Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Carleton University

Oscillating Pseudo-Dirac Gauginos:

A New Twist on Leptogenesis and Neutrino Masses

Cem Murat Ayber

(pronounced as “ ”)

NSERC CRSNG

Based on Phys. Rev. D 113, 115046
JHEP 11 (2023) 085

cap

Works with Seyda Ipek, and Tammi Chowdhury

Outlook

In this talk, I will try to reignite your excitement for SUSY!

$U(1)_{R-L}$ -symmetric SUSY

→ Neutrino Masses

CMA, Ipek, JHEP 11 (2023) 085

→ Leptogenesis

CMA, Chowdhury, Ipek, J Phys. Rev. D 113, 115046

$U(1)_{R'}$ symmetric SUSY is great!

Gauginos are pseudo-Dirac fermions in $R' = R - L$ global symmetric SUSY!

Frugiuele, et.al. JHEP 2013, 156

Giudice, et. al., JHEP 12 (1998) 027
Randall, Sundrum Nucl. Phys. B557 (1999) 79

Fox, et.al., JHEP 08 (2002) 035

Anomaly mediation

Supersoft SUSY breaking

$$\mathscr{L} \supset m_{\tilde{B}}\tilde{B}\,\tilde{B} + m_{\tilde{W}}\tilde{W}\,\tilde{W} + m_S S\,S + m_T T\,T + M_{\tilde{B}} S\,\tilde{B} + M_{\tilde{W}} T\,\tilde{W}$$

$$m_{\tilde{B},\tilde{W},S,T} \sim \mathcal{O}(m_{3/2})$$ Gravitino mass

we call them $\psi^T_{\tilde{B}} = \left(\tilde{B},\ S^\dagger\right)^T$: "biνo" $\psi^T_{\tilde{W}} = \left(\tilde{W},\ T^\dagger\right)^T$: "wiνo"

Coloma, Ipek, Phys.Rev.Lett. 117 (2016) 11, 111803

CMA, Ipek JHEP 11 (2023) 085

$U(1)_{R'}$ **is approximate when** $m_{3/2} \ll M_{\tilde{B}}, M_{\tilde{W}}$

Superfields	$SU(2)_L$	$U(1)_{R'}$
L_i	2	0
E^c_i	1	2
$H_{u,d}$	2	0
$R_{u,d}$	2	2
$W^\alpha_{\tilde{B}}$	1	1
Φ_S	1	0
$W^\alpha_{\tilde{W}}$	3	1
Φ_T	3	0

Neutrino Masses

$$\mathscr{L} \supset \frac{f^i_{\tilde{B}} M_{\tilde{B}}}{\Lambda_M} \bar{\ell} h_u \tilde{B} + M_{\tilde{B}} S \tilde{B} + \frac{d^i_S m_{3/2}}{\Lambda_M} \bar{\ell} h_u S^\dagger + m_{\tilde{B}} \tilde{B}\tilde{B} + m_S SS$$

$$+ \frac{f^i_{\tilde{W}} M_{\tilde{W}}}{\Lambda_M} \bar{\ell} h_u \tilde{W} + M_{\tilde{W}} T \tilde{W} + \frac{d^i_T m_{3/2}}{\Lambda_M} \bar{\ell} h_u T^\dagger + m_{\tilde{W}} \tilde{W}\tilde{W} + m_T TT$$

$U(1)_{R-L}$-conserving

$U(1)_{R-L}$-violating

biνo and wiνo act as *RH* neutrinos!

Hybrid Type I+III ISS

The neutrino mass matrix

in the $(\nu_i, \tilde{B}, \tilde{W}, S, T)$ basis

$$Y^i_{\tilde{B},\tilde{W}} = \frac{f^i_{\tilde{B},\tilde{W}} M_{\tilde{B},\tilde{W}}}{\Lambda_M} \quad G^i_{S,T} = \frac{d^i_{S,T} m_{3/2}}{\Lambda_M}$$

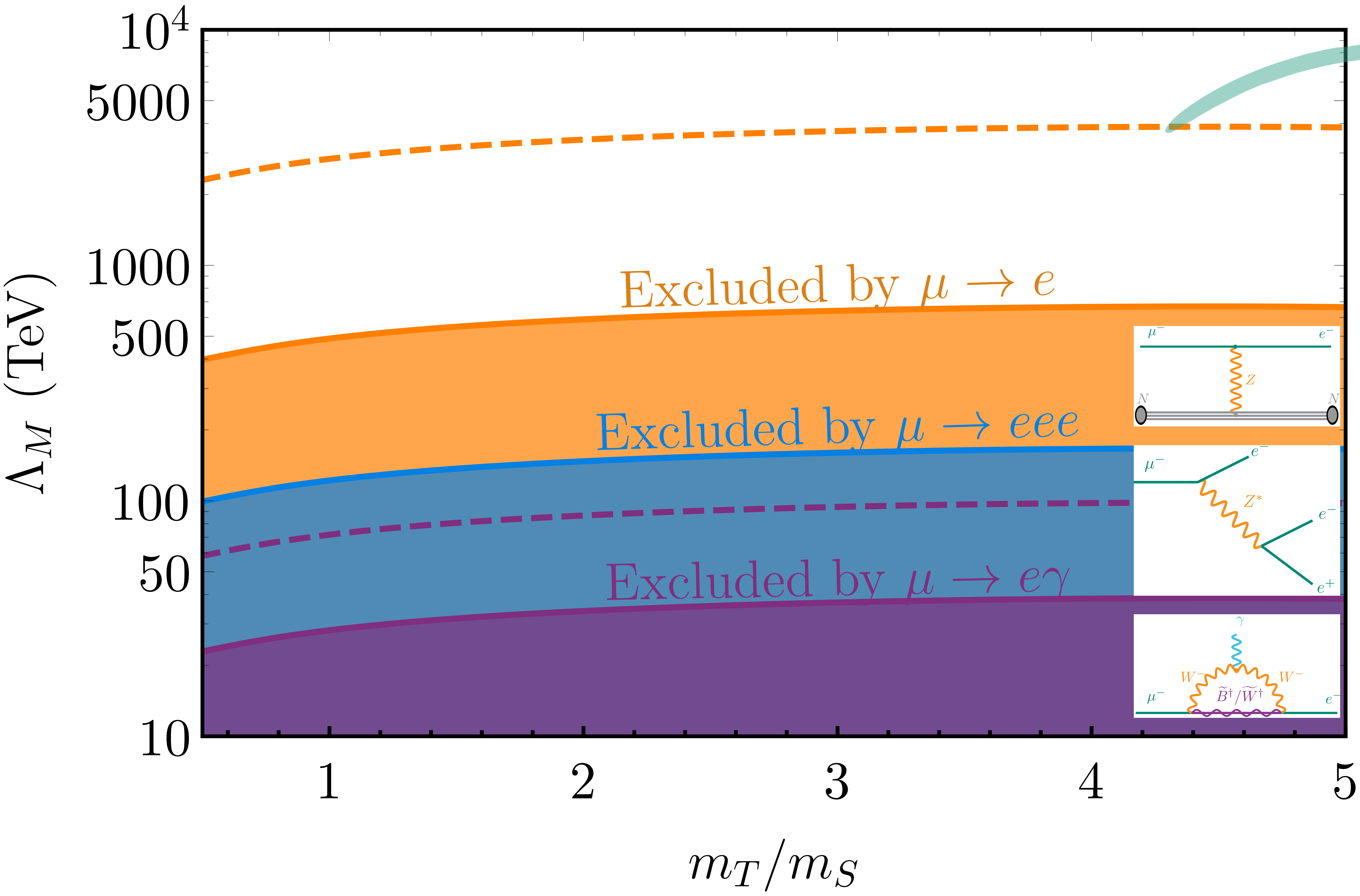
$$M_\nu = \begin{pmatrix} \mathbf{0}_{3\times3} & \mathbf{Y}_{\tilde{B}} v & \mathbf{Y}_{\tilde{W}} v & \mathbf{G}_S v & \mathbf{G}_T v \\ \mathbf{Y}^T_{\tilde{B}} v & m_{\tilde{B}} & 0 & M_{\tilde{B}} & 0 \\ \mathbf{Y}^T_{\tilde{W}} v & 0 & m_{\tilde{W}} & 0 & M_{\tilde{W}} \\ \mathbf{G}^T_S v & M_{\tilde{B}} & 0 & m_S & 0 \\ \mathbf{G}^T_T v & 0 & M_{\tilde{W}} & 0 & m_T \end{pmatrix}$$

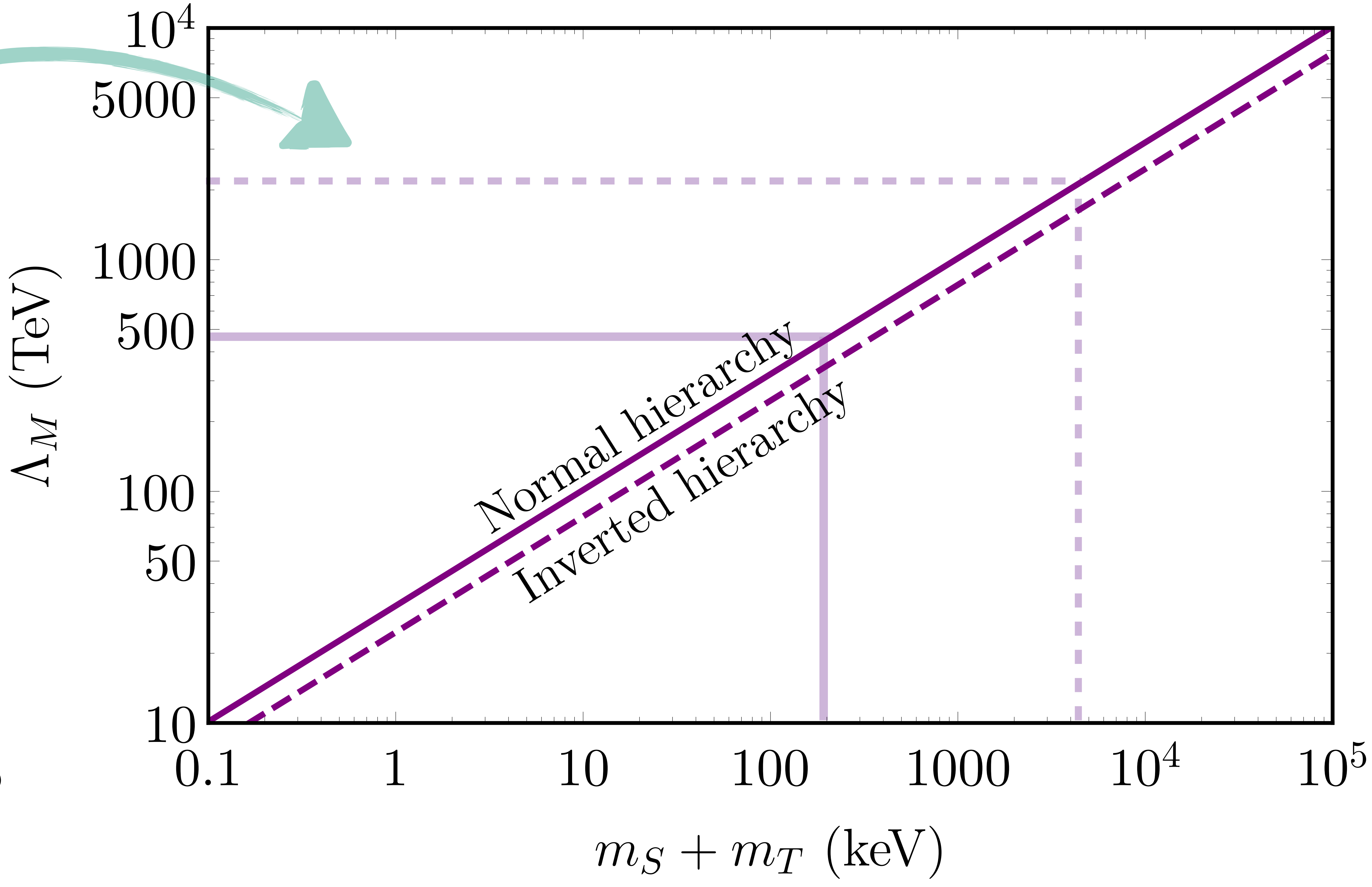
Can generate three massive light neutrinos with the correct mass splittings!

CMA, Ipek, JHEP 11 (2023) 085

A Simplified Scenario

$U(1)_{R-L}$-violating terms ($G^i_{S,T} = 0$) are turned off





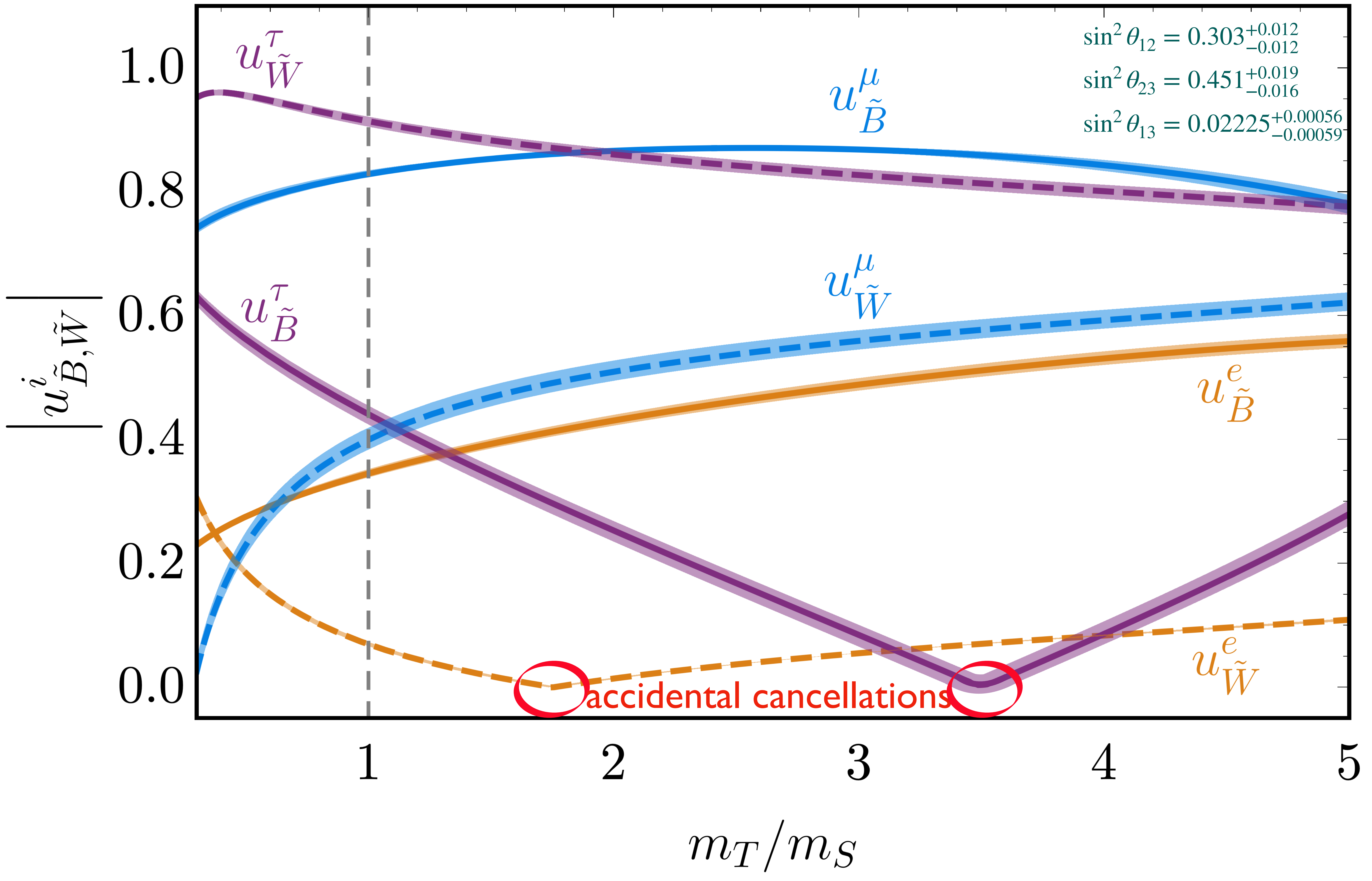
$$\Lambda_M \gtrsim (500 - 1000)\ \text{TeV}$$

$$m_S + m_T \sim (0.1 - 10)\text{MeV}$$

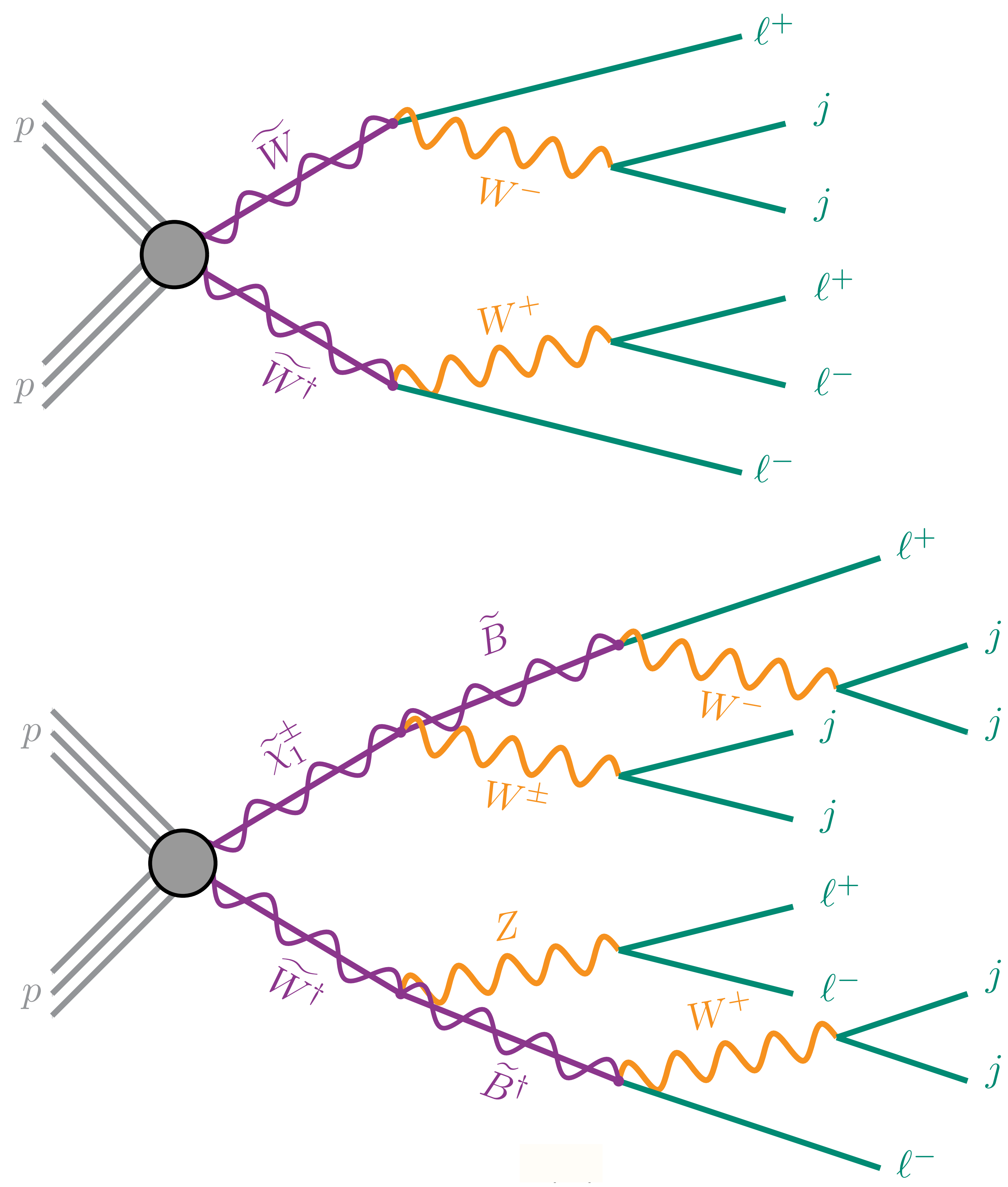
CMA, Ipek, JHEP 11 (2023) 085

LHC Phenomenology

Hybrid Mixing Scenario $\Lambda_M \gtrsim (500 - 1000)$ TeV



representative LHC final states



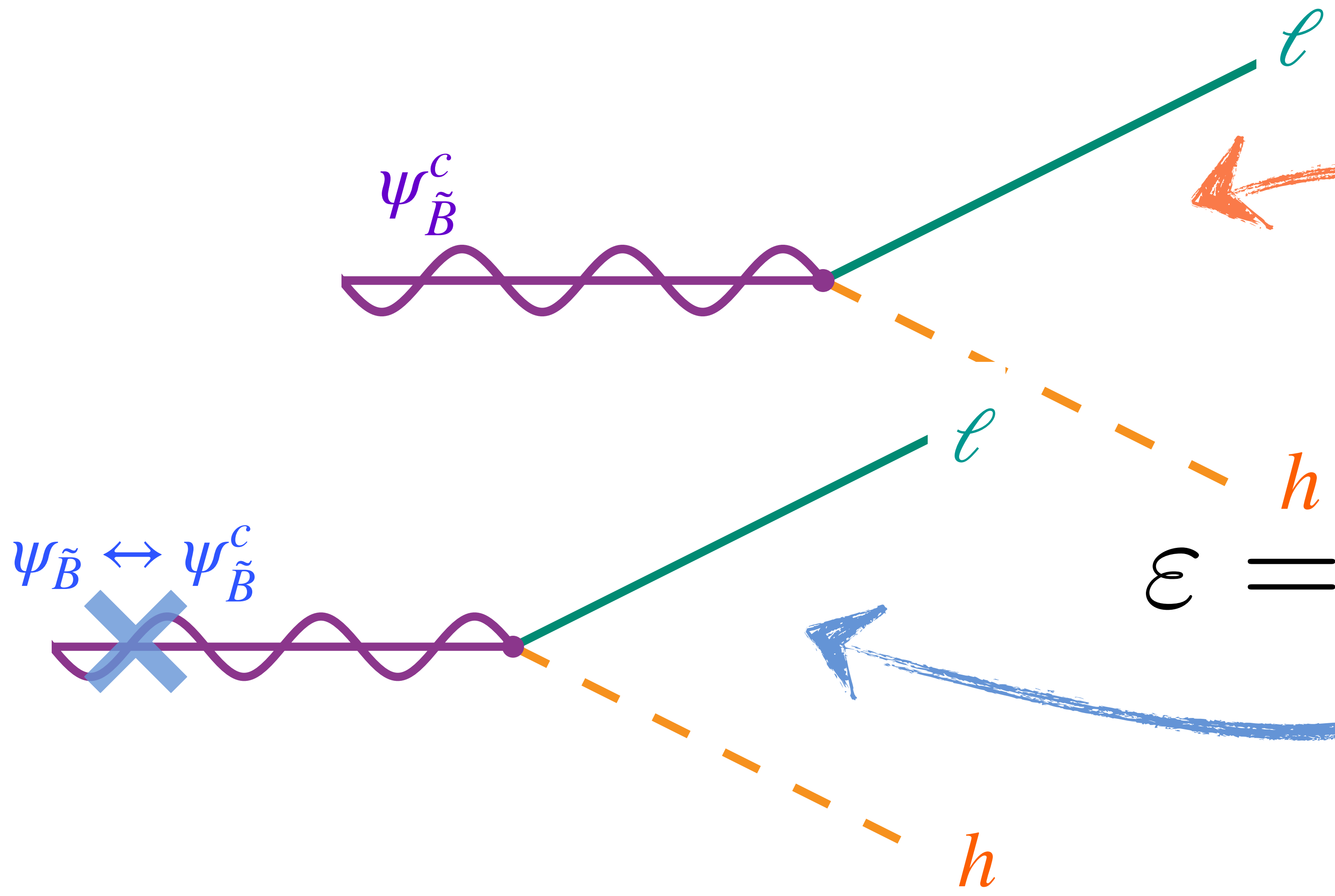
CMA, Ipek, JHEP 11 (2023) 085

Bino-antibino Oscillations

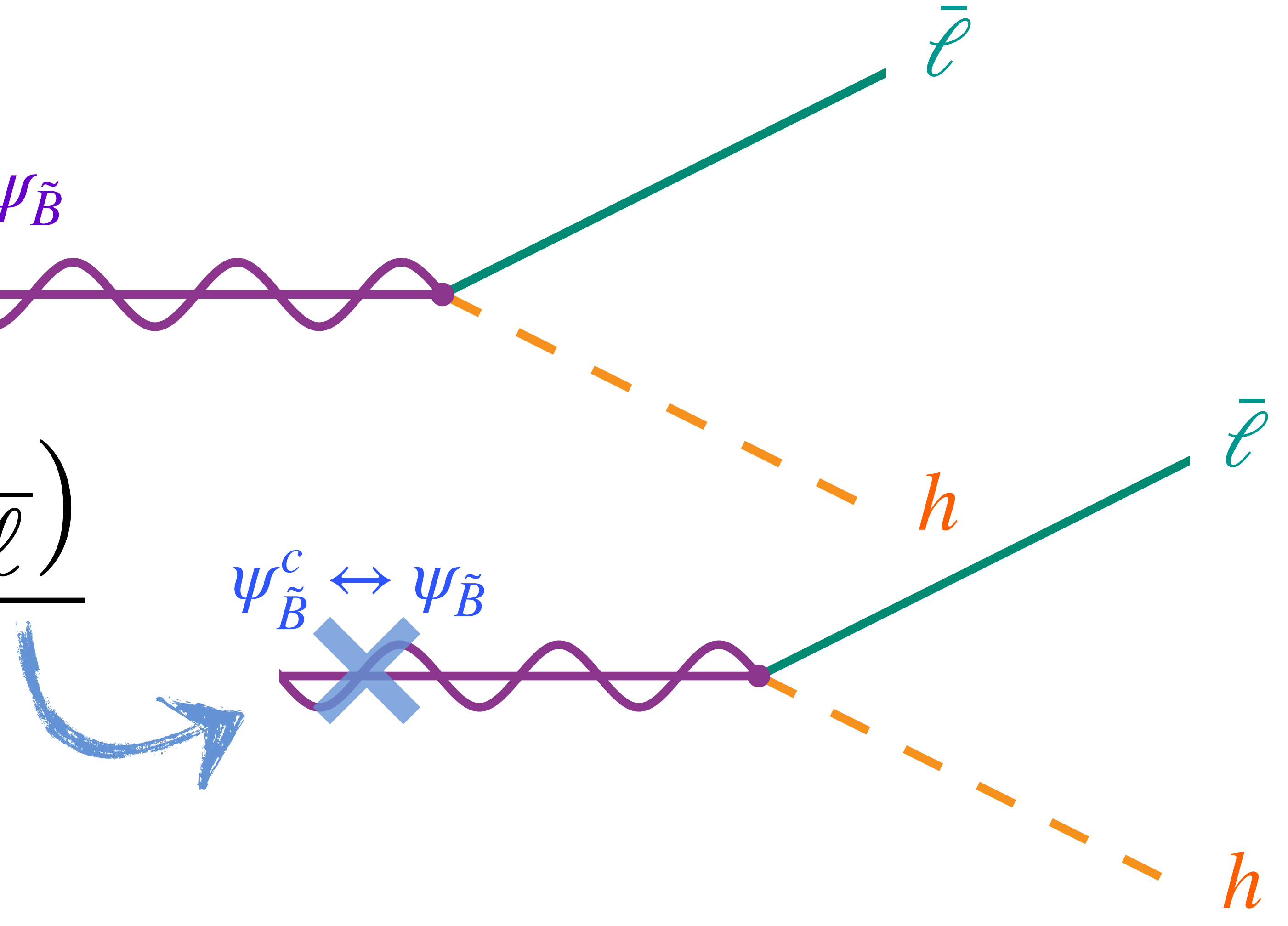
*Analogous to neutral meson oscillations

Bino-antibino oscillations* can generate CP violation

with a frequency $\omega \sim 2m$



$$\varepsilon = \frac{(N_\ell + \bar{N}_\ell) - (N_{\bar{\ell}} + \bar{N}_{\bar{\ell}})}{N_\ell + \bar{N}_\ell + N_{\bar{\ell}} + \bar{N}_{\bar{\ell}}}$$



$$r = \left| \frac{g_{\tilde{B}} g_S}{g^2_{\tilde{B}} + g^2_S} \right| \simeq \frac{M_{\tilde{B}} \tilde{m}}{M^2_{\tilde{B}} + \tilde{m}^2}$$

$$\varepsilon \simeq \frac{2 \sin\phi \, x}{(1+x^2)} \frac{r(1-r^2)}{(1+r^2)}$$

$$x \equiv \Delta m / \Gamma_{\tilde{B}} \simeq 2m/\Gamma_{\tilde{B}}$$

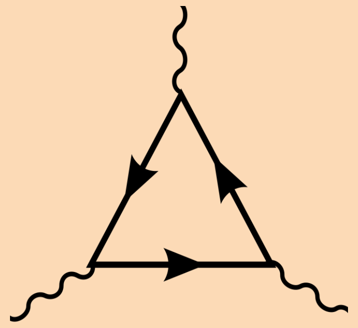
To have enough CP violation we require $m_{\tilde{B}} + m_S \ll M_{\tilde{B}}$ and $G_S / Y_{\tilde{B}} \sim \mathcal{O}(10^{-5} - 1)$

Ipek, March-Russell, Phys.Rev.D 93 (2016) 12, 123528

Chowdhury, M.Sc.Thesis

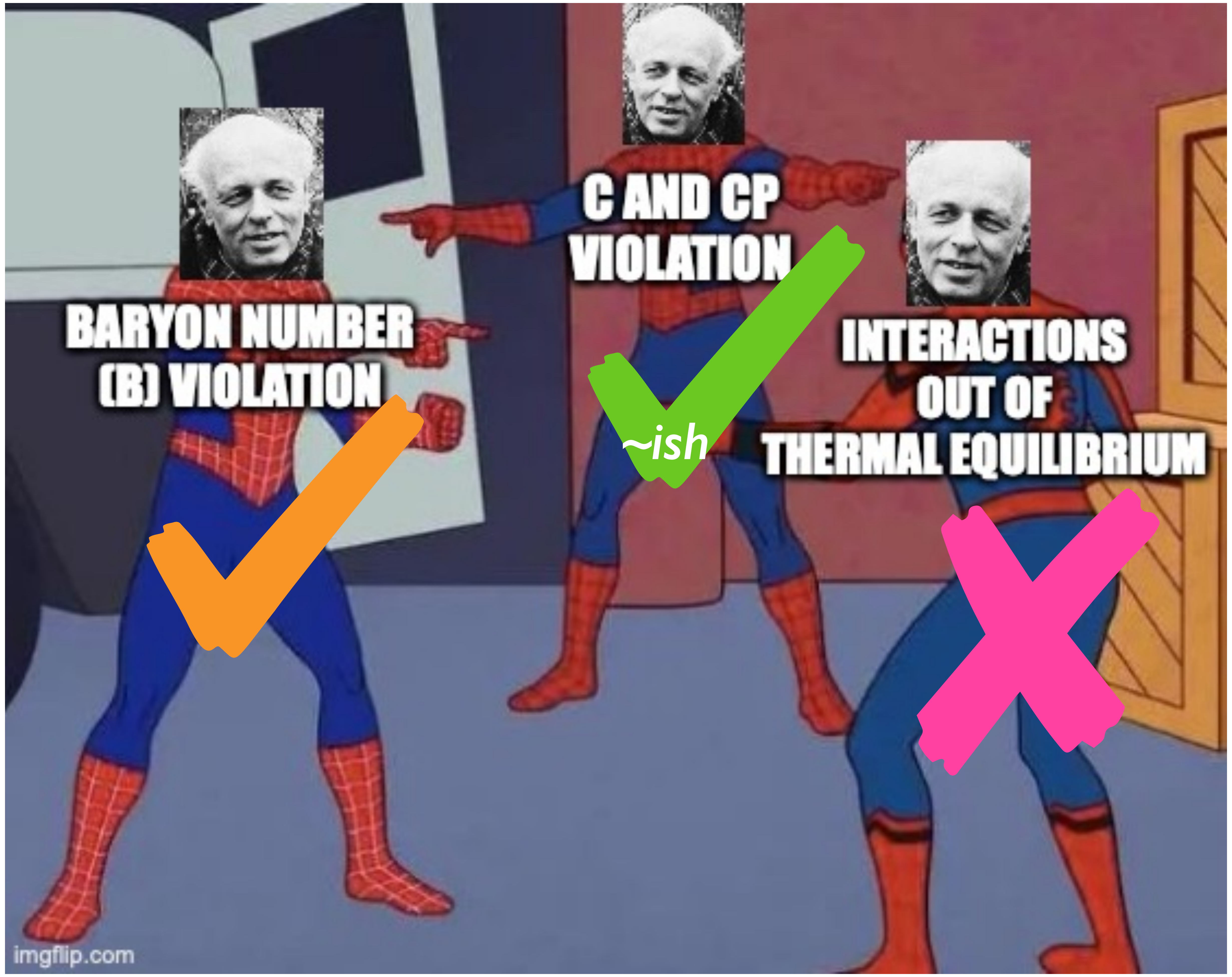
Sakharov Conditions

violated via the triangle anomaly



$$\partial_\mu j^\mu_{B,L} = \frac{n_g}{32\pi^2}\left(g^2 W^a_{\mu\nu}\widetilde{W}^{\mu\nu}_a - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

non-conservation of $B+L$



irreducible complex phase in the CKM matrix, though its very small

Absent!

Sakharov, JETP Lett. 5 (1967) 24

$U(1)_{R'}$ Symmetric SUSY vs Sakharov

Our model has enough freedom to explain both

light neutrino masses and the BAU! with a *tweak**

*The *tweak*

We consider a hierarchy $m_S \ll m_T$ and $G_S \ll G_T$

wino generates the neutrino masses

out-of-equilibrium decays of bino create the BAU!

We allow the following operator to appear*

$$\frac{d^i_\eta \tilde{m}}{\Lambda_M} \int d^2\theta \, \Phi_\eta H_u L_i$$

a new mass scale, $\tilde{m} \gg m_{3/2}$

* future work.

→

For successful leptogenesis

$$M_{\tilde{B}} > 130 \text{ GeV}$$

$$\Lambda_M \gtrsim \mathcal{O}(10^7 \text{ TeV})$$

Boltzmann Equations

We use density matrix formalism to incorporate the oscillation dynamics in the early universe

Tulin,et.al., JCAP 05, 013 (2012)
Elor,et.al., Phys. Rev. D 99, 035031 (2019)
Aitken, et.al., Phys. Rev. D 96, 075009 (2017)
Alonso-Alvarez, et.al. ,JHEP03,046(2020)

Valid in the non-relativistic regime!

$$zH\frac{d\mathbf{Y}}{dz} = -i(\mathbf{HY} - \mathbf{YH}^\dagger) - \sum_{+,-}\frac{\Gamma_\pm}{2}\left[O_\pm\left[O_\pm, \mathbf{Y}\right]\right] - \sum_{+,-} s\langle\sigma v\rangle_\pm \left(\frac{1}{2}\{\mathbf{Y}, O_\pm\bar{\mathbf{Y}}O_\pm\} - Y_{\rm eq}^2\right)$$

Vacuum oscillations — Scatterings — Annihilations

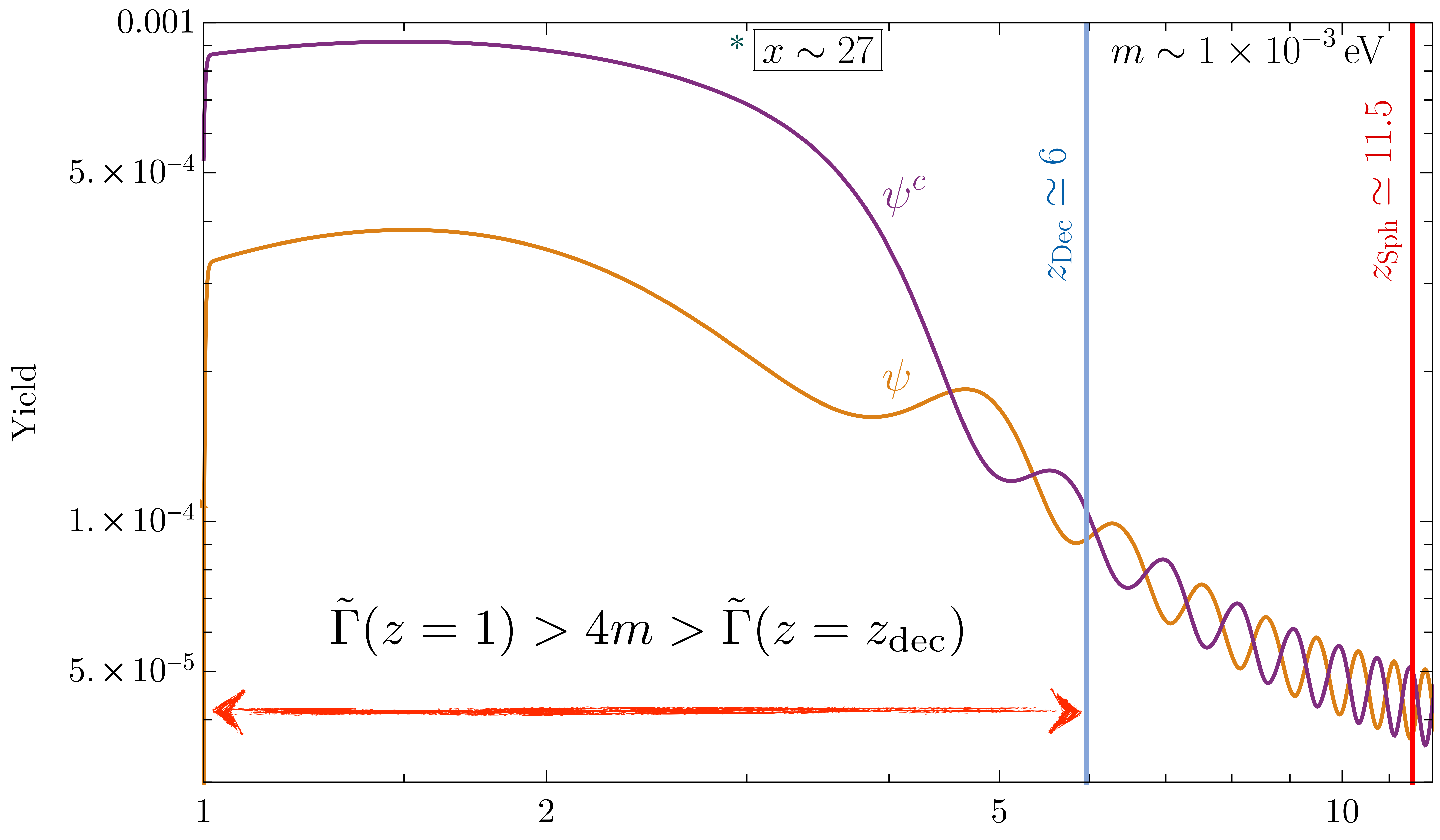
$$\langle\sigma\, v\rangle^{\rm scat}_{\rm blind} \simeq \frac{C\, M^2_{\tilde{B}}}{4M^4_{\rm sf}}\frac{3}{2z^2}$$

$$\langle\sigma\, v\rangle^{\rm ann}_{\rm blind} = \frac{C\, M^2_{\tilde{B}}}{4M^4_{\rm sf}}\frac{1}{z} \qquad \langle\sigma\, v\rangle^{\rm ann}_{\rm sens} = \frac{C\, M^2_{\tilde{B}}}{4M^4_{\rm sf}}$$

$$Y_{\rm eq} = \frac{n_{\rm eq}}{s} = \frac{45}{4\pi^3\sqrt{2\pi}g_*}z^{3/2}e^{-z}$$

$$\Gamma^{\rm scat} = \frac{3\zeta(3)}{2\pi^2}\left(\frac{M_{\tilde{B}}}{z}\right)^3\langle\sigma v\rangle^{\rm scat}$$

Bino-antibino Oscillations



$z = \frac{M_{\tilde{B}}}{T}$

*meson-antimeson oscillations $x_{B_s^0} \simeq 27$

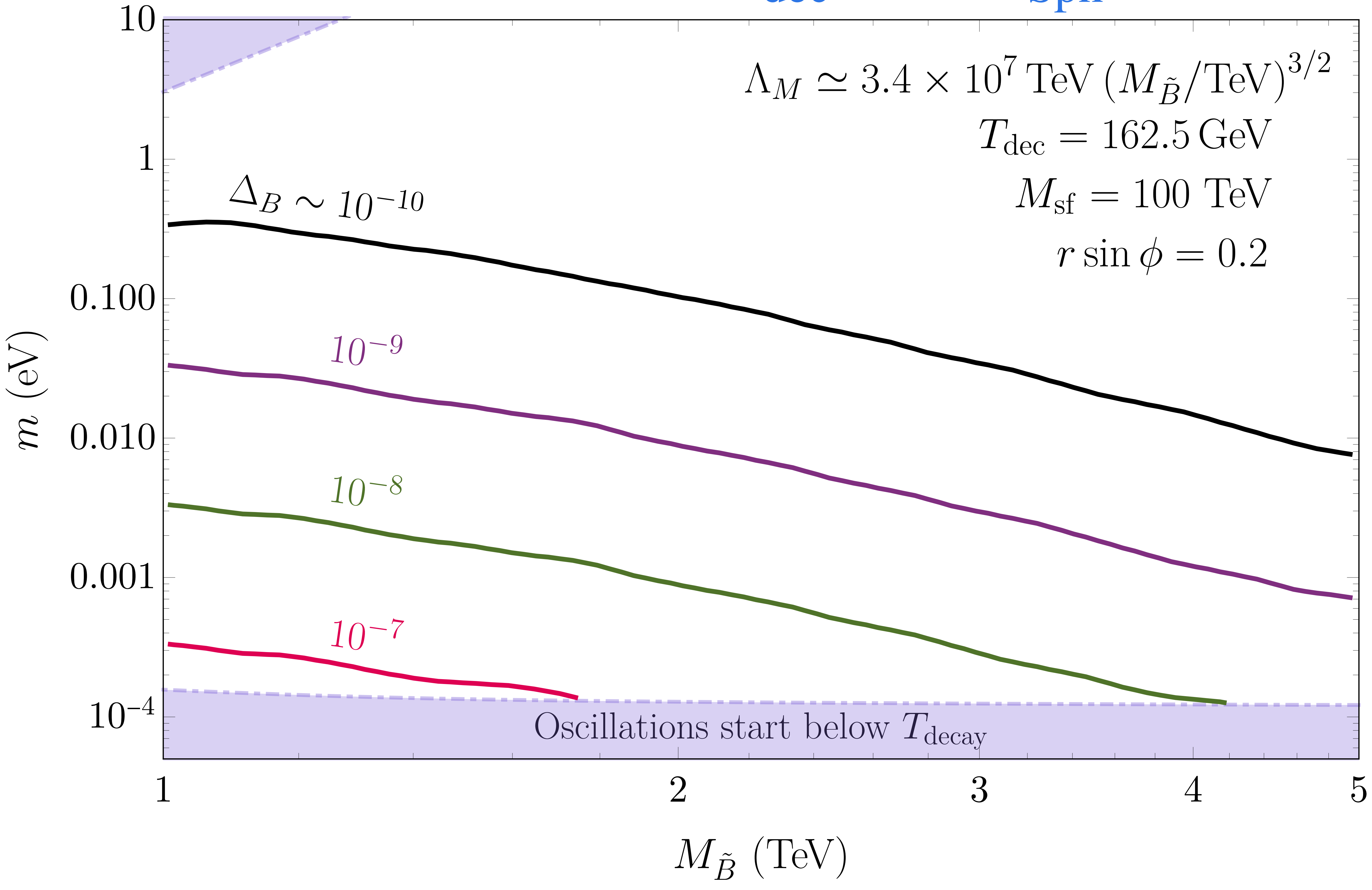
$x \equiv \Delta m/\Gamma_{\tilde{B}} \simeq 2m/\Gamma_{\tilde{B}}$

Results: Two Benchmark Scenarios

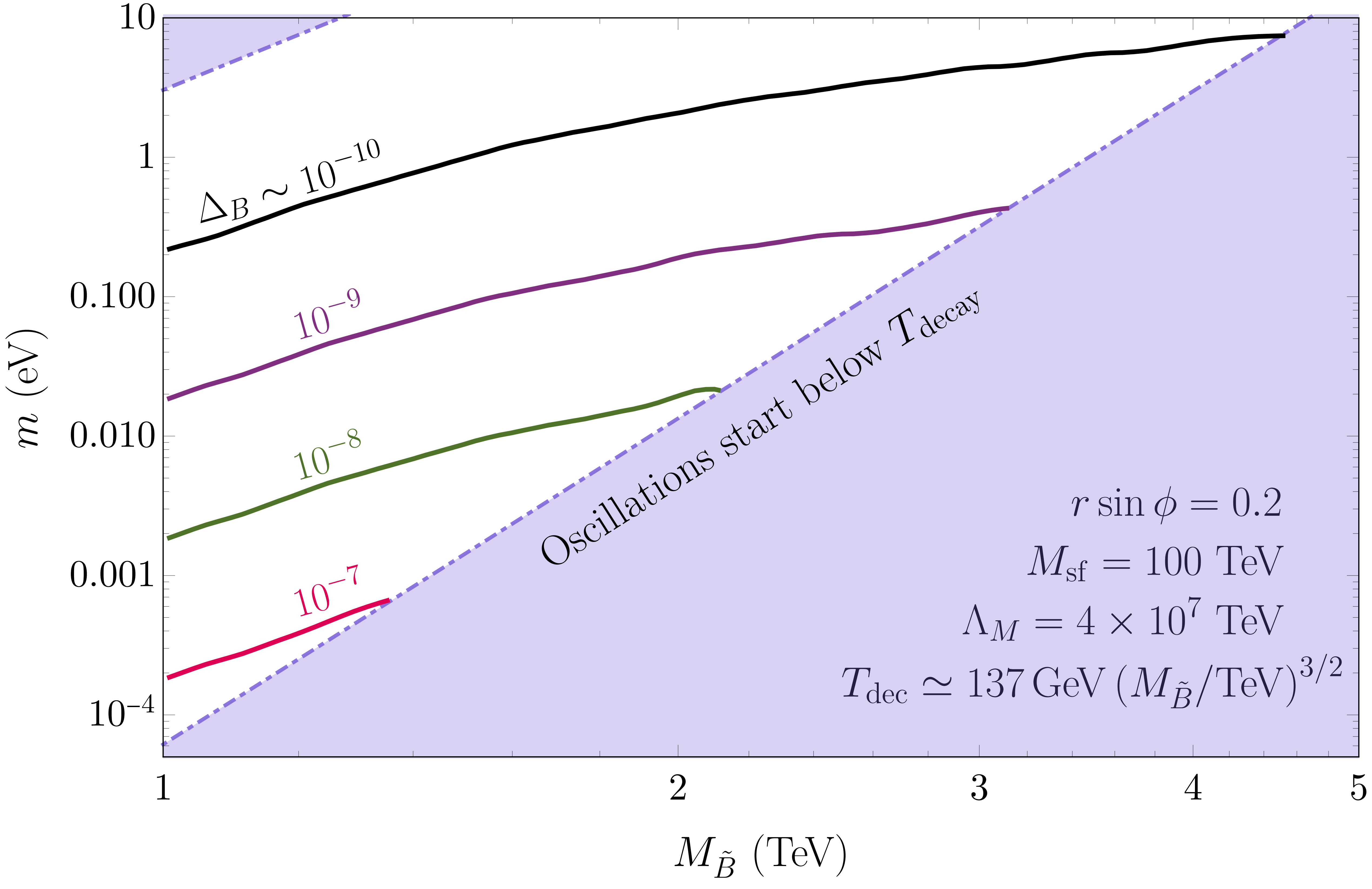
$$zH(z)\frac{d\Delta_L(z)}{dz} = \varepsilon\,\Gamma_{\tilde{B}}\left(\Sigma(z) - 2Y_{\rm eq}\right) \longrightarrow \Delta_B = 0.348 \times \Delta_L(z_{\rm sph})$$

$\Delta_L = Y_L - Y_{\bar{L}}$

fixed decay rate $z_{\rm dec} \sim 0.8 z_{\rm Sph}$



constant messenger scale



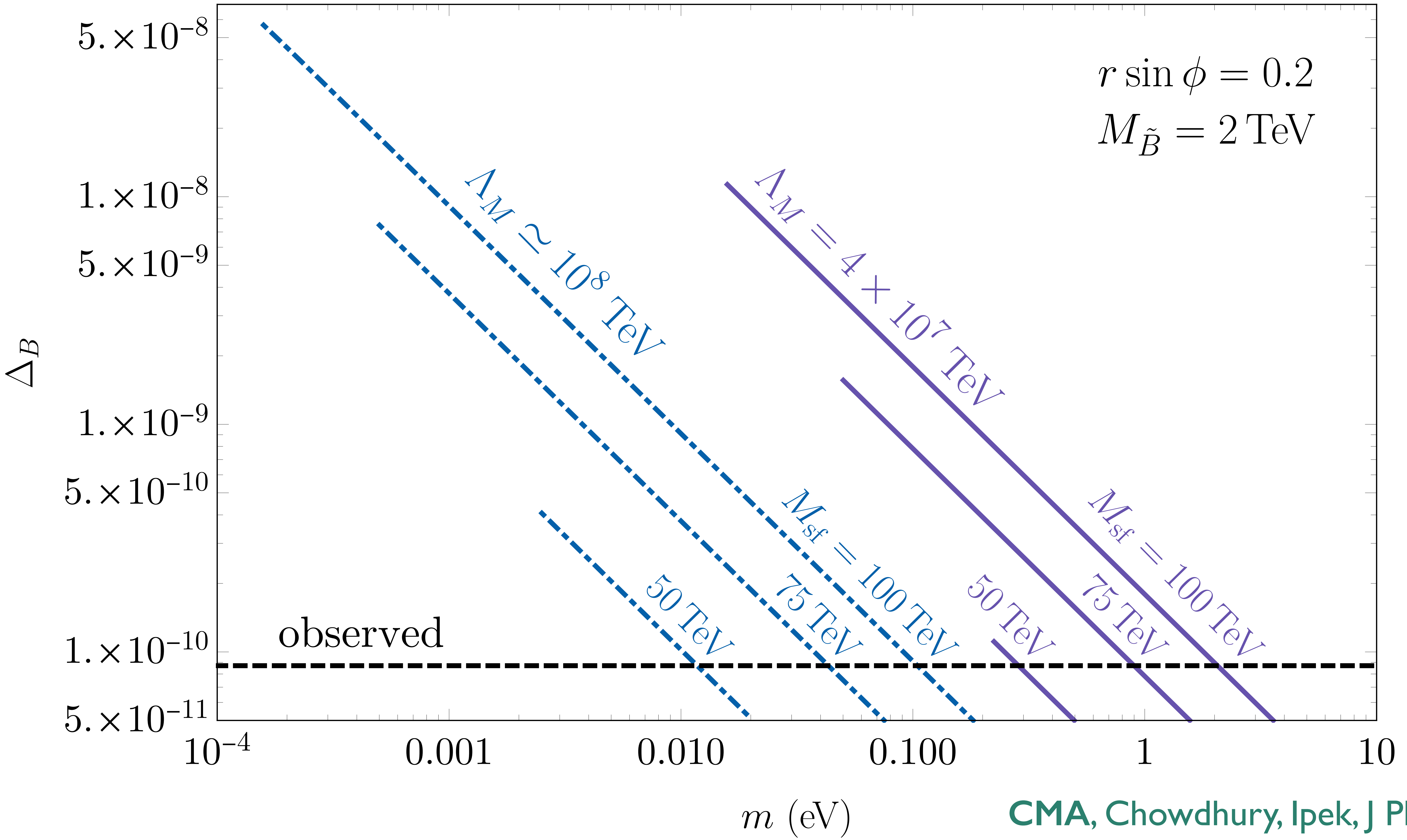
CMA, Chowdhury, Ipek, J Phys. Rev. D 113, 115046

Baryon Asymmetry vs Majorana Mass

bino is relativistic

$x \simeq \mathcal{O}(1 - 1000)$

bino-antibino oscillations are too fast



$$r \simeq \frac{M_{\tilde{B}}\tilde{m}}{M_{\tilde{B}}^2 + \tilde{m}^2}$$

CMA, Chowdhury, Ipek, J Phys. Rev. D 113, 115046

Summary of the Results

To generate the observed BAU, the leptogenesis scenario requires

Messenger Scale	Biνo Dirac mass	Majorana mass	Sfermion masses
$\Lambda_M \gtrsim \mathcal{O}(10^8\,\mathrm{TeV})$	$M_{\tilde{B}} \sim \text{a few TeV}$	$m \sim (10^{-4} - 10)\,\mathrm{eV}$	$M_{\mathrm{sf}} \gtrsim 50\,\mathrm{TeV}$

long-lived biνo

decays could result in displaced vertices

In the FCC target range!

ATLAS, Phys.Rev.Lett. 133 (2024) 16, 161803
ATLAS, JHEP 11 (2024) 036J
CMS, JHEP 05 (2024) 047
CMS, Rept.Prog.Phys. 88 (2025) 3, 037801

Current	*Future*	
LHC	MATHUSLA	CODEX-b

Takeaways

- The neutrino-bino/wino mixing follows a **hybrid type I+III ISS** pattern and can generate non-zero masses for all three neutrinos in its most general form.
- Out-of-equilibrium decay of a long-lived bino in the early universe can explain the **BAU** via **leptogenesis**.
- The smallness of the **Majorana gaugino masses** can be related to the $U(1)_{R-L}$ breaking and how it is mediated to the supersymmetric sector.
- **Uneaten Goldstino** and the **gravitino** could be a **DM candidate**.
- Branching fractions to different lepton families (e, μ, τ) are determined by the observed **neutrino mixing structure**.
- Offers **rich** LHC phenomenology.

Back-up Slides

Other Leptogenesis Scenarios

The most notable difference of our leptogenesis model is the production of heavy neutral leptons, which are binos in our case

→ Binos can be produced copiously through non-neutrino interactions with the SM

→ Out-of-equilibrium bino decay is governed by their mixing with neutrinos

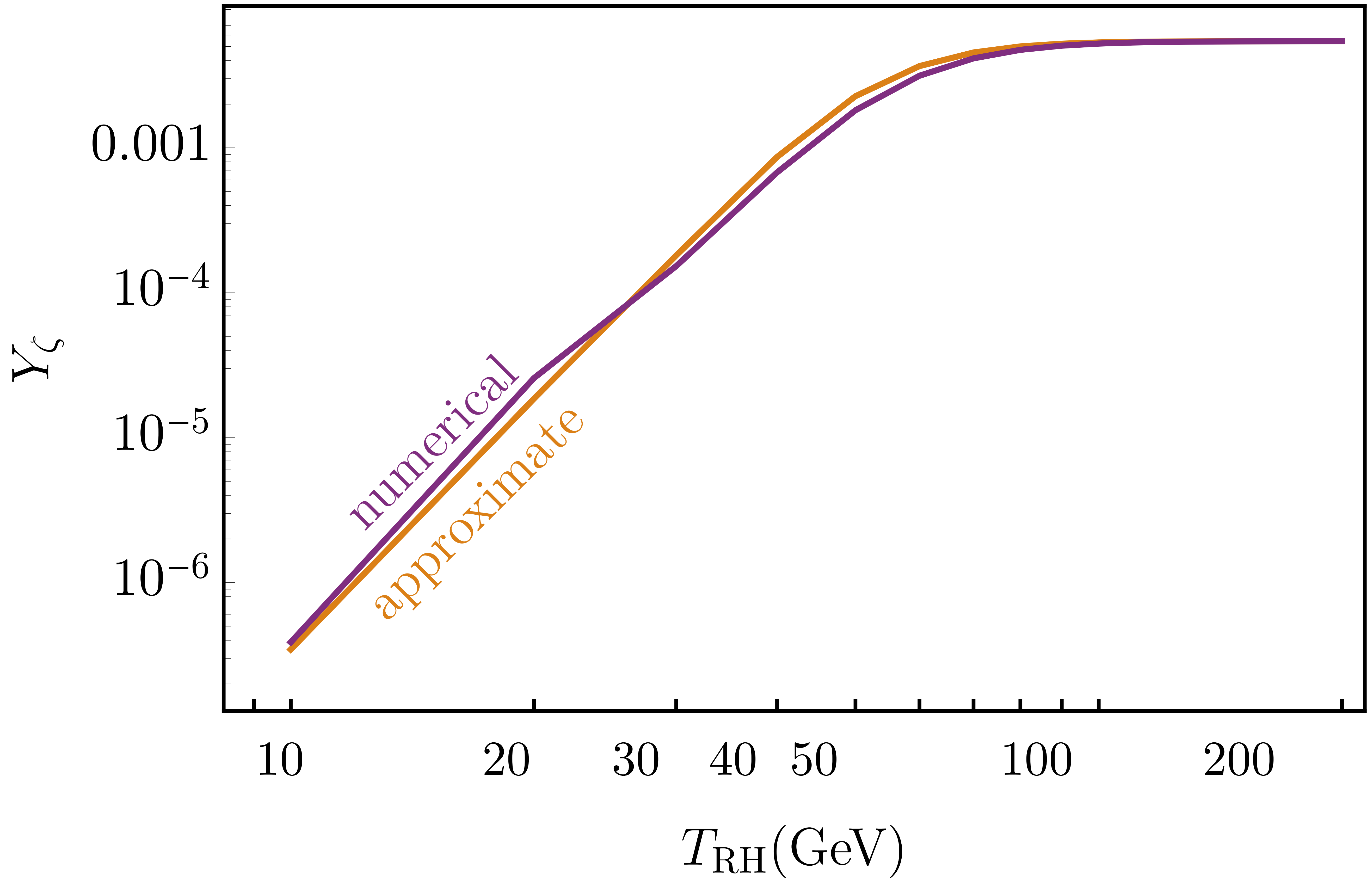
Unlike the freeze-in scenario of ARS leptogenesis, we are always in the freeze-out regime, as in resonant leptogenesis

Gravitino/Goldstino DM with low $T_{\rm RH}$

For the range of gravitino mass, $m_{3/2} \sim \mathcal{O}(1\,\mathrm{keV} - 10\,\mathrm{MeV})$

A. Monteux and C. S. Shin, Phys. Rev. D92, 035002 (2015)

If the reheating temperature is sufficiently high, $T_{\rm RH} \sim \mathcal{O}(\mathrm{TeV})$, gravitino/goldstino will overpopulate the universe!



$$m_{3/2},\ T_{\rm RH} \ll \tilde{m} \sim \mathcal{O}(\mathrm{TeV}) \lesssim \mathrm{T_{MAX}}$$

Supersoft SUSY Breaking

SUSY is broken in a hidden sector

P. J. Fox, A. E. Nelson and N. Weiner, JHEP 08 (2002) 035

SUSY breaking is communicated to the visible sector at a **messenger scale** Λ_M.

Dirac gaugino masses are generated via D-term spurions.

$$\int d^2\theta \sqrt{2} c_{\tilde{B}} \frac{W'_\alpha}{\Lambda_M} W^\alpha W_{\tilde{B}} \Phi_S \Rightarrow \frac{\sqrt{2} c_{\tilde{B}} D}{\Lambda_M} \tilde{B} S \equiv M_{\tilde{B}} \tilde{B} S$$

$$\int d^2\theta \sqrt{2} c_{\tilde{W}} \frac{W'_\alpha}{\Lambda_M} W^\alpha W_{\tilde{W}} \Phi_T \Rightarrow \frac{\sqrt{2} c_{\tilde{W}} D}{\Lambda_M} \tilde{W} T \equiv M_{\tilde{W}} \tilde{W} T$$

$D = \langle W'_\alpha \rangle$: SUSY–breaking vev of a D–term spurion field

Electroweak sector

After EWSB, S and T participate in both neutralino and chargino mixing due to the presence of $U(1)_R$ symmetry.

The relevant part of the superpotential:

G.D. Kribs, A. Martin and T.S. Roy, JHEP 01 (2009) 023

$$\mathscr{W} = \mu_u H_u R_u + \mu_d H_d R_d + \Phi_S \left(\lambda^u_{\tilde{B}} H_u R_u + \lambda^d_{\tilde{B}} H_d R_d\right) + \Phi_T \left(\lambda^u_{\tilde{W}} H_u R_u + \lambda^d_{\tilde{W}} H_d R_d\right)$$

In the large $\tan\beta \equiv v_u / v_d$ limit, ($v_d \to 0$), the mixing matrices in neutral and charged sectors:

$$\mathbb{M}_N \simeq \begin{pmatrix} M_{\tilde{B}} & 0 & g_Y v/2 & 0 \\ 0 & M_{\tilde{W}} & -g_2 v/\sqrt{2} & 0 \\ \lambda^u_{\tilde{B}} v/2 & -\lambda^u_{\tilde{W}} v/2 & \mu_u & 0 \\ 0 & 0 & 0 & \mu_d \end{pmatrix}$$

In the basis $(\tilde{B}, \tilde{W}^0, \tilde{R}^0_u, \tilde{R}^0_d) \times (S, T^0, \tilde{h}^0_u, \tilde{h}^0_d)$

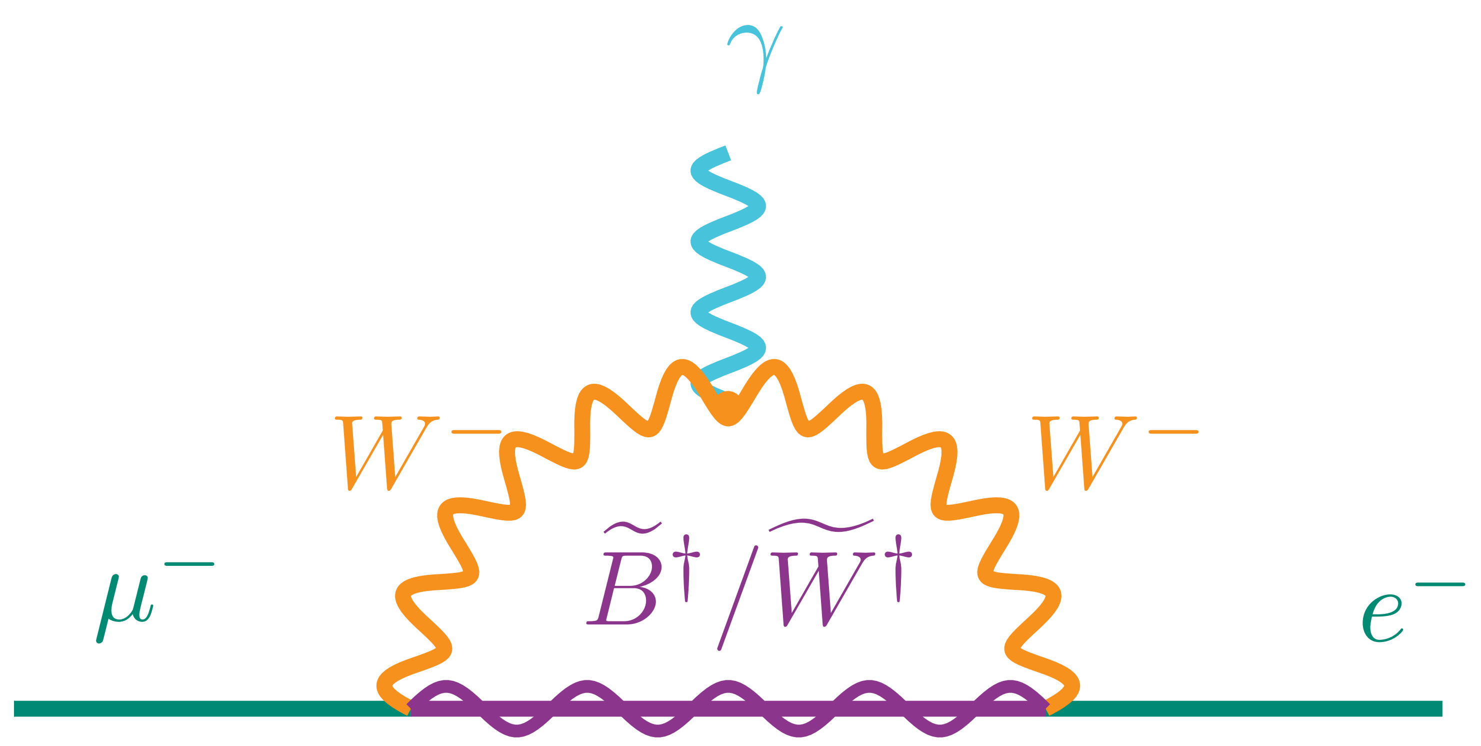
$$\mathbb{M}_C \simeq \begin{pmatrix} M_{\tilde{W}} & -g_2 v/\sqrt{2} & 0 \\ 0 & \mu_u & 0 \\ 0 & 0 & \mu_d \end{pmatrix}$$

In the basis $(\tilde{W}^+, \tilde{R}^+_u, \tilde{R}^+_d) \times (\Phi^-_T, \tilde{h}^-_u, \tilde{h}^-_d)$

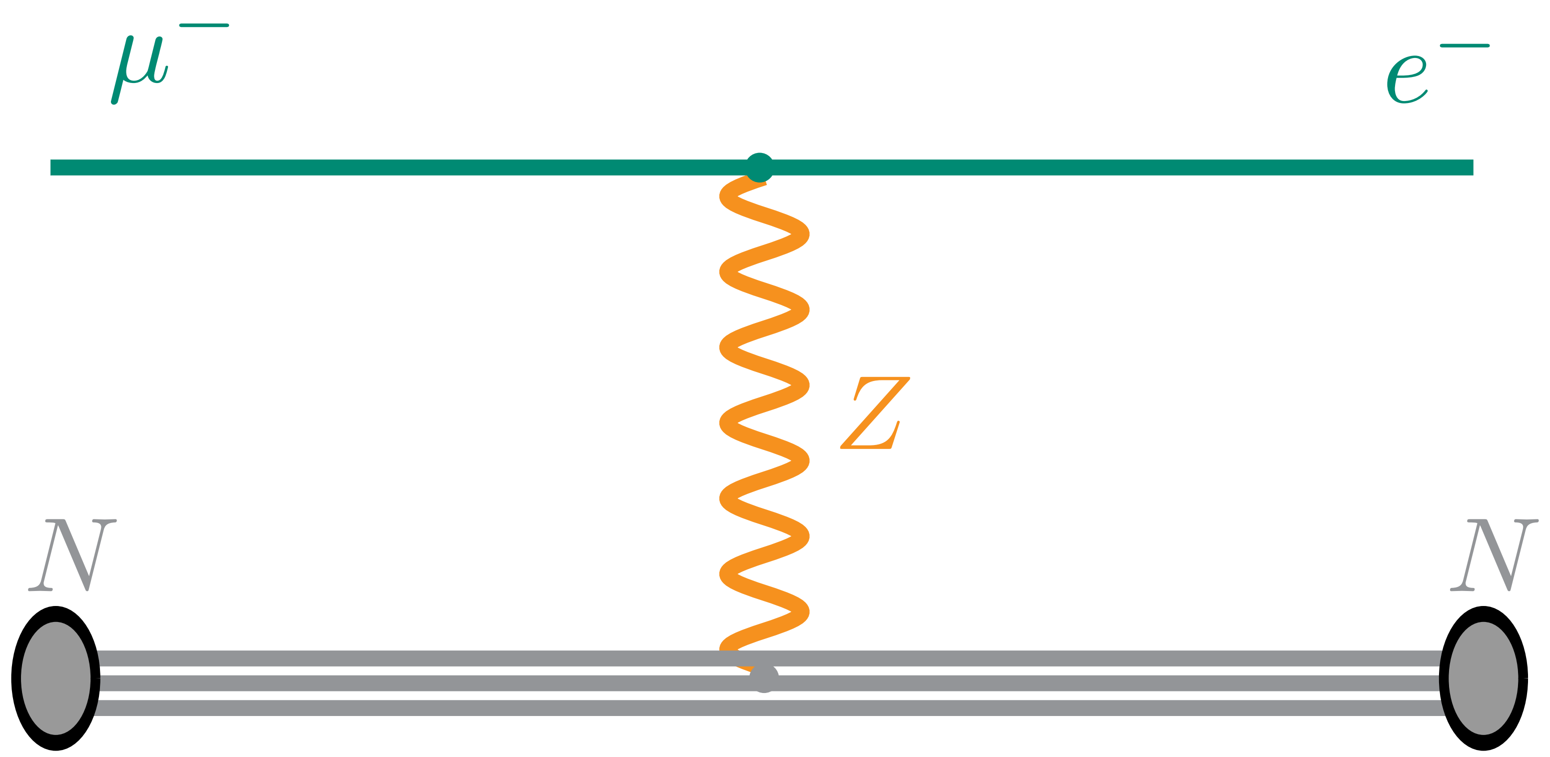
We further assume $\lambda^u_{\tilde{B},\tilde{W}} = 0$ such that bino, wino and Higgsinos do not mix

Experimental Bounds

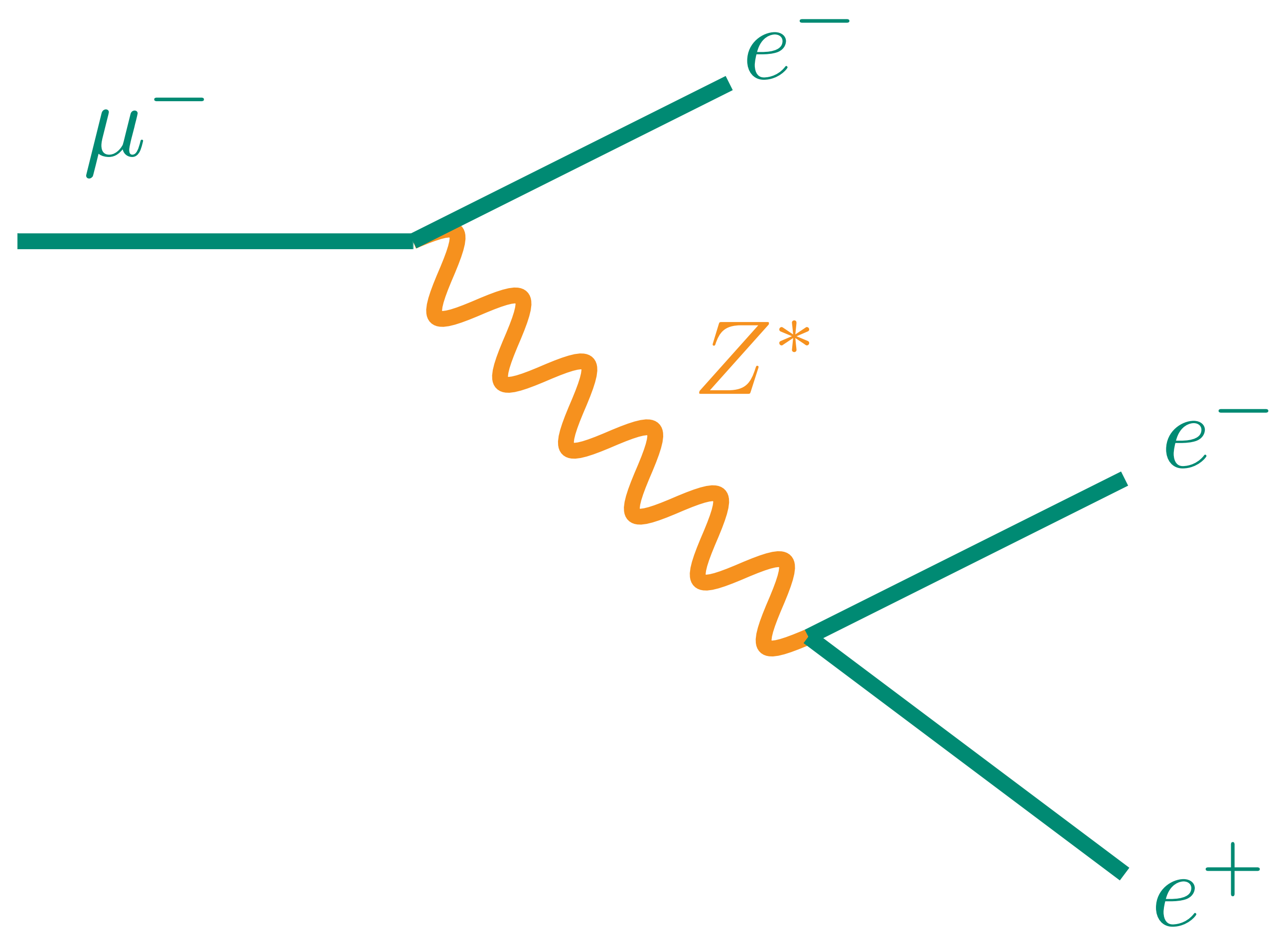
$\mu \to e\,\gamma$



$\mu - e$ conversion in nuclei



$\mu \to e\,e\,e$



$$\mathrm{Br}(\mu \to e\gamma)\Big|_{\text{now}} < 4.2 \times 10^{-13}$$

MEG Collaboration, Eur. Phys. J. C 76 (2016) 8, 434

$$\mathrm{Br}(\mu \to e\gamma)\Big|_{\text{future}} \lesssim 10^{-14}$$

MEG II Collaboration, PoS NuFact2021 (2022) 120

$$\mathrm{R}_{\mu e}\Big|_{\text{now}} < 7 \times 10^{-13}$$

SINDRUM II Collaboration, Eur. Phys. J. C 47 (2006) 337

$$\mathrm{R}_{\mu e}\Big|_{\text{future}} < 6.2 \times 10^{-16}$$

Mu2e Collaboration. Universe 2023, 9, 54

strongest constraint

$$\mathrm{Br}(\mu \to eee) < 1.0 \times 10^{-12}$$

SINDRUM collaboration, Nucl. Phys. B 299 (1988) 1

Combined Constraints

A. Abada et.al., Phys. Rev. D 78 (2008) 033007
A. Abada, et.al., JHEP 12 (2007) 061

Type-I

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_N^\dagger \frac{1}{|M_N|^2} Y_N|_{\alpha\beta} \lesssim \begin{pmatrix} 10^{-2} & 7.0\cdot 10^{-5} & 1.6\cdot 10^{-2} \\ 7.0\cdot 10^{-5} & 10^{-2} & 1.0\cdot 10^{-2} \\ 1.6\cdot 10^{-2} & 1.0\cdot 10^{-2} & 10^{-2} \end{pmatrix}$$

Stronger than type-I due to tree level FCNC

Type-III

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger}\frac{1}{M_\Sigma} Y_\Sigma|_{\alpha\beta} \lesssim \begin{pmatrix} 3\cdot 10^{-3} & < 1.1\cdot 10^{-6} & < 1.2\cdot 10^{-3} \\ < 1.1\cdot 10^{-6} & 4\cdot 10^{-3} & < 1.2\cdot 10^{-3} \\ < 1.2\cdot 10^{-3} & < 1.2\cdot 10^{-3} & 4\cdot 10^{-3} \end{pmatrix}$$

$\alpha, \beta = e, \mu, \tau$

By far the strongest constraints are on the $e - \mu$ element

$$\left(\epsilon^{d=6}\right)_{e\mu} = \frac{v^2}{\Lambda_M^2}\left| u_{\tilde{B}}^e u_{\tilde{B}}^\mu + u_{\tilde{W}}^e u_{\tilde{W}}^\mu \right|$$

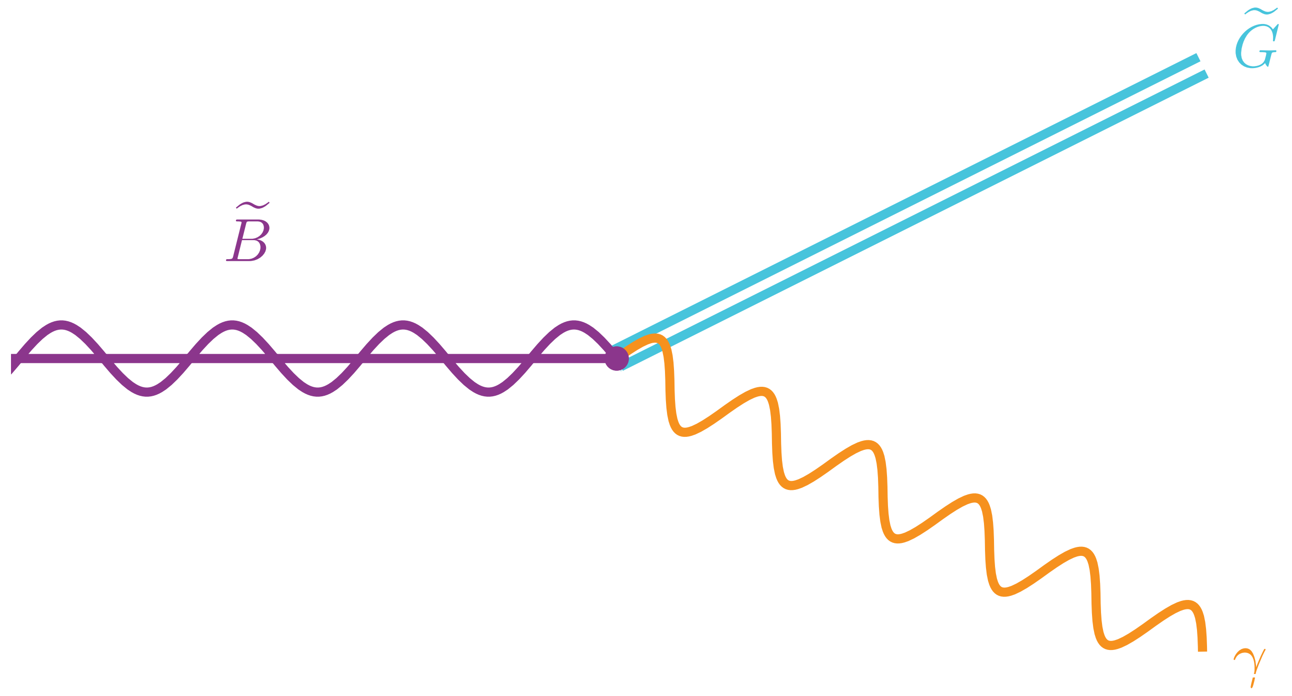
MEG Collaboration, Eur. Phys. J. C 76 (2016) 8, 434
MEG II Collaboration, PoS NuFact2021 (2022) 120
SINDRUM II Collaboration, Eur. Phys. J. C 47 (2006) 337
Mu2e Collaboration. Universe 2023, 9, 54
SINDRUM collaboration, Nucl. Phys. B 299 (1988) 1

Bino Decays

$m_{3/2} \sim 10$ MeV $\quad M_{\tilde{B}} \sim 500$ GeV $\quad \Lambda_M \sim 500$ TeV

If kinematically allowed

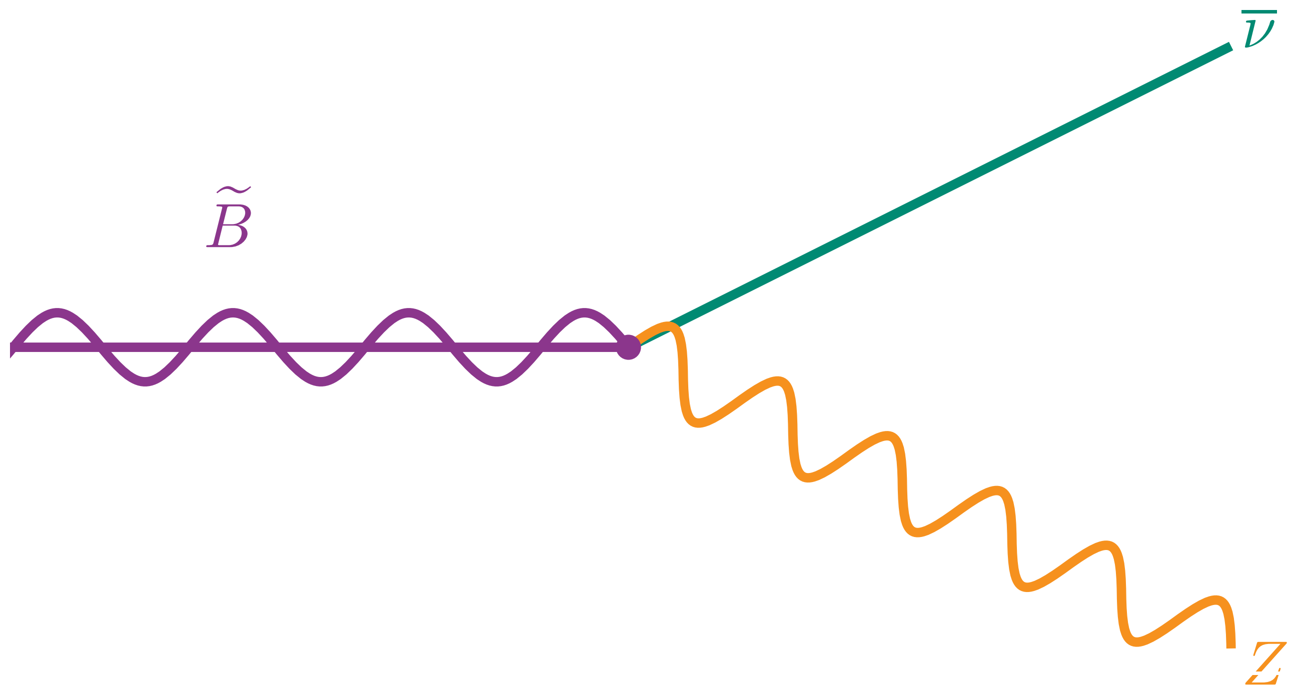
$\tilde{B} \to \tilde{G}\,\gamma$



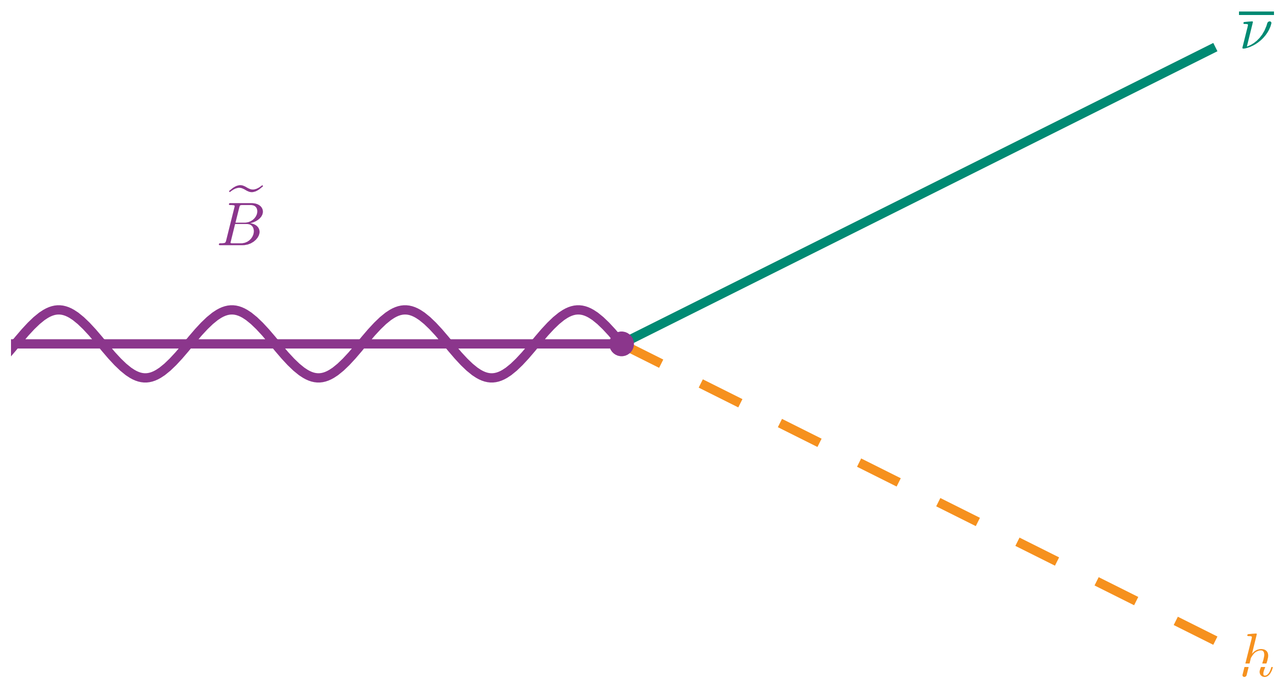
Suppressed by the Planck mass

$$\Gamma\left(\tilde{B} \to \tilde{G}\gamma\right) \sim \frac{M_{\tilde{B}}^5}{M_{\rm Pl}^2 m_{3/2}^2} \sim 10^{-12}\ \text{eV}$$

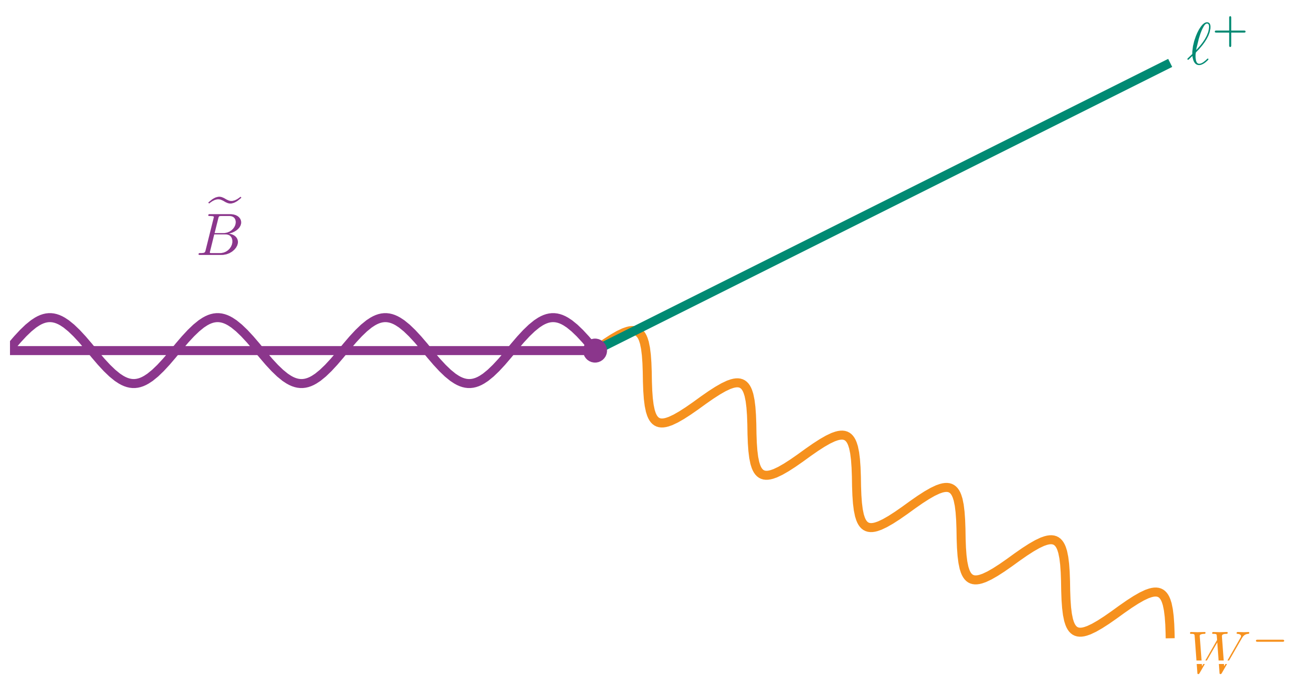
$\tilde{B} \to Z\bar{\nu}$



$\tilde{B} \to h\,\bar{\nu}$



$\tilde{B} \to W^-\ell^+$



Total decay width

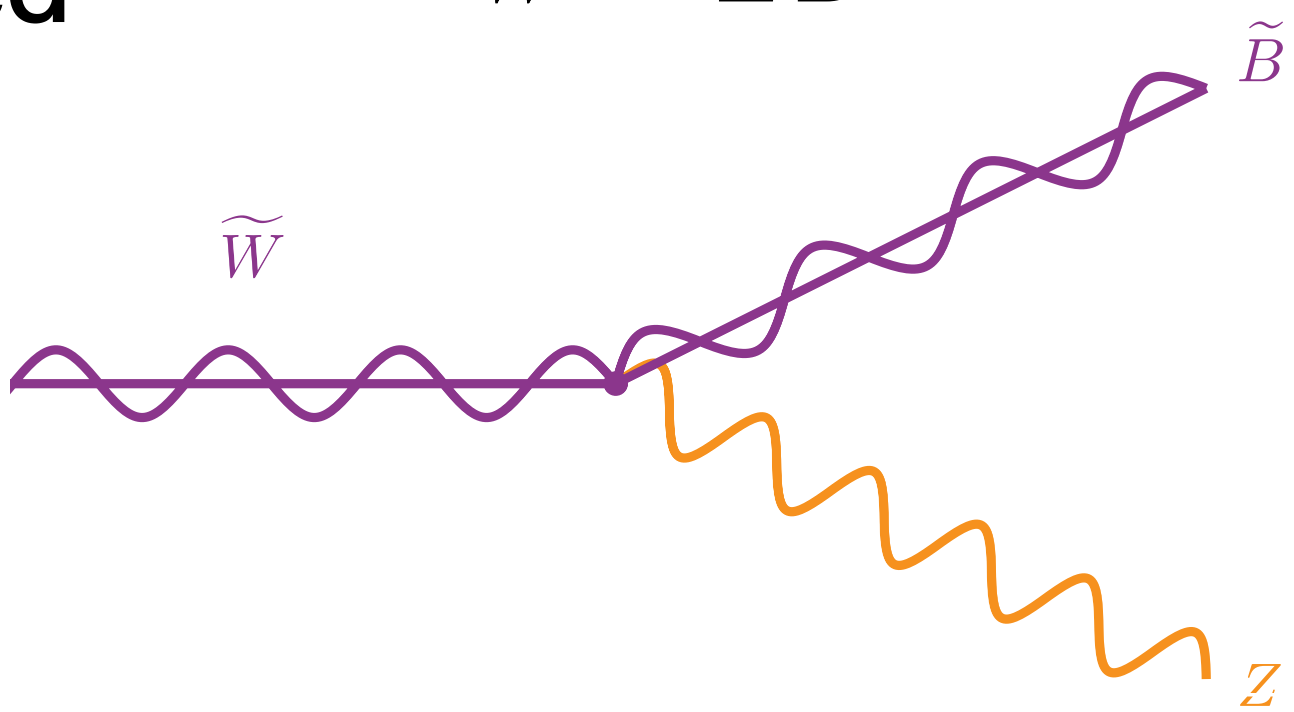
$$\Gamma_{\tilde{B},\,\rm tot} = \sum_i Y_i^2 M_{\tilde{B}} \sim \frac{M_{\tilde{B}}}{\Lambda_M^2} \sim 0.5\ \text{MeV}$$

decays promptly at the LHC

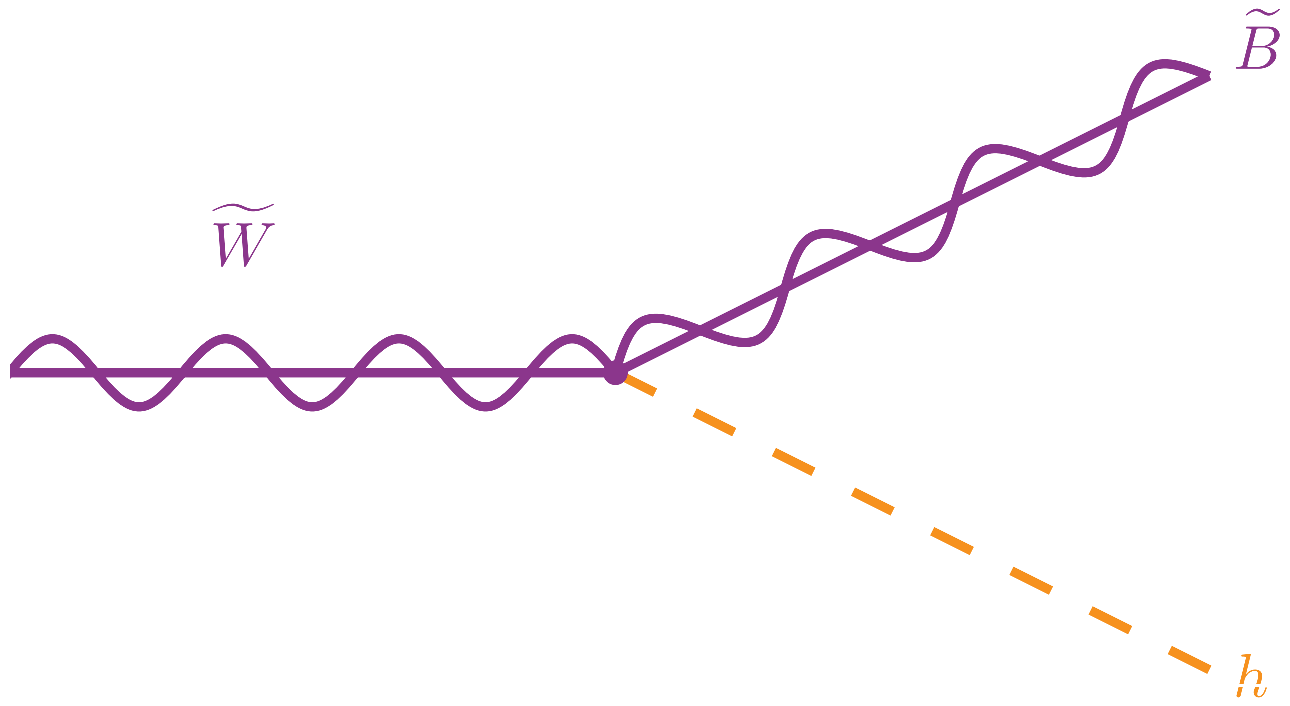
Wino Decays

If kinematically allowed

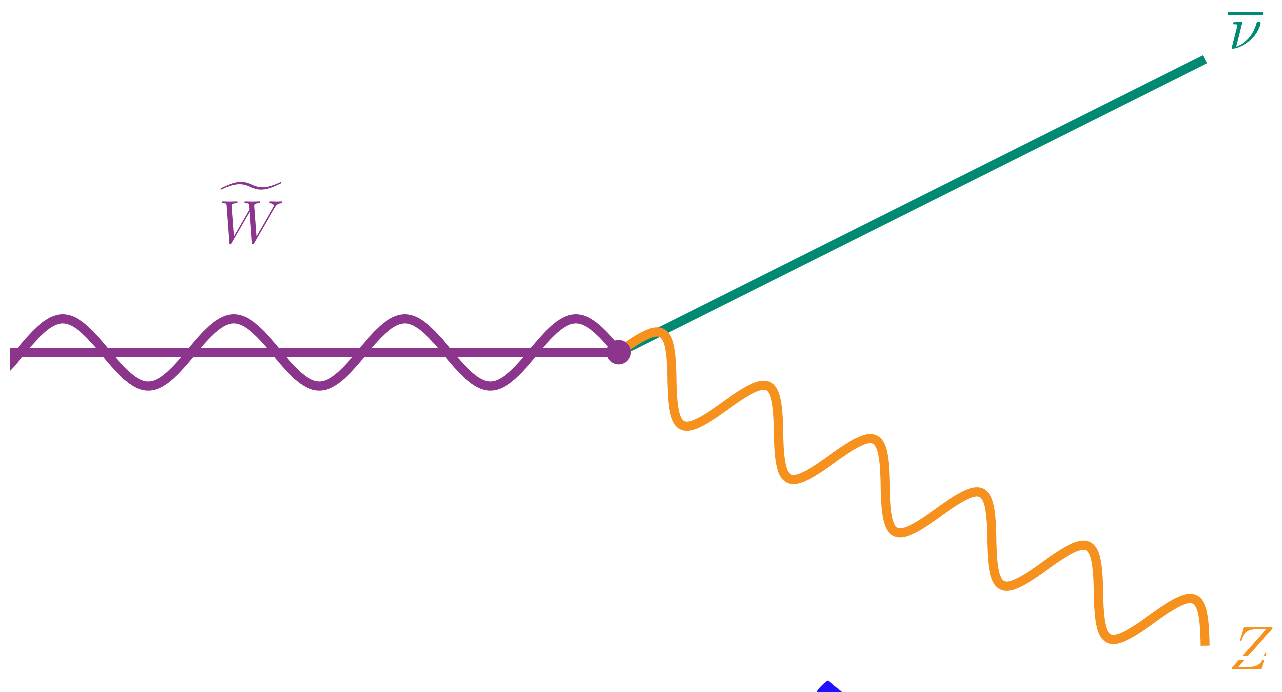
$\tilde{W} \to Z\tilde{B}$



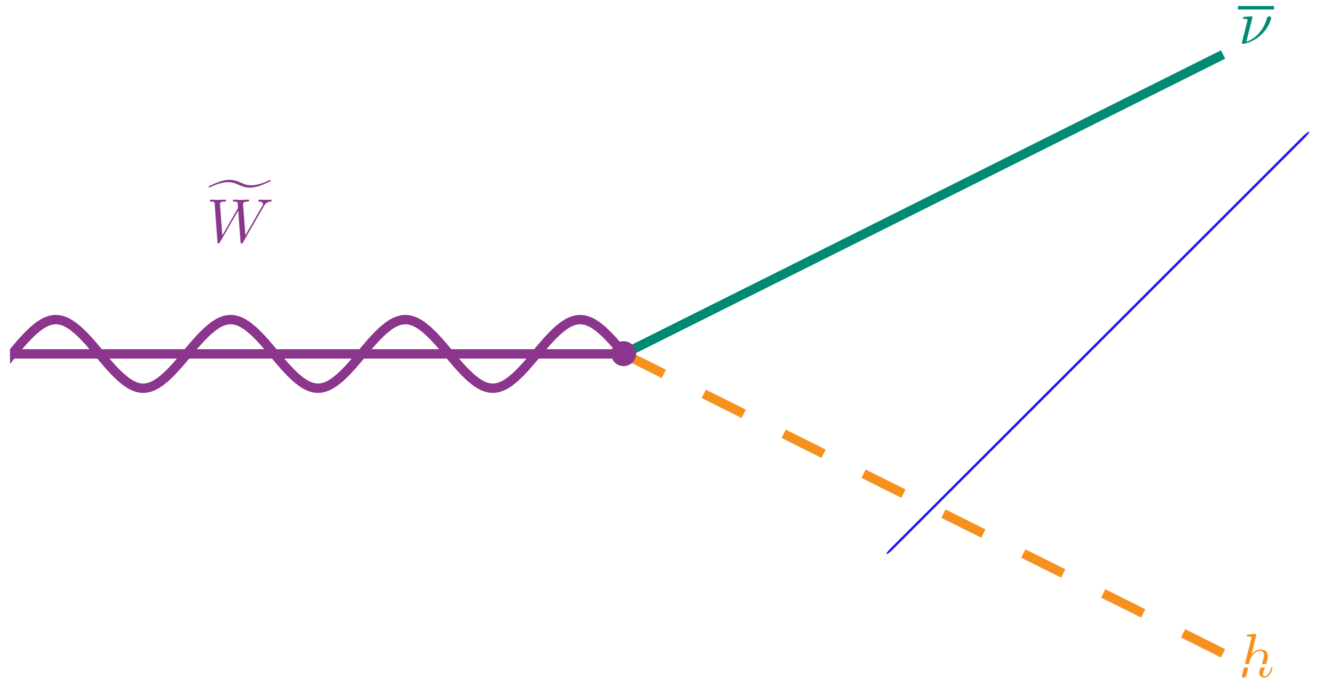
$\tilde{W} \to h\tilde{B}$



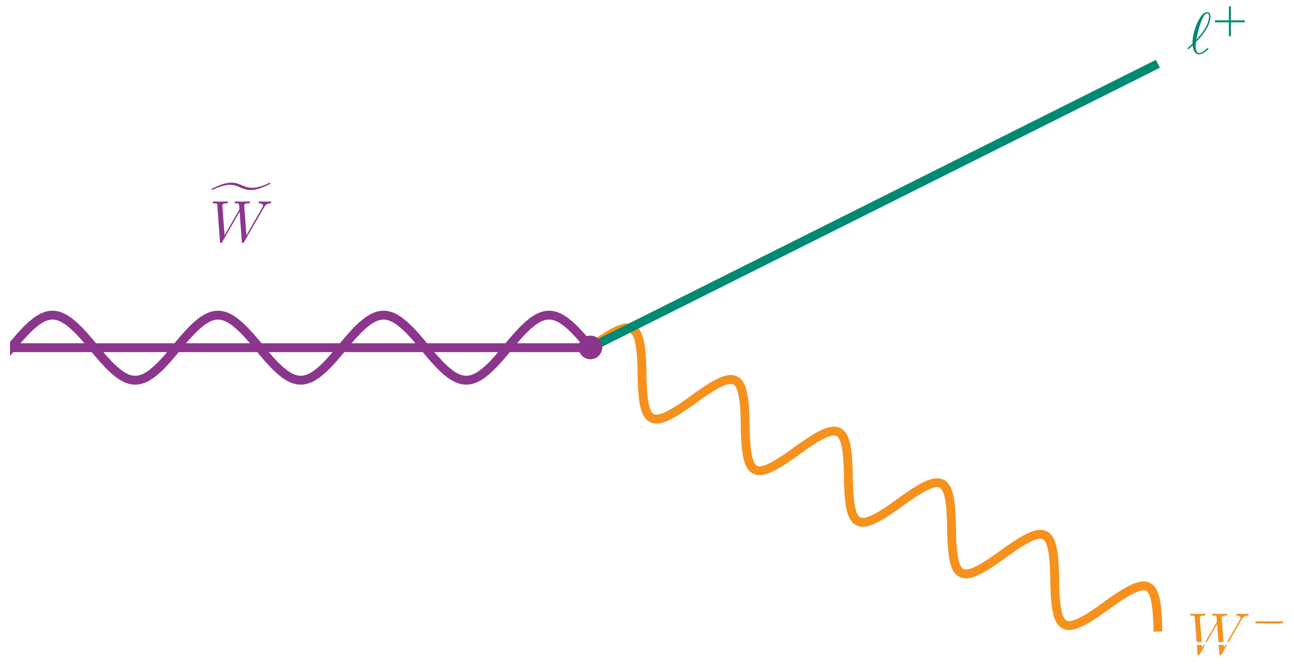
$\tilde{W} \to Z\bar{\nu}$



$\tilde{W} \to h\bar{\nu}$



$\tilde{W} \to W^{-}\ell^{+}$

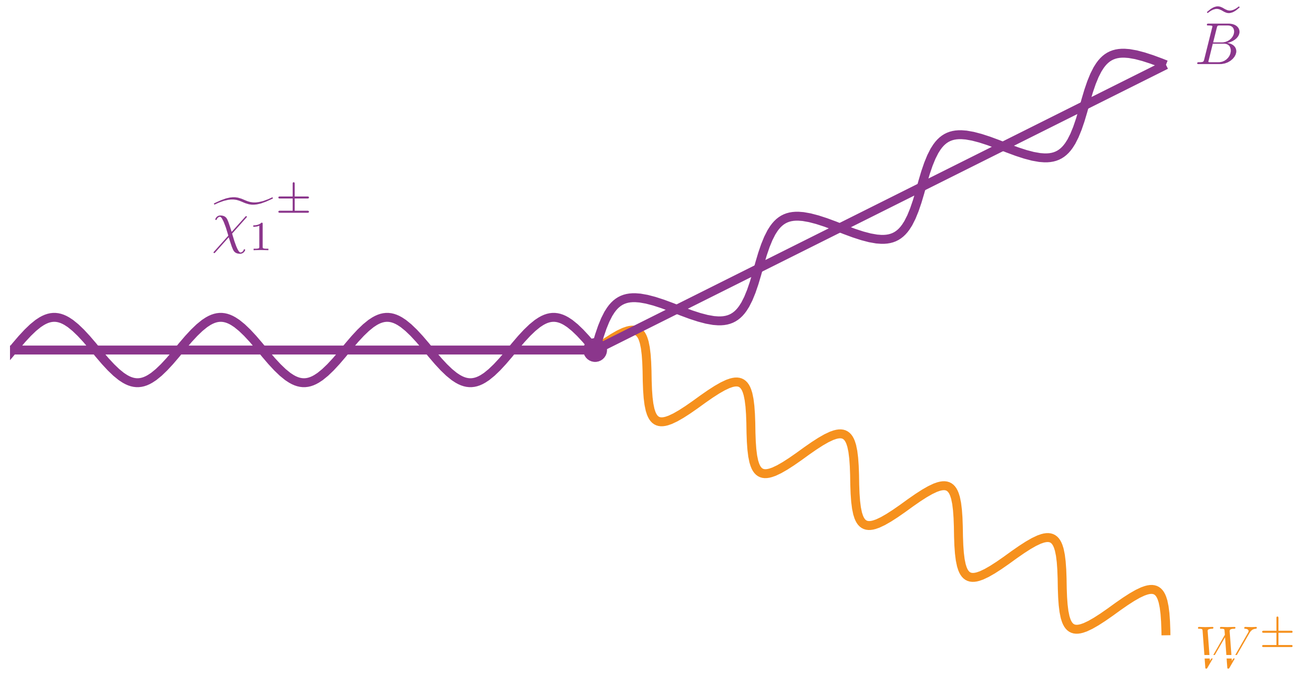


These channels are suppressed by the mixing angle: $\theta^2 \sim \left(\frac{y_{\tilde{W}}v}{M_{\tilde{W}}}\right) \sim \frac{v^2}{\Lambda_M^2} \sim 10^{-7}$

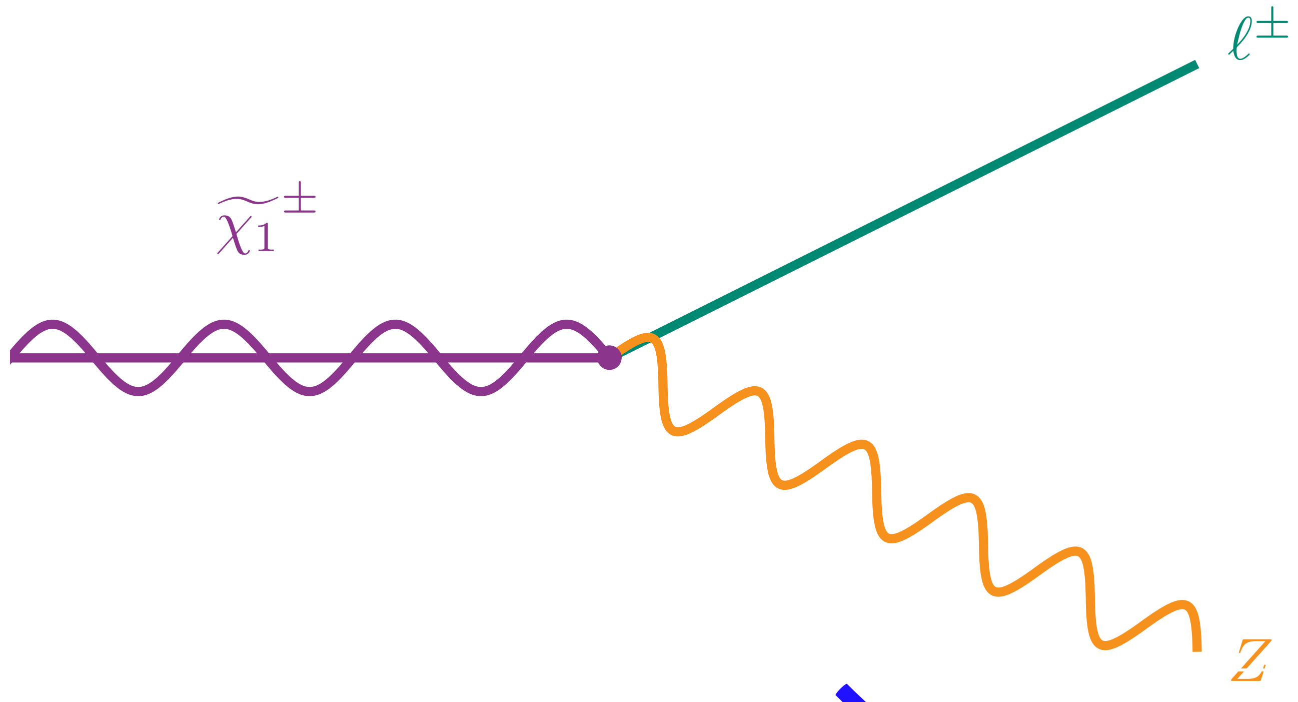
Chargino Decays

If kinematically allowed

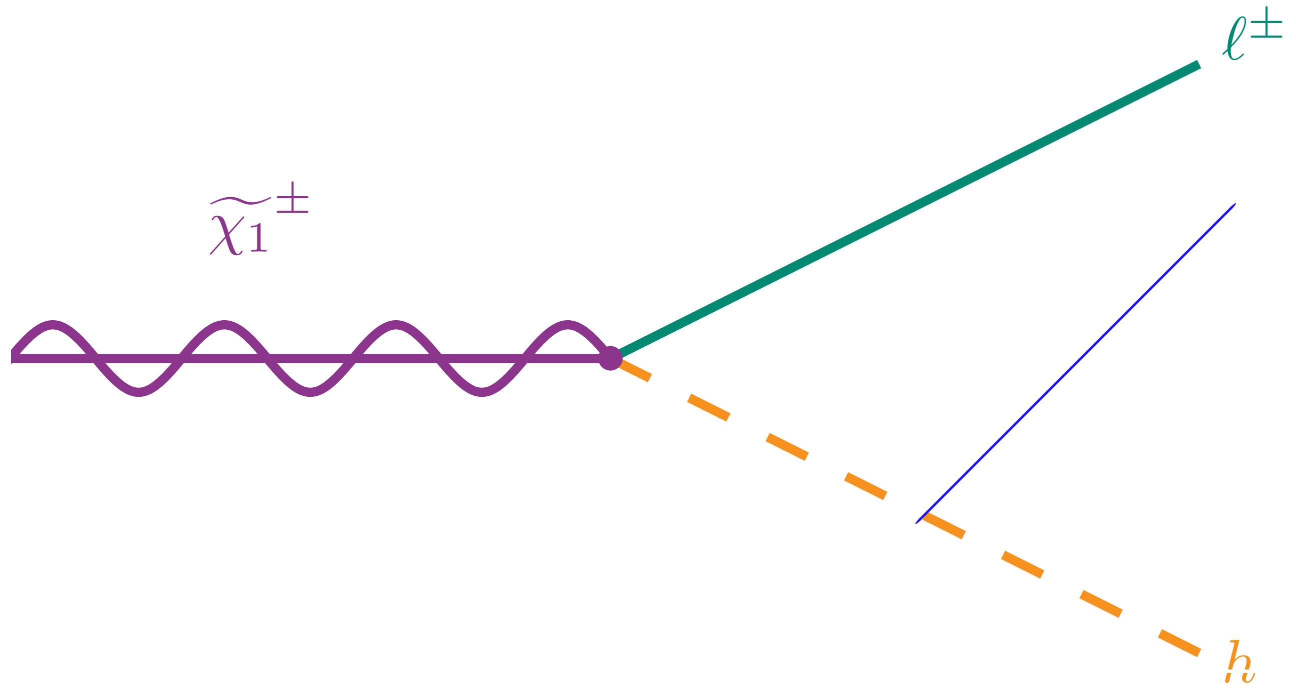
$\widetilde{\chi}_1^\pm \to W^\pm \tilde{B}$



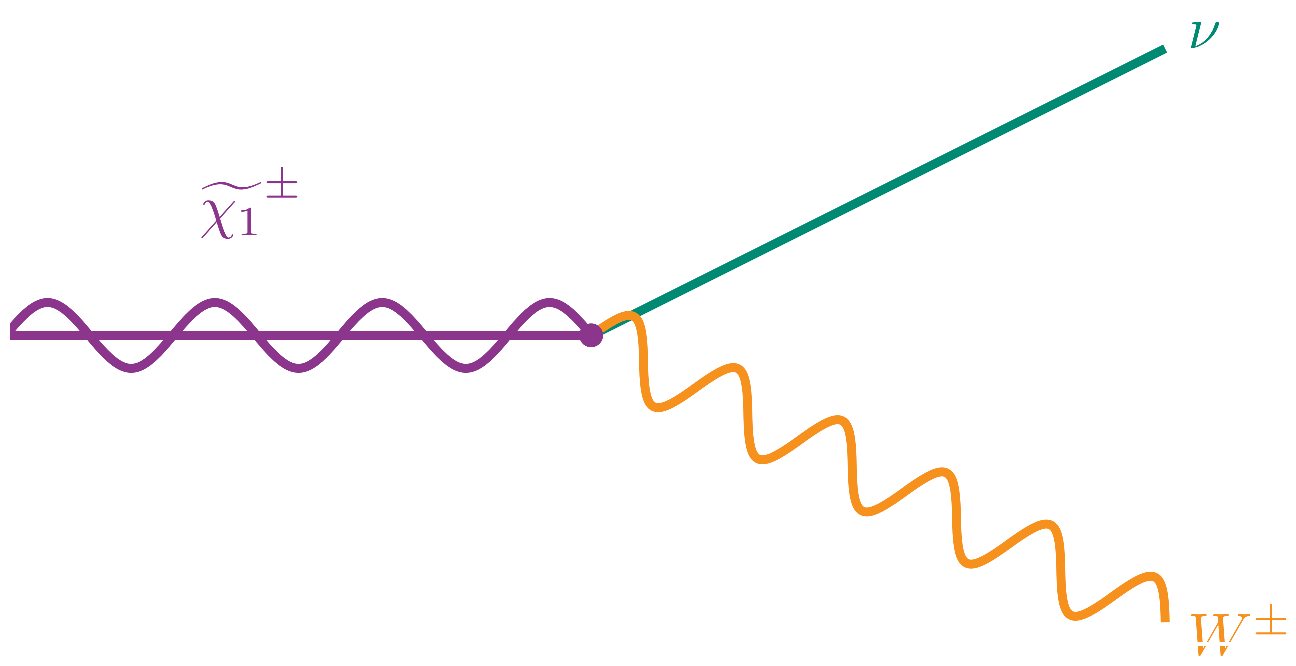
$\widetilde{\chi}_1^\pm \to Z \ell^\pm$



$\widetilde{\chi}_1^\pm \to h \, \ell^\pm$



$\widetilde{\chi}_1^\pm \to W^\pm \nu$



These channels are suppressed by the mixing angle: $\theta^2 \sim \left(\frac{y_{\tilde{W}} v}{M_{\tilde{W}}}\right) \sim \frac{v^2}{\Lambda_M^2} \sim 10^{-7}$