Illuminating Scalar Dark Matter Co-Scattering with Monophoton Signatures

Abhishek Roy

Based on

arXiv: 2508.06040

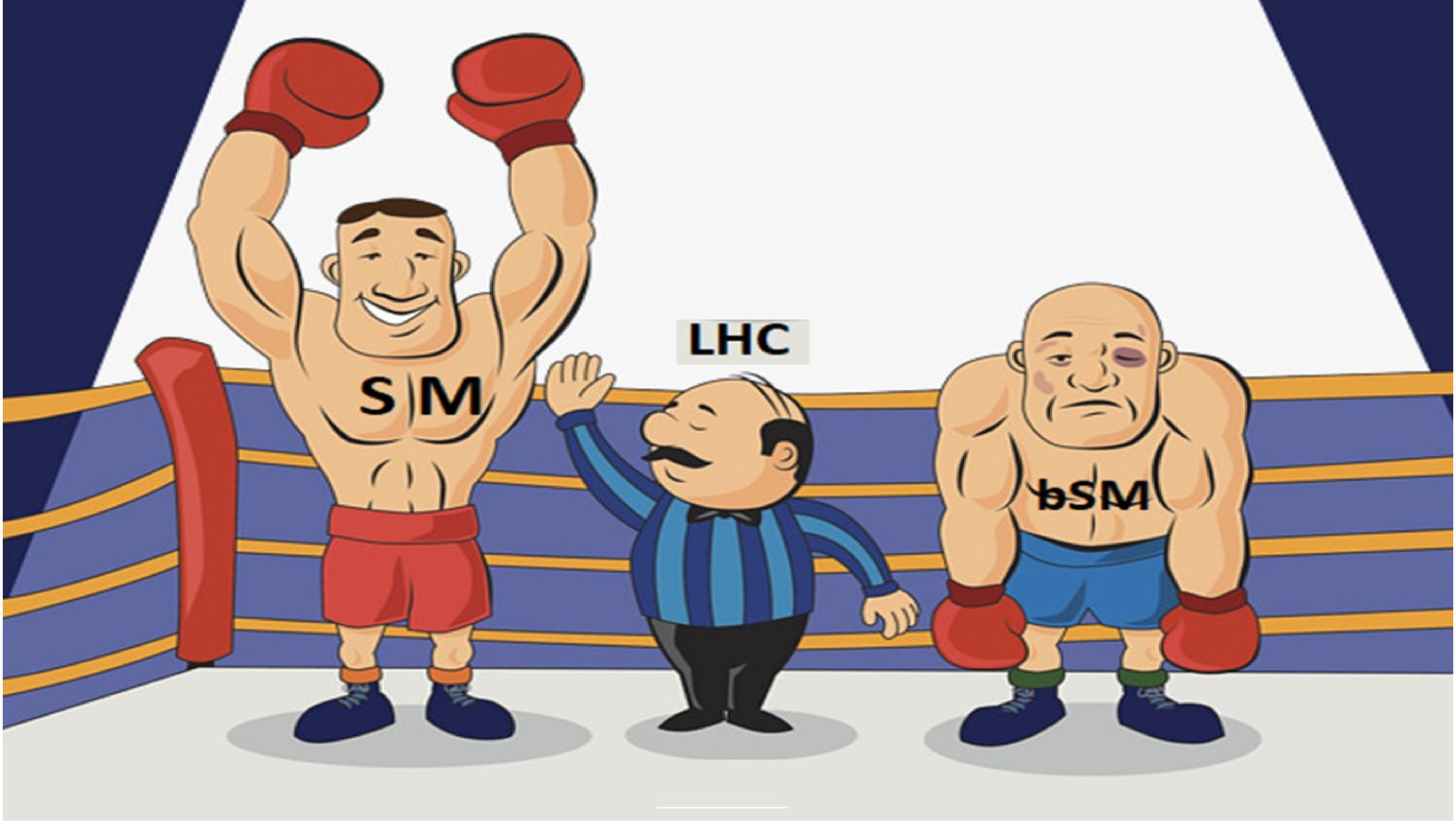
In collaboration with **Geneviève Bélanger, Manimala Mitra and Rojalin Padhan**

Center for Quantum SpaceTime

Scalars 2025- Warsaw, Poland

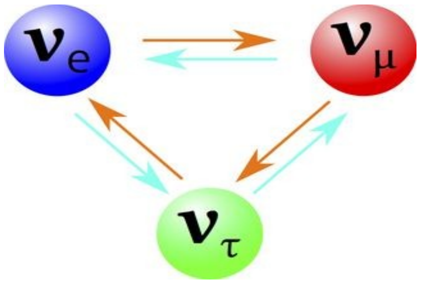
24 September 2025

서강대학교 1960 IHS SOGANG UNIVERSITY

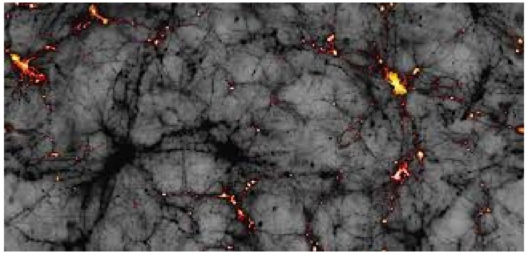

LHC
SM

Do we have a good reason to go Beyond the Standard Model?

- SM fails to explain neutrino mass and mixings.



- SM doesn’t have DM candidate.



- SM fails to explain observed baryon asymmetry.

Who can be a DM ?

- Should be massive
- Should be electrically neutral
- Should be present in early universe
- Should be stable or at least with half life greater than the age of the universe

Need a symmetry

Singlet Scalar

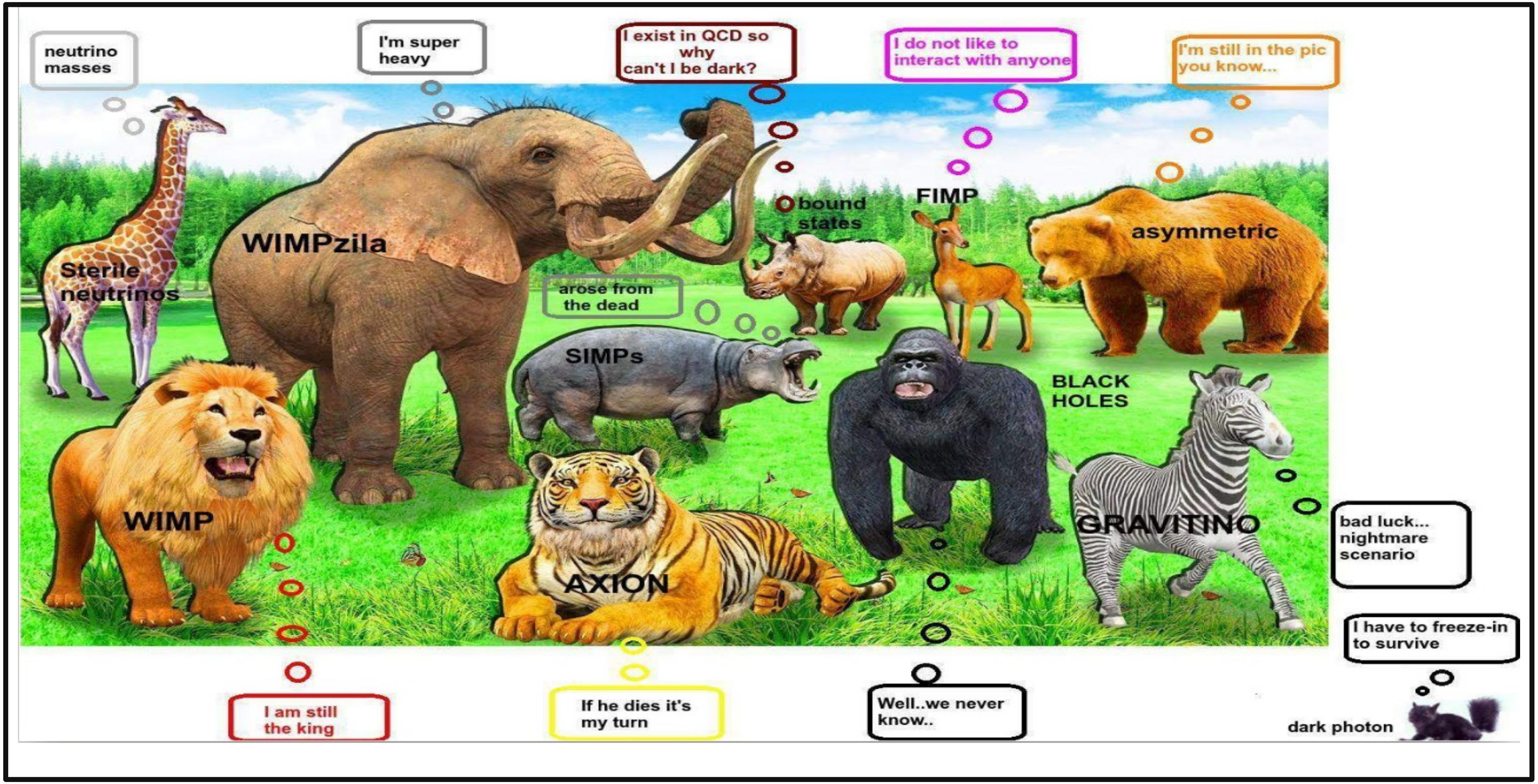
Singlet Fermion

Scalar in triplet repn

Fermion in triplet repn

...and many more

Zoo of Dark Matter Candidates



Higgs Portal : Singlet Scalar DM

$$V_{DM} = \frac{1}{2}\mu_\chi^2\chi^2 + \frac{1}{4}\lambda v^2\chi^2 + \frac{1}{2}\lambda v h\chi^2 + \frac{\lambda}{4}h^2\chi^2$$

Dark Matter Mass

$$M_\chi^2 = \mu_\chi^2 + \frac{1}{2}\lambda v^2$$

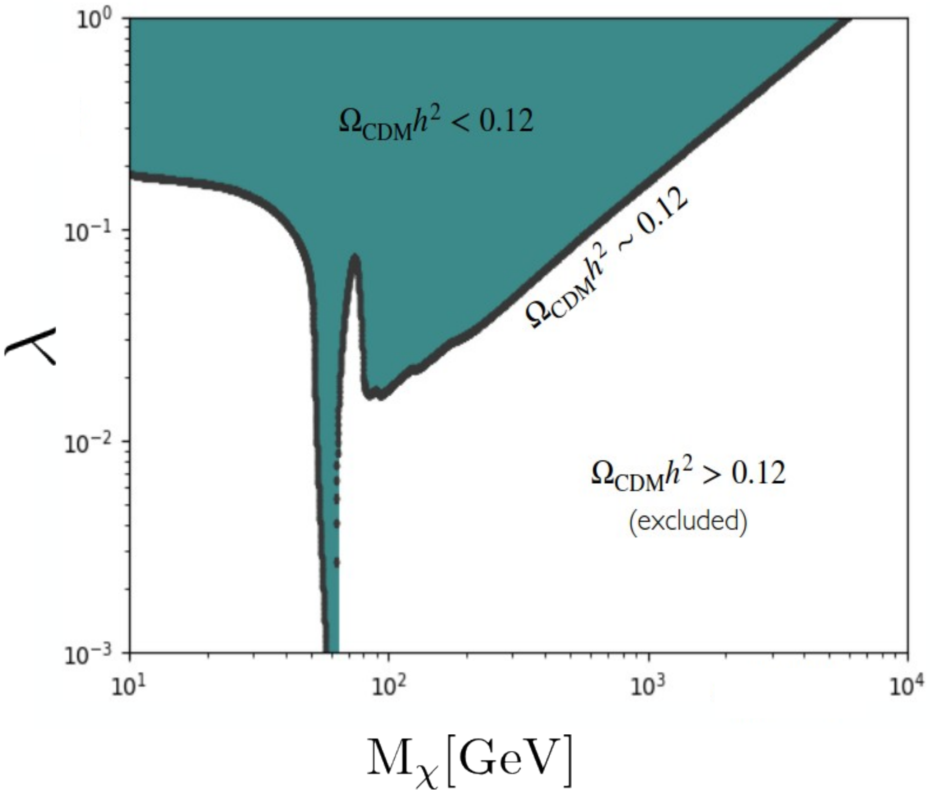
Dark Matter Couplings

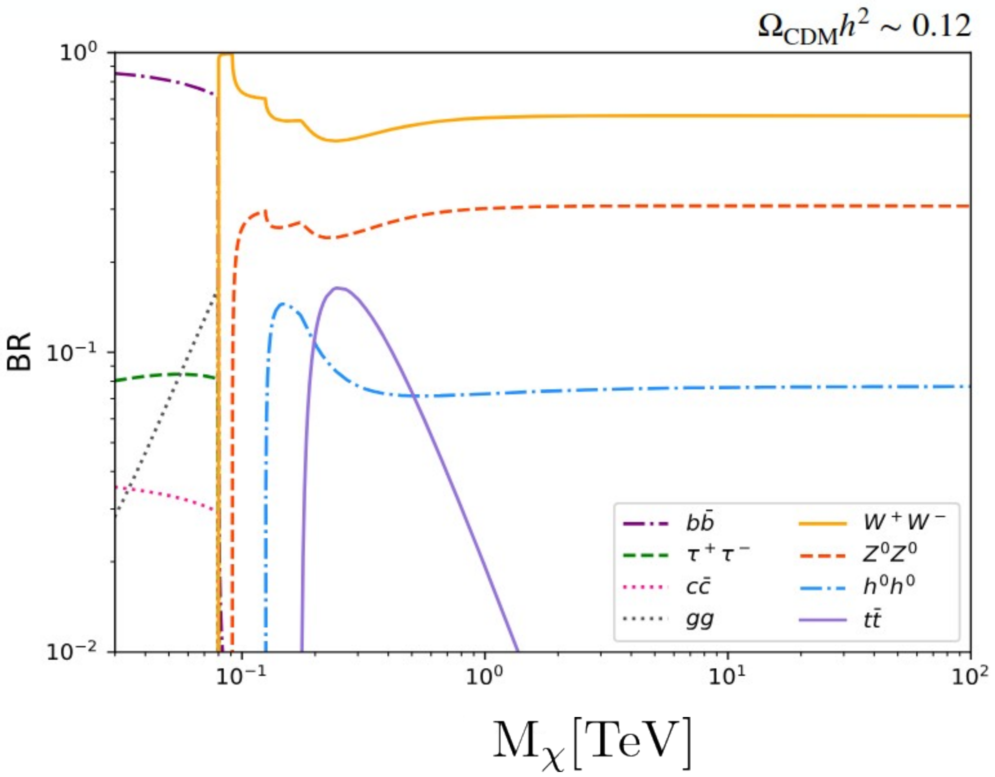
"Higgs Portal"

Simplest extension of the Standard Model…

- dark matter: **real scalar singlet** (stable due to $\mathcal{Z}_2$ imposed symmetry)
- phenomenology (at the tree-level) governed by only **two parameters**
- One coupling (to Higgs) drives all DM observables – **DM relic, Direct Detection, Indirect Detection.**

Higgs Portal : Singlet Scalar DM

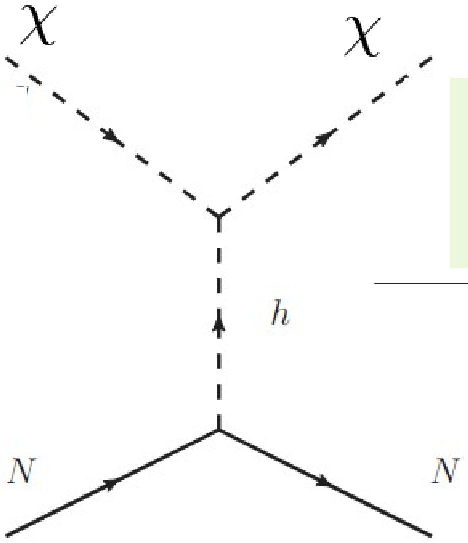




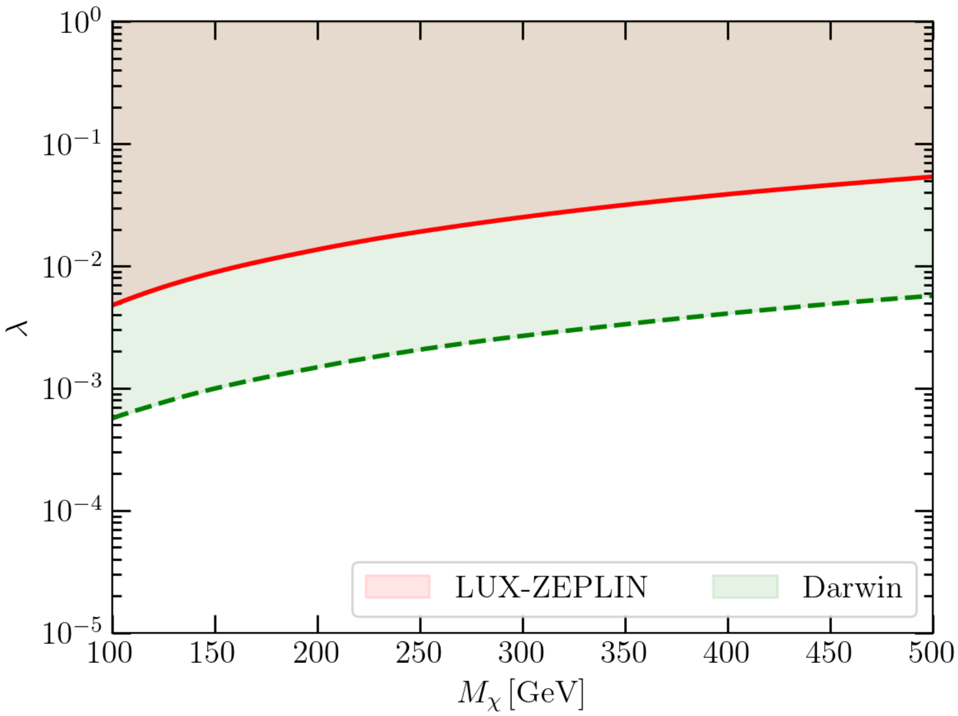
Dark matter annihilation into: gauge bosons, Higgs bosons, quarks, leptons.

Higgs Portal : Singlet Scalar DM

Higgs portal interactions give spin-independent nuclear scattering via t-channel Higgs exchange.

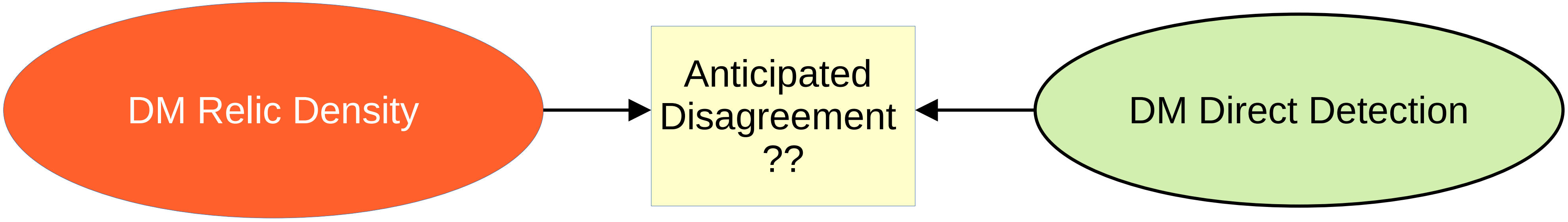


$$\sigma_{\rm SI} = \frac{\lambda^2 f_N^2 \mu_N^2 m_N^2}{4\pi M_h^4 M_\chi^2}$$



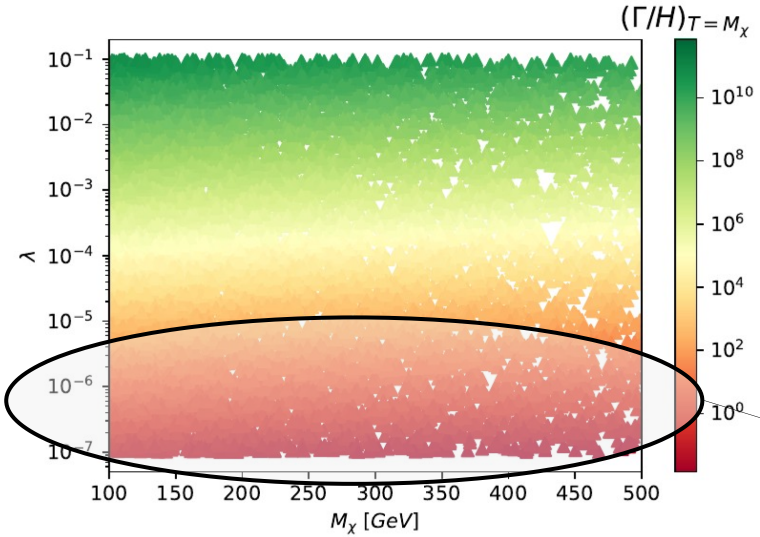
Direct detection limits imply that the Higgs-portal coupling must be suppressed.

Higgs Portal : Singlet Scalar DM



Requires large Higgs Portal Couplings

Requires Suppressed Higgs Portal Couplings



- **DD constraint ->** DM annihilation primarily to gauge bosons decouples from thermal bath due to suppressed "Higgs Portal" coupling.
- If Singlet Scalar is **viable WIMP DM**, we need alternate production mechanism to realize the observed DM relic density.

DM never thermalizes, it behaves as non-thermal particle

Singlet Scalar DM + dimension-5 Operators

Assumptions

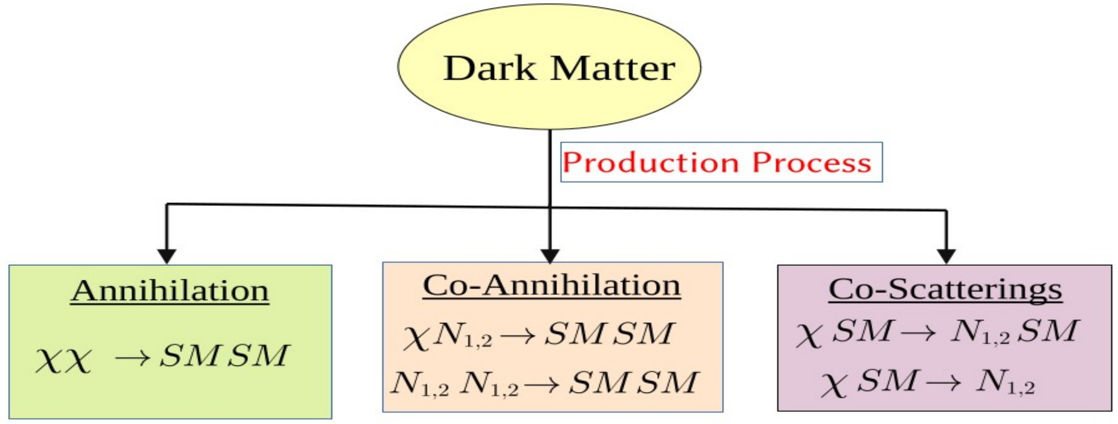
$$\chi \to -\chi, \quad N_{1,2} \to -N_{1,2}$$

Tree level neutrino mass:
forbidden by Z_2 symmetry

$$\mathrm{L}_{eff} \supset \lambda \Phi^\dagger \Phi \chi^2 + \frac{c_5}{\Lambda}(\overline{L^c}\tilde{\Phi})(\tilde{\Phi}^\dagger L) + \frac{Y}{\Lambda}\overline{L}\tilde{\Phi} N \chi + \frac{c_3}{\Lambda}\overline{N^c}\sigma_{\mu\nu} N B^{\mu\nu}.$$

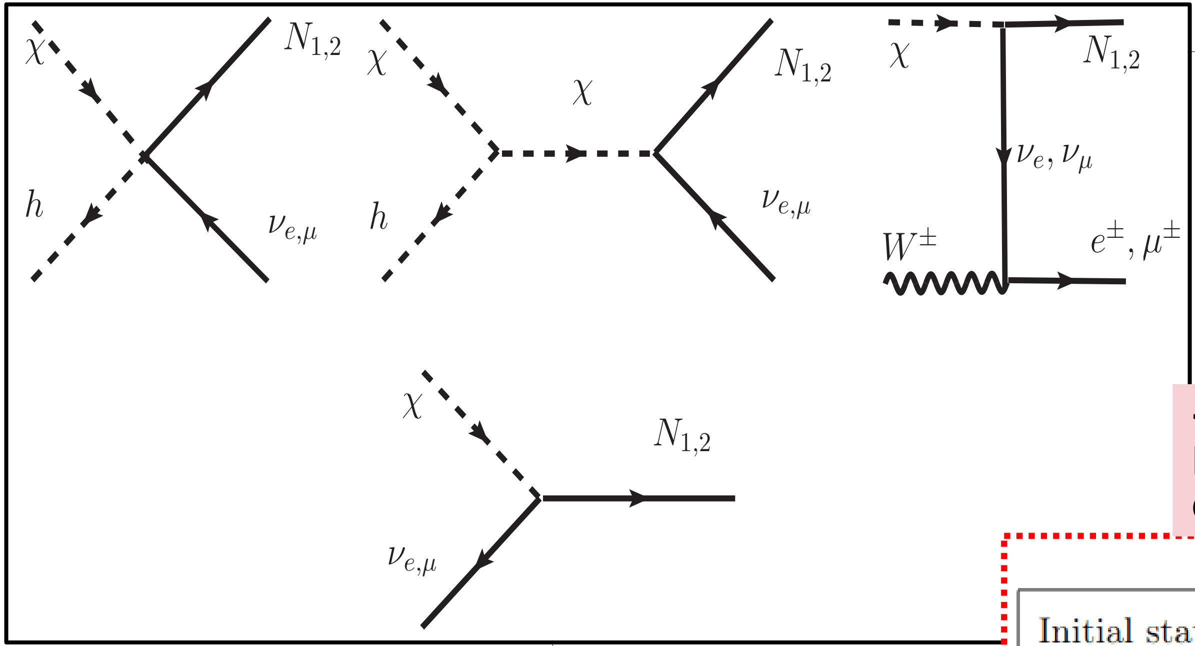
Suppressed due DD constraint

Introduces additional DM dilution processes



- χ and $N_{1,2}$ may or may not be in equillibrium with each other.
- $\Omega_\chi h^2$ is set either through co-annihilation or co-scattering.

Singlet Scalar DM + dimension-5 Operators



DM dilution through inelastic process

$$\delta_1 = \frac{M_{N_1} - M_\chi}{M_\chi}$$

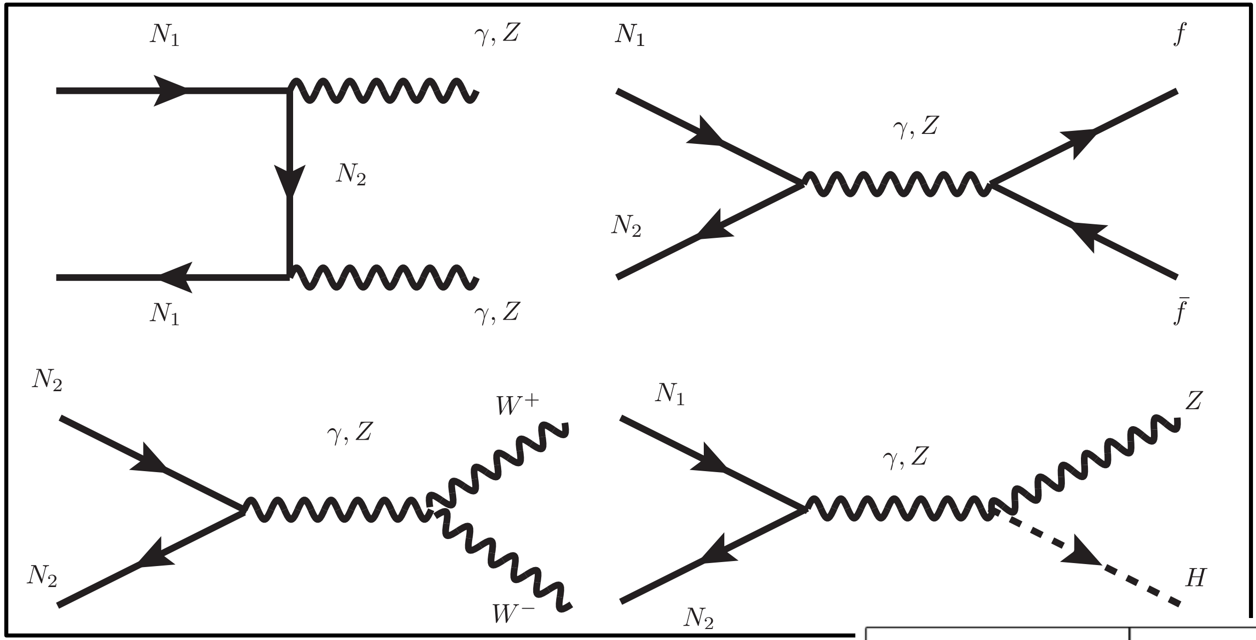
<0.5,
Either Co- Annihilation or Co-Scattering

>0.5,
Only χ Annihilation

Initial state		Final state		Scaling with couplings
χ	h	$N_{1,2}$	$\nu_{e,\mu}$	$Y'^2_{11(22)}$
χ	$W^\pm$	$N_{1,2}$	$e^\pm\mu^\pm$	$Y'^2_{11(22)}$ (**t-channel process**)
χ	$\nu_{e,\mu}$	$N_{1,2}$	–	$Y'^2_{11(22)}$ (**Inverse Decay**)

Rotating each diagram anti-clockwise by 90 degree corresponds DM co-annihilation diagrams

Singlet Scalar DM + dimension-5 Operators



$$\delta_2 = \frac{M_{N_2} - M_{N1}}{M_{N_1}}$$

<0.5, N1-N2 CoAnnihilation Dominant

>0.5, N1-N1 Pair-Annihilation Dominant

Initial state		Final state		Scaling with couplings
$N_{1,2}$	$N_{1,2}$	γ, Z	γ, Z	${c_3^{'}}^4$ (t- channel process)
N_1	N_2	f	$\bar{f}$	${c_3^{'}}^2$ (s-channel process)
N_1	N_2	W^+	W^-	${c_3^{'}}^2$ (s-channel process)
N_1	N_2	Z	H	${c_3^{'}}^2$ (s-channel process)

Dominant co-annhilation process

Contribute less than 1% due to cancellation b/w the Z and γ exchange diagram

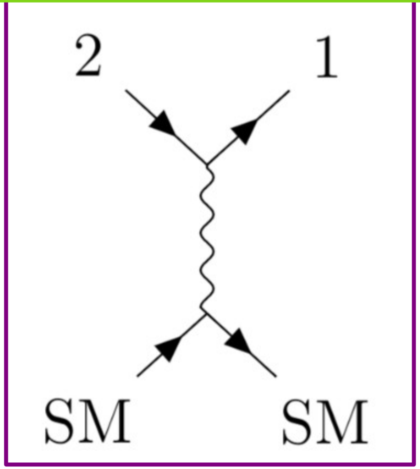
Coscattering equations (conversion-driven freeze-out)

- if DM is very weakly coupled to the SM, DM self-annihilation is negligible
- in the following, 0 : SM, 1: N (=N1 + N2), 2: Dark Matter DM

$$\frac{dY_1}{dx} = -\frac{1}{x^2}\frac{s(M_\chi)}{\tilde{H}(M_\chi)}\left[\langle\sigma_{1100}v\rangle(Y_1^2 - Y_1^{eq2}) - \frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\right],$$

$$\frac{dY_2}{dx} = -\frac{1}{x^2}\frac{s(M_\chi)}{\tilde{H}(M_\chi)}\left[\frac{\Gamma_{2\to1}}{s}\left(Y_2 - Y_1\frac{Y_2^{eq}}{Y_1^{eq}}\right)\right].$$

Inelastic Processes



$Y', \lambda \sim \mathcal{O}(10^{-6} - 10^{-10})$ → DM pair annihilation, co-annihilation, and exchange Process becomes negligible

Coscattering fraction

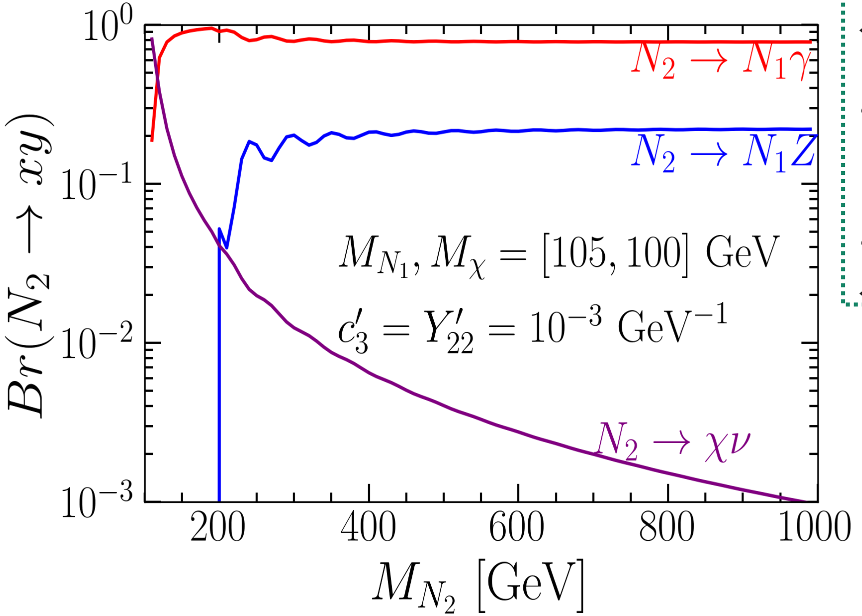
- When Y' and δ_1 is small, co-scattering keeps χ coupled to the N(=N1+N2).
- without coscattering, DM freezes out very early ⇒ too high relic density
- to quantify when coscattering is necessary to keep χ coupled to the N(=N1+N2).

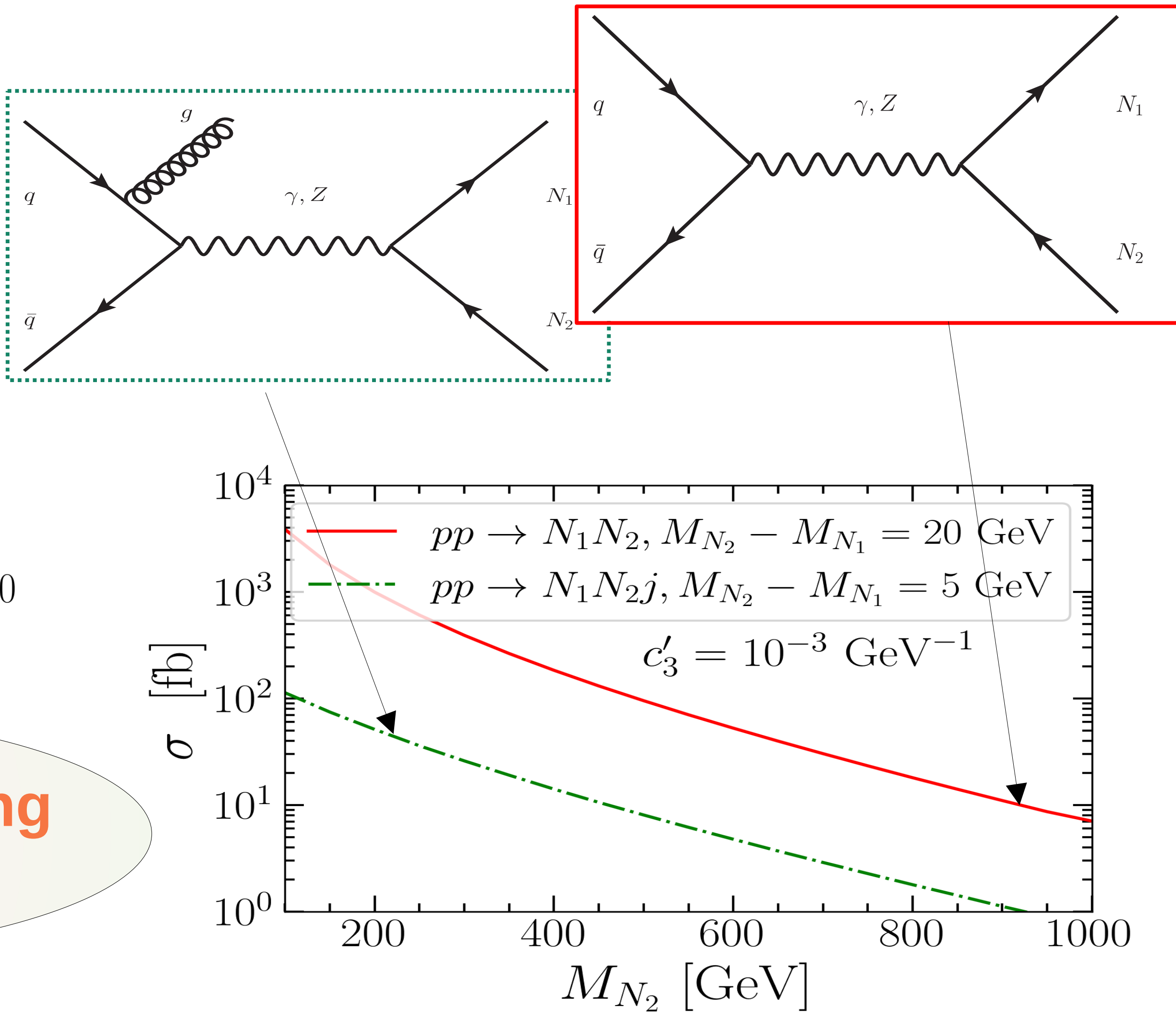
$$\Delta^1_\chi \equiv 1 - \frac{\Omega h^2(\mathrm{Single})}{\Omega h^2(\mathrm{Coupled})}.$$

➔ **if co-annihilation dominant** ⇒ $\Delta^1_\chi = 0\,(Y' > 10^{-7})$

➔ **if co-scattering dominant** ⇒ $\Delta^1_\chi = 1\,(Y' < 10^{-7})$

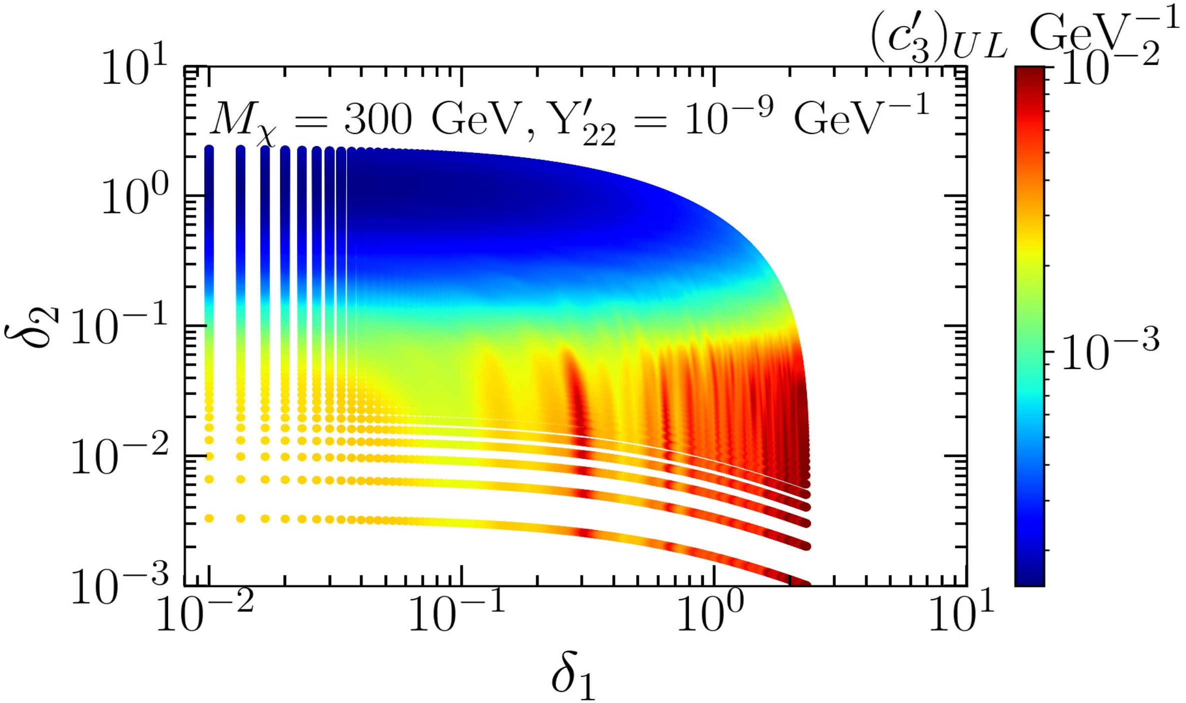
Collider Limit





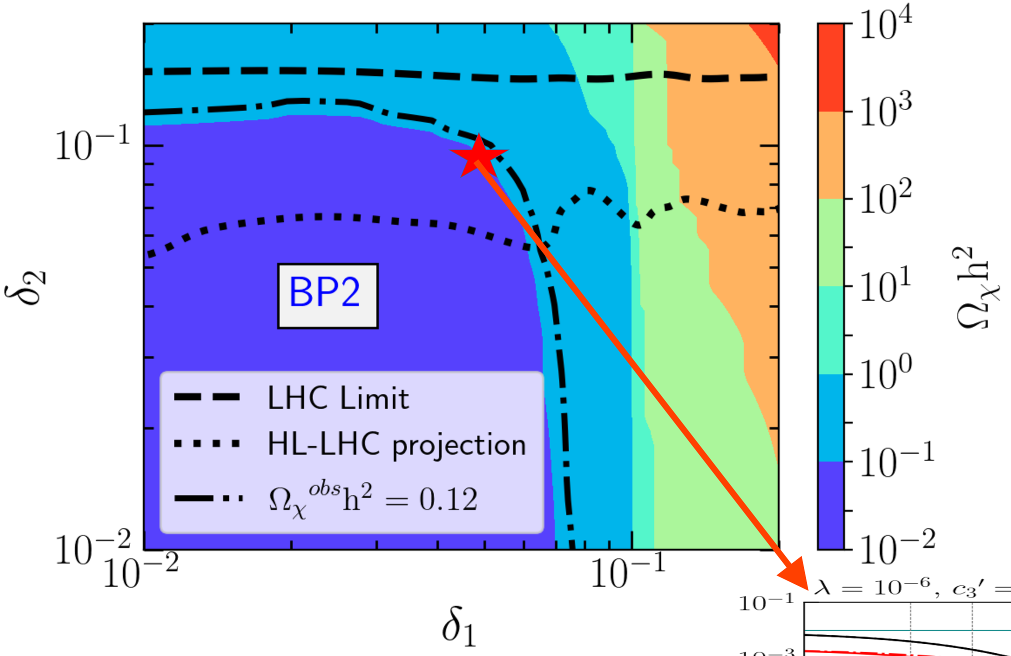
mono-γ gives the leading signal.

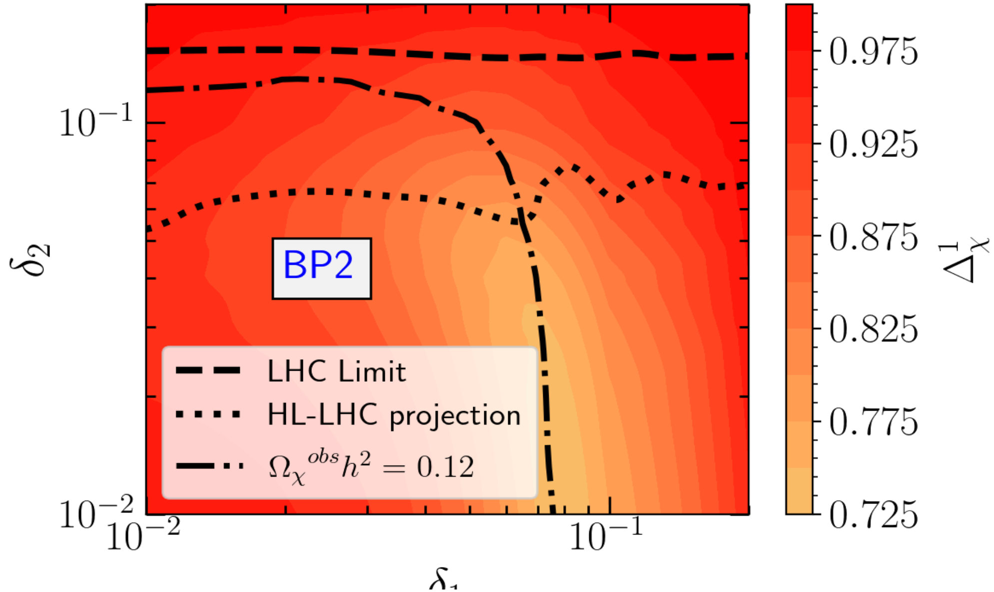
Numerical results

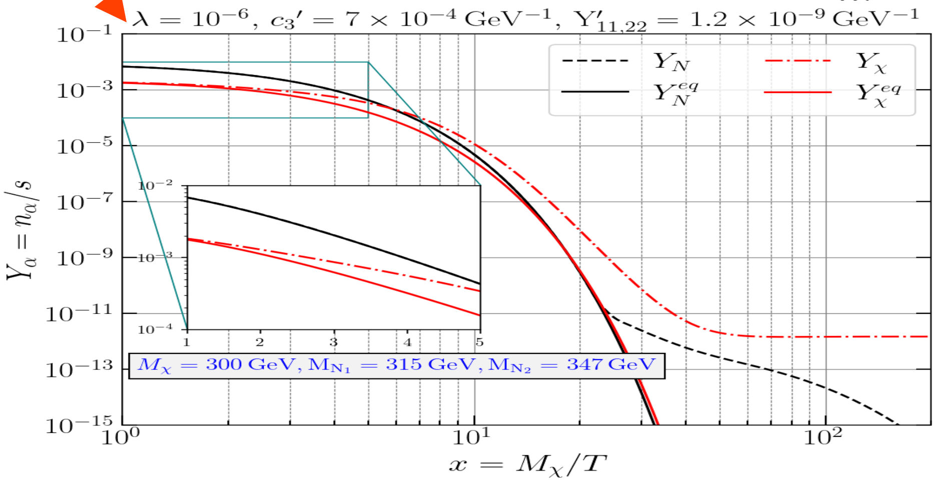


- "Dark matter + energetic photon in ATLAS (arXiv: 2011.05259): **parameter space constraints**
- Large δ_2 leads to energetic photons. Hence, stringent constraints.

Numerical results







Summary

Features of co-scattering dark matter:

- small coupling to visible matter
- compressed dark sector
- freeze-out works for a wide range of energies

Singlet Scalar DM + dim-5 operators: consistent with DD, ID & collider bounds

Viable parameter space can be probed at HL-LHC

THANK YOU
for your
ATTENTION!