Sterile Neutrino Dark Matter

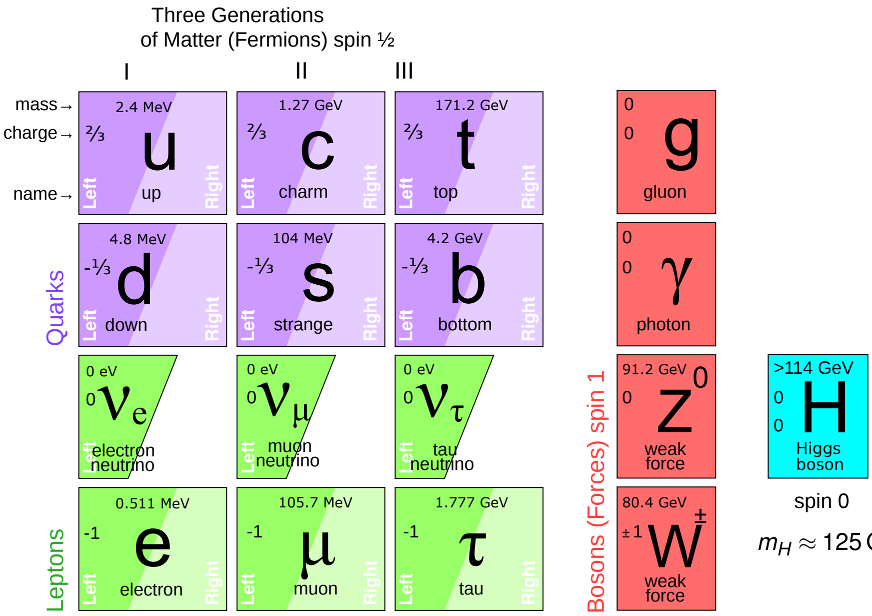
Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

Workshop on Dark Matter candidates

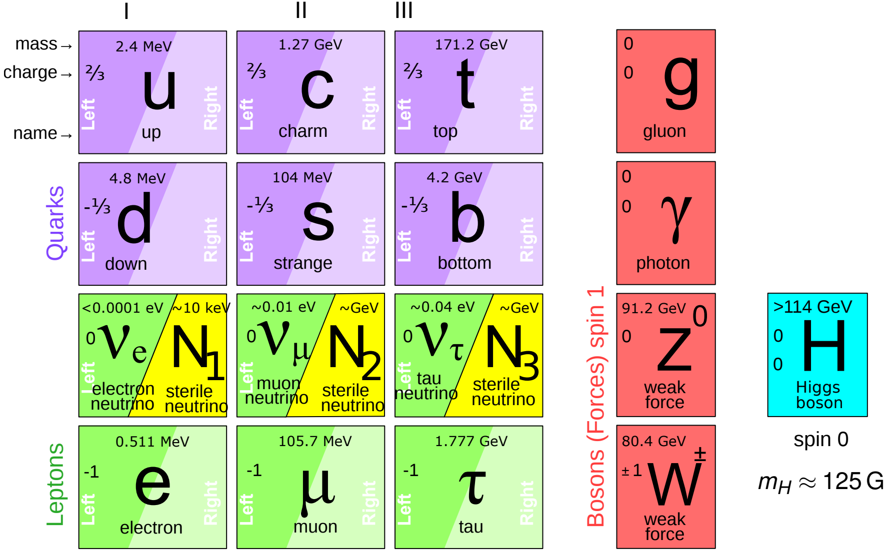
JINR, Dubna, Russia

(alas ... via 'zoom' from Moscow)



$m_H \approx 125\,\text{GeV}$

Three Generations
of Matter (Fermions) spin ½



$m_H \approx 125\,\mathrm{GeV}$

Seesaw mechanism: $M_N \gg 1\,\text{eV}$

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

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

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

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

For a hierarchy $M_N \gg M^D = v\,\frac{f}{\sqrt{2}}$ 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: 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 $M_N < M_W$)

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

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

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

Sterile neutrino: indirect searches

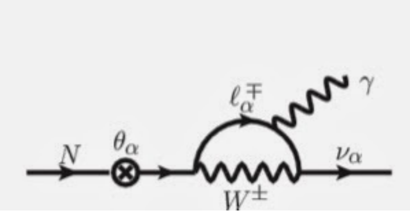
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- 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

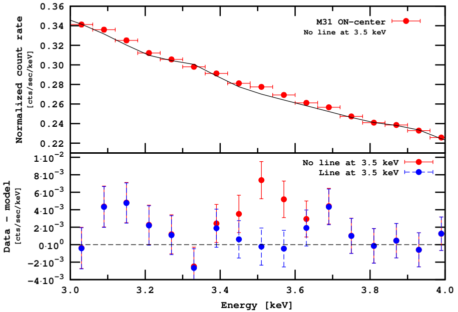


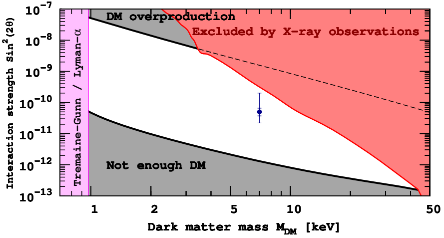
a narrow line $\quad (\delta E_\gamma / E_\gamma \sim v \sim 10^{-3})$

at photon frequency $\quad E_\gamma = M_N/2$

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

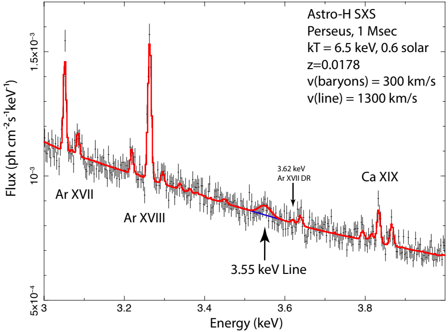
…6 years ago: Dark Matter decay observed in X-ray?





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

1402.2301, 1402.4119



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)

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

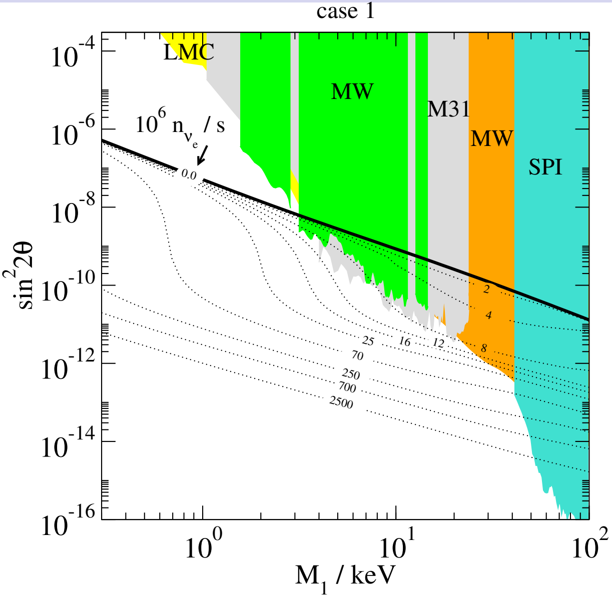
non-resonant:

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

resonant production in the lepton asymmetric plasma

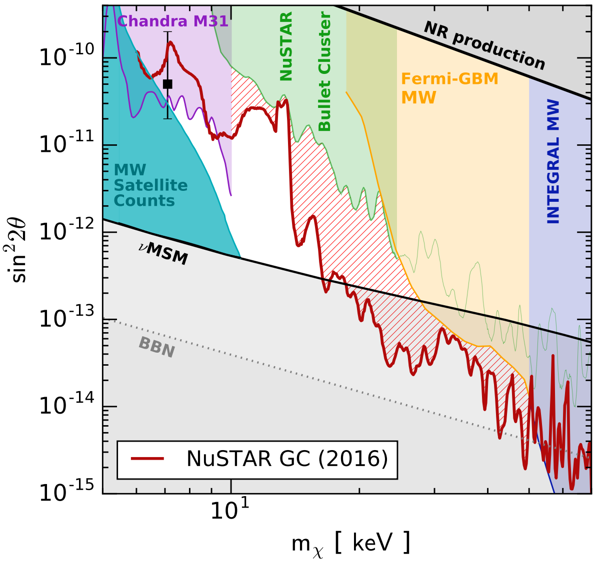
$$V_{\alpha\alpha} \sim +\# G_F T^2 \mu_{L_\alpha}$$

1601.07553



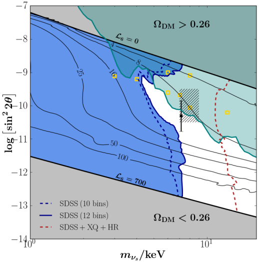
. . . present searches

1609.00667, 1706.03118

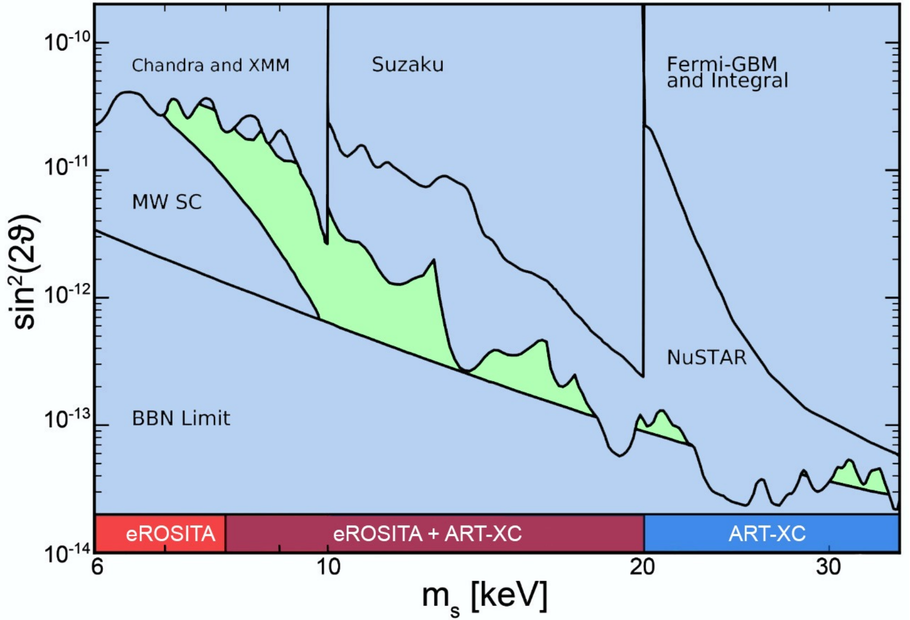


- upper limits on mixing: from X-ray searches
- lower limits on mass: from structure formation with $p_N \sim T$, DM free streaming

  too fast at $T = 1$ eV

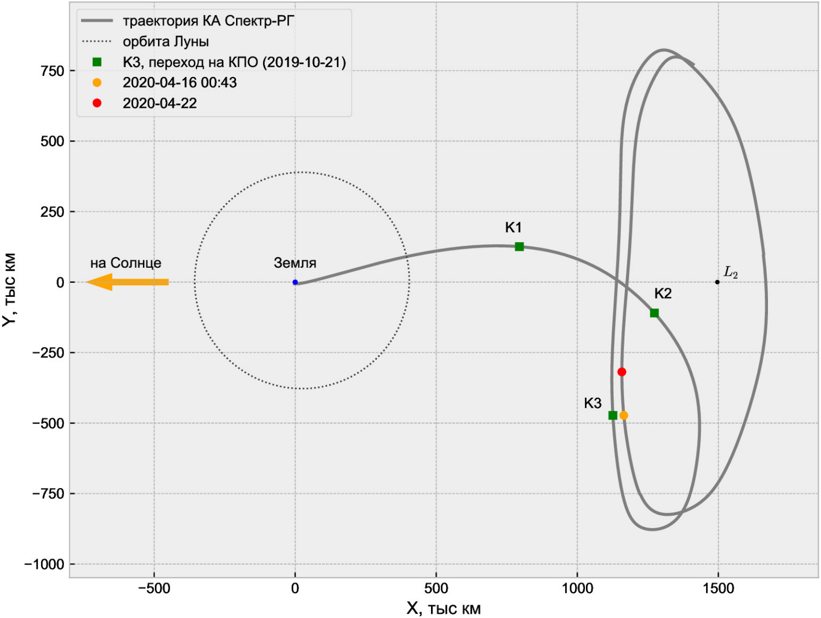


eROSITA (0.2-10 keV), ART-XC (4-30 keV)

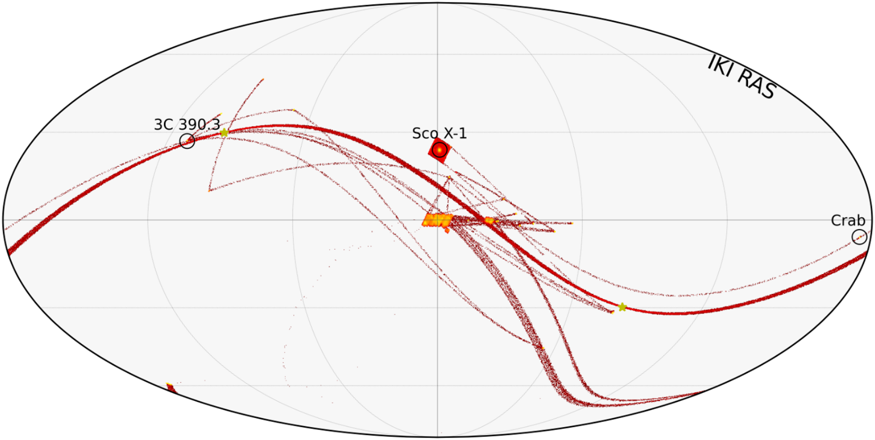


1908.09037, 2007.07969

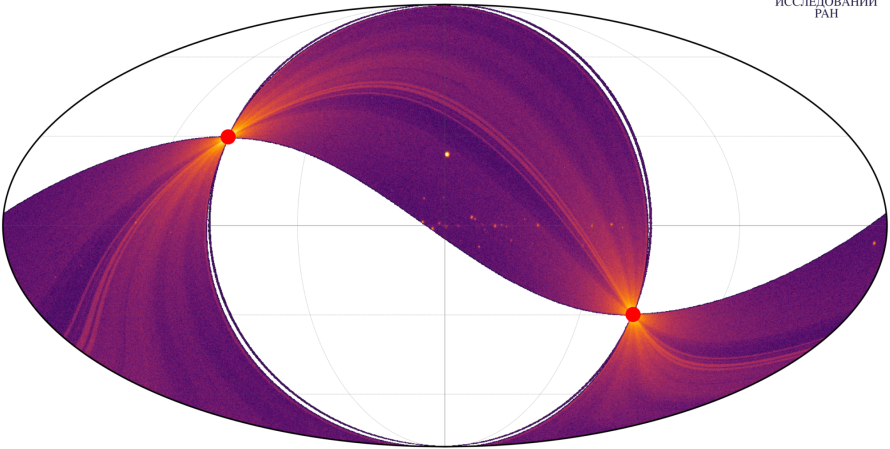

Launch on 13 July 2019 from Baikonur


траектория КА Спектр-РГ
орбита Луны
К3, переход на КПО (2019-10-21)
2020-04-16 00:43
2020-04-22
750
500
250
0
−250
−500
−750
−1000
−500
0
500
1000
1500
Y, тыс км
X, тыс км
на Солнце
Земля
K1
K2
K3
L_2

ART-XC sky, September 2019

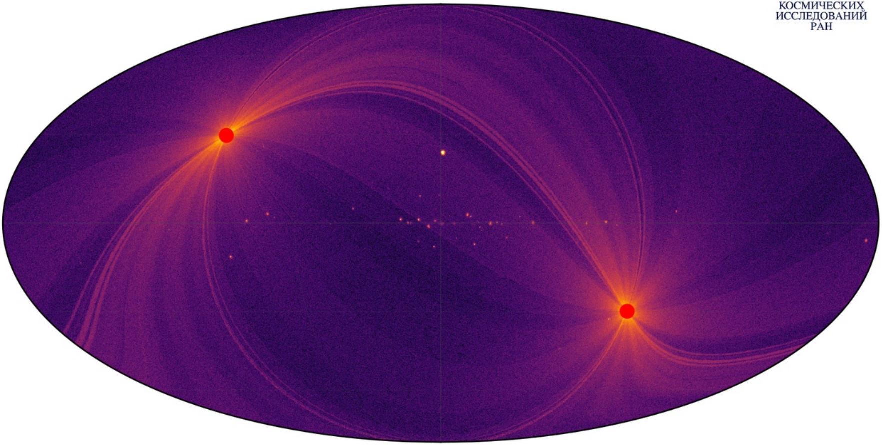


SRG/ART-XC: полнеба сделано



ИНСТИТУТ КОСМИЧЕСКИХ ИССЛЕДОВАНИЙ РАН

ИКИ
ИНСТИТУТ
КОСМИЧЕСКИХ
ИССЛЕДОВАНИЙ
РАН



Main goal of the SRG mission

To build a map of the brightest X-ray sources on the sky

- Find all the galaxy clusters emitting X-rays ($M > 3 \times 10^{14} M_\odot$)
  find filaments, galaxy groups emitting X-rays
  — study the structure formation and probe Dark Energy
- Active Galactic Nuclei
  — one more population to investigate BAO
  — millions of supermassive BH in AGN centers
- Galactic sources of X-rays
  — accretion of White Dwarfs, Neutron stars, BH in binary system
- Transient sources
- Search for new sources of X-rays, e.g. Dark Matter

Searches for DM with SRG

Specific DM candidates with signatures in X-rays

- WIMPs with bremstruhlung

$$X + \bar{X} \longrightarrow e^+ + e^- + \gamma$$

excess of a certain form in the spectrum

- annihilation into photons, e.g. DM models with hidden photons

$$X + \bar{X} \longrightarrow \gamma + \gamma^{(\prime)}$$

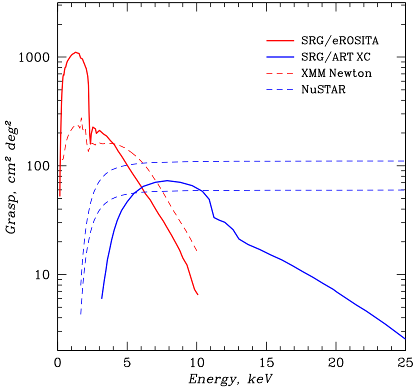
a line of 10^{-4}-10^{-3} width in galactic spectra

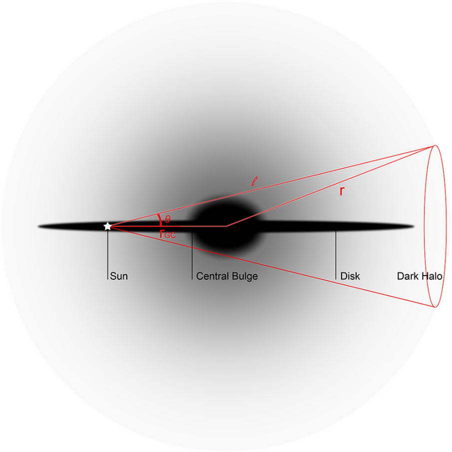
- DM radiative decay, e.g. axions, sterile neutrinos, etc

$$a \longrightarrow \gamma + \gamma, \qquad \nu_s \longrightarrow \nu + \gamma$$

Huge advantage thanks to the survey mode

2007.07969





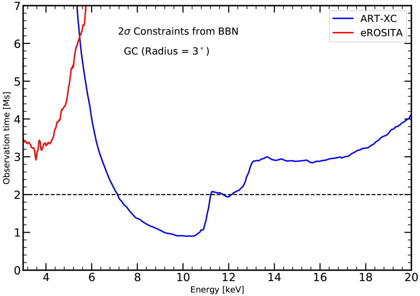
Drop the regions with visible matter (e.g. Galactic center, disc)

take mostly dark halo

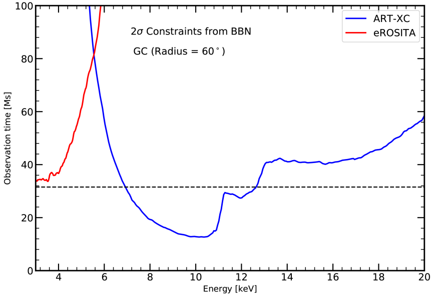
SRG observation of MW

2007.07969

time needed to reach the BBN limit



24 days. . .

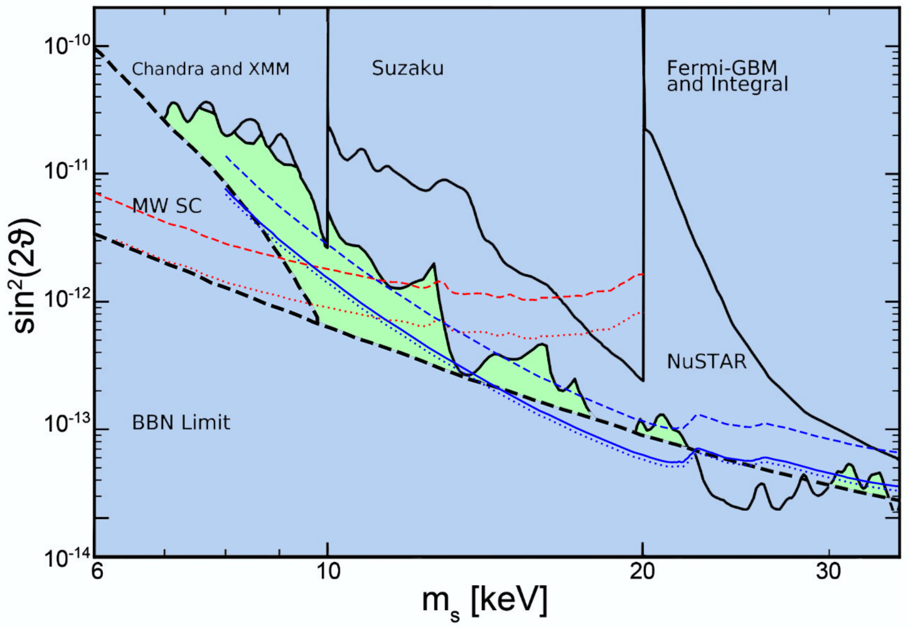


1 year

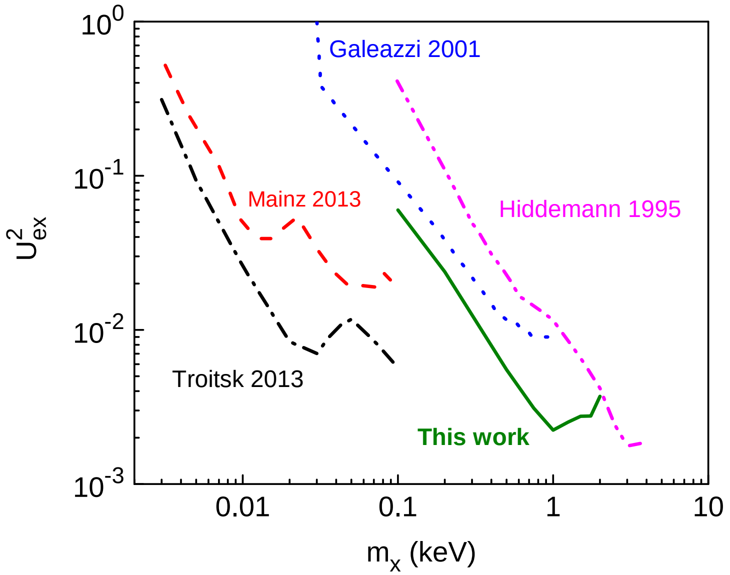
one can amplify the DM production with more ingredients, e.g. scalars

1705.02184, 1809.09123

it can be just one of the DM components. . .


10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$\sin^2(2\vartheta)$
Chandra and XMM
Suzaku
Fermi-GBM and Integral
MW SC
NuSTAR
BBN Limit
6
10
20
30
m_s [keV]

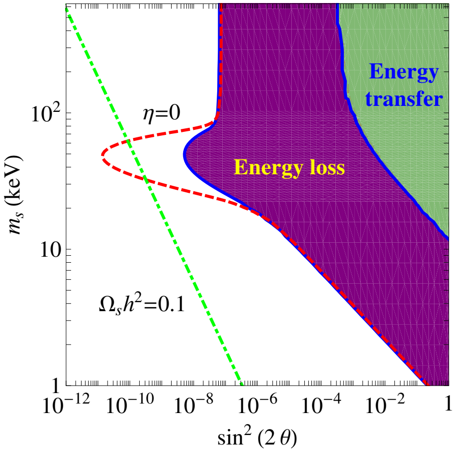
Direct searches are deep inside the forbidden region



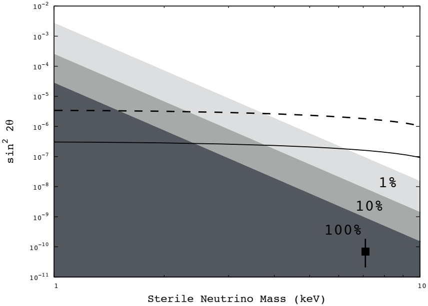
1703.10779

Backup slides

Limits form SN



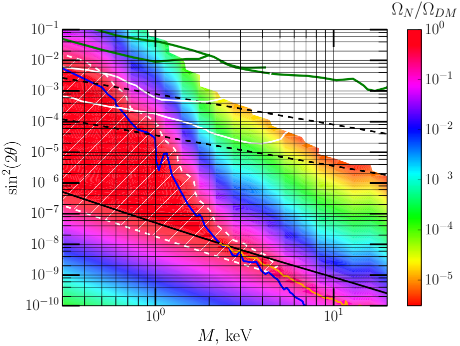
1102.5124

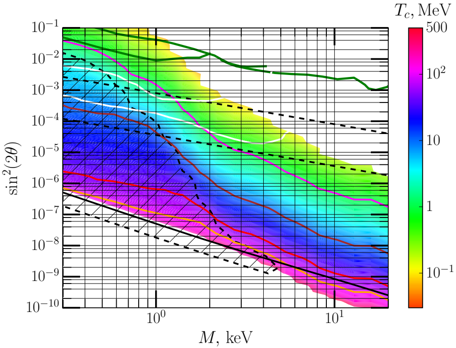


1603.05503

Results

for details see 1705.02184



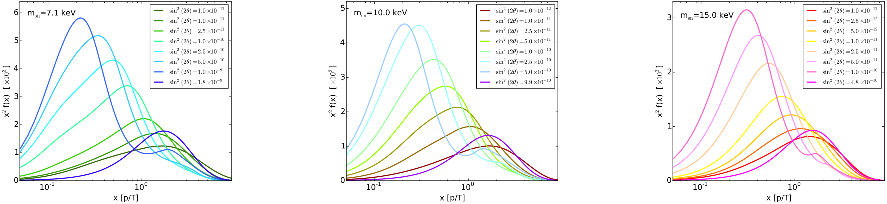


Important:

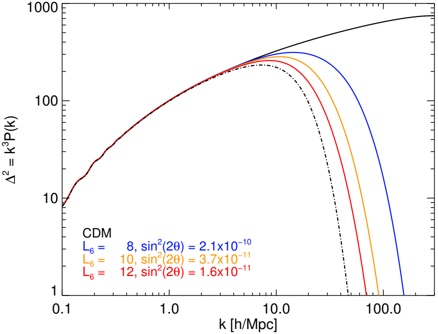
$m_a \sim \theta^2 M_N$

1. seesaw light sterile neutrino (dashed lines: $m_a \sim 0.008 - 0.2\,\text{eV}$)
2. can be directly tested !! (between green and white lines)

Sterile neutrino spectra from resonant production



1601.07553



1611.00005

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

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 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

Sterile neutrinos: a part of dark matter

1701.03128