Moduli Decays

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At $H \simeq M_\Phi$: Φ field starts to oscillate coherently; same as collection of Φ particles at rest.

$\rho_\Phi \propto a^{-3}, \ \rho_{\rm rad} \propto a^{-4} \Longrightarrow$
If lifetime τ_Φ is sufficiently large, ρ_Φ will dominate the total energy density: “period of early matter domination”!

Moduli Cosmology (cont'd)

Typically: Φ couplings suppressed by $1/M_{\rm Pl} \Longrightarrow$

$$\Gamma_\Phi = \kappa \frac{M_\Phi^3}{M_{\rm Pl}^2} \quad \kappa = \frac{C}{8\pi},\ M_{\rm Pl} = 1.22 \cdot 10^{19}\ {\rm GeV}$$

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BBN $\Longrightarrow T_{\rm RH} > \text{few GeV} \Longrightarrow$

$$M_\Phi > 10^5 \kappa^{-1/3}\ \mathrm{GeV}$$

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- Direct $\Phi \to \chi$ decays: increase Ω_χ
- ρ_Φ increases $H \Longrightarrow$ increases Ω_χ (if χ was in equilibrium)
- Φ decays increase entropy: reduces Ω_χ (after normalization to CMB)

Equations

$$H^2 = \frac{8\pi\rho_{\rm tot}}{3M_{\rm Pl}^2} \qquad \rho_{\rm tot} = \rho_{\rm rad} + \rho_\chi + \rho_\Phi$$

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$\frac{ds}{dt} + 3Hs \simeq \frac{1}{T}(1 - \bar{B})\Gamma_\Phi \rho_\Phi$

$\rho_{\rm rad} = \frac{\pi^2}{30} g_* T^4 \,, \quad s = \frac{2\pi^2}{45} h_* T^3$: entropy density

$B_\chi \propto B_\chi =$Br for $\Phi \rightarrow \chi$ decays

Note: This form of eqs works even if g_*, h_* are not constant!
They change rapidly around $T = 150$ MeV.

Results

MD, F. Hajkarim, JCAP 1802 (2018), 057 & JHEP 1812 (2018) 042

Generally: final Ω_χ depends on $\langle \sigma v \rangle$, m_χ, B_χ, Γ_Φ, M_Φ, initial densities

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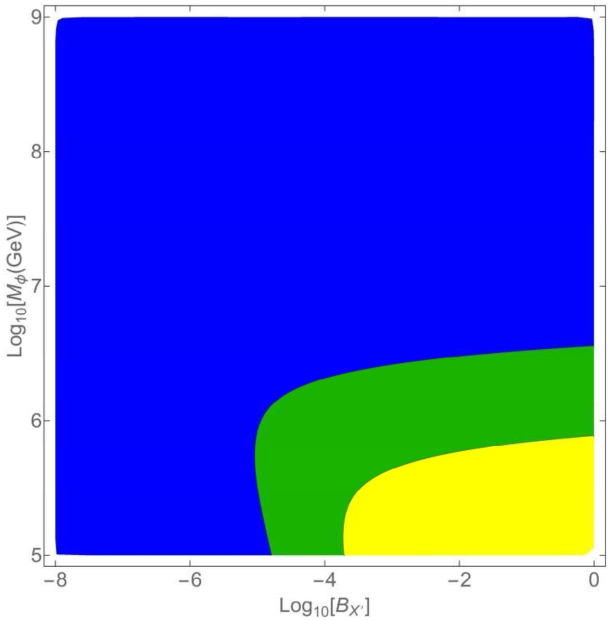
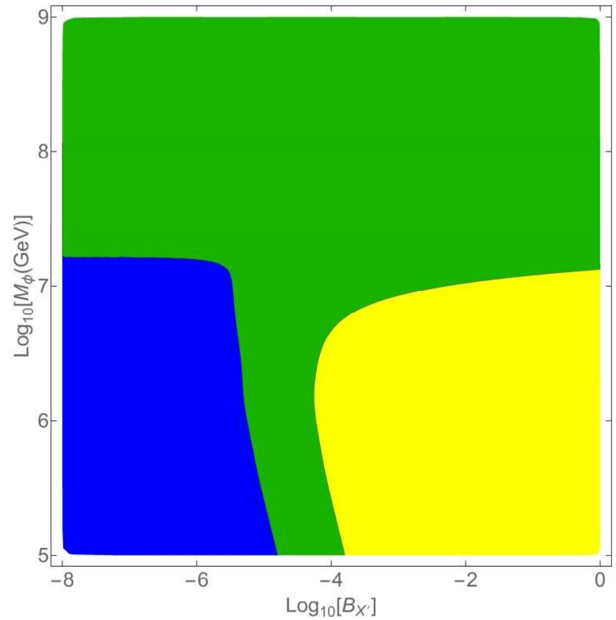
One application:
WIMP with $\langle \sigma v \rangle < \langle \sigma v \rangle_{\rm thermal\ WIMP}$: has too high relic density in standard cosmology.
Example: bino-like LSP!
Can be ok if $B_\chi < 10^{-4}$ and $M_\Phi \lesssim 10^7$ GeV! ($\kappa = 1$)

$m_\chi = 100$ **GeV**

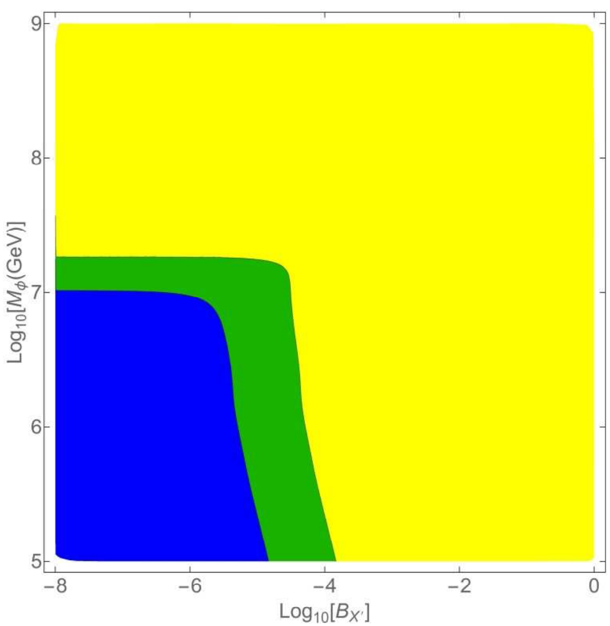
$\sigma_{\rm ann} =$
$10^{-6}\ \mathrm{GeV}^{-2}$
("too large")

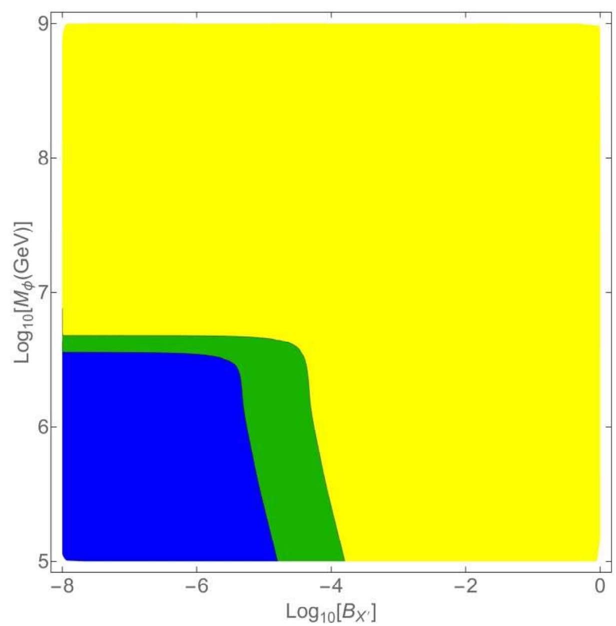




$10^{-8}\ \mathrm{GeV}^{-2}$
("just right")

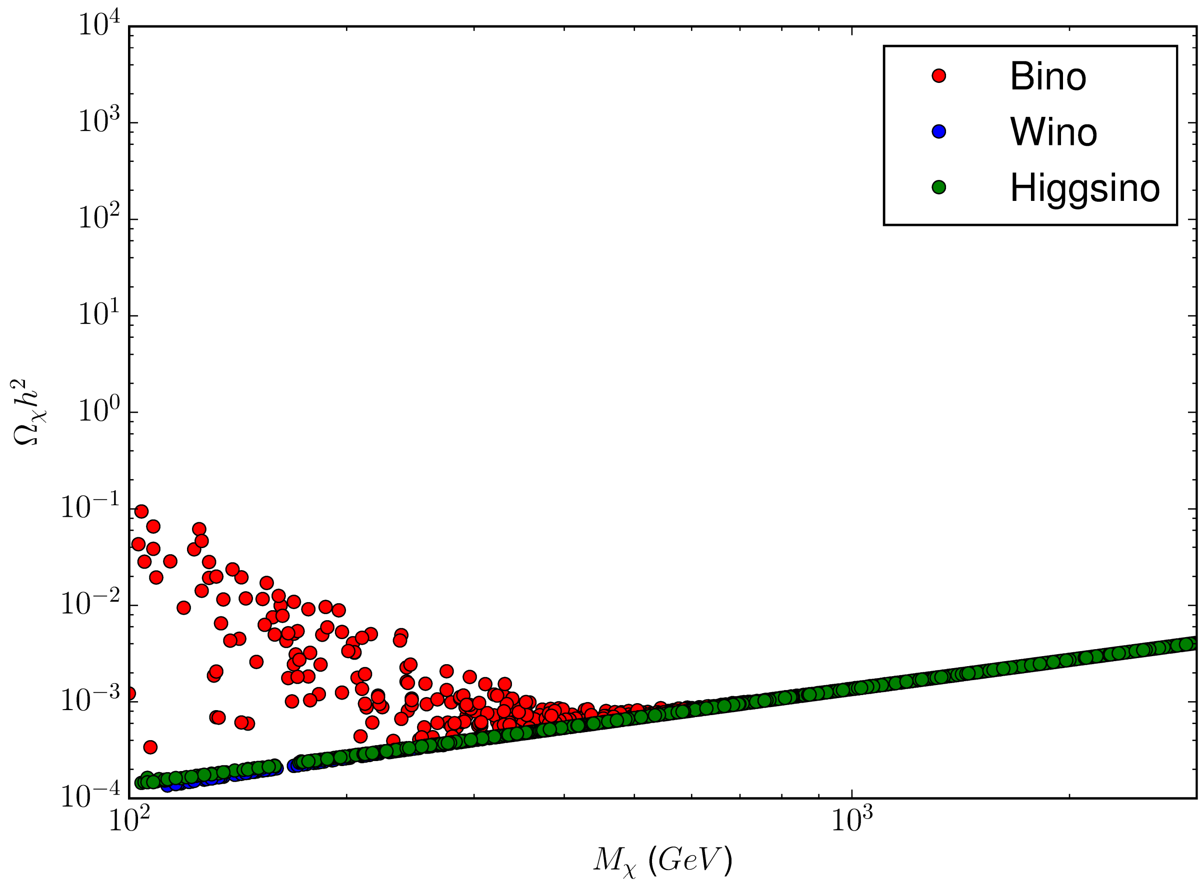
$10^{-9}\ \mathrm{GeV}^{-2}$
("too small")





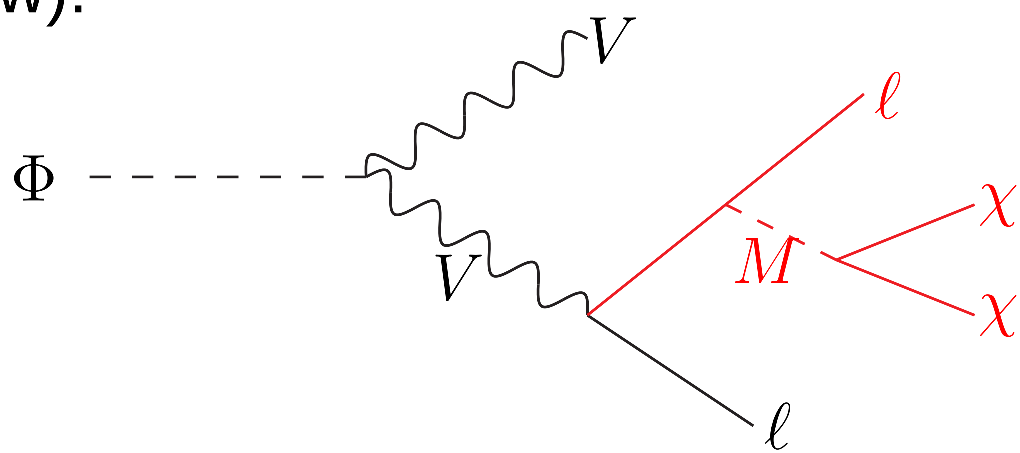
$10^{-14}\ \mathrm{GeV}^{-2}$
("much too small")

In the pMSSM: $B_\chi = 10^{-5}$, $M_\Phi = 5 \cdot 10^6$ GeV



Is that realistic?

In “simplified model”: No Problem! E.g. couple WIMP χ via mediator M to leptons; Φ decays into gauge bosons (see below):



Is 5-body final state: $B_\chi \sim \alpha\alpha_\chi^2$ is automatically small if $\langle \sigma v \rangle$ is small due to small coupling α_χ.

Moduli Decays in SUSY

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All superparticles will decay into LSPs!

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$B_\chi \ll 1$ only possible if *all* $\Phi \to$ sparticle decays are strongly suppressed!

At leading order

Assumption: Φ is SM gauge singlet! Gauge invariant couplings:

- dim. 3: $\Phi H_u \cdot H_d$: "Higgs" mode
- dim. 5: $\Phi G_{\mu\nu} G^{\mu\nu}, \; \Phi W_{\mu\nu} W^{\mu\nu}, \; \Phi B_{\mu\nu} B^{\mu\nu}$: "gauge"
  $\Phi \overline{f_L} f_R H$: "fermion" mode

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Can these vertices be derived from supersymmetric Lagrangians?

Let $\hat{\Phi} = (\Phi, \tilde{\Phi})$: chiral modulus superfield.

Higgs mode

Superpot. $W \supset \hat{\Phi}\hat{H}_u \cdot \hat{H}_d$: SUSY invariant, but would give
$\Gamma(\Phi \to H_u H_d) \ll \Gamma(\Phi \to \tilde{h}_u \tilde{h}_d)$
$\Longrightarrow B_\chi \sim \mathcal{O}(1)$: no good!

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Instead: introduce SUSY breaking
spurion $\hat{F} = \theta\theta F$

$$\Longrightarrow \mathcal{L} \supset \frac{c_H}{M_{\rm Pl}} \int d^2\theta\, \hat{F}\hat{\Phi}\hat{H}_u \cdot \hat{H}_d$$

$\Longrightarrow \Phi H_u H_d$ vertex factor $c_H F/M_{\rm Pl}$: is soft breaking term!

Fermion mode

$\overline{f_L} f_R H$ comes from $W \supset \hat{f}_L \hat{f}_R^c \hat{H}$:
Also generates $\overline{f_L} \tilde{f}_R \tilde{h},\ \tilde{f}_L \overline{f_R} \tilde{h}$ terms

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$\Longrightarrow$ supersymmetric $\Phi f \bar{f} H$ vertex will *always* lead to $B_\chi \sim \mathcal{O}(1)$, if $M_\Phi \gg m_{\rm sparticle}$!

Gauge mode

$\mathcal{L} \supset \frac{c_g}{M_{\mathrm{Pl}}} \int d^2\theta \hat{\Phi} \hat{W}_A \hat{W}^A$

$\hat{W}_A$: Gauge field strength superfield

$\Longrightarrow \Phi$ couples to $\int d^2\theta \hat{W}_A \hat{W}^A = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + i\lambda^a \sigma^\mu D_\mu \lambda^a$

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Also gives rise to $\Phi \tilde{g} \tilde{g}$ vertex, but

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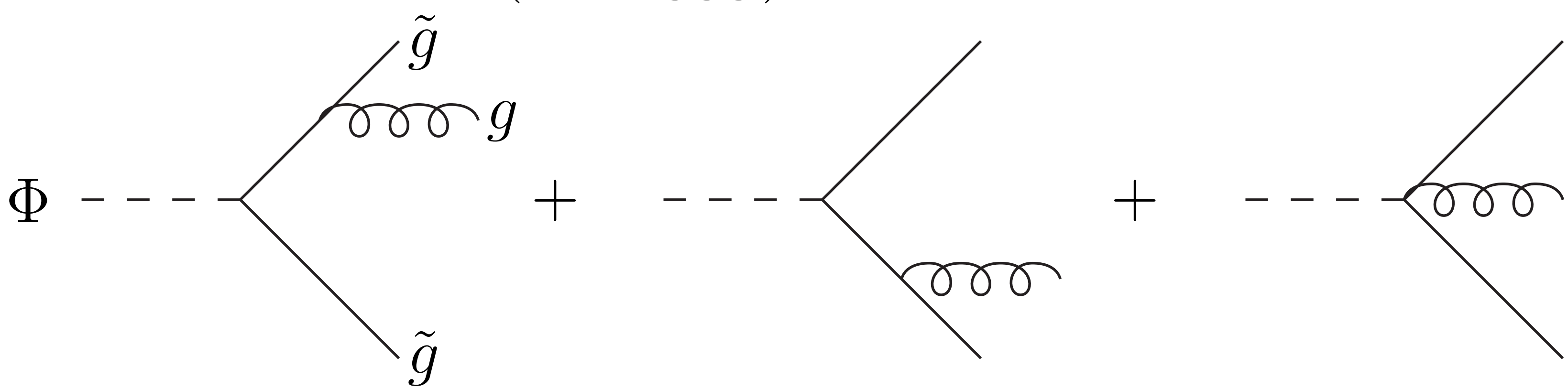
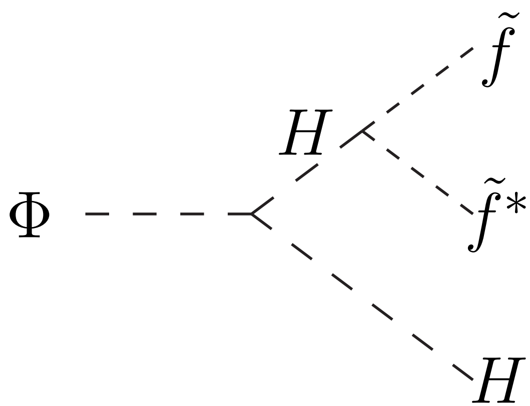
Remains true for $\mathcal{M}(\Phi \to \tilde{g}\tilde{g}g)$ from:



Higher Orders: Higgs

A. Banik, MD, to appear



$B_\chi \propto |T_{H\tilde{f}\tilde{f}}|^2/M_\Phi^2$: small!

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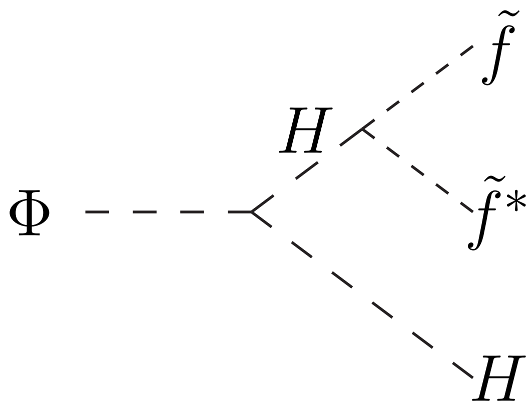

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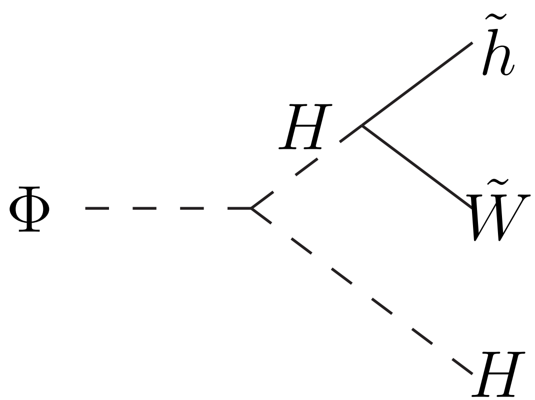
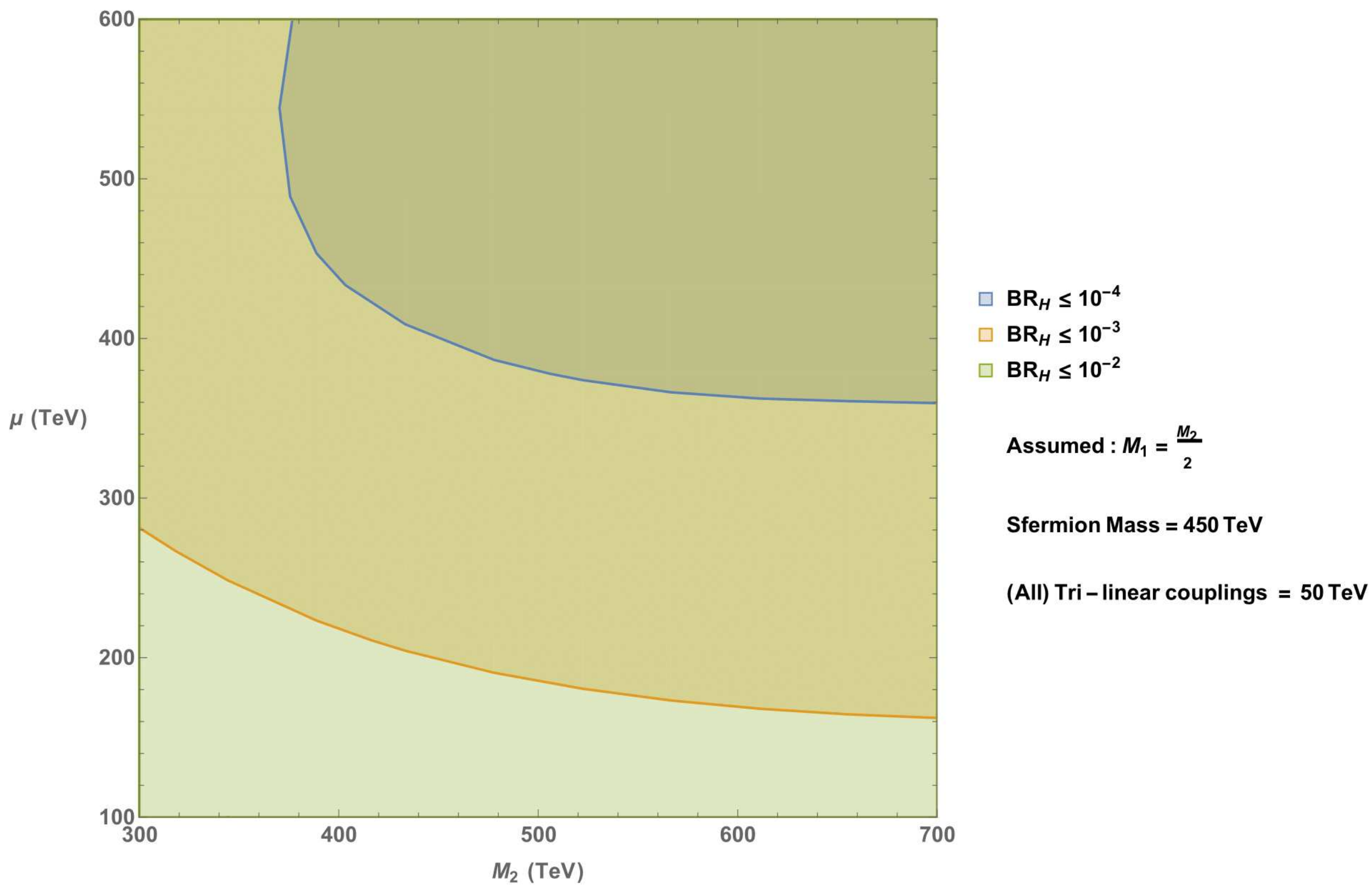


No extra suppression,

except elw cplg, phase space!

Results: $M_\Phi = 10^6$ GeV, $\Phi \to H_u H_d$



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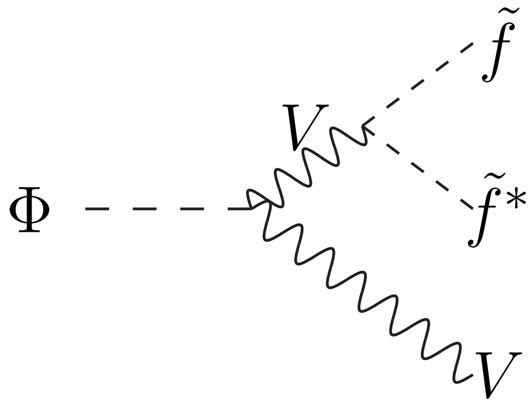

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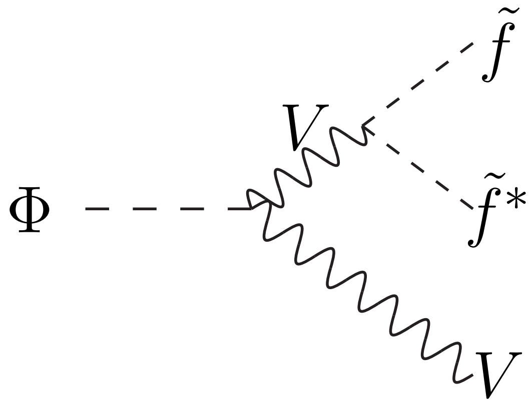

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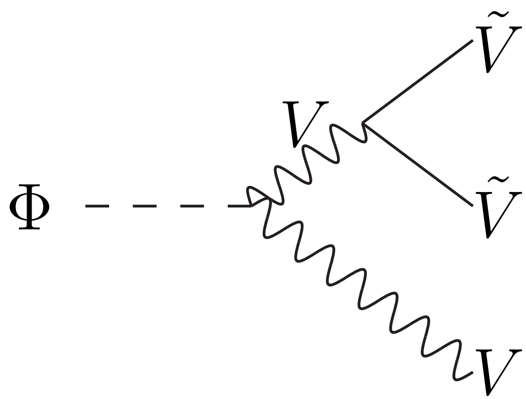

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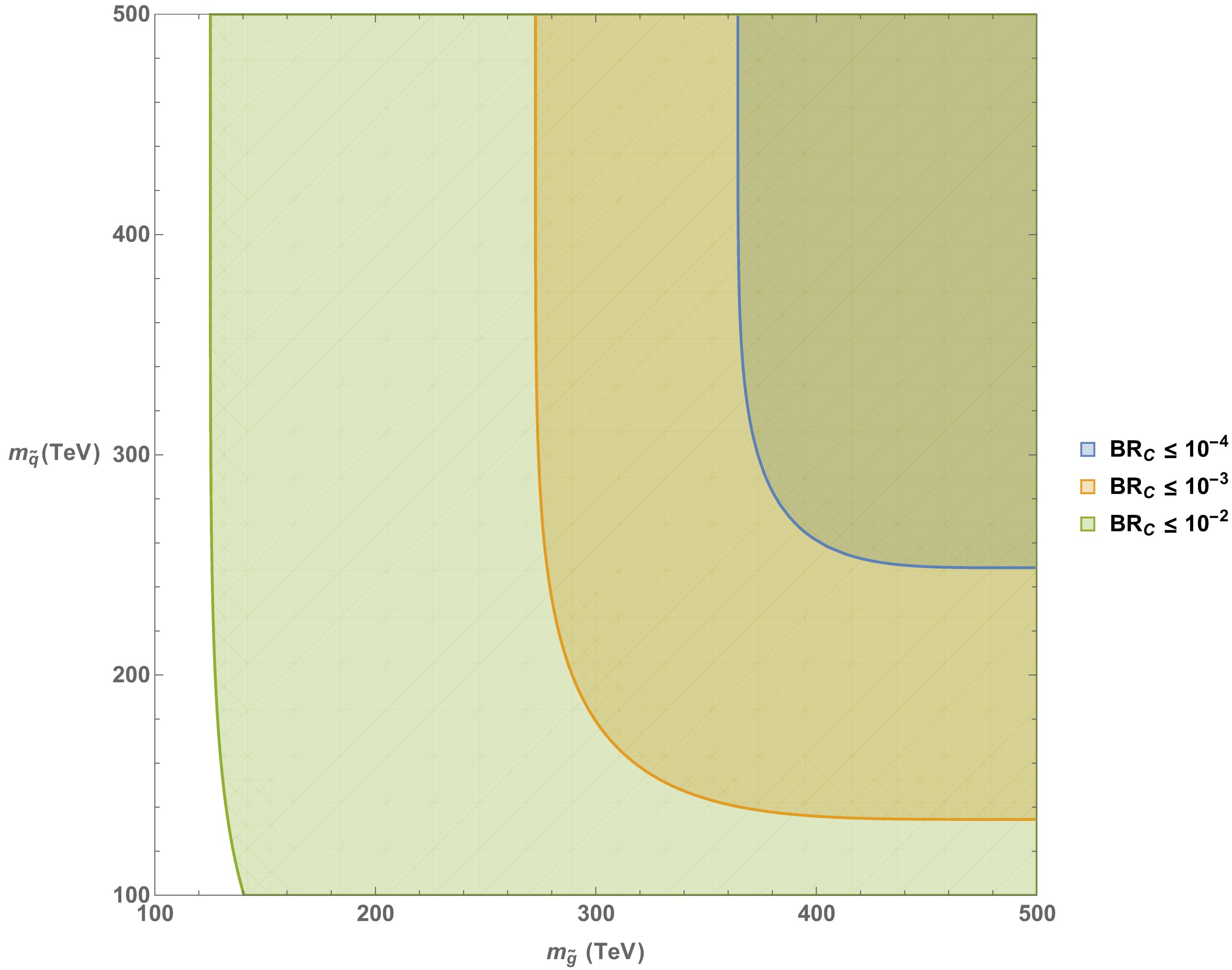

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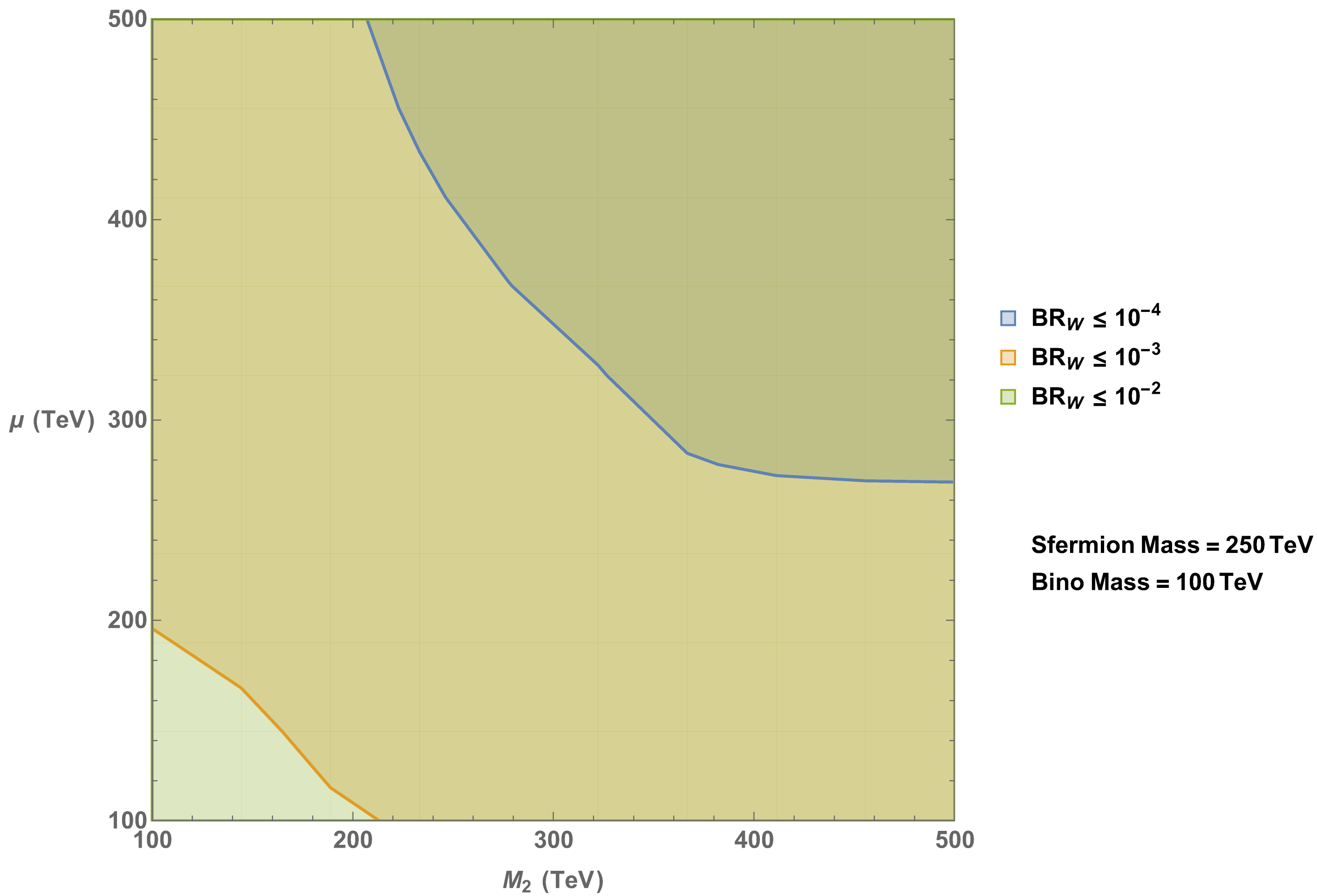

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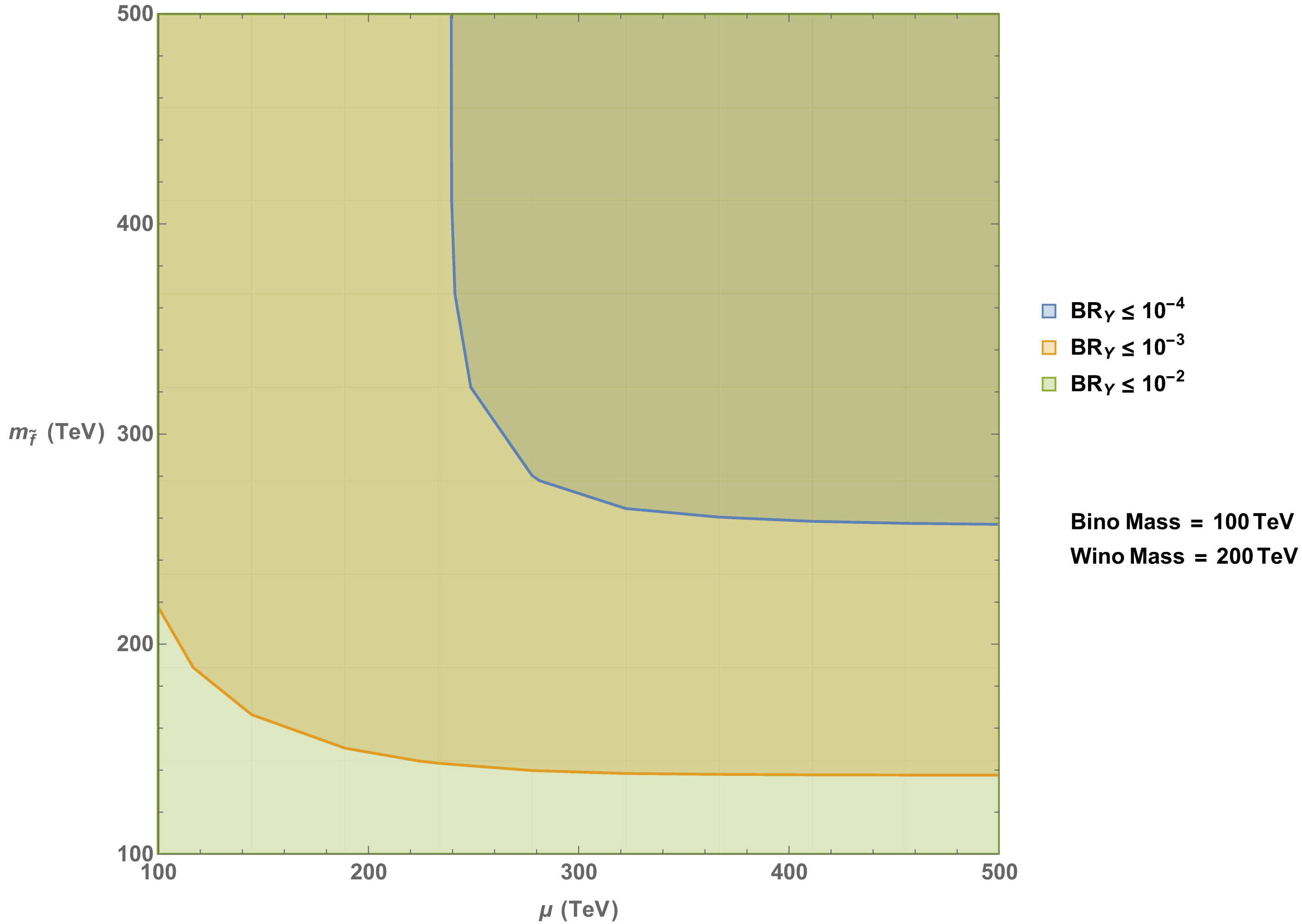

Higher order decays: Summary

$B_\chi \gtrsim 10^{-2}$ (10^{-3}) for LO Φ decays into strongly (weakly) interacting particles, unless $m_{\rm sparticle} \gtrsim M_\Phi/3$: Not natural!

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  Φ couplings should be suppressed much more than $1/M_{\rm Pl}$!
- Higgs mode: $\Phi H_u H_d$ cplg should be much smaller than usual soft breaking masses.

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- At leading order: can write supersymmetric $\Phi gg/\Phi VV$ vertex, soft breaking $\Phi H_u H_d$ vertex with desired properties
- Three-body final states will give $B(\Phi \rightarrow \tilde\chi_1^0) > 10^{-3}$ if $m_{\rm sparticle} \ll M_\Phi$; can be corrected by increasing M_Φ, if Φ couplings are $\lesssim 0.03/M_{\rm Pl}$.