Baryon Number Violation and Leptophobic Dark Matter

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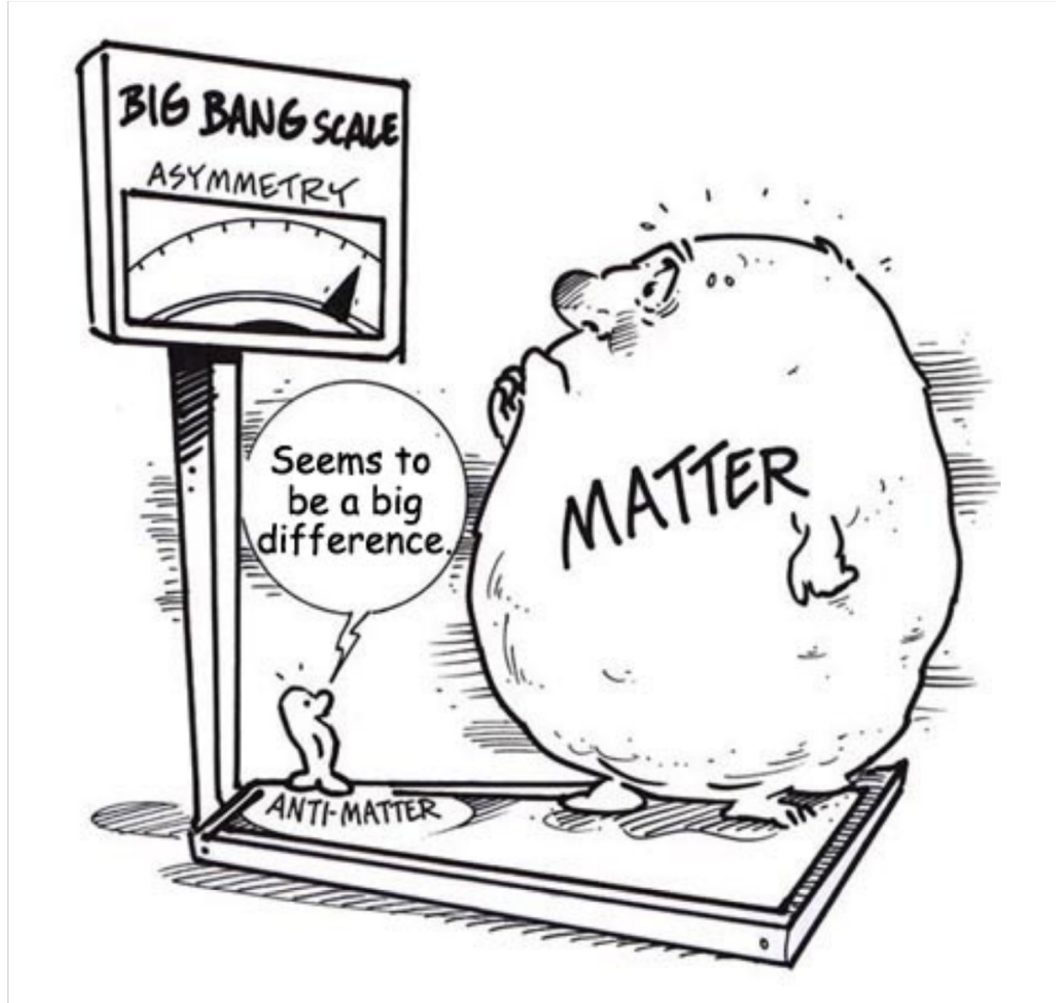
Baryon Asymmetry



Baryon excess:

$$\eta_b \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.05 \times 10^{-10}$$

Sakharov Conditions

Let's assume that the Universe started out baryon-symmetric.

3 necessary conditions for baryogenesis: Sakharov 1967

- Baryon number violation

$$X \to Y + B$$

- C- and CP-violation
  - C conservation:

$$\Gamma(X \to Y + B) = \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$

  - CP conservation: $X \to q_L q_L \qquad \bar{X} \to \bar{q}_R \bar{q}_R$

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L) + \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R)$$

- Departure from thermal equilibrium

$$\Delta E = m_{\text{matter}} - m_{\text{antimatter}} = 0$$

Baryon Number Violation

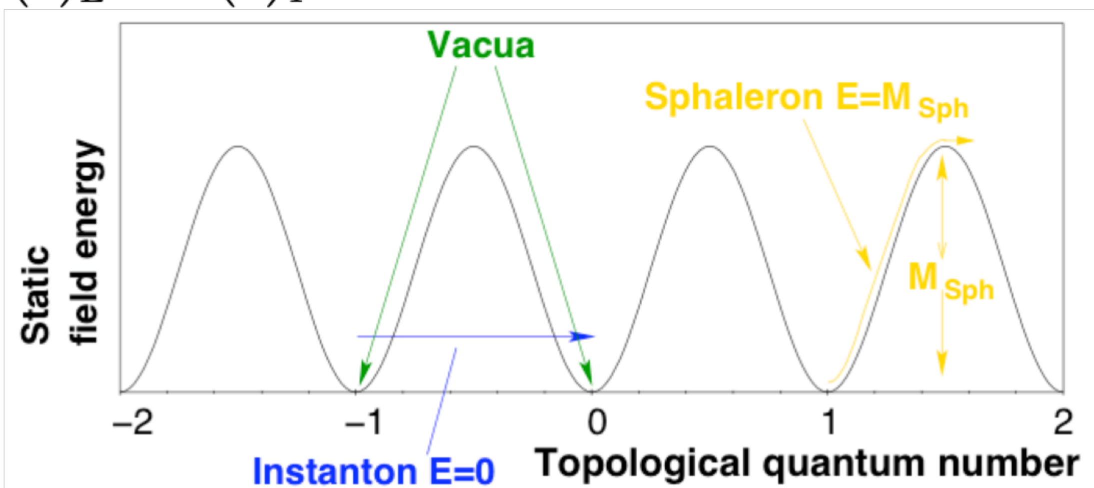
In the Standard Model (SM)

- Chiral anomaly: Adler 1969; Bell, Jackiw 1969

$$\partial_\mu j_B^\mu = \frac{3}{64\pi^2}\epsilon^{\alpha\beta\gamma\delta}(g_2^2 W^a_{\alpha\beta}W^a_{\gamma\delta} + g_1^2 B_{\alpha\beta}B_{\gamma\delta}) \neq 0$$

- This anomaly is 1-loop exact! ⇒ non-perturbative effect

$SU(2)_L \times U(1)_Y$ 't Hooft 1976; Manton 1983; Klinkhamer, Manton 1984



$$\Delta B = \int_{t_i}^{t_f} \mathrm{d}t \int \mathrm{d}^3x\ \partial_\mu j_B^\mu = 3[n_{\rm CS}(t_f) - n_{\rm CS}(t_i)]$$

$$\Gamma_{\rm sph}(T \gtrsim m_h) \sim \left(\frac{g_2^2}{4\pi}\right)^5 T^4$$

Baryon Number Violation

However, baryogenesis in the SM suffers from 2 issues:

- CP violations coming from the CKM matrix is insufficient
  Gavela, Hernandez, Orloff, Pene, Quimbay 1994; Huet, Sather 1995
- Cannot accommodate a large enough departure from equilibrium – no 1st order phase transition
  Kajantie, Laine, Rummukainen, Shaposhnikov 1996; Csikor, Fodor, Heitger 1998

Beyond the SM

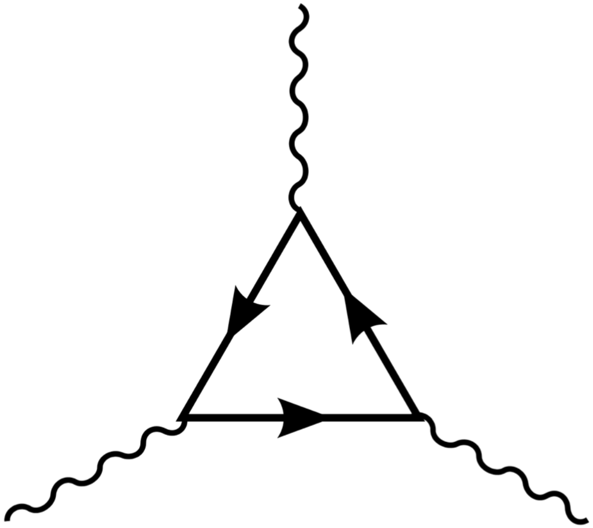
- Explicit breaking of B
  - GUTs: SU(5), SO(10), etc.
    Dimension-6 effective operators: e.g. $\dfrac{Q_L Q_L Q_L \ell_l}{\Lambda^2_{\mathrm{GUT}}}$
    Proton decay: $\tau_p \gtrsim 8.2 \times 10^{33}$ years $\Longrightarrow$ $\Lambda_{\mathrm{GUT}} \gtrsim 10^{15-16}$ GeV
  - MSSM: impose a discrete symmetry "R-parity" $R \equiv (-1)^{3(B-L)+2s}$
    Still dimension-5 effective operators: e.g. $\dfrac{\hat{Q}\hat{Q}\hat{Q}\hat{L}}{\Lambda}$
- Spontaneous breaking of B
  - B as a local symmetry: $U(1)_B$ ⇒ low-scale baryon number violation
    Pias 1973; Fileviez Perez, Wise 2010; Duerr, Fileviez Perez, Wise 2013

$U(1)_B$ – Anomaly Cancellation

- Gauge group: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B$

- Baryonic anomalies:

$$\mathcal{A}_1(SU(3)^2 \otimes U(1)_B)$$
$$\mathcal{A}_2(SU(2)^2 \otimes U(1)_B)$$
$$\mathcal{A}_3(U(1)_Y^2 \otimes U(1)_B)$$
$$\mathcal{A}_4(U(1)_Y \otimes U(1)_B^2)$$
$$\mathcal{A}_5(U(1)_B)$$
$$\mathcal{A}_6(U(1)_B^3)$$



$$\mathcal{A}_2^{\text{SM}} = -\mathcal{A}_3^{\text{SM}} = 3/2 \neq 0$$

We need to introduce additional particles to make these anomalies vanish.

Particle Content

- Anomaly cancellation requires:

$$Y_2^2 + Y_3^2 - 2Y_1^2 = 0$$
$$B_1 - B_2 = -3$$

- Let's investigate:

$$Y_1 = -1/2, Y_2 = -1, Y_3 = 0$$

- Focus on

$$\mathcal{L}_B \ni i\bar{\chi}_L \gamma^\mu (\partial_\mu - B_2 Z_\mu^B)\chi_L + i\bar{\chi}_R \gamma^\mu (\partial_\mu - B_1 Z_\mu^B)\chi_R + \lambda_\chi \bar{\chi}_R \chi_L S_B + \text{h.c.}$$

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$\ell_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$	**1**	**2**	$-\frac{1}{2}$	0
e_R^i	**1**	**1**	-1	0
$Q_L = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	**3**	**2**	$\frac{1}{6}$	$\frac{1}{3}$
u_R^i	**3**	**1**	$\frac{2}{3}$	$\frac{1}{3}$
d_R^i	**3**	**1**	$-\frac{1}{3}$	$\frac{1}{3}$
H	**1**	**2**	$\frac{1}{2}$	0
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	**1**	**2**	Y_1	B_1
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	**1**	**2**	Y_1	B_2
η_R	**1**	**1**	Y_2	B_1
η_L	**1**	**1**	Y_2	B_2
χ_R	**1**	**1**	Y_3	B_1
χ_L	**1**	**1**	Y_3	B_2
S_B	**1**	**1**	0	-3

Higgs Sector

- Spontaneous symmetry breaking
  - Scalar potential:

$$V = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_B^2 S_B^\dagger S_B + \lambda_B (S_B^\dagger S_B)^2 + \lambda_{HB} (H^\dagger H)(S_B^\dagger S_B)$$

  - SSB: $H \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_0 + h_0 \end{pmatrix}, \quad S_B \to \frac{1}{\sqrt{2}} (v_B + h_B)$
  - DM & gauge boson masses: $M_\chi = \frac{\lambda_\chi v_B}{\sqrt{2}} \qquad M_{Z_B} = 3 g_B v_B$
- Higgs mixing
  - Physical Higgses (mass eigenstates)

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_B & \sin\theta_B \\ \cos\theta_B & -\sin\theta_B \end{pmatrix} \begin{pmatrix} h_0 \\ h_B \end{pmatrix}$$

  - Mixing angle experimentally constrained by the SM Higgs signal strength:

$\theta_B \leq 0.36$ arXiv:1606.02266 [hep-ex]

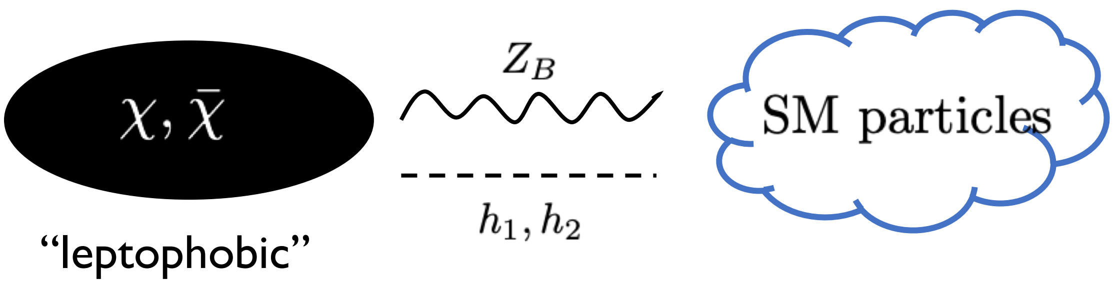
Leptophobic Dark Matter

- Let's fix the baryon numbers for the DM candidate:

$$B \equiv B_1 + B_2 = -1, \;\; B_1 - B_2 = -3$$

$$\Rightarrow \;\; B_1 = -2, \;\; B_2 = 1$$

- So we have a Dirac fermion $\chi = \chi_L + \chi_R$!
- And we have three mediators Z_B, h_2, h_1 (assuming non-zero Higgs mixing) that allow the dark sector to "talk" to the SM sector.



- Free parameters of the theory:

$$\{M_\chi, M_{Z_B}, M_{h_2}, g_B, \theta_B\}$$

$\Rightarrow$ Constrain the $U(1)_B$ symmetry breaking scale by constraining properties of the DM

DM Relic Density

- Cosmological bound on the DM relic density (Planck):

$$\Omega_{\mathrm{DM}} h^2 \leq 0.1199 \pm 0.0027$$ arXiv:1303.5076 [astro-ph.CO]

- Relic density by solving the Boltzmann equation: Gondolo, Gelmini 1991

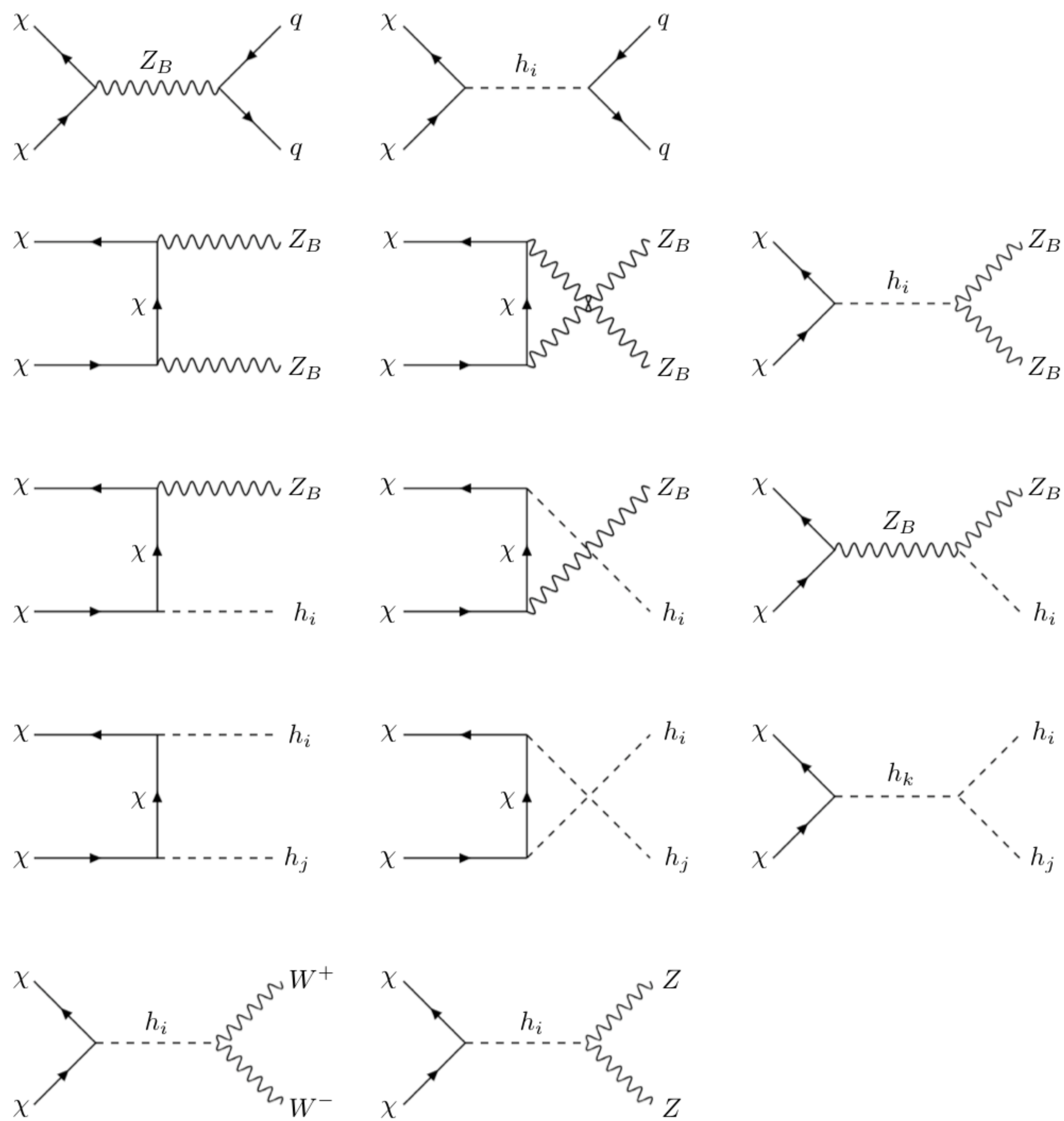
$$\Omega_{\mathrm{DM}} h^2 = \frac{1.07 \times 10^9 \ \mathrm{GeV}^{-1}}{M_{\mathrm{Pl}}} \left(\int_{x_f}^{\infty} \mathrm{d}x \ \frac{g_*^{1/2}(x) \langle \sigma v \rangle (x)}{x^2} \right)^{-1}$$

$$\langle \sigma v \rangle (x) = \frac{x}{8 M_\chi^5 K_2^2(x)} \int_{4M_\chi^2}^{\infty} \mathrm{d}s \ \sigma \times (s - 4M_\chi^2) \sqrt{s} K_1 \left(\frac{x \sqrt{s}}{M_\chi} \right)$$

$$x_f \equiv \frac{M_\chi}{T_f}$$

DM annihilation cross section
– model-dependent quantity!

DM Annihilations

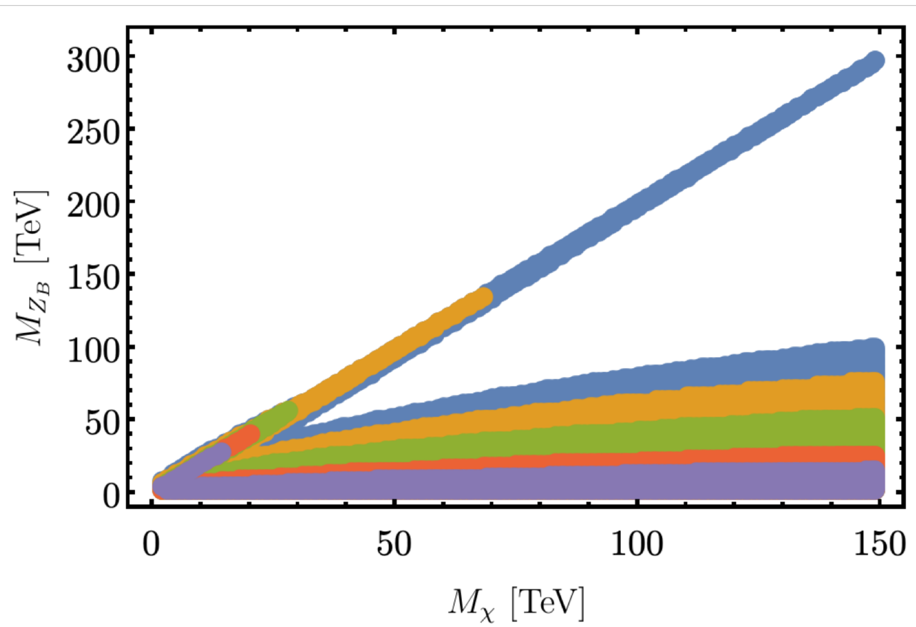


Relic Density Constraint

Zero mixing: $\theta_B = 0$

$\bar{\chi}\chi \to \bar{q}q, Z_B Z_B, Z_B h_2, h_2 h_2$

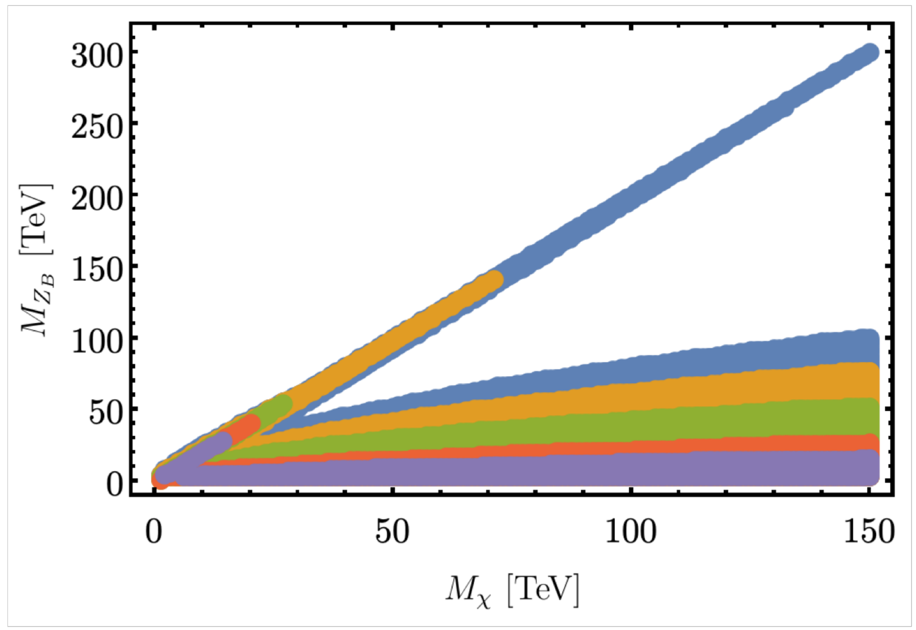
Take $M_{h_2} = 1$ TeV:



Maximal mixing: $\theta_B = 0.36$

$\bar{\chi}\chi \to \bar{q}q, Z_B Z_B, Z_B h_i, h_i h_j, W^+W^-, ZZ$

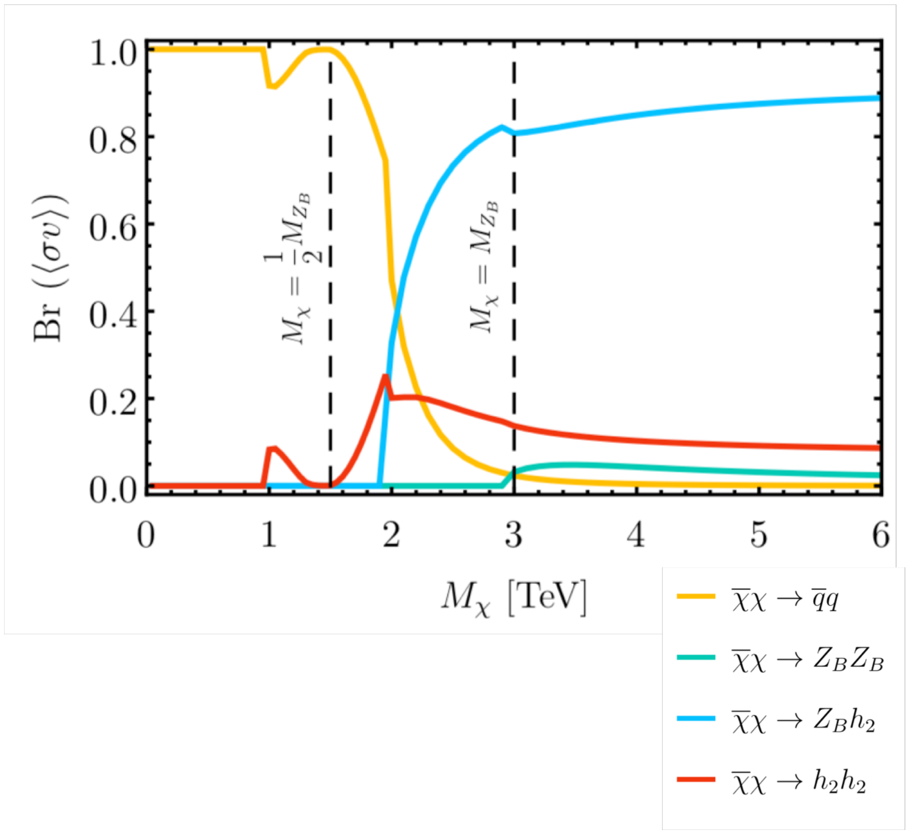
$(i, j = 1, 2)$

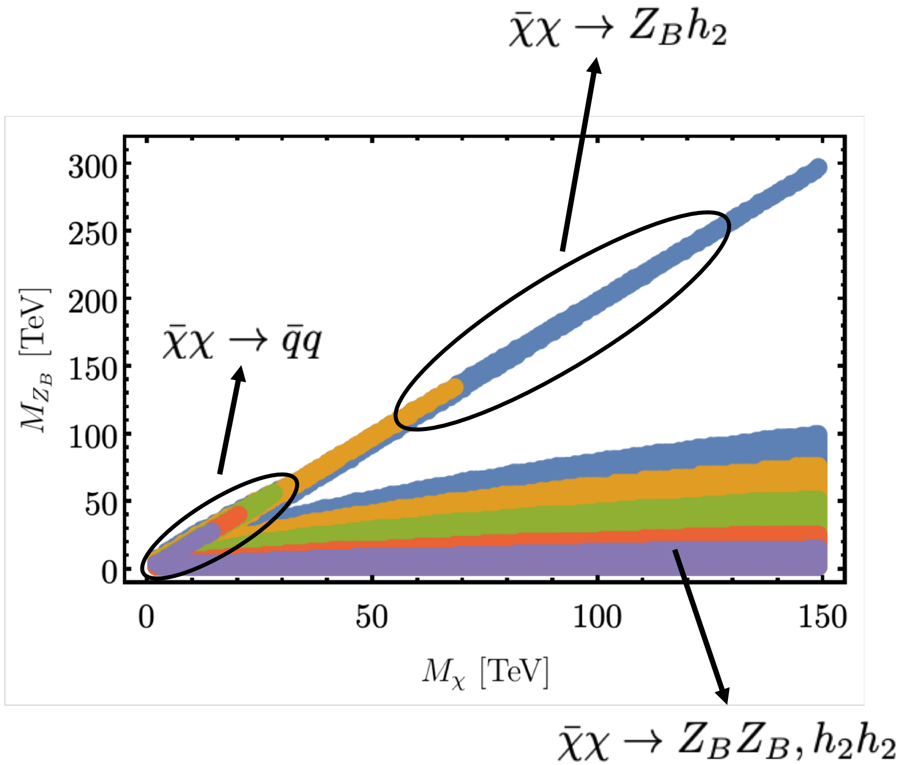


$g_B = 0.3$ $g_B = 0.5$ $g_B = 1.0$ $g_B = 1.5$ $g_B = 2.0$

Relic Density Constraint

Let's inspect the zero mixing case in a bit more detail.

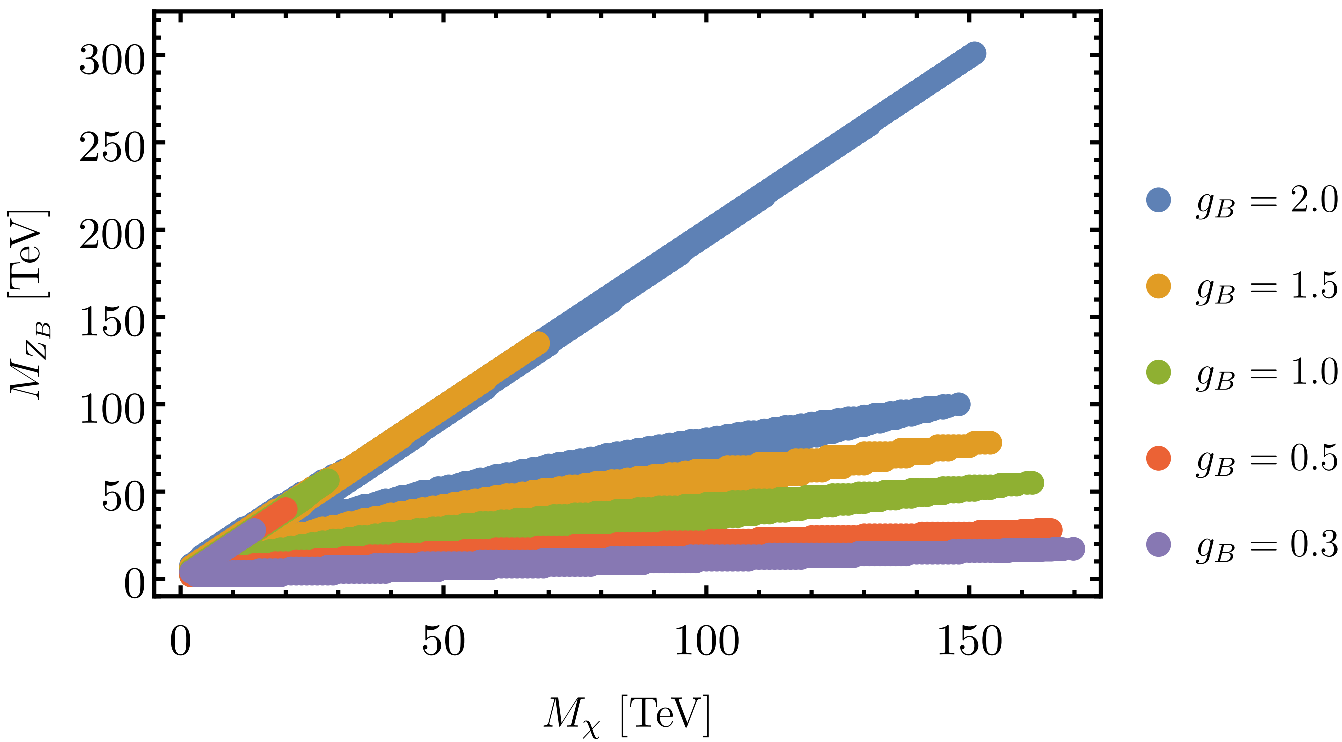




Perturbativity Constraint

Recall: $M_\chi = \dfrac{\lambda_\chi v_B}{\sqrt{2}}$ $\qquad M_{Z_B} = 3 g_B v_B$

Perturbativity: $\lambda_\chi = \dfrac{3\sqrt{2} g_B M_\chi}{M_{Z_B}} \leq 4\pi$



Unitarity Constraint

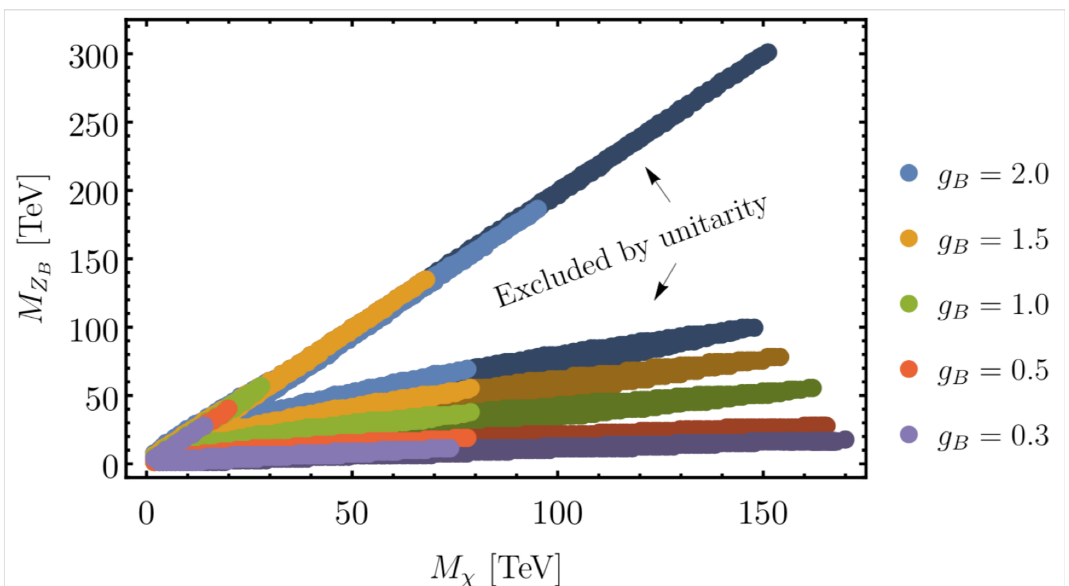
- Unitarity of the S-matrix: $S^\dagger S = 1$
- Partial wave expansion on the scattering amplitude:

$$f(\alpha \to \beta) = \sum_J (2J+1) P_J(\cos\theta) a_J(\alpha \to \beta)$$

$$\sigma(\alpha \to \beta) = \int \mathrm{d}\Omega \, |f(\alpha \to \beta)|^2 = \sum_J \sigma_J$$

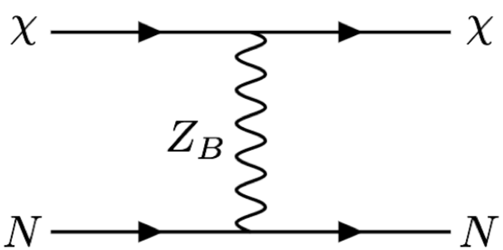
$$\bar{\sigma}_0 \leq \frac{4\pi}{M_\chi^2 v_{\rm rel}^2}$$

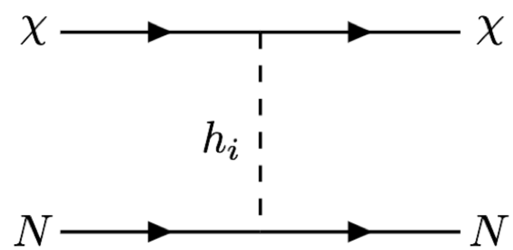
Griest, Kamionkowski 1990



Direct Detection

- DM-nucleon scattering:





$$\sigma_{\chi N}^{\mathrm{SI}} = \frac{g_B^2 M_N^2 M_\chi^2}{4\pi M_{h_1}^4 M_{h_2}^4 M_{Z_B}^4 v_0^2 (M_\chi + M_N)^2} \left[2B g_B v_0 M_{h_1}^2 M_{h_2}^2 + 3 f_N M_\chi M_N M_{Z_B} \sin(2\theta_B)(M_{h_1}^2 - M_{h_2}^2)\right]^2$$

Direct Detection

- DM-nucleon scattering:

arXiv:1512.07501 [physics.ins-det]
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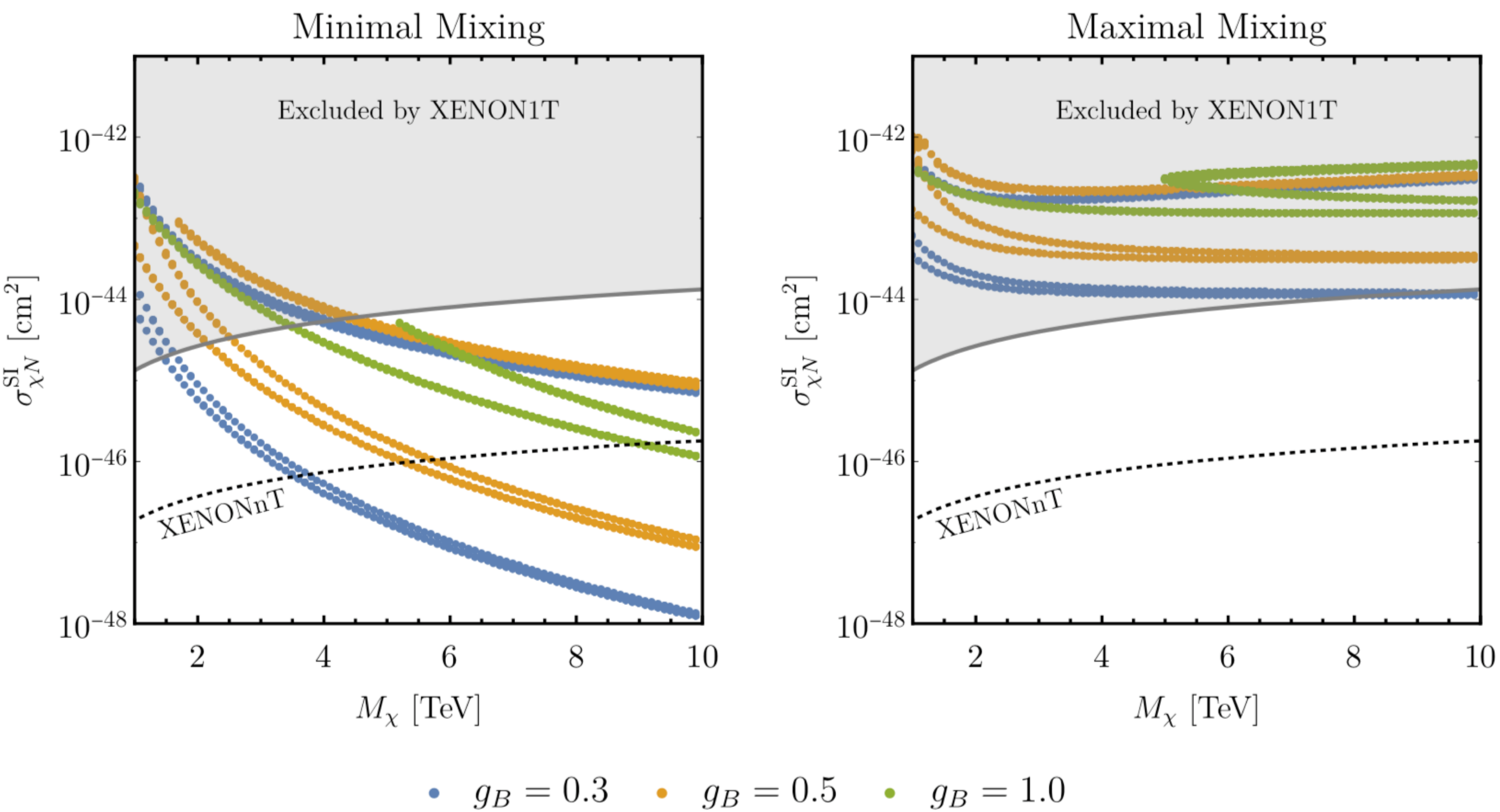
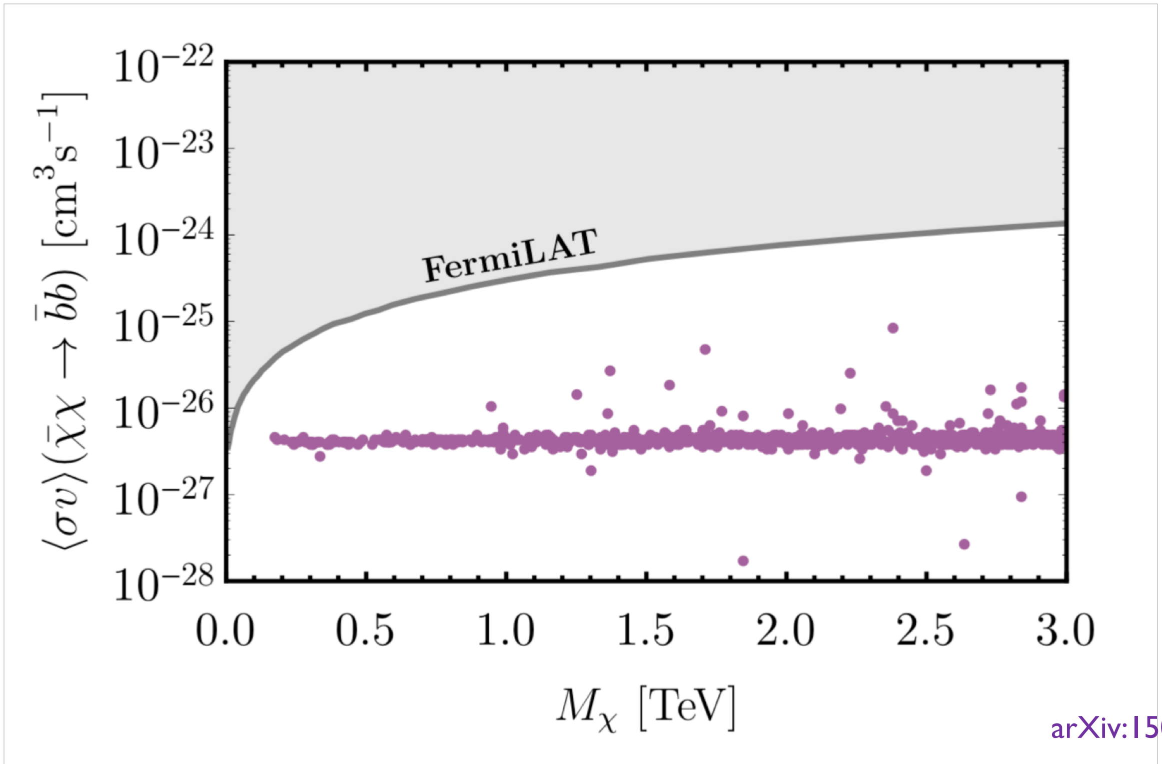


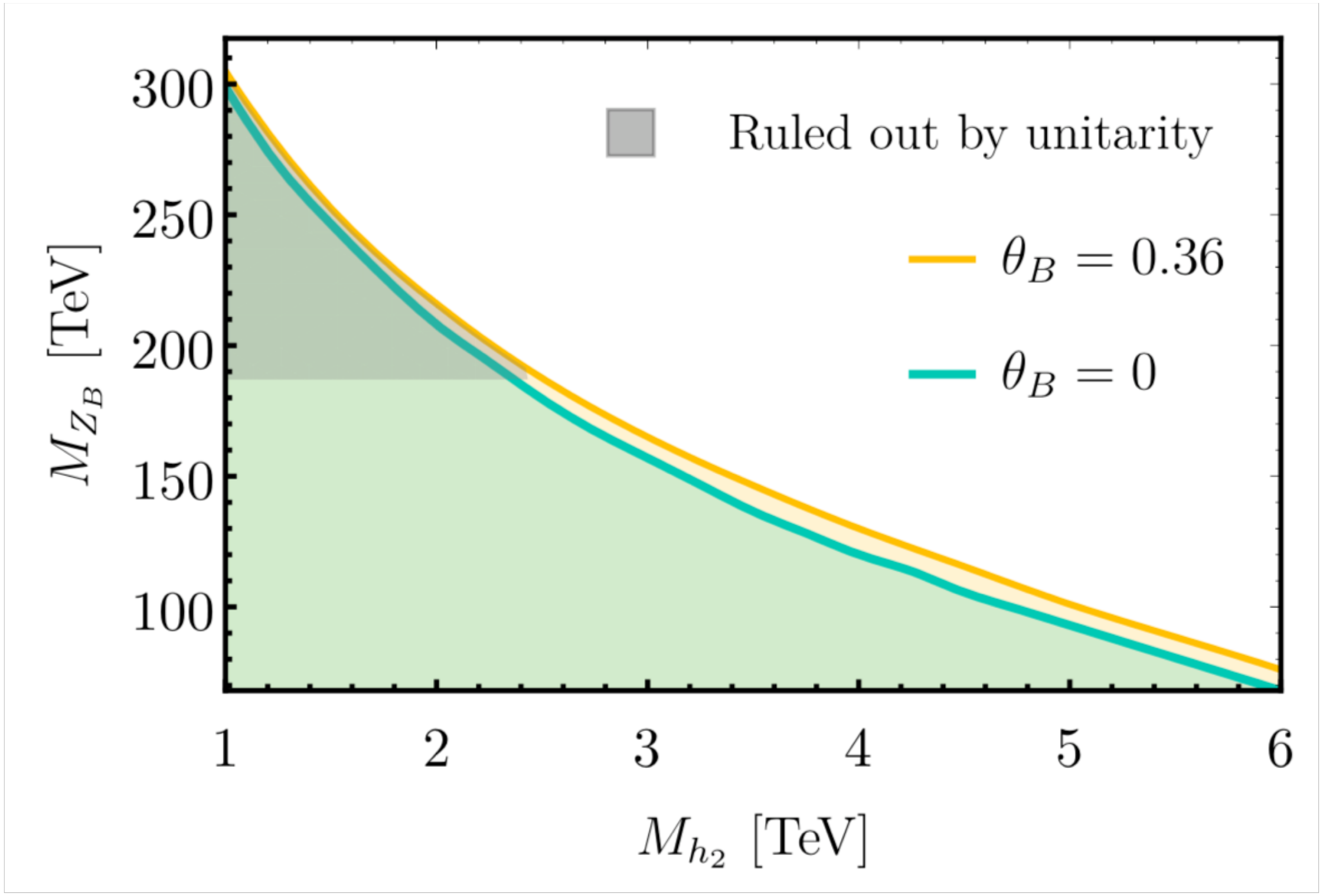
Indirect Detection

- Look for gamma ray lines:
  - DM direct annihilation into photons: loop suppressed
  - DM annihilation to leptons or quarks, which produce secondary photons – most relevant channel: $\bar{\chi}\chi \to \bar{b}b$



arXiv:1503.02641 [astro-ph.HE]

Baryon Number Violation Scale



$$g_B = 2 \quad \Longrightarrow \quad v_B = \frac{M_{Z_B}}{3 g_B} \sim 33 \text{ TeV}$$

Reachable in future colliders!

Summary

- A simple gauge theory for baryon number $U(1)_B$, where baryon number can be spontaneous broken at a low scale.

- The theory predicts the existence of a leptophobic (baryonic) dark matter candidate.

- Using the cosmological bounds on the relic density as well as the unitarity constraint, the baryon number symmetry breaking scale is below $O(10^2)$ TeV.

- It can be tested in future collider experiments and predict different signatures in dark matter experiments.

Q & A

Thank you!