Multipartite Dark Matter and Phenomenology.

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SUSY 2017 , TIFR Mumbai

Based on

JCAP 1704 (2017) 043, S. Bhattacharya, P.Ghosh and P. Poulose
JHEP 1710 (2017) 088 , S. Bhattacharya, P.Ghosh, T.N. Maity and T.S.Ray
arXiv:1706.04931, P.Ghosh, A. Saha and A. Sil.

Outline

Evidence of Dark Matter

•Strong evidence of DM coming from Rotational curves,Bullet Cluster, Gravitational Lesing.

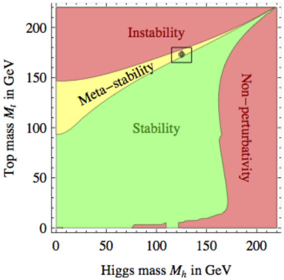
• WMAP and PLANCK data suggest that around 24% of universe made of DM. $\Omega_{CDM} h^2 = 0.1161 \pm 0.0028$(WMAP+PLANCK)

• DM particles are **EM charge neutral**, **Weakly-interacting**, **Stable**, and **Massive**. (WIMP)

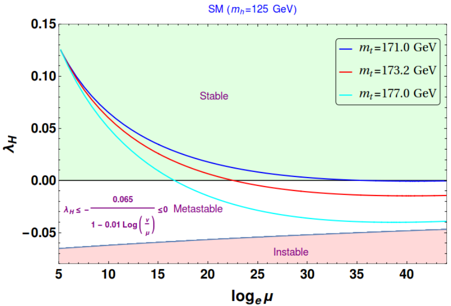
• What are the possible candidates of DM ?

We are interested in **Scalar DM** and its **mutipartite feature**.

SM EW Vacuum



Instability
Meta–stability
Stability
Non–perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200

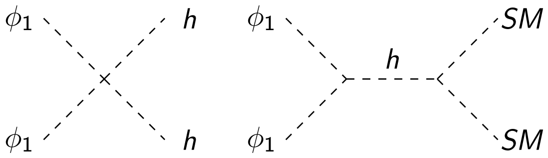


SM (m_h=125 GeV)
m_t=171.0 GeV
m_t=173.2 GeV
m_t=177.0 GeV
Stable
$\lambda_H \leq -\frac{0.065}{1-0.01\,\mathrm{Log}\left(\frac{v}{\mu}\right)} \leq 0$ Metastable
Instable
λ_H
$\log_e \mu$
0.15
0.10
0.05
0.00
−0.05
5
10
15
20
25
30
35
40

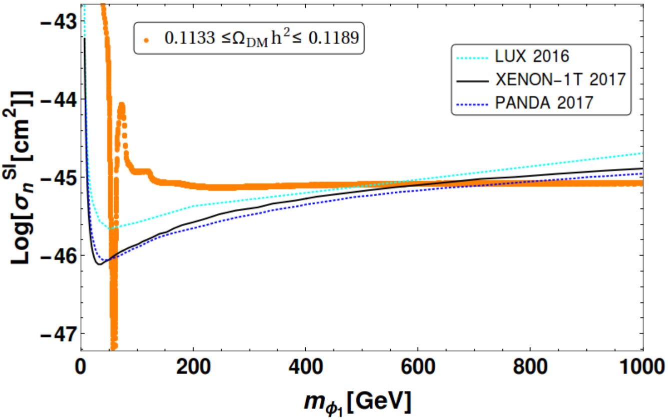
- ϕ_1 be the real singlet scalar DM.
- $\mathcal{Z}_2 : \phi_1 \to -\phi_1$.

$$V(\phi_1, H) = -\mu_H^2\left(H^\dagger H - \frac{v^2}{2}\right) + \lambda_H\left(H^\dagger H - \frac{v^2}{2}\right)^2 + \frac{1}{2}m_{\phi_1}^2\phi_1^2 + \frac{1}{4!}\lambda_4\phi_1^4 + \frac{1}{2}\lambda_1\left(H^\dagger H - \frac{v^2}{2}\right)\phi_1^2 .$$

- DM annihilation

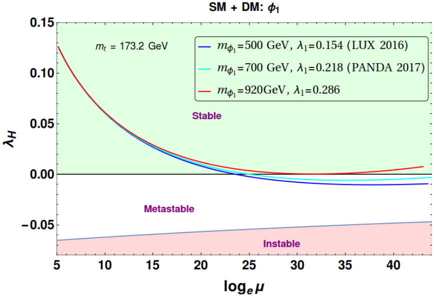


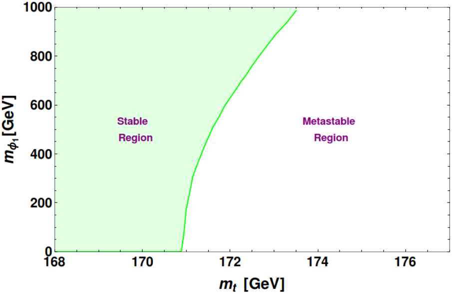
R.N.Lerner, J. McDonald ,PRD 80,(2009),123507



JHEP 1710 (2017) 088 , S. Bhattacharya, P.Ghosh, T.N. Maity and T.S.Ray

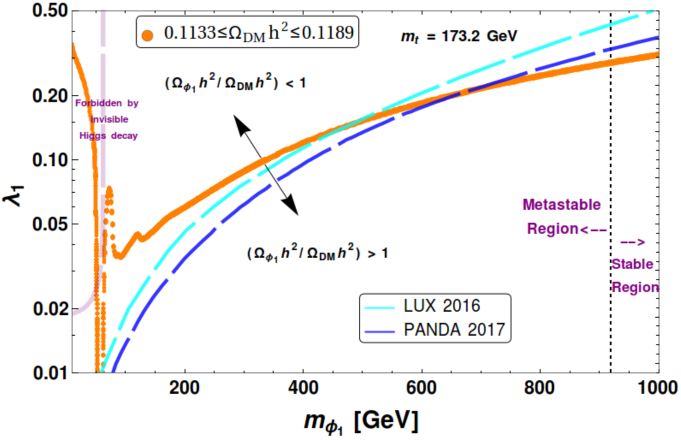
Vacuum Stability with Presence of DM ϕ_1





P.Ghosh, A. Saha and A. Sil, arXiv:1706.04931

Parameter space of DM ϕ_1



P.Ghosh, A. Saha and A. Sil, arXiv:1706.04931

Two interacting real singlet scalar fields ϕ_1 and ϕ_2

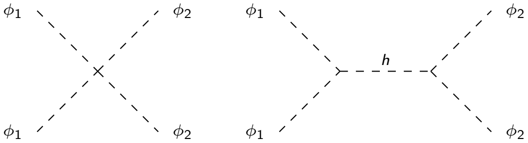
$$\mathcal{Z}_2 \times \mathcal{Z'}_2 : \phi_1 \to (-,+); \phi_2 \to (+,-)$$

$$\begin{aligned} V(\phi_1, \phi_2, H) \supset & \frac{1}{2} m_{\phi_1}^2 \phi_1^2 + \frac{1}{2} m_{\phi_1}^2 \phi_2^2 + \frac{1}{4}\lambda_3 \phi_1^2 \phi_2^2 + \frac{\lambda_4}{4!}\phi_1^4 + \frac{\lambda_5}{4!}\phi_2^4 \\ & + \frac{1}{2}\lambda_1 \phi_1^2 (H^\dagger H - \frac{v^2}{2}) + \frac{1}{2}\lambda_2 \phi_2^2 (H^\dagger H - \frac{v^2}{2}) \end{aligned}$$

Free parameters of this framework

$$\{m_{\phi_1},\ m_{\phi_2},\ \lambda_1,\ \lambda_2,\ \lambda_3\}$$

- DM DM Exchange



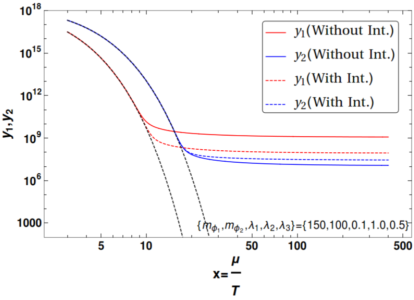
S. Bhattacharya, P.Ghosh and P. Poulose , JCAP 1704 (2017) no.04, 043

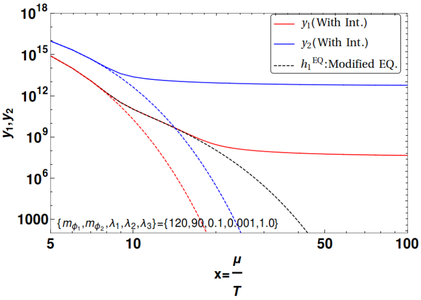
CBEQs for two component interacting DM

$$\frac{dy_1}{dx} = -\frac{1}{x^2}\Bigg[\langle\sigma v_{11\to SM}\rangle(y_1^2 - {y_1^{EQ}}^2) + \langle\sigma v_{11\to 22}\rangle(y_1^2 - \frac{{y_1^{EQ}}^2}{{y_2^{EQ}}^2}y_2^2)$$
$$-\langle\sigma v_{22\to 11}\rangle(y_2^2 - \frac{{y_2^{EQ}}^2}{{y_1^{EQ}}^2}y_1^2)\Bigg]$$
$$\frac{dy_2}{dx} = -\frac{1}{x^2}\Bigg[\langle\sigma v_{22\to SM}\rangle(y_2^2 - {y_2^{EQ}}^2) - \langle\sigma v_{11\to 22}\rangle(y_1^2 - \frac{{y_1^{EQ}}^2}{{y_2^{EQ}}^2}y_2^2)$$
$$+\langle\sigma v_{22\to 11}\rangle(y_2^2 - \frac{{y_2^{EQ}}^2}{{y_1^{EQ}}^2}y_1^2)\Bigg]$$

where

$$\boxed{y_i^{EQ}(x) = 0.03828 M_{Pl}\frac{g}{\sqrt{g_*}}x^{\frac{3}{2}}m_{\phi_i}(\frac{m_{\phi_i}}{\mu})^{\frac{3}{2}}e^{-x(\frac{m_{\phi_i}}{\mu})}}$$





- [Left]Freeze-out depends on DM-DM interaction hence Relic density
- [Right]When the lighter component freeze-out early, heavier one reaches modified equillibrium

$$\frac{dy_1}{dx} = -\frac{\langle \sigma v_{11 \to SM} \rangle + \langle \sigma v_{11 \to 22} \rangle}{x^2} [y_1^2 - h_1^{EQ\,2}];$$

$$h_1^{EQ\,2} = y_1^{EQ\,2} \left[\frac{\langle \sigma v_{11 \to SM} \rangle}{\langle \sigma v_{11 \to SM} \rangle + \langle \sigma v_{11 \to 22} \rangle} + \frac{\langle \sigma v_{11 \to 22} \rangle}{\langle \sigma v_{11 \to SM} \rangle + \langle \sigma v_{11 \to 22} \rangle} \left(\frac{y_2}{y_2^{EQ}} \right)^2 \right]$$

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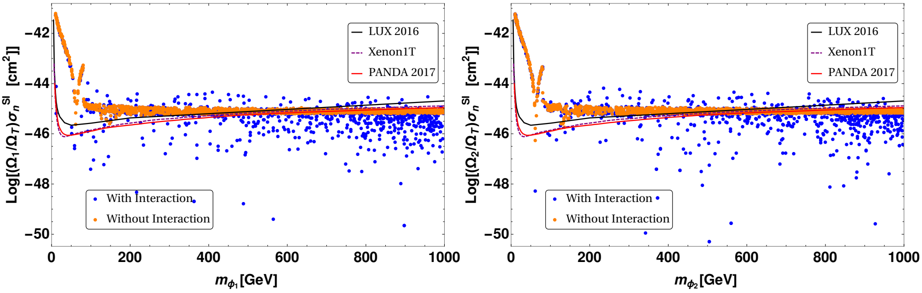
SI DD effective cross-section



- Due to presence of DM-DM interaction, the annihilation of the heavier component into the lighter one, yields a larger freedom for that component to go beyond the direct search limit.

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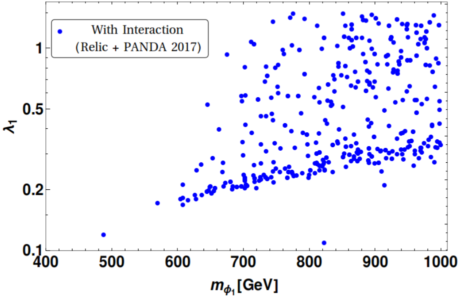
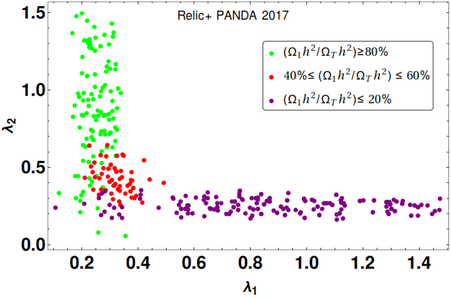
Relic Density+DD PANDA 2017 Limit





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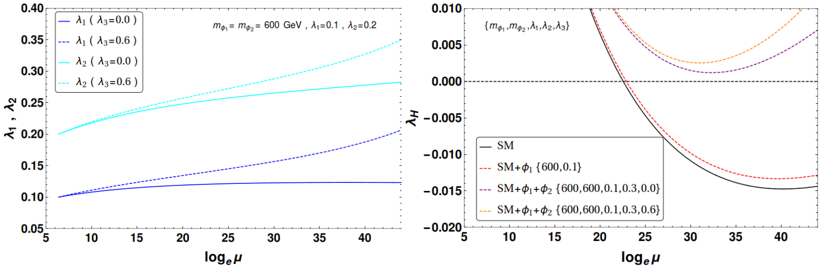
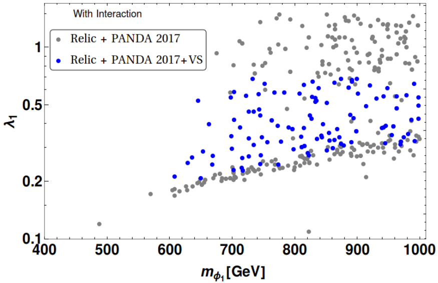
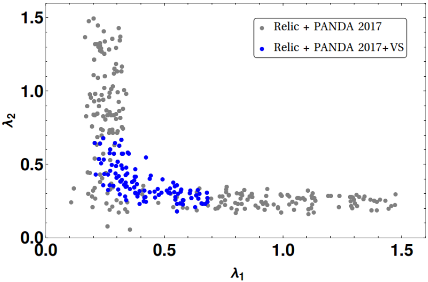
Vacuum Stability with Presence of DM ϕ_1 and ϕ_2



$$
\begin{aligned}
\beta^{(1)}_{\lambda_1} &= \frac{1}{(4\pi)^2}\Big(-\frac{9}{10}g_1^2\lambda_1 - \frac{9}{2}g_2^2\lambda_1 + 4\lambda_1^2 + \lambda_2\lambda_3 + \lambda_1\lambda_4 + 12\lambda_1\lambda_H + 6\lambda_1 y_t^2\Big) \\
\beta^{(1)}_{\lambda_2} &= \frac{1}{(4\pi)^2}\Big(-\frac{9}{10}g_1^2\lambda_2 - \frac{9}{2}g_2^2\lambda_2 + 4\lambda_2^2 + \lambda_1\lambda_3 + \lambda_2\lambda_5 + 12\lambda_2\lambda_H + 6\lambda_2 y_t^2\Big) \\
\beta_{\lambda_H} &= \beta^{SM}_{\lambda_H} + \frac{1}{(4\pi)^2}\frac{1}{2}(\lambda_1^2 + \lambda_2^2) \\
\beta_{\lambda_3} &= \frac{1}{(4\pi)^2}\Big(4\lambda_1\lambda_2 + \lambda_3(4\lambda_3 + \lambda_4 + \lambda_5)\Big)
\end{aligned}
$$

Validity of Parameter Space at $\Lambda = 10^{16}$ GeV + EW Vacuum Stability



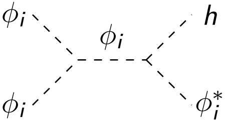


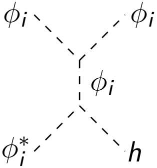
- Bounded from below : $\lambda_H(\mu) > 0,\ \lambda_{4,5}(\mu) > 0,\ \lambda_1(\mu) + \sqrt{\frac{3}{2}\lambda_H(\mu)\lambda_4(\mu)} > 0,\ \lambda_2(\mu) + \sqrt{\frac{3}{2}\lambda_H(\mu)\lambda_5(\mu)} > 0,\ \lambda_3(\mu) + \sqrt{\frac{1}{9}\lambda_4(\mu)\lambda_5(\mu)} > 0$
- Perturbativity : $\lambda_i(\mu) < 4\pi \quad (\lambda_i = \lambda_{1,2,\ldots 5}, \lambda_H)$; Stability : $\lambda_H(\mu) > 0$
- Stability + Perturbativity : $0 < \lambda_H(\mu) < 4\pi$

Two complex scalar ϕ_1 and ϕ_2, transforming under $\mathcal{Z}_3$ and $\mathcal{Z}_3^{'}$ respectively.

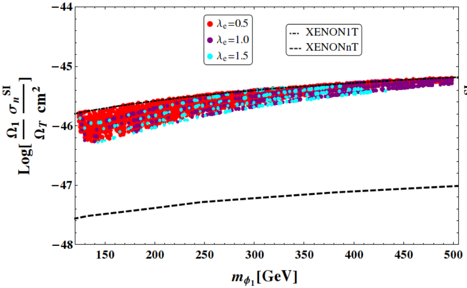
$$V(\phi_1, \phi_2, H) \supset \mu_1(\phi_1^3 + \mathrm{h.c}) + \mu_2(\phi_2^3 + \mathrm{h.c}) + \lambda_e(\phi_1^*\phi_1 + \phi_2^*\phi_2)^2 + \lambda_{1h}(\phi_1^*\phi_1)(H^\dagger H) + \lambda_{2h}(\phi_2^*\phi_2)(H^\dagger H).$$

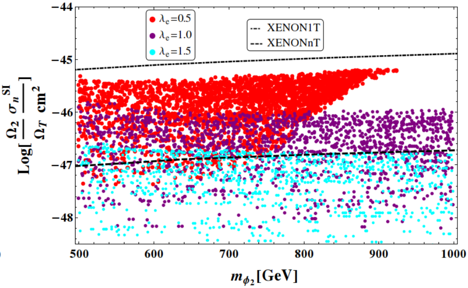
Semi-annihilation:





S. Bhattacharya, P.Ghosh, T.N. Maity and T.S.Ray, (JHEP 1710 (2017) 088)





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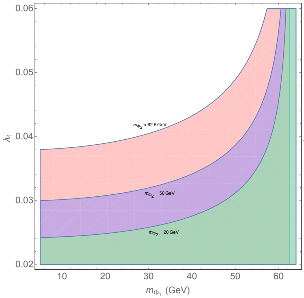
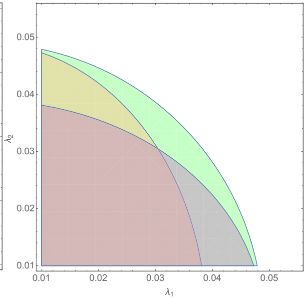
- **Non observation in Direct search** puts strong constraints on single component DM parameter space.
- **Hint of additional scalar** come from the **metastability of SM Higgs potential**. By adding a scalar DM , we achieved both **DM Phenomenology** and **absolute EW vacuum** for DM mass ,$m_{\phi_1} \geq 920$ GeV.
- For two component case DM-DM interaction plays a crucial role and yields lagrer region of allowed parameter space.
- And DM-DM interaction yields modified freeze-out for individual components changing relic density.
- In this scenario, we have achieved simultaneously **DM Relic , DD** and **absolute EW vacuum** comparably low DM mass $(m_{\phi_1}, m_{\phi_2} > 600$ GeV).
- For two components $\mathcal{Z}_3 \times \mathcal{Z}_3^{'}$ scenario, **Semi-annihilation** contributes to relic density and brings down the coupling in the vicinity of Higgs mass.

- The possibilities of multipartite frameworks with scalar and fermion DM is being looked at and they can have interesting outcome in relic, direct and collider searches.

thank you!


0.06
0.05
0.04
0.03
0.02
λ_1
10
20
30
40
50
60
m_{Φ_1} (GeV)
$m_{\phi_2} > 62.5$ GeV
$m_{\phi_2} = 50$ GeV
$m_{\phi_2} = 20$ GeV


0.05
0.04
0.03
0.02
0.01
λ_2
0.01
0.02
0.03
0.04
0.05
λ_1