Extra U(1), effective operators, anomalies and dark matter

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Introduction : Motivations

Simplest extension of SM $\rightarrow$ add a $U(1)'$ symmetry

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- **Charged SM fermions**
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  $\longrightarrow$ Stringy light Z', anomaly cancellation a la Green-Schwarz

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- **Uncharged SM fermions**
  $\longrightarrow$ Motivations from string theory (D-brane models)
  $\longrightarrow$ Heavy mediators $\rightsquigarrow$ effective higher-dimensional operators

Introduction : The model

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	ψ_{DM}	Ψ_M	ψ_{SM}
$U(1)'$	$\bullet$	$\bullet$	
$U(1) \times SU(2) \times SU(3)$		$\bullet$	$\bullet$

Introduction : The model

- **Heavy mediators : heavy SM fermions**

Heavy mass scale : breaking of the heavy $U(1)'$ higgs sector

Stueckelberg realization

$$\Phi = \frac{V+\phi}{\sqrt{2}} exp(ia_X/V) \longrightarrow \Phi = \frac{V}{\sqrt{2}} exp(ia_X/V)$$

$U(1)'$ transformations

$$\delta Z'_\mu = \partial_\mu \alpha \quad , \quad \delta\theta_X = \frac{g_X}{2}\alpha \quad \text{where} \quad \theta_X \equiv \frac{a_X}{V}$$

Introduction : The model

Initial lagrangian

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} + \mathcal{L}_2(\Psi^i, A_\mu^{SM}) + \frac{1}{2}(\partial_\mu a_X - M_{Z'} Z'_\mu)^2 - \frac{1}{4} F^X_{\mu\nu} F^{X\,\mu\nu} \\ &+ \bar{\Psi}^i_L \left(i\gamma^\mu \partial_\mu + \frac{1}{2} g_X X^i_L \gamma^\mu Z'_\mu \right) \Psi^i_L + \bar{\Psi}^i_R \left(i\gamma^\mu \partial_\mu + \frac{1}{2} g_X X^i_R \gamma^\mu Z'_\mu \right) \Psi^i_R \\ &- \left(\bar{\Psi}^i_L M_{ij} e^{\frac{i a_X (x^i_L - x^j_R)}{v}} \Psi^i_R + \mathrm{h.c.} \right) \qquad (1.1)\end{aligned}$$

where $$M_{Z'} \equiv g_X \frac{V}{2} \,. \qquad (1.2)$$

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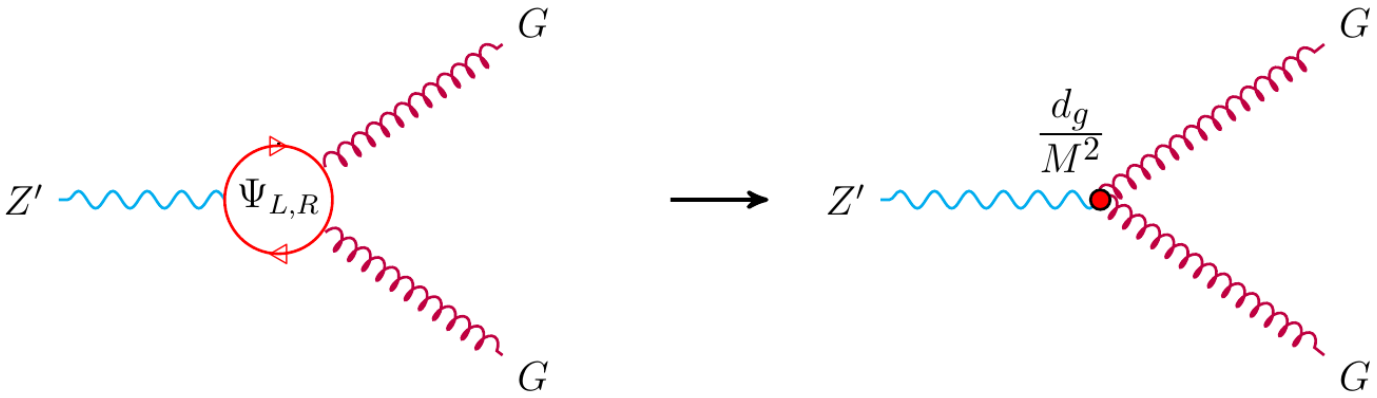
↪ Kinetic mixing term $\frac{\delta}{2} F^{\mu\nu}_X F^Y_{\mu\nu}$ is neglected Why ?...

Effective couplings



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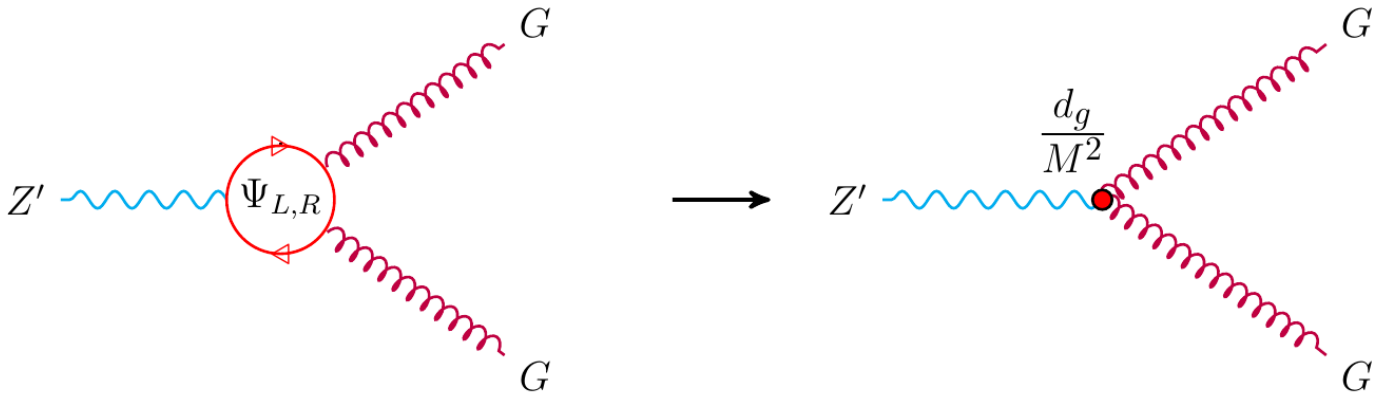
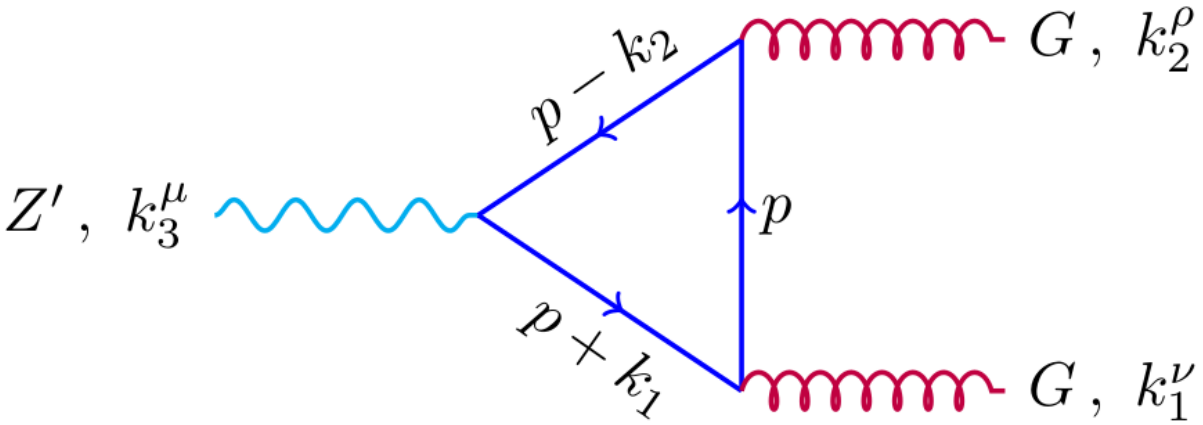
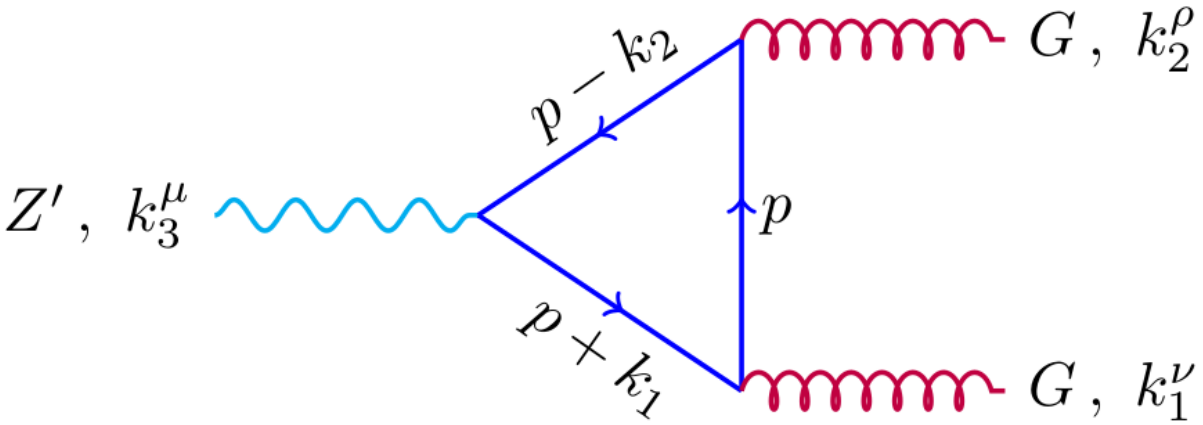


$$
\begin{aligned}
\mathcal{L}^{(6)}_{\text{CP even}} &= \frac{1}{M^2}\left\{ d_g \partial^\mu D_\mu \theta_X \mathcal{T}r(G\tilde{G}) + d'_g \partial^\mu D^\nu \theta_X \mathrm{Tr}(G_{\mu\rho}\tilde{G}^\rho_\nu) \right. \\
&+ \left. e_g D^\mu \theta_X \mathrm{Tr}(G_{\nu\rho}\mathcal{D}_\mu \tilde{G}^{\rho\nu}) + e'_g D_\mu \theta_X \mathrm{Tr}(G_{\alpha\nu}\mathcal{D}^\nu \tilde{G}^{\mu\alpha}) \right\} \\
&+ \frac{1}{M^2}\left\{ D^\mu \theta_X \left[i(D^\nu H)^\dagger (c_1 \tilde{F}^Y_{\mu\nu} + 2c_2 \tilde{F}^W_{\mu\nu}) H + h.c. \right] \right. \\
&+ \partial^m D_m \theta_X (d_1 \mathcal{T}r(F^Y \tilde{F}^Y) + 2d_2 \mathcal{T}r(F^W \tilde{F}^W)) \\
&+ d'_{ew} \partial^\mu D^\nu \theta_X \mathrm{Tr}(F_{\mu\rho}\tilde{F}^\rho_\nu) \\
&+ \left. e_{ew} D^\mu \theta_X \mathrm{Tr}(F_{\nu\rho}\mathcal{D}_\mu \tilde{F}^{\rho\nu}) + e'_{ew} D_\mu \theta_X \mathrm{Tr}(F_{\alpha\nu}\mathcal{D}^\nu \tilde{F}^{\mu\alpha}) \right\} \quad , \qquad (1.3)
\end{aligned}
$$


Z' , k_3^μ
$p - k_2$
p
$p + k_1$
G , k_2^ρ
G , k_1^ν



$$\mathcal{O} = \frac{g_3^2}{24\pi^2} \sum_i \mathrm{Tr}\left(\frac{(X_L - X_R)\, T_a T_a}{M^2}\right)_i \times \left[\partial^\mu D_\mu \theta_X \mathcal{T}r(G\tilde{G}) - 2 D_\mu \theta_X \mathrm{Tr}(G_{\alpha\nu} \mathcal{D}^\nu \tilde{G}^{\mu\alpha})\right] . \quad (1.4)$$

DM annihilation into Gluons

couplings

$$\mathcal{L}_{\text{CP even}} = \frac{1}{M^2}\Big\{ d_g \partial^\mu D_\mu \theta_X \mathcal{T}r(G\tilde{G}) + \cancel{d'_g \partial^\mu D^\nu \theta_X \mathrm{Tr}(G_{\mu\rho}\tilde{G}^\rho_\nu)} + \cancel{e_g D^\mu \theta_X \mathrm{Tr}(G_{\nu\rho}\mathcal{D}_\mu \tilde{G}^{\rho\nu})} + e'_g D_\mu \theta_X \mathrm{Tr}(G_{\alpha\nu}\mathcal{D}^\nu \tilde{G}^{\mu\alpha}) \Big\} \quad (2.1)$$

$$\mathcal{L}_{DM} = \bar{\psi}^{DM}_L \frac{1}{2} g_X X^{DM}_L \gamma^\mu Z'_\mu \psi^{DM}_L + \bar{\psi}^{DM}_R \frac{1}{2} g_X X^{DM}_R \gamma^\mu Z'_\mu \psi^{DM}_R \quad (2.2)$$

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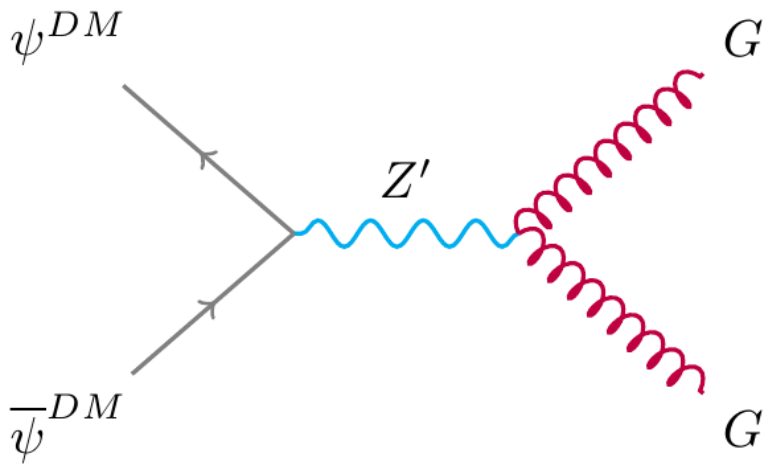

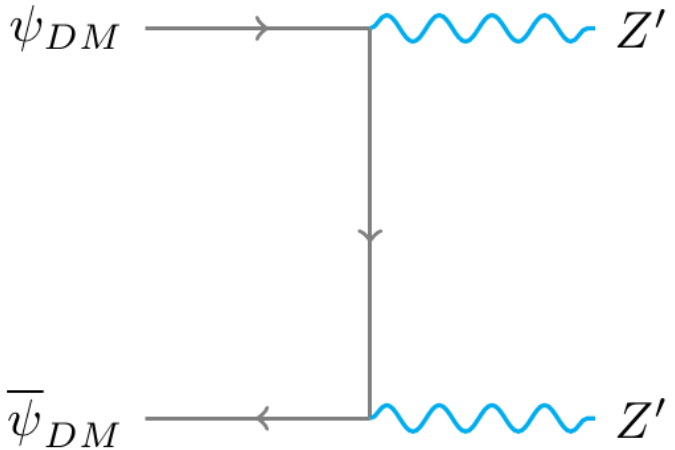

DM annihilation into Gluons

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↪Chiral dark matter :

$$\langle \sigma v \rangle_{s-channel} \simeq \frac{d_g^2}{M^4} \frac{g_X^4 m_\psi^6 (X_L - X_R)^2}{\pi M_{Z'}^4} \left\{ \frac{2\left(M_{Z'}^2 - 4m_\psi^2\right)^2}{\left(M_{Z'}^2 \Gamma^2(Z') + \left(M_{Z'}^2 - 4m_\psi^2\right)^2\right)} \right\}$$

$$\langle \sigma v \rangle_{t-channel} \simeq \frac{g_X^4 \sqrt{m_\psi^2 - M_{Z'}^2}}{128\pi^2 m_\psi M_{Z'}^2 \left(2m_\psi^2 - M_{Z'}^2\right)^2} P_4\left(m_\psi^2, M_{Z'}^2, X_R^2, X_L^2\right)$$

Experimental constraints

A few parameters in this model : $M_{Z'}$, m_ψ, g_X, $\frac{d_g}{M^2}$, X_L, X_R.

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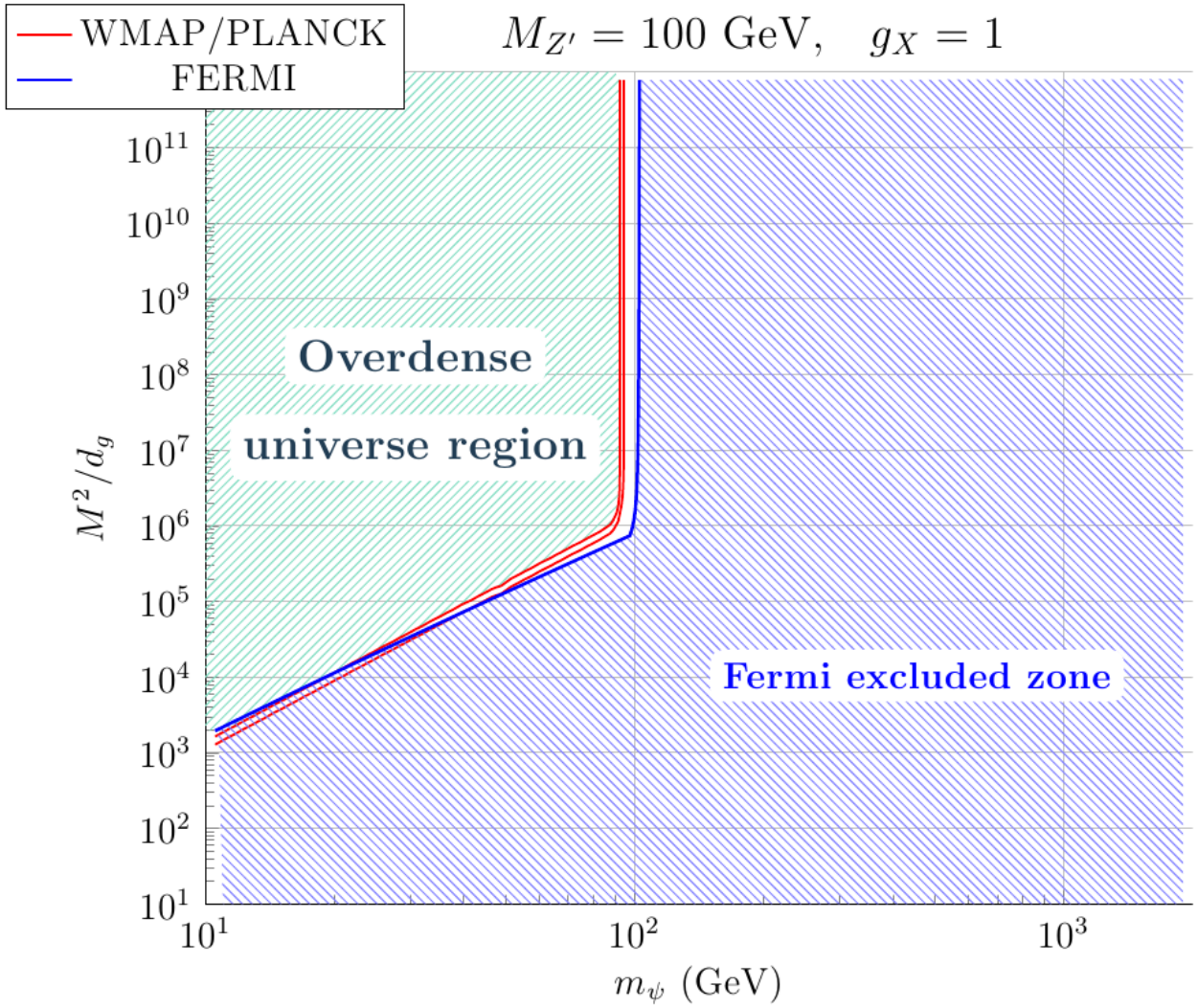
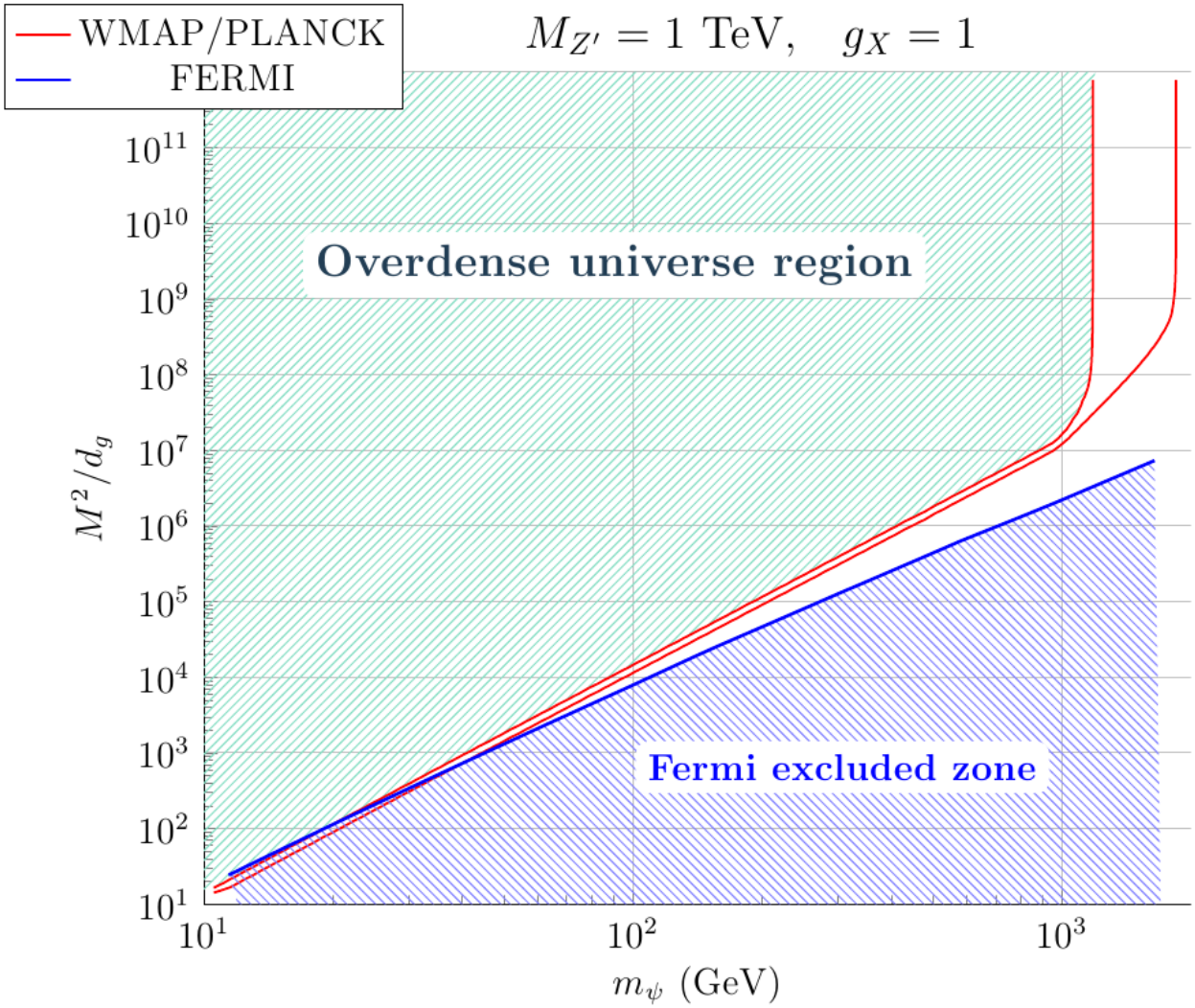
- LHC mono-jets events

Relic abundance and indirect detection



Other curves

Relic abundance and indirect detection



Other curves

LHC constraints

Possible mono-jets final states

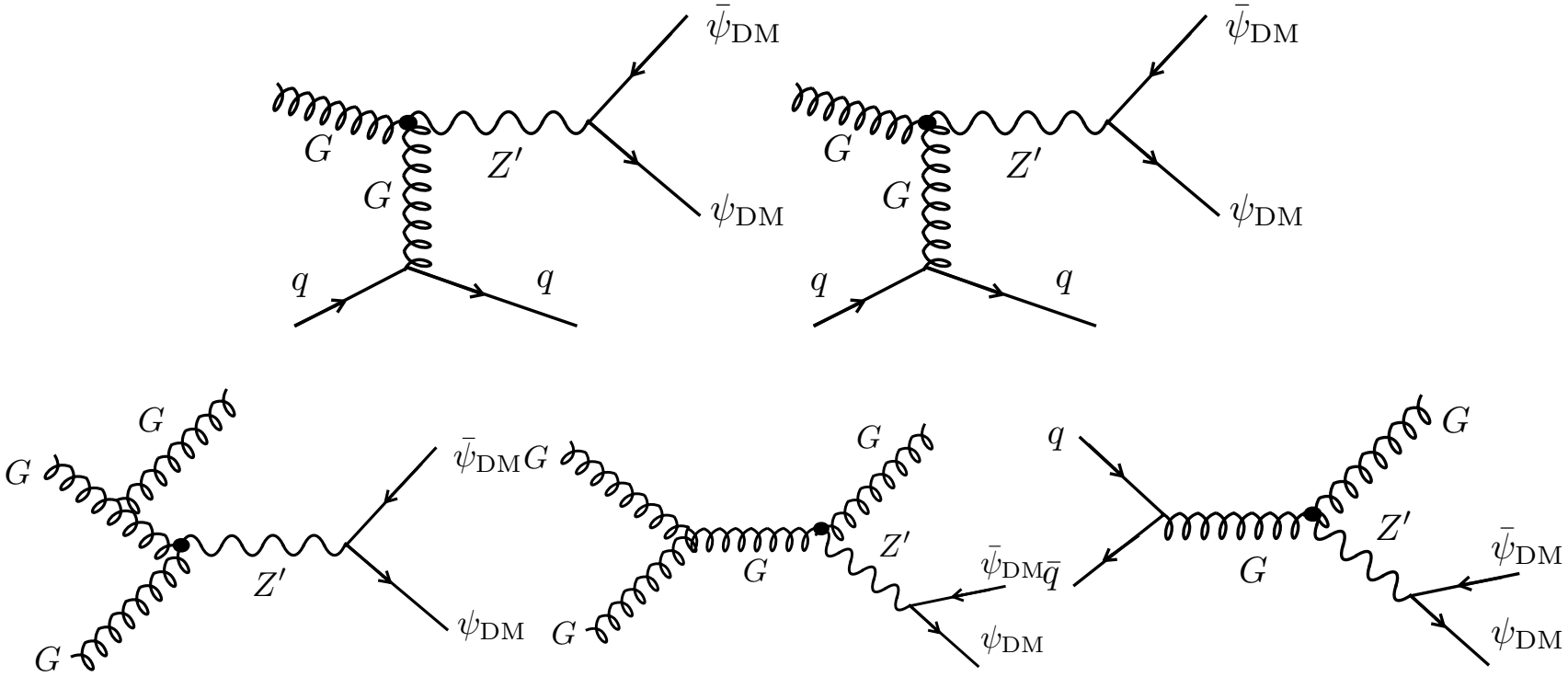


Figure: Dark matter production processes at the LHC (at partonic level), in association with 1 jet : $p\ p \to j\bar{\psi}_{\rm DM}\psi_{\rm DM}$.

LHC constraints

Using CMS data [[CMS Collaboration], CMS-PAS-EXO-12-048], E_{CM} = 8 TeV :

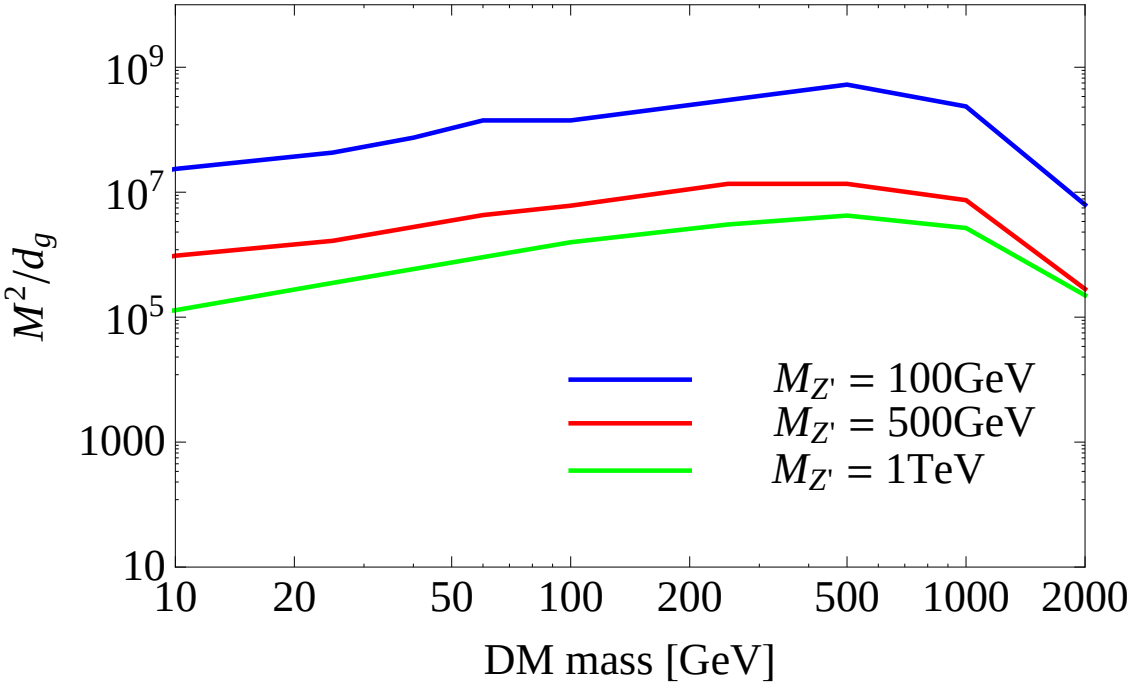
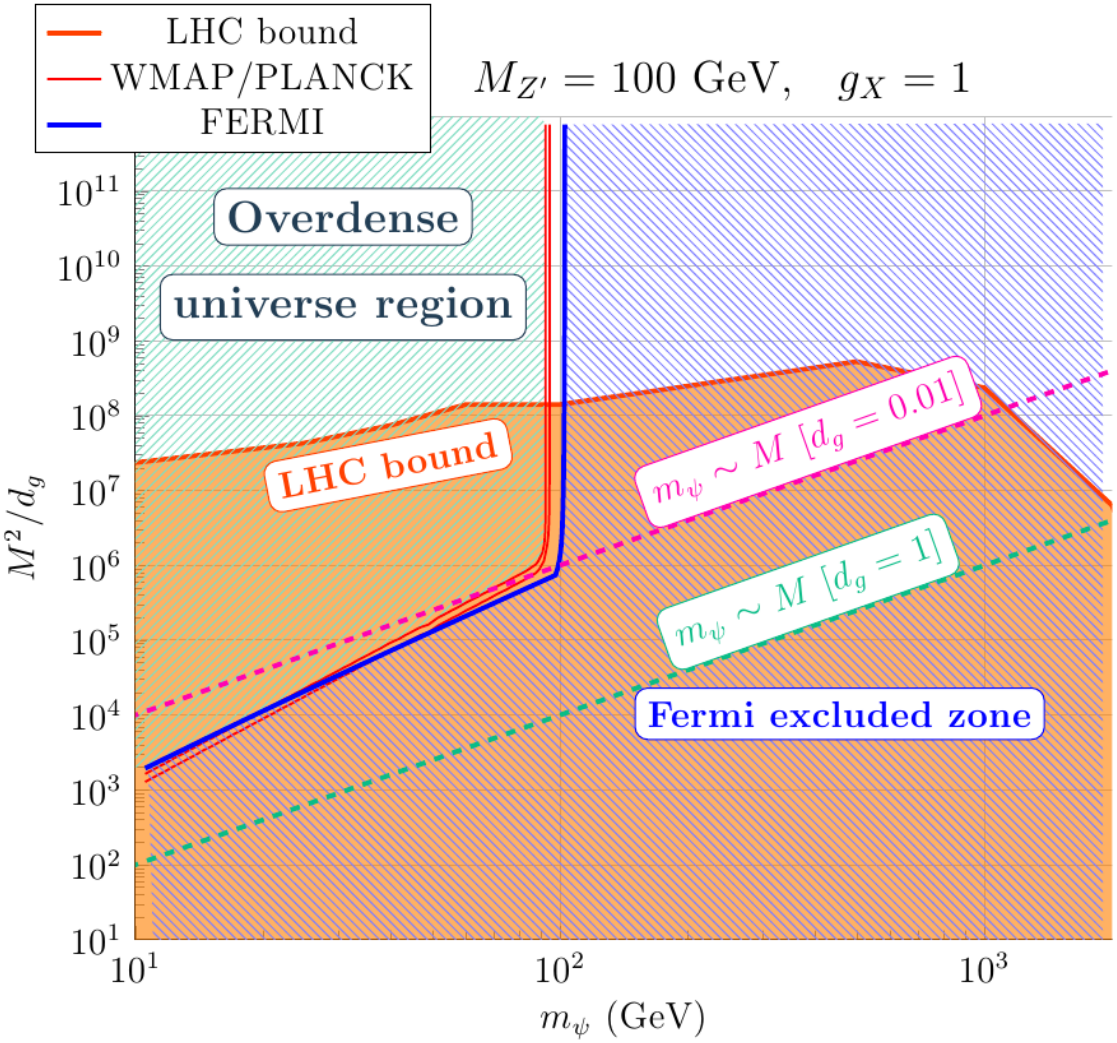


Figure: 90% CL lower bounds on the quantity M^2/d_g as a function of the dark matter mass, for $M_{Z'}$ = 100 GeV (blue), 500 GeV (red) and 1 TeV (green). Based on the CMS analysis with collected data using a center-of-mass energy of 8 TeV and a luminosity of 19.5/fb.

Synthesis



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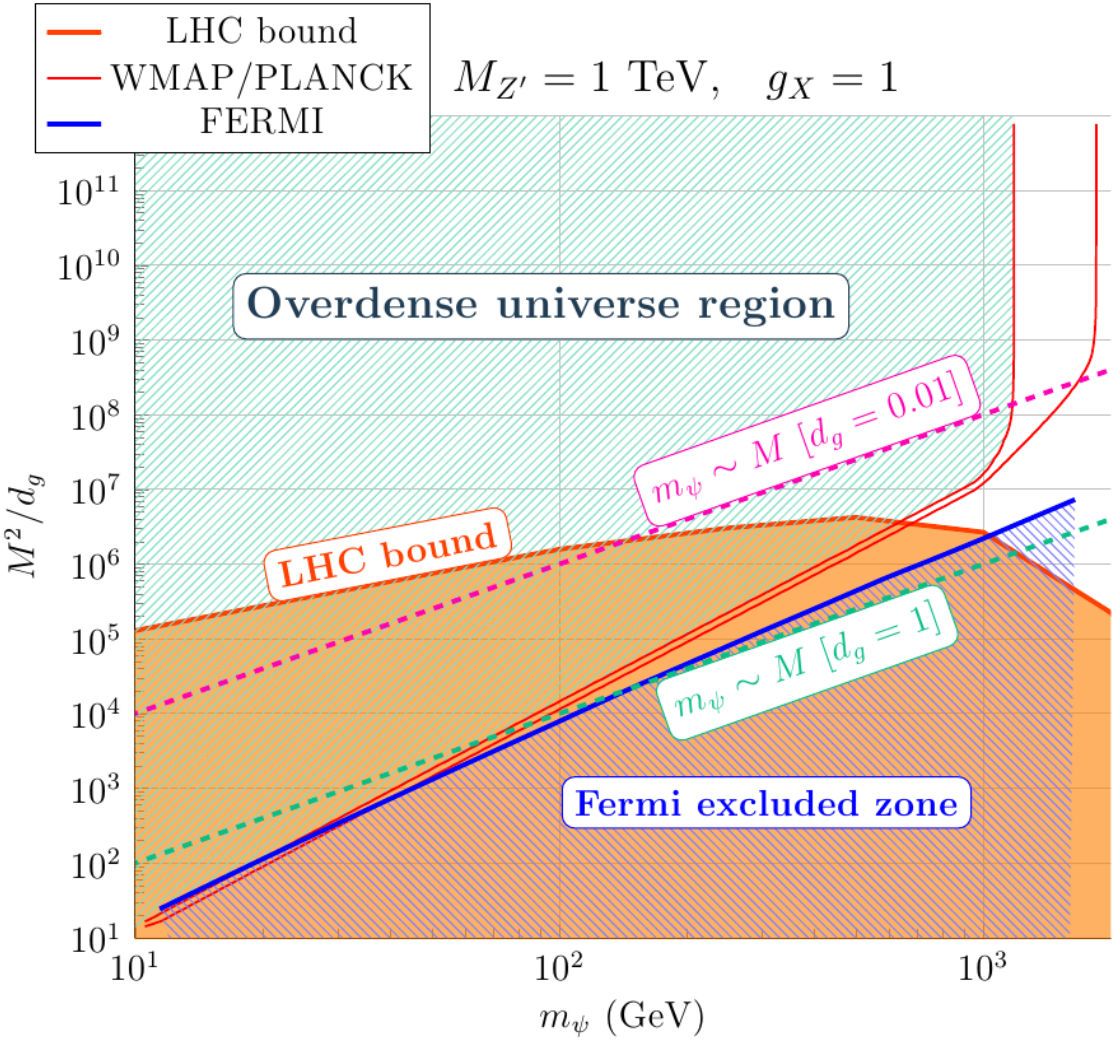
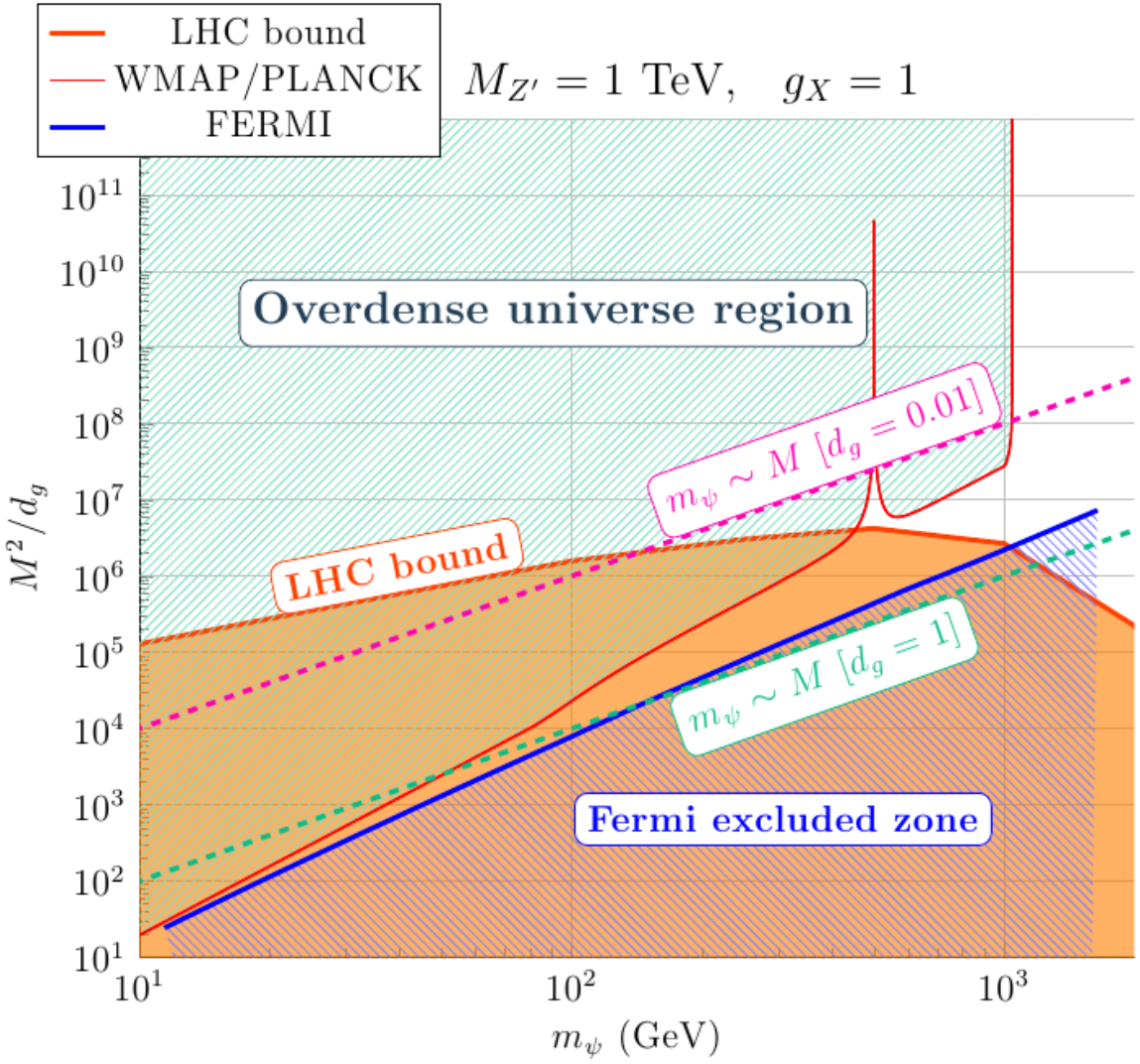


Other curves

Comparison with EW sector



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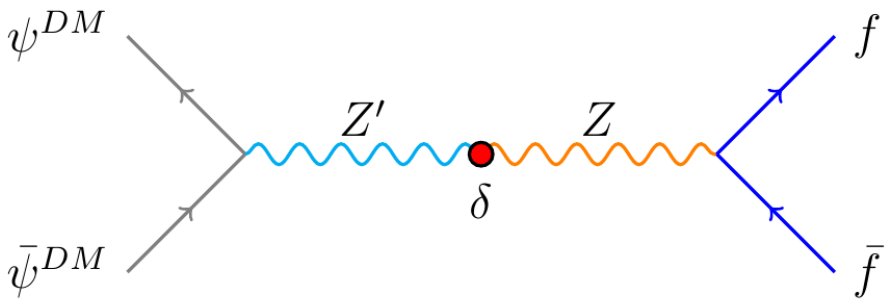
- A way to investigate with more accuracy the presence of dark matter production in LHC data
- Microscopic computations of effective coupling to be extended to other interactions

The End

Thank you !

Constraints on kinetic mixing

If not neglected $\longrightarrow$ new diagrams



$$\langle \sigma v \rangle_{GG} \simeq \frac{d_g^2}{M^4} \frac{2 g_X^4}{\pi} \frac{m_\psi^6}{M_{Z'}^4} \ . \tag{4.1}$$

$\rightarrow$[*X. Chu, Y. Mambrini, J. Quevillon and B. Zaldivar, arXiv :1306.4677 [hep-ph]*]

$$\langle \sigma v \rangle_\delta \simeq \frac{16}{\pi} g_X^2 g^2 \delta^2 \frac{m_\psi^2}{M_{Z'}^4} \quad , \quad m_\psi < M_Z$$

$$\langle \sigma v \rangle_\delta \simeq \frac{g_X^2 g^2 \delta^2 M_Z^4}{\pi m_\psi^2 M_{Z'}^4} \quad , \quad m_\psi > M_Z . \tag{4.2}$$

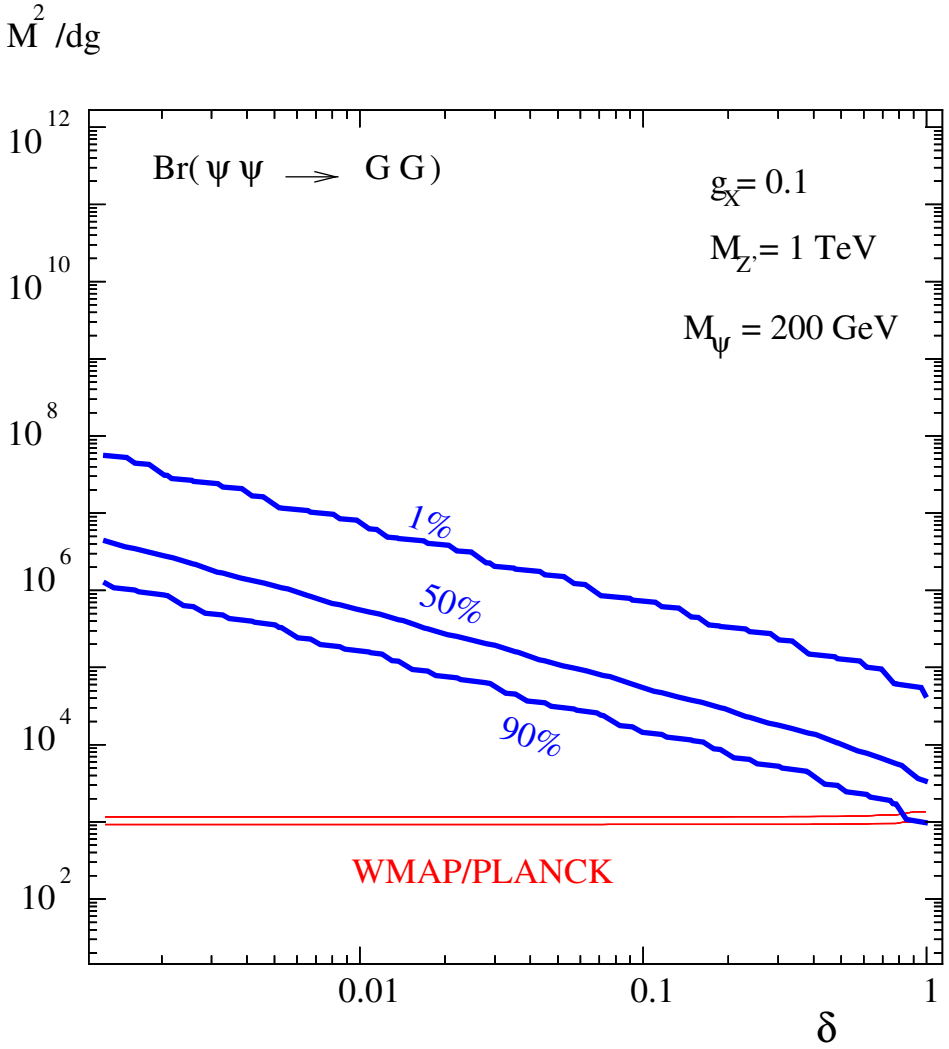
Constraints on kinetic mixing

Kinetic mixing competes with other effective operators if

$$\delta \gtrsim \frac{d_g}{M^2} \frac{g_X}{2\sqrt{2}g} m_\psi^2 \quad , \quad m_\psi < M_Z$$
$$\delta \gtrsim \frac{d_g}{M^2} \frac{\sqrt{2}g_X}{g} \frac{m_\psi^4}{M_Z^2} \quad , \quad m_\psi > M_Z \tag{4.3}$$

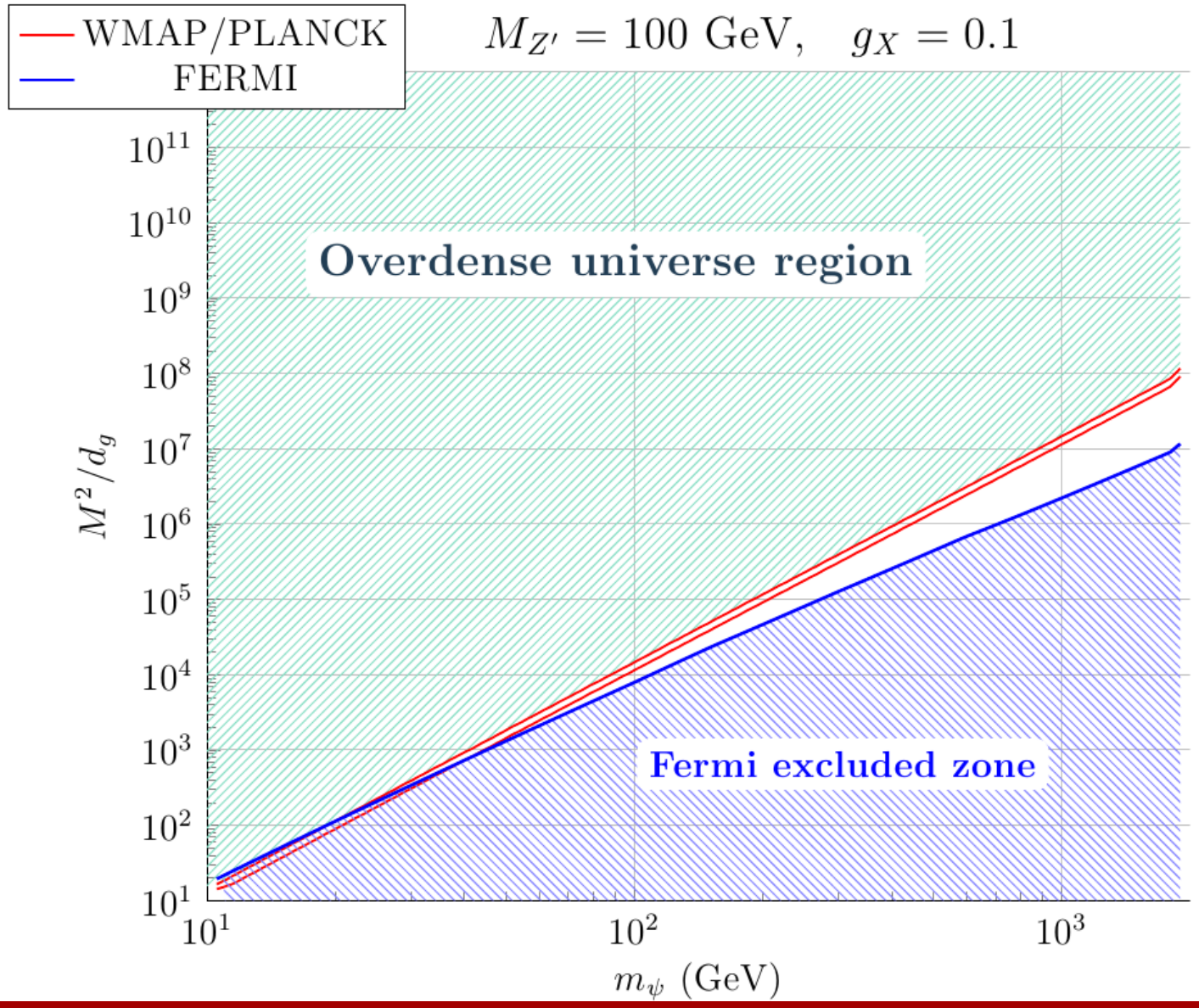
$\hookrightarrow$ For $m_\psi = 200$ GeV : $\frac{d_g}{M^2} \lesssim 10^{-4} \times \delta \ GeV^{-2}$

Constraints on kinetic mixing



↪ $\delta \gtrsim 0.8$ excluded by LEP experiments...

Relic abundance and indirect detection



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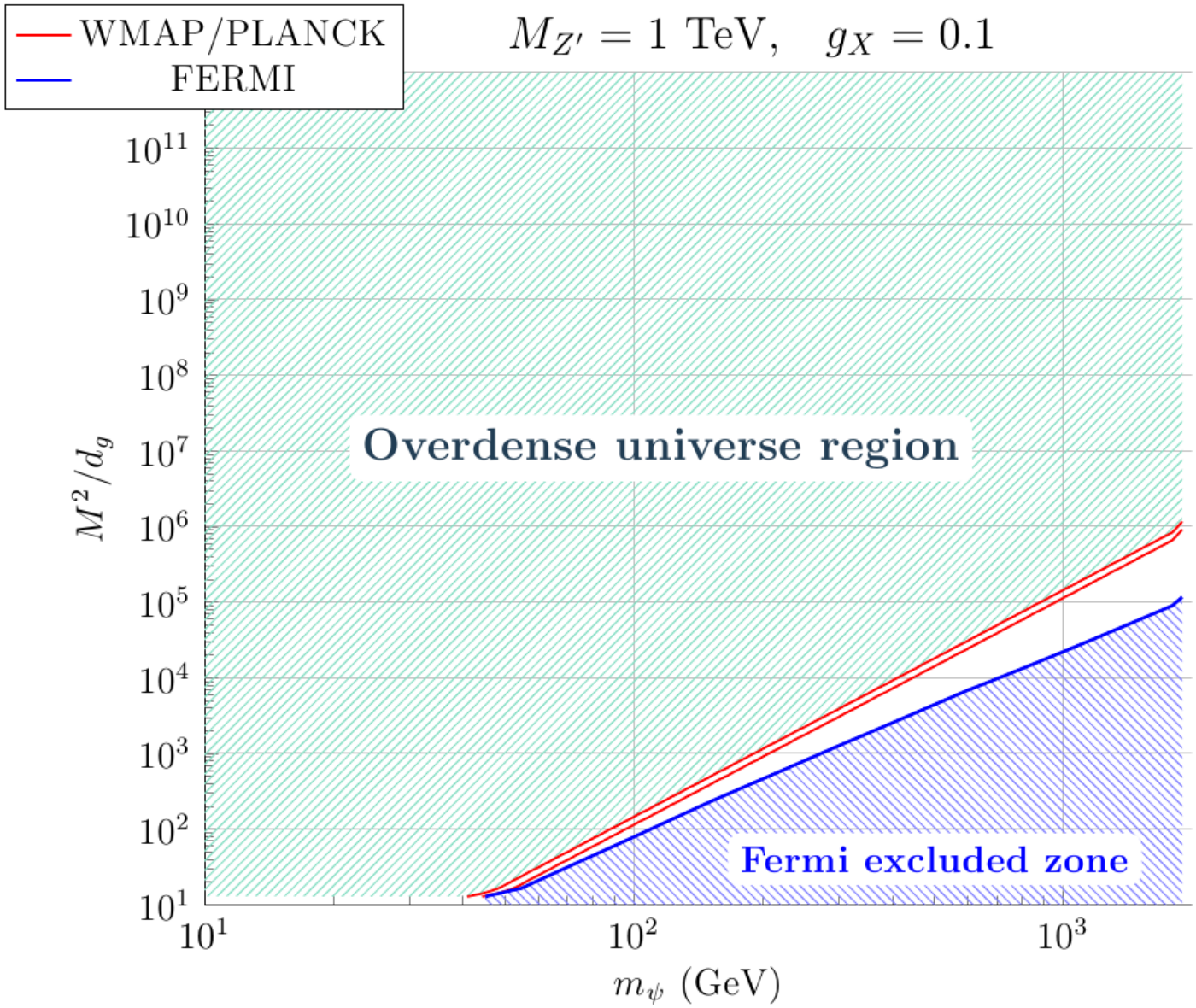
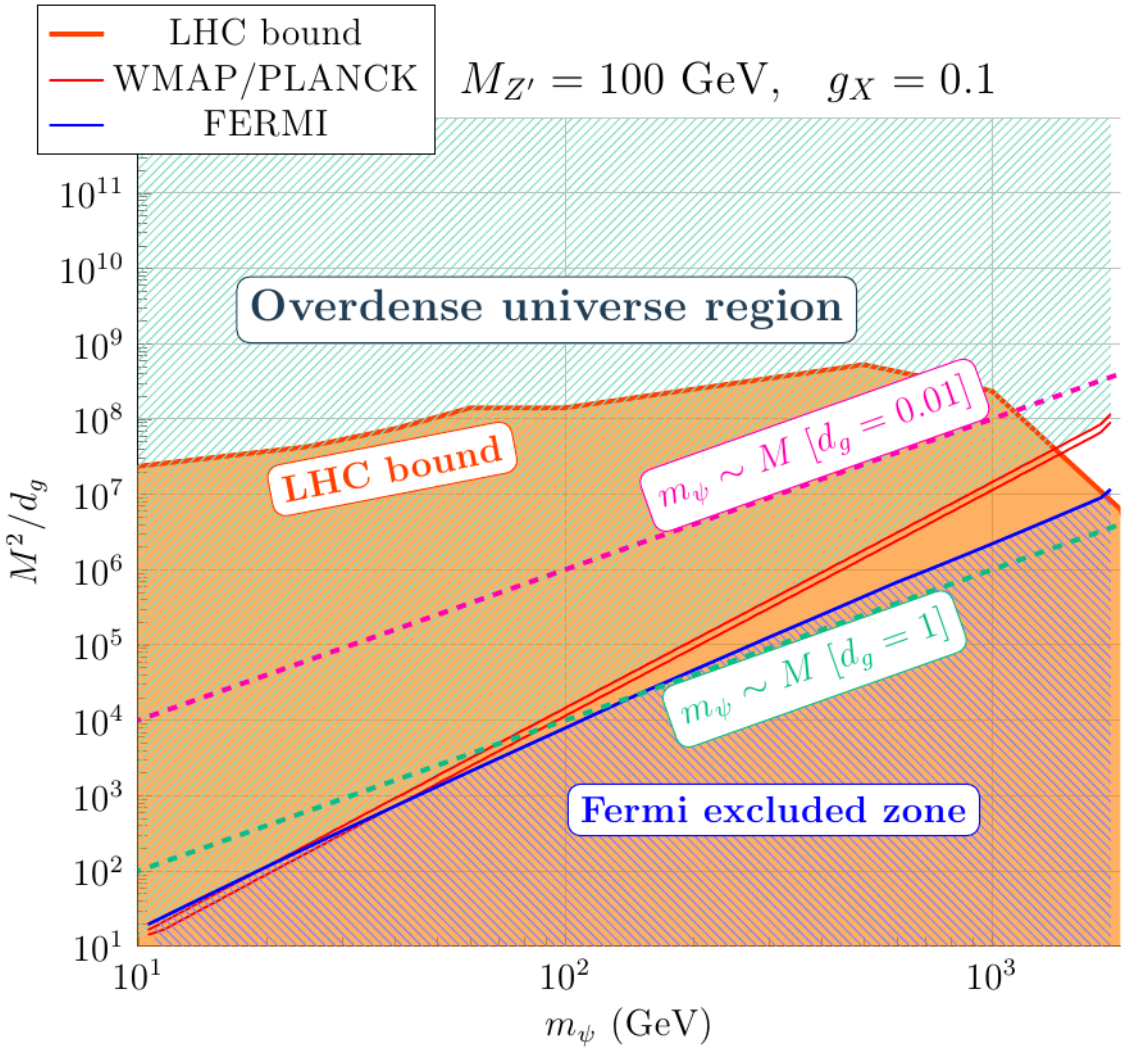
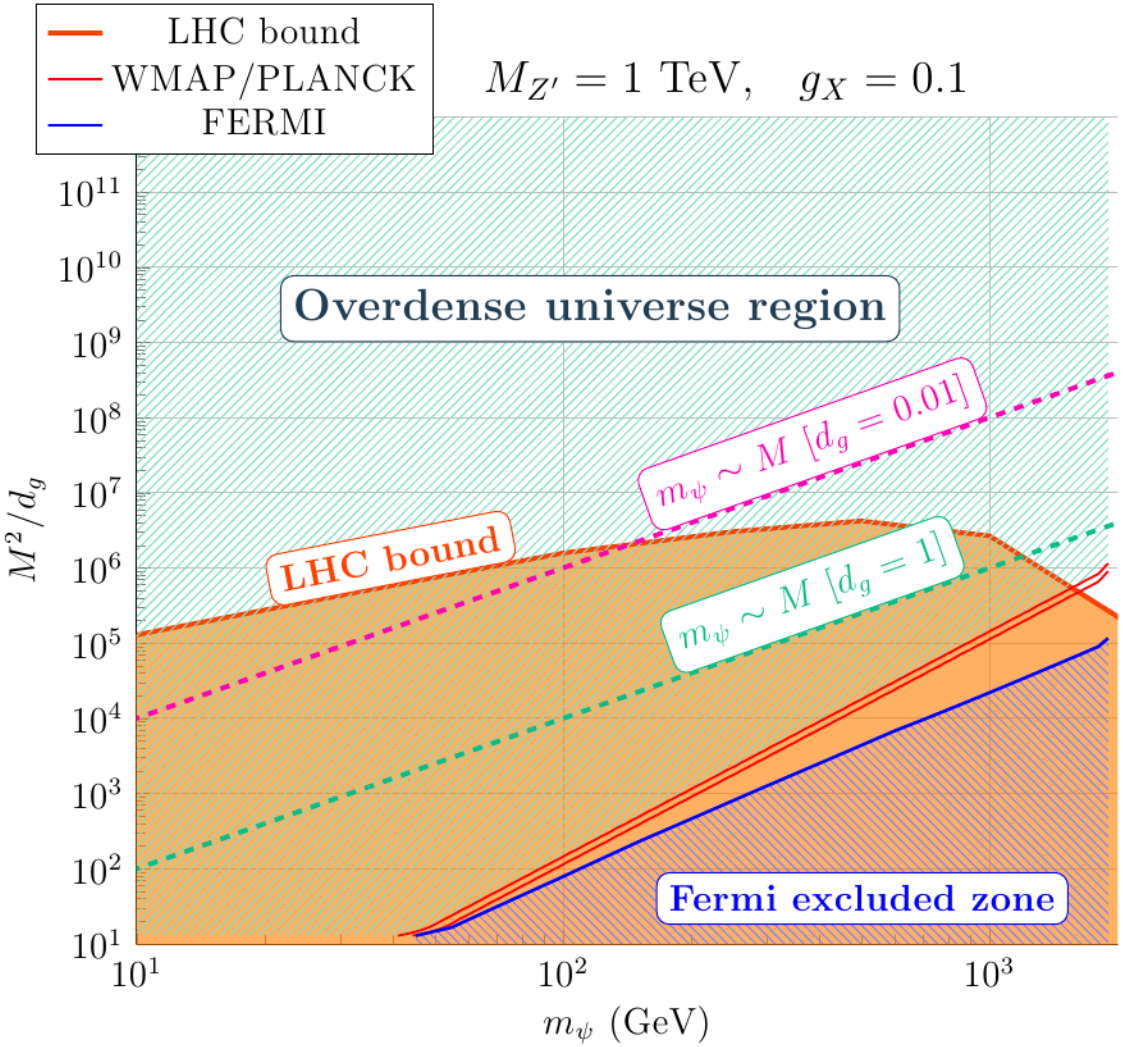


Synthesis


LHC bound
WMAP/PLANCK
FERMI
$M_{Z'} = 100$ GeV, $g_X = 0.1$
Overdense universe region
LHC bound
$m_\psi \sim M$ [$d_g = 0.01$]
$m_\psi \sim M$ [$d_g = 1$]
Fermi excluded zone
M^2/d_g
m_ψ (GeV)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

Synthesis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M^2/d_g
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