

# Sterile neutrino dark matter with dipole interaction

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

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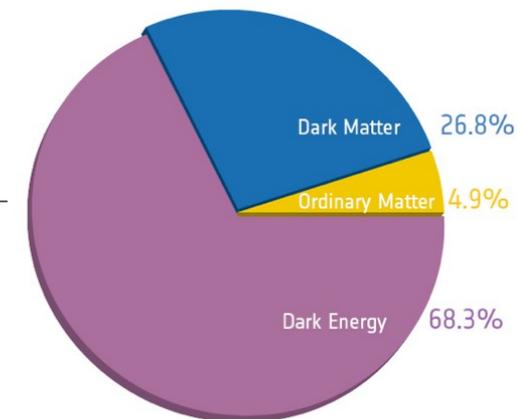
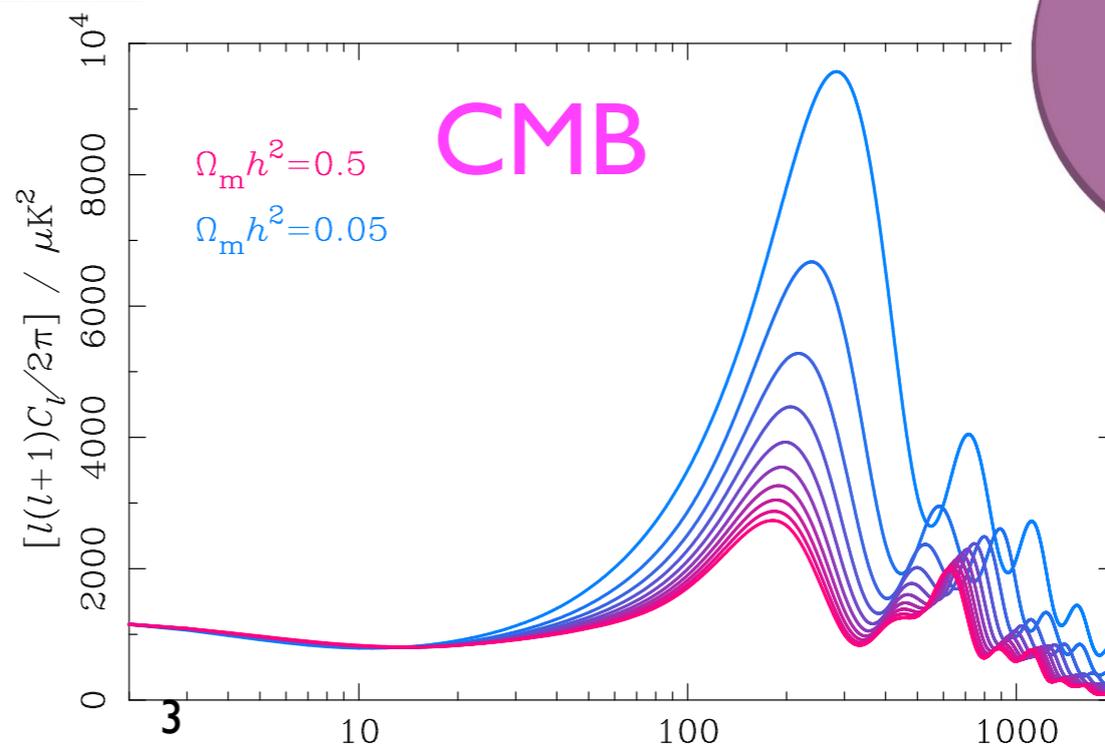
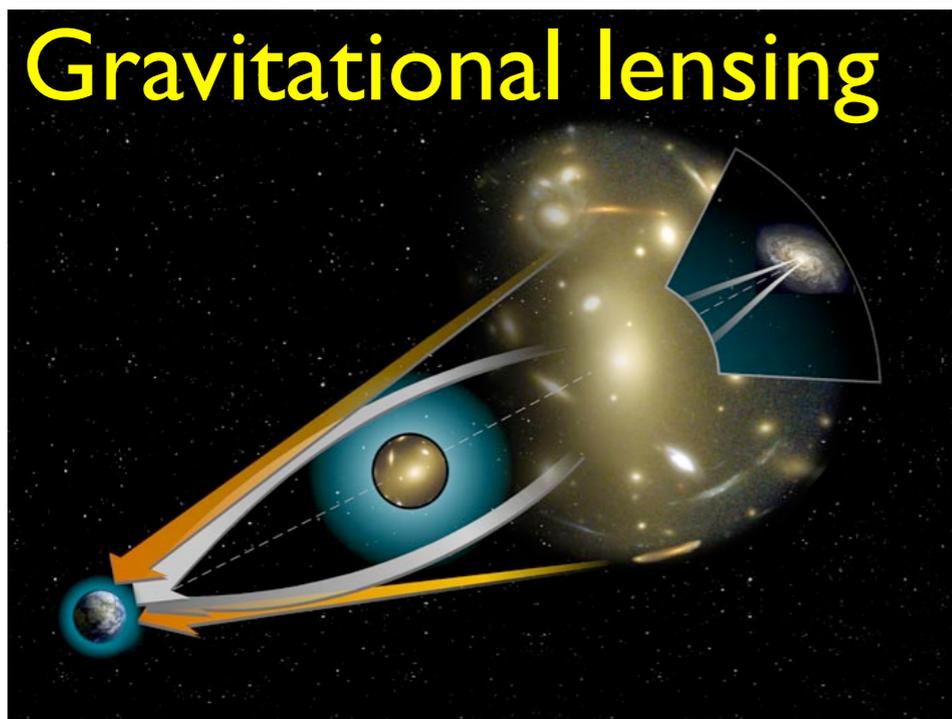
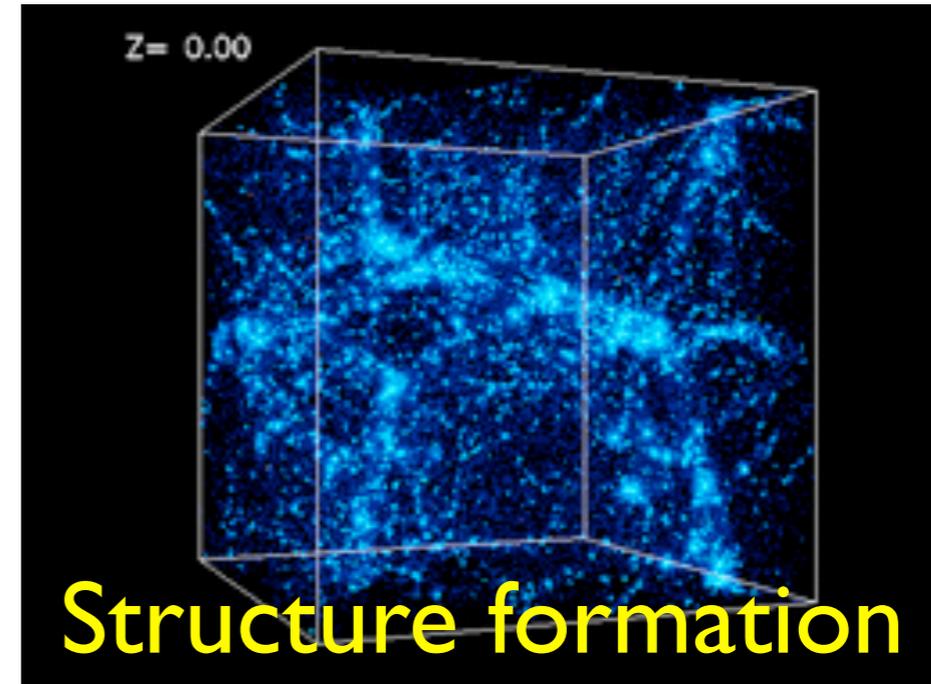
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# Dark Matter



# Candidates of DM in BSM

Strong CP problem : axion

Neutrino sector : **sterile neutrino, RH neutrino**, Majoron

Technicolor : Techni-baryon, Techni-dilaton

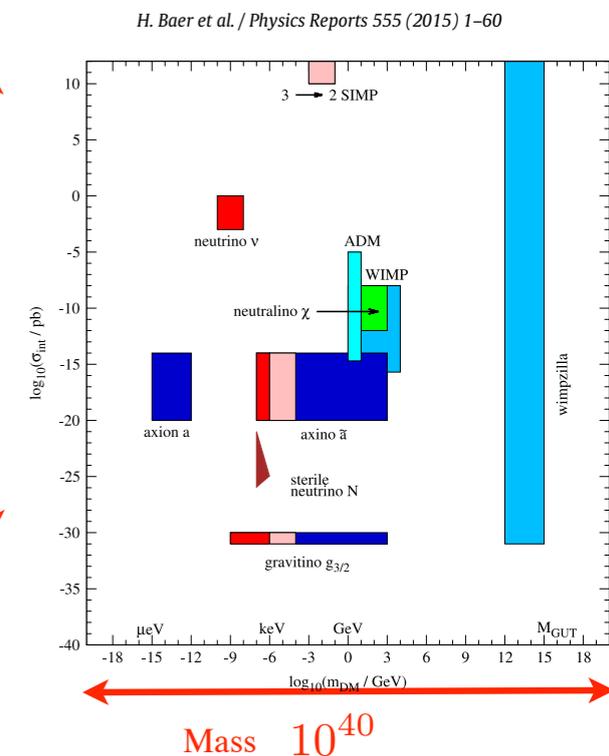
Supersymmetry : neutralino, gravitino, axino, scalar neutrino

Extra dimension : Kaluza-Klein particle

and WIMPzillas, primordial Black-Hole, dilaton

and more ....

Interaction  
 $10^{40}$



# 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  $T \sim 1$  MeV in the early Universe with a relic density today as

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

**It is too small!**

With observational constraints

$$\sum m_\nu < 0.12 \text{ eV} \quad (95 \% \text{ CL}). \quad [\text{Planck 2018}]$$

The fluctuations are damped smaller than the neutrino free streaming scale

$$\lambda_{FS} \sim 20 \left( \frac{30 \text{ eV}}{m_\nu} \right) \text{ Mpc} \quad \text{It is too hot!} \quad \text{top-down structure formation}$$

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]  $(\nu_R)^c \equiv C \bar{\nu}_R^T$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\bar{\nu}_R \not{\partial} \nu_R - \underbrace{\bar{\ell}_L F \nu_R \tilde{\Phi}}_{\text{Yukawa coupling: Dirac mass with non-zero Higgs VEV}} - \underbrace{\tilde{\Phi}^\dagger \bar{\nu}_R F^\dagger \ell_L}_{\text{singlet RH neutrino}} - \frac{1}{2} \underbrace{(\bar{\nu}_R^c M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)}_{\text{Majorana mass}}.$$

$\ell_L = (\nu_L, e_L)^T$   
 $\tilde{\Phi} = \epsilon \Phi^*$

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

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

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

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

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

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

and the light active neutrino mass

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

# Interaction of RH Neutrino

RH sterile neutrinos can interact with SM sector through

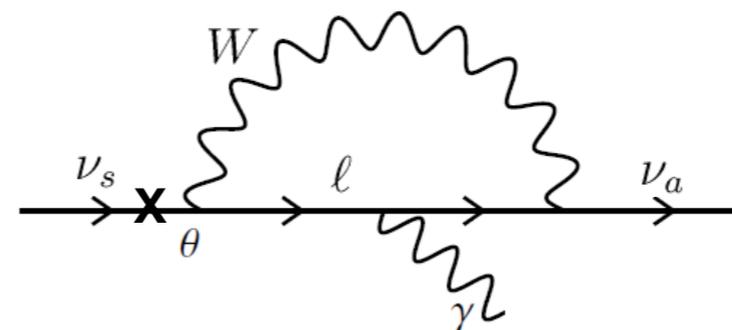
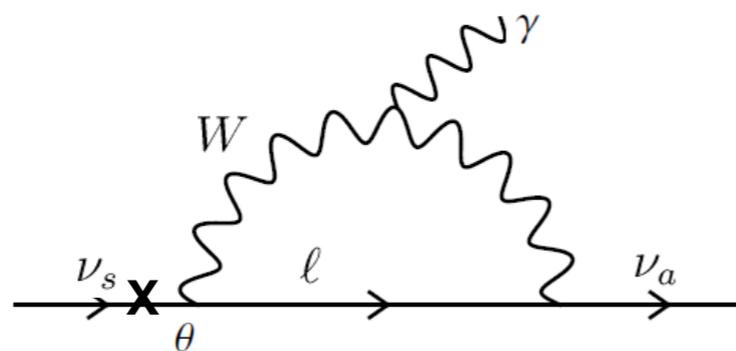
- **Mass mixing** after electroweak symmetry breaking
- **Yukawa interaction** with Higgs and LH neutrino

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

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

The interaction induces

- Decay of sterile neutrinos into SM neutrino and photon



# 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

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

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

## Decay of DM

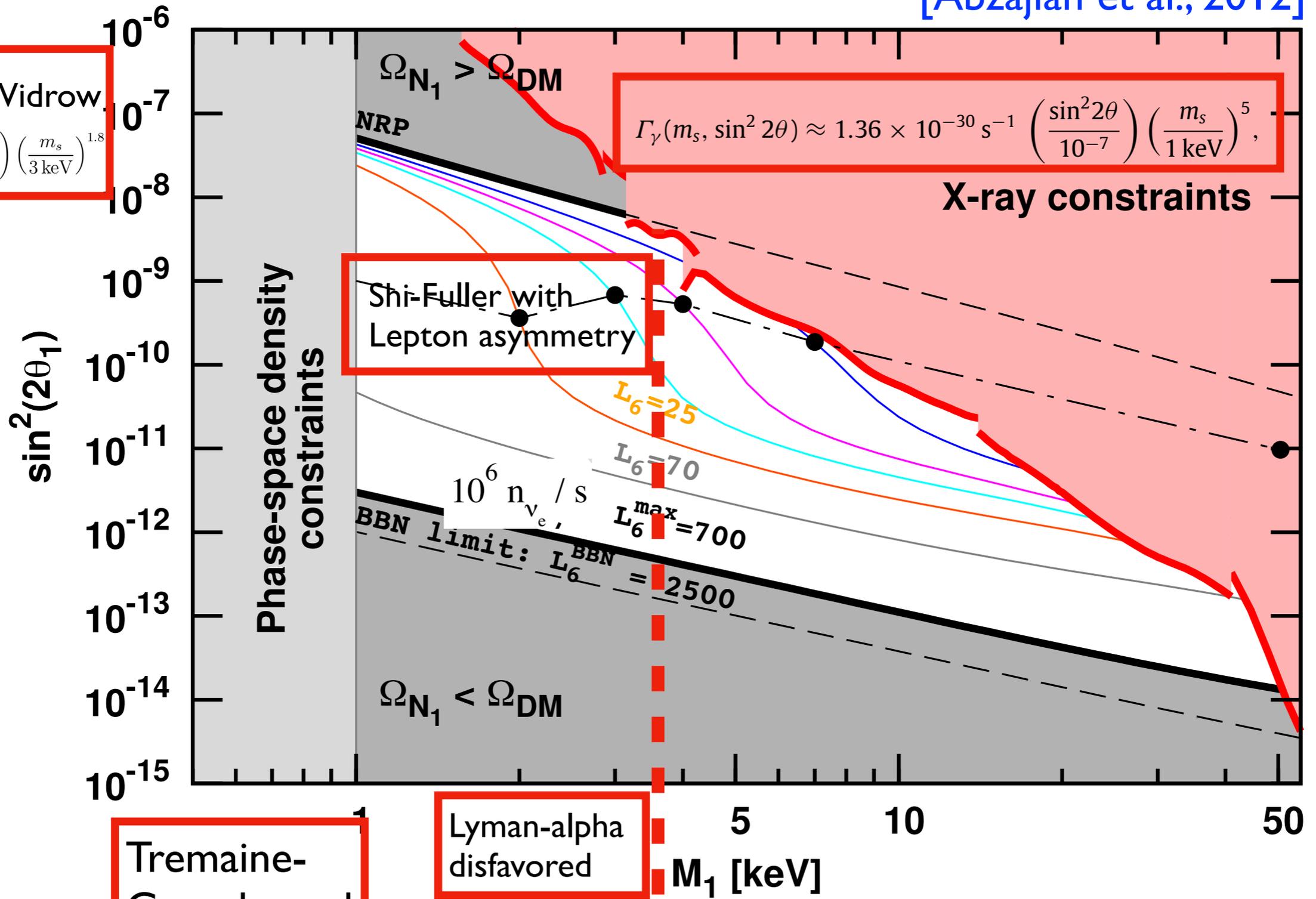
$$\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36 \times 10^{-30} \text{ s}^{-1} \left( \frac{\sin^2 2\theta}{10^{-7}} \right) \left( \frac{m_s}{1 \text{ keV}} \right)^5,$$

# Sterile Neutrino DM in the nuMSM

[Abzajian et al., 2012]

Dodelson-Widrow

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



Tremaine-Gunn bound

# 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]

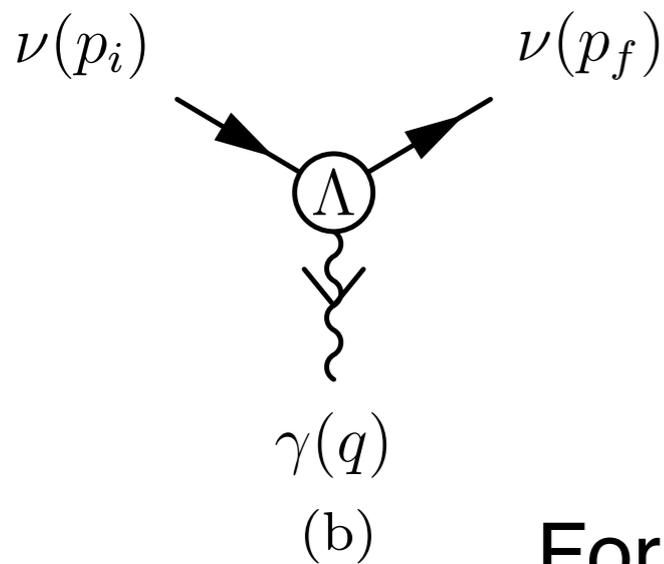
[Kim, Mathur, Okubo, 1974] [Kim, 1976] [Kim, 1978]

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

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

.....

# Majorana Neutrino Form Factor with flavors



$$\Lambda_{\mu}^{\text{M}}(q) = (\gamma_{\mu} - q_{\mu} \not{q} / q^2) [\mathbb{f}_{\text{Q}}^{\text{M}}(q^2) + \mathbb{f}_{\text{A}}^{\text{M}}(q^2) q^2 \gamma_5] - i\sigma_{\mu\nu} q^{\nu} [\mathbb{f}_{\text{M}}^{\text{M}}(q^2) + i\mathbb{f}_{\text{E}}^{\text{M}}(q^2) \gamma_5], \quad (3.65)$$

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

For Majorana neutrinos,

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

$$\mathbb{f}_{\text{A}}^{\text{M}} = (\mathbb{f}_{\text{A}}^{\text{M}})^T.$$

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

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

$U(1)_Y$  gauge field  $B_\mu$  in the SM

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

RH Majorana mass Yukawa coupling

dipole moment

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

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

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

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

# Dipole Moment of RH Neutrino DM

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

We consider

$U(1)_Y$  gauge field  $B_\mu$  in the SM

seesaw, DM in nuMSM	effect on DM
$\mathcal{L}_{\nu_R} = -\frac{1}{2}\overline{\nu_{Ri}^c}M_{\nu Rij}\nu_{Rj} + y_{\nu\alpha i}\overline{L}_\alpha\tilde{\Phi}\nu_{Ri} +$	$C_{ij}\overline{\nu_{Ri}^c}[\gamma^\mu, \gamma^\nu]\nu_{Rj}B_{\mu\nu} + \text{h.c.}$
<p>RH Majorana mass    Yukawa coupling</p>	<p>magnetic moment</p>

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

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

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

# 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]

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



DM has no mixing  
with active neutrinos

with the relation  
[Casas, Ibarra, 2001]

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

complex orthogonal  
matrix  $\Omega \Omega^T = 1$

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

# 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]

$$\mathcal{L}_{\text{DI}} = (c_W F_{\mu\nu} - s_W Z_{\mu\nu}) (\bar{\nu}_i (C_V^{\nu\nu} + C_A^{\nu\nu} \gamma_5)_{ij} [\gamma^\mu, \gamma^\nu] \nu_j + \bar{\nu}_i (C_V^{\nu\nu_s} + C_A^{\nu\nu_s} \gamma_5)_{ij} [\gamma^\mu, \gamma^\nu] \nu_{sj} + \bar{\nu}_{si} (C_V^{\nu_s\nu} + C_A^{\nu_s\nu} \gamma_5)_{ij} [\gamma^\mu, \gamma^\nu] \nu_l + \bar{\nu}_{si} (C_V^{\nu_s\nu_s} + C_A^{\nu_s\nu_s} \gamma_5)_{ij} [\gamma^\mu, \gamma^\nu] \nu_{sj}).$$

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

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

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

↓  
btn LH and RH neutrinos

↓  
dipole interaction between sterile neutrinos

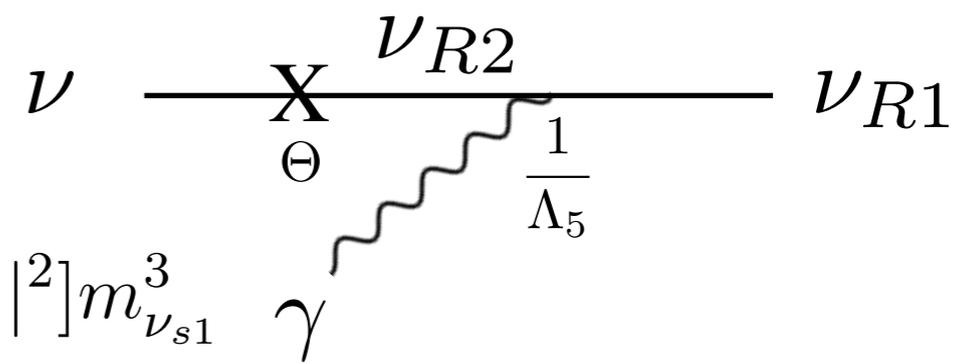
suppressed by  $C_{ij} = \frac{c_{ij}}{\Lambda_5}$

# 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



$$\Gamma(\nu_s \rightarrow \nu \gamma) \simeq \frac{1}{2\pi} c_W^2 \sum_{i=2}^3 [|C_{Vi1}^{\nu\nu_s}|^2 + |C_{Ai1}^{\nu\nu_s}|^2] m_{\nu_{s1}}^3$$

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

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

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

# 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 ignored since their number density is too small

Boltzmann equation

from thermal particles

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

Thermal production from scattering and decay

[Choi, Hwang, Kim, 1999]

$$Y_{ij}^{\text{scat}} = \int_{T_0}^{T_R} dT \frac{\langle \sigma(i+j \rightarrow \tilde{N} + \dots) v_{rel} \rangle n_i n_j}{sHT},$$
$$Y_i^{\text{dec}} = \int_{T_0}^{T_R} dT \frac{\langle \Gamma(i \rightarrow \tilde{N} + \dots) \rangle n_i}{sHT}.$$

# Thermal Production of DM

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

$$Y_{\nu_s}^{TP} = \int_{T_0}^{T_R} \frac{1}{sTH} \langle \sigma v(ij \rightarrow \nu_{s1} X) \rangle n_i n_j dT,$$

and the relic density by

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

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

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

# Thermal Production of DM

The lightest RH neutrino DM can be 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

$$\text{t-channel} \quad f \nu_{sj} \rightarrow f \nu_{si}$$

$$\text{s-channel} \quad f \bar{f} \rightarrow \nu_s \nu_{sj}$$

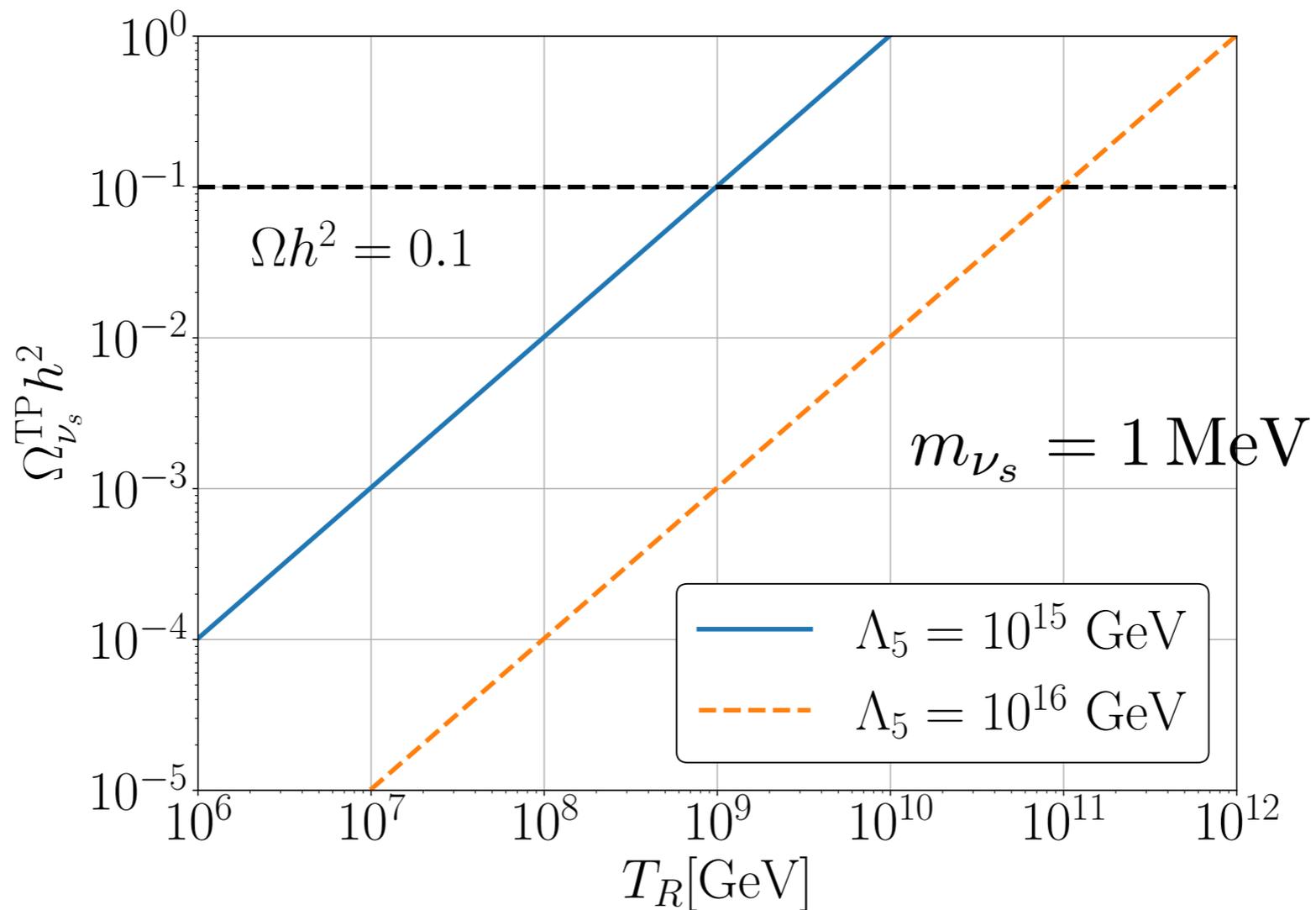
$$\sigma_t \simeq \frac{N_c (Y_f g_Y)^2 c_{1j}^2 g_f g_{\nu_{sj}}}{2\pi \Lambda_5^2} \left[ -2 - (1 + 2m_B^2/s) \log \left( \frac{m_B^2}{s + m_B^2} \right) \right],$$

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

# Thermal Production of DM

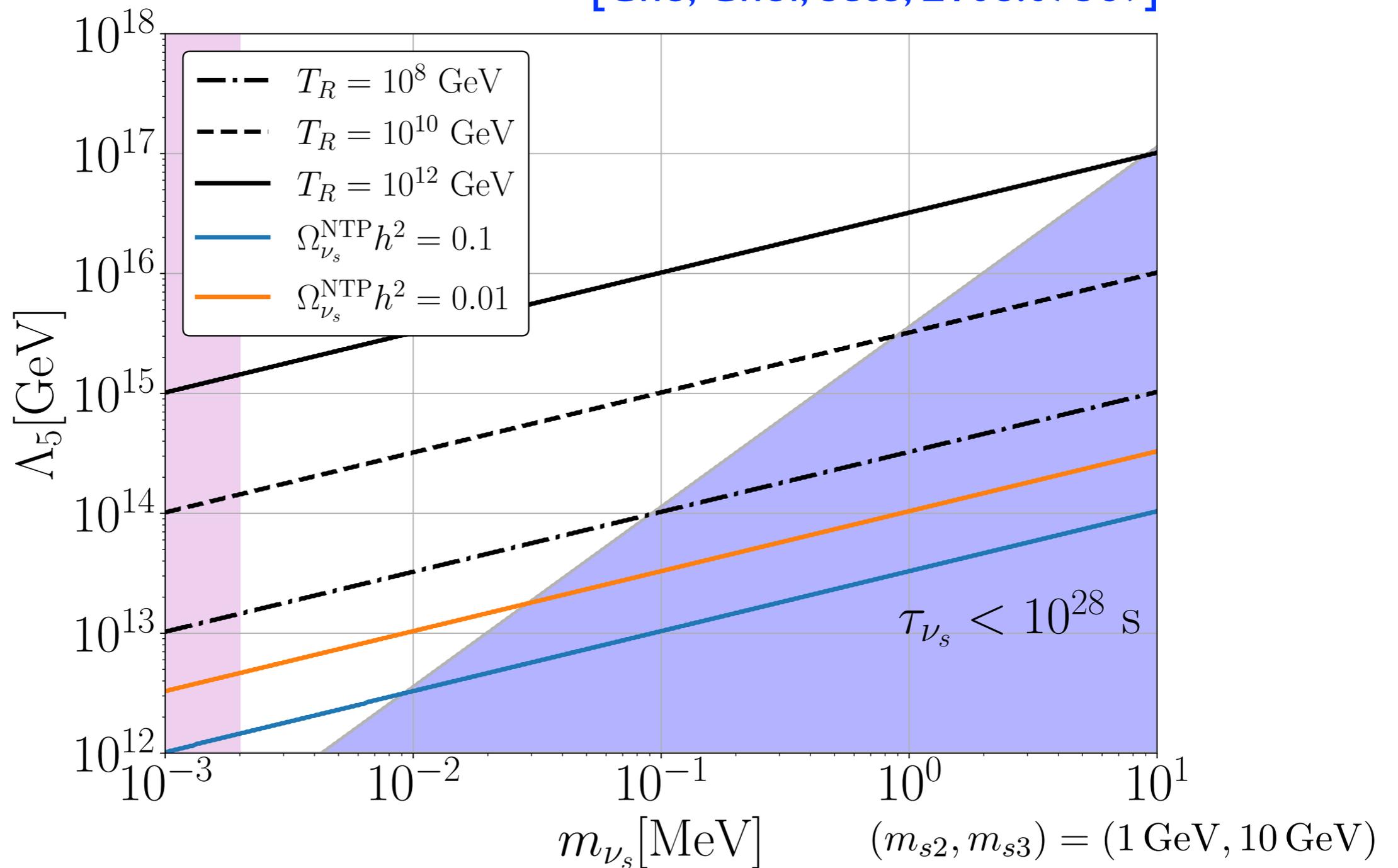
$$\Omega_{\nu_s}^{\text{TP}} h^2 \simeq 0.2 \left( \frac{m_s}{1 \text{ MeV}} \right) \left( \frac{10^{16} \text{ GeV}}{\Lambda_5} \right)^2 \left( \frac{T_R}{10^{11} \text{ GeV}} \right)$$

[Cho, Choi, Seto, 2108.07569]



# Thermal Production of DM

[Cho, Choi, Seto, 2108.07569]



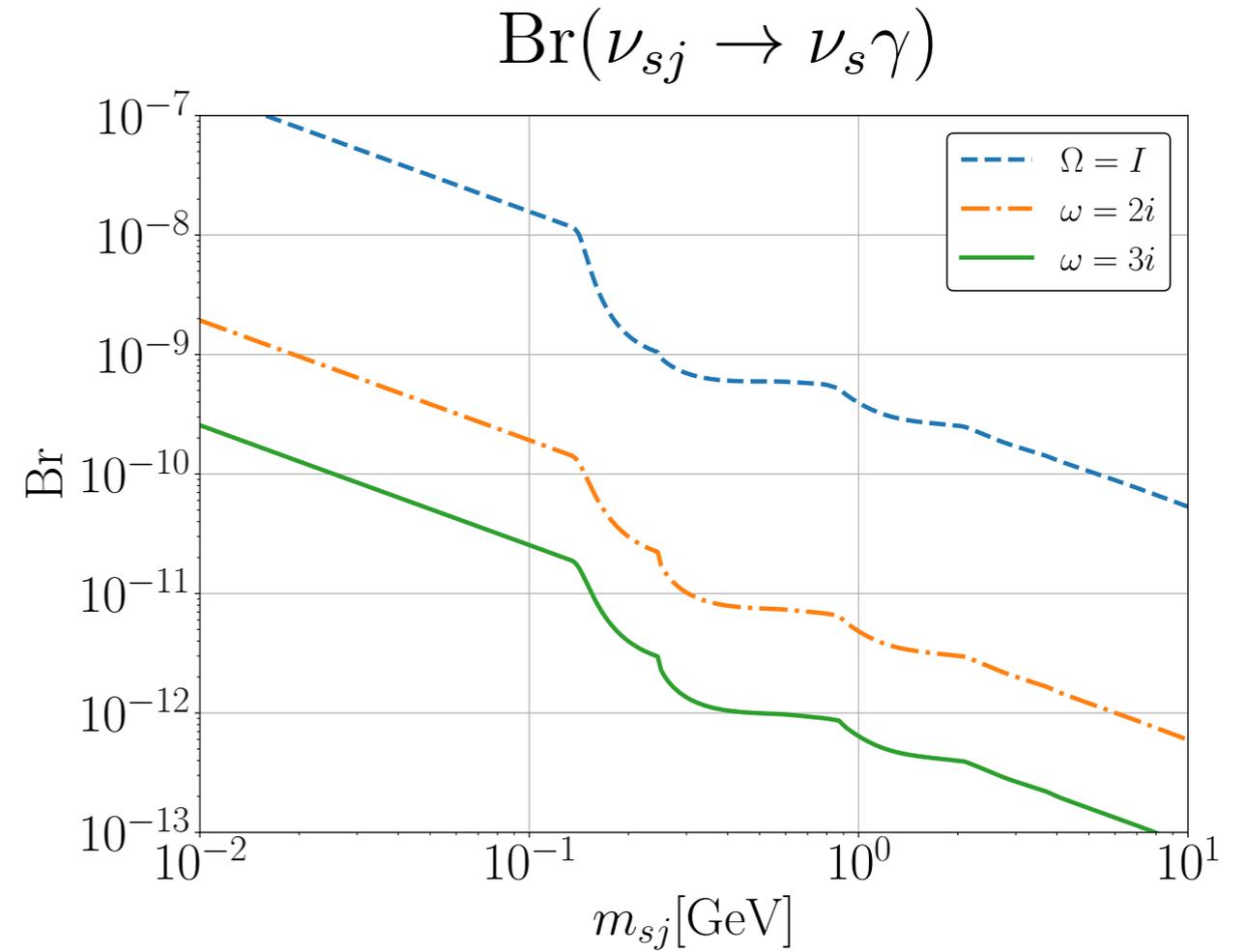
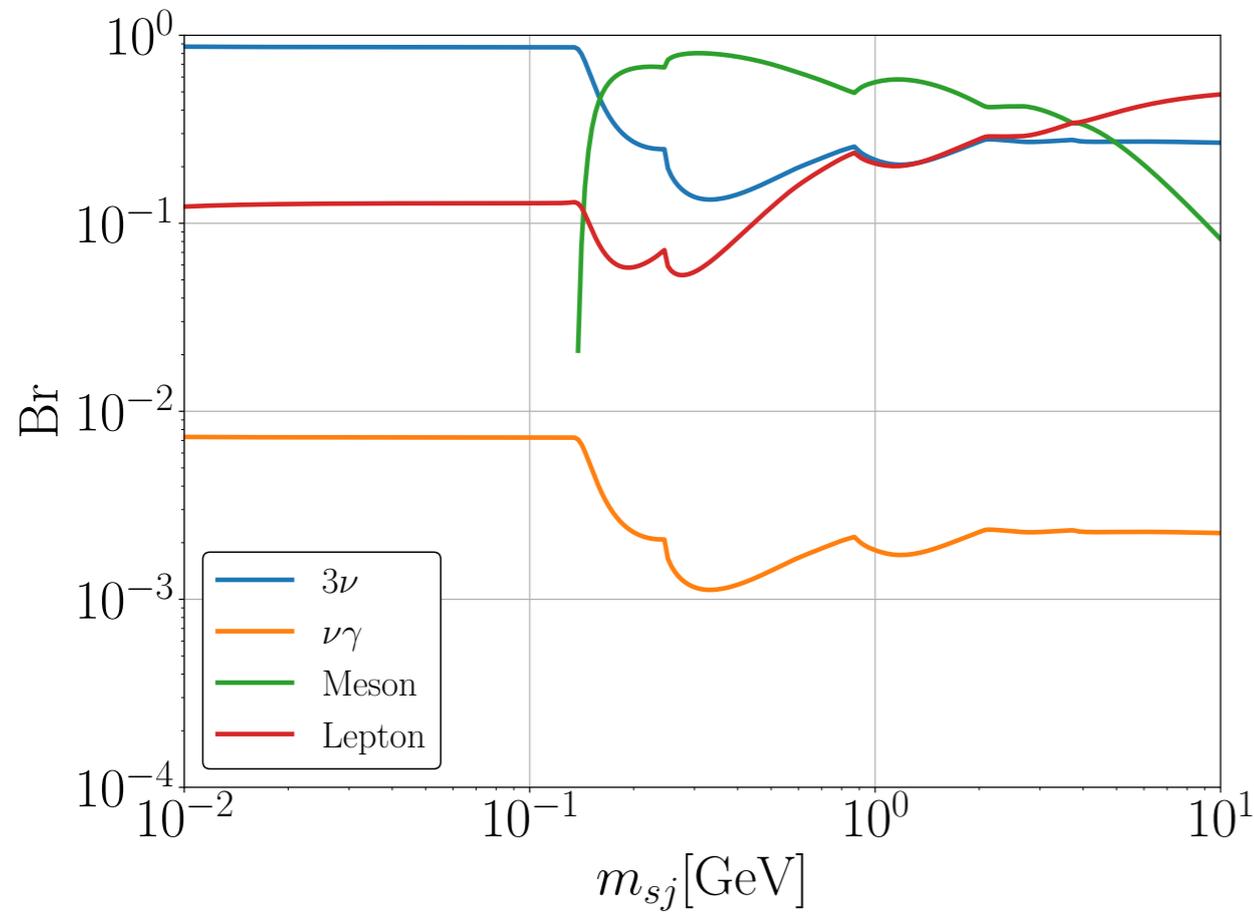
# Non-Thermal Production of DM

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

$$\Omega_{\nu_s}^{\text{NTP}} h^2 = \frac{m_{\nu_s} s_0}{\rho_{\text{crit}}} \sum_{i=2,3} \text{Br}(\nu_{sj} \rightarrow \gamma \nu_s) \times Y_{\nu_{sj}}^{\text{dec}}$$
$$\simeq 1 \times 10^{-6} \left( \frac{m_{\nu_s}}{1 \text{ MeV}} \right) \left( \frac{1 \text{ GeV}}{m_{sj}} \right) \left( \frac{10^{16} \text{ GeV}}{\Lambda_5} \right)^2 \left( \frac{9 \times 10^{-12}}{\sum_{\alpha} |\Theta_{\alpha j}|^2} \right).$$

It is much suppressed compared to that from thermal production.

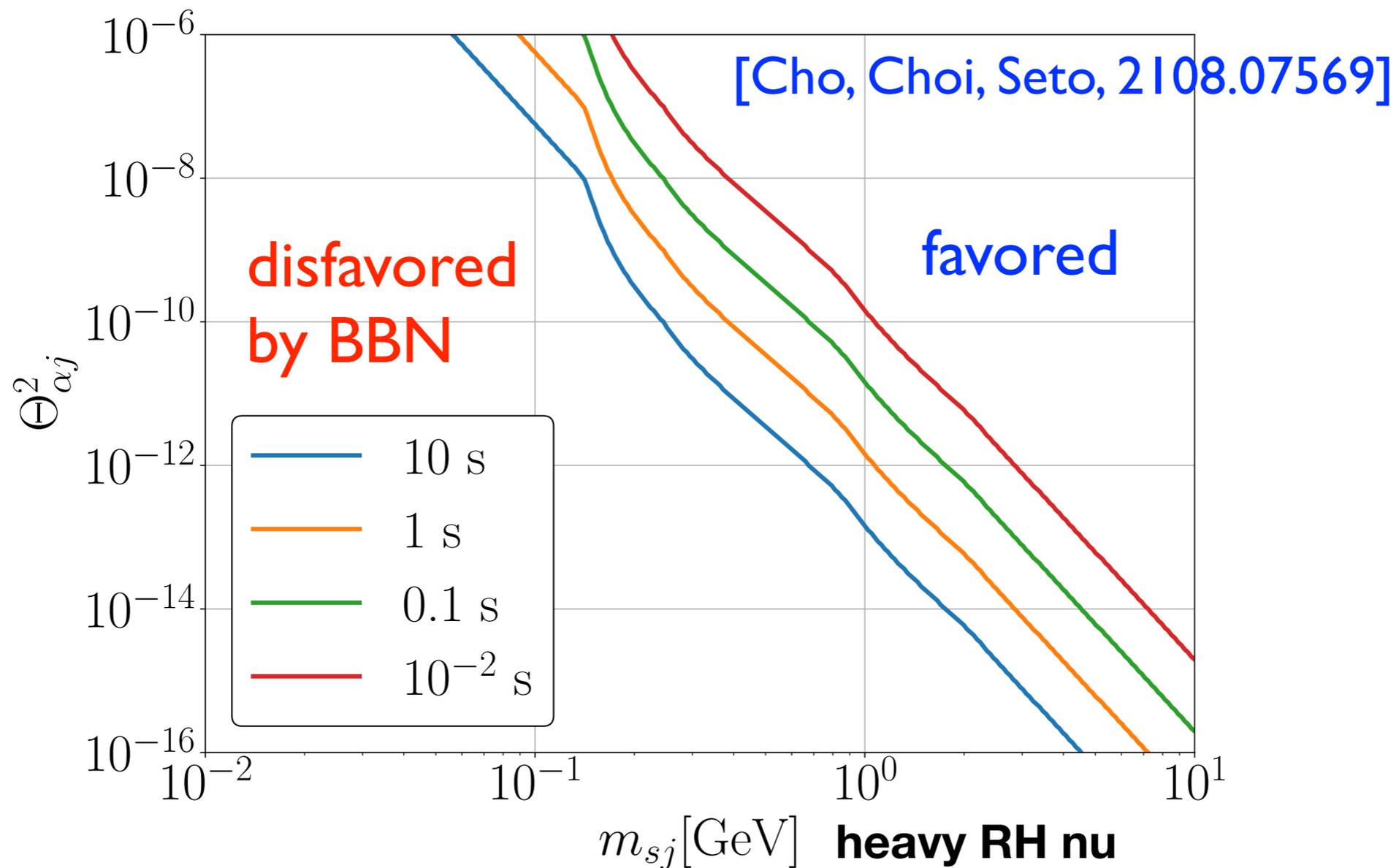
# Decay of heavier RH neutrino



$$\Gamma(\nu_{sj} \rightarrow 3\nu) = \sum_{\alpha,i} \Gamma(\nu_{sj} \rightarrow \nu_{\alpha} \nu_i \bar{\nu}_i) = \frac{G_F^2 m_{sj}^5}{96\pi^3} \sum_{\alpha} |\Theta_{\alpha j}|^2,$$

# Constraints from BBN

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



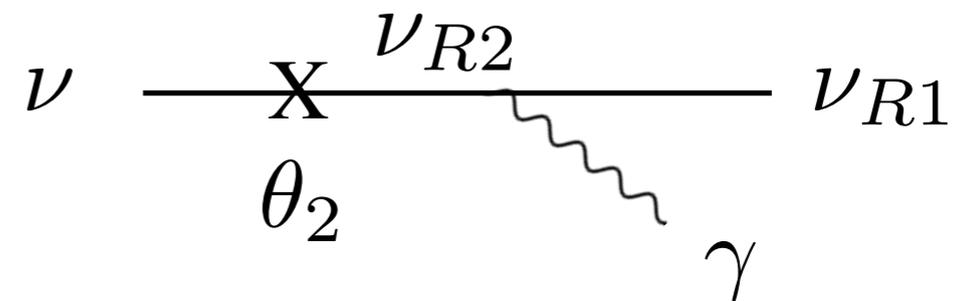
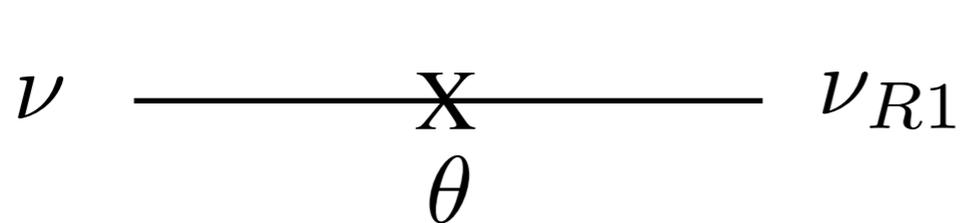
# Summary

## nuMSM

**SM +3 RH neutrinos**  
 $\nu_1, \nu_2, \nu_3$        $\nu_{R1}, \nu_{R2}, \nu_{R3}$   
  
 mixing  $\theta$

## dipole interaction

**Dipole interaction  
 between 3RH neutrinos**  
 $C_{ij} \overline{\nu_{Ri}^c} [\gamma^\mu, \gamma^\nu] \nu_{Rj} B_{\mu\nu}$



**Production and decay of DM (the lightest RH neutrino)**

# 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 - 10 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!**