShF)

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

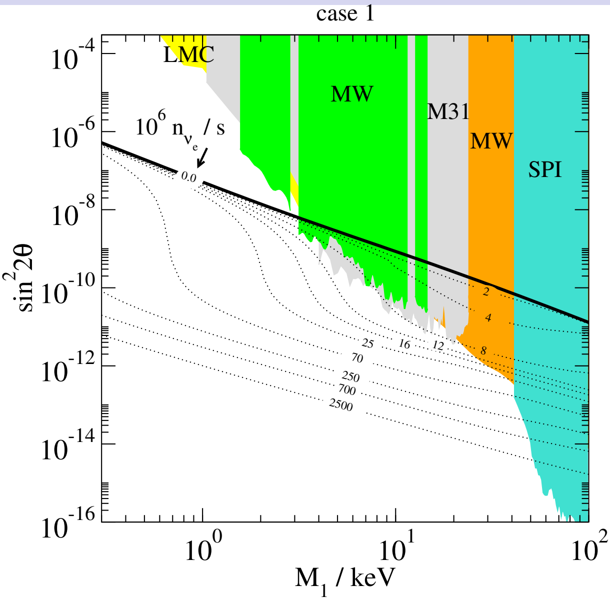
non-resonant:

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

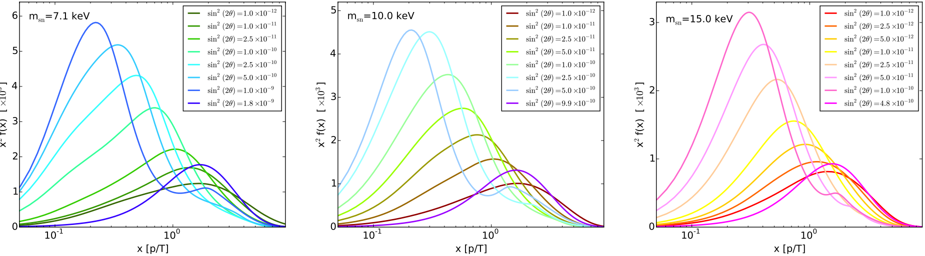
resonant production in the lepton asymmetric plasma

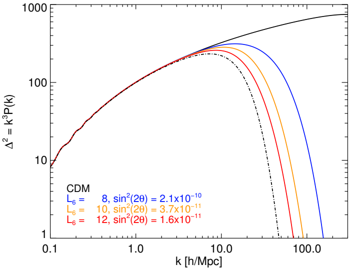
$$V_{\alpha\alpha} \sim +\# G_F T^2 \mu_{L_\alpha}$$

1601.07553



Sterile neutrino spectra from oscillations





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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

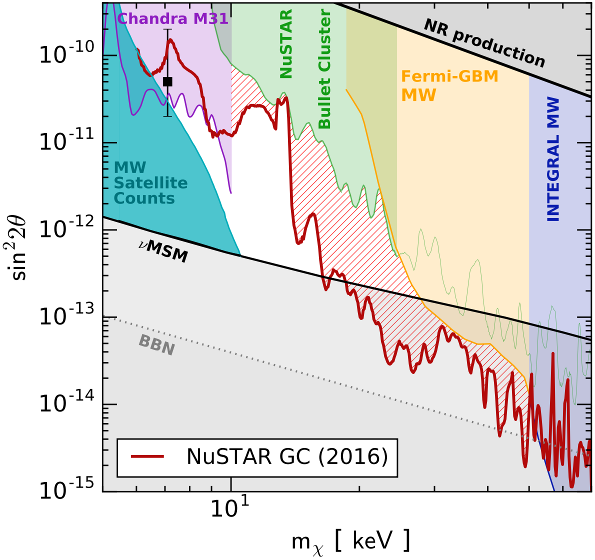
for non-resonance production D.G., A.Khmelnitsky, V.Rubakov (2008)

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

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

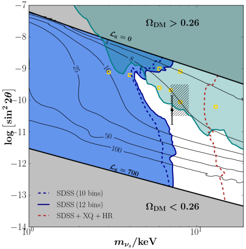
. . . present searches

1609.00667, 1706.03118



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

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



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

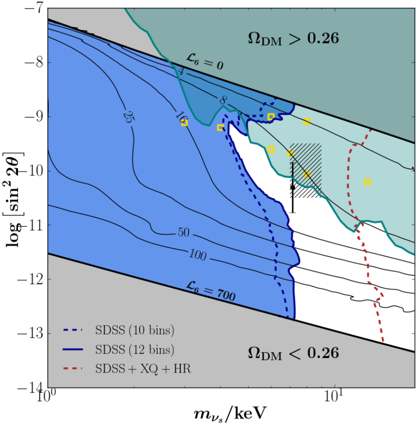
  can be seesaw neutrino

- small mixing: dominant DM

  testing with future telescopes

- reopen small masses with $v_N \ll v_{WDM}$,

  e.g. cold sterile neutrino



Larger mixing: Suppression of production

Form only a fraction of DM !!

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

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

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)

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

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

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

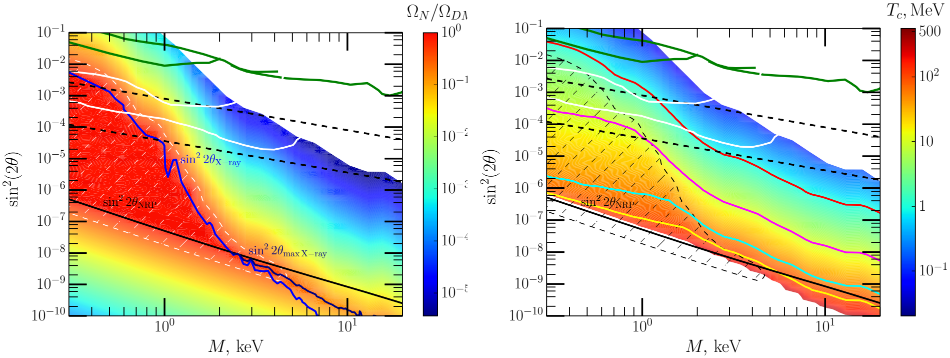
$$T_c < T_{max} \approx 133\,\text{MeV}\left(\frac{1\,\text{keV}}{M_N}\right)^{1/3}$$

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: $m_a \sim 0.008 - 0.2\,\mathrm{eV}$)
2. can be directly tested !! (between green and white lines)
3. Warm, so most probably only a part of DM

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, $\quad m_\phi = H_{osc} = \frac{T_{osc}^2}{M_{Pl}^*}$

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

Cool and Cold sterile neutrinos

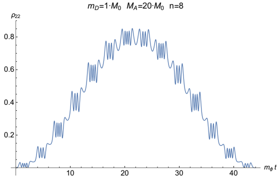
F.Bezrukov, A.Chudaykin, D.G. (2018)

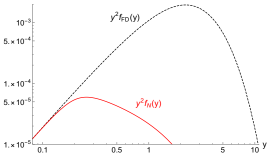
sterile neutrino mass

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

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

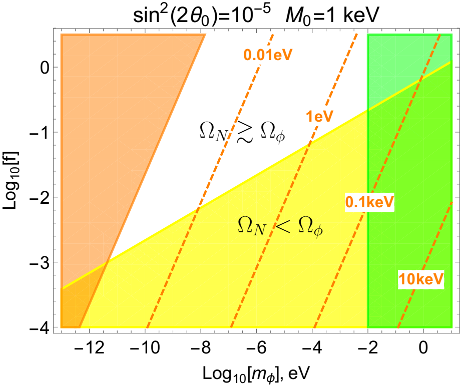
2) Both L_{osc} and θ_{eff} change with $M(t)$, which oscillates !! — resonance
very complicated system: three oscillators with time-dependent couplings — cool

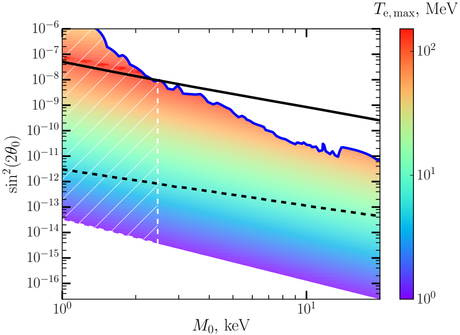




Allowed regions for each mechanism

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





- $m_\phi < 2M_N$
- $\Gamma_{\phi\to\nu\nu} < \dots$
- $\rho_\phi + \rho_N \leq \rho_{DM}$
-

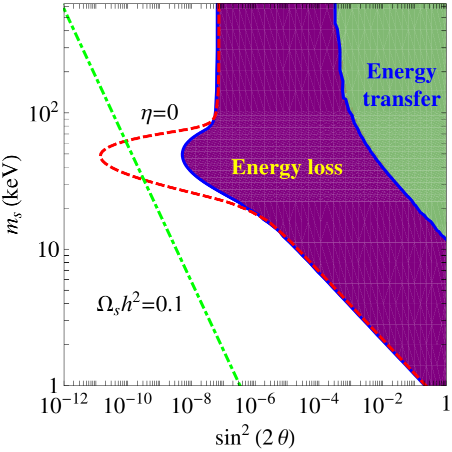
Summary and Outlook

- Still there is a room for minimal model of sterile neutrino dark matter

  but it is not a seesaw sterile neutrino, in fact
- With a simple modification by a scalar field one obtains
  – subdominant DM with large mixing angle, including the seesaw neutrino
  – DM with small mixing angle
  – 1 keV sterile neutrino forming CDM
- Within a physically motivated model (e.g. majoron) one checks for
  – sterile neutrino back reaction
  – production of light scalars
  – . . .
  – quantum corrections to the scalar potential
  – . . .

Backup slides

Limits form SN



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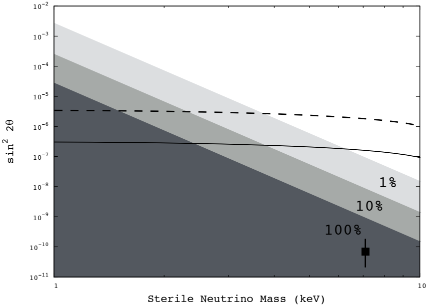
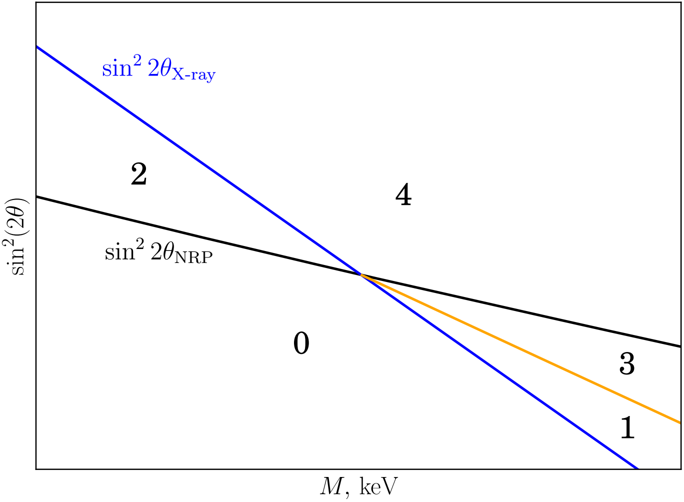


1603.05503

A sketch of model parameter space

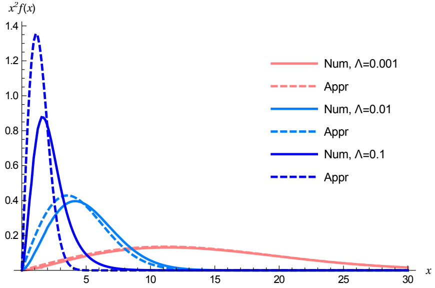


0,1: allowed even w/o scalar field

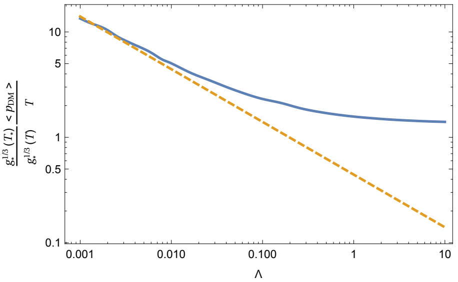
2: scalar helps to avoid *X*-ray bound and make $\Omega_N = \Omega_{DM}$, but free-streaming...

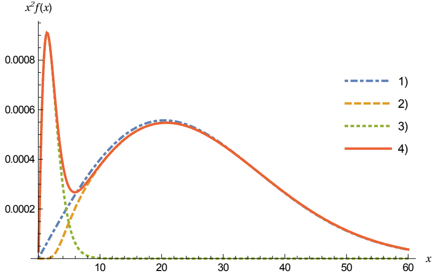
3,4: Ω_N is determined by *X*-ray bound

DM from Heavy scalar (Majoron?) decay



F.Bezrukov, D.G., 2014





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

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

Decoupling of relativistic Dark Matter

Assumptions

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

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

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 heavy stable feebly coupled to SM particles !

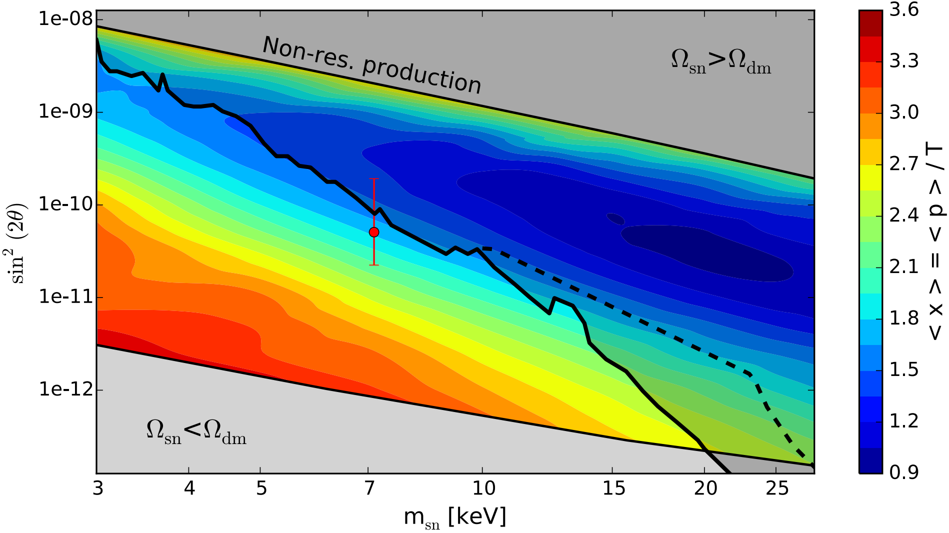
– NO realistic DM models:

Pauli blocking prevents fermionic DM

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

too energetic for the proper structure formation

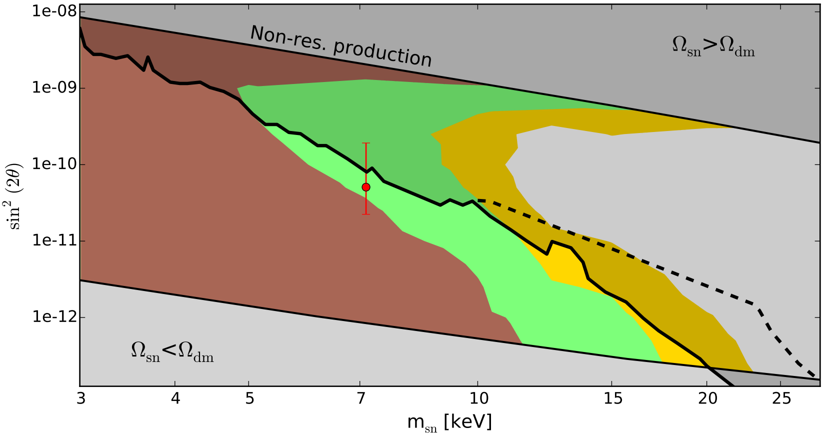
Sterile neutrino Dark Matter



A.Schneider (2016)

Sterile neutrino Dark Matter: ... gone?

A.Schneider (2016)

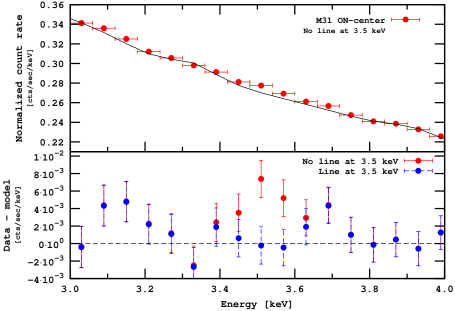


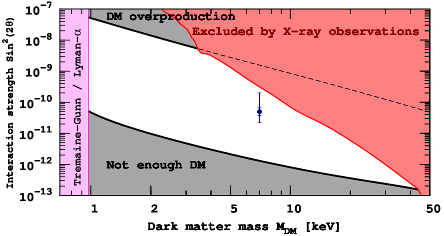
brown: MW satellite counts

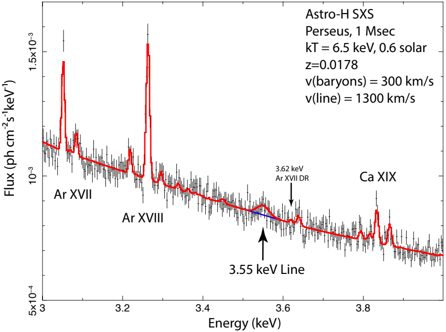
green and yellow: Lyman-α

production by inflaton

…4 years ago: Dark Matter decay observed in X-ray?



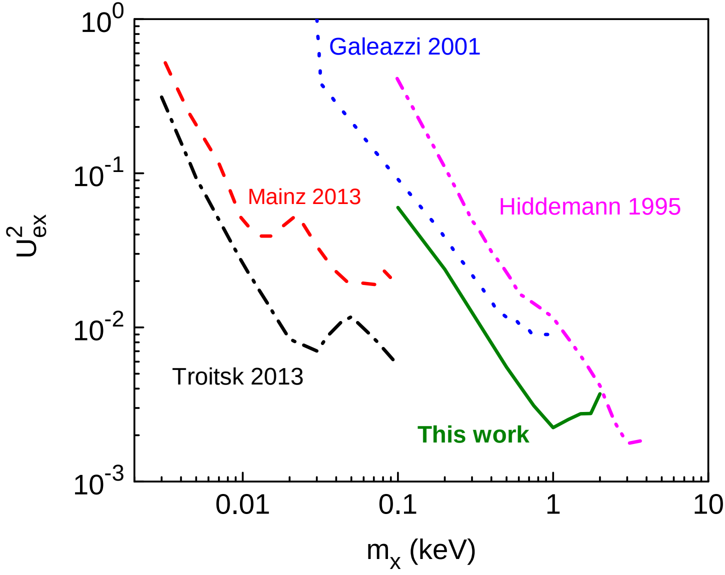




Stacking signals from many galaxies, especially Perseus cluster, then Andromeda

1402.2301, 1402.4119

Searches for DM are deep inside the forbidden region



1703.10779