Sterile neutrino dark matter

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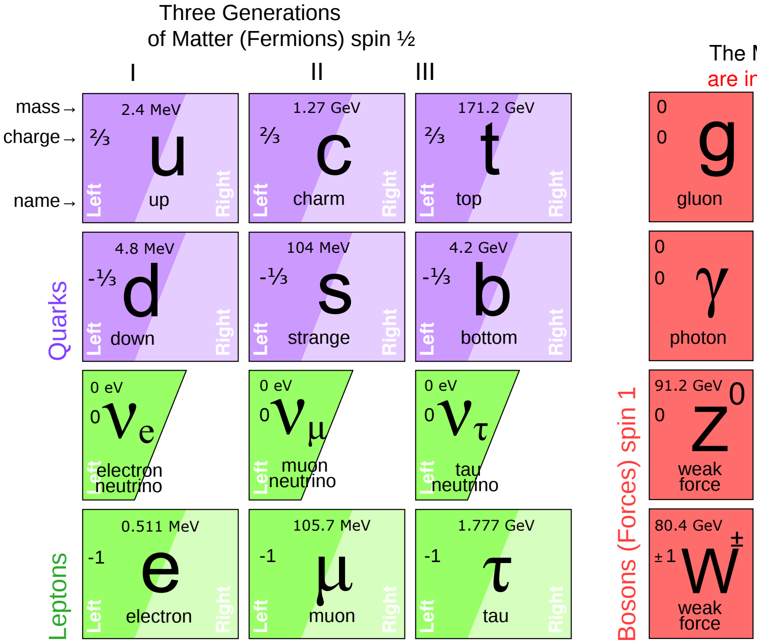
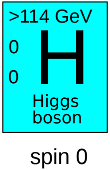


The Matter generations
are indistinguishable by
electric
weak and
strong
forces

distinguishable
by gravity
and Yukawa
forces



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

Standard Model + GR : Major Problems

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

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 (anomalies: $g-2$, B-physics, . . .)
- Does not describe (PHENO)
  - Neutrino oscillations (and anomalies. . .)
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Why the Universe is flat and homogeneous?
  - Where did the matter perturbations come from?

(THEORY)

- Dark energy (Ω_Λ)
- Strong CP-problem
- Gauge hierarchy
- Quantum gravity
- Quantization of electric charge
- Why 3 generations?
- Why $Y_e \ll Y_\mu \ll .. \ll Y_t$

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:

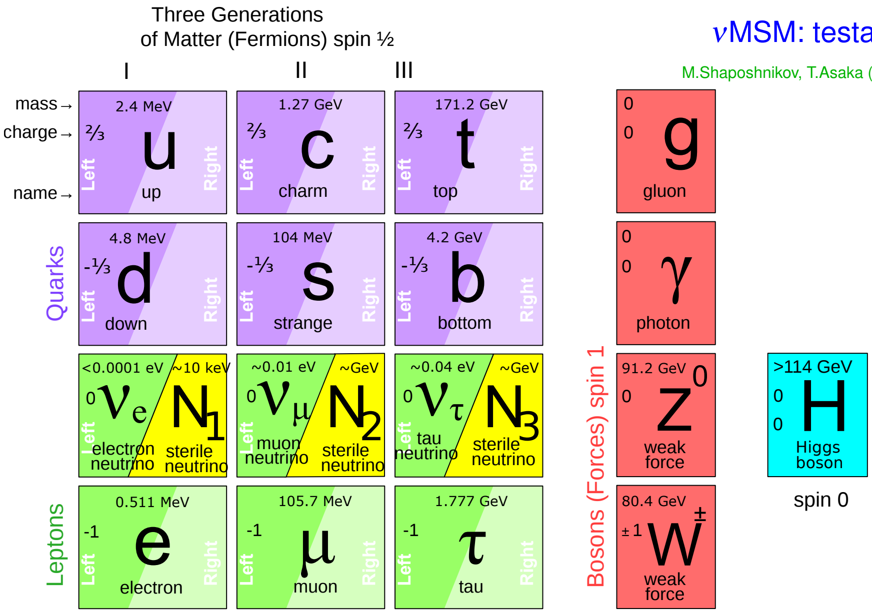
- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)

Disappointing feature:

Major part of parameter space is UNTESTABLE

νMSM: testable

M.Shaposhnikov, T.Asaka (2006)



Seesaw mechanism: $M_N \gg 1$ eV spinor portal

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 $M_N \gg M^D = v \frac{f}{\sqrt{2}}$ 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
  (and C- and CP-symmetry with several N's)

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 3 sterile neutrinos is viable

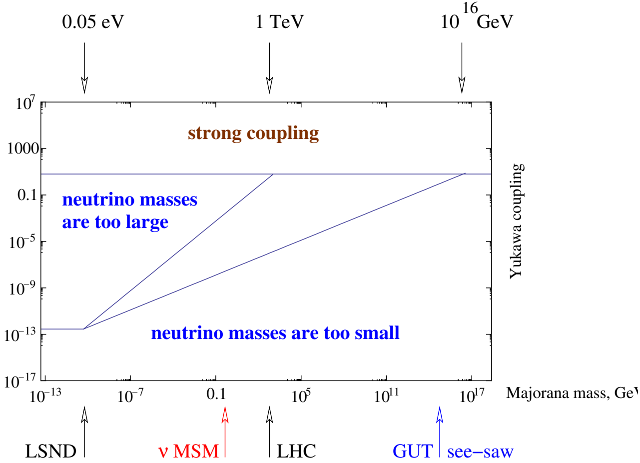
$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$

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

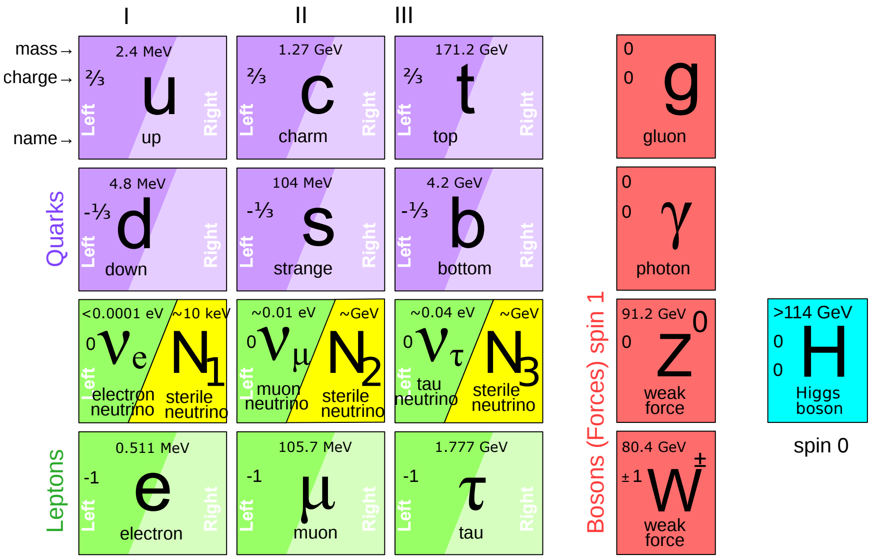
$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



Seesaw diagram

Three Generations
of Matter (Fermions) spin ½



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 $M_N < M_W$)

$$\theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\text{keV}}{M_N} \right)^5$$

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

$$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

Sterile neutrino: indirect searches

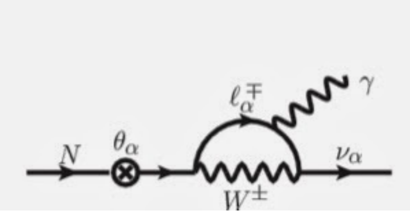
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- 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 $E_\gamma = M_N/2$

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

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

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

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

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

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:

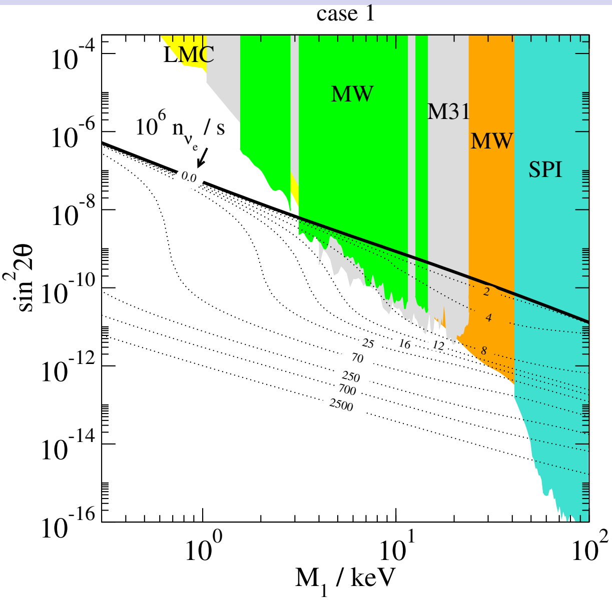
$$V_{\alpha\alpha} \sim -\# G_F^2 T^4 E$$

resonant production in the lepton asymmetric plasma

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

0804.4543

$$n_{\nu_\alpha} - n_{\bar\nu_\alpha} = \mu_\alpha T^2/6$$



Non-resonant production is excluded now...

- too large mixing to avoid X-ray limits
- light DM $m_{\nu_s} < 2\,\text{keV}$ is forbidden by phase space density 2412.20585
- light DM is disfavored by Ly-α forest
- light DM is closed by MW satellite counts

too warm to be the main component of DM

Primordial Nucleosynthesis: solving kinetic equations

Neutrons freeze out ($p + e \leftrightarrow n + \nu_e$) at $T_n \approx 0.8\,\mathrm{MeV}$, and then

$$p + n \leftrightarrow D + \gamma$$

D survive γ-hitting later, at $T < T_{NS} \approx 65\,\mathrm{keV}$

$$n_{^4\mathrm{He}}(T_{NS}) = \frac{1}{2} n_n(T_{NS}) \,,$$

neutron-to-proton ratio

$\tau_n \approx 880$ s

$$\frac{n_n(T_{NS})}{n_p(T_{NS})} = \mathrm{e}^{-\frac{m_n - m_p}{T_n}} \cdot \mathrm{e}^{-\frac{t_{NS}}{\tau_n}} \cdot \mathrm{e}^{-\frac{\mu_{\nu_e}}{T_n}} \approx \frac{1}{7} \,,$$

$$Y_p \equiv X_{^4\mathrm{He}} = \frac{m_{^4\mathrm{He}} \cdot n_{^4\mathrm{He}}(T_{NS})}{m_p \left(n_p(T_{NS}) + n_n(T_{NS})\right)} = \frac{2}{\frac{n_p(T_{NS})}{n_n(T_{NS})} + 1} \approx 25\%$$

Present limits from BBN:

BBN: PDG-2022 and 2208.03201

$$\frac{|\mu_{\nu_e}|}{T_\nu} \equiv |\xi_e| < 0.03 \quad 95\%\,\text{CL}$$

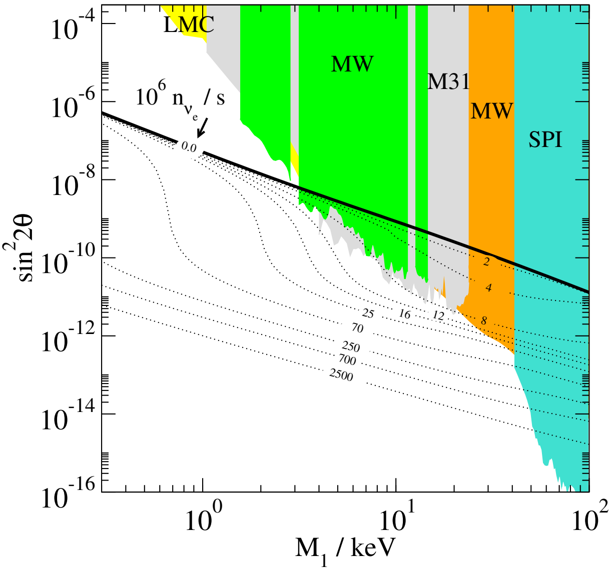
and

$$L_e = \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{s} = \frac{15}{43\pi^2} \times \xi_e$$

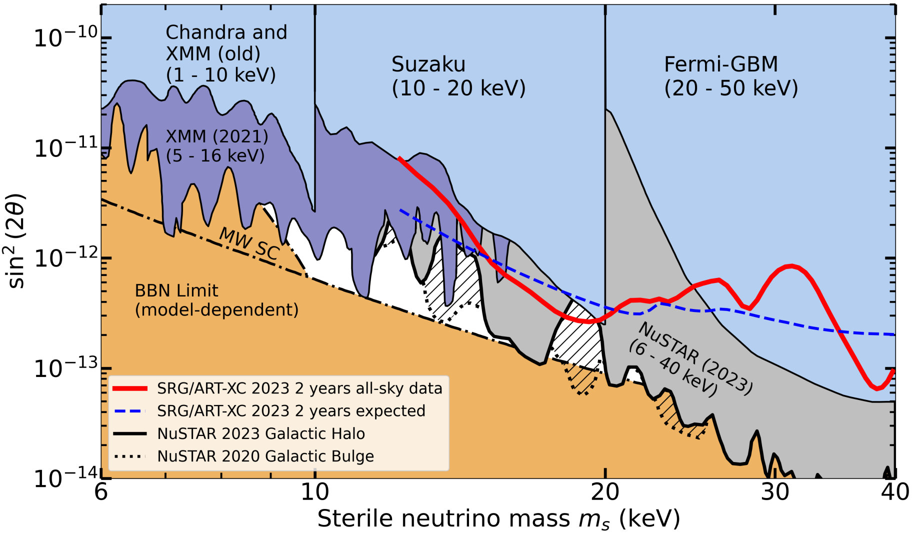
Simple case:
after DM production
asymmetry is in one flavor α:
oscillations $\nu_\alpha \leftrightarrow \nu_\beta$ at
$T < 10\,\text{MeV}$
redistribute it, so $\mu_{\nu_e} = \mu_\alpha/3$
then

$$L_e < 3.2 \times 10^{-3} \;\rightarrow\; 3200$$

case 1



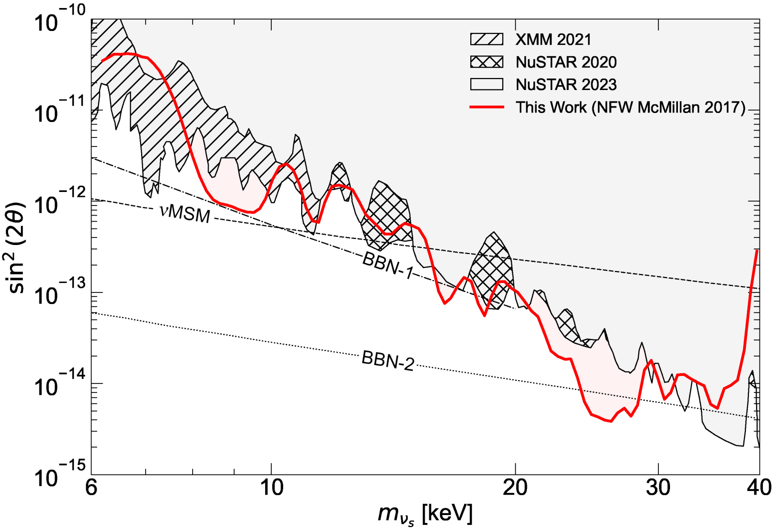
eROSITA (0.2-10 keV), ART-XC (4-30 keV)



Chandra and
XMM (old)
(1 - 10 keV)
Suzaku
(10 - 20 keV)
Fermi-GBM
(20 - 50 keV)
XMM (2021)
(5 - 16 keV)
MW SC
BBN Limit
(model-dependent)
NuSTAR (2023)
(6 - 40 keV)
SRG/ART-XC 2023 2 years all-sky data
SRG/ART-XC 2023 2 years expected
NuSTAR 2023 Galactic Halo
NuSTAR 2020 Galactic Bulge
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$\sin^2(2\theta)$
6
10
20
30
40
Sterile neutrino mass m_s (keV)

2303.12673

NuSTAR: the latest and strongest limits



2405.17861

Production in lepton-asymmetric plasma: Shi–Fuller

$$\langle P(\nu_\alpha \to \nu_s)\rangle = \frac{1}{2}\,\frac{\frac{m_{\nu_s}^4}{4T^2y^2}\sin^2 2\theta_\alpha}{\frac{m_{\nu_s}^4}{4T^2y^2}\sin^2 2\theta_\alpha + \frac{\Gamma_{\nu_\alpha}^2}{4} + \left(\frac{m_{\nu_s}^2}{2yT}\cos 2\theta_\alpha - V_\alpha^L - V_\alpha^T\right)^2}\,.$$

with neutrino thermal potential (omitting factors) $y \equiv p/T$

$$V_\alpha^T(p) = -G_F^2 T^5 y$$

and lepton asymmetry potential (omitting factors)

$$V_\alpha^L = G_F T^3 \xi_{\nu_\alpha}$$

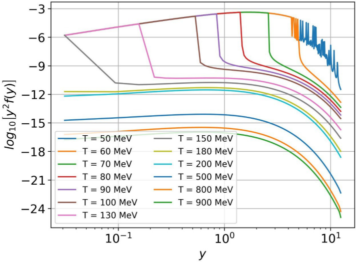
the resonance condition

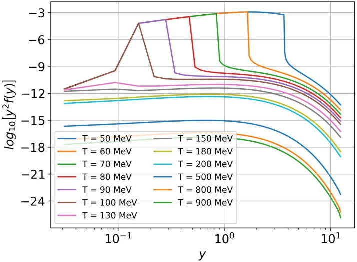
$$\frac{m_{\nu_s}^2}{2y} - G_F T^4 \xi_{\nu_\alpha} + G_F^2 T^6 y \approx 0$$

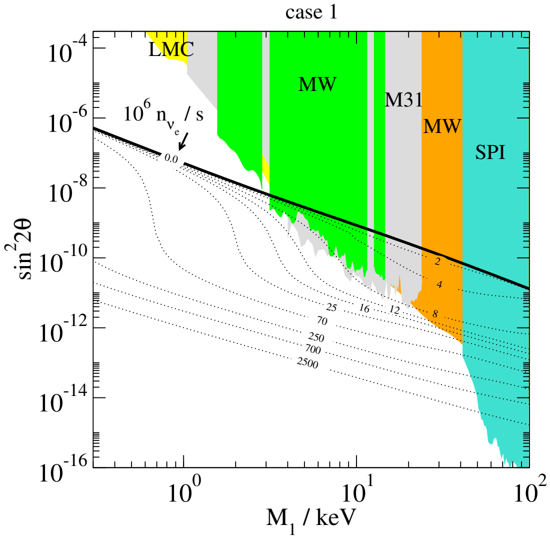
implies high temperature and low temperature solutions

$$y \simeq \frac{\xi_{\nu_\alpha}}{G_F T^2}\,,\qquad y \simeq \frac{m_{\nu_s}^2}{2\xi_{\nu_\alpha} G_F T^4}$$

DM from oscillations: (DW & ShF)





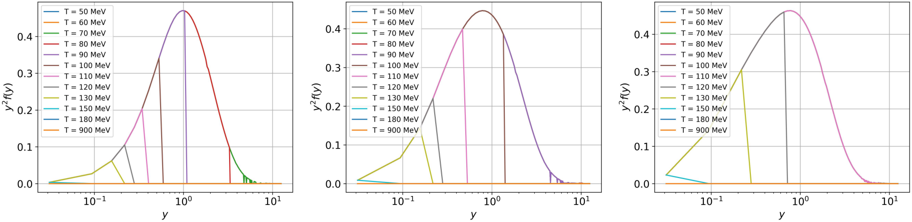


2502.17374 with help of

dmpheno code 1601.07553

Make them colder changing the asymmetry

Reference: thermal spectrum gives $\langle p/T \rangle = \langle y \rangle = 3$



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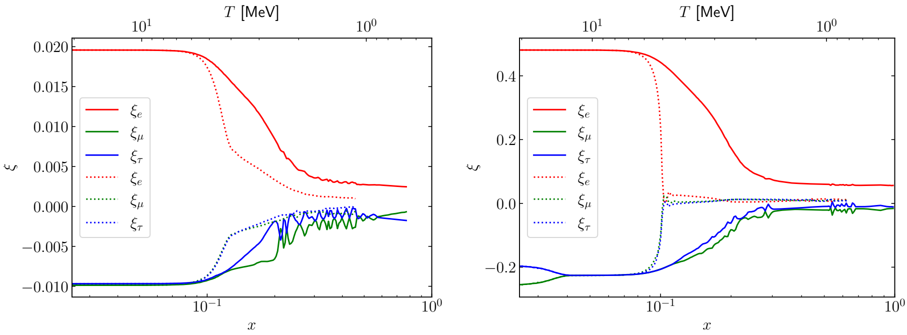
Reduce the remained lepton asymmetry, if $\sum \approx 0$

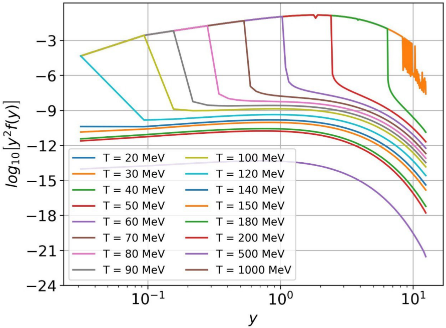
Via oscillations of active neutrinos which starts at $T \sim 20 - 10\,\text{MeV}$ FortEPiaNO

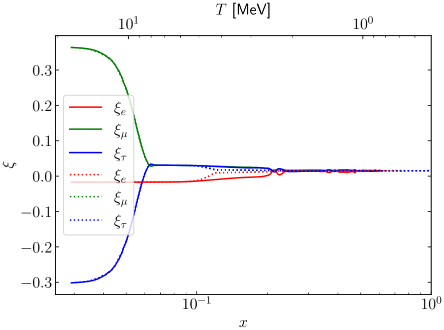


solid lines for normal and dotted lines for inverse hierarchy 2502.17374

Reduce the lepton asymmetry, mixing with ν_μ

Via oscillations of active neutrinos which starts at $T \sim 20 - 10\,\mathrm{MeV}$ FortEPiaNO

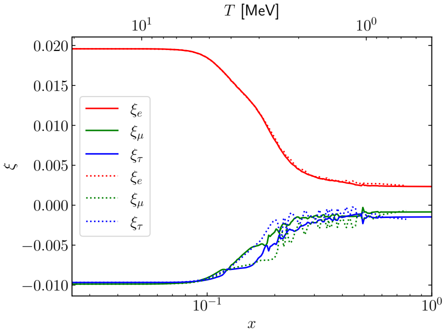


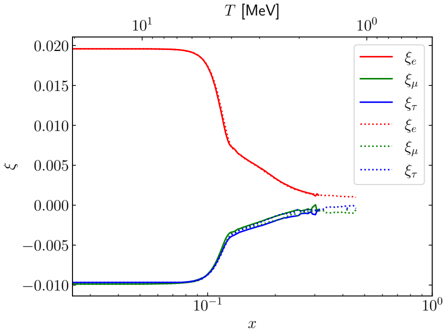


solid lines for normal and dotted lines for inverse hierarchy 2502.17374

Reduce the remained lepton asymmetry, if $\sum \approx 0$

Via oscillations of active neutrinos which starts at $T \sim 20 - 10$ MeV FortEPiaNO



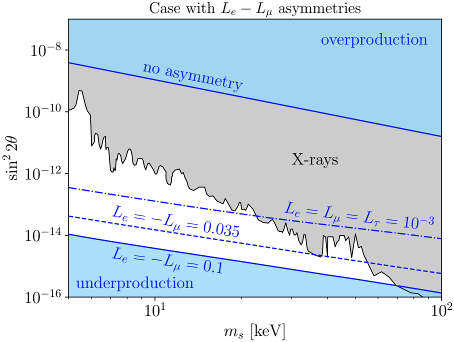


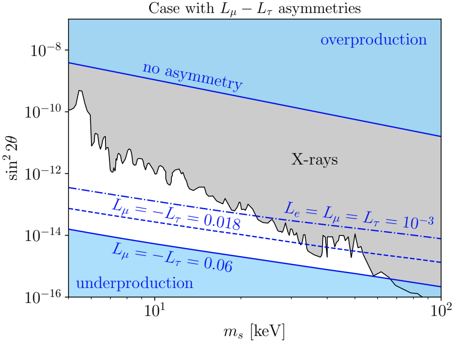
normal (left) and inverse (right) hierarhy

with solid lines for zero *CP* and dotted for *CP* phase from PDG

2502.17374

Recent predictions





2507.20659

Summary

- sterile neutrino is a viable DM candidate
- it can be produced in the early Universe via resonant oscillations
- more room with tuned asymmetry in neutrino flavors
- this is a task for next generation X-ray telescopes
- νMSM is minimalistic SM extension (3 majorana fermions)
  capable of explaining
  neutrino oscillations
  baryon asymmetry of the Universe
  dark matter phenomenon

Backup slides

Anomalies with matter structures at small scales

- Core-cusp problem

  Dark Matter density profiles in the centers of simulated halos are cusped
  while in observed dwarf galaxies are cored

- Lack of dwarf galaxies

  Matter perturbations of almost flat spectrum produce flat halo mass spectrum
  low abundance of small galaxies

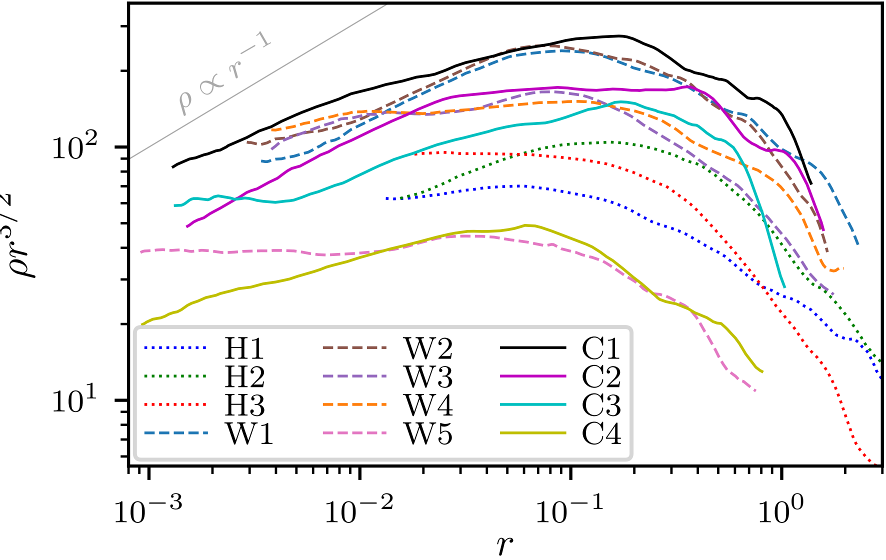
- Too-big-To-fail problem

  There must be galaxies heavy enough to keep baryons inside
  Milky Way hosts only two such galaxies

WDM, SIDM, Fuzzy DM etc: to suppress structures at small scales

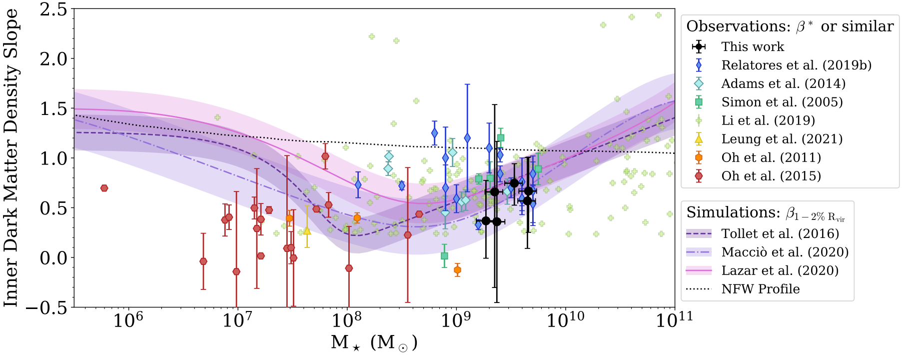
Cusps in simulations

2207.05082

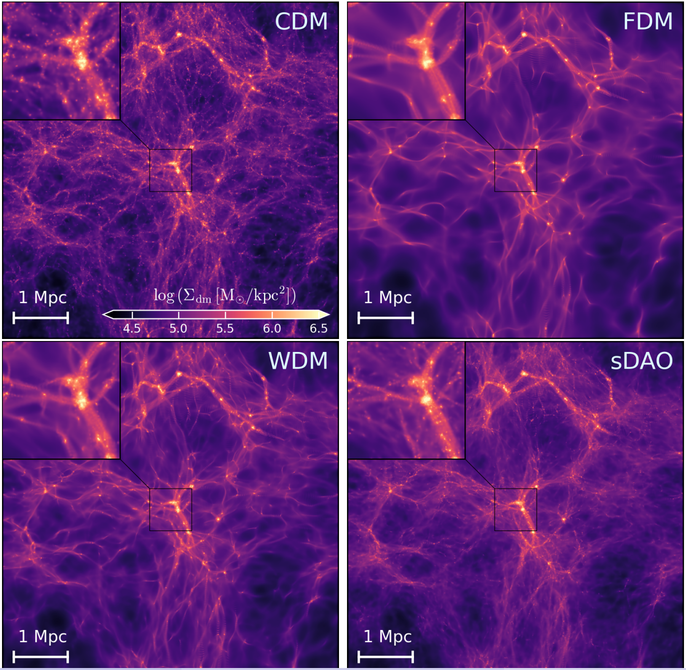


Core vs cusp in a galaxy...

2203.00694



$$\rho(r) \propto \frac{1}{r^{\beta^*}}$$

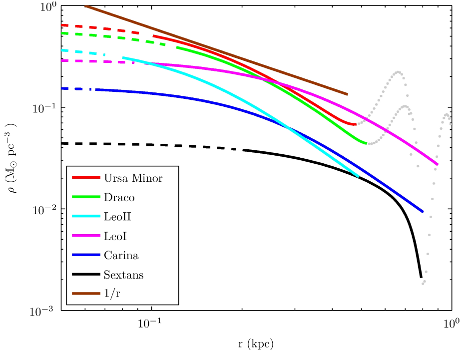

CDM
FDM
WDM
sDAO
1 Mpc
$\log(\Sigma_{dm}\,[M_\odot/\mathrm{kpc}^2])$
4.5
5.0
5.5
6.0
6.5

2304.06742

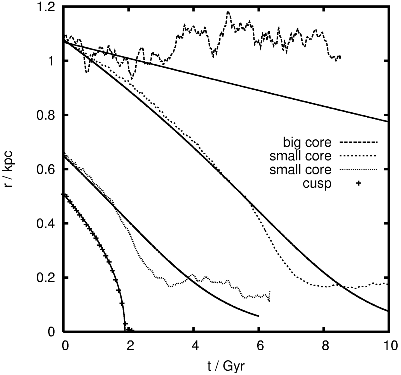
CDM Problems

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 30 instead of 300
- Galactic density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp

Cores observed (?)

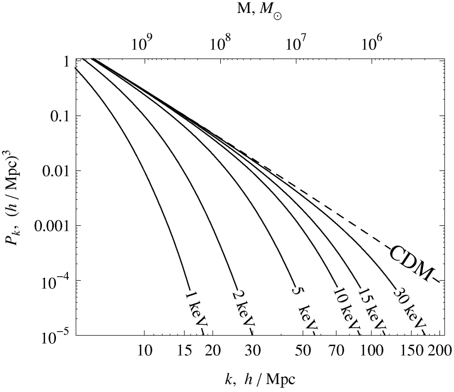


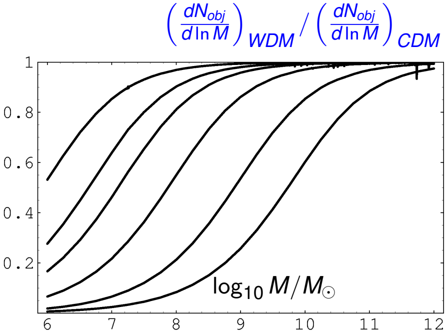
5 Clusters in the Fornax dSph



CDM Problems

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 30 instead of 300
- Galactic density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
- Might be solved with Warm Dark Matter (sterile neutrino, gravitino)
  - Is non-relativistic ($v \sim 10^{-3}$) at $T \sim 1$ eV free-streaming scale $l \sim vt_H$
  - Nonthermal production is needed





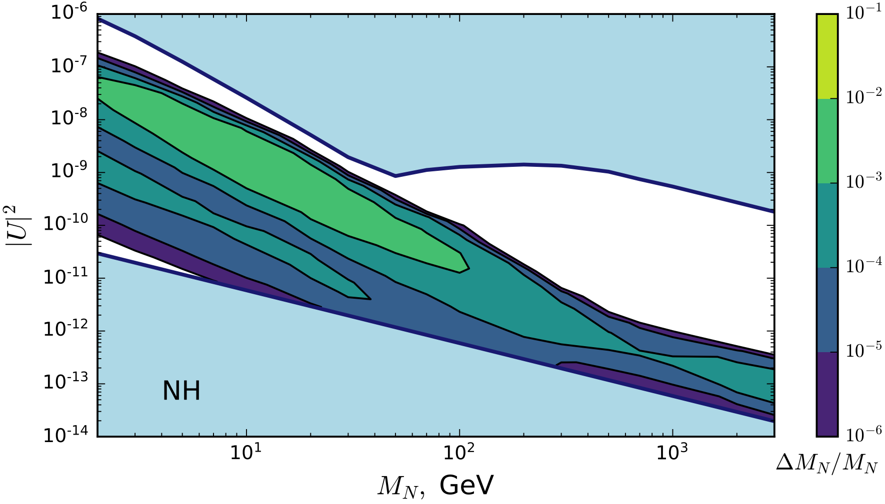
Generation of lepton asymmetry with νMSM

Sakharov's condition of a successful baryogenesis

- *B*, *L*-violation
- *C*-, *CP*-violation
- departure from thermal equilibrium
  Oscillations in primordial plasma to get $\sim 10^{-9}$ before EW transition
  generation of higher lepton asymmetry (upto 10^{-3} later)

Degeneracy for Leptogenesis

2008.13771



Mixing angle in primordial plasma

$$\langle P(\nu_\alpha \to \nu_s)\rangle = \frac{1}{2}\frac{\frac{m_{\nu_s}^4}{4p^2}\sin^2 2\theta_\alpha}{\frac{m_{\nu_s}^4}{4p^2}\sin^2 2\theta_\alpha + \frac{\Gamma_{\nu_\alpha}^2}{4} + \left(\frac{m_{\nu_s}^2}{2p}\cos 2\theta_\alpha - V_\alpha^L - V_\alpha^T\right)^2}\,.$$

with neutrino thermal potential

$$V_\alpha^T(p) = -\frac{8\sqrt{2}}{3}G_F\left(\frac{\rho_{\nu_\alpha}}{M_Z^2} + \frac{\rho_\alpha}{M_W^2}\right)p\,, \quad \rho_{\nu_\alpha} \propto T^4$$

and lepton asymmetry potential

$$V_\alpha^L = \sqrt{2}G_F\left[\left(1-2\sin^2\theta_W\right)\Delta n_Q - \frac{1}{2}\Delta n_B + \sum_\beta \left(\left(1+\delta_{\alpha\beta}\right)\Delta n_{\nu_\beta}\right) + \left(\delta_{\alpha\beta} - \frac{1}{2} + 2\sin^2\theta_W\right)\Delta_\beta\right]$$

with lepton asymmetry $\Delta n_{\nu_\beta} \propto \mu_{\nu_\beta} T^2 \propto \xi_{\nu_\beta} T^2$