The dynamics and detection possibility of a pseudo FIMP in presence of a thermal Dark Matter

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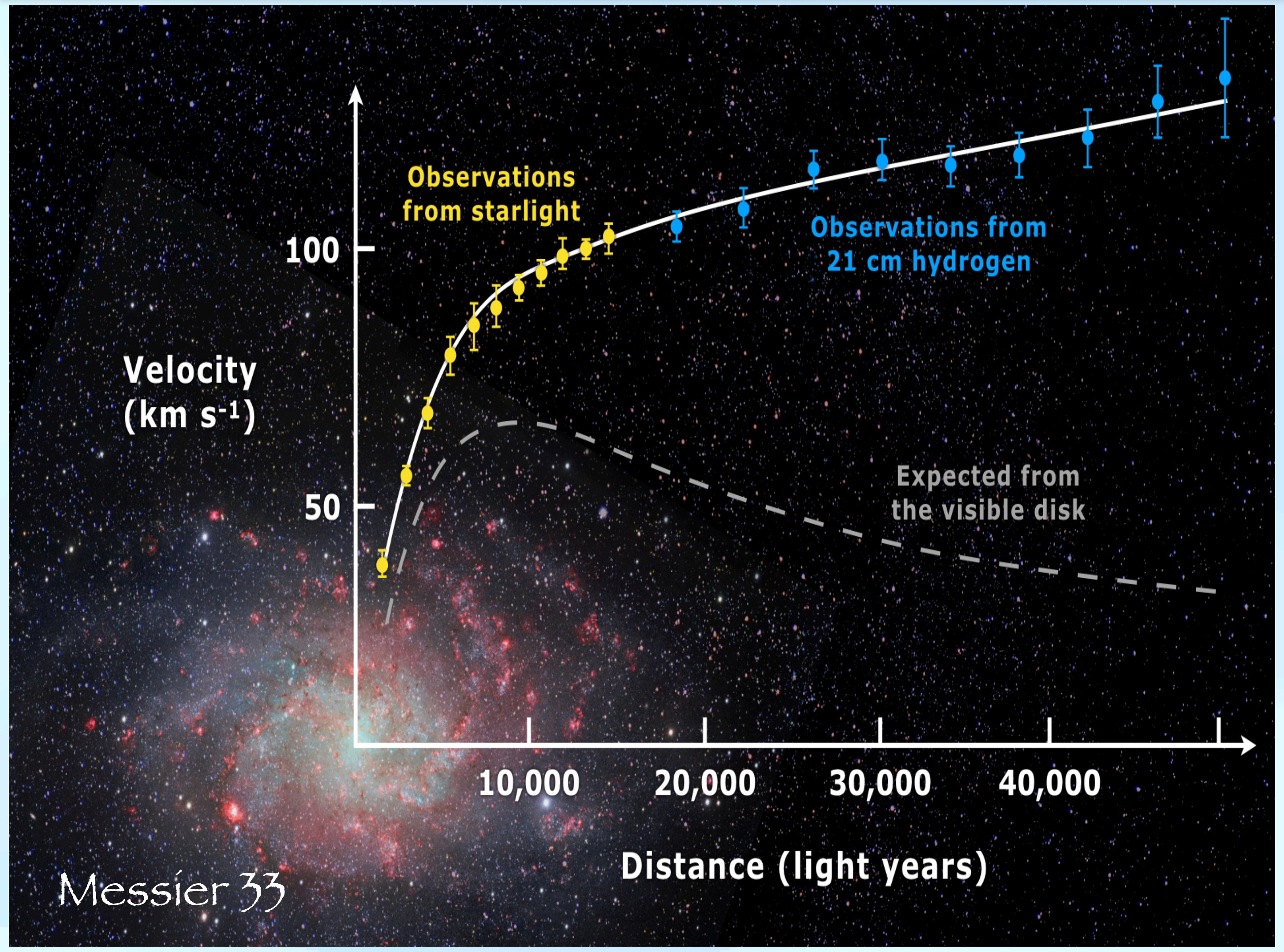
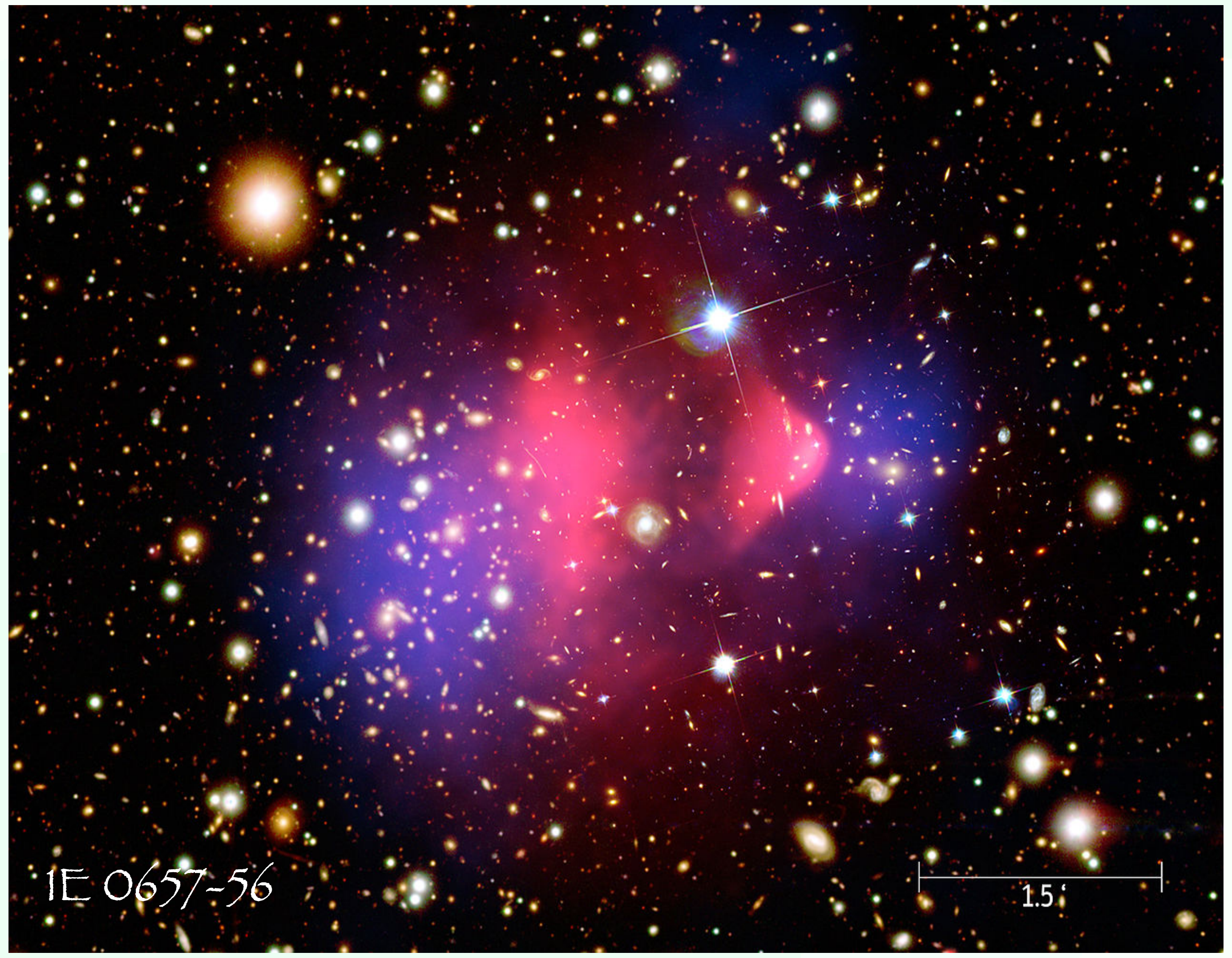
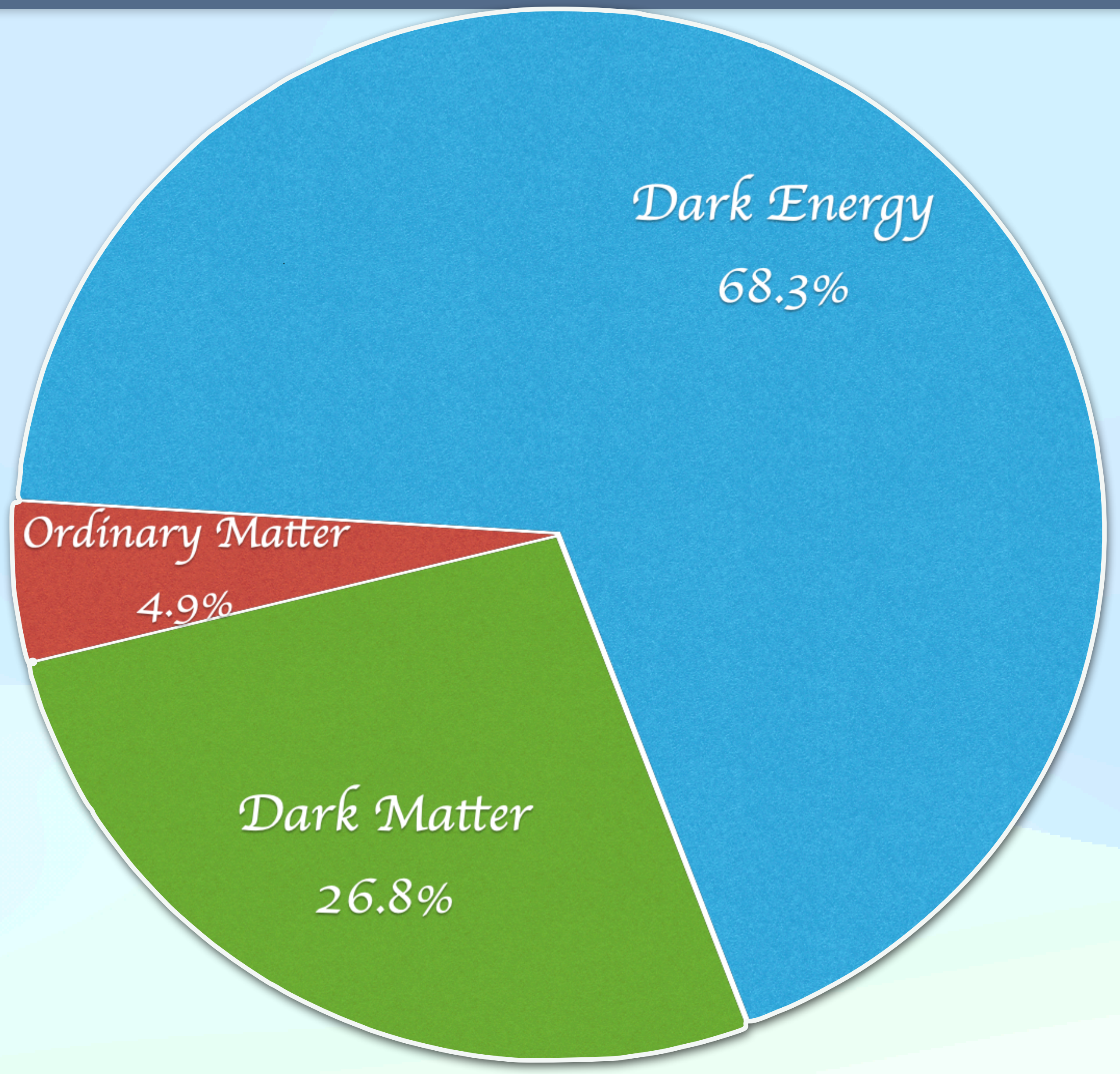
Dark Matter



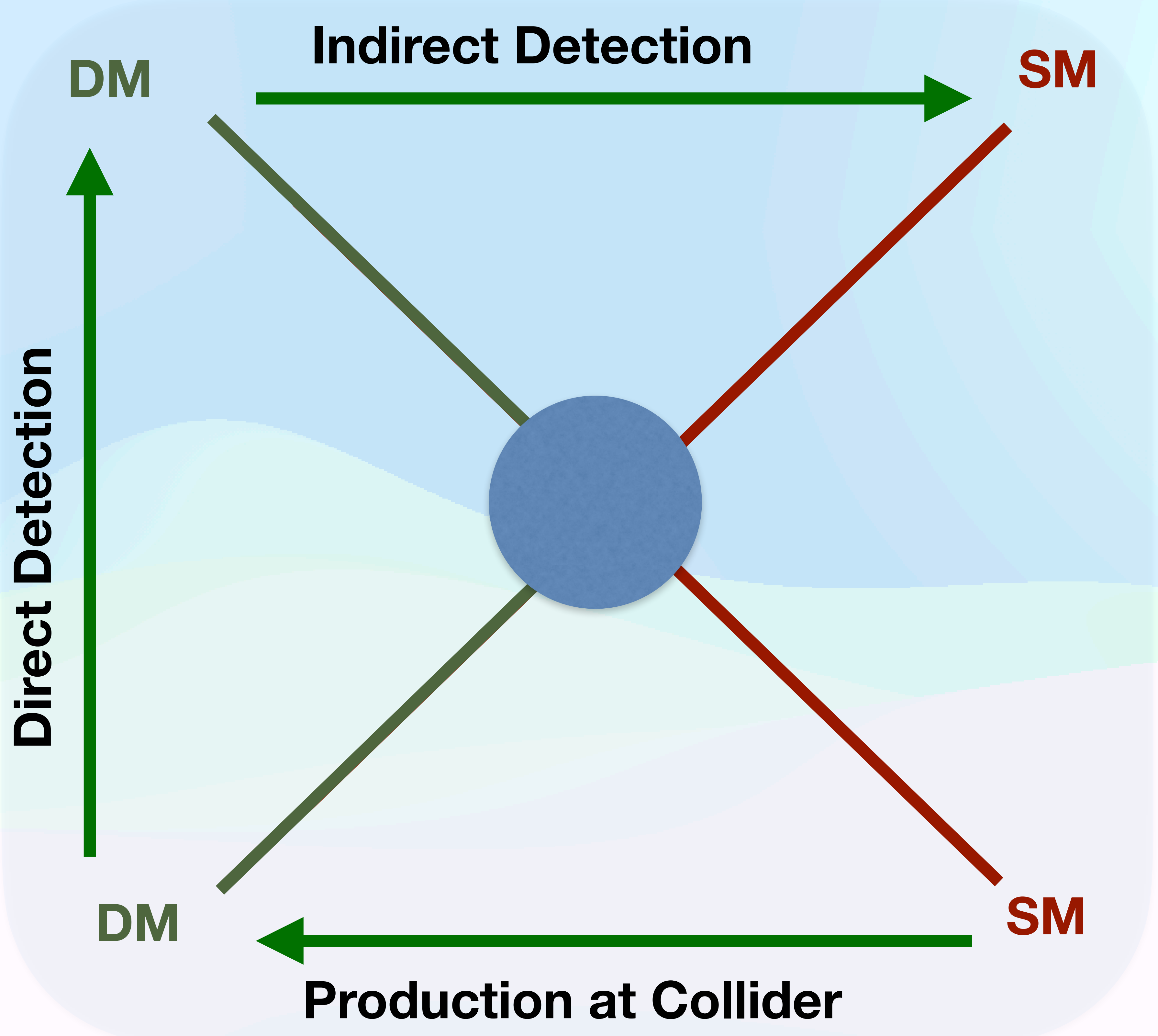
Galaxy Rotation Curve



Bullet Cluster



CMBR



Summary of DM evidence

$$\Omega_{DM}h^2 = 0.1200 \pm 0.0012$$

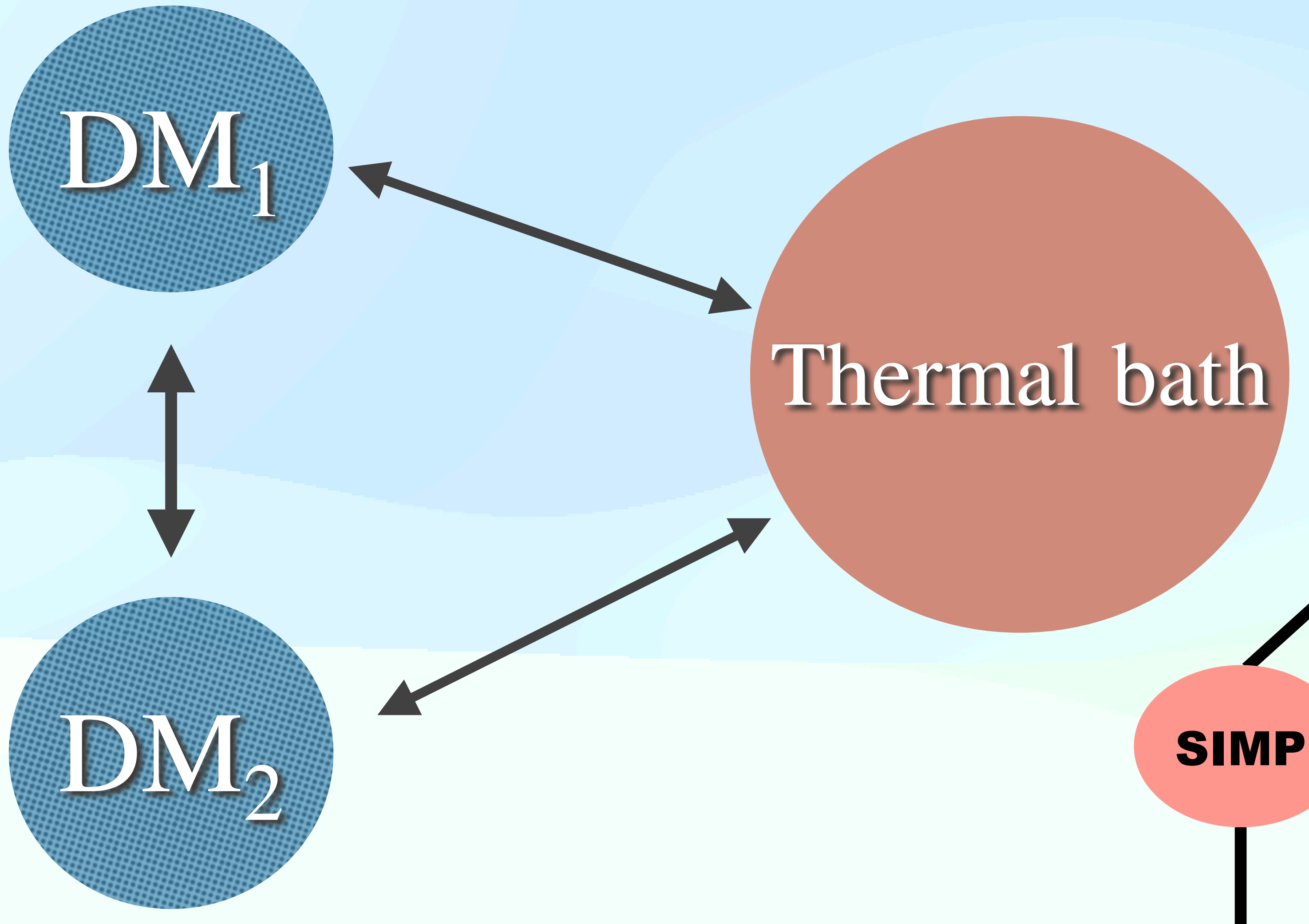
- What we know about DM ?
- What we don't know about DM ?

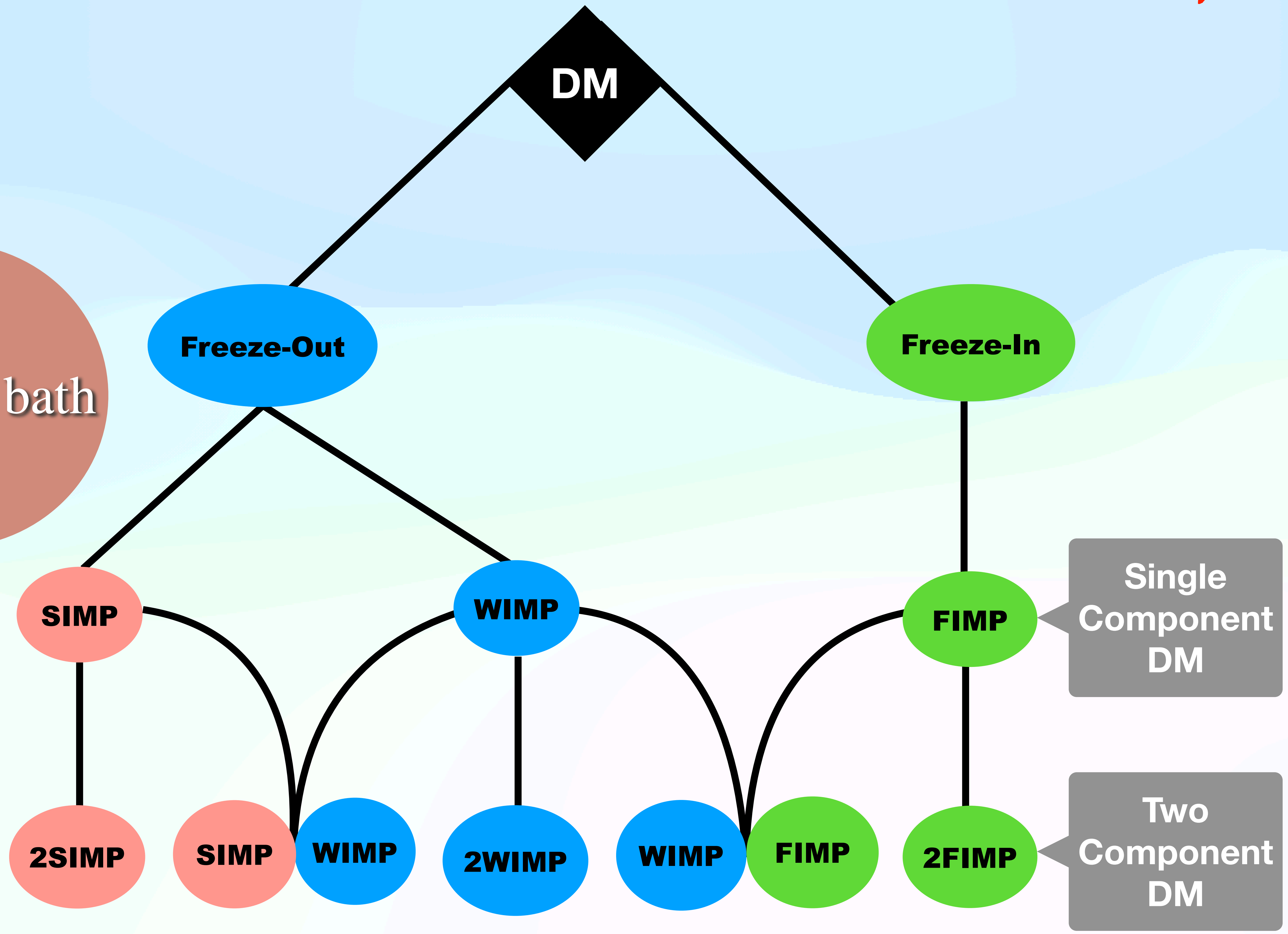
Main two mechanisms to produce Dark Matter

Particle	Mechanism
Weakly Interacting Massive Particle: WIMP	Thermal Freeze out
Strongly Interacting Massive Particle: SIMP	Thermal Freeze out
Feebly Interacting Massive Particle: FIMP	Non-thermal Freeze in

Multicomponent DM

- Why Multicomponent is unanswered: Because single component is a simplification.





We observe a new DM candidate also, called pseudo-FIMP (pFIMP), only possible in a multi-component framework, and this is a new outcome.

- The interaction between DM components play a crucial role in two-component DM case.
- Focus: two component DM involving pFIMP together with WIMP and SIMP.

What is pseudo FIMP?

Dynamics of pseudo-FIMP (pFIMP) in presence of a thermal DM

Published in: Phys. Rev. D 108, L111702.

Detection possibility of pFIMP in presence of a WIMP

Published in: Phys. Rev. D 109, 095031.

pFIMP dynamics in presence of a thermal WIMP

Two Dark Matters : DM_1 and DM_2

Equilibrated with thermal bath having weak interaction with SM bath.

Have a feeble interaction with SM particle but might have sizeable interaction with another DM

Coupled Boltzmann Equation:
$$\frac{dY_1}{dx} = -\frac{\mathbf{s}}{x\,H(x)}\left[\left(Y_1^2 - Y_1^{\mathrm{eq}^2}\right)\langle\sigma v\rangle_{1\,1\to \mathrm{SM\,SM}} + \left(Y_1^2 - Y_1^{\mathrm{eq}^2}\frac{Y_2^2}{Y_2^{\mathrm{eq}^2}}\right)\langle\sigma v\rangle_{1\,1\to 2\,2}\right]$$

annihilation

conversion

$$\frac{dY_2}{dx} = \frac{2\,\mathbf{s}}{x\,H(x)}\left[\frac{1}{\mathbf{s}}\left(Y_{\mathrm{SM}}^{\mathrm{eq}} - Y_{\mathrm{SM}}^{\mathrm{eq}}\frac{Y_2^2}{Y_2^{\mathrm{eq}^2}}\right)\langle\Gamma\rangle_{\mathrm{SM}\to 2\,2} + \left(Y_{\mathrm{SM}}^{\mathrm{eq}^2} - Y_{\mathrm{SM}}^{\mathrm{eq}^2}\frac{Y_2^2}{Y_2^{\mathrm{eq}^2}}\right)\langle\sigma v\rangle_{\mathrm{SM\,SM}\to 2\,2} + \left(Y_1^2 - Y_1^{\mathrm{eq}^2}\frac{Y_2^2}{Y_2^{\mathrm{eq}^2}}\right)\langle\sigma v\rangle_{1\,1\to 2\,2}\right]$$

production

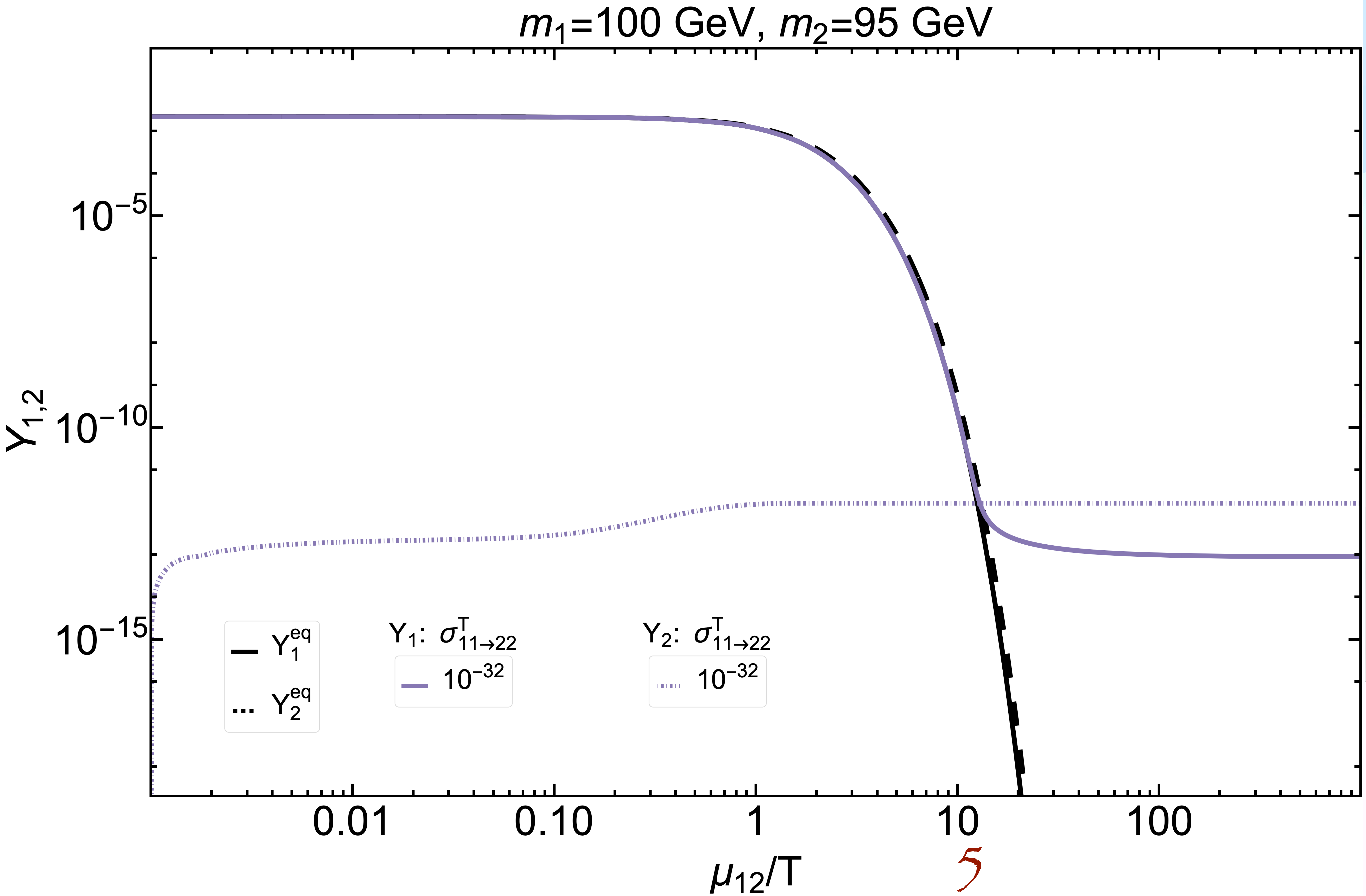
Mass hierarchy :

(I) $\mathrm{m}_1 > \mathrm{m}_2$ and (II) $\mathrm{m}_1 < \mathrm{m}_2$

Phys. Rev. D 108, L111702

pFIMP dynamics in presence of a thermal WIMP

Solution of cBEQ for hierarchy I ($m_1 > m_2$) :



$$m_{SM} = 300\ \text{GeV}$$
$$\Gamma^T_{SM\to 22} = 10^{-23}\text{GeV}^{-1}$$
$$\sigma^T_{SM\to 22} = 10^{-32}\text{GeV}^{-2}$$
$$\sigma^T_{11\to SM} = 10^{-7}\text{GeV}^{-2}$$

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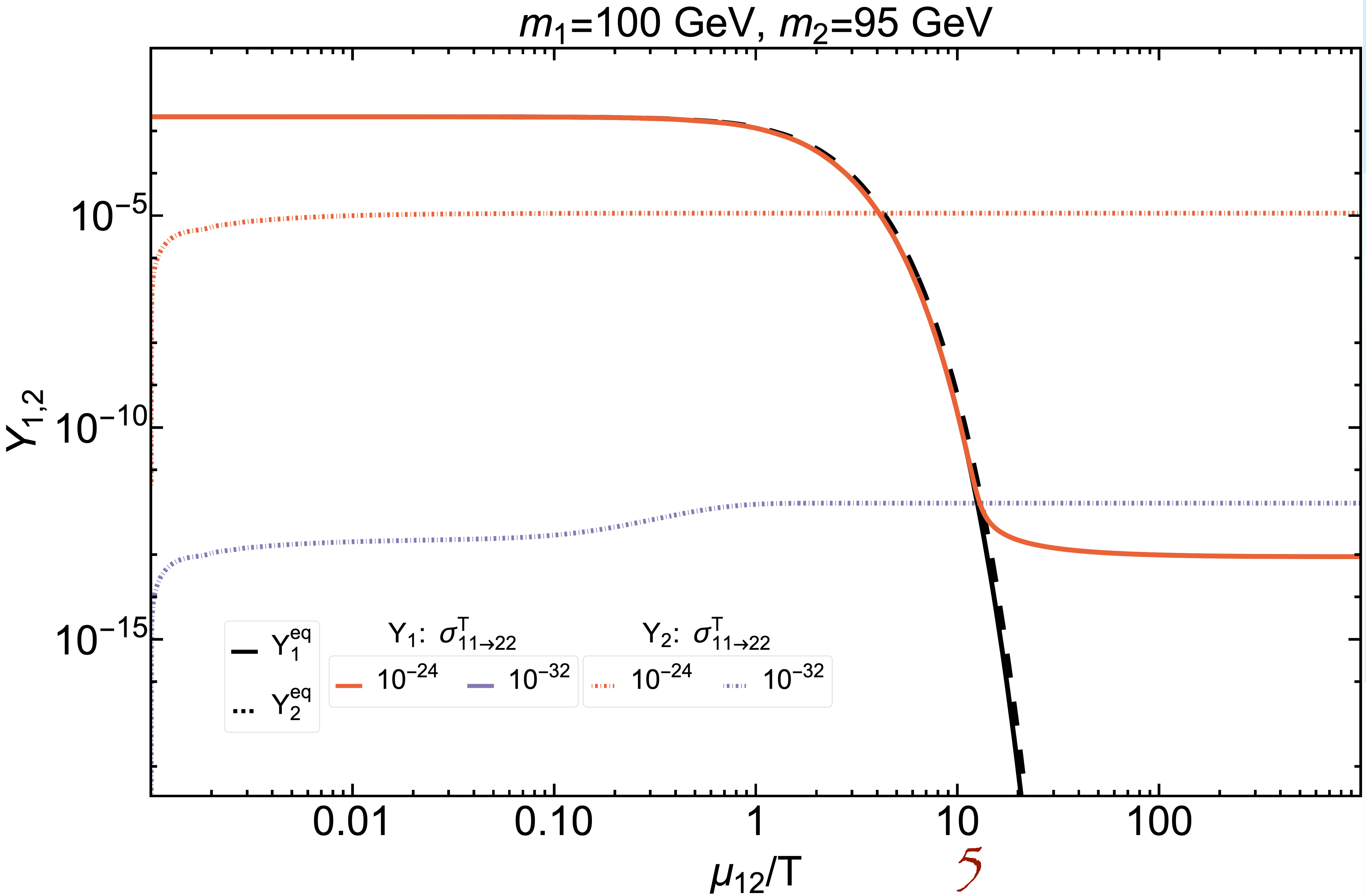

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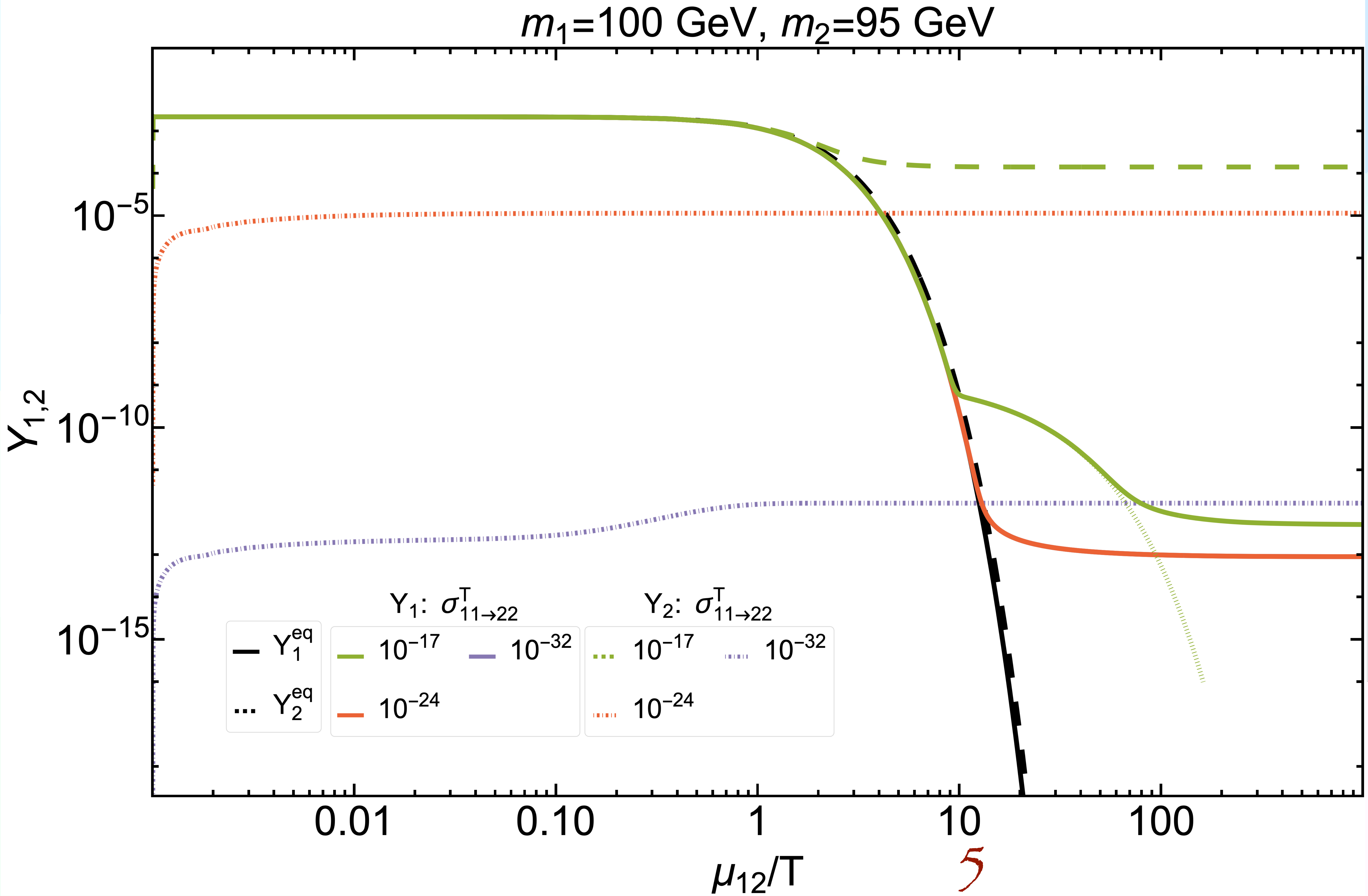

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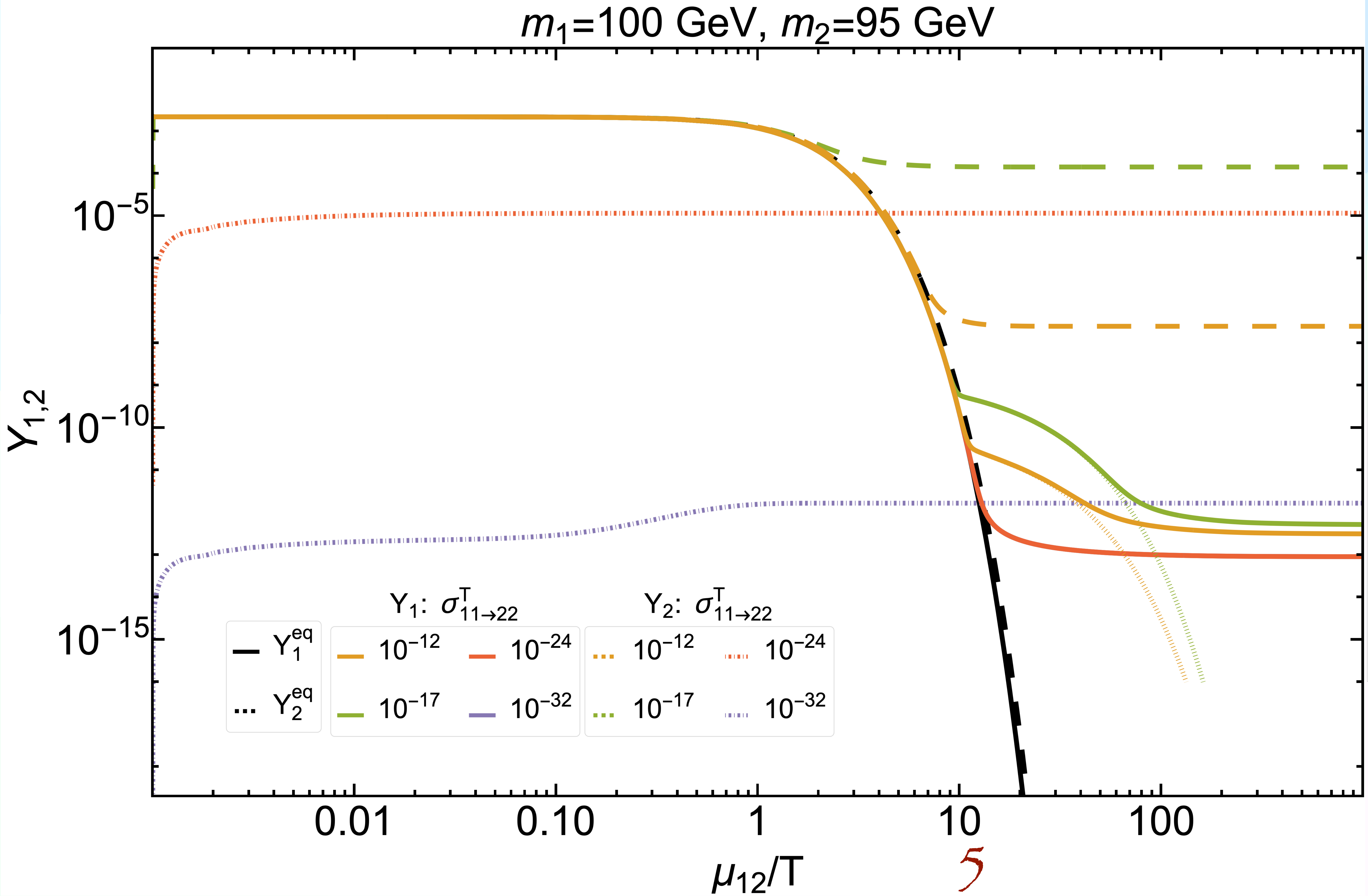

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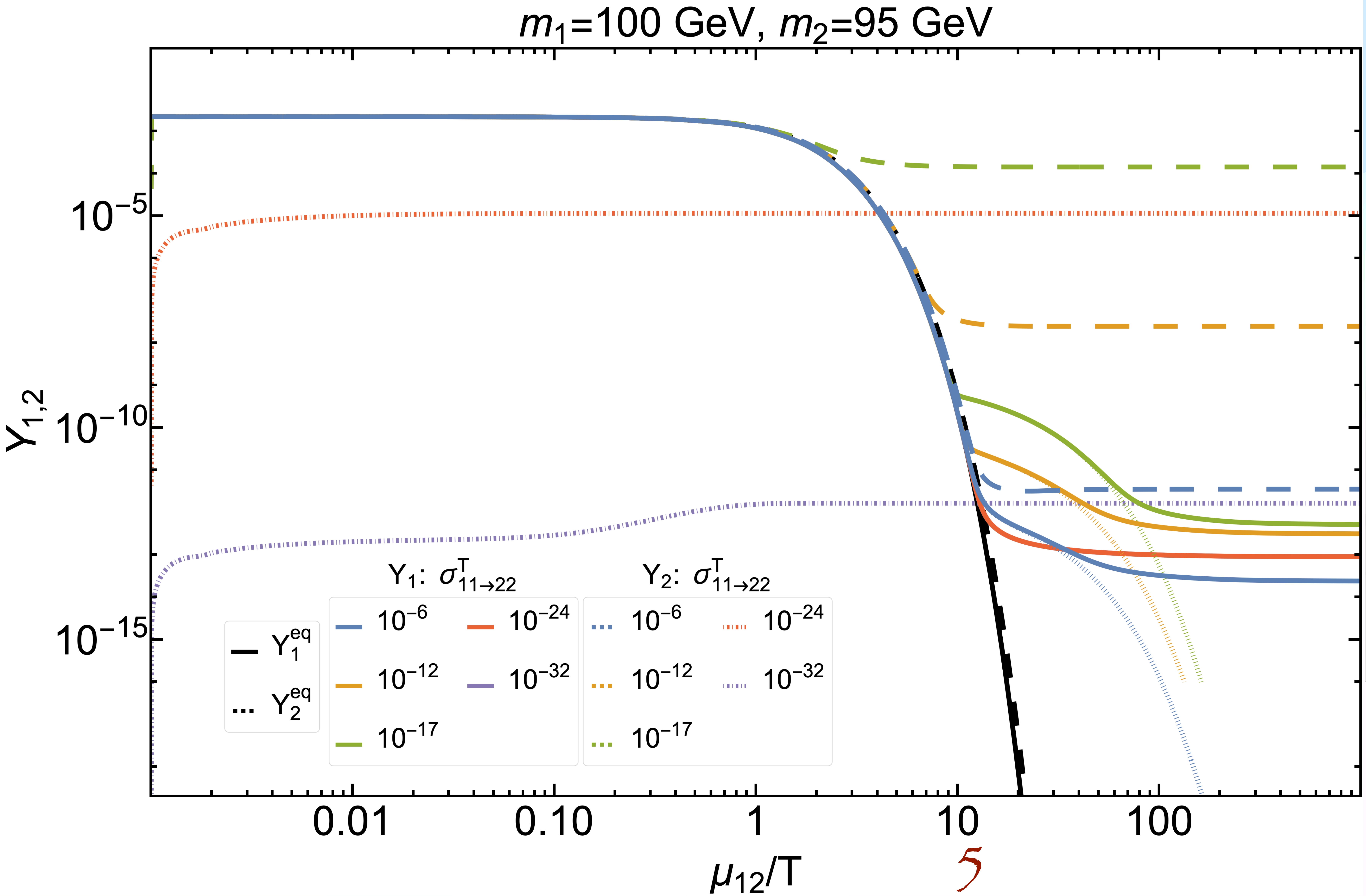

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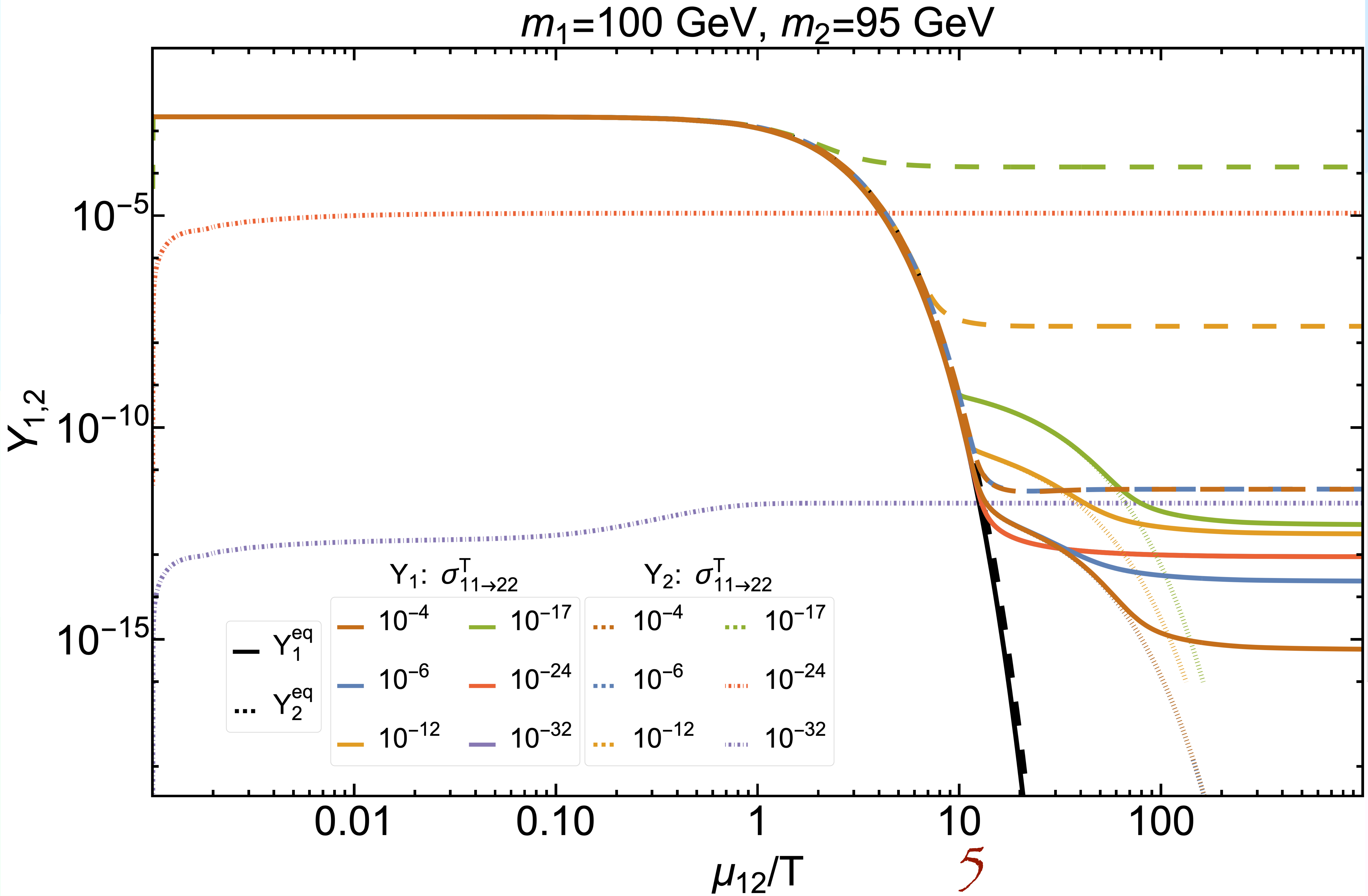

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Phys. Rev. D 108, L111702

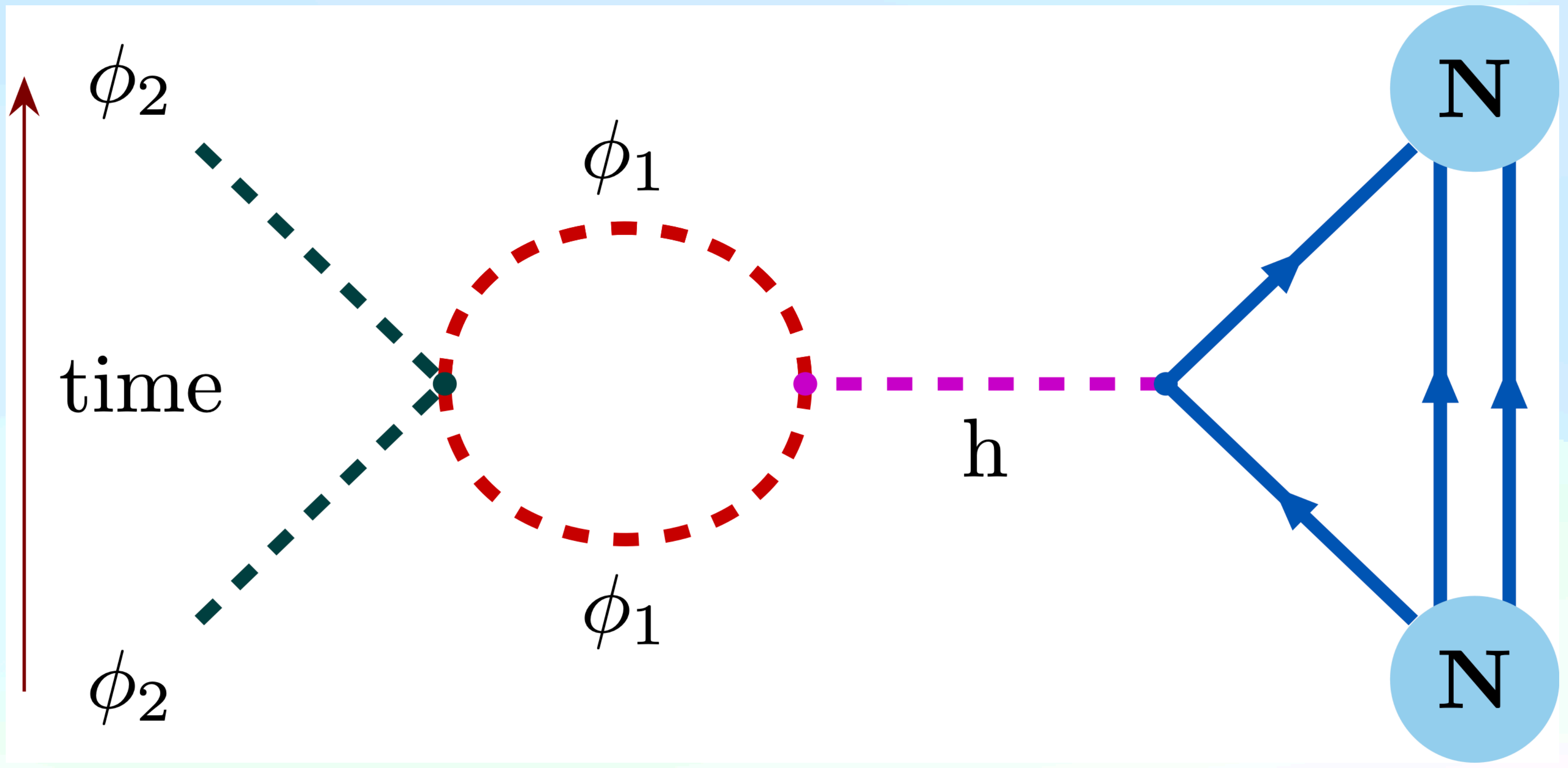
pFIMP dynamics in presence of a scalar WIMP

Simplest example: Two Component Real Scalar DM ϕ_1 and ϕ_2 are stable under $\mathbb{Z}_2 \otimes \mathbb{Z}_2'$ symmetry.

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - \frac{1}{2}\mu^2_{\phi_1}\phi_1^{\,2} - \frac{1}{4!}\lambda_{\phi_1}\phi_1^{\,4} - \frac{1}{2}\lambda_{1H}H^\dagger H\phi_1^{\,2} + \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - \frac{1}{2}\mu^2_{\phi_2}\phi_2^{\,2} - \frac{1}{4!}\lambda_{\phi_2}\phi_2^{\,4} - \frac{1}{2}\lambda_{2H}H^\dagger H\phi_2^{\,2} - \frac{1}{4}\lambda_{12}\phi_1^{\,2}\phi_2^{\,2}.$$

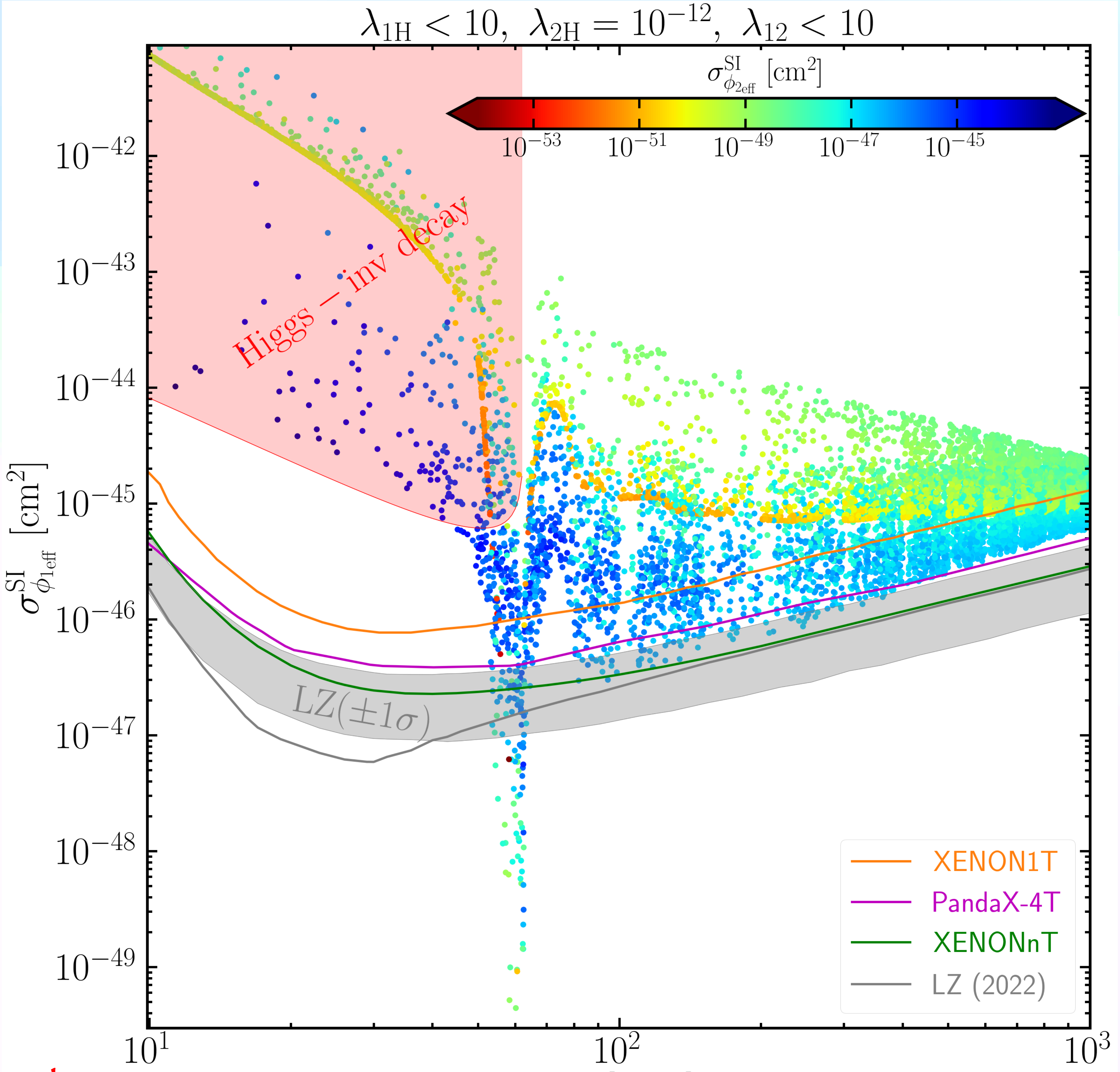
$\phi_1 \rightarrow$ WIMP

$\phi_2 \rightarrow$ pFIMP



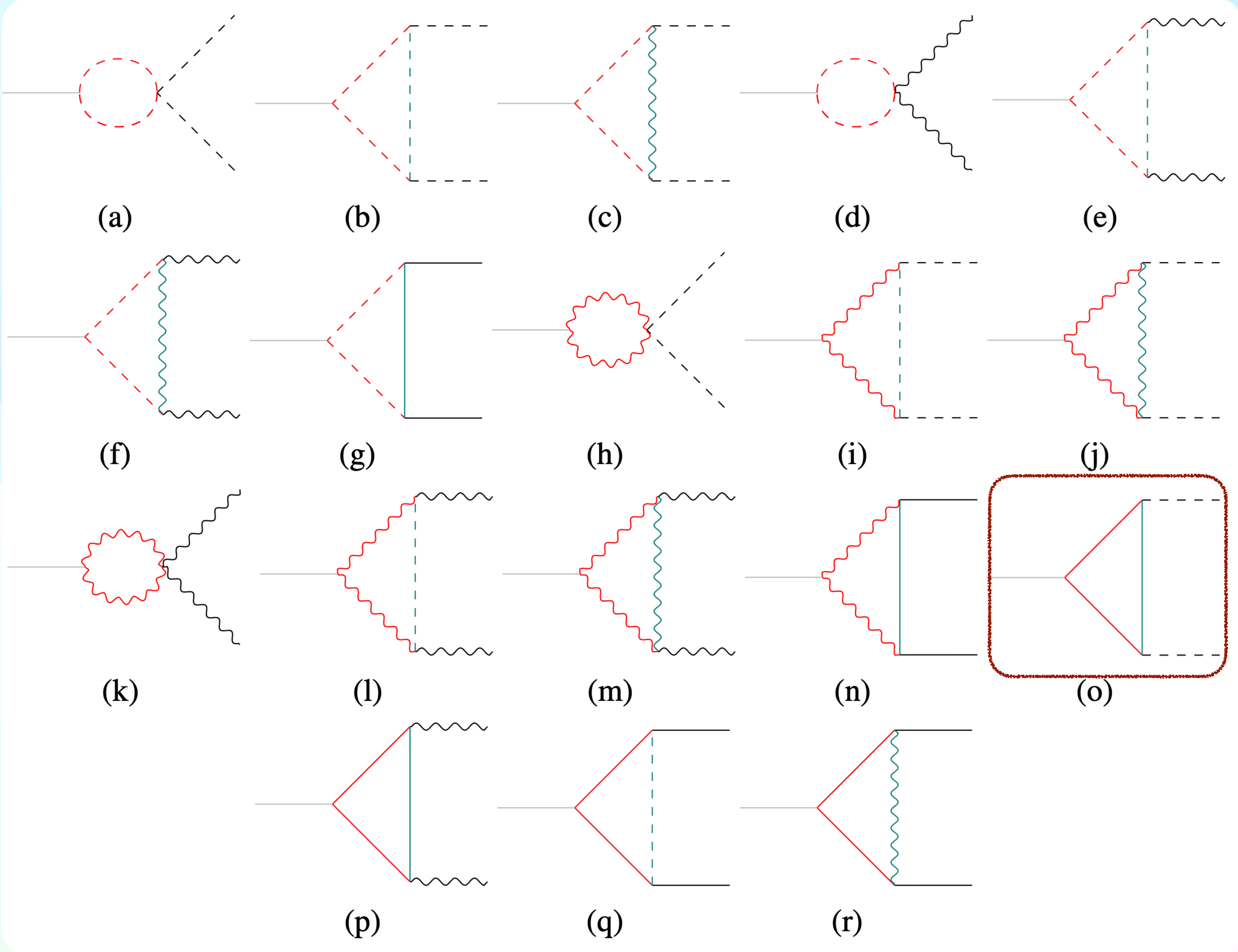
$$\sigma^{SI}_{\phi_{2\rm eff}} = \frac{\Omega_{\phi_2}h^2}{\Omega_{\phi_1}h^2 + \Omega_{\phi_2}h^2}\,\frac{\mu_n^2 m_n^2}{4\pi v^2 m^2_{\phi_2}}\,\frac{f_n^2}{m_h^4}\,\left|\Gamma^{\rm total}_{h\phi_2\phi_2}\right|^2_{t\to 0}$$

- WIMP gets large relic-allowed parameter space due to opening up a new annihilation channel to pFIMP, and both contribute to the total observed DM Relic abundance.
- Although this pFIMP has a very feeble connection with SM, but still has (In-)direct detection search possibility via the WIMP loop. The Higgs resonance region is allowed by all observational constraints.



Phys. Rev. D 108, L111702 m_{ϕ_1} [GeV]

Possible pFIMP-SM interactions via WIMP loop



WIMP–pFIMP stabilising symmetry: $\mathbb{Z}_2 \otimes \mathbb{Z}'_2$

- Grey lines corresponds to SM particles.
- Red lines corresponds to WIMP.
- Black lines corresponds to pFIMP.
- Tilde lines corresponds to heavy bath particle odd under both symmetry.

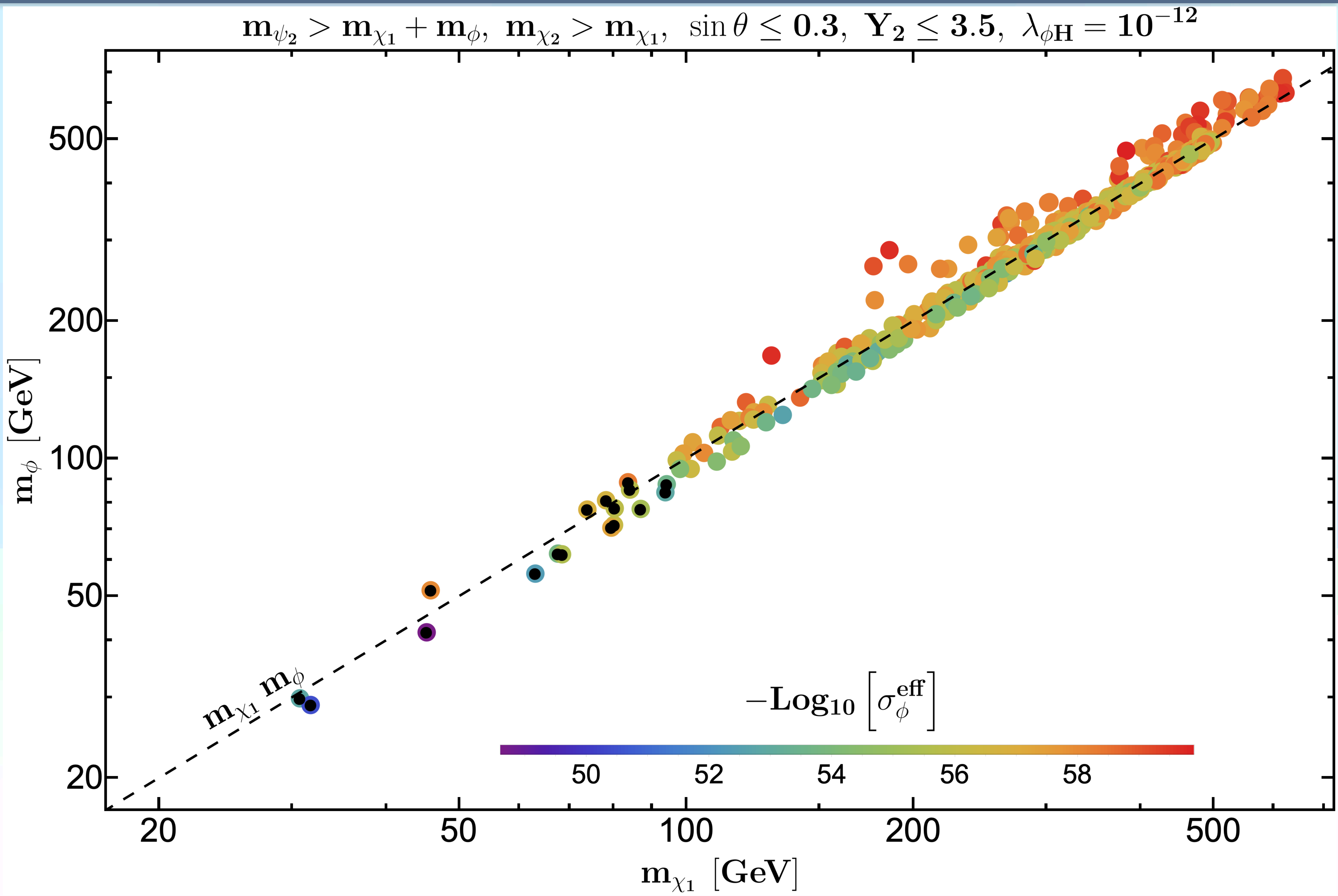
Phys. Rev. D 109, 095031

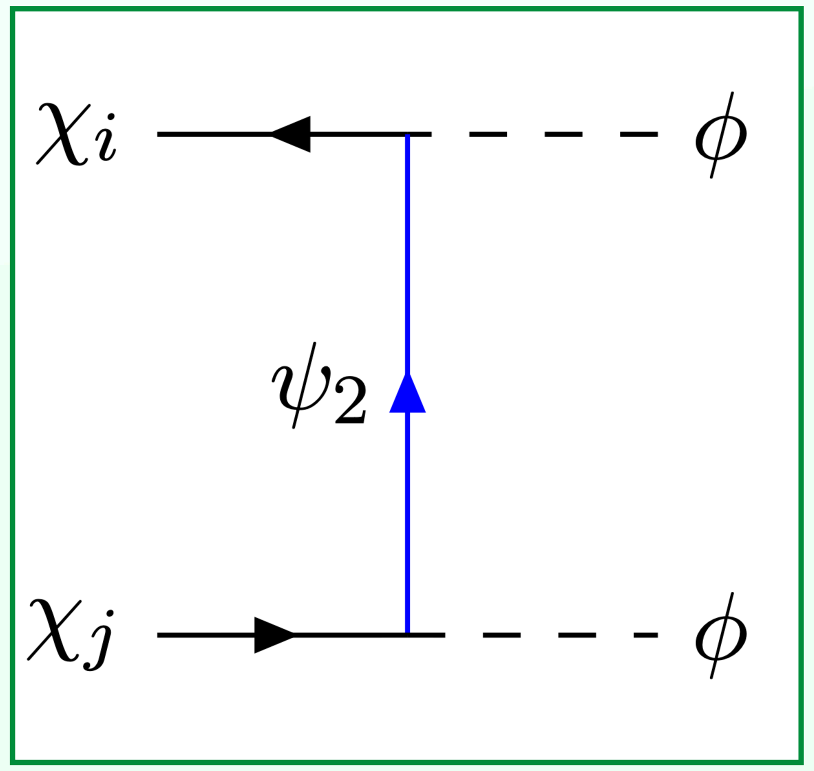
Scalar pFIMP and Fermion WIMP

Dark Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$	$\mathbb{Z}'_2$
$\psi = \begin{pmatrix}\psi^0 \\ \psi^-\end{pmatrix}$	1	2	-1	$-$	$+$
ψ_1	1	1	0	$-$	$+$
ψ_2	1	1	0	$+$	$-$
ϕ	1	1	0	$-$	$-$

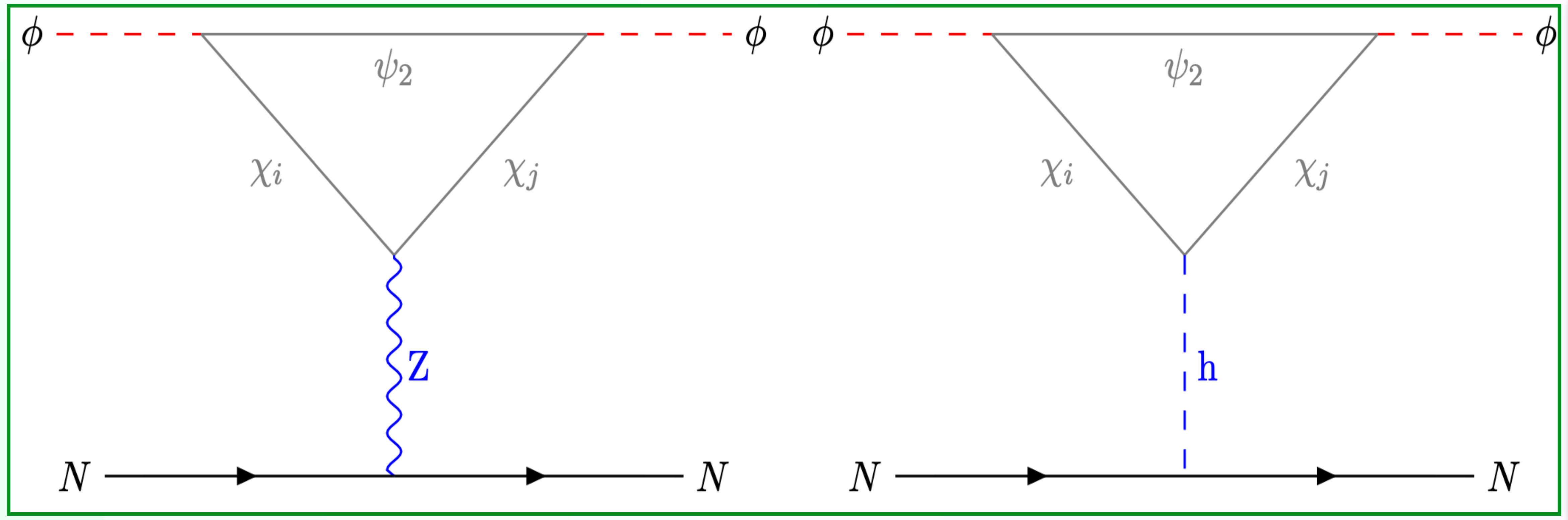
$$\mathscr{L}_{\rm Scalar} = \frac{1}{2}|\partial_\mu \phi|^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4!}\lambda_\phi\phi^4 - \frac{1}{2}\lambda_{\phi H}\phi^2 H^\dagger H$$

$$\mathscr{L}_{\rm VF} = \overline{\psi}\left[i\gamma^\mu\left(\partial_\mu + ig\frac{\sigma^a}{2}W^a_\mu + ig'\frac{Y}{2}B_\mu\right) - m_\psi\right]\psi + \sum_{\alpha=1,2}\overline{\psi}_\alpha\left(i\gamma^\mu\partial_\mu - m_{\psi_\alpha}\right)\psi_\alpha - (Y_1\overline{\psi}\widetilde{H}\psi_1 + Y_2\overline{\psi}_2\psi_1\phi + {\rm h.c.})$$





WIMP-pFIMP conversion



pFIMP direct detection

- pFIMP dynamics and detection possibilities have been discussed.
- We studied both DM mass hierarchy regimes.
- The most detectable regime in future experiments is above 100 GeV.
- Collider search prospect of pFIMP might be possible via thermal WIMP loop.

Phys. Rev. D 109, 095031

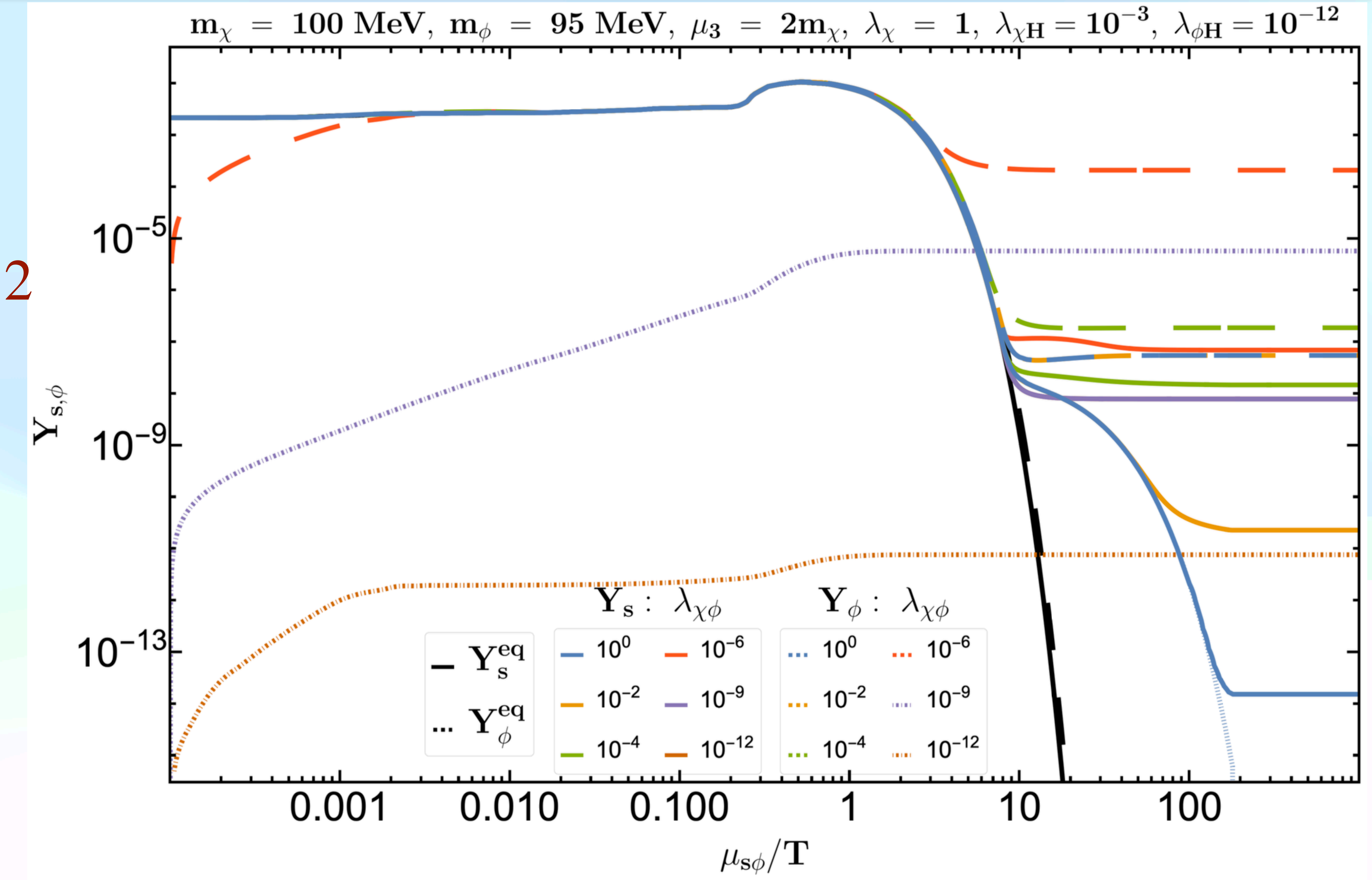
SIMP-pFIMP phenomenology focusing low mass regime

Ongoing Work

pFIMP-SIMP Model

$$\phi \xrightarrow{\mathbb{Z}_2} -\phi \; ; \quad \chi \xrightarrow{\mathbb{Z}_3} \omega_3 \chi \, .$$

$$\begin{aligned}\mathscr{L} \; = \; & \mathscr{L}_{\rm SM} + \mu_H^2 H^\dagger H - \lambda_H (H^\dagger H)^2 + \frac{1}{2} |\partial_\mu \phi|^2 \\ & -\lambda_\chi |\chi^* \chi|^2 - \frac{1}{2}\mu_3(\chi^3 + \chi^{*3}) - \frac{1}{2}\lambda_{\phi H}\phi^2 H^\dagger H \\ & -\frac{1}{2}\mu_\phi^2 \phi^2 - \frac{1}{4\,!}\lambda_\phi \phi^4 + |\partial_\mu \chi|^2 - \mu_\chi^2 |\chi|^2 \\ & -\lambda_{\chi H}|\chi|^2 H^\dagger H - \frac{1}{2}\lambda_{\chi\phi}|\chi|^2 \phi^2 \, .\end{aligned}$$



$$\frac{dY_s}{dx} = -\frac{\mathbf{s}}{x\,\mathscr{H}(x)}\left[\frac{1}{2}(Y_s^2 - Y_s^{\rm eq^2})\langle\sigma v\rangle_{\chi\,\chi^* \to {\rm SM\ SM}} + \frac{\mathbf{s}}{4}(Y_s^3 - Y_s^2 Y_s^{\rm eq})\langle\sigma v^2\rangle_{3\chi\to 2\chi} + \frac{1}{2}\left(Y_s^2 - Y_s^{\rm eq^2}\frac{Y_\phi^2}{Y_\phi^{\rm eq^2}}\right)\langle\sigma v\rangle_{\chi\,\chi^*\to\phi\,\phi}\right]$$

$$\frac{dY_\phi}{dx} = \frac{2\,\mathbf{s}}{x\,\mathscr{H}(x)}\left[\frac{1}{\mathbf{s}}\left(Y_{\rm h}^{\rm eq} - Y_{\rm h}^{\rm eq}\frac{Y_\phi^2}{Y_\phi^{\rm eq^2}}\right)\langle\Gamma\rangle_{{\rm h}\to\phi\,\phi} + \left(Y_{\rm SM}^{\rm eq^2} - Y_{\rm SM}^{\rm eq^2}\frac{Y_\phi^2}{Y_\phi^{\rm eq^2}}\right)\langle\sigma v\rangle_{{\rm SM\ SM}\to\phi\,\phi} + \frac{1}{4}\left(Y_{\rm s}^2 - Y_{\rm s}^{\rm eq^2}\frac{Y_\phi^2}{Y_\phi^{\rm eq^2}}\right)\langle\sigma v\rangle_{\chi\,\chi^*\to\phi\,\phi}\right]$$

The genesis and detectability of a pFIMP under $\mathbb{Z}_N$ symmetry

Ongoing Work

Motivation

- Two DM components are naturally stable with two distinct discrete symmetries.
- However, the heavier dark sector particle can also be made **kinematically stable** under one symmetry and lightest one **naturally stable.**
- The DM, which has feeble interaction with the visible sector, would always be a pFIMP.
- We study such possibilities under $\mathbb{Z}_N$ symmetry.

Two complex scalar DM under $\mathbb{Z}_3$ symmetry

A generic two – component DM scenario under a discrete symmetry, $\mathbb{Z}_3$: $\chi_1 \xrightarrow{\mathbb{Z}_3} \omega_3^{q_1}\chi_1 \quad \chi_2 \xrightarrow{\mathbb{Z}_3} \omega_3^{q_2}\chi_2$

Scenarios	Interaction terms of two DMs: χ_1 and χ_2 under $\mathbb{Z}_3$ symmetry
	$\boldsymbol{q_1 = 1,\ q_2 = 2}$ **or** $\boldsymbol{q_1 = 2,\ q_2 = 1}$
A	$\lvert\chi_1\rvert^2 H^\dagger H,\ \lvert\chi_2\rvert^2 H^\dagger H,\ \chi_1^3,\ \chi_2^3,\ \lvert\chi_1\rvert^4,\ \lvert\chi_2\rvert^4,\ \chi_1\chi_2 H^\dagger H,\ \chi_1^2\chi_2^2,\ \lvert\chi_1\chi_2\rvert^2,\ \chi_2^2\chi_1^*,\ \chi_1^2\chi_2^*,\ \chi_1\chi_2(\lvert\chi_1\rvert^2+\lvert\chi_2\rvert^2)$
B	$\lvert\chi_1\rvert^2 H^\dagger H,\ \lvert\chi_2\rvert^2 H^\dagger H,\ \chi_1^3,\ \chi_2^3,\ \lvert\chi_1\rvert^4,\ \lvert\chi_2\rvert^4,\ \chi_1\chi_2 H^\dagger H,\ \chi_1^2\chi_2^2,\ \lvert\chi_1\chi_2\rvert^2,\ \chi_2^2\chi_1^*,\ \chi_1^2\chi_2^*,\ \chi_1\chi_2(\lvert\chi_1\rvert^2+\lvert\chi_2\rvert^2)$
C	$\lvert\chi_1\rvert^2 H^\dagger H,\ \lvert\chi_2\rvert^2 H^\dagger H,\ \chi_1^3,\ \chi_2^3,\ \lvert\chi_1\rvert^4,\ \lvert\chi_2\rvert^4,\ \chi_1\chi_2 H^\dagger H,\ \chi_1^2\chi_2^2,\ \lvert\chi_1\chi_2\rvert^2,\ \chi_2^2\chi_1^*,\ \chi_1^2\chi_2^*,\ \chi_1\chi_2(\lvert\chi_1\rvert^2+\lvert\chi_2\rvert^2)$
	$\boldsymbol{q_1 = q_2 = 1,\ 2}$
D	$\lvert\chi_1\rvert^2 H^\dagger H,\ \lvert\chi_2\rvert^2 H^\dagger H,\ \chi_1^3,\ \chi_2^3,\ \lvert\chi_1\rvert^4,\ \lvert\chi_2\rvert^4,\ \chi_1\chi_2^* H^\dagger H,\ (\chi_1\chi_2^*)^2,\ \lvert\chi_1\chi_2\rvert^2,\ \chi_2^2\chi_1,\ \chi_1^2\chi_2,\ \chi_1\chi_2^*(\lvert\chi_1\rvert^2+\lvert\chi_2\rvert^2)$
E	$\lvert\chi_1\rvert^2 H^\dagger H,\ \lvert\chi_2\rvert^2 H^\dagger H,\ \chi_1^3,\ \chi_2^3,\ \lvert\chi_1\rvert^4,\ \lvert\chi_2\rvert^4,\ \chi_1\chi_2^* H^\dagger H,\ (\chi_1\chi_2^*)^2,\ \lvert\chi_1\chi_2\rvert^2,\ \chi_2^2\chi_1,\ \chi_1^2\chi_2,\ \chi_1\chi_2^*(\lvert\chi_1\rvert^2+\lvert\chi_2\rvert^2)$
F	$\lvert\chi_1\rvert^2 H^\dagger H,\ \lvert\chi_2\rvert^2 H^\dagger H,\ \chi_1^3,\ \chi_2^3,\ \lvert\chi_1\rvert^4,\ \lvert\chi_2\rvert^4,\ \chi_1\chi_2^* H^\dagger H,\ (\chi_1\chi_2^*)^2,\ \lvert\chi_1\chi_2\rvert^2,\ \chi_2^2\chi_1,\ \chi_1^2\chi_2,\ \chi_1\chi_2^*(\lvert\chi_1\rvert^2+\lvert\chi_2\rvert^2)$

Two complex scalar DM under $\mathbb{Z}_3$ symmetry

Tree and 1 – loop and 2 – loop level decays of χ_2 ($m_{\chi_2} > m_{\chi_1}$) :

Two complex scalar DM under $\mathbb{Z}_3$ symmetry

A generic two – component DM scenario under discrete symmetry, $\mathbb{Z}_3$:

Scenarios	Interaction terms of two DMs: χ_1 and χ_2 under $\mathbb{Z}_3$ symmetry
	$\boldsymbol{q_1 = 1,\ q_2 = 2}$ **or** $\boldsymbol{q_1 = 2,\ q_2 = 1}$
✓	$\|\chi_1\|^2\,\mathrm{H}^\dagger\mathrm{H},\ \|\chi_2\|^2\,\mathrm{H}^\dagger\mathrm{H},\ \chi_1^3,\ \chi_2^3,\ \|\chi_1\|^4,\ \|\chi_2\|^4,\ \chi_1\chi_2\mathrm{H}^\dagger\mathrm{H},\ \chi_1^2\chi_2^2,\ \|\chi_1\chi_2\|^2,\ \chi_2^2\chi_1^*,\ \chi_1^2\chi_2^*,\ \chi_1\chi_2(\|\chi_1\|^2+\|\chi_2\|^2)$
B	$\|\chi_1\|^2\,\mathrm{H}^\dagger\mathrm{H},\ \|\chi_2\|^2\,\mathrm{H}^\dagger\mathrm{H},\ \chi_1^3,\ \chi_2^3,\ \|\chi_1\|^4,\ \|\chi_2\|^4,\ \chi_1\chi_2\mathrm{H}^\dagger\mathrm{H},\ \chi_1^2\chi_2^2,\ \|\chi_1\chi_2\|^2,\ \chi_2^2\chi_1^*,\ \chi_1^2\chi_2^*,\ \chi_1\chi_2(\|\chi_1\|^2+\|\chi_2\|^2)$

- After imposing the stabilising conditions, $\tau_{\chi_2} > \tau_{\rm univ}$ by the minimal choice of couplings associated with red color terms, χ_2 becomes a long-lived DM with a stable lightest DM χ_1, and both would be contributed in DM relic.
- If we ignore those red color terms, which are very tiny, these scenarios are reduced to a scenario where both DMs are absolutely stable only under mass kinematics.

◉ $\mathrm{A,\ D} \xrightarrow{\text{absence of red terms}} \mathbb{Z}_3 \otimes \mathbb{Z}_3'\,.$

◉ $\mathrm{B,\ C} \xrightarrow{\text{absence of red terms}} \mathbb{Z}_6\ (\mathrm{q}_1 = 1,\ \mathrm{q}_2 = 2)$ and $(\mathrm{q}_1 = 2,\ \mathrm{q}_2 = 1)\,.$

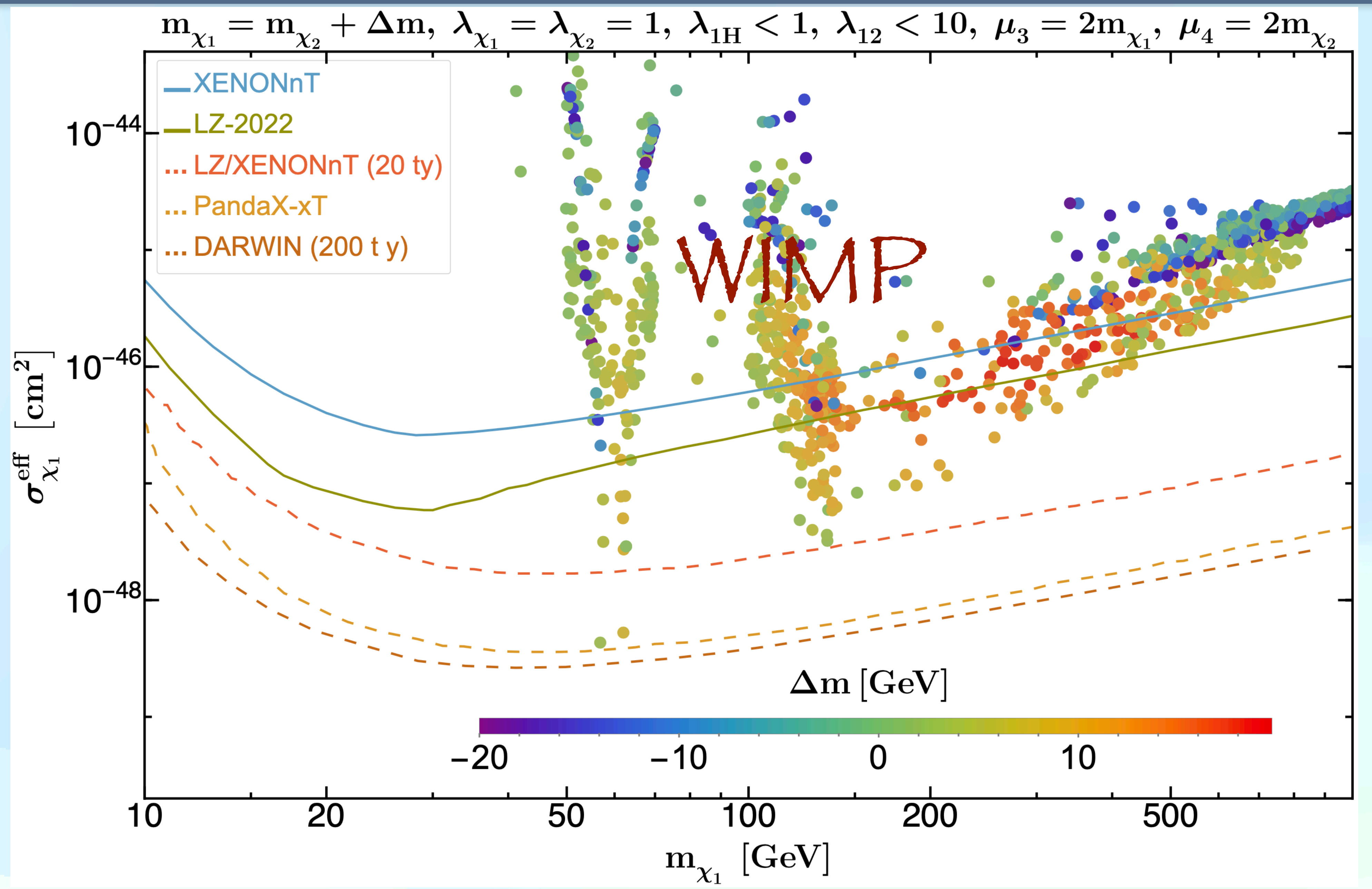
◉ $\mathrm{E,\ F} \xrightarrow{\text{absence of red terms}} \mathbb{Z}_6\ (\mathrm{q}_1 = 1,\ \mathrm{q}_2 = 4)$ and $(\mathrm{q}_1 = 4,\ \mathrm{q}_2 = 1)\,.$

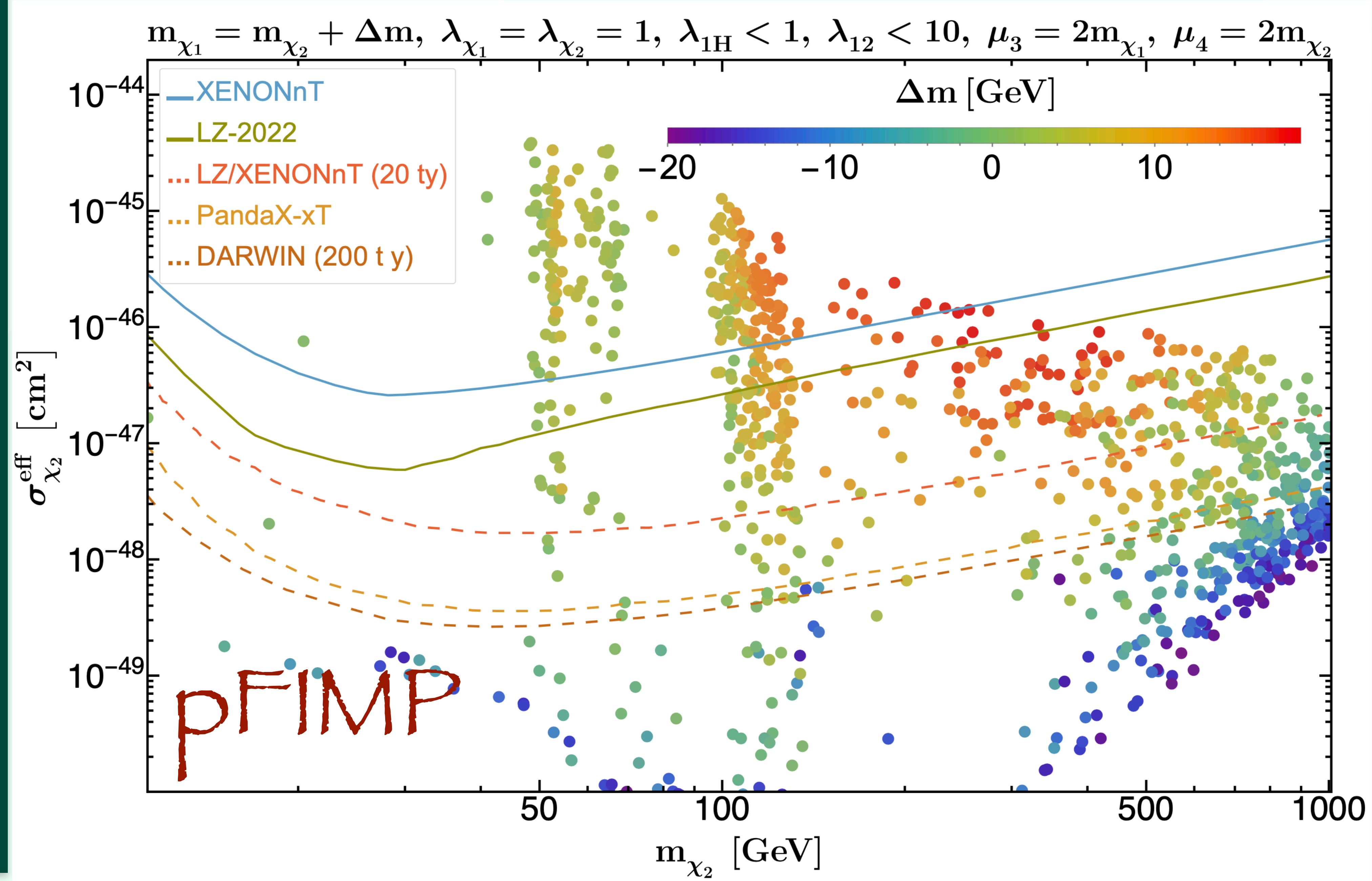
Scenario A

- The heavier component stabilisation needs tiny couplings associated with interaction terms ($\chi_1\chi_2 H^\dagger H$, $\chi_1^2\chi_2^2$, $\chi_2^2\chi_1^*$, $\chi_1^2\chi_2^*$, $\chi_1\chi_2|\chi_1|^2$, $\chi_1\chi_2|\chi_2|^2$), giving one LLP and one stable DM.
- Depending on the value of λ_{2H}, we get two scenarios:
  - WIMP – WIMP (λ_{2H} ~ weak scale).
  - WIMP – pFIMP (λ_{2H} is feeble). ✔

Results

Direct detection limits on WIMP – pFIMP





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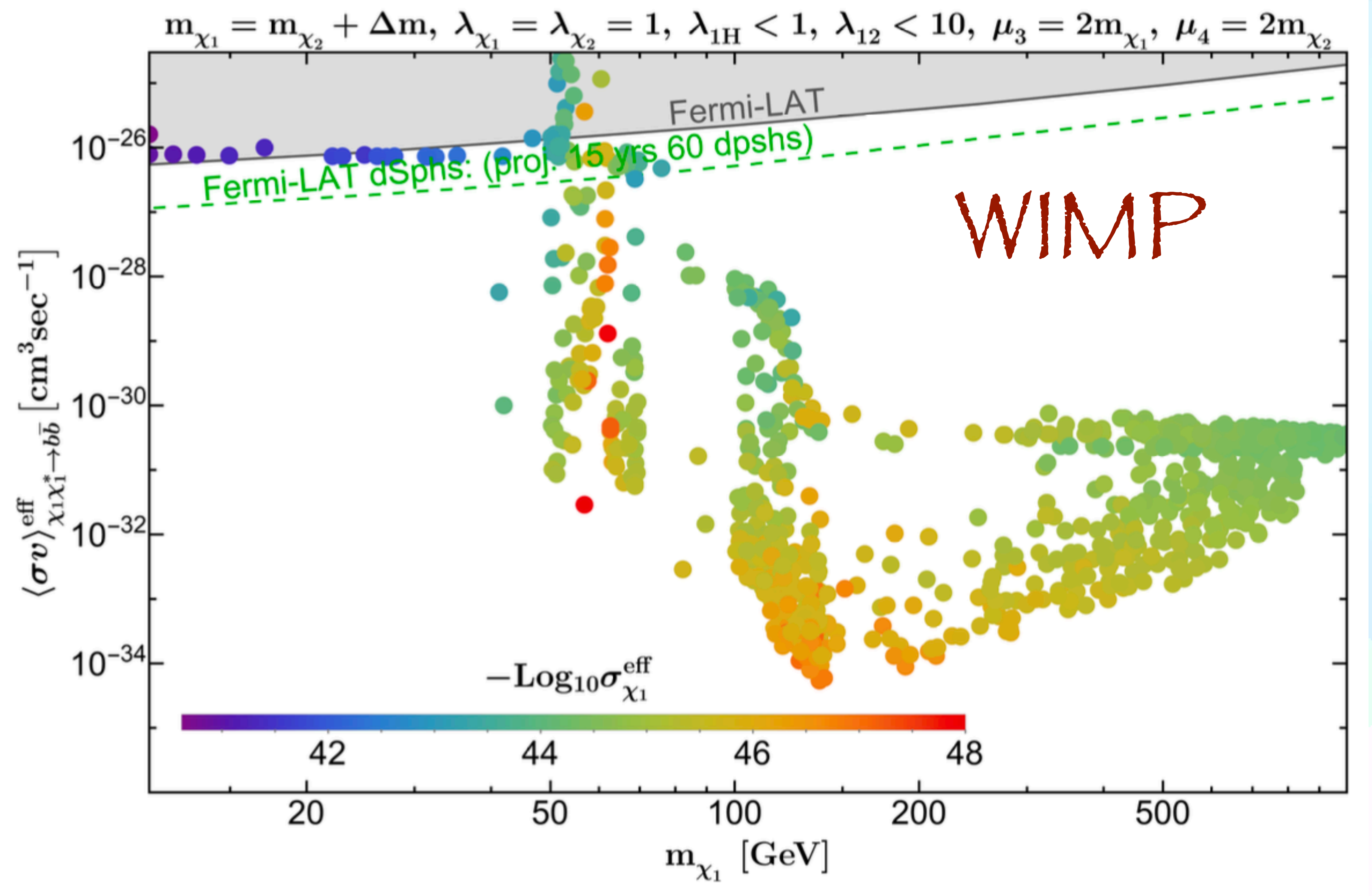

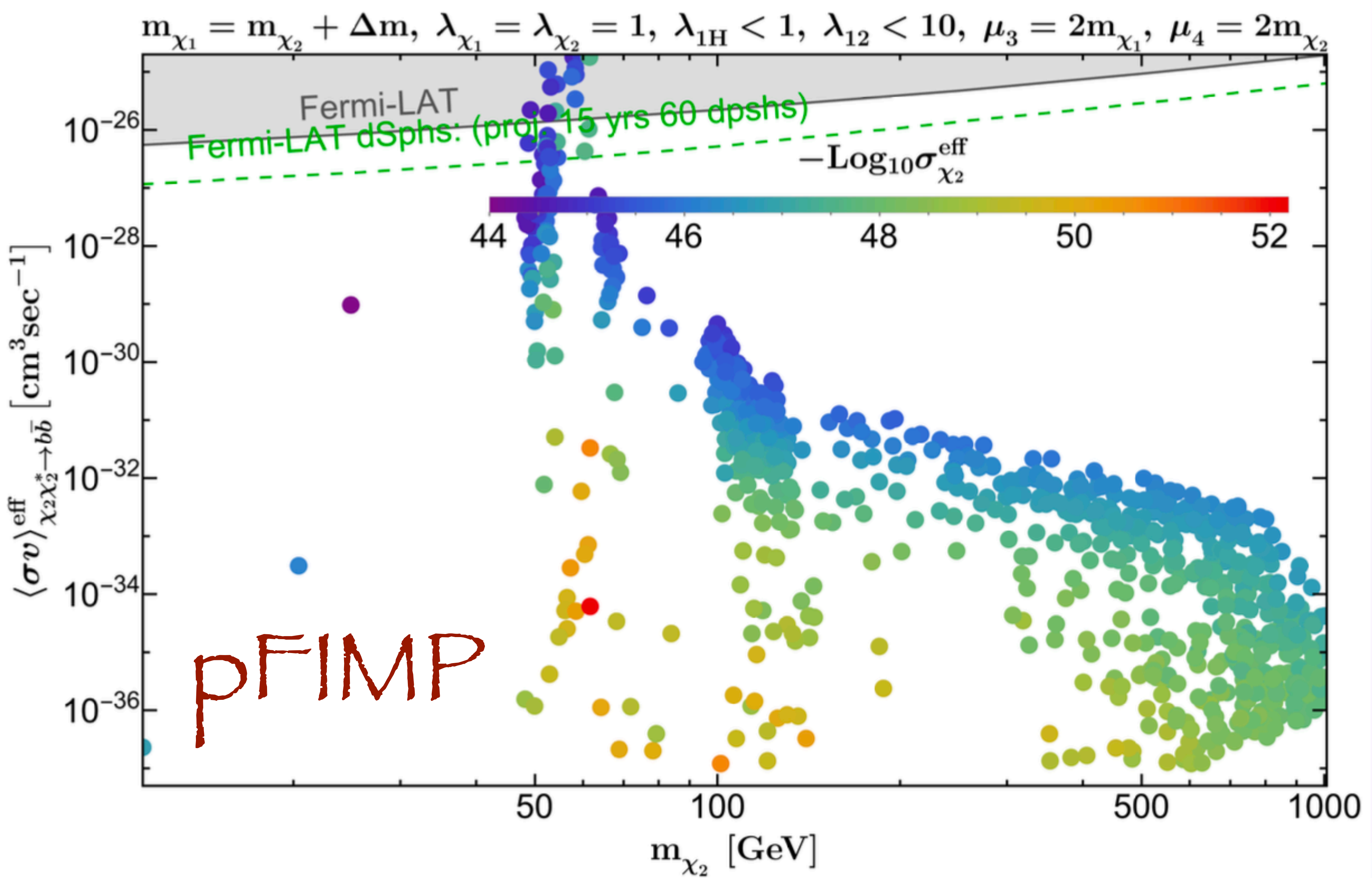

Summary

- Different possibilities of DM, like WIMP, SIMP or FIMP, account for correct relic density via freeze-out or freeze-in. Having more than one DM component greatly enhances the phenomenological possibility via DM-DM interaction.
- A new kind of DM, pseudo-FIMP (pFIMP), can arise in two-component DM scenarios having a thermal DM, providing loop-induced search prospects.
- The pFIMP could also be achievable in the sub-GeV regime in the presence of SIMP.
- We can obtain two dark matter candidates with a single discrete symmetry: one is a long-lived particle (LLP), while the other remains a stable dark matter candidate.

Thank

You