Testing νMSM with present and next generation experiments

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Widely accepted statements

- Standard Model nicely explains
  almost all results of particle physics experiments
- We definitely need New particle Physics
  - neutrino oscillations
  - baryon asymmetry
  - dark matter
  - inflation-like stage in the early Universe

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- New Heavy particle contribution to the Higgs boson mass lifts it up
  but miraculously $m_h \sim E_{EW}$

Guesswork: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?

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Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar S

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta\, H^\dagger H S^\dagger S - \mu H^\dagger H S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion N

  sterile neutrino !!

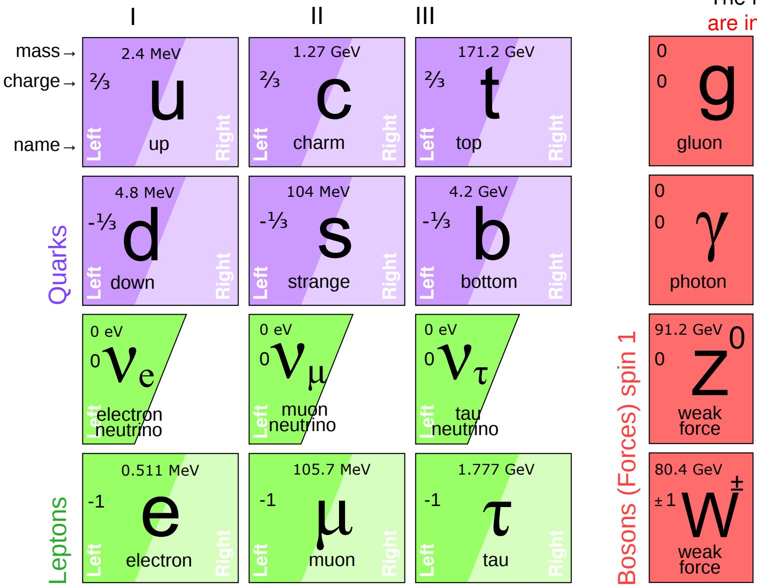
$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

  hidden photon

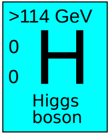
$$\mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Three Generations
of Matter (Fermions) spin ½



The Matter generations are indistinguishable by electric weak and strong forces

distinguishable by gravity and Yukawa forces



spin 0

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

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; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, d_R, u_R

- Describes all experiments dealing with
  - electroweak and strong interactions (anomalies: $g-2$, B-physics, ...)
- Does not describe (PHENO) (THEORY)

(PHENO)

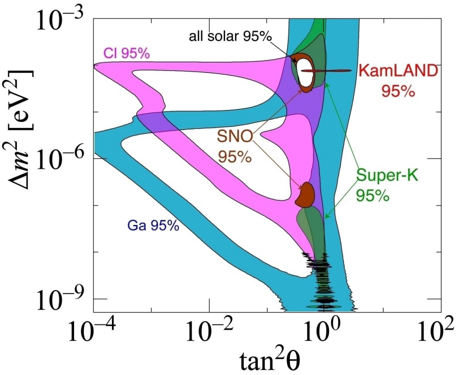
- Neutrino oscillations (and anomalies...)
- Dark matter (Ω_{DM})
- Baryon asymmetry (Ω_B)
- Why the Universe is flat and homogeneous?
- Where did the matter perturbations come from?

(THEORY)

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

Neutrino oscillations: masses and mixing angles

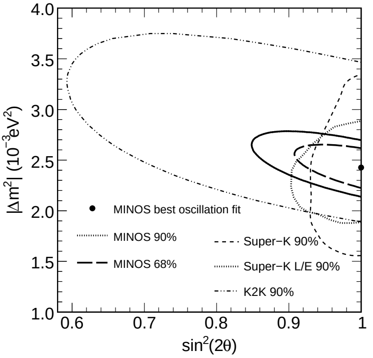
Solar 2 × 2 "subsector"



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

$m^2_{sol} \approx 7.5 \times 10^{-5}\,\text{eV}^2$

Atmospheric 2 × 2 "subsector"

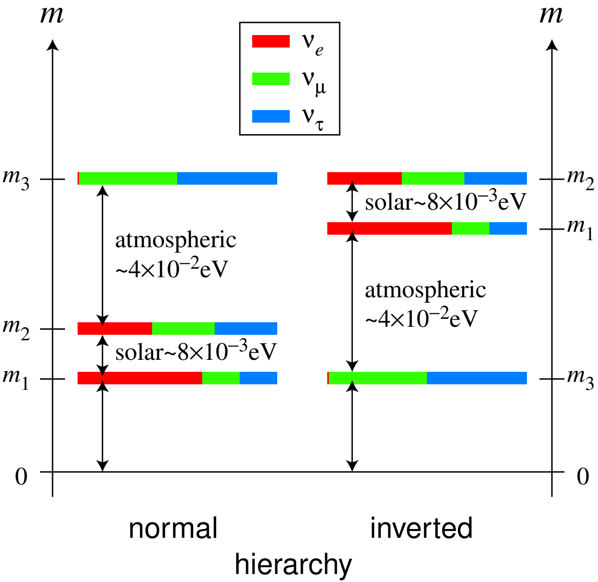


arXiv:0806.2237

$m^2_{atm} \approx 2.5 \times 10^{-3}\,\text{eV}^2$

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

Physics behind the neutrino oscillations is still elusive



$7.5 \cdot 10^{-5}\text{eV}^2 = m_{\text{sol}}^2 \ll$

$m_{\text{atm}}^2 = 2.5 \cdot 10^{-3}\text{eV}^2$

implies lower limits:

$m_I > 0.05\,\text{eV}, \quad m_{II} > 0.009\text{eV}$

hence

$$\sum m_\nu > 0.06\,\text{eV}$$

if much larger, then

$$m_i \approx \sum m_\nu/3$$

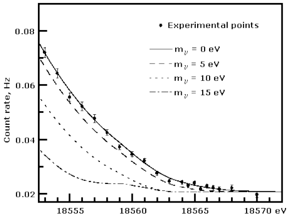
anyway

$$\sum m_\nu \geq 0.06, \; \sum m_\nu \geq 0.1$$

Direct searches for m_ν: cut in e-spectrum

$$\mathrm{T} \to {}^3\mathrm{He} + e + \bar{\nu}_e$$

$$(pnn) \to (ppn) + e + \bar{\nu}_e$$



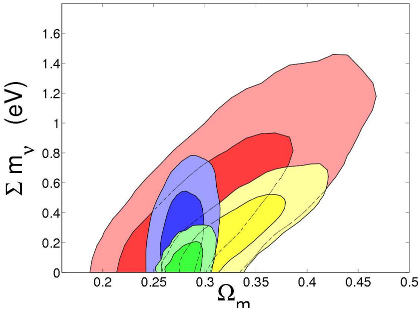
INR RAS, 1990-2000 years: $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

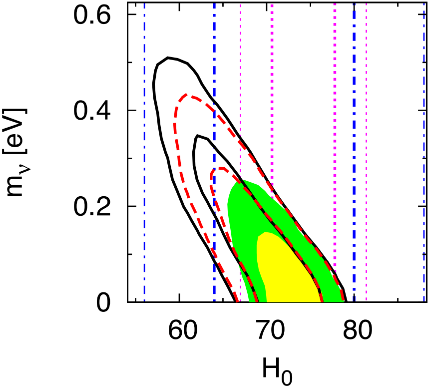
Mainz, 2000... : $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

limits from KATRIN (2022)

$m_{\bar{\nu}_e} \lesssim 0.8\,\mathrm{eV}$

similarly: $m_{\bar{\nu}_e} \lesssim 17\,\mathrm{keV}$, $m_{\bar{\nu}_e} \lesssim 17\,\mathrm{MeV}$





LRG+BAO+WMAP5+SNe+BAO

$\sum m_\nu < 0.28$ eV (95% CL)

0911.5291

CMB+Hubble measurements

$\sum m_\nu < 0.20$ eV (95% CL)

0911.0976

Physics behind the neutrino oscillations is still elusive

- nature of neutrino mass (Dirac vs Majorana)
- neutrino mass hierarchy
- *CP*-violation
- may be relevant for the matter-antimatter asymmetry
- neutrino anomalies are just anomalies

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:

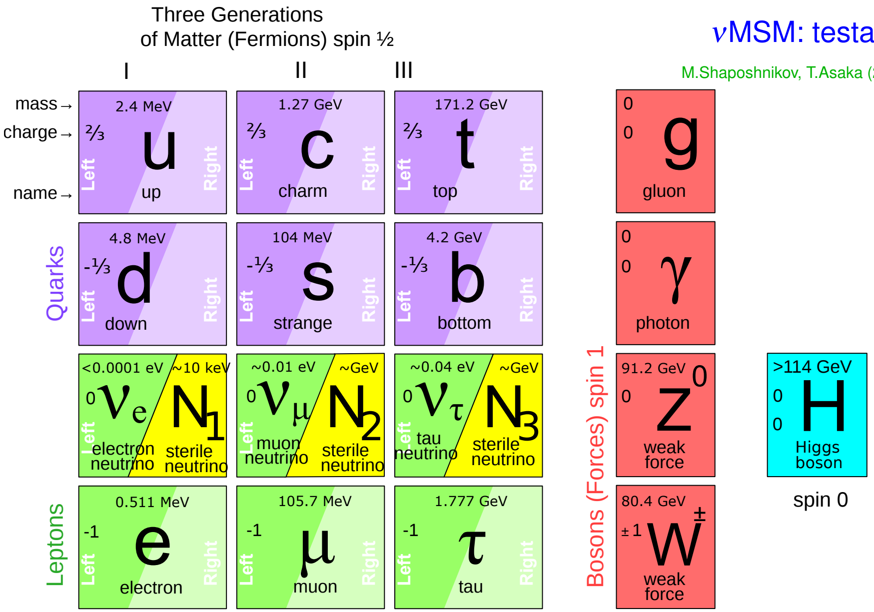
- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- light(?) sterile neutrinos might be responsible for neutrino anomalies. . . ?

Disappointing feature:

Major part of parameter space is UNTESTABLE

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

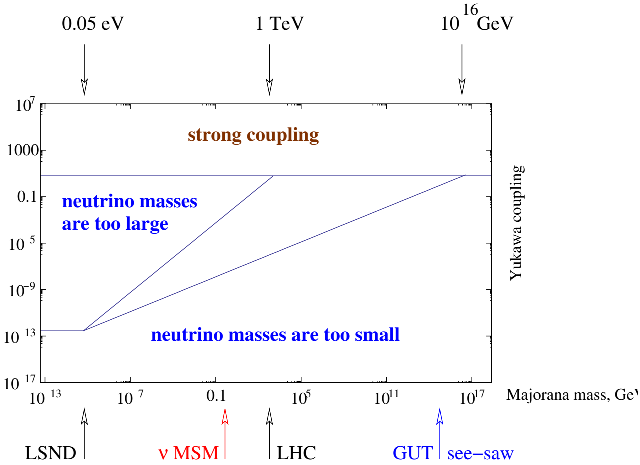
$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$

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

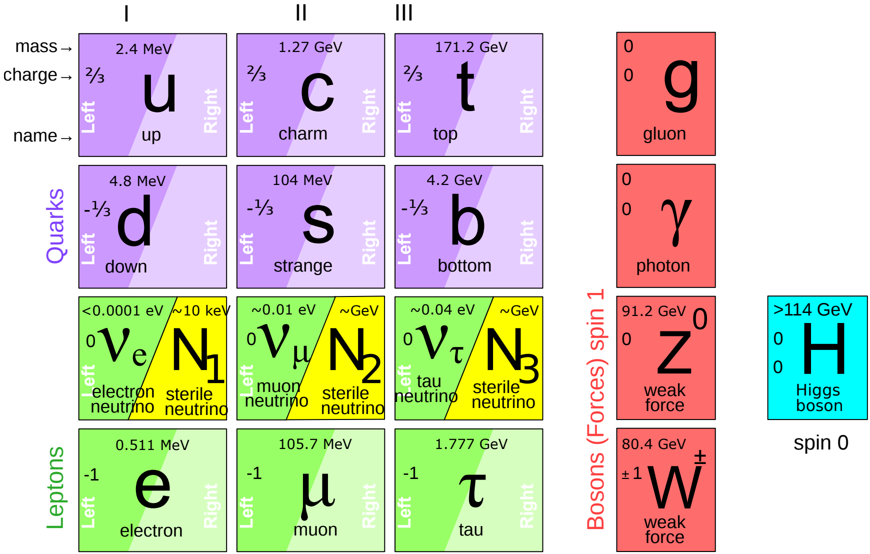
$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

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 $m_a \sim \theta^2 M_N$

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

Generation of lepton asymmetry with νMSM

Sakharov's condition of a successful baryogenesis

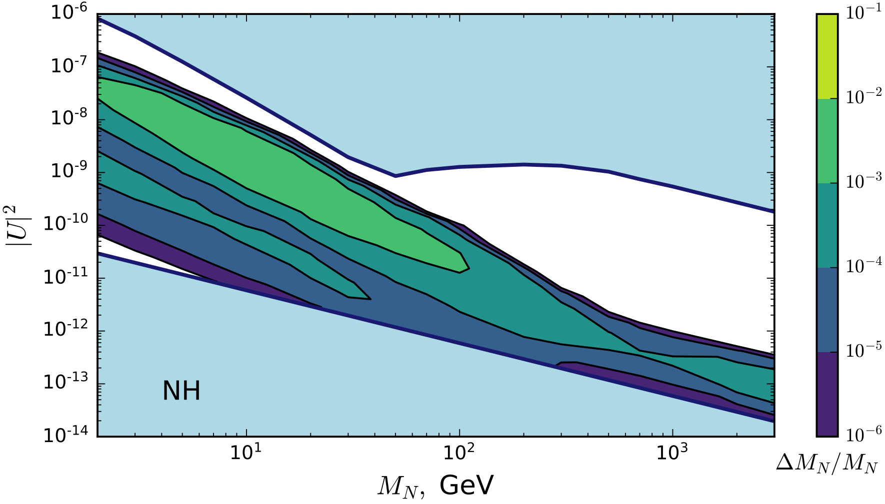
- *B*, *L*-violation
- *C*-, *CP*-violation
- departure from thermal equilibrium

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



Sterile neutrino: indirect searches

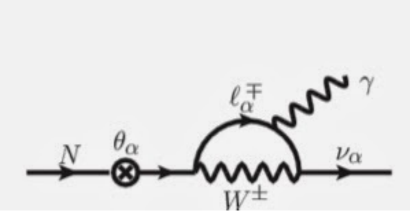
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- 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

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

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

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

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:

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

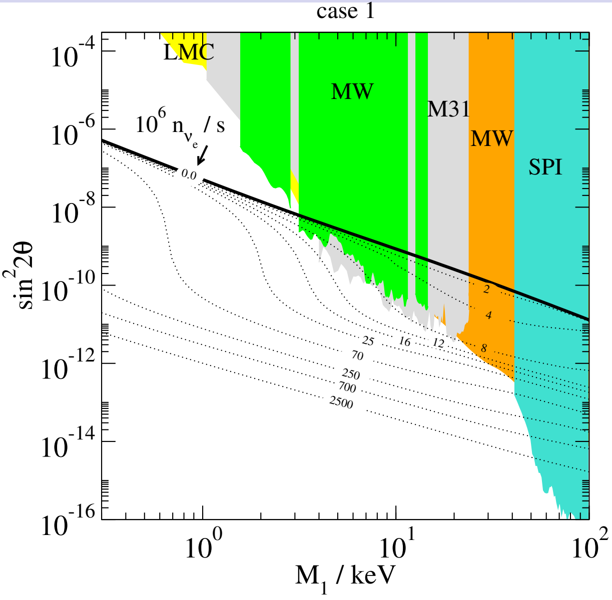
resonant production in the lepton asymmetric plasma

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

1601.07553

BAU-DM relation?

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



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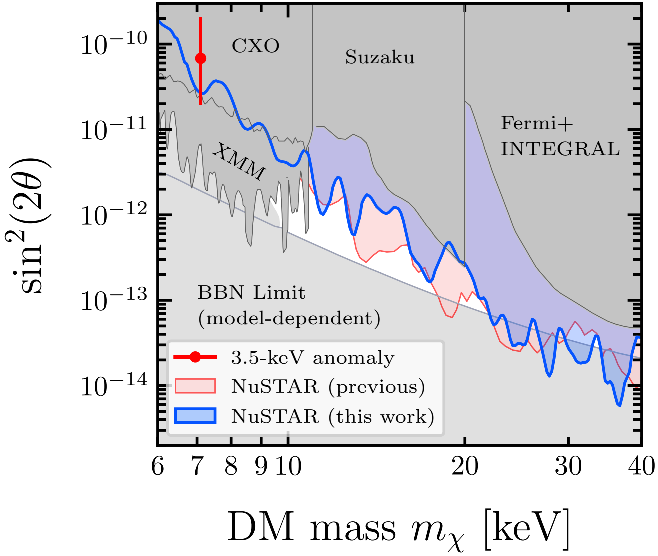
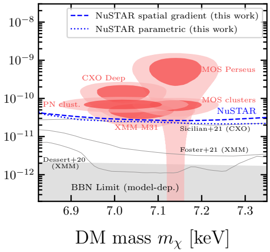
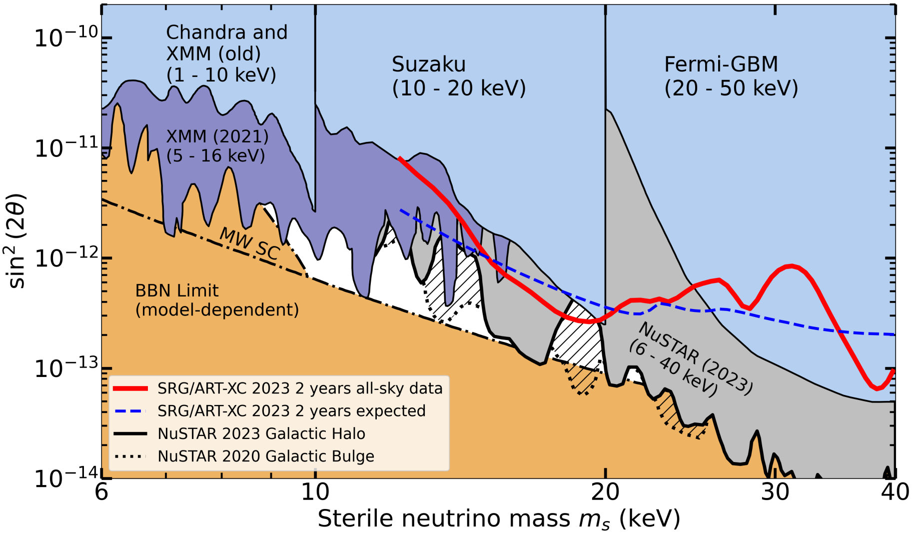


- upper limits on mixing: from *X*-ray searches
- lower limits on mass: from structure formation

  and BBN predictions



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}
6
10
20
30
40
$\sin^2(2\theta)$
Sterile neutrino mass m_s (keV)

2303.12673

Seesaw type I mechanism: $M_N \gg m_{active}$

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

where $I = 1,2,3$ and $\alpha = e,\mu,\tau$ $\quad \tilde{H}_a = \varepsilon_{ab} H_b^*$

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

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \frac{1}{2}\left(\overline{\nu}_\alpha\,,\overline{N}_I^c\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^c\,,N_I\right)^{\mathrm{T}} + \text{h.c.}$$

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

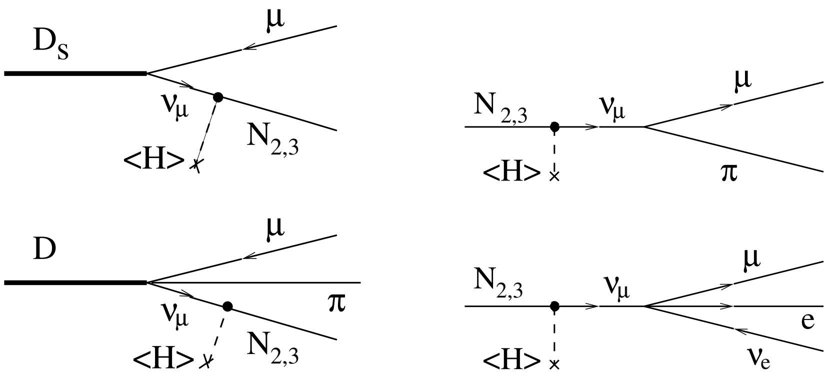
$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D\frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2\frac{v^2}{M_N} \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

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

active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

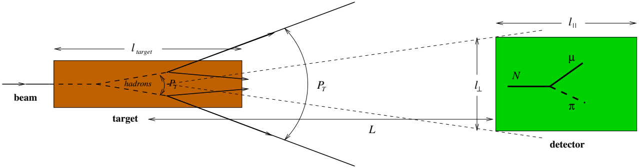
Sterile neutrinos: production and decays



Interaction via neutral and charged weak hadronic currents

Fixed target and similar

However for the feebly coupled light particle best place to show up is
the intensity frontier fixed target experiment

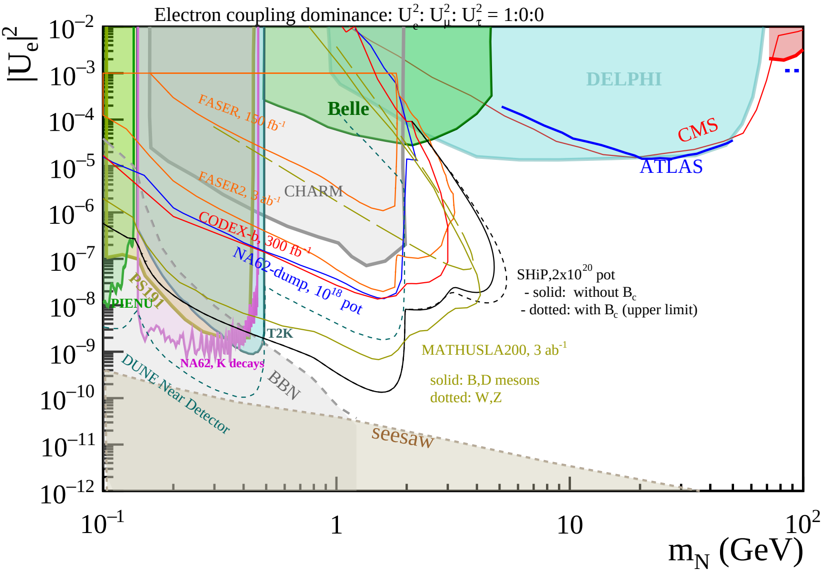


Variations and specifics

- dedicated (e.g. NA64) or working as by-product (e.g. T2K)
- thin target (e.g. T2K) or dump (e.g. NA64)
- decays or hits as the signature
- production by cosmic rays
- …

mixing with ν_e

2102.12143



mixing with ν_μ

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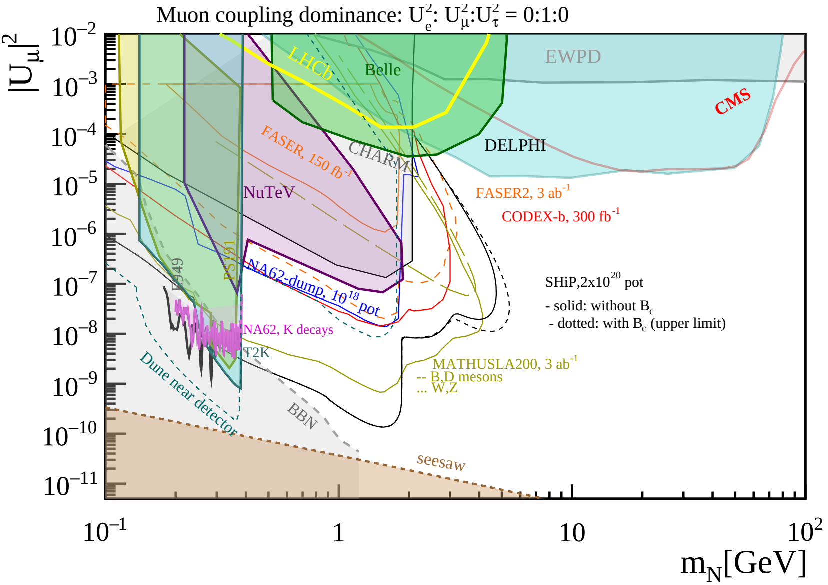

mixing with ν_τ

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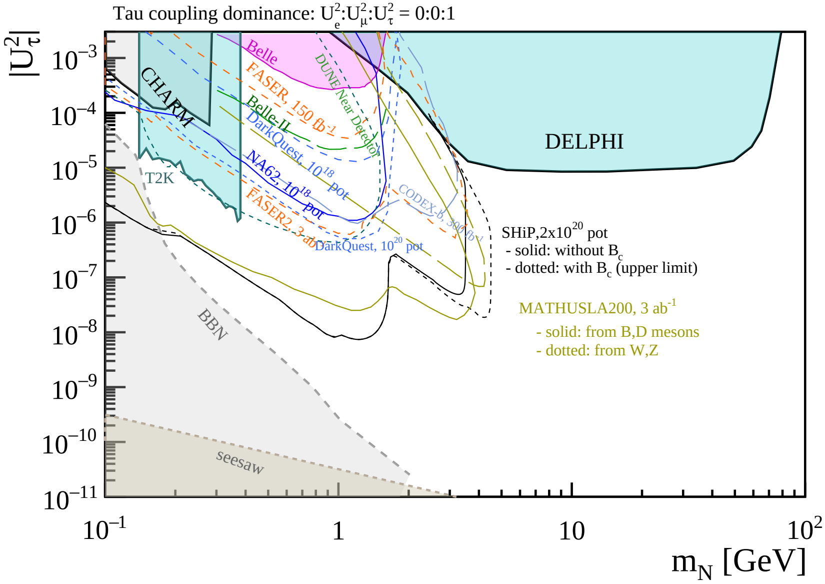

Summary

- νMSM is minimalistic SM extension (3 majorana fermions)
  capable of explaining
  neutrino oscillations
  baryon asymmetry of the Universe
  dark matter phenomenon
- Nicely testable with present experimental technique
- Can be fully explored with indirect searches (at X-ray telescopes) for sterile neutrino dark matter …
- We are waiting just for... discovery !!

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

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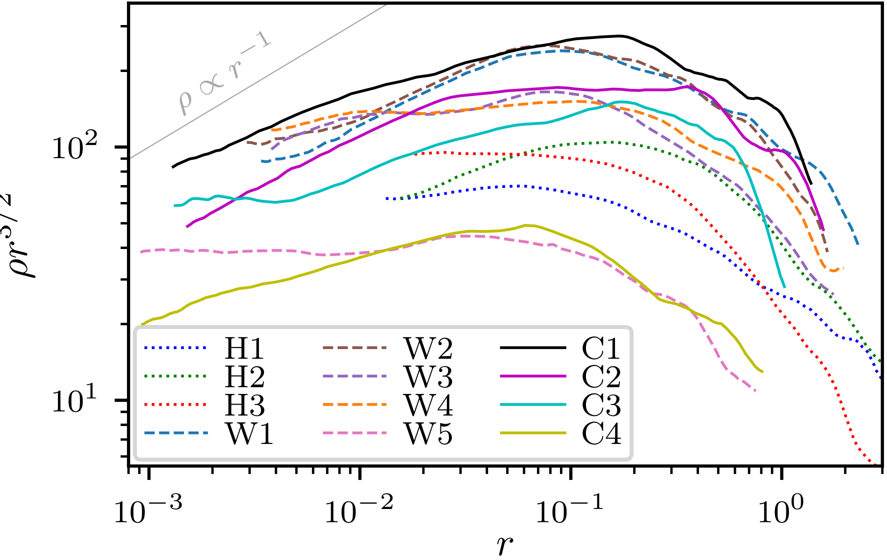

Core vs cusp in a galaxy...

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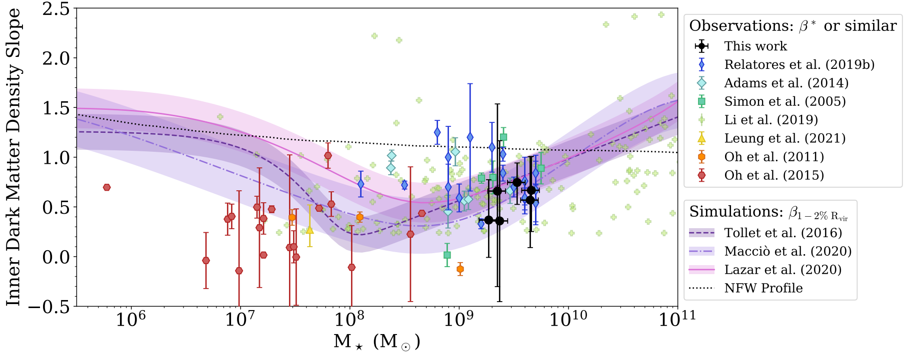
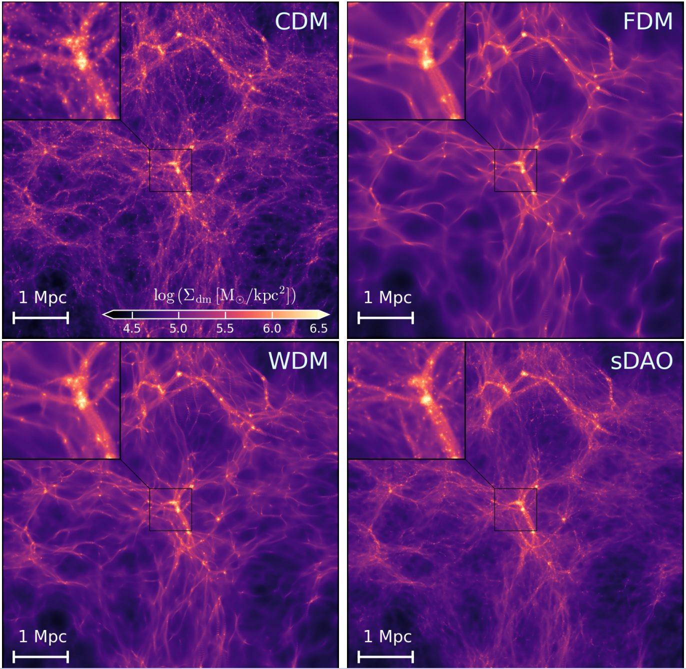


$$\rho(r) \propto \frac{1}{r^{\beta^*}}$$

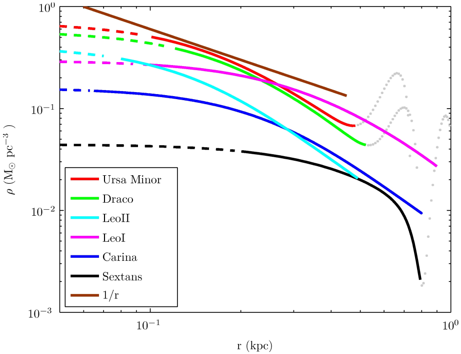

CDM
FDM
WDM
sDAO
1 Mpc
1 Mpc
1 Mpc
1 Mpc
$\log(\Sigma_{\rm dm}\,[M_\odot/{\rm kpc}^2])$
4.5
5.0
5.5
6.0
6.5

2304.06742

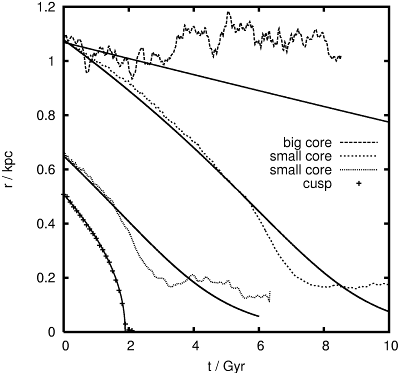
CDM Problems

- 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