Illuminating Scalar Dark Matter Co-Scattering with Monophoton Signatures

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Based on

arXiv: 2508.06040(accepted in JHEP)

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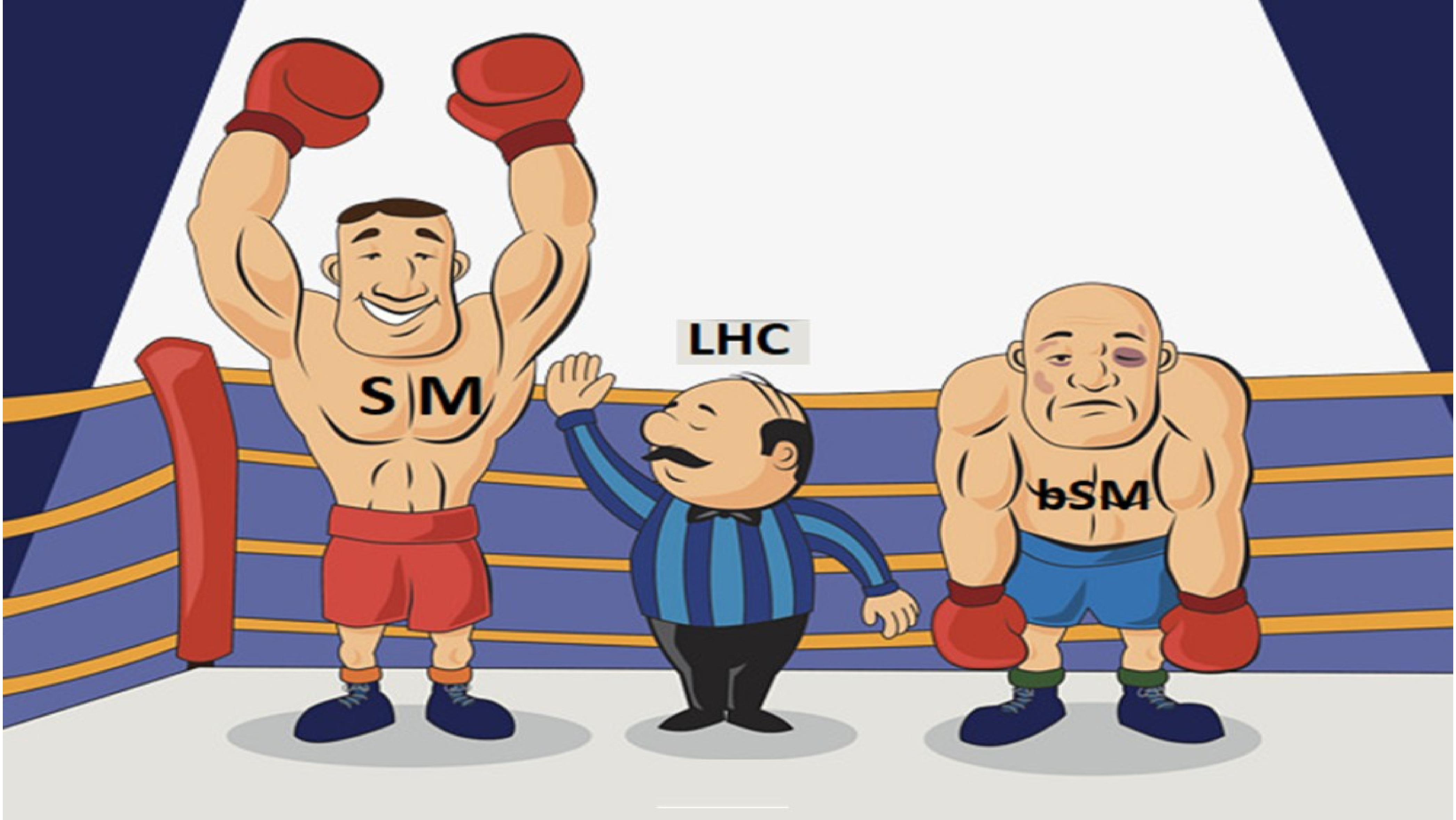
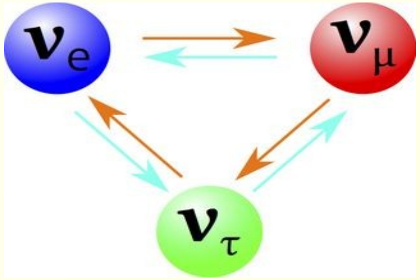
Sogang University

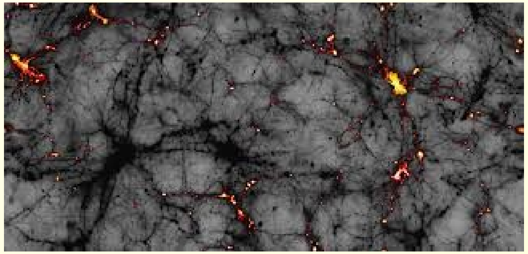

LHC
SM
bSM

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

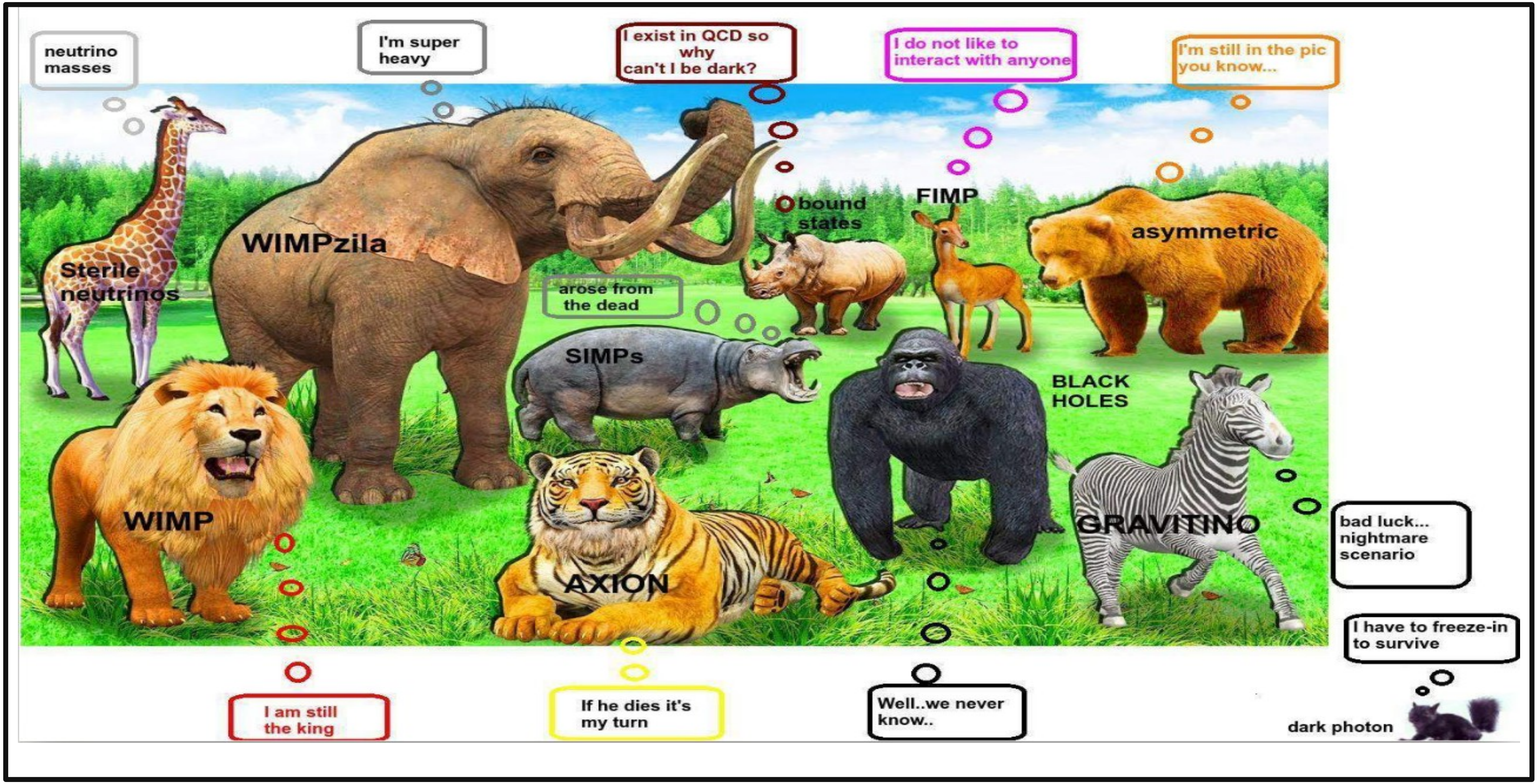
Singlet Fermion

Scalar in triplet repn

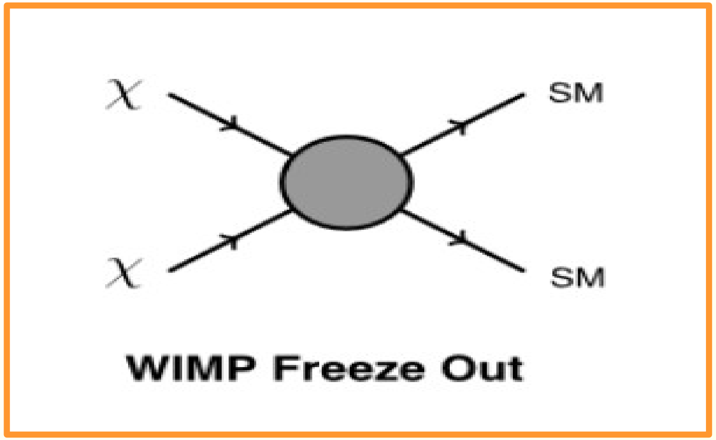
Fermion in triplet repn

...and many more

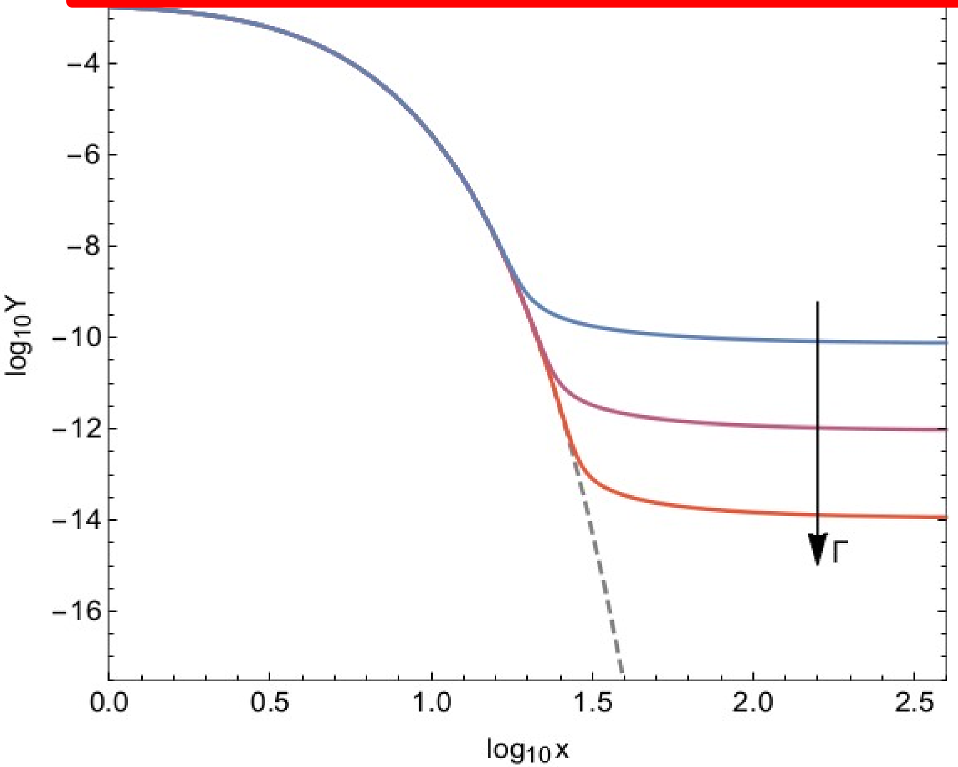
Zoo of Dark Matter Candidates



Overview WIMP Mechanism



$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$



Classic WIMP Paradigm

- Initially in **thermal equilibrium** with the SM plasma.
- Relic abundance set by **freeze-out** via pair annihilation

$$\chi\chi \to \mathrm{SM\ SM}$$

- Predicts the canonical thermal relic cross section

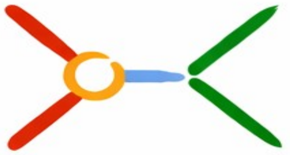
$$\langle\sigma v\rangle \sim 3\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

- Strongly constrained by **direct and indirect detection experiments**.

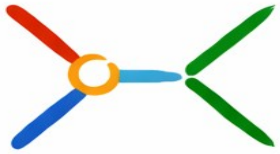
The new WIMP

In the early universe:

pair annihilation

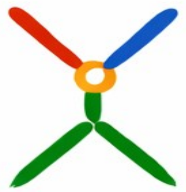


co-annihilation



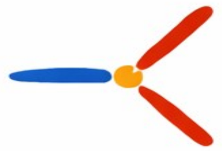
Griest, Seckel 1991

co-scattering



Ruderman et al. 2017

freeze-in



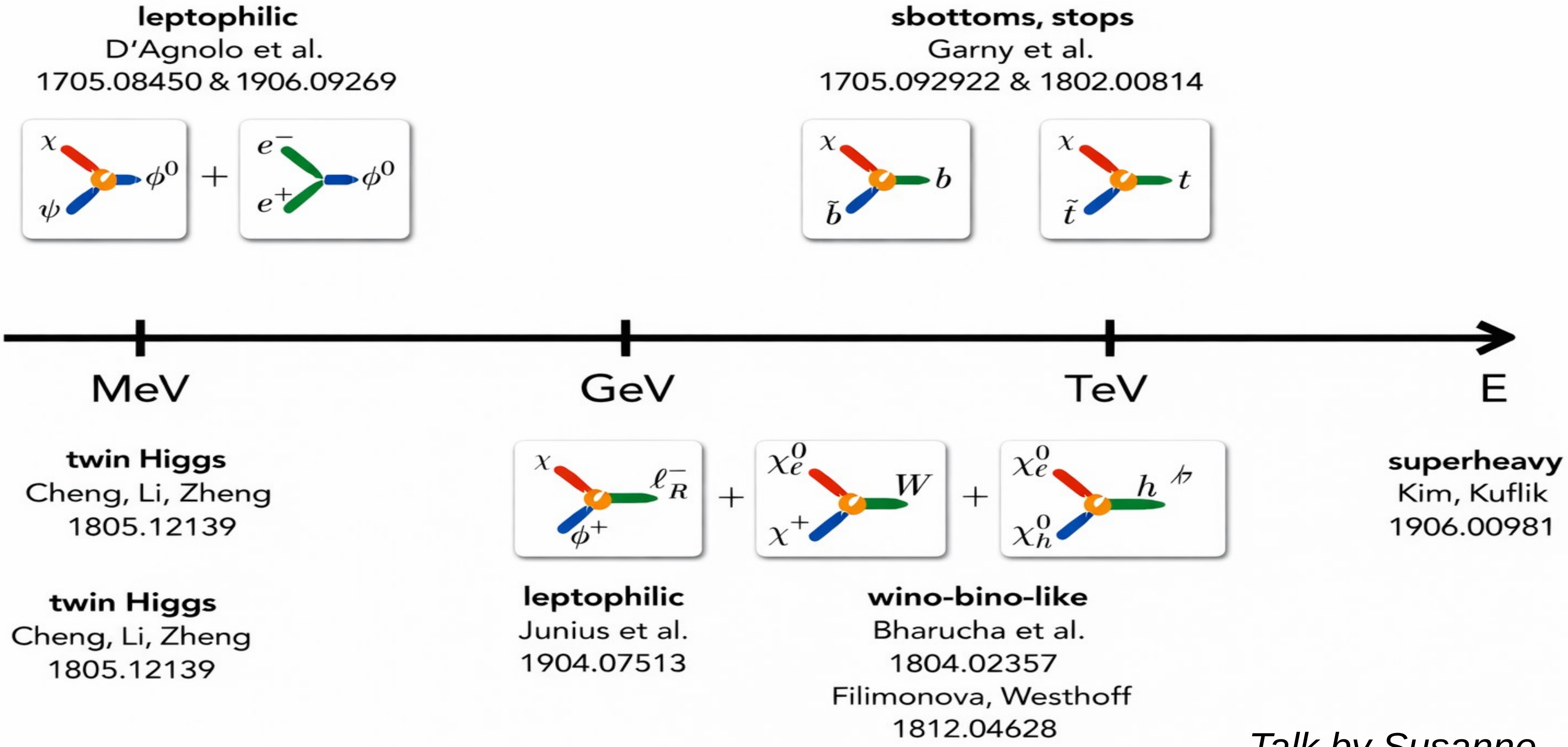
Hall et al. 2009

smaller coupling / longer lifetime

in thermal equilibrium

out of equilibrium

Models with co-scattering



Talk by Susanne

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

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

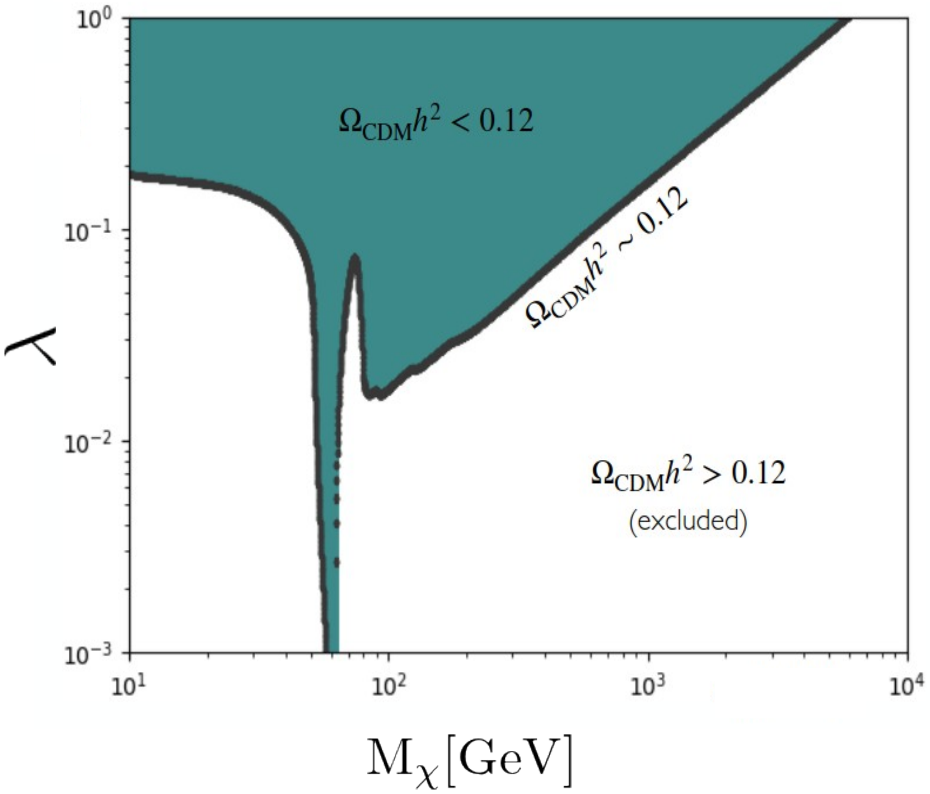
Dark Matter Couplings

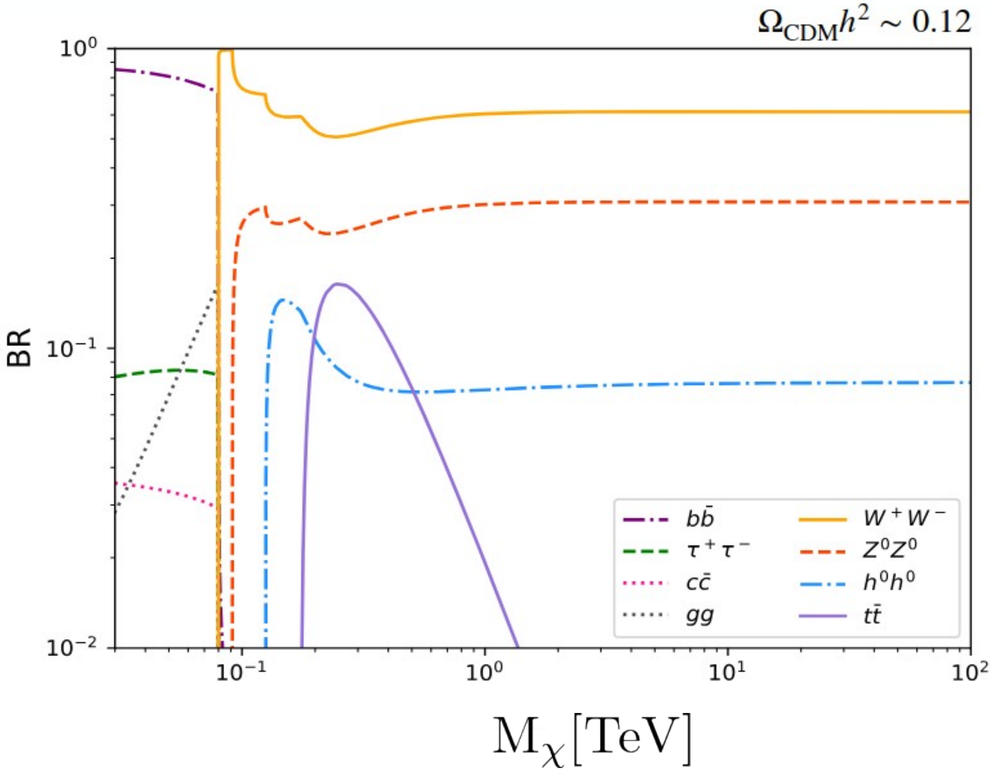
"Higgs Portal"

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

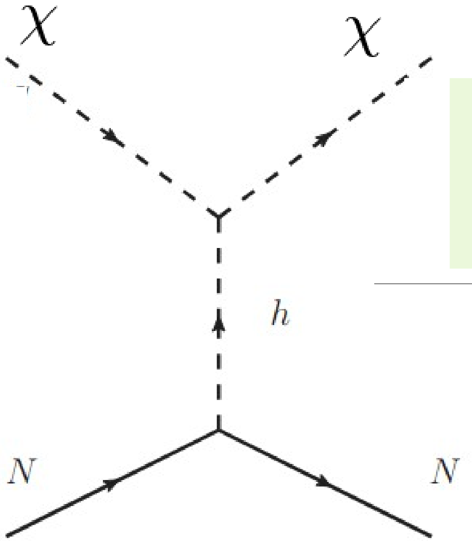




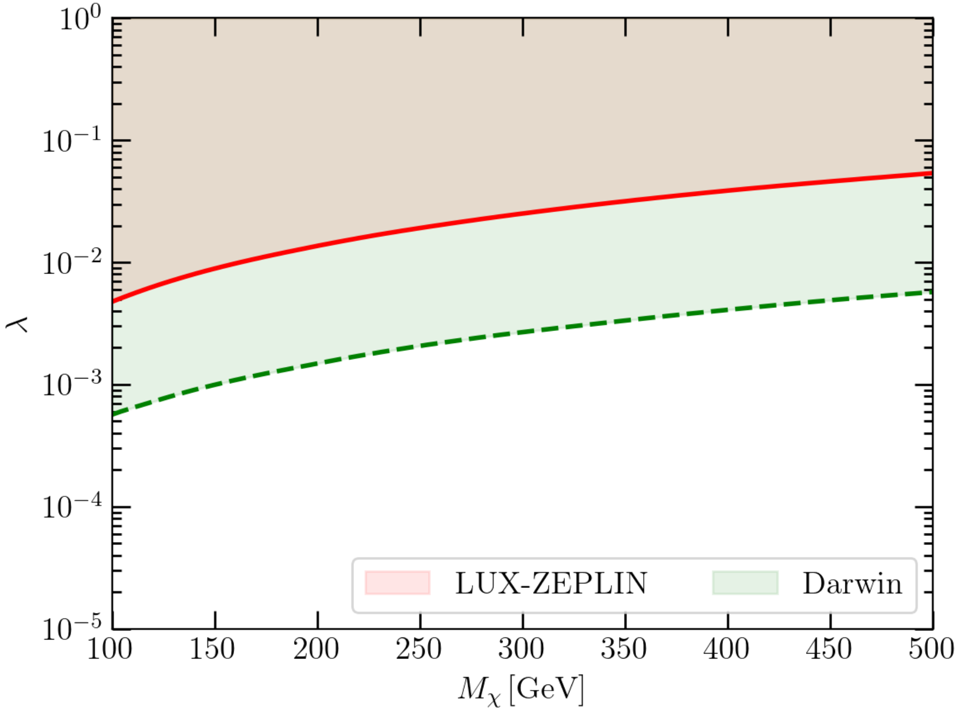
Dark matter annihilation into: gauge bosons, Higgs bosons, quarks, leptons.

Higgs Portal : Singlet Scalar DM

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

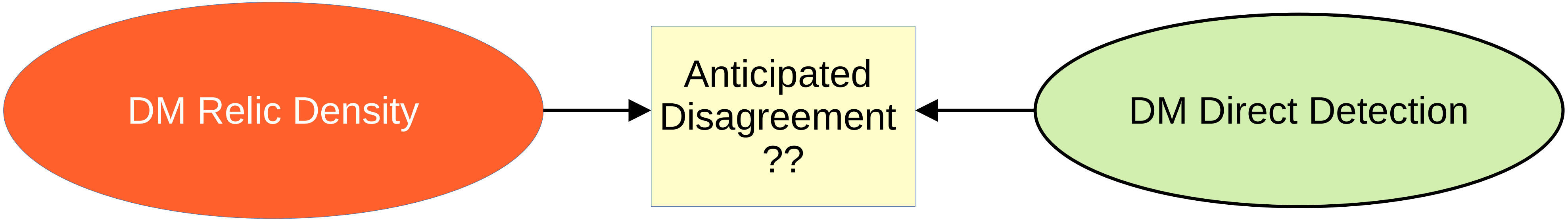


$$\sigma_{\rm SI} = \frac{\lambda^2 f_N^2 \mu_N^2 m_N^2}{4\pi M_h^4 M_\chi^2}$$



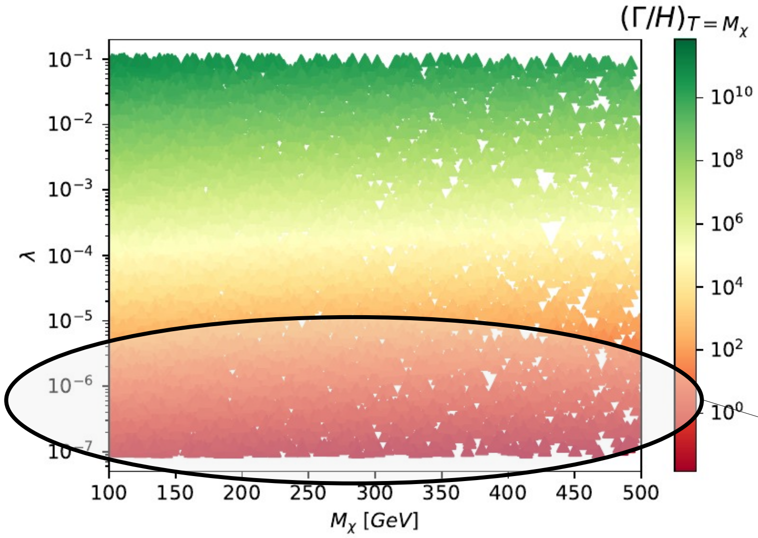
Direct detection limits imply that the Higgs-portal coupling must be suppressed.

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

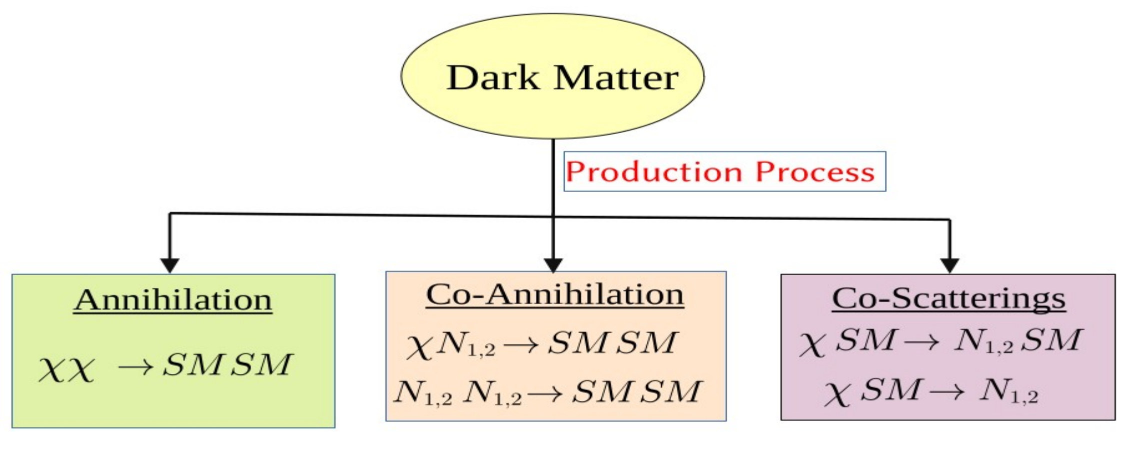
$$\chi \to -\chi, \quad N_{1,2} \to -N_{1,2}$$

Tree level neutrino mass:
forbidden by Z_2 symmetry

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

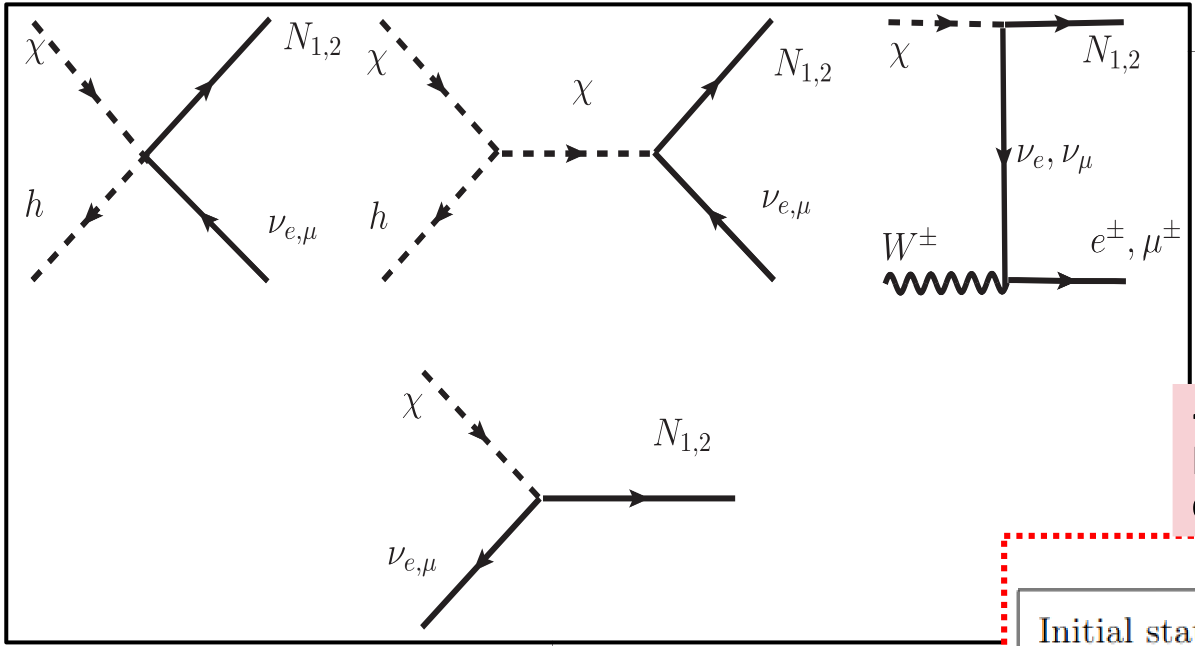
Suppressed due DD constraint

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

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

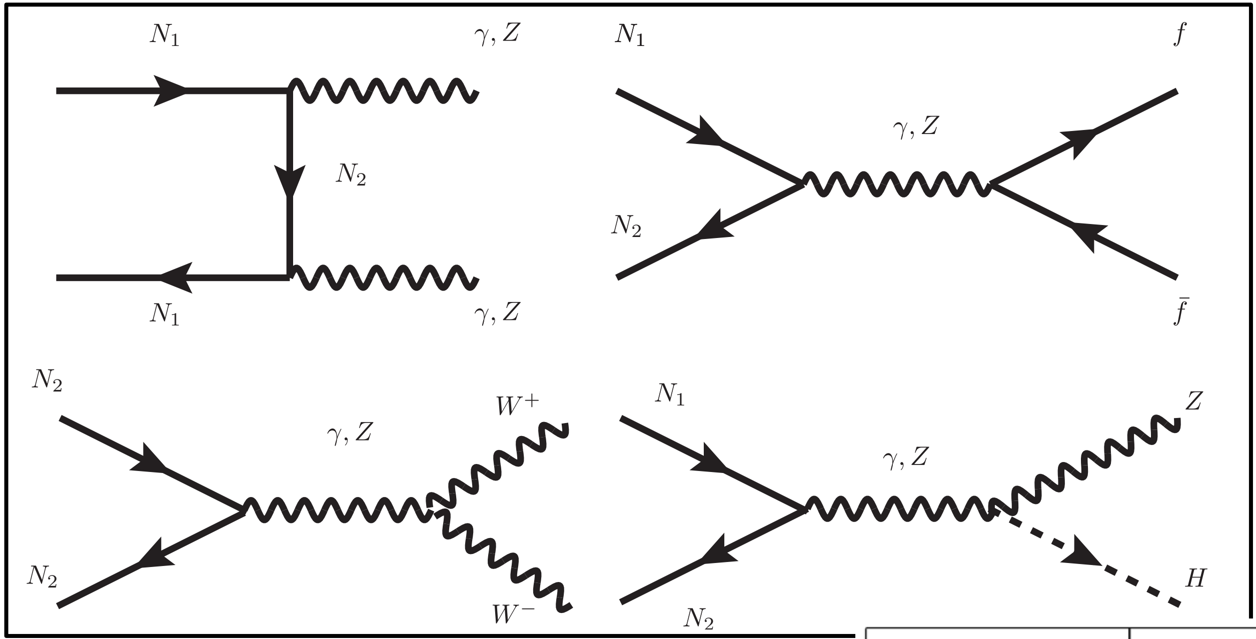
<0.5,
Either Co- Annihilation or Co-Scattering

>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	$c_3^{\prime\,4}$ (**t- channel process**)
N_1	N_2	f	$\bar{f}$	$c_3^{\prime\,2}$ (**s-channel process**)
N_1	N_2	W^+	W^-	$c_3^{\prime\,2}$ (**s-channel process**)
N_1	N_2	Z	H	$c_3^{\prime\,2}$ (**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)

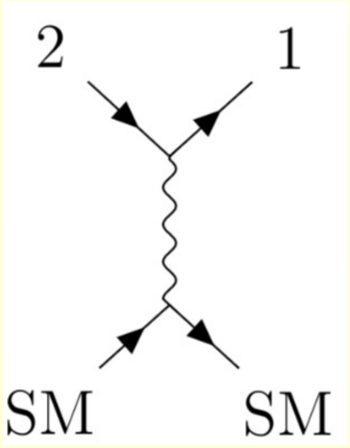
- if DM is very weakly coupled to the SM, DM self-annihilation is negligible

- 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

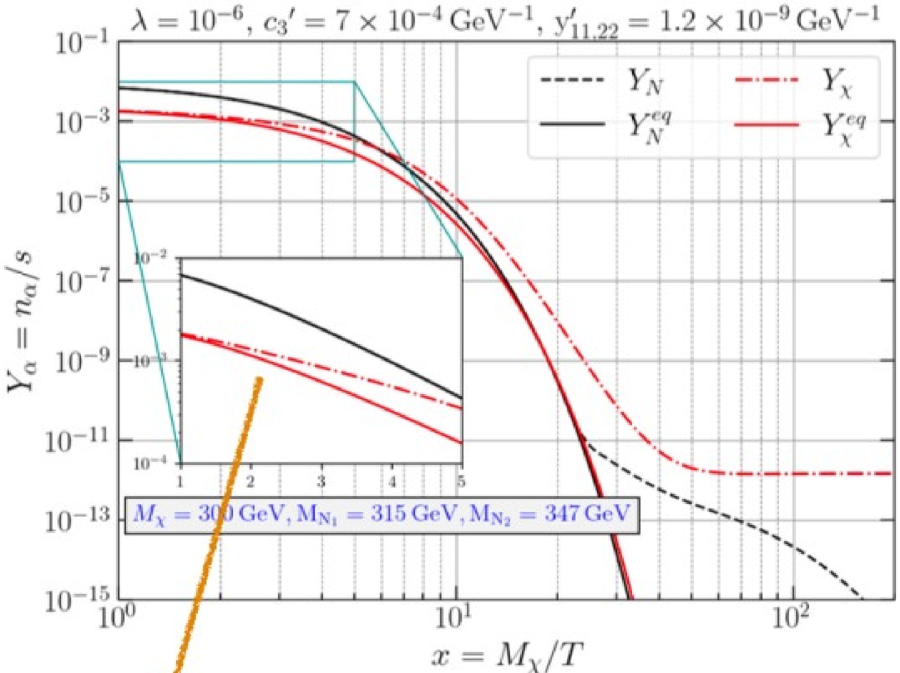
- When Y' and δ_1 is small, co-scattering keeps χ coupled to the N(=N1+N2).
- without coscattering, DM freezes out very early ⇒ too high relic density
- to quantify when coscattering is necessary to keep χ coupled to the N(=N1+N2).

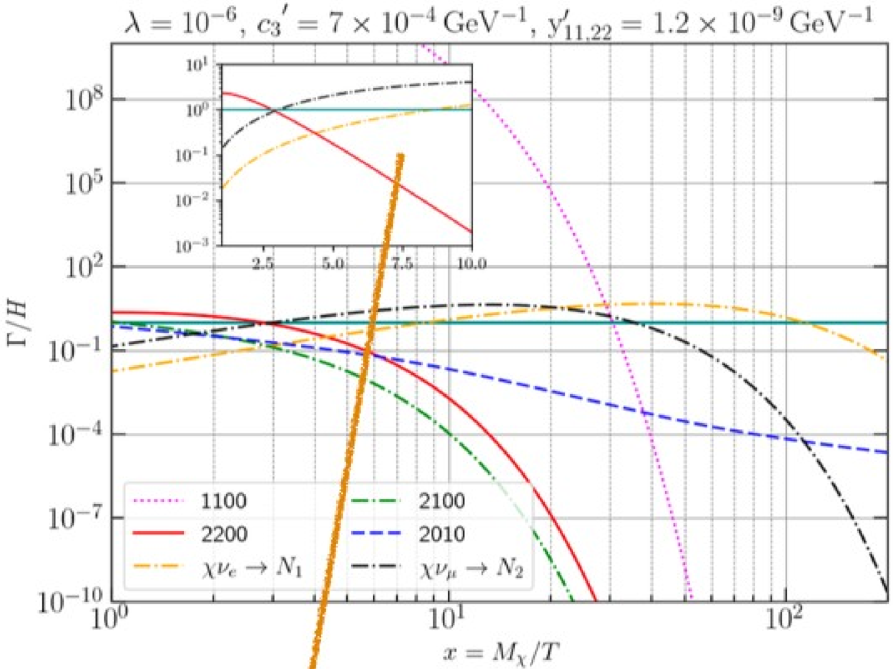
$$\Delta_\chi^1 \equiv 1 - \frac{\Omega h^2(\text{Single})}{\Omega h^2(\text{Coupled})}.$$

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

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

Evolution of DM: co-scattering





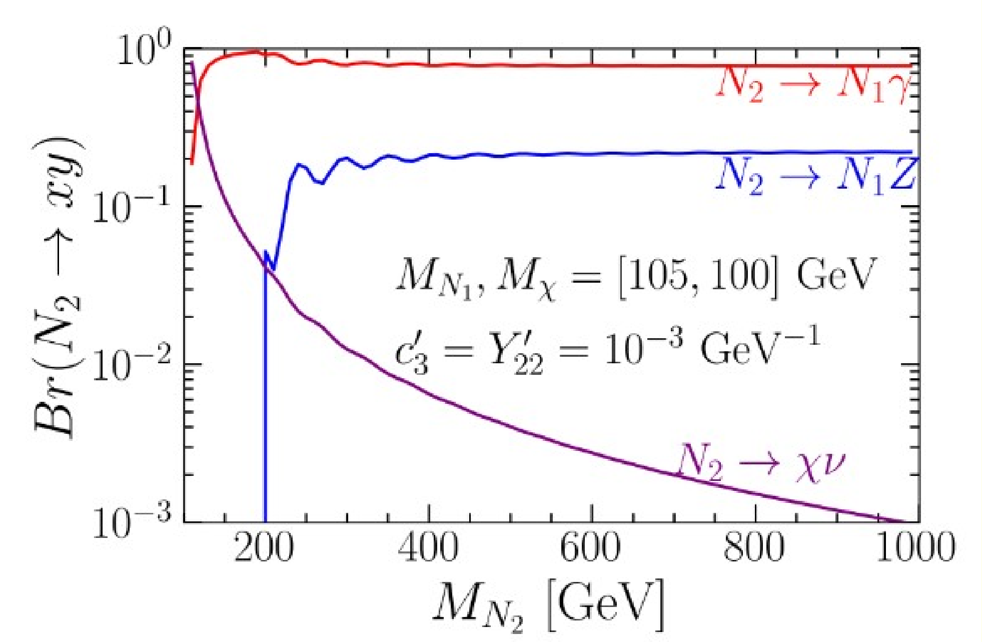
- DM is chemically decoupled at early times x~2
- All $2 \to 2$ process of DM decouple and inverse decay is inefficient to restore chemical equilibrium
- Freeze-out occurs at late times when inverse decay $\chi\nu \to N_1$ stops

Decay of N1 and N2

$N_2 \to N_1\gamma$, $N_2 \to N_1 Z$ via $c_3' \, \overline{N^c}\sigma_{\mu\nu}N \, B^{\mu\nu}$

$N_2 \to \chi\nu$ via $y'\overline{L}\tilde{\Phi}N\chi$

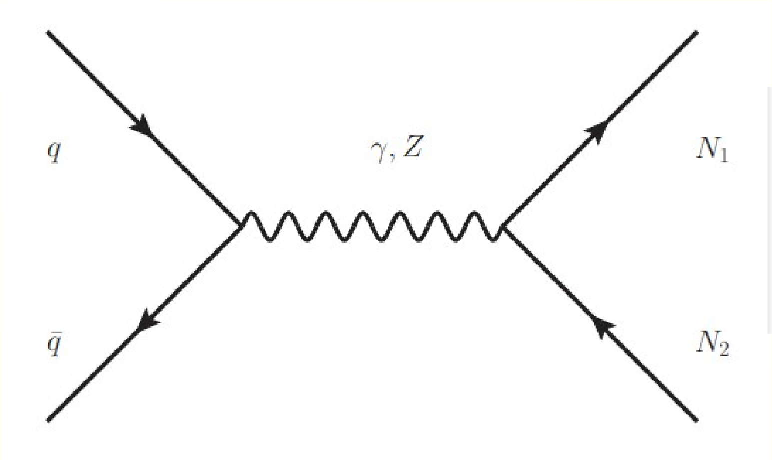
$N_1 \to \chi\nu$ via $y'\overline{L}\tilde{\Phi}N\chi$



N1 invisible at collider and N2 dominantly decay to photon + MET

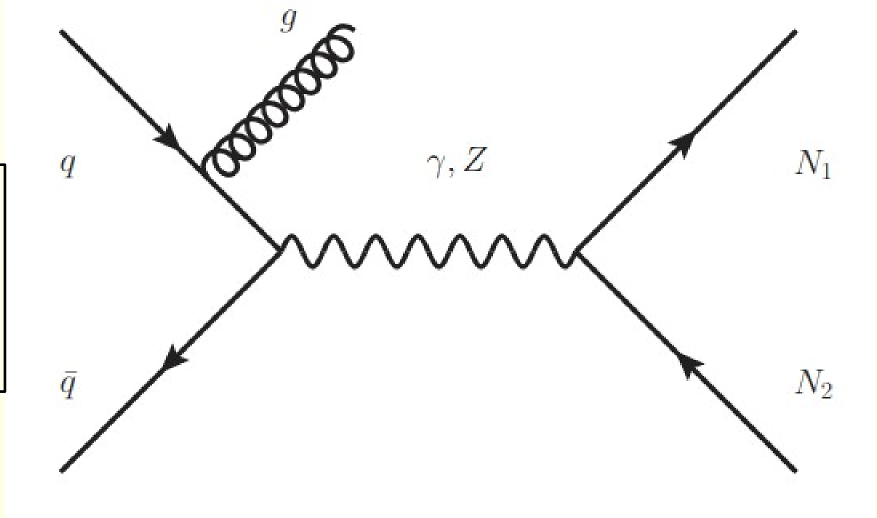
Collider Signal

γ + MET (mono-photon)



$$c_3' \, \overline{N^c} \sigma_{\mu\nu} N \, B^{\mu\nu}$$

jet + MET (mono-jet)

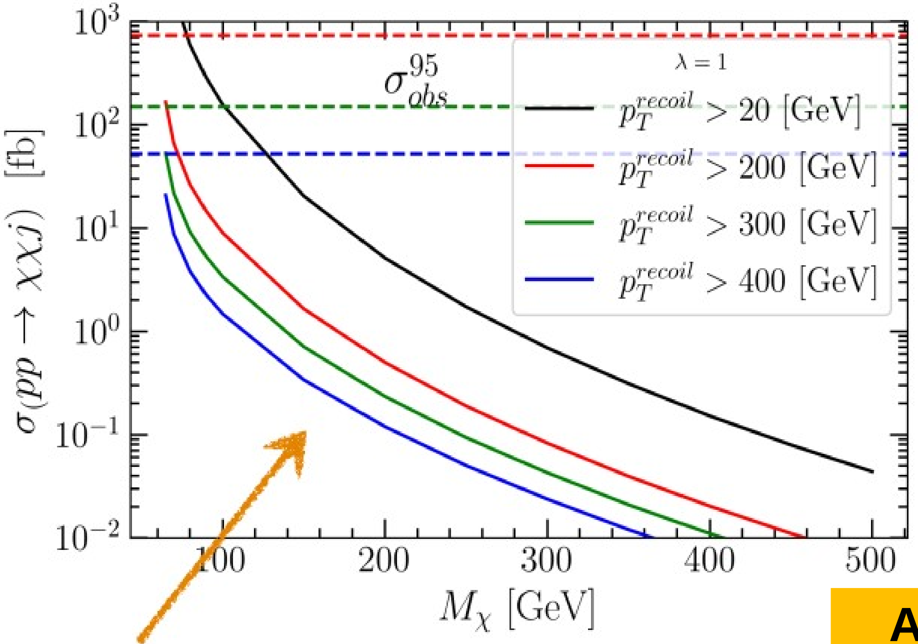


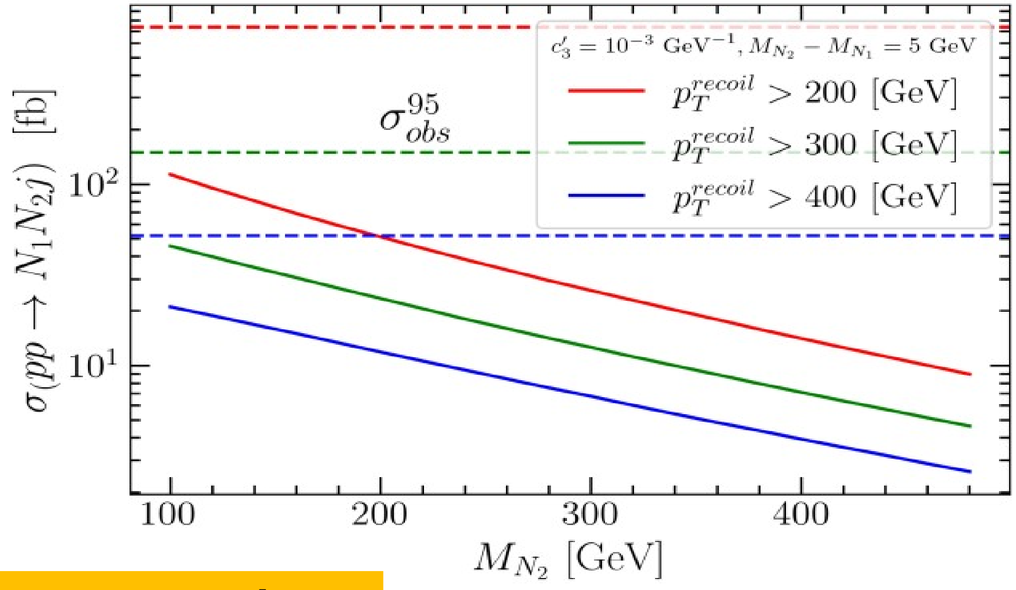
MN2 > MN1 > Mχ

- N2 → N1+γ (leading mode), N2 → N1Z, N2 → χν
- N1 → χ ν (MET)

pp → h → χχ j can also lead to mono-jet but suppressed

Mono-jet signal



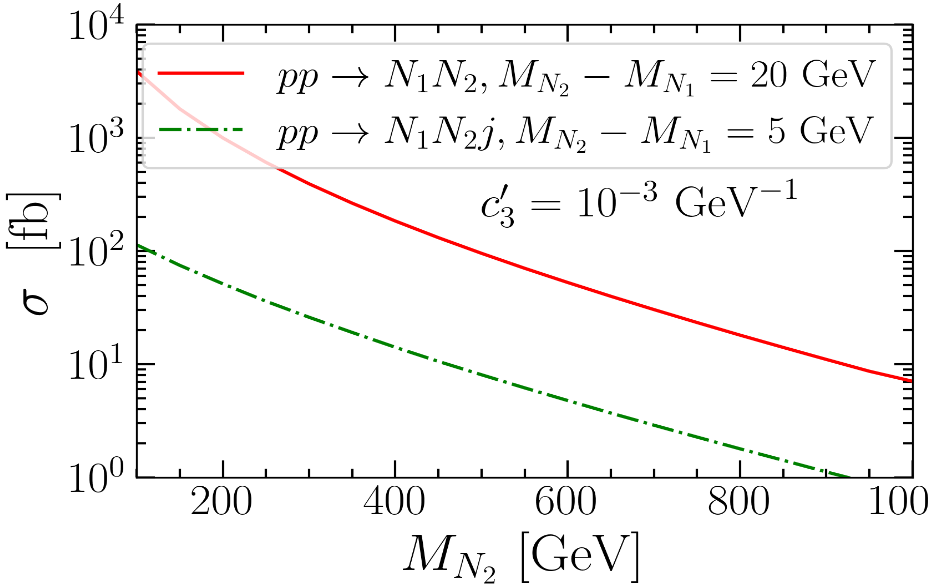


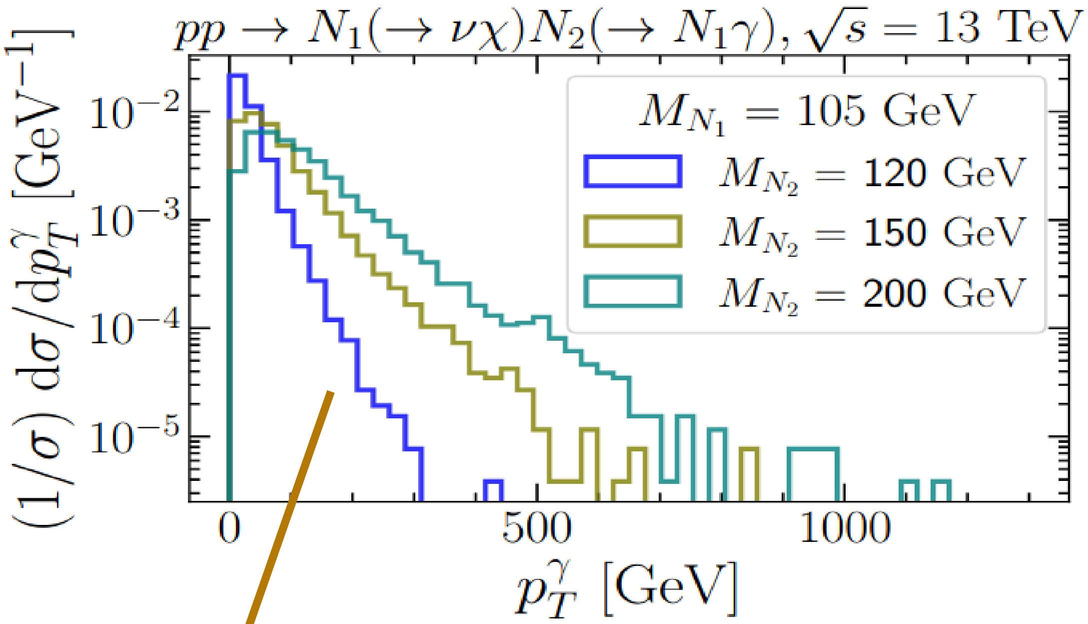
- $pp \to h \to \chi\chi\, j$, for $\lambda = 1$. further suppressed as $\lambda = 10^{-6}$
- Not sensitivity to mono-jet

ATLAS Mono-jet

Selection	$\langle\sigma\rangle_{\text{obs}}^{95}$ [fb]
$p_{\text{T}}^{\text{recoil}} > 200$ GeV	736
$p_{\text{T}}^{\text{recoil}} > 250$ GeV	296
$p_{\text{T}}^{\text{recoil}} > 300$ GeV	150
$p_{\text{T}}^{\text{recoil}} > 350$ GeV	86
$p_{\text{T}}^{\text{recoil}} > 400$ GeV	52

Collider Signal



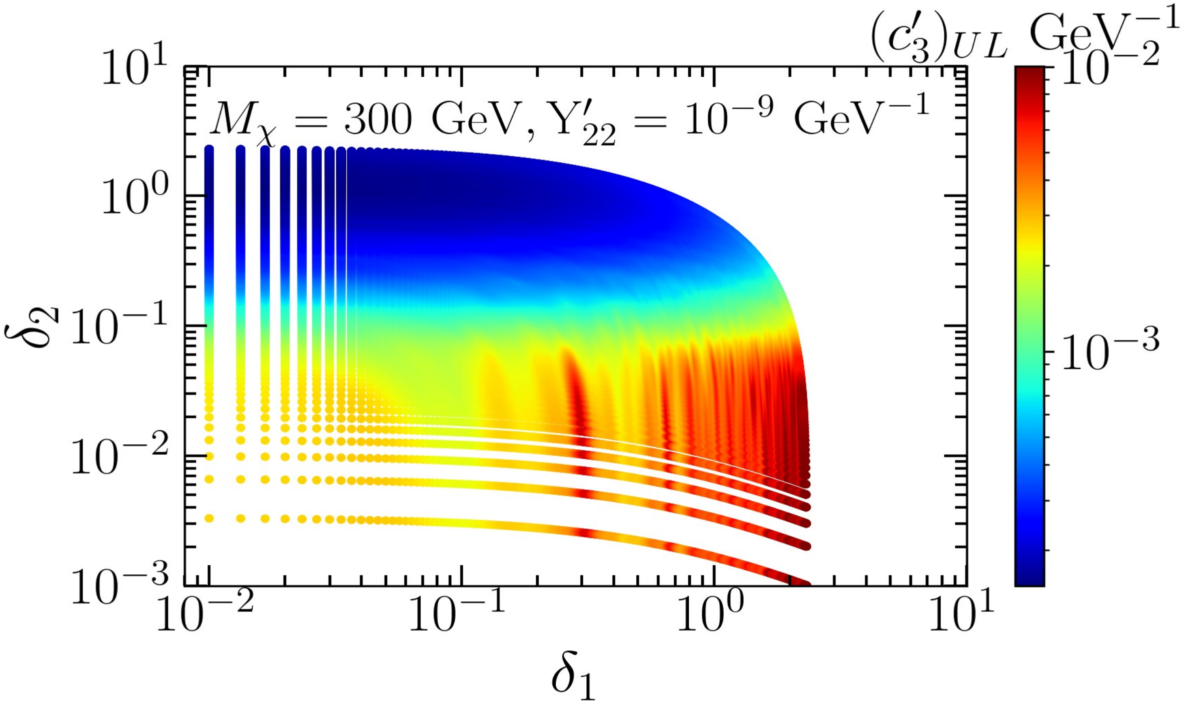


- Cross-section scale as $(c'_3)^2$
- Mono-photon via $pp \to N_1(\to \chi\ \nu)\ N_2(\to N_1\ \gamma)$ is leading channel
- Mono-jet : $pp \to N_1N_2\ j$ (rates drops for $p_T(j) > 200$ GeV)

Higher M_{N2}-M_{N1} -> energetic photon -> stronger limit

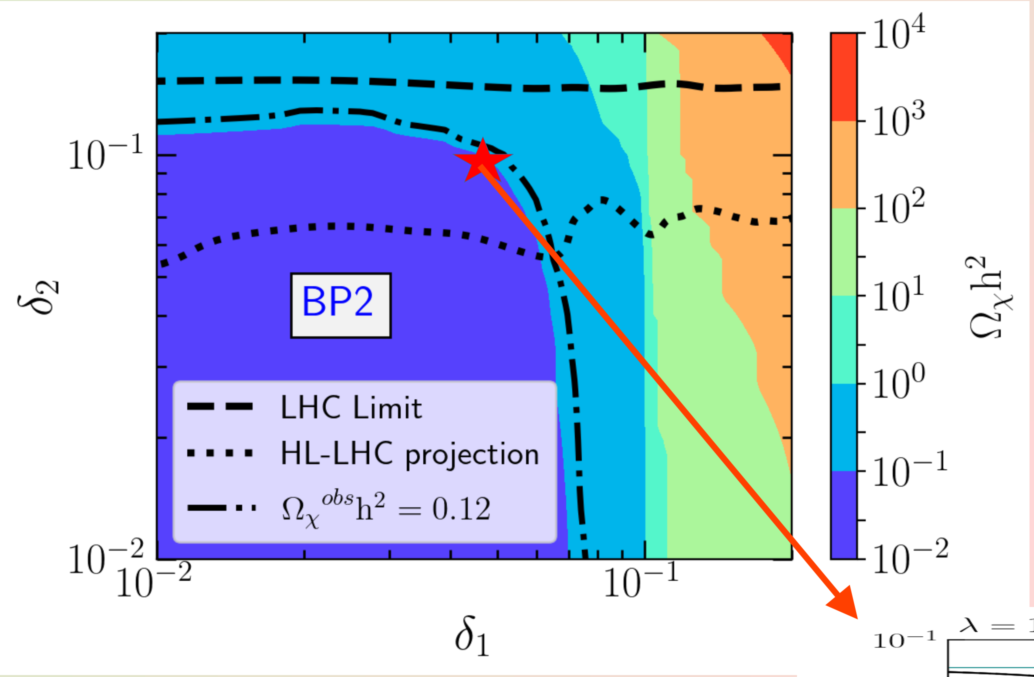
mono-γ gives the leading signal.

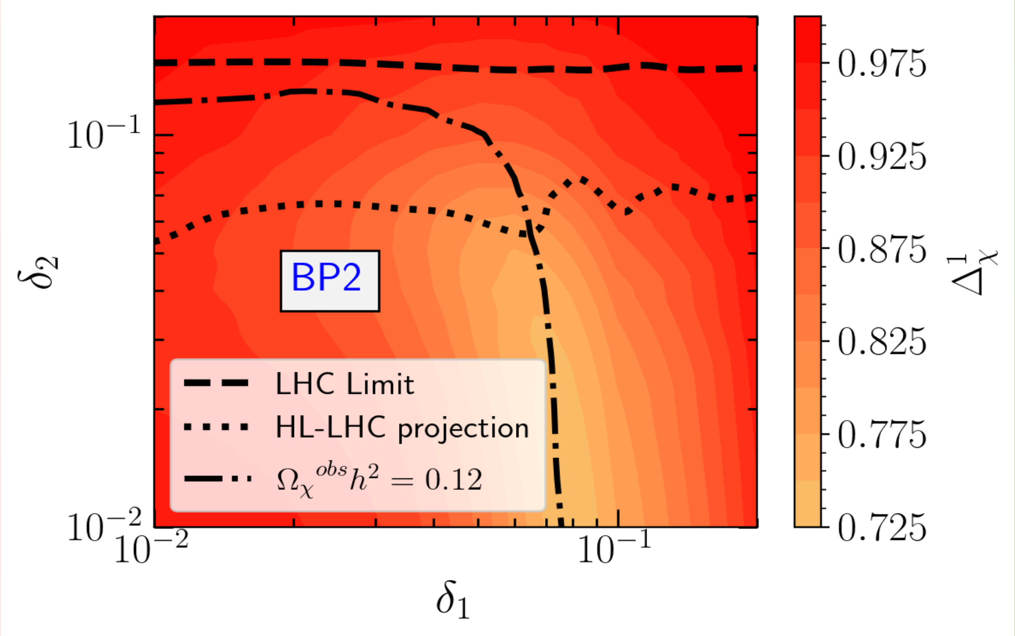
Numerical results

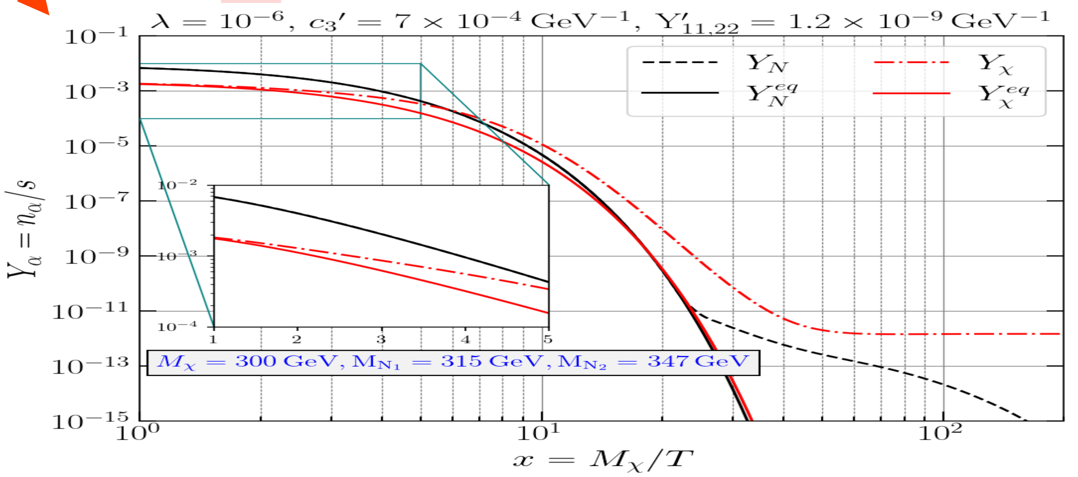


- "Dark matter + energetic photon in ATLAS (**arXiv: 2011.05259**): **parameter space constraints**
- Large δ_2 leads to energetic photons. Hence, stringent constraints.

Numerical results



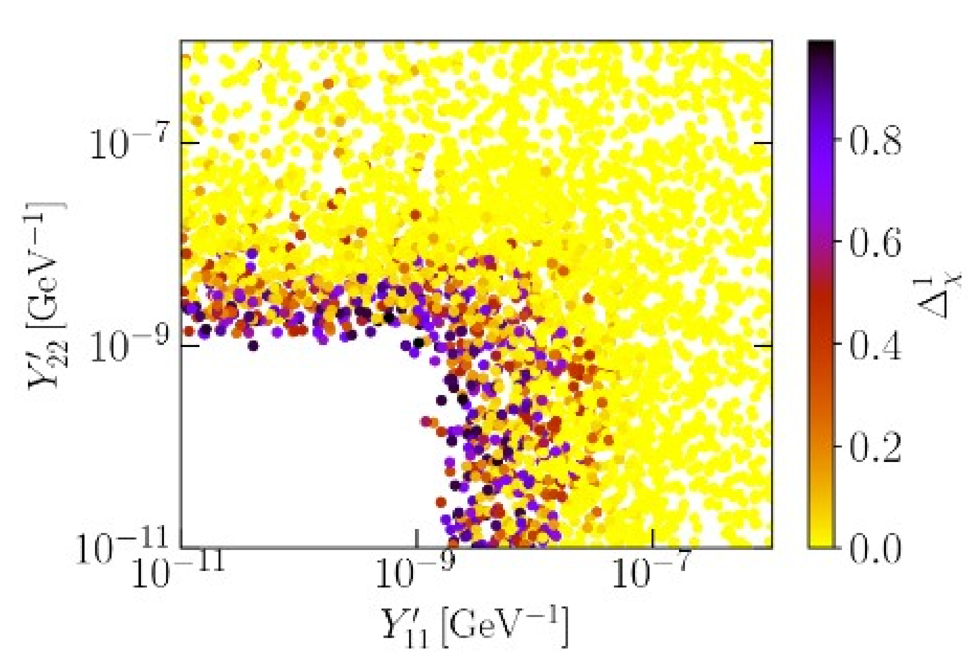




- Relic density primarily govern by co-scattering
- Consistent with mono-photon limit
- Can be probed at HL-LHC

Parameter Scan

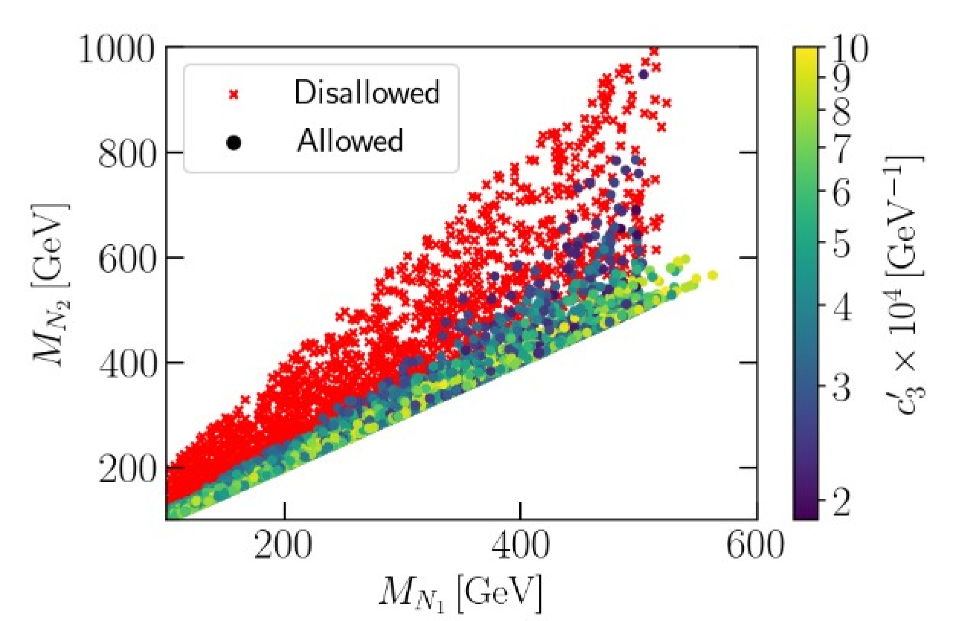
Parameter	Scanned range
M_χ [GeV]	[100 , 500]
$\delta_1(M_{N_1}$ [GeV])	[10^{-3} , 0.5] ([$\approx M_\chi$, 750])
$\delta_2(M_{N_2}$ [GeV])	[10^{-3} , 1] ([$\approx M_{N_1}$, 1500])
y'_{11} [GeV^{-1}]	[10^{-11} , 10^{-6}]
y'_{22} [GeV^{-1}]	[10^{-11} , 10^{-6}]
c'_3 [GeV^{-1}]	[10^{-6} , 10^{-3}]



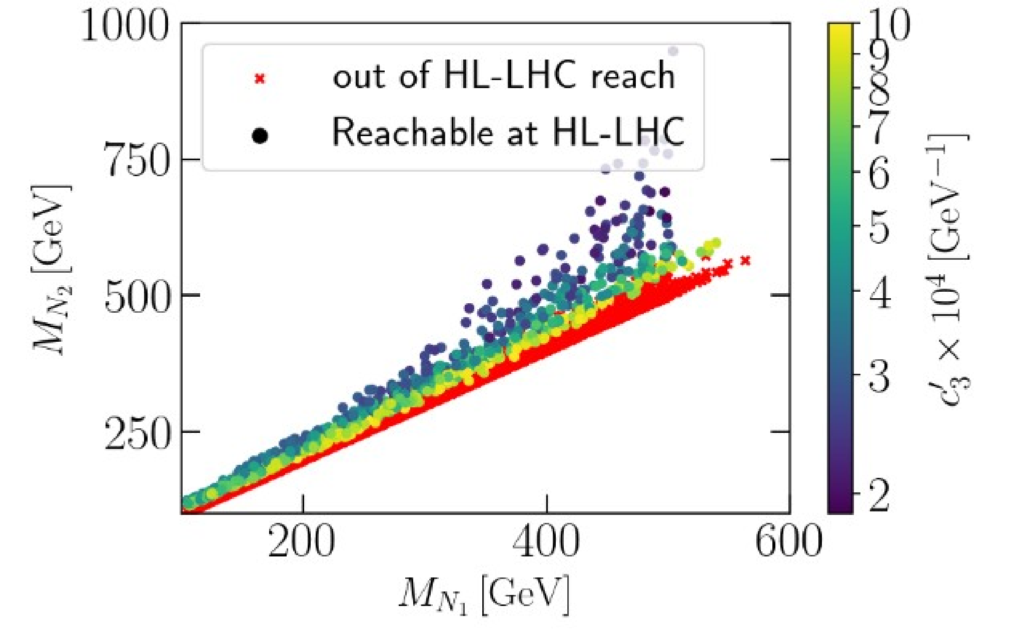
- *Relic density:* $10^{-4} \leq \Omega_\chi h^2 \leq 0.1224$
- *Mono-photon search constrain larger* $M_{N_2} - M_{N_1}$
- *Parameter space can be probed at HL-LHC*

Numerical results

LHC Limit



HL-LHC Projection



Higher M_{N2}-M_{N1} -> energetic photon -> stronger limit

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!