Sterile neutrinos and cosmology

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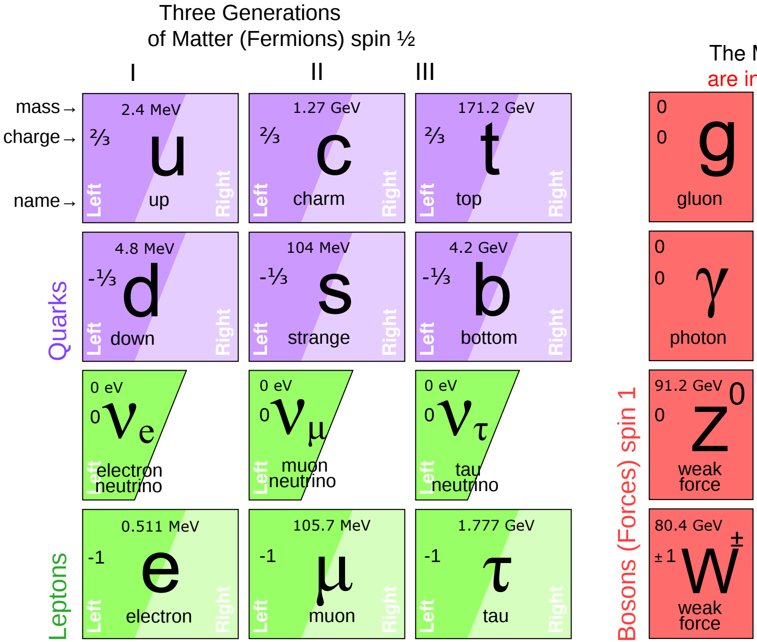
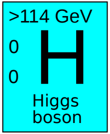


The Matter generations
are indistinguishable by
electric
weak and
strong
forces

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; $Q = \binom{u_L}{d_L}$, d_R, u_R

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

(PHENO)

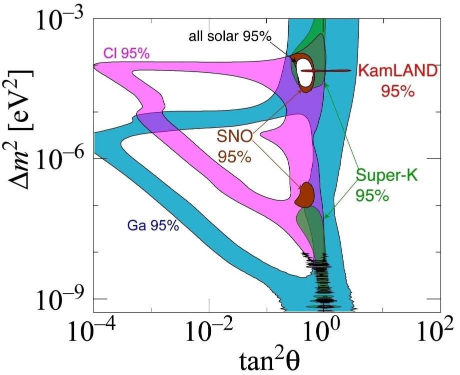
- Neutrino oscillations (and anomalies...)
- Dark matter (Ω_{DM})
- Baryon asymmetry (Ω_B)
- Why the Universe is flat and homogeneous?
- Where did the matter perturbations come from?

(THEORY)

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

Neutrino oscillations: masses and mixing angles

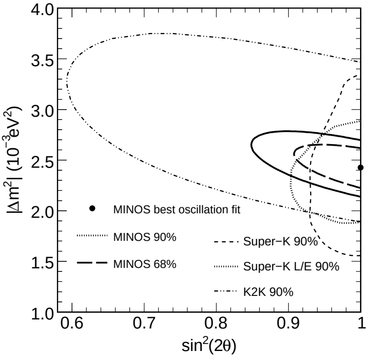
Solar 2 × 2 "subsector"



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

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

Atmospheric 2 × 2 "subsector"

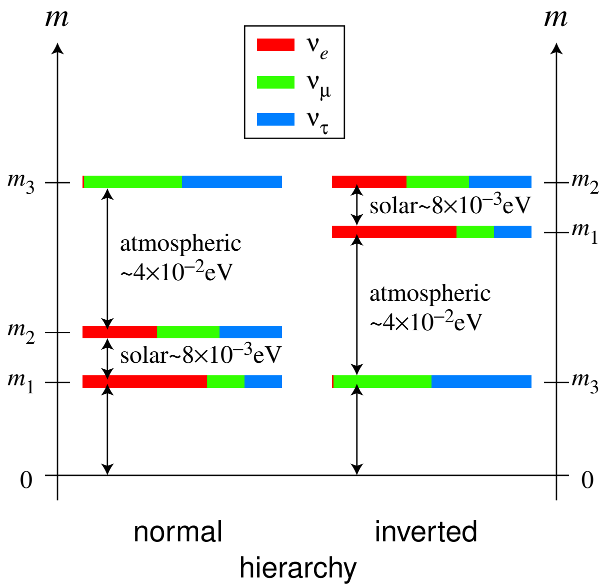


arXiv:0806.2237

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

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

Physics behind the neutrino oscillations is still elusive



$$7.5\cdot 10^{-5}\mathrm{eV}^2 = m^2_{\mathrm{sol}} \ll$$
$$m^2_{\mathrm{atm}} = 2.5\cdot 10^{-3}\mathrm{eV}^2$$

implies lower limits:

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

hence

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

if much larger, then

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

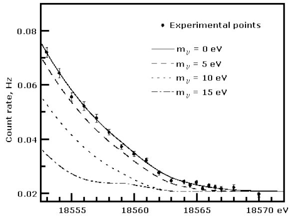
anyway

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

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

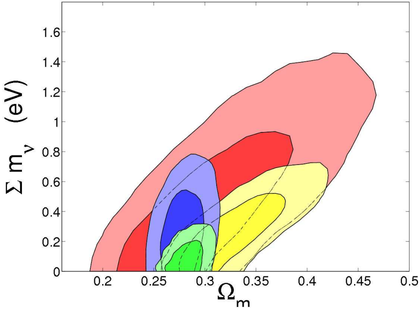
Mainz, 2000... : $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

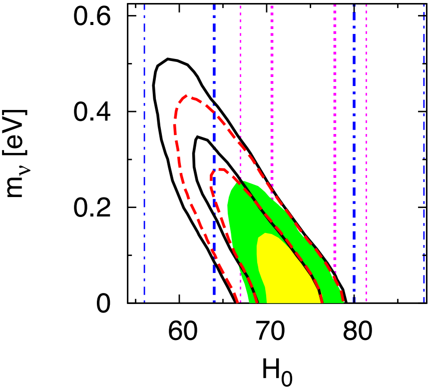
limits from KATRIN (2022)

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

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

Cosmological limits: sub-eV scale... 15 years ago!!





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

talk by N. Nedel'ko at QUARKS-2024

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

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

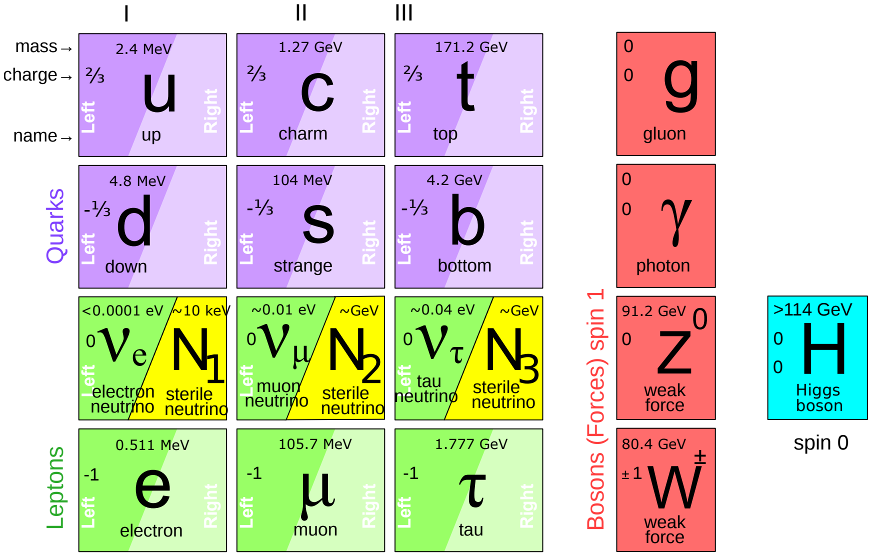
Attractive features:

- 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

Three Generations
of Matter (Fermions) spin ½



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

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

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

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

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

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 'neutrino'
- $M_N = 0 \quad \longrightarrow \quad$ 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

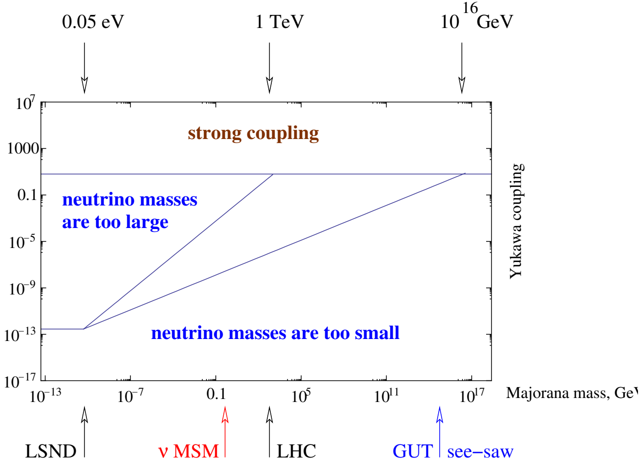
$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$

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

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

Baryogenesis

– Need BAU $\eta_B \equiv n_B/n_\gamma \approx 6\times 10^{-10}$ starting from BBN epoch, $T \lesssim 1$ MeV
– The same number at recombination and later

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)$ $XY\dots \to X'Y'\dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)$ $\bar{X}\bar{Y}\dots \to \bar{X}'\bar{Y}'\dots \bar{B}$
- processes above are out of equilibrium $X'Y'\dots B \to XY\dots$

At 100 GeV$\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

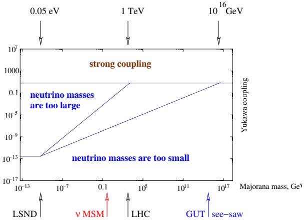
$$B - L\,,\quad L_e - L_\mu\,,\quad L_e - L_\tau$$

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe … due to sterile neutrinos

Bonus: depends on the sterile neutrino mass range

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



There are different regions:

$M_N \sim$ 1 eV-100 GeV

- keV-scale dark matter
- BAU via leptogenesis
- Neutrino anomalies (1 eV sterile neutrinos?)

direct searches!

$M_N \sim$ 100 GeV-5 TeV

- BAU via leptogenesis

$f \sim 10^{-6} \simeq Y_e$

but with fine tuning or new global or gauge symmetries (e.g. $SU(2)_L \times SU(2)_R$)

direct searches at colliders

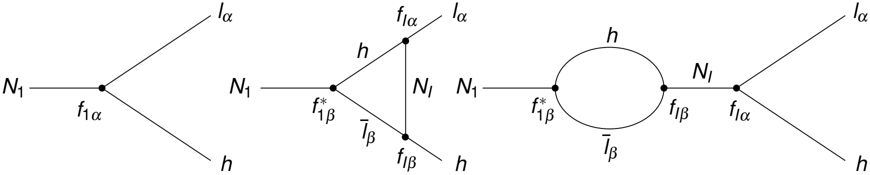
$M_N \sim 10^{12}$-10^{14} GeV

- BAU via leptogenesis

$f \simeq 0.01 - 1$

Untestable. . . ?
or already confirmed?

Lepton asymmetry δ at 1-loop level $\qquad f_{I\alpha}\bar{L}_\alpha N_I \widetilde{H}$



$$\Gamma(N_1 \to lh) = \frac{M_1}{8\pi} \cdot \sum_\alpha \left| f_{1\alpha} + \frac{1}{8\pi} \sum_{\beta,I} F\left(\frac{M_1}{M_I}\right) \cdot f^*_{1\beta} f_{I\alpha} f_{I\beta} \right|^2 , \quad m_\nu \ll M_I$$

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = -\frac{1}{8\pi} \sum_{I=2,3} \mathrm{Im}\left[F\left(\frac{M_1}{M_I}\right)\right] \cdot \frac{\mathrm{Im}\left(\sum_\alpha f_{1\alpha} f^*_{I\alpha}\right)^2}{\sum_\gamma |f_{1\gamma}|^2} .$$

for $M_{2,3} \gg M_1$, $f\left(\frac{M_1}{M_I}\right) = -\frac{3}{2}\frac{M_1}{M_I}$, $\delta = \frac{3\,M_1}{16\pi} \frac{1}{\sum_\gamma |y_{1\gamma}|^2} \sum_{\alpha\beta I} \mathrm{Im}\left[y_{1\alpha} y_{1\beta} \left(y^*_{I\alpha} \frac{1}{M_I} y^*_{I\beta}\right)\right]$.

Superheavy sterile neutrinos: $M_N \simeq 10^{12}$-10^{14} GeV

- Motivation: close to GUT scales, e.g. $SO(10)$
- Bad fact: huge finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \gg m_H^2 (\Rightarrow M_N < 10^7$ GeV)
  SUSY solution? (New fileds...new problems: e.g. gravitino overproduction with high T_{reh} for leptogenesis)
- Good fact: If $T > M_N$ decays of thermal sterile neutrino yield the lepton asymmetry in the early Universe: M.Fukugita, T.Yanagita (1986)

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{l=2,3} f\left(\frac{M_{N_1}}{M_{N_l}}\right) \cdot \frac{\text{Im}\left(\sum_\alpha f_{1\alpha} f_{l\alpha}^*\right)^2}{\sum_\gamma |f_{1\gamma}|^2} \,.$$

  Needs $M_{N_1} \gtrsim 10^9$ GeV or $M_{N_1} \gtrsim 10^{12}$ GeV without fine tuning in $\hat{f}$
- Exciting fact: to avoid washing out of Δ_L in $hl_\alpha \leftrightarrow h\bar{l}_\beta$ we need ...
  $M^\nu < 0.1 - 0.3$ eV !!!
- Cooling down: No way to test further. Can get $\Delta_B \sim 10^{-10}$ even with
  $\theta_{13} = \delta_{\text{CP}} = 0$!

NB: can work for nonthermal case as well

production by inflaton decay G.Lazaridies, Q.Shafi (1991) e.g. in R^2-inflation D.G., A.Panin (2010)

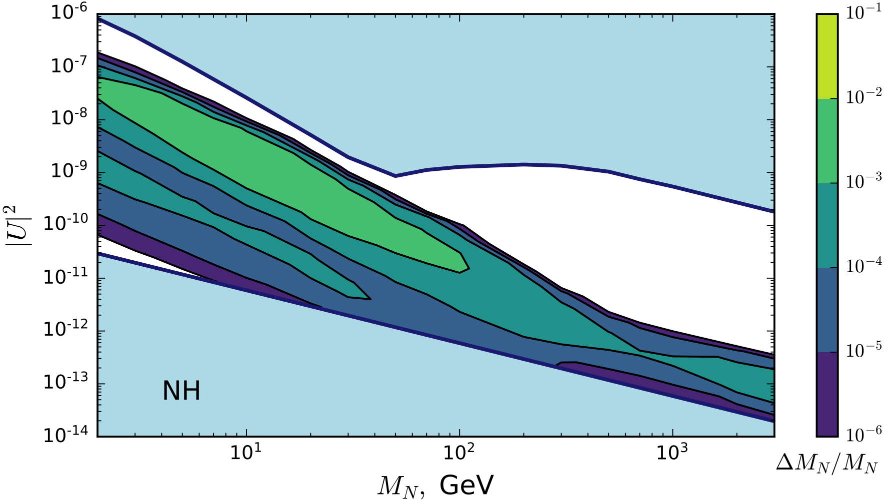
Very heavy sterile neutrinos: $M_N \simeq 100\,\text{GeV-}5\,\text{TeV}$

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  No hierarchy between Λ_ν and Λ_{EW}
- Bad fact: Without extra symmetries, fine tuning or new interactions generation of lepton asymmetry and hence No BAU
- Way out: fine tunning can help: e.g. resonant enhancement of CP-violation in out-of-equilibrium sterile neutrino decays:
  leptogenesis for $M_N \gtrsim 1\,\text{TeV}$ if $\Delta M_N \sim \Gamma_N$ Pilaftsis (1997,...)
- Further cooling down:
  can be directly produced but at a tiny amount only: as small as $f \sim 10^{-6}$!
- Conclusion: Seesaw type I is generally untestable in direct searches:
  Yuakawa couplings are too small, while sterile neutrinos are quite heavy.

To make interesting either NEW fields or fine tuning (larger f)
or symmetries, e.g. $SU(2)_L \times SU(2)_R$ are required!!!

Degeneracy for Leptogenesis

2008.13771



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

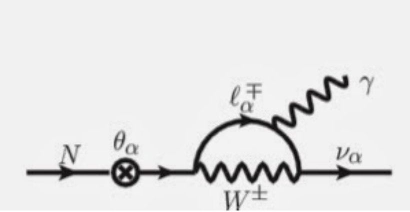
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

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

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

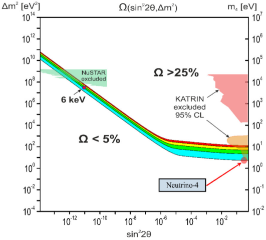
talk by V.Barinov at QUARKS-2024

Can seesaw neutrino serve as DM ? NO !!

$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\text{ keV}}{M_N}\right)^4 \qquad \frac{\theta^2}{10^{-5}} \sim \left(\frac{m_a}{0.1\,\text{eV}}\right)\left(\frac{10\,\text{keV}}{M_N}\right)$$

one order down

$$\frac{\theta^2}{10^{-7}} \lesssim \left(\frac{1\text{ keV}}{M_N}\right)^4 \qquad \frac{\theta^2}{10^{-4}} \sim \left(\frac{m_a}{0.1\,\text{eV}}\right)\left(\frac{1\,\text{keV}}{M_N}\right)$$



A.P.Serebrov et al (2023)

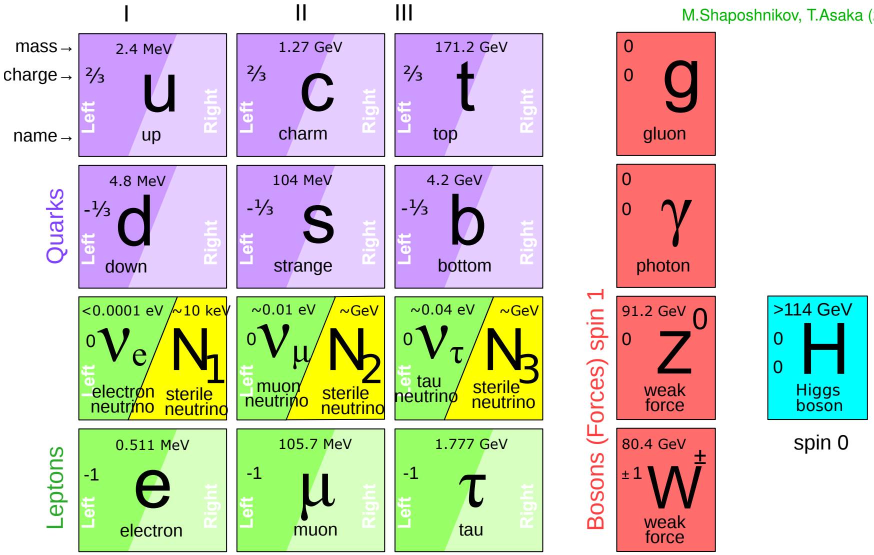
do not explain neutrino masses

$M_N\theta^2 \ll m_\nu$ not a “neutrino”

νMSM: testable

M.Shaposhnikov, T.Asaka (2006)

Three Generations
of Matter (Fermions) spin ½



T

zero abundance of N_I

thermal production of N_2, N_3

→ lepton asymmetry generated

200 GeV T_{EW} **Electroweak Symmetry Breaking**

→ lepton Asymmetry converted to baryon asymmetry

T_+ N_2, N_3 reach equilibrium

→ lepton asymmetry washed out

few GeV T_- N_2, N_3 freeze out

→ lepton asymmetry generated

T_d N_2, N_3 decay

→ lepton asymmetry generated

100 MeV T_{DM} **resonant N_1 Dark Matter production**

t

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:

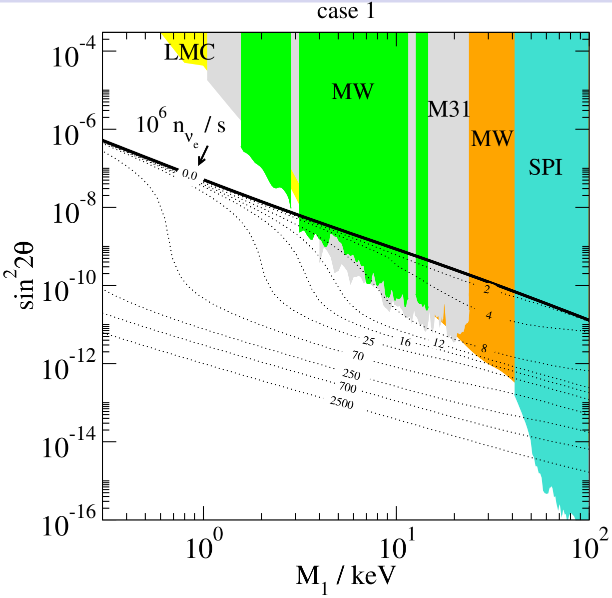
$$V_{\alpha\alpha} \sim -\# G_F^2 T^4 E$$

resonant production in the lepton asymmetric plasma

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

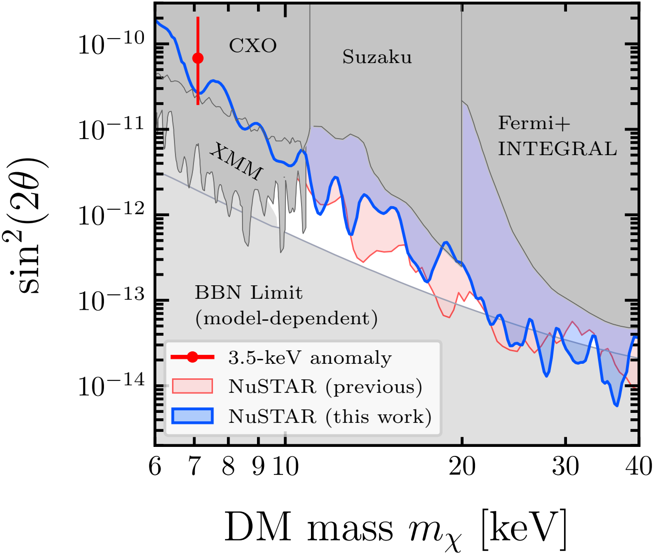
0804.4543

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



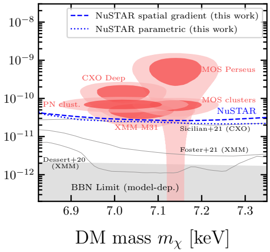
. . . present searches: NuSTAR

2207.04572



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

  and BBN predictions



Primordial Nucleosynthesis: solving kinetic equations

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

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

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

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

neutron-to-proton ratio $\quad \tau_n \approx 880$ s

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

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

Present limits from BBN:

BBN limits on ν_e-asymmetry

$$\xi_e \equiv \frac{\mu_{\nu_e}}{T_\nu}$$

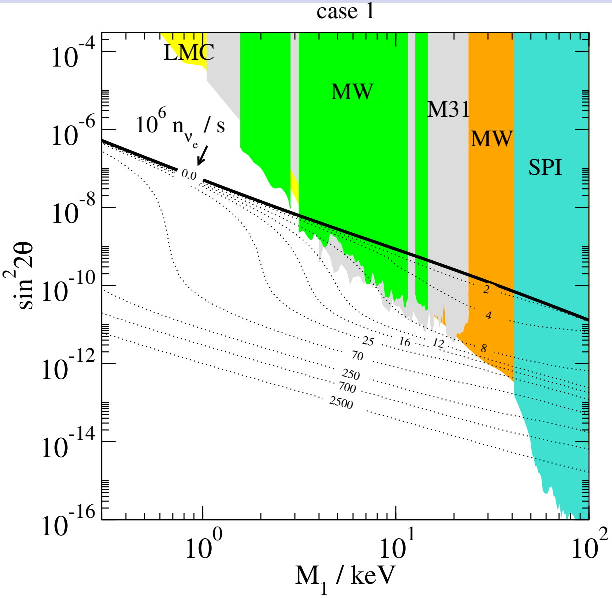
is PDG-2022 and 2208.03201

$$|\xi_e| < 0.03 \quad 95\%\,\mathrm{CL}$$

then

$$L_e = \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{s} = \frac{\mu_{\nu_e} T_\nu^2/6}{\frac{2\pi^2}{45}\left(2 \times T^3 + 6 \times 7/8 \times T_\nu^3\right)} = \frac{15}{43\pi^2} \times \xi_e$$

with $T_\nu = T \times (4/11)^{1/3}$



Present limits from BBN:

BBN: PDG-2022 and 2208.03201

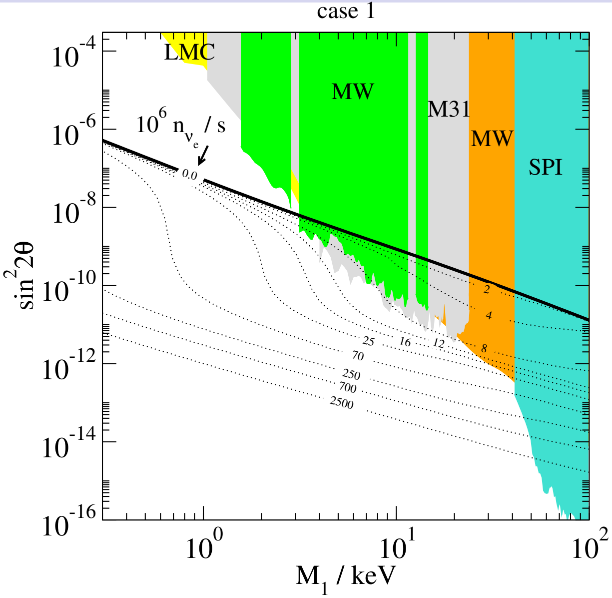
$$|\xi_e| < 0.03 \quad 95\%\,\mathrm{CL}$$

and

$$L_e = \frac{15}{43\pi^2} \times \xi_e$$

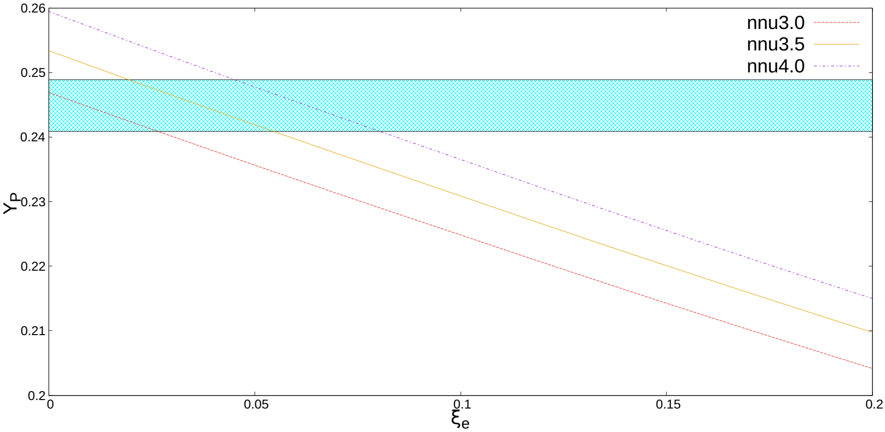
Simple case:
after DM production asymmetry is in one flavor α:
oscillations $\nu_\alpha \leftrightarrow \nu_\beta$ at $T < 10\,\mathrm{MeV}$
redistribute it, so $\mu_{\nu_e} = \mu_\alpha/3$
then

$$L_e < 3.2 \times 10^{-3} \quad \to \quad 3200$$



BBN: extra-radiation and lepton asymmetry

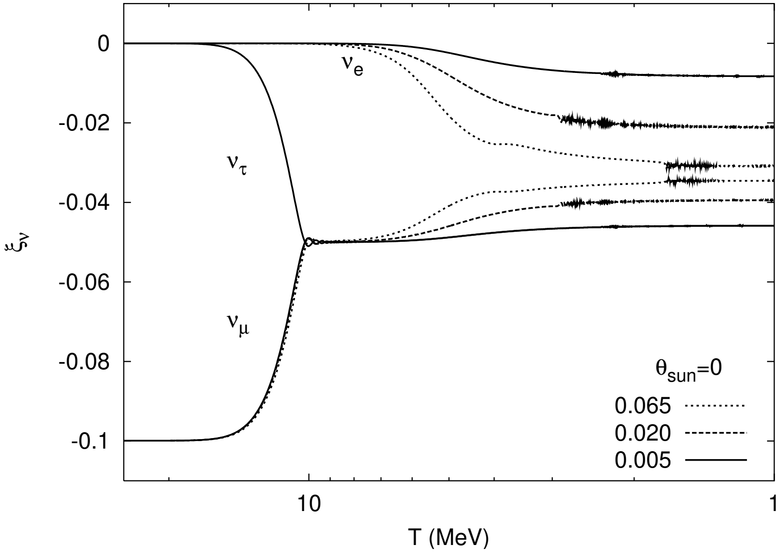
2104.04381



may be interesting for anomalous, 1-3 eV sterile neutrinos !?

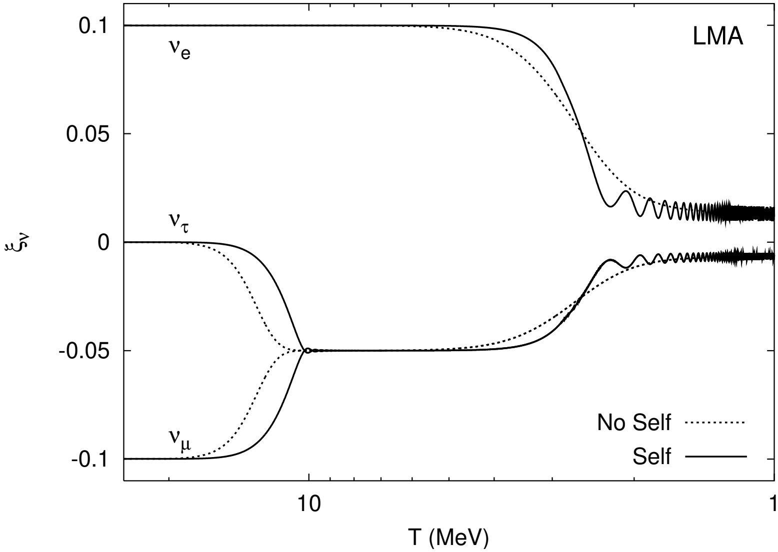
redistribution. . . can be hidden by other means?

hep-ph0201287



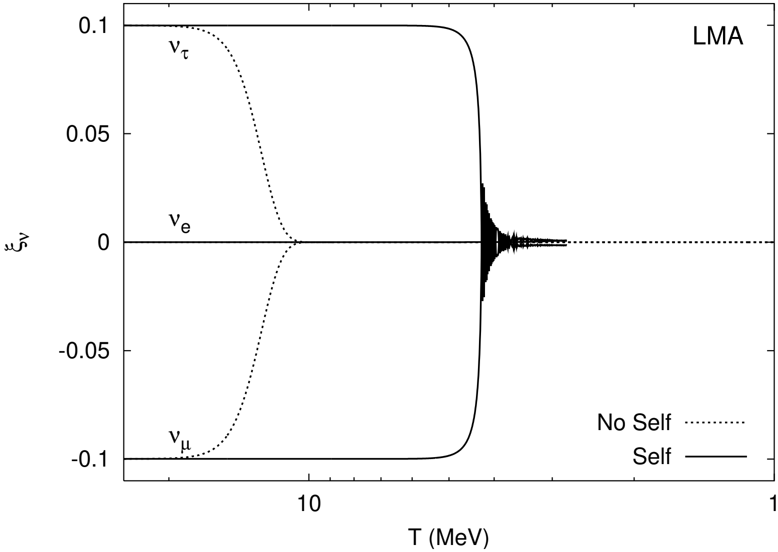
redistribution. . .

hep-ph0201287

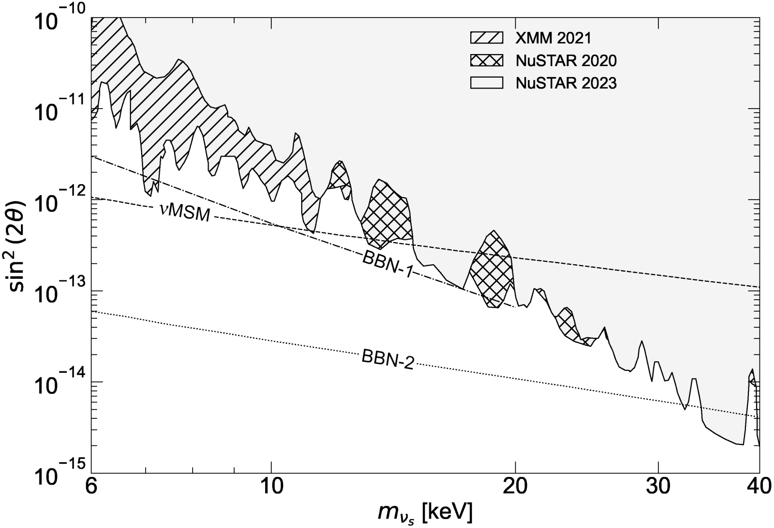


redistribution. . .

hep-ph0201287

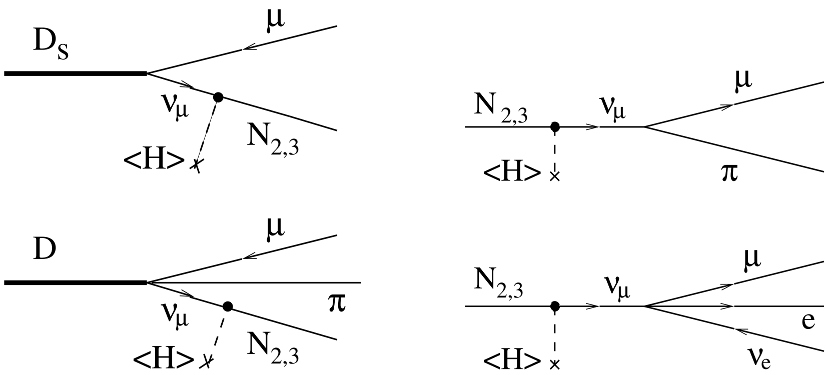


if redistributed equally... two different codes: `sterile-dm` and `dmpheno`



many thanks to D.Kalashnikov and V.Barinov (see also talk by V.Barinov at QUARKS-2024)

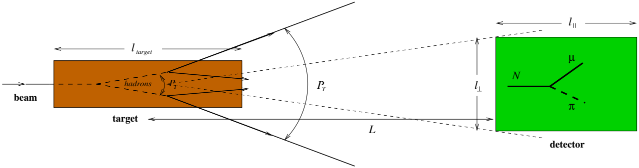
Sterile neutrinos: production and decays



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

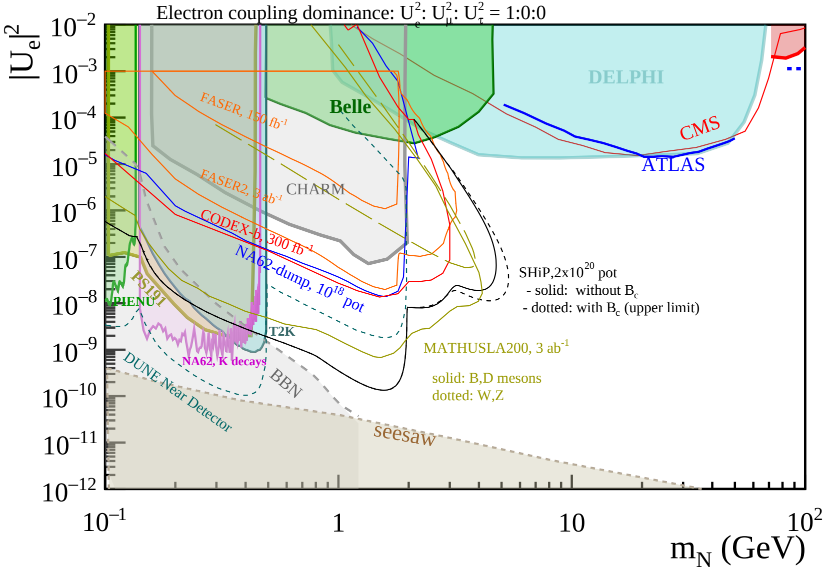


Variations and specifics

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

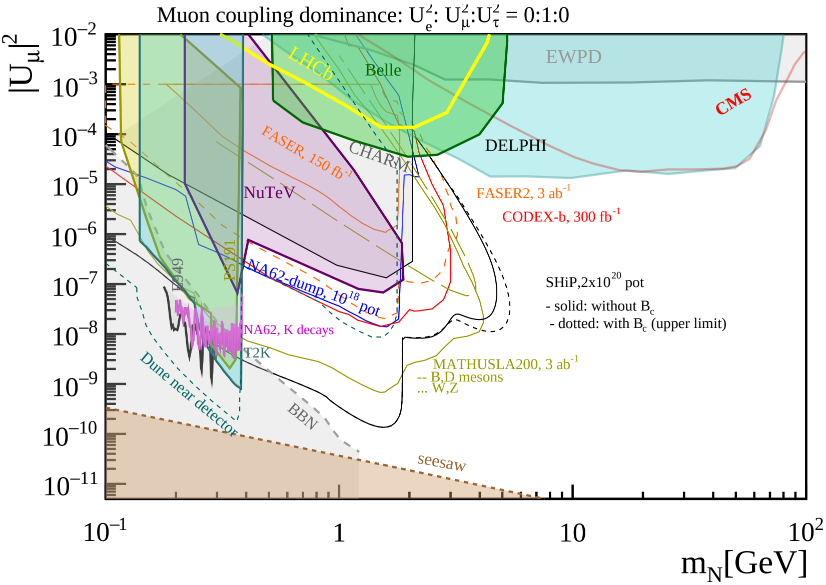
mixing with ν_e

2102.12143



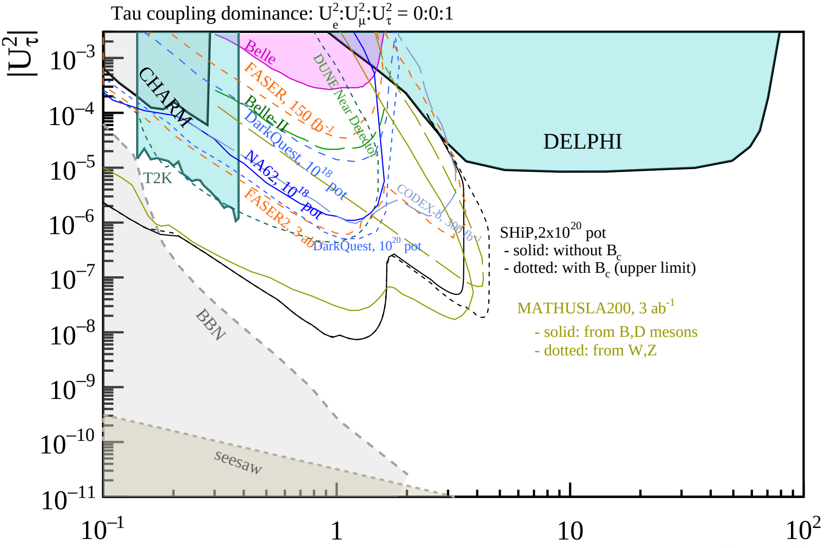
mixing with ν_μ

2102.12143



mixing with ν_τ

2102.12143



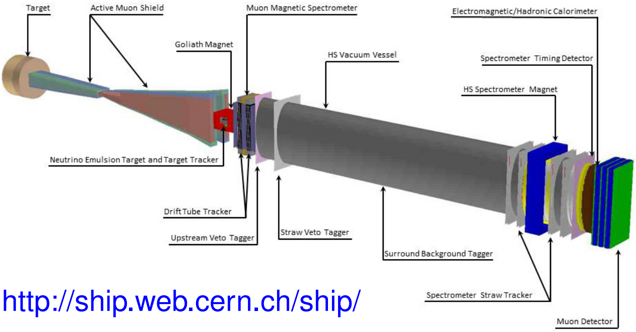
Towards a dedicated experiment

- νMSM: T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005),
- direct tests of νMSM: D.G., M.Shaposhnikov (2007)
- proposal for direct searches, to European Strategy Group, 2012 D.G., M.Shaposhnikov
- sketch of realistic experiment S.Gninenko, D.G., M.Shaposhnikov (2013)
- Expression Of Interests: Proposal to Search for Heavy Neutral Leptons at the SPS

  W. Bonivento, ... D.G., et al, 1310.1762
- Technical Proposal and Physics Paper 1504.04956, 1504.04855
- included in the CERN GreyBook (2016) approved in 2024 !! 46 institutes from 16 countries

SHiP

Search for Hidden Particles



http://ship.web.cern.ch/ship/