Mechanisms of sterile neutrino dark matter production

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Based on:

Shintaro Eijima, MS, and Inar Timiryasov:

Freeze-in and freeze-out generation of lepton asymmetries after baryogenesis in the νMSM, 2011.12637, JCAP 04 (2022) 04, 049

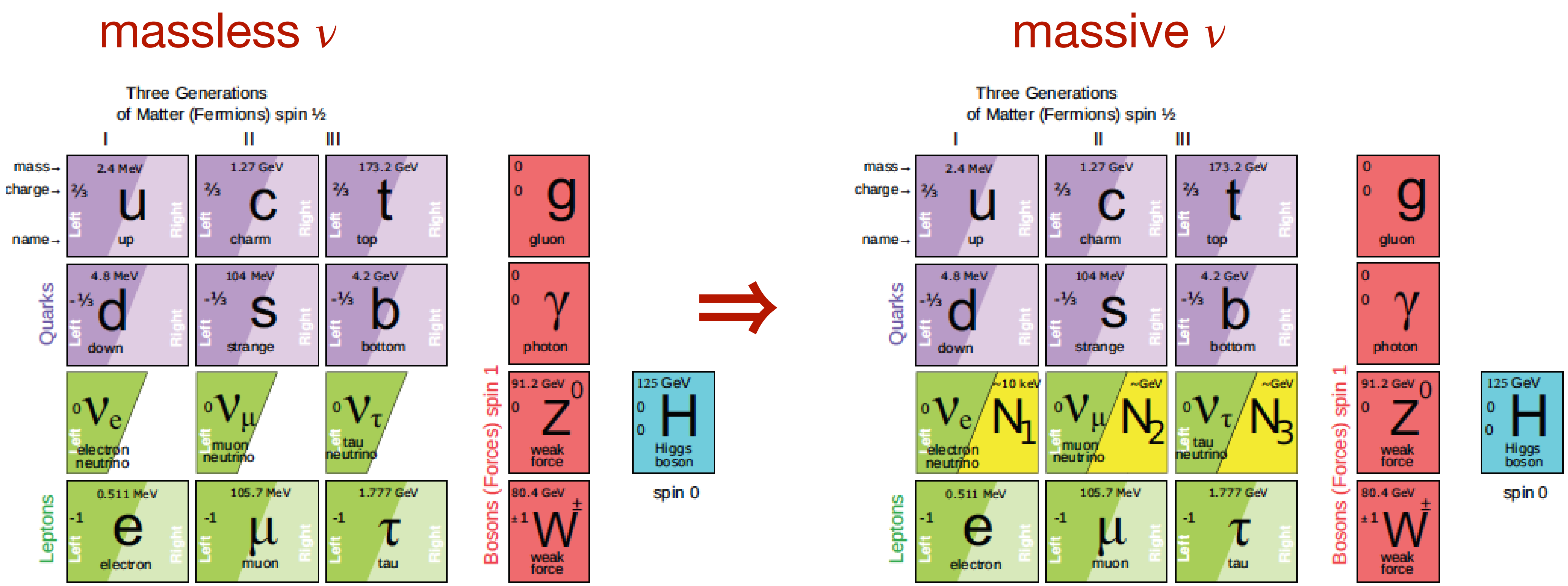
MS, Andrey Shkerin, Inar Timiryasov and Sebastian Zell:

Einstein-Cartan Portal to Dark Matter, 2008.11686, Phys. Rev. Lett. 126 (2021) 16, 161301

Outline

- DM sterile neutrino production at low temperatures:
  - Non-resonant production
  - Resonant production
  - Leptogenesis at few GeV
- DM sterile neutrino production at high temperatures
  - Metric, Palatini, and Einstein-Cartan gravities
  - Einstein-Cartan portal to sterile neutrino dark matter
- Conclusions

Framework: νMSM

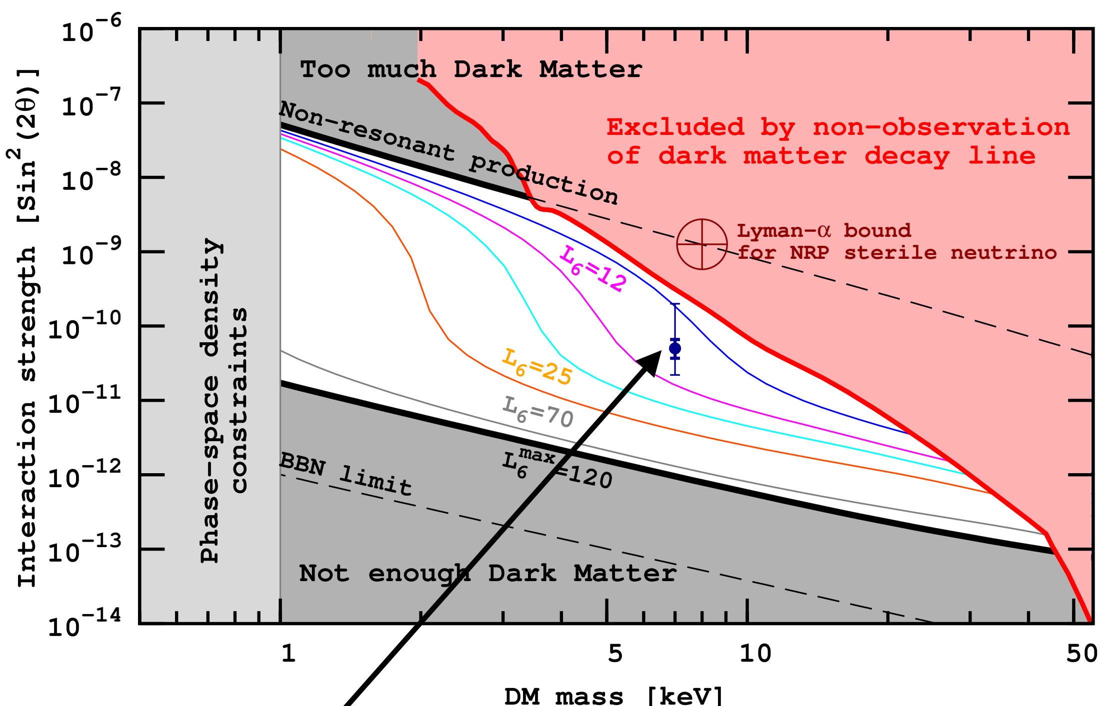


- Role of Heavy Neutral leptons (HNLs) N_2, N_3 with masses above 100 MeV: "give" masses to neutrinos and produce baryon asymmetry of the Universe.
- Role of N_1 with mass in keV region: dark matter.
- Role of the Higgs boson: break the symmetry and inflate the Universe - Higgs inflation.

Dark Matter in the νMSM: N_1

Dark matter sterile neutrino N_1: long lived light particle (mass in the keV region) with the life-time greater than the age of the Universe. It can decay as $N_1 \rightarrow \gamma\nu$, what allows for experimental detection by X-ray telescopes in space.

Available parameter space, current situation



Possible detection (?), controversial
Bulbul et al; Boyarsky et al

Future experimental searches:
Hitomi-like satellite (2021?),
Large ESA X-ray mission
Athena + (2028?)

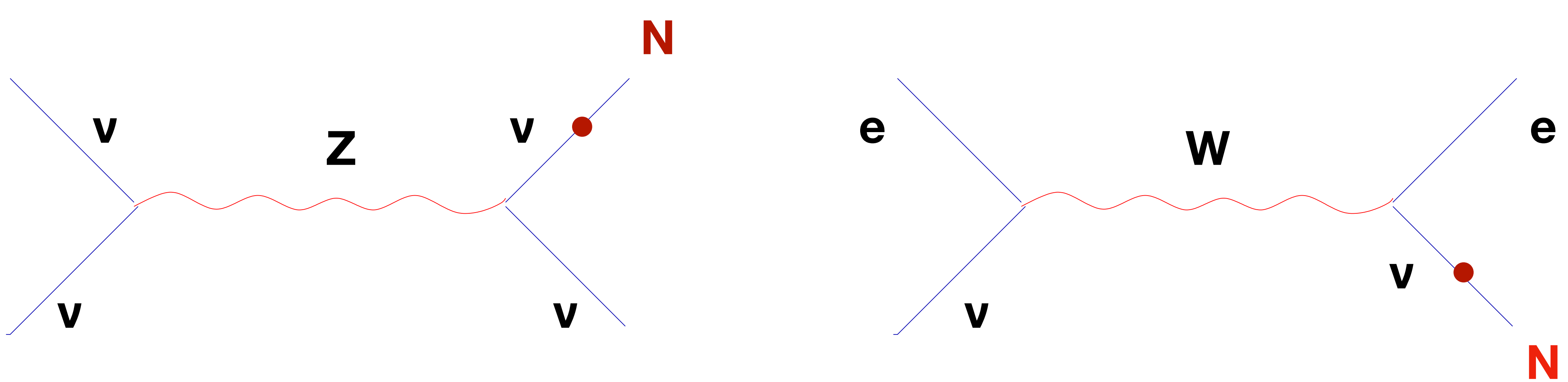
Theoretical challenges:
How DM sterile neutrinos are produced in the early Universe?
What is their spectrum?
Warm or cold Dark Matter?

DM sterile neutrino production at low temperatures

Dark matter candidate: long lived ($\tau_N > t_{Universe}$), but unstable, sterile neutrino N1 with the mass in keV range

Dodelson, Widrow; Shi, Fuller; Abazajian, Fuller, Patel; … Asaka, Laine, MS;…

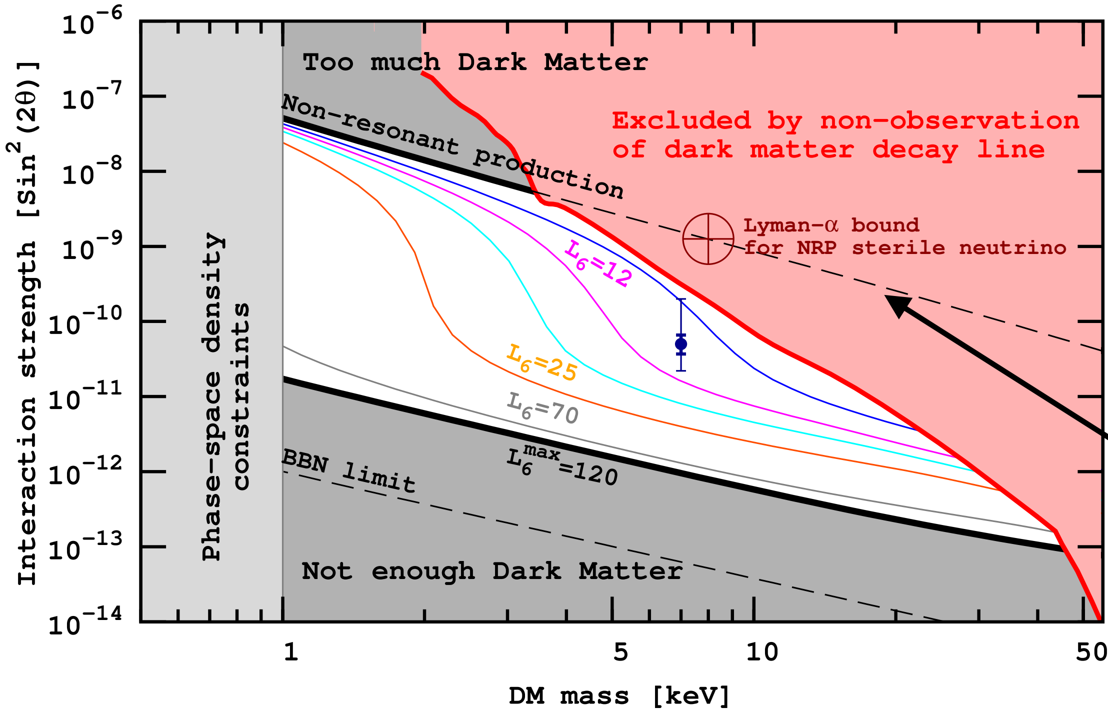
Production of Dark matter in the early Universe.

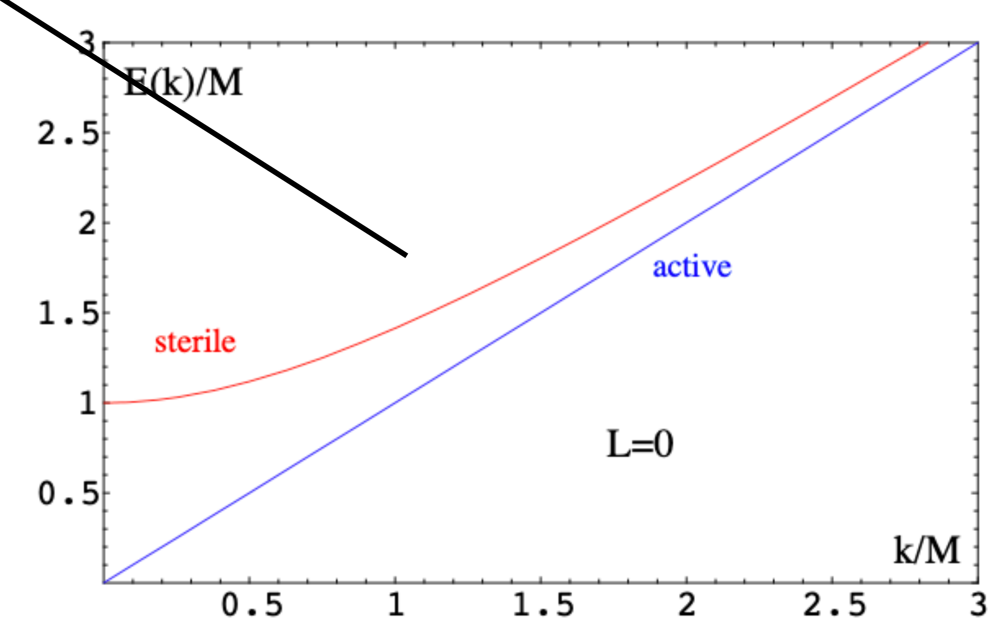


The temperature of production of DM sterile neutrinos:

$$T \sim 130 \left(\frac{M_1}{1\ \textbf{keV}} \right)^{1/3} \ \textbf{MeV}$$

Non-resonant production

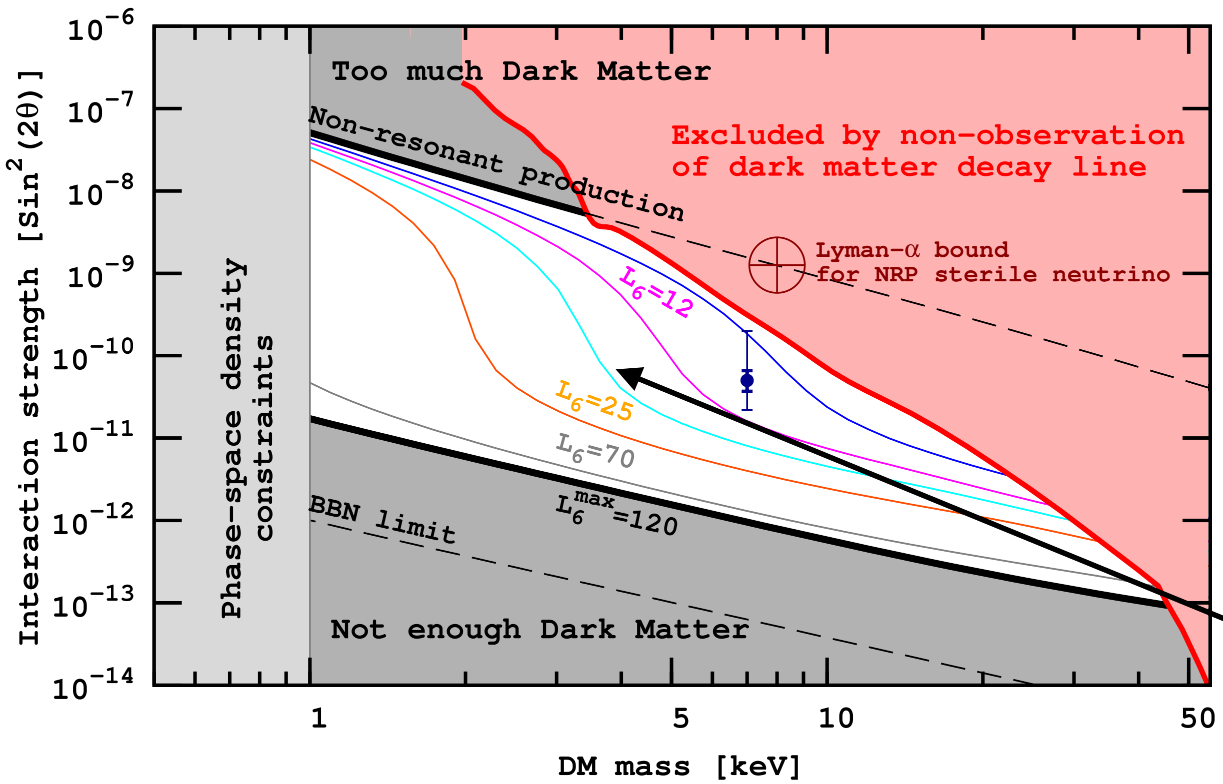




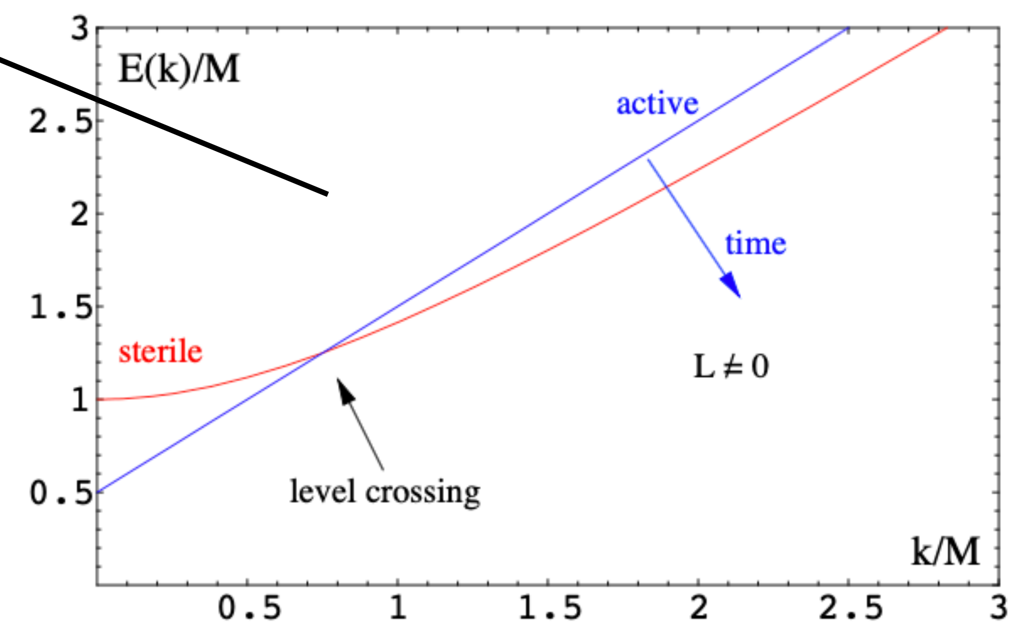
Transitions $\nu \rightarrow N_1$

Dodelson-Widrow

Resonant production



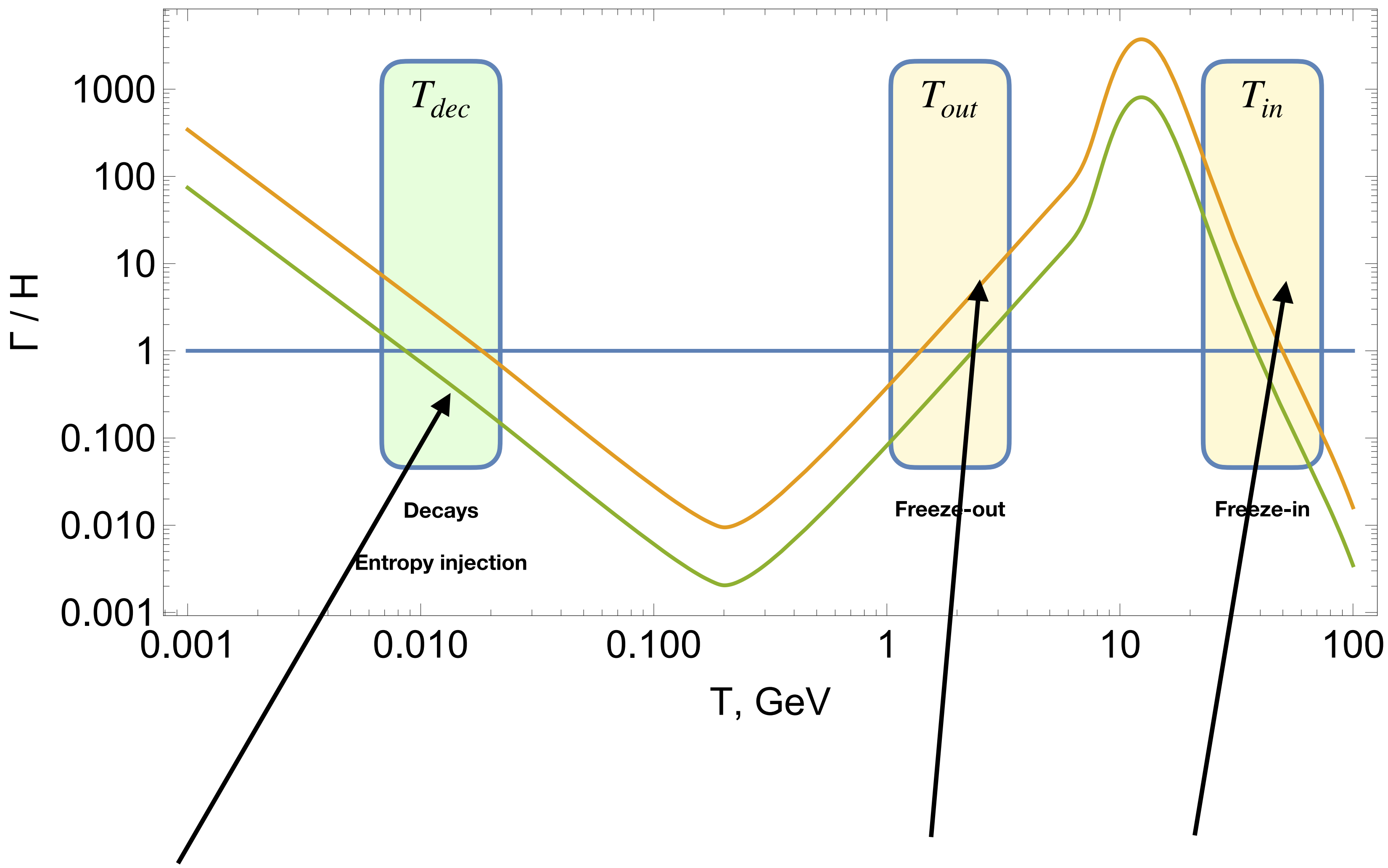
L_6 - lepton asymmetry in units 10^{-6}



Resonant transitions

Shi-Fuller

Leptogenesis at few GeV



Low scale leptogenesis can ensure 100% of DM

Low scale leptogenesis can ensure ~50% of DM

MS; Canetti, Drewes, Frossard, MS; Eijima, Timiryasov, MS; Laine, Ghiglieri

DM sterile neutrino production at high temperatures

Metric, Palatini and Einstein-Cartan gravities

Reminder of metric gravity

Riemann curvature tensor is expressed via connection $\Gamma^{\rho}_{\nu\sigma}$ as:

$$R^{\rho}_{\sigma\mu\nu} = \partial_{\mu}\Gamma^{\rho}_{\nu\sigma} - \partial_{\nu}\Gamma^{\rho}_{\mu\sigma} + \Gamma^{\rho}_{\mu\lambda}\Gamma^{\lambda}_{\nu\sigma} - \Gamma^{\rho}_{\nu\lambda}\Gamma^{\lambda}_{\mu\sigma}$$

$\Gamma^{\rho}_{\nu\sigma}$ is symmetric with respect to lower indices, from $g_{\mu\nu;\alpha} = 0$ one gets expression for $\Gamma^{\rho}_{\nu\sigma}$ in terms of the metric. Lowest order action (without cosmological constant) is

$$\frac{M_P^2}{2}\int d^4x\sqrt{|g|}R$$

The dynamical variable is $g_{\mu\nu}$, variation with respect to $g_{\mu\nu}$ gives vacuum Einstein equations. (We use mostly positive metric.)

Metric, Palatini and Einstein-Cartan gravities

Reminder of Palatini gravity

Riemann curvature tensor is expressed via connection $\Gamma^{\rho}_{\nu\sigma}$ as:

Same as in metric gravity

$$R^{\rho}_{\sigma\mu\nu} = \partial_\mu \Gamma^{\rho}_{\nu\sigma} - \partial_\nu \Gamma^{\rho}_{\mu\sigma} + \Gamma^{\rho}_{\mu\lambda}\Gamma^{\lambda}_{\nu\sigma} - \Gamma^{\rho}_{\nu\lambda}\Gamma^{\lambda}_{\mu\sigma}$$

$\Gamma^{\rho}_{\nu\sigma}$ is symmetric with respect to lower indices. Lowest order action (without cosmological constant) is

$$\frac{M_P^2}{2}\int d^4x\sqrt{|g|}R$$

The dynamical variables are $\Gamma^{\rho}_{\nu\sigma}$ and $g_{\mu\nu}$, variation with respect to $\Gamma^{\rho}_{\nu\sigma}$ gives $g_{\mu\nu;\alpha} = 0$, i.e. the relation between $\Gamma^{\rho}_{\nu\sigma}$ and $g_{\mu\nu}$, the variation with respect to $g_{\mu\nu}$ gives vacuum Einstein equations.

Palatini pure gravity is equivalent to metric gravity

Metric, Palatini and Einstein-Cartan gravities

Reminder of Einstein-Cartan gravity (gauging of the Poincare group, Utiyama '56, Kibble '61)

Riemann curvature tensor is expressed via connection $\Gamma^{\rho}_{\nu\sigma}$ as:

$$R^{\rho}_{\sigma\mu\nu} = \partial_{\mu}\Gamma^{\rho}_{\nu\sigma} - \partial_{\nu}\Gamma^{\rho}_{\mu\sigma} + \Gamma^{\rho}_{\mu\lambda}\Gamma^{\lambda}_{\nu\sigma} - \Gamma^{\rho}_{\nu\lambda}\Gamma^{\lambda}_{\mu\sigma}$$

Same as in metric gravity

Symmetry of $\Gamma^{\rho}_{\nu\sigma}$ with respect to lower indices is not assumed. Torsion tensor: $T^{\rho}_{\nu\sigma} = \Gamma^{\rho}_{\nu\sigma} - \Gamma^{\rho}_{\sigma\nu}$

Lowest order action (without cosmological constant) is

Same as in metric gravity — Holst term — Nieh-Yan invariant

$$\frac{M_P^2}{2}\int d^4x\sqrt{|g|}R + \frac{M_P^2}{2\gamma}\int \mathrm{d}^4x\sqrt{|g|}\,\epsilon^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} + M^2\int \mathrm{d}^4x\,\partial_{\mu}\left(\sqrt{|g|}\,\epsilon^{\mu\nu\rho\sigma}T_{\nu\rho\sigma}\right)$$

Barbero-Immirzi parameter

The dynamical variables are $\Gamma^{\rho}_{\nu\sigma}$ and $g_{\mu\nu}$, variation with respect to $\Gamma^{\rho}_{\nu\sigma}$ gives the relation between $\Gamma^{\rho}_{\nu\sigma}$ and $g_{\mu\nu}$, the variation with respect to $g_{\mu\nu}$ gives vacuum Einstein equations. On the solution $T^{\rho}_{\nu\sigma} = 0$.

Einstein-Cartan pure gravity is equivalent to metric gravity

Bosonic action in EC gravity with Higgs field

Inclusion of the scalar field (Higgs field of the Standard Model, unitary gauge)

Scalar action

$$S_h = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}\left(\partial_\mu h\right)^2 - U(h)\right), \quad U(h) = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$$

Gravity part

Same as in metric gravity

$$S_{\text{grav}} = \frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left(M_P^2 + \xi h^2\right)R$$

Holst term

$$+\frac{1}{2\bar{\gamma}}\int \mathrm{d}^4x\sqrt{-g}\left(M_P^2 + \xi_\gamma h^2\right)\epsilon^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma}$$

Nieh-Yan invariant

$$+\frac{1}{2}\int \mathrm{d}^4x\xi_\eta h^2\partial_\mu\left(\sqrt{-g}\epsilon^{\mu\nu\rho\sigma}T_{\nu\rho\sigma}\right)$$

Three non-minimal couplings: $\xi, \xi_\gamma, \xi_\eta$

For $1/\bar{\gamma} = \xi_\gamma = \xi_\eta = 0$ we get the Palatini action.

Bosonic action in EC gravity with Higgs field

- Torsion is not dynamical
- Same number of degrees of freedom as in the metric gravity + scalar field : 2 (graviton) +1 (scalar)
- Equivalent metric theory : use the Weyl transformation of the metric field

$$g_{\mu\nu} \to \Omega^2 g_{\mu\nu}, \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

Modified kinetic term: essential for non-perturbative generation of the electroweak scale and inflation

Metric action:

$$S_{\text{metric}} = \frac{M_P^2}{2} \int d^4x \sqrt{|g|} \left\{ R - \left[\frac{1}{2\Omega^2} (\partial_\mu h)^2 + \frac{U}{\Omega^4} \right] - \frac{3M_P^2}{4(\gamma^2+1)} \left(\frac{\partial_\mu \bar{\eta}}{\Omega^2} + \partial_\mu \gamma \right)^2 \right\}$$

$$\gamma = \frac{1}{\bar{\gamma}\Omega^2} \left(1 + \frac{\xi_\gamma h^2}{M_P^2} \right), \quad \bar{\eta} = \frac{\xi_\eta h^2}{M_P^2}$$

Flat potential: essential for inflation

Fermion action in EC gravity and Dark Matter production

Inclusion of fermions

Better variables:

- e^I - tetrad one-form (frame field, translations)
- ω^{IJ} - spin connection (gauge field of the local Lorentz group)
- $F^{IJ} = d\omega^{IJ} + \omega^I_K \omega^{KJ}$ - curvature two-form

Fermion action:

$$S_f = \frac{i}{12} \int \epsilon_{IJKL} e^I e^J e^K \Big(\bar{\Psi} \big(1 - i\alpha - i\beta\gamma^5\big)\gamma^L D\Psi - \overline{D\Psi} \, \big(1 + i\alpha + i\beta\gamma^5\big)\gamma^L \Psi \Big)$$

$$D\Psi = d\Psi + \frac{1}{8}\omega_{IJ}[\gamma^I, \gamma^J]\Psi$$

Real parameters α, β are non-minimal fermion couplings. They vanish in the case of zero torsion, but in the general case, they contribute to the interactions between the fermionic currents in the effective metric theory.

Fermion action in EC gravity and Dark Matter production

Integrating out torsion one arrives at new universal four-fermion interaction:

$$\int \mathrm{d}^4x\sqrt{-g}\,\frac{3}{16M_P^2\left(\gamma^2+1\right)}\left(\left(1+2\gamma\beta-\beta^2\right)A_\mu^2+2\alpha(\gamma-\beta)A_\mu V^\mu-\alpha^2V_\mu^2\right)$$

Vector current: $V_\mu = \bar{N}\gamma_\mu N + \sum \bar{X}\gamma_\mu X$

New fermion - dark matter particle

All fermions of the SM

Axial current: $A_\mu = \bar{N}\gamma_5\gamma_\mu N + \sum \bar{X}\gamma_5\gamma_\mu X$

Einstein-Cartan portal to dark matter

The four- fermion interaction opens up the production channel of N-particles through the annihilation of the SM fermions X, via the reaction $X + \bar{X} \to N + \bar{N}$ .The kinetic equation corresponding to this reaction takes the form

$$\left(\frac{\partial}{\partial t} - Hq_i \frac{\partial}{\partial q_i}\right) f_N(t, \vec{q}) = R(\vec{q}, T)$$

Maximal production temperature

Abundance:

$$\frac{\Omega_N}{\Omega_{DM}} \simeq 3.6 \cdot 10^{-2} C_f \left(\frac{M_N}{10\text{keV}}\right)\left(\frac{T_{\text{prod}}}{M_P}\right)^3$$

with coefficient C_f is different for Dirac and Majorana fermions,

$$C_M = \frac{9}{4}\left\{24\left(1+\alpha^2-\beta^2\right)^2 + 21\left(1-(\alpha+\beta)^2\right)^2\right\}$$

$$C_D = \frac{9}{4}\left\{45\left(1+\alpha^2-\beta^2\right)^2 + 21\left(1-(\alpha+\beta)^2\right)^2 + 24\left(1-(\alpha-\beta)^2\right)^2\right\}$$

Einstein-Cartan portal to dark matter

After the Higgs inflation the reheating is almost instantaneous (DeCross, Kaiser, Prabhu, Prescod-Weinstein, Sfakianakis; Ema, Jinno, Mukaida, Nakayama ; Rubio, Tomberg; Bezrukov, Shepherd), so we can take $T_{\rm prod} = T_{\rm reh}$, with

$$T_{\rm reh} \simeq \left(\frac{15\lambda}{2\pi^2 g_{\rm eff}}\right)^{\frac{1}{4}} \frac{M_P}{\sqrt{\xi}}$$

Two "natural" choices of non-minimal couplings α, β:

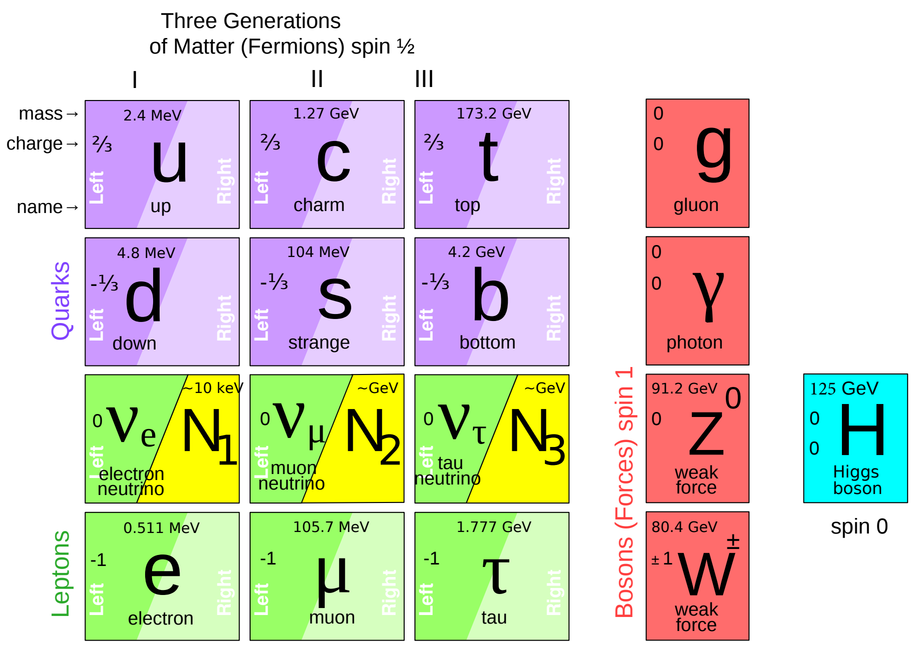
- $\alpha = \beta = 0$ (absence of non-minimal couplings). Then for Palatini Higgs inflation the correct DM abundance is obtained for $(3-6)\times 10^8$ GeV fermion, Dirac or Majorana.

- $\alpha \sim \beta \sim \sqrt{\xi}$ (the universal UV cutoff $\Lambda \sim M_P/\sqrt{\xi}$). Then for Palatini Higgs inflation the correct DM abundance is obtained for a keV scale fermion.

A new mechanism for production of sterile neutrino Dark matter!

Einstein-Cartan portal to dark matter

Application to the νMSM

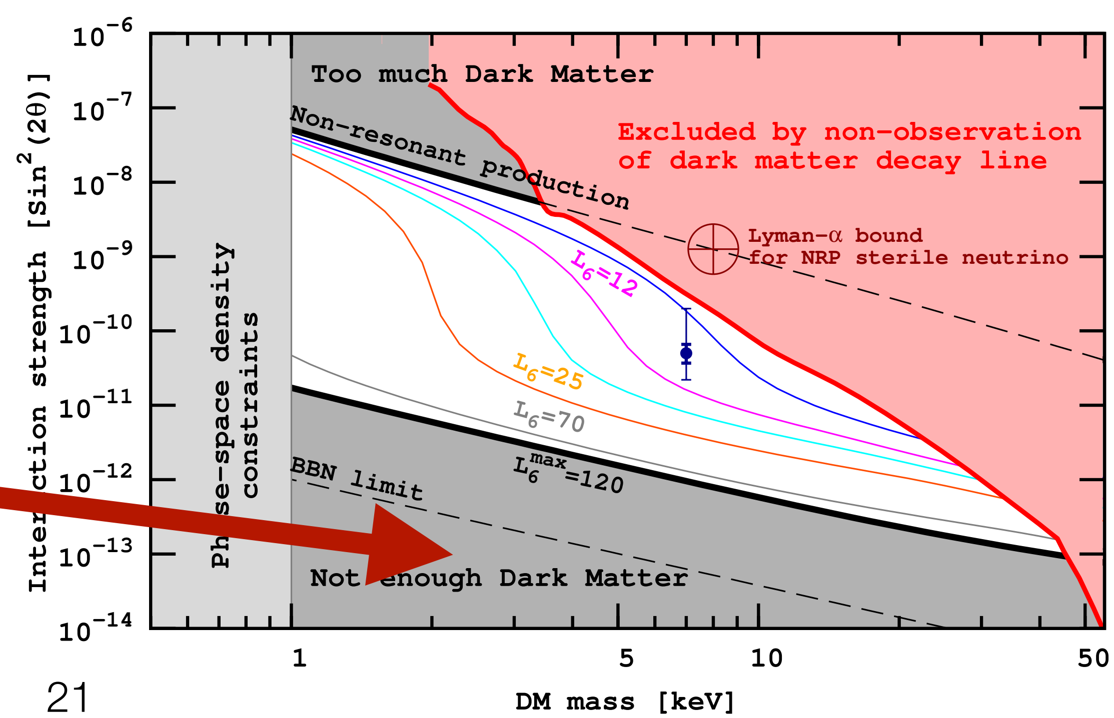


Higgs boson: EW symmetry breaking and inflation

Heavier N_2 and N_3, GeV range - neutrino masses and baryogenesis

Lightest HNL N_1, keV range - dark matter

Lower bound on the sterile neutrino mixing angle disappears!



Conclusions

- Sterile neutrino DM can be produced in the νMSM both at low and high temperatures
- Low temperatures: large lepton asymmetry production in decays of HNLs is needed and possible
- High temperatures: Einstein-Cartan gravity leads to a new universal mechanism for fermion dark matter production operating for masses as small as few keV and as large as $(3-6)\times 10^8$ GeV