Dark Matter in Lmu-Ltau Extensions of the Standard Model

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Who can be a DM candidate

- Should be massive
- Should be electrically neutral
- Should be present in the early universe
- Should be stable or at least with half life greater than the age of the universe
- Should be non-relativistic

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singlet scalar

singlet fermion

scalar in doublet repn

fermion in doublet repn

scalar in triplet repn

fermion in triplet repn

…and many more

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Who can be a DM candidate

- Should be massive
- Should be electrically neutral
- Should be present in the early universe
- Should be stable or at least with half life greater than the age of the universe

need a symmetry

- Should be non-relativistic when it's abundance freezes

singlet scalar

singlet fermion

scalar in doublet repn

fermion in doublet repn

scalar in triplet repn

fermion in triplet repn

…and many more

Your BSM model should explain all observations

neutrino mass

neutrino mixing

muon (g-2)

baryon asymmetry

flavor anomalies

inflation

dark energy

He,Joshi,Lew,Volkas PRD 43 and 44 (1991)

Ma, Roy, Roy, PLB 525 (1991)

$U(1)_{L_\mu - L_\tau}$ to explain muon (g-2) DM and neutrino mass

SC, Rodejohann EPJC 40 (2005)

Biswas, SC, Khan JHEP 1609 (2016)
Biswas, SC, Khan JHEP 1702 (2017)

new particles

Gauge Group	Baryon Fields			Lepton Fields			Scalar Fields		
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	$\boxed{N_R^i}$	ϕ_h	$\boxed{\phi_H}$	$\boxed{\phi_{DM}}$
$SU(2)_L$	2	1	1	2	1	1	2	1	1
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	1/2	0	0

Gauge Group	Baryonic Fields	Lepton Fields			Scalar Fields		
	(Q_L^i, u_R^i, d_R^i)	(L_L^e, e_R, N_R^e)	$(L_L^\mu, \mu_R, N_R^\mu)$	$(L_L^\tau, \tau_R, N_R^\tau)$	ϕ_h	ϕ_H	ϕ_{DM}
$U(1)_{L_\mu - L_\tau}$	0	0	1	−1	0	1	$n_{\mu\tau}$

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{DM} + (D_\mu \phi_H)^\dagger (D^\mu \phi_H) - V(\phi_h, \phi_H) - \frac{1}{4} F^{\alpha\beta}_{\mu\tau} F_{\mu\tau\,\alpha\beta}$$

$$\begin{aligned}\mathcal{L}_N = & \sum_{i=e,\mu,\tau} \frac{i}{2} \bar{N}_i \gamma^\mu D_\mu N_i - \frac{1}{2} M_{ee} \bar{N}^c_e N_e - \frac{1}{2} M_{\mu\tau} (\bar{N}^c_\mu N_\tau + \bar{N}^c_\tau N_\mu) \\ & - \frac{1}{2} h_{e\mu} (\bar{N}^c_e N_\mu + \bar{N}^c_\mu N_e) \phi^\dagger_H - \frac{1}{2} h_{e\tau} (\bar{N}^c_e N_\tau + \bar{N}^c_\tau N_e) \phi_H \\ & - \sum_{i=e,\mu,\tau} y_i \bar{L}_i \tilde{\phi}_h N_i + h.c.\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{DM} = & (D^\mu \phi_{DM})^\dagger (D_\mu \phi_{DM}) - \mu^2_{DM} \phi^\dagger_{DM} \phi_{DM} - \lambda_{DM} (\phi^\dagger_{DM} \phi_{DM})^2 \\ & - \lambda_{Dh} (\phi^\dagger_{DM} \phi_{DM})(\phi^\dagger_h \phi_h) - \lambda_{DH} (\phi^\dagger_{DM} \phi_{DM})(\phi^\dagger_H \phi_H) \,.\end{aligned}$$

$$V(\phi_h, \phi_H) = \mu^2_H \phi^\dagger_H \phi_H + \lambda_H (\phi^\dagger_H \phi_H)^2 + \lambda_{hH} (\phi^\dagger_h \phi_h)(\phi^\dagger_H \phi_H)$$

$$D_\nu X = (\partial_\nu + i\, g_{\mu\tau}\, Q_{\mu\tau}(X)\, Z_{\mu\tau\,\nu})\, X \qquad F^{\alpha\beta}_{\mu\tau} = \partial^\alpha Z^\beta_{\mu\tau} - \partial^\beta Z^\alpha_{\mu\tau}.$$

gauge coupling

$L_\mu - L_\tau$ charge

Φ_H *or* Φ_{DM}

$L_\mu - L_\tau$ symmetry breaks spontaneously when ϕ_H acquires VEV

$\mu_h^2 < 0,\ \ \mu_H^2 < 0$ and $\mu_{DM}^2 > 0$ → ground state is defined as $\langle \phi_h \rangle = \frac{v}{\sqrt{2}},\ \langle \phi_H \rangle = \frac{v_{\mu\tau}}{\sqrt{2}}$ and $\langle \phi_{DM} \rangle = 0$

$$\phi_h = \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}, \qquad \phi_H = \left(\frac{v_{\mu\tau} + H_{\mu\tau}}{\sqrt{2}} \right)$$

$$\begin{aligned} h_1 &= H\cos\alpha + H_{\mu\tau}\sin\alpha\,, \\ h_2 &= -H\sin\alpha + H_{\mu\tau}\cos\alpha\,. \end{aligned}$$

- Because of our choice of $n_{\mu\tau}$ the $U(1)_{L_\mu - L_\tau}$ breaks into a residual Z2 symmetry which makes the dark matter stable.

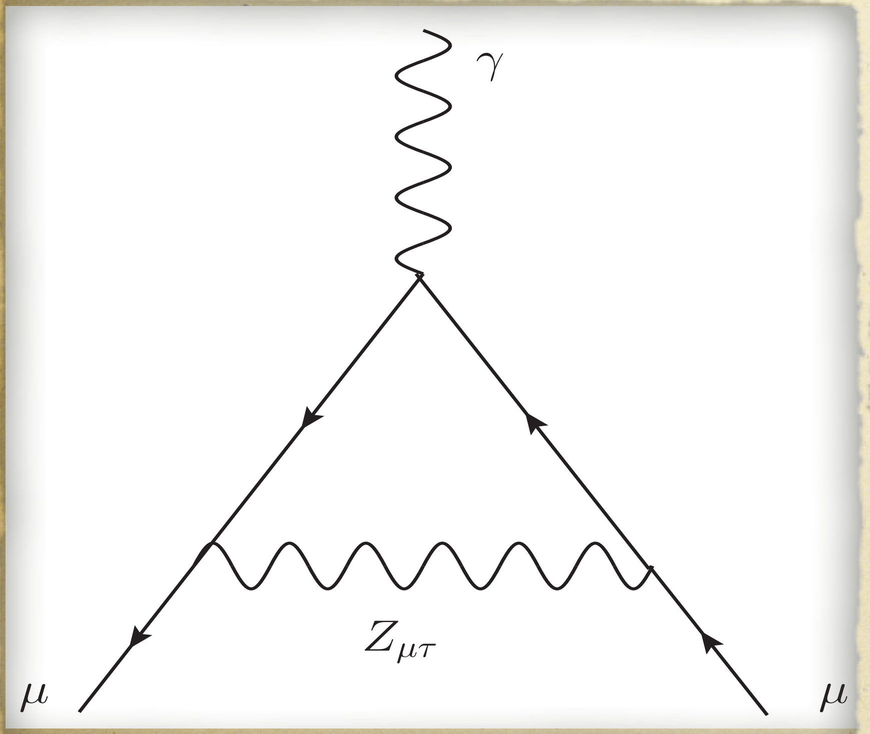
Muon (g-2)

Ma, Roy, Roy, PLB 525 (1991)

$$a_\mu^{\rm th} = 1.1659179090(65) \times 10^{-3}$$

$$a_\mu^{\rm exp} = 1.16592080(63) \times 10^{-3}$$

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm th} = (29.0 \pm 9.0) \times 10^{-10}$$



$$\Delta a_\mu(Z_{\mu\tau}) = \frac{g_{\mu\tau}^2}{8\pi^2}\int_0^1 dx \frac{2x(1-x)^2}{(1-x)^2 + rx}$$

$$r = (M_{Z_{\mu\tau}}/m_\mu)^2$$

for $M_{Z_{\mu\tau}} = 100$ MeV and $g_{\mu\tau} = 9 \times 10^{-4}$ the value of $\Delta a_\mu = 22.6 \times 10^{-10}$

Neutrino Masses and Mixing

$$\mathcal{L}_N = \sum_{i=e,\,\mu,\,\tau} \frac{i}{2}\bar{N}_i\gamma^\mu D_\mu N_i - \frac{1}{2}M_{ee}\,\bar{N}_e^c N_e - \frac{1}{2}M_{\mu\tau}\,(\bar{N}_\mu^c N_\tau + \bar{N}_\tau^c N_\mu)$$
$$-\frac{1}{2}h_{e\mu}(\bar{N}_e^c N_\mu + \bar{N}_\mu^c N_e)\phi_H^\dagger - \frac{1}{2}h_{e\tau}(\bar{N}_e^c N_\tau + \bar{N}_\tau^c N_e)\phi_H$$
$$-\sum_{i=e,\,\mu,\,\tau} y_i \bar{L}_i\tilde{\phi}_h N_i + h.c.$$

$$\mathcal{M}_R = \begin{pmatrix} M_{ee} & \frac{v_{\mu\tau}}{\sqrt{2}}h_{e\mu} & \frac{v_{\mu\tau}}{\sqrt{2}}h_{e\tau} \\ \frac{v_{\mu\tau}}{\sqrt{2}}h_{e\mu} & 0 & M_{\mu\tau}\,e^{i\xi} \\ \frac{v_{\mu\tau}}{\sqrt{2}}h_{e\tau} & M_{\mu\tau}\,e^{i\xi} & 0 \end{pmatrix}$$

$$M_D = \begin{pmatrix} f_e & 0 & 0 \\ 0 & f_\mu & 0 \\ 0 & 0 & f_\tau \end{pmatrix}$$

- In the $L_\mu - L_\tau$ symmetric phase the $v_{\mu\tau} = 0$ and we have exact mu-tau symmetry $\Rightarrow$ $\theta_{13} = 0$ and $\theta_{23} = \pi/4$ and 2 of the mass eigenstates are degenerate

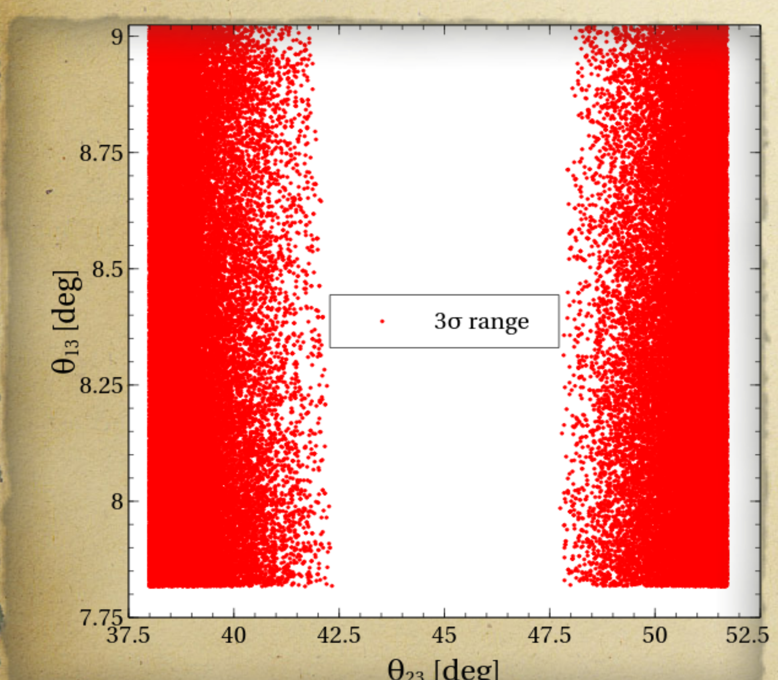
Neutrino Masses and Mixing

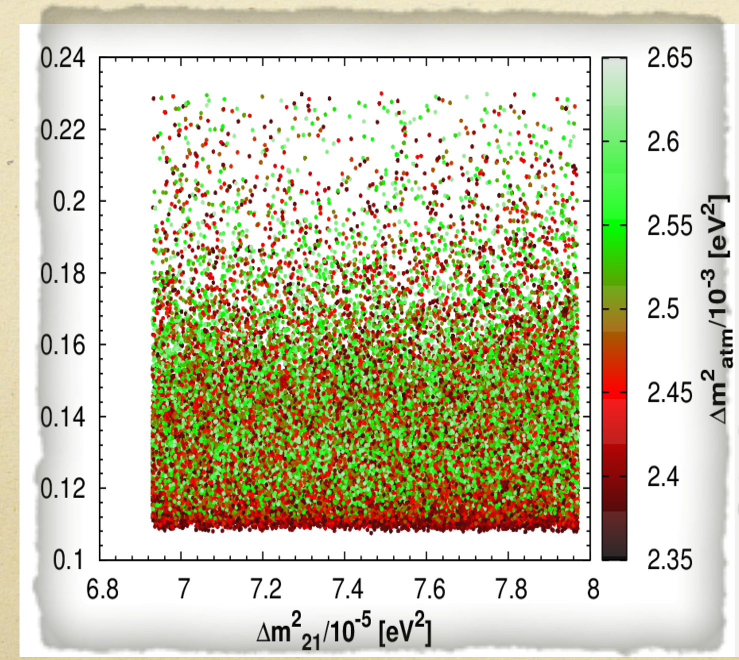
$$M = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

$$m_\nu \simeq -M_D\, M_R^{-1} M_D^T\,,$$
$$m_N \simeq M_R\,.$$

$$p = h_{e\mu}\, h_{e\tau}\, v_{\mu\tau}^2 - M_{ee}\, M_{\mu\tau}\, e^{i\xi}.$$

$$m_\nu = \frac{1}{2\,p}\begin{pmatrix} 2\, f_e^2 M_{\mu\tau}^2 e^{i\xi} & -\sqrt{2}\, f_e f_\mu\, h_{e\tau} v_{\mu\tau} & -\sqrt{2}\, f_e f_\tau\, h_{e\mu} v_{\mu\tau} \\ -\sqrt{2}\, f_e f_\mu\, h_{e\tau} v_{\mu\tau} & \dfrac{f_\mu^2\, h_{e\tau}^2\, v_{\mu\tau}^2\, e^{-i\xi}}{M_{\mu\tau}} & \dfrac{f_\mu\, f_\tau}{M_{\mu\tau}}(M_{ee}\, M_{\mu\tau} - p\, e^{-i\xi}) \\ -\sqrt{2}\, f_e f_\tau\, h_{e\mu} v_{\mu\tau} & \dfrac{f_\mu\, f_\tau}{M_{\mu\tau}}(M_{ee}\, M_{\mu\tau} - p\, e^{-i\xi}) & \dfrac{f_\tau^2\, h_{e\mu}^2\, v_{\mu\tau}^2\, e^{-i\xi}}{M_{\mu\tau}} \end{pmatrix}$$



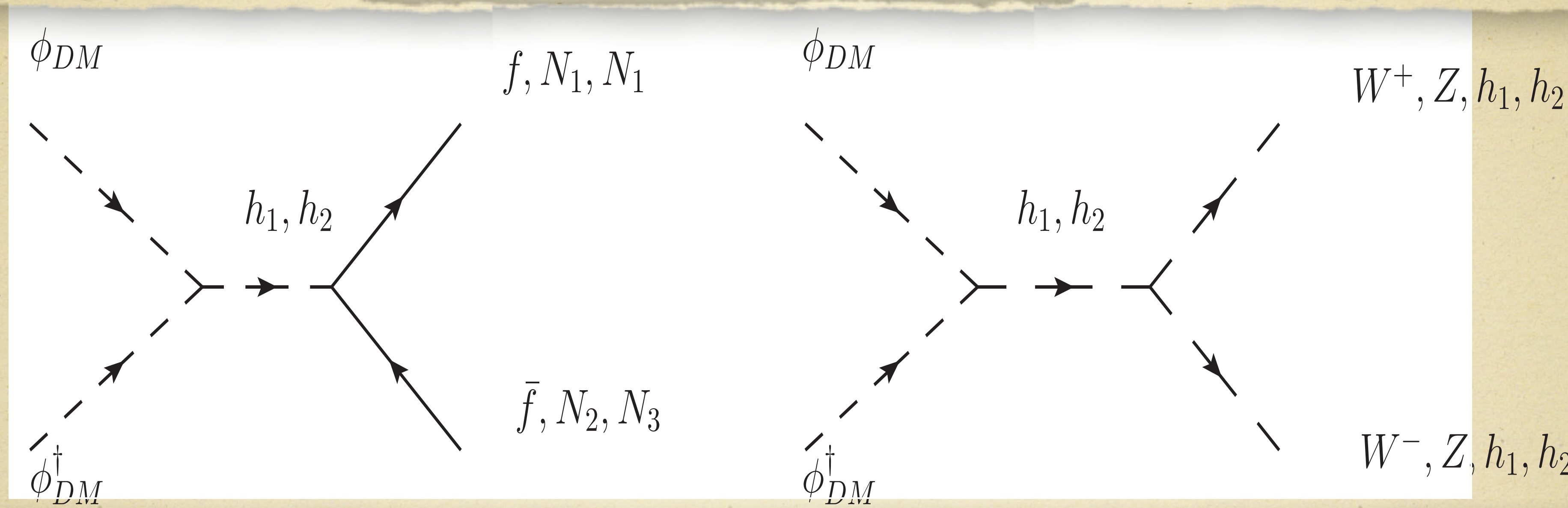


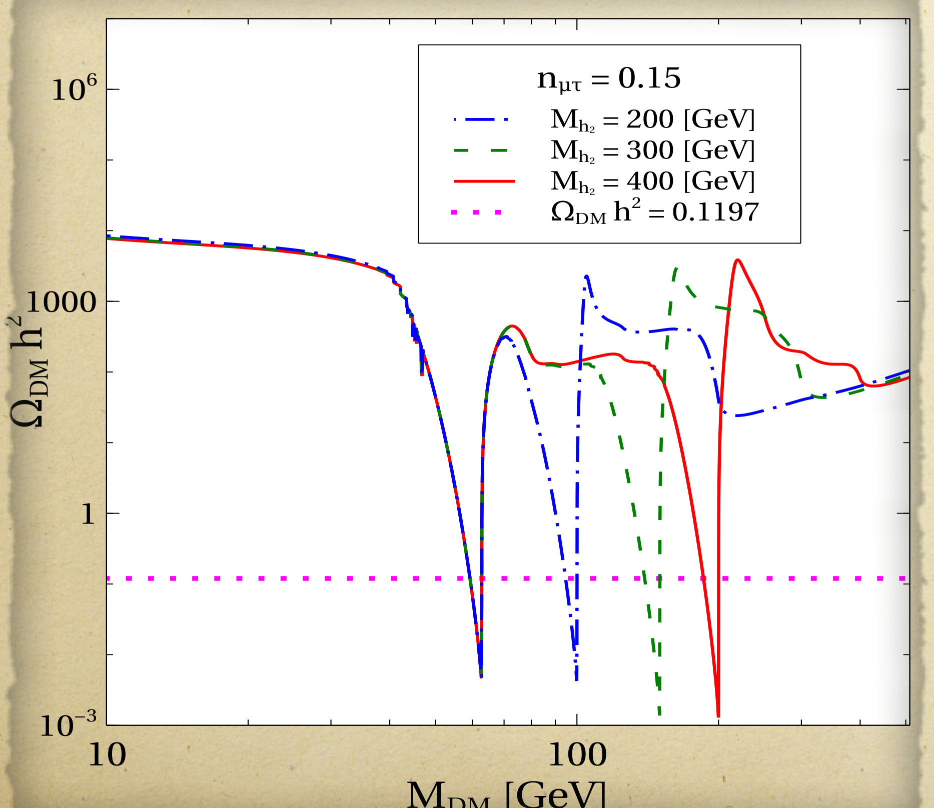
$$\begin{array}{cclcl} 0 & \leq & \xi\,[\text{rad}] & \leq & 2\pi\,, \\ 1 & \leq & M_{ee},\ M_{\mu\tau}\,[\text{GeV}] & \leq & 10^4\,, \\ 1 & \leq & V_{e\mu},\ \ V_{e\tau}\ \ [\text{GeV}] & \leq & 280\,, \\ 0.1 & \leq & \dfrac{(f_e,\ f_\mu,\ f_\tau)}{10^{-4}}\,[\text{GeV}] & \leq & 10\,. \end{array}$$

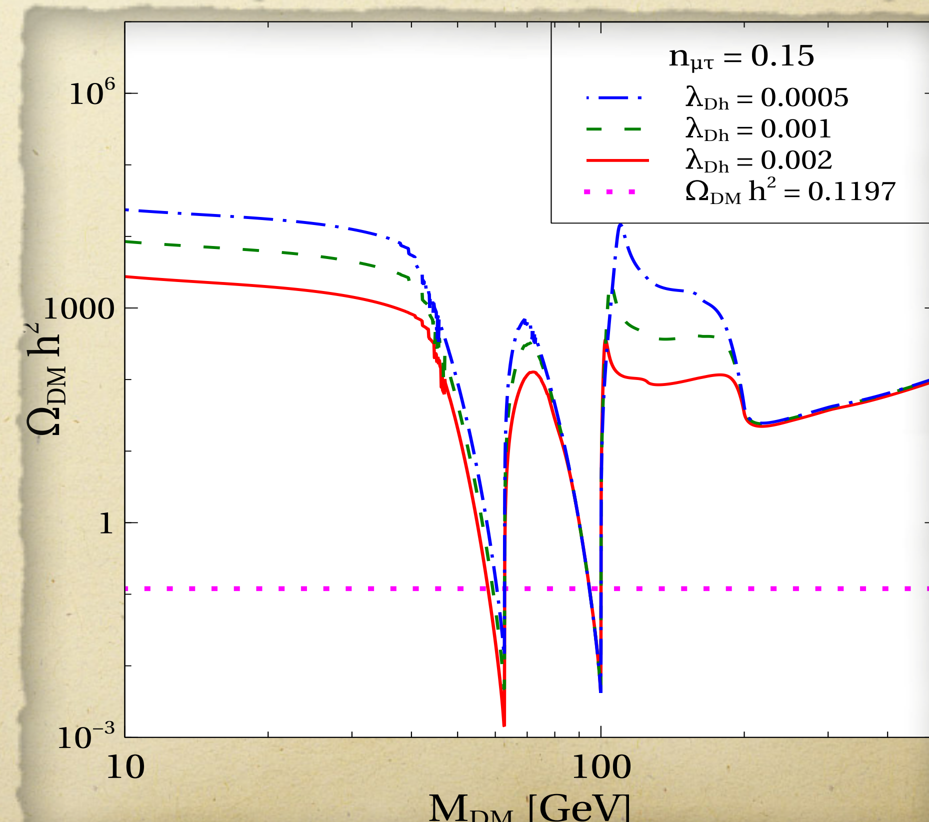
WIMP Dark Matter Relic Density

Biswas, SC, Khan JHEP 1609 (2016)

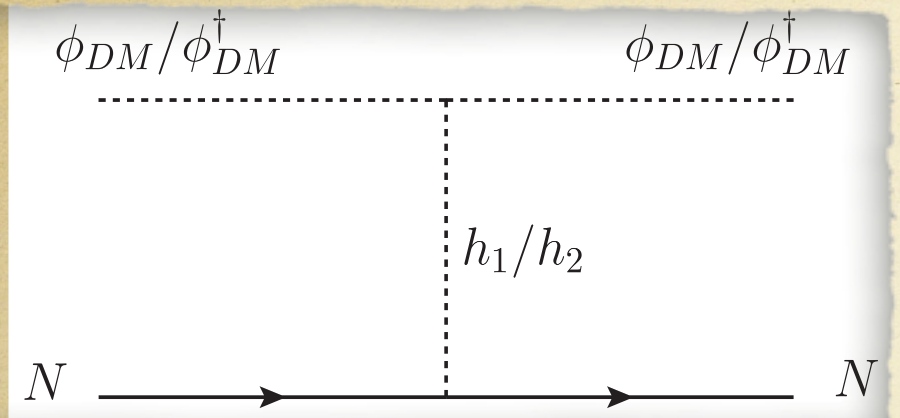
Boltzmann equation
$$\frac{dn}{dt} + 3n\mathrm{H} = -\frac{1}{2}\langle\sigma \mathrm{v}\rangle\left(n^2 - n_{eq}^2\right)$$





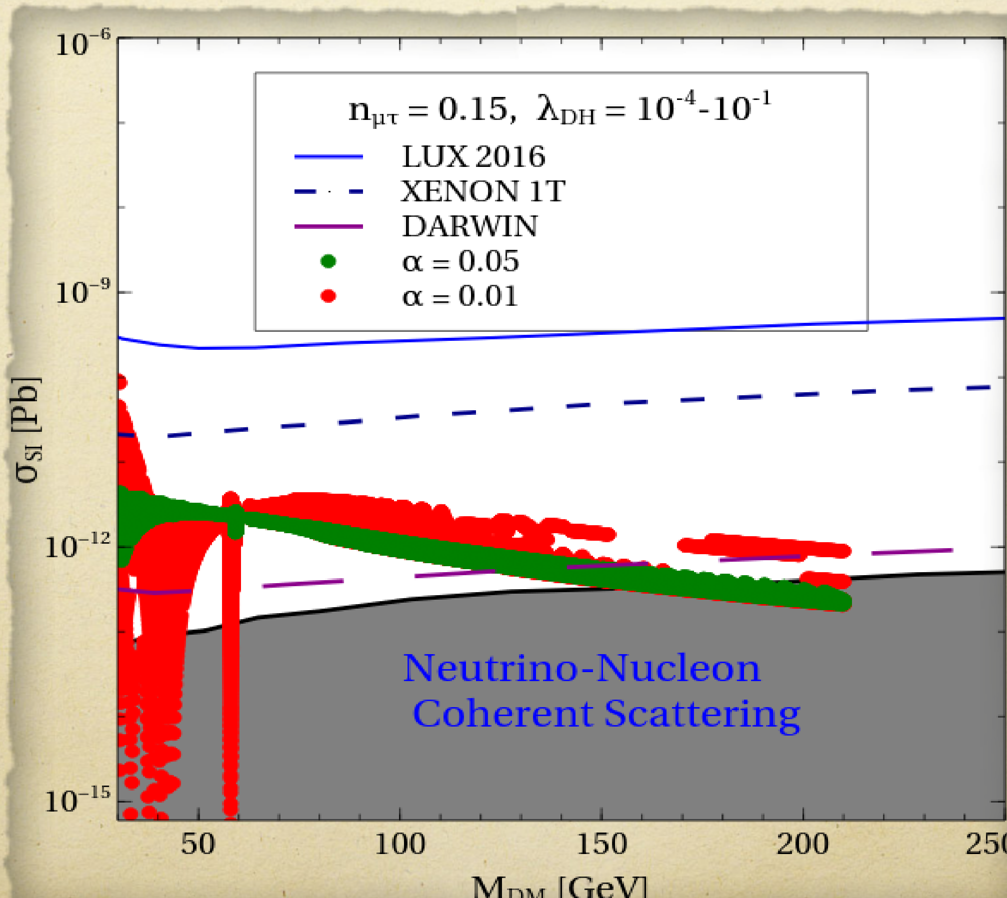


Direct Detection Constraint

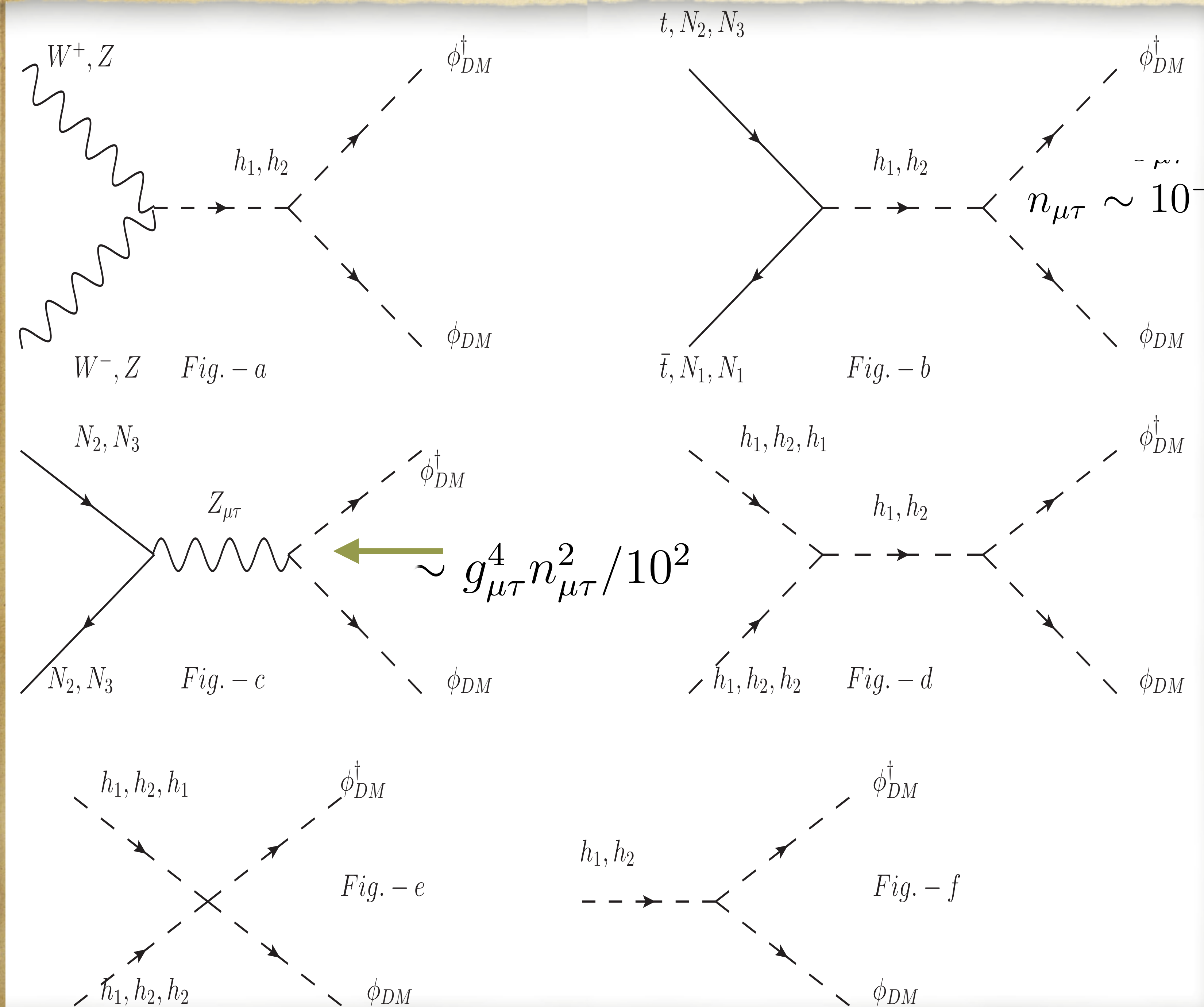


$$\sigma_{\rm SI} = \frac{\mu^2}{4\pi}\left[\frac{M_N\, f_N\, \cos\alpha}{M_{DM}\, v}\left(\frac{\tan\alpha\, g_{\phi_{DM}\phi_{DM}^\dagger h_2}}{M_{h_2}^2} - \frac{g_{\phi_{DM}\phi_{DM}^\dagger h_1}}{M_{h_1}^2}\right)\right]^2$$

$60\,\text{GeV} \leq M_{h_2} \leq 430$ GeV, $0.001 \leq \lambda_{DH} \leq 0.1$ and $\lambda_{Dh} = 0.001$



FIMP Dark Matter



$\sim g^4_{\mu\tau} n^2_{\mu\tau}/10^2$

λ_{Dh} and $\lambda_{DH} \sim 10^{-12}$

$n_{\mu\tau} \sim 10^{-5}$ to keep $\sigma_{N_j N_j \to \phi^\dagger_{DM}\phi_{DM}}$ small enough

Biswas, SC, Khan JHEP 1702 (2017)

FIMP Dark Matter

Boltzmann equation

$$\frac{dY_{\phi_{DM}}}{dz} = \frac{2M_{pl}}{1.66M_{h_2}^2}\frac{z\sqrt{g_\star(z)}}{g_s(z)}\left[\sum_{i=1,2}\langle\Gamma_{h_i\to\phi_{DM}^\dagger\phi_{DM}}\rangle(Y_i^{eq}-Y_{\phi_{DM}})\right]$$

$$+\frac{4\pi^2}{45}\frac{M_{pl}M_{h_2}}{1.66}\frac{\sqrt{g_\star(z)}}{z^2}\Bigg[\sum_{p=W,Z,h_1,h_2,f}\langle\sigma\mathrm{v}_{p\bar{p}\to\phi_{DM}^\dagger\phi_{DM}}\rangle(Y_p^{eq\,2}-Y_{\phi_{DM}}^2)$$

$$+\sum_{i=1,j=2,3}\langle\sigma\mathrm{v}_{N_iN_j\to\phi_{DM}^\dagger\phi_{DM}}\rangle(Y_{N_i}^{eq}Y_{N_j}^{eq}-Y_{\phi_{DM}}^2)+\langle\sigma\mathrm{v}_{h_1h_2\to\phi_{DM}^\dagger\phi_{DM}}\rangle(Y_{h_1}^{eq}Y_{h_2}^{eq}-Y_{\phi_{DM}}^2)\Bigg].$$

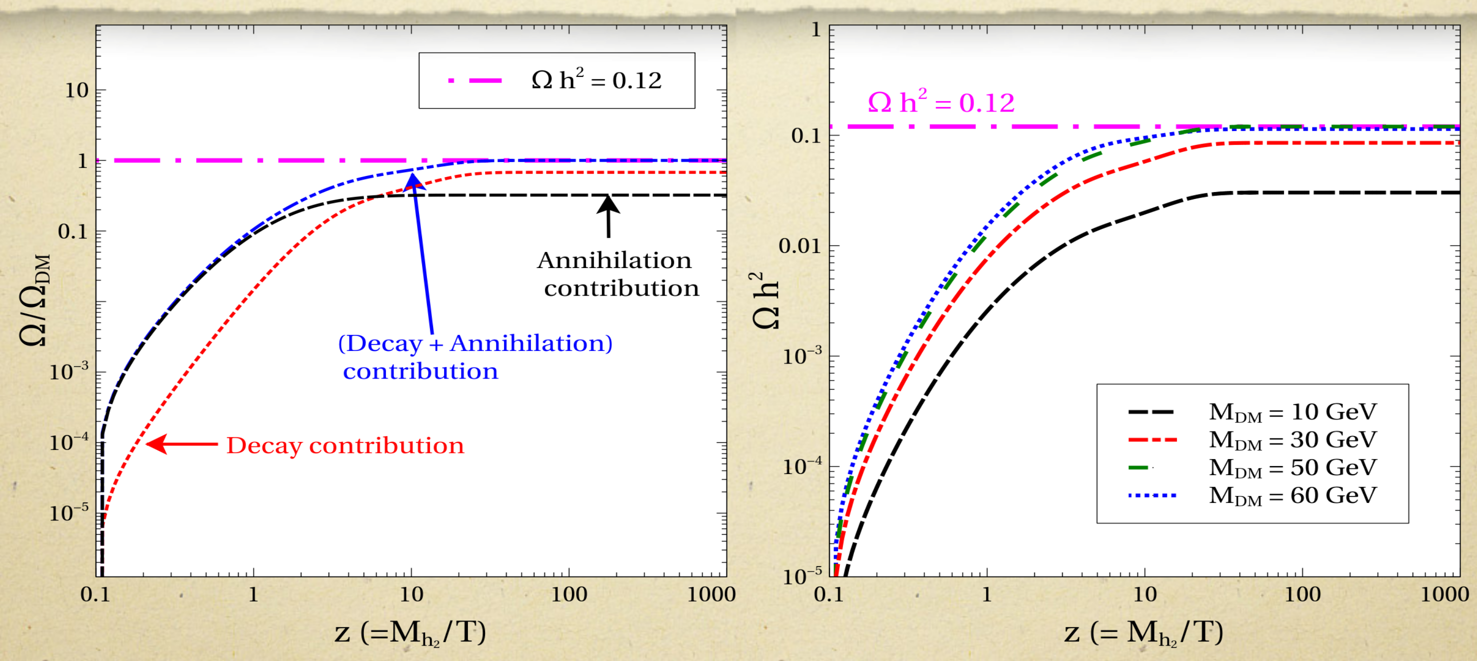
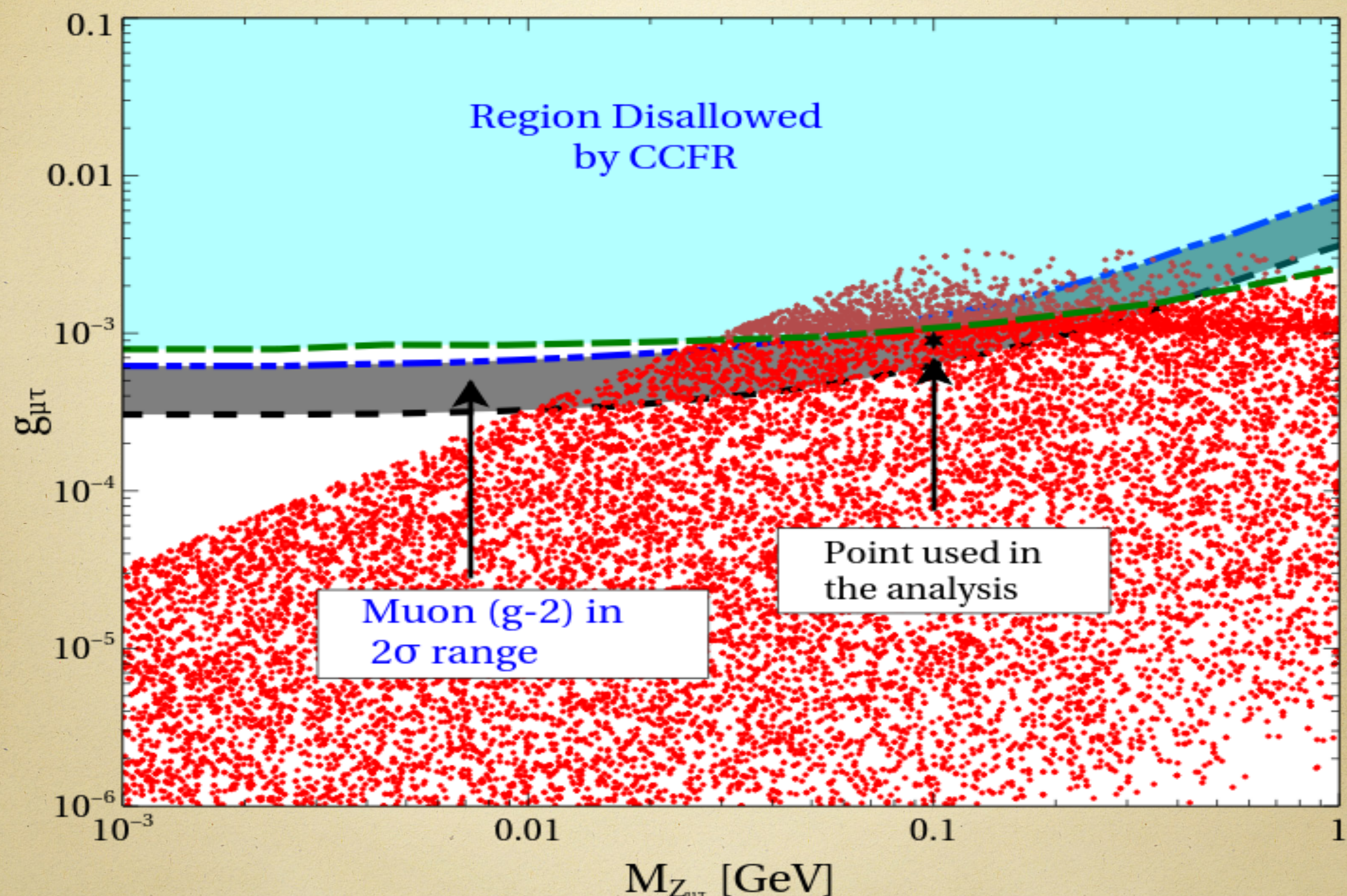
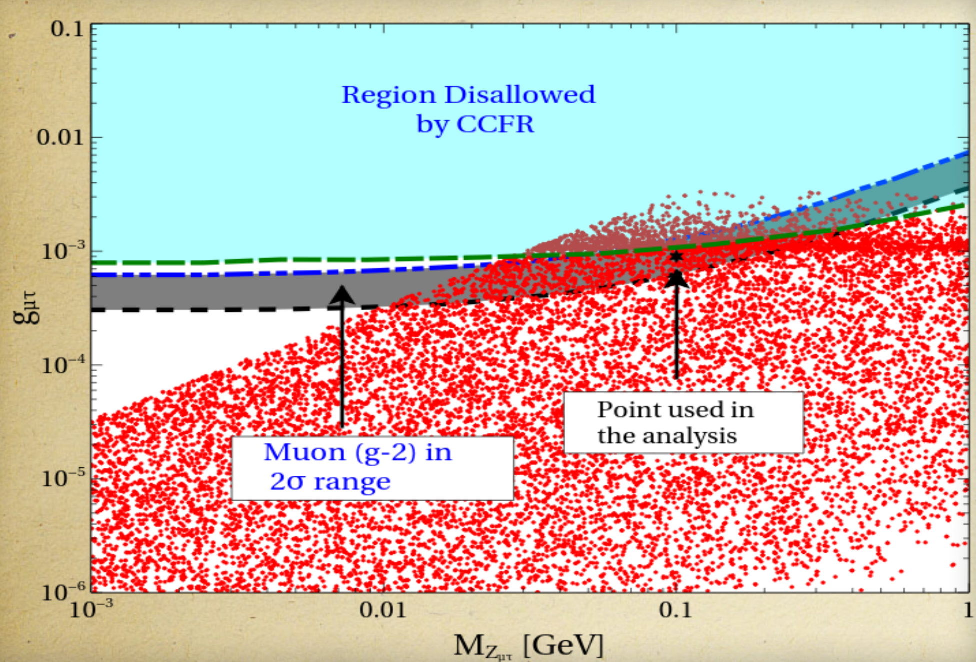


Figure 4: Left panel showing the contributions of decay and annihilation in the total relic density. Right panel: Variation of dark matter relic density with z for four different values of dark matter mass M_{DM}. The other parameters are kept fixed at $M_{Z_{\mu\tau}} = 0.1$ GeV, $g_{\mu\tau} = 9.0\times10^{-4}$, $\alpha = 0.01$, $\lambda_{Dh} = 9.8\times10^{-13}$, $\lambda_{DH} = 1.3\times10^{-11}$, $M_{DM} = 50.0$ GeV (LP), $n_{\mu\tau} = 5.5\times10^{-5}$.



Region Disallowed
by CCFR
Muon (g-2) in
2σ range
Point used in
the analysis
$g_{\mu\tau}$
$M_{Z_{\mu\tau}}$ [GeV]
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-3}
0.01
0.1
1



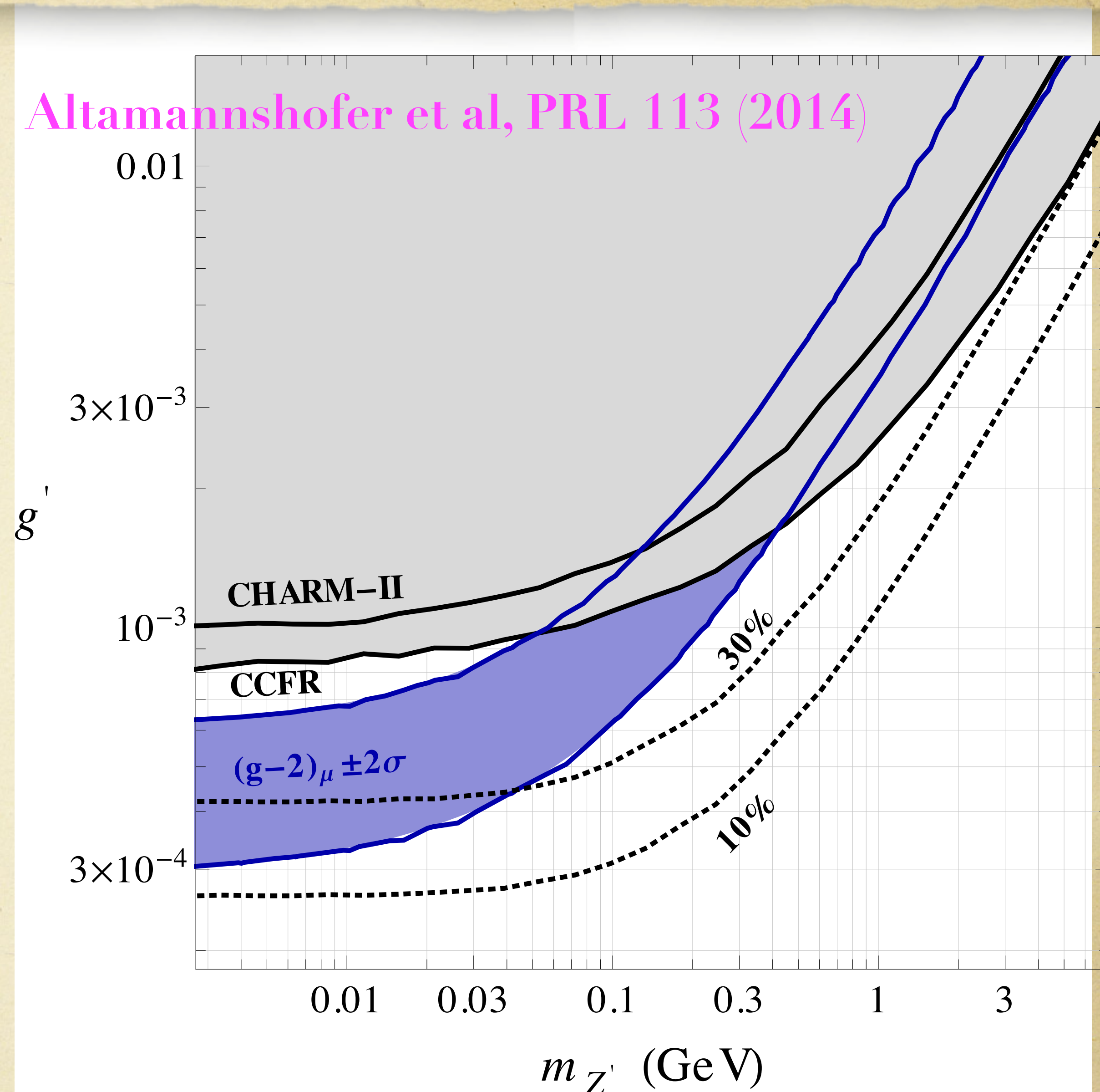
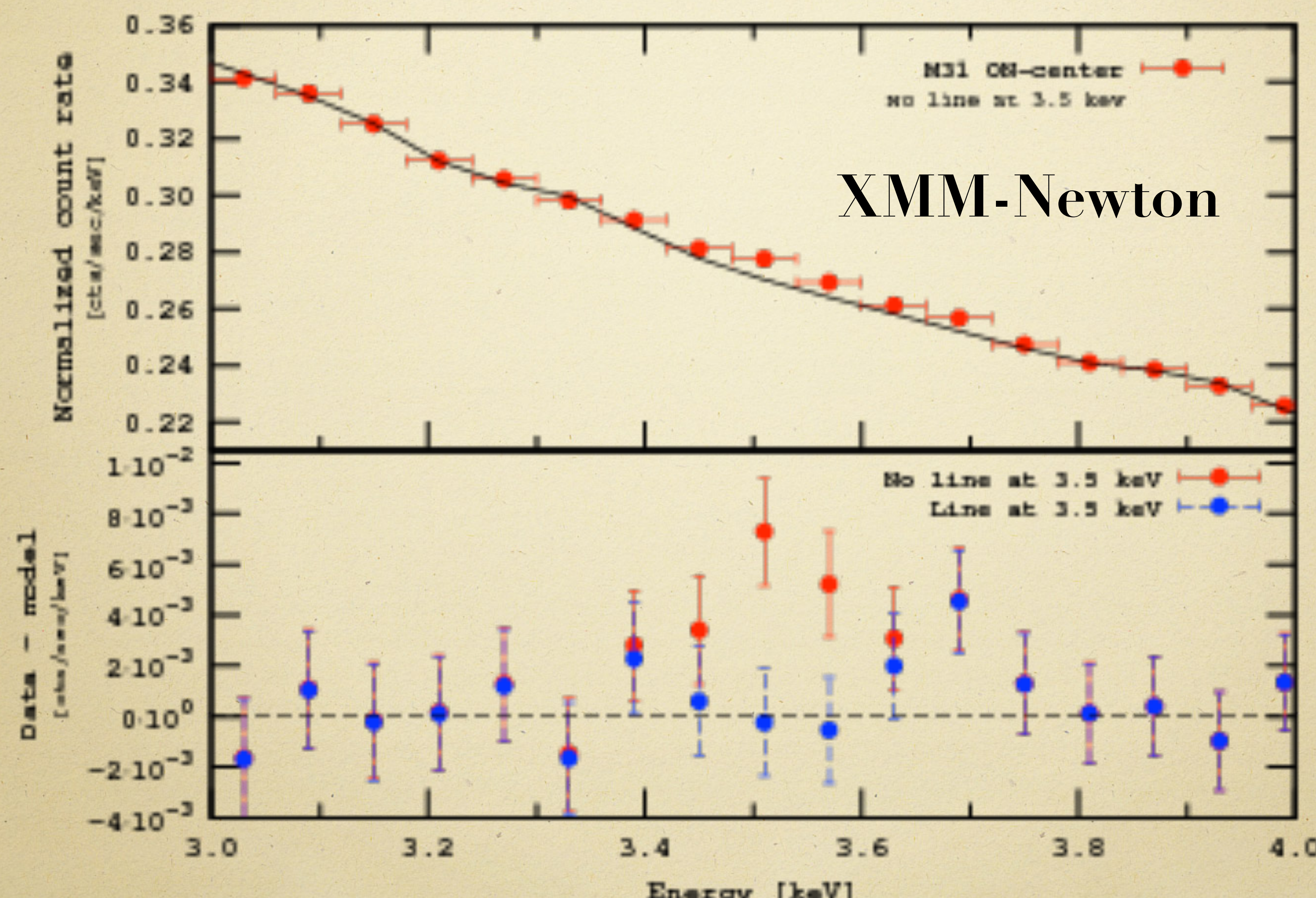


FIG. 3. Same as Fig. 2 but focusing on the low mass region. Constraints from CHARM-II and CCFR, Eqs. (15) and (16) are shown separately. We do not attempt a statistical combination of the results. The dashed lines show the expected limit if the trident cross-section could be measured with 10% or 30% accuracy using 5 GeV neutrinos scattering on Argon.

The 3.5 keV X-ray line



Consistent with Chandra observations of Perseus cluster

$U(1)_{L_\mu - L_\tau}$ to explain DM relic density and the 3.5 keV line

Biswas, SC, Covi, Khan JCAP 1802 (2018)

new particles

Gauge Group	Baryon Fields			Lepton Fields			Scalar Fields		
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	$\boxed{N_R^i}$	ϕ_h	$\boxed{\phi_H}$	$\boxed{\eta}$
$SU(2)_L$	2	1	1	2	1	1	2	1	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	1/2	0	1/2
$\mathbb{Z}_2$	+	+	+	+	+	−	+	+	−

inert doublet

Gauge Group	Baryonic Fields	Lepton Fields			Scalar Fields		
	(Q_L^i, u_R^i, d_R^i)	(L_L^e, e_R, N_R^e)	$(L_L^\mu, \mu_R, N_R^\mu)$	$(L_L^\tau, \tau_R, N_R^\tau)$	ϕ_h	ϕ_H	η
$U(1)_{L_\mu - L_\tau}$	0	0	1	−1	0	1	0

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + (D_\mu \phi_H)^\dagger (D^\mu \phi_H) + (D_\mu \eta)^\dagger (D^\mu \eta) + \sum_{j=\mu,\tau} Q^j \, \bar{L}_j \gamma_\rho L_j Z^\rho_{\mu\tau}$$
$$-\frac{1}{4} F_{\mu\tau\,\rho\sigma} F_{\mu\tau}{}^{\rho\sigma} - V(\phi_h, \phi_H, \eta)\,,$$

$$\mathcal{L}_N = \sum_{i=e,\mu,\tau} \frac{i}{2} \bar{N}_i \gamma^\mu D_\mu N_i - \frac{1}{2} M_{ee} \, \bar{N}^c_e N_e - \frac{1}{2} M_{\mu\tau} \, (\bar{N}^c_\mu N_\tau + \bar{N}^c_\tau N_\mu)$$
$$-\frac{1}{2} h_{e\mu} (\bar{N}^c_e N_\mu + \bar{N}^c_\mu N_e) \phi^\dagger_H - \frac{1}{2} h_{e\tau} (\bar{N}^c_e N_\tau + \bar{N}^c_\tau N_e) \phi_H$$
$$- \sum_{\alpha=e,\mu,\tau} h_\alpha \bar{L}_\alpha \tilde{\eta} N_\alpha + h.c.\,,$$

$$V(\phi_h, \phi_H, \eta) = -\mu_H^2 \phi_H^\dagger \phi_H - \mu_h^2 \phi_h^\dagger \phi_h + \mu_\eta^2 \eta^\dagger \eta + \lambda_1 (\phi_h^\dagger \phi_h)^2 + \lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (\phi_H^\dagger \phi_H)^2$$
$$+\lambda_{12} (\phi_h^\dagger \phi_h)(\eta^\dagger \eta) + \lambda_{13} (\phi_h^\dagger \phi_h)(\phi_H^\dagger \phi_H) + \lambda_{23} (\phi_H^\dagger \phi_H)(\eta^\dagger \eta) + \lambda_4 (\phi_h^\dagger \eta)(\eta^\dagger \phi_h)$$
$$+\frac{1}{2} \lambda_5 \left((\phi_h^\dagger \eta)^2 + h.c. \right) .$$

The RH Neutrino Masses

Dark Matter

Lmu-Ltau Symmetric

$$\mathcal{M}_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau}\, e^{i\xi} \\ 0 & M_{\mu\tau}\, e^{i\xi} & 0 \end{pmatrix}$$

Dark Matter

$$\begin{aligned} M'_{2/3} &= \pm M_{\mu\tau} e^{i\xi} \\ M'_1 &= M_{ee}\,, \end{aligned}$$

N_2 and N_3 are exactly degenerate and serve as a two-component DM of the Universe

The RH Neutrino Masses

Dark Matter

Lmu-Ltau Symmetric

$$\mathcal{M}_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau}\, e^{i\xi} \\ 0 & M_{\mu\tau}\, e^{i\xi} & 0 \end{pmatrix}$$

Lmu-Ltau Broken

$$\mathcal{M}_R = \begin{pmatrix} M_{ee} & \frac{v_{\mu\tau}}{\sqrt{2}} h_{e\mu} & \frac{v_{\mu\tau}}{\sqrt{2}} h_{e\tau} \\ \frac{v_{\mu\tau}}{\sqrt{2}} h_{e\mu} & 0 & M_{\mu\tau}\, e^{i\xi} \\ \frac{v_{\mu\tau}}{\sqrt{2}} h_{e\tau} & M_{\mu\tau}\, e^{i\xi} & 0 \end{pmatrix}$$

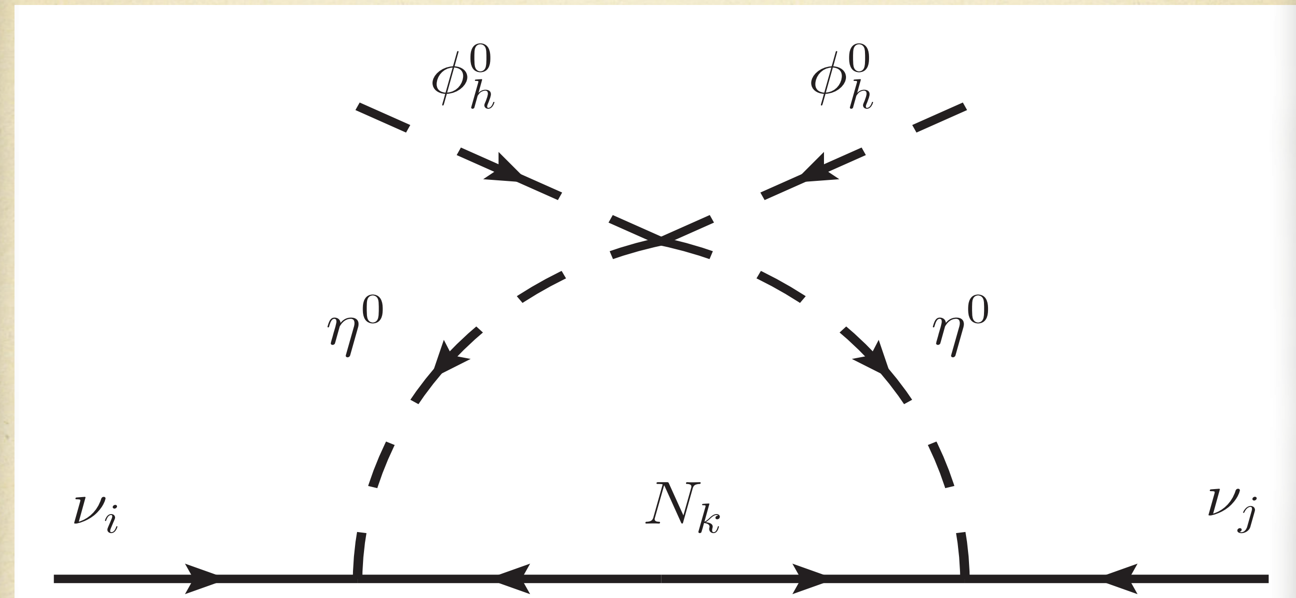
Dark Matter

$$\begin{aligned} M'_{2/3} &= \pm M_{\mu\tau} e^{i\xi} \\ M'_1 &= M_{ee}\,, \end{aligned}$$

The mass splitting between them is given at first order for $M_{ee} \gg M_{\mu\tau}$ by

$$\Delta M_{23} = \frac{(h_{e\mu} + h_{e\tau})^2 v_{\mu\tau}^2}{2M_{ee}}$$

The Light Neutrino Mass



$$M^\nu_{ij} = \sum_k \frac{y_{ik}\, y_{jk}\, M_k}{16\,\pi^2} \left[\frac{M^2_{\eta^0_R}}{M^2_{\eta^0_R} - M^2_k} \ln \frac{M^2_{\eta^0_R}}{M^2_k} - \frac{M^2_{\eta^0_I}}{M^2_{\eta^0_I} - M^2_k} \ln \frac{M^2_{\eta^0_I}}{M^2_k} \right]$$

$M_{\eta^0_{R,I}} \sim 10^6$ GeV $\quad \lambda_5 \sim 10^{-3} \quad y^2_{ji} \sim 10^{-1} \quad \rightarrow \quad M_\nu \sim 10^{-11}$ GeV

Creating N_2/N_3 by Freeze-in

solve the relevant Boltzmann equation for N_2 and N_3,

$$\frac{dY_{N_j}}{dr} = \frac{V_{ij}\, M_{pl}\, r\, \sqrt{g_\star(r)}}{1.66\, M_{sc}^2\, g_s(r)} \left[\sum_{k=1,2}\sum_{i=1,2,3} \langle \Gamma_{h_k \to N_j\, N_i}\rangle (Y_{h_k} - Y_{N_j} Y_{N_i})\right] + \frac{V_{ij}\, M_{pl}\, r\, \sqrt{g_\star(r)}}{1.66\, M_{sc}^2\, g_s(r)} \sum_{i=1,2,3} \langle \Gamma_{Z_{\mu\tau} \to N_j N_i}\rangle_{NTH}\, (Y_{Z_{\mu\tau}} - Y_{N_j} Y_{N_i})$$

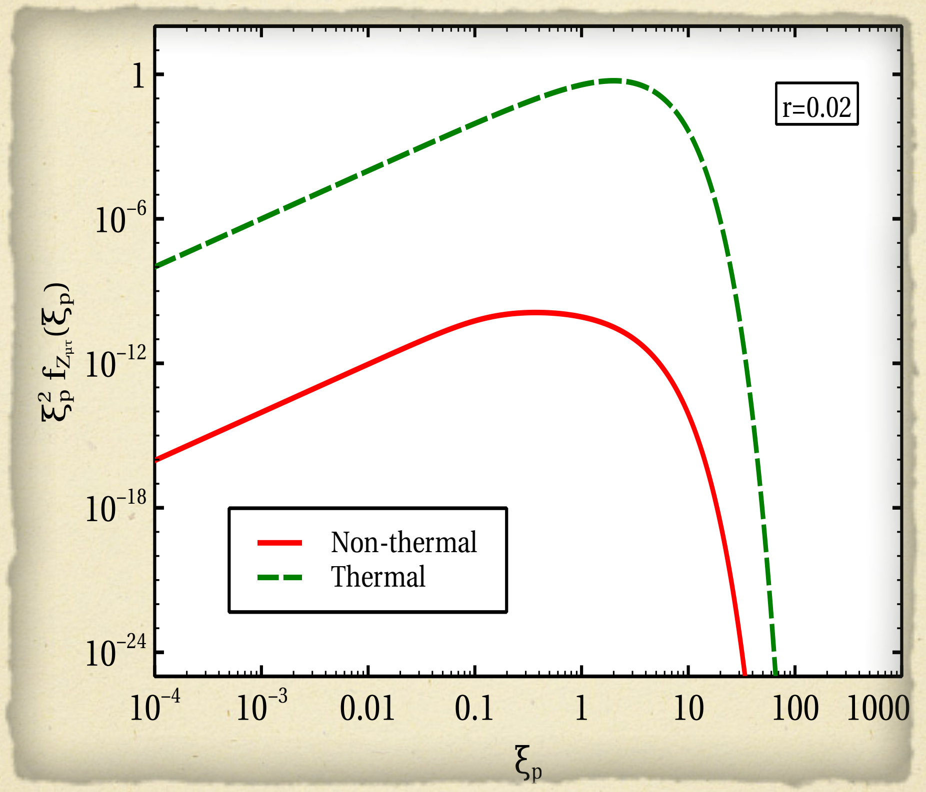
- h_1 and h_2 are in thermal equilibrium

$$\langle \Gamma_{h_k \to N_j\, N_i}\rangle = \Gamma_{h_k \to N_j\, N_i} \frac{K_1\left(r\, \frac{M_{h_k}}{M_{sc}}\right)}{K_2\left(r\, \frac{M_{h_k}}{M_{sc}}\right)}$$

modified Bessel Functions

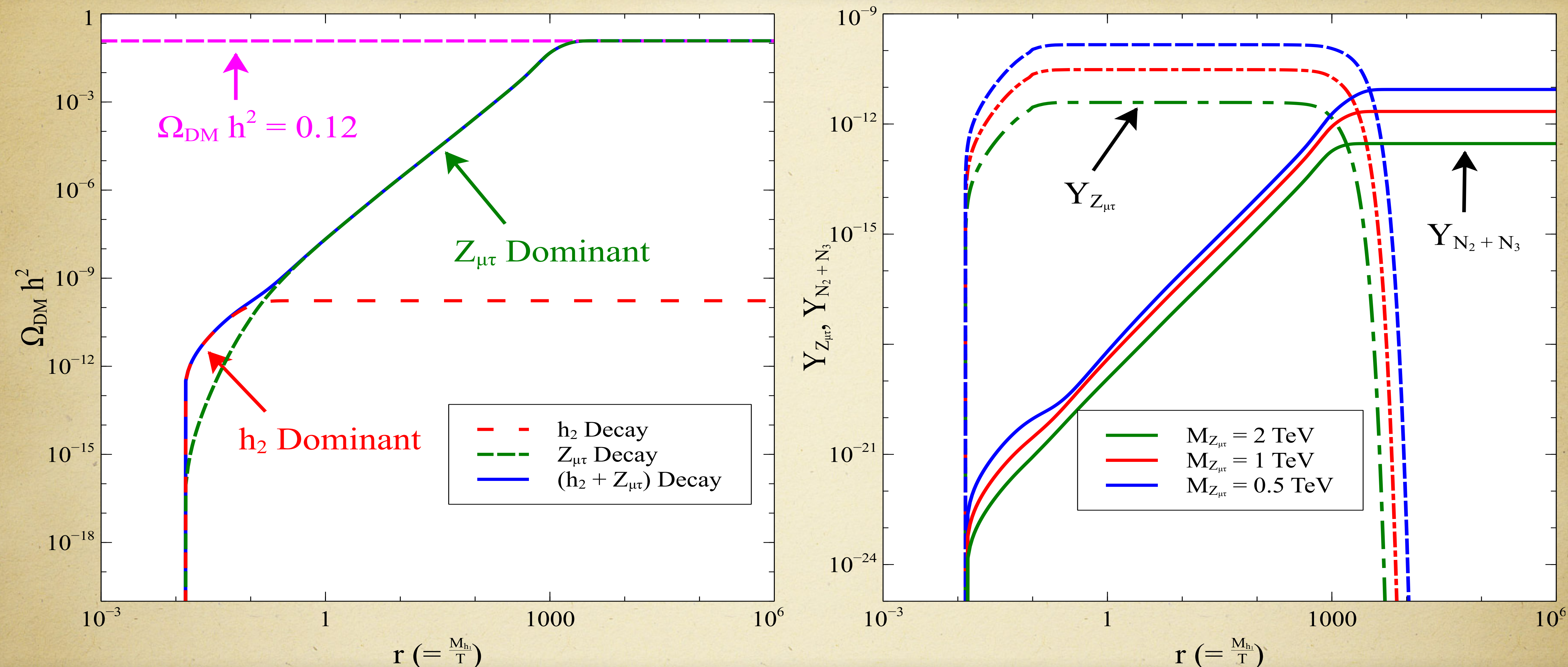
- $Z_{\mu\tau}$ in not in thermal equilibrium since $g_{\mu\tau}$ is very small

$$\hat{L} f_{Z_{\mu\tau}} = \sum_{i=1,2} \mathcal{C}^{h_i \to Z_{\mu\tau} Z_{\mu\tau}} + \mathcal{C}^{Z_{\mu\tau} \to \, all}$$



- **First get the non-thermal distribution of $Z_{\mu\tau}$ by solving the BE, next compute the non-thermal average of the decay width $\Gamma_{Z_{\mu\tau} \to N_j N_i}$ and finally solve for the non-thermal abundance of N_2 and N_3**

$$\Omega_{DM} h^2 \; = \; 2.755 \times 10^8 \left(\frac{M_{N_2}}{\text{GeV}} \right) Y_{N_2}(T_{\text{Now}}) + 2.755 \times 10^8 \left(\frac{M_{N_3}}{\text{GeV}} \right) Y_{N_3}(T_{\text{Now}})$$

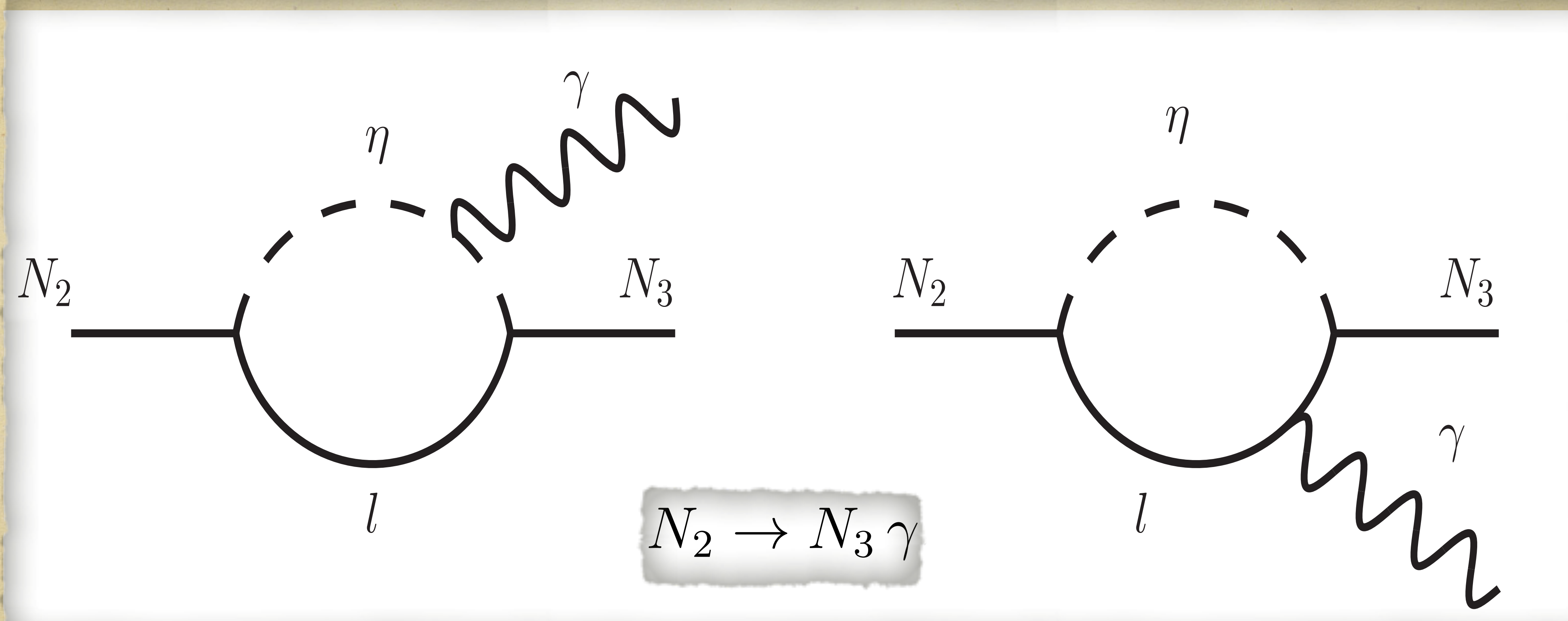


$$\frac{\Gamma_{Z_{\mu\tau}\to N_i N_j}}{\Gamma_{h_2\to N_i N_j}} \propto \frac{g^2_{\mu\tau}}{h_{e\alpha} h_{e\beta}}$$

splitting of 3.5 keV between N_2 and N_3 $\Rightarrow$ $V_{e\alpha} = \dfrac{h_{e\alpha} v_{\mu\tau}}{\sqrt{2}} \sim 0.1$ GeV

$\Rightarrow$ $$\frac{\Gamma_{Z_{\mu\tau}\to N_i N_j}}{\Gamma_{h_2\to N_i N_j}} \propto \frac{M^2_{Z_{\mu\tau}}}{V^2_{e\alpha}}$$ explaining the dominance of the $Z_{\mu\tau}$ decay channel.

The 3.5 keV X-ray line



photon flux for a decaying Dark Matter candidate is given by

$$\Phi = \frac{1}{4\pi M_{N_2}\tau_{N_2}} \int_{l.o.s.} \rho_{N_2}(\vec{r})d\vec{r}$$

lifetime of the heavier DM particle N_2.

$$\Gamma(N_2 \to N_3\gamma) = (0.72 - 6.6) \times 10^{-52}\,\mathrm{GeV}\left(\frac{M_{N_2}}{3.5\,\mathrm{keV}}\right) = (0.2 - 1.9) \times 10^{-44}\,\mathrm{GeV}\left(\frac{M_{N_2}}{100\,\mathrm{GeV}}\right)$$

$M_{ee} = 11$ TeV and $M_{\mu\tau} = 100$ GeV which gives us M_{N_2} and $M_{N_3} \sim 100$ GeV with opposite CP parities

$V_{e\alpha} = \frac{h_{e\alpha} v_{\mu\tau}}{\sqrt{2}} \sim 0.1$ GeV

by suitably adjusting the $V_{e\alpha}$ parameters we can generate the 3.5 keV mass gap

$$\Gamma(N_2 \to N_3\gamma) = \frac{\mu_{23}^2}{4\pi}\,\delta^3\left(1 - P\,\frac{M_{N_3}}{M_{N_2}}\right)^2$$

where $\delta = \frac{M_{N_2}}{2}(1 - \frac{M_{N_3}^2}{M_{N_2}^2})$, P gives the relative CP of the two neutrino states, which in the present model is $P = -1$. The magnetic moment coefficient μ_{23} in our model is given by

$$\mu_{23} = \sum_i \frac{e}{2}\frac{1}{(4\pi)^2}\frac{M_{N_2}}{M_\eta^2}(y_{i2}y_{i3})\,, \qquad y_{ij} = h_i U_{ij}$$

correct lifetime for 3.5 keV line

$$\tau_{N_2} \sim \mathcal{O}(10^{-44})\mathrm{GeV} \sim 10^{19}s > \text{age of universe}$$

Conclusions

- Gauged $\mathbf{U(1)_{L_\mu - L_\tau}}$ can simultaneously explain muon (g-2), neutrino mixing and dark matter
- The dark matter could be either WIMP type or FIMP type in this model.
- $\mathbf{U(1)_{L_\mu - L_\tau}}$ has exact mu-tau symmetry $\theta_{13} = 0$ and $\theta_{23} = \pi/4$ Breaking it shifts these from maximal and zero, consistent with data
- $\mathbf{U(1)_{L_\mu - L_\tau}}$ naturally can give two nearly degenerate sterile neutrino dark matter, which could explain the observed 3.5 keV line