Freeze-in Bino Dark Matter

in High Scale Supersymmetry

arXiv: **2308.14438** (to appear in ***Physical Review D***)

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17th workshop on
TeV Physics and Beyond SM
Dec. 15-19, 2023, Nanjing

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-/commutating generators are considered

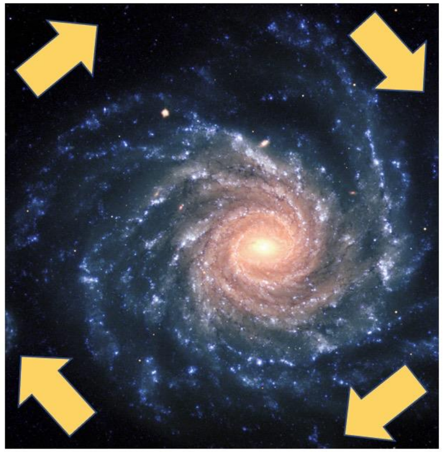
- necessary for string theory
- may solve the naturalness problem (aesthetical choice)

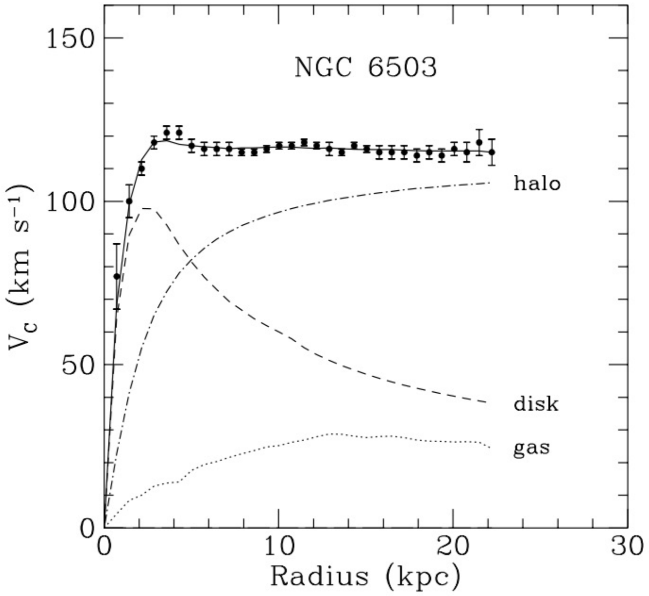
Phenomenologically rich

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

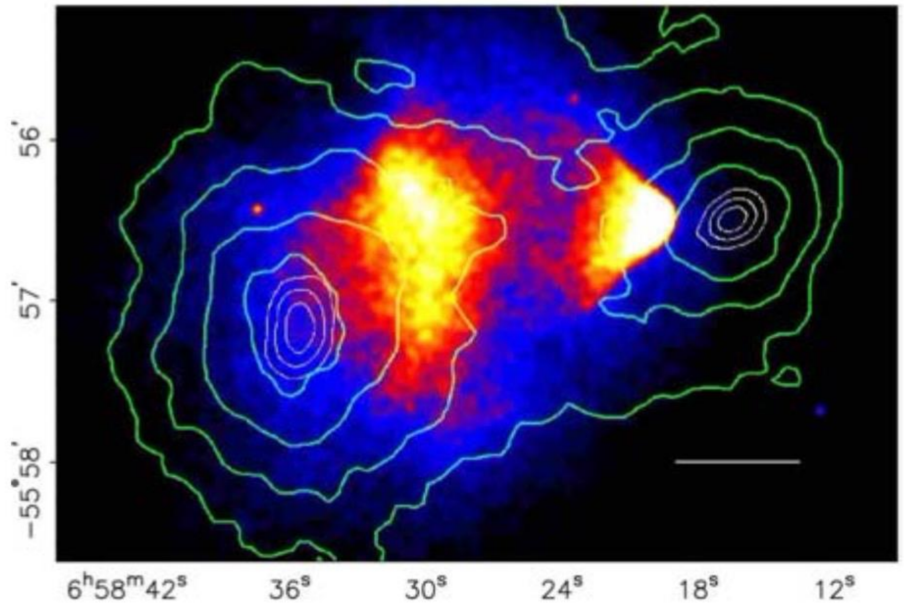
Nature of DM is still unknow

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





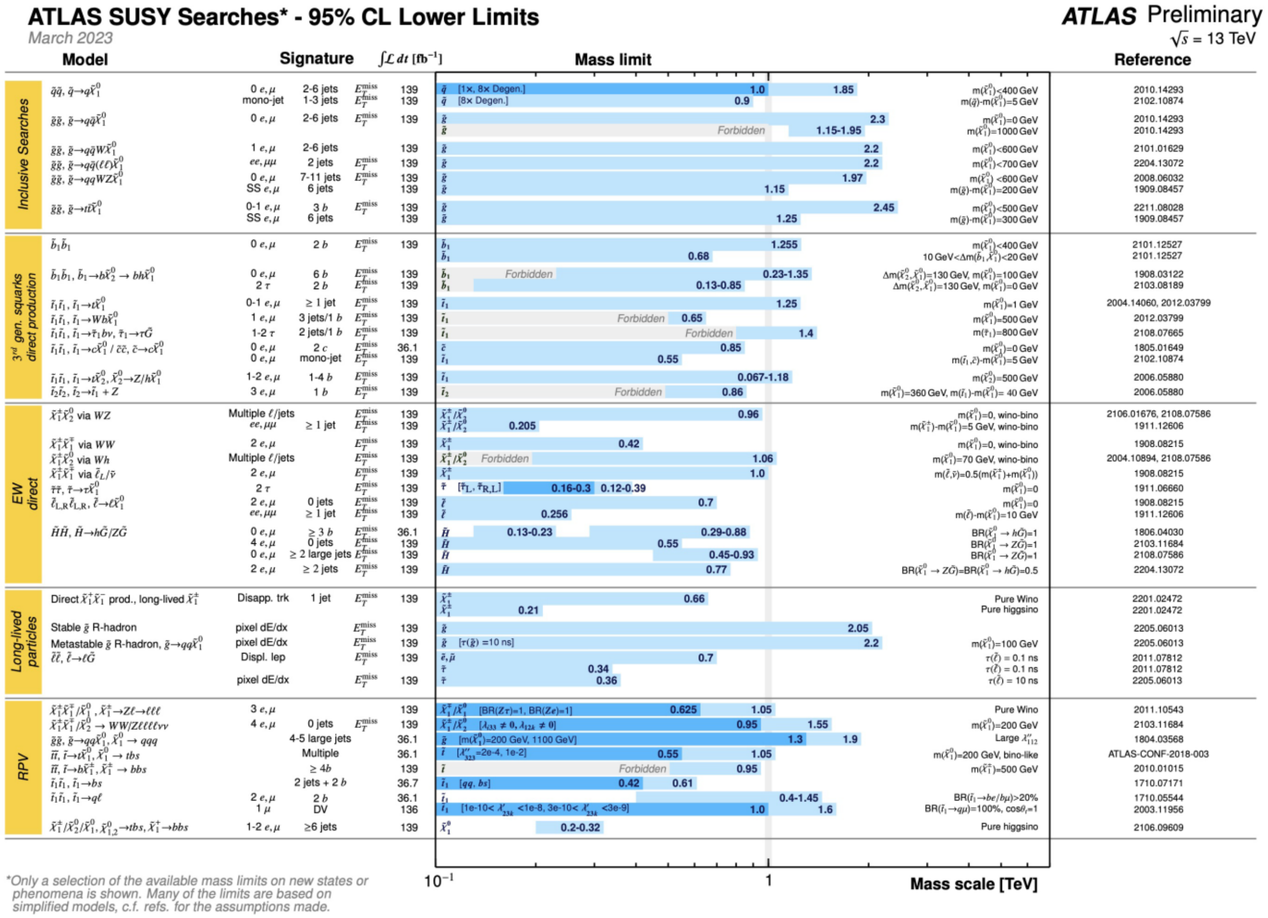
Begeman et al, 1991, MNRAS, 249, 523.



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

Some SUSY particles seems to be heavy

- Esthetical requirement about naturalness problem may need to be relaxed



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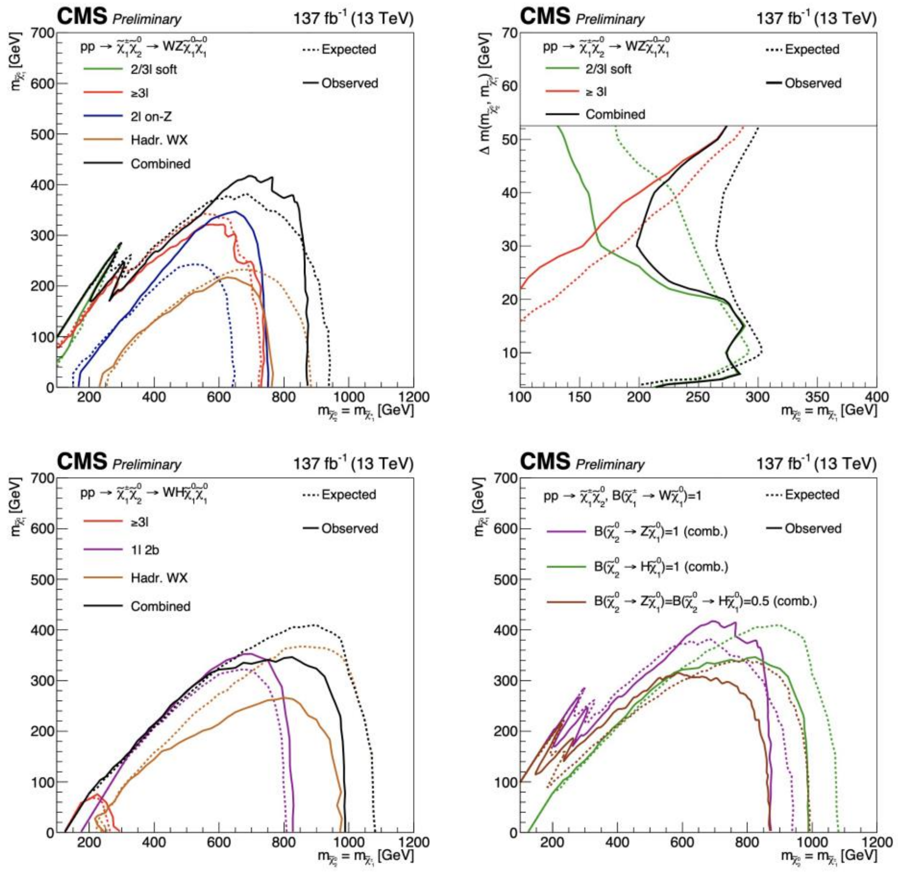

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DM-focused SUSY particle spectrum, concerning exp. results

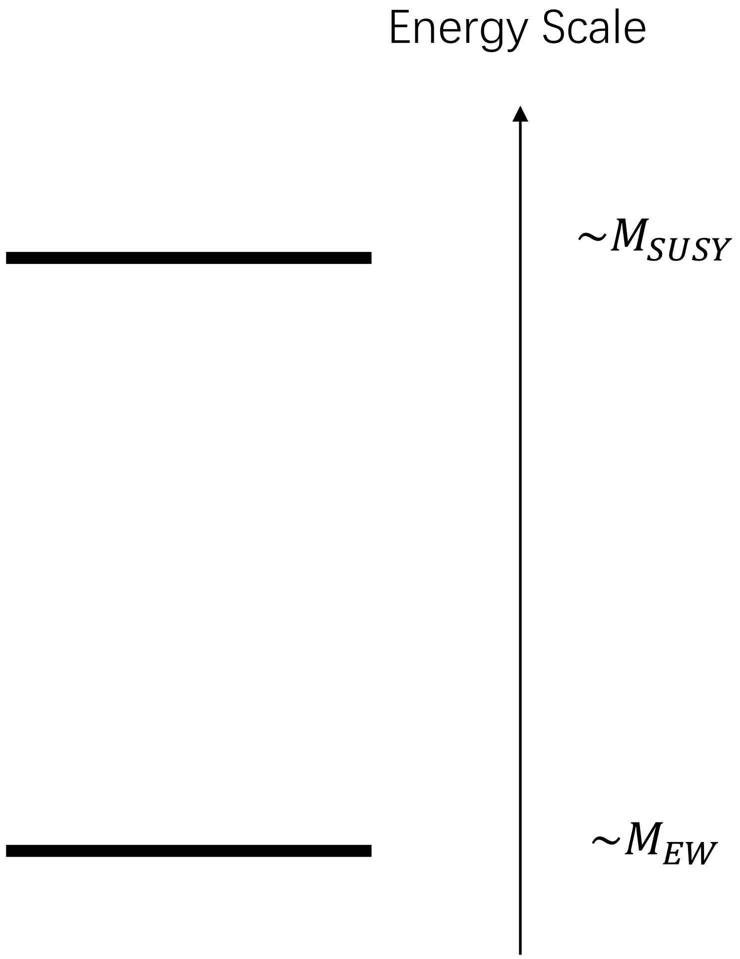
- High Scale SUSY,   Split SUSY,   other variations…

- 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

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



in this work

DM-focused MSSM particle spectrum

- High Scale SUSY, Split SUSY, other variations…

- most SUSY sparticles are assumed to be heavy

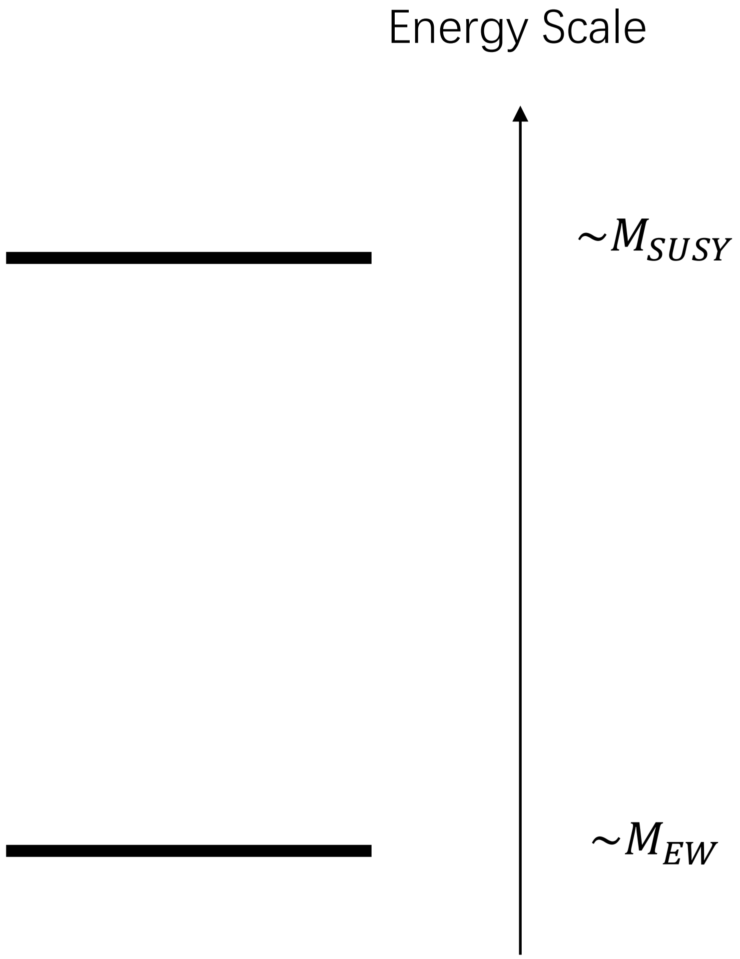
$$\{\,\tilde{f}, \tilde{G}, H^0, A^0, H^{\pm}\,\} \quad \{\widetilde{H}_u, \widetilde{H}_d\}$$

in this work

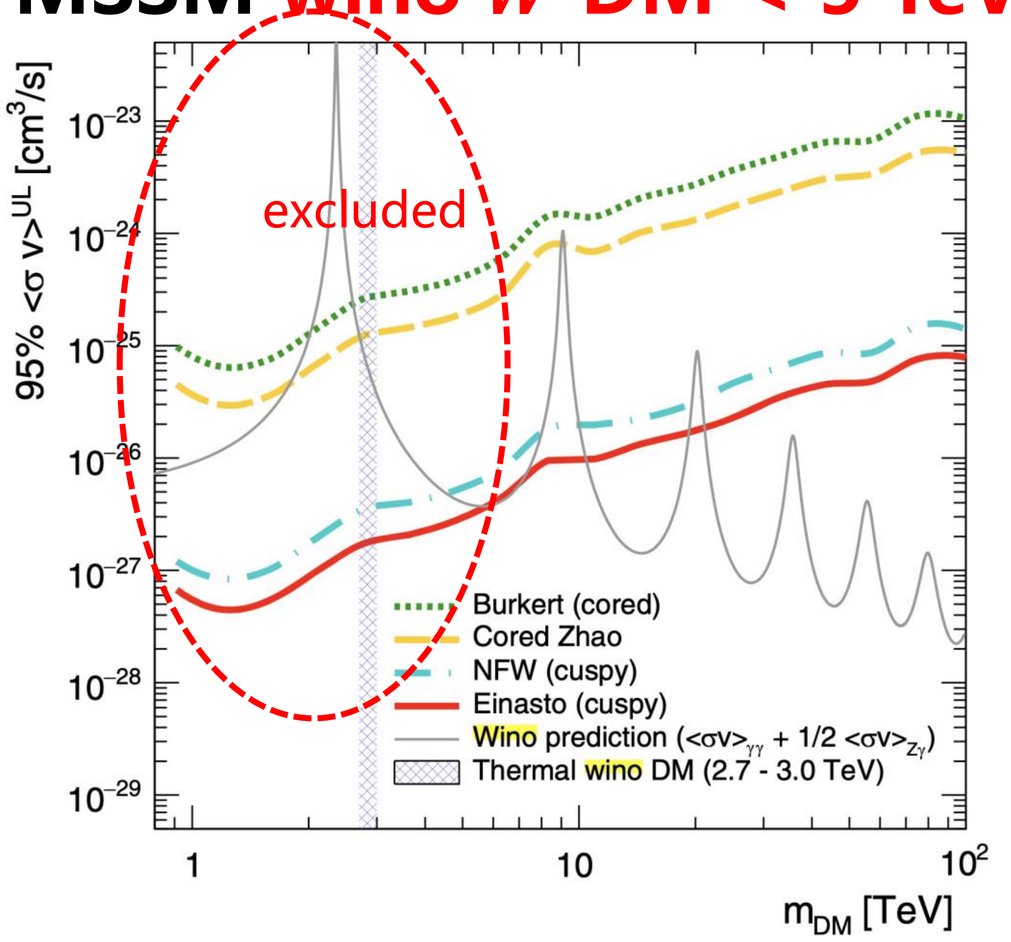
- all/part of Electroweak-ino sector are light

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

in this work



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



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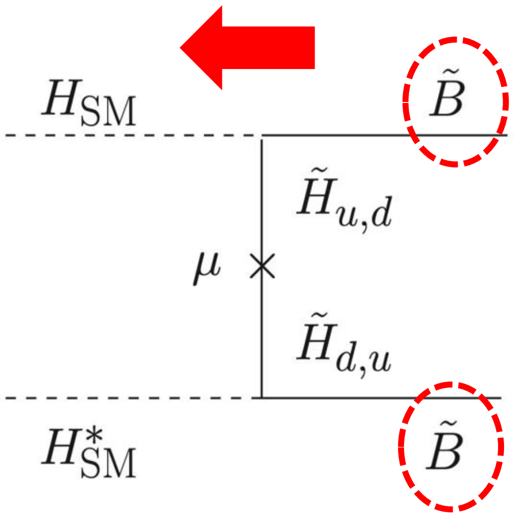
respective masses. Therefore, for the cuspy profiles, we can exclude wino annihilations for masses below 5 TeV and

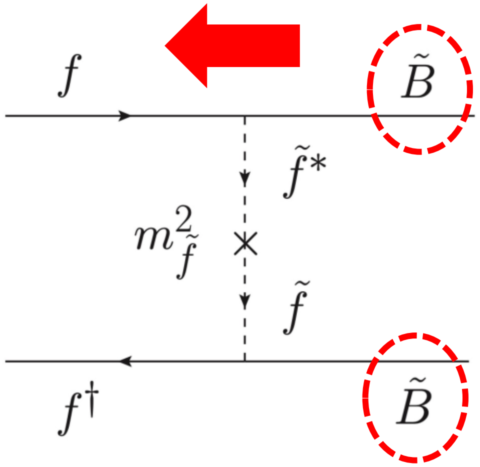
FIG. 3. Upper limits for the four DM density profiles considered in this Letter: the cuspy Einasto Galactic density profile (red solid line), the NFW profile (cyan dashed line), a DM core according to Ref. [56] (yellow dashed line), and the Burkert fit from Ref. [53] (green dotted line), compared against 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].

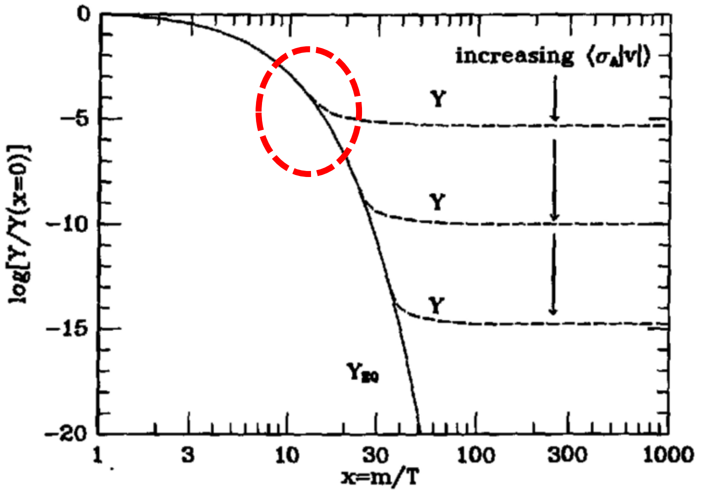
$$\{ \tilde{B}, \widetilde{W}, \widetilde{H}_u, \widetilde{H}_d \}$$

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

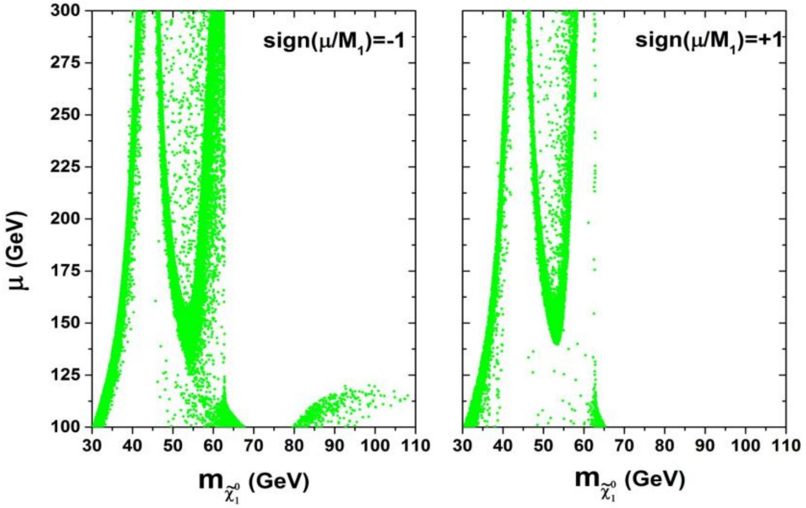
Freeze-***Out*** scenario usually difficult to meet







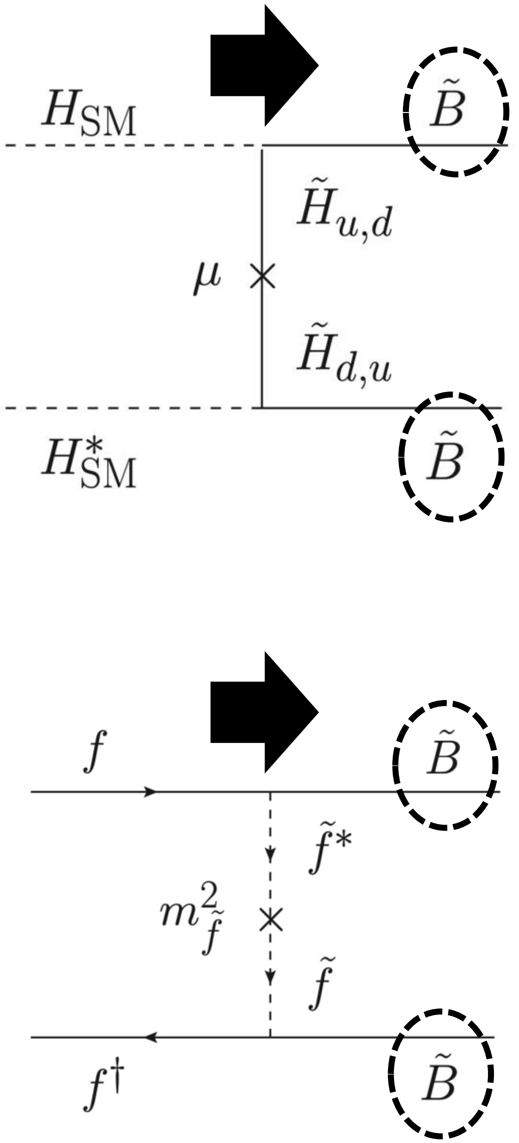
Freeze-***Out*** too early, overly abundant



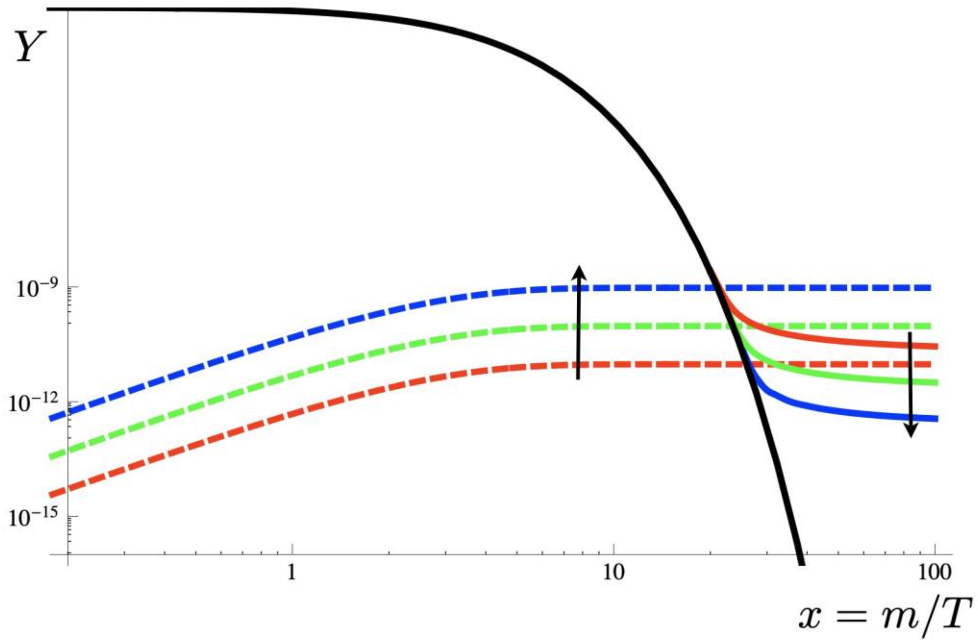
Abdughani, Wu, Yang 1705.09164

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

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

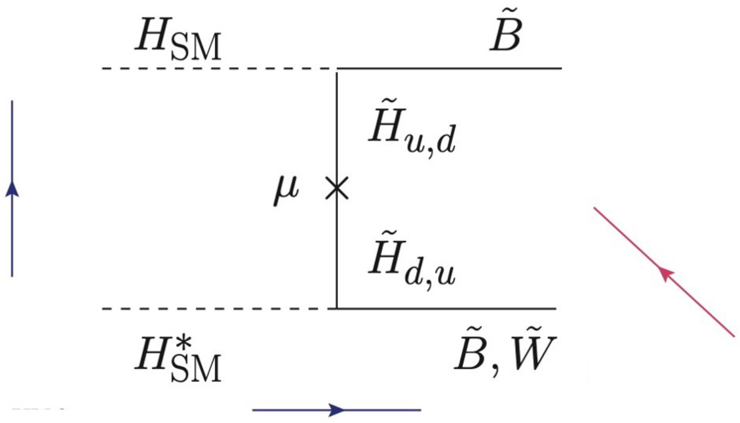


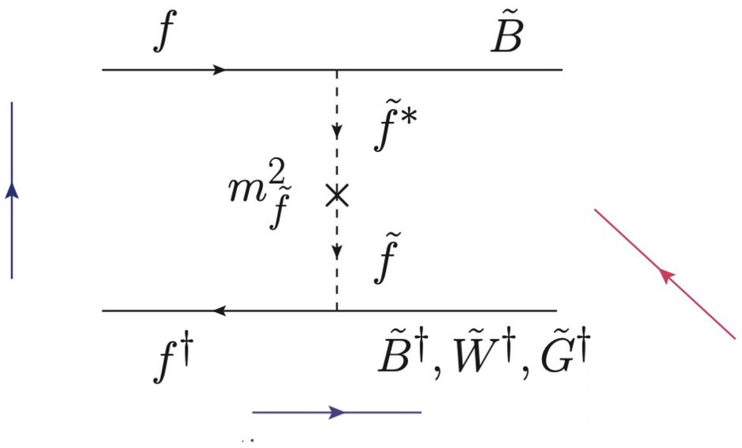
How about *Freeze-**In*** ?

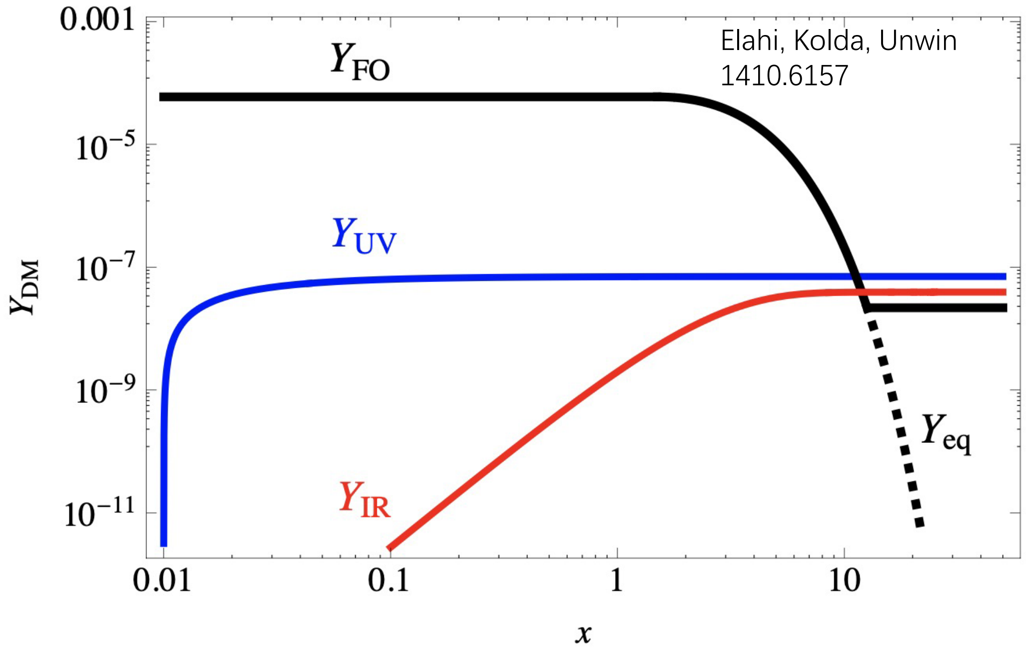


Hall, Jedamzik, March-Russell, West
0911.1120

Freeze-In Bino, UV or IR type ?







Boltzmann equation

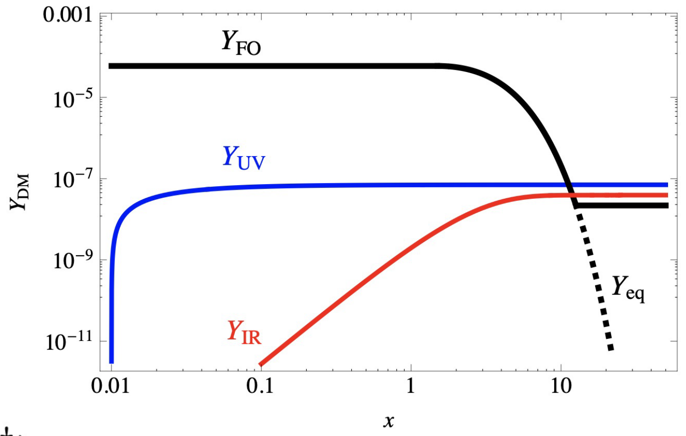
$$\frac{d}{dt} n_{\tilde{B}} + 3\mathcal{H} n_{\tilde{B}} = \mathbf{C}$$

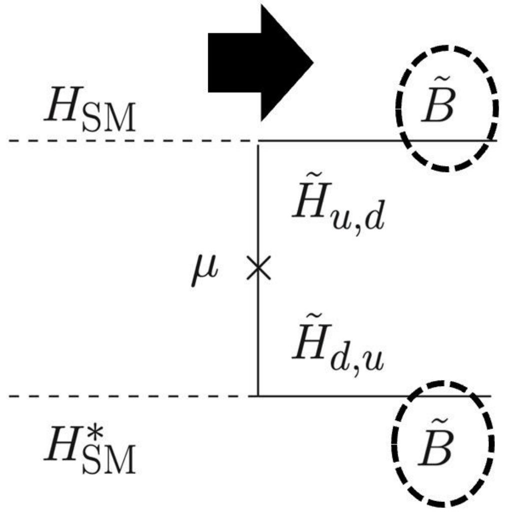
$$\frac{dY_{HH^* \to \tilde{B}\tilde{B}}(T)}{dT} = -\frac{\mathbf{C}_{HH^* \to \tilde{B}\tilde{B}}}{ST\mathcal{H}}$$

dependence behavior on temperature T
determines production efficiency

UV Freeze-In: dim-5, $2 \to 2$ fusion

Elahi, Kolda, Unwin
1410.6157





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

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

$$\frac{dY_{HH^*\to\tilde{B}\tilde{B}}(T)}{dT} = -\frac{\mathbf{C}_{HH^*\to\tilde{B}\tilde{B}}}{ST\mathcal{H}} \approx -(1.25\times10^{-3})\times M_{\rm Pl}\frac{\mathbf{C}_{HH^*\to\tilde{B}\tilde{B}}}{T^6} \approx -(1\times10^{-6})\times M_{\rm Pl}\;g_1^4\frac{\sin^2\beta\cos^2\beta}{\mu^2}$$

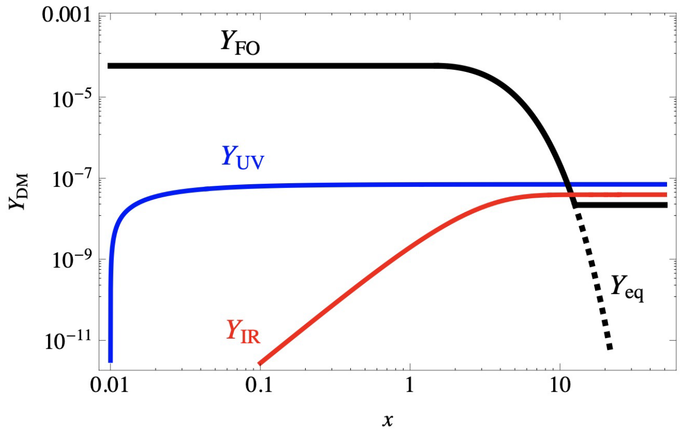
$$Y_{HH^*\to\tilde{B}\tilde{B}}(\infty) \approx (1\times10^{-6})\times M_{\rm Pl}\;g_1^4\frac{\sin^2\beta\cos^2\beta}{\mu^2}\boxed{T_{\rm RH}}$$

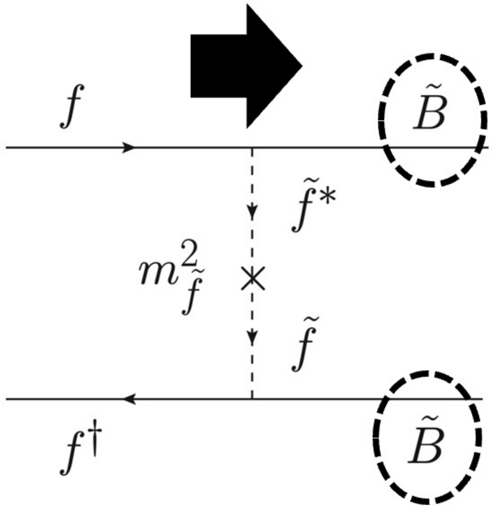
depending on Reheating Temperature T_{RH}, sensitive to UV physics,
Thus UV Freeze-In

$$(\Omega_{\tilde{B}}h^2)_{HH^*\to\tilde{B}\tilde{B}} = M_1\frac{Y_{HH^*\to\tilde{B}\tilde{B}}(\infty)S_0}{\rho_{cr}} \approx Y_{HH^*\to\tilde{B}\tilde{B}}(\infty)\left(\frac{M_1}{\rm TeV}\right)\times(2.72\times10^{11})$$

UV Freeze-In: dim-6, 2 → 2 fusion

Elahi, Kolda, Unwin
1410.6157





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

$$\frac{dY_{HH^*\to\tilde{B}\tilde{B}}(T)}{dT} = -\frac{\mathbf{C}_{HH^*\to\tilde{B}\tilde{B}}}{ST\mathcal{H}} \approx -(1.25\times10^{-3})\times M_{\text{Pl}}\frac{\mathbf{C}_{f\bar{f}\to\tilde{B}\tilde{B}}}{T^6} \approx -(8.6\times10^{-5})\times M_{\text{Pl}}\frac{g_1^4}{M^4_{\tilde{f}}}T^2$$

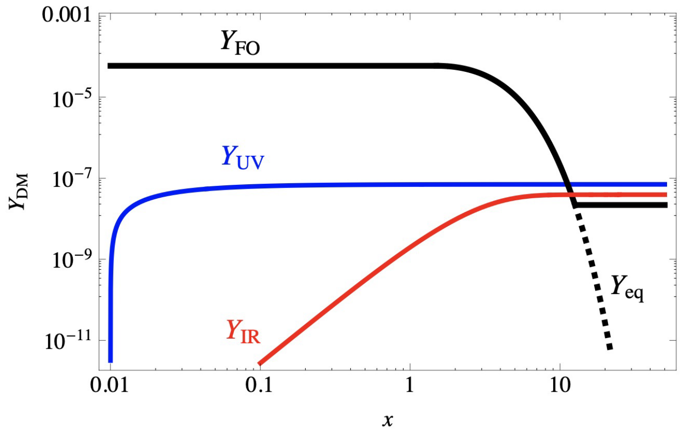
$$Y_{f\bar{f}\to\tilde{B}\tilde{B}}(\infty) \approx (4.7\times10^{-7})\times\frac{M_{\text{Pl}}}{M^4_{\tilde{f}}}T^3_{\text{RH}}$$

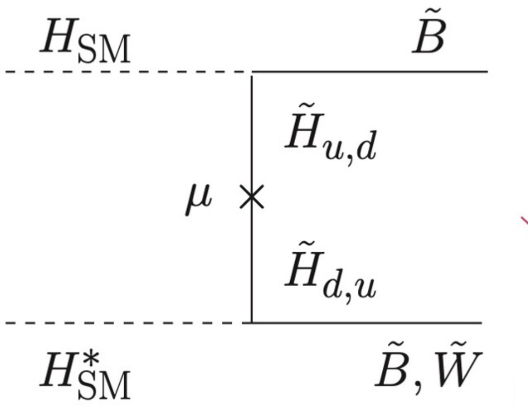
UV Freeze-In

$$(\Omega_{\tilde{B}}h^2)_{f\bar{f}\to\tilde{B}\tilde{B}} = M_1\frac{Y_{f\bar{f}\to\tilde{B}\tilde{B}}(\infty)S_0}{\rho_{cr}} \approx Y_{f\bar{f}\to\tilde{B}\tilde{B}}(\infty)\left(\frac{M_1}{\text{TeV}}\right)\times(2.72\times10^{11})$$

IR Freeze-In: decay production

Elahi, Kolda, Unwin
1410.6157



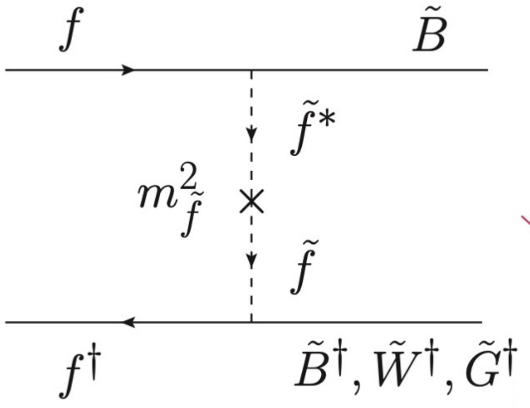


$$\frac{d}{dt} n_{\tilde{B}} + 3\mathcal{H} n_{\tilde{B}} = \mathbf{C}$$

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

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

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

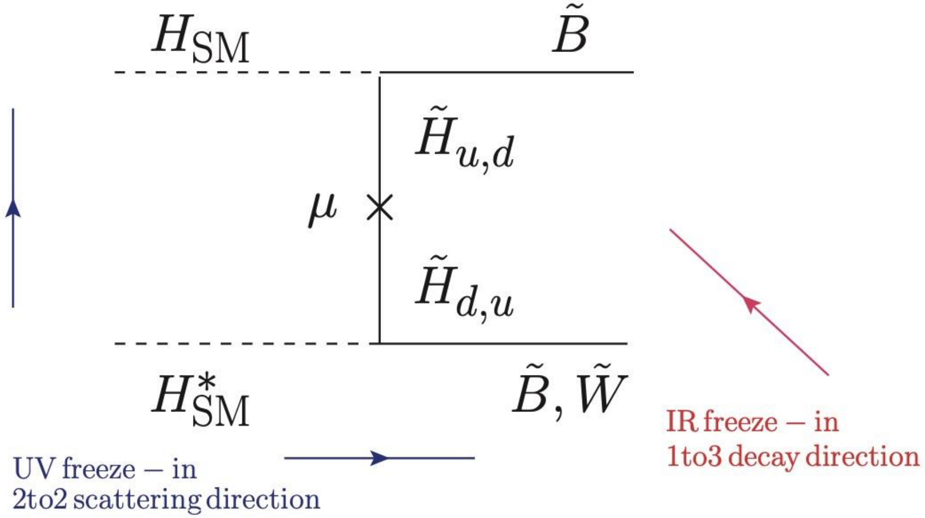


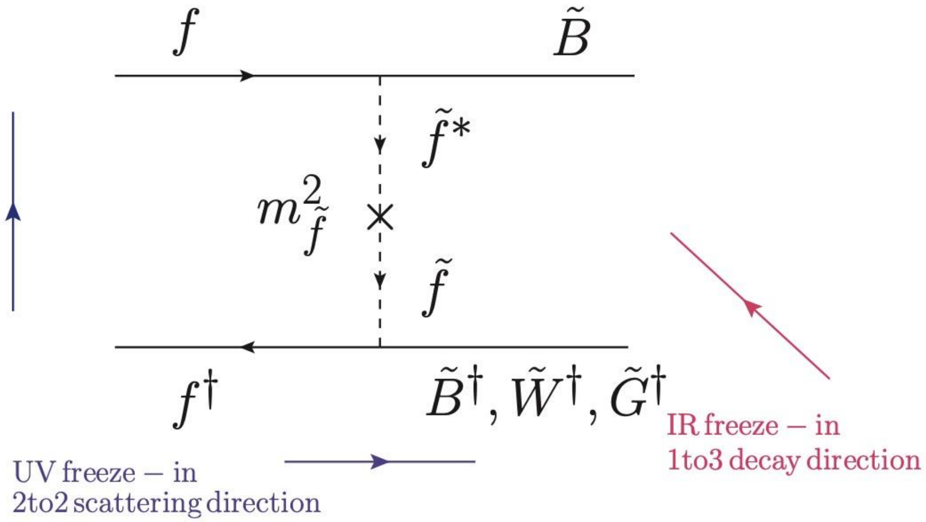
$$Y_{\tilde{B}}^{1\to 3}(\infty) \approx \int_{T_{min}}^{T_{\rm RH}} \frac{\mathbf{C}}{S T \mathcal{H}} dT$$

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

MSSM setup in this work

Mass spectrum and DM production processes





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

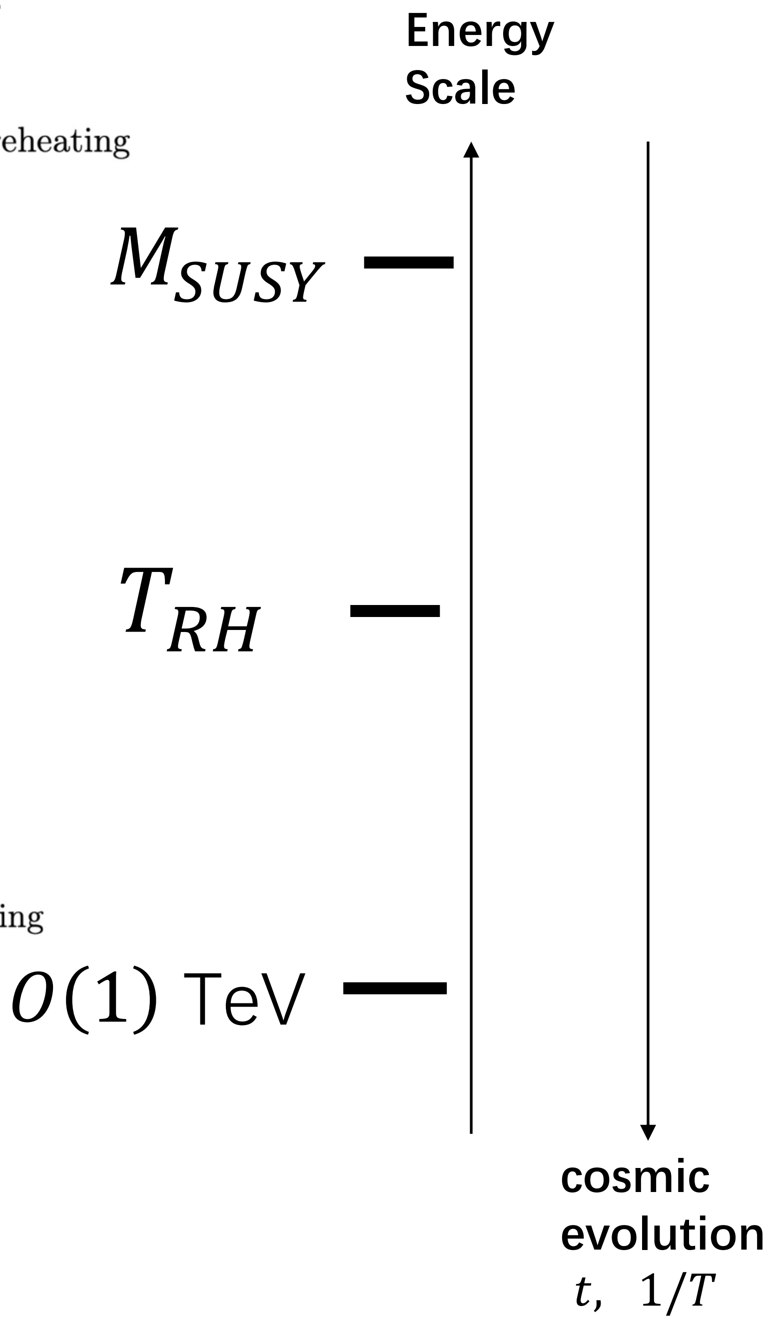
  Mass: $M \sim M_{\rm SUSY} \gg T_{RH}$

  - ⋆ Higgs bosons not in SM: $H^0_{\rm NP}$, A, $H^\pm_{\rm NP}$
  - ⋆ Sfermions $\tilde{f}$
  - ⋆ Higgsinos $\tilde{H}_u, \tilde{H}_d$

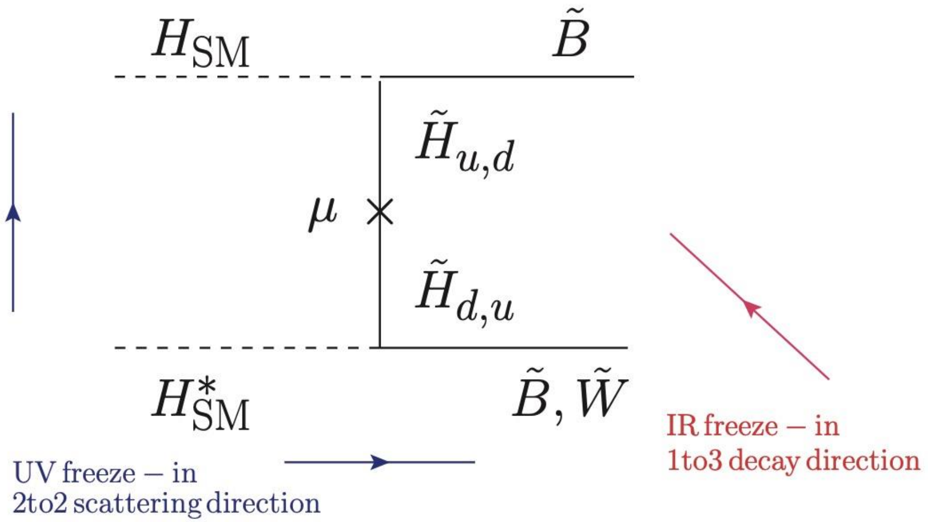
- **Light** sector, **active** after cosmological reheating

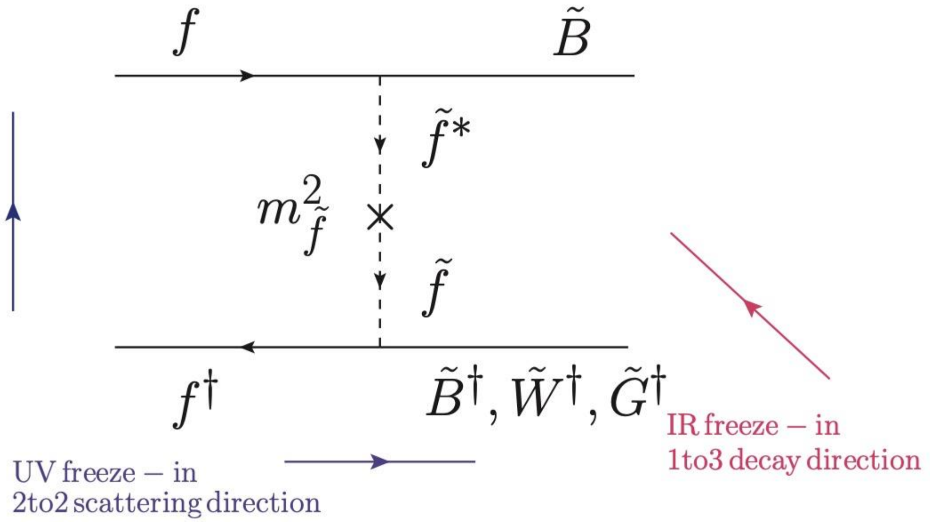
  Mass: $M \sim \mathcal{O}(1)$ TeV $\ll M_{\rm SUSY}$

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



Phenomenology

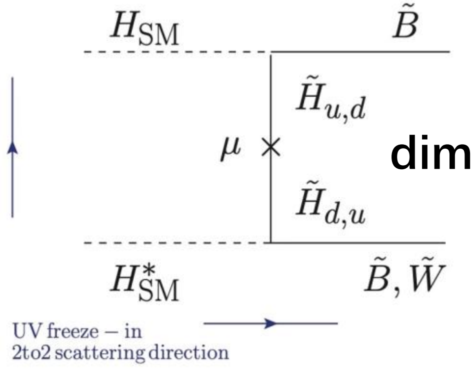




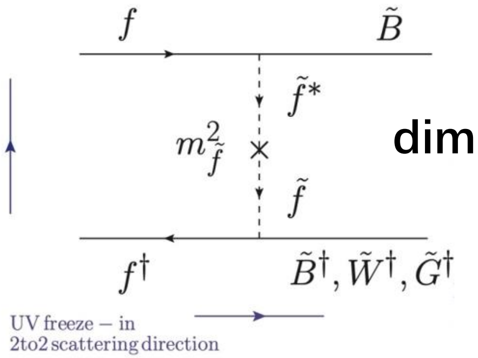
- to meet the observed DM abundance
  - interplay with Big Bang Nuclear-synthesis (BBN)
- collider constraints on Long-Lived particle (LLP)
  - disappearing / displaced track
- DM direct/indirect signal
  - negligible for bino in our setup

Main results

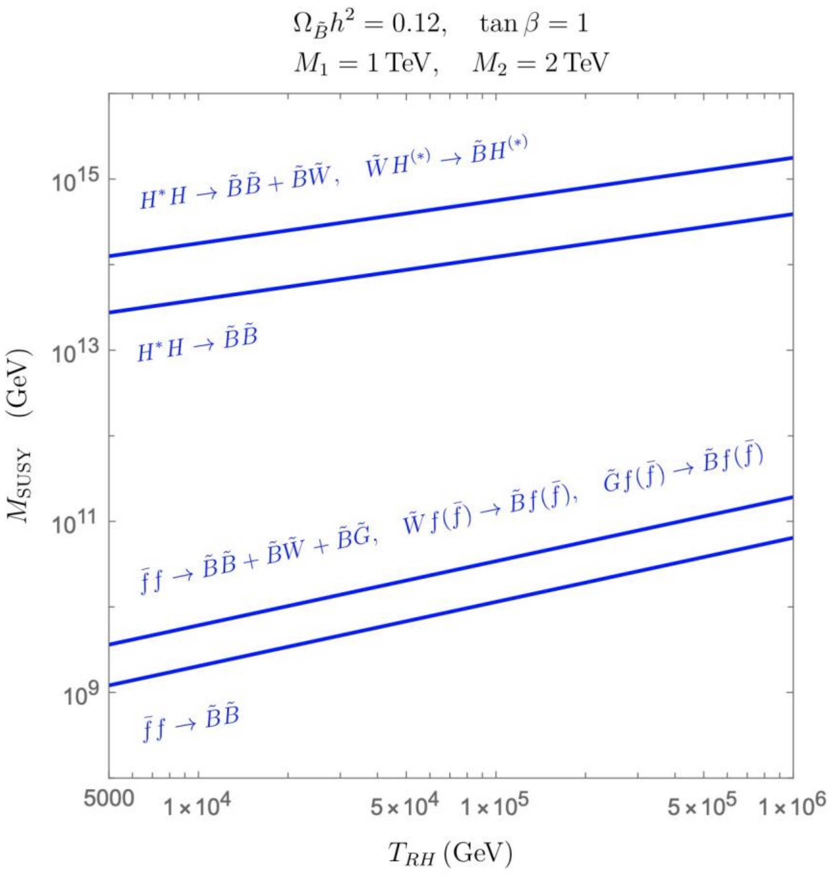
DM abundance, mass scale of heavy sector



dim-5



dim-6



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

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  ⋆ SM particles

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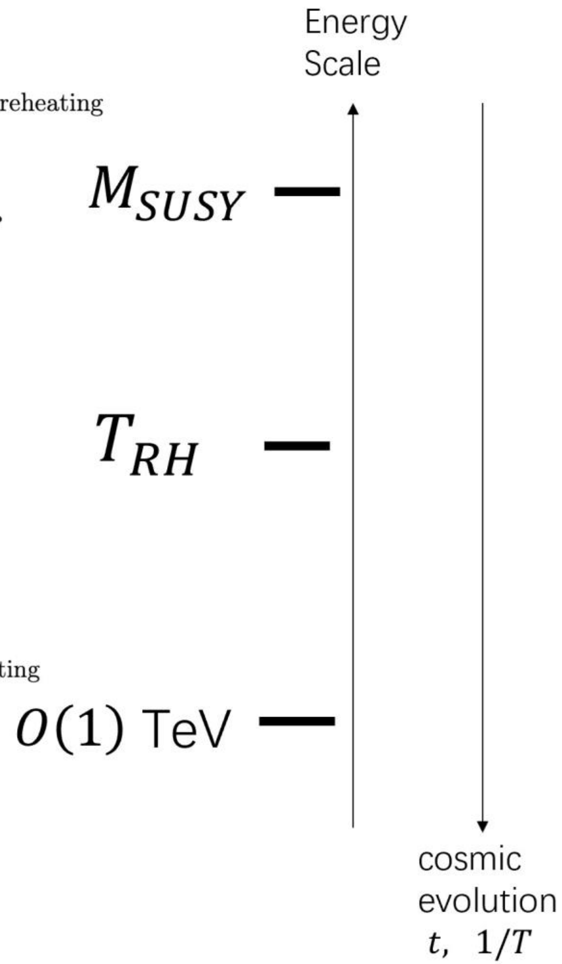
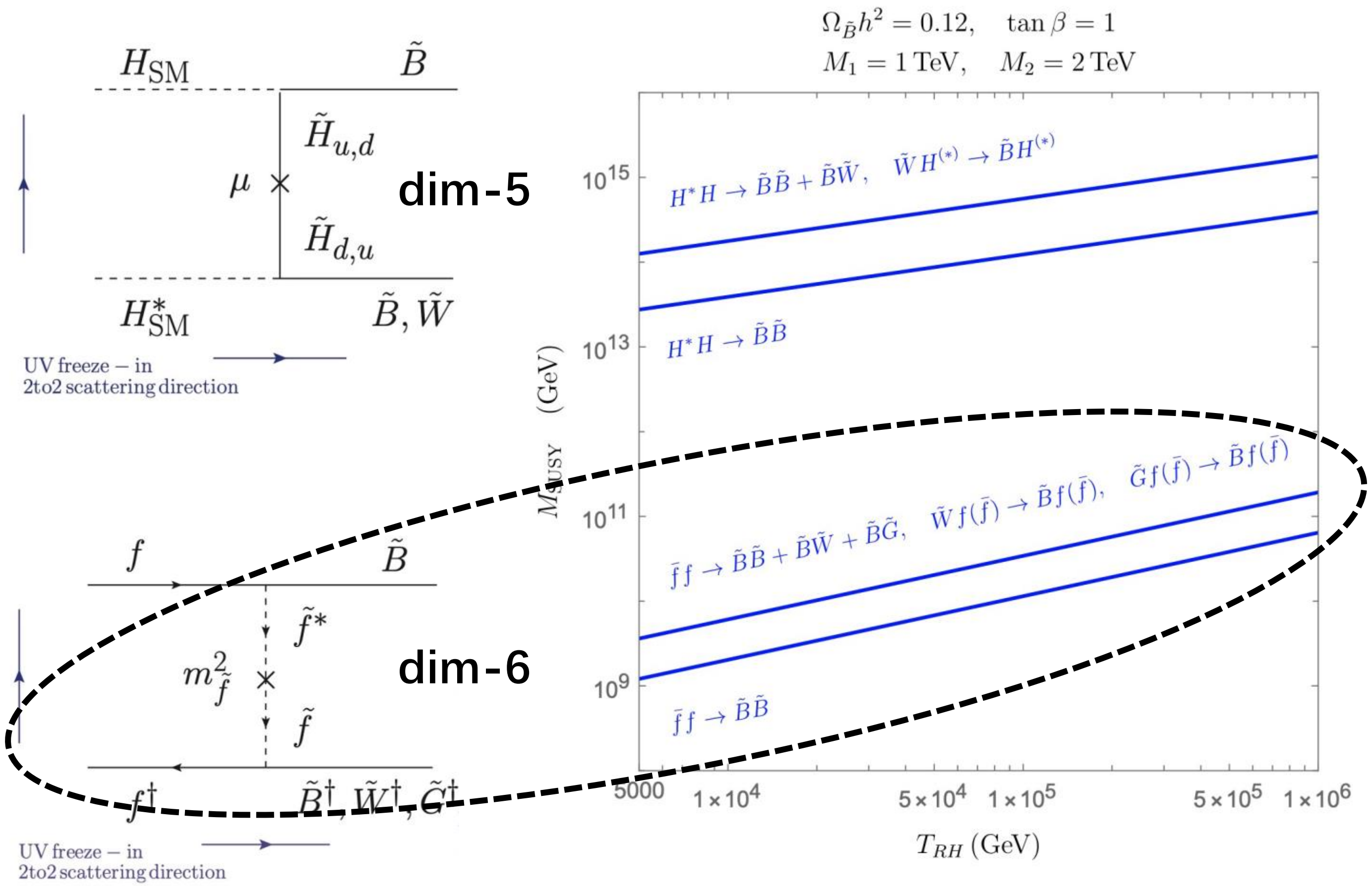


DM abundance, mass scale of heavy sector



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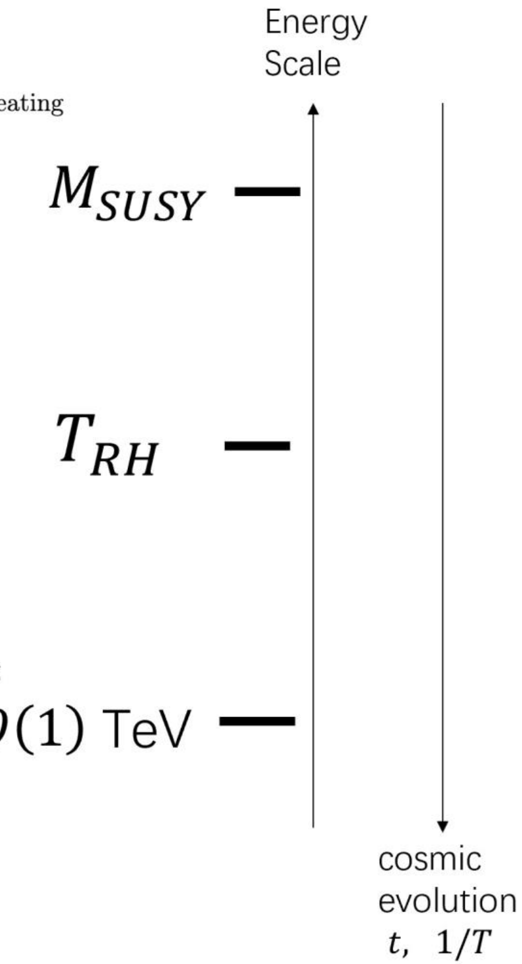


if a universal heavy scale is assumed: $O(\mu) \sim O(m_{\tilde{f}})$
dim-6 contributions will be negligible

Wino Freeze-Out effects properly included

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

Hall, Jedamzik, March-Russell, West
0911.1120

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

our case

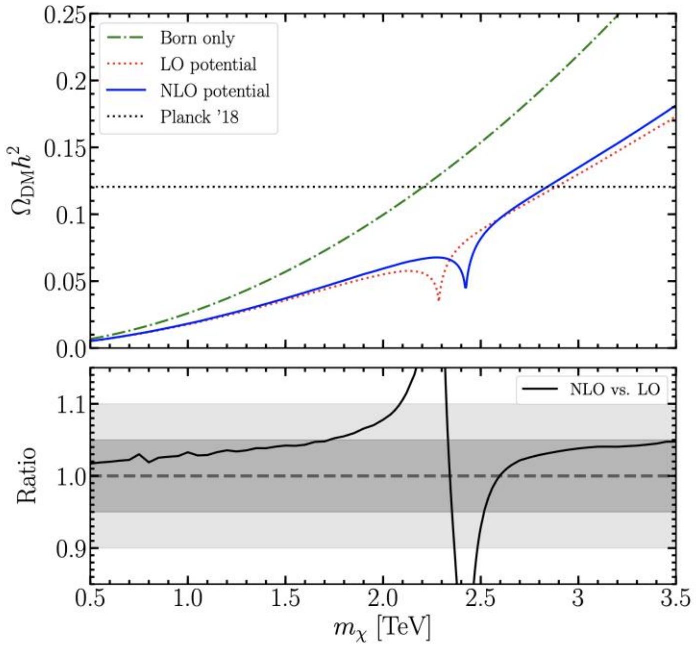
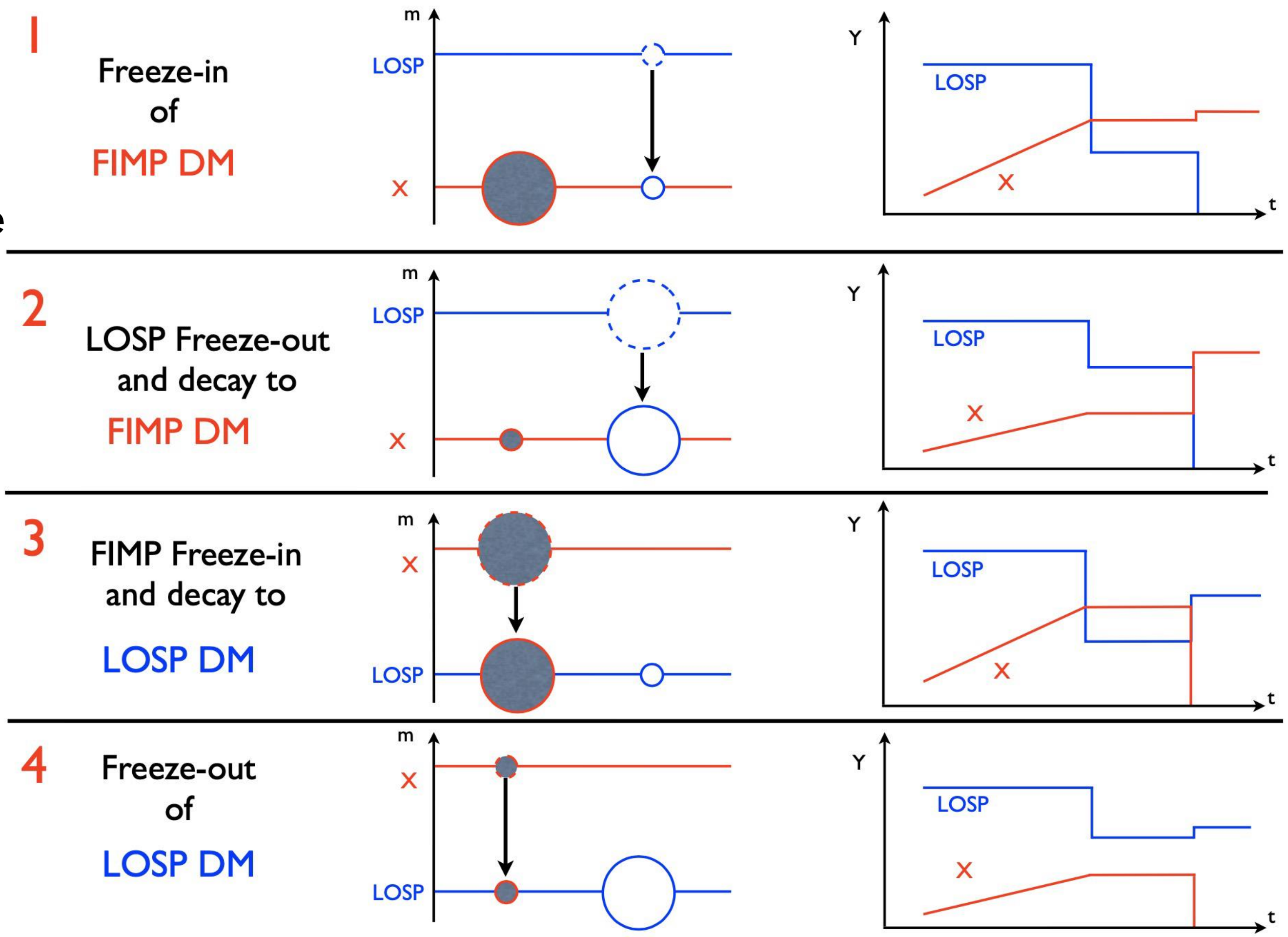
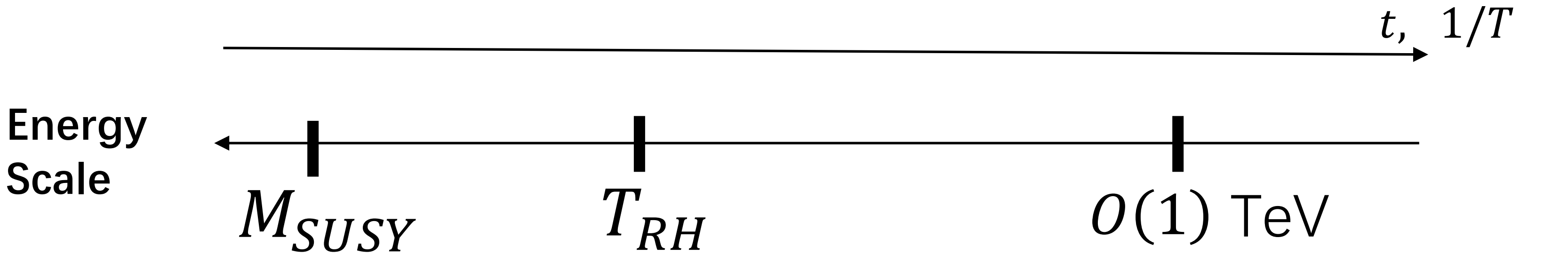


Figure 9. Wino DM relic abundance as function of DM mass m_χ computed with Born cross



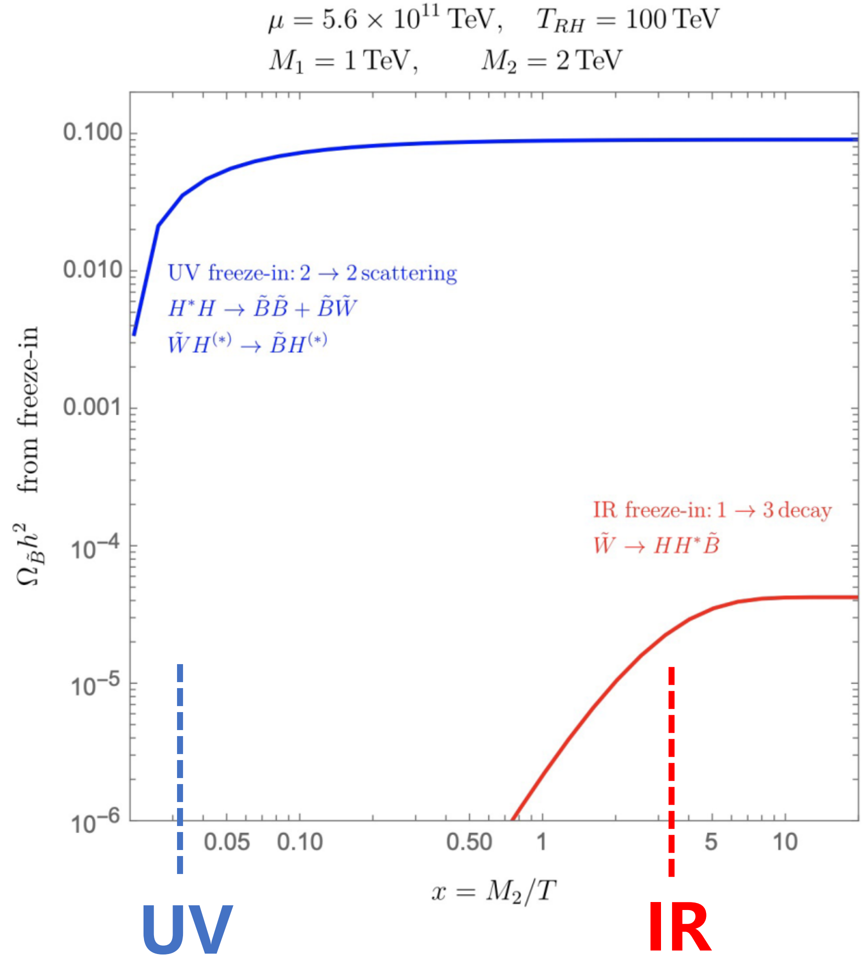
Beneke, Szafron, Urban
2009.00640

UV & IR feature of different Freeze-In processes



- we focus on dim-5 operators

- Bino mass choice can affect the specific IR/UV ratio



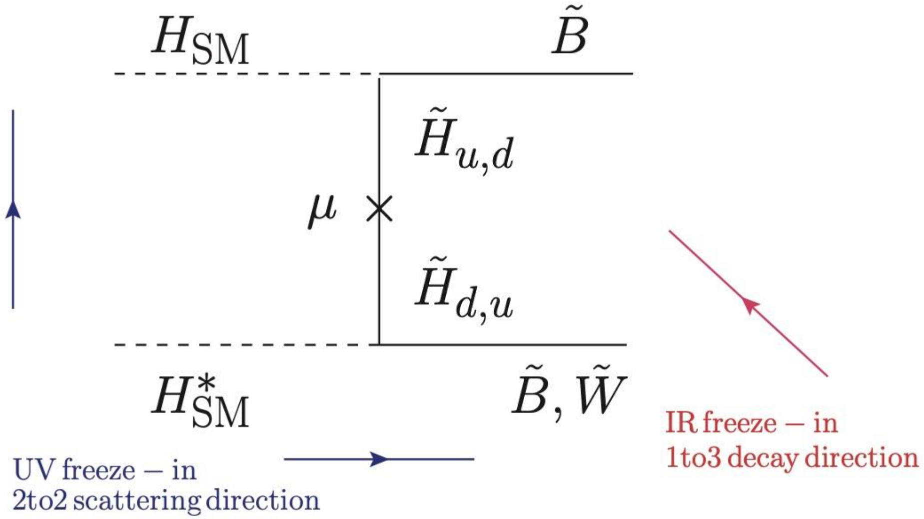
Interplay between DM abundance & BBN: *constrained* T_{RH} range:

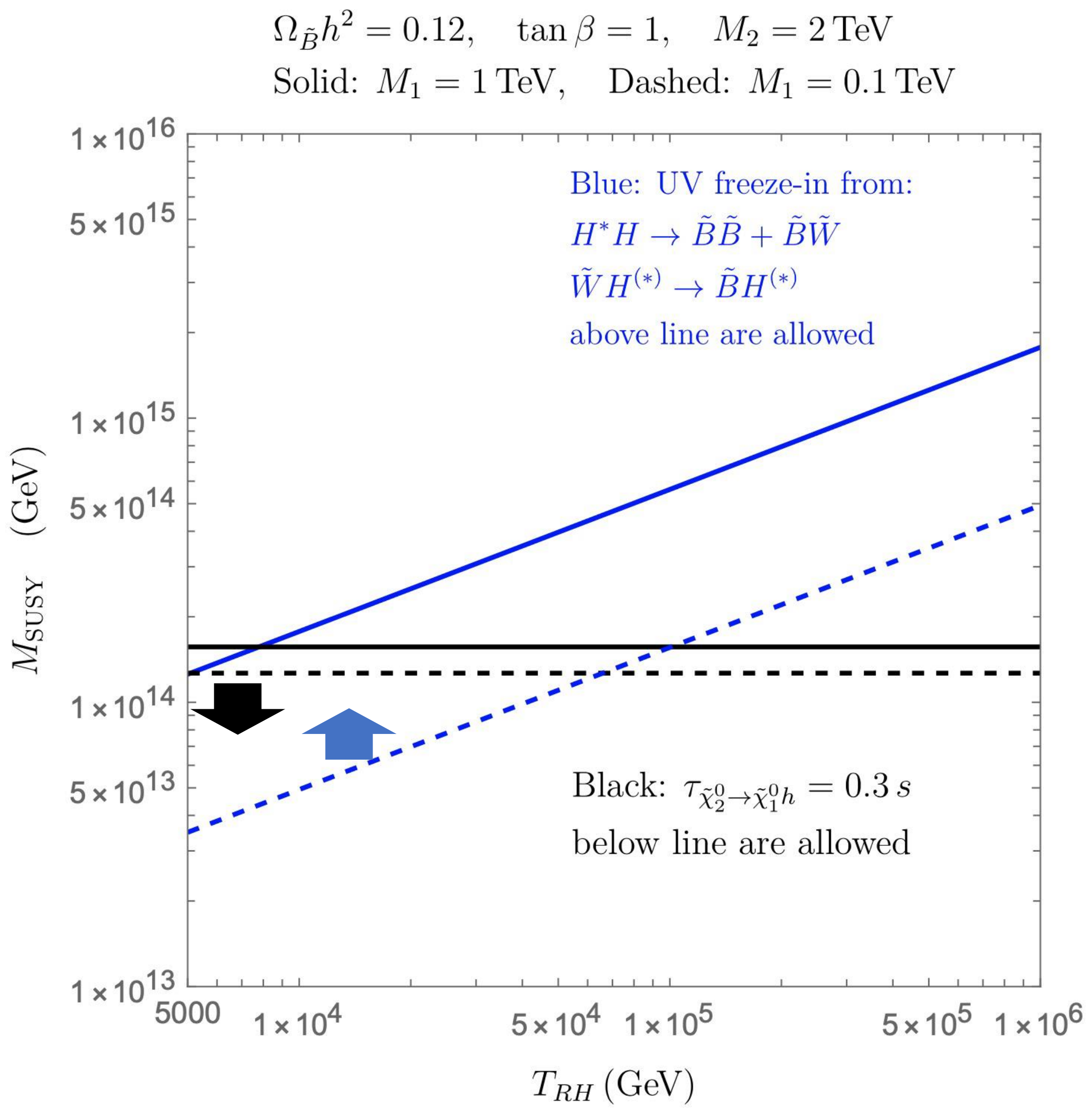
SUSY electroweak-inos must decay before BBN epoch

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

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

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





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

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

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

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

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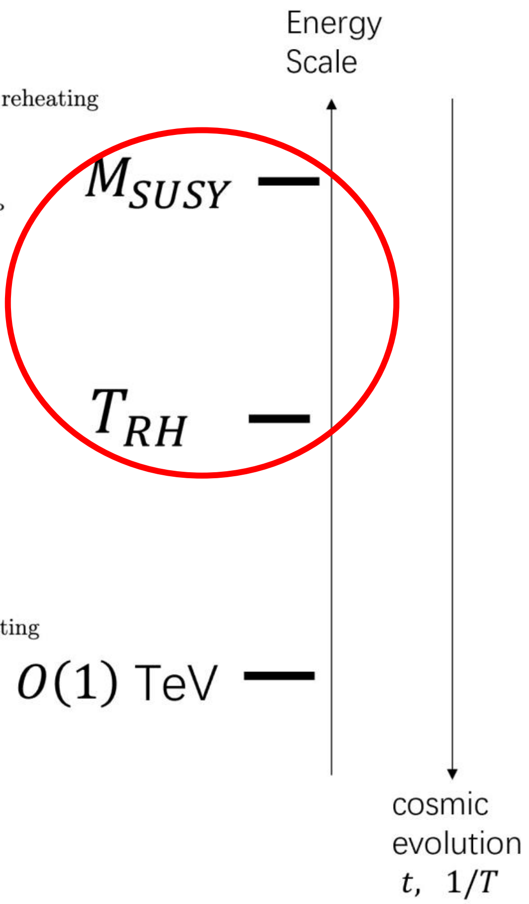
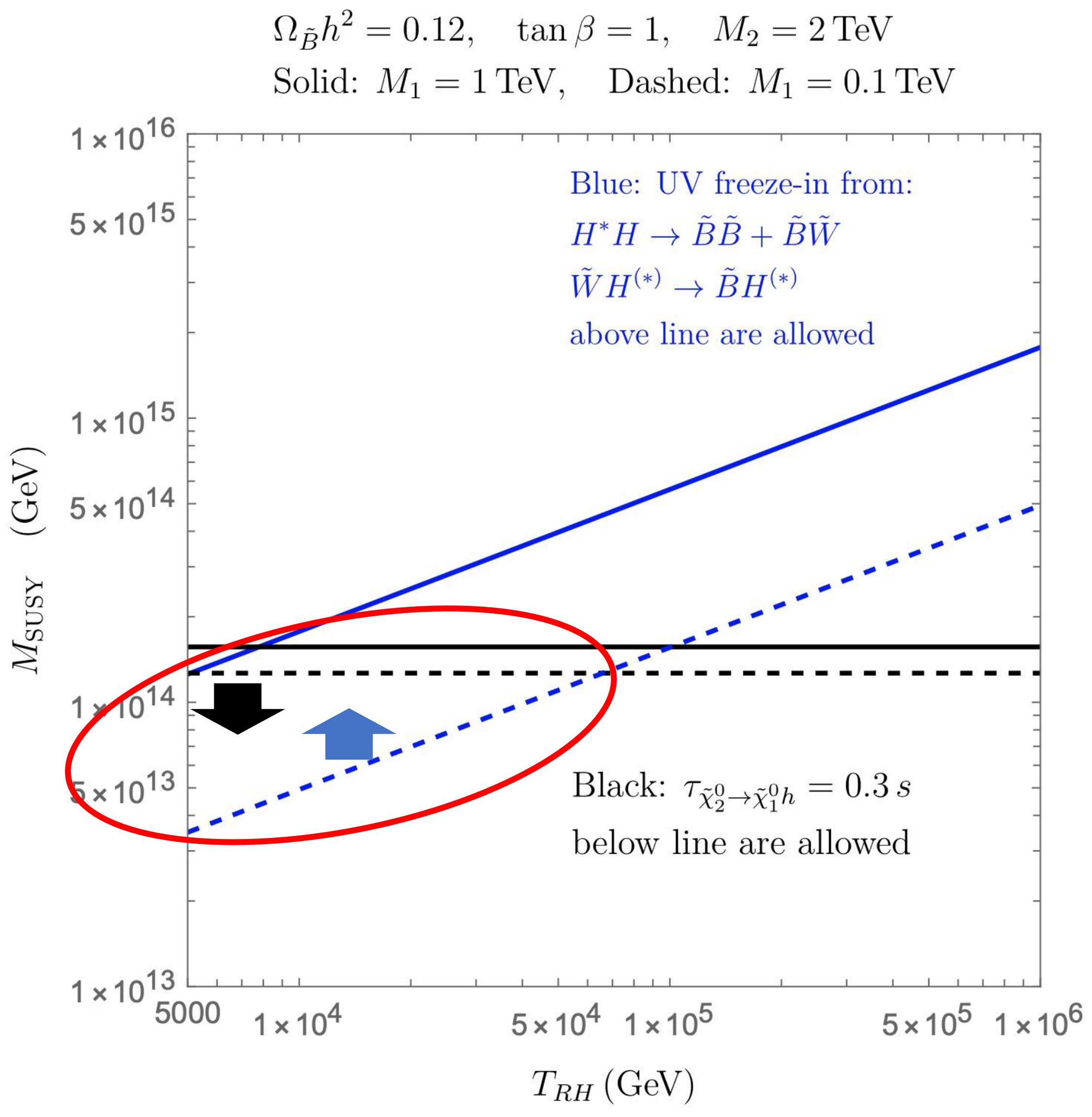
  - ⋆ Bino $\tilde{B}$
  - ⋆ Winos $\tilde{W}$, with mass M_2
  - ⋆ Gluinos $\tilde{G}$, with mass M_3





Collider signal profile

$\tilde{\chi}_1^\pm \to \tilde{\chi}_2^0 \pi^\pm$ disappearing track, $M_{\tilde{W}} > 0.5$ TeV is allowed. our benchmark $M_{\tilde{W}} = 2$ TeV still allowed

$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ $\tau > O(10^{-2})\ s$ making $\tilde{\chi}^0$ leave the whole detector before decay.
BBN limits on our set-up result in NO displaced vertex at collider.

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

ATLAS 2201.02472.pdf

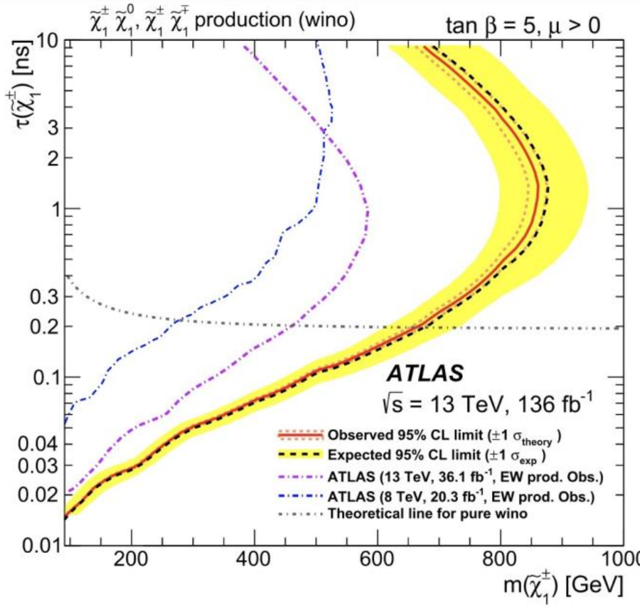


Fig. 7 Exclusion limits at 95% CL obtained in the electroweak production channel with the pure-wino scenario. The limits are shown as a function of the chargino lifetime and mass. The black dashed line shows the median expected value, and the yellow band shows the 1σ uncertainty band around the expected 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]

CMS 2004.05153.pdf

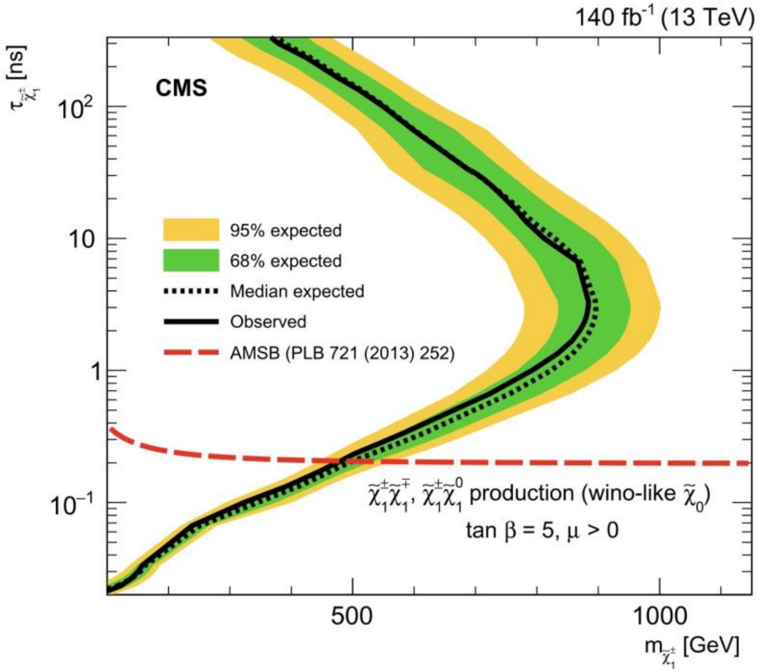
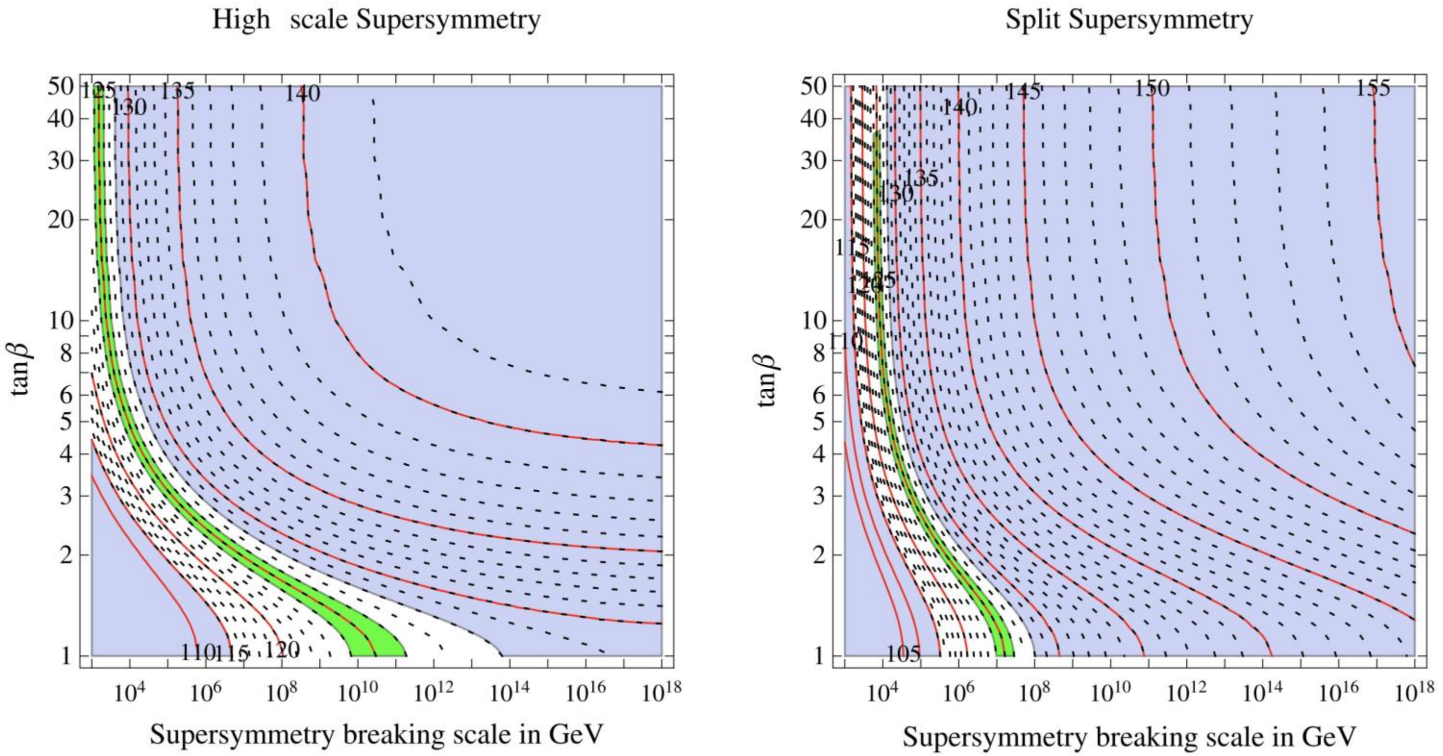


Fig. 2. The expected and observed constraints on chargino lifetime and mass for a purely wino LSP in the context of AMSB, where the chargino lifetime is explicitly varied. The chargino branching fraction is set to 100% for $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm$. Shown are the full Run 2 results, 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:

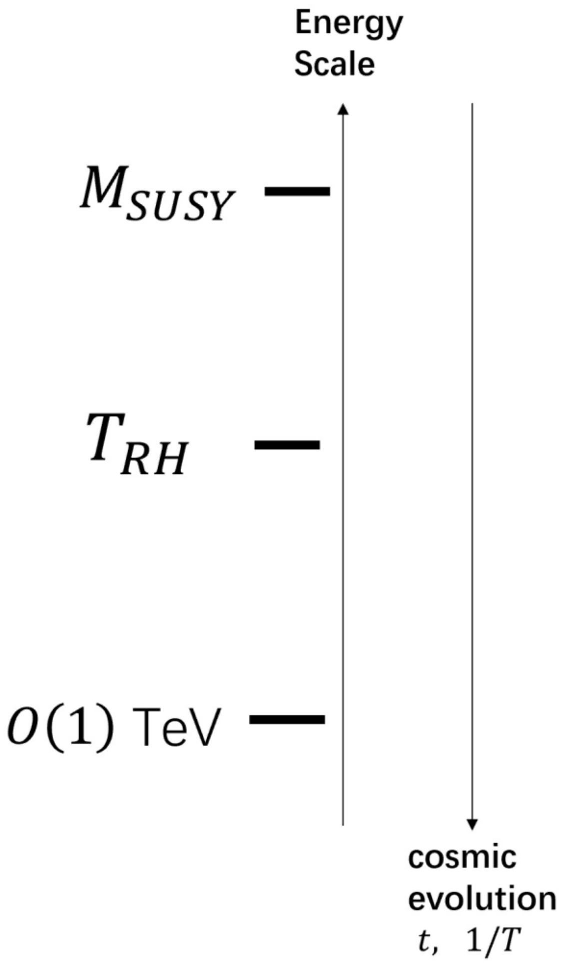
possible UV completion

- 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

Martin, 0903.3568



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