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

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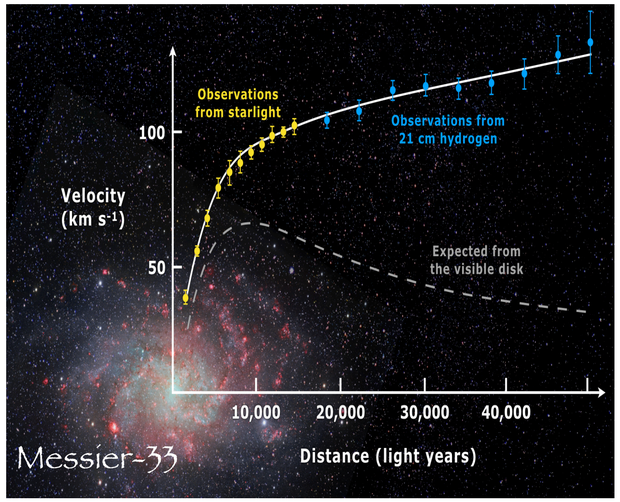
Based on:

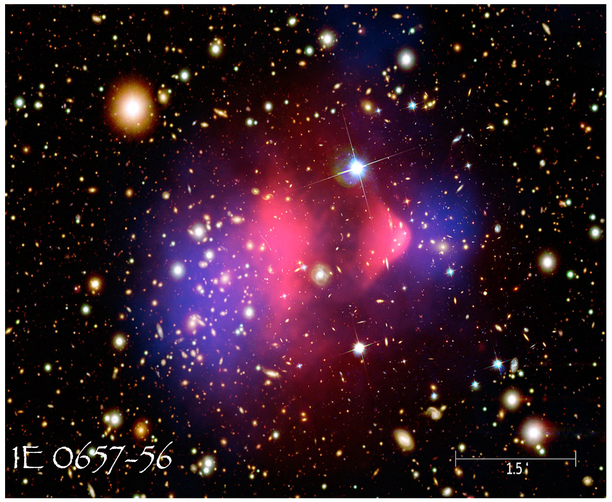
Subhaditya Bhattacharya, Jayita Lahiri and DP: PhysRevD.108.L111702 & 2212.07622

19/12/2023

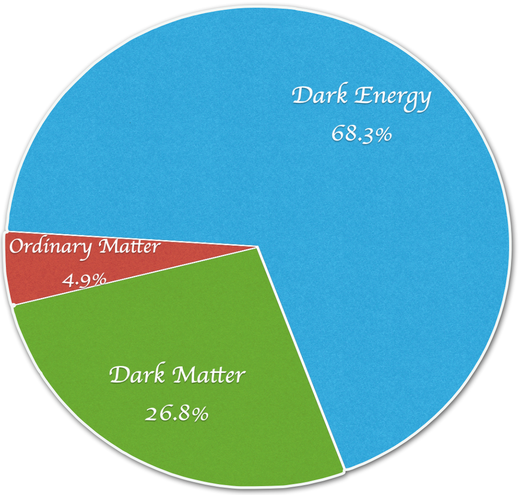
Dark Matter



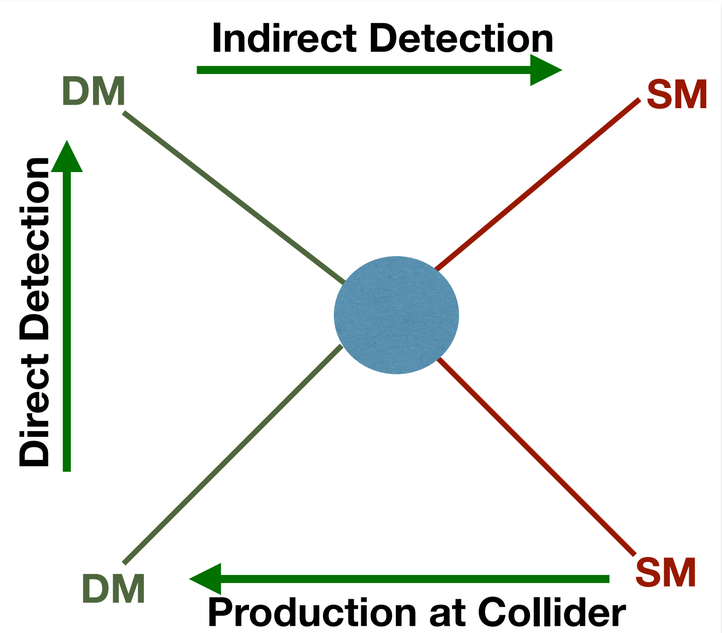
Galaxy Rotation Curve



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 ?

Popular candidates

- Weakly interacting massive particle (WIMP)
- Feeble interacting massive particle (FIMP)
- Strongly interacting massive particle (SIMP)

Motivation

DM-DM conversion has an important key role in Multi-component DMs Relic density and its phenomenology.

- Conversion ✗

Two DMs show their independent behaviour

2WIMP, 2FIMP, 2SIMP, WIMP-FIMP, SIMP-FIMP etc.

- Conversion ✓

Both are implicitly dependent on each other

2WIMP, 2FIMP, 2SIMP, WIMP-pFIMP, SIMP-pFIMP etc.

- What is pFIMP? When the conversion between WIMP and FIMP is strong enough ~ weak scale.

- Our aim is to study this pFIMP dynamics and its phenomenology in presence of a thermal DM.

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:

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

annihilation

conversion

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

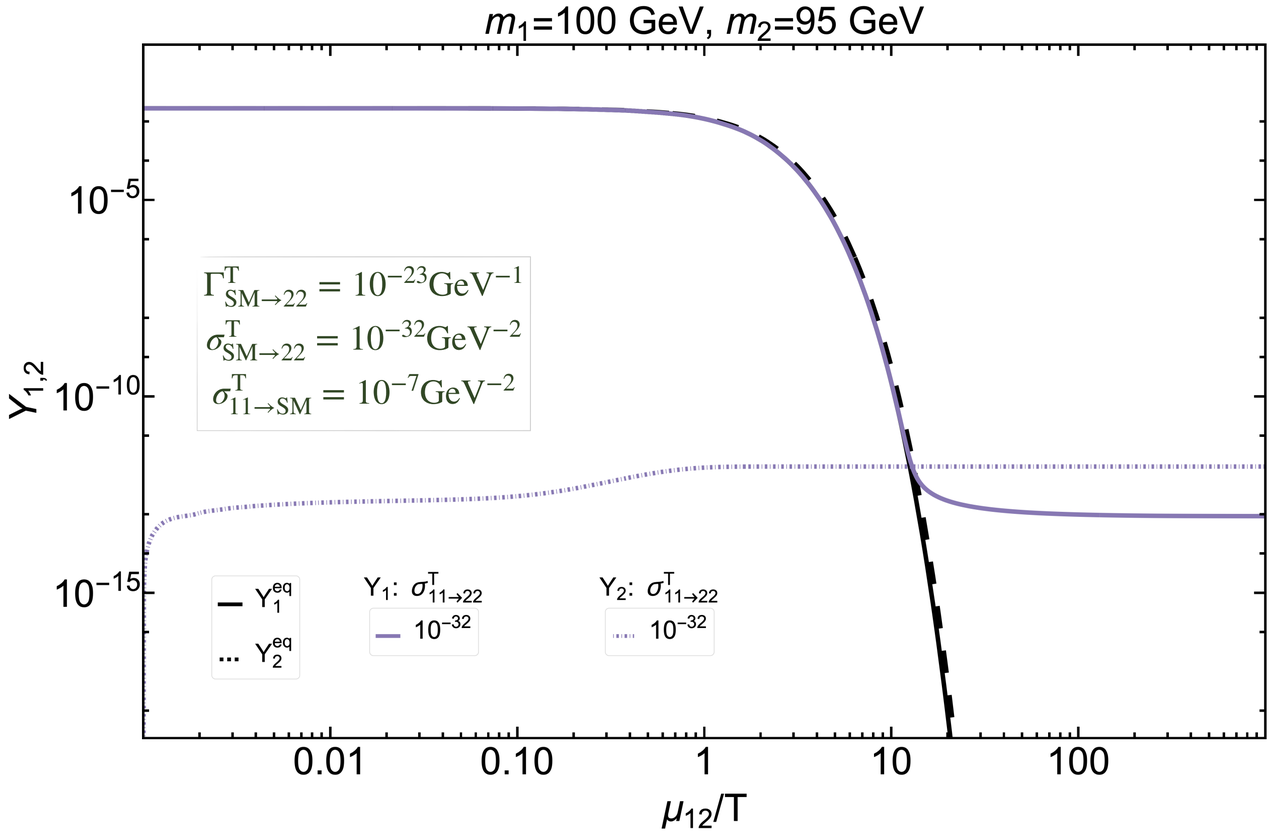
production

Mass hierarchy :

(I) $m_1 > m_2$ and (II) $m_1 < m_2$

pFIMP dynamics in presence of a thermal WIMP

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



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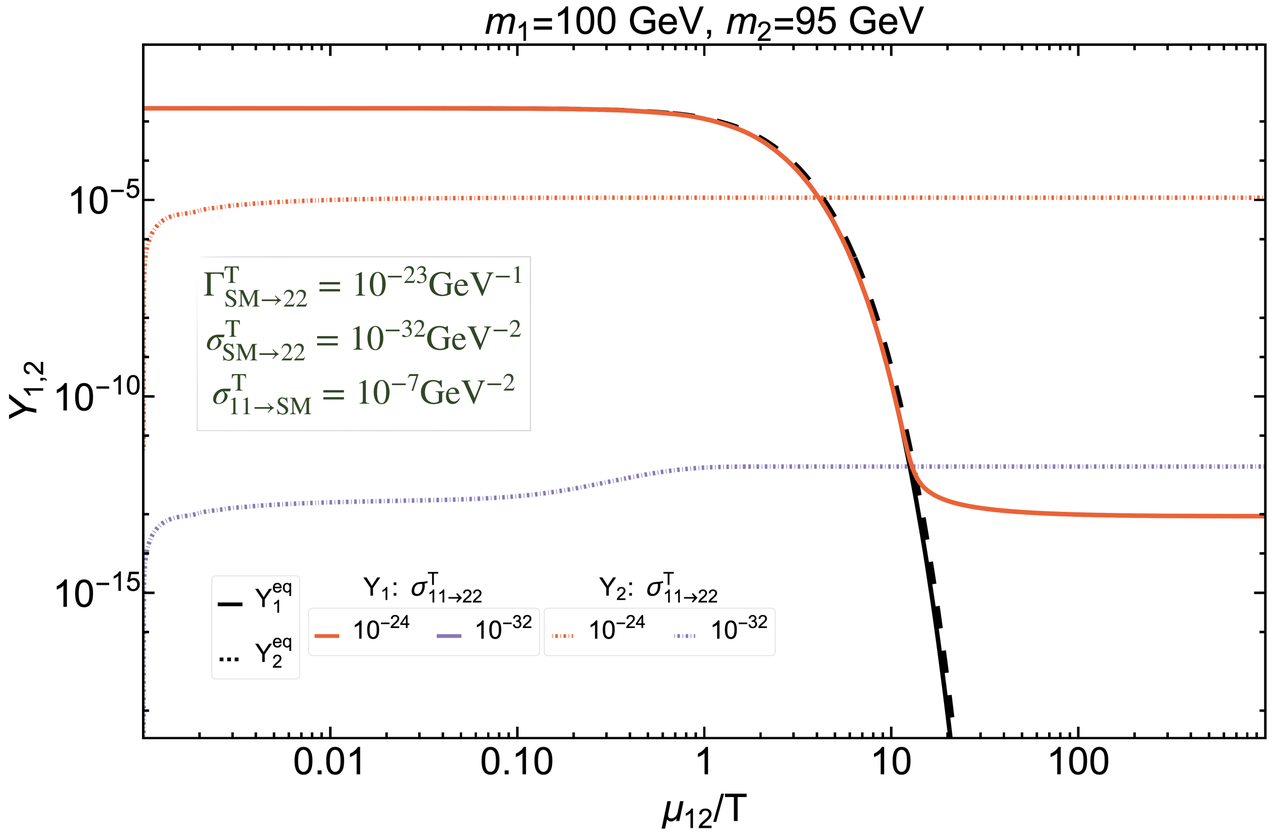

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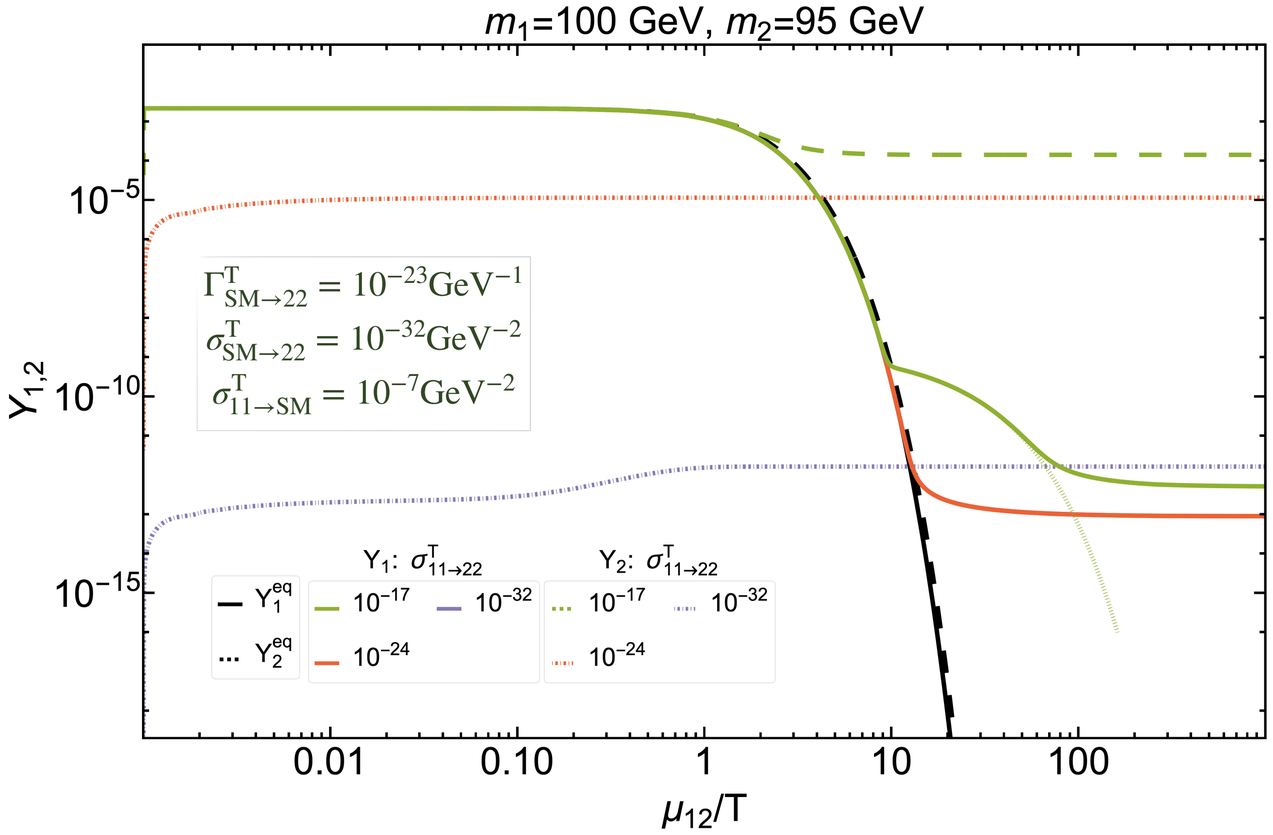

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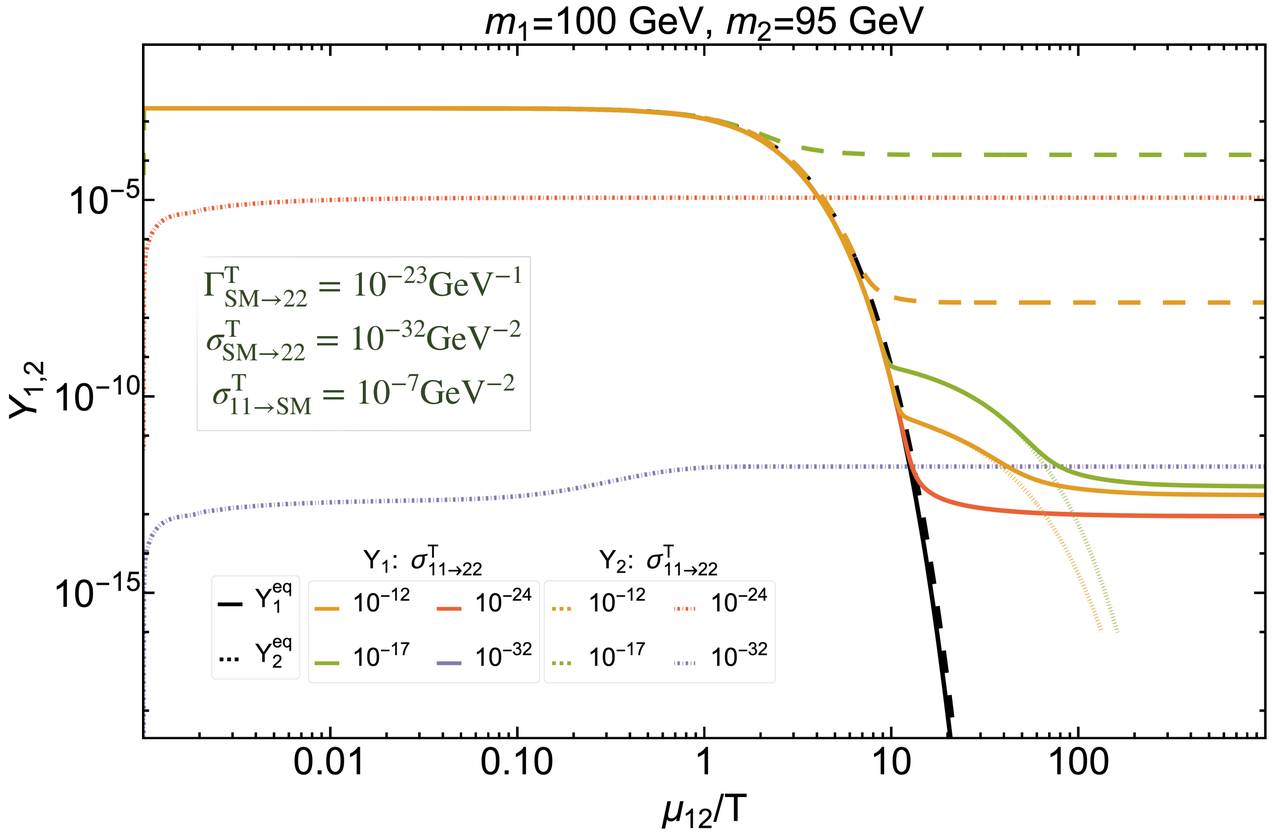

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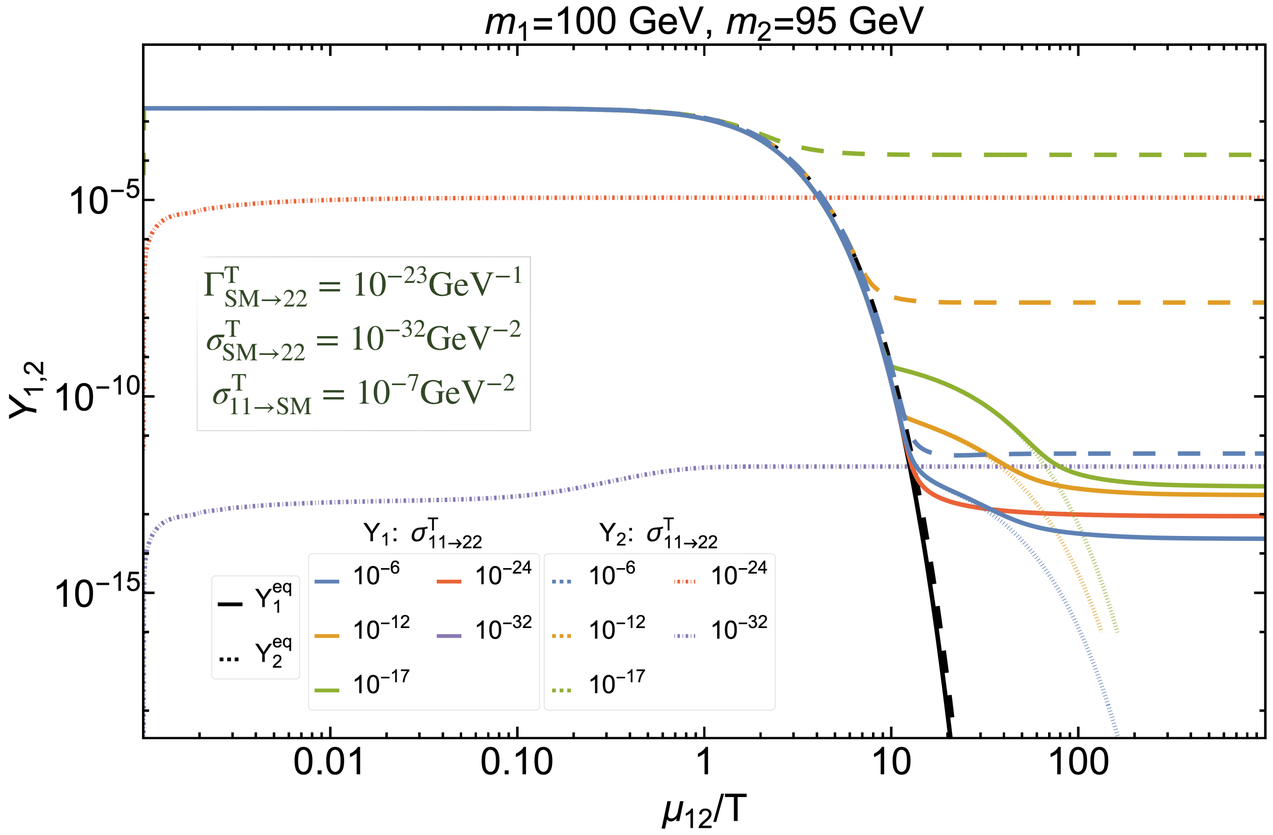

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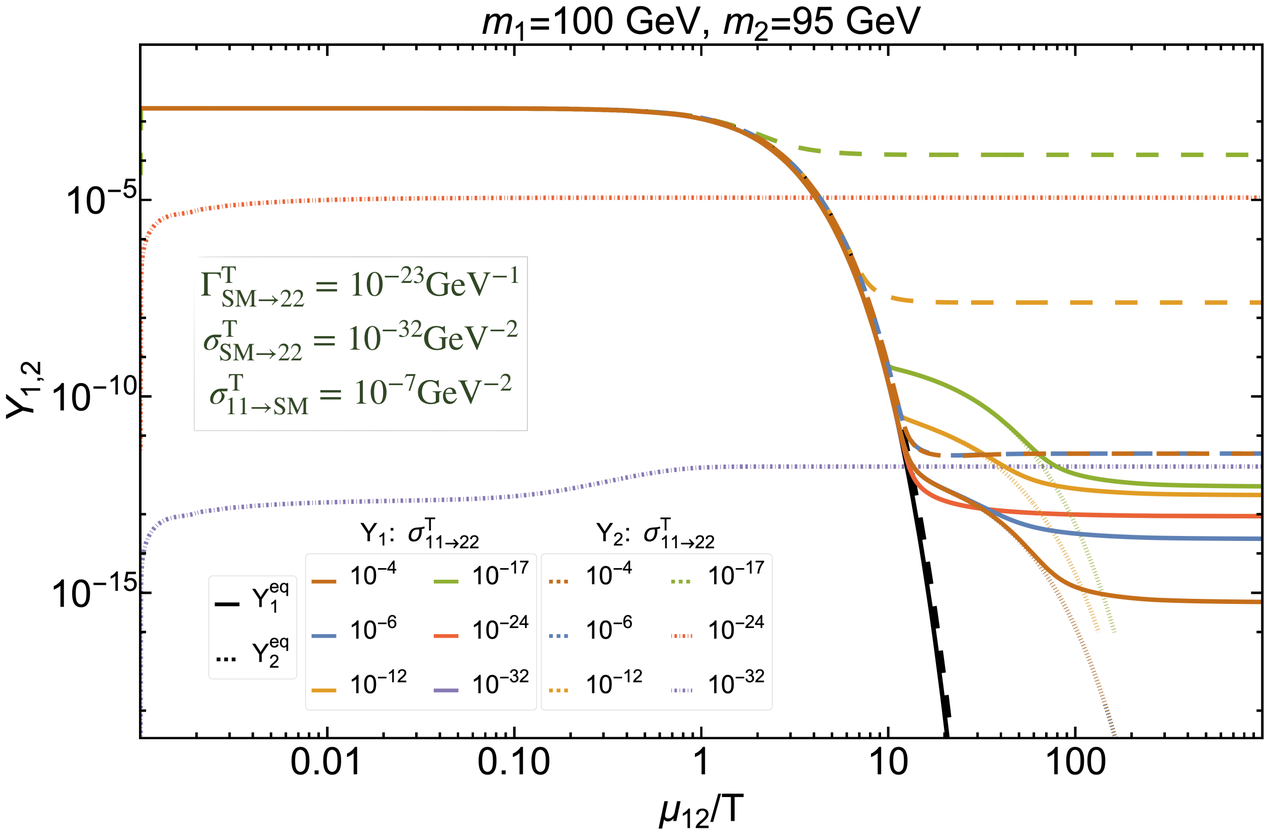

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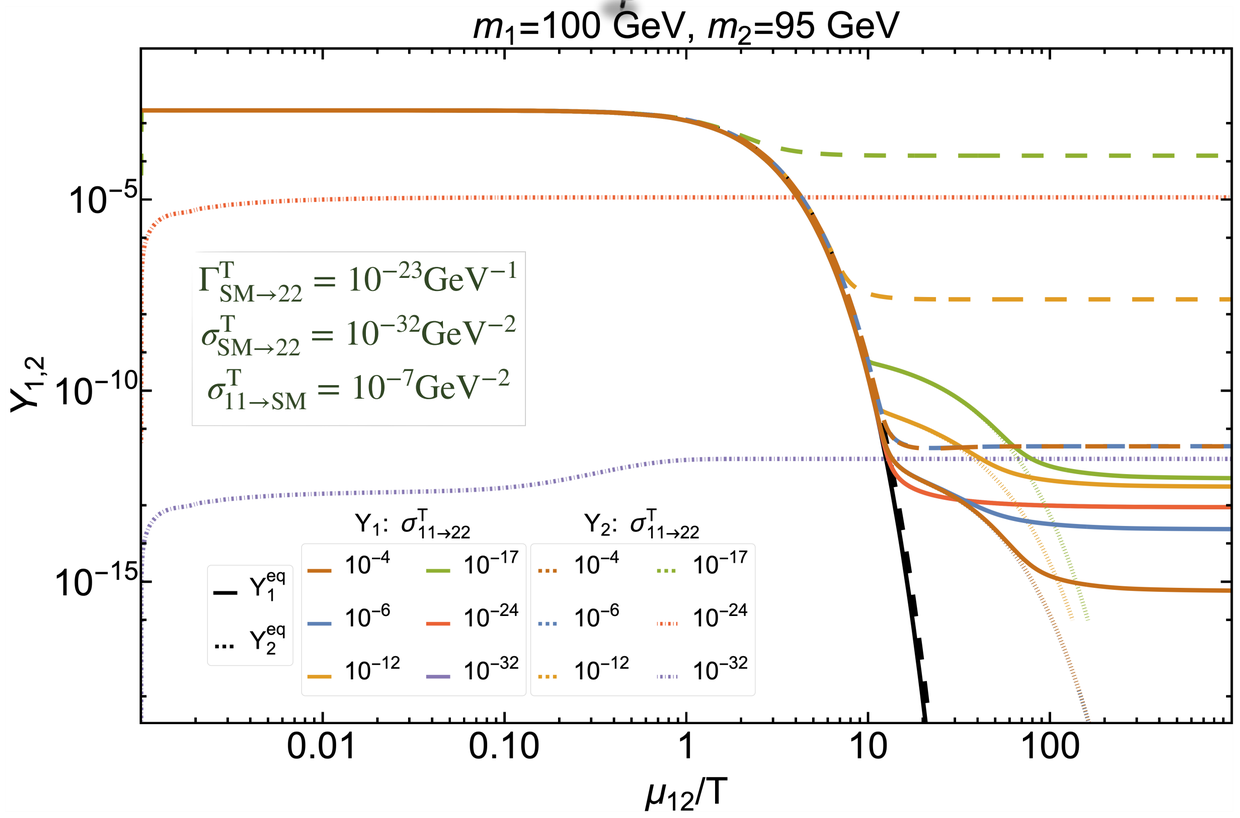
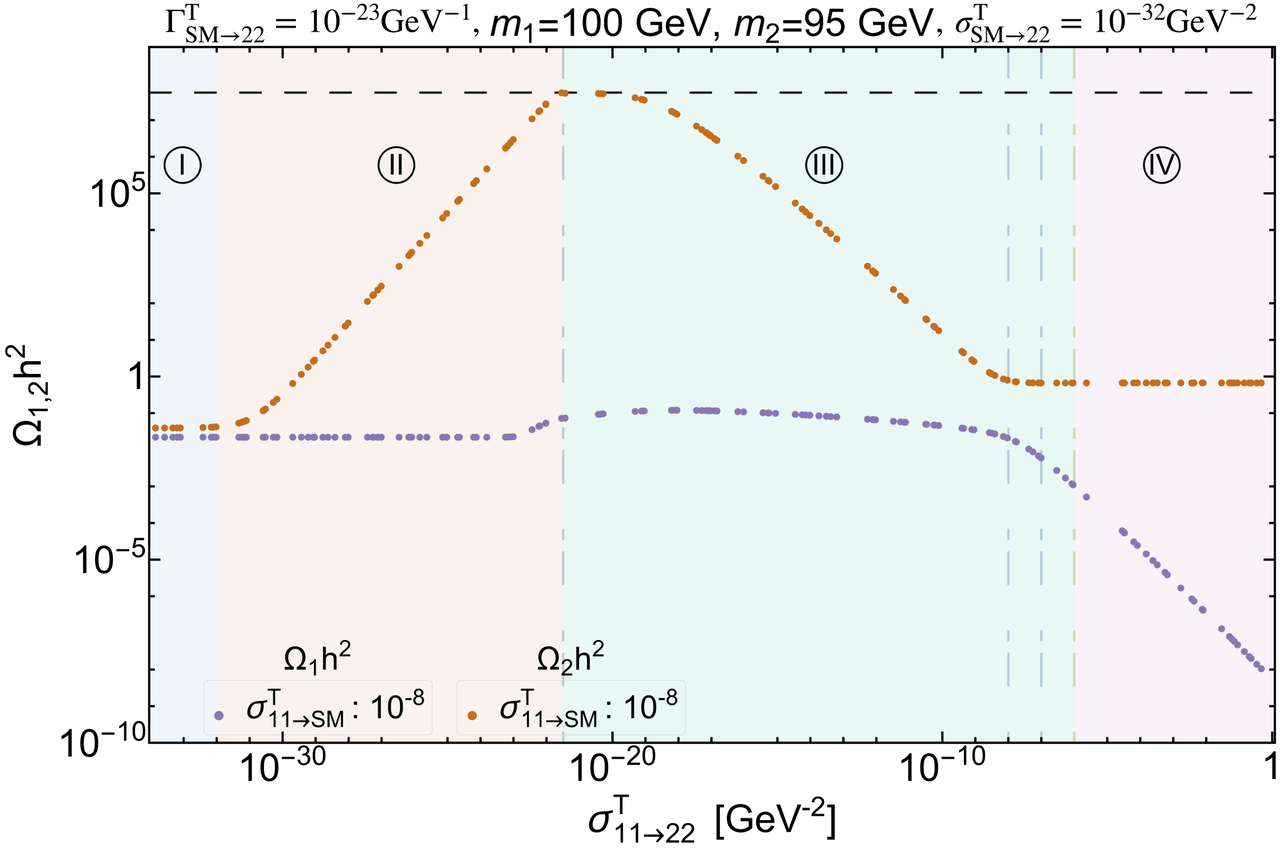




Ⅰ $\sigma^{T}_{11\to 22} < \sigma^{T}_{SM\to 22}$

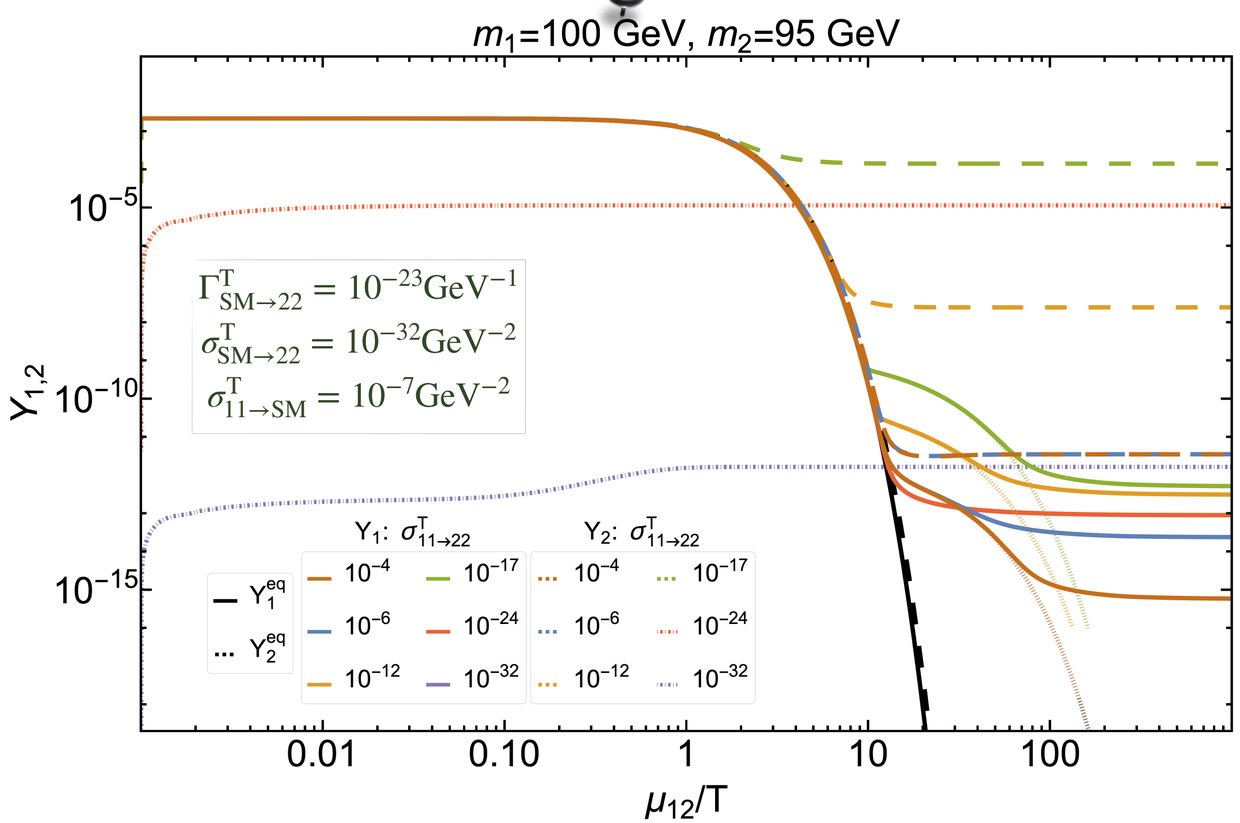
Ⅱ $\sigma^{T}_{SM\to 22} \lesssim \sigma^{T}_{11\to 22} \ll \sigma^{T}_{11\to SM}$

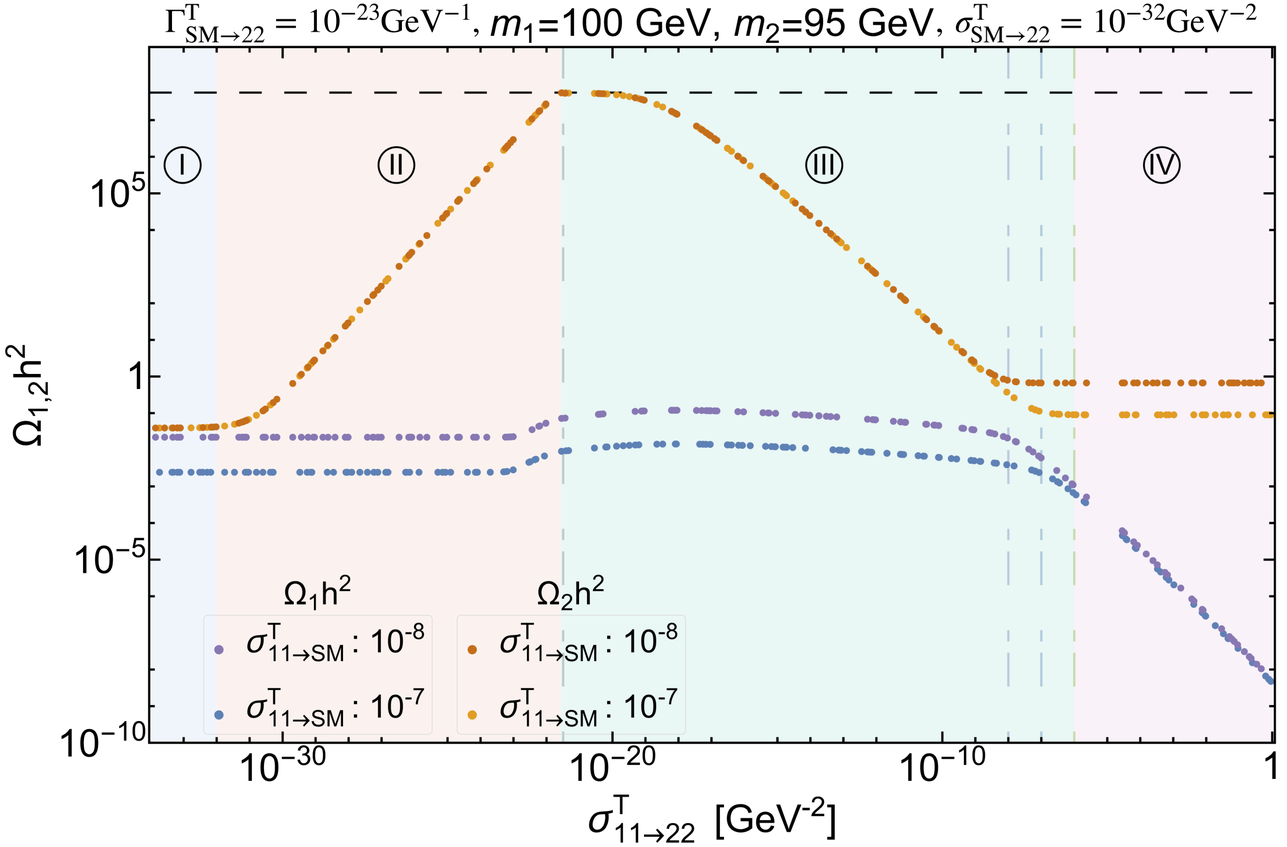
Ⅲ $\sigma^{T}_{SM\to 22} \ll \sigma^{T}_{11\to 22} < \sigma^{T}_{11\to SM}$

Ⅳ $\sigma^{T}_{11\to SM} \lesssim \sigma^{T}_{11\to 22}$

pFIMP dynamics in presence of a thermal WIMP

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





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pFIMP dynamics in presence of a thermal WIMP

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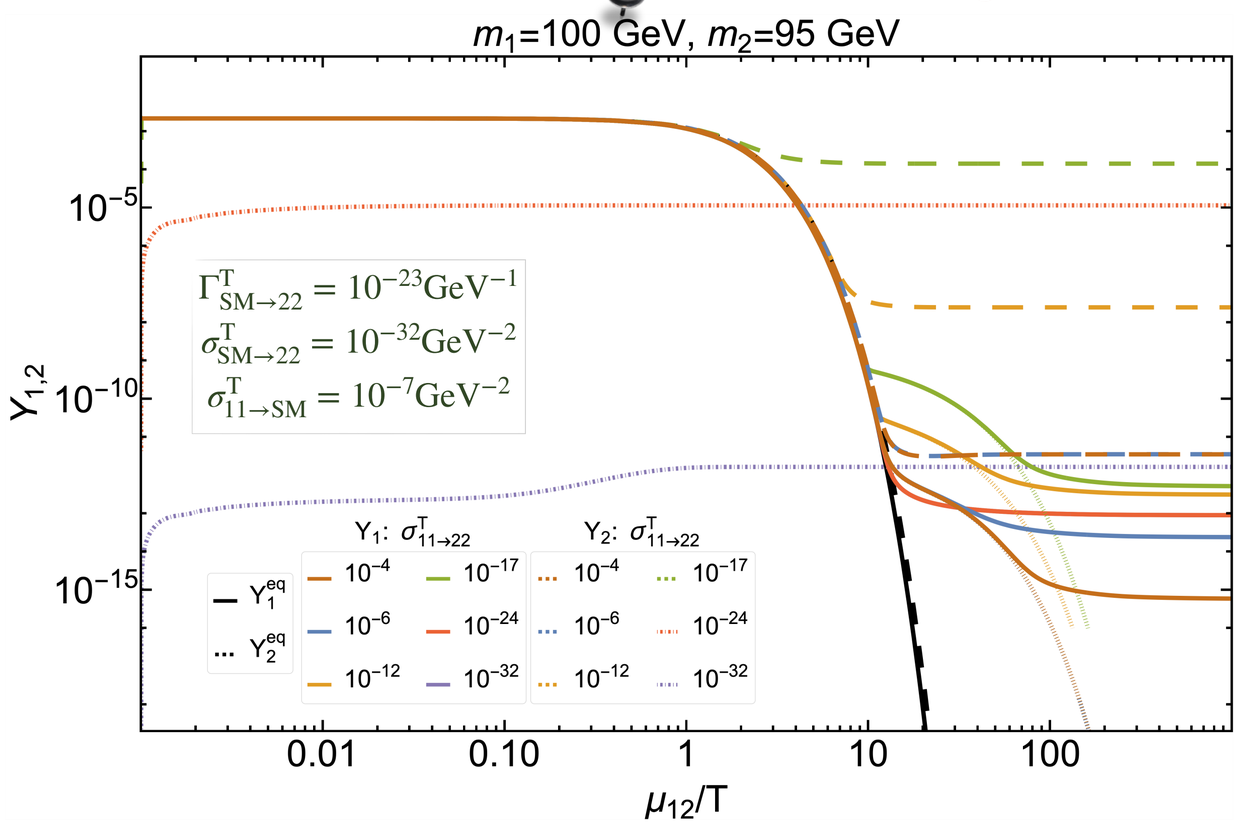

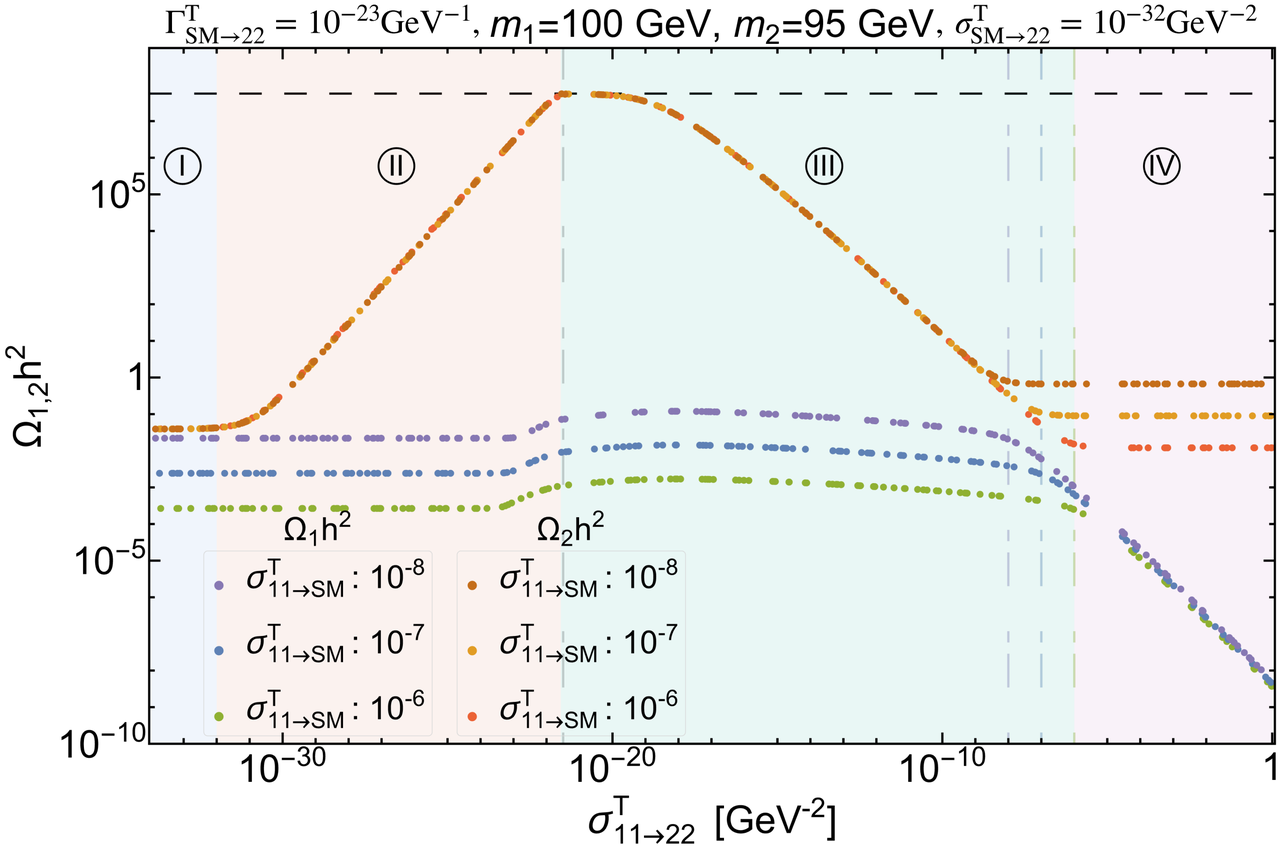

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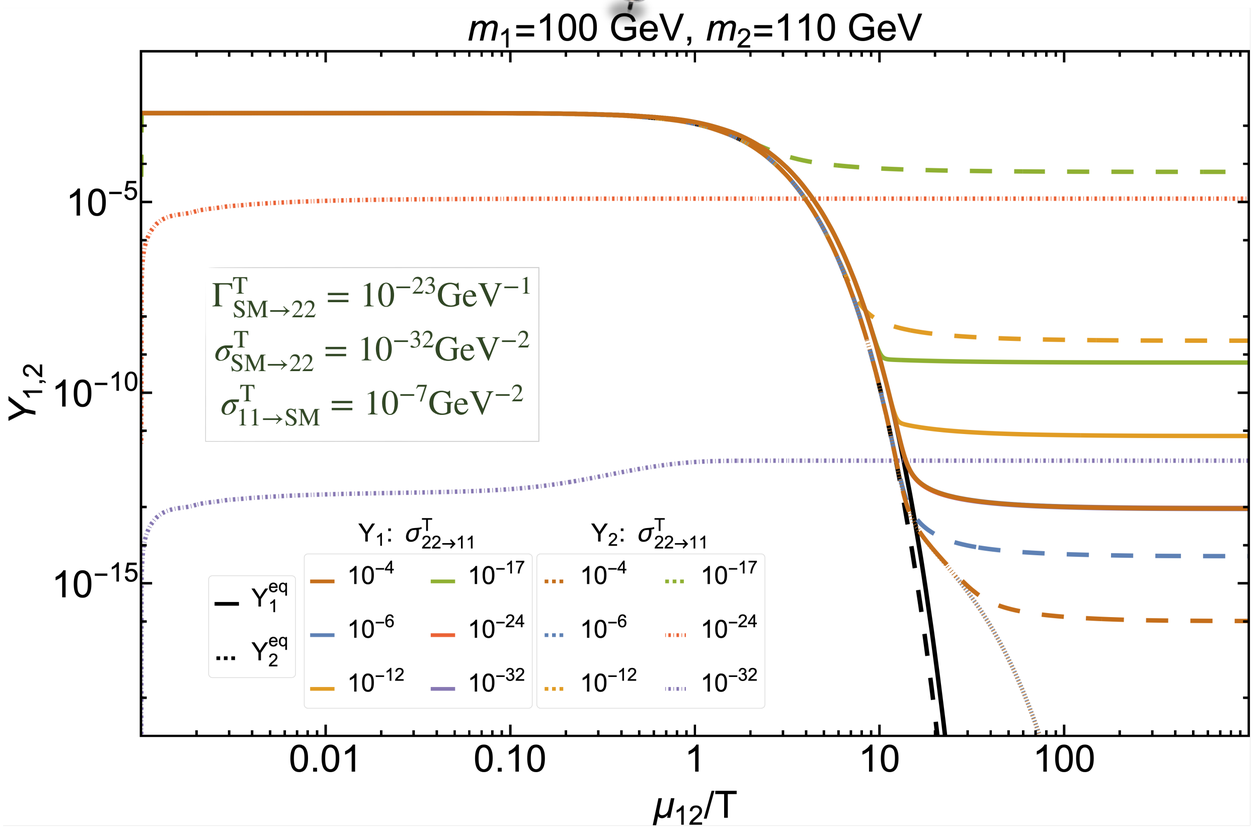
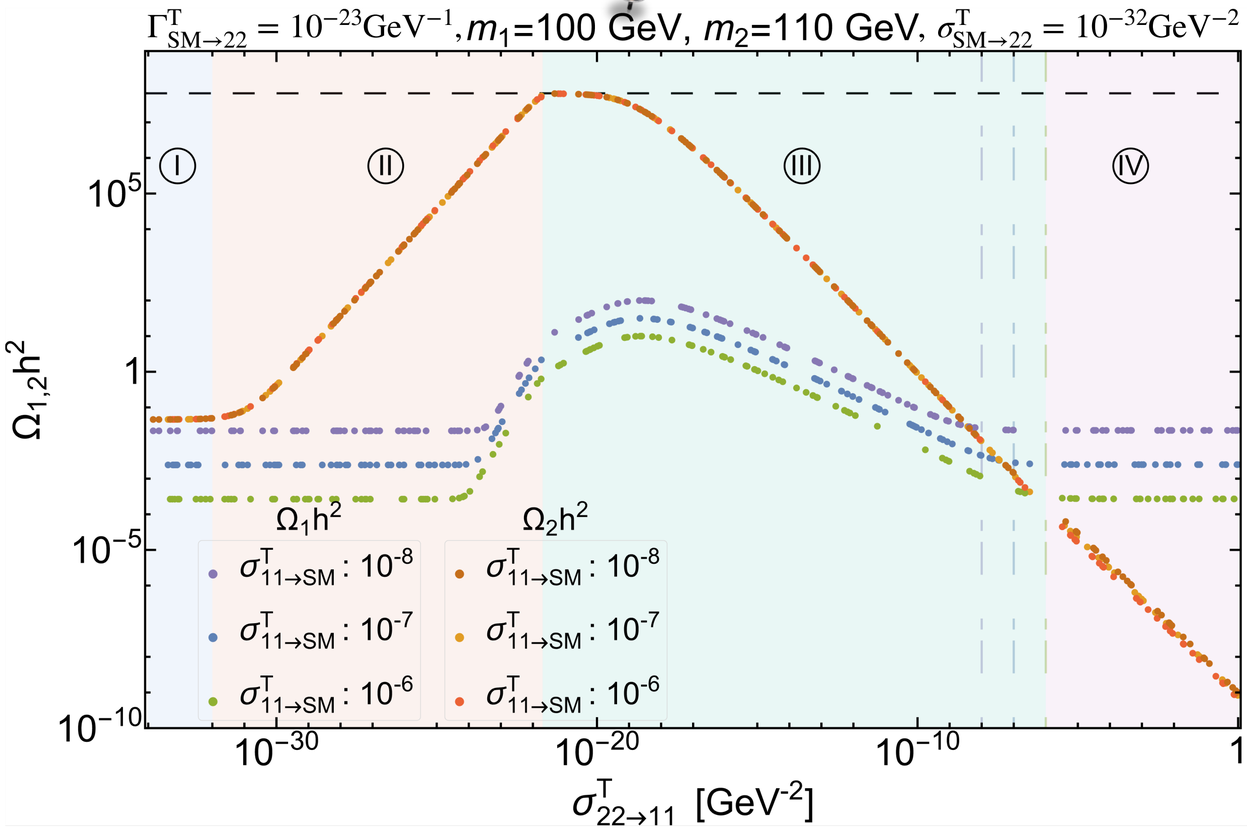
pFIMP dynamics in presence of a thermal WIMP

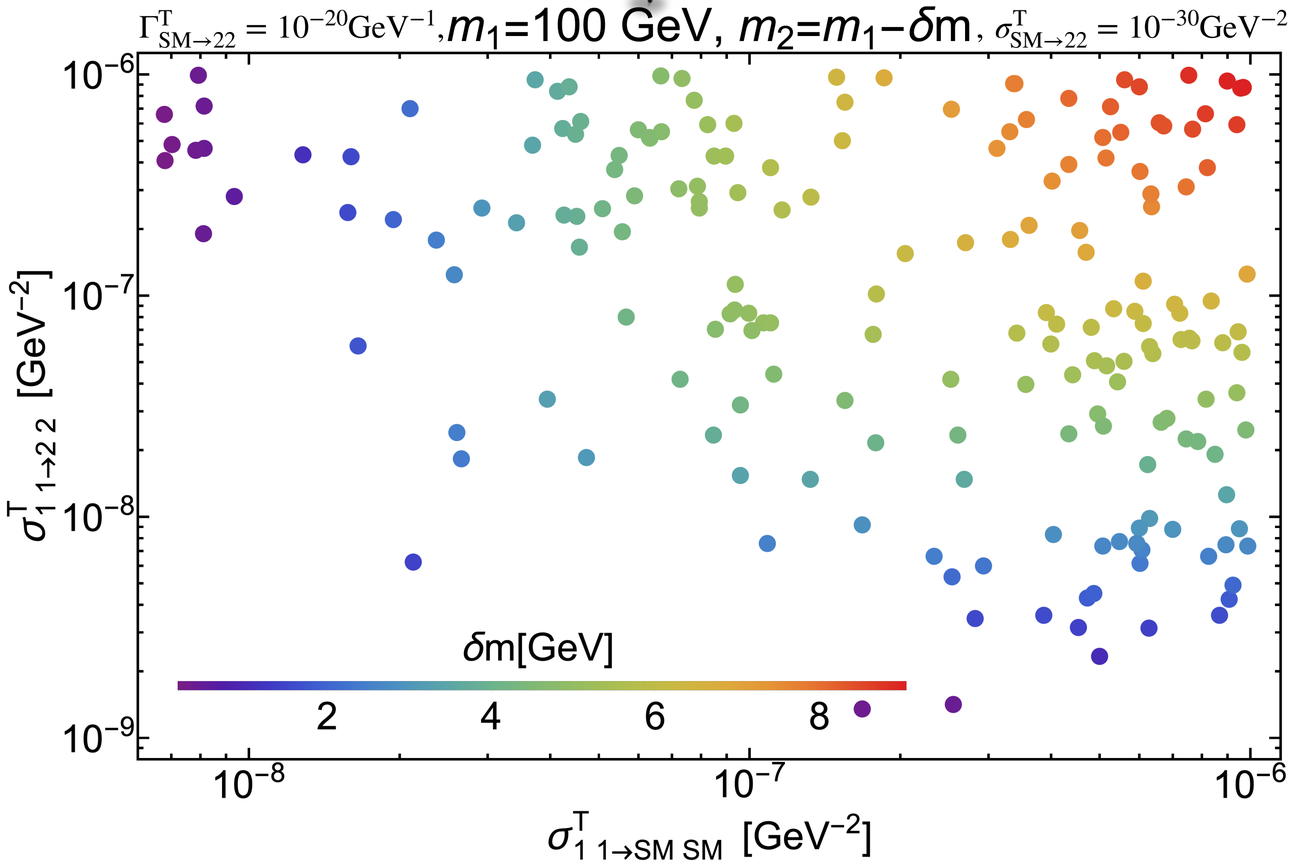
Solution of cBEQ for hierarchy II ($m_1 < m_2$) :



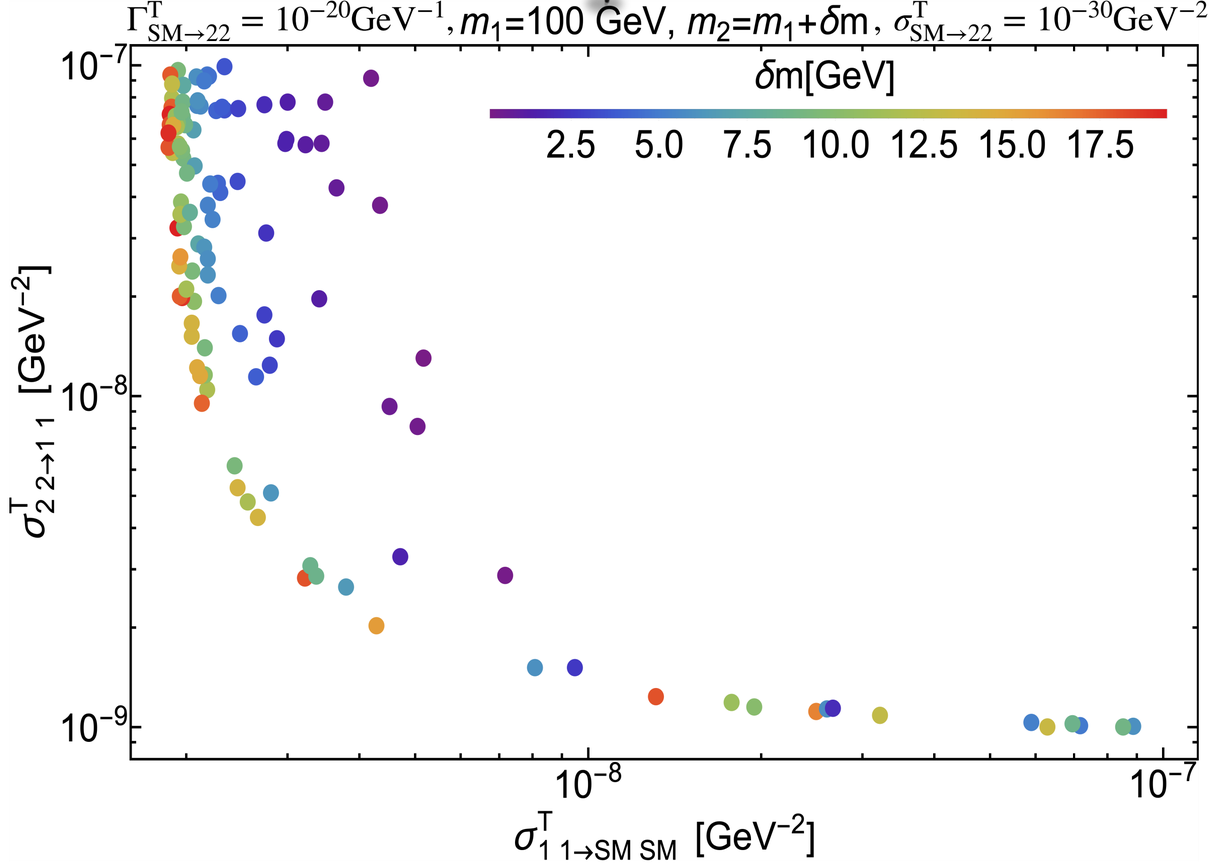


pFIMP dynamics in presence of a thermal WIMP

Role of dark matters mass hierarchy in DM phenomenology:



$m_1 > m_2$



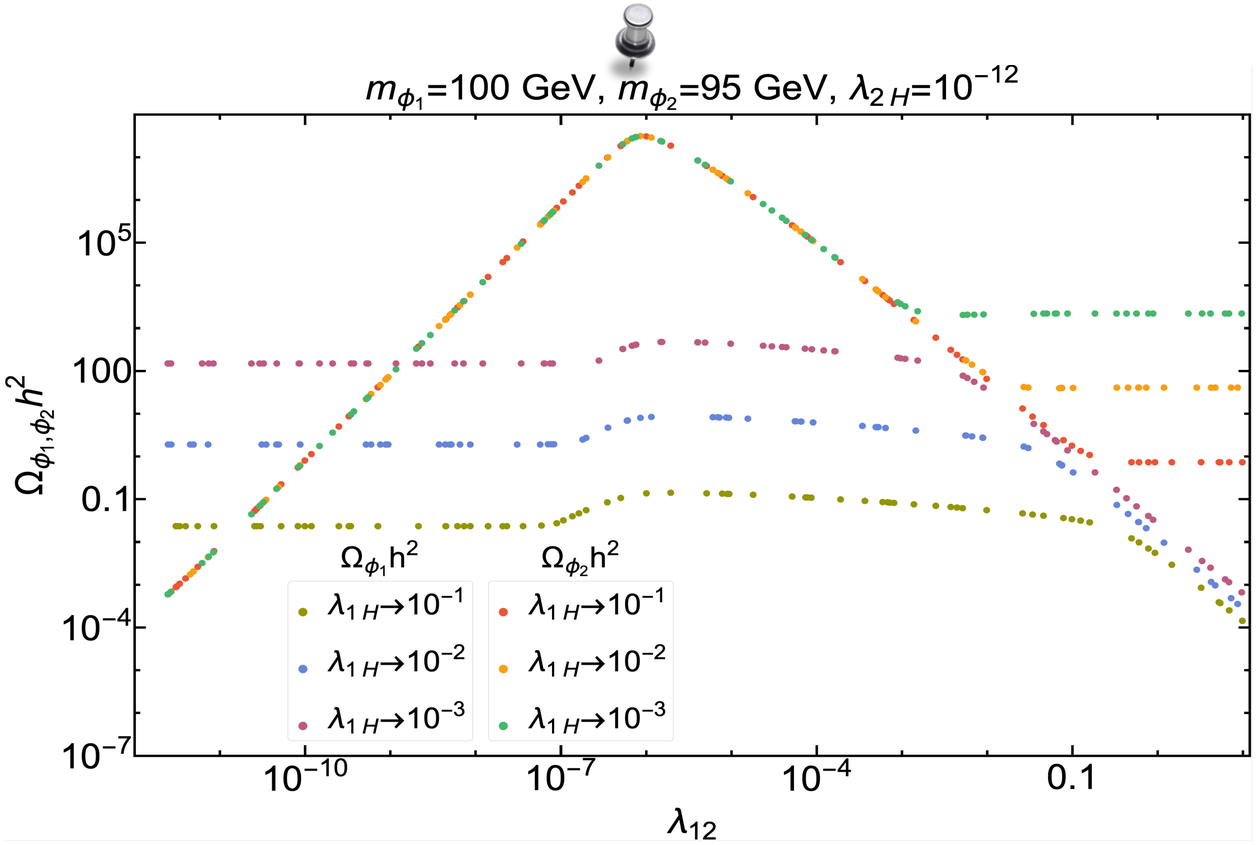
$m_1 < m_2$

Mass splitting between pFIMP and WIMP/SIMP has to be small.

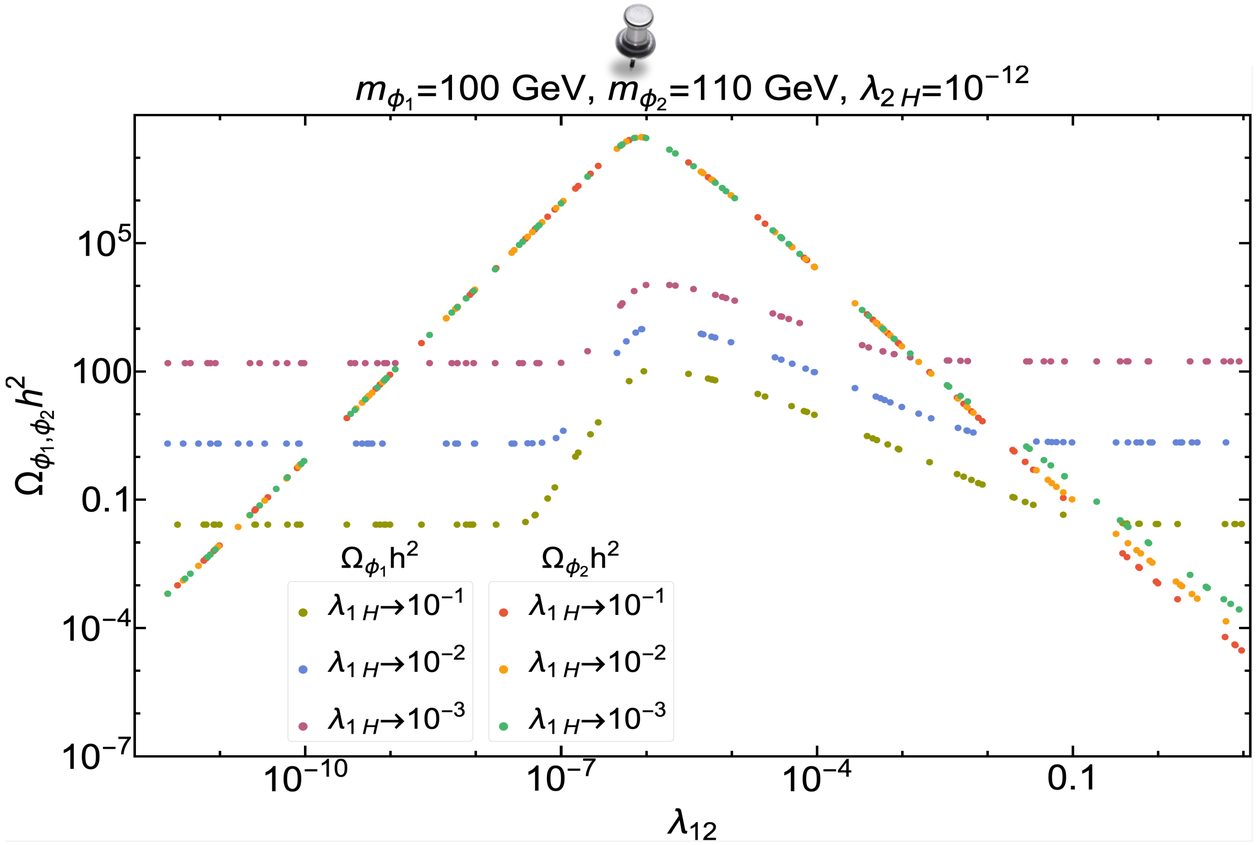
pFIMP dynamics in presence of a thermal WIMP

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

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

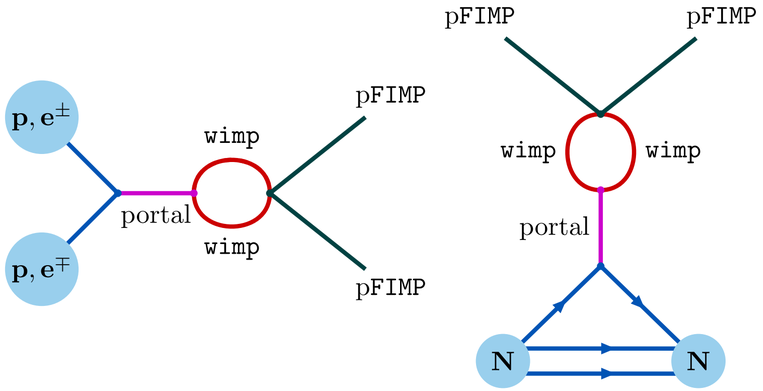


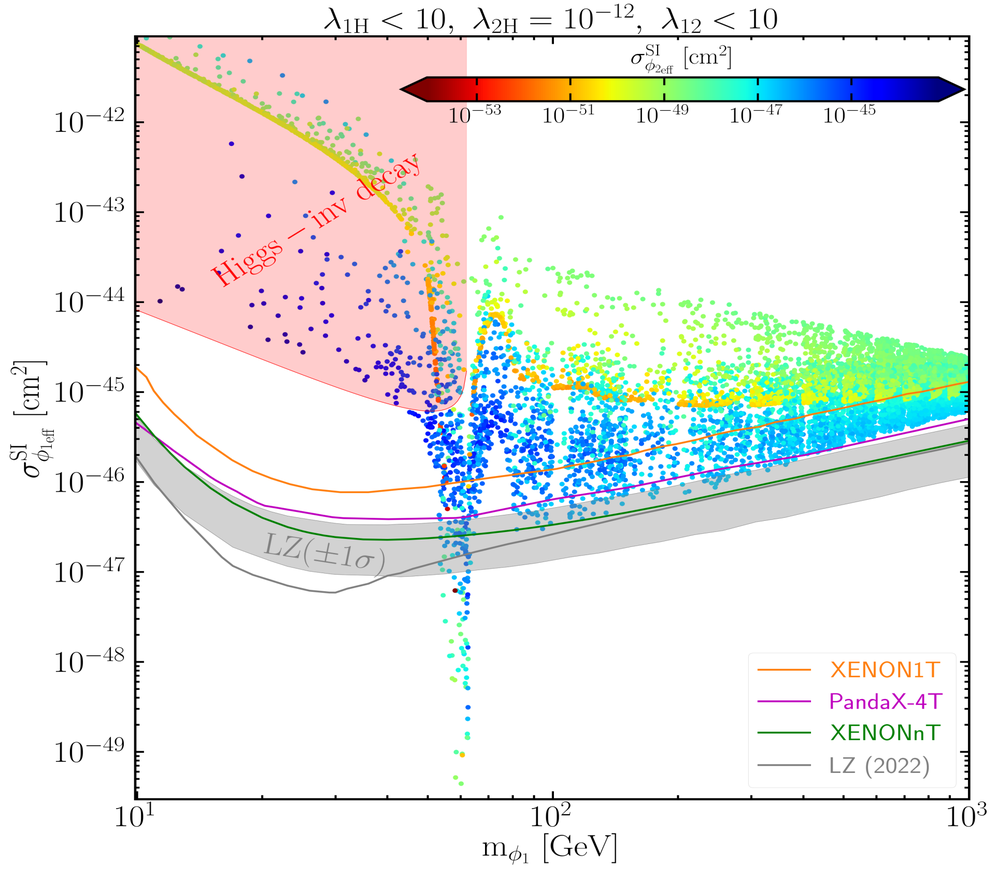
$m_{\phi_1} > m_{\phi_2}$



$m_{\phi_1} < m_{\phi_2}$

pFIMP phenomenology in presence of a thermal DM

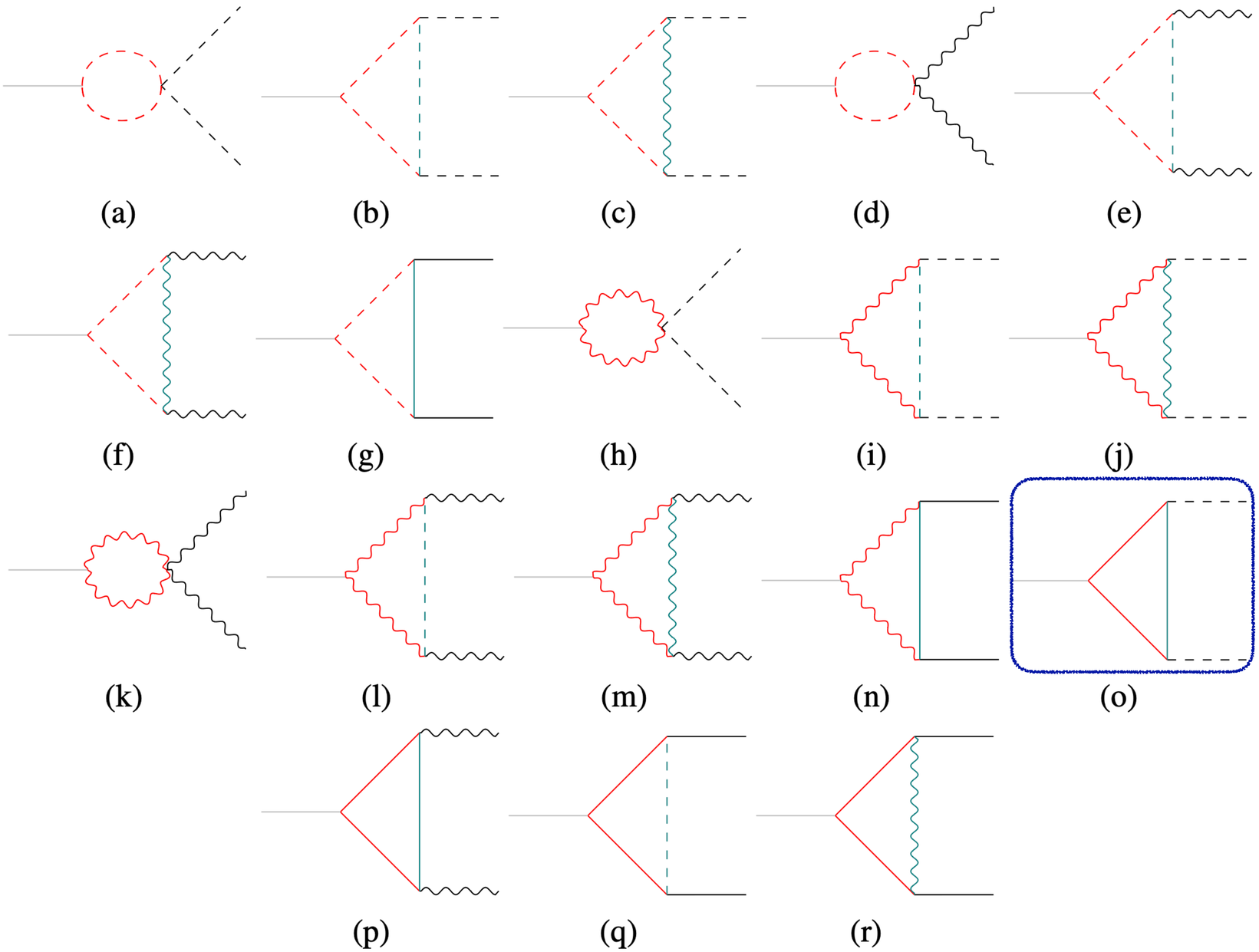




$$\sigma^{SI}_{\phi_{2eff}} = \frac{\Omega_{\phi_2}h^2}{\Omega_{\phi_1}h^2 + \Omega_{\phi_2}h^2} \frac{\mu_n^2 m_n^2}{4\pi v^2 m_{\phi_2}^2} \frac{f_n^2}{m_h^4} |\Gamma^{total}_{h\phi_2\phi_2}|^2_{t\to 0}$$

- WIMP gets large relic allowed parameter space due to open up a new annihilation channel to pFIMP and both are contributing in total observed DM Relic abundance.
- Although this pFIMP has very feeble connection with SM but still has (In-)direct detection search possibility via WIMP loop. According to recent LZ-2022 data within $\pm1\sigma$ some parameter space is available upto 0.5 TeV and Higgs resonance region is allowed by all observational constraint.

Possible pFIMP-SM interactions via WIMP loop



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

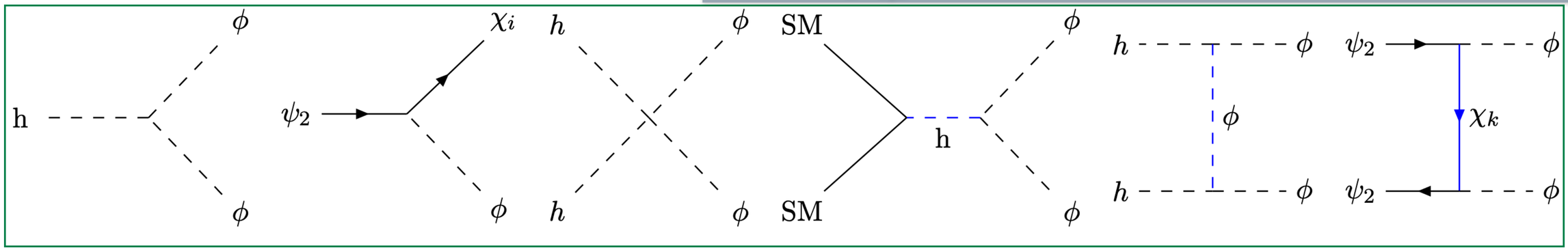
- Grey lines corresponds to SM Higgs and Z boson.
- Red lines corresponds to WIMP.
- Black lines corresponds to pFIMP.
- Tilde lines corresponds to heavy bath particles odd under both symmetry.

Model

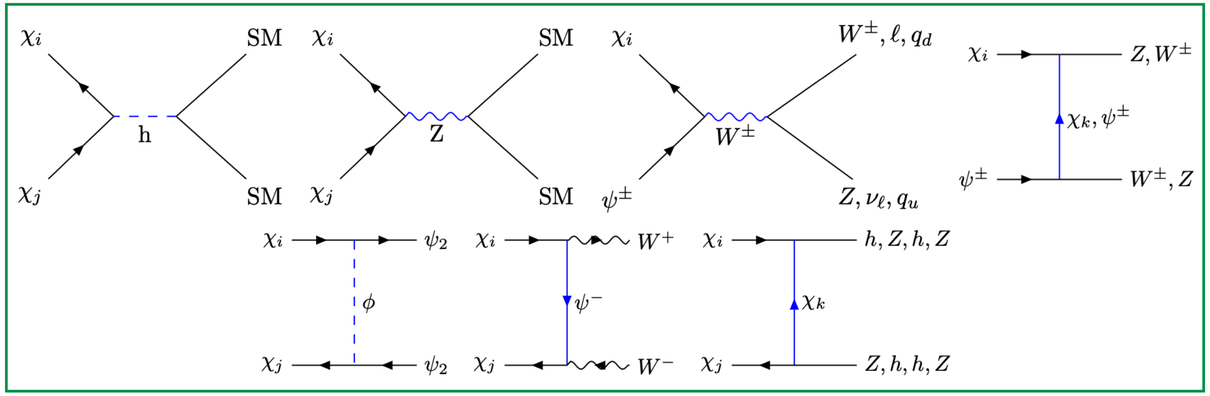
Dark Fields	$SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathbb{Z}_2 \times \mathbb{Z}'_2$				
$\psi = \begin{pmatrix} \psi^0 \\ \psi^- \end{pmatrix}$	1	2	-1	$-$	$+$
ψ_1	1	1	0	$-$	$+$
ψ_2	1	1	0	$+$	$-$
ϕ	1	1	0	$-$	$-$

$$\mathscr{L}_{\text{Scalar}} = \frac{1}{2}|\partial_\mu \phi|^2 - \frac{1}{2}\mathfrak{m}_\phi^2 \phi^2 - \frac{1}{4!}\lambda_\phi \phi^4 - \frac{1}{2}\lambda_{\phi H}\phi^2 H^\dagger H\,.$$

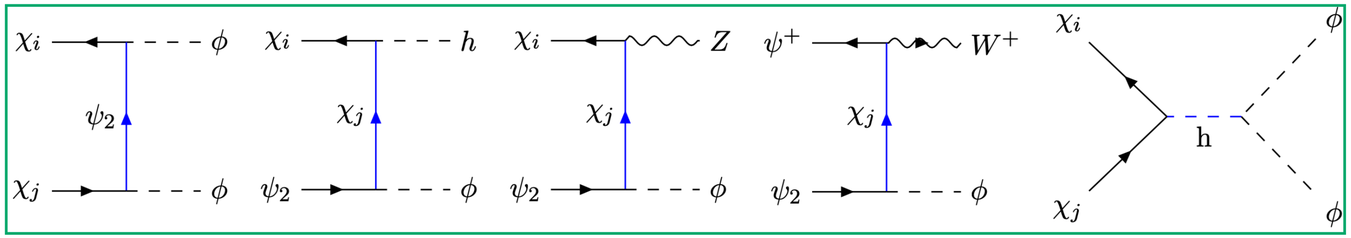
$$\mathscr{L}_{\text{VF}} = \bar{\psi}\left[i\gamma^\mu\left(\partial_\mu + ig\frac{\sigma^a}{2}W_\mu^a + ig'\frac{Y}{2}B_\mu\right) - m_\psi\right]\psi + \sum_{\alpha=1,2}\bar{\psi}_\alpha\left(i\gamma^\mu\partial_\mu - m_{\psi_\alpha}\right)\psi_\alpha - \left(Y_1\bar{\psi}\widetilde{H}\psi_1 + Y_2\bar{\psi}_2\psi_1\phi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



pFIMP production from thermal bath

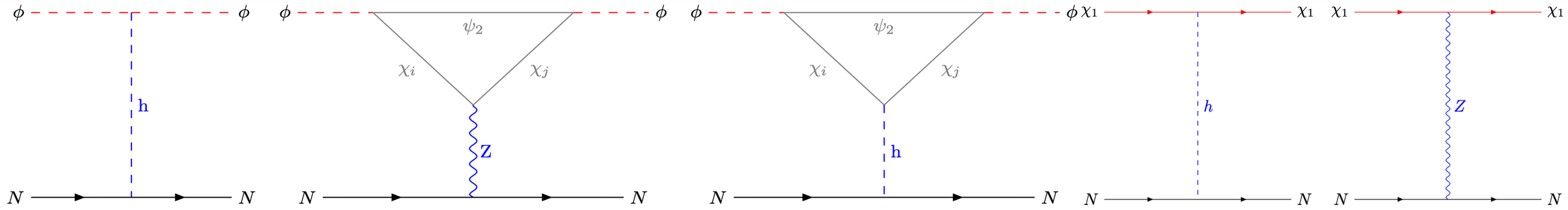


Annihilation and co-annihilation channels of WIMP



WIMP-pFIMP conversion

Direct detection of WIMP and pFIMP



Loop calculation has been done analytically and available in our paper.

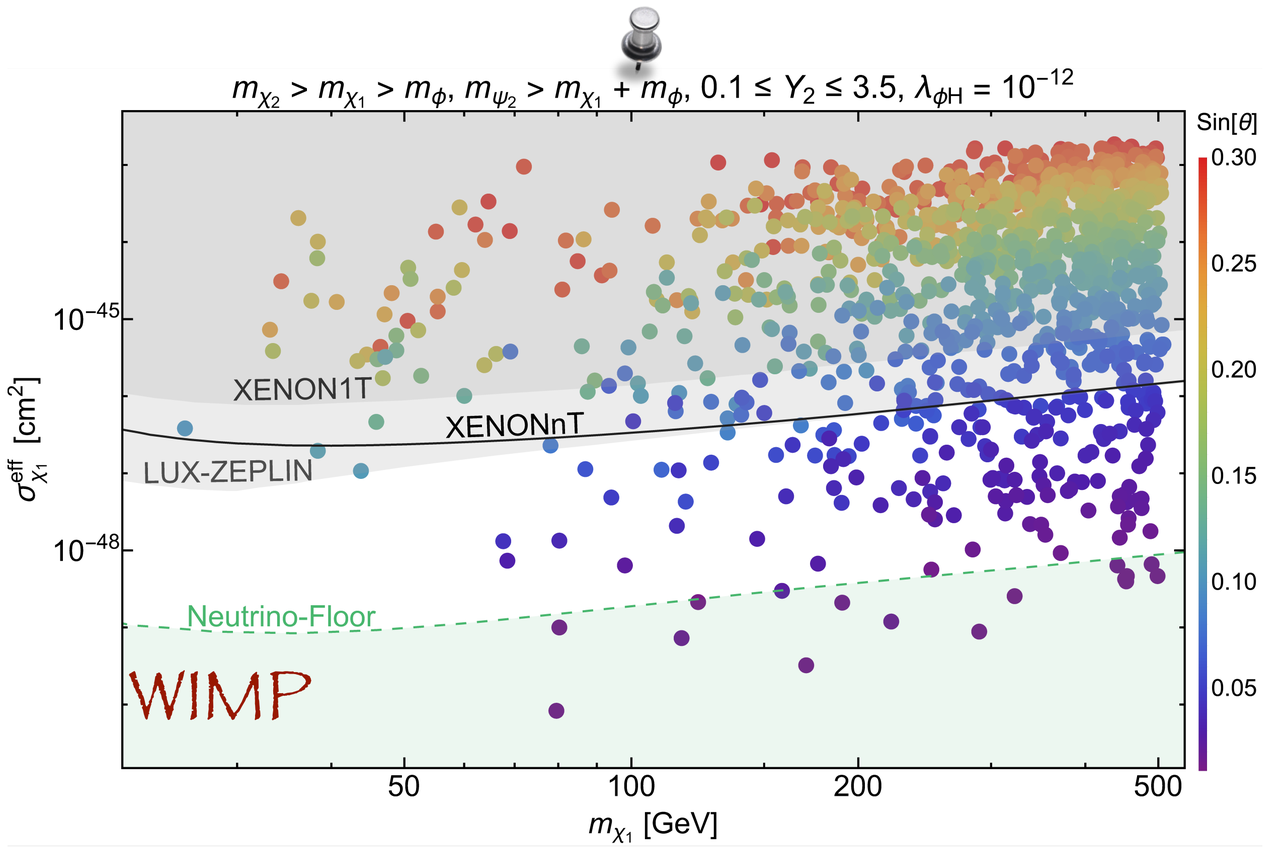
$$\Gamma_{ij}^{1-\text{loop}} = \frac{i}{4\pi^2}\lambda_{h\chi_i\chi_j}\lambda_{\phi\psi_2\chi_j}\lambda_{\phi\psi_2\chi_i}\int_0^1 dx\ dy\ dz\left[\frac{\delta m_{ij}}{\Delta_{ij}} - 2c_{ij}\left(\frac{1}{\epsilon} - \gamma_E + \ln[4\pi] - \frac{1}{2} + \ln\frac{\mu^2}{\Delta_{ij}}\right) + \mathcal{O}(\epsilon)\right]\delta(x+y+z-1)\,.$$

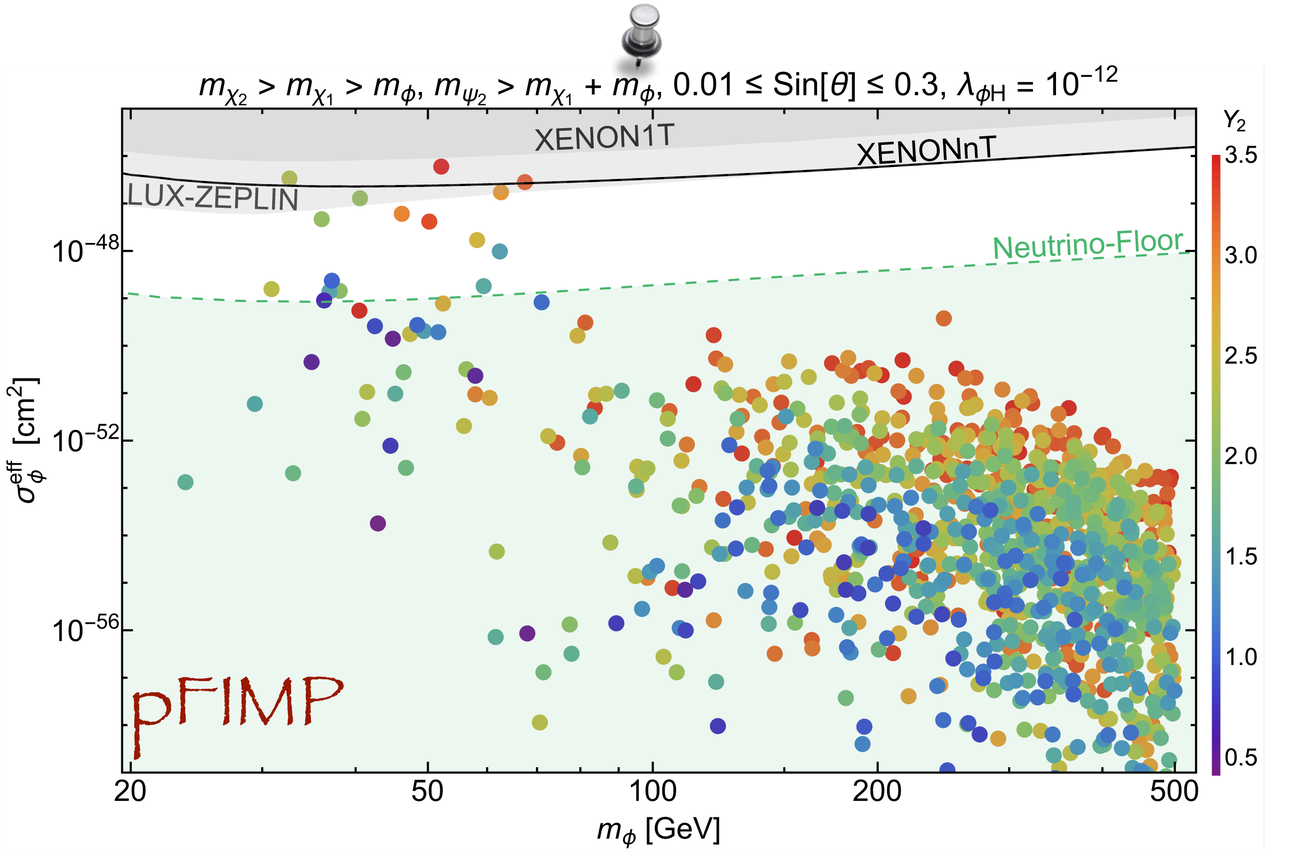
$$\mathbb{L}_h = -i\lambda_{h\phi\phi} + \sum_{i,j}\Gamma_{ij}^{1-\text{loop}}\Big|_{t\to 0} - \sum_{i,j}\Gamma_{ij}^{1-\text{loop}}\Big|_{q_h^2\to 4m_\phi^2}$$

Here we choose DM relic density observation scale as a physical renormalization scale.

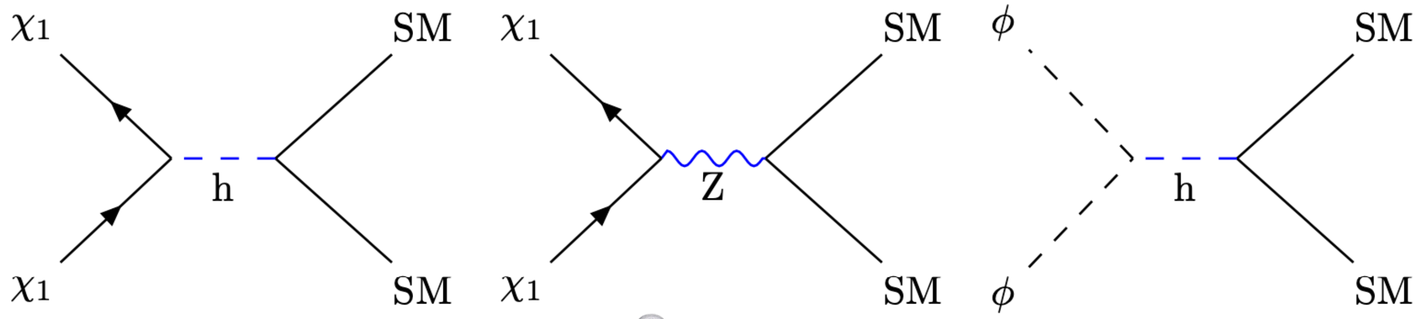
$$\mathbb{L}_\mu^Z = \frac{i}{4\pi^2}\sum_{i,j=1,2}\lambda_{\phi\psi_2\chi_j}\lambda_{\phi\psi_2\chi_i}\lambda_{Z\chi_i\chi_j}\int_0^1 dx\ dy\ dz\left[\frac{\delta m_\mu^{ij}}{\Delta^{ij}} + (2c_\mu - yq_{2_\mu} - zq_{4_\mu})\ln\Delta^{ij}\right]\delta(x+y+z-1)\,.$$

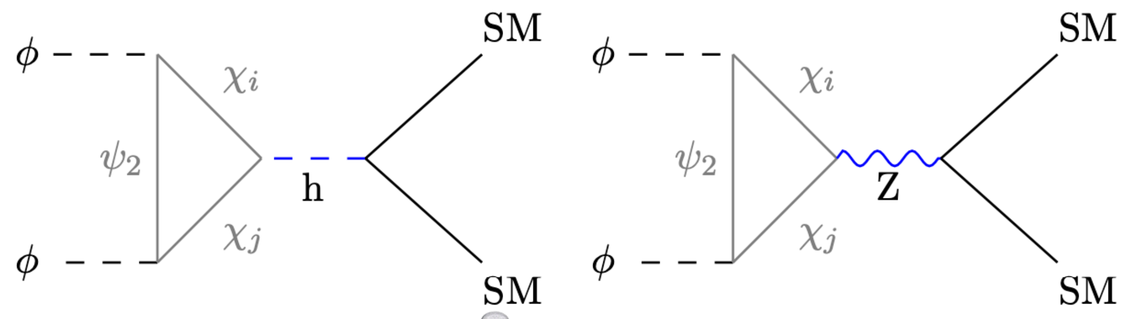
Direct detection of WIMP and pFIMP

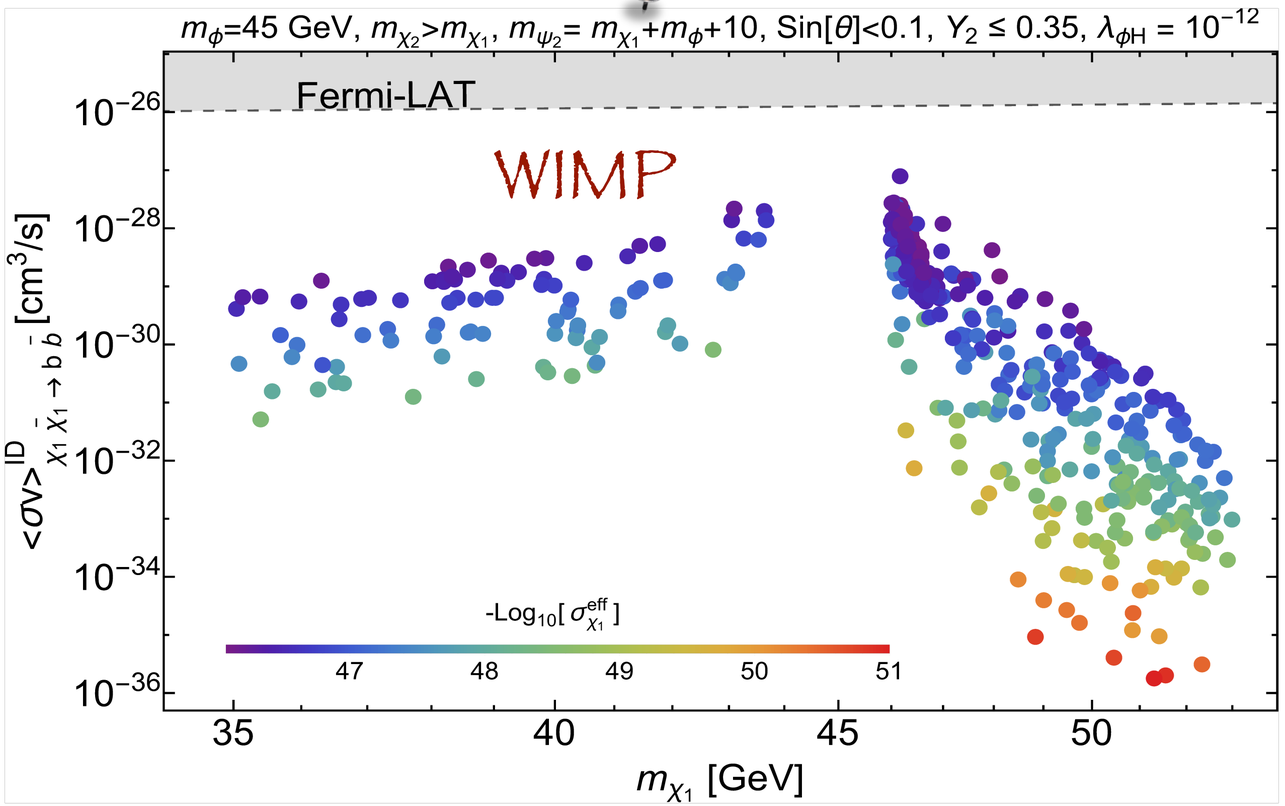


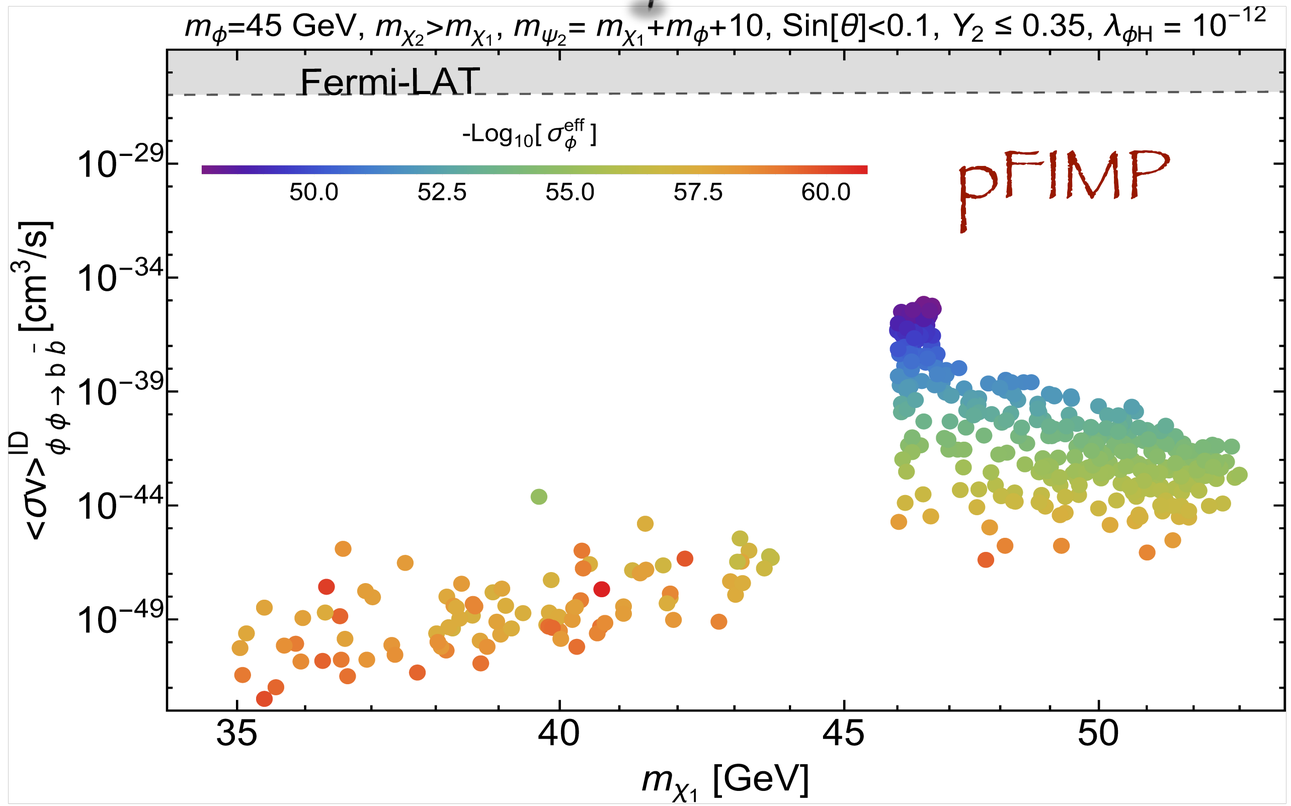


Indirect detection limits on WIMP and pFIMP

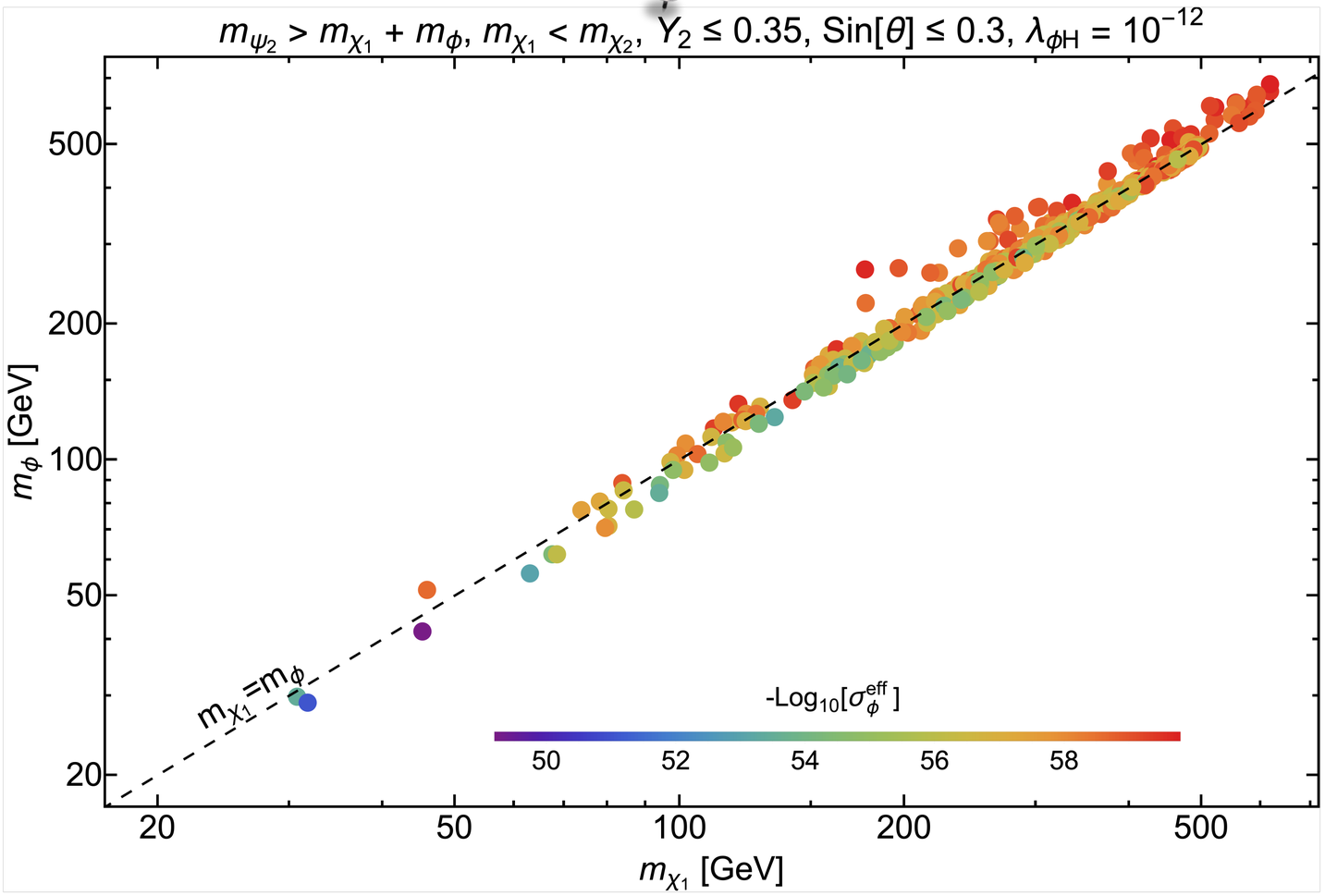








Summary



- pFIMP dynamics and detection possibility has been discussed in detail.
- We studied both DM hierarchy regime.
- Most detectable regime for future experiments near Z-resonance above neutrino floor.
- Collider search prospect of pFIMP might be possible via thermal DM loop.

Thank

You