

Freeze-in Bino Dark Matter in High Scale Supersymmetry

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Outline

- Motivation
 - Freeze-In bino DM in SUSY
- Model setup and phenomenology
 - particle spectrum: modified High Scale SUSY
 - interactions: dim-5 vs dim-6
 - DM production feature: UV vs IR
- Results and discussion
- Summary

Supersymmetry

Theoretically important

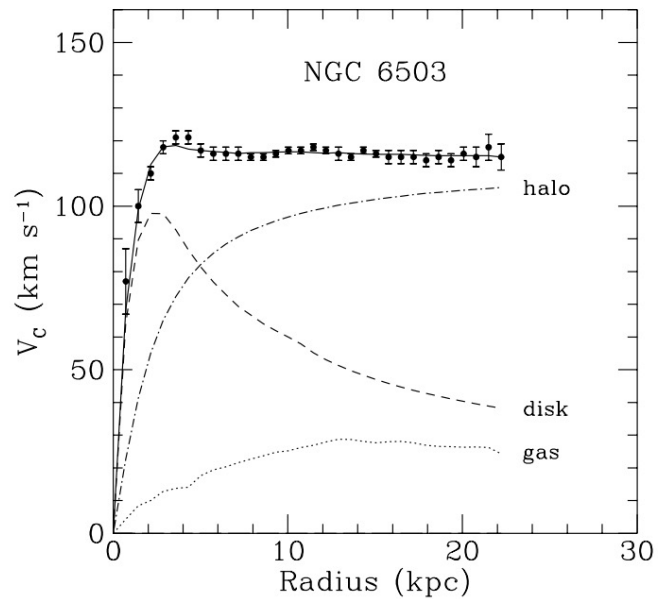
- Haag–Łopuszański–Sohnius (**HLS**) theorem
 - SUSY is the **only way** to nontrivially mix **4-D Minkowski spacetime** and **continuous internal** symmetries, when **both** anti-/commuting generators are considered
- necessary for string theory
- may solve the naturalness problem (aesthetical choice)

Phenomenologically rich

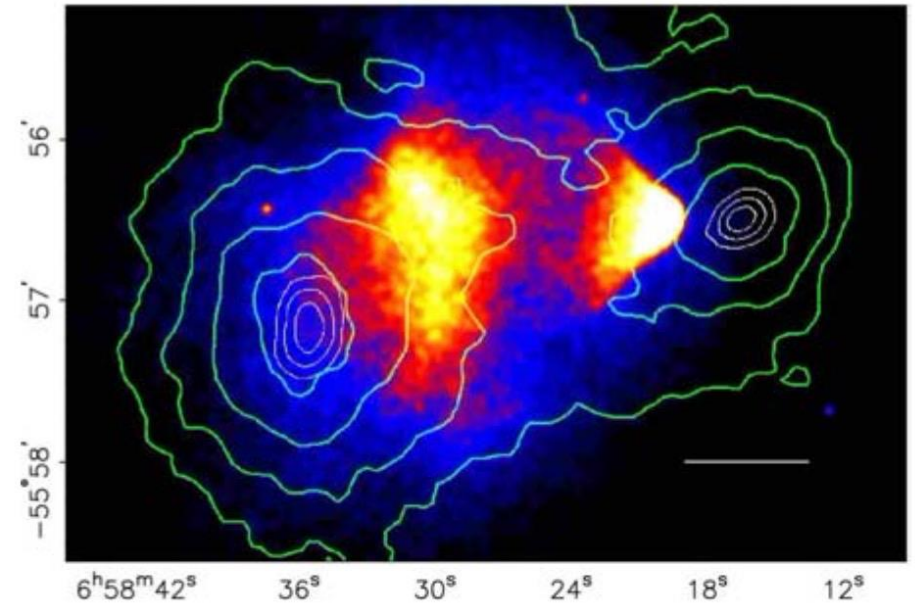
- viable DM candidate
- SM gauge coupling unification
- possible origins of exp. anomalies

Nature of DM is still unknown

- cosmological / astrophysical hints of existence of DM are strong
- among various possibilities, particle nature of DM is under search in many experiments



Begeman et al, 1991, MNRAS, 249, 523.



D. Clowe, et al, astro-ph/0608407

Some SUSY particles seems to be heavy

- Esthetical requirement about naturalness problem may need to be relaxed

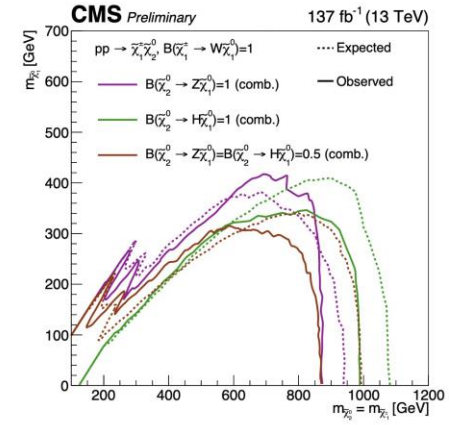
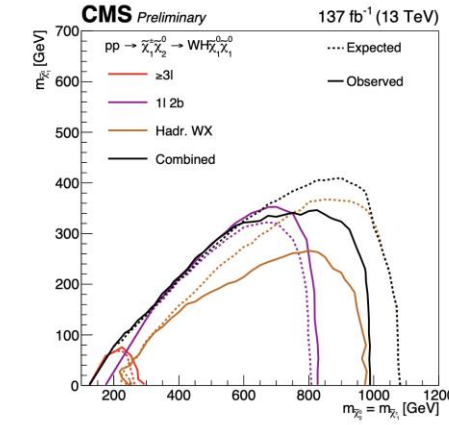
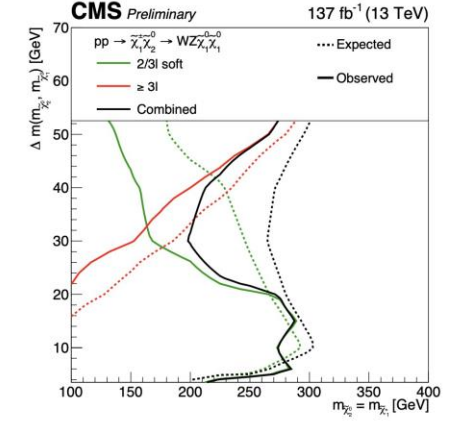
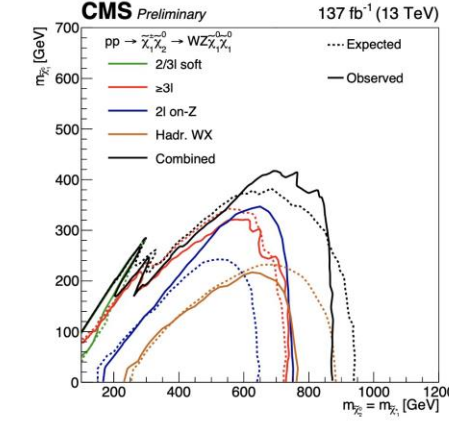
ATLAS SUSY Searches* - 95% CL Lower Limits
March 2023

ATLAS Preliminary
 $\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$]	Mass limit	Reference							
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{q}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_{T}^{miss} E_{T}^{miss}	139	\tilde{q} [1% 8x Degen] \tilde{q} [8x Degen]	1.0 0.9	1.85	$m(\tilde{q}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{q}_1^0) = 5$ GeV	2010.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}_1^0$	0 e, μ	2-6 jets	E_{T}^{miss}	139	\tilde{g}	Forbidden	1.15-1.95	2.3	$m(\tilde{g}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{X}_1^0$	1 e, μ	2-6 jets	E_{T}^{miss}	139	\tilde{g}	Forbidden	1.15-1.95	2.2	$m(\tilde{g}_1^0) = 600$ GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(t\bar{t})\tilde{X}_1^0$	$ee, \mu\mu$	2 jets	E_{T}^{miss}	139	\tilde{g}	Forbidden	1.15-1.95	2.2	$m(\tilde{g}_1^0) < 700$ GeV	2204.13072
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{X}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets	E_{T}^{miss} E_{T}^{miss}	139 139	\tilde{g}	Forbidden	1.15	1.97	$m(\tilde{g}_1^0) = 600$ GeV $m(\tilde{g}) - m(\tilde{g}_1^0) = 200$ GeV	2008.06032 1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{X}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_{T}^{miss} E_{T}^{miss}	139 139	\tilde{g}	Forbidden	1.25	2.45	$m(\tilde{g}_1^0) = 500$ GeV $m(\tilde{g}) - m(\tilde{g}_1^0) = 300$ GeV	2211.08028 1909.08457
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_{T}^{miss}	139	\tilde{b}_1	Forbidden	0.68	1.255	$m(\tilde{b}_1^0) = 400$ GeV $10 \text{ GeV} < \Delta m(\tilde{b}_1, \tilde{b}_1^0) < 20$ GeV	2101.12527 2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{b}_1^0$	0 e, μ	6 b 2 b	E_{T}^{miss} E_{T}^{miss}	139 139	\tilde{b}_1 \tilde{b}_1	Forbidden	0.13-0.85	0.23-1.35	$\Delta m(\tilde{b}_1^0, \tilde{b}_1) = 130$ GeV, $m(\tilde{b}_1^0) = 100$ GeV $\Delta m(\tilde{b}_2^0, \tilde{b}_1^0) = 130$ GeV, $m(\tilde{b}_1^0) = 0$ GeV	1908.03122 2103.08189
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}_1^0$	0-1 e, μ	≥ 1 jet	E_{T}^{miss}	139	\tilde{t}_1	Forbidden	0.65	1.25	$m(\tilde{t}_1^0) = 1$ GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{t}_1^0$	1 e, μ	3 jets/1 b	E_{T}^{miss}	139	\tilde{t}_1	Forbidden	0.65	1.25	$m(\tilde{t}_1^0) = 500$ GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau_1 b\nu, \tau_1 \rightarrow \tau G$	1-2 τ	2 jets/1 b	E_{T}^{miss}	139	\tilde{t}_1	Forbidden	0.65	1.4	$m(\tilde{t}_1) = 800$ GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{t}_1^0 / c\bar{c}, \tilde{t}_1 \rightarrow c\tilde{t}_1^0$	0 e, μ 0 e, μ	2 c mono-jet	E_{T}^{miss} E_{T}^{miss}	139 139	\tilde{t}_1 \tilde{t}_1	Forbidden	0.55	0.85	$m(\tilde{t}_1^0) = 0$ GeV $m(\tilde{t}_1) - m(\tilde{t}_1^0) = 5$ GeV	1805.01649 2102.10874
EW direct	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}_1^0, \tilde{t}_1^0 \rightarrow Z/h\tilde{t}_1^0$	1-2 e, μ 3 e, μ	1-4 b 1 b	E_{T}^{miss} E_{T}^{miss}	139 139	\tilde{t}_1 \tilde{t}_1	Forbidden	0.067-1.18	0.86	$m(\tilde{t}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{t}_1^0) = 40$ GeV	2006.05880 2006.05880
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets $ee, \mu\mu$	≥ 1 jet	E_{T}^{miss} E_{T}^{miss}	139 139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ $\tilde{\chi}_1^0\tilde{\chi}_2^0$	Forbidden	0.205	0.96	$m(\tilde{\chi}_1^0) = 0$, wino-bino $m(\tilde{\chi}_1^0) - m(\tilde{\chi}_2^0) = 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via WW	Multiple ℓ /jets	≥ 1 jet	E_{T}^{miss}	139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	Forbidden	0.42	1.06	$m(\tilde{\chi}_1^0) = 0$, wino-bino $m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	1908.08215 2004.10894, 2108.07586
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via Wh	Multiple ℓ /jets	≥ 1 jet	E_{T}^{miss}	139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	Forbidden	0.16-0.3	0.12-0.39	$m(\tilde{\chi}_1^0) = 0$, wino-bino $m(\tilde{\chi}_1^0) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	1908.08215 1911.06660
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ via $\ell\ell/\nu\bar{\nu}$	2 τ	0 jets ≥ 1 jet	E_{T}^{miss} E_{T}^{miss}	139 139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ $\tilde{\chi}_1^0\tilde{\chi}_2^0$	Forbidden	0.256	0.7	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^0) - m(\tilde{\chi}_2^0) = 10$ GeV	1908.08215 1911.12606
	$\tilde{\tau}_1\tilde{\tau}_1, \tilde{\tau}_1 \rightarrow \tau\tilde{\tau}_1^0$	2 τ	0 jets ≥ 1 jet	E_{T}^{miss} E_{T}^{miss}	139 139	$\tilde{\tau}_1$ $\tilde{\tau}_1$	Forbidden	0.13-0.23	0.29-0.88	$m(\tilde{\tau}_1^0) = 0$ $\text{BR}(\tilde{\tau}_1^0 \rightarrow hZ) = 1$	1908.08215 2103.11684 2108.07586
Long-lived particles	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow hG/ZG$	0 e, μ 4 e, μ 0 e, μ 2 e, μ	≥ 3 b 0 jets ≥ 2 large jets	E_{T}^{miss} E_{T}^{miss} E_{T}^{miss} E_{T}^{miss}	36.1 139 139 139	\tilde{H} \tilde{H} \tilde{H} \tilde{H}	Forbidden	0.45-0.93	0.77	$\text{BR}(\tilde{H}^0 \rightarrow ZG) = 1$ $\text{BR}(\tilde{H}^0 \rightarrow ZG) = 1$ $\text{BR}(\tilde{H}^0 \rightarrow ZG) = 0.5$	2108.04030 2103.11684 2108.07586 2204.13072
	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	E_{T}^{miss}	139	$\tilde{\chi}_1^0$	Forbidden	0.21	0.66	Pure Wino Pure Higgsino	2201.02472 2201.02472
	Stable \tilde{g} R-hadron	pixel dE/dx		E_{T}^{miss}	139	\tilde{g}	Forbidden	2.05	2.2	$m(\tilde{g}) = 100$ GeV	2205.06013 2205.06013
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}_1^0$	pixel dE/dx		E_{T}^{miss}	139	\tilde{g}	Forbidden	0.34	0.7	$\tau(\tilde{g}) = 10$ ns	2011.07812 2011.07812
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell G$	Disapp. lep		E_{T}^{miss}	139	$\tilde{\ell}$	Forbidden	0.36	0.7	$\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 10$ ns	2011.07812 2011.07812 2205.06013
	pixel dE/dx			E_{T}^{miss}	139	$\tilde{\ell}$	Forbidden	0.36	0.7	$\tau(\tilde{\ell}) = 10$ ns	2205.06013
RPV	$\tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow Z\ell\ell$	3 e, μ	0 jets	E_{T}^{miss}	139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	Forbidden	0.625	1.05	Pure Wino $m(\tilde{\chi}_1^0) = 200$ GeV	2011.10543 2103.11684
	$\tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow WZZ\ell\ell\nu\nu$	4 e, μ	0 jets	E_{T}^{miss}	139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	Forbidden	0.95	1.55	$[\text{BR}(\tilde{\chi}_1^0 \rightarrow \text{Large } \tilde{A}_1^0)] = 1$	1804.02568
	$\tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow q\tilde{q}\nu\bar{\nu}$	36.1	4-5 large jets	E_{T}^{miss}	139	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	Forbidden	0.55	1.3	$m(\tilde{\chi}_1^0) < 200$ GeV, 1100 GeV	2011.05444
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\nu\bar{\nu}$	Multiple	≥ 4 b	E_{T}^{miss}	139	\tilde{g}	Forbidden	0.55	1.05	Large \tilde{A}_1^0 $m(\tilde{g}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{H}, \tilde{H} \rightarrow b\tilde{t}_1^0, \tilde{t}_1^0 \rightarrow b\tilde{b}_s$	Multiple	≥ 4 b	E_{T}^{miss}	139	\tilde{H}	Forbidden	0.42	0.61	$m(\tilde{H}^0) = 500$ GeV	2010.01015
	$\tilde{H}, \tilde{H} \rightarrow b\tilde{t}_1^0, \tilde{t}_1^0 \rightarrow b\tilde{b}_s$	2 e, μ 1 μ	2 jets + 2 b DV	E_{T}^{miss} E_{T}^{miss}	36.1 136	\tilde{H} \tilde{H}	Forbidden	0.42	0.61	$\text{BR}(\tilde{H}^0 \rightarrow b\tilde{t}_1^0) > 20\%$ $\text{BR}(\tilde{H}^0 \rightarrow \nu\bar{\nu}) = 100\%$, $\cos\beta = 1$	1710.07171 1710.05544
$\tilde{\chi}_1^0\tilde{\chi}_2^0/\tilde{\chi}_1^0\tilde{\chi}_1^0/\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow t\bar{t}b_s, \tilde{\chi}_1^0 \rightarrow b\tilde{b}_s$	1-2 e, μ	≥ 6 jets	E_{T}^{miss}	139	$\tilde{\chi}_1^0$	Forbidden	0.2-0.32	1.0	1.6	2003.11956 2106.09609	

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]



DM-focused SUSY particle spectrum, concerning exp. results

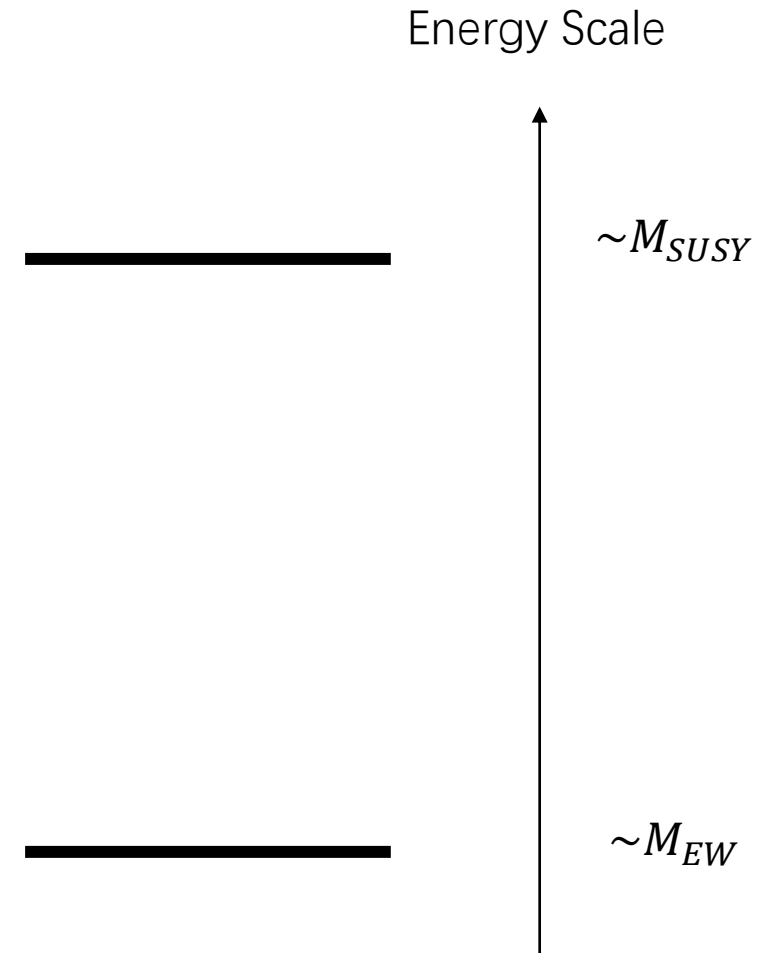
- High Scale SUSY, Split SUSY, other variations...

- most SUSY sparticles are assumed to be heavy

$$\{ \tilde{f}, \tilde{G}, H^0, A^0, H^\pm \}$$

- all/part of Electroweak-ino sector are light

$$\{ \tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d \}$$



DM-focused ^{in this work} **MSSM** particle spectrum

- High Scale SUSY, Split SUSY, other variations...

- most SUSY sparticles are assumed to be heavy

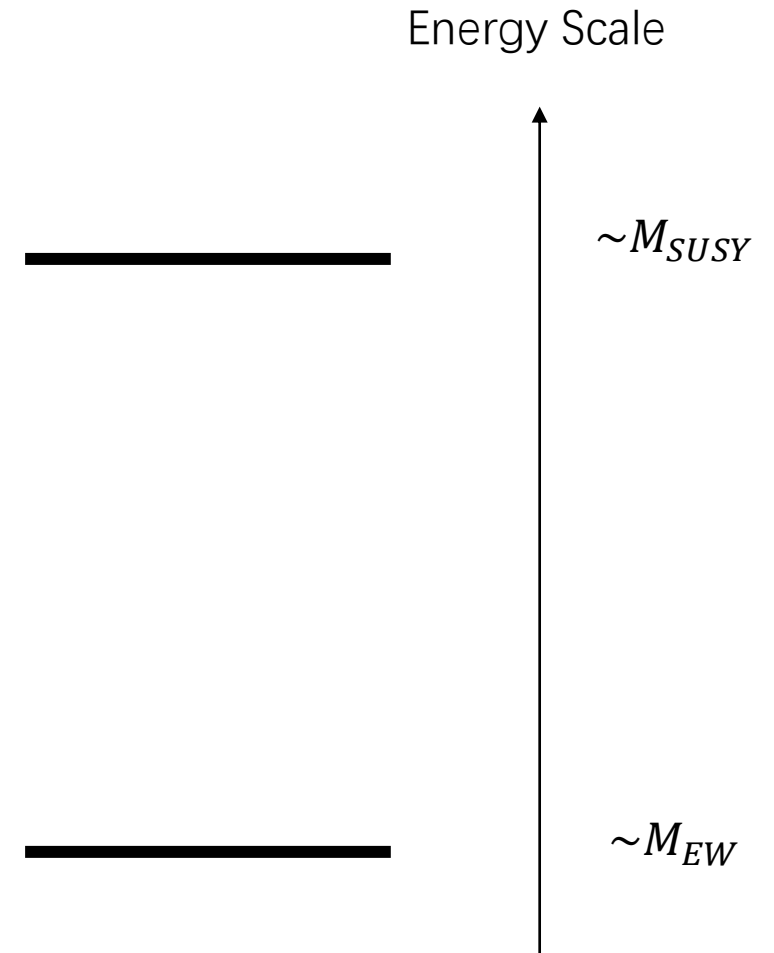
$$\{ \tilde{f}, \tilde{G}, H^0, A^0, H^\pm \} \quad \{ \tilde{H}_u, \tilde{H}_d \}$$

^{in this work}

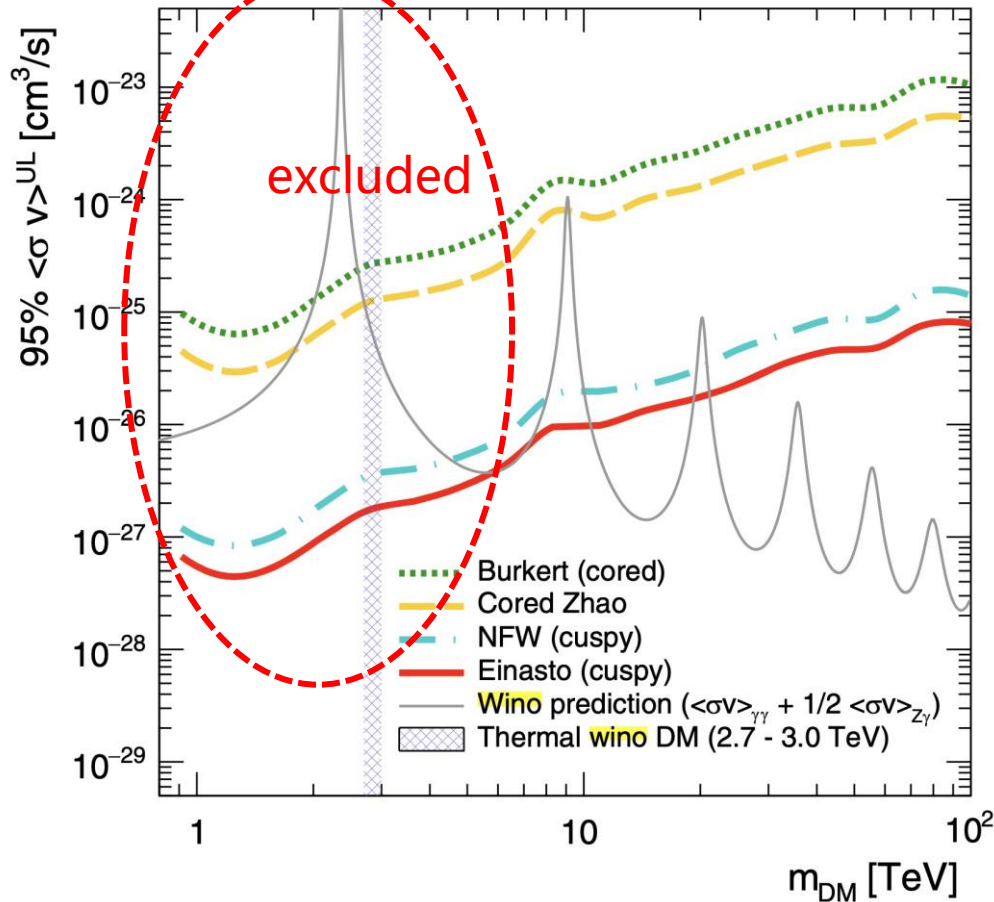
- all/part of Electroweak-ino sector are light

$$\{ \tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d \}$$

^{in this work}



MSSM wino \tilde{W} DM < 5 TeV is NOT favored by indirect exp.



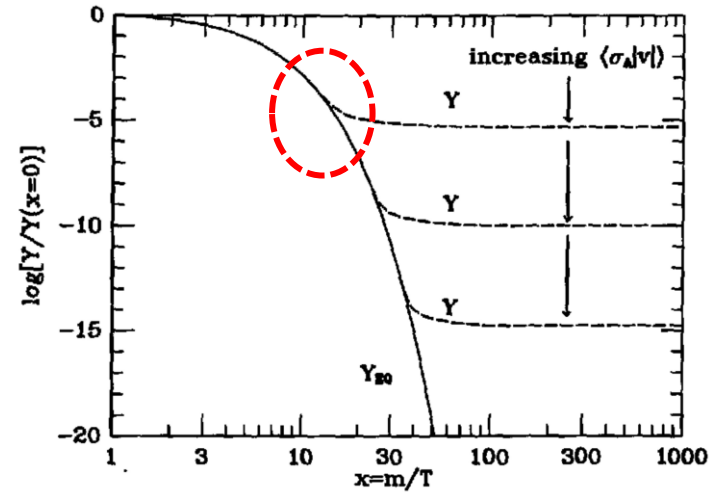
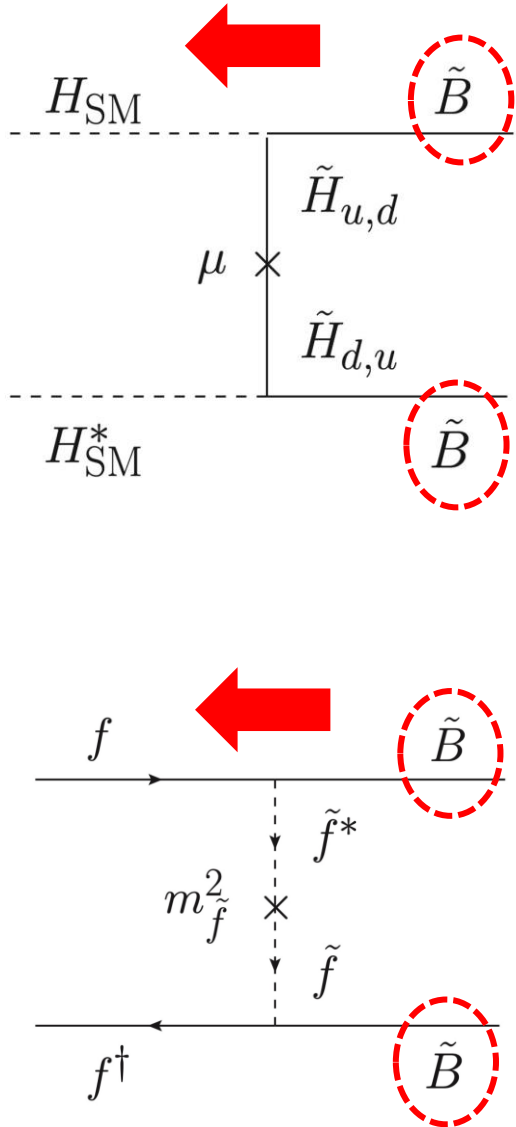
respective masses. Therefore, for the cuspy profiles, we can exclude wino annihilations for masses below 5 TeV and

FIG. 3. Upper limits for the four DM density profiles considered in this Letter: the cuspy Einasto Galactic density profile (red solid line), the NFW profile (cyan dashed line), a DM core according to Ref. [56] (yellow dashed line), and the Burkert fit from Ref. [53] (green dotted line), compared against the total $\langle \sigma v \rangle$ corresponding to annihilation of two SUSY winos [i.e., $SU(2)_L$ triplets] into a $\gamma\gamma$ pair according to Refs. [11, 13–15] (gray solid line; see text for details). The vertical blue hatched region indicates wino masses from 2.7 to 3.0 TeV which are consistent with the observed DM relic density [14].

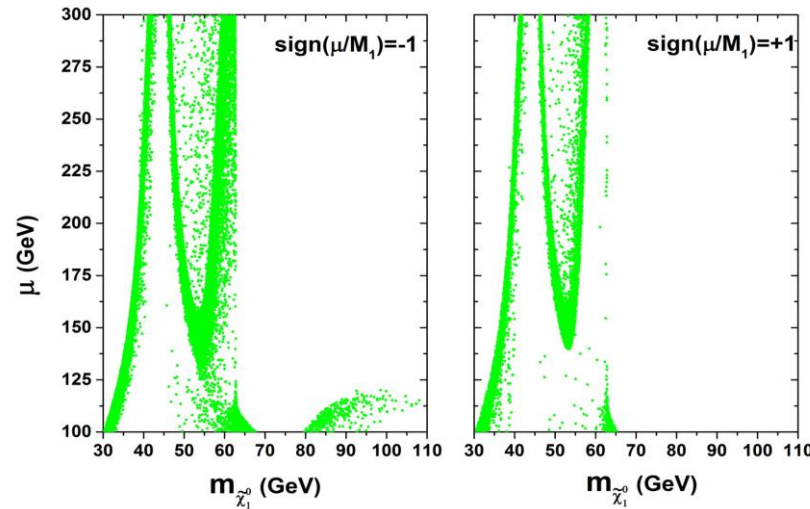
$$\{ \tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d \}$$

binos \tilde{B} DM is the opposite, interacting *too weakly* with SM

Freeze-*Out* scenario usually difficult to meet



Freeze-*Out* too early, overly abundant

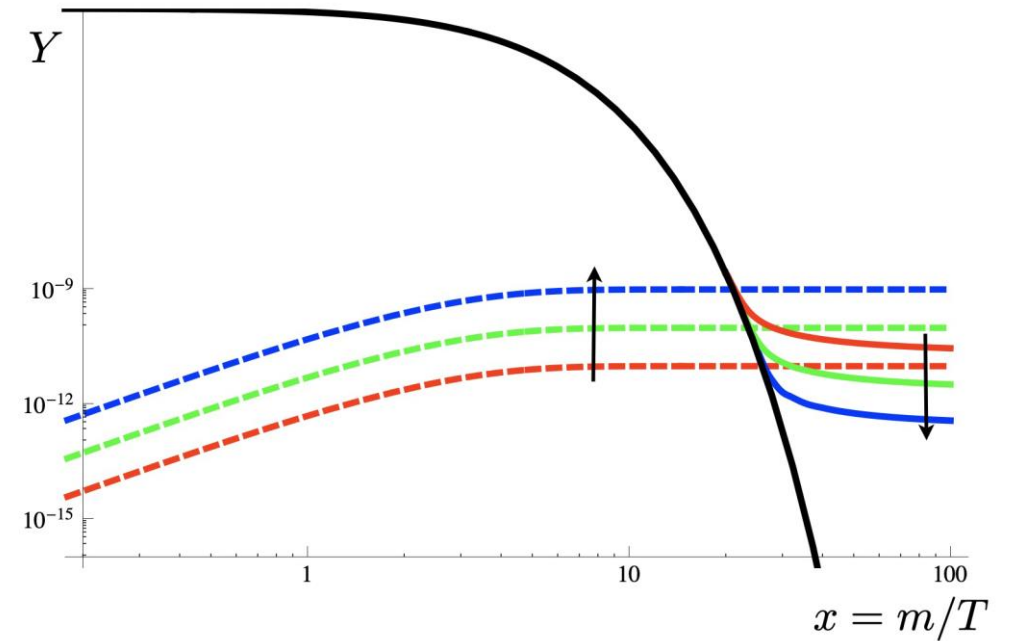
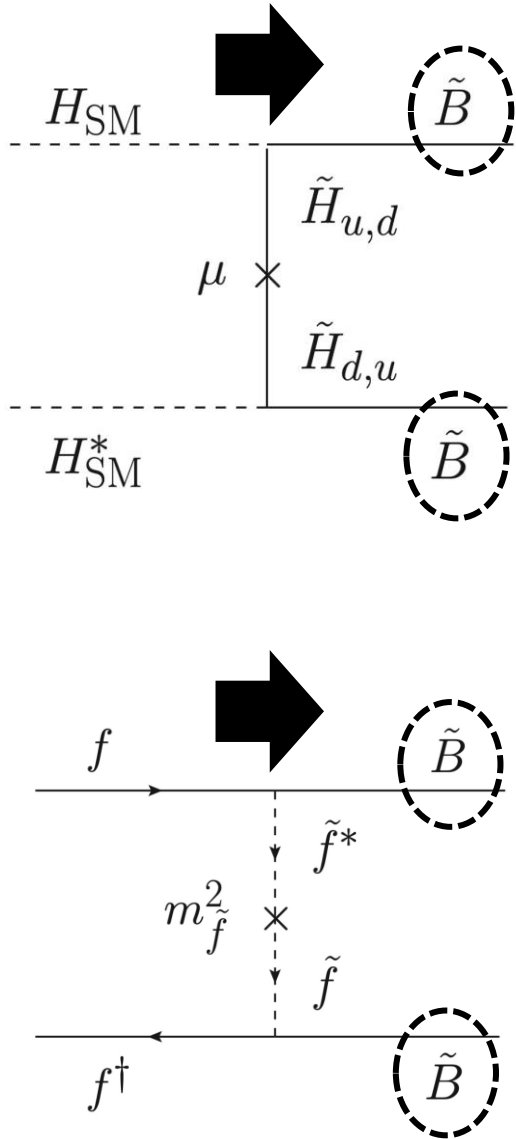


Abdughani, Wu, Yang
1705.09164

some Higgsino \tilde{H}_u, \tilde{H}_d components is needed in bino-dominated DM

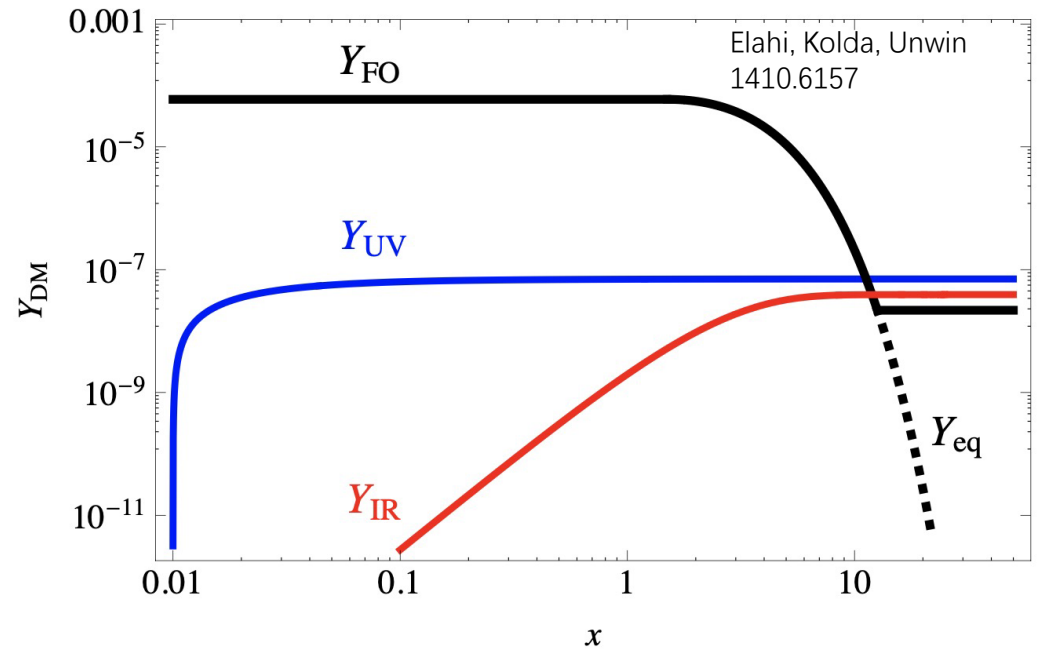
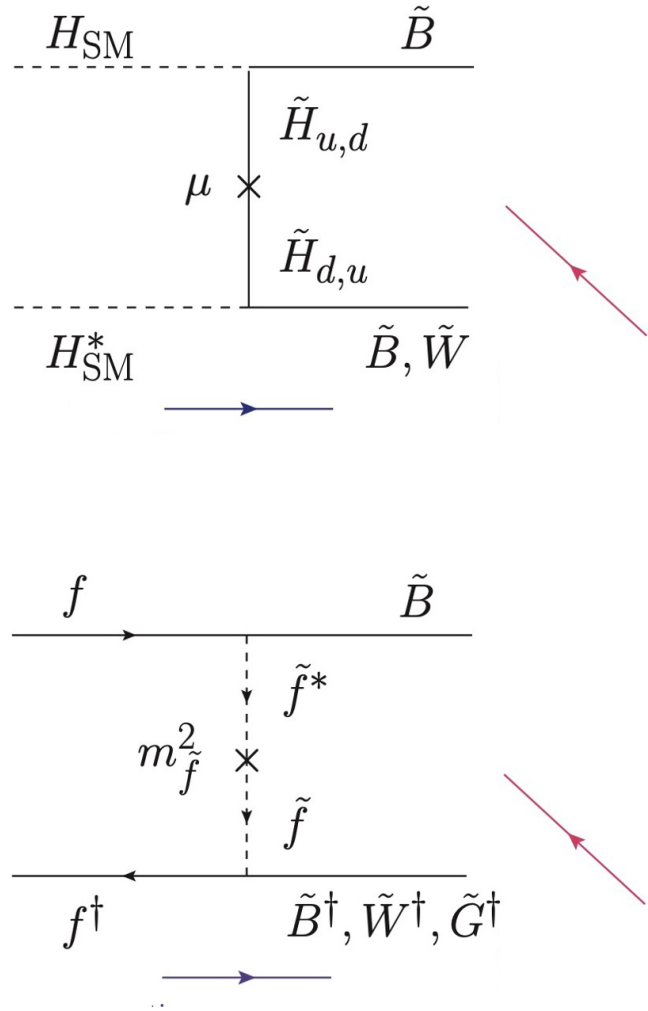
binos \tilde{B} DM is the opposite, interacting *too weakly* with SM

How about *Freeze-In* ?



Freeze-In Bino,

UV or IR type ?



Boltzmann equation

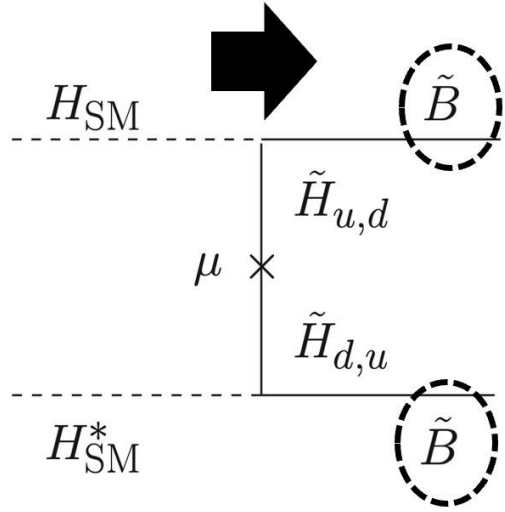
$$\frac{d}{dt}n_{\tilde{B}} + 3\mathcal{H}n_{\tilde{B}} = \mathbf{C}$$

$$\frac{dY_{HH^* \rightarrow \tilde{B}\tilde{B}}(T)}{dT} = -\frac{\mathbf{C}_{HH^* \rightarrow \tilde{B}\tilde{B}}}{ST\mathcal{H}}$$

dependence behavior on temperature T
determines production efficiency

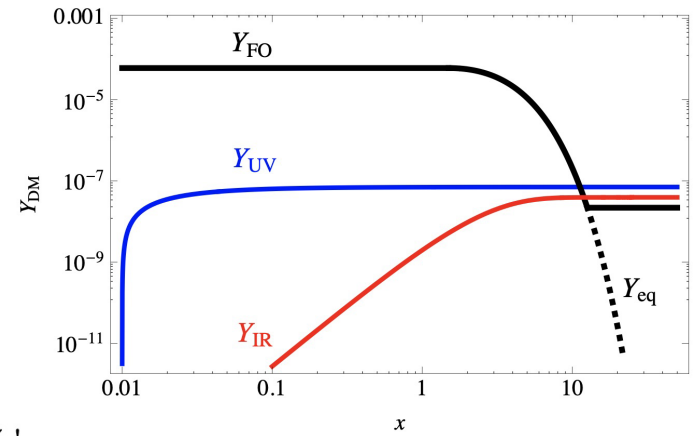
UV Freeze-In: dim-5, 2 → 2 fusion

Elahi, Kolda, Unwin
1410.6157



$$\mathcal{L}_{HH^* \rightarrow \tilde{B}\tilde{B}}^{\text{eff}} = \frac{2g_1^2 Y_H^2}{\mu} \sin \beta \cos \beta (|H_{\text{SM}}|^2) (\tilde{B}\tilde{B} + \tilde{B}^\dagger \tilde{B}^\dagger)$$

$$\frac{d}{dt} n_{\tilde{B}} + 3\mathcal{H} n_{\tilde{B}} = \mathbf{C}_{HH^* \rightarrow \tilde{B}\tilde{B}} \approx \frac{g_1^4}{4} \frac{1}{\pi^5} \frac{\sin^2 \beta \cos^2 \beta}{\mu^2} T^6$$



$$\frac{dY_{HH^* \rightarrow \tilde{B}\tilde{B}}(T)}{dT} = -\frac{\mathbf{C}_{HH^* \rightarrow \tilde{B}\tilde{B}}}{ST\mathcal{H}} \approx -(1.25 \times 10^{-3}) \times M_{\text{Pl}} \frac{\mathbf{C}_{HH^* \rightarrow \tilde{B}\tilde{B}}}{T^6} \approx -(1 \times 10^{-6}) \times M_{\text{Pl}} g_1^4 \frac{\sin^2 \beta \cos^2 \beta}{\mu^2}$$

$$Y_{HH^* \rightarrow \tilde{B}\tilde{B}}(\infty) \approx (1 \times 10^{-6}) \times M_{\text{Pl}} g_1^4 \frac{\sin^2 \beta \cos^2 \beta}{\mu^2} T_{\text{RH}}$$

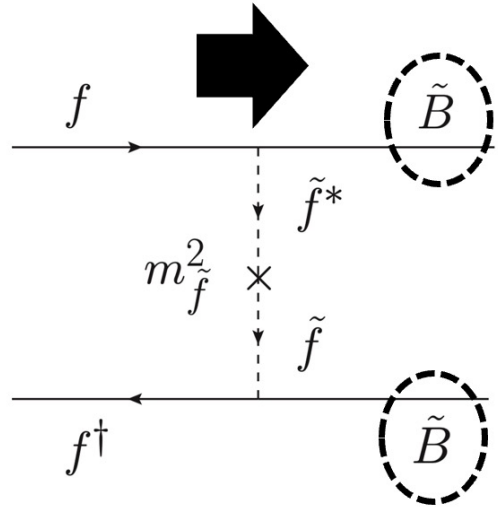
depending on Reheating Temperature T_{RH} , sensitive to UV physics,

Thus UV Freeze-In

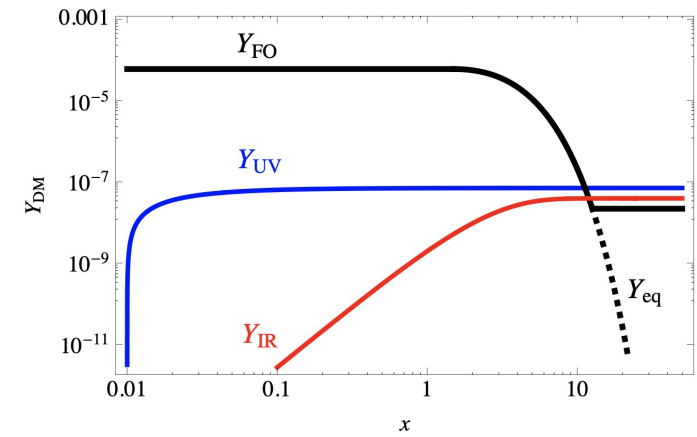
$$(\Omega_{\tilde{B}} h^2)_{HH^* \rightarrow \tilde{B}\tilde{B}} = M_1 \frac{Y_{HH^* \rightarrow \tilde{B}\tilde{B}}(\infty) S_0}{\rho_{\text{cr}}} \approx Y_{HH^* \rightarrow \tilde{B}\tilde{B}}(\infty) \left(\frac{M_1}{\text{TeV}} \right) \times (2.72 \times 10^{11})$$

UV Freeze-In: dim-6, $2 \rightarrow 2$ fusion

Elahi, Kolda, Unwin
1410.6157



$$\mathcal{L}_{f\bar{f} \rightarrow \tilde{B}\tilde{B}}^{\text{eff}} = \sum_{f=q,l} \frac{(\sqrt{2}g_1 Y_f)(\sqrt{2}g_1 Y_f)}{M_{\tilde{f}}^2} (f^\dagger \tilde{B}^\dagger)(f \tilde{B})$$



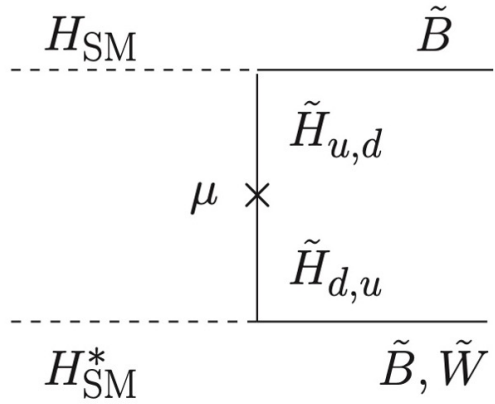
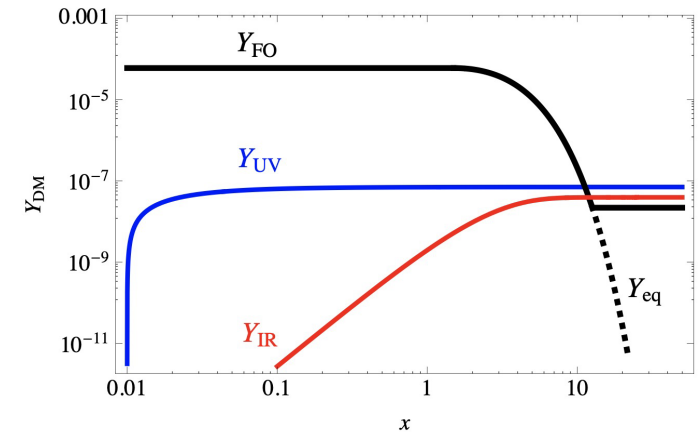
$$\frac{dY_{HH^* \rightarrow \tilde{B}\tilde{B}}(T)}{dT} = -\frac{C_{HH^* \rightarrow \tilde{B}\tilde{B}}}{ST\mathcal{H}} \approx -(1.25 \times 10^{-3}) \times M_{\text{Pl}} \frac{C_{f\bar{f} \rightarrow \tilde{B}\tilde{B}}}{T^6} \approx -(8.6 \times 10^{-5}) \times M_{\text{Pl}} \frac{g_1^4}{M_{\tilde{f}}^4} T^2$$

$$Y_{f\bar{f} \rightarrow \tilde{B}\tilde{B}}(\infty) \approx (4.7 \times 10^{-7}) \times \frac{M_{\text{Pl}}}{M_{\tilde{f}}^4} \boxed{T_{\text{RH}}^3} \quad \leftarrow \text{UV Freeze-In}$$

$$(\Omega_{\tilde{B}} h^2)_{f\bar{f} \rightarrow \tilde{B}\tilde{B}} = M_1 \frac{Y_{f\bar{f} \rightarrow \tilde{B}\tilde{B}}(\infty) S_0}{\rho_{\text{cr}}} \approx Y_{f\bar{f} \rightarrow \tilde{B}\tilde{B}}(\infty) \left(\frac{M_1}{\text{TeV}} \right) \times (2.72 \times 10^{11})$$

IR Freeze-In: decay production

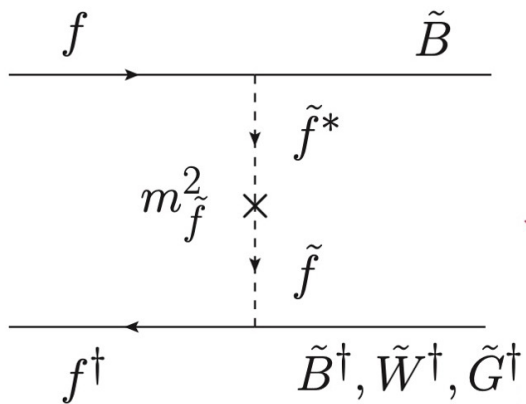
Elahi, Kolda, Unwin
1410.6157



$$\frac{d}{dt}n_{\tilde{B}} + 3\mathcal{H}n_{\tilde{B}} = \mathbf{C}$$

$$\approx \frac{g_{\tilde{G}}M_3^2}{2\pi^2} T K_1\left(\frac{M_3}{T}\right) \Gamma_{\tilde{G} \rightarrow f\tilde{f}\tilde{B}} + \frac{g_{\tilde{W}}M_2^2}{2\pi^2} T K_1\left(\frac{M_2}{T}\right) (\Gamma_{\tilde{W} \rightarrow f\tilde{f}\tilde{B}} + \Gamma_{\tilde{W} \rightarrow HH^*\tilde{B}})$$

peaks at $x = \frac{M}{T} \sim 3$



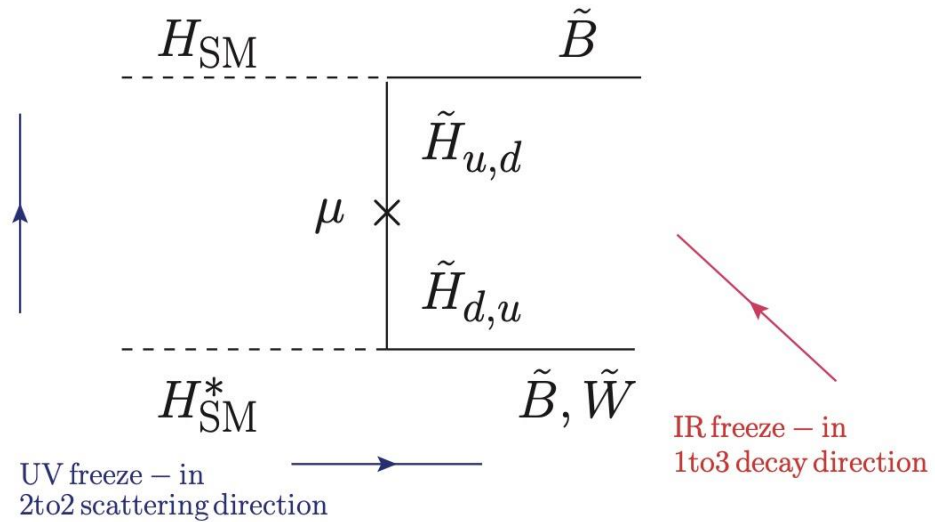
Not sensitive to T_{RH} , IR-dominated production

$$Y_{\tilde{B}}^{1 \rightarrow 3}(\infty) \approx \int_{T_{min}}^{T_{RH}} \frac{\mathbf{C}}{ST\mathcal{H}} dT$$

$$\approx (3 \times 10^{-4}) \times M_{Pl} \left(\frac{1}{M_3^2} g_{\tilde{G}} \Gamma_{\tilde{G} \rightarrow f\tilde{f}\tilde{B}} + \frac{1}{M_2^2} g_{\tilde{W}} \Gamma_{\tilde{W} \rightarrow f\tilde{f}\tilde{B}} + \frac{1}{M_2^2} g_{\tilde{W}} \Gamma_{\tilde{W} \rightarrow HH^*\tilde{B}} \right)$$

MSSM setup in this work

Mass spectrum and DM production processes



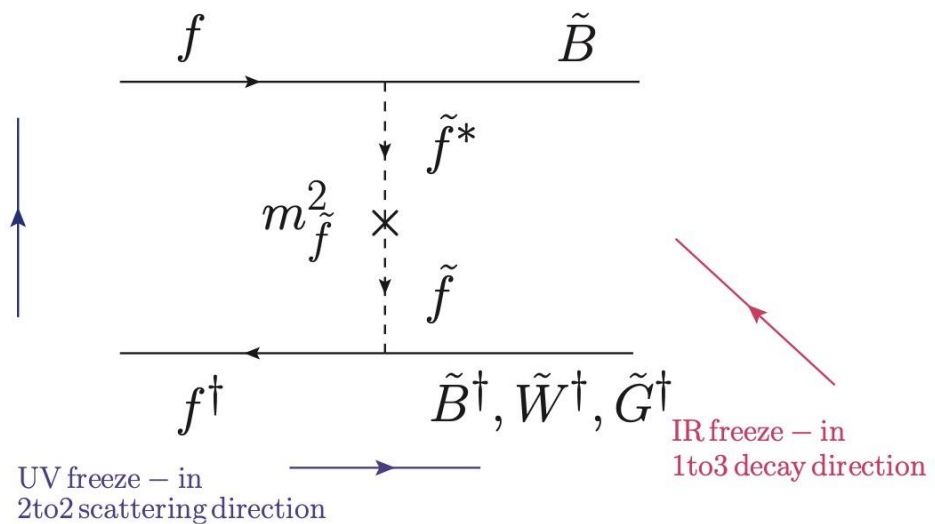
- **Heavy sector, inactive** after cosmological reheating

Mass: $M \sim M_{SUSY} \gg T_{RH}$

- ★ Higgs bosons not in SM: H_{NP}^0, A, H_{NP}^\pm
- ★ Sfermions \tilde{f}
- ★ Higgsinos \tilde{H}_u, \tilde{H}_d

M_{SUSY} —

T_{RH} —



- **Light sector, active** after cosmological reheating

Mass: $M \sim \mathcal{O}(1) \text{ TeV} \ll M_{SUSY}$

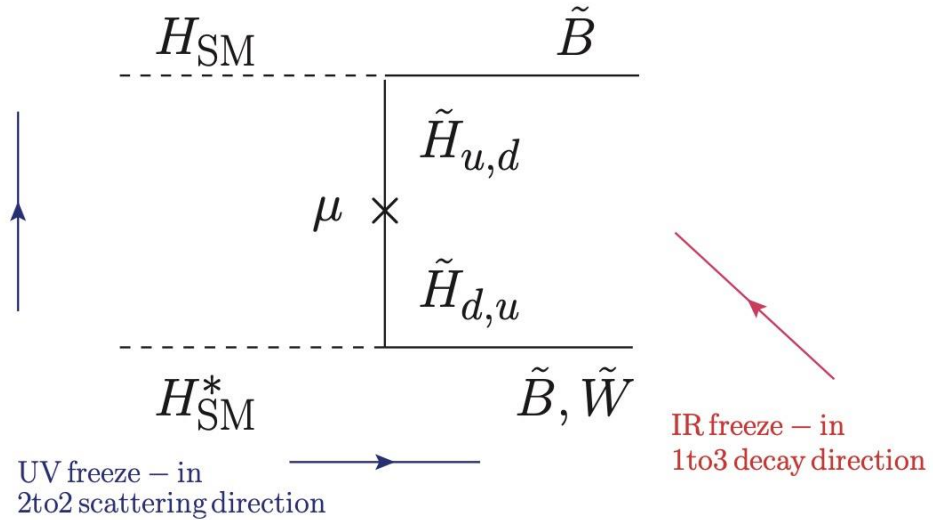
- ★ SM particles
- ★ Bino \tilde{B}
- ★ Winos \tilde{W} , with mass M_2
- ★ Gluinos \tilde{G} , with mass M_3

$\mathcal{O}(1) \text{ TeV}$ —

Energy
Scale

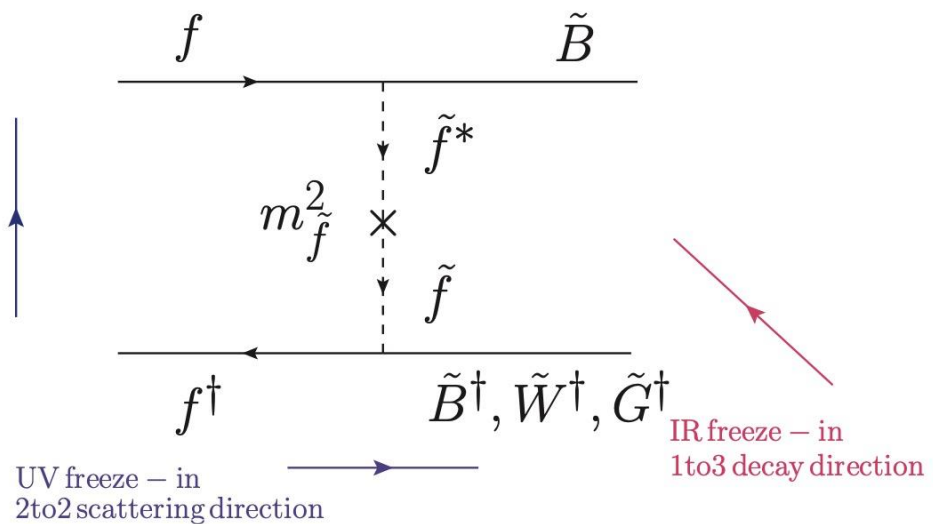
cosmic
evolution
 $t, 1/T$

Phenomenology



- to meet the observed DM abundance
 - interplay with Big Bang Nuclear-synthesis (BBN)

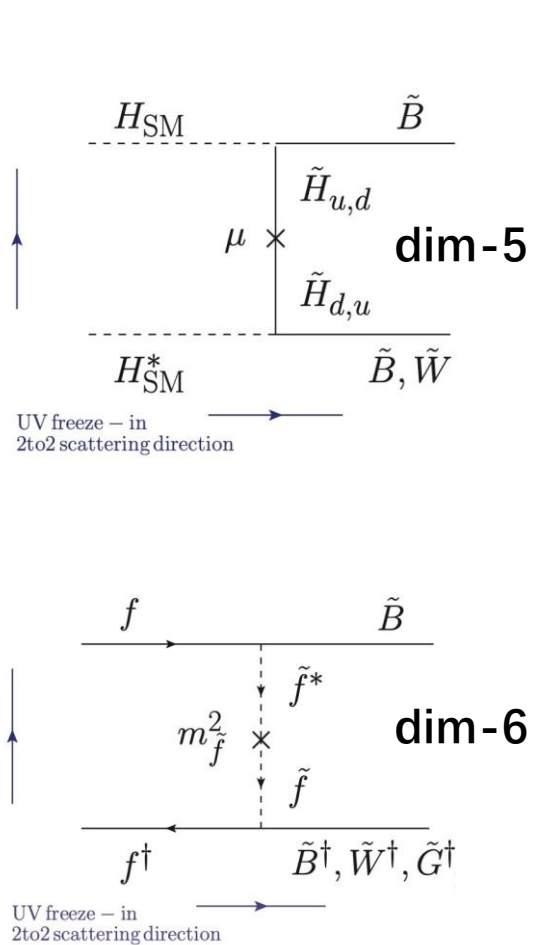
- collider constraints on Long-Lived particle (LLP)
 - disappearing / displaced track



- DM direct/indirect signal
 - negligible for bino in our setup

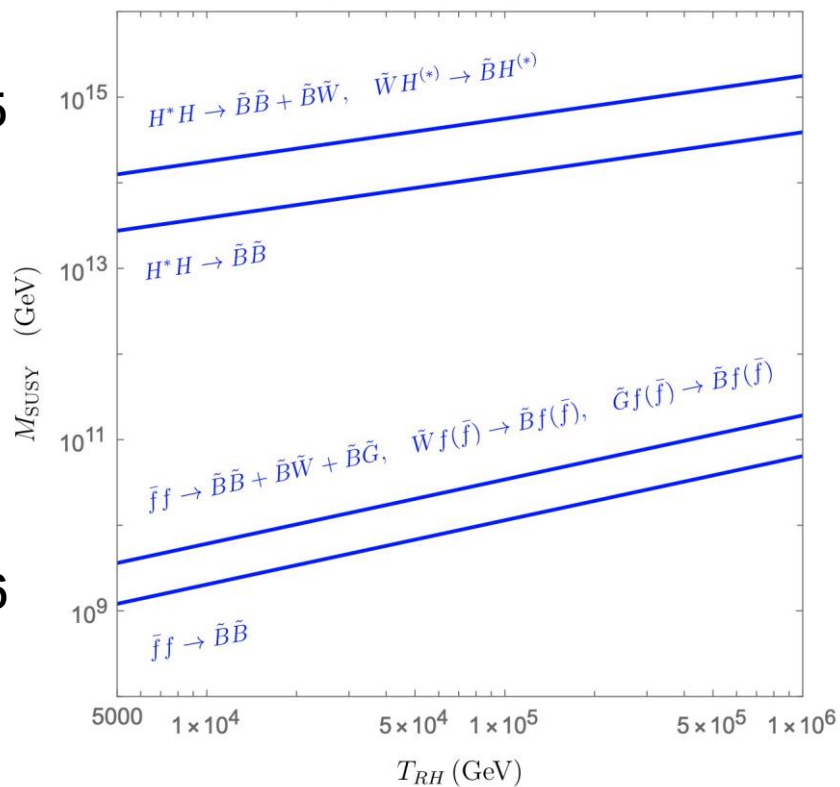
Main results

DM abundance, mass scale of heavy sector



$$\Omega_{\tilde{B}} h^2 = 0.12, \quad \tan \beta = 1$$

$$M_1 = 1 \text{ TeV}, \quad M_2 = 2 \text{ TeV}$$



• Heavy sector, inactive after cosmological reheating

Mass: $M \sim M_{\text{SUSY}} \gg T_{RH}$

- ★ Higgs bosons not in SM: $H_{\text{NP}}^0, A, H_{\text{NP}}^\pm$
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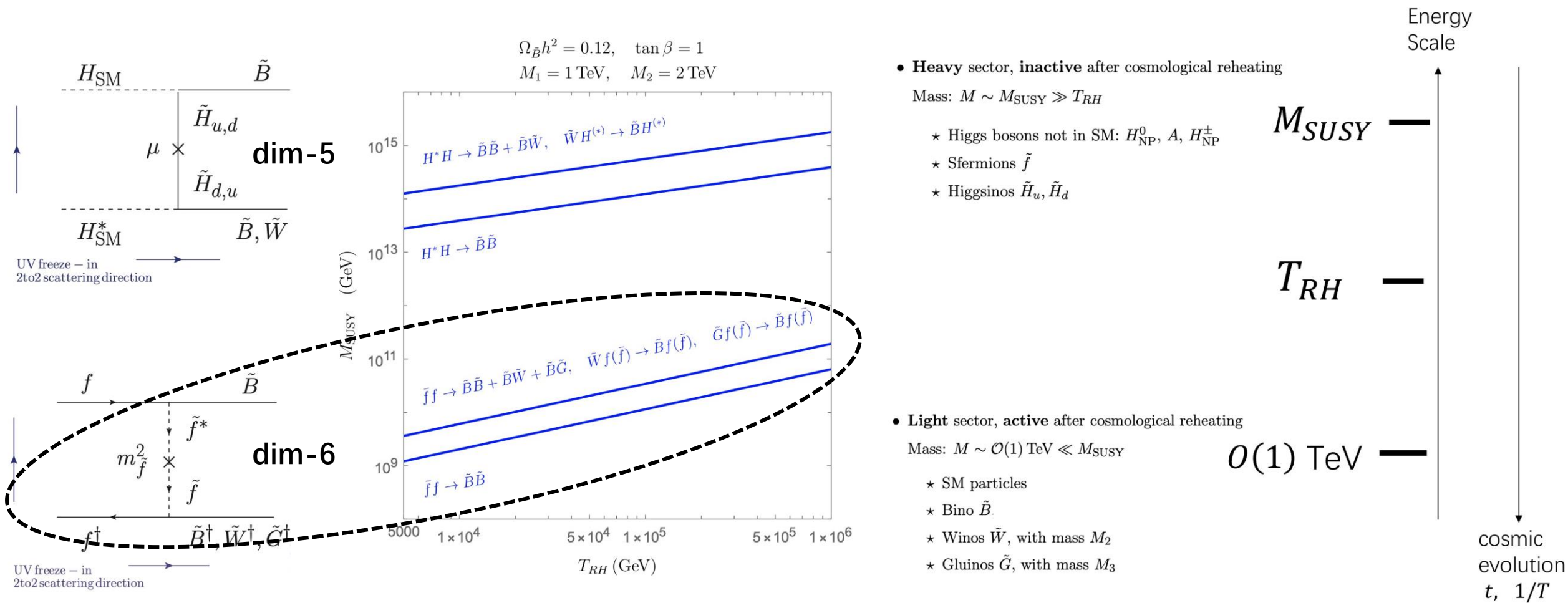
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- ★ Gluinos \tilde{G} , with mass M_3

$\mathcal{O}(1) \text{ TeV}$ —

Energy Scale

cosmic evolution
 $t, 1/T$

DM abundance, mass scale of heavy sector



if a universal heavy scale is assumed: $O(\mu) \sim O(m_{\tilde{f}})$
 dim-6 contributions will be negligible

Wino Freeze-Out effects properly included

For benchmark wino mass $M_{\tilde{W}} = 2$ TeV

Hall, Jedamzik, March-Russell, West
0911.1120

$\tilde{W} \rightarrow \tilde{B} h$ contribute 25% (1%)
to $Y_{\tilde{B}}$ for $M_{\tilde{B}} = 1$ (0.1) TeV



our case

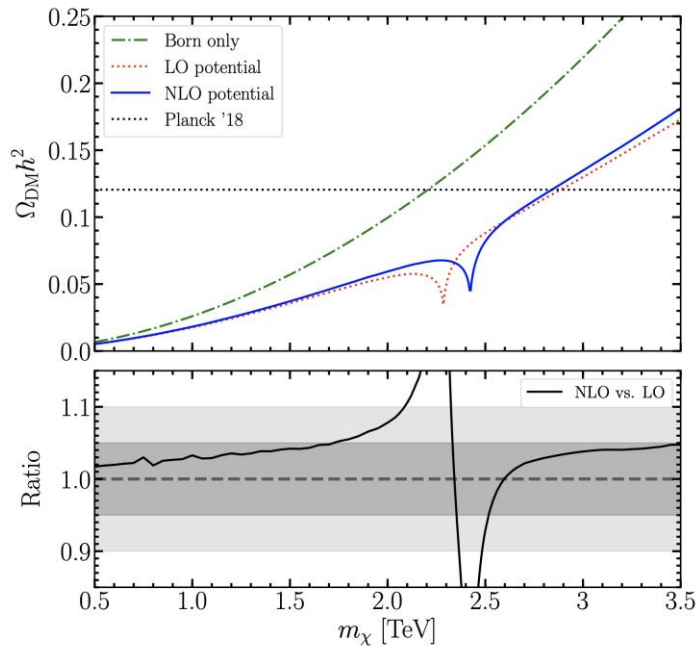
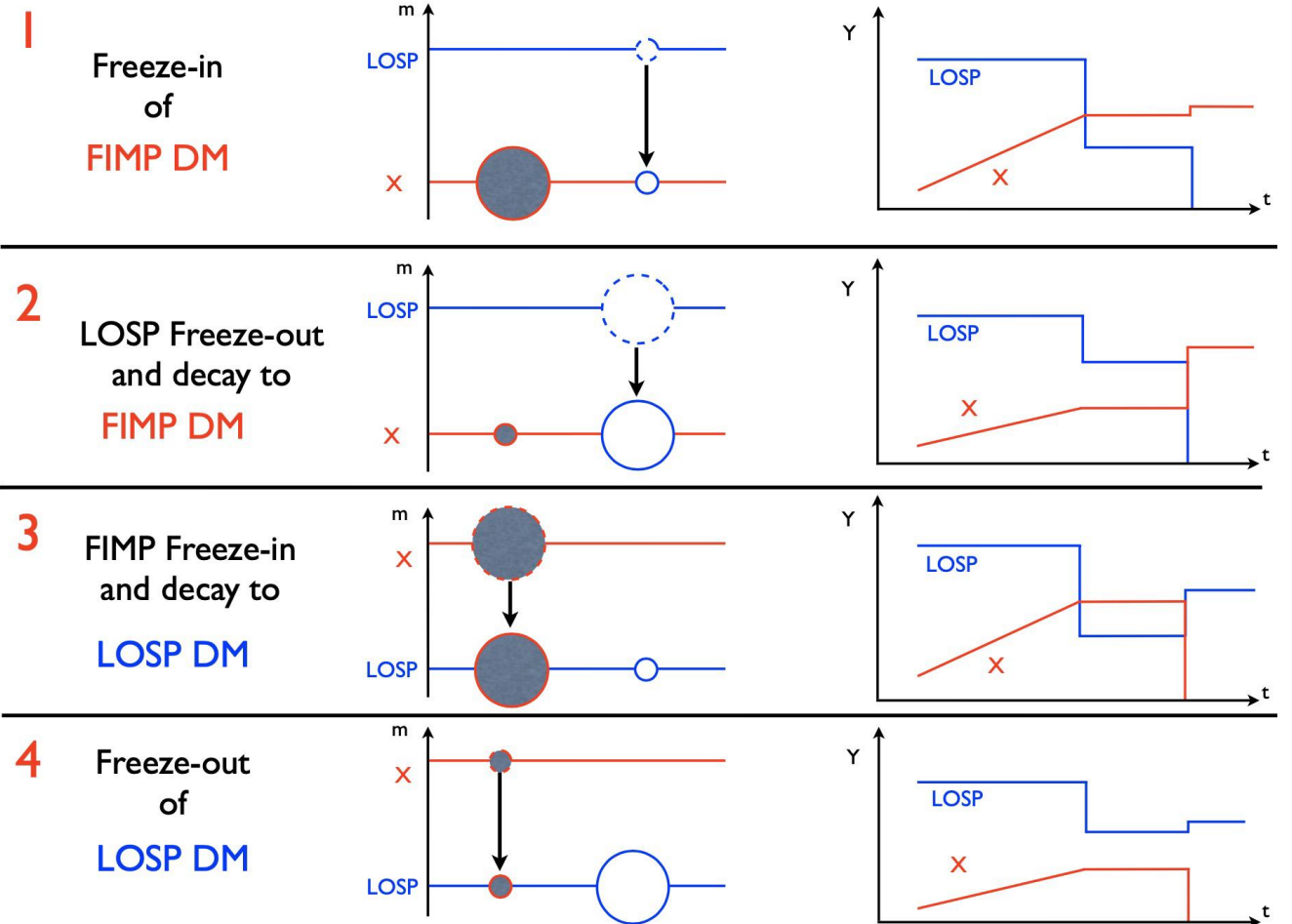


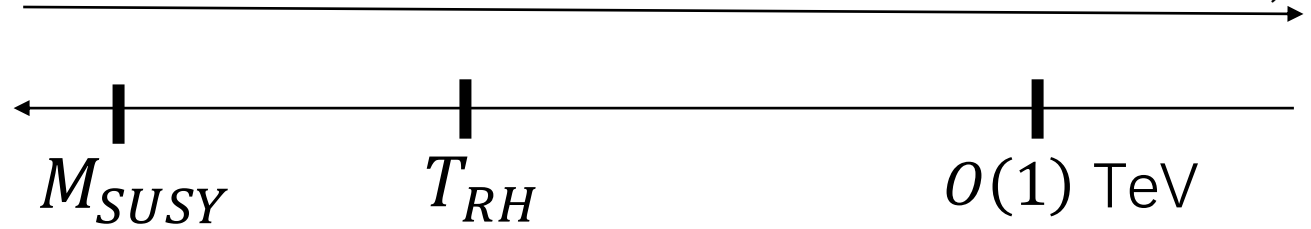
Figure 9. Wino DM relic abundance as function of DM mass m_χ computed with Born cross



UV & IR feature of different Freeze-In processes

cosmic evolution
 $t, 1/T$

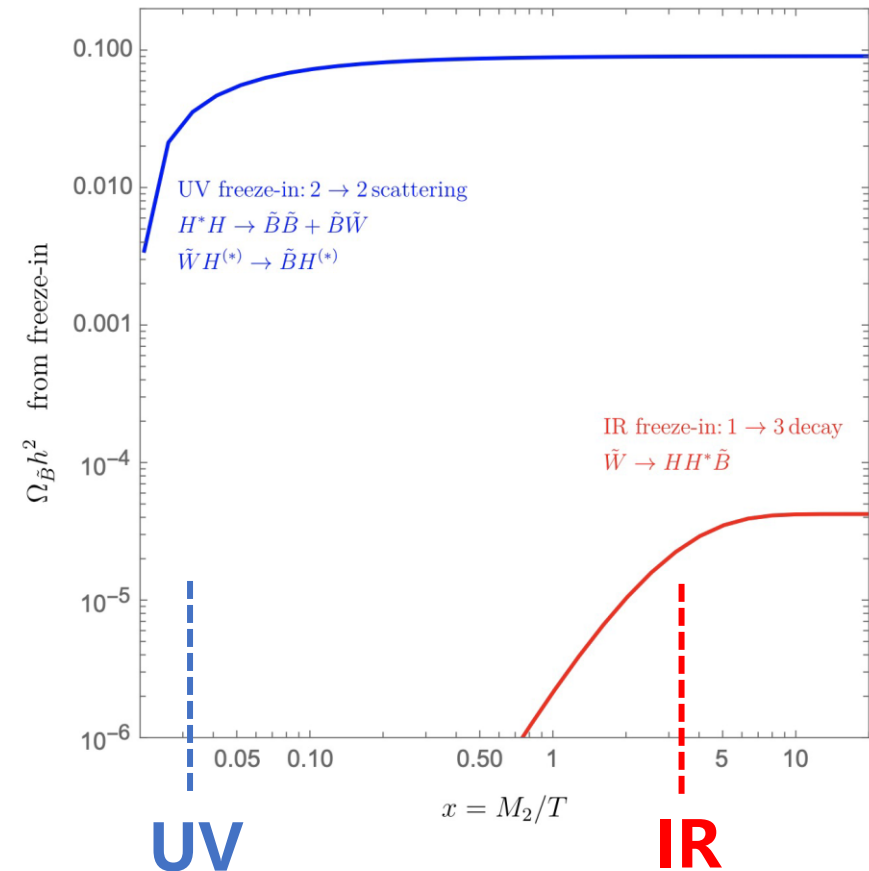
Energy Scale



$$\mu = 5.6 \times 10^{11} \text{ TeV}, \quad T_{RH} = 100 \text{ TeV}$$

$$M_1 = 1 \text{ TeV}, \quad M_2 = 2 \text{ TeV}$$

- we focus on dim-5 operators
- Bino mass choice can affect the specific IR/UV ratio



Interplay between DM abundance & BBN: constrained T_{RH} range:

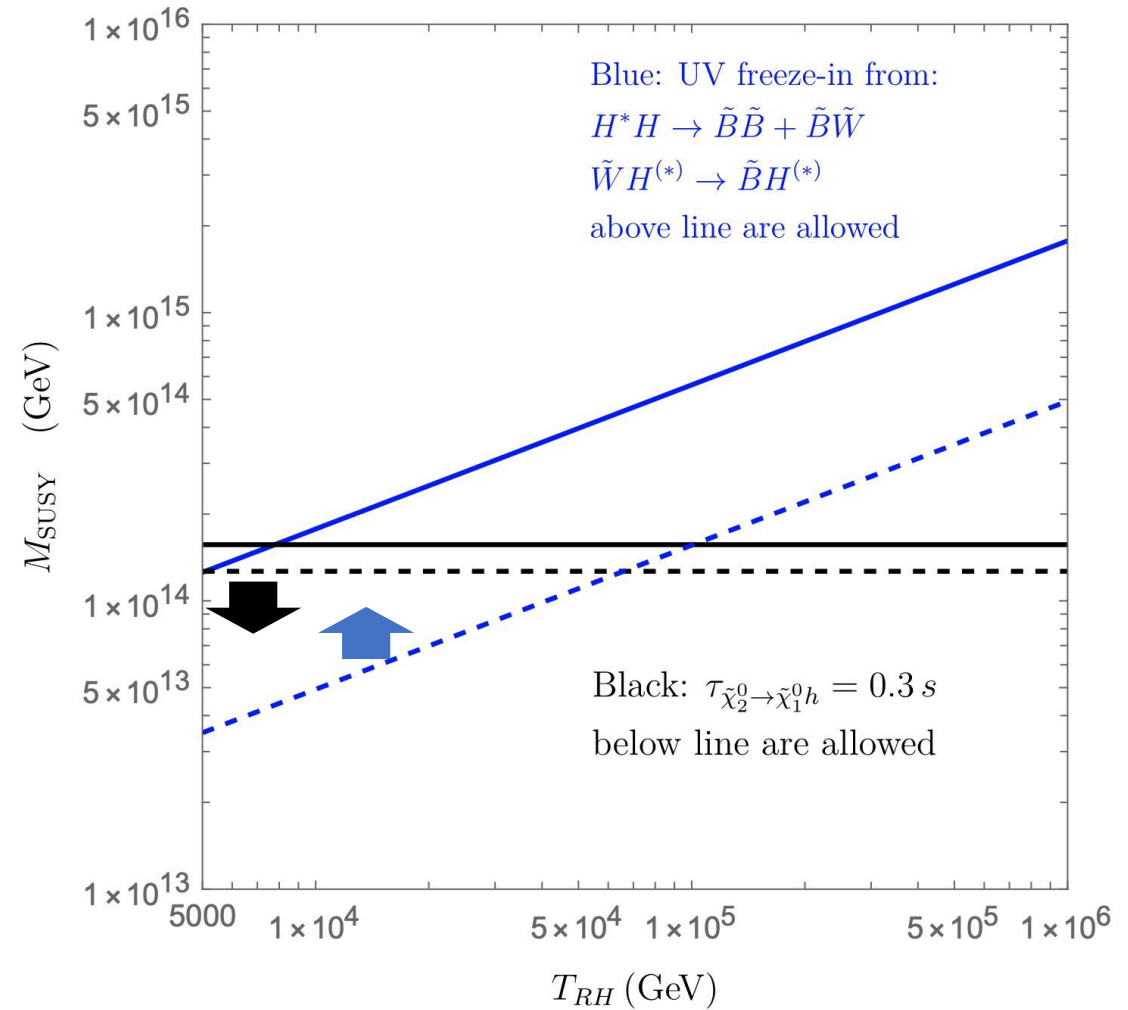
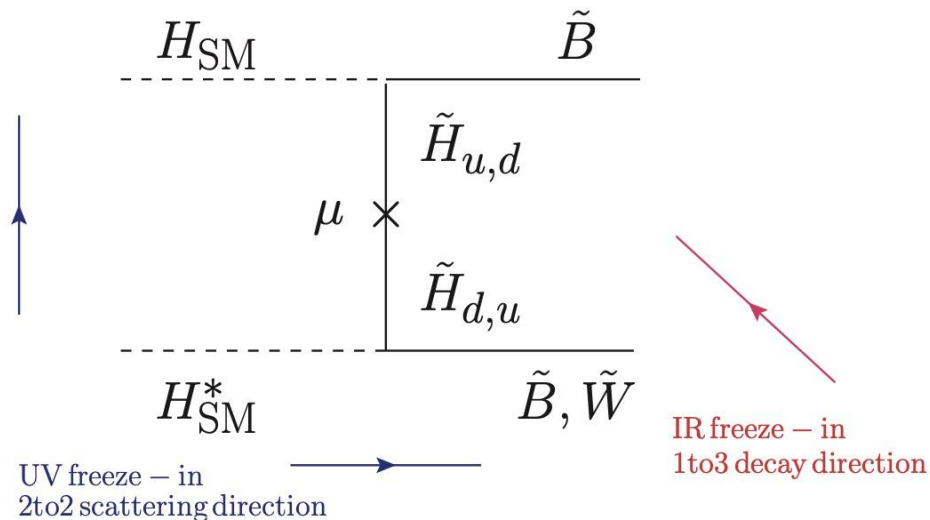
SUSY electroweak-inos must decay before BBN epoch

$\Omega_{\tilde{B}} h^2 = 0.12, \quad \tan \beta = 1, \quad M_2 = 2 \text{ TeV}$
 Solid: $M_1 = 1 \text{ TeV}, \quad$ Dashed: $M_1 = 0.1 \text{ TeV}$

$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_2^0 \pi^\pm$ **safely fast**, generated by loop

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ **dangerous**, μ cannot be too large

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$ not helping decay,
 Γ has extra $\frac{1}{\mu^2}$ suppression



Interplay between DM abundance & BBN: constrained T_{RH} range:

Freeze-In bino scenario imply connection between the two characteristic scales in MSSM

$\Omega_{\tilde{B}} h^2 = 0.12, \quad \tan \beta = 1, \quad M_2 = 2 \text{ TeV}$
 Solid: $M_1 = 1 \text{ TeV}, \quad$ Dashed: $M_1 = 0.1 \text{ TeV}$

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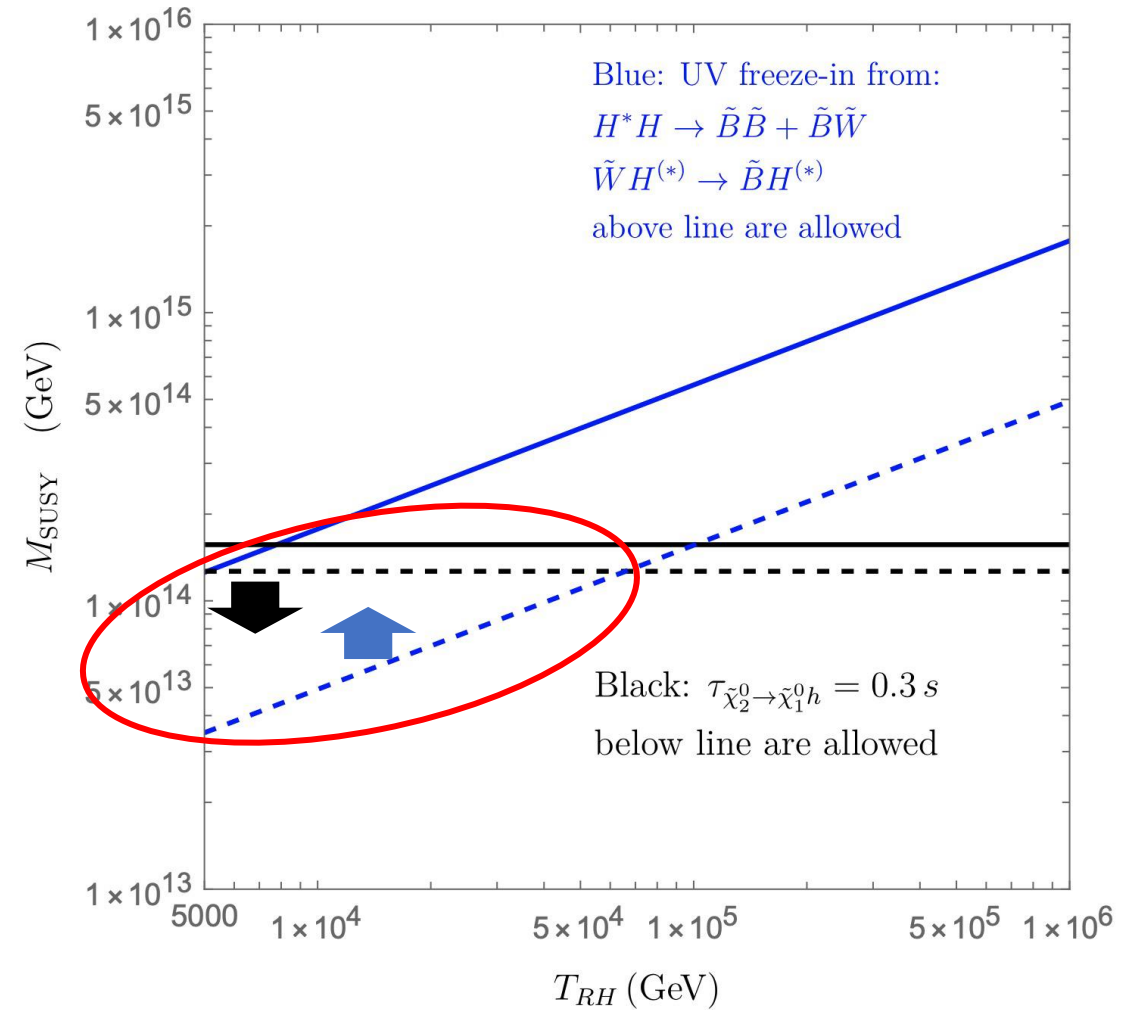
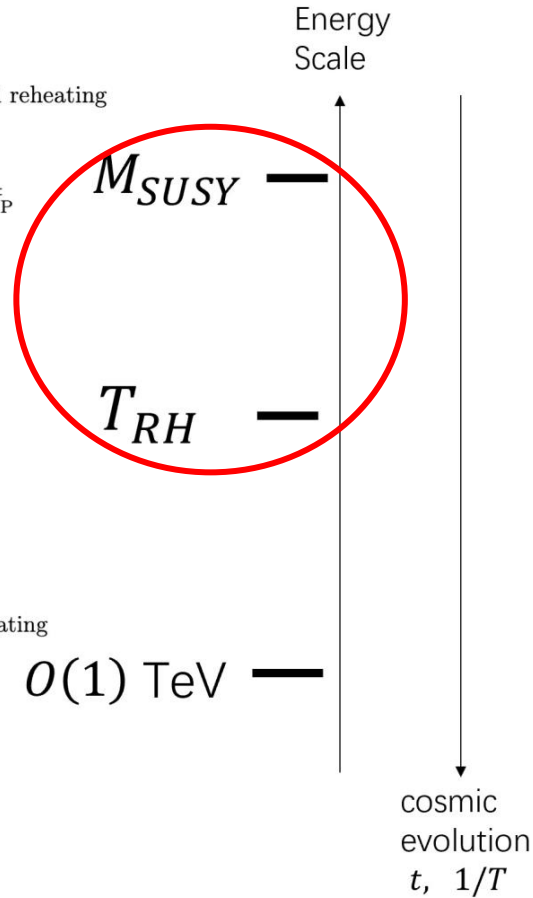
Mass: $M \sim M_{SUSY} \gg T_{RH}$

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- ★ Winos \tilde{W} , with mass M_2
- ★ Gluinos \tilde{G} , with mass M_3



Collider signal profile

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_2^0 \pi^\pm$$

disappearing track, $M_{\tilde{W}} > 0.5$ TeV is allowed. our benchmark $M_{\tilde{W}} = 2$ TeV still allowed

$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$$

$\tau > O(10^{-2})$ s making $\tilde{\chi}^0$ leave the whole detector before decay.

BBN limits on our set-up result in NO displaced vertex at collider.

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp, \tilde{\chi}_1^\pm \tilde{\chi}_2^0$$

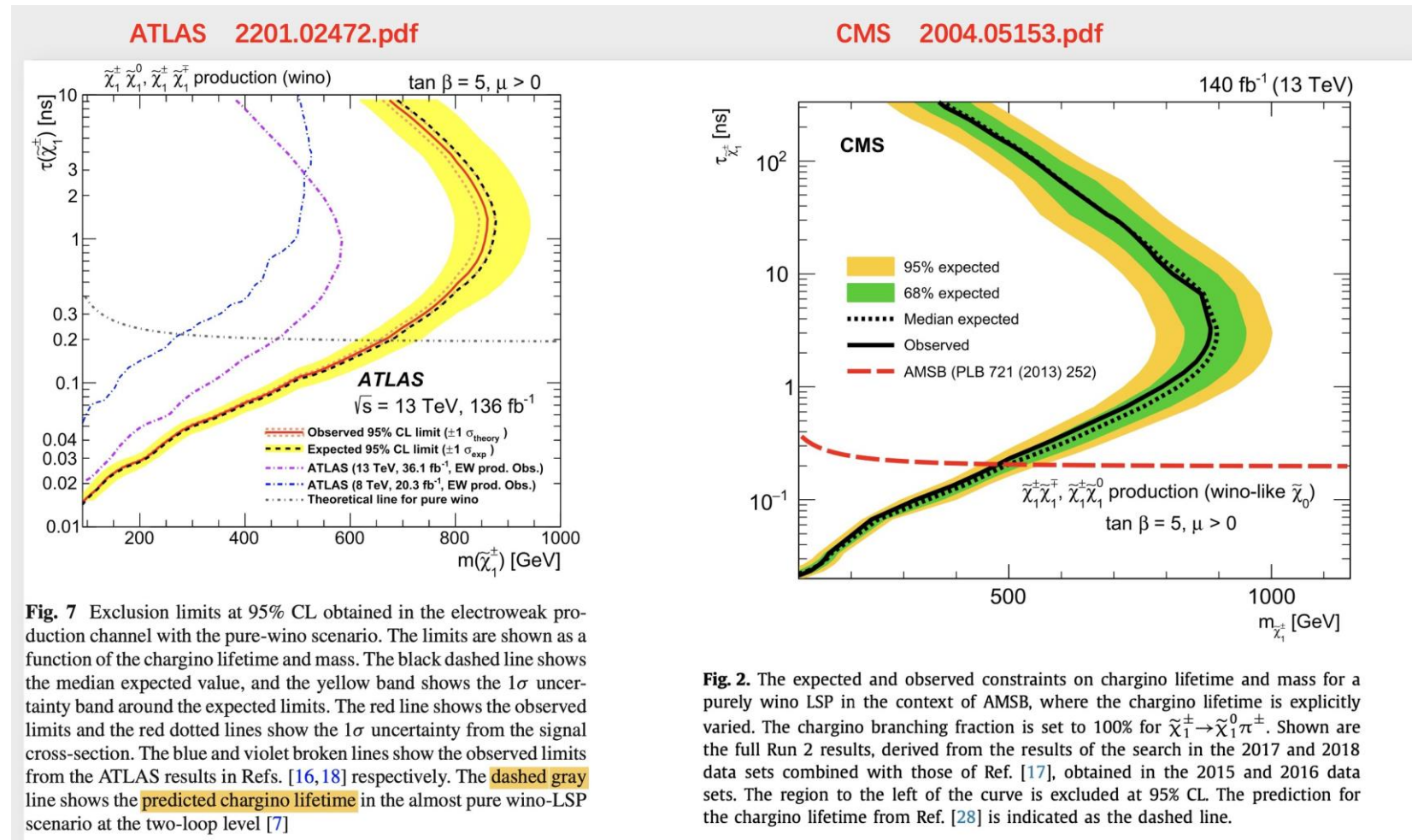


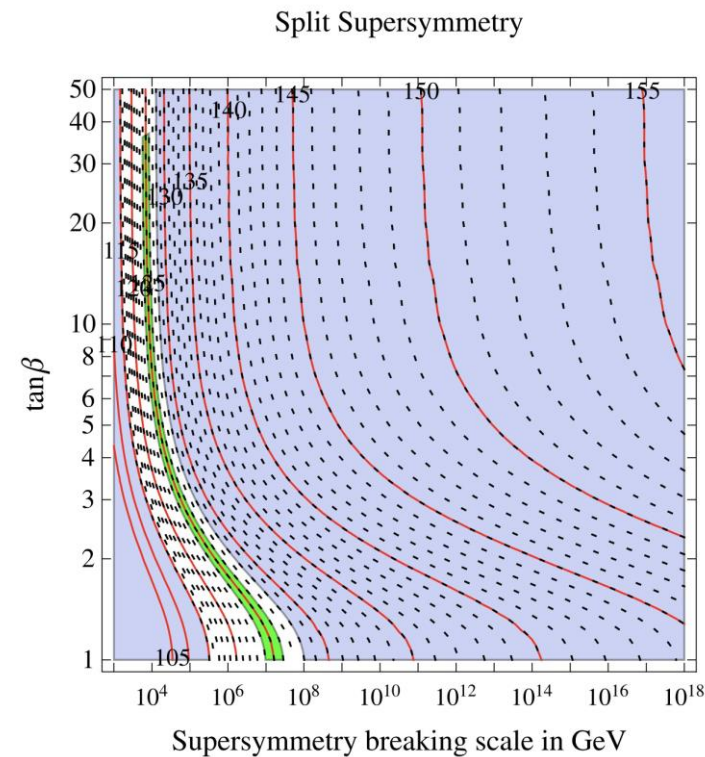
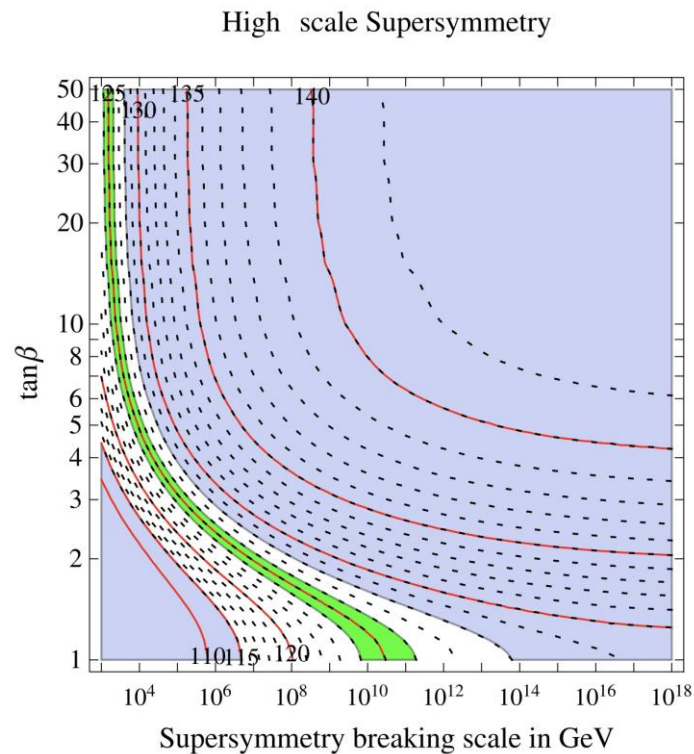
Fig. 7 Exclusion limits at 95% CL obtained in the electroweak production channel with the pure-wino scenario. The limits are shown as a function of the chargino lifetime and mass. The black dashed line shows the median expected value, and the yellow band shows the 1σ uncertainty band around the expected limits. The red line shows the observed limits and the red dotted lines show the 1σ uncertainty from the signal cross-section. The blue and violet broken lines show the observed limits from the ATLAS results in Refs. [16, 18] respectively. The dashed gray line shows the predicted chargino lifetime in the almost pure wino-LSP scenario at the two-loop level [7]

Fig. 2. The expected and observed constraints on chargino lifetime and mass for a purely wino LSP in the context of AMSB, where the chargino lifetime is explicitly varied. The chargino branching fraction is set to 100% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$. Shown are the full Run 2 results, derived from the results of the search in the 2017 and 2018 data sets combined with those of Ref. [17], obtained in the 2015 and 2016 data sets. The region to the left of the curve is excluded at 95% CL. The prediction for the chargino lifetime from Ref. [28] is indicated as the dashed line.

Discussion

Higgs sector

- current limits rely on the chosen uncertainty range of SM inputs (e.g. top Yukawa), relaxing e.g. to 3σ can easily make out setup compatible with 125 GeV Higgs
- fine tuned, as expected



Giudice, Strumia
1108.6077

Discussion

non-universal gaugino masses

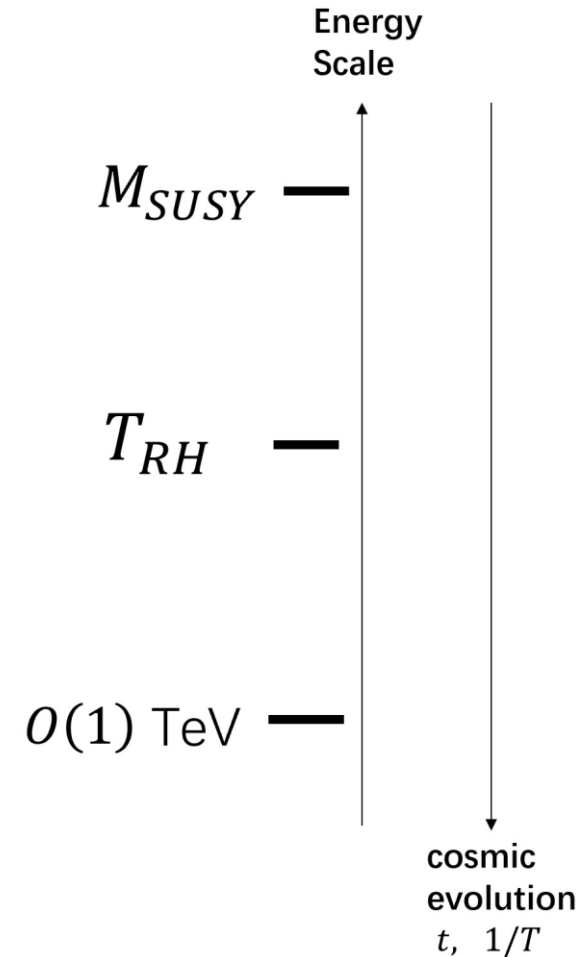
- \tilde{B}, \tilde{W} at $O(1)$ TeV, \tilde{G} at high scale:

possible UV completion

- ascribing distinct representations to SUSY breaking superfield Φ with non-vanishing F-terms, then applying linear combination
- fine tuned, as expected

TABLE II. Ratios of gaugino masses for F -terms in representations of $SU(5) \subset SO(10)$, with the normal (nonflipped) embedding.

$SO(10)$	$SU(5)$	$M_1:M_2:M_3$
1	1	1:1:1
54	24	$-\frac{1}{2}:-\frac{3}{2}:1$
210	1	1:1:1
	24	$-\frac{1}{2}:-\frac{3}{2}:1$
	75	-5:3:1
770	1	1:1:1
	24	$-\frac{1}{2}:-\frac{3}{2}:1$
	75	-5:3:1
	200	10:2:1



Summary

- Supersymmetry manifests the **symmetry faith** of modern physics, but **may not** meet aesthetical taste in pheno. studies
- if sparticles are heavy, Freeze-In bino can be a simple DM realization
 - only gauge couplings involved
 - UV / IR features highlighted in cosmic DM production
 - linking scales of $M_{SUSY} \sim 10^{13-14}$ GeV and $T_{RH} \sim 10^{4-6}$ GeV
 - cosmic history (e.g. BBN) apply further interplay between M_{SUSY} and T_{RH}which may reveal underlying details of SUSY breaking & inflation

