New Gauge Symmetries: Dark Matter and CP Violation

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A Rainbow of Dark Sectors

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[arXiv: 1904.01017] PRD 100 (2019) 015017

[arXiv: 2003.09426] JHEP 07 (2020) 087

[arXiv: 2008.09116] JHEP (2021) 185

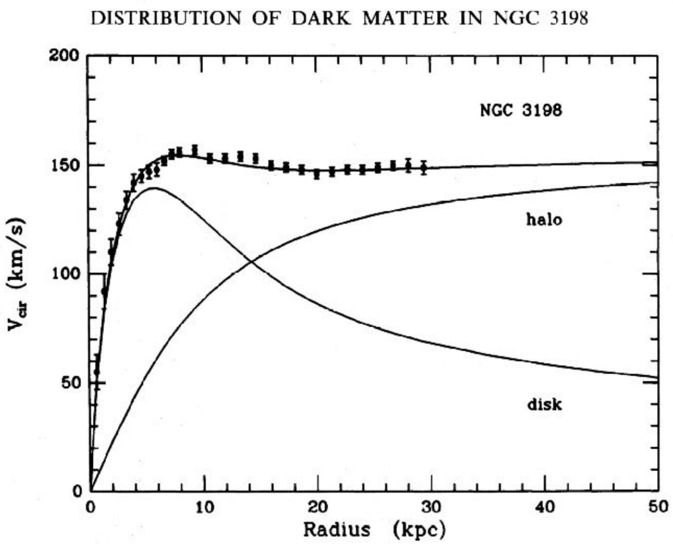
Aim of the talk

Discuss the phenomenology of minimal gauge extensions of the SM that predict dark matter.

These theories must live at the low scale and can be fully probed in the near future.

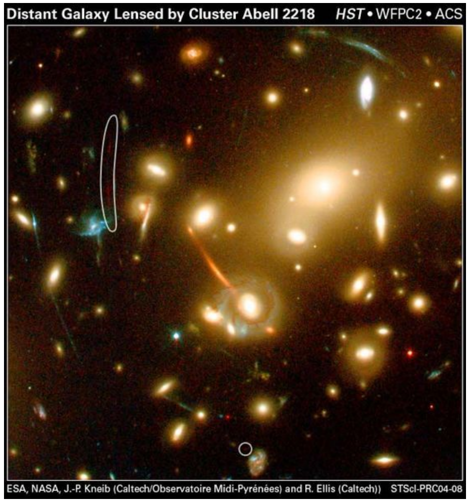
Dark Matter

Rotation curves



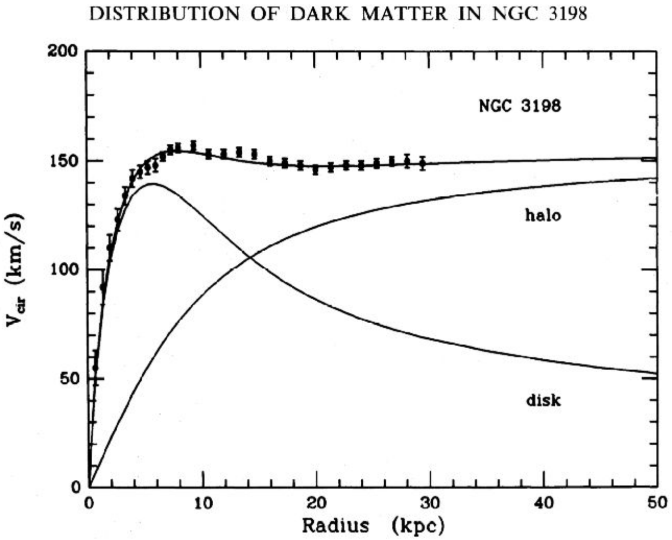
Bullet cluster

Gravitational lensing



Dark Matter

Rotation curves



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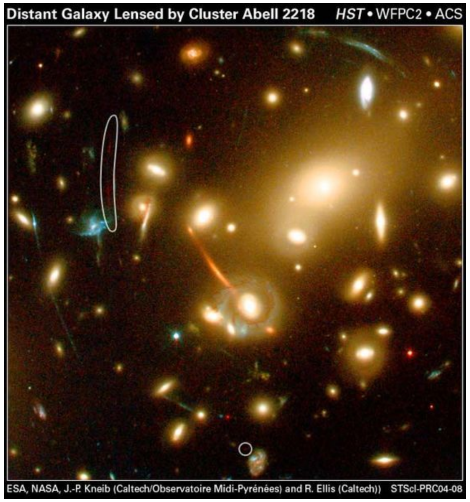
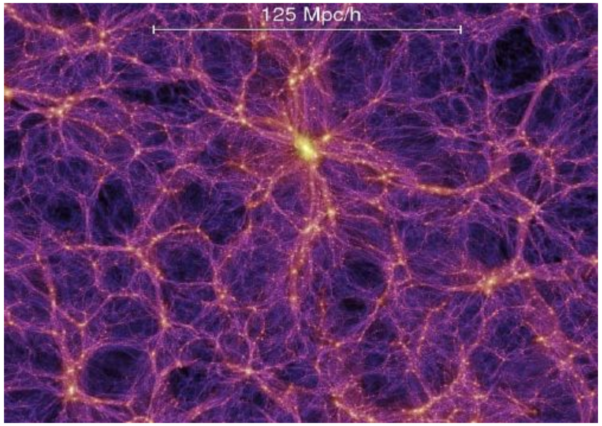
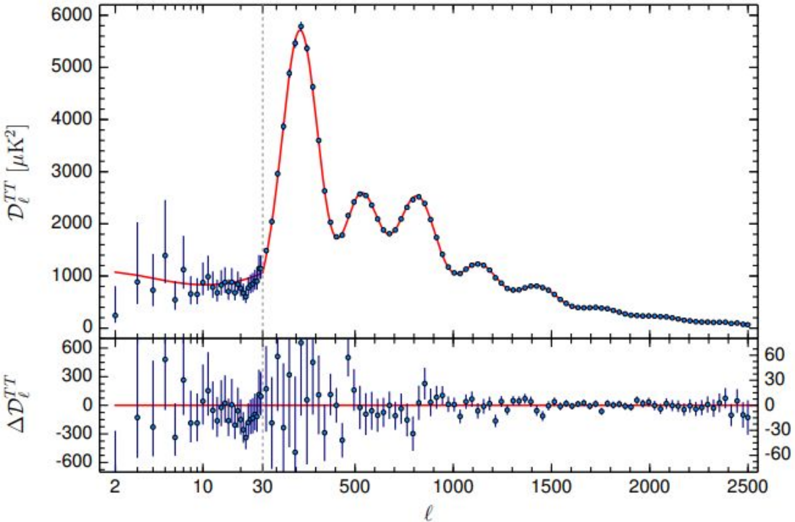


Structure formation



CMB



New Gauge Symmetries at the Low Scale

- Anomalous gauge symmetries, predict a new sector needed for Anomaly Cancellation

- Predict a DM candidate from Anomaly Cancellation

- The new Symmetry Breaking Scale must be low to be in agreement with Cosmology

New Gauge Symmetries at the Low Scale

- Anomalous gauge symmetries, predict a new sector needed for Anomaly Cancellation
- Predict a DM candidate from Anomaly Cancellation
- The new Symmetry Breaking Scale must be low to be in agreement with Cosmology
- Predict new CP-violating interactions
- Can be complementary tested at LHC, dark matter and Electric Dipole Moment experiments

$U(1)_B$

Dark matter, LHC pheno and EDMs

[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]

[Fileviez Perez, Murgui, ADP 2003.09426]

[Fileviez Perez, ADP 2008.09116]

Gauging baryon number

- Baryon number is an accidental global symmetry in the SM
- Only broken by non-perturbative effects - SU(2) instantons
- Anomalous in the Standard Model

$$\underbrace{\mathrm{U}(1)_B}_{\text{Local gauge symmetry}} \qquad \qquad \langle S_B \rangle \neq 0$$

gauge boson: $\boldsymbol{Z_B}$

- Spontaneous breaking of baryon number
- Consistent completion of simplified models of dark matter

[Pais 1973]

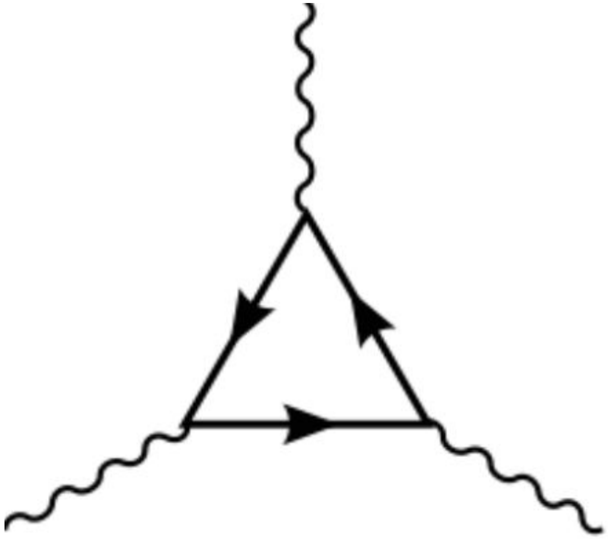
[Fileviez Perez, Wise 2011]

Anomaly cancellation

- Baryon number broken in 3 units: $\Delta B = \pm 3$ interactions

  → No proton decay

- Need to add new fermions to cancel anomalies



$$\mathcal{A}_1(\mathrm{SU}(3)^2 \otimes \mathrm{U}(1)_B),\ \mathcal{A}_2(\mathrm{SU}(2)^2 \otimes \mathrm{U}(1)_B),$$

$$\mathcal{A}_3(\mathrm{U}(1)_Y^2 \otimes \mathrm{U}(1)_B),\ \mathcal{A}_4(\mathrm{U}(1)_Y \otimes \mathrm{U}(1)_B^2),$$

$$\mathcal{A}_5(\mathrm{U}(1)_B),\ \mathcal{A}_6(\mathrm{U}(1)_B^3),$$

In the SM the non-zero values are:

$$\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$$

Anomaly-free model

[Fileviez Perez, Ohmer, Patel 1403.8029]

Fields	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_B$
$\Psi_L = \begin{pmatrix} \Psi_L^+ \\ \Psi_L^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$-\frac{3}{2}$
$\Sigma_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \Sigma_L^0 & \sqrt{2}\Sigma_L^+ \\ \sqrt{2}\Sigma_L^- & -\Sigma_L^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{3}$	0	$-\frac{3}{2}$
χ_L^0	$\mathbf{1}$	$\mathbf{1}$	0	$-\frac{3}{2}$

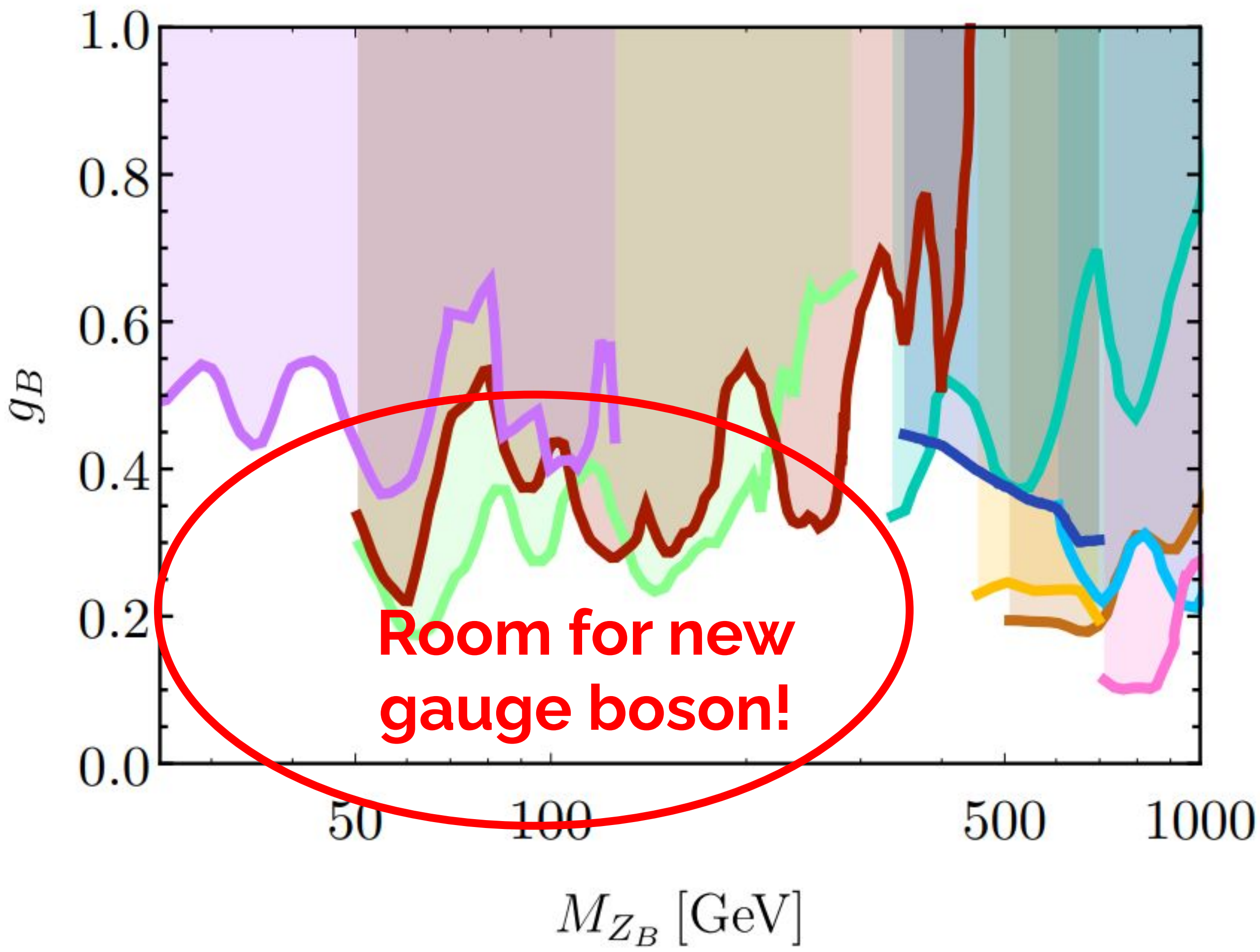
Model with 6 representations: **[Duerr, Fileviez Perez, Wise 1304.0576]**

- Neutral fermion required for anomaly cancellation
- Automatically stable from remnant U(1)⟶Z_2 symmetry

→ DM Candidate 🙂

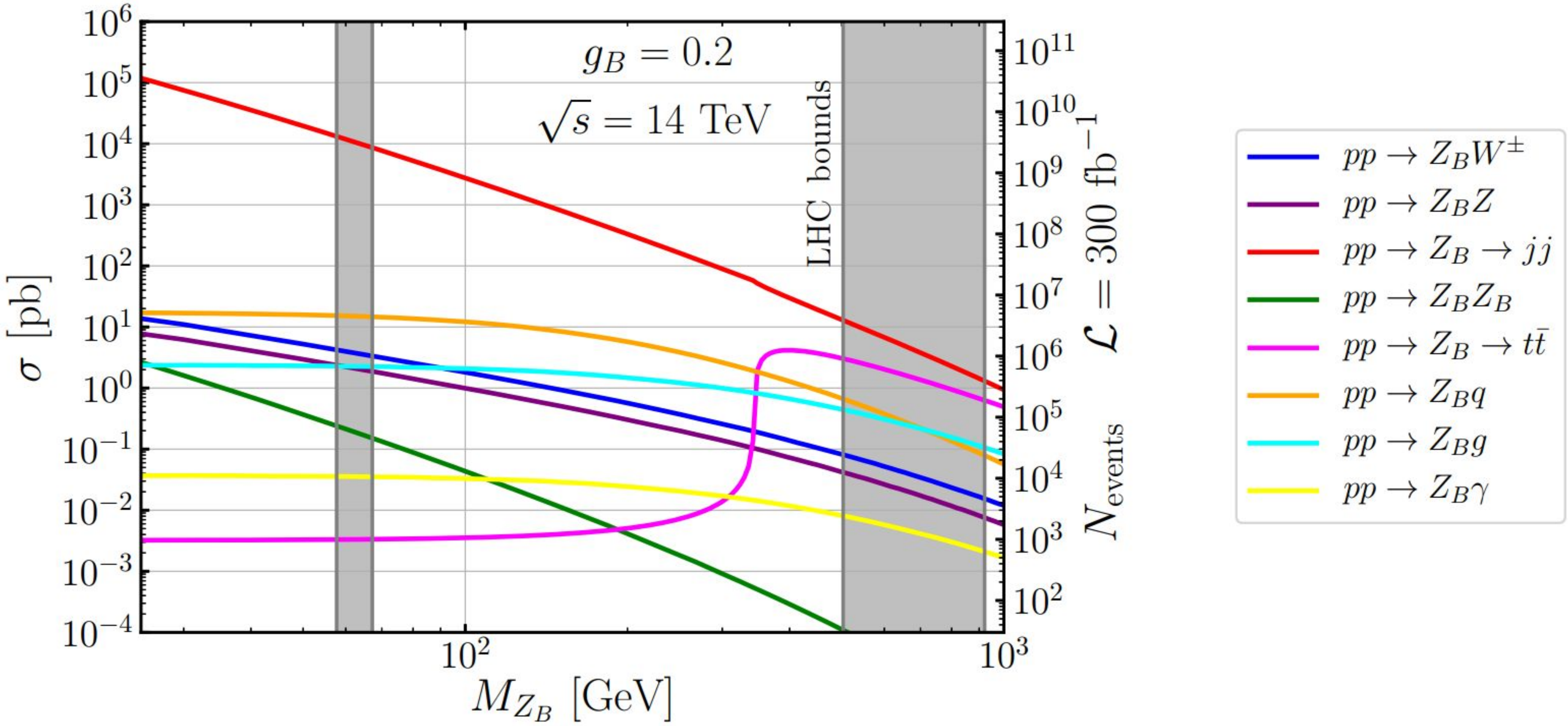
LHC bounds on leptophobic gauge boson

- Di-jet searches at CMS and ATLAS - Run I & II



[Fileviez Perez, Murgui, ADP 2003.09426]

LHC production cross-sections



[Fileviez Perez, Golias, Murgui, ADP 2003.09426]

Simplified Dark Matter

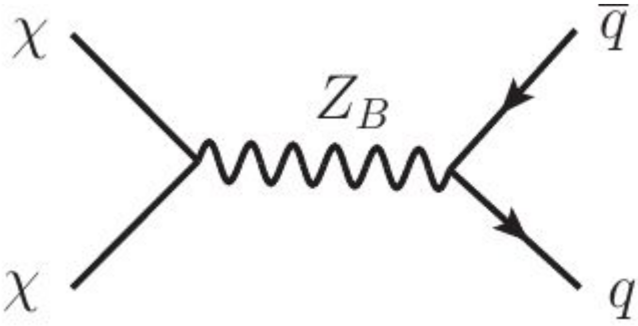
χ: Majorana DM

Z_B : Leptophobic mediator

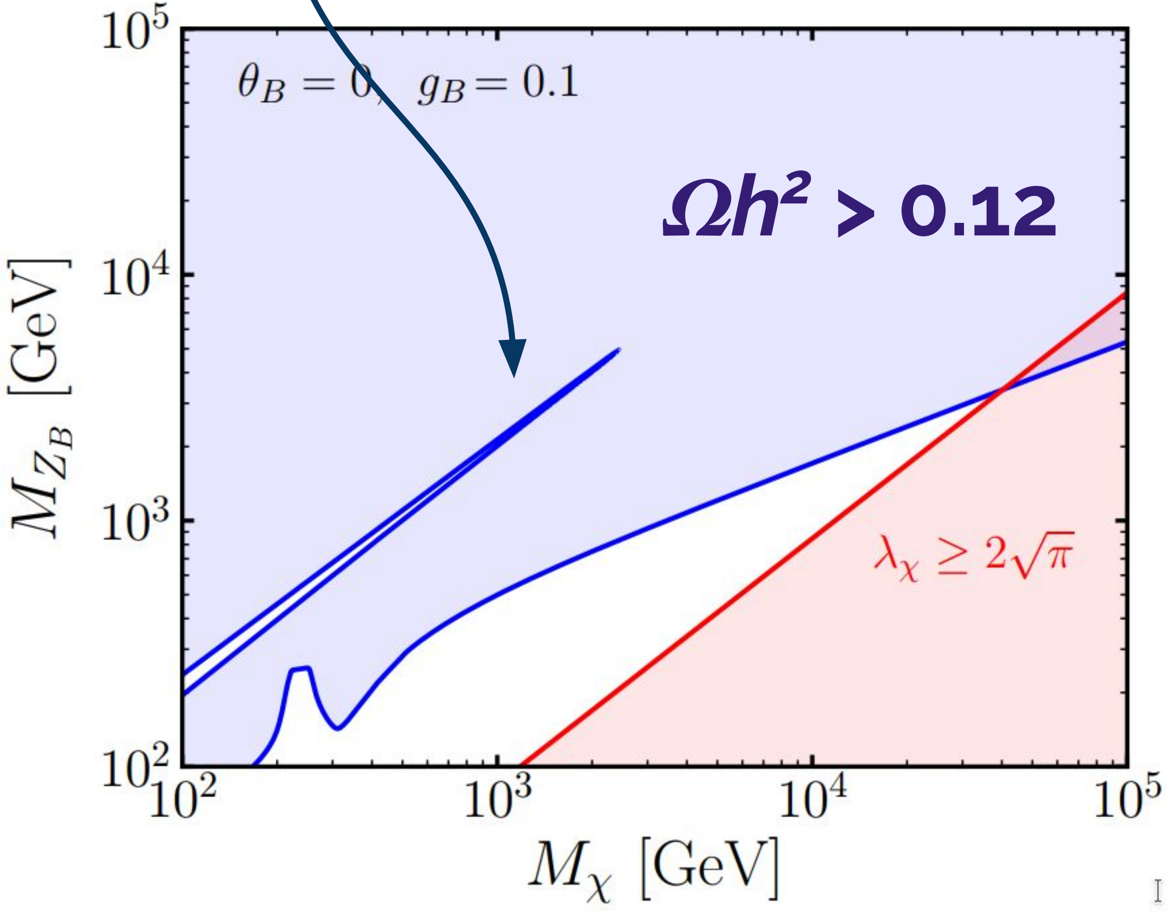
$$\boxed{\mathcal{L} \supset \frac{3}{4} \underbrace{g_B \bar{\chi} \gamma^\mu \gamma^5 \chi}_{\textbf{Axial}} Z_\mu^B - \frac{1}{3} \underbrace{g_B \bar{q} \gamma^\mu q}_{\textbf{Vector}} Z_\mu^B + \frac{M_\chi}{2 v_B} \sin\theta_B \bar{\chi} \chi h_1 - \frac{M_\chi}{2 v_B} \cos\theta_B \bar{\chi} \chi h_2}$$

the free parameters in the model are:

$$\boxed{M_\chi, \quad M_{Z_B}, \quad M_{h_2}, \quad \theta_B, \quad g_B.}$$

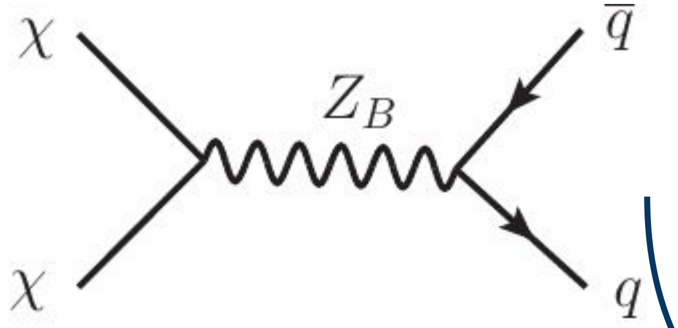


$$M_\chi \approx M_{Z_B}/2$$



$\Omega h^2 > 0.12$

[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]



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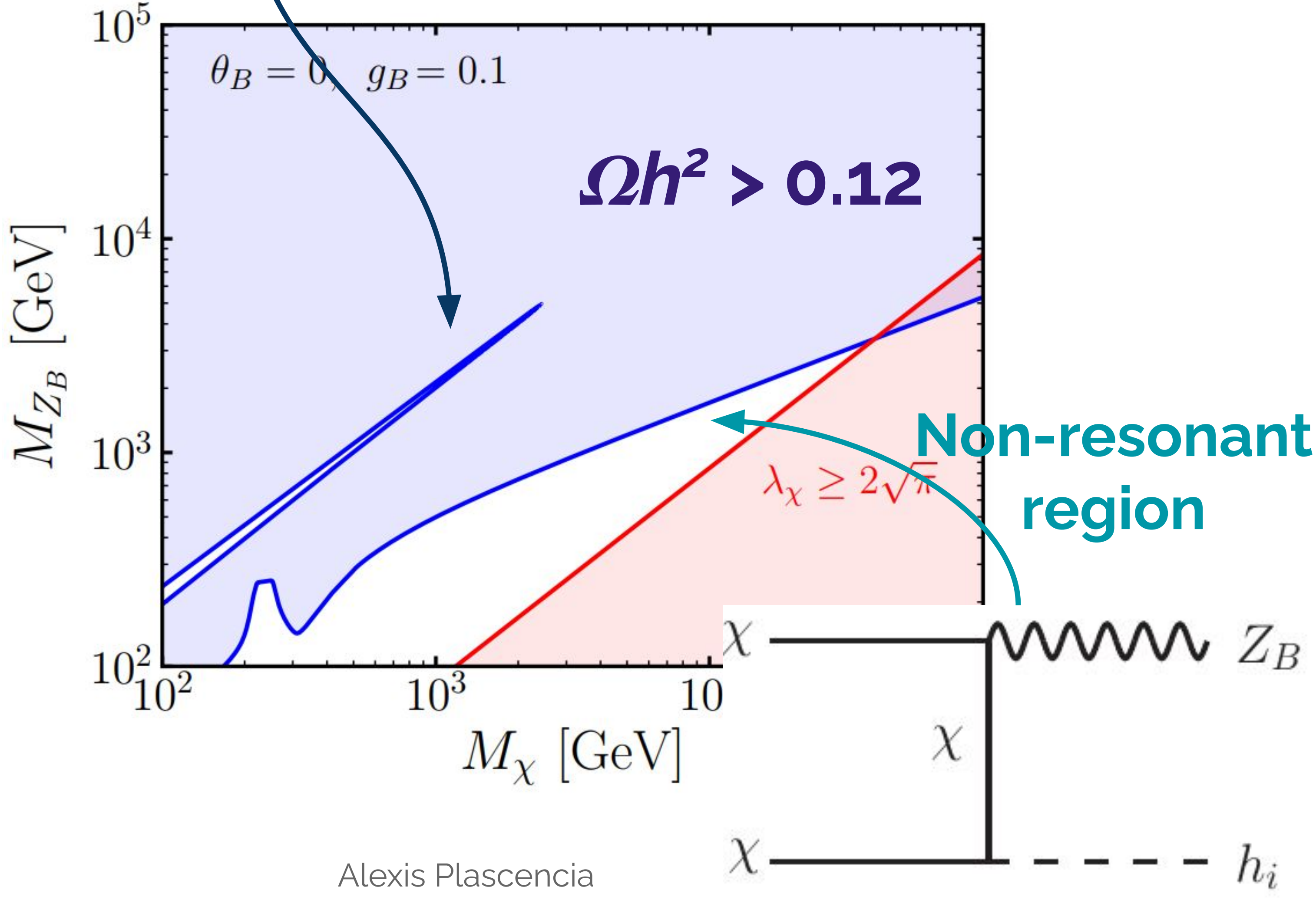
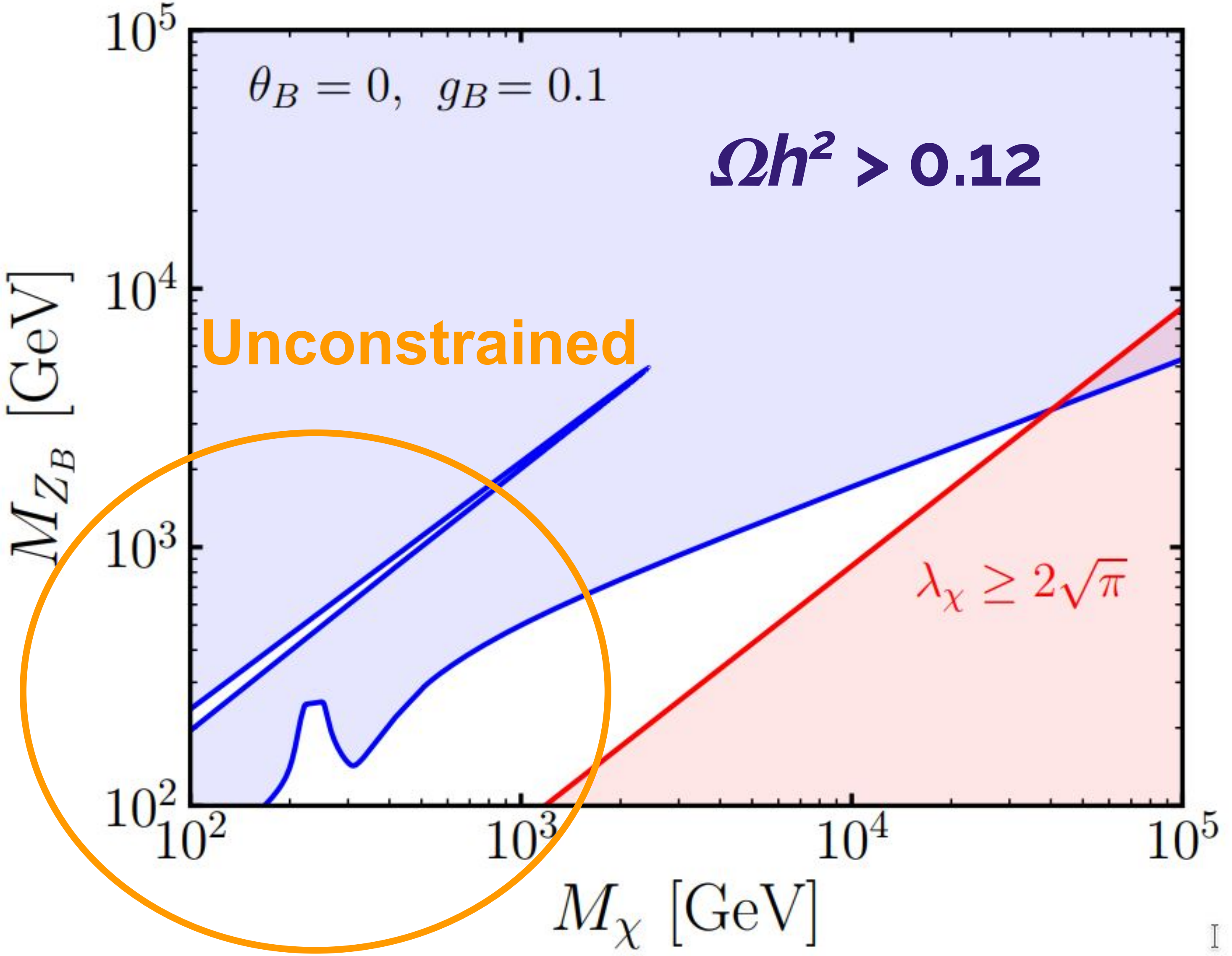


$\Omega h^2 > 0.12$

Non-resonant region

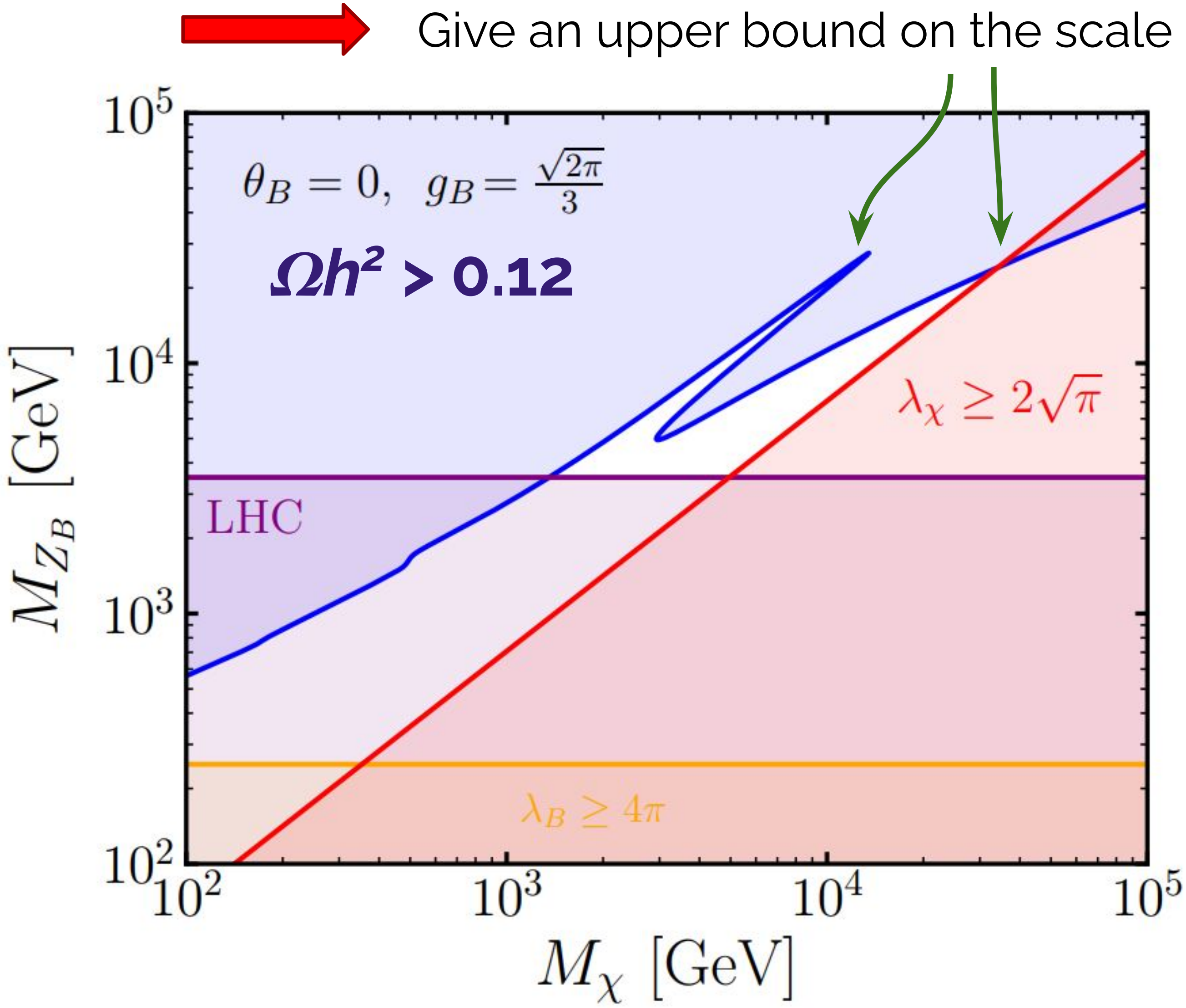
Results



[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]

Perturbativity $g_B \leq \frac{\sqrt{2\pi}}{3} \approx 0.84$ and $\Omega h^2 \leq 0.12$

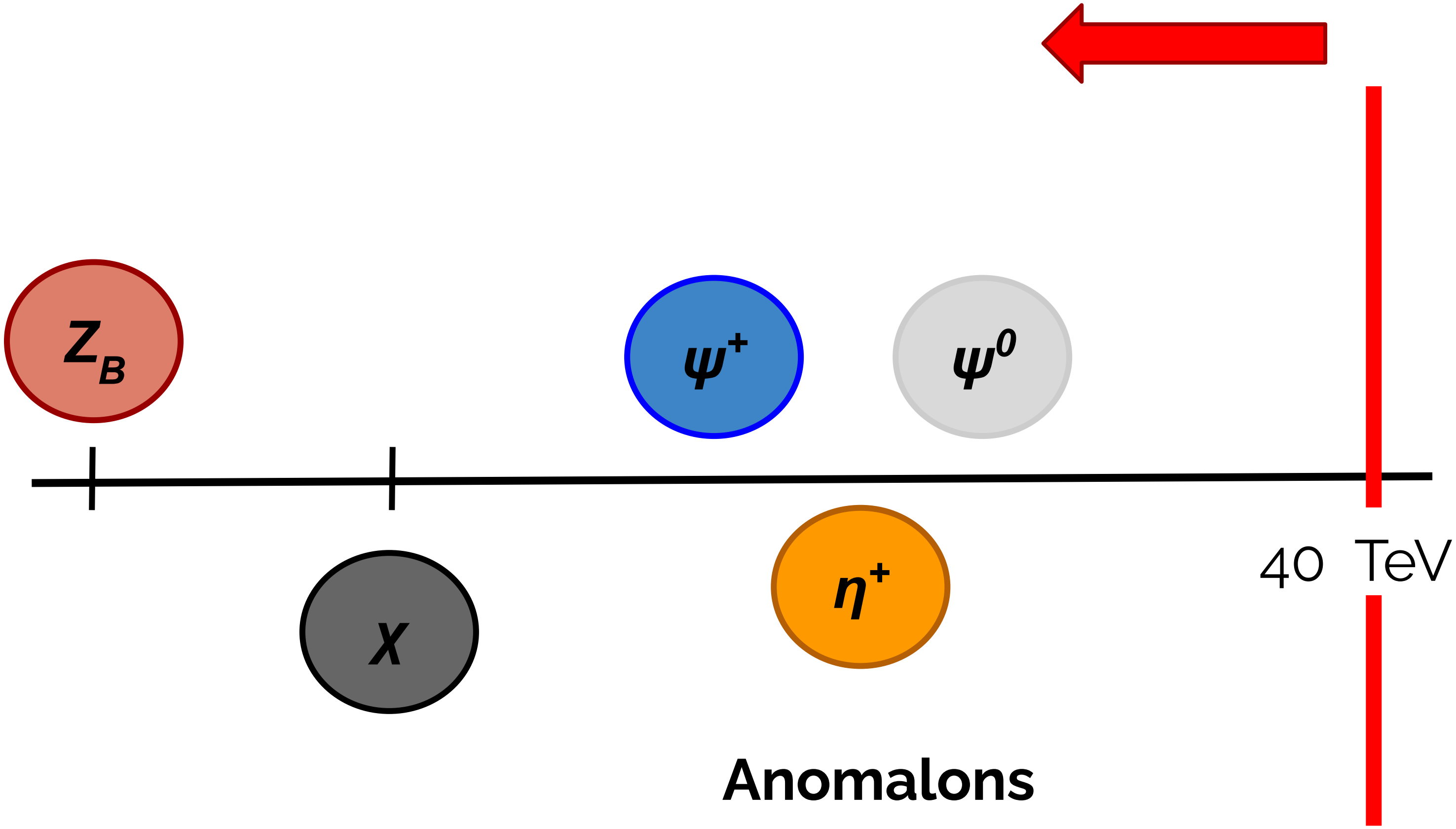
Give an upper bound on the scale



[Fileviez Perez, Golias, Li, Murgui, ADP 1904.01017]

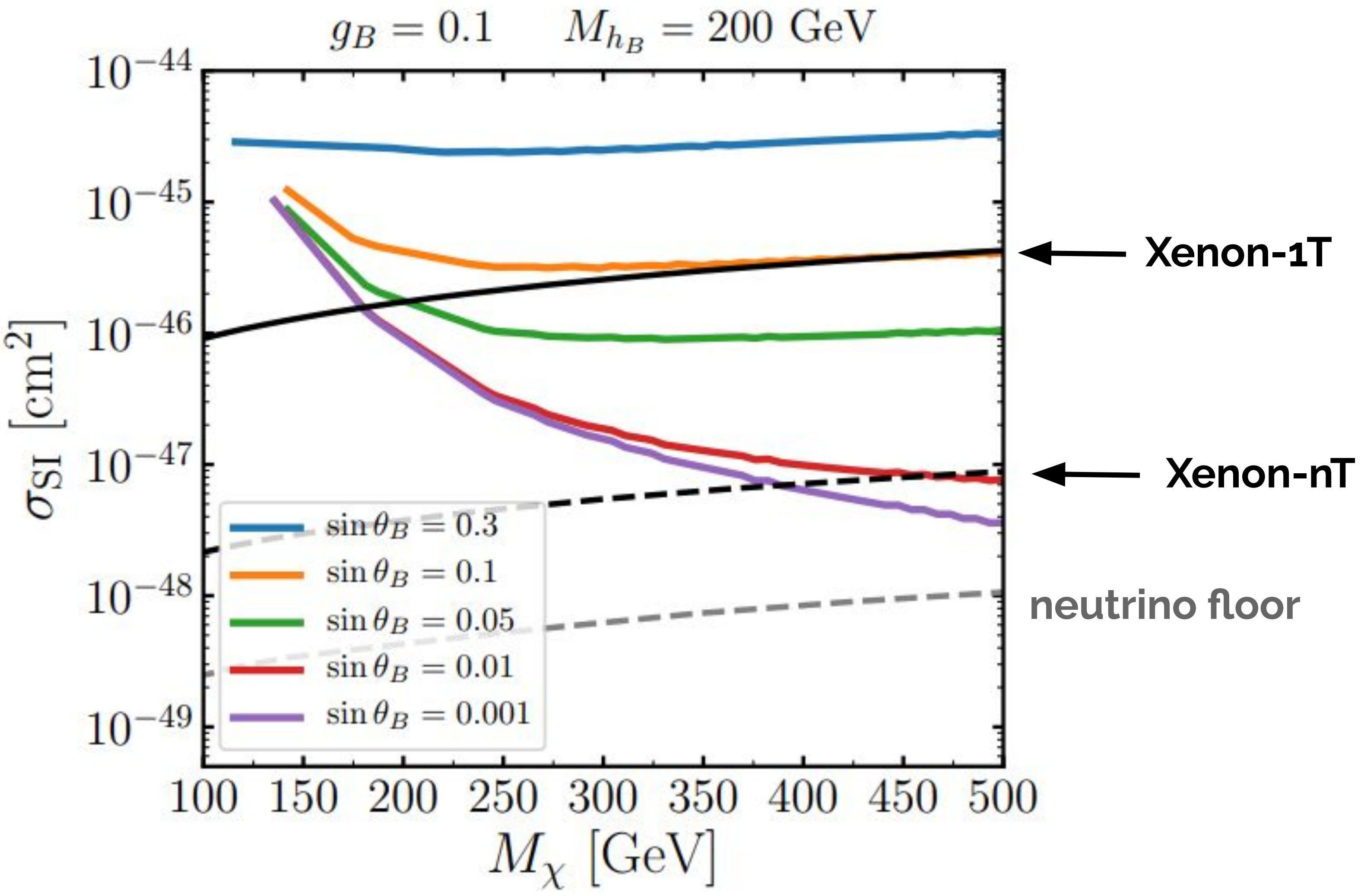
Upper bound on baryon number breaking scale

All masses connected to v_B , and hence, there is an upper bound for the full model



Direct Detection

All points satisfy: $\Omega h^2 = 0.12 \pm 0.0022$



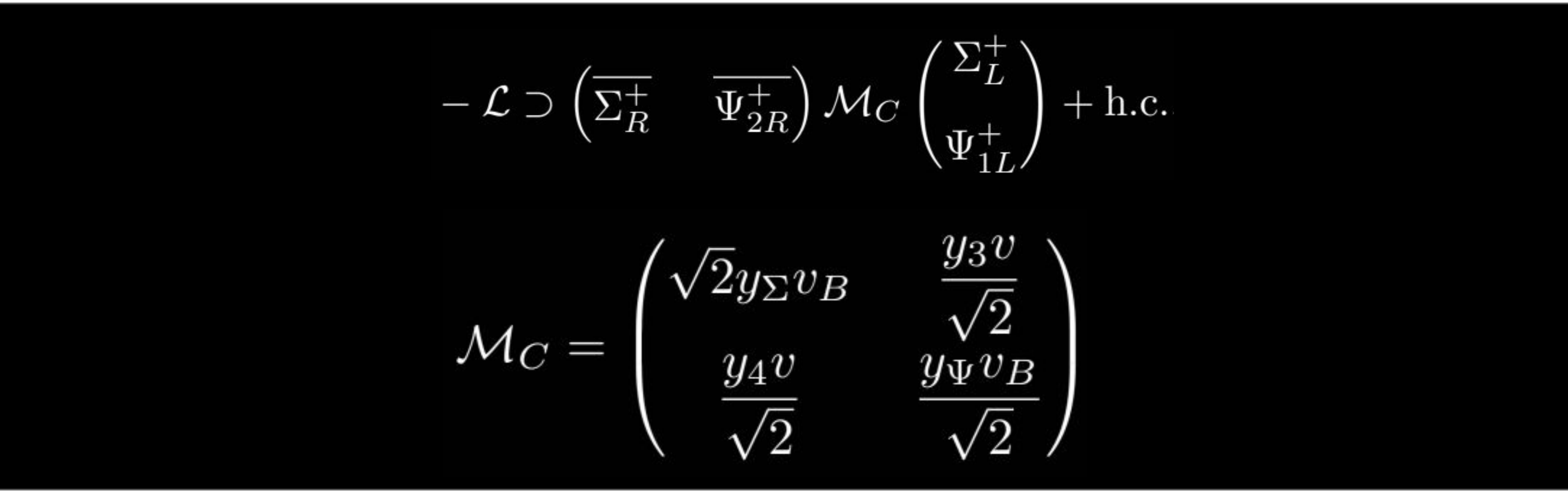
[Fileviez Perez, Murgui, ADP 2012.06599]

EDM

CP Violation and Electric Dipole Moments

CP violation and EDMs

$$-\mathcal{L} \supset y_1 \bar{\Psi}_R H \chi_L + y_2 H^\dagger \Psi_L \chi_L + y_3 H^\dagger \Sigma_L \Psi_L + y_4 \bar{\Psi}_R \Sigma_L H$$
$$+ \lambda_\Psi \bar{\Psi}_R \Psi_L S_B^* + \frac{\lambda_\chi}{\sqrt{2}} \chi_L \chi_L S_B + \lambda_\Sigma \mathrm{Tr}(\Sigma_L \Sigma_L) S_B + \mathrm{h.c.},$$



$$-\mathcal{L} \supset \begin{pmatrix} \overline{\Sigma_R^+} & \overline{\Psi_{2R}^+} \end{pmatrix} \mathcal{M}_C \begin{pmatrix} \Sigma_L^+ \\ \Psi_{1L}^+ \end{pmatrix} + \mathrm{h.c.}$$

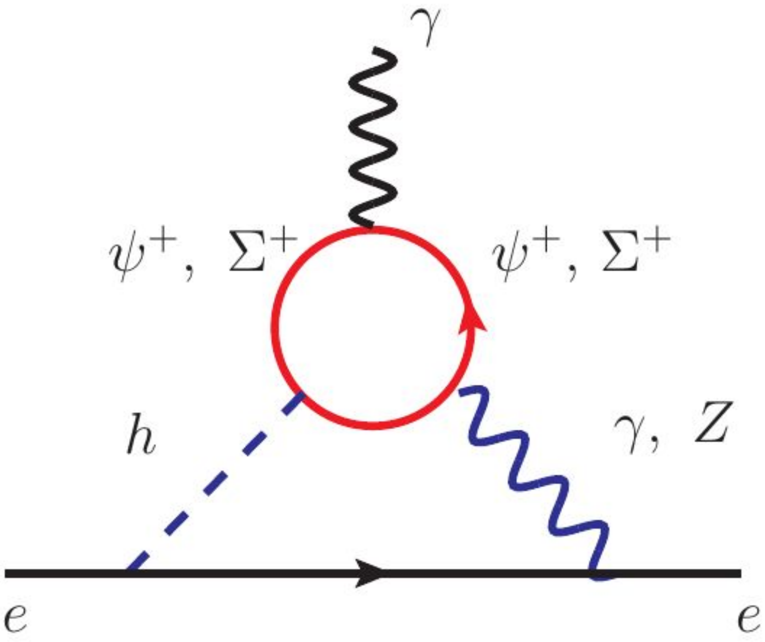
$$\mathcal{M}_C = \begin{pmatrix} \sqrt{2} y_\Sigma v_B & \frac{y_3 v}{\sqrt{2}} \\ \frac{y_4 v}{\sqrt{2}} & \frac{y_\Psi v_B}{\sqrt{2}} \end{pmatrix}$$

$$\boxed{\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi)}$$

[Fileviez Perez, ADP 2008.09116]

CP violation and EDMs

- This new CP-violating phase contributes to the electron and neutron electric dipole moments
- The new contribution comes from two-loop Barr-Zee diagrams with the charged anomaly-canceling fermions in the loop



$$\boxed{\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi)}$$

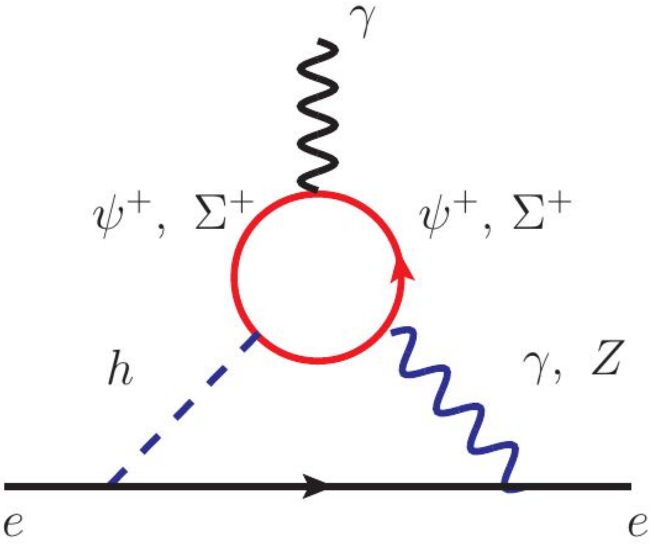
[Fileviez Perez, ADP 2008.09116]

CP violation and EDMs

$$\boxed{d_e^{\gamma h} = \frac{\alpha^2 \cos\theta_B \, Q_e \, m_e}{8\pi^2 s_W \, m_h^2 \, m_W} \sum_{i=1}^{2} M_{\chi_i^\pm} \, \mathrm{Im}[C_h^{ii}] \, I_{\gamma h}^i(M_{\chi_i^\pm})}$$

$$C_h^{ij} = \frac{1}{\sqrt{2}} \cos\theta_B \left[y_3 (V_R^{1i})^* V_L^{2j} + y_4 (V_R^{2i})^* V_L^{1j} \right] + \frac{1}{\sqrt{2}} \sin\theta_B \left[y_\Psi (V_R^{2i})^* V_L^{2j} + 2 y_\Sigma (V_R^{1i})^* V_L^{1j} \right]$$

$$I_{\gamma h}^i(M_{\chi_i^\pm}) = \int_0^1 \frac{dx}{x} j\left(0, \frac{M_{\chi_i^\pm}^2}{m_h^2} \frac{1}{x(1-x)}\right)$$



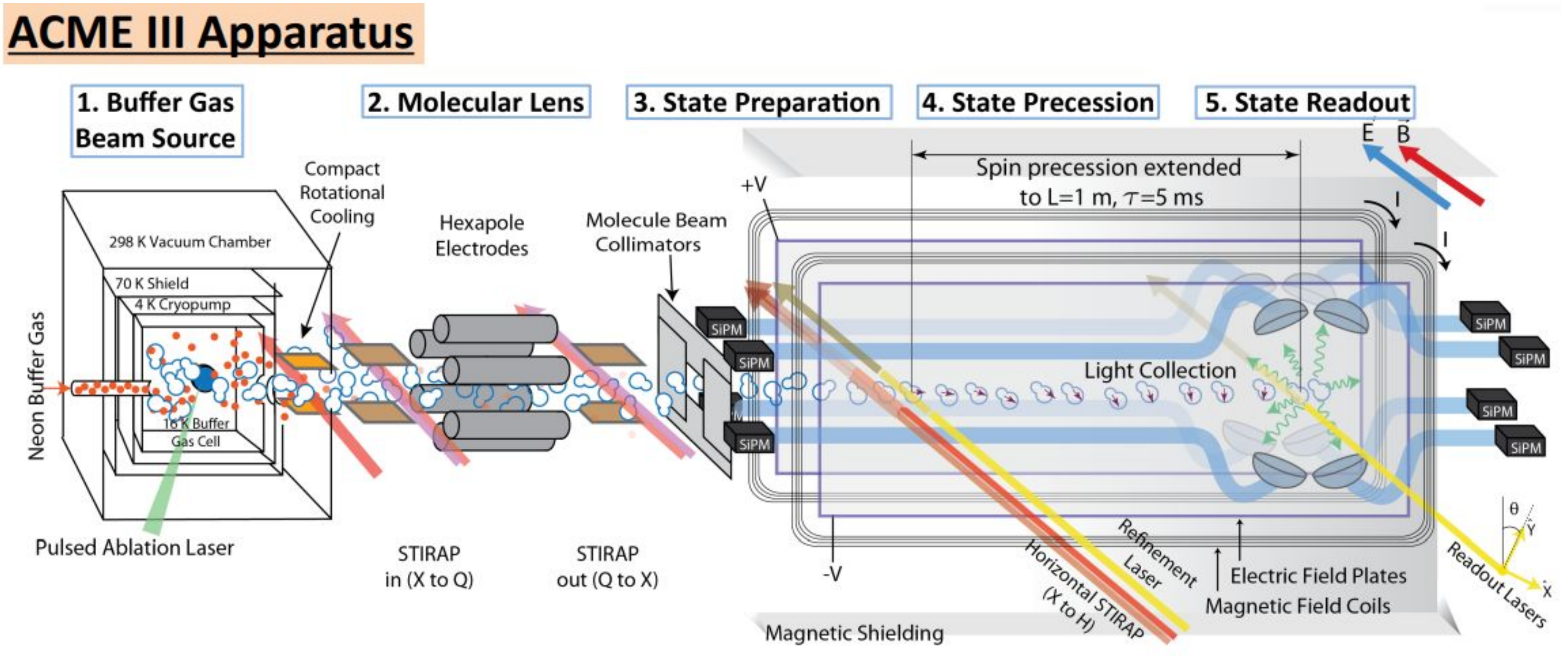
[Fileviez Perez, ADP 2008.09116] **[Nakai, Reece 1612.08090]**

ACME experiment

- Measures the electron EDM
- Beam of thorium monoxide molecule
- ThO has a strong internal electric field

$$\frac{|d_e|}{e} < 1.1 \times 10^{-29}\ \text{cm}$$

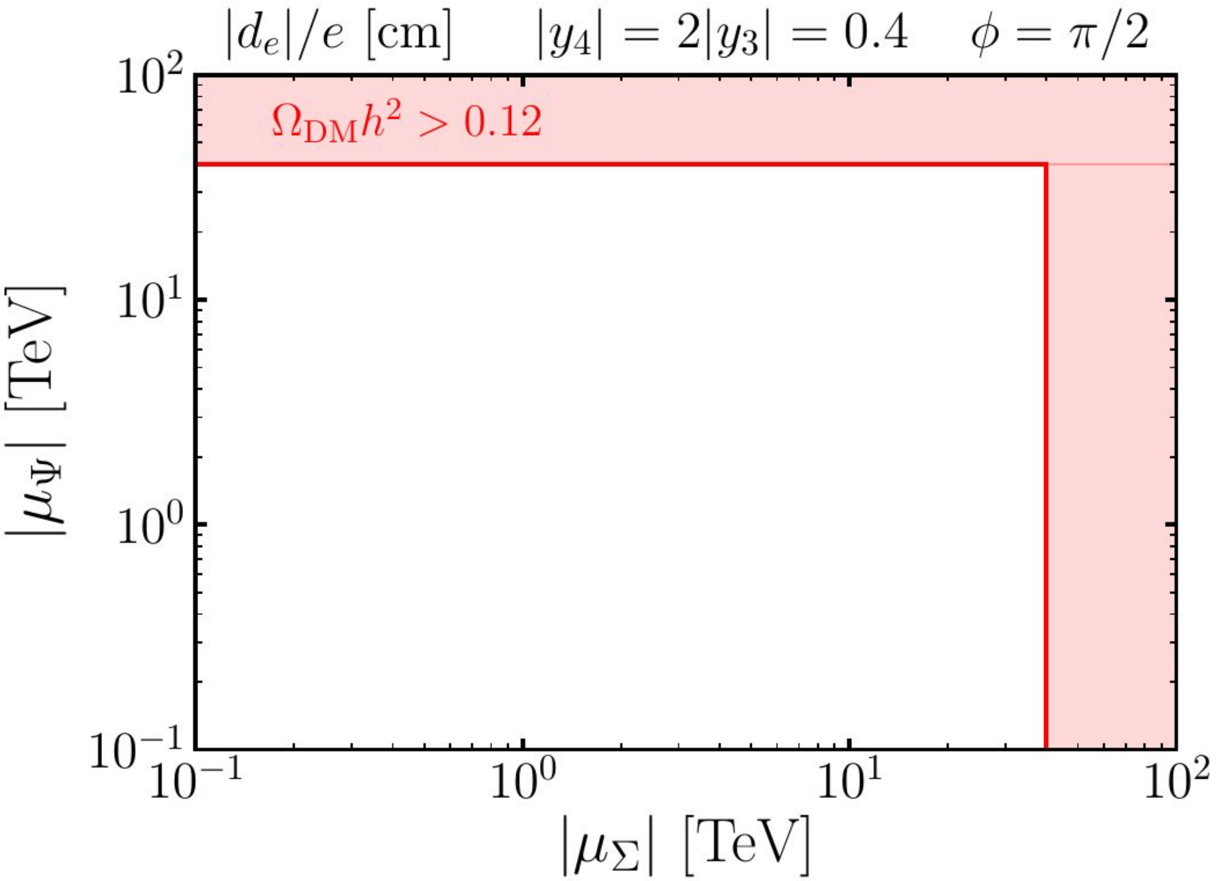
[ACME, Nature 2018]



[ACME collaboration]

Electron EDM

$$\boxed{\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = \pi/2}$$



DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

[Fileviez Perez, ADP 2008.09116]

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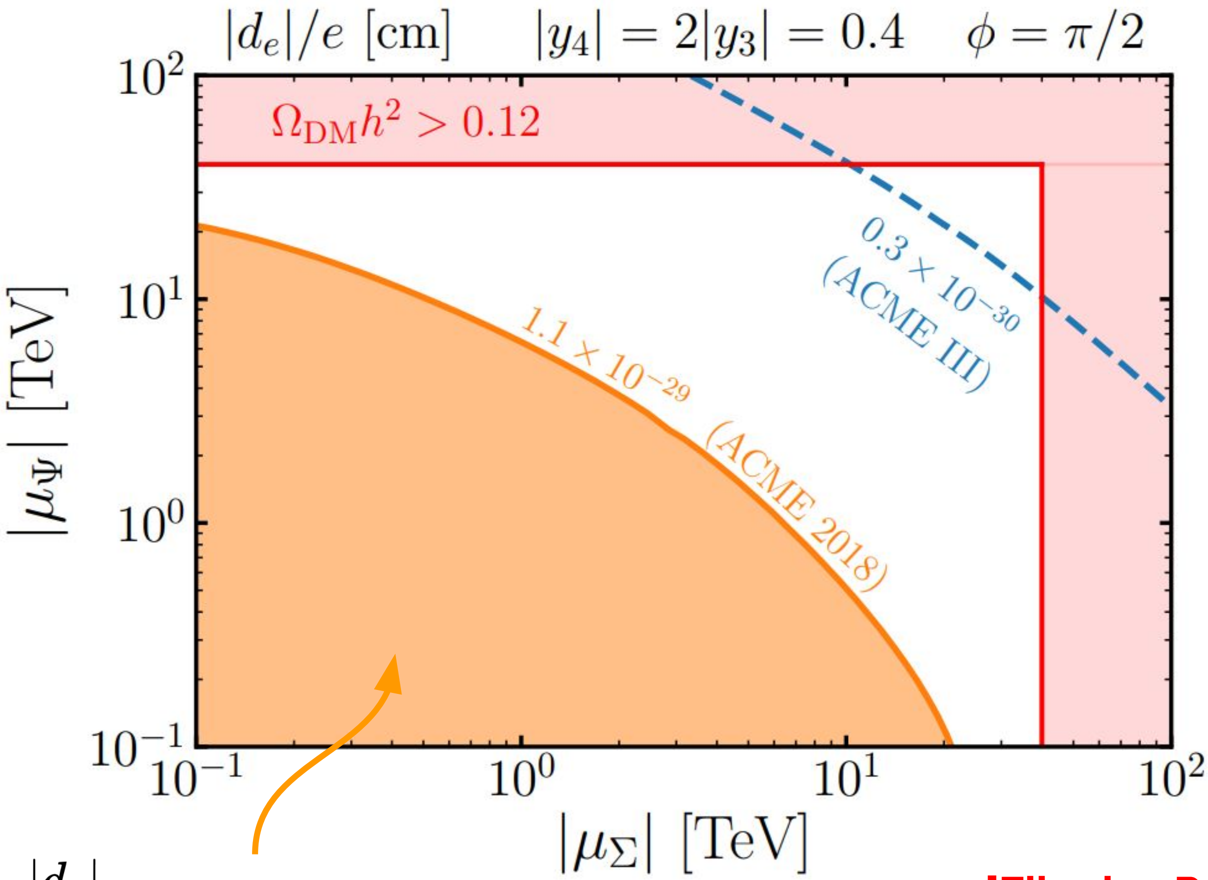


$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm}$$

[ACME, Nature 2018]

DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

ACME bound implies:

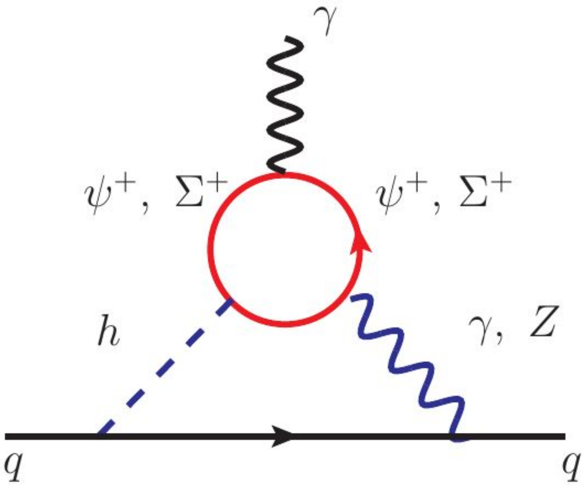
$$|\mu_\Sigma|, |\mu_\Psi| > 20 \text{ TeV}$$

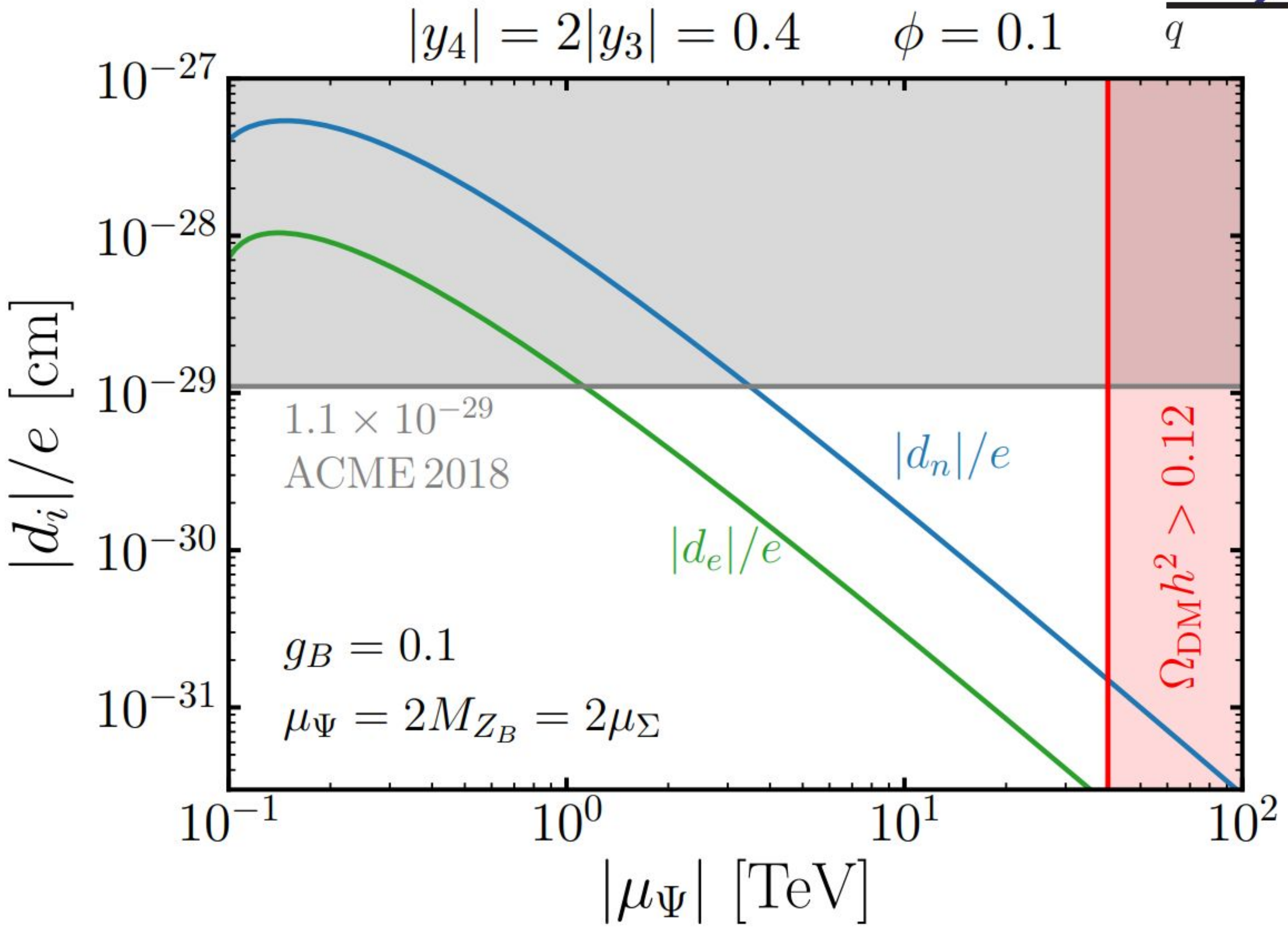
[Fileviez Perez, ADP 2008.09116]

Neutron EDM

$$d_n = (1.4 \pm 0.6)\,(d_d - 0.25 d_u)$$

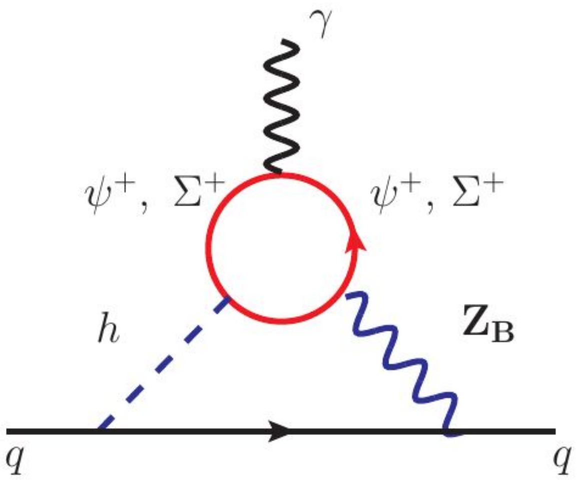
[Pospelov, Ritz hep-ph/0504231]

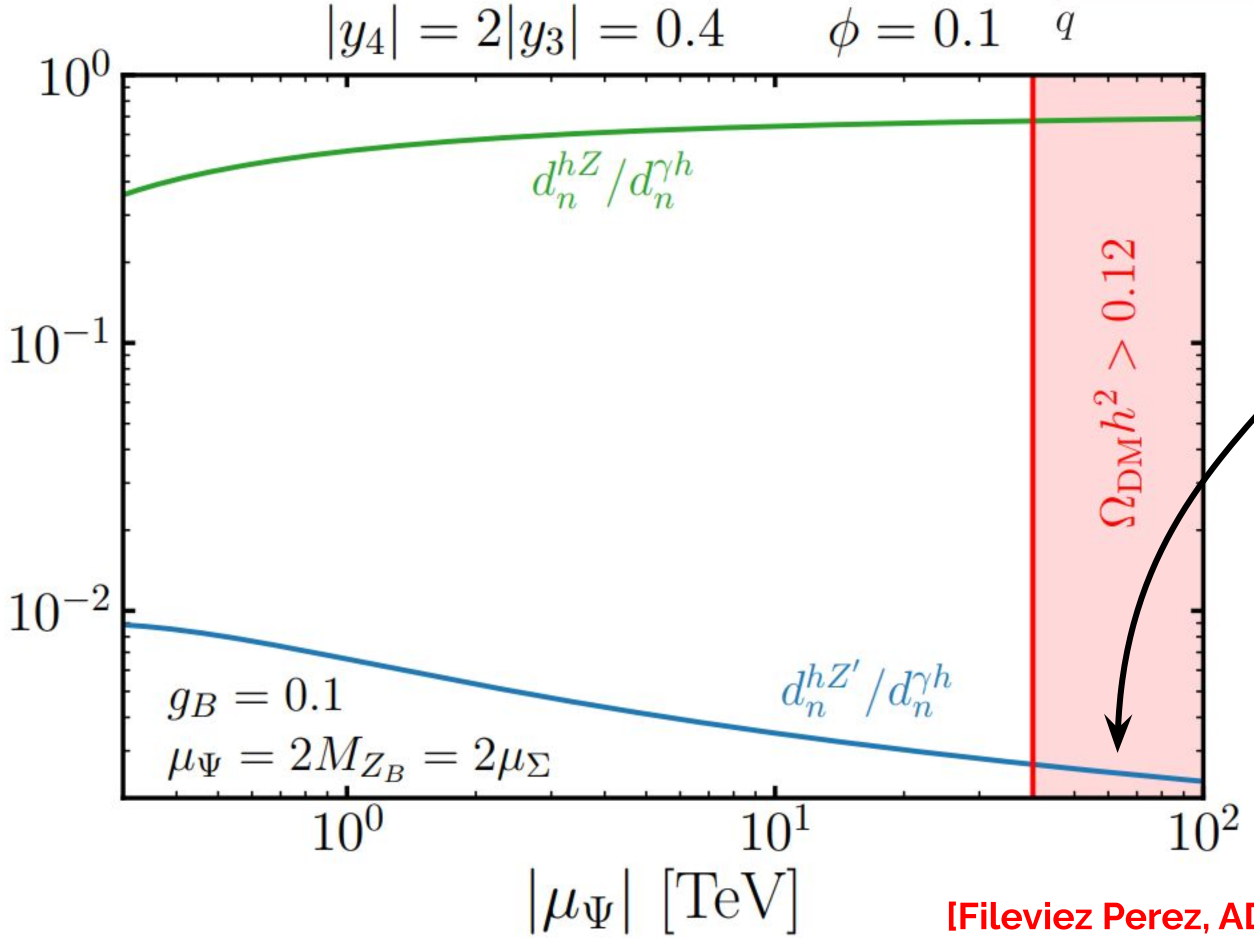




Neutron EDM

- New contribution from the gauge boson $\boldsymbol{Z_B}$

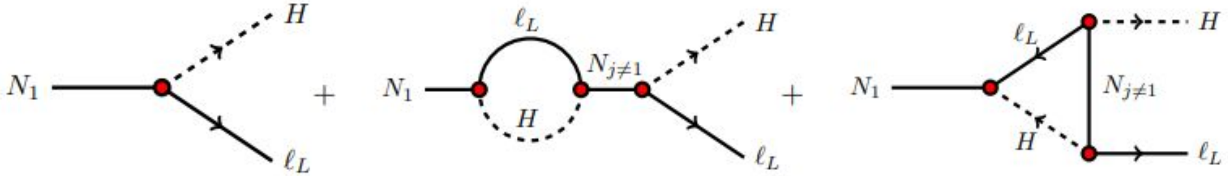


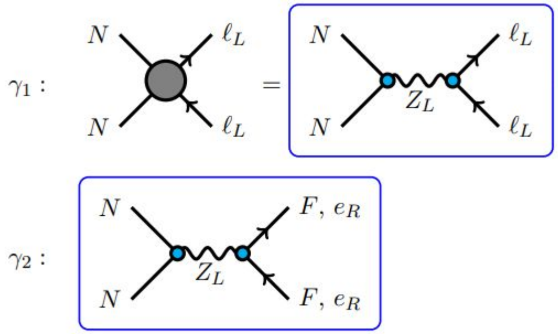


[Fileviez Perez, ADP 2008.09116]

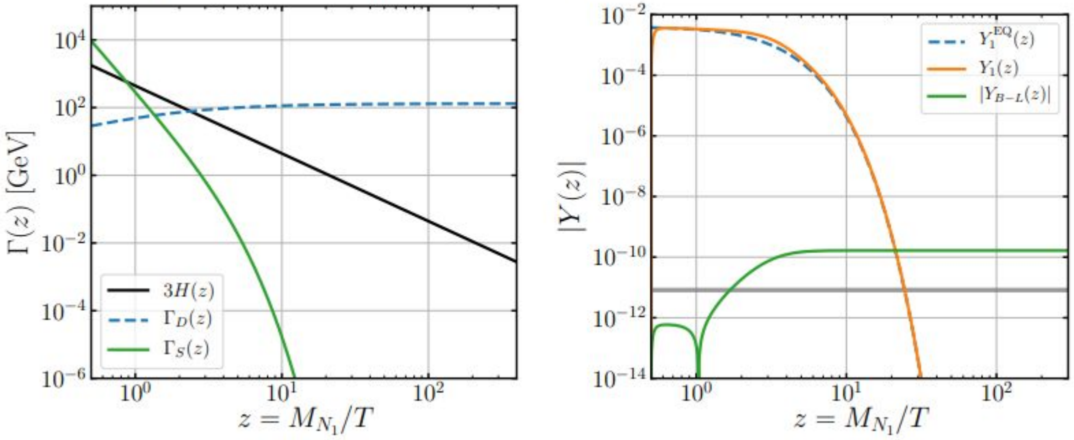
Baryon Asymmetry

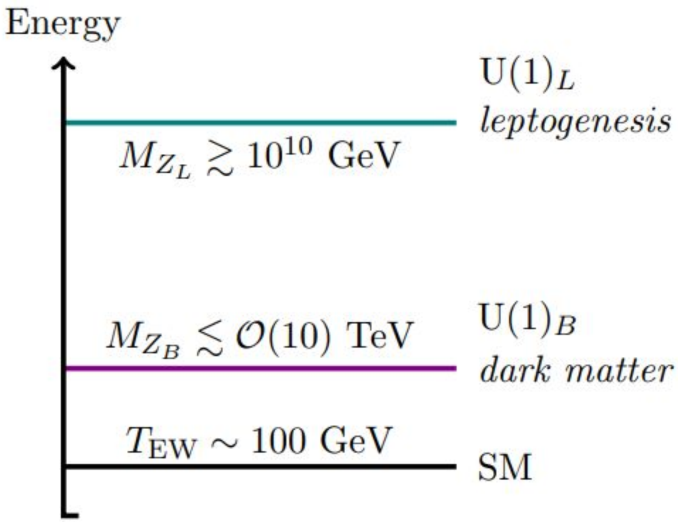
What about gauging lepton number? **U(1)$_L$**





$M_{N_1} = 10^{10}$ GeV $M_{Z_L} = 10^{12}$ GeV $g_L = 1.0$ $\varepsilon_1 = 6 \cdot 10^{-8}$ $\widetilde{m}_1 = 10^{-3}$ eV





[Fileviez Perez, Murgui, ADP 2103.13397]

Conclusions

- Promoting Baryon Number to a local symmetry predicts a new sector from anomaly cancellation
- One of these new fermions is neutral and stable, and hence, a good dark matter candidate
- Not overproducing dark matter gives an upper bound on the full theory at the multi-TeV scale
- Leptophobic mediator leads to interesting phenomenology at the LHC.
- New sources of CP violation that lead to large EDMs. Experiments such as ACME could fully probe the predictions for the electron EDM

Thank you!

Thanks for your attention!

Questions & comments are welcome

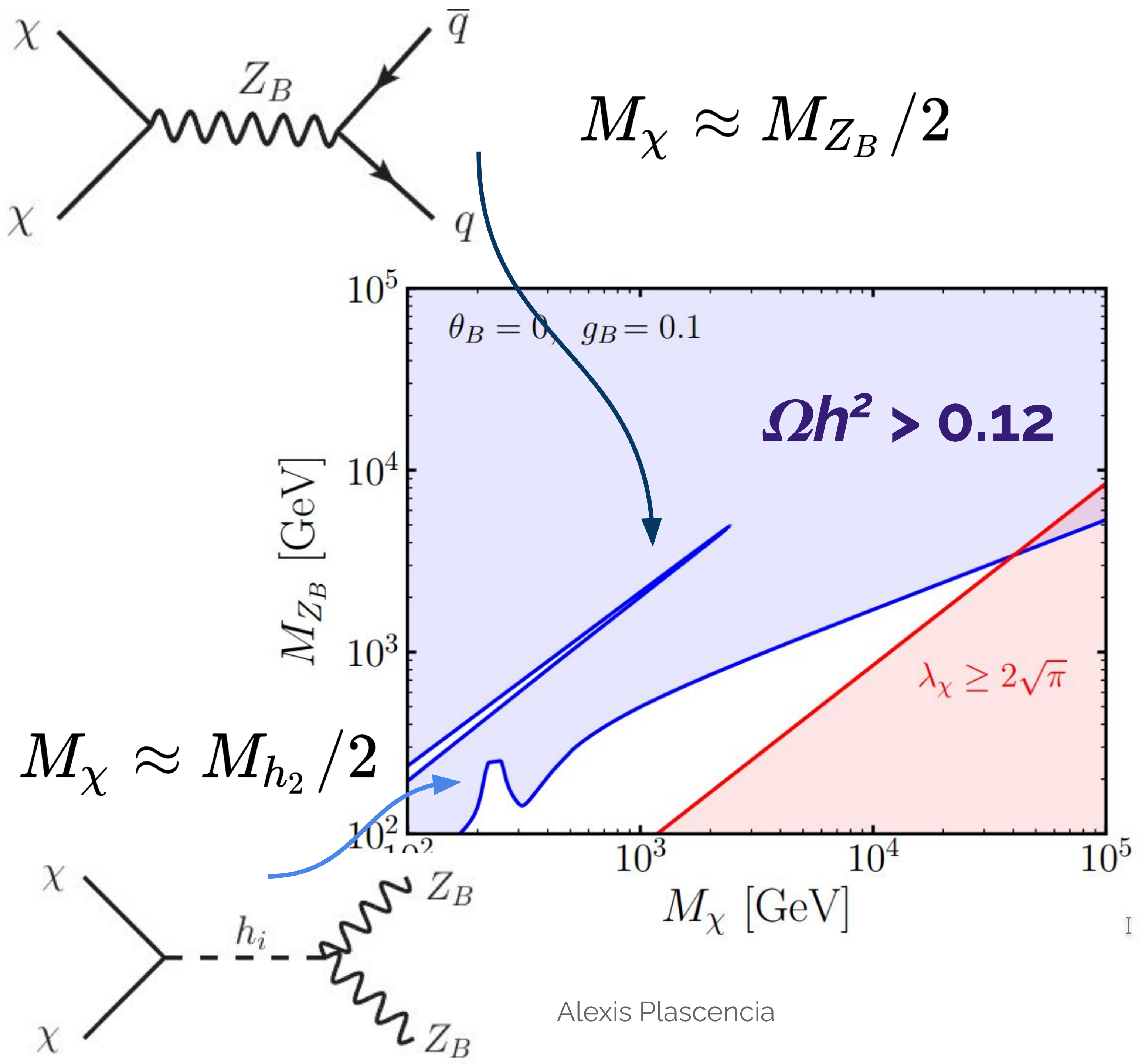
Back-up

Model II

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$
$\Psi_L = \begin{pmatrix} \Psi_L^0 \\ \Psi_L^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$-\frac{3}{2}$
$\Psi_R = \begin{pmatrix} \Psi_R^0 \\ \Psi_R^- \end{pmatrix}$	1	2	$-\frac{1}{2}$	$\frac{3}{2}$
η_R^-	1	1	-1	$-\frac{3}{2}$
η_L^-	1	1	-1	$\frac{3}{2}$
χ_R^0	1	1	0	$-\frac{3}{2}$
χ_L^0	1	1	0	$\frac{3}{2}$

DM

[Duerr, Fileviez Perez & Wise 2013]



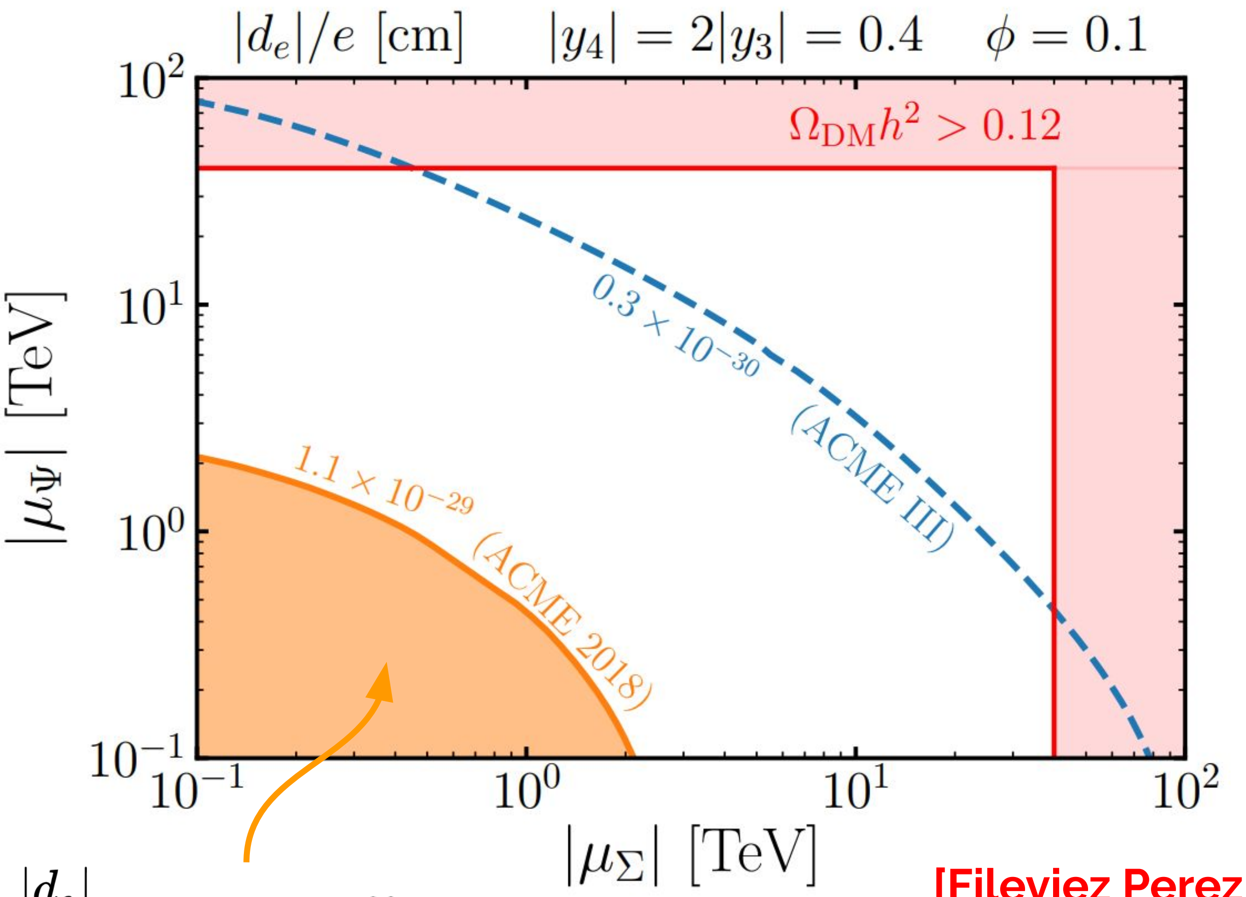
$$M_\chi \approx M_{Z_B}/2$$

$\Omega h^2 > 0.12$

$$M_\chi \approx M_{h_2}/2$$

Electron EDM

$$\boxed{\phi = \arg(y_3^* y_4^* \mu_\Sigma \mu_\Psi) = 0.1}$$



DM relic density requires:

$$|\mu_\Sigma|, |\mu_\Psi| < 40 \text{ TeV}$$

ACME bound implies:

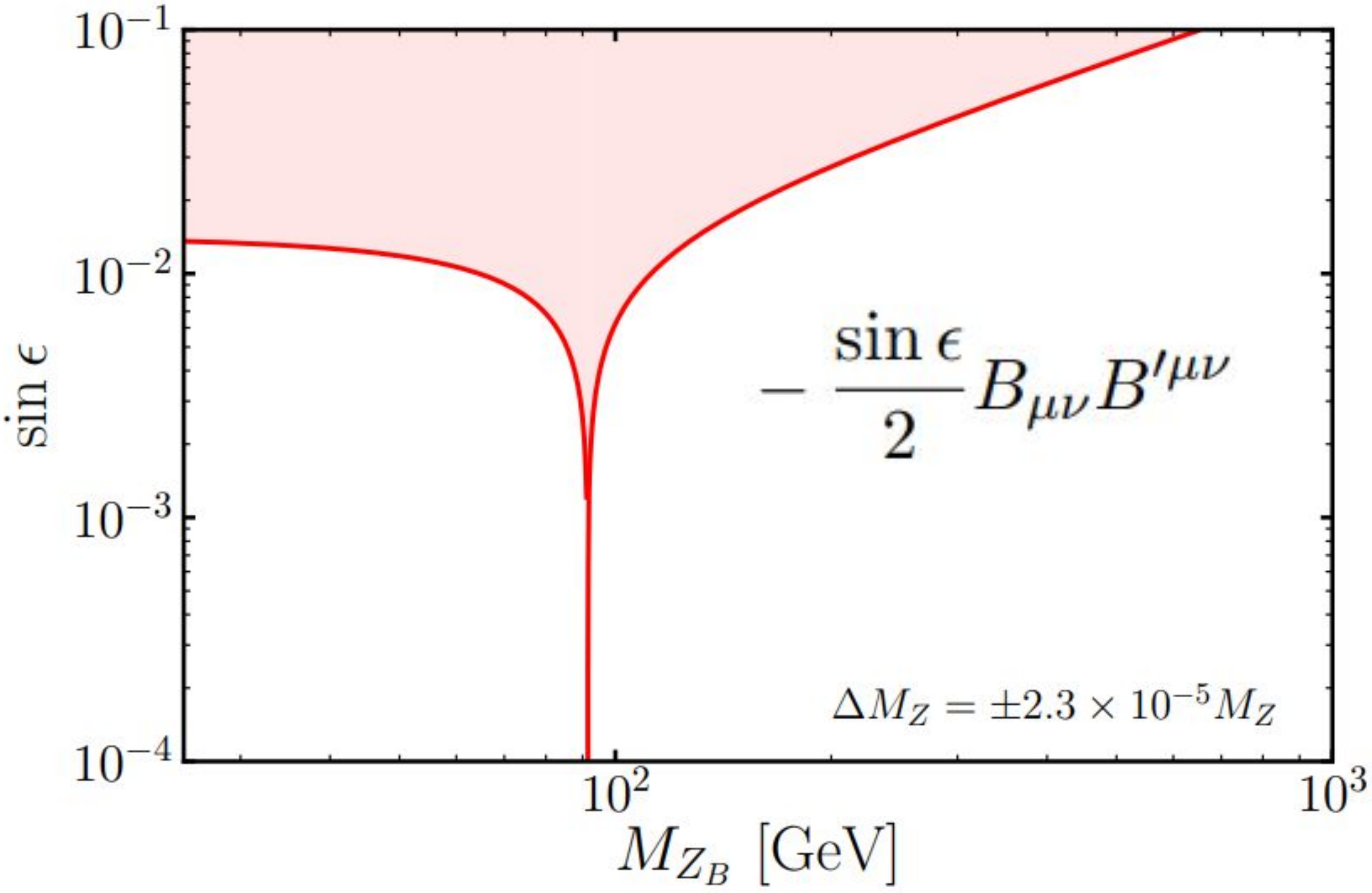
$$|\mu_\Sigma|, |\mu_\Psi| > 2 \text{ TeV}$$

[Fileviez Perez, ADP 2008.09116]

$$\frac{|d_e|}{e} < 1.1 \times 10^{-29} \text{ cm}$$

[ACME, Nature 2018]

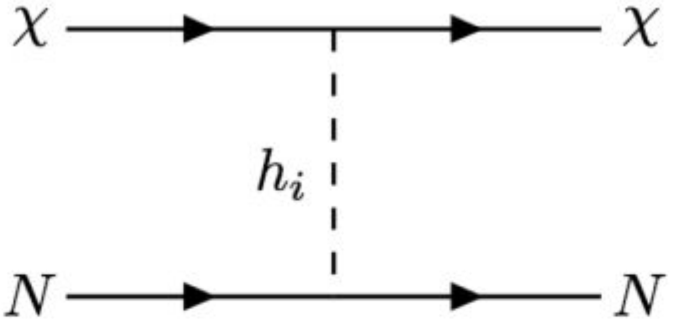
Kinetic Mixing

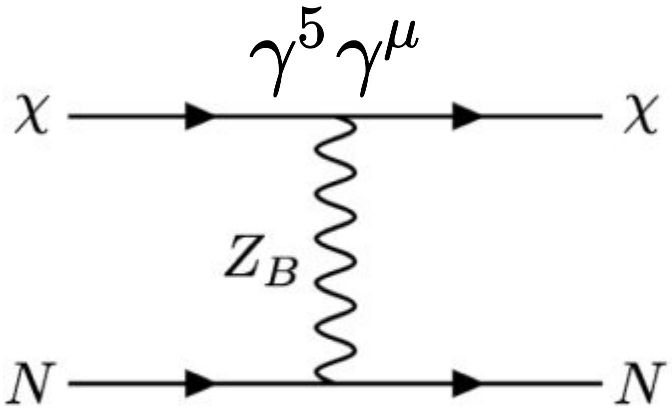


[Fileviez Perez, Murgui, ADP 2003.09426]

Direct Detection

$$\sigma_{\chi N}^{\rm TOT} = \sigma_{\chi N}(h_i) + \sigma^0_{\chi N}(Z_B) v^2$$





suppressed by Higgs mixing

$\theta < 0.3$ for $M_{H2} > 200$ GeV

For lighter M_{H2} stronger bound

[Ilnicka, Robens, Stefaniak 2018]

Due to axial coupling,

velocity suppressed $v \sim 10^{-3}$