Phenomenology of Dark Matter in Single and Multipartite framework

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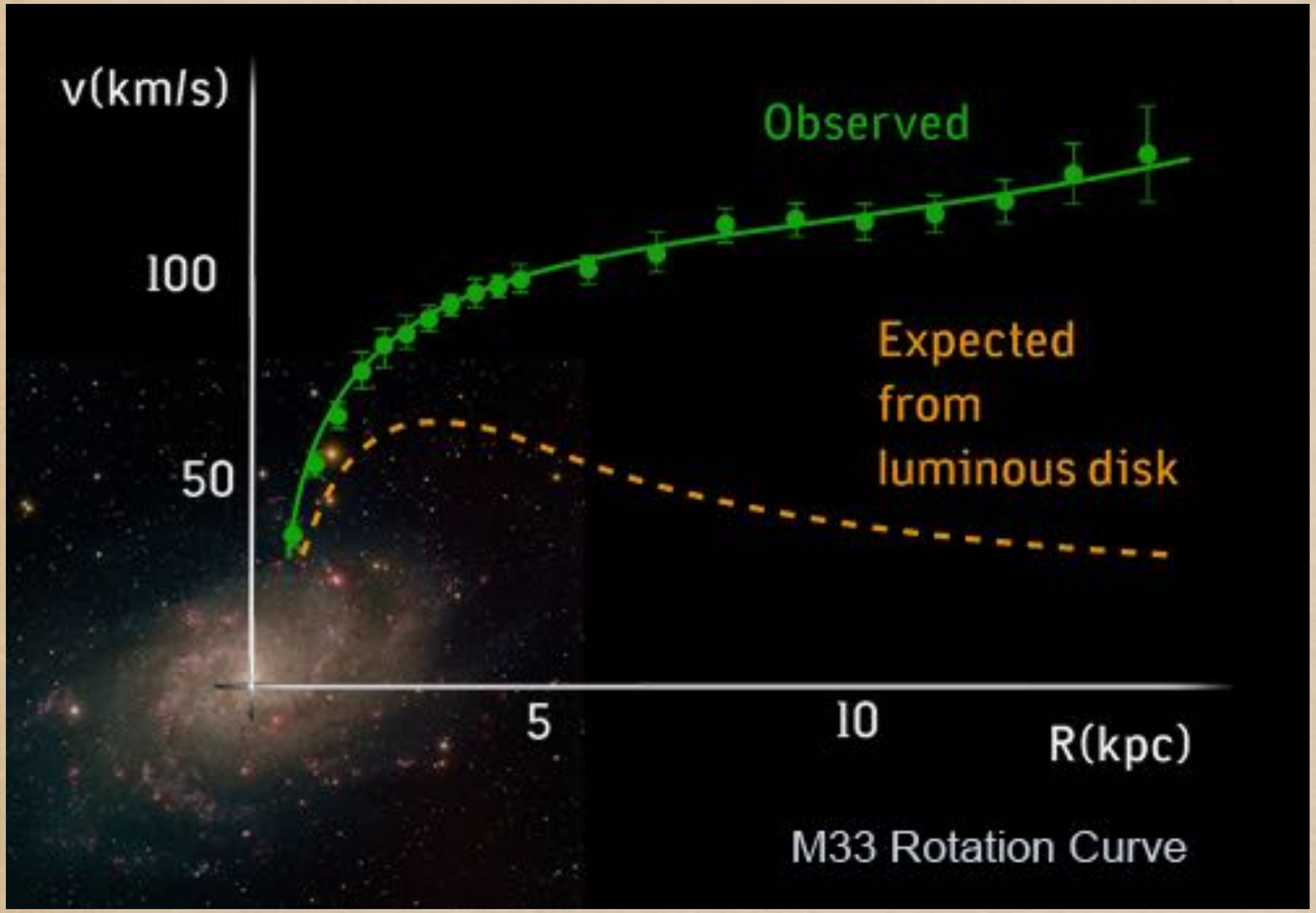
Evidences of Dark Matter (DM)

The first evidence for DM came from the observation of rotation curve of spiral galaxy in galaxy cluster: Zwicky 1930



$$\frac{mv^2(r)}{r} = \frac{GM(r)m}{r^2}$$

Within visible galaxy cluster:

$$M(r) = \frac{4}{3}\pi r^3 \rho$$

$$v(r) \sim r$$

Beyond visible galaxy cluster:

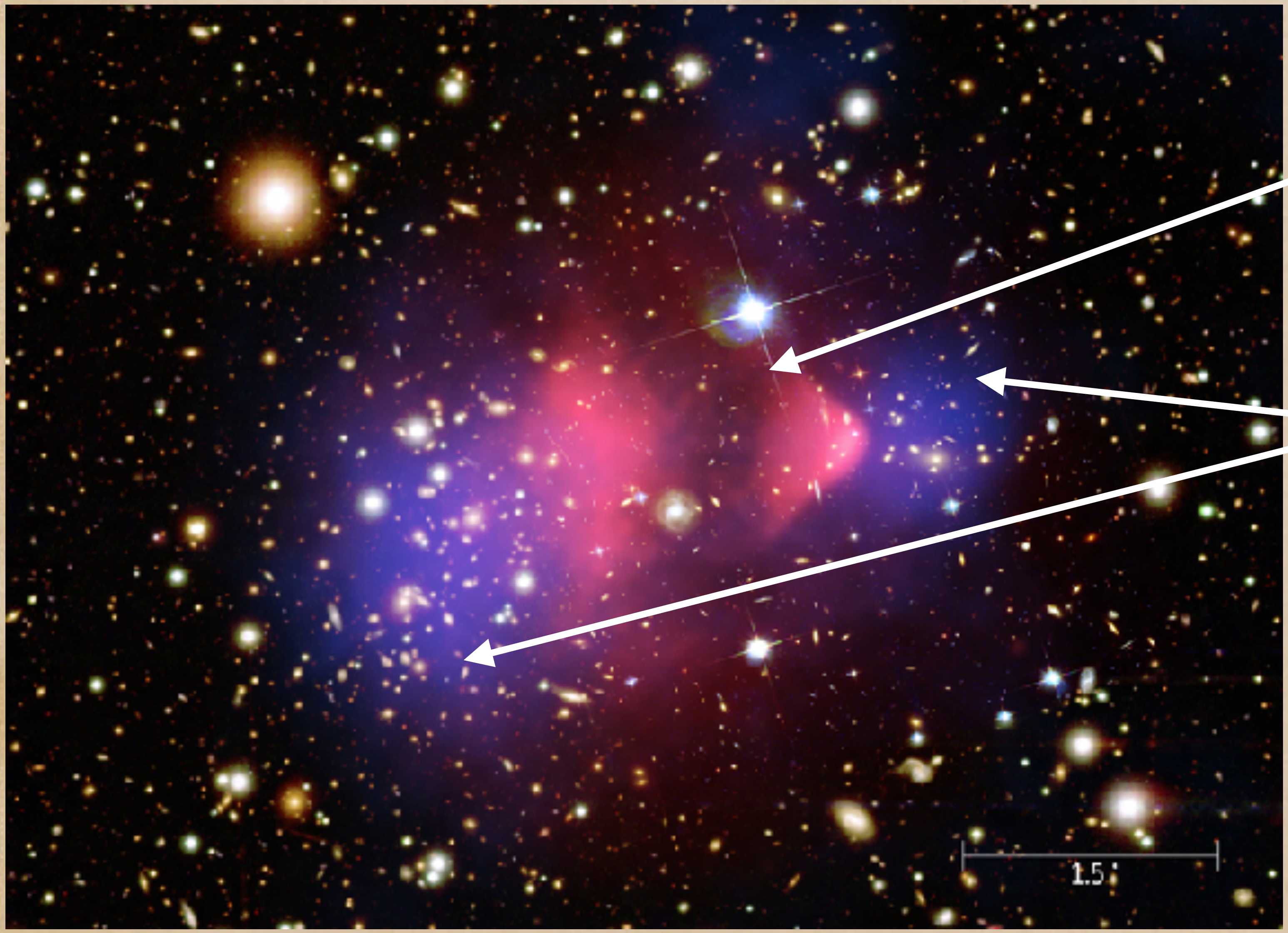
$$M(r) = M$$

$$v(r) \propto r^{-1/2}$$

There is a discrepancy between the observed and expected → Non-luminous Dark Matter

Dark Matter in Bullet Cluster

An event of merging of two galaxy clusters observed in 2006 by Chandra X-Ray Observatory



Luminous matter seen is shown by the Pink region in middle

The blue regions are obtained by gravitational lensing

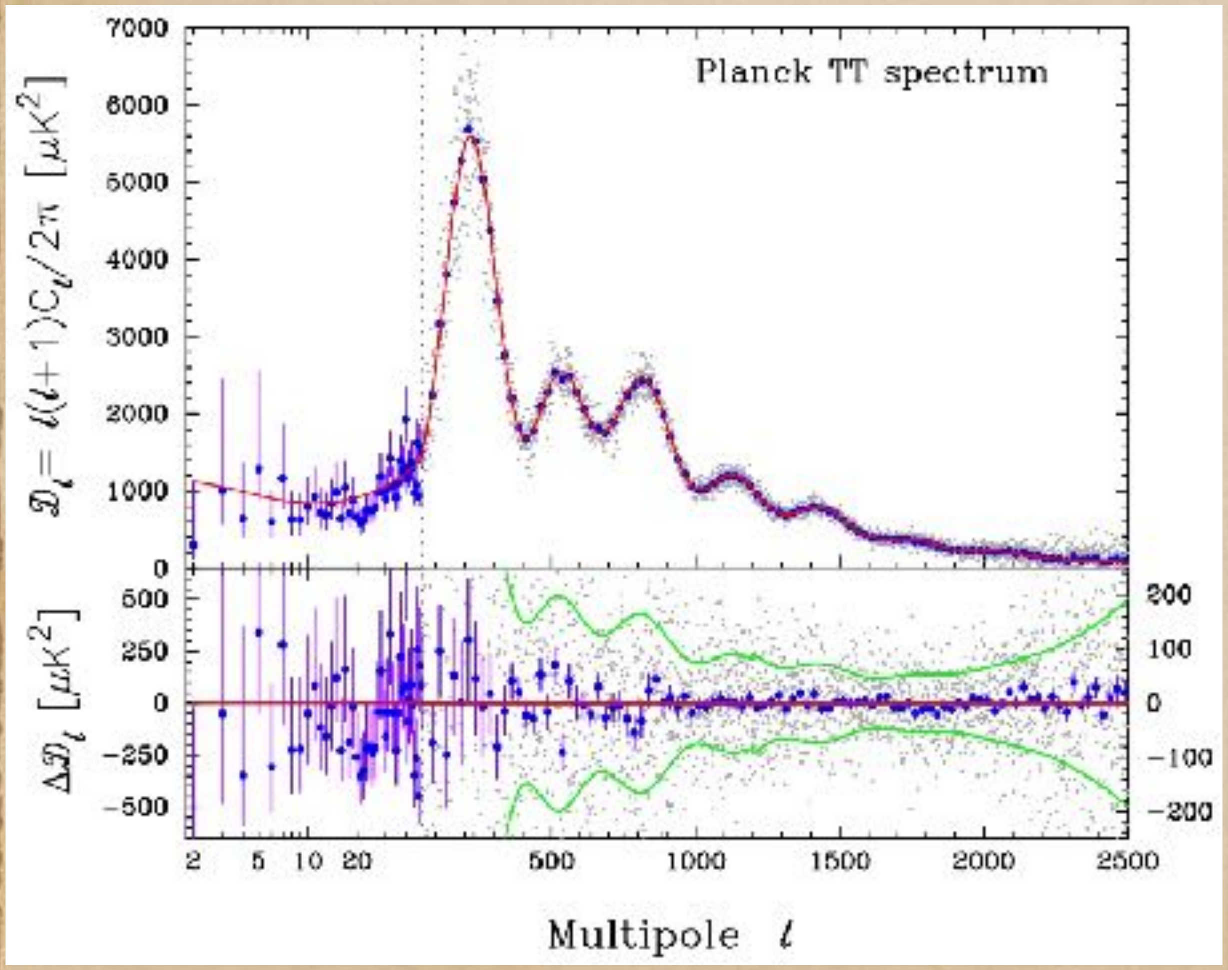
As if some non-luminous matter has passed by collision less !

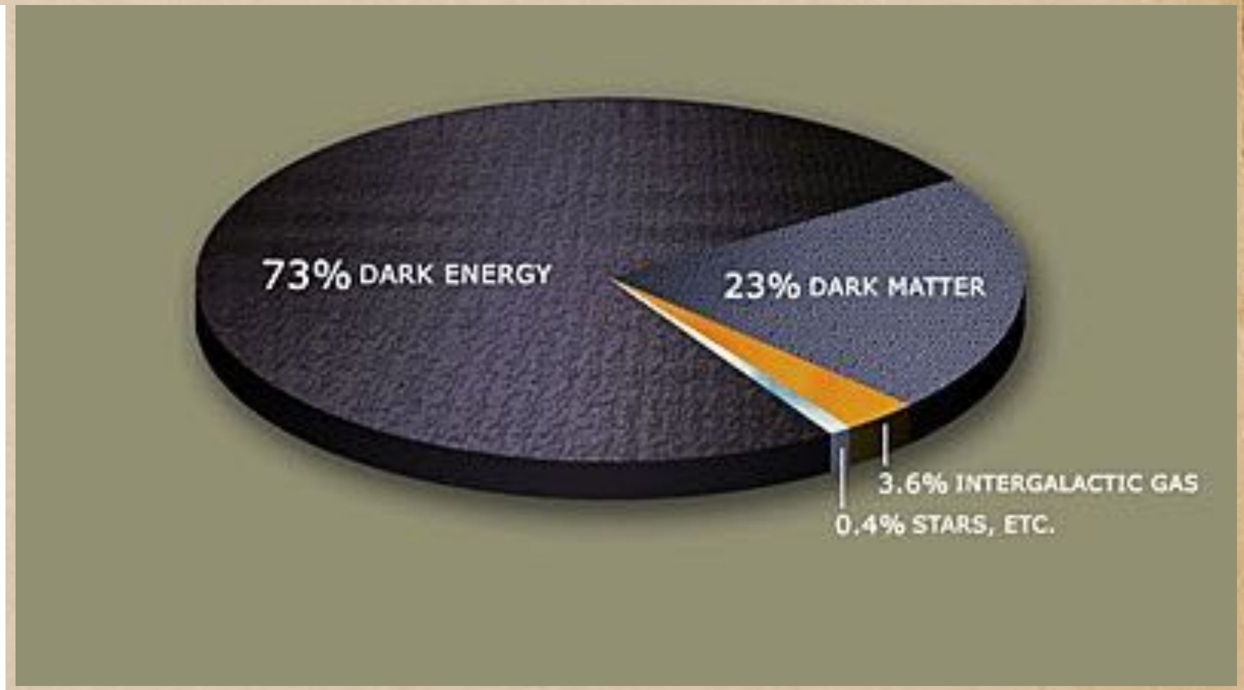
Non-luminous mass turns out to be much larger than the visible one.

Evidence of DM from Cosmology

Anisotropies in Cosmic Microwave background radiation (CMBR) yields a very precise measure of dark matter present in the universe.

CMBR: Radiation left 380,000 years before. After Hydrogen formation, photon started moving freely.





A tiny amount of visible matter and large amount of dark matter and huge amount of dark energy

CMBR yields Dark Matter density

Relic density: $0.1133 \leq \Omega h^2 \leq 0.1189$

WMAP and PLANCK data at 67% CL

Cosmological density $\Omega = \frac{\rho}{\rho_c}, \ \rho_c = \frac{3H^2}{8\pi G}$ $\longrightarrow$ $\Omega_{tot} = 1$

Reduced Hubble constant $h = H/100$

In units of $\mathrm{km\ s^{-1} Mpc^{-1}}$

What does this mean ?

The density of dark matter is very precisely measured and it is constant in co-moving volume of the universe: DM Stable !

Any Dark Matter candidate must yield correct relic density as mentioned

What kind of particles are DM?

Something that we know..

EM charge neutral: Dark
Stable : don't decay
Massive: gravitational effect

✓ Weakly Interacting massive particle: WIMP

Feebly Interacting Massive Particle: FIMP

Strongly Interacting massive particle: SIMP

Something that we still don't know..

- ✓Scalars, ✓fermions, vector bosons ?
- Single component or multi component ?
- Mass, couplings.....

WIMPs are the most popular candidates

What does WIMP do ?

Thermal freeze out of DM

A DM is assumed to be in equilibrium with hot soup of SM through interaction (2 <-> 2 primarily)

Early universe: hot and dense, interaction rate prevailed over the expansion for everything to stay intact

As universe expands and cools down, WIMPs decouple from thermal soup: freeze-out

When rate of interaction falls short of expansion

$$\Gamma \leq H$$

If those decoupled are stable, their density is relic density

Thermal freeze-out of WIMPs

The number density of DM evolution is described by Boltzmann Equation

$$\dot{n}_\psi + 3Hn_\psi = -\langle \sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle (n_\psi n_{\bar{\psi}} - {n_\psi}^{EQ} {n_{\bar{\psi}}}^{EQ})$$

$$n(t) \equiv \frac{g}{(2\pi)^3} \int d^3p \, f(E,t)$$

phase space density

Equilibrium distributions are Maxwell-Boltzmann type

$$f_\psi^{EQ} = \exp(-E_\psi/T) \qquad f_{\bar{\psi}}^{EQ} = \exp(-E_{\bar{\psi}}/T)$$

- Thermal average of annihilation cross-section

$$\langle \sigma_{\psi\bar{\psi}\leftrightarrow X\bar{X}}|v|\rangle \equiv (n_\psi^{EQ})^{-2} \int d\Pi_\psi d\Pi_{\bar{\psi}} d\Pi_X d\Pi_{\bar{X}} \times (2\pi)^4 \, \delta^4(p_\psi + p_{\bar{\psi}} - p_X - p_{\bar{X}}) \times \left|\mathcal{M}_{\psi\bar{\psi}\leftrightarrow X\bar{X}}\right|^2 \exp(-E_\psi/T) \exp(-E_{\bar{\psi}}/T)$$

Thermal freeze out of WIMPs

$$Y \equiv \frac{n_\psi}{s} \qquad x \equiv \frac{m}{T}$$

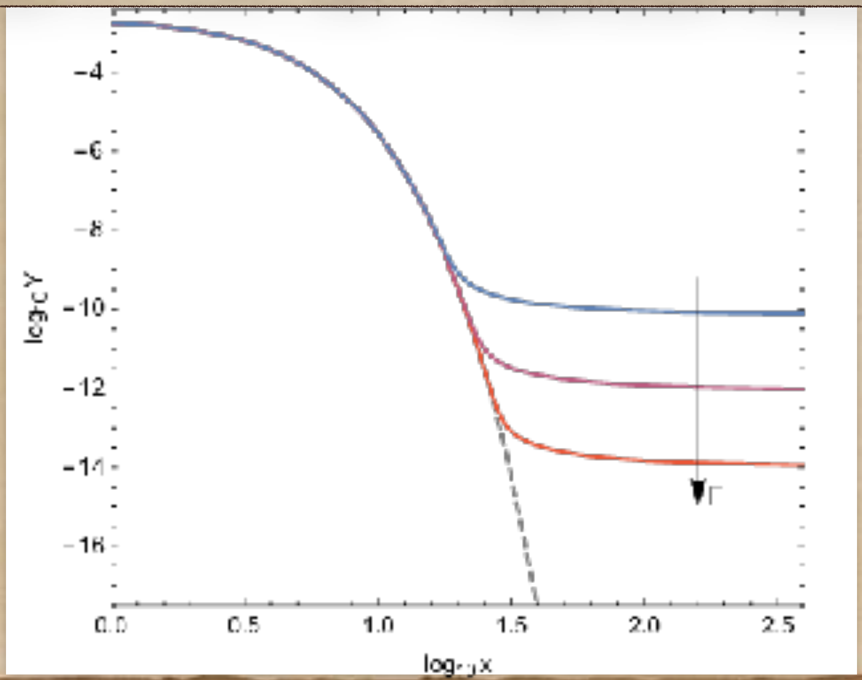
$$\frac{dY}{dx} = -\frac{x \langle \sigma_{\psi\bar{\psi}\leftrightarrow X\bar{X}} |v| \rangle s}{H(m)} \left[Y^2 - (Y_{EQ})^2\right]$$

Scaling out the effect of expansion by looking at the number of particles per coming volume.

Recast the BEQ in terms of $\Gamma = n^{EQ}\langle \sigma v \rangle$.

$$\frac{x}{Y_{EQ}}\frac{dY}{dx} = -\frac{\Gamma}{H}\left[\left(\frac{Y}{Y_{EQ}}\right)^2 - 1\right]$$

For $\Gamma >> H$: Particle is in Equilibrium $Y(x < x_{fo}) = Y_{EQ}$.
For $\Gamma << H$: Particle freezes out: $Y(x > x_{fo}) = Y(x = x_{fo})$.

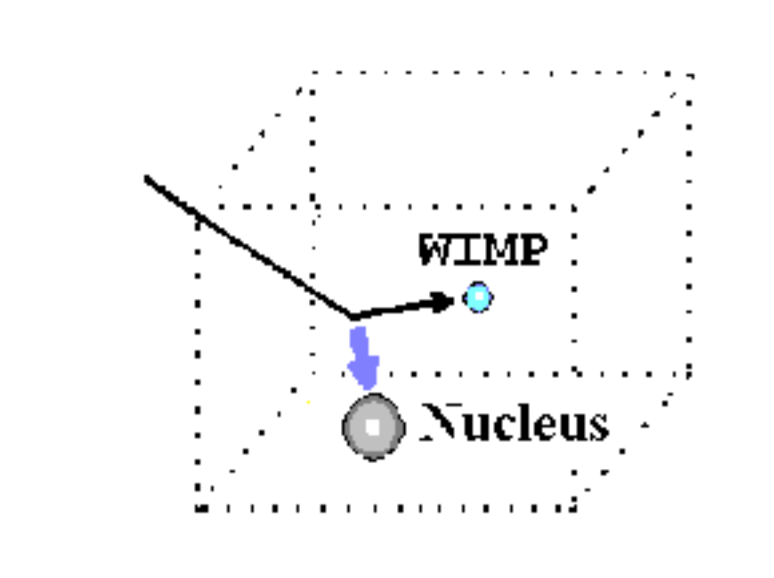


Freeze-out density yields relic density

Relic density is inversely proportional to annihilation cross-section

Can we detect DM ?

Yes, WIMP DM can be found by Direct search



- Our galaxy is immersed in a WIMP halo
- WIMPs in the halo has a velocity distribution
- Elastic scattering of DM with detector
- Nuclear recoil should be observed if such events detected

Recoil energy:

$$E_R = \frac{q^2}{2m_N} = \frac{\mu^2\nu^2}{m_N}(1 - cos\theta)$$

- q = momentum transfer
- m_N = target nucleus mass
- μ = reduced mass
- ν = mean WIMP-velocity on respect to the target
- θ = scattering angle in the center of mass

Differential rate spectrum:

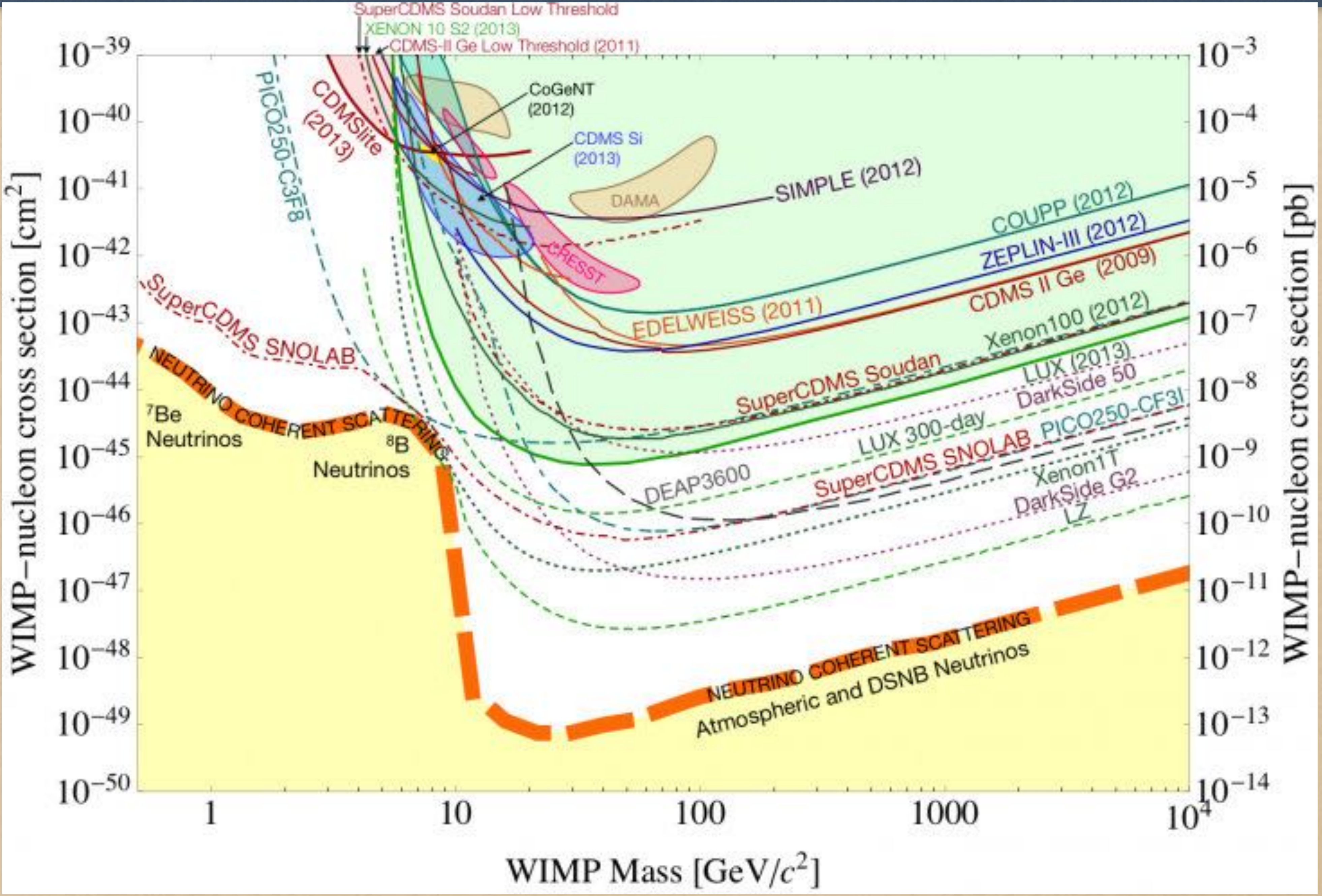
$$\frac{dN}{dE_R} \sim \frac{\rho_o}{2m_\chi\mu}\left[\sigma^{SI}F_{SI}^2 + \sigma^{SD}F_S^2\right]\int_{v_{min}}^{v_{esc}} \frac{\hat{\mathbf{f}}_{lab}(\hat{\mathbf{v}}, t)}{v} d^3v$$

spin-independent cross-section (↑ σ^{SI})

spin-dependent cross-section (↑ σ^{SD})

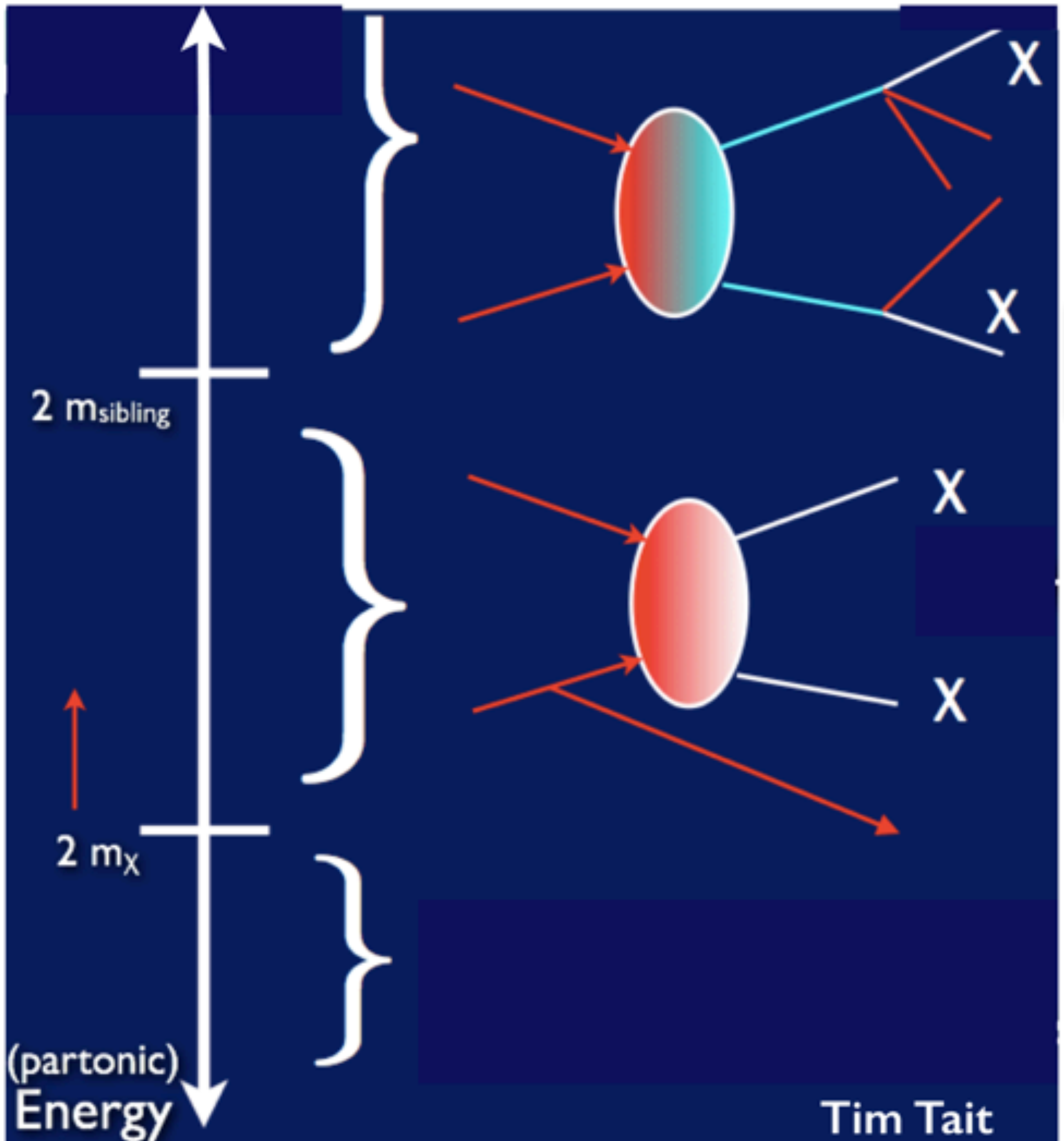
Status of DM direct search

Direct detection of DM has not been confirmed yet !



Strong bound on dark matter models from direct search

DM can also be produced at Collider (LHC)



LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

Multilepton/jet signatures

for e.g.: SUSY

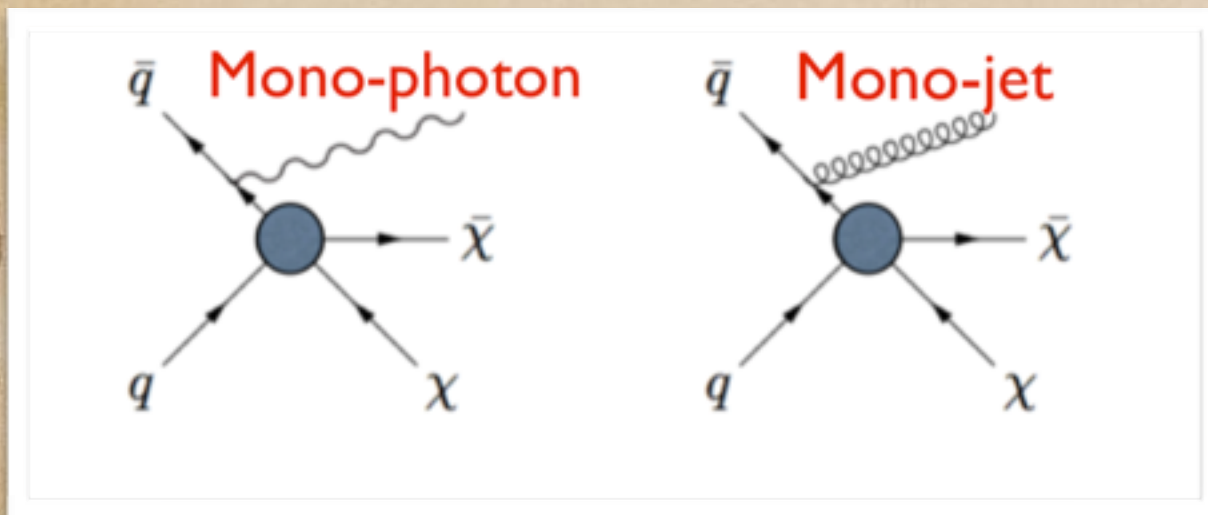
LHC can directly produce WIMP pairs

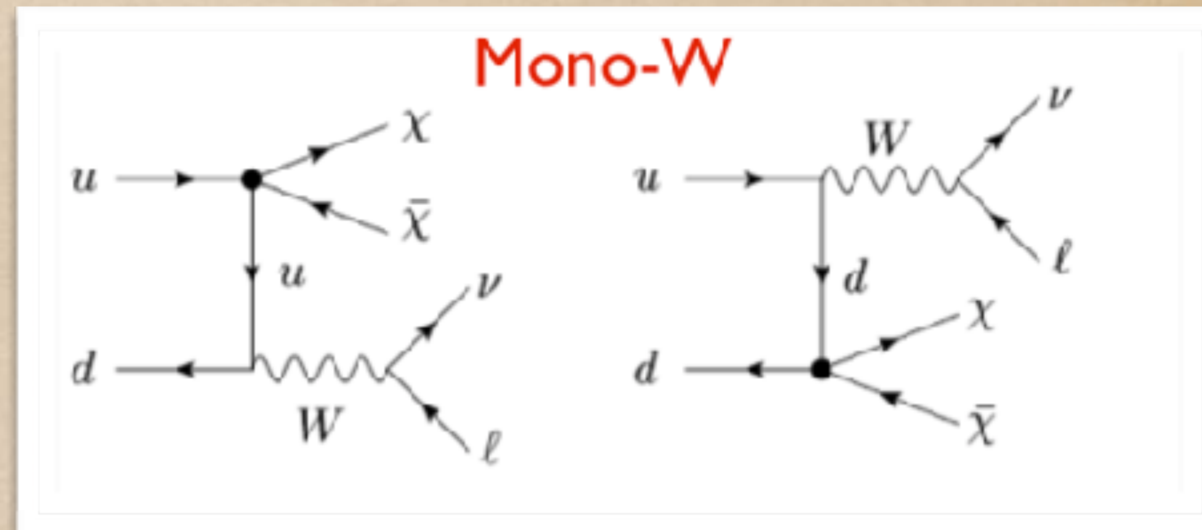
Mono-X signatures

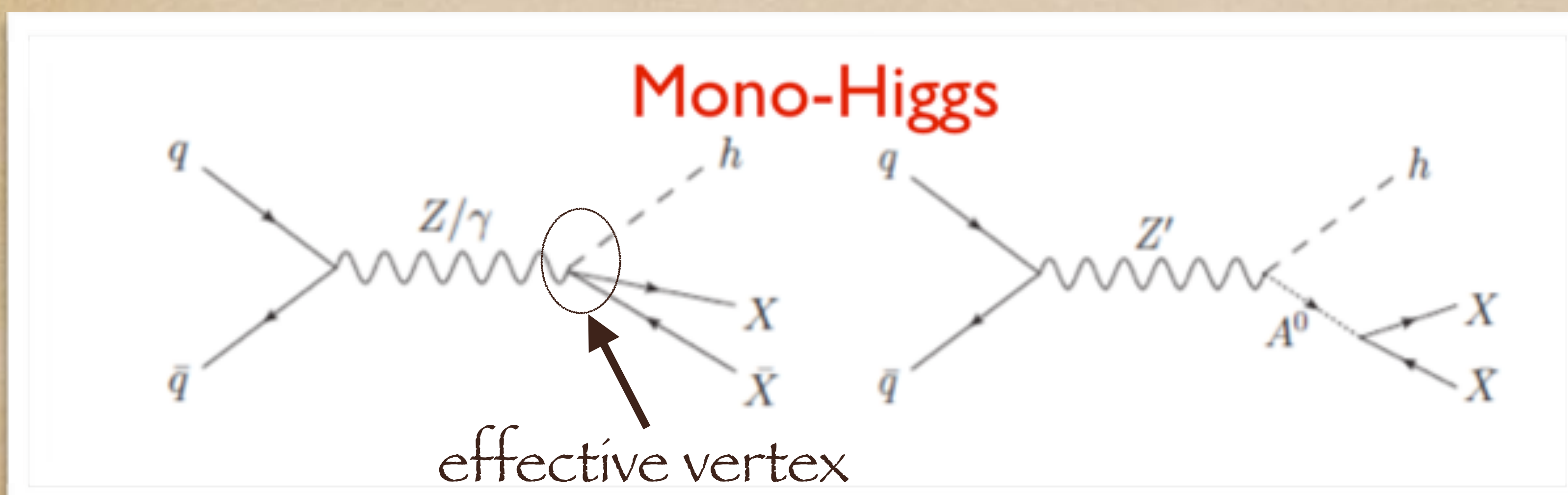
LHC cannot produce WIMPs

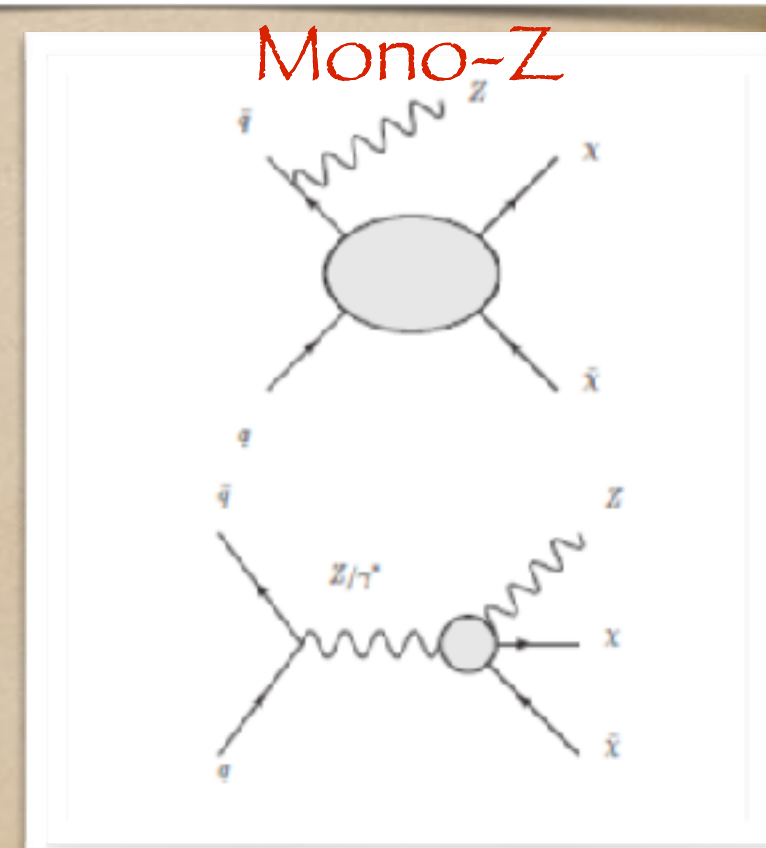
Slide adapted from Tim Tait talk at Moriond

Mono-X signatures at LHC: A generic possibility









Signature: X+Missing Energy

X=photon, jet, W, Z, H

What is Missing Energy ?

Consider: a+b -> c+d+e → Dark matter

$$\not{E}_T = \sqrt{(p_{x_d} + p_{x_e})^2 + (p_{y_d} + p_{y_e})^2}$$

Missing transverse momentum

$$= \sqrt{(p_{x_c})^2 + (p_{y_c})^2} = (P_T)_{vis}$$

The collision occurs along Z direction.

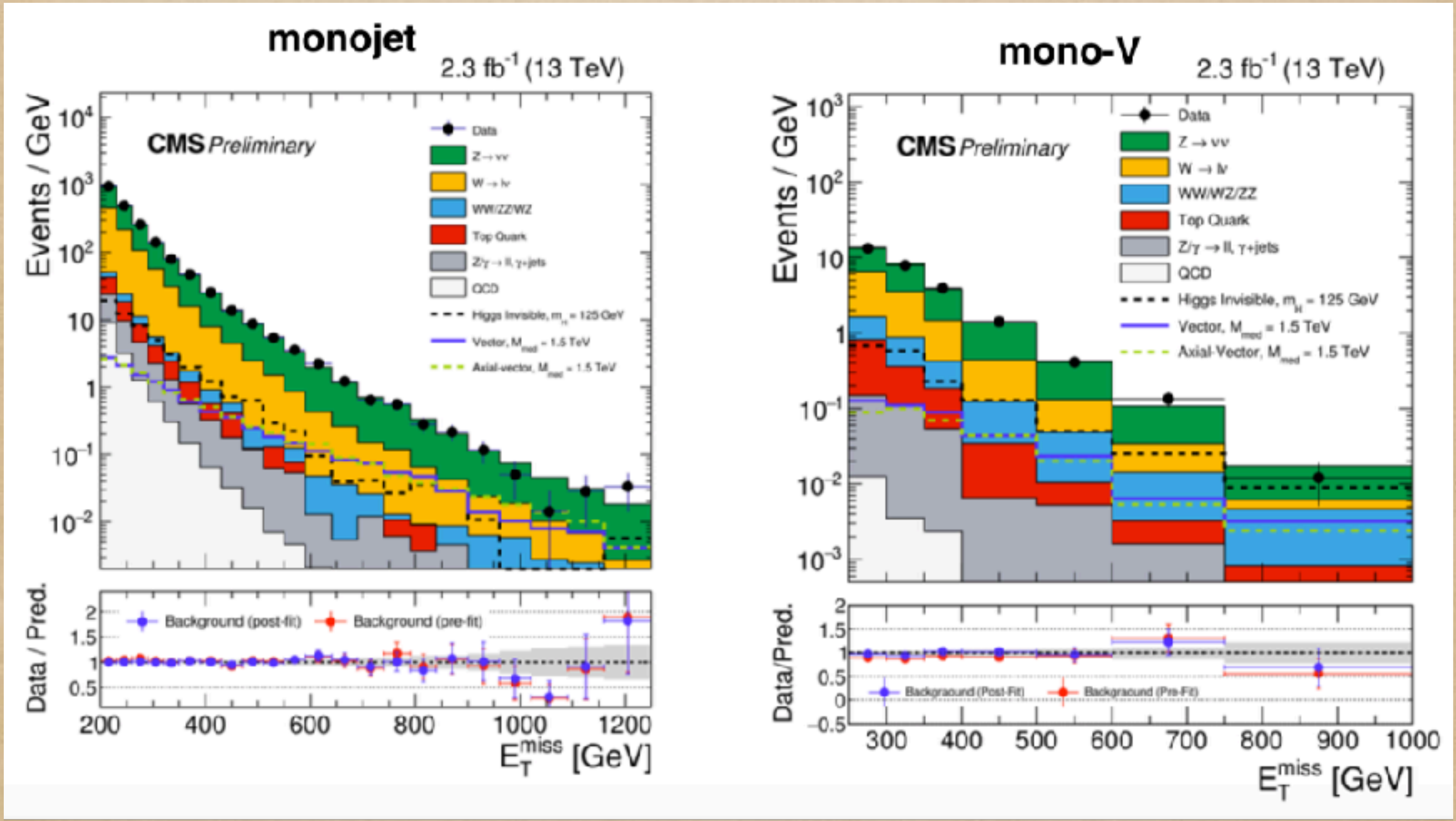
$$p_{x_c} + p_{x_d} + p_{x_e} = 0 \;\rightarrow\; p_{x_d} + p_{x_e} = -p_{x_c}$$

$$p_{y_c} + p_{y_d} + p_{y_e} = 0 \;\rightarrow\; p_{y_d} + p_{y_e} = -p_{y_c}$$

$$\not{E}_T = (p_T)_{mis} = -(p_T)_{vis}, \;\; (p_T)_{vis} = \sqrt{(\sum_{\ell,j} p_x)^2 + (\sum_{\ell,j} p_y)^2}\,.$$

Hence, unless we have some visible particles to recoil against, missing energy makes no sense.

CMS Monojet/Mono-V search: results

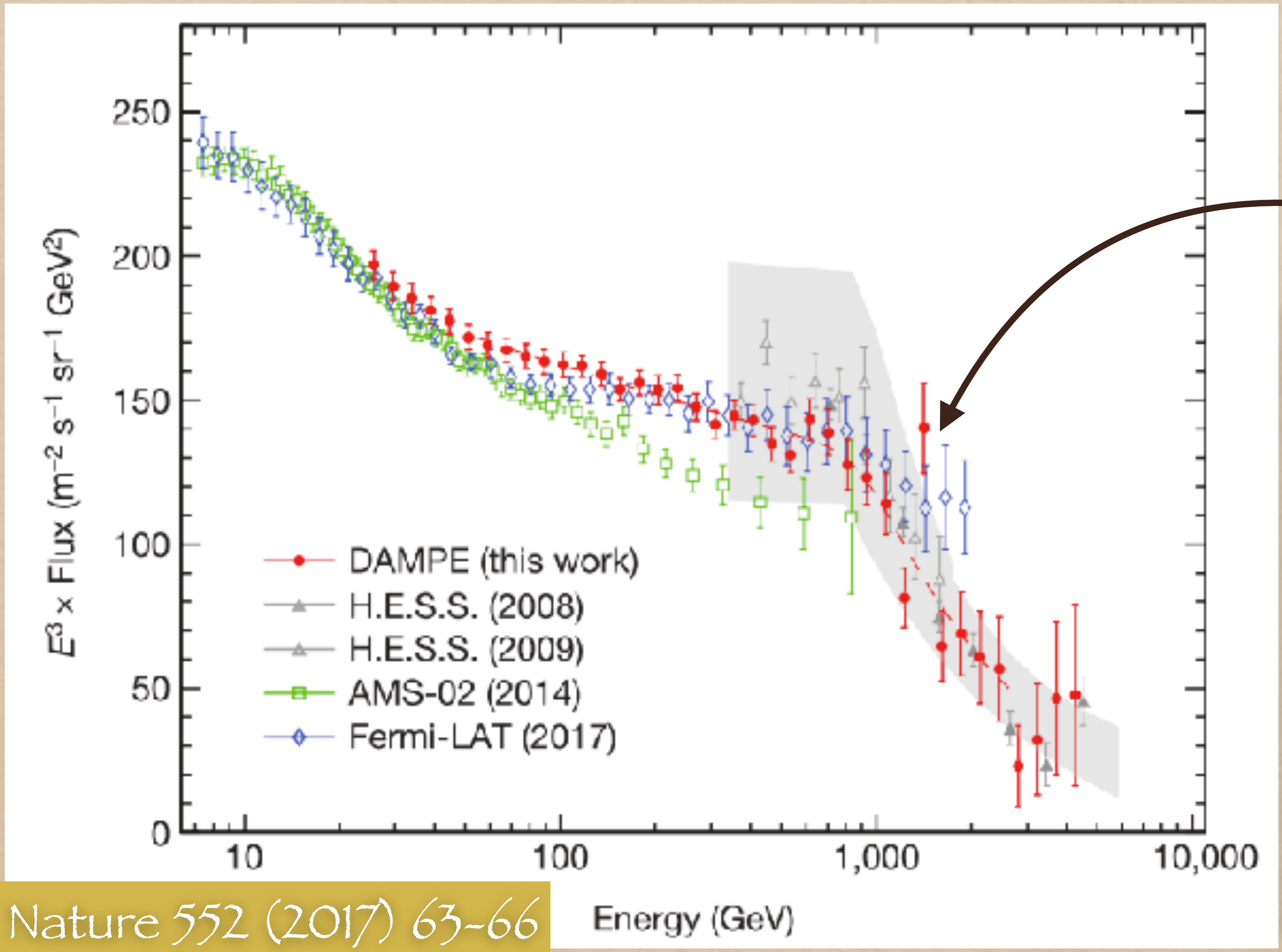


What did we see ?

No DM signal yet !

Indirect DM search

DM can annihilate and produce cosmic ray anti-particle ! ??



Excess !

Its a challenging task to fit the spectrum fully and we will refrain from further discussion in indirect search.

Nature 552 (2017) 63-66

Electron and positron spectra reported by DAMPE

Possible DM (WIMP) candidates

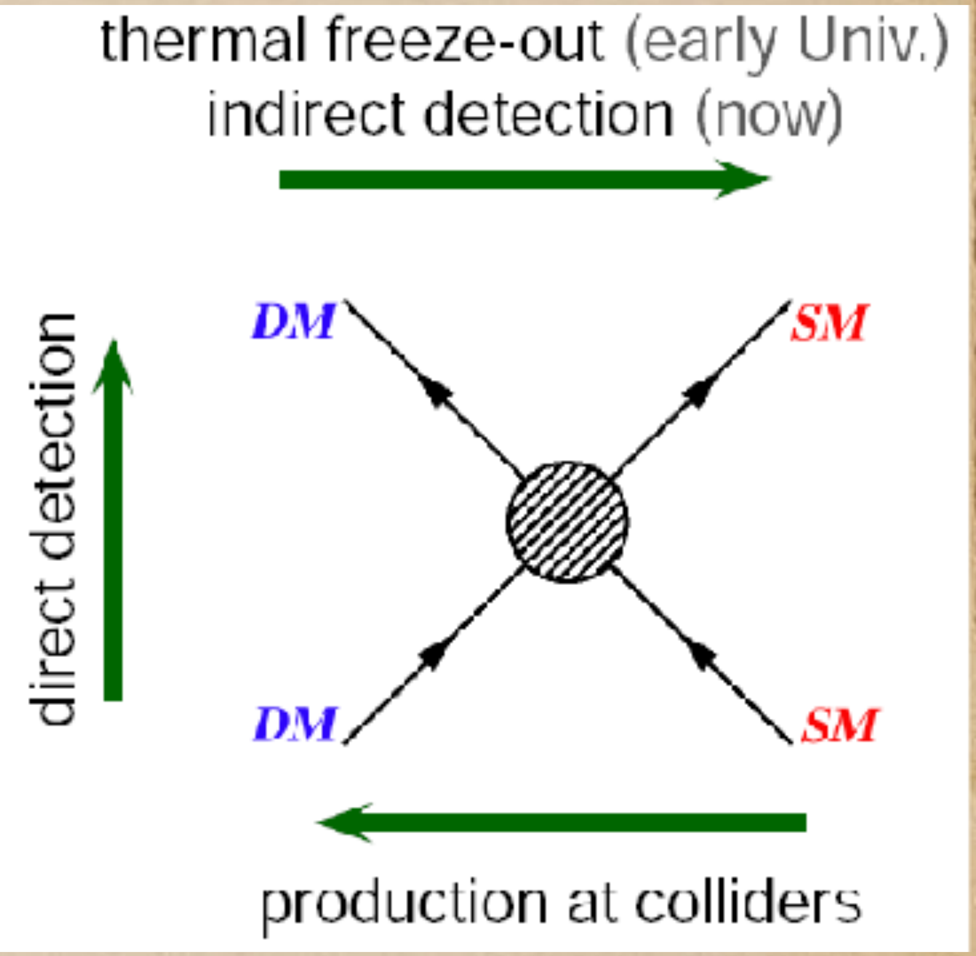
DM-SM interactions

$$\mathcal{L}_{\mathrm{DM-SM}} \sim \frac{1}{\Lambda^{(n-4)}} \mathcal{O}_{\mathrm{DM}} \mathcal{O}_{\mathrm{SM}}$$

Renormalisable interactions :

$$\mathcal{O}_{\mathrm{DM}} \leq 2 \longrightarrow \mathcal{O}_{\mathrm{SM}} : \; H^\dagger H, \; B_{\mu\nu}$$

$$\mathcal{L}_{\mathrm{DM-SM}} \sim H^\dagger H \phi^2$$



ϕ is a DM ! provided no em charge → simplest possibility

To ensure the stability of DM, I do not want a single DM in vertex, and hence one has to impose at least a Z_2 symmetry

$$\phi \to -\phi$$

Single component scalar DM

A scalar singlet ϕ with $\mathcal{Z}_2$ symmetry and Hypercharge $Y = 0$.

Scalar potential

$$V(H,\phi) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{1}{2}\mu_\phi^2 \phi^2 + \frac{1}{4!}\lambda_\phi \phi^4 + \frac{1}{2}\lambda_1 H^\dagger H \phi^2$$

Vacuum expectation value of the scalar is zero $\langle \phi \rangle = 0$

DM mass is achieved by spontaneous symmetry breaking

$$m_\phi^2 = \mu_\phi^2 + \frac{\lambda_1 v^2}{2}$$

Two parameters to represent the dark sector:

$$\{m_\phi, \lambda_1\}$$

Annihilation X-section

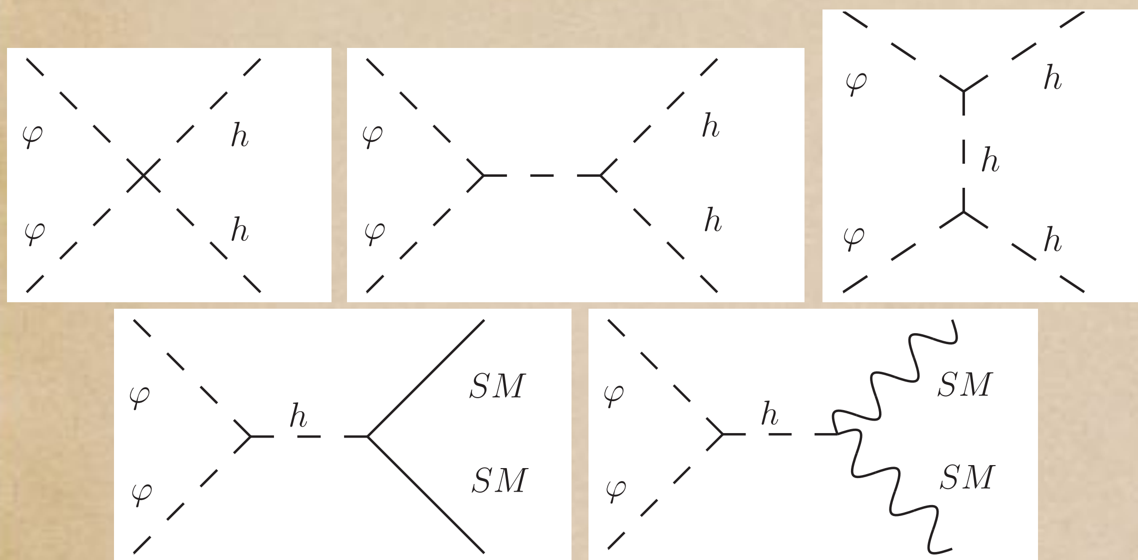


Figure 1: Diagrams contributing to the scalar $\varphi\varphi$ annihilation into SM particles.

$$(\sigma v)_{\phi_1\phi_1\to f\bar{f}} = \frac{1}{4\pi s\sqrt{s}}\frac{N_c\lambda_1^2 m_f^2}{(s-m_h^2)^2+m_h^2\Gamma_h^2}(s-4m_f^2)^{\frac{3}{2}}$$

$$(\sigma v)_{\phi_1\phi_1\to W^+W^-} = \frac{\lambda_1^2}{8\pi}\frac{s}{(s-m_h^2)^2+m_h^2\Gamma_h^2}(1+\frac{12m_W^4}{s^2}-\frac{4m_W^2}{s})(1-\frac{4m_W^2}{s})^{\frac{1}{2}}$$

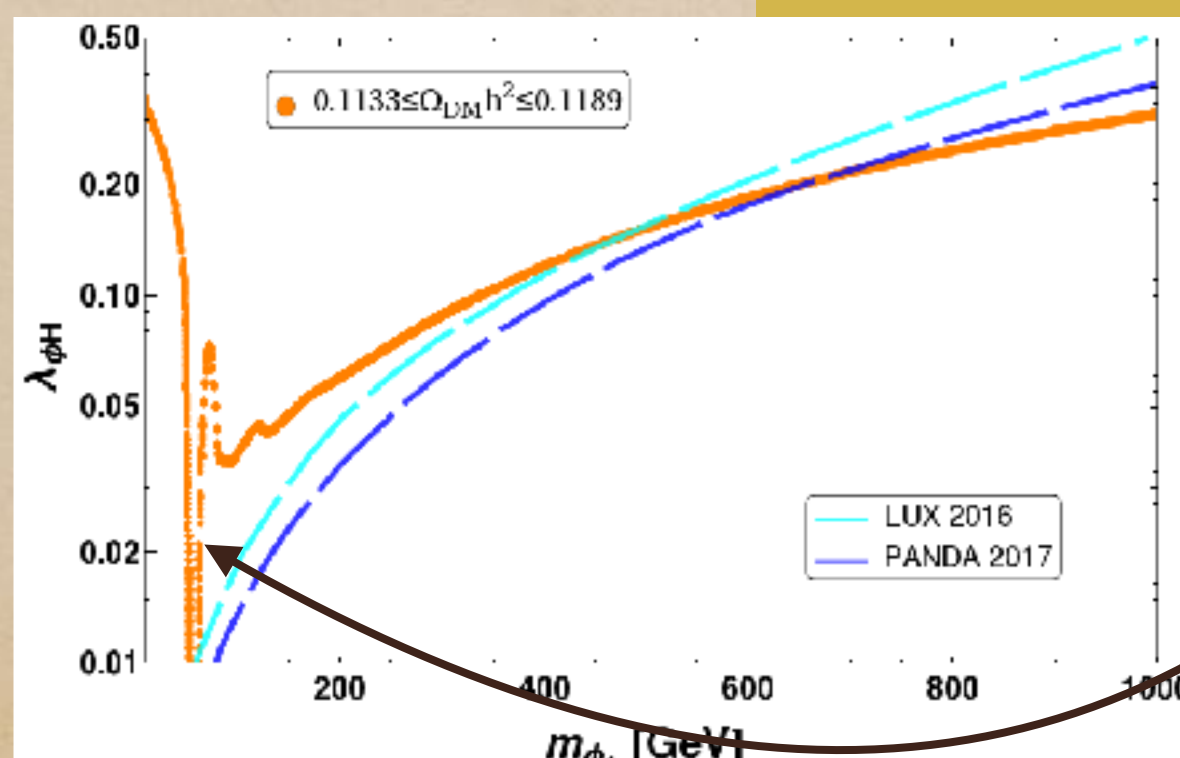
$$(\sigma v)_{\phi_1\phi_1\to ZZ} = \frac{\lambda_1^2}{16\pi}\frac{s}{(s-m_h^2)^2+m_h^2\Gamma_h^2}(1+\frac{12m_Z^4}{s^2}-\frac{4m_Z^2}{s})(1-\frac{4m_Z^2}{s})^{\frac{1}{2}}$$

$$(\sigma v)_{\phi_1\phi_1\to hh} = \frac{\lambda_1^2}{16\pi s}\left[1+\frac{3m_h^2}{(s-m_h^2)}-\frac{4\lambda_1 v^2}{(s-2m_h^2)}\right]^2(1-\frac{4m_h^2}{s})^{\frac{1}{2}}$$

$$(\sigma v)_{\phi_1\phi_1\to SM} = (\sigma v)_{\phi_1\phi_1\to f\bar{f}}+(\sigma v)_{\phi_1\phi_1\to W^+W^-}+(\sigma v)_{\phi_1\phi_1\to ZZ}+(\sigma v)_{\phi_1\phi_1\to hh}$$

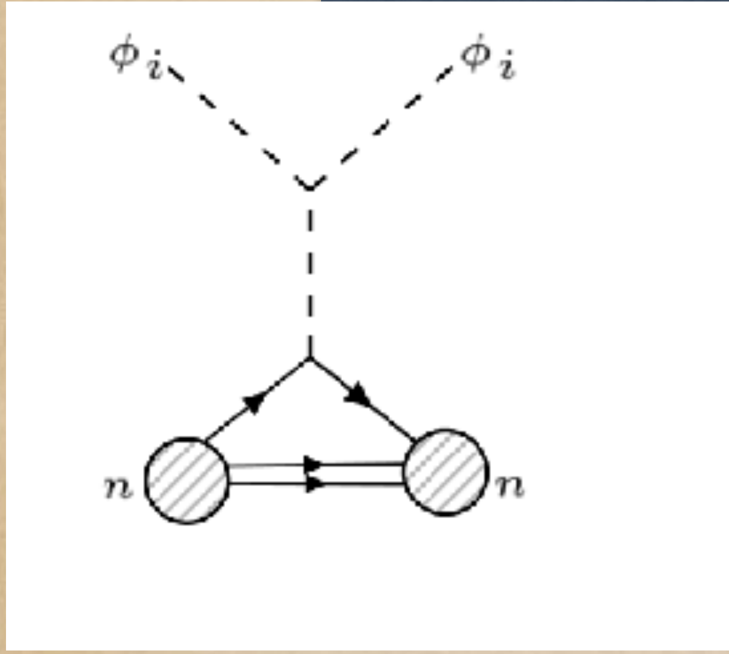
$$\Omega h^2 \sim \frac{2.4\times 10^{-10}\,\mathrm{GeV}^{-2}}{(\sigma v)_{\phi\phi\to SM}}$$

Relic density allowed parameter space



Resonance drop at 62.5 GeV

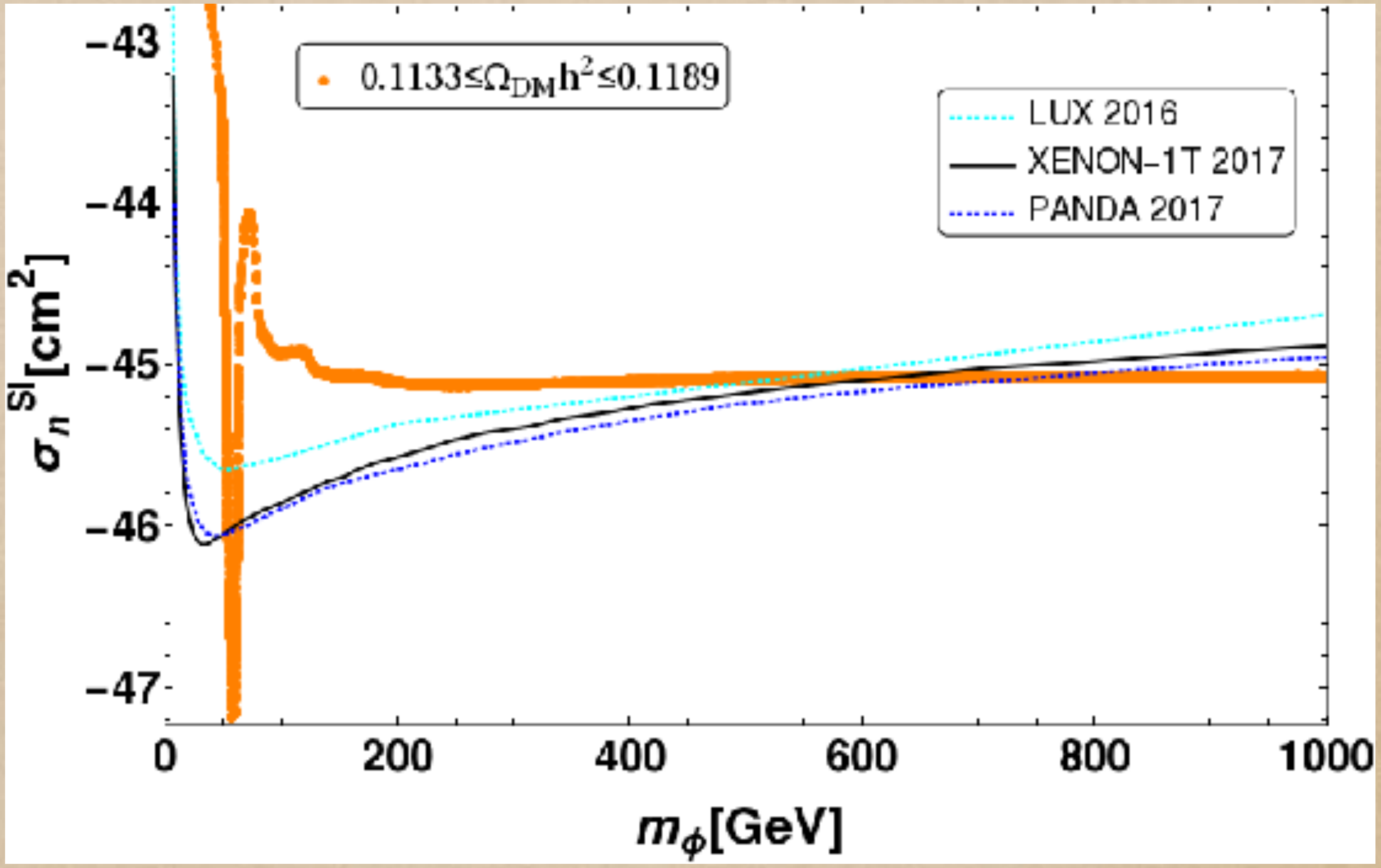
Direct search for scalar singlet DM



$$\sigma^{SI}_{n_i} = \frac{\alpha_n^2 \mu_n^2}{4\pi m_{\phi_i}^2}$$

$$\alpha_n = m_n \sum_{u,d,s} f^{(n)}_{T_q} \frac{\alpha_q}{m_q} + \frac{2}{27} f^{(n)}_{T_g} \sum_{q=c,t,b} \frac{\alpha_q}{m_q}$$
$$= m_n \sum_{u,d,s} f^{(n)}_{T_q} \frac{\alpha_q}{m_q} + \frac{2}{27}(1 - \sum_{u,d,s} f^{(n)}_{T_q}) \sum_{q=c,t,b} \frac{\alpha_q}{m_q}$$
$$= \frac{m_n \lambda_i}{m_h^2}[(f^{(n)}_{T_u} + f^{(n)}_{T_d} + f^{(n)}_{T_s}) + \frac{2}{9}(f^{(n)}_{T_u} + f^{(n)}_{T_d} + f^{(n)}_{T_s})]$$

Excepting for resonance, ruled out to a sufficiently heavy mass



Multi-component DM

$$\sigma^{SI}_{eff}(n_i) = (\frac{\Omega_i}{\Omega_T})\sigma^{SI}_{n_i} = \frac{\Omega_i}{\Omega_T}\frac{\alpha_n^2 \mu_n^2}{4\pi m_{\phi_i}^2} \qquad (i = 1, 2)$$

Simplest multicomponent DM: $\mathcal{O}(n)$

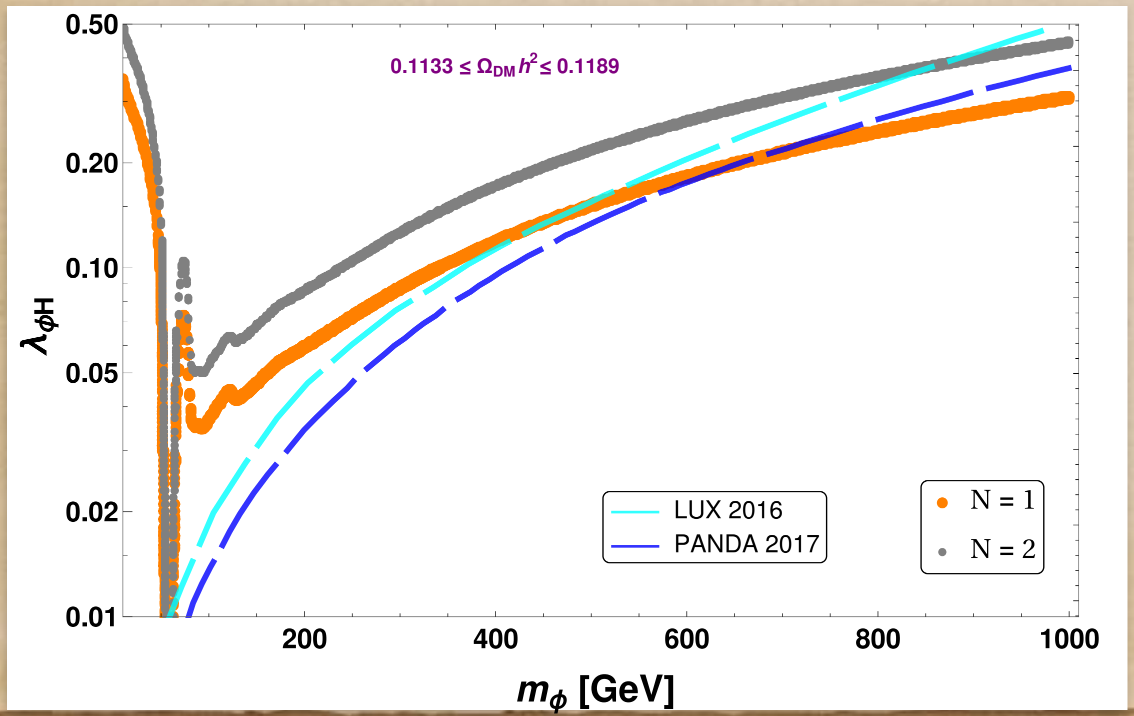
Many Singlet scalars: $\vec{\phi} = \{\phi_1, \phi_2, ...\phi_n\}$ $\quad \mathcal{Z}_2 : \vec{\phi} \to -\vec{\phi}$

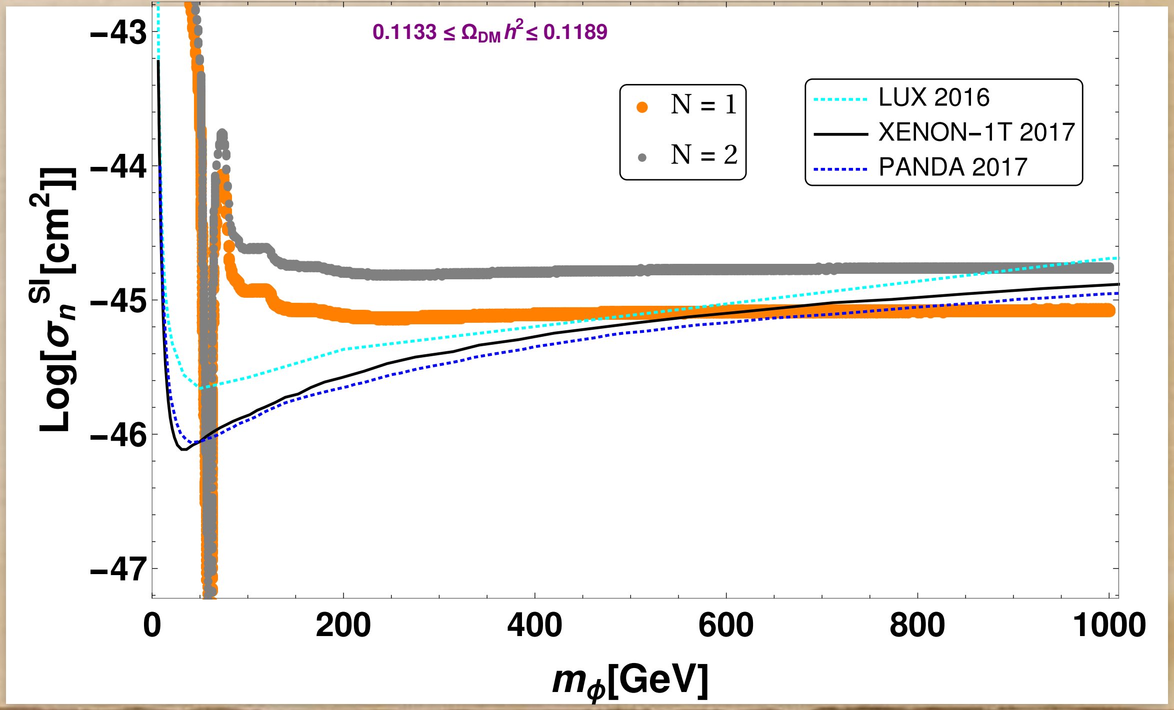
$$V(H,\vec{\phi}) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{1}{2}\mu_{\vec{\phi}}^2 \vec{\phi}^2 + \frac{1}{4!}\lambda_{\vec{\phi}}(\vec{\phi}^2)^2 + \frac{1}{2}\lambda_1 H^\dagger H \vec{\phi}^2$$

All the DMs have same mass

- No effective DM-DM Interactions !
- $\Omega = N\Omega^i$

Severe direct search constraints





A Drozd, B Gradskowski, J Wudka, JHEP 1204 (2012) 006

Dual DM in $\mathcal{Z}_2 \times \mathcal{Z}_2^{'}$

$$\mathcal{Z}_2 : \phi_1 \to -\phi_1 \;;\; \mathcal{Z}_2^{'} : \phi_2 \to -\phi_2$$

$$\mathcal{L}_{DM} = \frac{1}{2}(\partial_\mu \phi_1)^2 + \frac{1}{2}(\partial_\mu \phi_2)^2 - \frac{1}{2}\mu_1^2\phi_1^2 - \frac{1}{2}\mu_2^2\phi_2^2 - \frac{1}{4}\lambda_3\phi_1^2\phi_2^2 - \frac{1}{4!}\lambda_6\phi_1^4 - \frac{1}{4!}\lambda_7\phi_2^4$$

$$-\mathcal{L}_{SM+DM} = \frac{1}{2}\lambda_1\phi_1^2 H^\dagger H + \frac{1}{2}\lambda_2\phi_2^2 H^\dagger H$$

Non-zero DM-DM interactions !

Coupled Boltzmann Equations

Non-degenerate DMs

$$\frac{dY_1}{dx} = -0.264 M_{Pl}\sqrt{g_*}\,\frac{\mu}{x^2}[\langle\sigma v_{11\to SM}\rangle(Y_1^2 - {Y_1^{EQ}}^2) + \langle\sigma v_{11\to 22}\rangle(Y_1^2 - \frac{{Y_1^{EQ}}^2}{{Y_2^{EQ}}^2}Y_2^2)$$

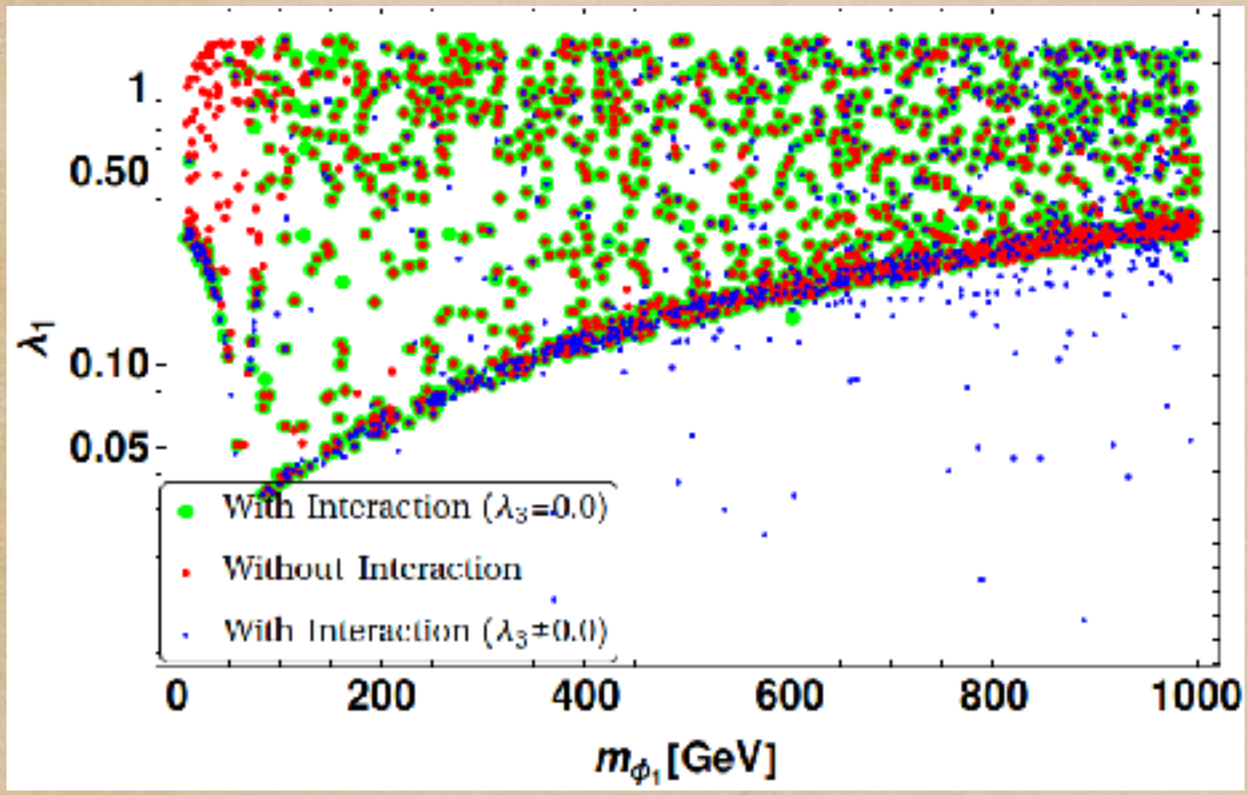
$$\frac{dY_2}{dx} = -0.264 M_{Pl}\sqrt{g_*}\,\frac{\mu}{x^2}[\langle\sigma v_{22\to SM}\rangle(Y_2^2 - {Y_2^{EQ}}^2) - \langle\sigma v_{11\to 22}\rangle(Y_2^2 - \frac{{Y_2^{EQ}}^2}{{Y_1^{EQ}}^2}Y_1^2)$$

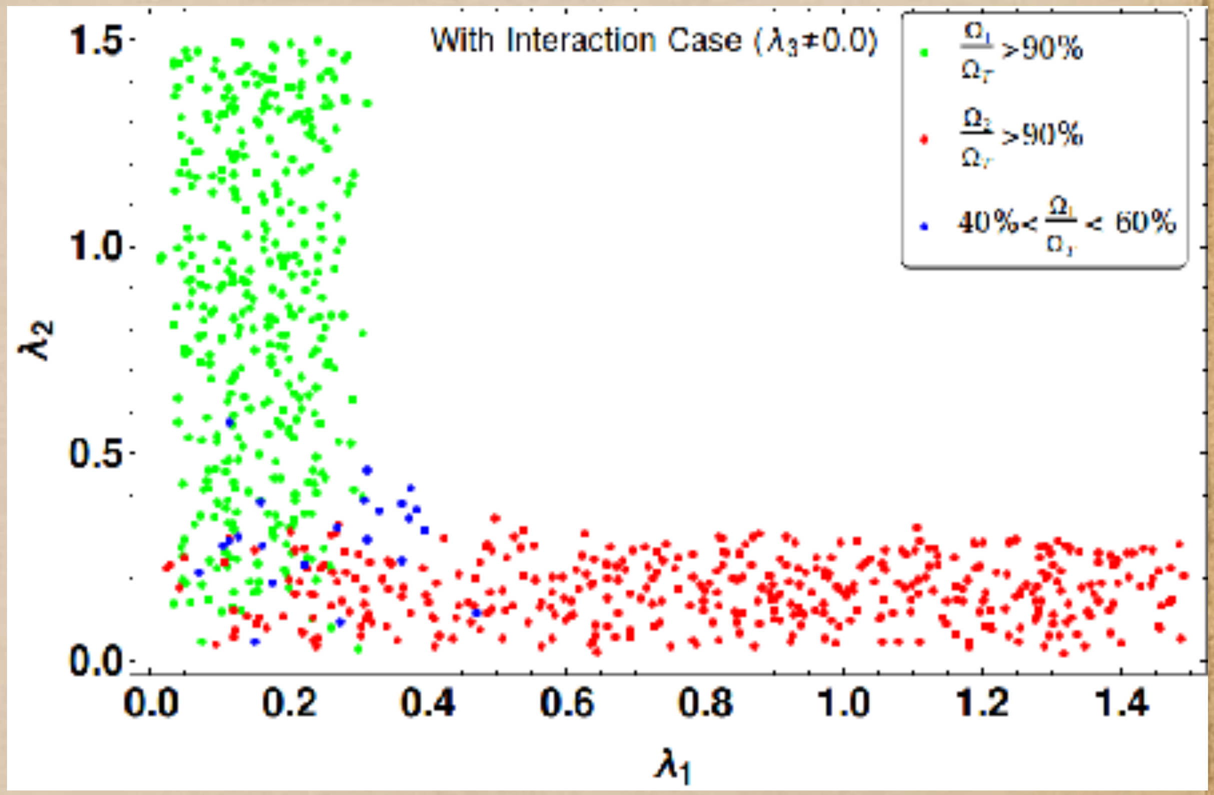
DM-DM interactions

(Assumed: $m_{\phi_1} > m_{\phi_2}$)

Relic Density: Dual DM $Z_2 \times Z_2'$

The heavier DM annihilates to lighter one and contributes to relic density

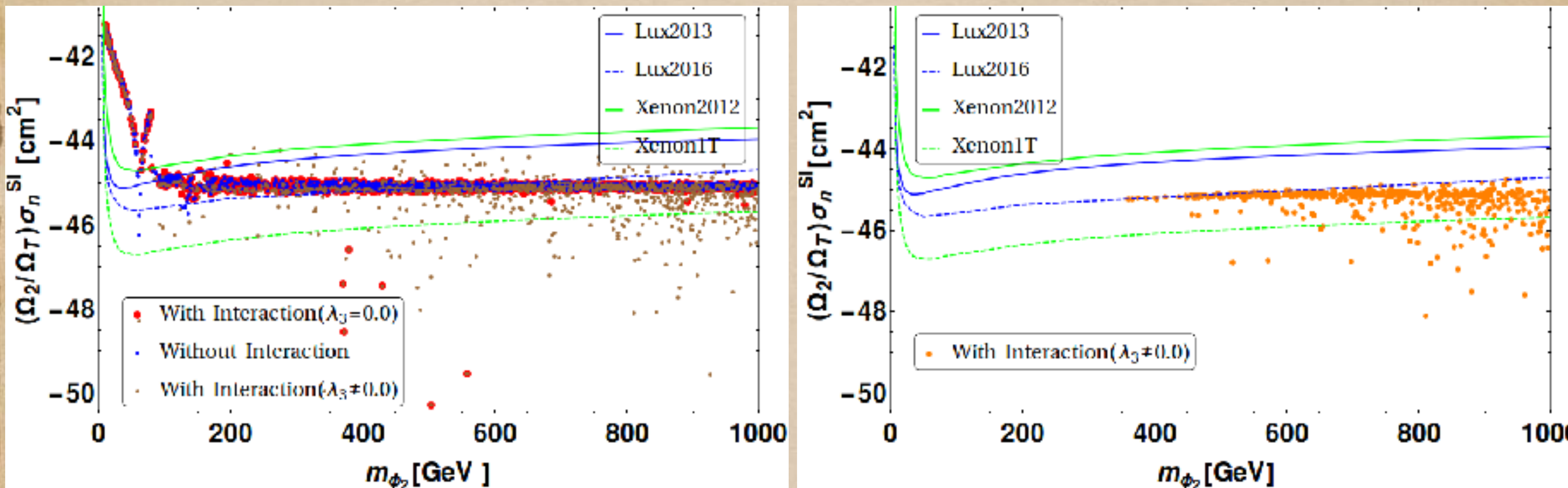




Much larger region of allowed parameter space spanning small and large DM-SM coupling: (i) Unequal share of relic density (ii) Annihilation of the heavier into the lighter.

SB, P.Ghosh, P. Poulose, JCAP 1704 (2017) no.04, 043

Direct search in dual DM: $\mathcal{Z}_2 \times \mathcal{Z}_2'$



Relic density allowed points with small DM-SM coupling allowed due to DM-DM interactions.

Direct detection of heavier component can be delayed beyond XENON 1T, as the freeze out can be dictated by annihilation into lighter component.

SB, P.Ghosh, P. Poulose, JCAP 1704 (2017) no.04, 043

Scalar DM with co-annihilation: $\mathcal{Z}_2$

Two scalar singlet particles odd under same symmetry:

$$\mathcal{Z}_2 : \phi_1 \to -\phi_1,\ \ \phi_2 \to -\phi_2$$

$$V(\phi_1,\phi_2,H) = -\mu_H^2(H^\dagger H - \frac{v^2}{2}) + \ \lambda_H(H^\dagger H - \frac{v^2}{2})^2 + \frac{1}{2}m_{\phi_1}^2\phi_1^2 + \frac{1}{2}m_{\phi_2}^2\phi_2^2 + m_{\phi_{12}}^2\phi_1\phi_2$$
$$+\lambda_e[\frac{1}{4}\phi_1^2\phi_2^2 + \frac{1}{3!}\phi_1^3\phi_2 + \frac{1}{3!}\phi_1\phi_2^3] + \frac{\lambda_{1s}}{4!}\phi_1^4 + \frac{\lambda_{2s}}{4!}\phi_2^4$$
$$+\frac{1}{2}\lambda_{1h}\phi_1^2(H^\dagger H - \frac{v^2}{2}) + \frac{1}{2}\lambda_{2h}\phi_2^2(H^\dagger H - \frac{v^2}{2}) + \lambda_{12h}\phi_1\phi_2(H^\dagger H - \frac{v^2}{2})$$

- The lightest is DM. The heavier decays $(\phi_2 \to \phi_1 f\bar{f})$ and can co annihilate $(\phi_1\phi_2 \to SMSM)$

BEQ:

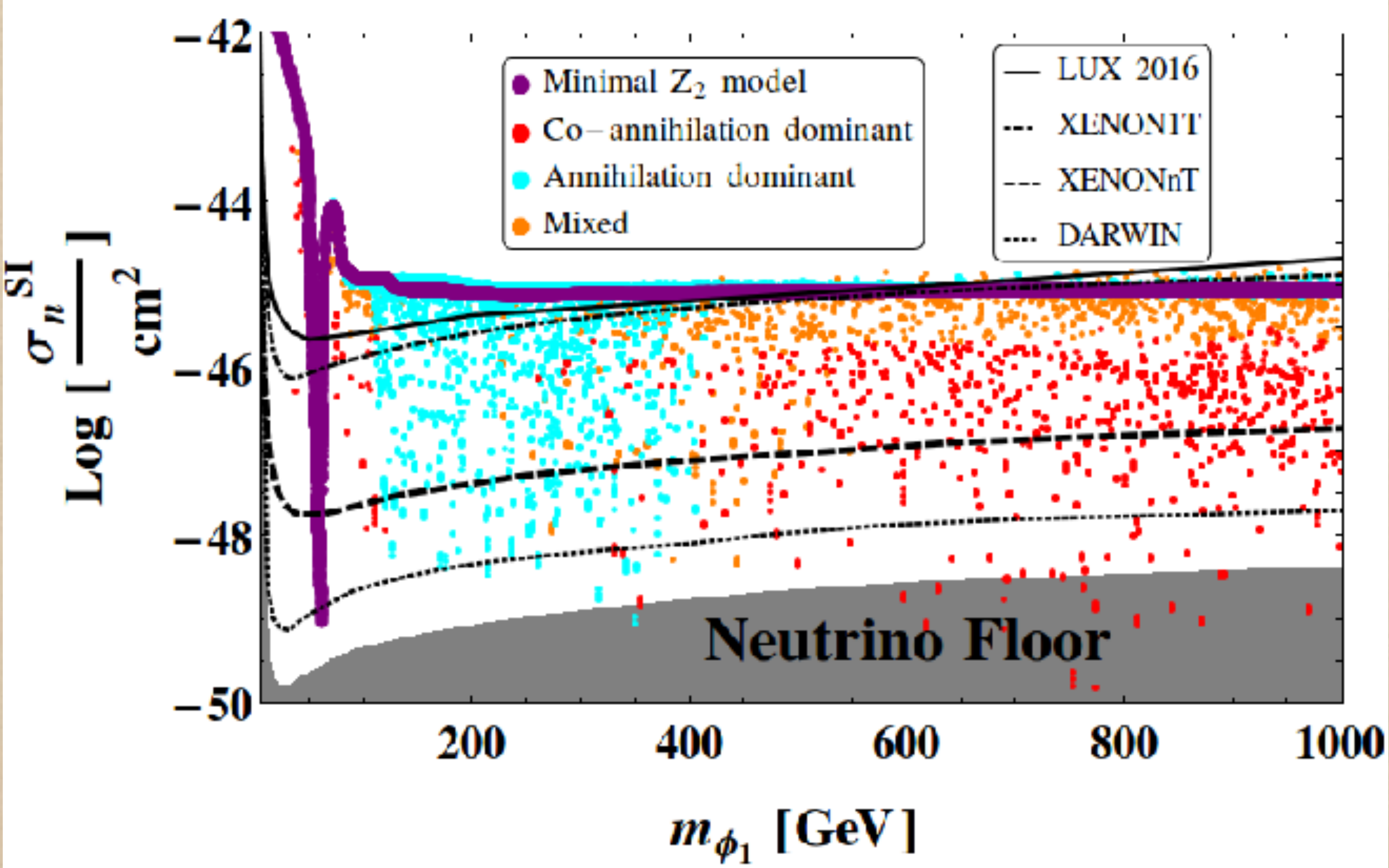
$$\frac{dn_{\phi_1}}{dt} + 3Hn_{\phi_1} = -\langle\sigma v\rangle_{\phi_1\phi_1\to SM}(n_{\phi_1}^2 - n_{\phi_1}^{eq\,2}) - \langle\sigma v\rangle_{\phi_1\phi_2\to SM}n^{eq}{}_{\phi_2}(n_{\phi_1} - n^{eq}{}_{\phi_1})$$

co-annihilation

$$\Omega h^2 \sim \frac{1}{\langle\sigma v\rangle_{eff}}$$

$$\langle\sigma v\rangle_{eff} = \langle\sigma v\rangle_{\phi_1\phi_1\to SM} + \langle\sigma v\rangle_{\phi_1\phi_2\to SM}(1+\frac{\Delta m}{m_1})^{3/2}e^{-\frac{\Delta m}{T}}$$

Direct Search with co annihilations: $\mathcal{Z}_2$



Co-annihilation contributes to relic density but not to direct search
Co-annihilation can bring direct search cross-sections down significantly

SB, P. Ghosh, T. Maity and T.S. Ray, JHEP1710(2017)088

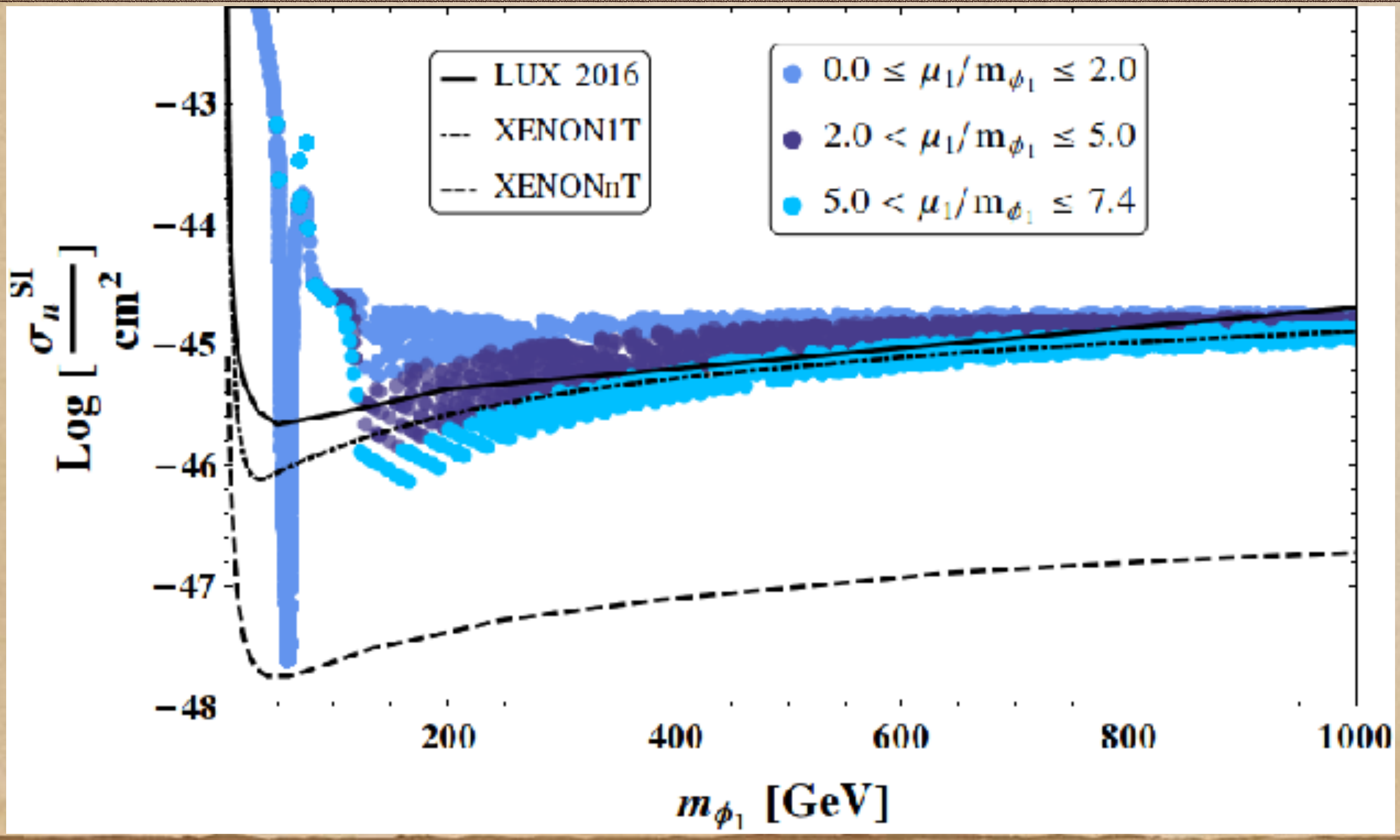
Semi-annihilation with $\mathcal{Z}_3$

Complex scalar field ϕ_1 transforming under $\mathcal{Z}_3$

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

Semi-annihilation $\phi_1 \phi_1 \to \phi_1 h$

$$\frac{dn_{\phi_1}}{dt} + 3Hn_{\phi_1} = -\langle\sigma v\rangle_{\phi_1\phi_1\to SM}(n_{\phi_1}^2 - n_{\phi_1}^{eq\,2}) - \langle\sigma v\rangle_{\phi_1\phi_1\to\phi_1 SM}(n_{\phi_1}^2 - n_{\phi_1}n^{eq}{}_{\phi_1})$$



Semi-annihilation contributes to relic density and brings the coupling down in the vicinity of Higgs mass

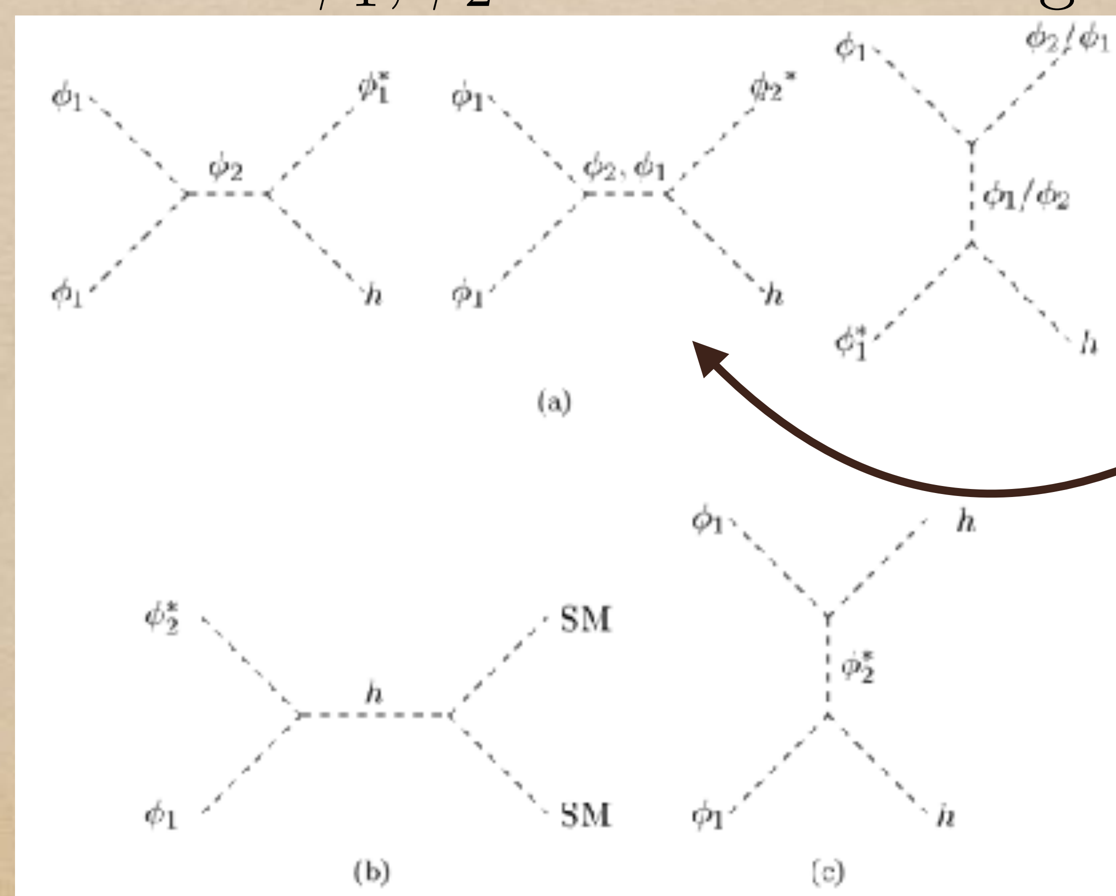
Semi-annihilation + Co-annihilation

ϕ_1 and ϕ_2 transforming under same $\mathcal{Z}_3$

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

Assumed that ϕ_1, ϕ_2 are transforming similarly under Z_3

Additional annihilation channels

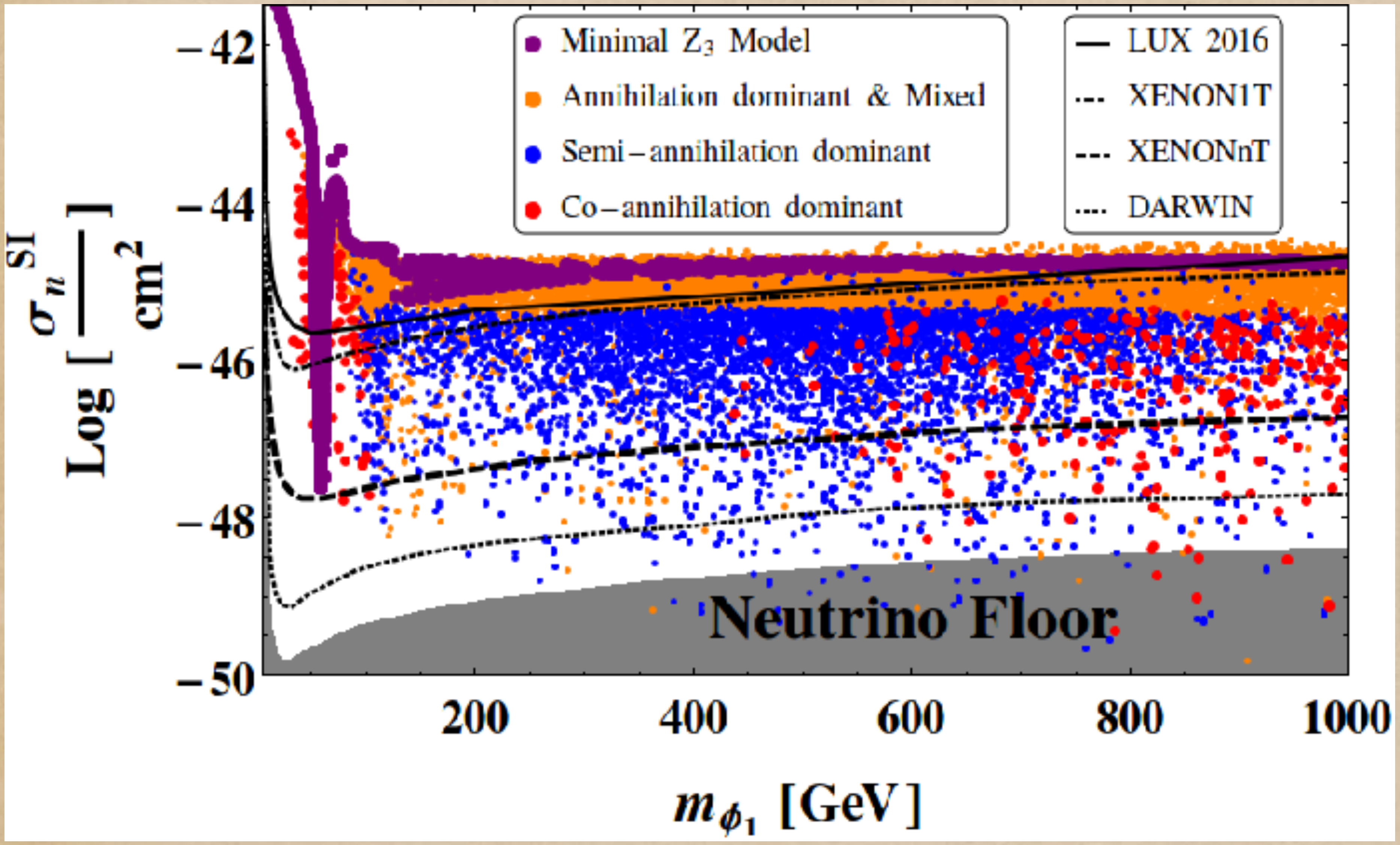


Mediated semi-annihilations

SB, P. Ghosh, T. Maity and T.S.Ray, JHEP1710(2017)088

Relic density and Direct search constraints

ϕ_1 and ϕ_2 transforming under same $\mathcal{Z}_3$

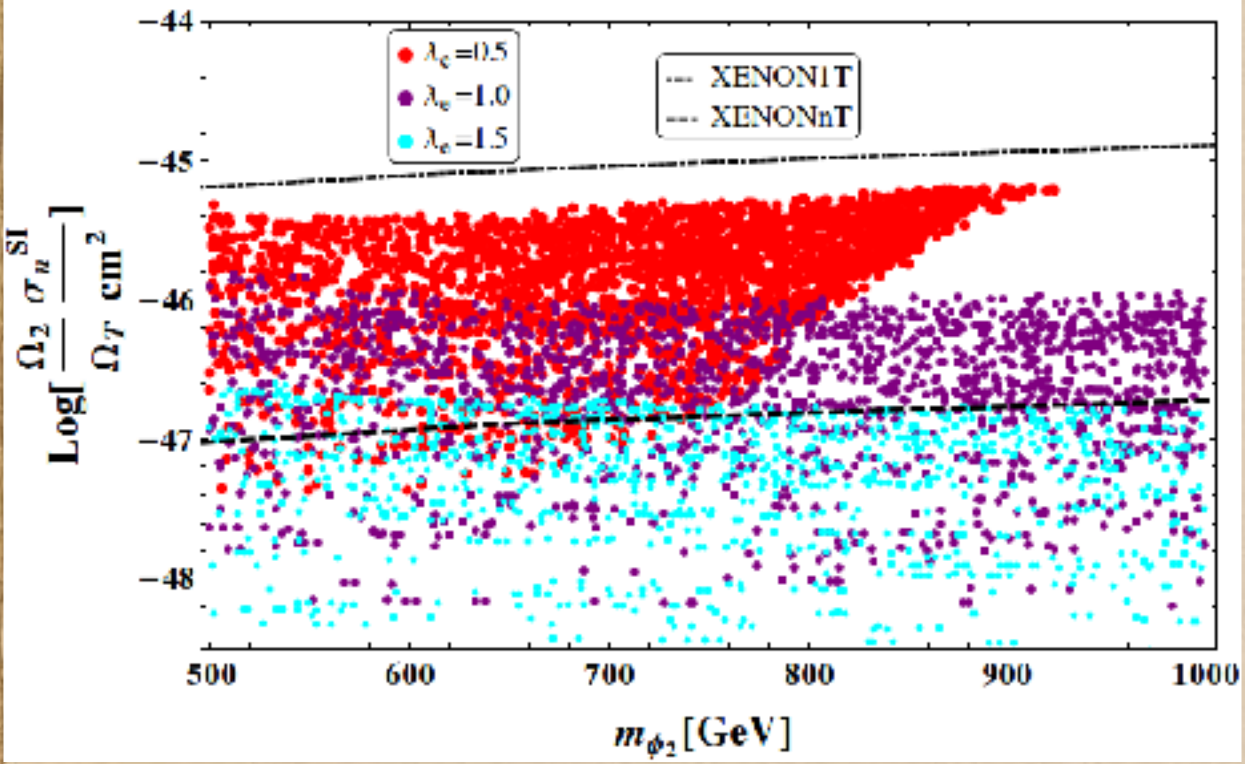


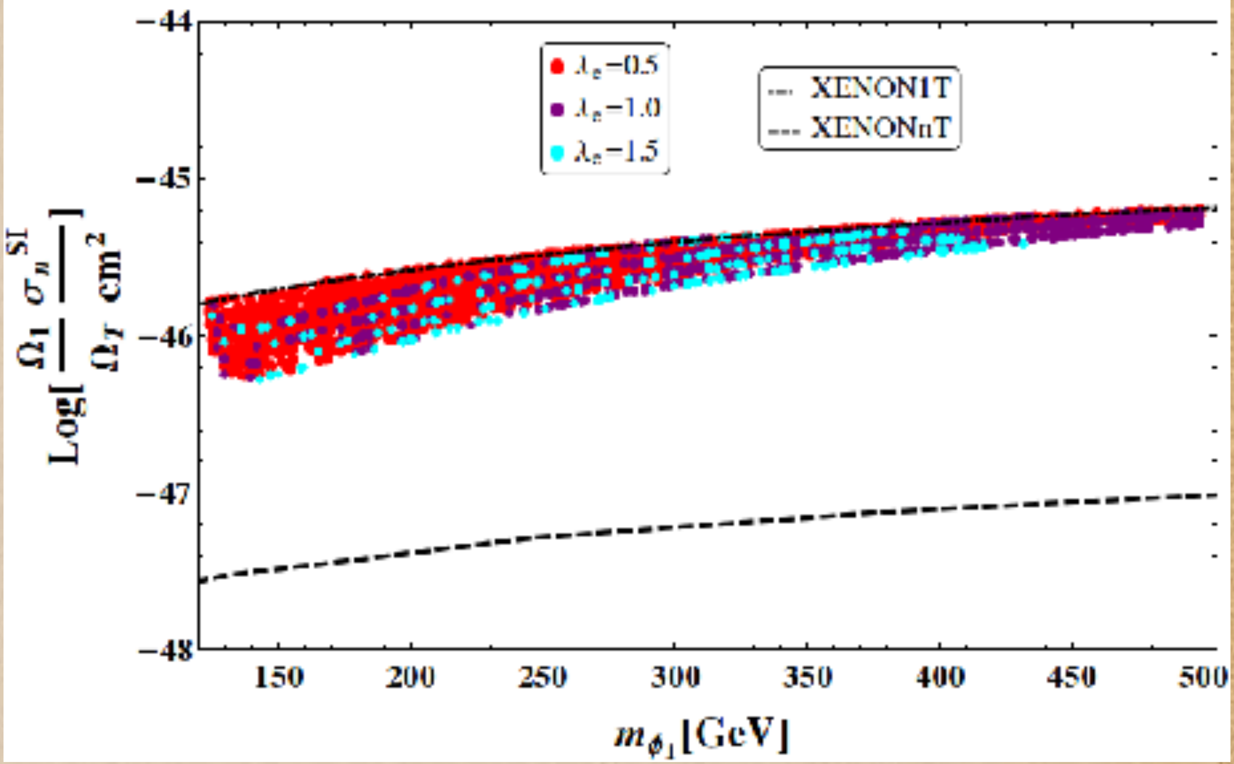
Resonant Semi-annihilations is an additional feature

SB, P. Ghosh, T. Maity and T.S.Ray, JHEP1710(2017)088

Semi Annihilation + DM-DM Interactions

ϕ_1 transforming under $\mathcal{Z}_3$; ϕ_2 transforming under $\mathcal{Z}_3^{'}$





Direct search cross-section for one component can be brought down below XENON1T, while the other component behaves similar to a single component framework

SB, P. Ghosh, T. Maity and T.S.Ray, JHEP1710(2017)088

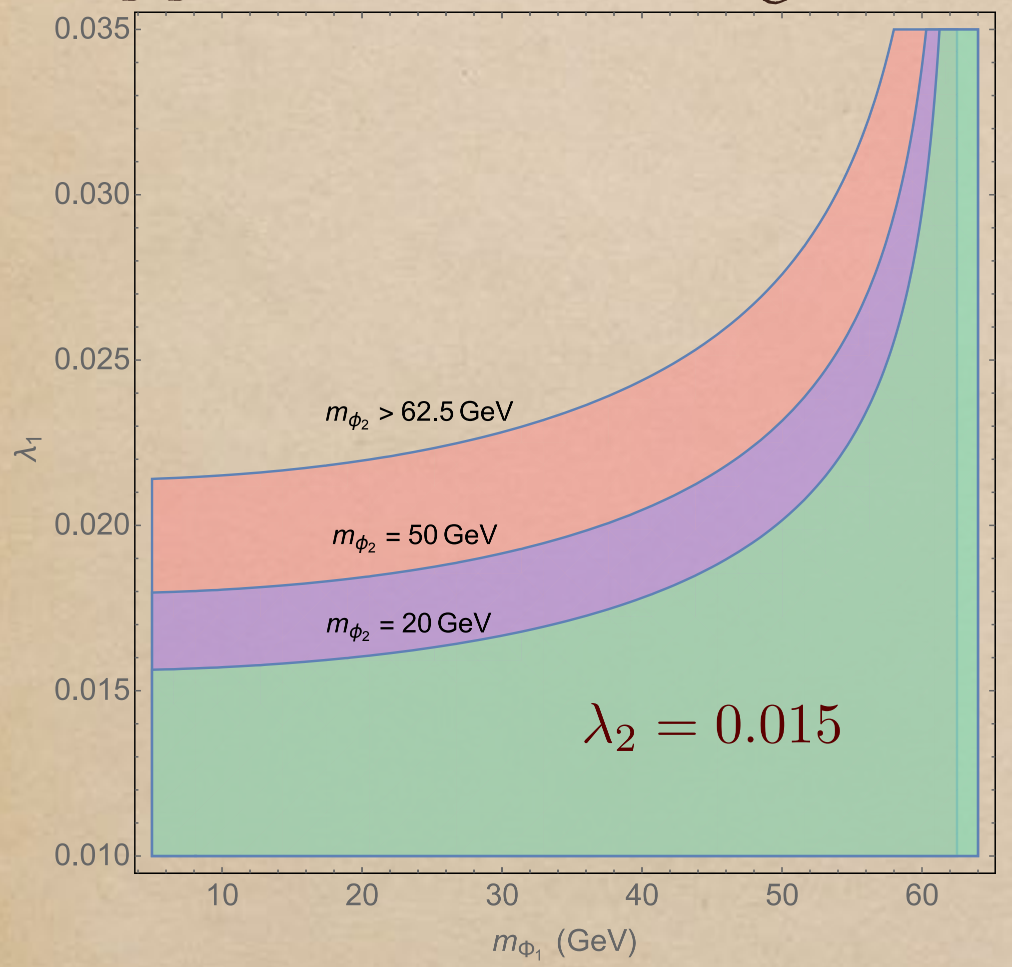
Semi-Annihilation + Co-Annihilation +DM-DM interaction

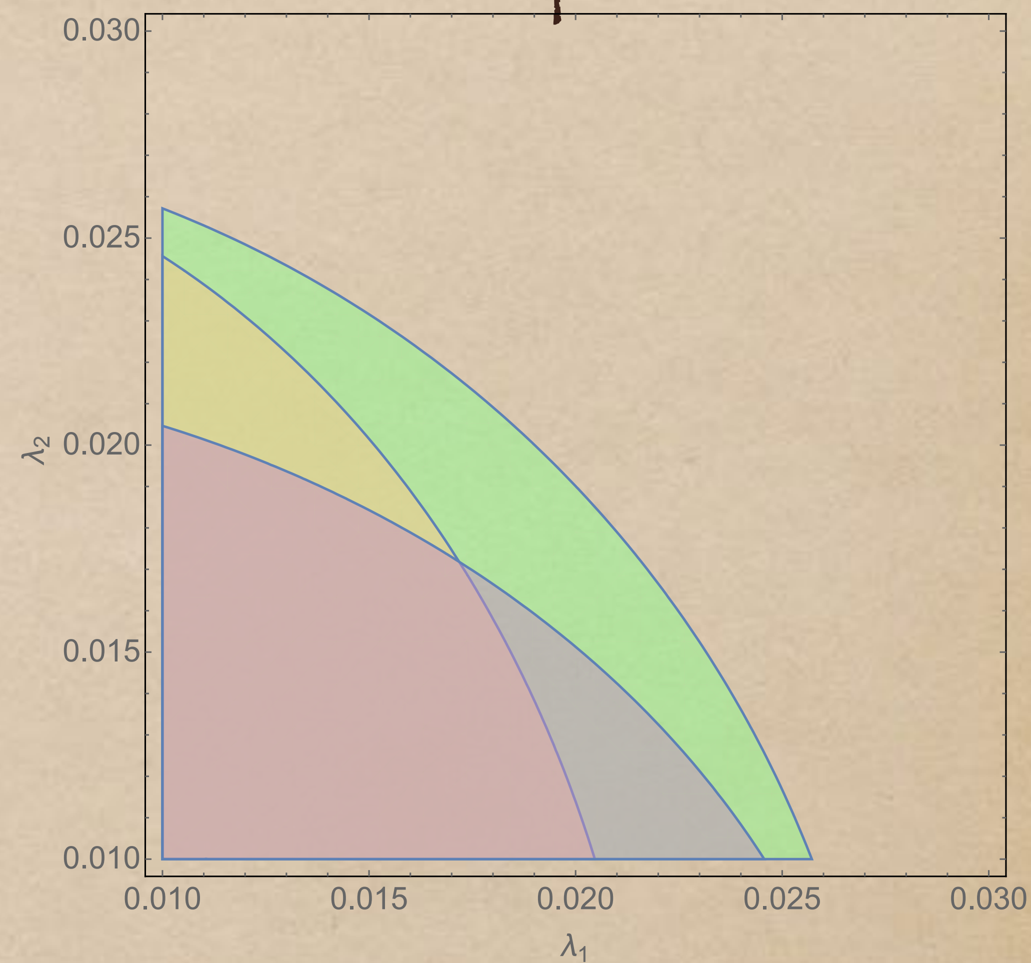
No published paper yet !

Collider Signature of Singlet Scalar DM

Monojet + Missing Energy → Signal cross-section can never rise over background for relic+direct search allowed parameter space.

Higgs Invisible decay constraint for two component DM





Region $m_\phi < \frac{m_h}{2}$ is ruled out by Higgs invisible decay

- Green and below: $\{m_{\phi_1}, m_{\phi_2}\} = \{50, 50\}$ GeV
- Yellow and below: $\{m_{\phi_1}, m_{\phi_2}\} = \{20, 50\}$ GeV
- Grey and below: $\{m_{\phi_1}, m_{\phi_2}\} = \{50, 20\}$ GeV

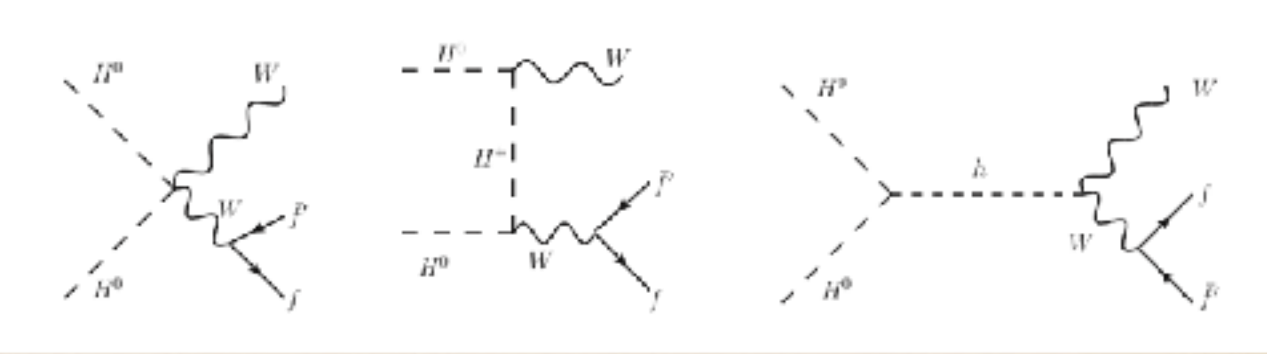
SB, P.Ghosh, P. Poulose, JCAP 1704 (2017) no.04, 043

What about scalar doublet to become Dark matter ?

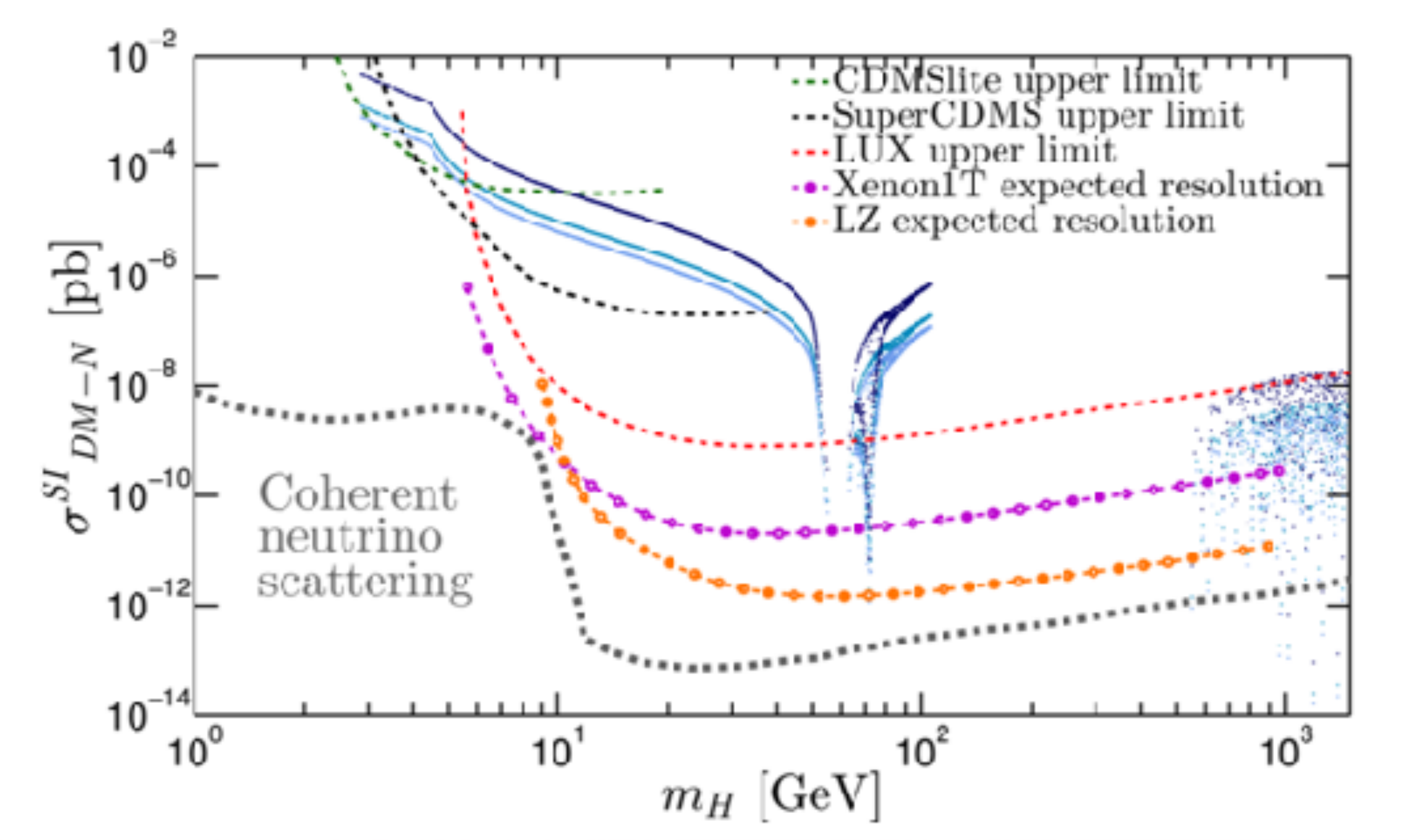
$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2^2| + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right] ,$$

Inert doublet: $\mathcal{Z}_2 : H_2 \to -H_2$

Larger Annihilation



This model is also allowed either in the resonance or at a very high mass



Marco Aurelio D´ıaz, Benjamin Koch, and Sebastia´n Urrutia-Quiroga* arXiv: 1511.04429

Singlet + Doublet Scalar DM

A scalar singlet S and a complex doublet Φ with hypercharge $\frac{1}{2}$.

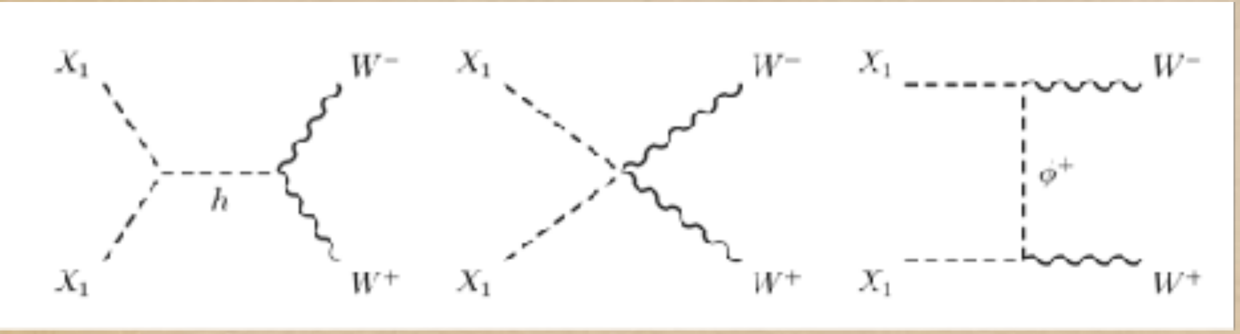
$$\Delta\mathcal{L} = D_\mu\Phi^\dagger D^\mu\Phi - m_D^2\Phi^\dagger\Phi + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2}S^2 - \boxed{g(S\Phi^\dagger H + \text{h.c.})}$$
$$-\frac{\lambda_S}{2}S^2 H^\dagger H - \lambda_1(H^\dagger H)(\Phi^\dagger\Phi) - \lambda_2\left((\Phi^\dagger H)^2 + \text{h.c.}\right) - \lambda_3(\Phi^\dagger H)(H^\dagger\Phi),$$

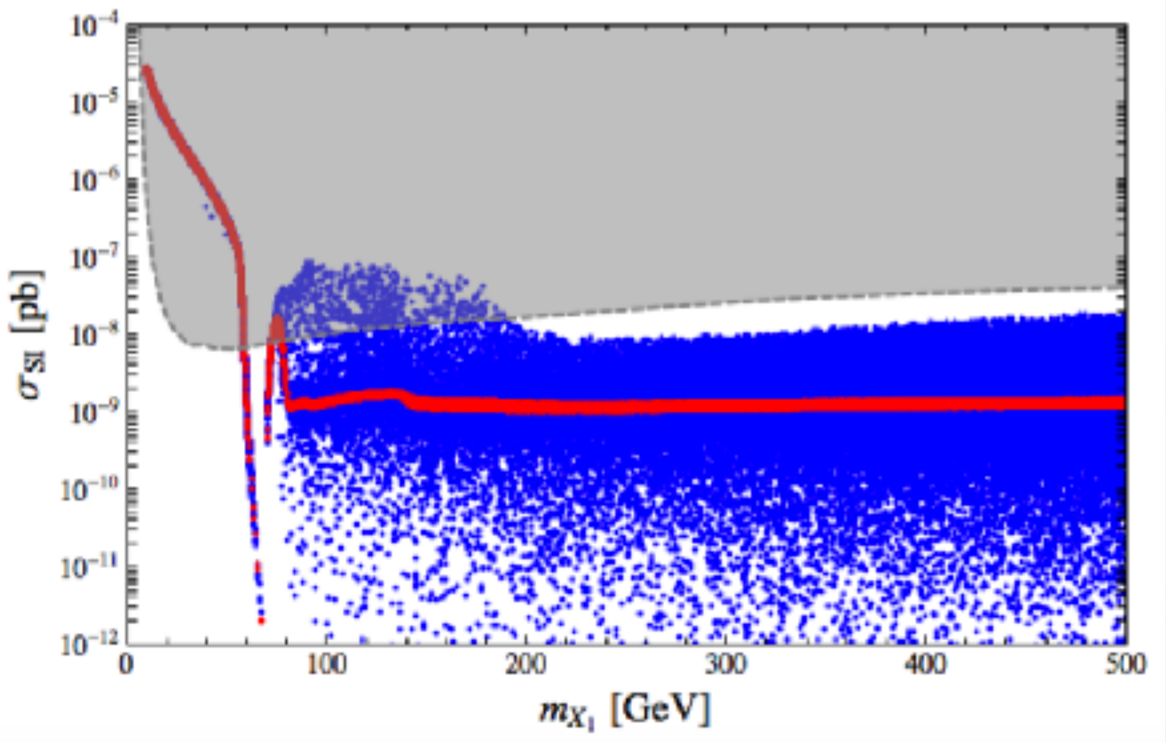
Both are odd under Z_2

After Spontaneous symmetry breaking :

$$X_1 = \cos\theta\, S + \sin\theta\, \phi^0.$$

Dominant annihilation channels are same as doublet DM, but one can play with mixing angles.





Timothy Cohen, John Kearney, Aaron Pierce, David Tucker-Smith **Phys.Rev. D85 (2012) 075003**

Simplest Fermion Dark matter

A fermion singlet.

Just one singlet can not provide renormalisable DM-SM interactions

$$\mathcal{L}_{DM-SM} \sim \frac{1}{\Lambda}(\bar{\chi}\chi H^\dagger H)$$

We need a messenger for the DM to talk to SM

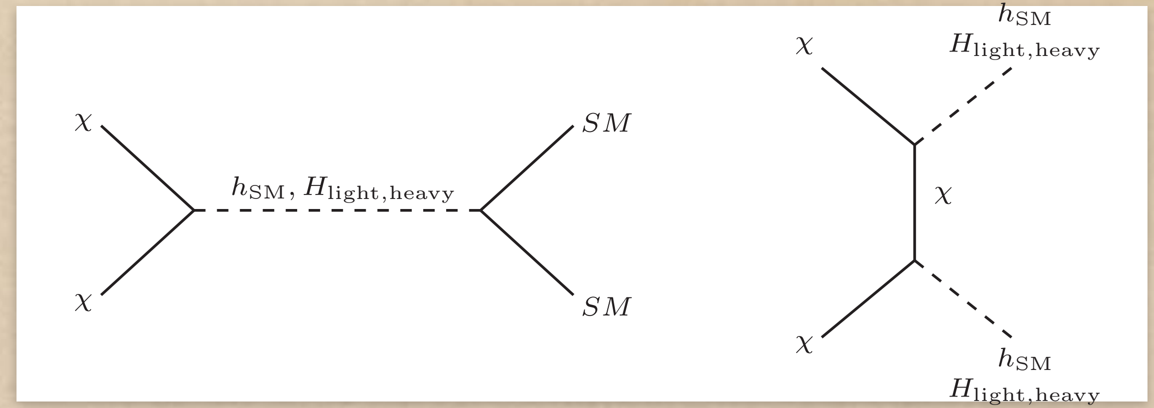
$$\mathcal{L} \supset \bar{\chi}\chi\phi + V(H,\phi) \qquad \mathcal{Z}_2 : \phi \to \phi, \chi \to -\chi$$

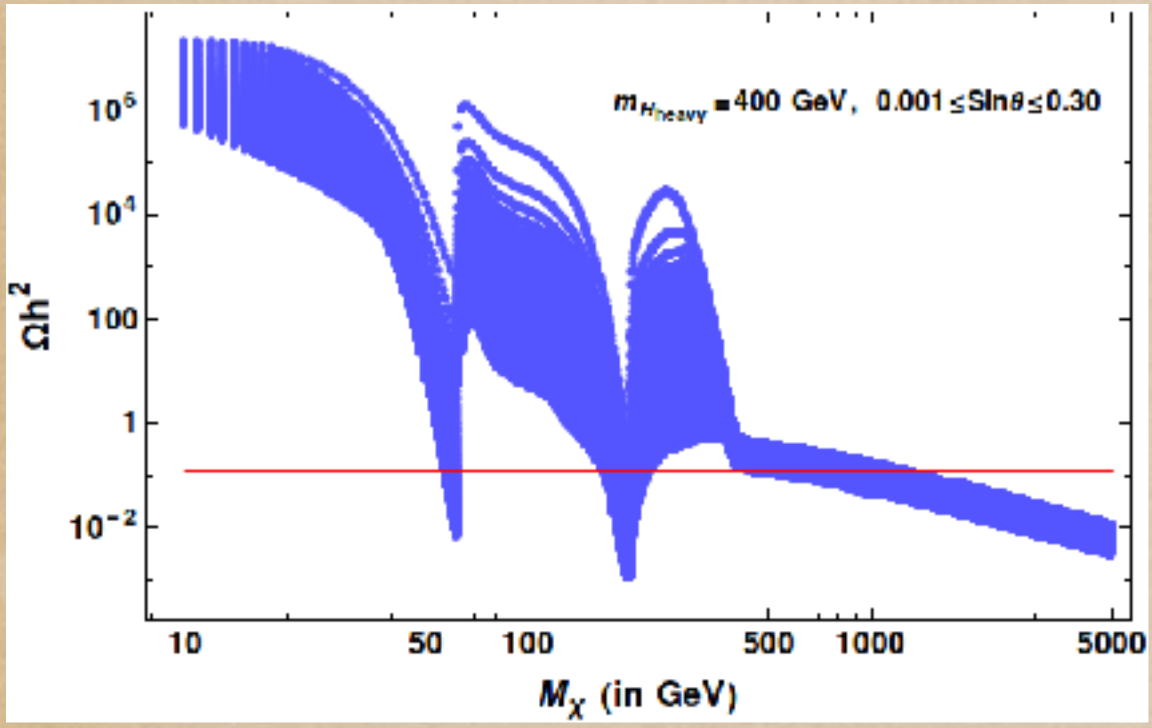
$$V(H,\phi) = -\mu_1 H^\dagger H + \lambda_1 (H^\dagger H)^2 - \mu_2^2\phi^2 + A\phi^3 + \lambda_2\phi^4 + \lambda_{12}\phi^2 H^\dagger H$$

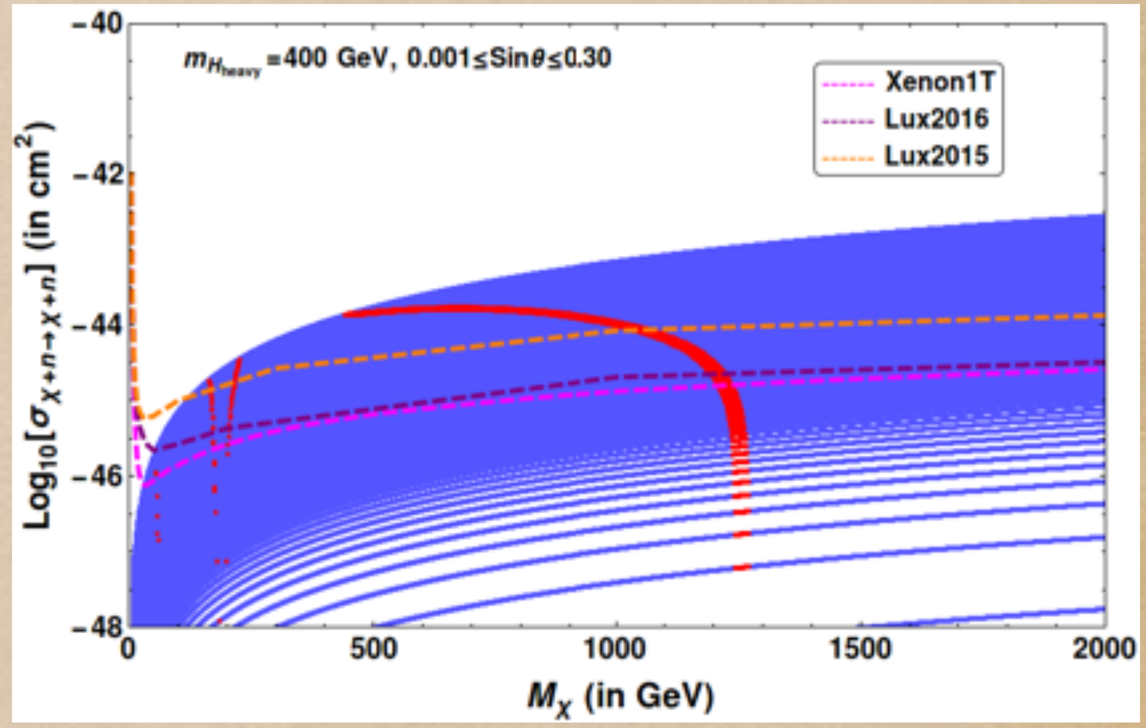
- The other scalar (phi) acquires a VEV.
- Mixes with SM Higgs doublet.
- We therefore obtain two physical scalars, One Higgs (dominantly a doublet), other BSM scalar (dominantly a singlet)

Relic density and direct search constraints on minimal fermion DM

DM Annihilations:







The model lives in resonance and at high DM mass, thanks to the second annihilation channel.

In preparation with B. Karmakar, A Sil et. al.

What about doublet fermions providing DM ?

- The neutral component of the doublet stabilised by a symmetry can be a DM candidate !
- The connection to SM is obvious and no need for additional particles

One doublet fermion will have gauge interactions to SM: $\bar{N}\gamma_\mu D^\mu N$

Too large annihilation cross-section through Z, W mediation

The DM is mostly under abundant to a large DM mass.
Direct search cross-section is also huge !

Fermion DM: Singlet-doublet

SM extended by N: doublet, χ^0: singlet fermions

$$-\mathcal{L}_{\rm Yuk} \supset M_N \overline{N} N + M_\chi \overline{\chi^0} \chi^0 + \left[Y \overline{N} \widetilde{H} \chi^0 + {\rm h.c.} \right]$$

Both are odd under Z_2

Mixing between doublet and singlet

Two neutral physical states

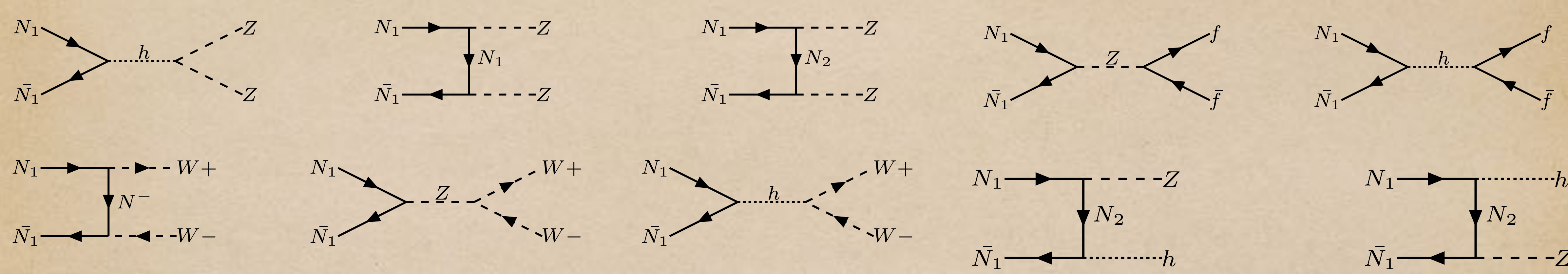
$$N_1 = \cos\theta \chi^0 + \sin\theta N^0 \rightarrow \text{Dark Matter}$$

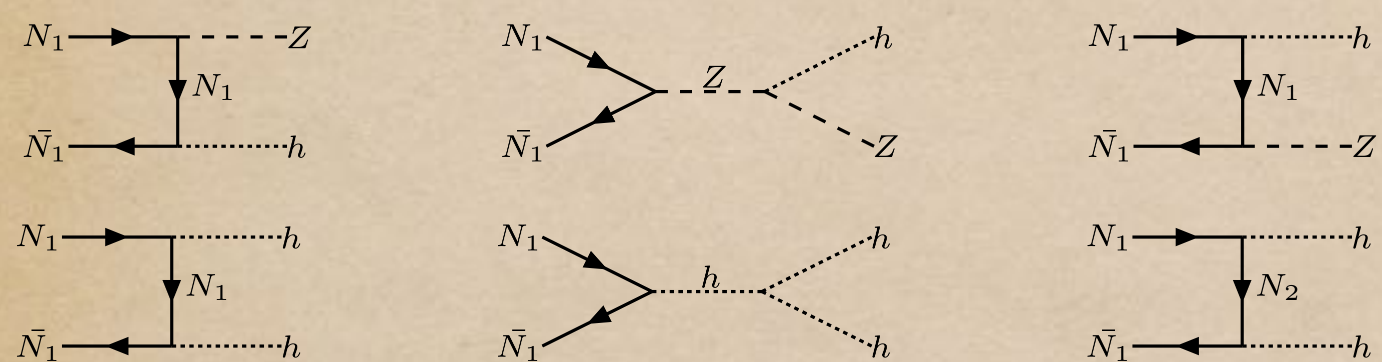
$$N_2 = \cos\theta N^0 - \sin\theta \chi^0$$

θ: Mixing between doublet and singlet

1. SB, *Nirakar Sahoo, Narendra Sahu*, Phys. Rev. D93(2016) no.11, 115040

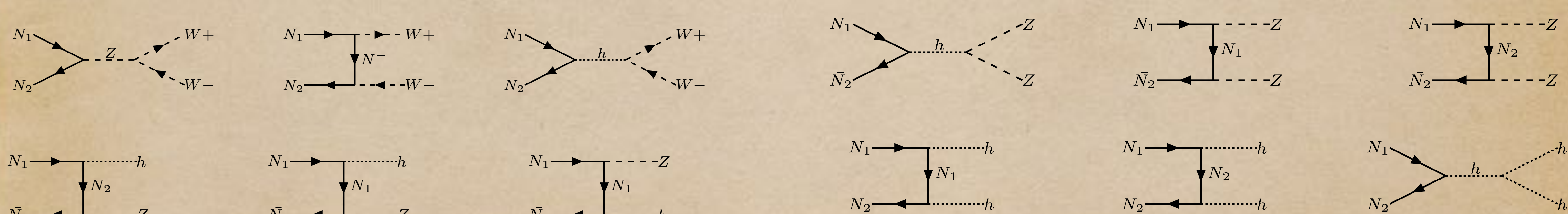
Annihilation channels

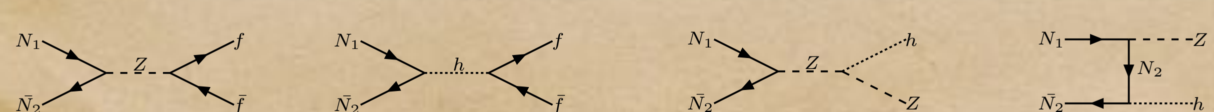




gauge interaction and Yukawa interaction play crucial part

Co-annihilation channels:

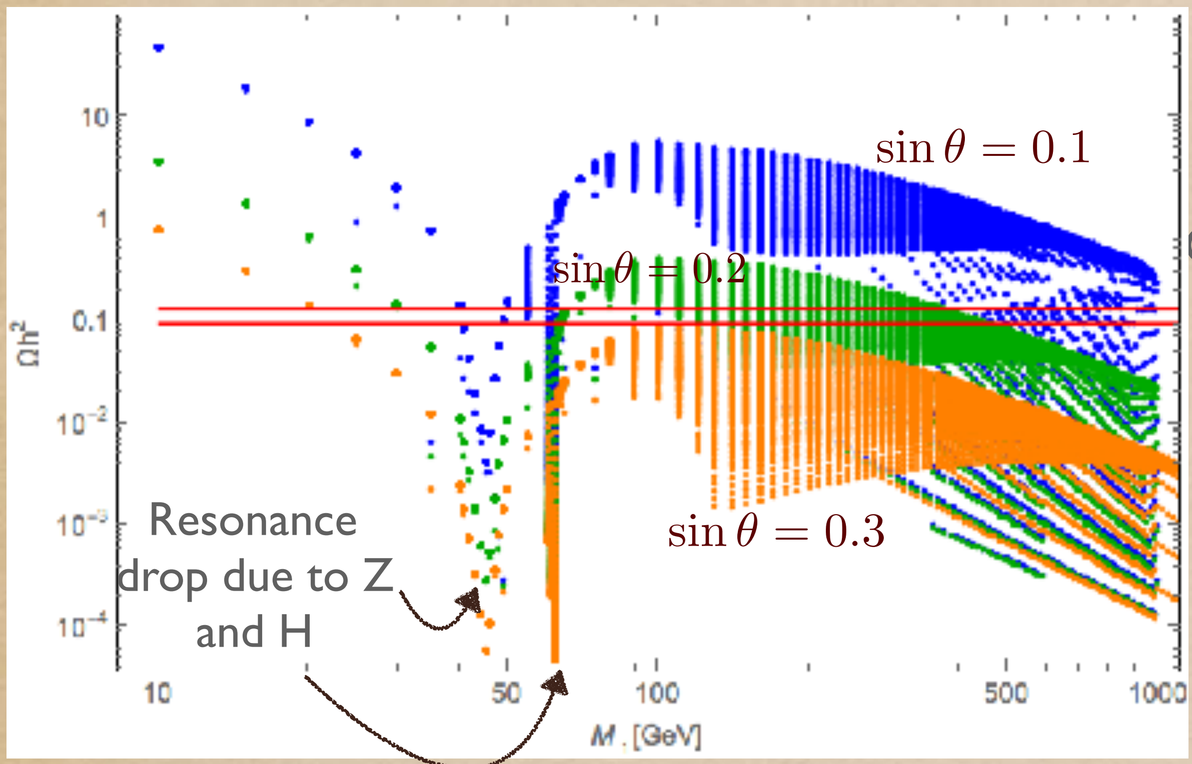




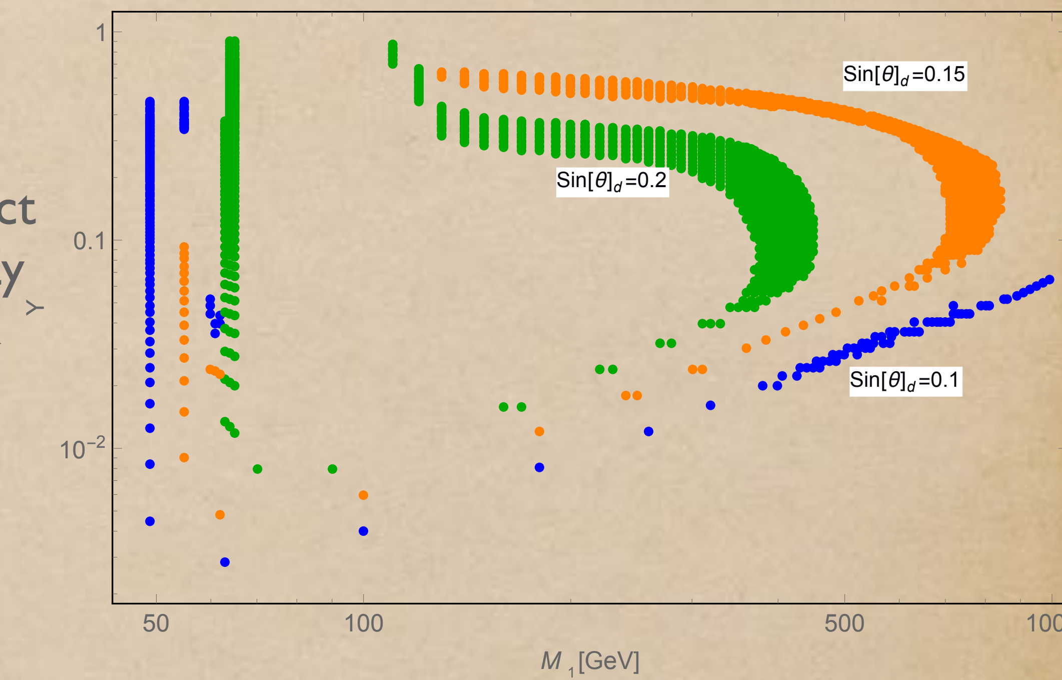
co-annihilations also occurs with $N^{\pm}$

1. SB, *Nirakar Sahoo, Narendra Sahu*, Phys. Rev. D93(2016) no.11, 115040

Relic density of fermion DM



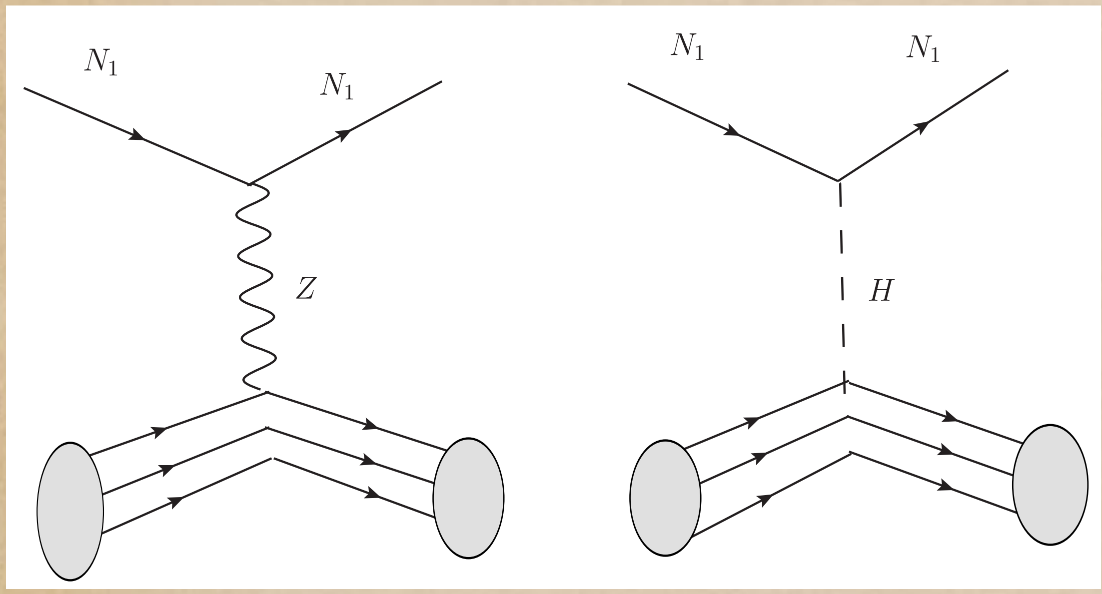
Correct density

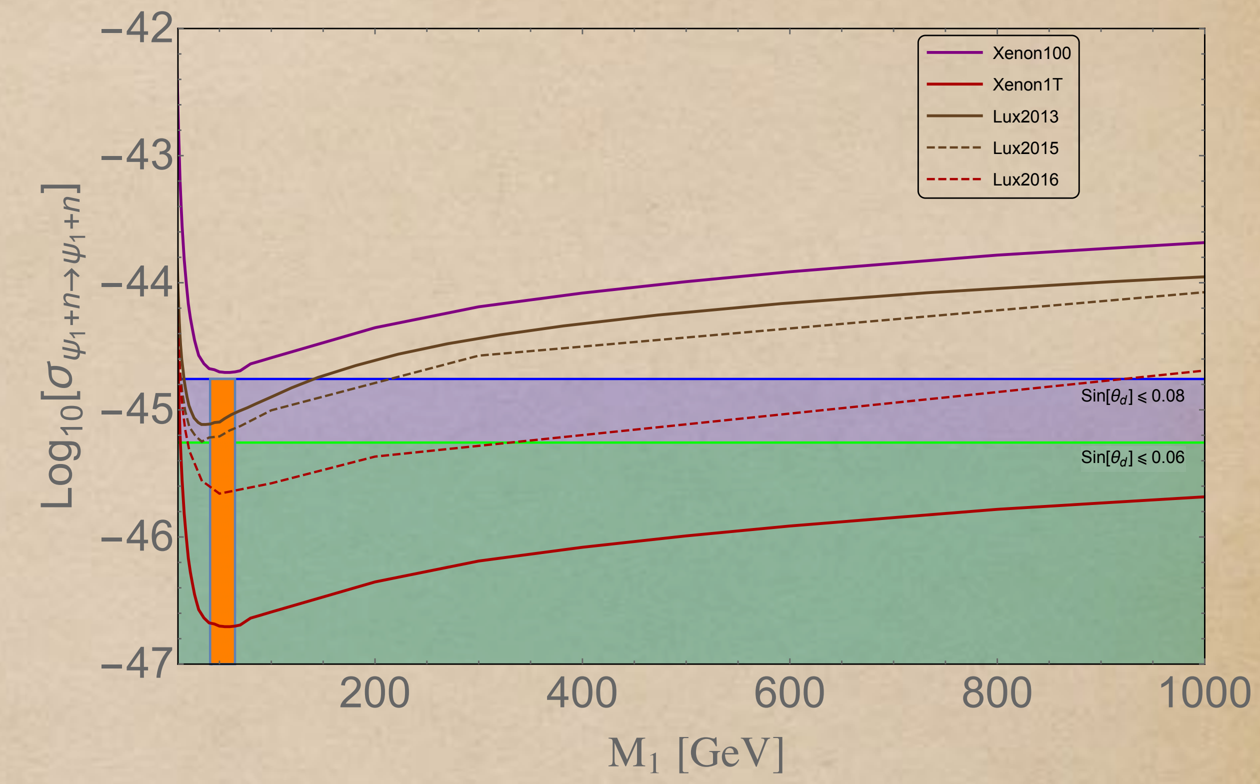


$$\langle\sigma|v|\rangle_{eff} = \frac{g_1^2}{g_{eff}^2}\sigma(\overline{N_1}N_1) + 2\frac{g_1 g_2}{g_{eff}^2}\sigma(\overline{N_1}N_2)(1+\Delta)^{3/2}exp(-x\Delta)$$
$$+ 2\frac{g_1 g_3}{g_{eff}^2}\sigma(\overline{N_1}N^-)(1+\Delta)^{3/2}exp(-x\Delta)$$
$$+ 2\frac{g_2 g_3}{g_{eff}^2}\sigma(\overline{N_2}N^-)(1+\Delta)^3 exp(-2x\Delta) + \frac{g_2 g_2}{g_{eff}^2}\sigma(\overline{N_2}N_2)(1+\Delta)^3 exp(-2x\Delta)$$
$$+ \frac{g_3 g_3}{g_{eff}^2}\sigma(N^+N^-)(1+\Delta)^3 exp(-2x\Delta)\,.$$

1. SB, *Nirakar Sahoo, Narendra Sahu*, Phys. Rev. D93(2016) no.11, 115040

Direct search of fermion DM



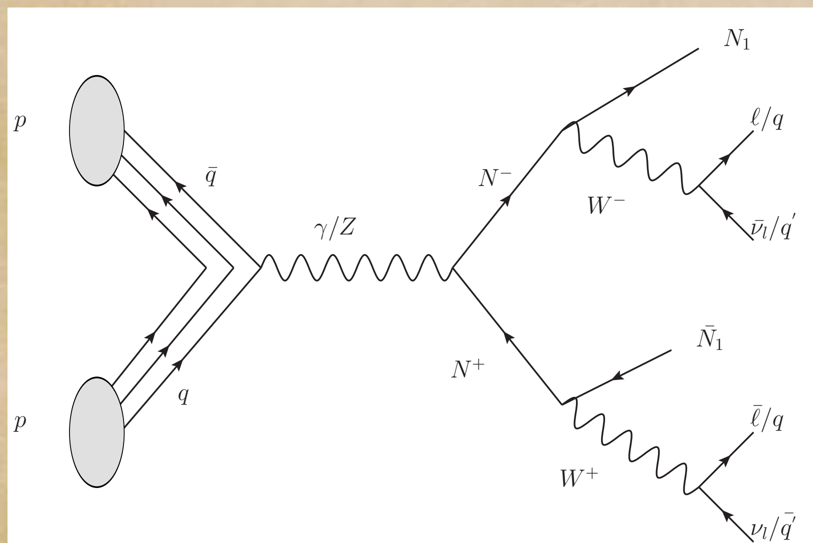


Direct search strongly constrains the mixing of singlet -doublet components due to Z mediation.

At very small mixing, annihilation is not enough to produce right cross section. Therefore, the model heavily depends on co-annihilation which requires a small mass splitting.

1. SB, *Nirakar Sahoo, Narendra Sahu*, Phys. Rev. D93(2016) no.11, 115040

Collider prospects at LHC

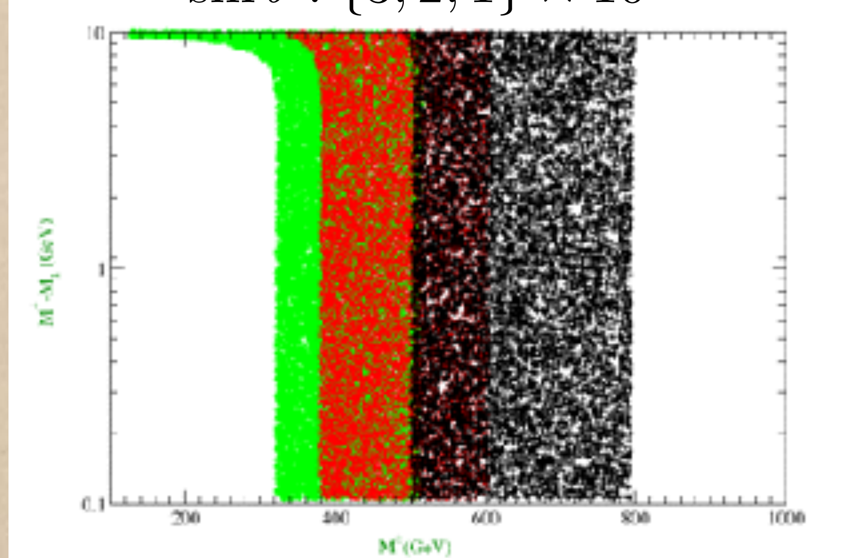


- Production of the charged lepton and their decay at LHC:
- One lepton+jets+Missing energy
- Two opposite sign leptons+Missing energy
- Jets+Missing energy

When the mass difference between the charged lepton and DM is small they can give rise to displaced vertex signature

$$\Gamma = \frac{G_F^2 sin^2\theta}{24\pi^3} M_N^5 I$$

$\sin\theta : \{3, 2, 1\} \times 10^{-4}$

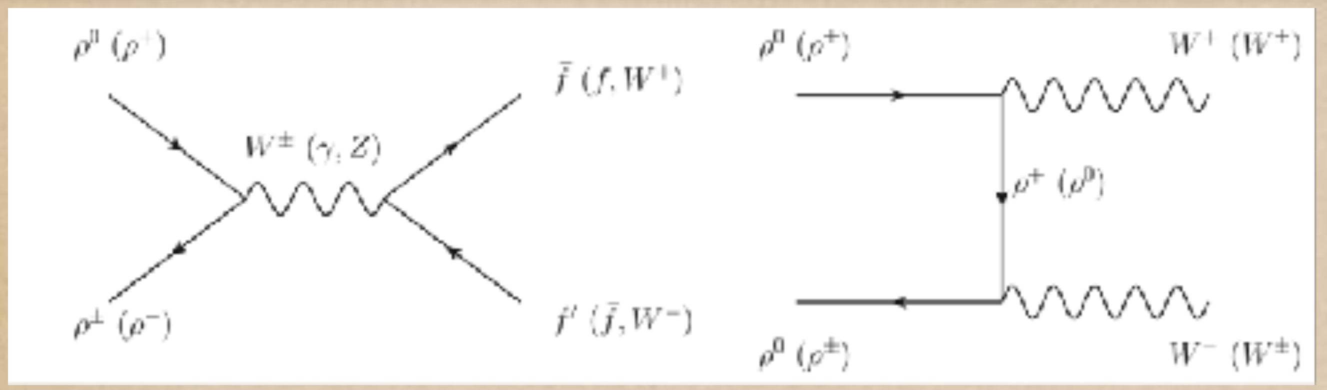


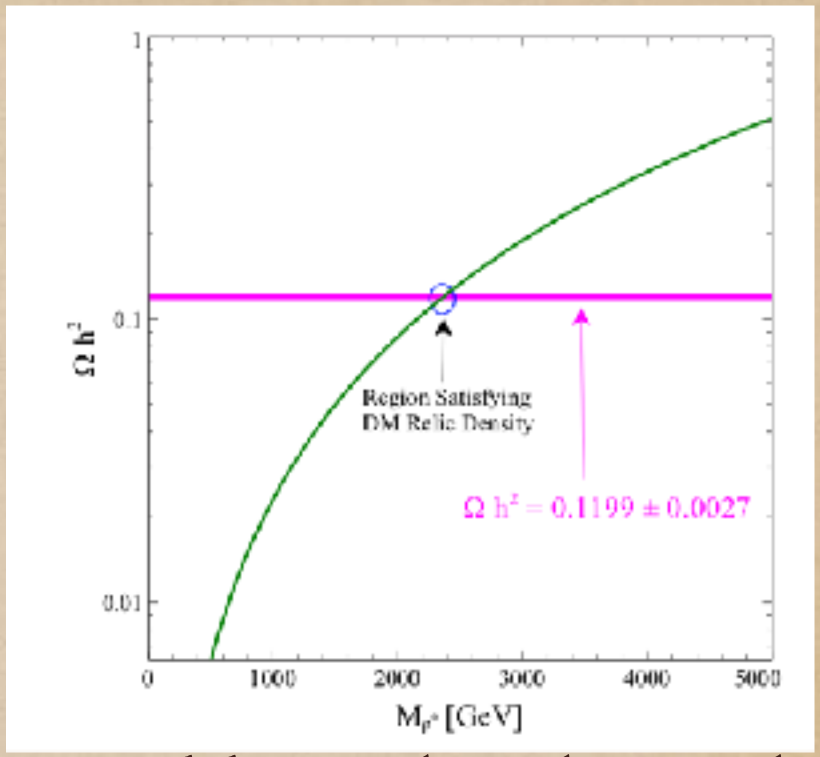
$\Gamma^{-1} : \{1, 10\}$ cm

Leptonic Signatures and displaced vertex are complementary

Fermion triplet

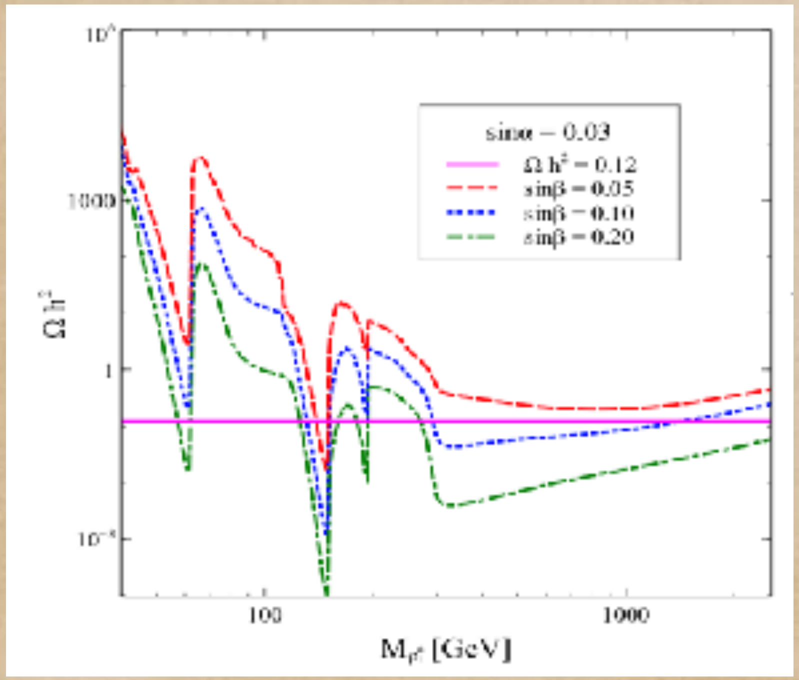
Triplet has lot of annihilation through gauge interaction and therefore the model only survives at very high DM mass

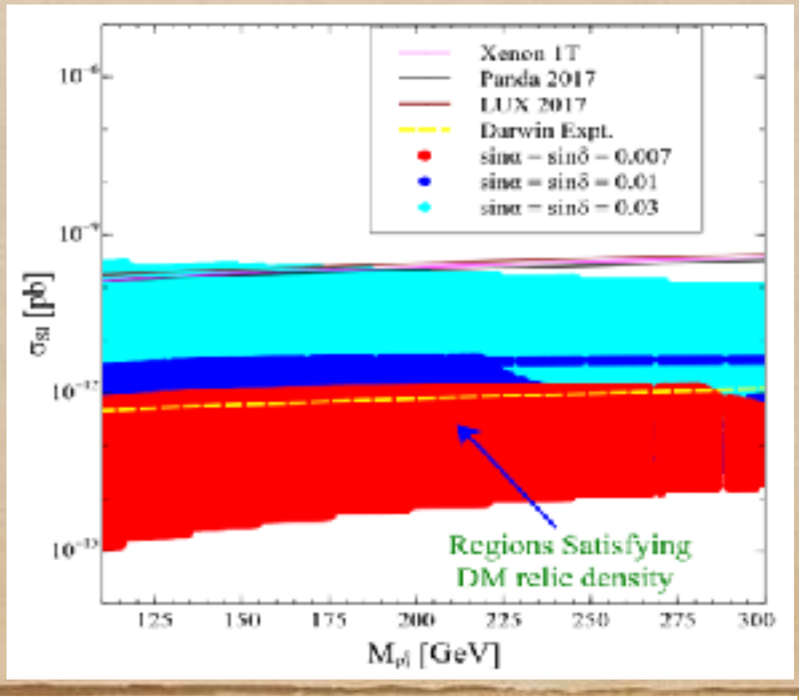




Singlet-Triplet Mixing

One has to assume an additional scalar triplet who can mix the singlet and triplet fermions.





Sandhya Choubey , Sarif Khan, Manimala Mitra , Subhadeep Mondal **arXiv:1711.08888**

Looking ahead

Some issues that we didn't illustrate:

Vector Boson Dark matter

Two component DM with scalar and fermion

The cases of FIMP and SIMP

Theoretical constraints like vacuum stability

Dark matter effective operators and simplified models

Connection between neutrino and dark matter sector

An automated tool for DM studies

micrOMEGAs : a tool for dark matter studies

G. Bélanger([1]), F. Boudjema([1]), A. Pukhov([2]), A. Semenov([3])

([1]) *LAPTH, U. de Savoie, CNRS, B.P.110, F-74941 Annecy-le-Vieux, France*
([2]) *Skobeltsyn Inst. of Nuclear Physics, Moscow State Univ., Moscow 119992, Russia*
([3]) *Joint Inst. of Nuclear Research (JINR) 141980, Dubna, Russia*

Summary. — `micrOMEGAs` is a tool for cold dark matter (DM) studies in generic extensions of the standard model with a R-parity like discrete symmetry that guarantees the stability of the lightest odd particle. The code computes the DM relic density, the elastic scattering cross sections of DM on nuclei relevant for direct detection, and the spectra of $e^+, \bar{p}, \gamma$ originating from DM annihilation including porpagation of charged cosmic rays. The cross sections and decay properties of new particles relevant for collider studies are included as well as constraints from the flavour sector on the parameter space of supersymmetric models.

PACS `12.60,95.35.+d` – ....

- One can calculate relic density, direct search and indirect search cross-sections using MicrOMEGAs
- One can insert models through LanHEP .
- Collider cross-sections can also be evaluated using CalcHep-Pythia interface or One needs to implement the model in Feynrules for a full Madgraph analysis.