Prospects of closing the window of sterile neutrino dark matter

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10th International Conference

on New Frontiers in Physics

OAC, Chania, Crete, Greece

Standard Model: Major Problems

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

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

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe (PHENO)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage

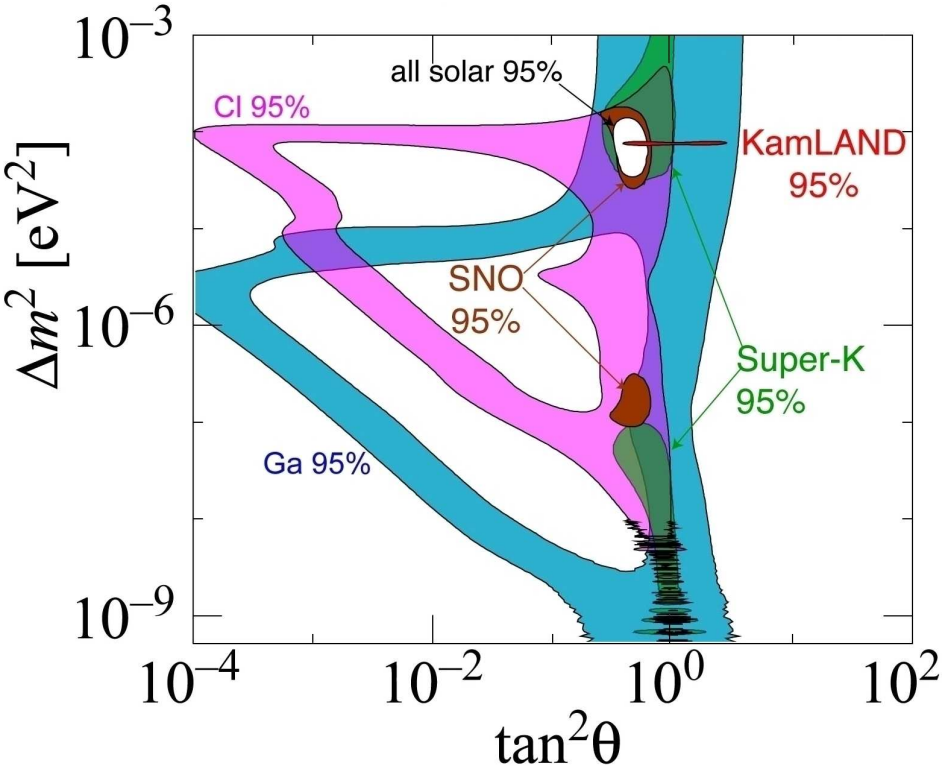
(THEORY)

- Dark energy (Ω_Λ)
- Strong CP-problem
- Gauge hierarchy
- Quantum gravity

Only direct evidence for New Physics ???

Neutrino oscillations: masses and mixing angles

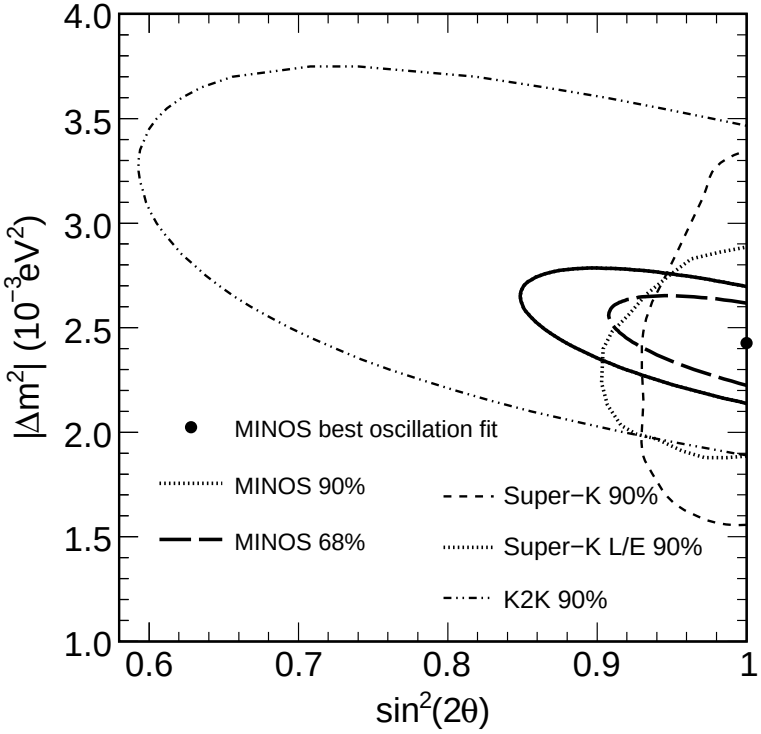
Solar 2×2 "subsector"



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

$m_1 > 0.008$ eV

Atmospheric 2×2 "subsector"



arXiv:0806.2237

$m_2 > 0.05$ eV

DAYA-BAY, RENO, 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

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. . . ?

Three Generations
of Matter (Fermions) spin ½

	I	II	III		
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0	>114 GeV
charge →	⅔	⅔	⅔	0	0
name →	u, up (Left / Right)	c, charm (Left / Right)	t, top (Left / Right)	g, gluon	H, Higgs boson
Quarks	4.8 MeV, -⅓, d, down (Left / Right)	104 MeV, -⅓, s, strange (Left / Right)	4.2 GeV, -⅓, b, bottom (Left / Right)	0, 0, γ, photon	
	<0.0001 eV, 0, ν_e, electron neutrino (Left) / ~10 keV, N_1, sterile neutrino	~0.01 eV, 0, ν_μ, muon neutrino (Left) / ~GeV, N_2, sterile neutrino	~0.04 eV, 0, ν_τ, tau neutrino (Left) / ~GeV, N_3, sterile neutrino	Bosons (Forces) spin 1: 91.2 GeV, 0, Z^0, weak force	spin 0
Leptons	0.511 MeV, -1, e, electron (Left / Right)	105.7 MeV, -1, μ, muon (Left / Right)	1.777 GeV, -1, τ, tau (Left / Right)	80.4 GeV, ±1, $W^\pm$, weak force	

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: $\theta = \dfrac{M^D}{M_N} = \dfrac{v f}{2 M_N} \ll 1$

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
  (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

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

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

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. (almost) electrically neutral — CMB distortion
2. (almost) collisionless — $p = 0$, $v_{\text{sound}} = 0$
3. stable on cosmological time-scale
   requires new (almost) conserved quantum number
4. produced in the early Universe — at $T > 10\,\text{eV}$
5. 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 $M_N < M_W$)

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

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

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

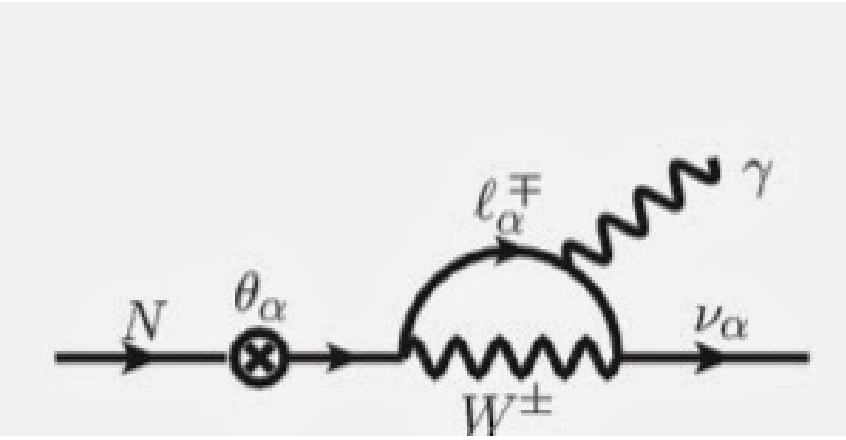
Sterile neutrino: indirect searches

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

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

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

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

Can seesaw neutrino serve as DM ?

X-ray limits (roughly)

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

see-saw relation

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

one order down

$$\frac{\theta^2}{10^{-7}} \lesssim \left(\frac{1\ \text{keV}}{M_N}\right)^4$$

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

...

How light can be this dark matter ?

Galactic Dark Matter

X-ray limits (roughly)

$$\frac{\theta^2}{10^{-7}} \lesssim \left(\frac{1\ \text{keV}}{M_N}\right)^4$$

see-saw relation

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

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

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

DM sterile neutrino cannot contribute much to neutrino masses

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:

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

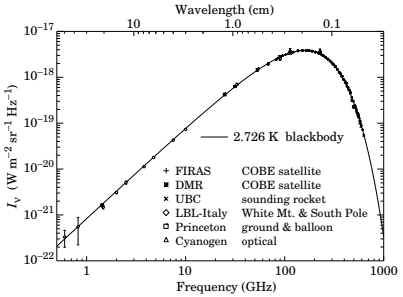
$$Q \simeq 3^{3/2} \frac{\rho_{DM}}{\langle v_{DM}^2 \rangle^{3/2}} = 3^{3/2} m^4 \frac{n}{\langle P^2 \rangle^{3/2}} = 3^{3/2} m^4 f(\mathbf{P}, \mathbf{x}).$$

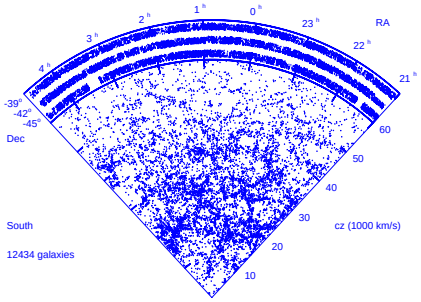
$$m^4 \gtrsim \frac{Q}{3^{3/2} \max f_i}$$

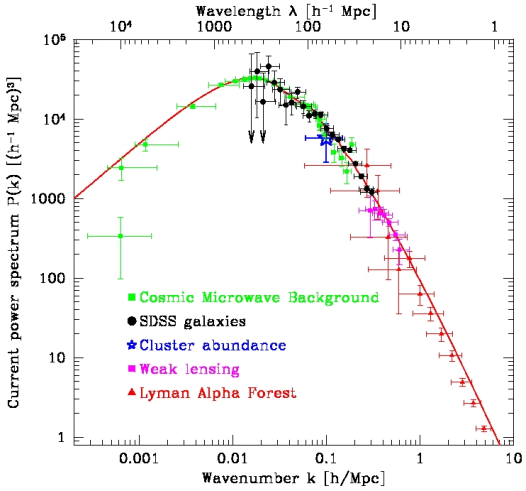
Matter perturbations are adiabatic: $\delta(n_B/n_{DM}) = 0$

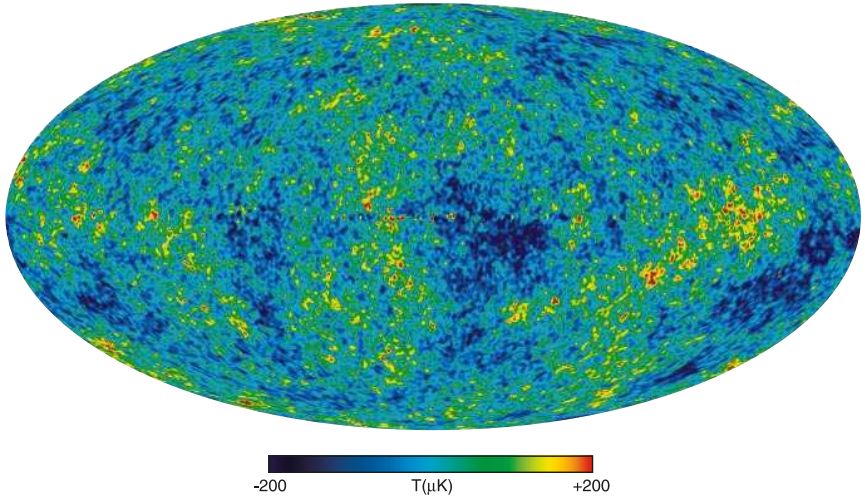
- CMB is isotropic, but "up to corrections, of course..."
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy: $\frac{\Delta T}{T} \sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage 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...

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

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

Warm Dark Matter:

all inhomogeneities of sizes smaller than (roughly)

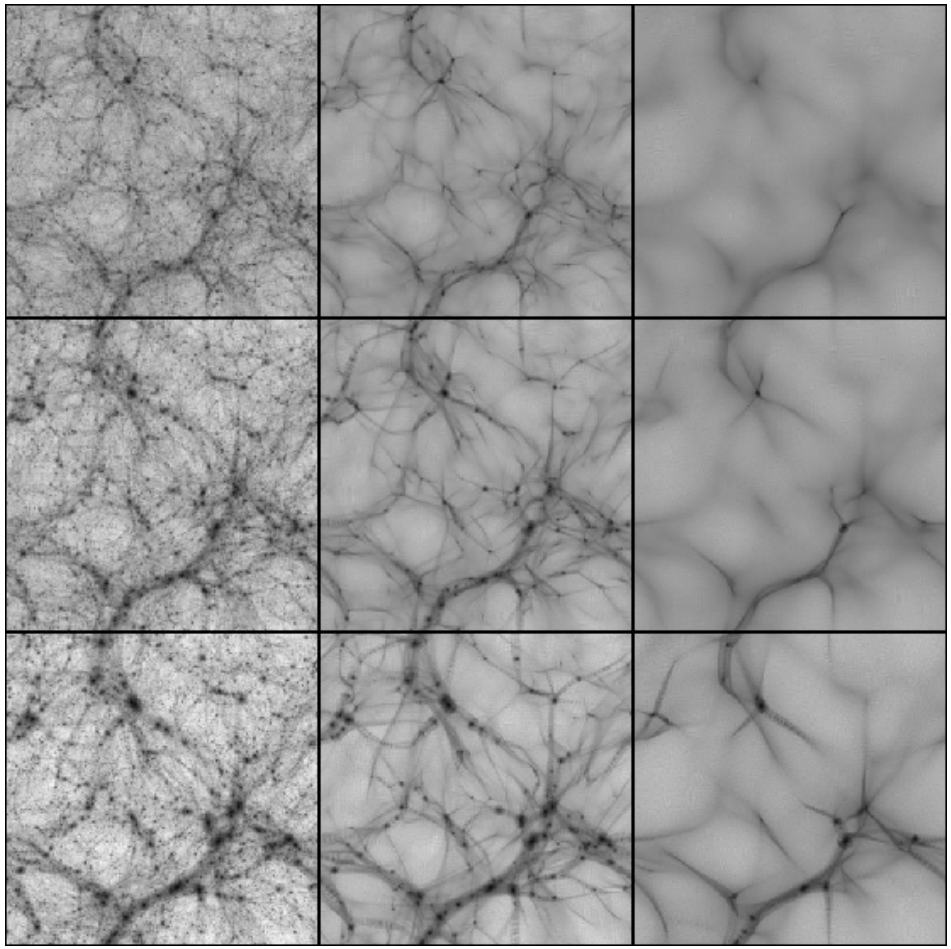
$$l = v \times t_{Universe}$$

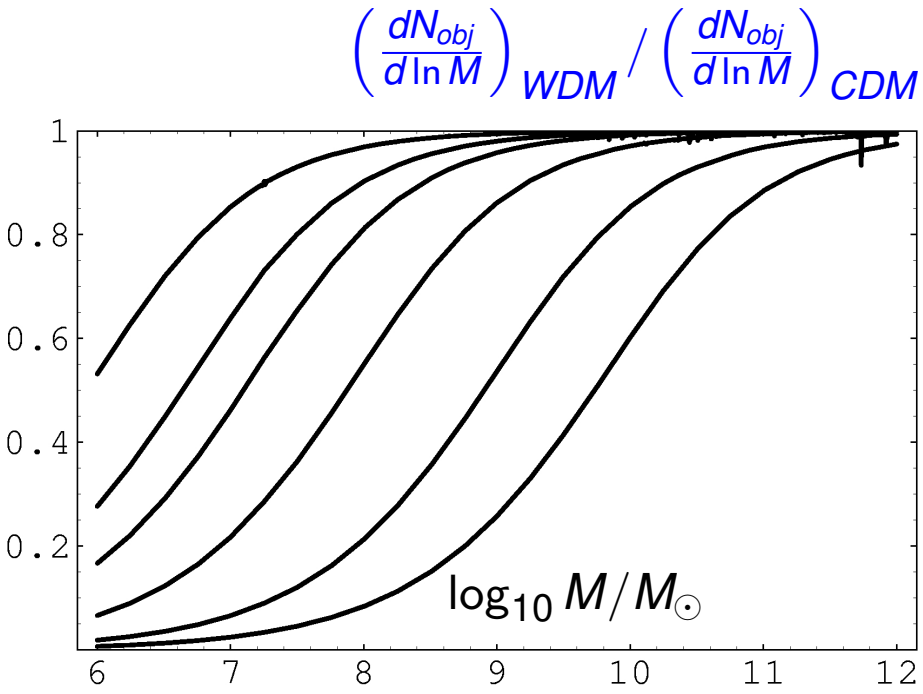
are smoothed out due to free streaming

it allows to test the model

Tesing with satellite counting...

Heavy (CDM-like) Light (WDM-like)





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

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

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

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

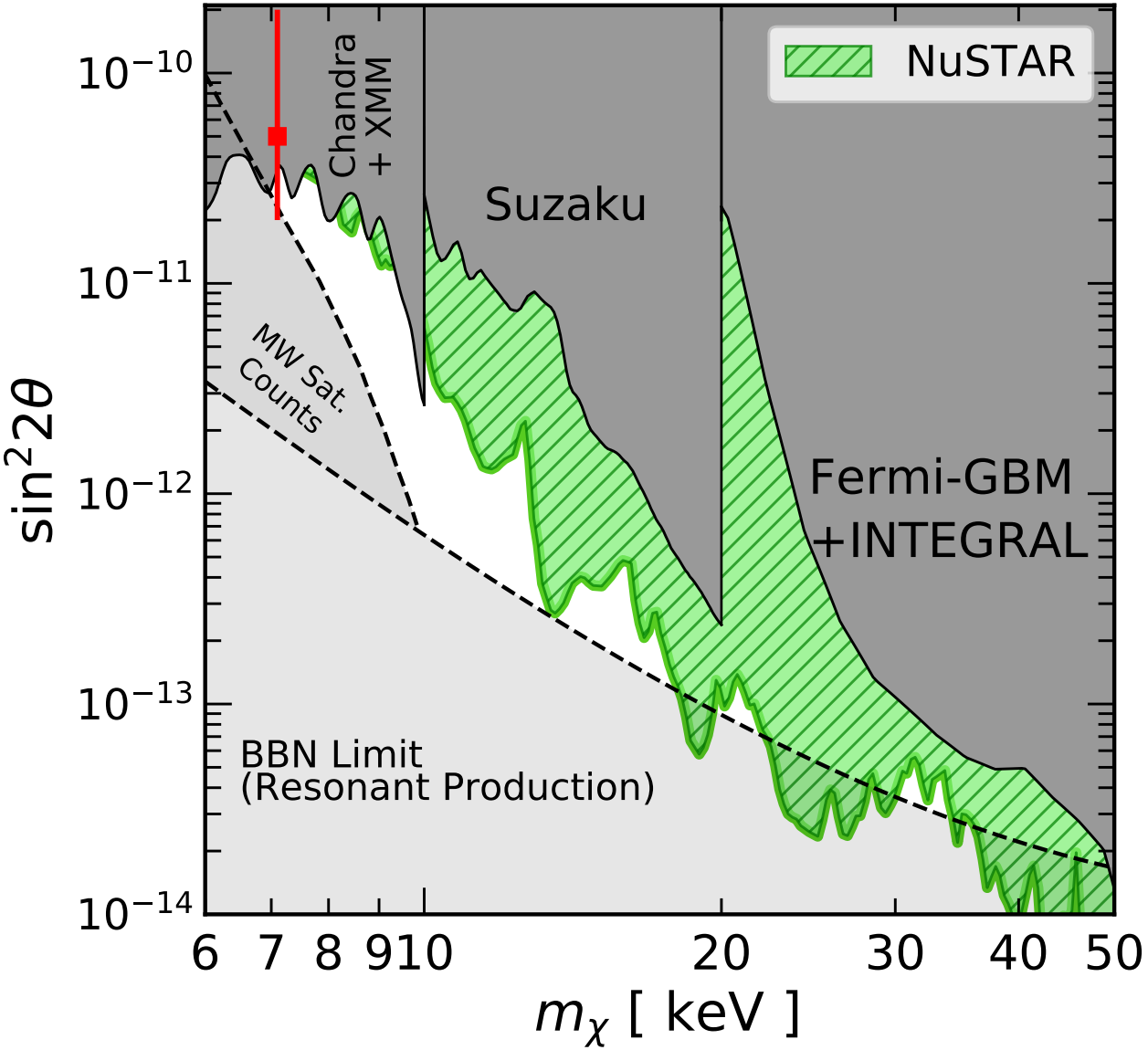
sign of the effective plasma potential matters:

$$V_{\alpha\alpha} < 0 \implies \text{mixing gets suppressed} \implies V_{\alpha\alpha} \sim \# G_F^2 T^4 E$$

$$V_{\alpha\alpha} > 0 \implies \text{amplification via resonance} \implies V_{\alpha\alpha} \sim \# G_F T^2 \mu_{L_\alpha}$$

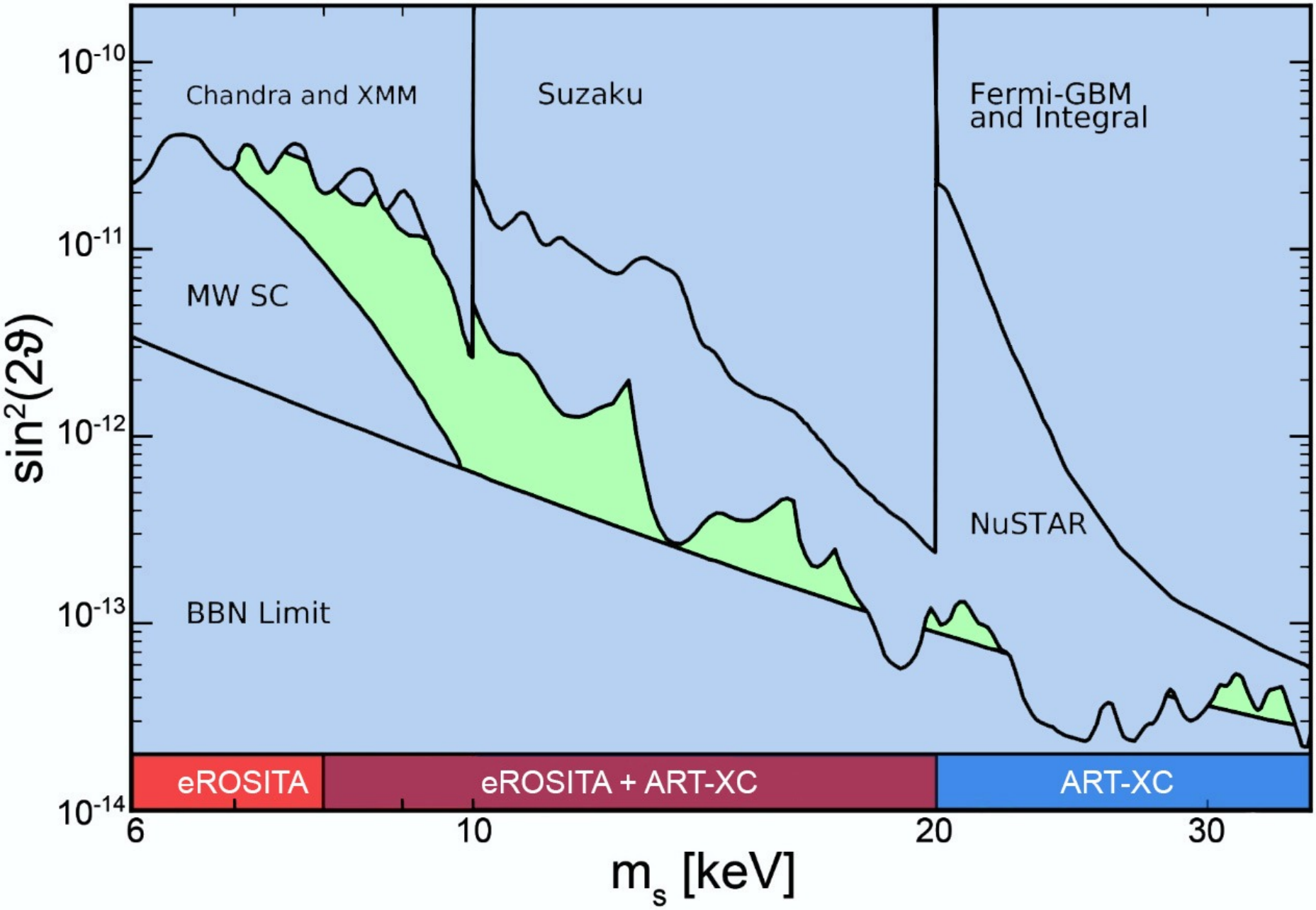
Most recent result of NuSTAR

1908.09037, see also XMM-Newton 2102.02207



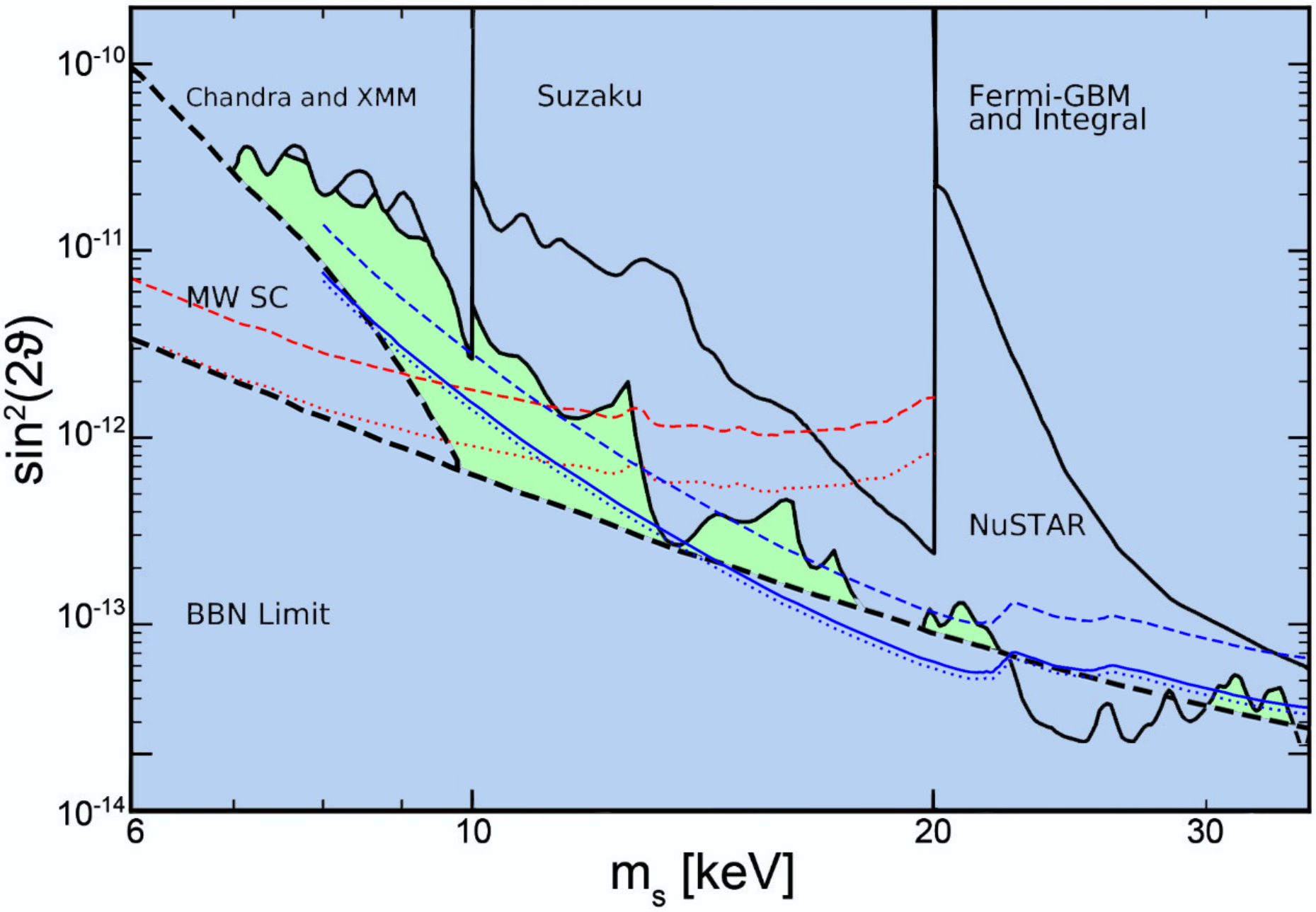
eROSITA (0.2-10 keV), ART-XC (4-30 keV)

Talk by R.Sunyaev



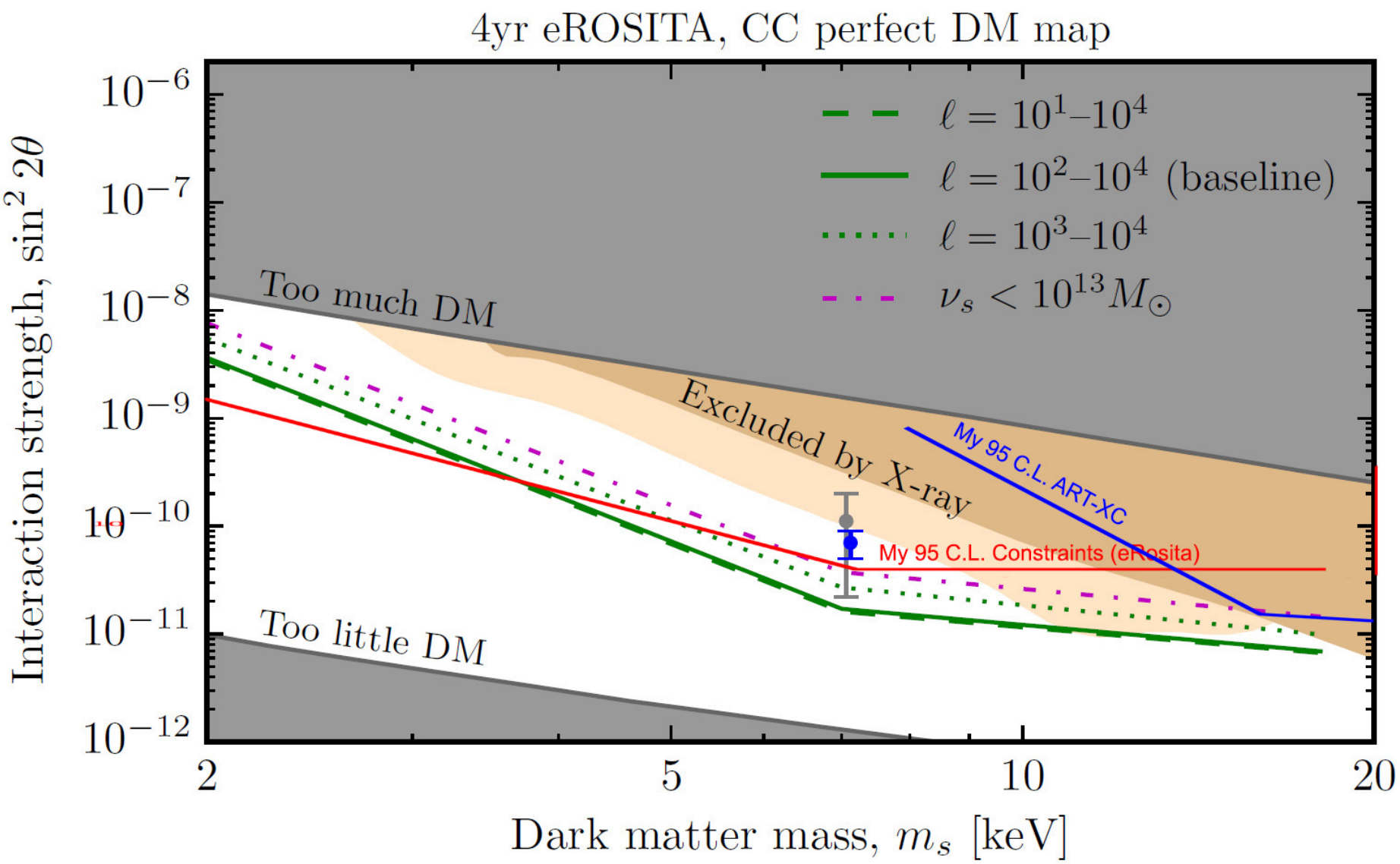
1908.09037

2007.07969 (V. Barinov, R. Burenin, D.G., R. Krivonos)


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

More robust, but less sensitive

1505.07829, V. Barinov, R. Burenin, D.G., R. Krivonos



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:

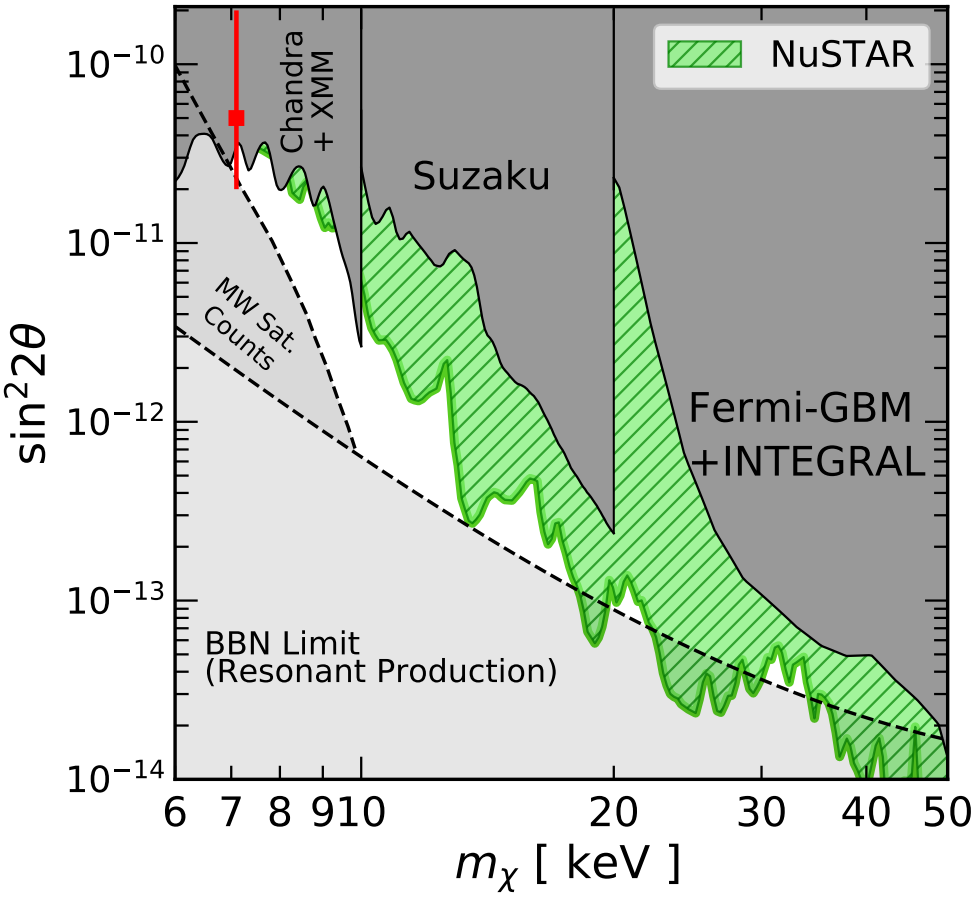
$$\theta^2_{X-ray} = \theta^2_{\alpha I} \frac{\Omega_N}{\Omega_{DM}}$$

  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



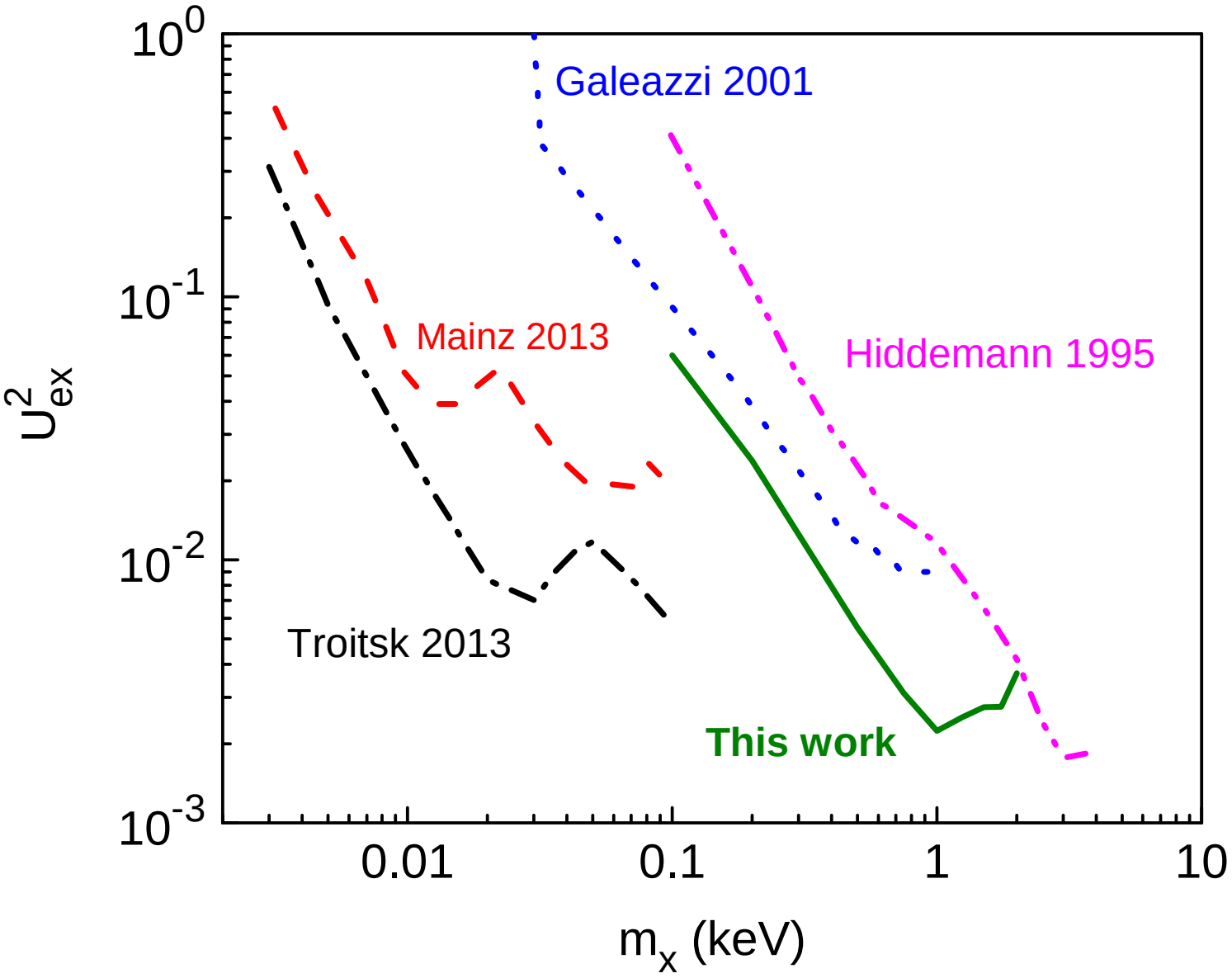
F.Bezrukov, A.Chudaykin, D.G. (2017,2018,2019)

Conclusions

- sterile neutrino DM implies one massless active neutrino
  (with $N = 3$ sterile neutrino seesaw)
- we can fully explore the model with
  new X-ray data (e.g. on board of SRG)
  more dwarf galaxies observed around us
  progress in checking BBN predictions
- much larger room with new ingredients in the sterile sector

Backup slides

Searches for DM are deep inside the forbidden region



1703.10779

Larger mixing: Suppression of production

Form only a fraction of DM !!

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

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

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)

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

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

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:

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

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

The production in oscillations will be suppressed, if

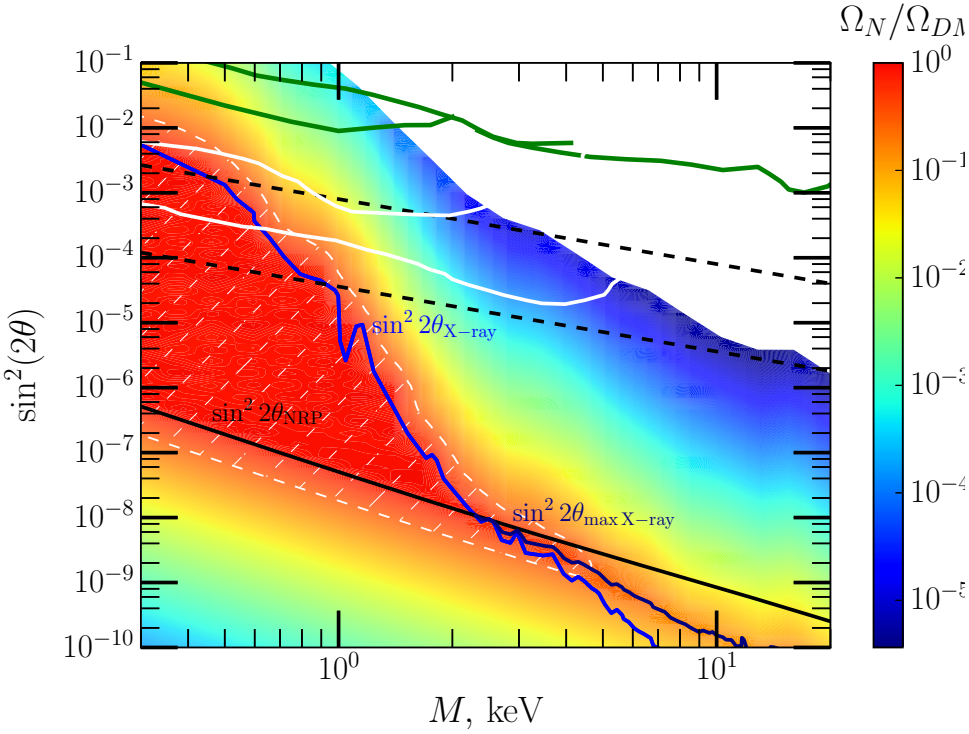
$$T_c < T_{max} \approx 133\,\text{MeV} \left(\frac{1\,\text{keV}}{M_N} \right)^{1/3}$$

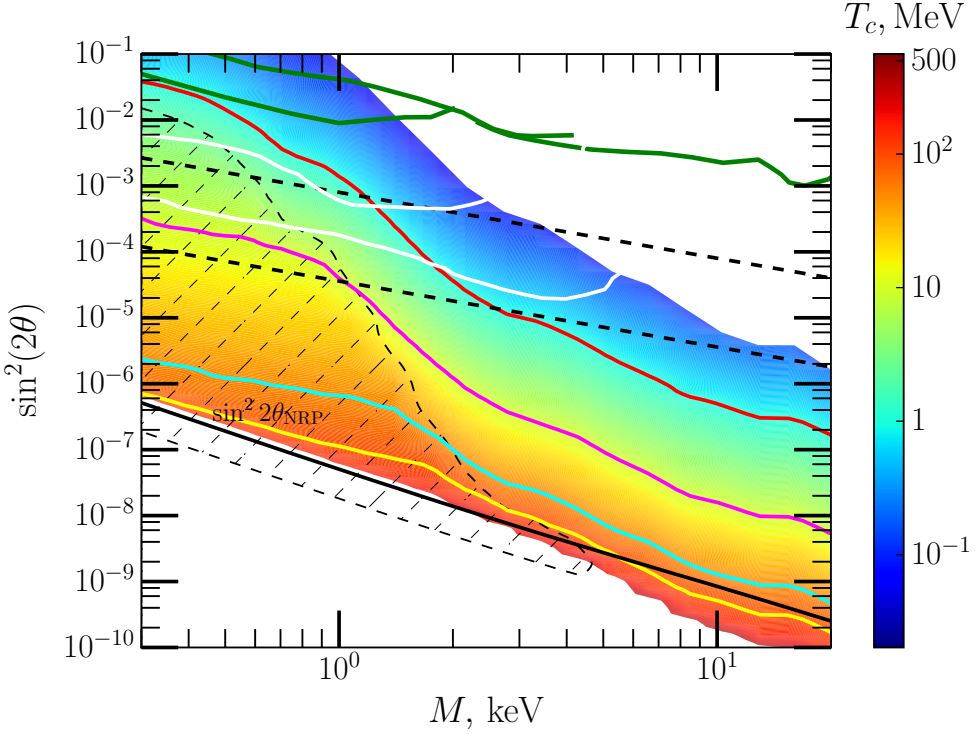
there is always a chirality flip contribution $\propto M_D^2 / E^2$

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

Results: large mixing is allowed

for details see 1705.02184





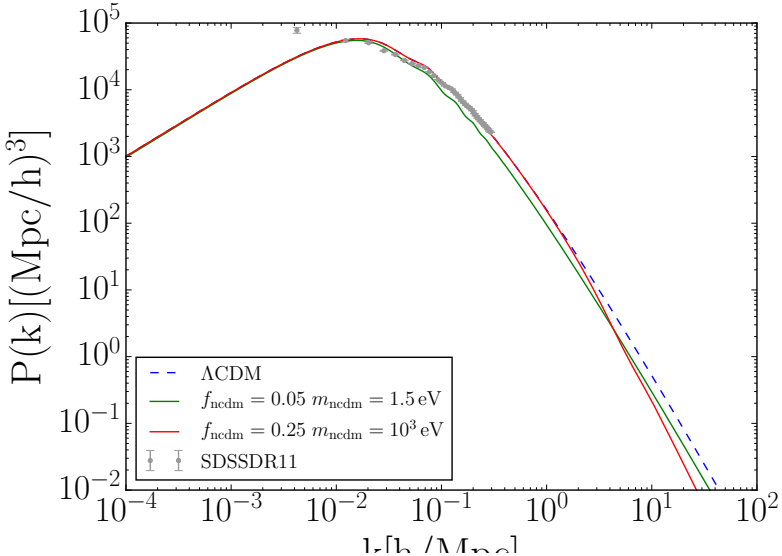
Important:

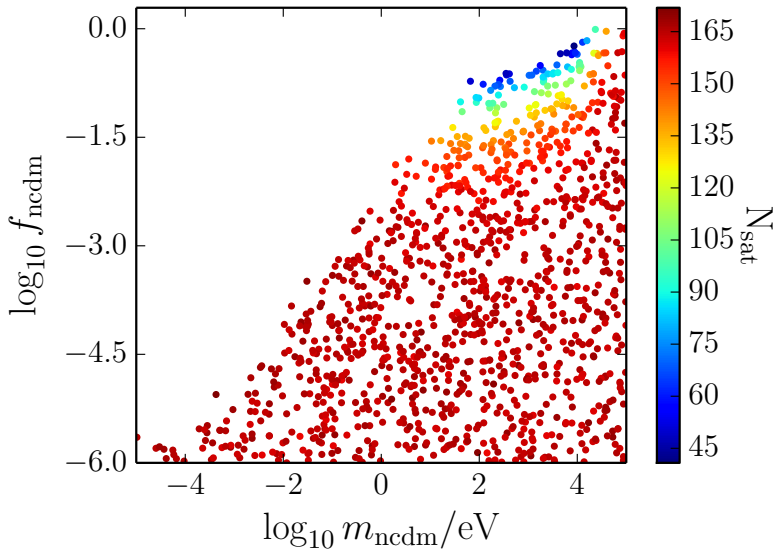
$m_a \sim \theta^2 M_N$

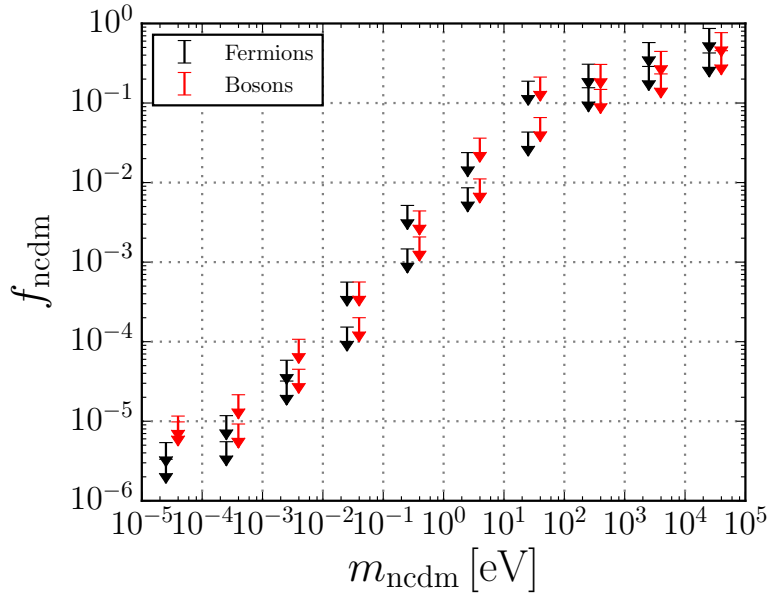
1. seesaw light sterile neutrino (dashed lines: $m_a \sim 0.008 - 0.2\,\text{eV}$)
2. can be directly tested !! (between green and white lines)
3. Warm, so most probably only a part of DM

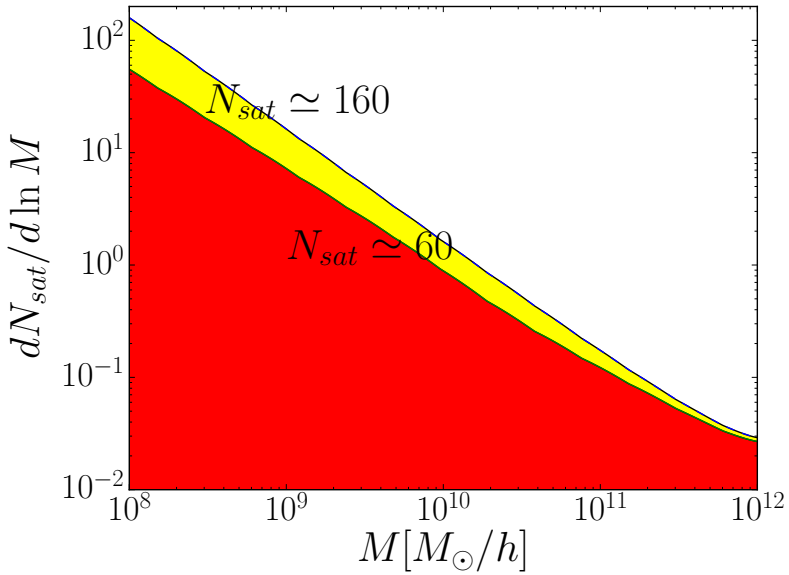
Sterile neutrinos: a part of dark matter

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:

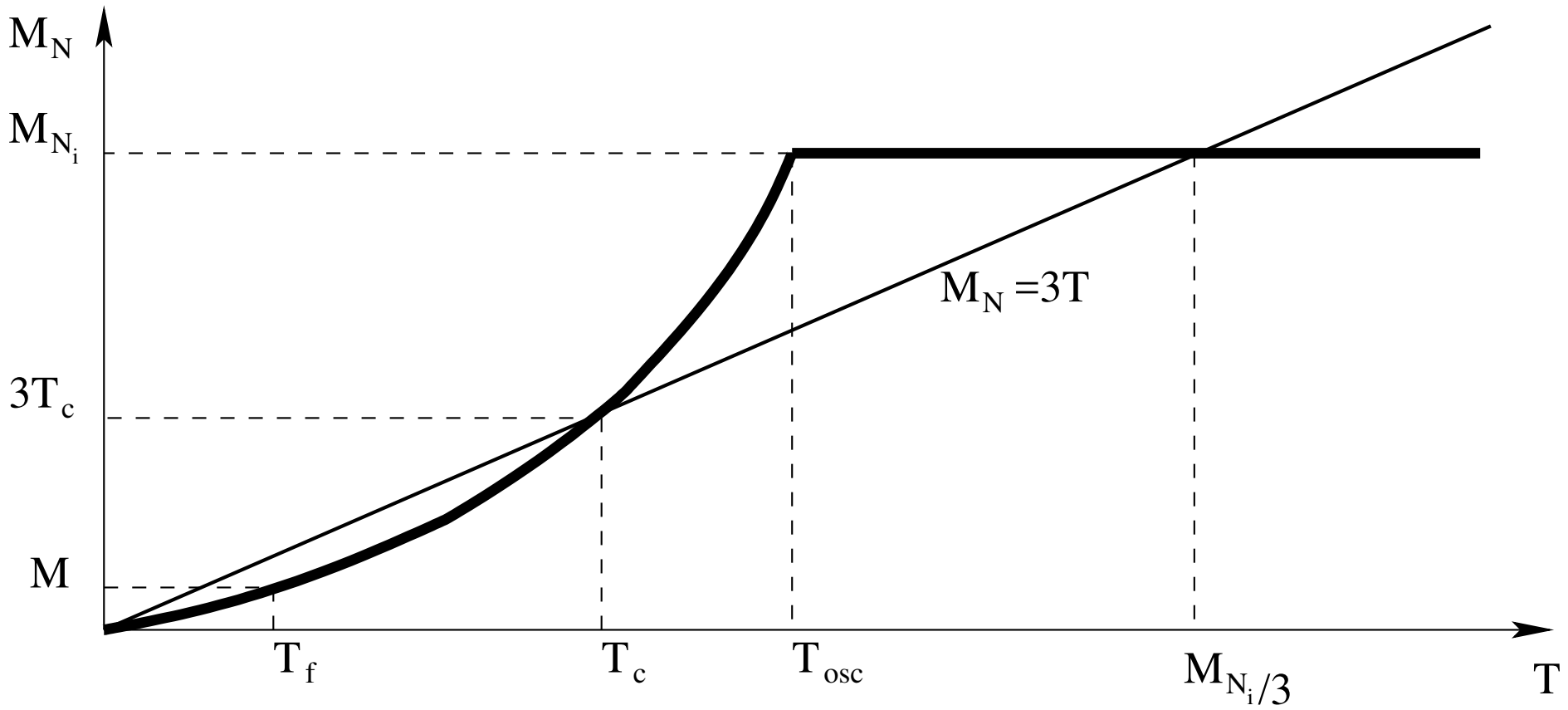
$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$

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

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

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

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

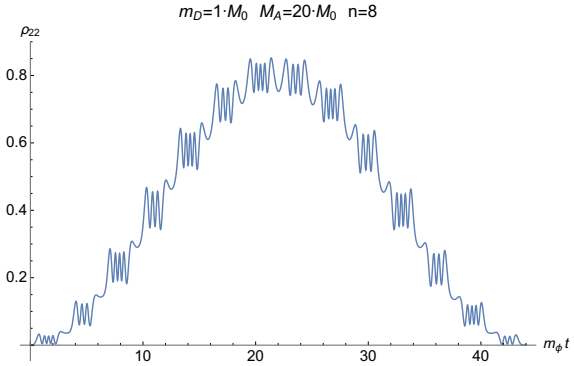
F.Bezrukov, A.Chudaykin, D.G. (2018)

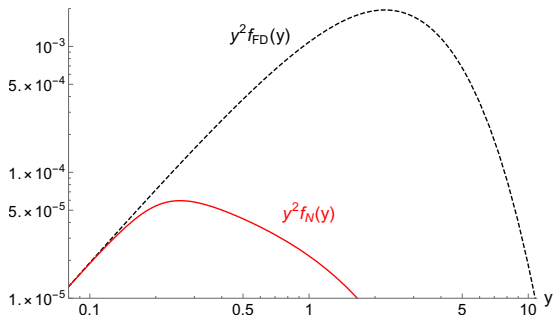
sterile neutrino mass

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

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

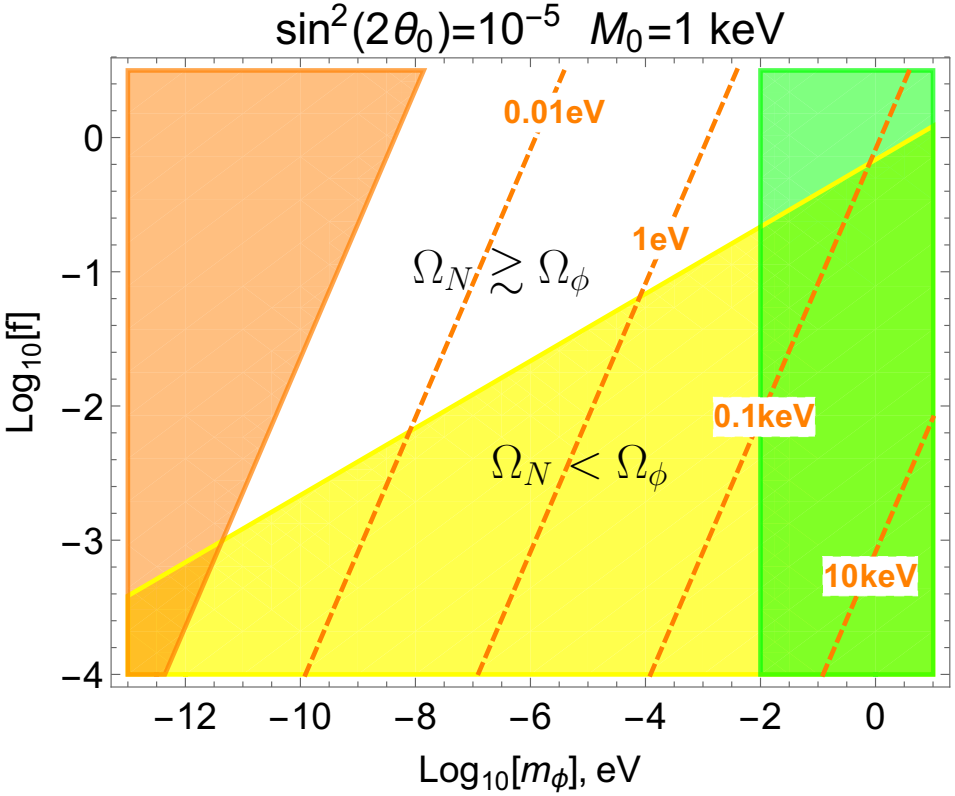
2) Both L_{osc} and θ_{eff} change with $M(t)$, which oscillates !! — resonance
very complicated system: three oscillators with time-dependent couplings — cool

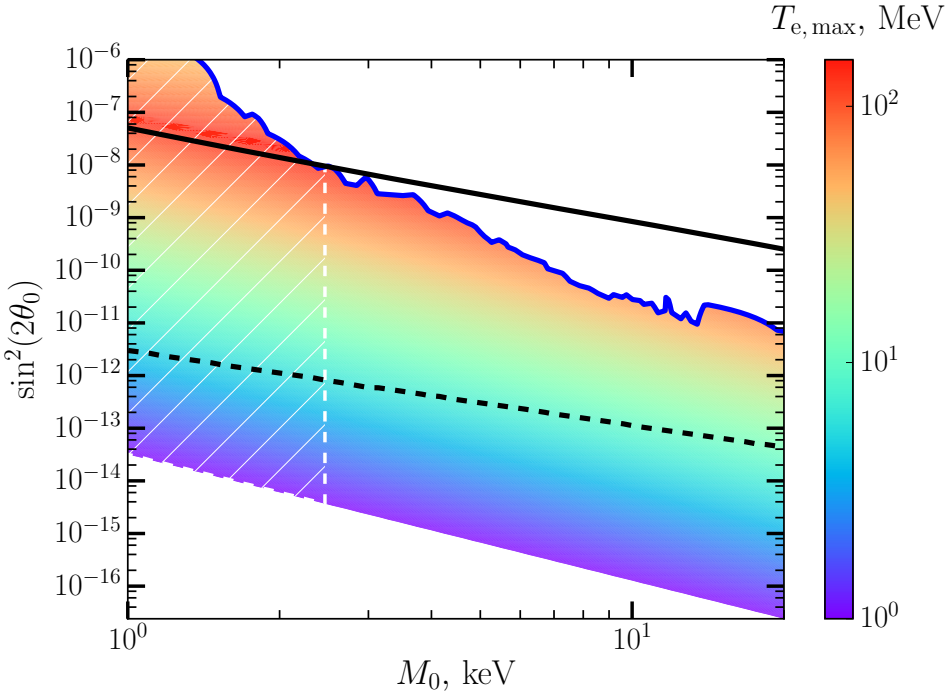




Allowed regions for each mechanism

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





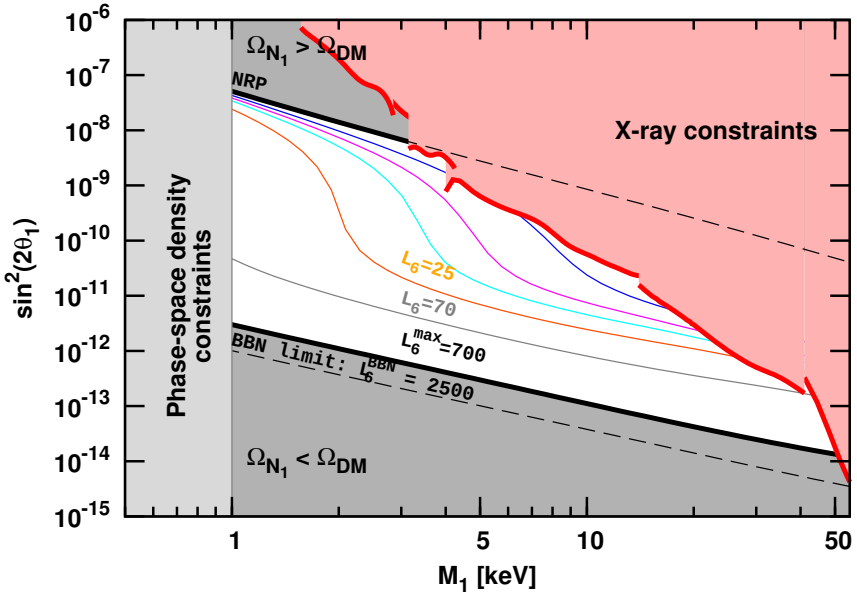
- $m_\phi < 2M_N$
- $\Gamma_{\phi\to\nu\nu} < \dots$
- $\rho_\phi + \rho_N \leq \rho_{DM}$
-

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)

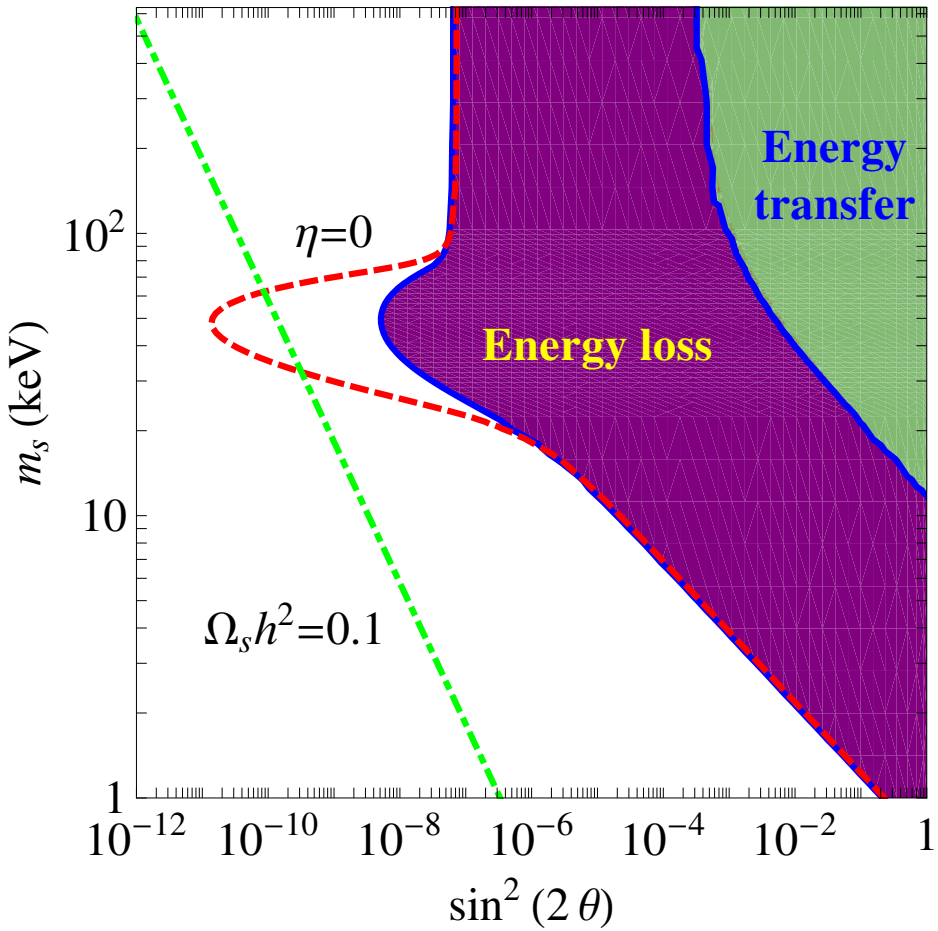
$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

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

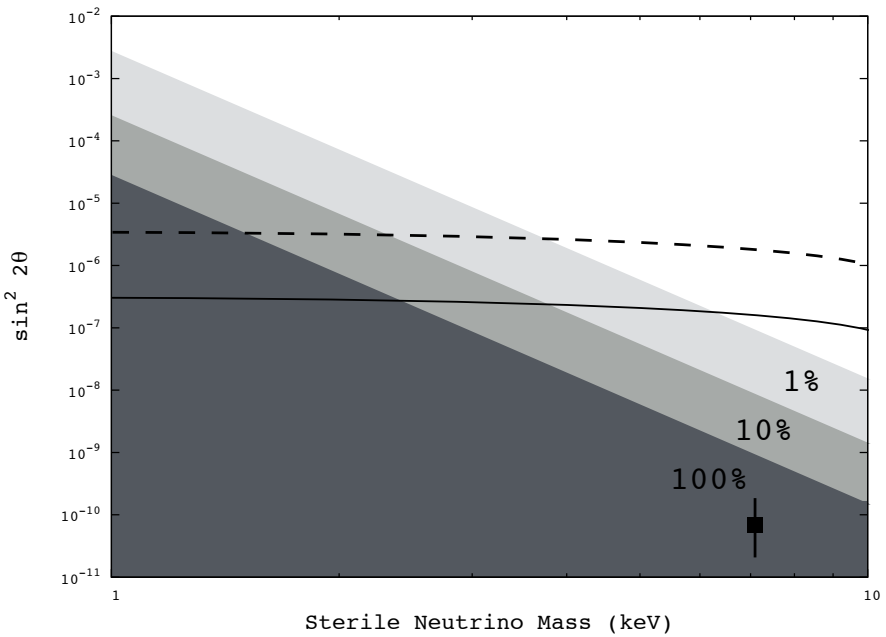
F.Bezrukov, D.G. (2009)

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

Limits form SN



1102.5124



1603.05503