Sterile neutrino dark matter with dipole interaction

Based on the work with Wonsub Cho, KYChoi, Osamu Seto, in preparation

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Darkness on the table: ideas on tabletop experiments for dark matter/exotic particle search

8-11 August 2021

Contents

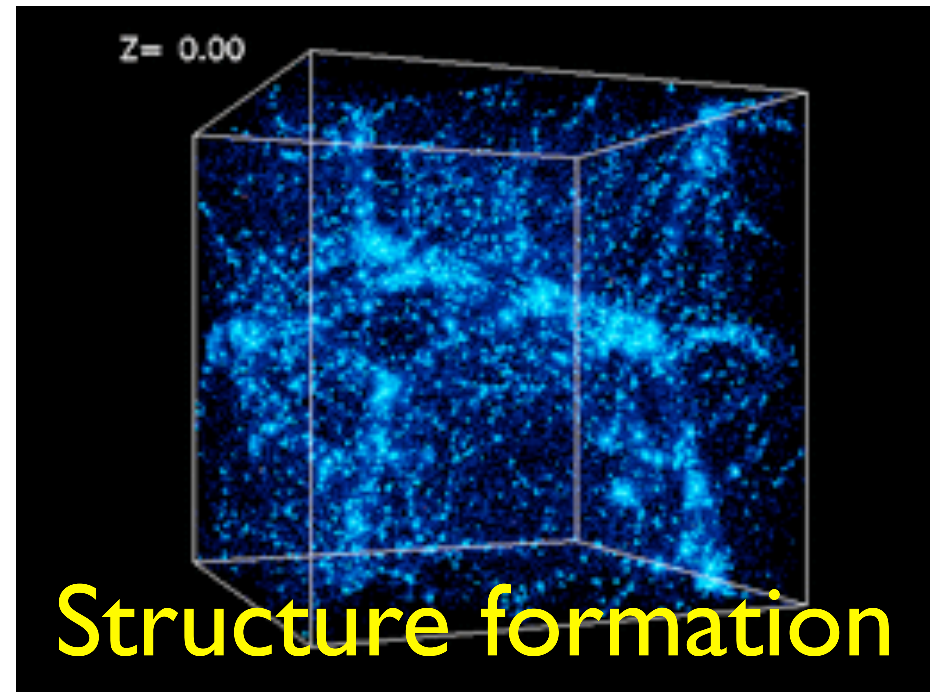
SM + RH neutrinos + dipole interaction

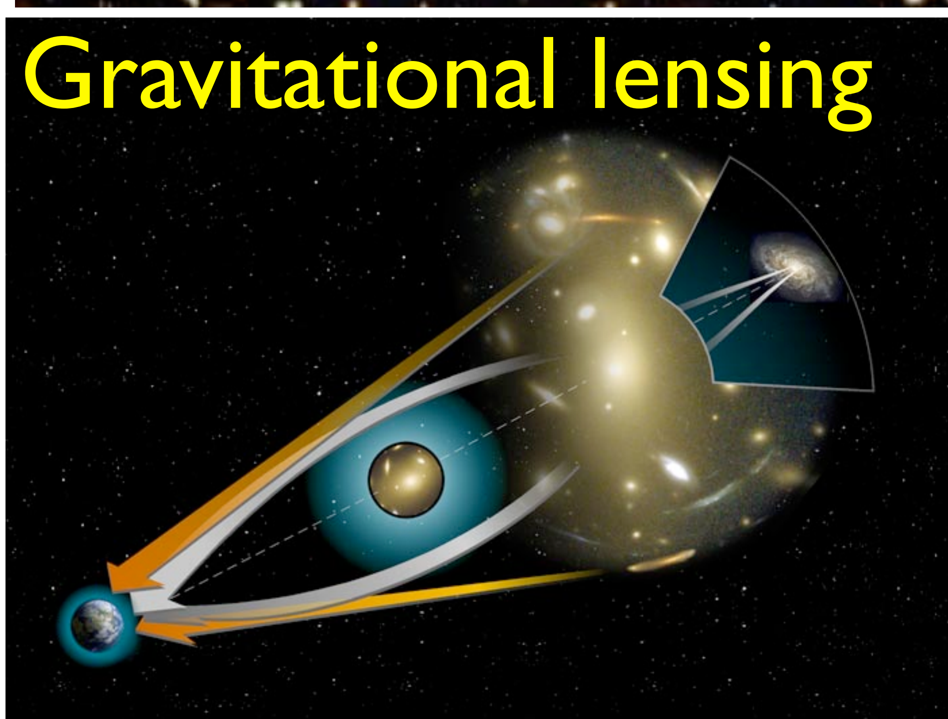
$\Downarrow$

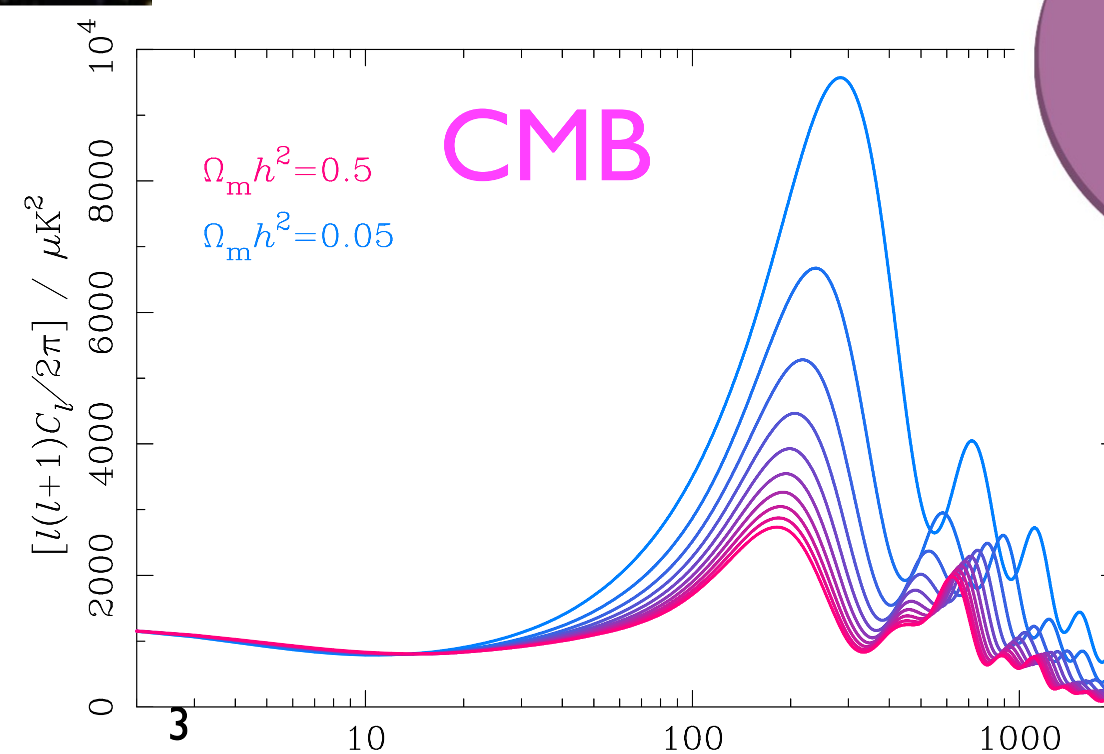
Dark Matter

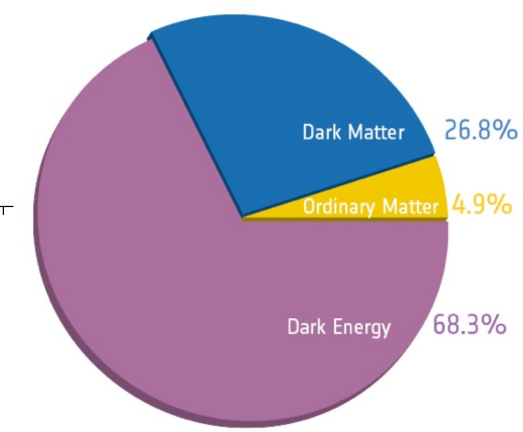
Dark Matter

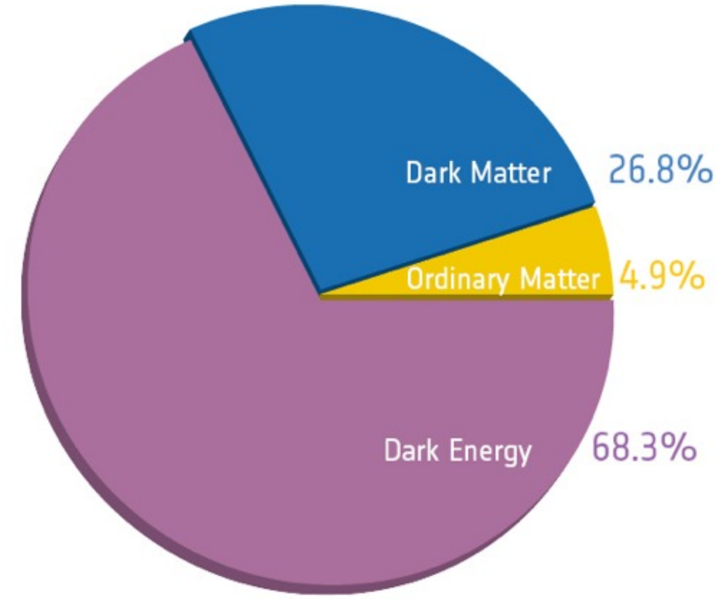

The bullet cluster
Optical X-ray Gas Dark Matter


Z= 0.00
Structure formation


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


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



Dark Matter as a particle must (be)

1. have existed from early Universe up to now and located around galaxies, clusters

➡ stable or lifetime longer than the age of universe

2. neutral : NO electromagnetic interaction

➡ Only upper bounds on the self interaction

$$\sigma/m \lesssim 10^{-24}\ \mathrm{cm}^2/\,\mathrm{GeV}$$ from bullet cluster

No lower bound down to gravity!

In fact all the evidences are gravitational.

3. 25% of the present energy density of the universe

4. cold (or warm) : non-relativistic to seed the structure formation

Candidates of DM

Strong CP problem : axion

Neutrino sector : sterile neutrino, RH neutrino, Majoron

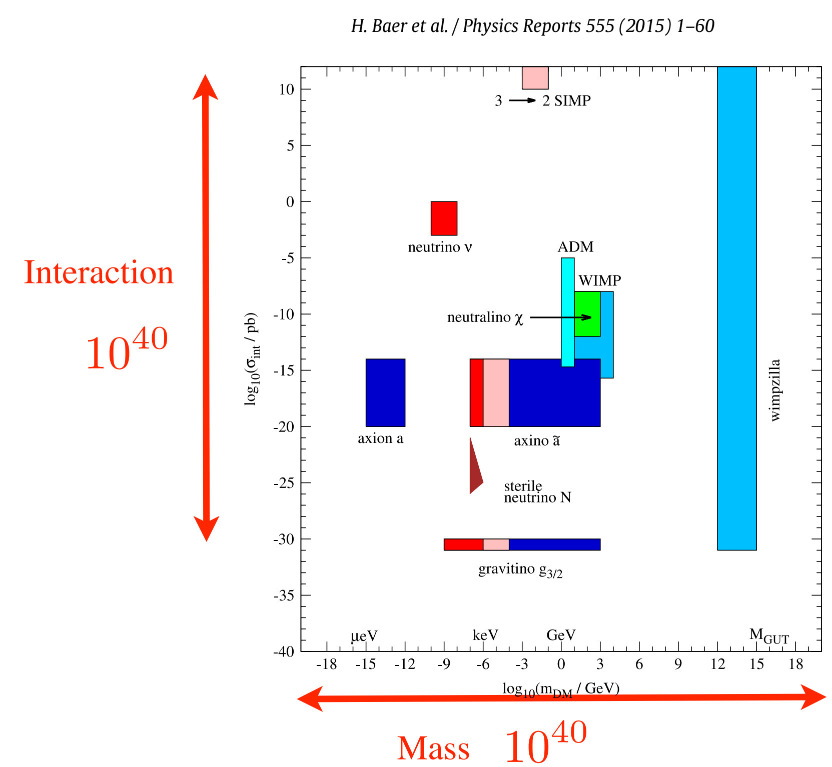
Technicolor : Techni-baryon, Techni-dilaton

Supersymmetry : neutralino, gravitino, axino, scalar neutrino

Extra dimension : Kaluza-Klein particle

and WIMPzillas, primordial Balck-Hole, dilaton

and more ....



Standard Model

List of fundamental particles
and interactions

Higgs

BOSONS

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

Neutrinos neutral and weakly
interacting but massless!

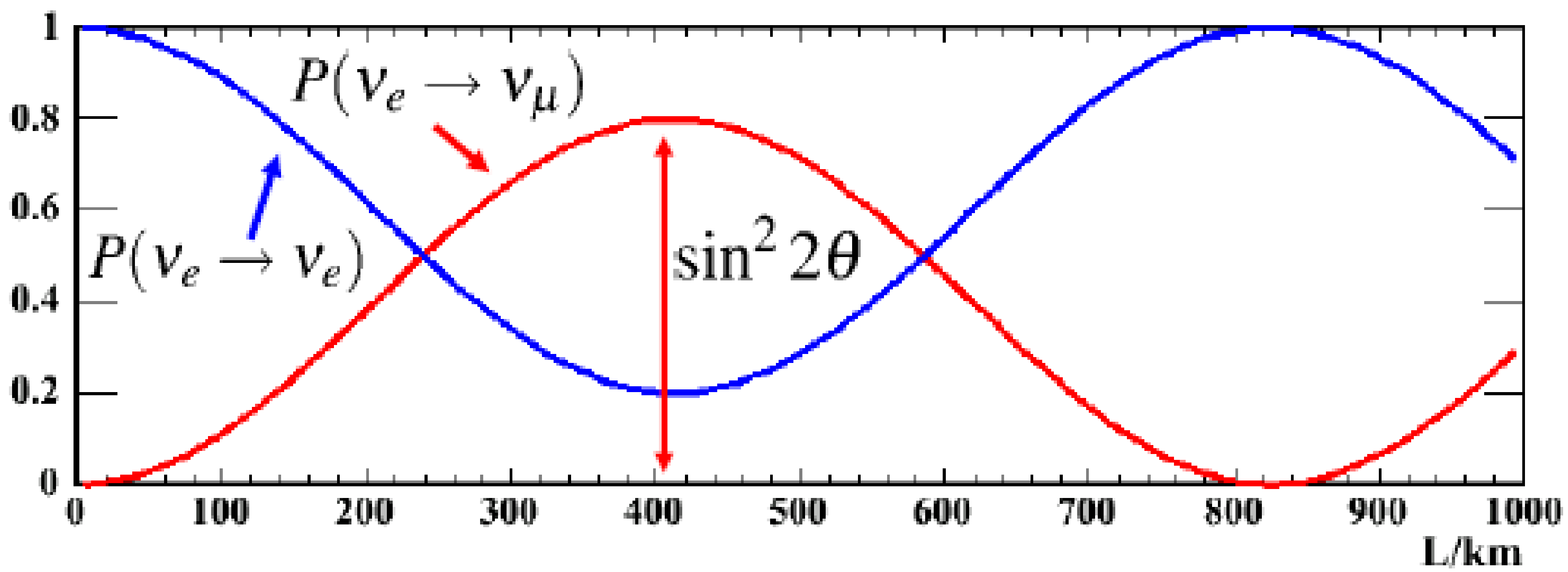
Neutrino Oscillation

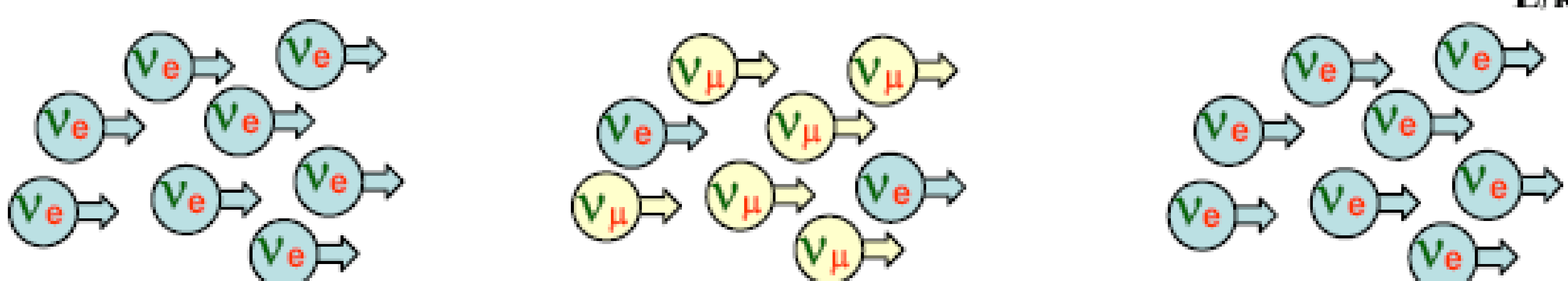
Change of flavors with time

For two-body case, $P(\nu_1 \to \nu_2) = |\langle \nu_2(0)|\nu_1(t)\rangle|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

- e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$

Pure
e-neutrino





Neutrino Oscillation

Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2] = 7.54^{+0.26}_{-0.22}$ solar neutrino $\sin^2\theta_{12} = 0.308 \pm 0.017$

$|\Delta m^2|$ $[10^{-3}\ \mathrm{eV}^2] = 2.43 \pm 0.06$ atm. neutrino $\sin^2\theta_{23} = 0.437^{+0.033}_{-0.023}$

Three masses with two conditions: one is free parameter.

Normal hierarchy

$$m_1 < m_2 < m_3, \quad \Delta m^2_A = \Delta m^2_{31} > 0, \quad \Delta m^2_\odot = \Delta m^2_{21} > 0,$$
$$m_{2(3)} = (m_1^2 + \Delta m^2_{21(31)})^{1/2}.$$

Inverted hierarchy

$$m_3 < m_1 < m_2, \quad \Delta m^2_A = \Delta m^2_{32} < 0, \quad \Delta m^2_\odot = \Delta m^2_{21} > 0,$$
$$m_2 = (m_3^2 + \Delta m^2_{23})^{1/2}, \quad m_1 = (m_3^2 + \Delta m^2_{23} - \Delta m^2_{21})^{1/2}.$$

Neutrino as 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

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

It is too small!

With observational constraints

$$\sum m_\nu < 1.3\,\mathrm{eV} \quad (95\%\, CL)$$ [Komatsu et al., 2011]

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 400 MeV due to exclusion principle It is too light!

Neutrinos become massive!

Dirac neutrino

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

See-saw mechanism

- suppressed mass from the heavy Majorana mass

Radiative mass

- 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)

$(\nu_R)^c \equiv C\,\overline{\nu_R}^T$

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

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

: the light active neutrino and heavy sterile neutrino.

Ki-Young Choi, Sungkyunkwan University, Korea

Sterile Neutrinos and mixing

After electroweak symmetry breaking, the mass eigenstates are

interaction eigenstates

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

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

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

and the light active neutrino mass

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

seesaw mechanism

Ki-Young Choi, Sungkyunkwan University, Korea

Interaction of RH Neutrino

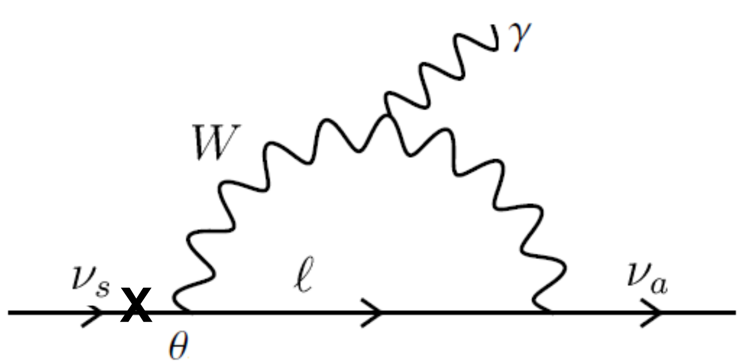
RH sterile neutrinos can interaction with SM sector through

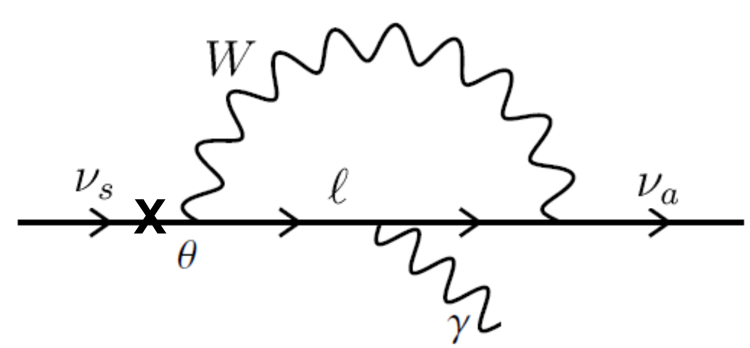
- mass mixing after electroweak symmetry breaking

-Yukawa interaction with Higgs and LH neutrino

The interactions induce

- Decay of sterile neutrino DM: X-ray signal





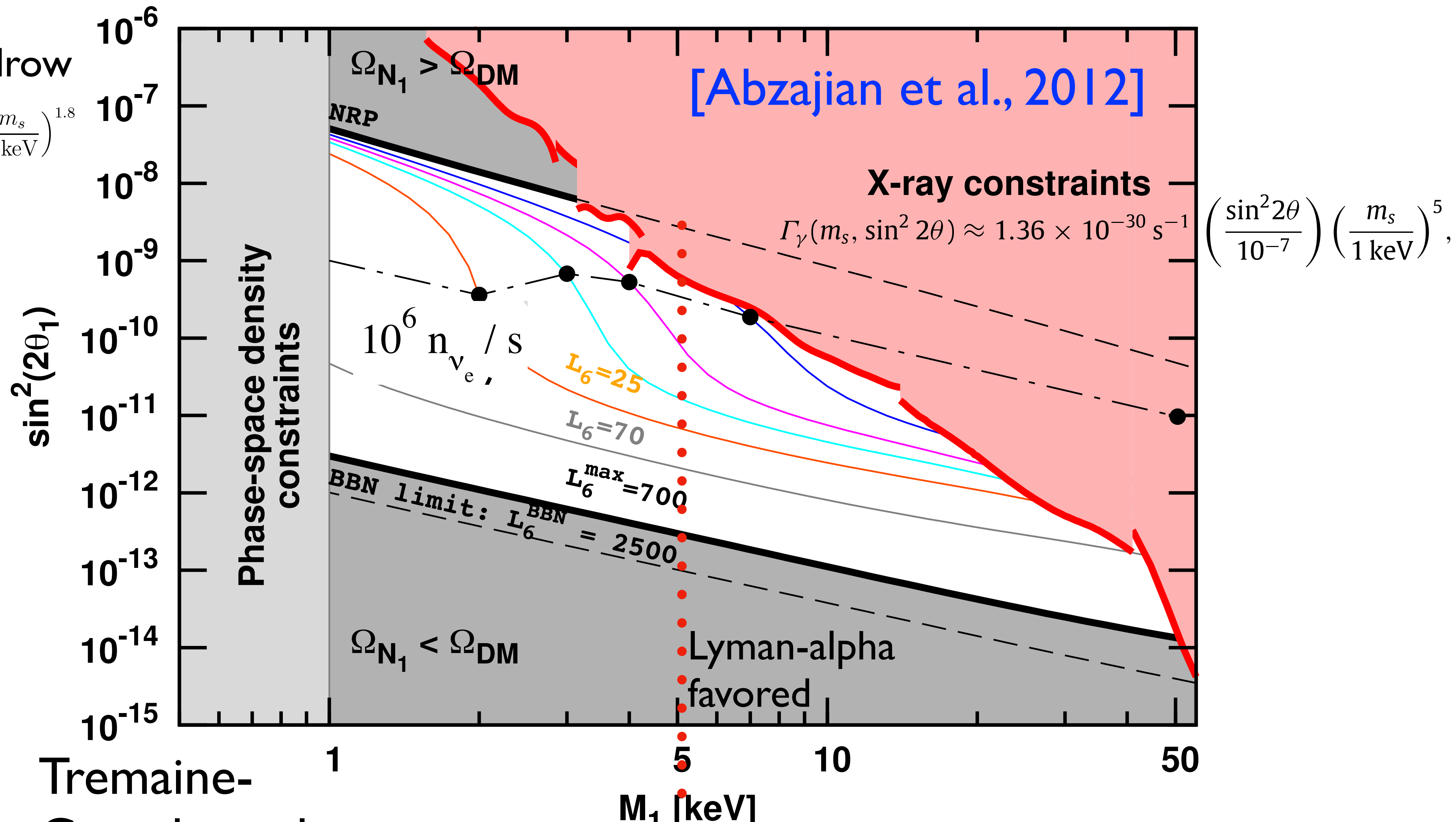
Sterile Neutrino DM in the nuMSM

To explain the mass-squared difference observed in the neutrino oscillation, only 2 RH neutrino are required. So the 3rd RH neutrino mass can be light and candidate dark matter. [Asaka et al., 2005]

Dodelson-Widrow

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

Shi-Fuller with Lepton asymmetry



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

Theoretical study on the neutrino magnetic moment

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

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

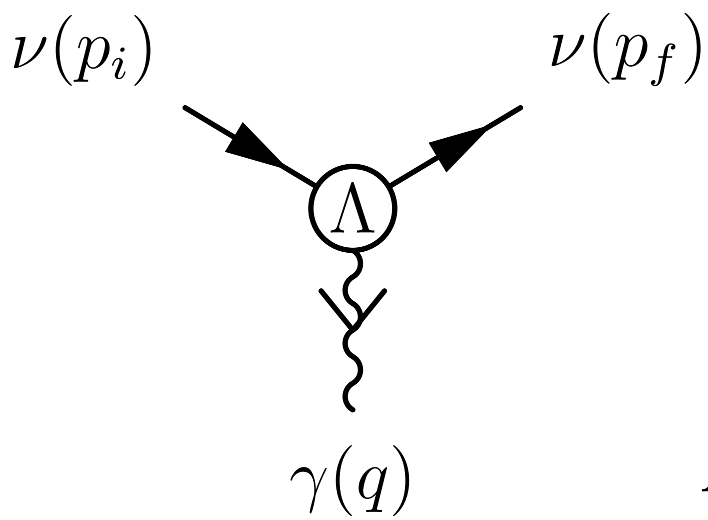
[Pal, Wolfenstein, 1982] [Shrock, 1982] [Bilenky, Fetcov, 1987]

……..

[44] J. Bernstein and T. D. Lee, Phys. Rev. Lett. **11** (1963), 512-516 doi:10.1103/PhysRevLett.11.512

Dirac Neutrino Magnetic Form Factor

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



(b)

$$\langle \nu(p_f)|j_\mu^{(\nu)}(0)|\nu(p_i)\rangle = \overline{u}(p_f)\Lambda_\mu(p_f,p_i)u(p_i).$$

charge magnetic electric dipole

$$\Lambda_\mu(q) = \mathbb{f}_Q(q^2)\gamma_\mu - \mathbb{f}_M(q^2)i\sigma_{\mu\nu}q^\nu + \mathbb{f}_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + \mathbb{f}_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5, \qquad (3.18)$$

anapole

At the zero momentum of photon,

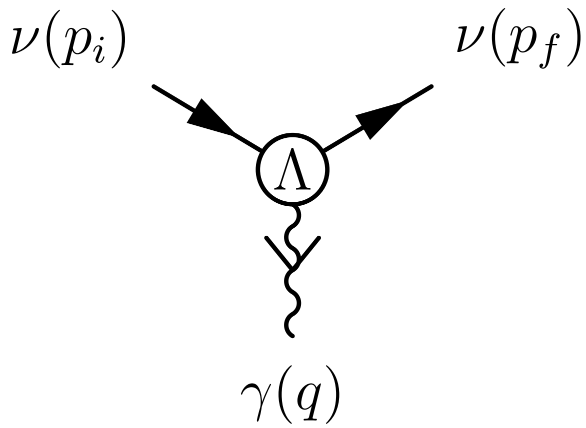
$$\mathbb{f}_Q(0) = \mathbb{q}, \quad \mathbb{f}_M(0) = \mathbb{\mu}, \quad \mathbb{f}_E(0) = \mathbb{e}, \quad \mathbb{f}_A(0) = \mathbb{a},$$

charge magnetic electric moment anapole moment (toroidal dipole moment)

Only EDM violates CP.

Dirac Neutrino Magnetic Form Factor with flavors

Review [Giunti, Studenikin, 1403.6344]



(b)

$$\Lambda_{\mu}^{fi}(q) = \left(\gamma_{\mu} - q_{\mu}\not{q}/q^2\right)\left[\mathbb{f}_Q^{fi}(q^2) + \mathbb{f}_A^{fi}(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^{\nu}\left[\mathbb{f}_M^{fi}(q^2) + i\mathbb{f}_E^{fi}(q^2)\gamma_5\right], \qquad (3.35)$$

$$\mathbb{f}_{\Omega}^{fi} = (\mathbb{f}_{\Omega}^{if})^{*} \qquad (\Omega = Q, M, E, A).$$

At the zero momentum of photon,

$$\mathbb{f}_Q^{fi}(0) = \mathbb{q}_{fi},\ \mathbb{f}_M^{fi}(0) = \mathbb{\mu}_{fi},\ \mathbb{f}_E^{fi}(0) = \mathbb{e}_{fi},\ \mathbb{f}_A^{fi}(0) = \mathbb{a}_{fi},$$

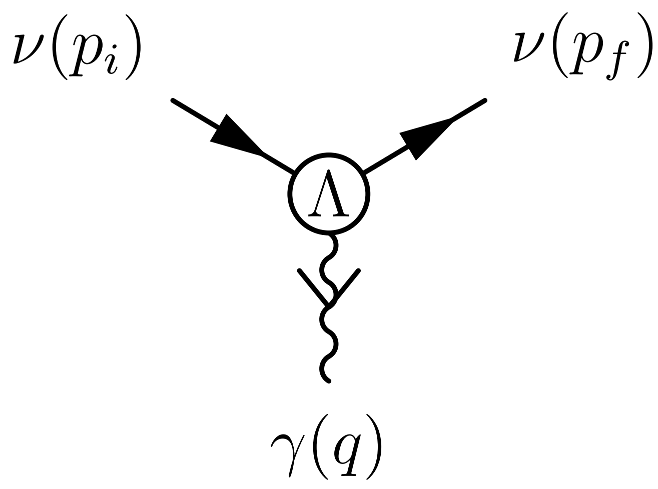
charge magnetic electric moment anapole moment

There are diagonal and off-diagonal (transition) types.

CP invariance

$$\mathrm{CP} \quad \Longleftrightarrow \quad \begin{cases} \mathbb{f}_{\Omega} = \mathbb{f}_{\Omega}^{\mathrm{T}} = \mathbb{f}_{\Omega}^{*} & (\Omega = Q, M, A), \\ \mathbb{f}_E = -\mathbb{f}_E^{\mathrm{T}} = -\mathbb{f}_E^{*}. \end{cases}$$

Majorana Neutrino Form Factor



(b)

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

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

For Majorana neutrinos,

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

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

Majorana neutrinos have only transition dipole moment.

Dipole Moment of RH Neutrinos

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

$U(1)_Y$ gauge field B_μ in the SM

We consider [Aparici etal, 0904.3244]

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

RH Majorana mass Yukawa coupling magnetic moment

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

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

dim-5 operator from new physics

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

We don't consider Dirac dipole operator, since it is dim-6 operator

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

Dipole Moment of RH Neutrino DM

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

$U(1)_Y$ gauge field B_μ in the SM

We consider [Cho, Choi, Seto, in preparation]

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

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

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

dim-5 operator from new physics

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We don't consider Dirac dipole operator, since it is dim-6 operator

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

Sterile Neutrino DM

To explain the mass-squared difference observed in the neutrino oscillation, only 2 RH neutrino are required. So the 3rd RH neutrino mass can be light and candidate dark matter. [Asaka et al., 2005]

In this case, the lightest active neutrino mass is effectively zero, and the Yukawa coupling can be written as

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

DM has no mixing with active neutrinos

with the relation

[Casas, Ibarra, 2001]

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

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

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

To be Dark Matter

Lifetime is long enough

Amount of present relic density

Other constraints

Lagrangian in the mass eigenstates

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

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

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

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

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

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

dipole interaction between sterile neutrinos

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

Stability of RH neutrino DM

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 [Cho, Choi, Seto, in preparation]

$$\Gamma(\nu_s \to \nu\gamma) \simeq \frac{1}{2\pi} c_W^2 \sum_{i=2}^{3} [|C_{Vi1}^{\nu\nu_s}|^2 + |C_{Ai1}^{\nu\nu_s}|^2] m_{\nu_{s1}}^3$$
$$\sim \frac{1}{10^{28}\,\mathrm{sec}} \left(\frac{10^{15}\,\mathrm{GeV}}{\Lambda_5}\right)^2 \left(\frac{|\Theta|}{10^{-6}}\right)^2 \left(\frac{m_{\nu_s}}{1\,\mathrm{MeV}}\right)^3.$$

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

It means large scale of new physics, and no constraints or signals from collider or astrophysics.

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 small, but small amount is produced, which is similar to that of FIMP.

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 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

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

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

Thermal Production of DM

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

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

and the relic density by

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

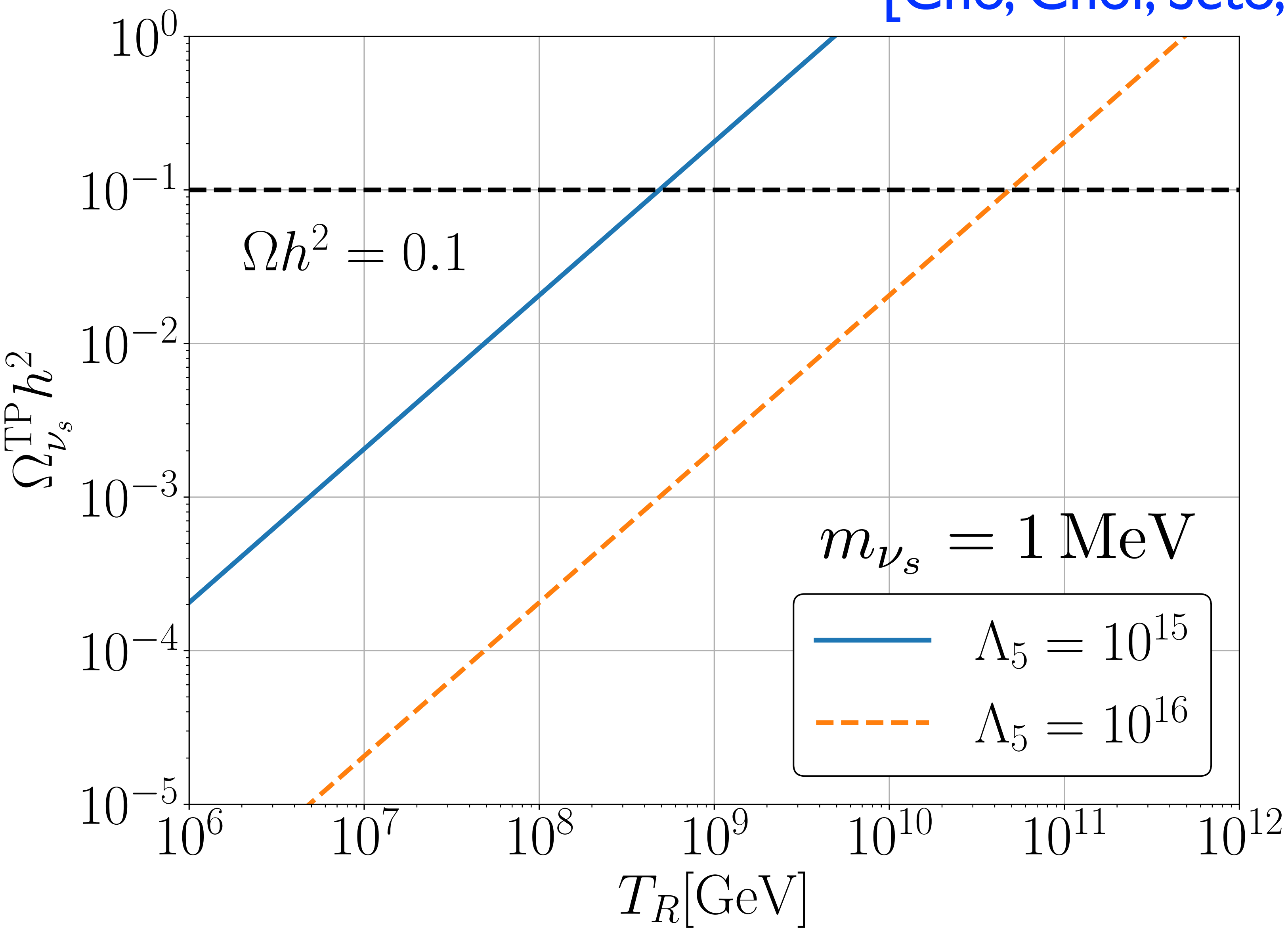
$s_0 = \frac{2\pi^2}{45} \times 3.91 \times T_0^3 \qquad (\rho_{\rm crit}/s_0)^{-1} = 2.8 \times 10^8/{\rm GeV}$

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

Thermal Production of DM

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

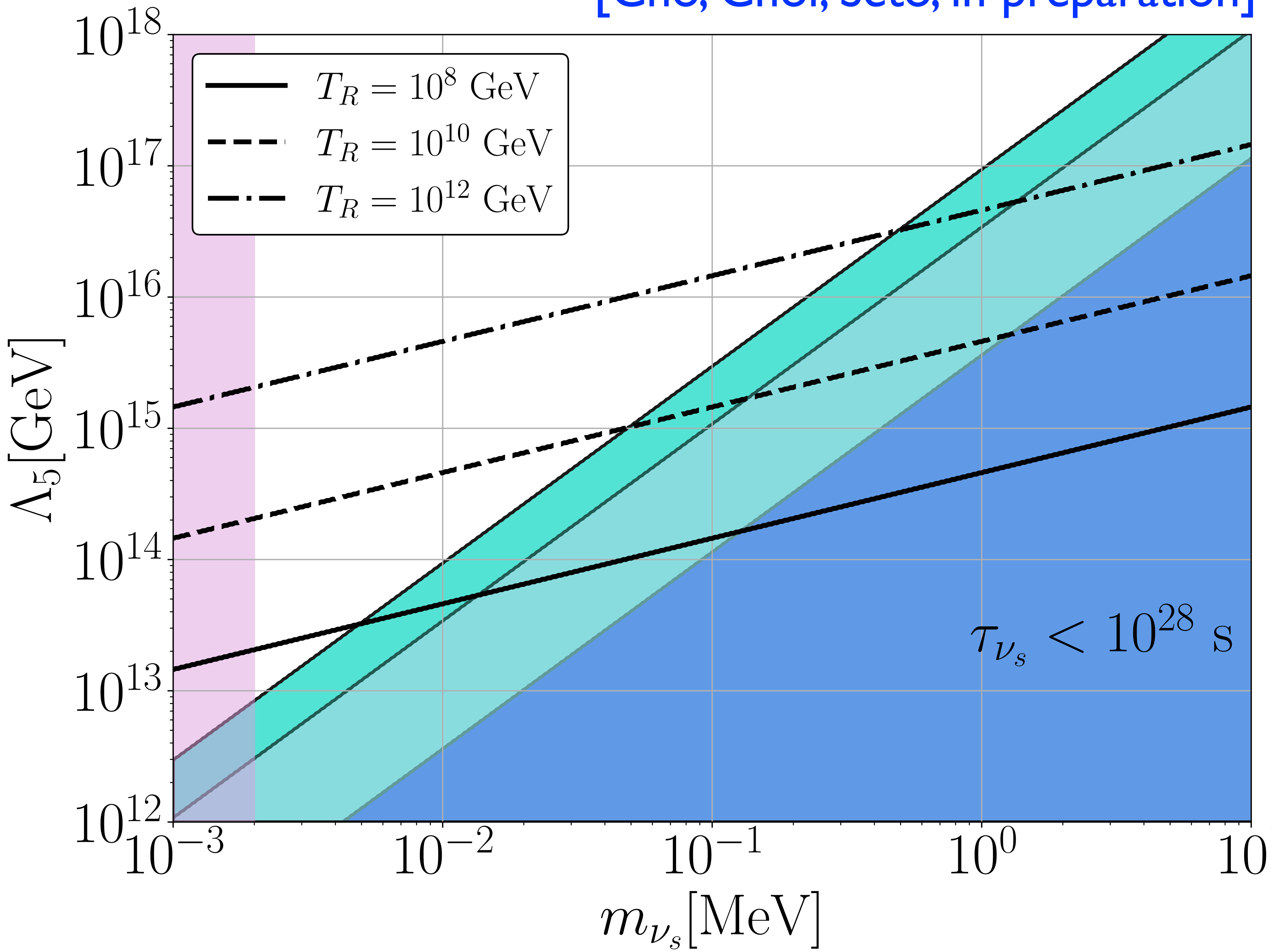
[Cho, Choi, Seto, in preparation]



Ki-Young Choi, Sungkyunkwan University, Korea

Thermal Production of DM

[Cho, Choi, Seto, in preparation]



Non-Thermal Production of DM

The lightest RH neutrino DM is produced from the decay of the heavier RH neutrinos

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

$$\simeq 2 \times 10^{-9} \left(\frac{m_s}{1\,{\rm MeV}}\right) \left(\frac{1\,{\rm GeV}}{m_{sj}}\right) \left(\frac{10^{16}\,{\rm GeV}}{\Lambda_5}\right)^2 \left(\frac{6 \times 10^{-9}}{\sum_\alpha |\Theta_{\alpha j}|^2}\right).$$

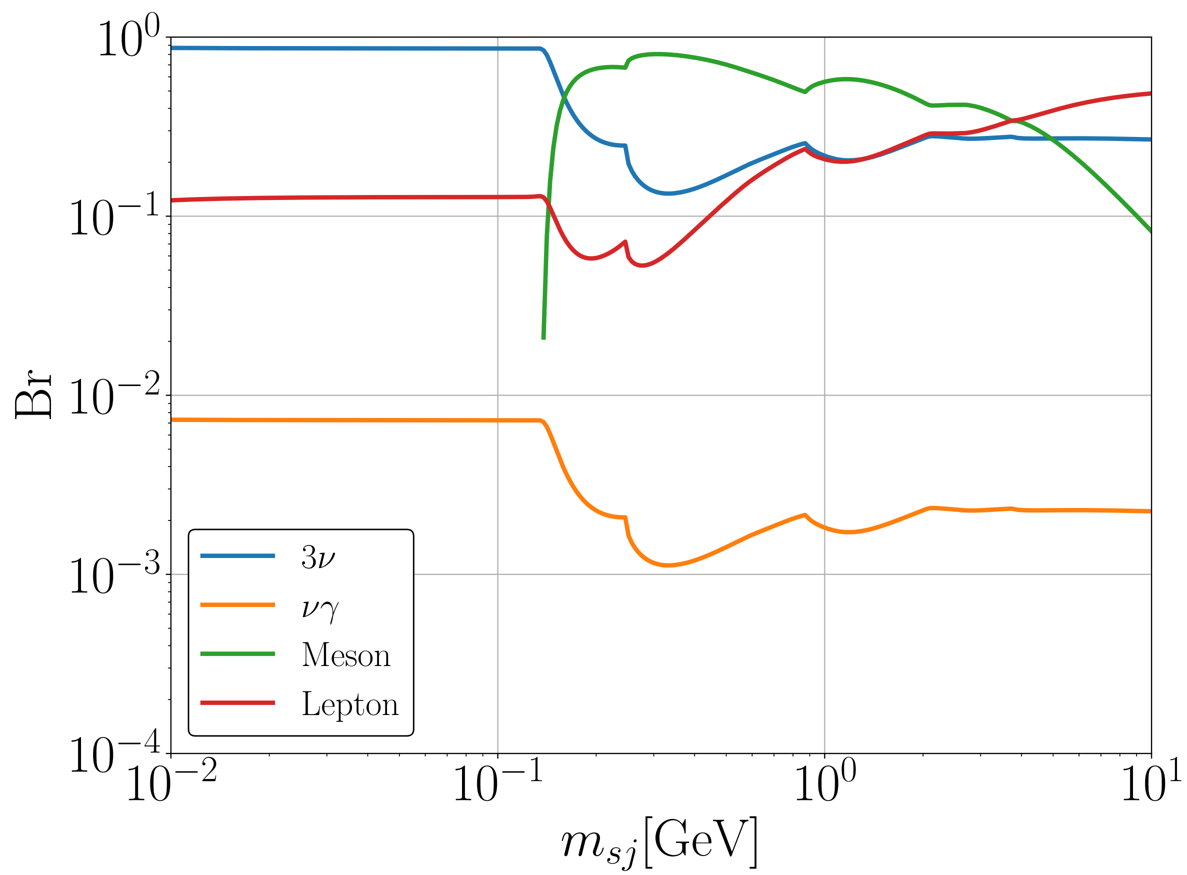
It is much suppressed compared to that from thermal production.

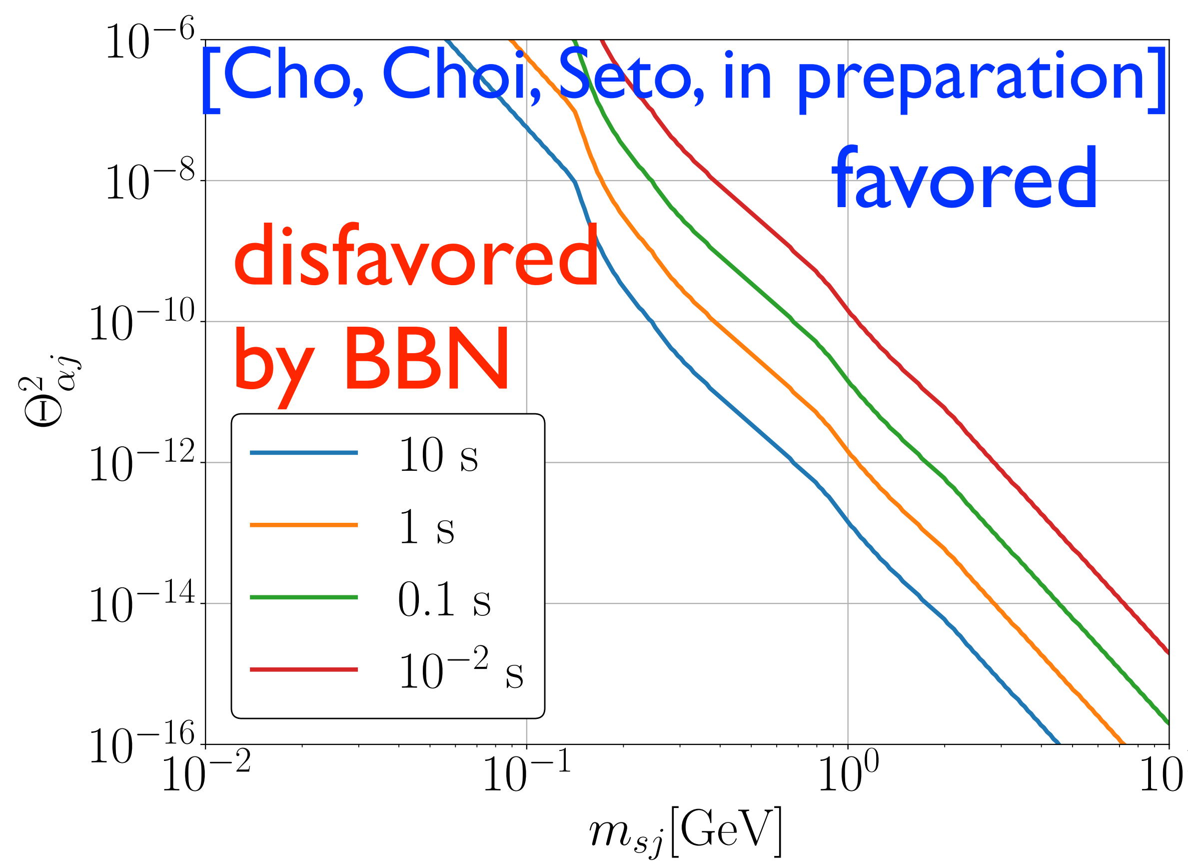
Ki-Young Choi, Sungkyunkwan University, Korea

Constraints from BBN

[Atre etal, 0901.3589]

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





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

Summary

- Neutrino mass and dark matter

SM + RH neutrinos + dipole interaction

nuMSM **dim-5 from new physics**

$\downarrow$

Dark Matter

- Production of RH neutrino dark matter

: thermal (scattering) + non-thermal

- 10 keV - 100 MeV mass cold dark matter, with GUT scale new physics
- Reheating temperature around 10^10 GeV
- No constraint from the structure formation
- Constraint and possible signal from X-ray or Gamma-ray

Thank You!