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Sterile neutrino dark matter with dipole interactions

Based on the work with Wonsub Cho, KYChoi, Osamu Seto, 2108.07569

Ki -Young Choi

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26-28 November 2021
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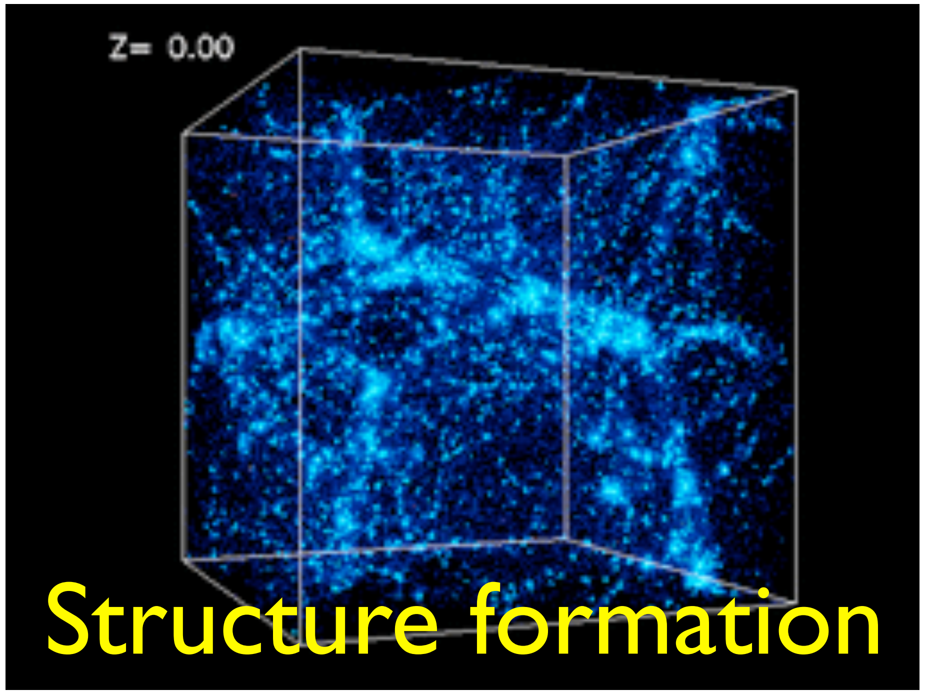
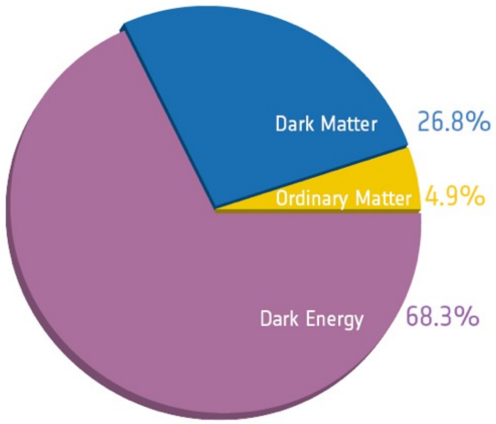
Dark Matter

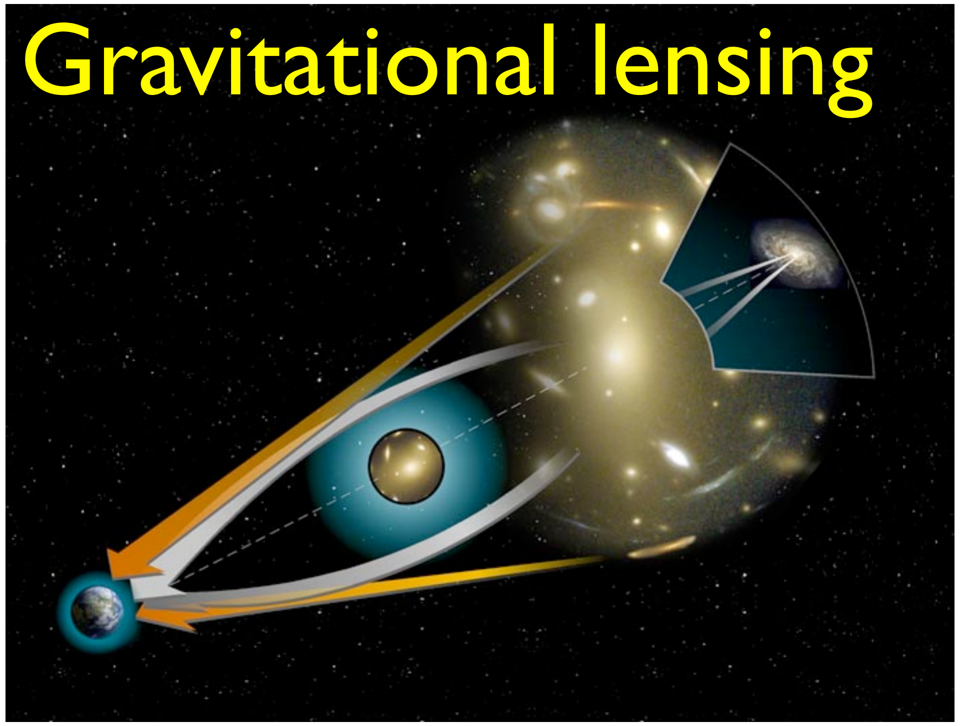
The bullet cluster
Optical X-ray Gas Dark Matter



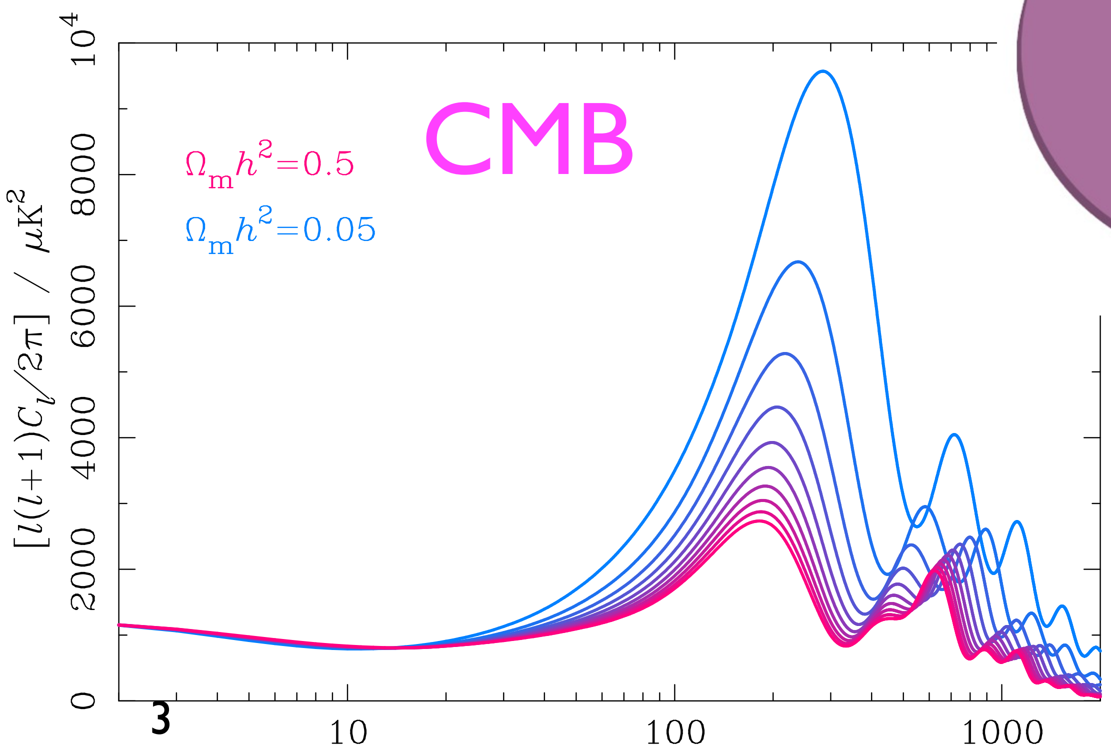
Z= 0.00
Structure formation



Dark Matter 26.8%
Ordinary Matter 4.9%
Dark Energy 68.3%



Gravitational lensing



CMB
$\Omega_m h^2$=0.5
$\Omega_m h^2$=0.05
$[l(l+1)C_l/2\pi]$ / μK^2
0
2000
4000
6000
8000
10^4
10
100
1000

Candidates of DM in BSM

Strong CP problem : axion

Neutrino sector : sterile neutrino, RH neutrino, Majoron

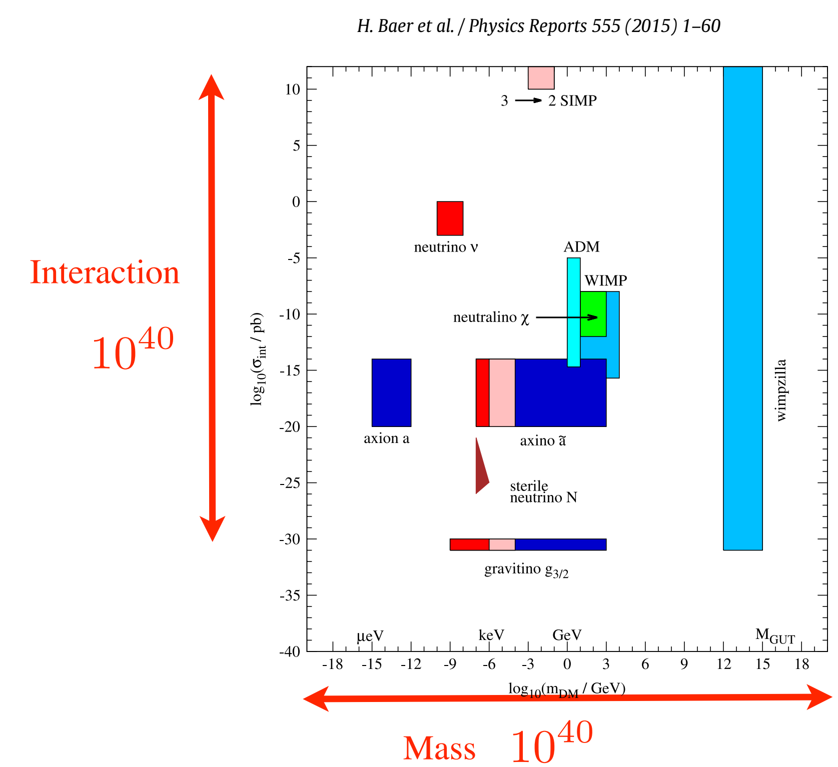
Technicolor : Techni-baryon, Techni-dilaton

Supersymmetry : neutralino, gravitino, axino, scalar neutrino

Extra dimension : Kaluza-Klein particle

and WIMPzillas, primordial Balck-Hole, dilaton

and more ....



LH Neutrino for DM?

The only EM neutral and stable particles, neutrino, was a candidate for hot dark matter.

Neutrinos decouple from a relativistic thermal bath at T~ 1 MeV in the early Universe with a relic density today as

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{90\ \mathrm{eV}} \ll \Omega_{DM} h^2$$

It is too small!

With observational constraints

$$\sum m_\nu < 0.12\,\mathrm{eV} \quad (95\,\%\ \mathrm{CL}).$$

[Planck 2018]

The fluctuations are damped smaller than the neutrino free streaming scale

$$\lambda_{FS} \sim 20 \left(\frac{30\ \mathrm{eV}}{m_\nu}\right)\ \mathrm{Mpc}$$

It is too hot! top-down structure formation

Tremaine-Gunn bound (1979): minimal mass for fermion DM around 1 keV due to exclusion principle It is too light!

Neutrinos become massive!

Dirac neutrino

- small Yukawa coupling $\sim 10^{-12}$

See-saw mechanism [Minkowski, 1977] [Yanagida, 1979] [Gell-Mann, Ramond, Slansky, 1979] [Mohapatra, Senjavic, 1980]

- suppressed mass from the heavy Majorana mass

Radiative mass [Zee, 1980, 1986] [Babu, 1988] ……

- massless at classical level, quantum correction generates mass with small couplings

Mass from the interaction with background matter

- massless at vacuum, effective mass generated when interacting with background medium [Choi, Chun, Kim, 2020]

and more …….

Neutrino Minimal Standard Model (nuMSM)

[Asaka, Blanchet, Shaposhnikov, 2005] $(\nu_R)^c \equiv C\,\overline{\nu_R}^T$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{\nu_R}\partial\!\!\!/\nu_R - \overline{\ell_L}F\nu_R\tilde{\Phi} - \tilde{\Phi}^\dagger\overline{\nu_R}F^\dagger\ell_L - \frac{1}{2}(\overline{\nu_R^c}M_M\nu_R + \overline{\nu_R}M_M^\dagger\nu_R^c).$$

singlet RH neutrino

Majorana mass

$\ell_L = (\nu_L, e_L)^T$

Yukawa coupling: Dirac mass with non-zero Higgs VEV $\tilde{\Phi} = \epsilon\Phi^*$

Three RH neutrinos with Majorana mass and Yukawa couplings.
After electroweak symmetry breaking, the mass term

$$\frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c})\begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.,$$

The hierarchy $m_D \equiv Fv \ll M_M$ gives mass eigenvalues with

three light active neutrinos and three heavy sterile neutrinos.

Sterile Neutrinos and mixing

After electroweak symmetry breaking, the mass eigenstates are

interaction eigenstates

$$
\begin{aligned}
B_\mu =& c_W A_\mu - s_W Z_\mu, \\
\nu_{L\alpha} =& U_{\alpha i}\nu_i + \Theta_{\alpha i}\nu^c_{si}, \\
\nu^c_{Ri} =& -(\Theta^\dagger U)_{ij}\nu_j + \nu^c_{si},
\end{aligned}
$$

mass eigenstates

with PMNS matrix U

$$
U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

and the mixing parameter

$$
\Theta = m_D M^{-1}_{\nu_R} \ll 1,
$$

and the light active neutrino mass

$$
m_\nu \simeq -m_D \frac{1}{M_{\nu_R}} m_D^T = -\Theta M_{\nu_R} \Theta^T.
$$

seesaw mechanism

Ki-Young Choi, Sungkyunkwan University, Korea

Interaction of RH Neutrino

RH sterile neutrinos can interaction with SM sector through

- Mass mixing after electroweak symmetry breaking

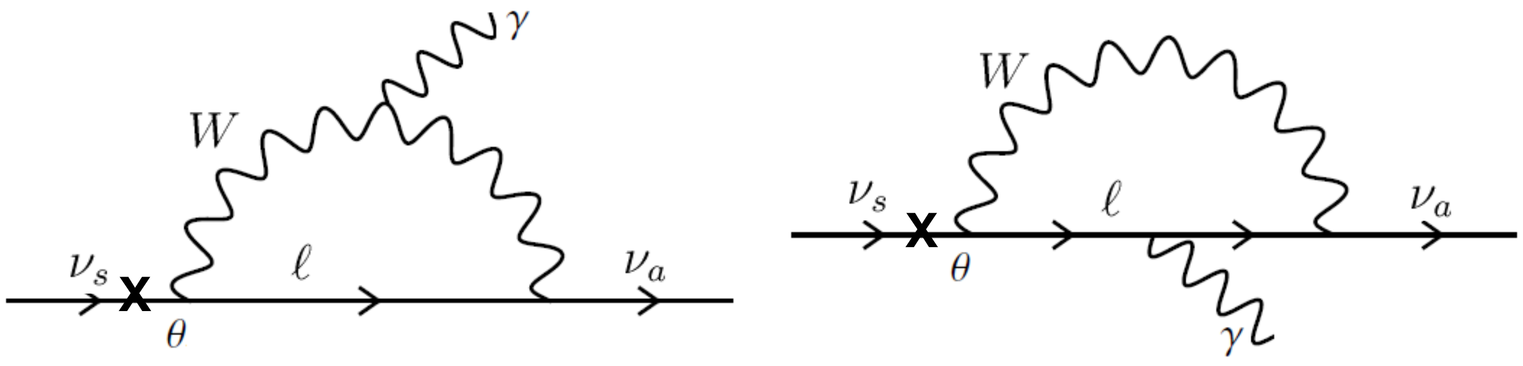
$$\Theta = m_D M_{\nu_R}^{-1} \ll 1,$$

- Yukawa interaction with Higgs and LH neutrino

$$y_{\nu\alpha i}\frac{v}{\sqrt{2}} = iU(m_\nu^{\rm diag})^{1/2}R(M_{\nu_R})^{1/2},$$

The interaction induces

- Decay of sterile neutrinos into SM neutrino and photon



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Sterile neutrino DM in nuMSM

To explain the two mass differences in the neutrino observations, two RH neutrinos are enough. The third RH neutrino, the lightest one around keV, can be DM candidate.

[Dodelson, Widrow, 1994] [Dolgov, Hansen, 2002] [Asaka, Blanchet, Shaposhnikov, 2005]

Production of DM

$$\Omega_s \sim 0.2 \left(\frac{\sin^2\theta}{3\times 10^{-9}}\right)\left(\frac{m_s}{3\,\mathrm{keV}}\right)^{1.8}$$

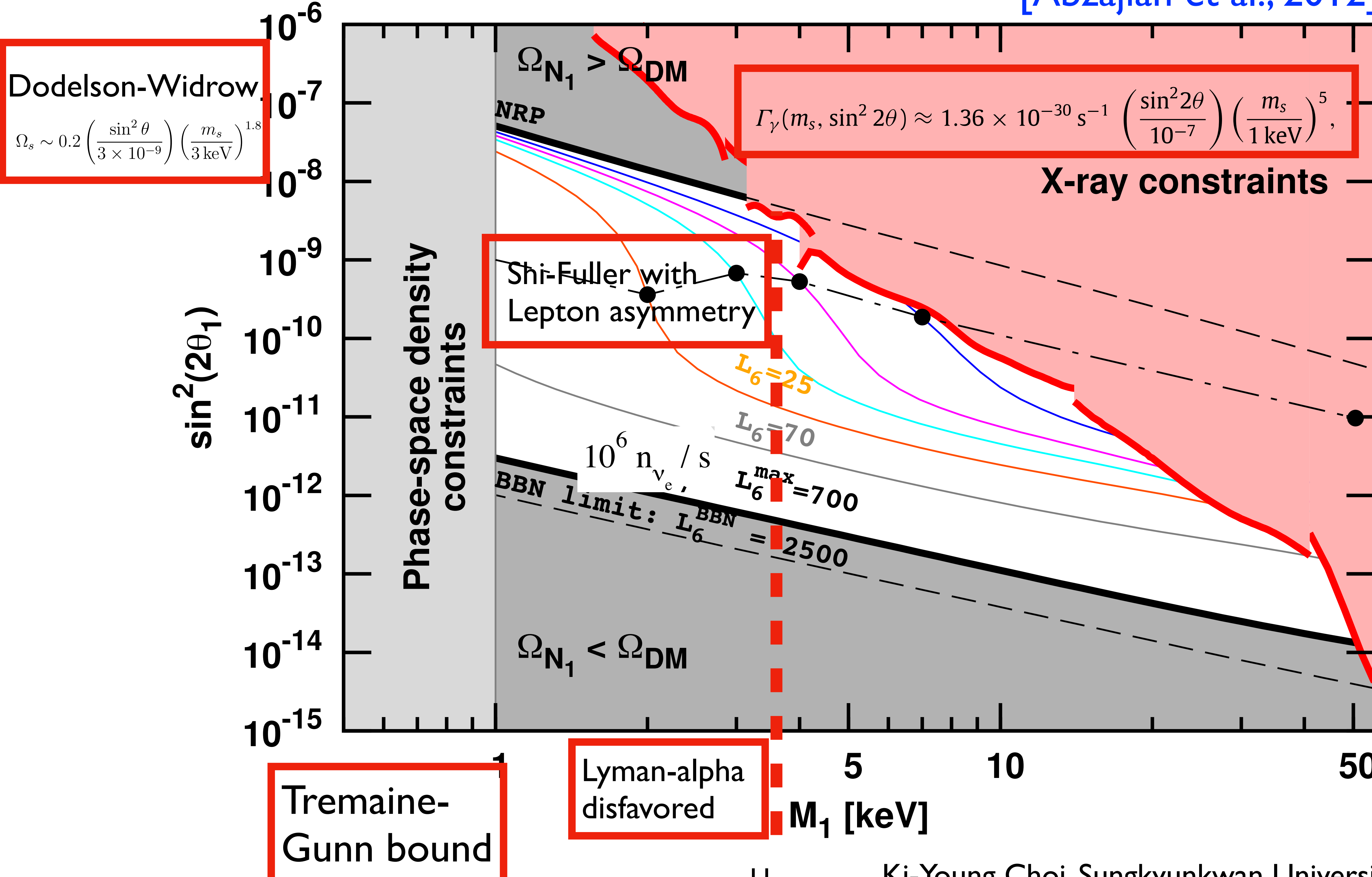
- Dodel-Widrow mechanism (Non-resonant production)
- Shi-Fuller (Resonant production) with lepton asymmetry

Decay of DM

$$\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36\times 10^{-30}\,\mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\,\mathrm{keV}}\right)^5,$$

Sterile Neutrino DM in the nuMSM

[Abzajian et al., 2012]



Magnetic Moment of Neutrino

Review [Giunti, Studenikin, 1403.6344]
and [Kim, 1911.06883]

Pauli in 1930 Letter

- as a possible interaction of neutrino

Study on the neutrino magnetic moment

[Cowan, Reines, 1957] [Bernstein, Lee, 1963]

[Kim, Mathur, Okubo, 1974] [Kim, 1976] [Kim, 1978]

[Marciano, Sanda, 1977] [Lee, Shrock, 1977] [Fetcov, 1977]

[Pal, Wolfenstein, 1982] [Shrock, 1982] [Bilenky, Fetcov, 1987]

……..

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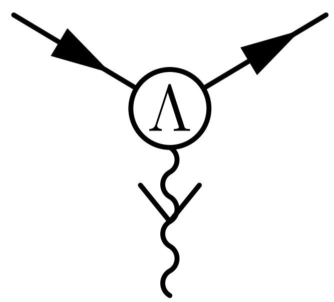
Majorana Neutrino Form Factor with flavors



(b)

$$\Lambda_\mu^{\rm M}(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) \left[\mathbb{f}_Q^{\rm M}(q^2) + \mathbb{f}_A^{\rm M}(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[\mathbb{f}_M^{\rm M}(q^2) + i\mathbb{f}_E^{\rm M}(q^2)\gamma_5\right], \qquad (3.65)$$

$$\mathbb{f}_\Omega^{\rm M} = (\mathbb{f}_\Omega^{\rm M})^\dagger \qquad (\Omega = Q, M, E, A).$$

For Majorana neutrinos,

$$\mathbb{f}_\Omega^{\rm M} = -(\mathbb{f}_\Omega^{\rm M})^T \quad (\Omega = Q, M, E),$$
$$\mathbb{f}_A^{\rm M} = (\mathbb{f}_A^{\rm M})^T.$$

charge, magnetic, and electric form factors are antisymmetric and anapole form factors are symmetric.

Majorana neutrinos have only transition (off-diagonal) dipole moment.

Dipole Moment of RH Neutrinos

We consider a Lagrangian

$\widetilde{\Phi} = \epsilon\Phi^*$

$U(1)_Y$ gauge field B_μ in the SM

$$\mathcal{L}_{\nu_R} = -\frac{1}{2}\overline{\nu^c_{Ri}}M_{\nu_{Rij}}\nu_{Rj} + y_{\nu\alpha i}\overline{L_\alpha}\widetilde{\Phi}\nu_{Ri} + C_{ij}\overline{\nu^c_{Ri}}[\gamma^\mu,\gamma^\nu]\nu_{Rj}B_{\mu\nu} + \text{h.c.}.$$

RH Majorana mass   Yukawa coupling   dipole moment

$$M_{\nu_{Rij}} = \text{diag}(M_{\nu_{R1}}, M_{\nu_{R2}}, M_{\nu_{R3}})$$

$$C_{ij} = \frac{c_{ij}}{\Lambda_5}$$ antisymmetric

dim-5 operator from new physics

Collider, astrophysical, cosmological study in [Aparici etal, 0904.3244]

We don't consider Dirac dipole operator btn LH and RH neutrinos, since it is dim-6 operator

$$\frac{1}{\Lambda_6^2}\overline{L}\widetilde{\Phi}[\gamma^\mu,\gamma^\nu]\nu_R B_{\mu\nu} \rightarrow \frac{v}{\Lambda_6^2}\overline{\nu}[\gamma^\mu,\gamma^\nu]\nu_s F_{\mu\nu},$$

Dipole Moment of RH Neutrino DM

$$\widetilde{\Phi} = \epsilon \Phi^*$$

$U(1)_Y$ gauge field B_μ in the SM

We consider

seesaw, DM in nuMSM — effect on DM

$$\mathcal{L}_{\nu_R} = -\frac{1}{2}\overline{\nu^c_{Ri}} M_{\nu_{Rij}} \nu_{Rj} + y_{\nu\alpha i}\overline{L_\alpha}\widetilde{\Phi}\nu_{Ri} + C_{ij}\overline{\nu^c_{Ri}}[\gamma^\mu,\gamma^\nu]\nu_{Rj}B_{\mu\nu} + \text{h.c.}.$$

RH Majorana mass — Yukawa coupling — magnetic moment

$$M_{\nu_{Rij}} = \mathrm{diag}(M_{\nu_{R1}}, M_{\nu_{R2}}, M_{\nu_{R3}})$$

$$C_{ij} = \frac{c_{ij}}{\Lambda_5}$$ antisymmetric

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$$\frac{1}{\Lambda_6^2}\overline{L}\widetilde{\Phi}[\gamma^\mu,\gamma^\nu]\nu_R B_{\mu\nu} \to \frac{v}{\Lambda_6^2}\overline{\nu}[\gamma^\mu,\gamma^\nu]\nu_s F_{\mu\nu},$$

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Sterile Neutrino DM

The direct mixing between SM neutrinos and RH neutrino DM has strong constraints from X-ray and Lyman-alpha.

We consider, the Yukawa coupling can be written as

[Cho, Choi, Seto, 2108.07569]

$$y_\nu = \begin{pmatrix} 0 & y_{\nu e2} & y_{\nu e3} \\ 0 & y_{\nu\mu 2} & y_{\nu\mu 3} \\ 0 & y_{\nu\tau 2} & y_{\nu\tau 3} \end{pmatrix} \longrightarrow$$

DM has no mixing with active neutrinos

with the relation

[Casas, Ibarra, 2001]

$$y_{\nu\alpha i}\frac{v}{\sqrt{2}} = iU(m_\nu^{\rm diag})^{1/2}R(M_{\nu_R})^{1/2},$$

complex orthogonal matrix $RR^T = 1$

$$U^\dagger m_\nu U^* = {\rm diag}(m_1, m_2, m_3) = m_\nu^{\rm diag}$$

To be Dark Matter

Lifetime of DM is long enough

Relic density of DM

Other constraints

Lagrangian in the mass eigenstates

[Cho, Choi, Seto, 2108.07569]

$$\mathcal{L}_{\rm DI} =(c_W F_{\mu\nu} - s_W Z_{\mu\nu})\left(\overline{\nu_i}(C_V^{\nu\nu} + C_A^{\nu\nu}\gamma_5)_{ij}[\gamma^\mu,\gamma^\nu]\nu_j + \overline{\nu_i}(C_V^{\nu\nu_s} + C_A^{\nu\nu_s}\gamma_5)_{ij}[\gamma^\mu,\gamma^\nu]\nu_{sj}\right.$$

$$\left. + \overline{\nu_{si}}(C_V^{\nu_s\nu} + C_A^{\nu_s\nu}\gamma_5)_{ij}[\gamma^\mu,\gamma^\nu]\nu_l + \boxed{\overline{\nu_{si}}(C_V^{\nu_s\nu_s} + C_A^{\nu_s\nu_s}\gamma_5)_{ij}[\gamma^\mu,\gamma^\nu]\nu_{sj}}\right).$$

$$(C_V^{\nu\nu} + C_A^{\nu\nu}\gamma_5)_{ij} =(U^\dagger\Theta)_{ik}C_{kl}(\Theta^T U^*)_{lj}P_L - (U^T\Theta^*)_{ik}C^\dagger_{kl}(\Theta^\dagger U)_{lj}P_R,$$

$$\frac{\Theta}{\Lambda_5}\left\{\boxed{\begin{aligned}(C_V^{\nu\nu_s} + C_A^{\nu\nu_s}\gamma_5)_{ij} &= -(U^\dagger\Theta)_{ik}C_{kj}P_L + (U^T\Theta^*)_{ik}C^\dagger_{kj}P_R,\\ (C_V^{\nu_s\nu} + C_A^{\nu_s\nu}\gamma_5)_{ij} &= -C_{ik}(\Theta^T U^*)_{kj}P_R + C^\dagger_{ik}(\Theta^\dagger U)_{kj}P_L,\end{aligned}}\right.$$

$$(C_V^{\nu_s\nu_s} + C_A^{\nu_s\nu_s}\gamma_5)_{ij} =C_{ij}P_R - C^\dagger_{ij}P_L,$$

btn LH and RH neutrinos

dipole interaction between sterile neutrinos

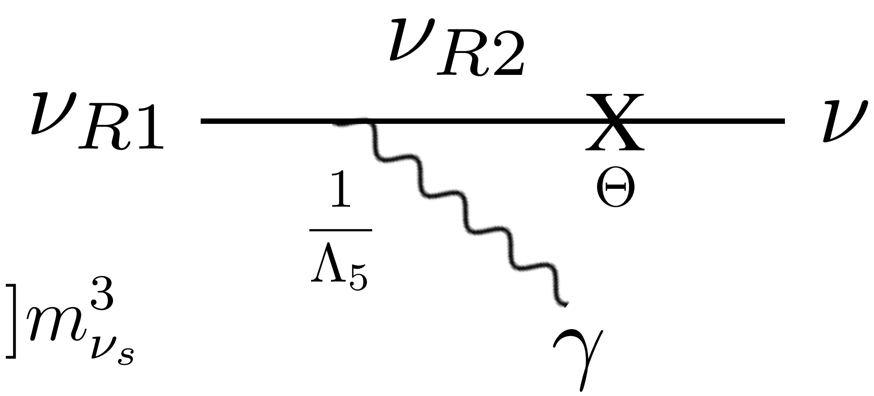
suppressed by $C_{ij} = \frac{c_{ij}}{\Lambda_5}$

Stability of RH neutrino DM

[Cho, Choi, Seto, 2108.07569]

DM has negligible direct mixing with active neutrinos but it can decay through the off-diagonal dipole term and mixing of the heavier sterile neutrinos with active neutrinos.

The decay rate and its lifetime is



$$\Gamma(\nu_s \to \nu\gamma) \simeq \frac{1}{2\pi} c_W^2 \sum_{i=1}^{3} [|C_{Vh1}^{\nu\nu_s}|^2 + |C_{Ah1}^{\nu\nu_s}|^2] m_{\nu_s}^3$$

$$\sim \frac{1}{10^{28}\,\mathrm{sec}} \left(\frac{10^{15}\,\mathrm{GeV}}{\Lambda_5}\right)^2 \left(\frac{|\Theta|}{10^{-6}}\right)^2 \left(\frac{m_{\nu_s}}{1\,\mathrm{MeV}}\right)^3$$

We require that the lifetime is longer than around $10^{28}\,\mathrm{sec}$.

$$\Lambda_5 \gtrsim 10^{15}\mathrm{GeV} \quad \text{and/or} \quad |\Theta| \lesssim 10^{-6}$$

mixing between heavy sterile neutrino and active neutrino

Production of DM

[Baer, Choi, Kim, Roszkowski, 2015]

Thermal Production (TP) : produced from thermal particles

Decouple out of thermal equilibrium (freeze-out)
: interaction is large enough - WIMP, WDM, SM neutrinos

Do not get to thermal equilibrium (freeze-in)
: interaction is very small - Dirac RH sneutrino, gravitino, axino, FIMP

Dodelson-Widrow mechanism, Shi-Fuller mechanism : RH neutrino

Non-Thermal Production (NTP) : produced non-thermally

Misalignment mechanism : coherent oscillation of axion

Decay of heavy particle

….

Thermal Production of very weakly interacting particles

: the destruction can be ignores since their number density is too small

Boltzmann equation

from thermal particles

$$\frac{dn_{\tilde{N}}}{dt} + 3Hn_{\tilde{N}} \simeq \sum_{i,j} \langle \sigma(i+j \to \tilde{N} + \cdots) v_{rel} \rangle n_i n_j + \sum_i \langle \Gamma(i \to \tilde{N} + \cdots) \rangle n_i,$$

Thermal production from scattering and decay

[Choi, Hwang, Kim, 1999]

$$Y_{ij}^{\rm scat} = \int_{T_0}^{T_R} dT \frac{\langle \sigma(i+j \to \tilde{N} + \cdots) v_{rel} \rangle n_i n_j}{sHT},$$

$$Y_i^{\rm dec} = \int_{T_0}^{T_R} dT \frac{\langle \Gamma(i \to \tilde{N} + \cdots) \rangle n_i}{sHT}.$$

Thermal Production of DM

The abundance of the super-weakly interacting particles from the scatterings are given by

$$Y_{\nu_s}^{\rm TP} = \int_{T_0}^{T_R} \frac{\langle \sigma v(ij \to \nu_{s1} X)\rangle n_i n_j + \Gamma(\nu_{sh} \to \gamma \nu_s) n_{\nu_{sh}}}{sTH} dT,$$

and the relic density by

$$\Omega_{\nu_s}^{\rm TP} h^2 = \frac{m_{\nu_s}}{\rho_{\rm crit}/s_0} Y_{\nu_s}^{TP} \simeq 0.28 \left(\frac{m_{\nu_s}}{1\,{\rm MeV}}\right)\left(\frac{Y_{\nu_s}^{TP}}{10^{-6}}\right),$$

$s_0 = \frac{2\pi^2}{45} \times 3.91 \times T_0^3$ $\qquad (\rho_{\rm crit}/s_0)^{-1} = 2.8 \times 10^8/{\rm GeV}$

$\rho_{\rm crit} = 3 M_P^2 H_0^2$

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Thermal Production of DM

The lightest RH neutrino DM can produced from the scatterings of the thermal particles through the off-diagonal magnetic dipole interaction. The interaction is very small, but enough for DM, similar to FIMP, gravitino or axino production.

The dominant ones are scatterings mediated by B-bosons

t-channel $f\nu_{sj} \to f\nu_{si}$

s-channel $f\bar{f} \to \nu_s\nu_{sj}$

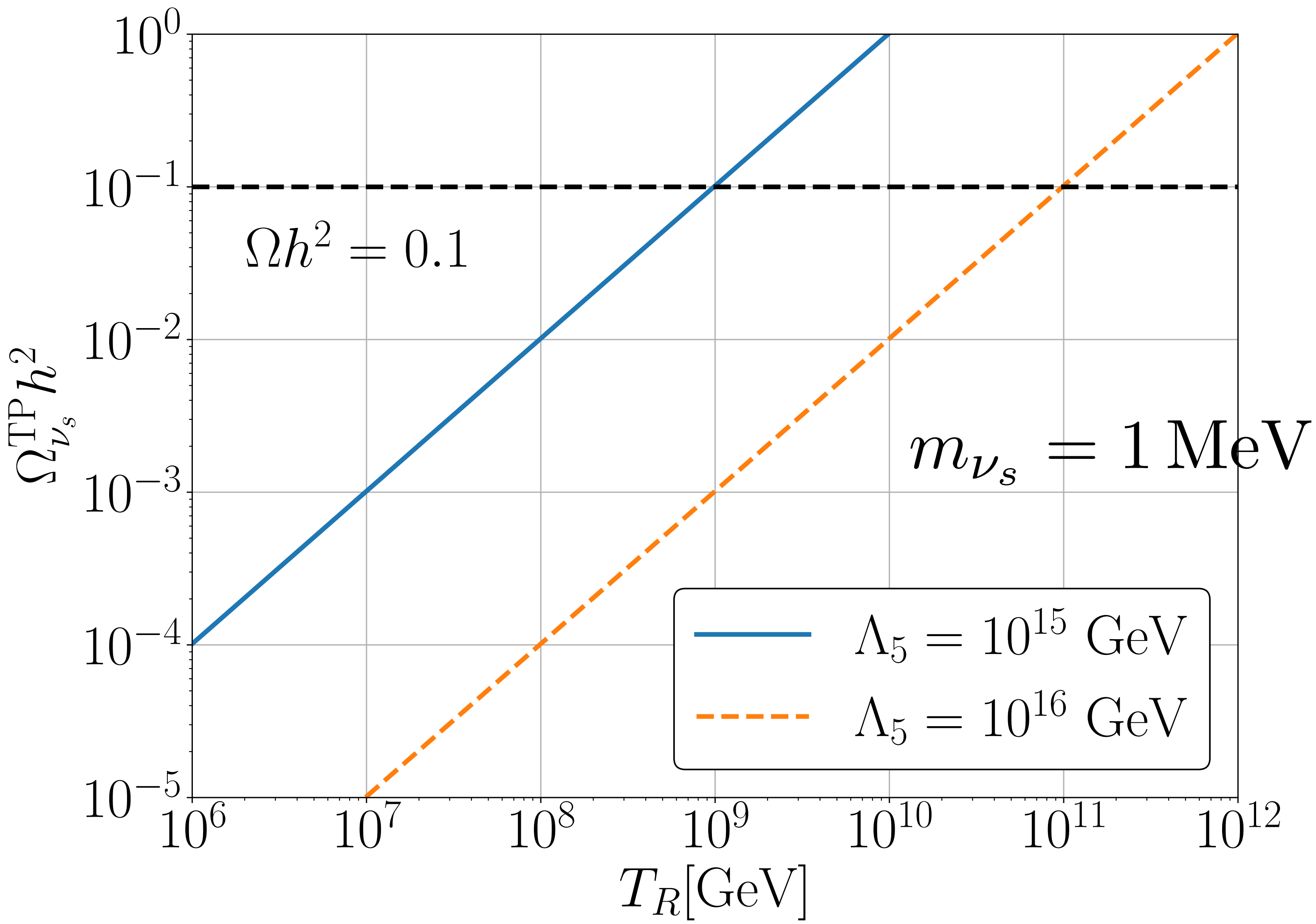
$$\sigma_t \simeq \frac{N_c(Y_f g_Y)^2 c_{1j}^2 g_f g_{\nu_{sj}}}{2\pi\Lambda_5^2}\left[-2-(1+2m_B^2/s)\log\left(\frac{m_B^2}{s+m_B^2}\right)\right],$$

$$\sigma_s \simeq \frac{N_c(Y_f g_Y)^2 c_{1j}^2 g_f g_{\bar{f}}}{12\pi\Lambda_5^2},$$

Thermal Production of DM

$$\Omega_{\nu_s}^{\rm TP} h^2 \simeq 0.2 \left(\frac{m_s}{1\,\rm MeV}\right)\left(\frac{10^{16}\,\rm GeV}{\Lambda_5}\right)^2\left(\frac{T_R}{10^{11}\,\rm GeV}\right)$$

[Cho, Choi, Seto, 2108.07569]



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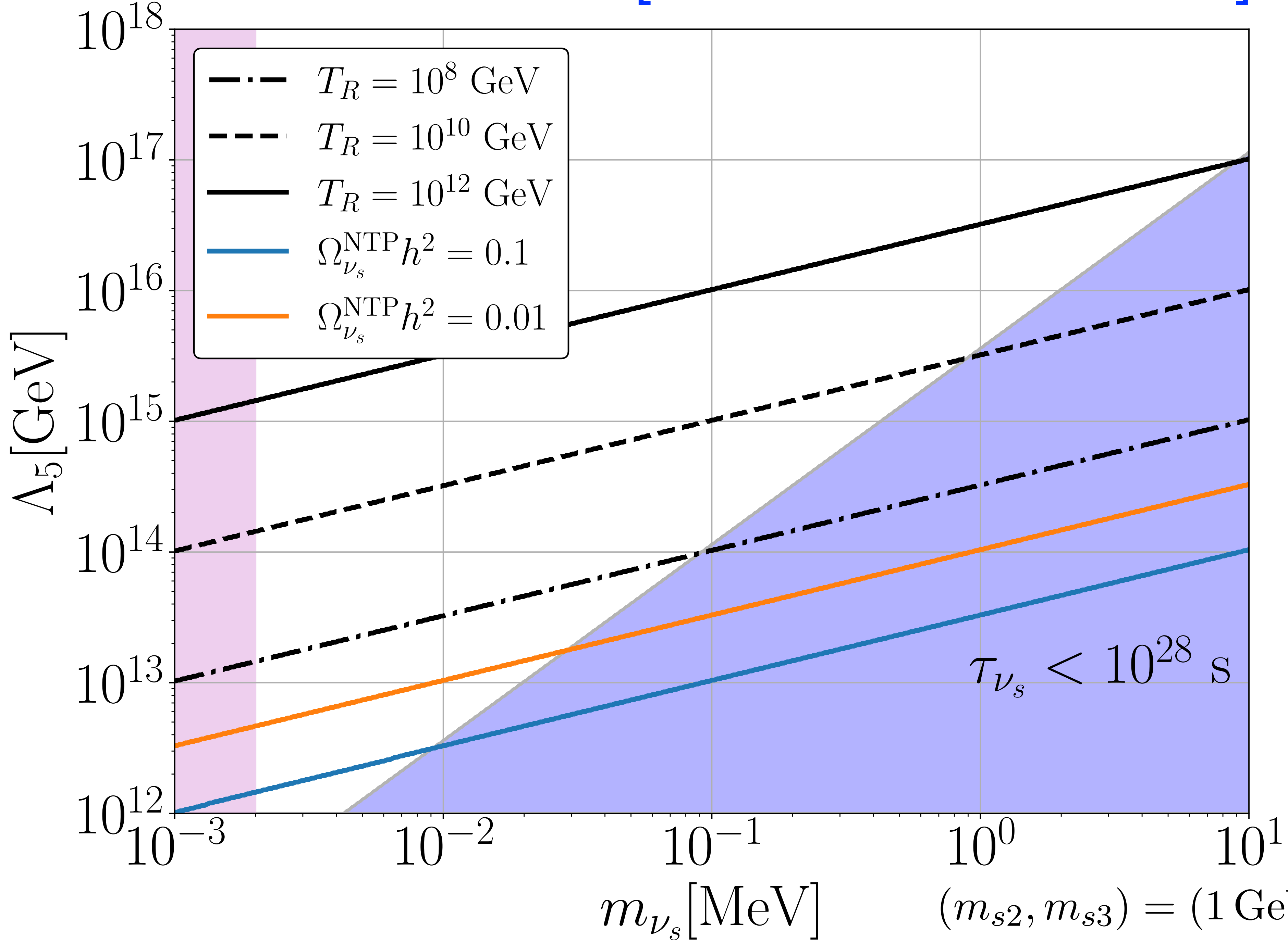
Thermal Production of DM

[Cho, Choi, Seto, 2108.07569]



$(m_{s2}, m_{s3}) = (1\,\mathrm{GeV}, 10\,\mathrm{GeV})$

Non-Thermal Production of DM

The heavier RH neutrinos decouple from thermal equilibrium and decay into the lightest Rh neutrino DM.

$$\Omega_{\nu_s}^{\rm NTP} h^2 = \frac{m_{\nu_s} s_0}{\rho_{\rm crit}} \sum_{h=2,3} {\rm Br}(\nu_{sh} \to \gamma \nu_s) \times Y_{\nu_{s_h}}^{\rm dec}$$

$$\simeq 1 \times 10^{-6} \left(\frac{m_{\nu_s}}{1\,{\rm MeV}}\right) \left(\frac{1\,{\rm GeV}}{m_{\nu_{sh}}}\right) \left(\frac{10^{16}\,{\rm GeV}}{\Lambda_5}\right)^2 \left(\frac{9 \times 10^{-12}}{\sum_\alpha |\Theta_{\alpha h}|^2}\right).$$

It is much suppressed compared to that from thermal production.

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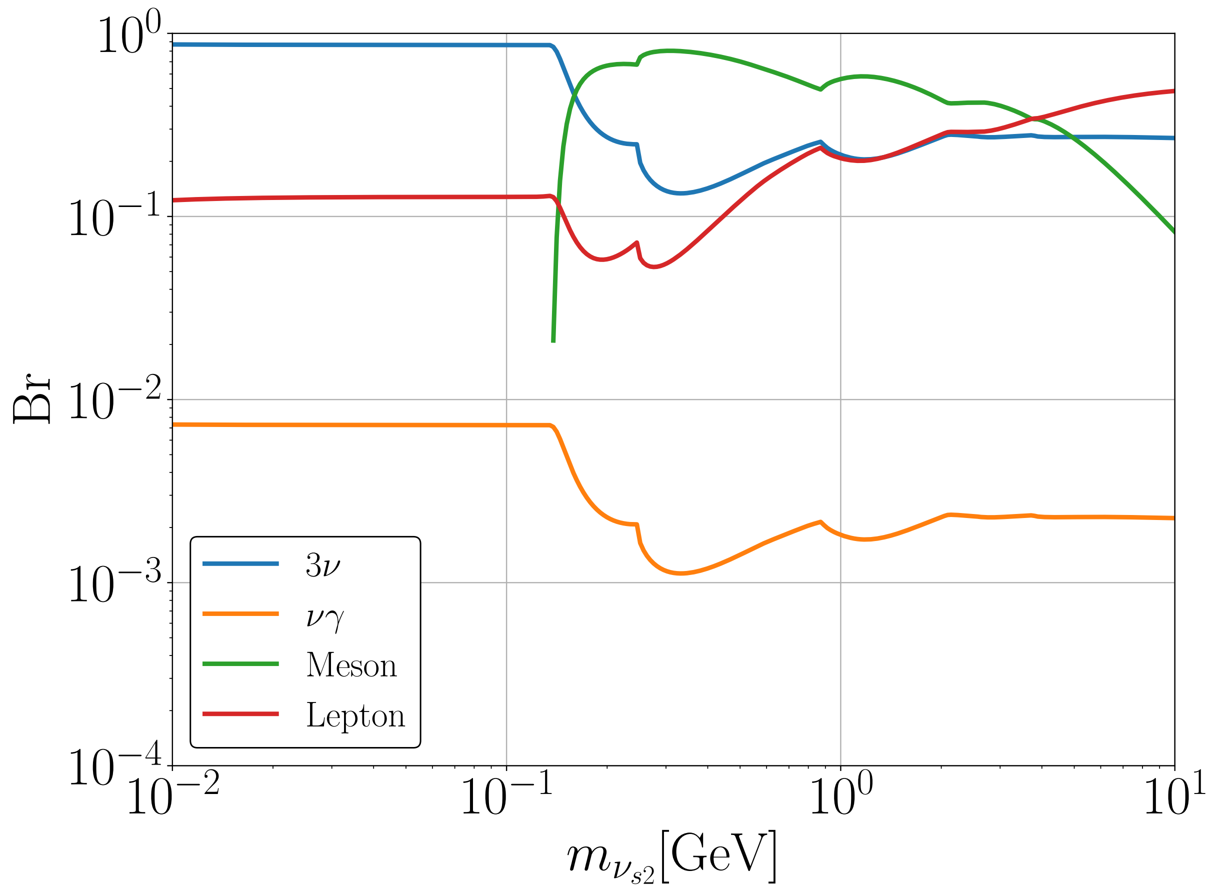
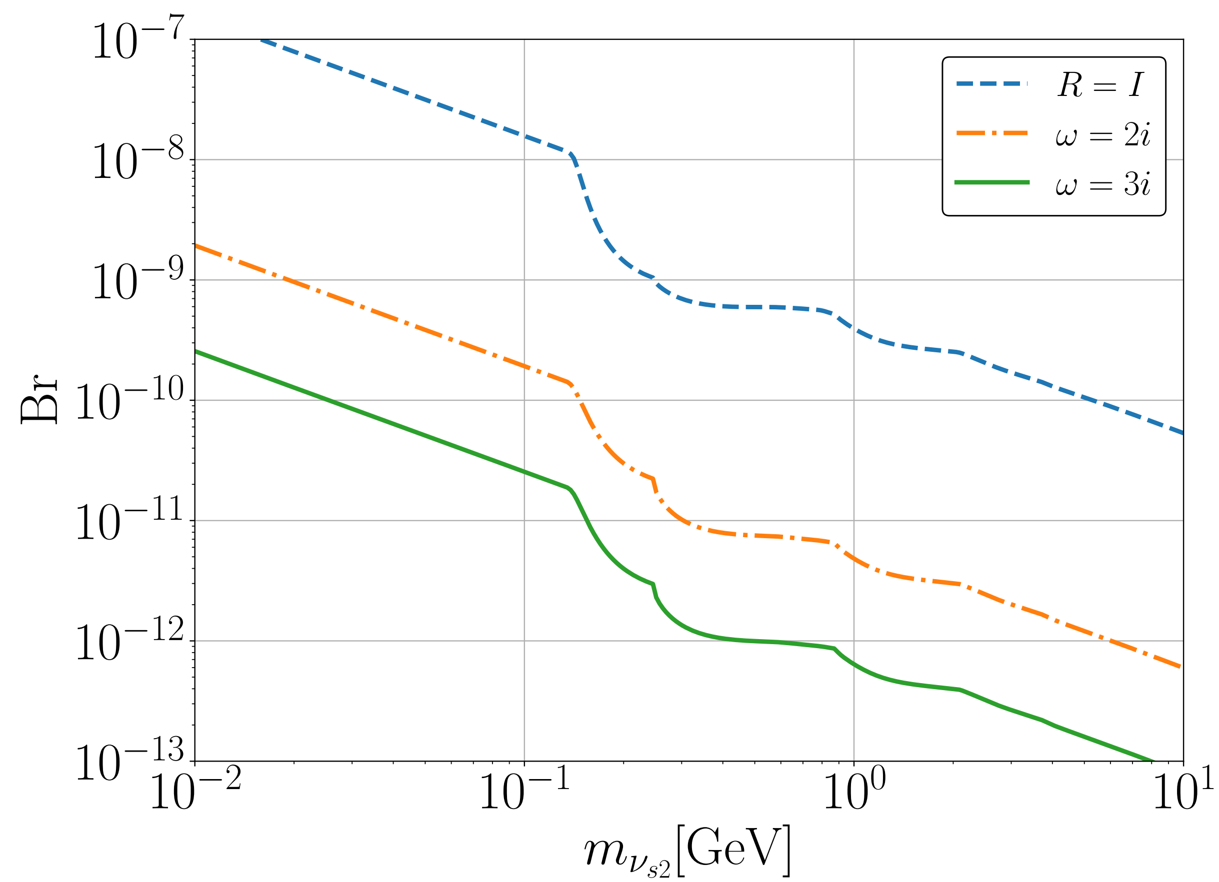
Decay of heavier RH neutrino



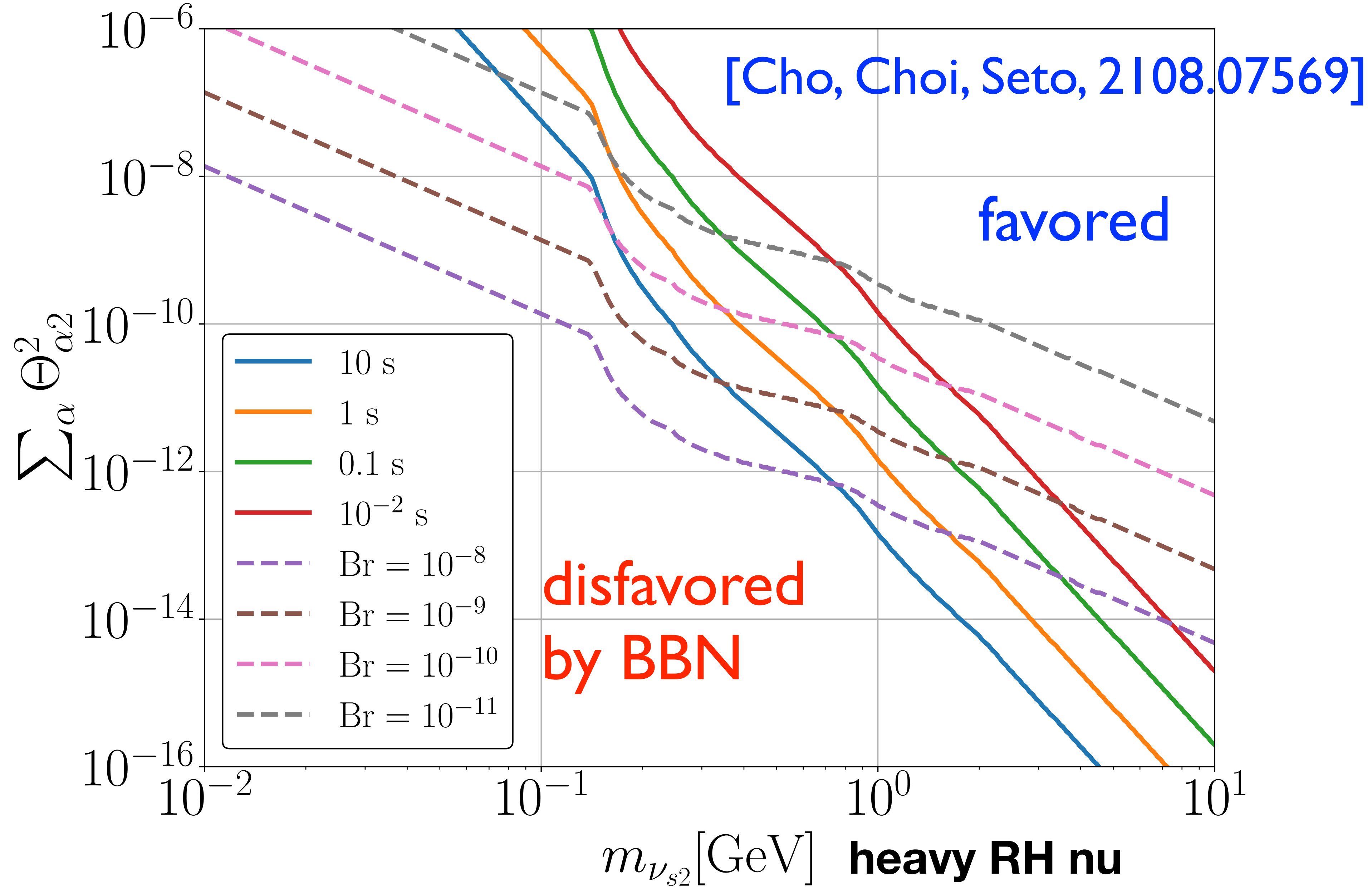
$\mathrm{Br}(\nu_{sj} \to \nu_s \gamma)$



$$\Gamma(\nu_{sh} \to 3\nu) = \sum_{\alpha,h} \Gamma(\nu_{sh} \to \nu_\alpha \nu_i \bar{\nu}_i) = \frac{G_F^2 m_{\nu_{sh}}^5}{96\pi^3} \sum_\alpha |\Theta_{\alpha h}|^2,$$

Constraints from BBN

The decay of the heavier RH neutrinos produce EM, hadronic and then affect the Big Bang Nucleosynthesis.



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Astrophysical Signatures

The decay of sterile neutrino DM can produce monochromatic photon line emission, and also electron and positron pair with the energy around from keV to GeV.

$$\frac{\Gamma(\nu_s \to e^- e^+ \nu_i)}{\Gamma(\nu_s \to \gamma \nu_i)} \sim \alpha_{\rm em} \left(\ln \frac{m_{\nu_s}}{m_e} - \frac{3}{2} \right)$$

with the constraint $\Gamma^{-1}(\nu_s \to \gamma\nu_i) > 10^{28}\,\mathrm{sec}$

- 3.5 keV line
- cosmic ray measurement with electron and positron
- 511 keV line spectrum from the Galactic center

Summary

nuMSM

SM +3 RH neutrinos

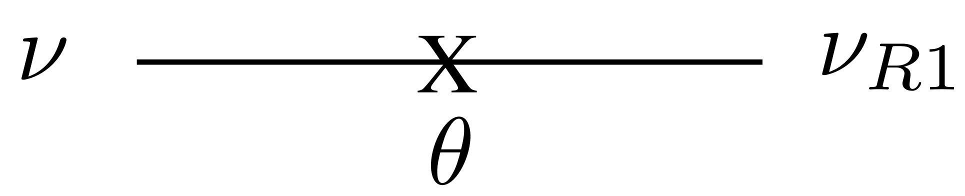
ν_1, ν_2, ν_3 $\longleftrightarrow$ $\nu_{R1}, \nu_{R2}, \nu_{R3}$

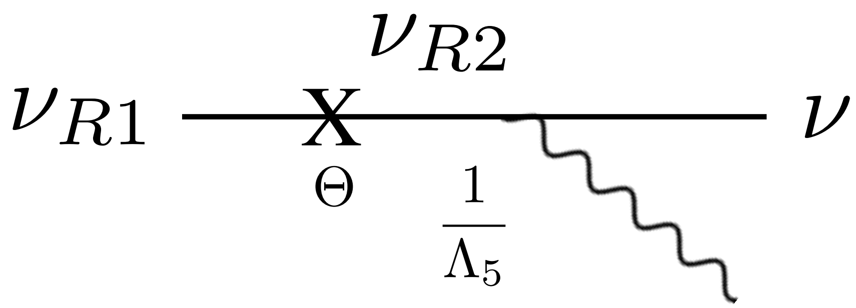
mixing θ

dipole interaction

Dipole interaction between 3RH neutrinos

$$C_{ij}\overline{\nu^c_{Ri}}[\gamma^\mu, \gamma^\nu]\nu_{Rj}B_{\mu\nu}$$





Production and decay of DM (the lightest RH neutrino)

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Summary

- Neutrino mass and dark matter

SM + RH neutrinos + dipole interaction

nuMSM ↓ **dim-5 from new physics**

Dark Matter

- Production of the lightest RH neutrino dark matter

: thermal (scattering) + non-thermal

- 10 keV - 1 MeV mass cold dark matter, with GUT scale new physics
- Reheating temperature around 10^7 - 10^12 GeV
- No constraint from the structure formation
- Constraint and possible signal from X-ray or Gamma-ray

Thank You!