Anatomy of singlet-doublet dark matter relic: Annihilation, coannihilation, coscattering and Freezein

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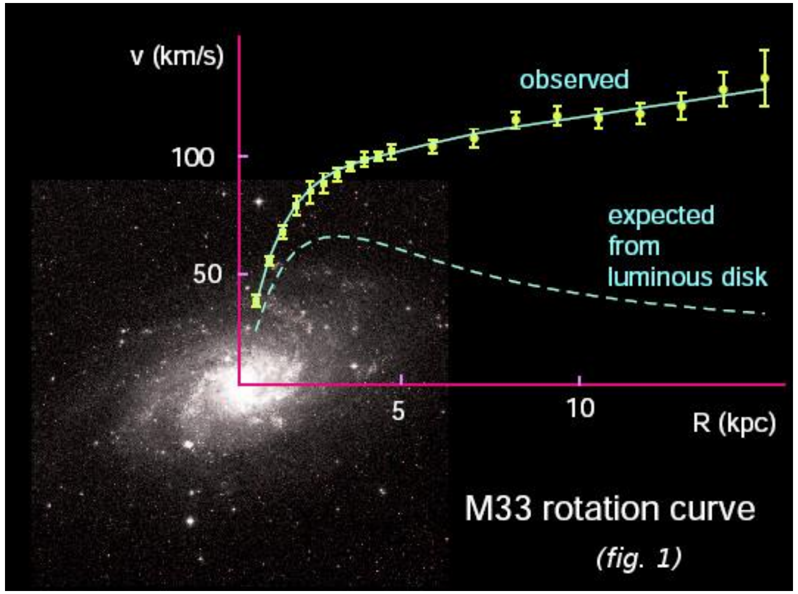
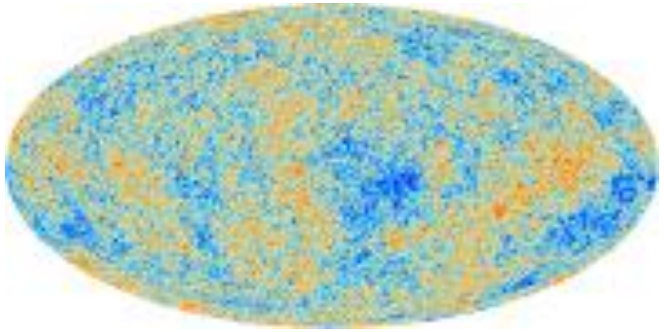
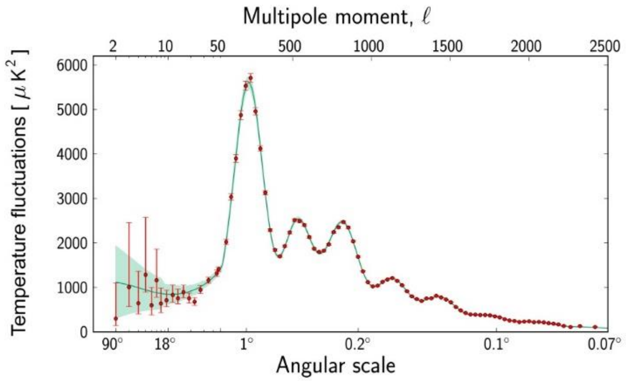
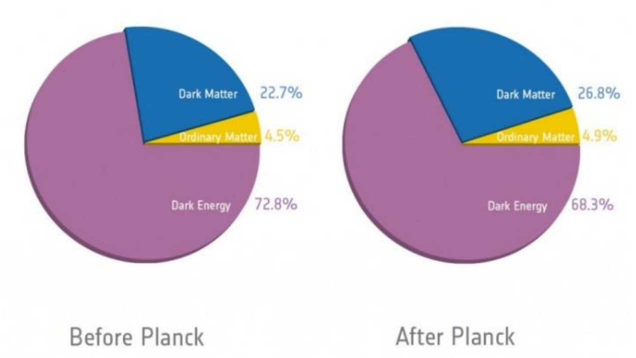
Evidence of dark matter









Nature of Dark Matter…

From the astrophysical evidences of dark matter one infers that…

- ✓ DM should be a massive particle and hence interact gravitationally.
- ✓ It is electrically neutral and colorless. Therefore it could hide itself easily.
- ✓ It is stable on the cosmological time scale and therefore the large scale structure exists.

However,
We don't know …

Mass of DM= ?
Spin of DM= ?, Charge of DM= ?
Interaction apart from gravity ?
Relic abundance
(symmetric/asymmetric ?)

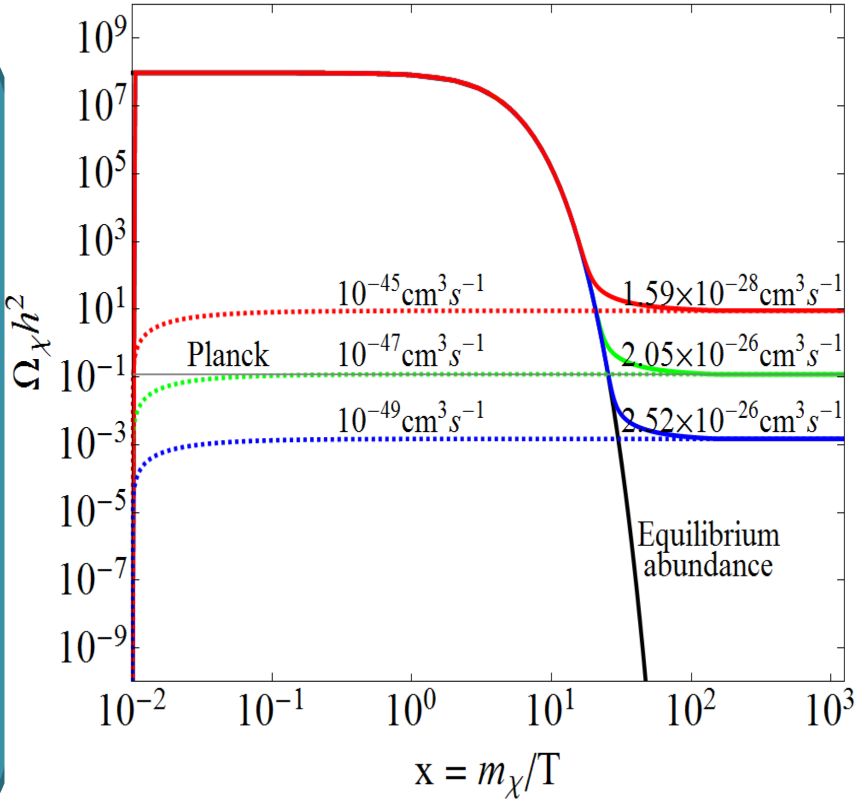
→ Many unanswered questions!

Q. How to probe the DM in a terrestrial laboratory (i.e., small scale), which is required for the existence of our Universe ?

Is DM a WIMP (Gravity+ weak) ?

Steigman and Turner, 1984

The DM is assumed to be in equilibrium in the early Universe via the weak interaction processes. As the temperature, due to expansion of the Universe, falls below the mass scale of DM, the latter gets freeze-out from the thermal bath and gives the correct relic abundance.



$$\frac{dY_\chi}{dx} = \frac{-x\langle\sigma|v|\rangle s}{H(m_\chi)}(Y_\chi{}^2 - Y_{eq}{}^2)$$

$$Y_\chi = \frac{n_\chi}{s}, x = \frac{m_\chi}{T}$$

$$\Omega_{DM} h^2 = \frac{1.1\times 10^9 GeV^{-1} x_F}{g_*^{1/2} M_{pl} \langle \sigma |v| \rangle_F} = 0.1198 \pm 0.0026$$

Analytical estimation of a WIMP relic density

The observed relic abundance of DM by WMAP and PLANCK

$$< \sigma |v| >|_F \approx 3\times 10^{-26} cm^3/\sec \approx 2.6\times 10^{-9} GeV^{-2}$$

$$\approx O(10^{-36}) cm^2$$

Which is typically a weak interaction cross-section.

WIMP Miracle

Therefore one believes that DM could be a WIMP.

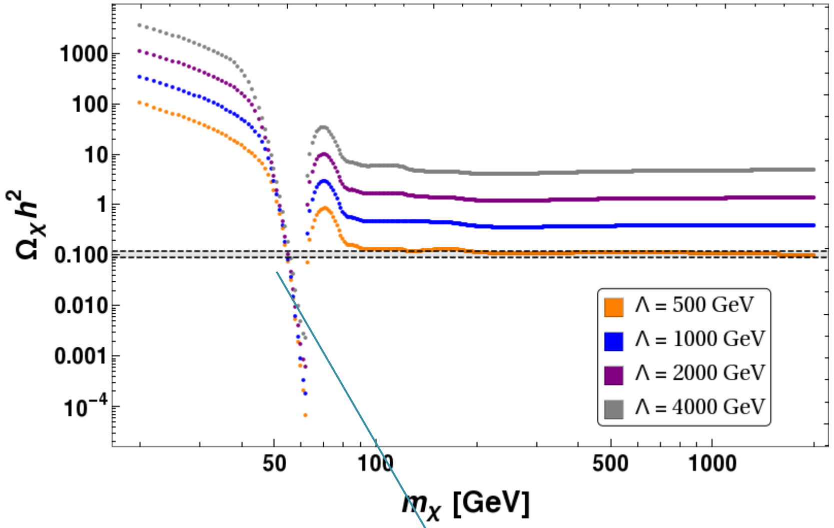
In this talk we assume…

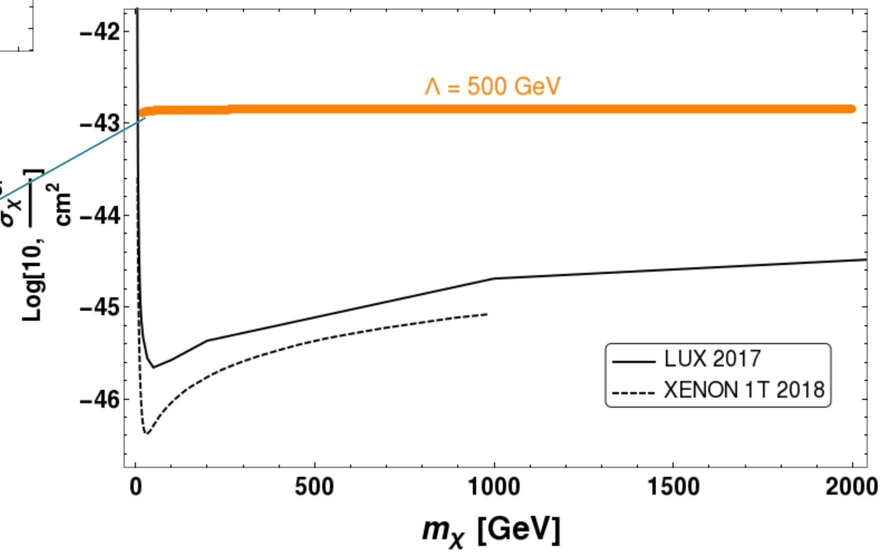
Weakly interacting vector-like leptons as candidate of dark matter

(1) Vector-like singlet fermion (lepton) dark matter
(2) Vector-like doublet fermion (lepton) dark matter
(3) Singlet-doublet fermion (lepton) dark matter

Vector-like Singlet fermion DM

$$\mathcal{L}_{DM} = \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - m_{\chi})\chi - \frac{1}{\Lambda}\left(H^{\dagger}H - \frac{v^2}{2}\right)\bar{\chi}\,\chi$$

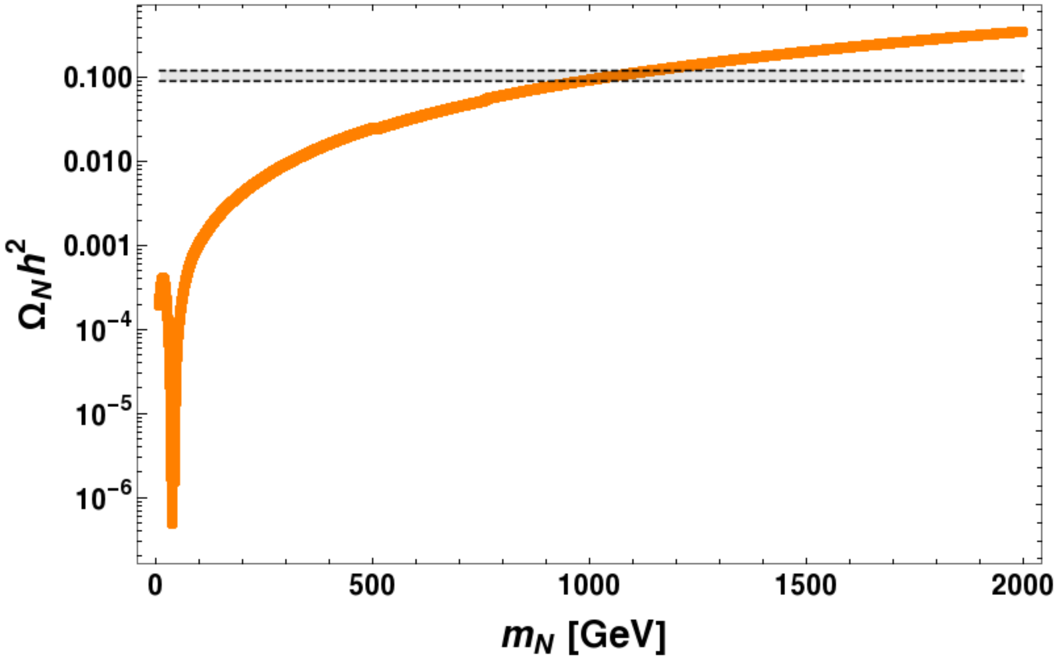


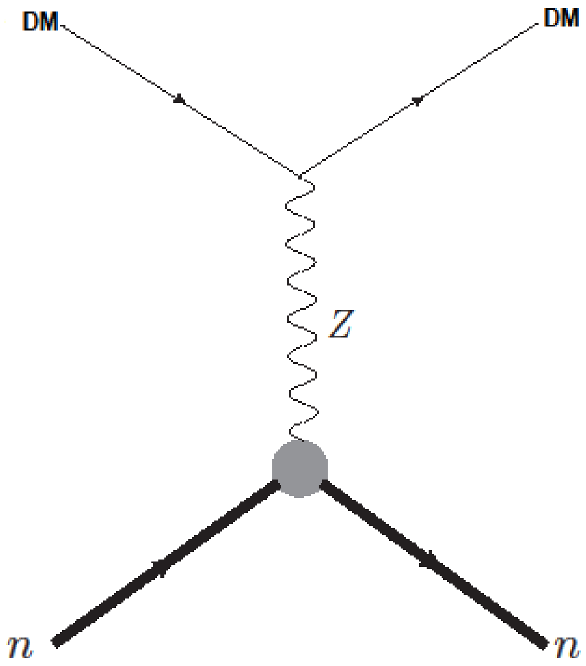


Allowed zone
of valid DM

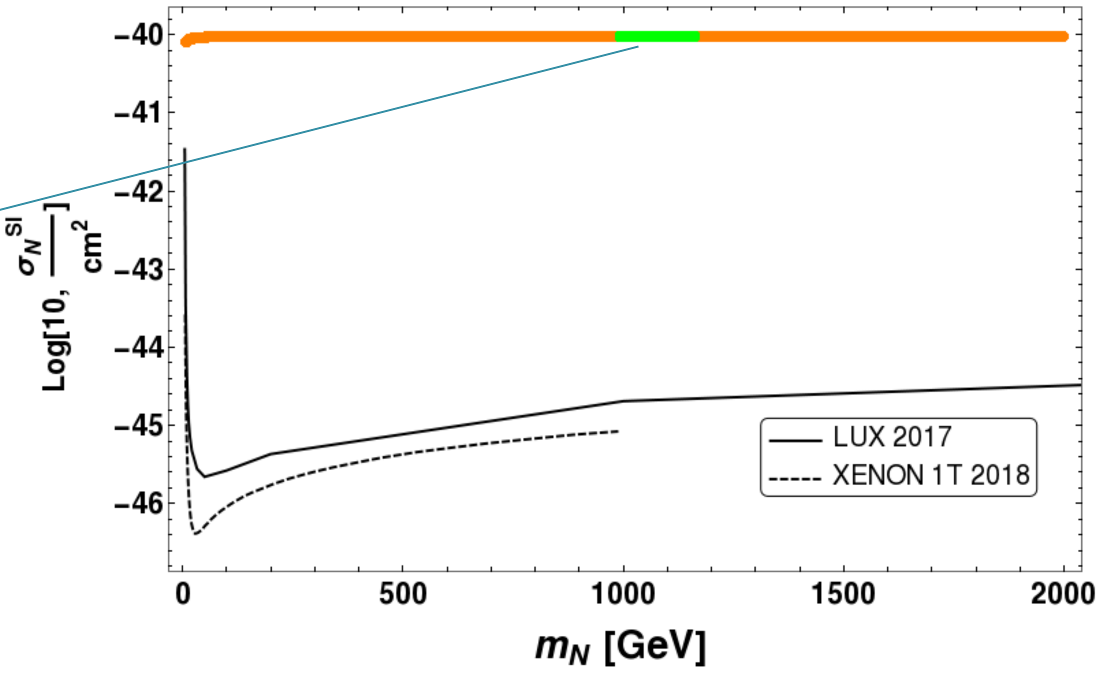
Vector-like Inert lepton doublet DM

$$\mathcal{L}_{DM} = \bar{N}(i\gamma^{\mu}D_{\mu} - m_N)\mathrm{N}$$





Inert lepton doublet DM alone is ruled out by direct search



Singlet-Doublet mixed Fermion DM

We overcome the problem of small relic abundance of doublet DM N by introducing a vector-like singlet fermion χ^0, which mixes with the neutral component of the doublet fermion and decreases the annihilation cross-section. As a result, we get the correct relic abundance.

$$\mathcal{L}_{DM} = M_N \overline{N} N + M_\chi \overline{\chi^0} \chi^0 + [Y \overline{N} \tilde{H} \chi^0 + h.c.] + \overline{N} i\gamma^\mu D_\mu N + \overline{\chi^0} i\gamma^\mu \partial_\mu \chi^0$$

where $N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix} \equiv (1,2,-1), H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \equiv (1,2,1), \chi^0 \equiv (1,1,0)$

Under Z_2 symmetry both χ^0 and N are odd. As a result the DM emerges as a mixture of singlet fermion χ^0 and the neutral component of the vector-like doublet fermion N.

(1) Singlet-doublet dark matter in light of gauge coupling unification: [hep-th/0501082] , [hep-ph/0510064] , [hep-ph/0705.4493]

(2) Singlet-doublet dark matter in light of electroweak physics: [arXiv: 0706.0918], [arXiv: 1109.2604], [arXiv: 1311.5896]. [arXiv: 1411.1335], [arXiv: 1504.07892], [arXiv: 1505.03867], [arXiv: 1506.04149], [arXiv: 1509.05323]

Singlet-Doublet dark matter parameter space in details along with neutrino mass and electroweak anomalies:

S. Bhattacharya, Nirakar Sahoo and **N. Sahu**, PRD93, 2016 [1510.02760]
S. Bhattacharya, S Patra, Nirakar Sahoo, **N.Sahu**, JCAP 1606, 2016 [1601.01569]
S. Bhattacharya, Nirakar Sahoo and **N. Sahu**, PRD96, 2017 [1704.03417]
S. Bhattacharya, Purusottam Ghosh, Nirakar Sahoo and **N. Sahu**, [1812.06505]
M. Dutta, S. Bhattacharya, P. Ghosh and **N. Sahu** [2009.00885]
D. Borah, M. Dutta, S. Mahapatra & **N. Sahu**., [2109.02699]
D. Borah, S. Mahapatra & **N. Sahu**, [2204. 09671]
D. Borah, S. Mahapatra, D. Nanda, S.K. Sahoo & **N. Sahu** [2310.03721]

Today's talk: "Anatomy of singlet-doublet dark matter relic: Annihilation, coannihilation, coscattering and freezein", by Partha Kumar Paul, Sujit Kumar Sahoo and **Narendra Sahu**, [arXiv: 2412. 02607]

Singlet-Doublet mixed Fermion DM

After EW phase transition the mass matrix for neutral vector-like fermions is given by

$$\begin{pmatrix} \overline{N^0} & \overline{\chi^0} \end{pmatrix} \begin{pmatrix} M_N & m_D \\ m_D & M_\chi \end{pmatrix} \begin{pmatrix} N^0 \\ \chi^0 \end{pmatrix}$$

Where $m_D = Y < H >$

After diagonalising one gets:

$$M_1 = M_\chi - \frac{m_D^2}{M_N - M_\chi}; N_1 = \cos\theta\chi^0 + \sin\theta N^0$$

$$M_2 = M_N + \frac{m_D^2}{M_N - M_\chi}; N_2 = \cos\theta N^0 - \sin\theta\chi^0$$

$$M^\pm = M_1 \sin^2\theta + M_2 \cos^2\theta = M_N; N^\pm$$

Where $\tan 2\theta = \frac{m_D}{M_N - M_\chi}$

The model contains three independent parameters: $\{M_1, M_2, \sin\theta\}$ or $\{Y, M_1, M_2\}$

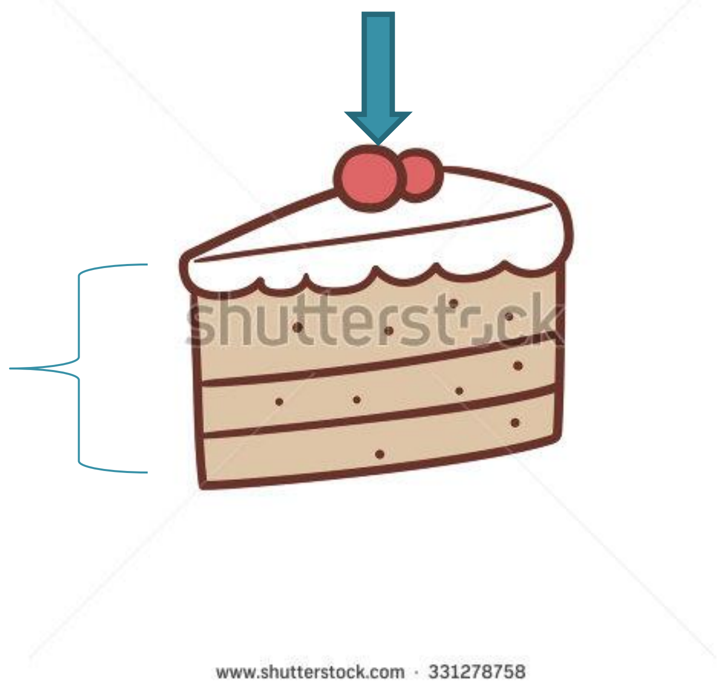
where, Y and $\sin\theta$ are related by

$$Y = \frac{\Delta M sin2\theta}{2v},$$

Where $\Delta M = M_2 - M_1$

DOUBLET CHERRY

SINGLET CAKE



The lightest particle is the N_1, which is candidate of dark matter with appropriate mixing angle θ

Relic density of SD-Fermion DM

The relic density can be obtained by solving the relevant Boltzmann equation:

$$\frac{dn}{dt} + 3\mathcal{H}n = -\langle\sigma v\rangle_{\rm eff}(n^2 - (n^{\rm eq})^2) \qquad \text{where } n = \sum_i n_i$$

Griest and Secklel: PRD 1991

$$\begin{aligned}\langle\sigma v\rangle_{eff} &= \frac{g_1^2}{g_{eff}^2}\langle\sigma v\rangle_{\overline{N_1}N_1} + \frac{2g_1g_2}{g_{eff}^2}\langle\sigma v\rangle_{\overline{N_1}N_2}\left(1+\frac{\Delta m}{m_{N_1}}\right)^{\frac{3}{2}} e^{-x\frac{\Delta m}{m_{N_1}}} \\ &+ \frac{2g_1g_3}{g_{eff}^2}\langle\sigma v\rangle_{\overline{N_1}N^-}\left(1+\frac{\Delta m}{m_{N_1}}\right)^{\frac{3}{2}} e^{-x\frac{\Delta m}{m_{N_1}}} \\ &+ \frac{2g_2g_3}{g_{eff}^2}\langle\sigma v\rangle_{\overline{N_2}N^-}\left(1+\frac{\Delta m}{m_{N_1}}\right)^{3} e^{-2x\frac{\Delta m}{m_{N_1}}} \\ &+ \frac{g_2^2}{g_{eff}^2}\langle\sigma v\rangle_{\overline{N_2}N_2}\left(1+\frac{\Delta m}{m_{N_1}}\right)^{3} e^{-2x\frac{\Delta m}{m_{N_1}}} \\ &+ \frac{g_3^2}{g_{eff}^2}\langle\sigma v\rangle_{N^+N^-}\left(1+\frac{\Delta m}{m_{N_1}}\right)^{3} e^{-2x\frac{\Delta m}{m_{N_1}}}.\end{aligned}$$

annihilation

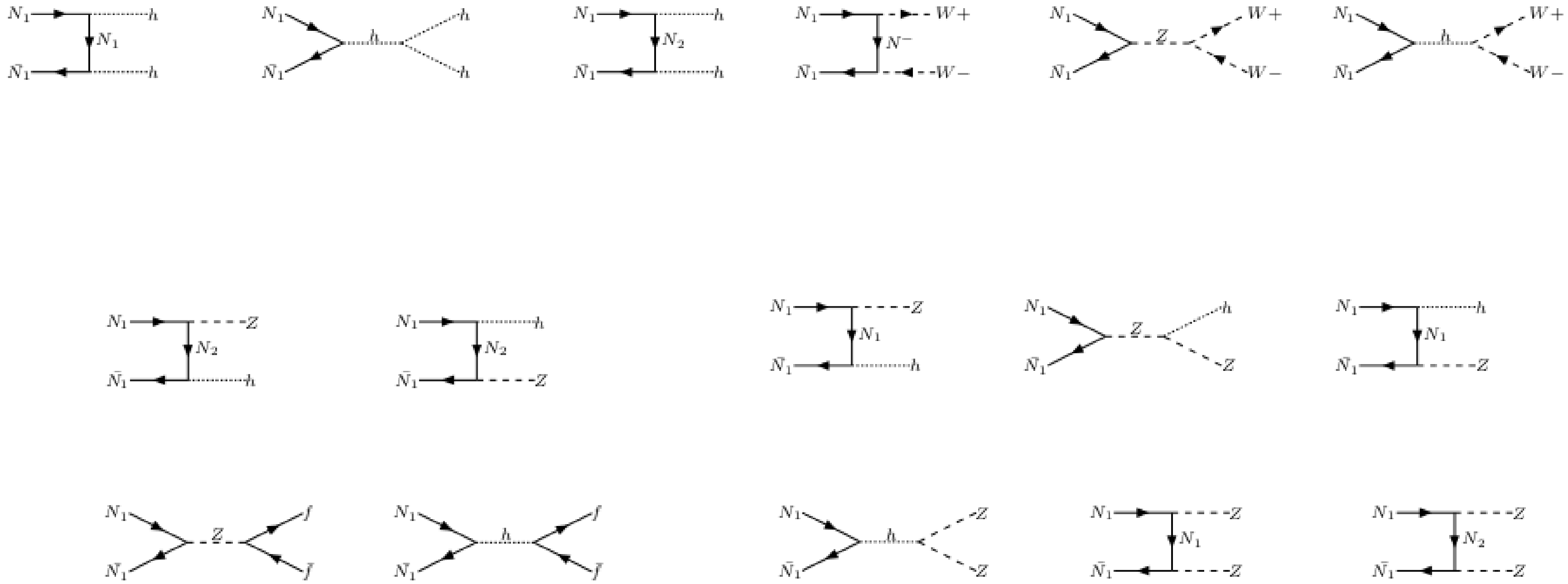
Independent of singlet-doublet mixing

Where $g_{eff} = g1 + g_2(1+\Delta)^{3/2}exp(-x\Delta) + g_3(1+\Delta)^{3/2}exp(-x\Delta)$.

With $\Delta = \frac{M_i - M_1}{M_1} \qquad x = \frac{M_1}{T}$

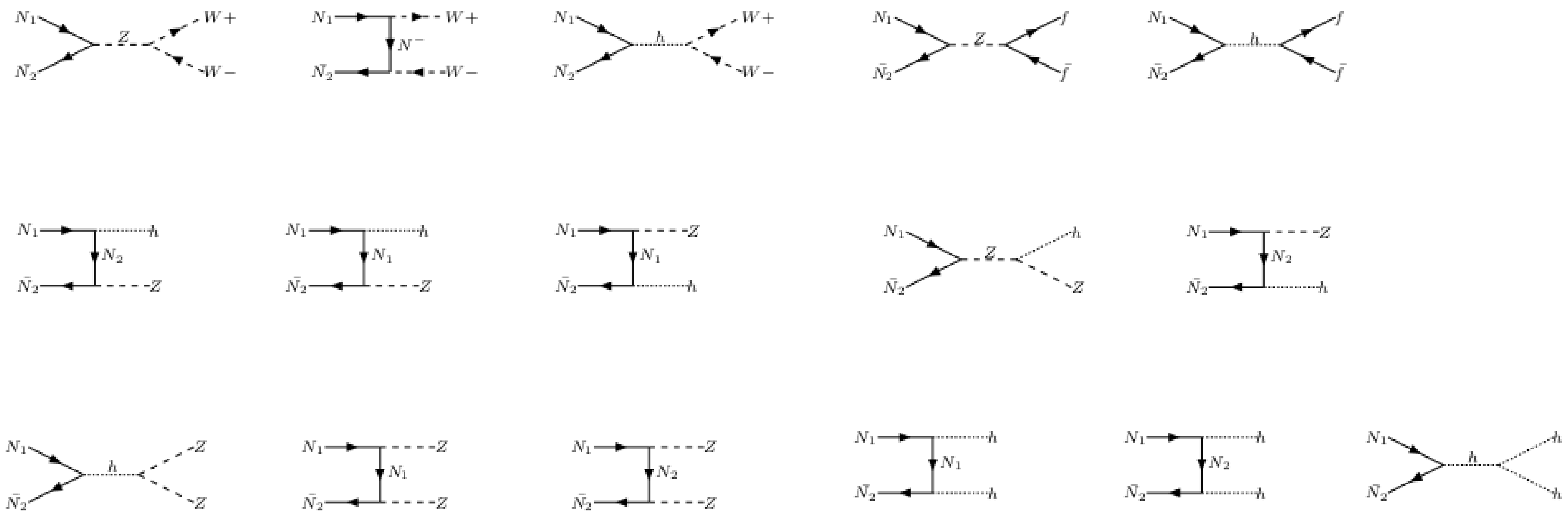
Annihilation processes

$$N_1 \overline{N_1} \rightarrow SM$$



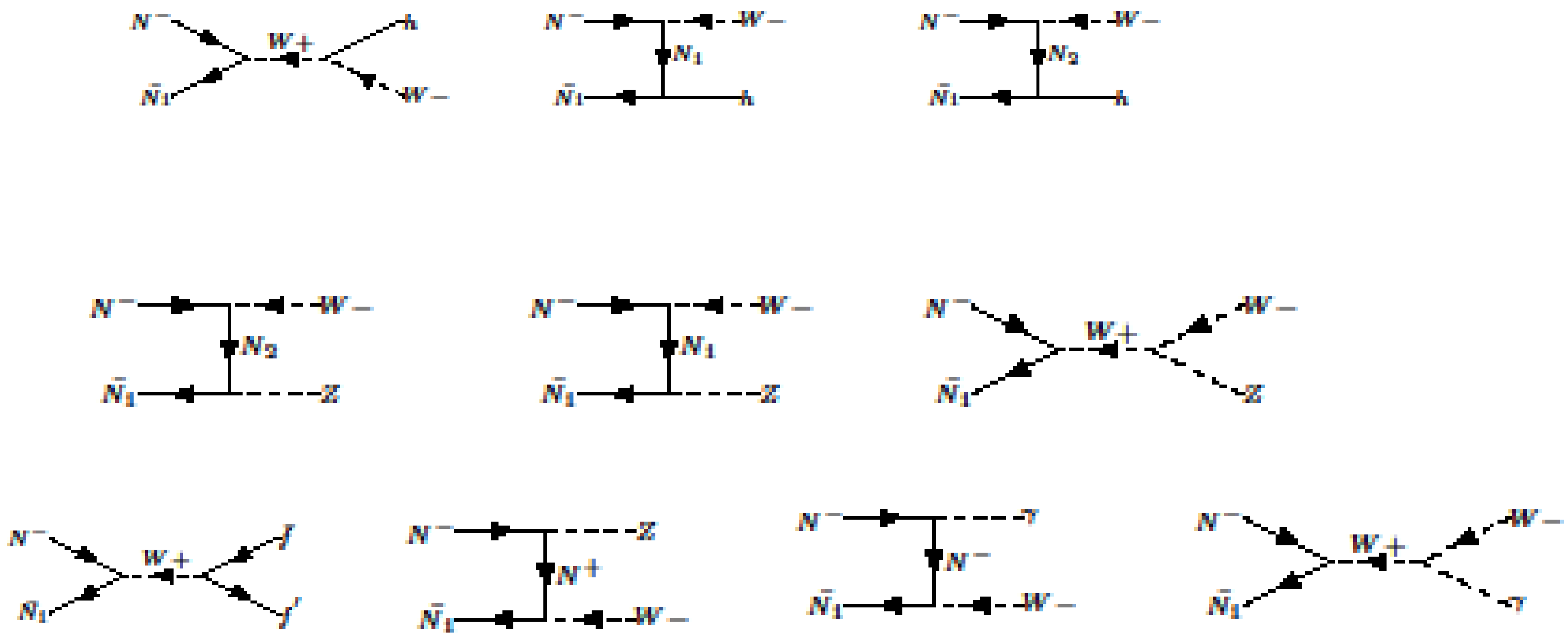
Co-annihilation processes

$$N_1 N_2 \rightarrow SM$$



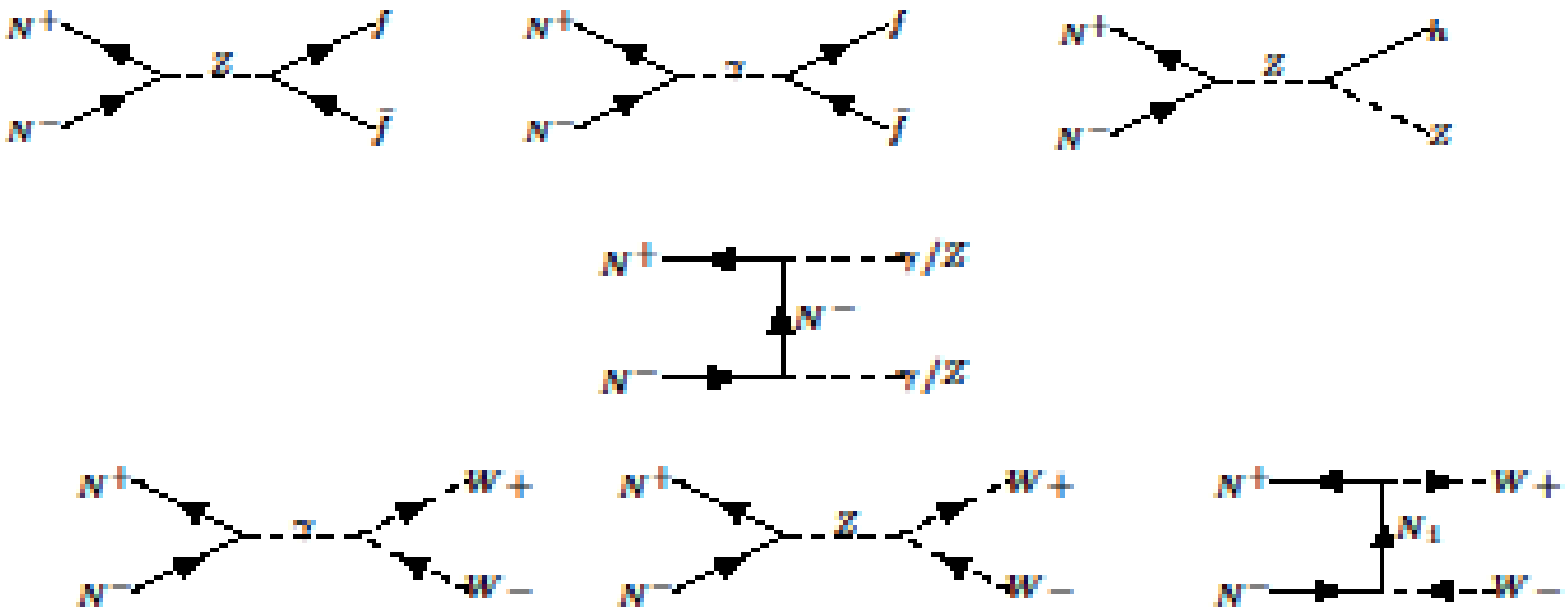
Co-annihilation processes

$$N_1 N^- \to SM$$



Co-annihilation processes

$$N^+ N^- \rightarrow SM$$

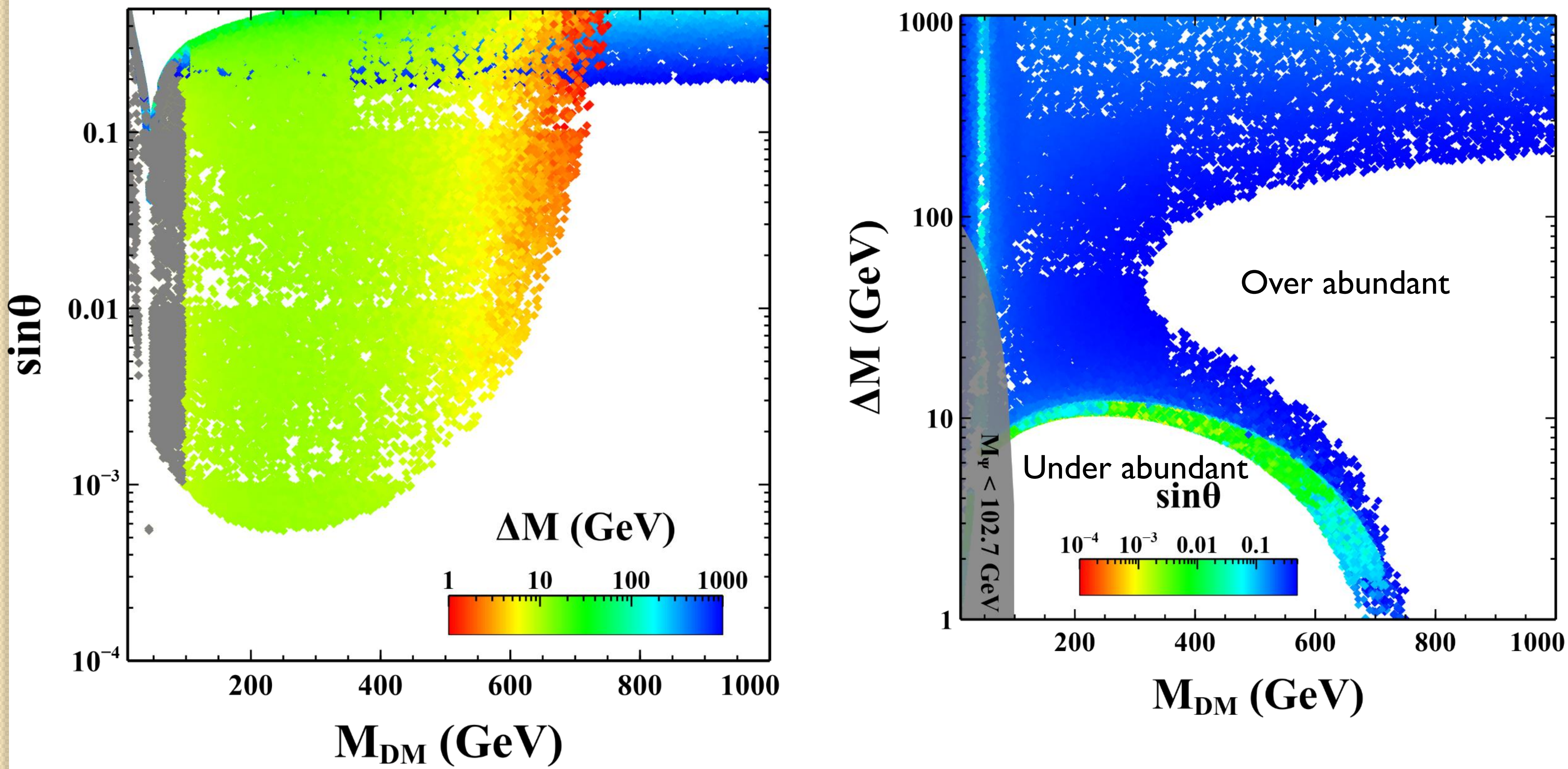


We look for the observed relic abundance in the parameter space spanned by

$$M_1, M_2 \approx M^{\pm}, \sin\theta$$

We assume both singlet and doublet components decouple at the same epoch. This is true only for relatively large singlet-doublet mixing as shown by the following diagram:

$M_1 = M_{DM}$



Two Boltzmann equations for the dark sector

As the singlet-Doublet mixing is reduced further, the singlet and doublet components decouple at different epochs. The singlet decouple early with a larger abundance, while the doublet components decouple at late epochs with a smaller abundance. Therefore, one needs two Boltzmann equations for the dark sector particles: $N_1, N_2, N^{\pm}$. One equation is not sufficient as $N^+N^- \rightarrow SM$ is independent of singlet-doublet mixing.

Sector-1: N_1 (Dominantly singlet with a little admixture of doublet)

Sector-2: N_2 (Dominantly doublet with a little admixture of singlet), $N^{\pm}$

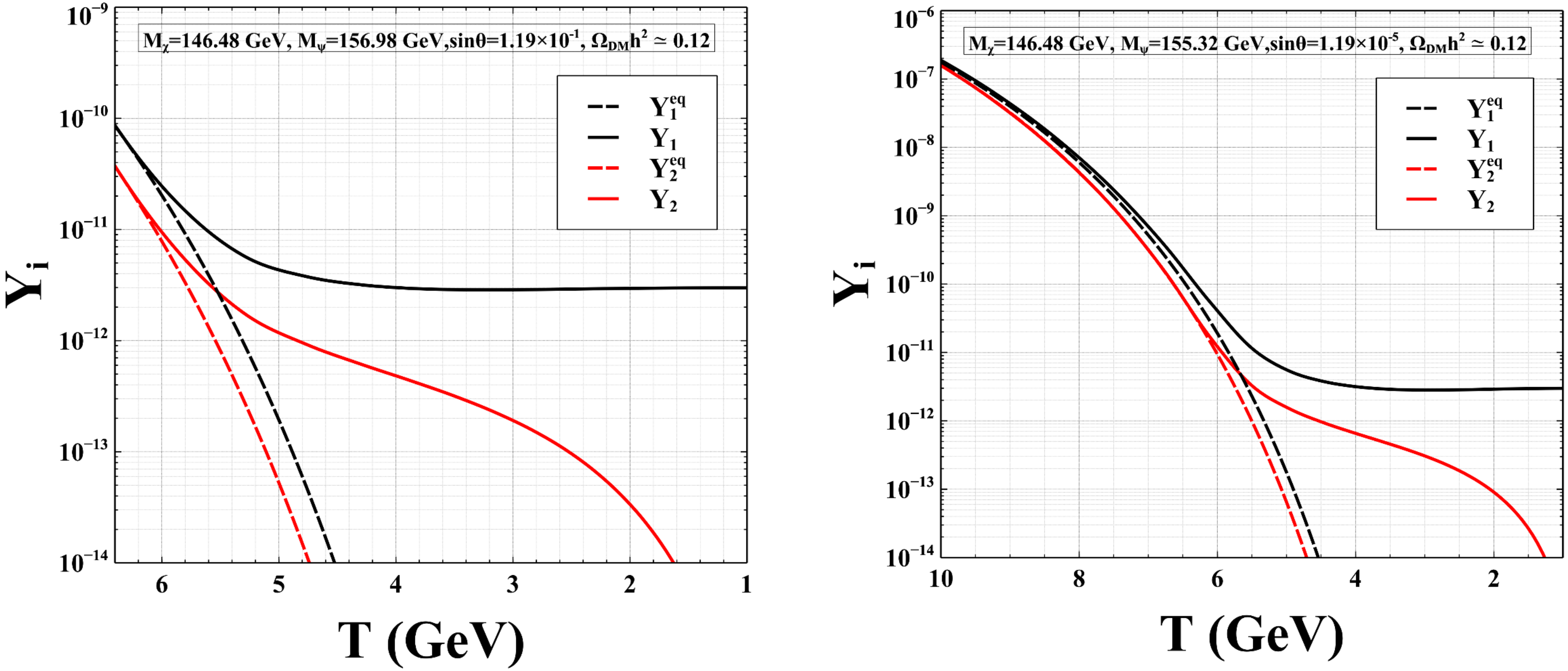
Sector-0: SM particles

$$\frac{dY_1}{dT} = \frac{1}{3\mathcal{H}}\frac{ds}{dT}\Bigg[\langle\sigma_{1100}v\rangle(Y_1^2 - Y_1^{eq2}) + \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_1^{eq2}}{Y_2^{eq2}}\right) + \langle\sigma_{1200}v\rangle(Y_1Y_2 - Y_1^{eq}Y_2^{eq})$$
$$+ \langle\sigma_{1222}v\rangle\left(Y_1Y_2 - Y_2^2\frac{Y_1^{eq}}{Y_2^{eq}}\right) - \langle\sigma_{1211}v\rangle\left(Y_1Y_2 - Y_1^2\frac{Y_2^{eq}}{Y_1^{eq}}\right) - \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\Bigg],$$

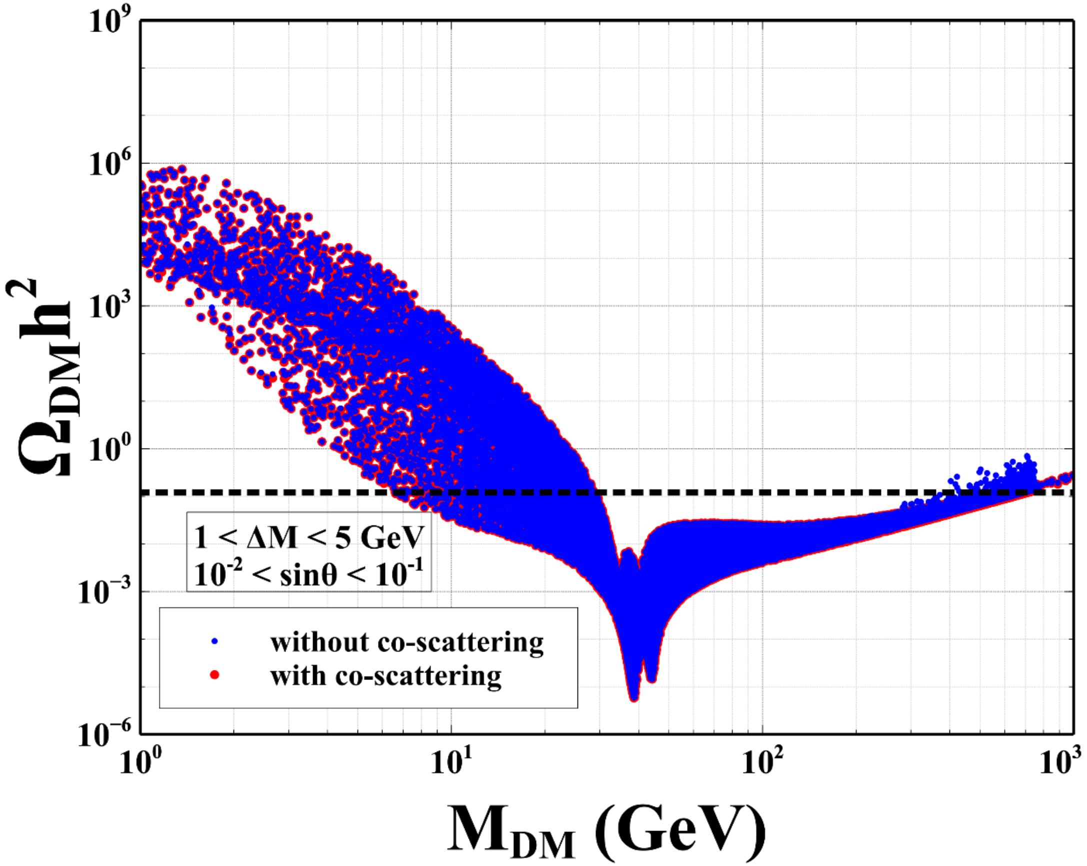
$$\frac{dY_2}{dT} = \frac{1}{3\mathcal{H}}\frac{ds}{dT}\Bigg[\langle\sigma_{2200}v\rangle(Y_2^2 - Y_2^{eq2}) - \langle\sigma_{1122}v\rangle\left(Y_1^2 - Y_2^2\frac{Y_1^{eq2}}{Y_2^{eq2}}\right) + \langle\sigma_{1200}v\rangle(Y_1Y_2 - Y_1^{eq}Y_2^{eq}) - \langle\sigma_{1222}v\rangle\left(Y_1Y_2 - Y_2^2\frac{Y_1^{eq}}{Y_2^{eq}}\right) + \langle\sigma_{1211}v\rangle\left(Y_1Y_2 - Y_1^2\frac{Y_2^{eq}}{Y_1^{eq}}\right) + \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\Bigg],$$

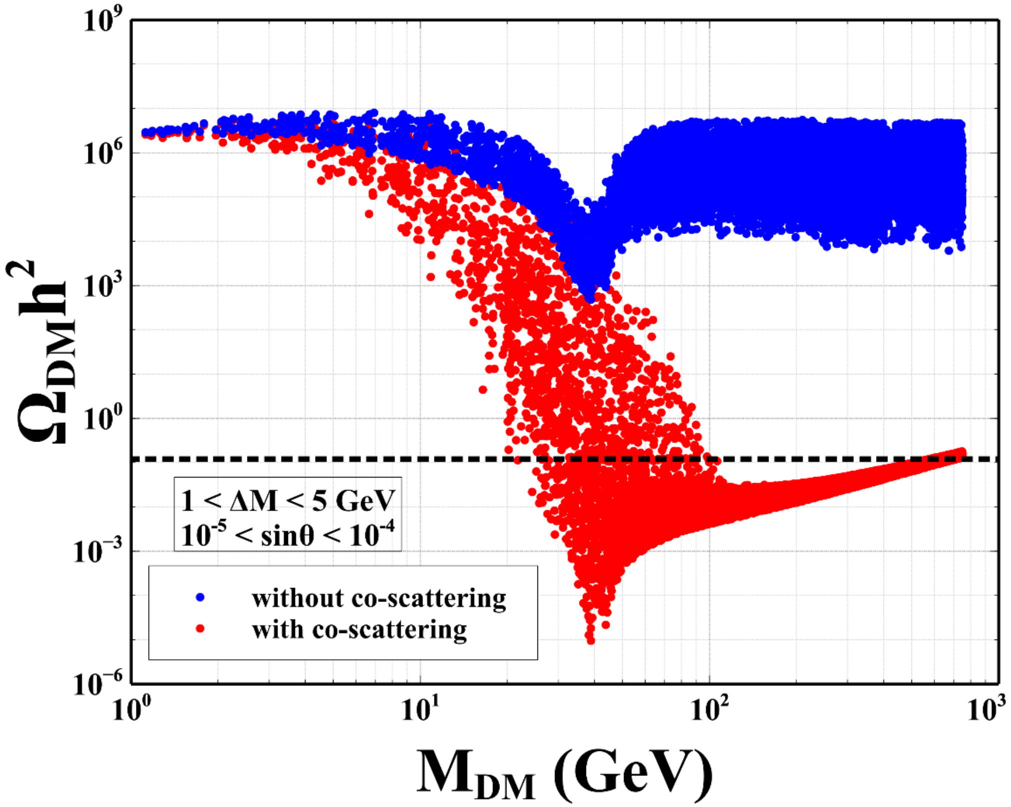
Decay + coscattering

Y_1 = Comoving number density of sector-1 particle
Y_2 = Comoving number density of sector-2 particles

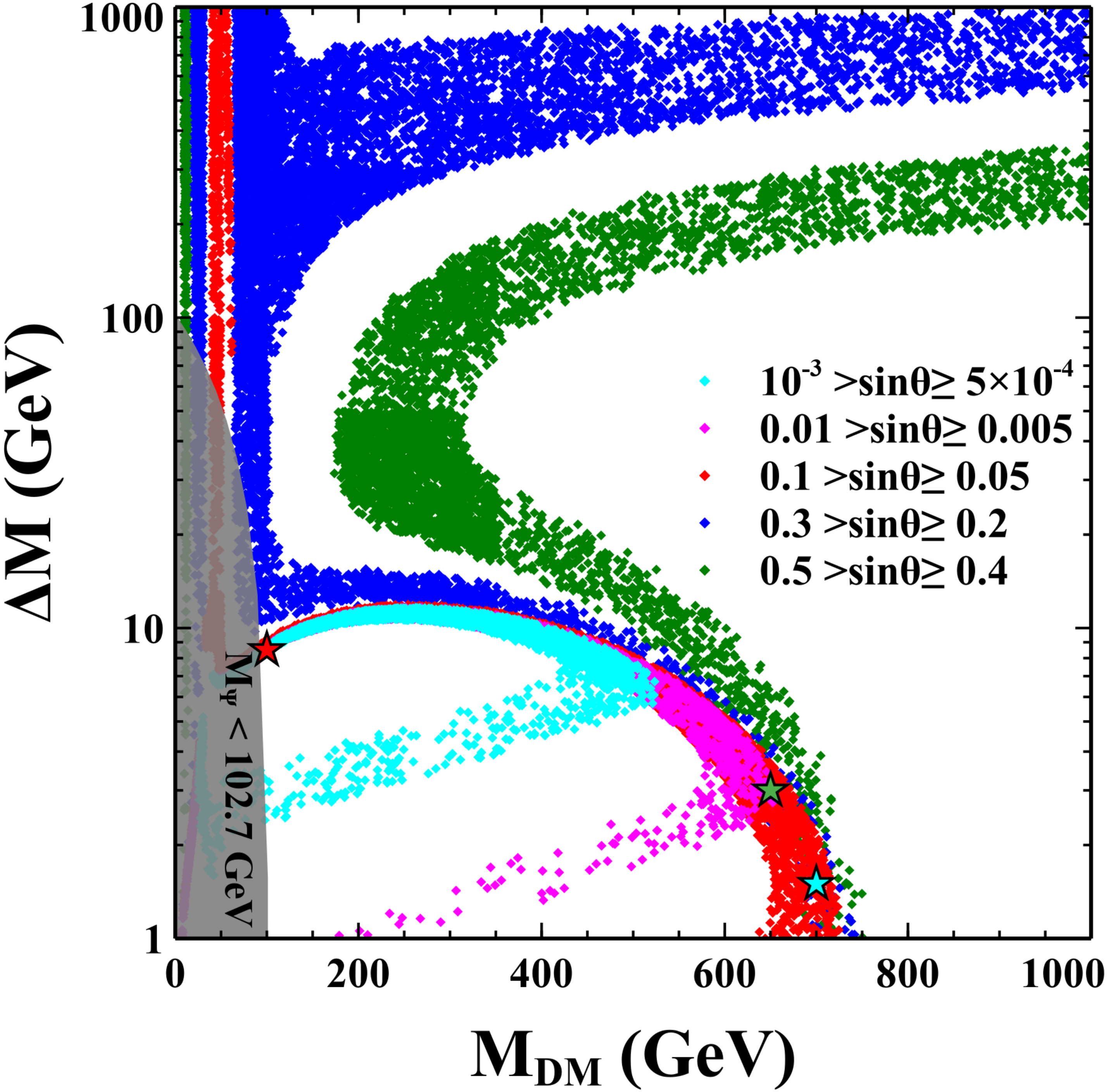


Effect of coscattering and decay on relic density

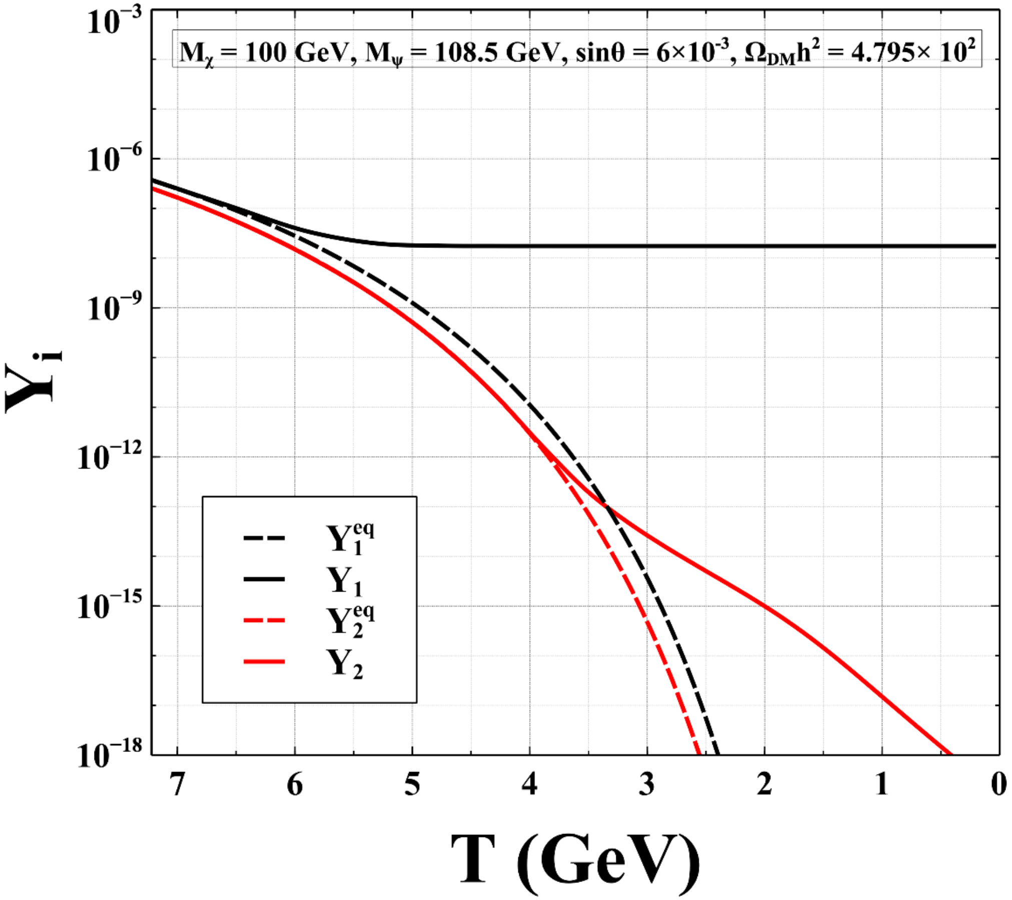


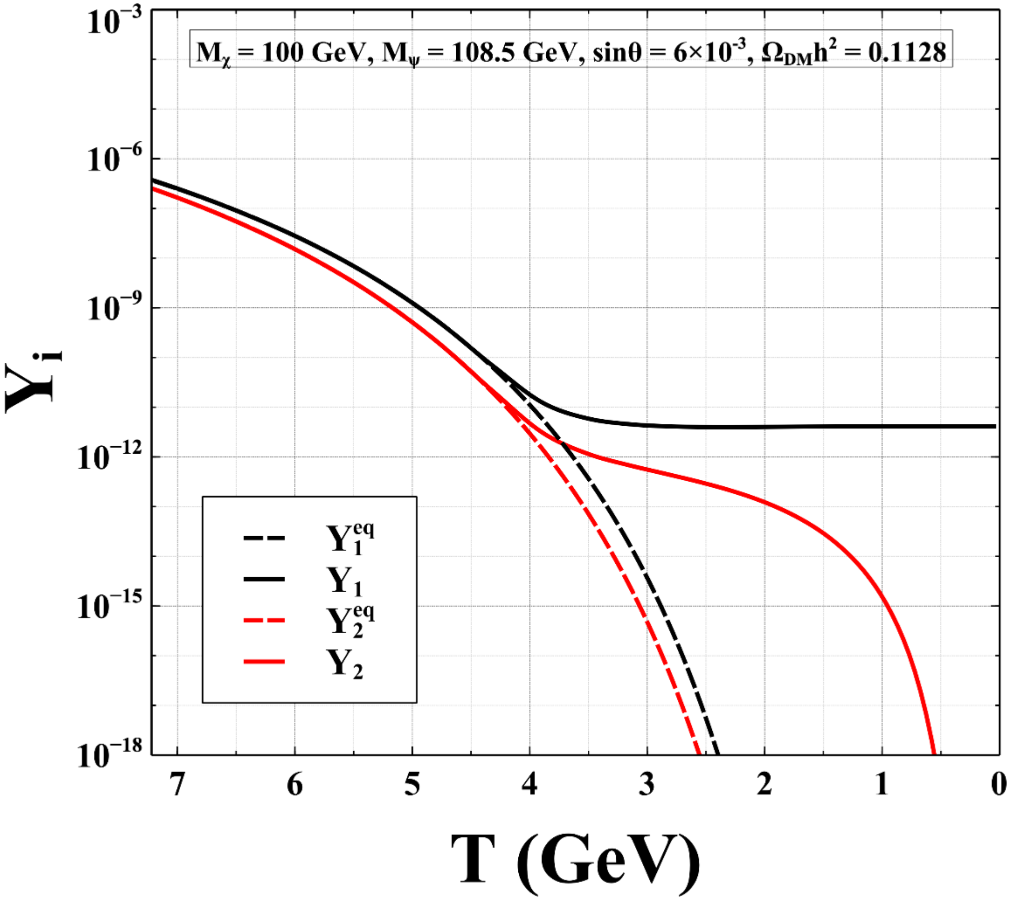


Without including coscattering effect, but decay included

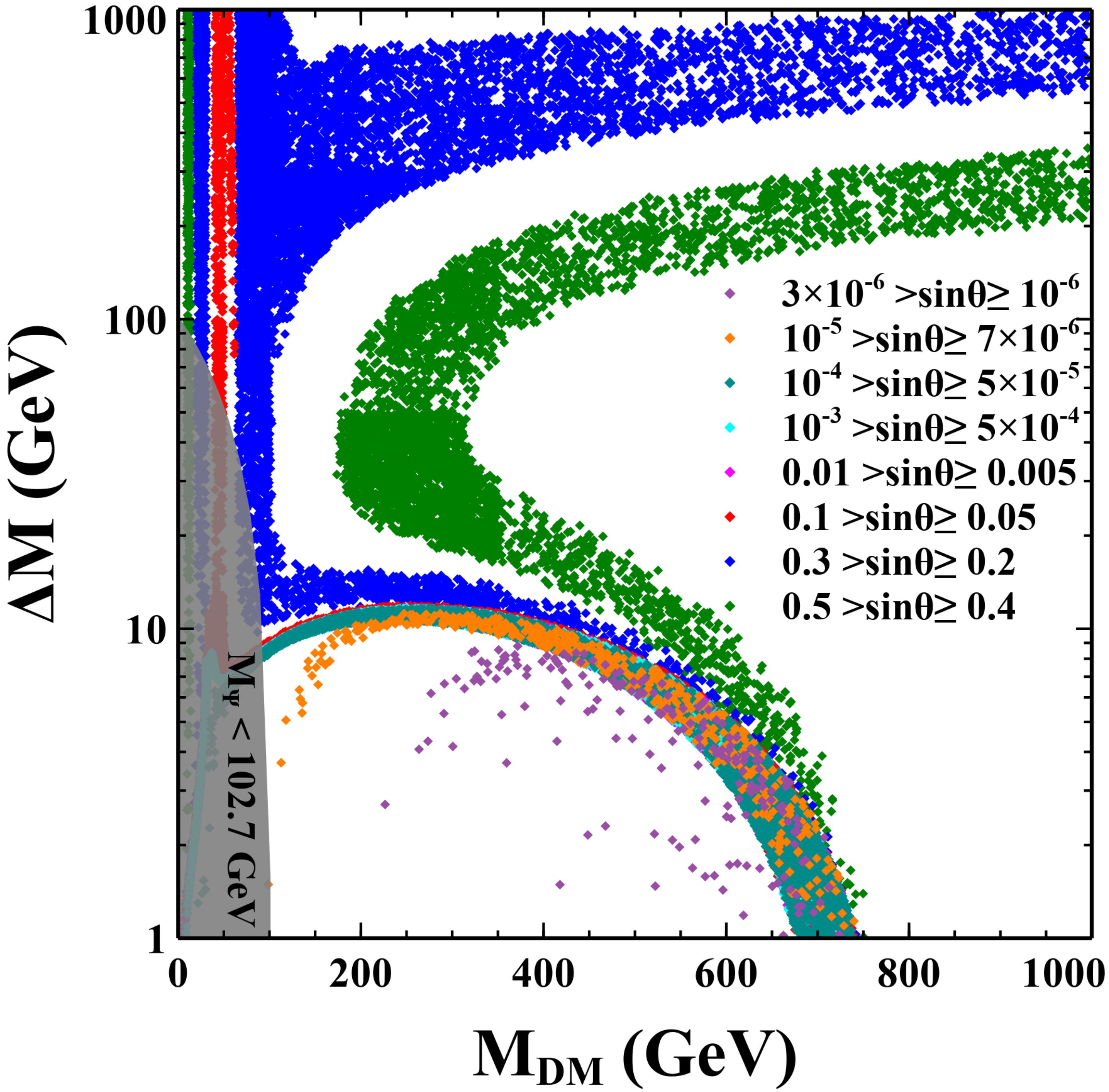


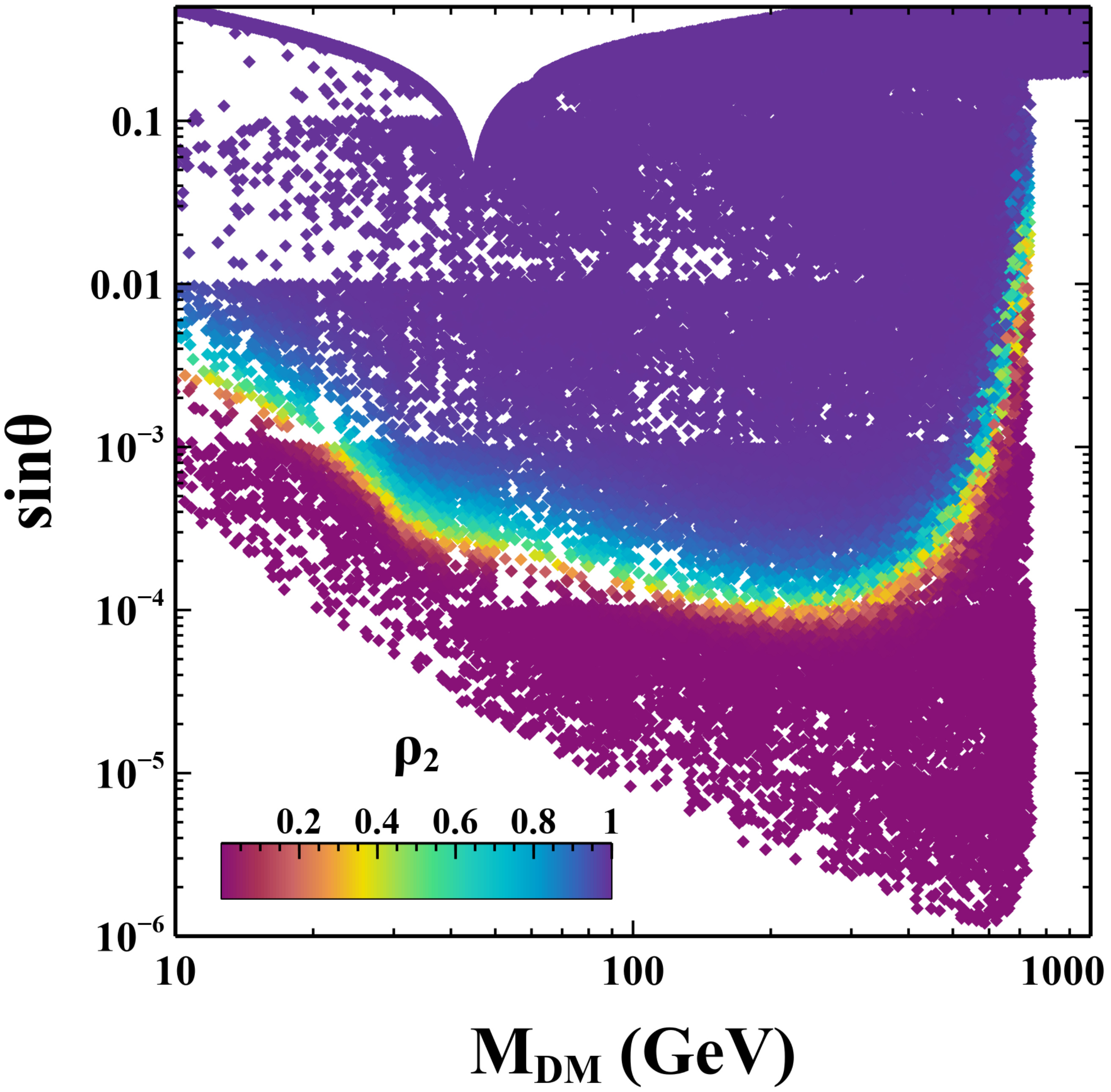
Point	$M_{\rm DM}$ (GeV)	ΔM (GeV)	$\sin\theta$	$\Omega_{2s}h^2$(no co-scattering)	$\Omega_{2s}h^2$(no co-scattering) without decay
A (★)	100	8.5	6×10^{-3}	0.1128	4.795×10^{2}
B (★)	650	3	9.5×10^{-3}	0.1269	2.503×10^{1}
C (★)	700	1.5	9.5×10^{-3}	0.3445	2.114×10^{1}
C (★)	700	1.5	9.9×10^{-2}	0.1234	0.1434





Including coscattering and decay effect



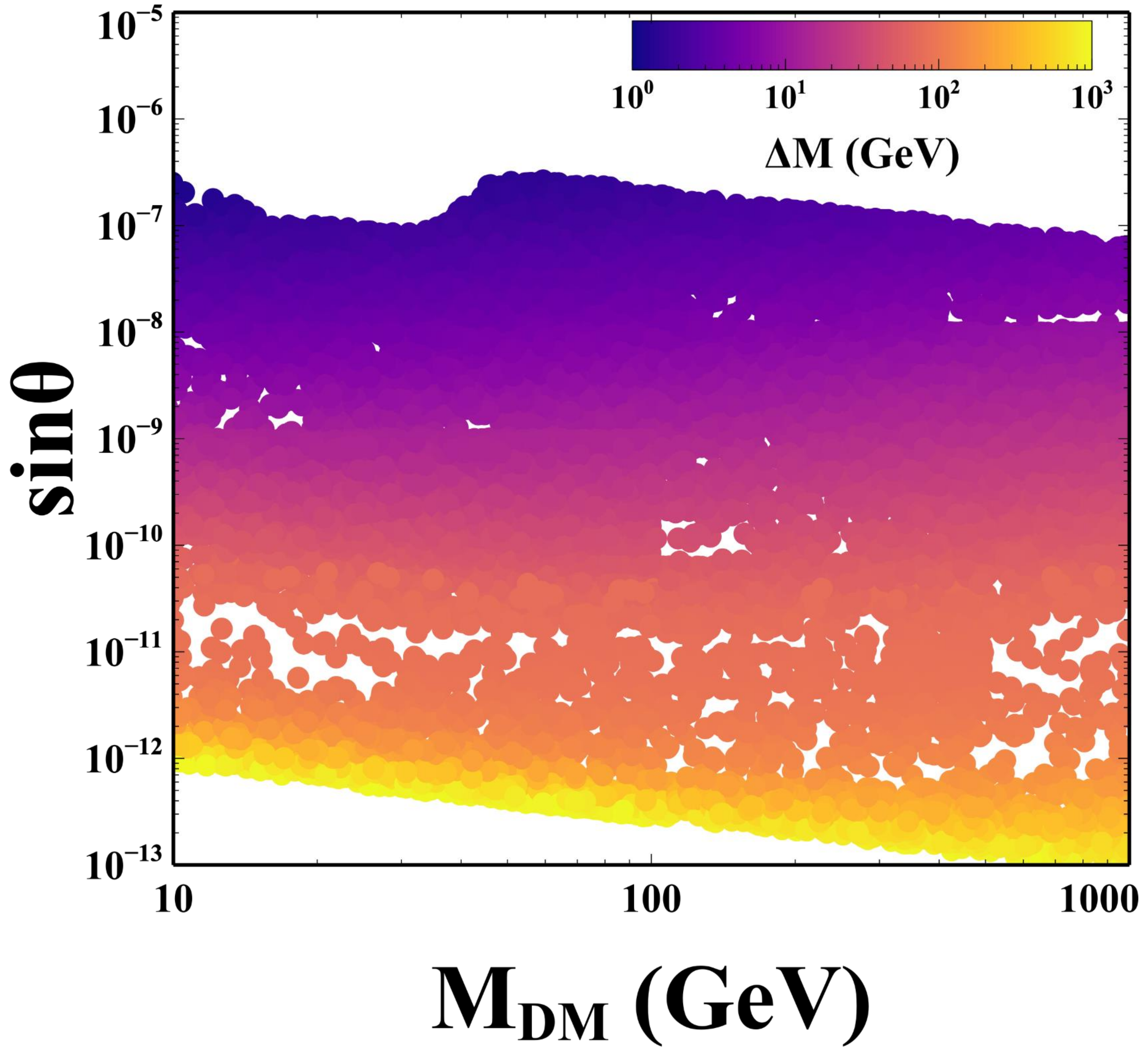


$$\rho_2 = \frac{\Omega_{2s}h^2}{\Omega_{2s}h^2(\text{no coscattering})},$$

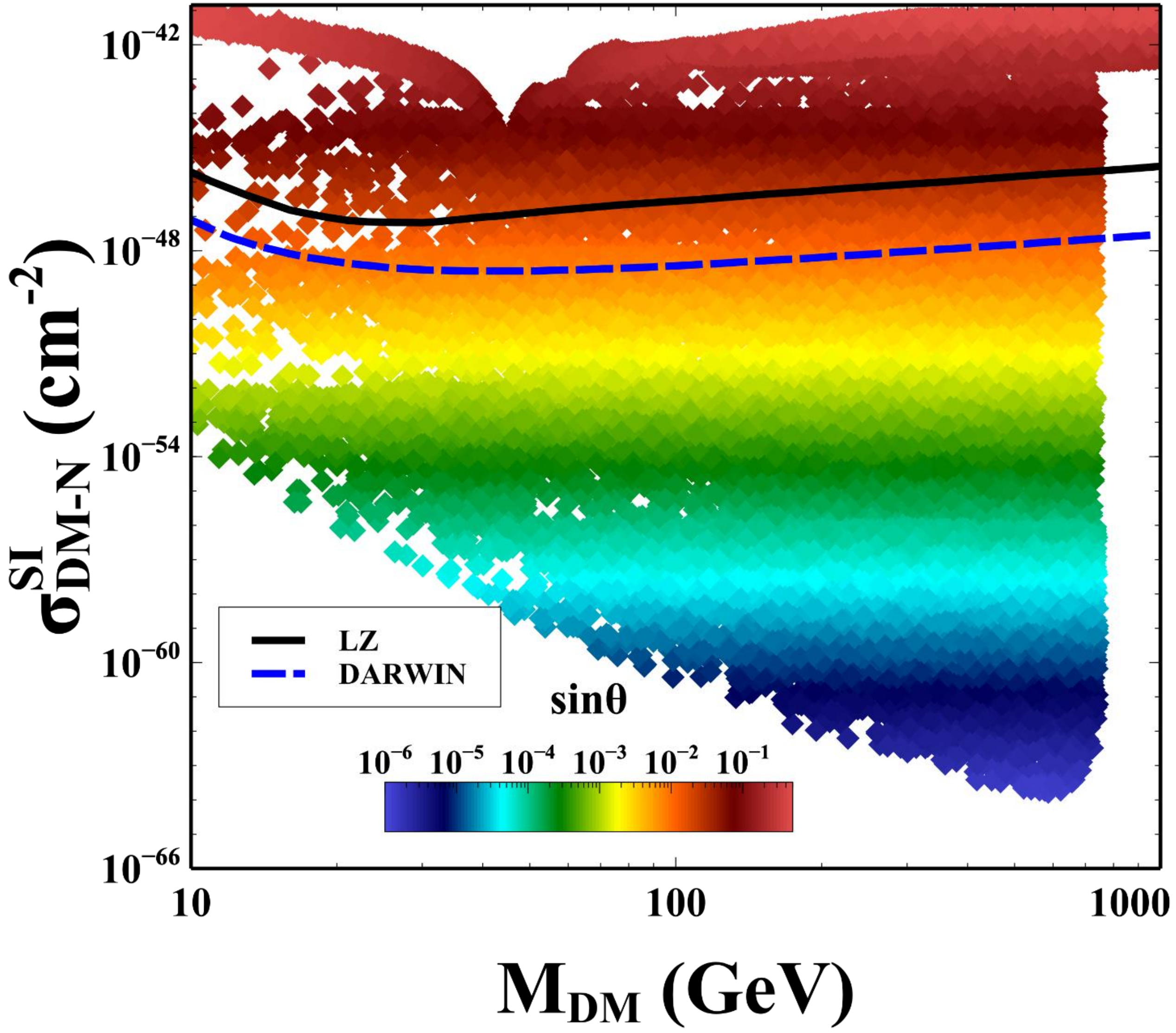
SD-Dark matter relic by Freeze-in ($\sin\theta < 10^{-6}$)

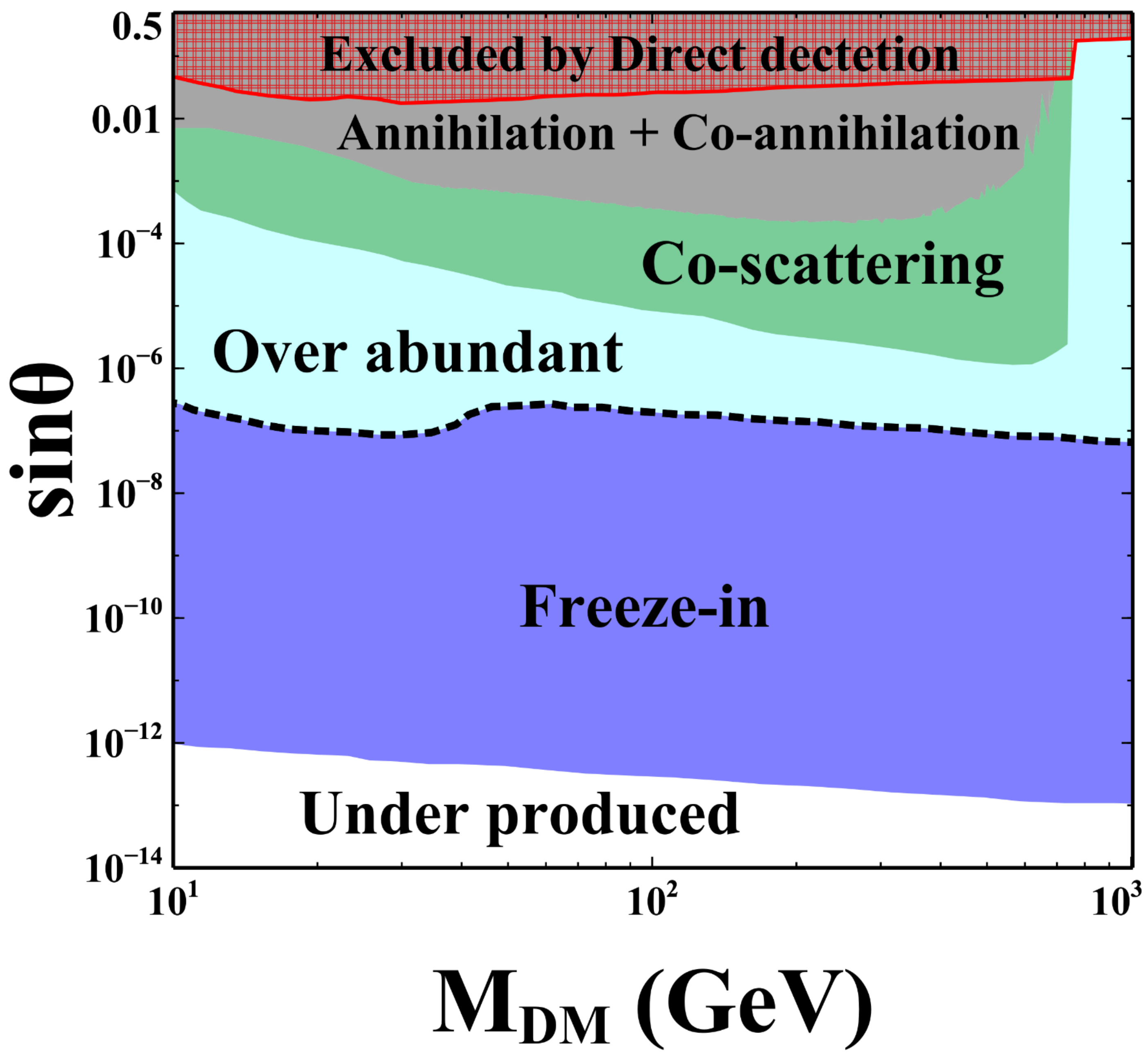
In this case the singlet does not equilibrate with the doublet. Therefore, freeze-out option is excluded. However, the relic can be produced via freezein mechanism. The relevant Boltzmann equation is

$$\frac{dY_1}{dx} = \frac{\Gamma_{tot}}{\mathcal{H}x}\frac{K_1(x)}{K_2(x)}Y_2^{eq};$$


10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
10^−12
10^−13
sinθ
10^0
10^1
10^2
10^3
ΔM (GeV)
10
100
1000
M_DM (GeV)

DD constraints on model parameters

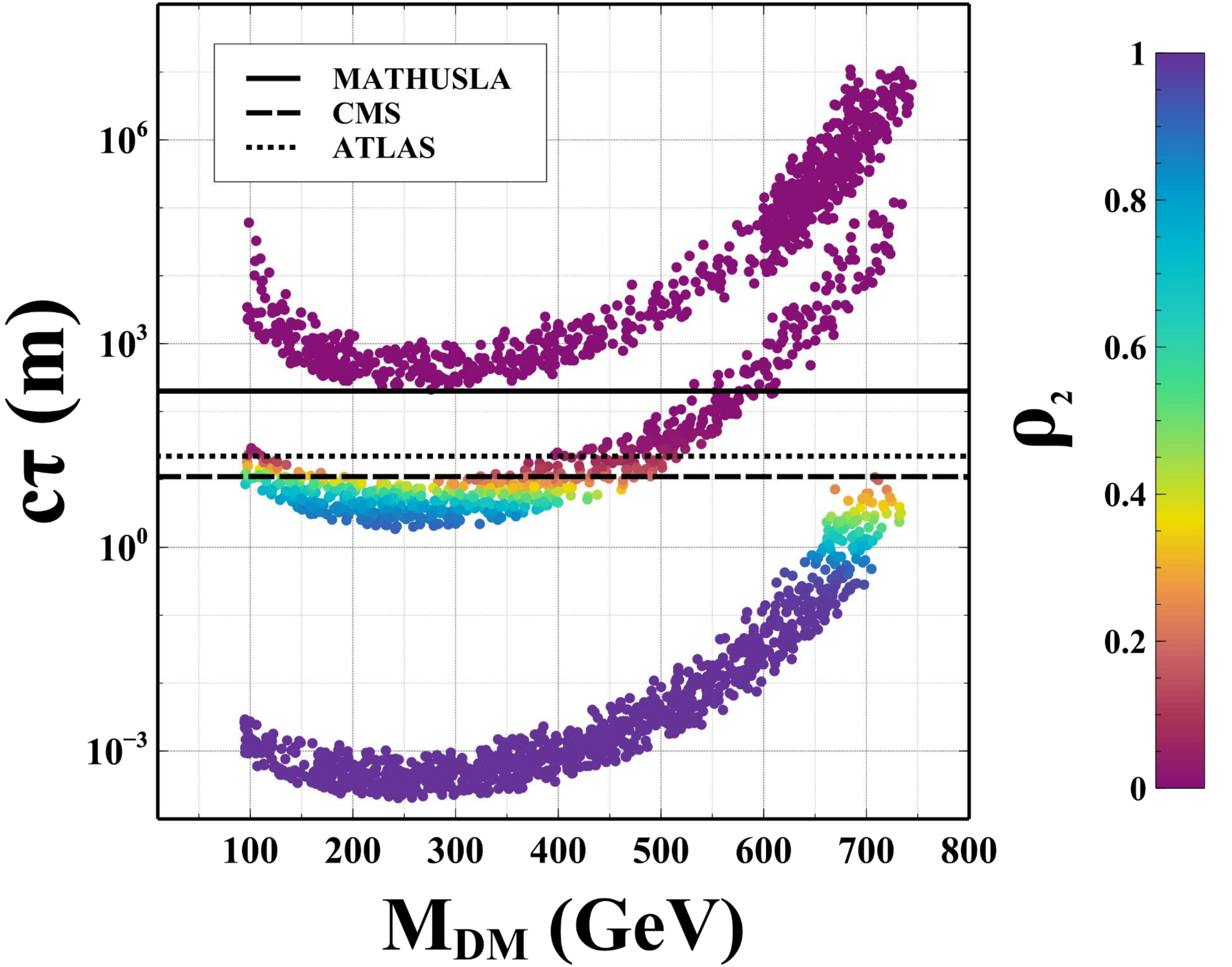



Excluded by Direct dectetion
Annihilation + Co-annihilation
Co-scattering
Over abundant
Freeze-in
Under produced
0.5
0.01
10^−4
10^−6
10^−8
10^−10
10^−12
10^−14
10^1
10^2
10^3
sinθ
M_DM (GeV)

Small singlet-doublet mixing

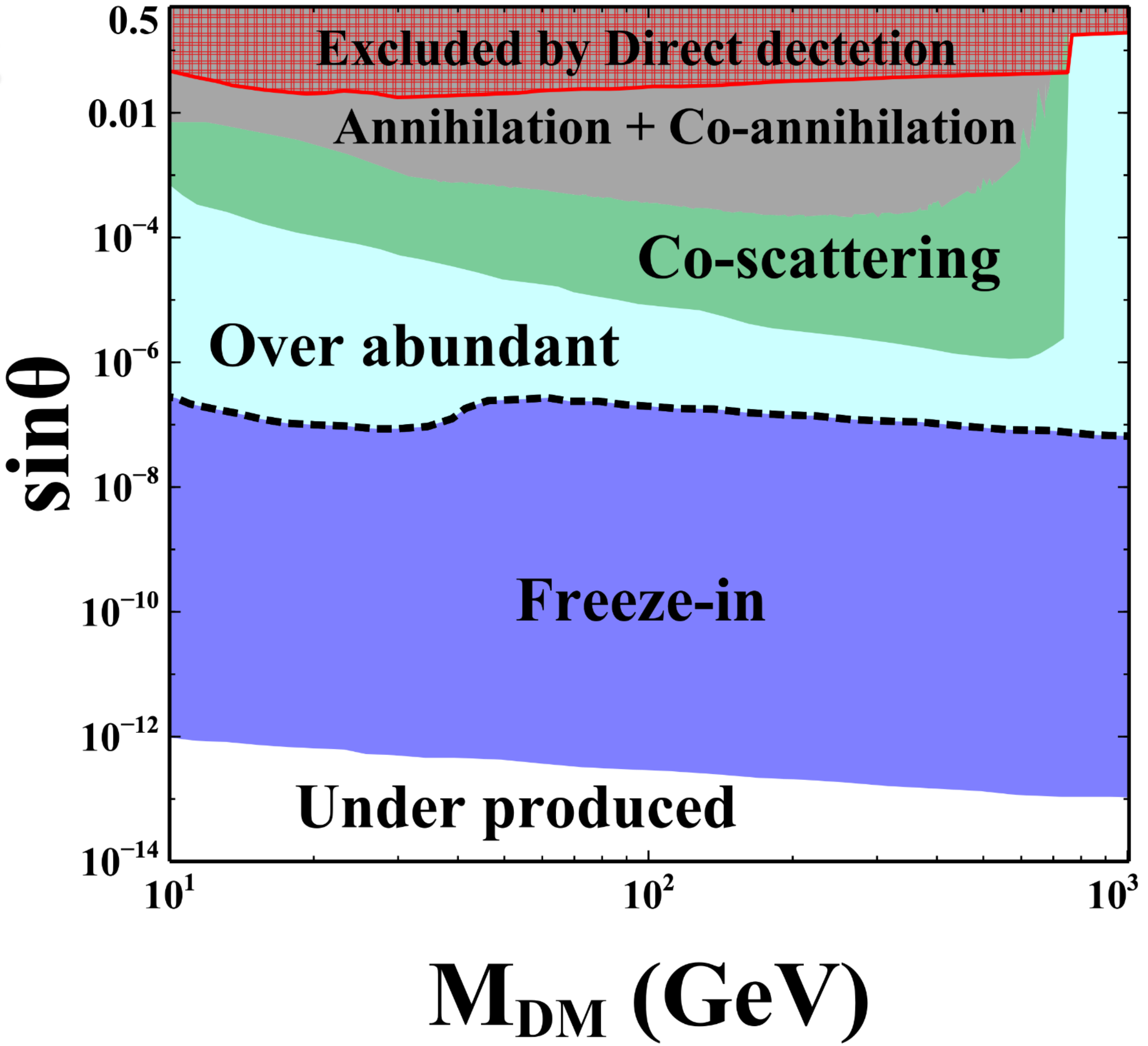
↓

Testing the Hypothesis at collider via displaced vertex signature…



MATHUSLA
CMS
ATLAS
10^6
10^3
10^0
10^{-3}
$c\tau$ (m)
100
200
300
400
500
600
700
800
M_{DM} (GeV)
1
0.8
0.6
0.4
0.2
0
ρ_2

Summary plot



Thank you