Non-standard annihilations in Scalar Dark Matter Models

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SUSY 2017

Based on :

JCAP 1703 (2017) 045 with U K Dey and T S Ray

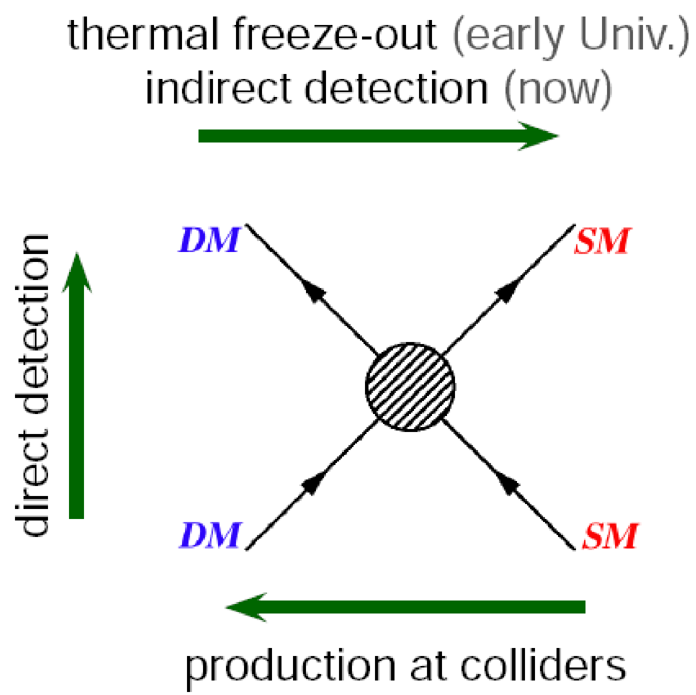
and JHEP 10 (2017) 088 with S Bhattacharya, P Ghosh and T S Ray

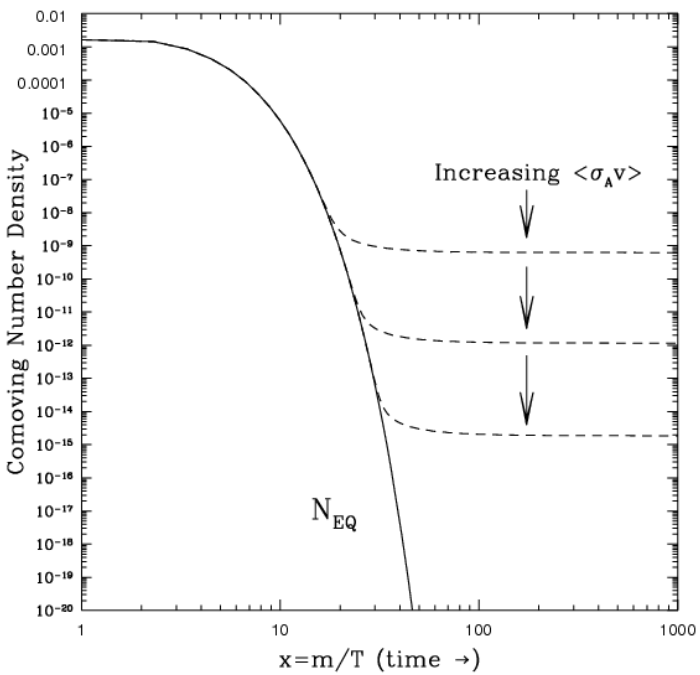
Outline

- Introduction : Status of Minimal Model
- Semi-annihilation, co-annihilation and multipartite feature
- Assisted Annihilation
- Summary

Standard framework and some limitations

- ➢ Weakly Interacting Massive Particle (WIMP).





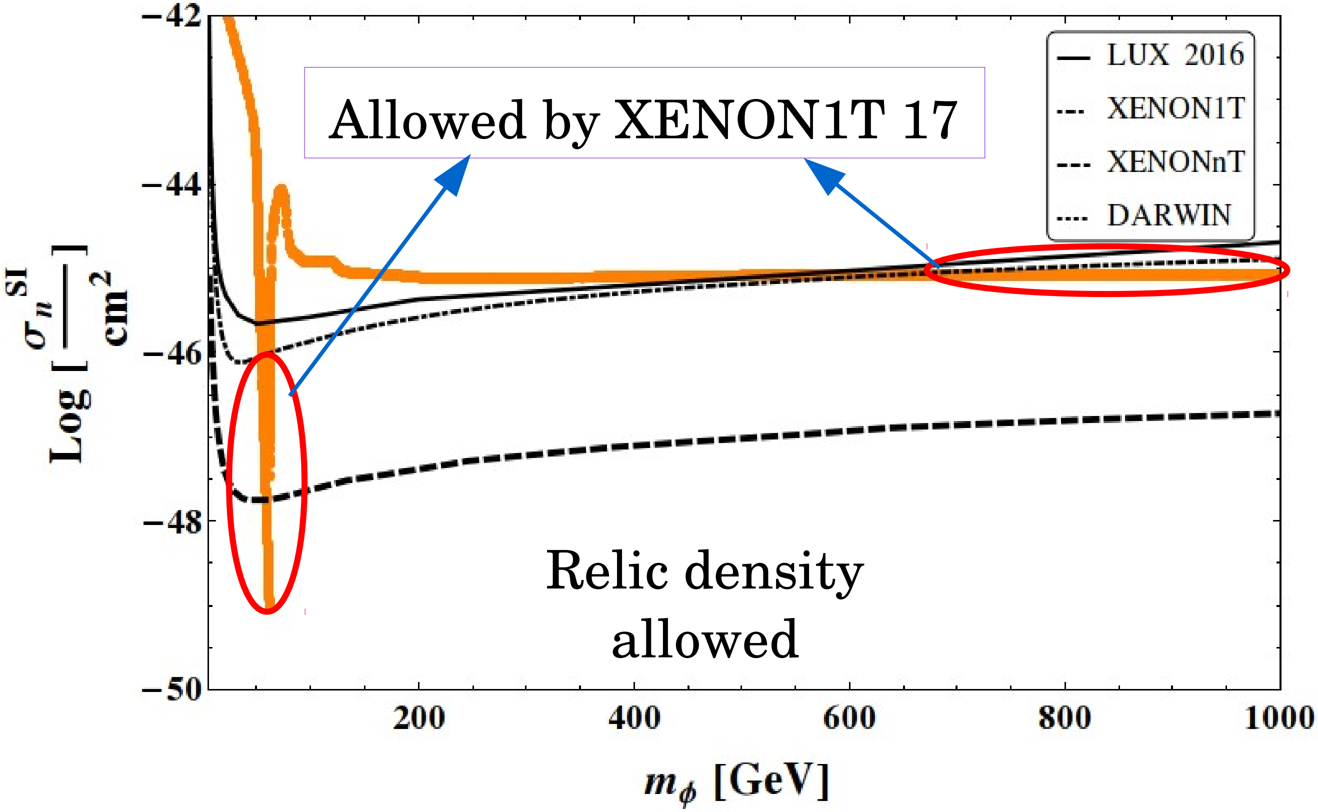
✗ No direct search signal.

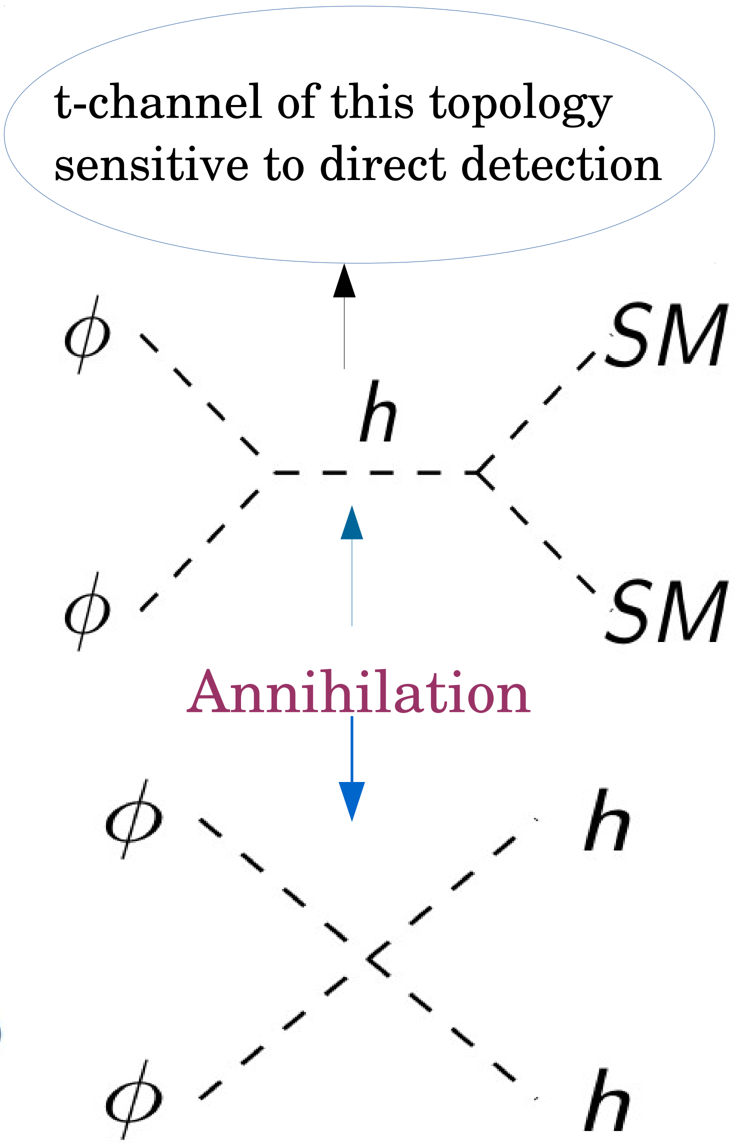
✗ Small scale controversies.

WIMP Higgs portal : Status of minimal model

- Real singlet scalar charged under $\mathbb{Z}_2$

$$-\mathcal{L}_{\mathrm{DM-Higgs}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{1}{2} m_\phi^2 \phi^2 + \frac{\lambda_s}{4!}\phi^4 + \frac{1}{2}\lambda_h H^\dagger H \phi^2 \, .$$





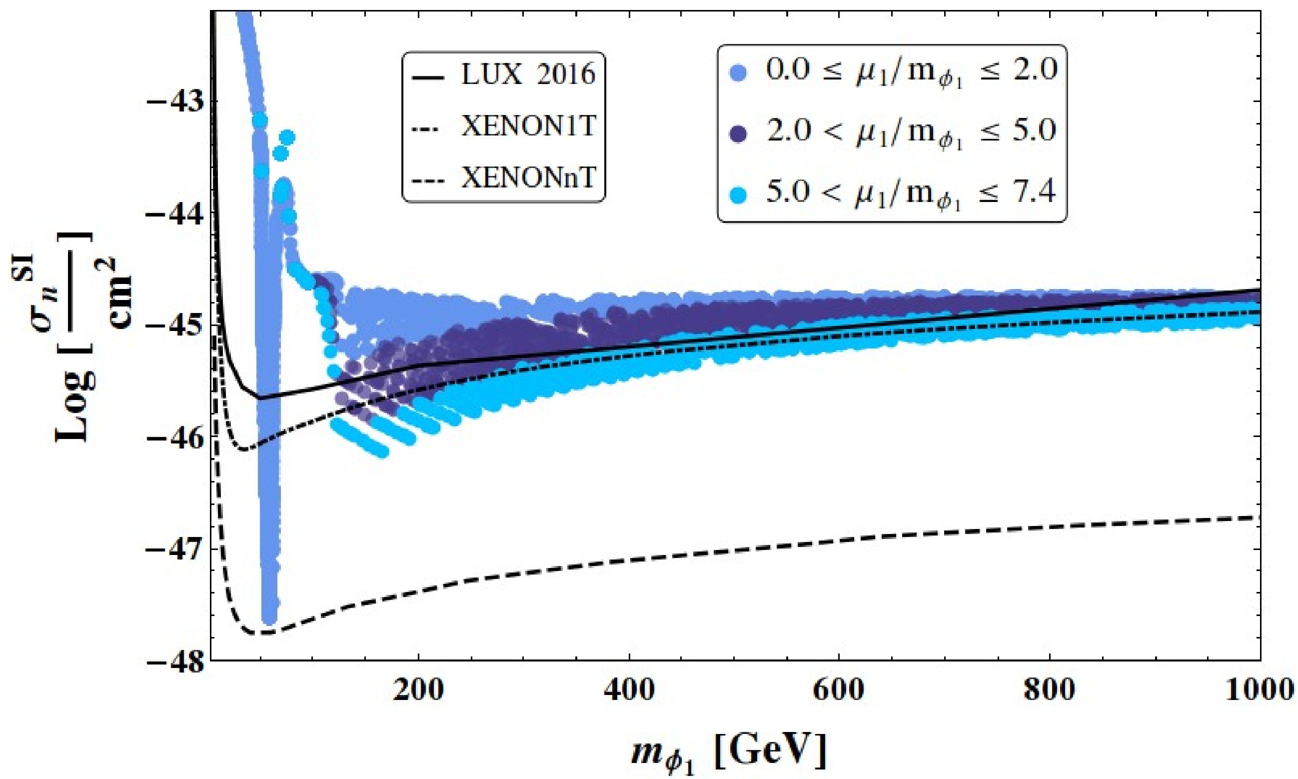
Lerner and McDonald PRD 80 123507

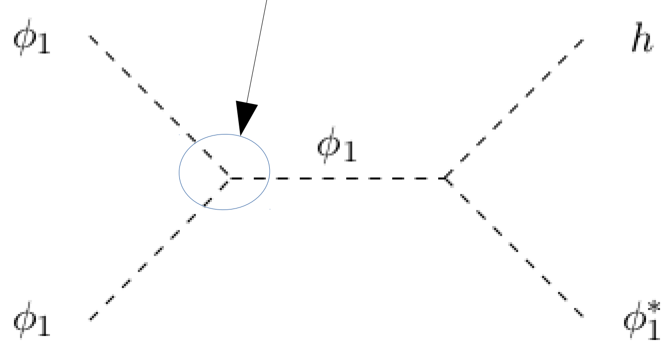
WIMP Higgs portal : Complex scalar under $\mathbb{Z}_3$

➢ Complex Singlet scalar charged under $\mathbb{Z}_3$

$$-\mathcal{L}_{DM-Higgs} = -\mu_H^2(H^\dagger H - \frac{v^2}{2}) + \lambda_H(H^\dagger H - \frac{v^2}{2})^2 + m_{\phi_1}^2\phi_1^*\phi_1 + \frac{\mu_1}{3!}(\phi_1^3 + \text{h.c}) + \lambda_{1s}(\phi_1^*\phi_1)^2 + \lambda_{1h}(\phi_1^*\phi_1)(H^\dagger H - \frac{v^2}{2}).$$

Constrained from stability of the potential





Semi- annihilation

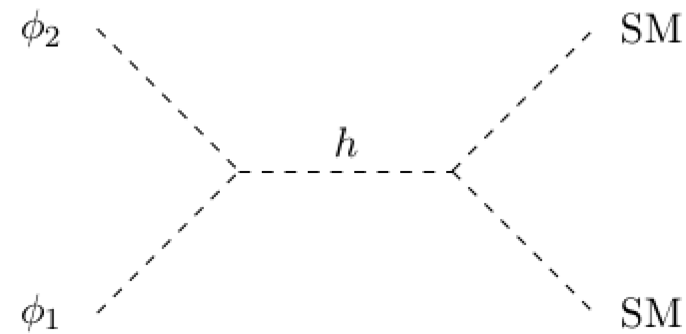
No DD signature

Belanger et al. JCAP 1301 022

Multipartite $\mathbb{Z}_2$

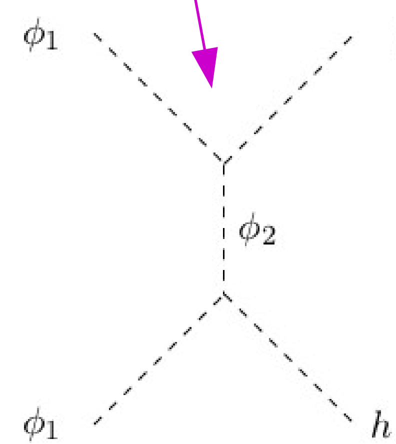
- Two non-degenerate particle ϕ_1, ϕ_2 under same $\mathbb{Z}_2$ symmetry.
- Annihilation, mediated-annihilaton, Co-annihilation operative here.

$$m_{\phi_1} < m_{\phi_2} \longrightarrow \phi_1 \textbf{ DM candidate}$$

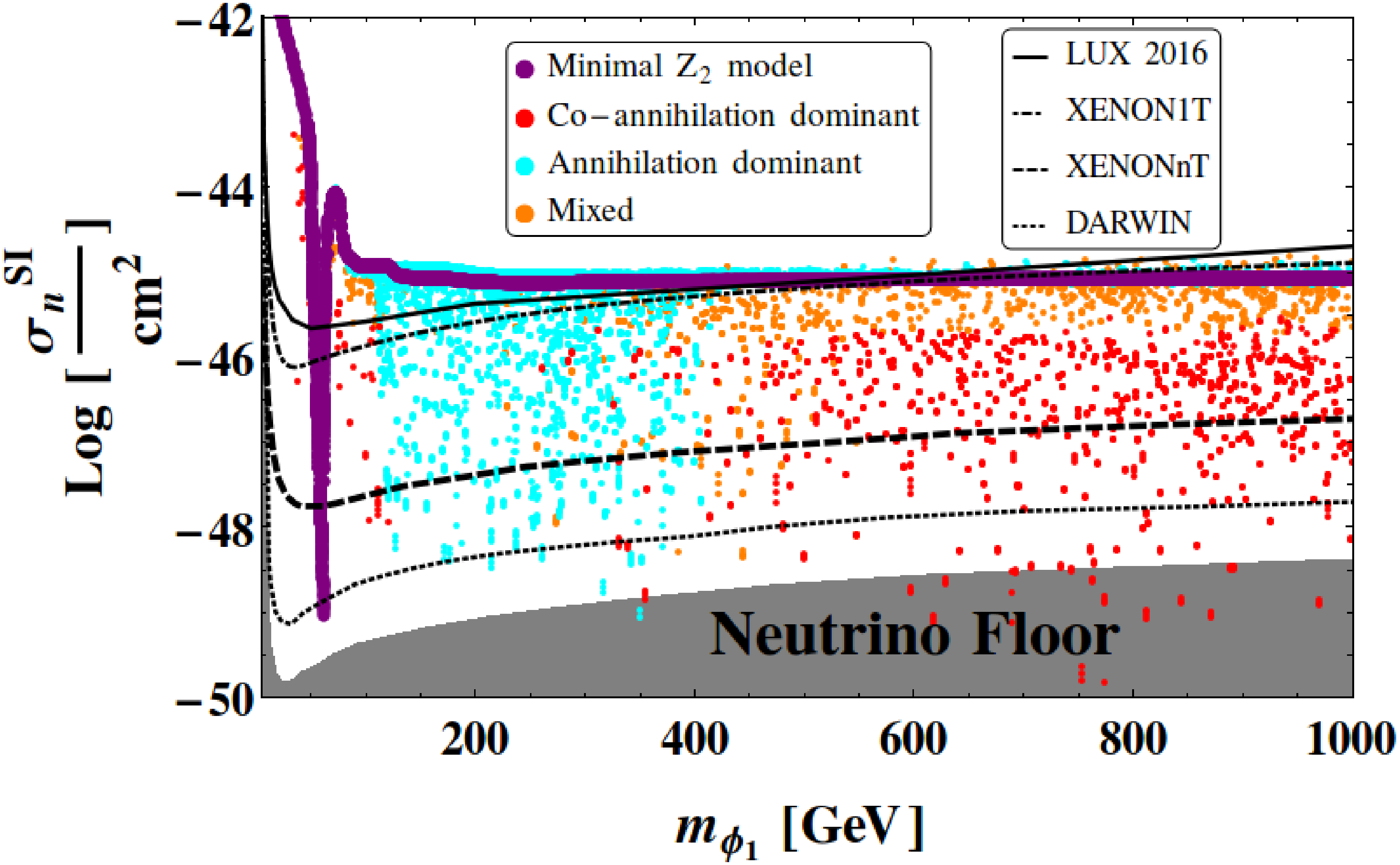


Co-annihilation

Direct detection insensitive



Mediated-annihilation

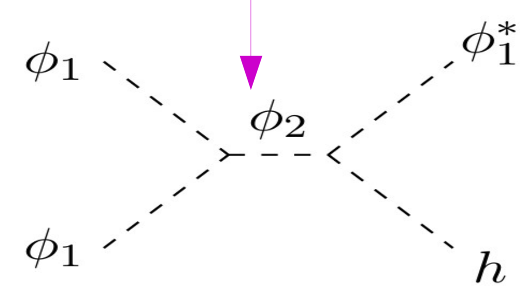


TNM, S Bhattacharya, P Ghosh, T S Ray 2017

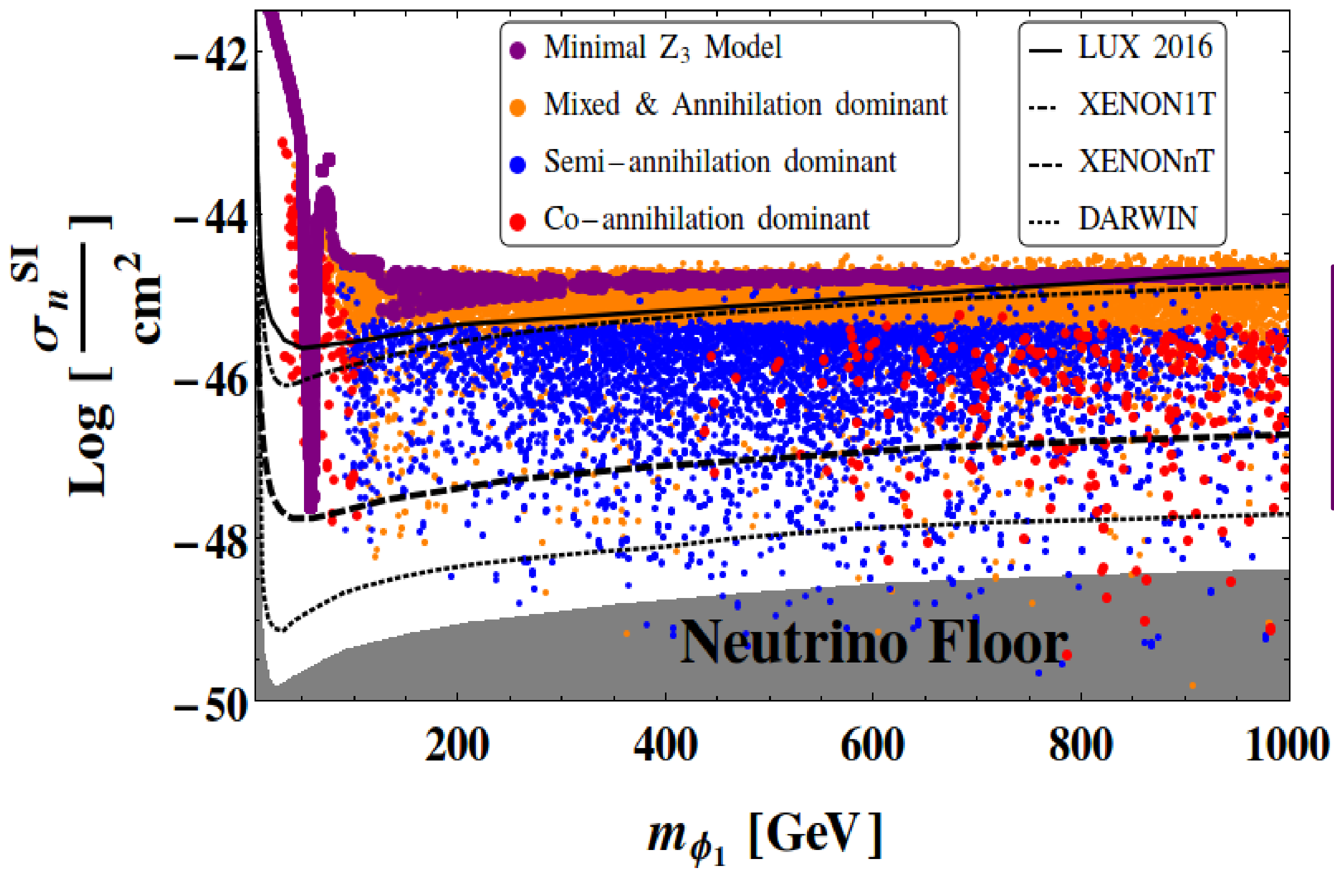
Multipartite $\mathbb{Z}_3$

- Two non-degenerate particle ϕ_1, ϕ_2 charged under same $\mathbb{Z}_3$ symmetry.
- Anihilation, co-annihilation, semi-annihilation and Mediated-annihialtion operative here.

Insensitive to DD



Resonant Semi-annihilation



TNM, S Bhattacharya, P Ghosh, T S Ray 2017

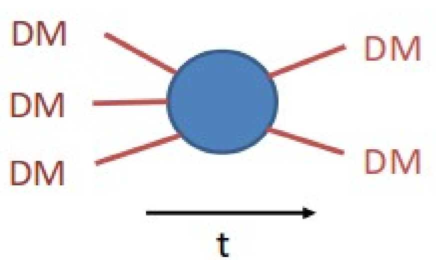
Resonance Condition

$$\mathbf{m_{\phi_2} = 2m_{\phi_1}}$$

$$\mathrm{m}_{\phi_1} < m_{\phi_2} \longrightarrow \phi_1\ \mathbf{DM}$$

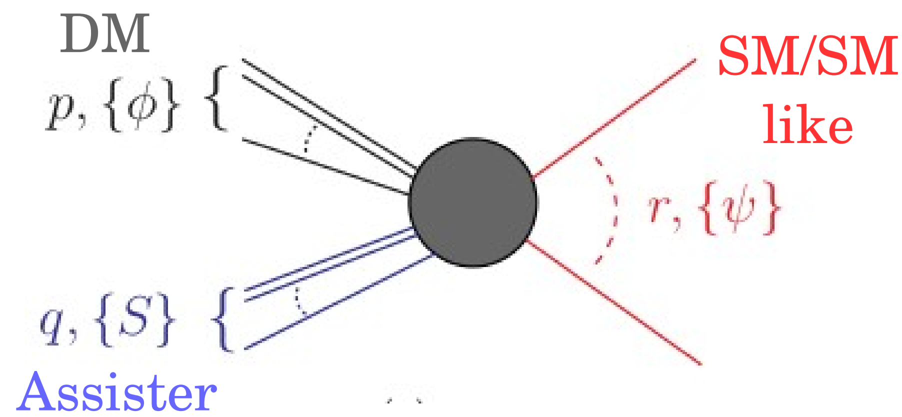
Beyond 2 → 2

- Recently, processes like 3(DM) → 2(DM) has been considered. With very tiny interaction with visible sector. [Hochberg et al. PRL 113 171301]

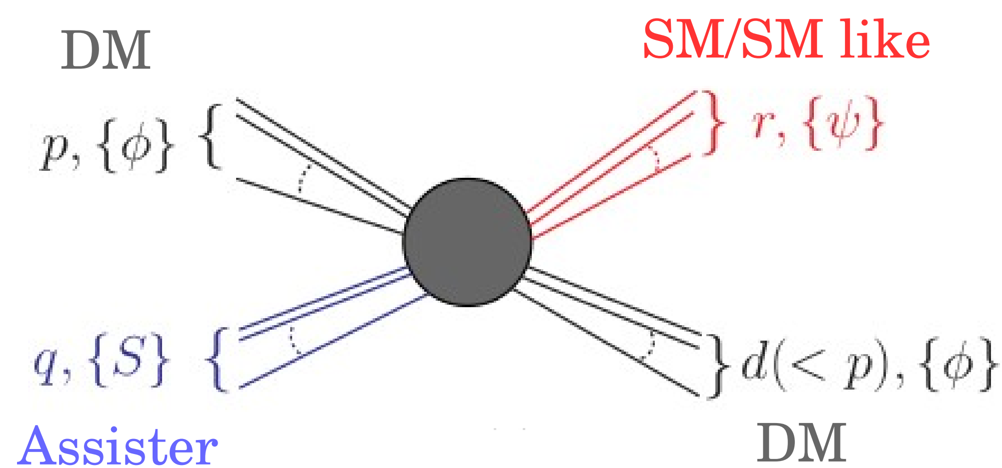


- Topology like 4(DM) → 2(DM) also considered. [Bernal et al. JCAP 1504 012 etc.]

- Assisted annihilation



- Assisted Semi-annihilation



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Novel features of Assisted Annihilation

$$\underbrace{\phi, \ldots, \phi}_{\mathbf{p}}{}^{\text{DM}}, \underbrace{S, \ldots, S}_{\mathbf{q}}{}^{\text{Assister}} \rightarrow \underbrace{\psi, \ldots, \psi}_{\mathbf{r}}{}^{\text{SM/SM like}}$$

- For simplicity, lets assume r = 2

$$\langle \sigma_{\mathbf{p+q\to 2}} \mathbf{v}^{\mathbf{p+q-1}} \rangle \sim \left[\mathbf{M}^{\mathbf{-3(p+q)+4}} \right]$$

- This suppression in cross section naturally leads to light DM.
- No direct detection, indirect detection signal.
- Unlike coannihilation here assister is not charged under the symmetry which makes DM stable.
- Region of interest : $\mathbf{m}_\phi < \mathbf{m_S}, \mathbf{m}_\psi$

$$\frac{dY_\phi}{dx} = -\frac{x s^{p+q-1}}{H(m_\phi)} N_{\text{Bolt}} \langle \sigma v^{p+q-1} \rangle \left[(Y_\phi)^p \left(Y_\phi^{\text{eq}} \right)^q - \left(Y_\phi^{\text{eq}} \right)^{p+q} \right], \quad N_{\text{Bolt}} = e^{qx(1-\epsilon)} \epsilon^{3q/2}$$

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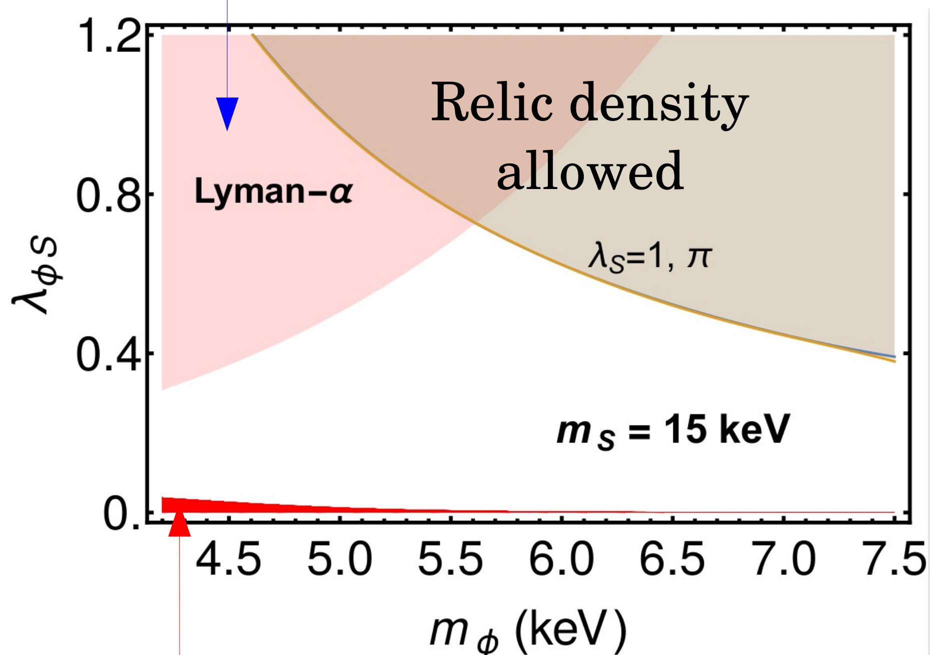
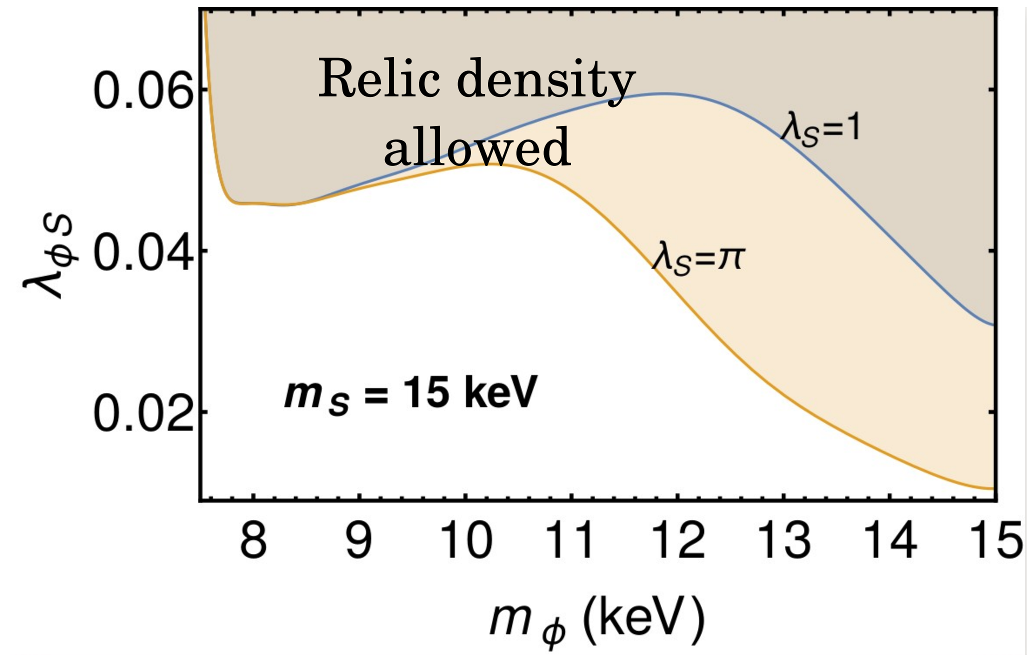
$4 \to 2$: keV scale DM

$\mathbf{T_f < 1}$ keV





Semi-relativistic freeee out

$$\mathcal{L}^{\rm dark} \supset \frac{1}{2}\mathbf{m}_\phi^2\phi^2 + \frac{1}{2}\mathbf{m}_\mathbf{S}^2\mathbf{S}^2 + \frac{\lambda_{\phi \mathbf{S}}}{4}\phi^2\mathbf{S}^2 + \frac{\lambda_\phi}{4!}\phi^4 + \frac{\lambda_\mathbf{S}}{4!}\mathbf{S}^4$$

DM Assister

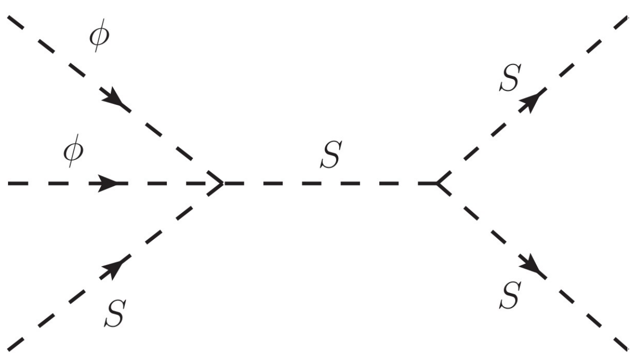
$$\mathbf{m}_\phi < \mathbf{m}_\mathbf{S}$$

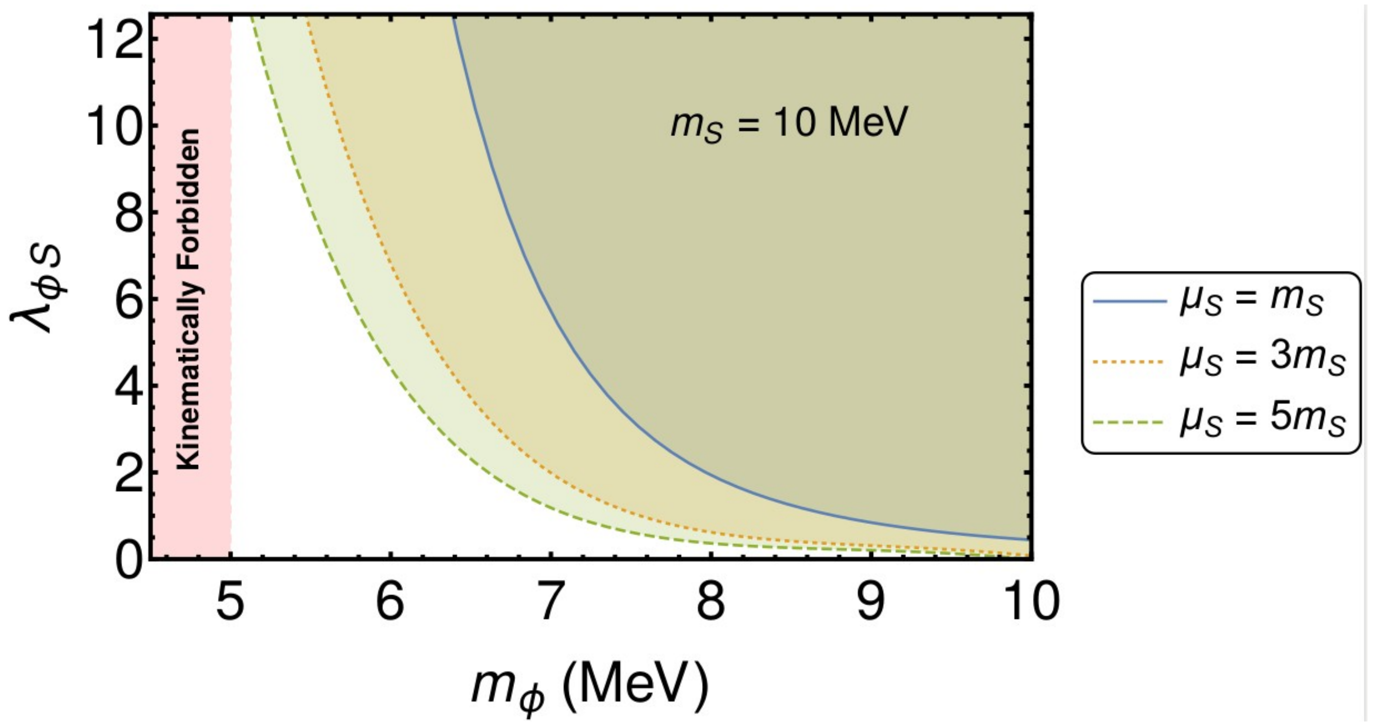
There will be strong constraint on such low mass DM from BBN & CMB.
(In preparation with U K Dey and T S Ray)

$3 \rightarrow 2$: MeV scale DM

- Lets introduce a term

$$\mathcal{L}_{3\rightarrow 2} = \frac{\mu_S}{3!} S^3.$$





$$\frac{m_S}{2} < m_\phi < m_S$$

Relic density allowed parameter space

Summary

- Minimal scalar singlet DM models are considerably constarined by recent reults of direct detection experiments.

- We show that the non-standard annihilation topologies like co-annihilation, semi-annihilation etc. play crucial role to evade such constarint.

- The interplay of this kind process yields plenty of region in the parameter space that is unconstrained by present and future direct detection experiments.

- Going beyond $2 \to 2$ secenario, we propose a non-standard annihilation mechanism "assisted annihilation" by which we can get sub-GeV dark matter.

- Such a light cold dark matter with self interaction may solve small scale structure formation issue.

Thank you

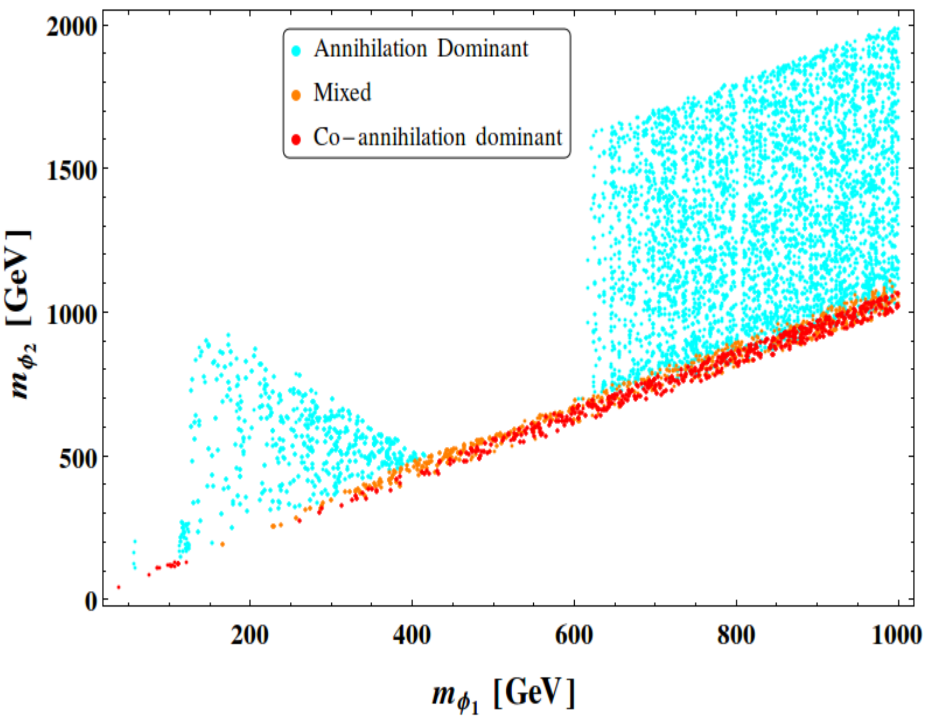
Lagarangian: Multiparticle $\mathbb{Z}_2$

$$
\begin{aligned}
-\mathcal{L}_{DM-Higgs} &= -\mu_H^2(H^\dagger H - \frac{v^2}{2}) + \ \lambda_H(H^\dagger H - \frac{v^2}{2})^2 \\
&+\frac{1}{2}m_{\phi_1}^2\phi_1^2 + \frac{1}{2}m_{\phi_2}^2\phi_2^2 + \frac{\lambda_{e_1}}{4}\phi_1^2\phi_2^2 + \frac{\lambda_{e_2}}{3!}\phi_1^3\phi_2 + \frac{\lambda_{e_3}}{3!}\phi_1\phi_2^3 \\
&+\frac{\lambda_{1s}}{4!}\phi_1^4 + \frac{\lambda_{2s}}{4!}\phi_2^4 + \frac{1}{2}\lambda_{1h}\phi_1^2(H^\dagger H - \frac{v^2}{2}) \\
&+\frac{1}{2}\lambda_{2h}\phi_2^2(H^\dagger H - \frac{v^2}{2}) + \lambda_{12h}\phi_1\phi_2(H^\dagger H - \frac{v^2}{2}).
\end{aligned}
$$

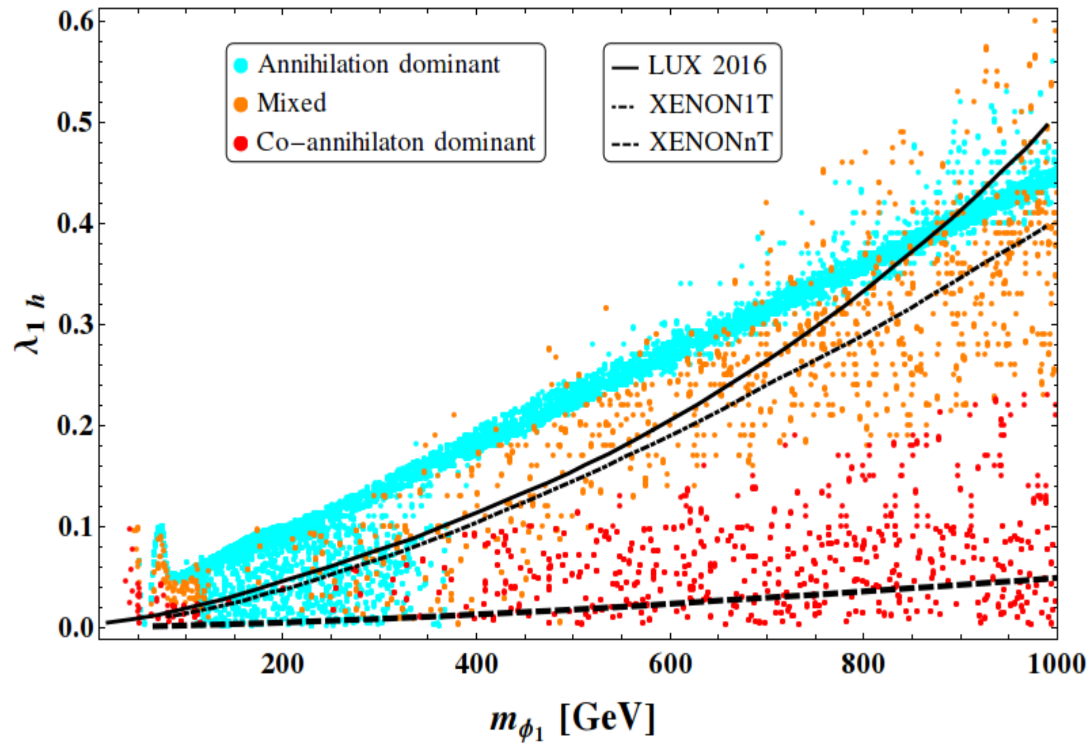
Parameter Space:

$$
1 \ \text{ GeV} \leq m_{\phi_1} \leq 1000 \text{ GeV}, \ 2 \leq \ \Delta m \equiv m_{\phi_2} - m_{\phi_1} \\
\leq 1000 \text{ GeV}, 0.001 \leq \lambda_{\mathrm{1h}} = \lambda_{\mathrm{2h}} \leq 0.1, \ 0 \leq \lambda_{\mathrm{12h}} \leq 1
$$

Multiparticle : $\mathbb{Z}_2$



Relic density and LUX 2016 allowed points in $\mathbf{m_{\phi_1} - m_{\phi_2}}$ plane



Relic density allowed points in $\mathbf{m_{\phi_1} - \lambda_{1h}}$ plane

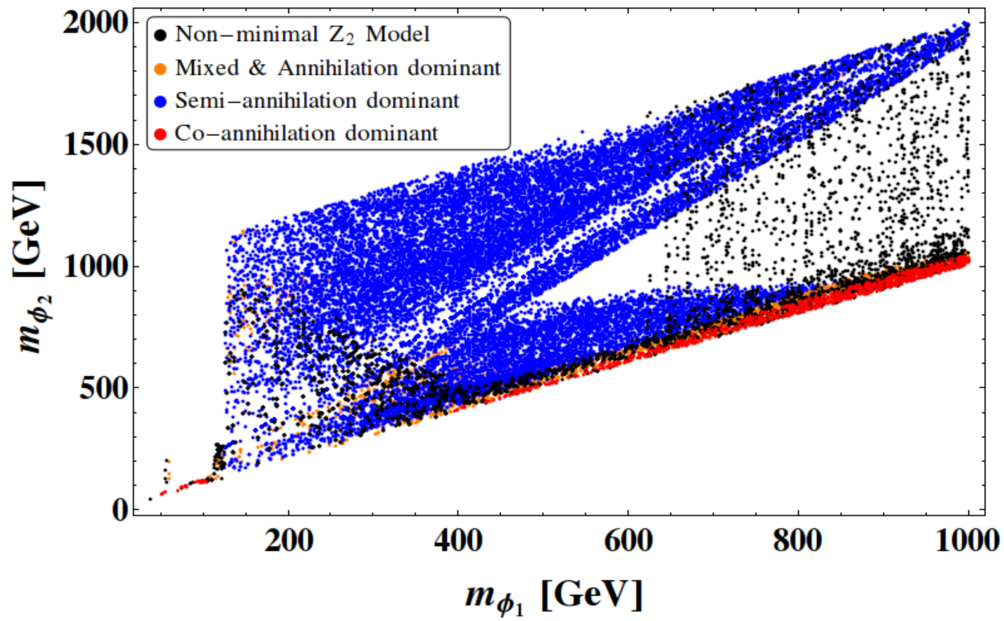
Lagarangian: Multiparticle $\mathbb{Z}_3$

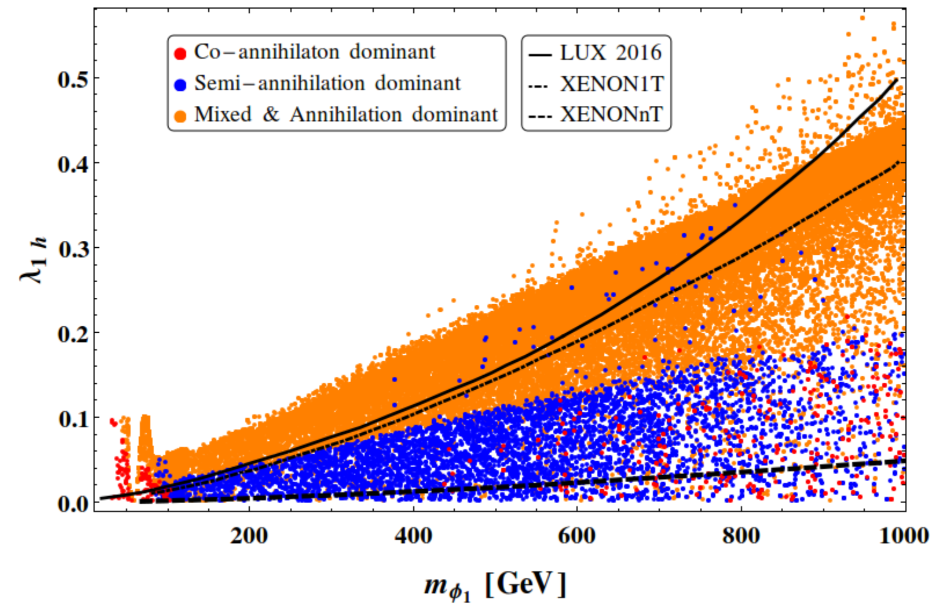
$$-\mathcal{L}_{DM-Higgs} = -\mu_H^2(H^\dagger H - \frac{v^2}{2}) + \lambda_H(H^\dagger H - \frac{v^2}{2})^2$$
$$+m_{\phi_1}^2\phi_1^*\phi_1 + m_{\phi_2}^2\phi_2^*\phi_2 + \frac{\mu_1}{3!}(\phi_1^3 + \mathrm{h.c}) + \frac{\mu_2}{3!}(\phi_2^3 + \mathrm{h.c})$$
$$+\frac{\mu_{12}}{2!}(\phi_1^2\phi_2 + \phi_2^2\phi_1 + \mathrm{h.c}) + \lambda_{1s}(\phi_1^*\phi_1)^2 + \lambda_{2s}(\phi_2^*\phi_2)^2$$
$$+\lambda_e[(\phi_1^*\phi_1)(\phi_2^*\phi_2) + \{(\phi_1^*\phi_2)^2 + \mathrm{h.c}\}] + \lambda_{1h}(\phi_1^*\phi_1)(H^\dagger H - \frac{v^2}{2})$$
$$+\lambda_{2h}(\phi_2^*\phi_2)(H^\dagger H - \frac{v^2}{2}) + \lambda_{12h}[\phi_1^*\phi_2 + \mathrm{h.c}](H^\dagger H - \frac{v^2}{2})\ .$$

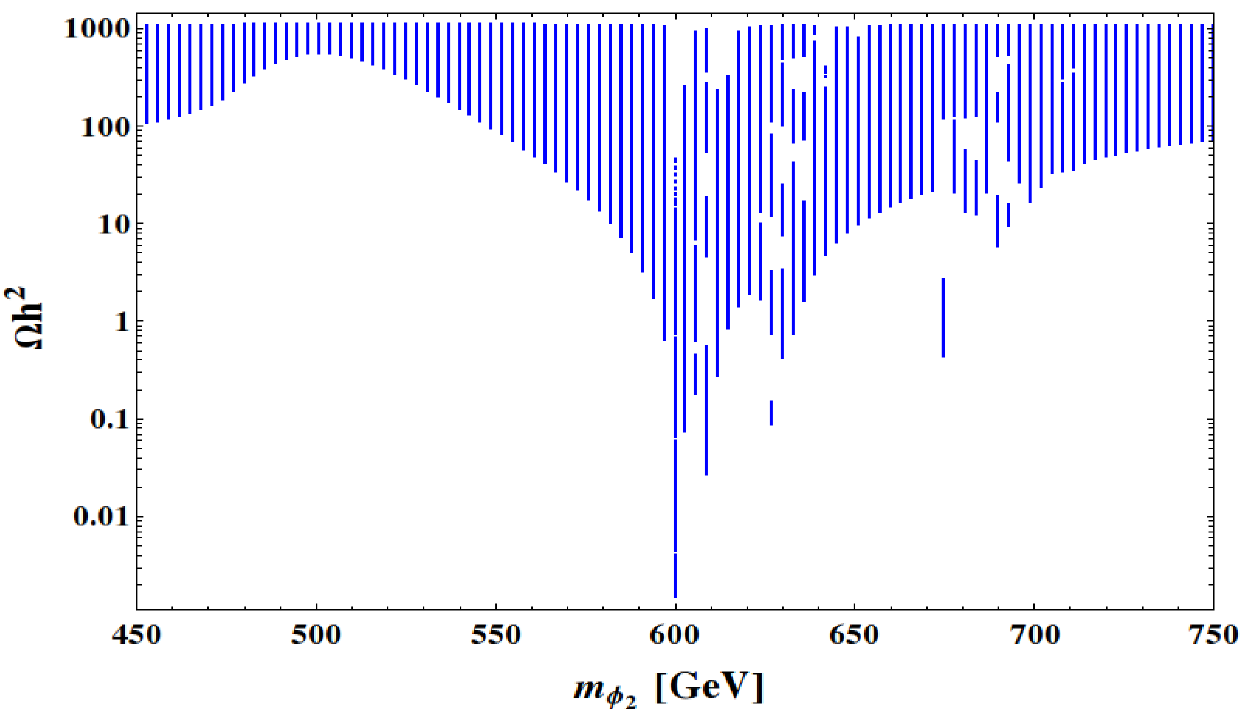
Parameter Space:

$$10\ \ \mathrm{GeV} \leq m_{\phi_1} \leq 1000\ \mathrm{GeV},\ \ 2 \leq\ \Delta m \leq 1000\ \mathrm{GeV},$$
$$\mu_\mathrm{i} \leq 2\mathrm{m_i},\ \ \mu_{12} \leq 2\mathrm{m}_1,\ \ 0.001 \leq \lambda_{\mathrm{1h}} = \lambda_{\mathrm{2h}} \leq 0.1,$$
$$0.1\ \ \leq \lambda_{\mathrm{12h}} \leq\ \ 1\ .$$

Multiparticle : $\mathbb{Z}_3$







(Top-left) Relic density and xenon 1T allowed points in $\mathbf{m_{\phi_1} - m_{\phi_2}}$ plane

(Top-right) Relic density allowed points in $\mathbf{m_{\phi_1} - \lambda_{1h}}$ plane

(Bottom) Resonance plot for $\mathbf{m_{\phi_1} = 300GeV}$