



# Z' boson : a portal between dark matter and gluons?

Lucien Heurtier

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*hep-ph 1307.0005 : E. Dudas <sup>a</sup>, L. Heurtier <sup>a</sup>, Y. Mambrini <sup>b</sup>, B. Zaldivar <sup>c</sup>*

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## Introduction : Why dark matter ?

Come Milou, must be  
something more in the  
universe...



# Introduction : Why dark matter ?

*Early times :*

*"The redshift of extragalactic nebulae" by F. Zwicky, 1933*

- Simple argument about Viriel Theorem
- Mass, radius  $\Rightarrow$  Potential Energy  $\Rightarrow$  Estimation of velocity
- Big disagreement with observed doppler effect !!

# Galaxy rotation velocity profile (1969)...

1970ApJ...159..159R

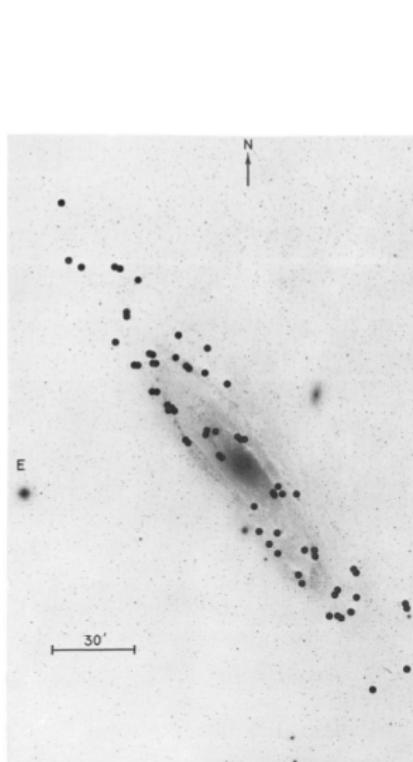


Fig. 1.—Identification chart for emission regions in M31 for which velocities have been obtained. Palomar 48-inch Schmidt ultraviolet photograph, 103aO plate + UG 1 filter, courtesy of Dr. S. van den Beek.

PLATE 1570ApJ...159..159R  
390

VERA C. RUBIN AND W. KENT FORD, JR.

24 kpc are  $1.66 \times 10^{11} M_{\odot}$  (low minimum) and  $1.67 \times 10^{11} M_{\odot}$  (higher minimum); those for the mass in the nucleus to  $R = 1$  kpc are  $5.2 \times 10^9 M_{\odot}$  and  $6.2 \times 10^9 M_{\odot}$ , respectively. When these values are increased 10 percent to compensate for the assumption of a flat disk (Brandt 1960), the total mass is  $1.8 \times 10^{11} M_{\odot}$  out to 24 kpc. Also shown in Figure 10 are the variation in the mass surface density as a function of distance from the center, and the variation in the angular velocity,  $V/R$ , as a function of  $R$ . Note that the solution with the high inner minimum has a positive mass density everywhere. The solution with the low minimum has a negative surface density near  $R = 1$  kpc. We take this to mean only that the density at this distance is vanishingly small for the low-minimum model.

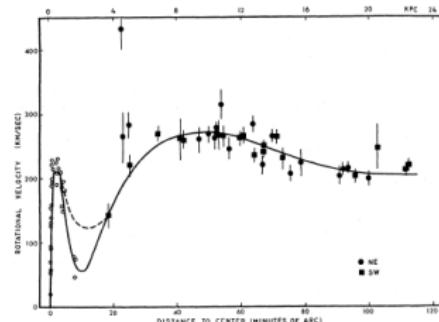


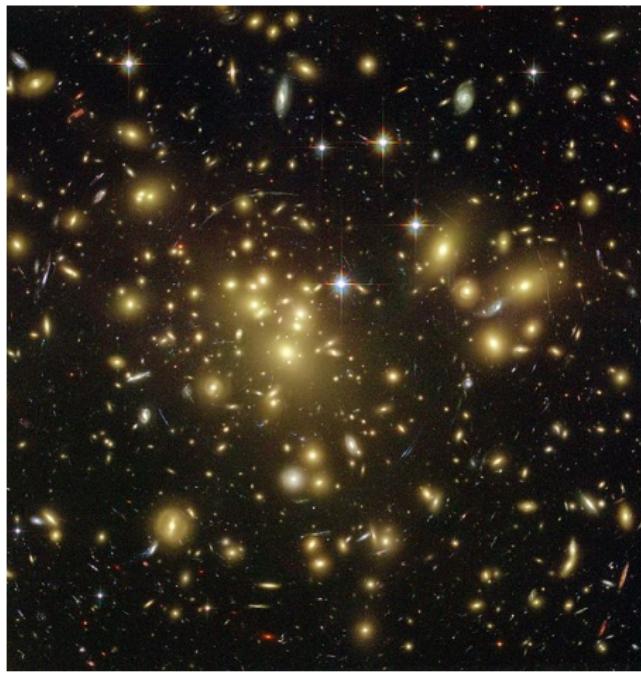
FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. Solid curve: adopted rotation curve based on the velocities shown in Fig. 4; for  $R \leq 12'$ , curve is fifth-order polynomial; for  $R > 12'$ , curve is nearly a second-order polynomial except to remain approximately flat near  $R = 120'$ . Dashed curve near  $R = 10'$  is a second rotation curve with higher inner minimum.

Various other rotation curves for the data in Figures 3 and 4 have been formed, all from least-squares solutions, with polynomials of third, fourth, or sixth order. In Figure 11 we show, superimposed, the fourteen rotation curves from the polynomial representations. The various mass determinations from these rotation curves are listed in Table 4. Successive columns list the order of the polynomial, the resulting total mass, 1.1 times the mass, and the value of the maximum distance to which the mass has been determined. The final columns list the depth of the inner minimum, and notes concerning the solutions.

It is apparent from the calculations that there is only a small spread in total mass out to  $R = 24$  kpc from all fourteen solutions. The shaded regions in Figure 12 indicate the range of masses which results from the fourteen rotation curves, as well as the range of surface densities. For the mass out to  $R = 24$  kpc, a value of  $M = (1.68 \pm 0.1) \times 10^{11} M_{\odot}$  lies midway between all values. When this is increased 10 percent to compensate for the disk approximation, we obtain a mass  $M = (1.85 \pm 0.1) \times 10^{11} M_{\odot}$  out to

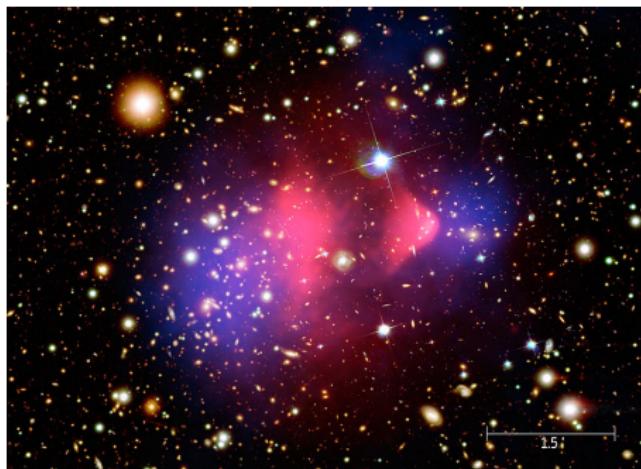


This gravitational lens bends...





# This gravitational lens bends...



Bullet Cluster : collision between two galaxy clusters

- Pink : x-ray emission (Chandra Telescope) of the colliding clusters
- Blue : Mass distribution of the clusters (reconstitution from lensing effects)

A big question : What is this ??



# Matter, what else ?

- GR failing ? → MOND theories : also need a few dark matter...
- (Very) weakly interacting (maybe not) dark matter particles...
  - ↪ Super-symmetry candidates (neutralino, gravitino,...) *Please Wait*
  - ↪ Simple Standard Model extensions...

# Introduction : Motivations

Let's extend the SM !

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

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$U(1)$



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↪  $\mathcal{L} = -m\bar{\psi}\psi - \bar{\psi}\gamma^\mu\partial_\mu\psi$  not invariant under  $\delta\psi = i\alpha$

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- Massive  $Z'$  : add a heavy higgs !

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- **Charged SM fermions**
  - FCNC constraints
  - $B - L$ ,  $\alpha(B - L) + \beta Y$  models heavy  $Z'$
  - Stringy light  $Z'$ , anomaly cancellation a la Green-Schwarz

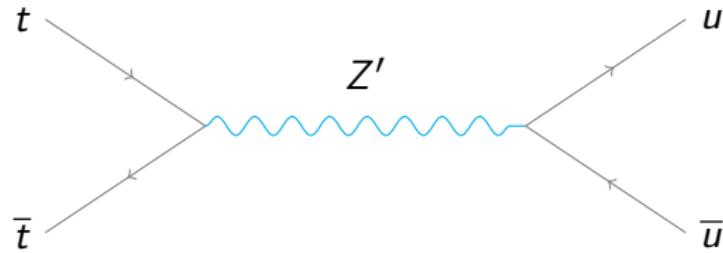
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- **Uncharged SM fermions**
  - Motivations from string theory (D-brane models)
  - Heavy mediators  $\rightsquigarrow$  effective higher-dimensional operators

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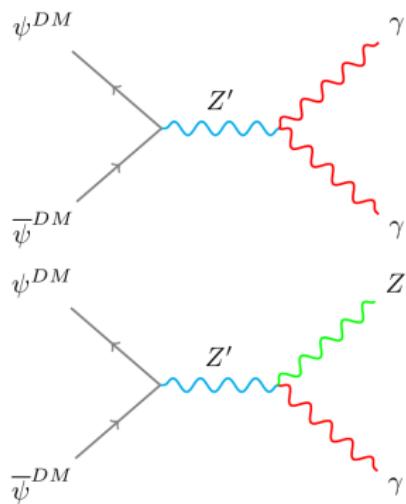
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Motivations ?

# The little story of a little light ray

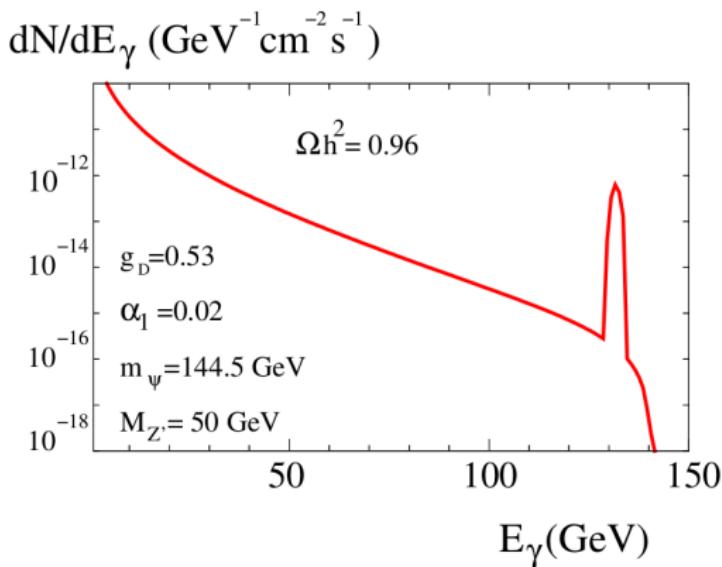
Annihilation into photons :



$$E_\gamma = m_{DM} \left( 1 - \frac{m_Z^2}{4m_{DM}^2} \right) \quad (1.1)$$

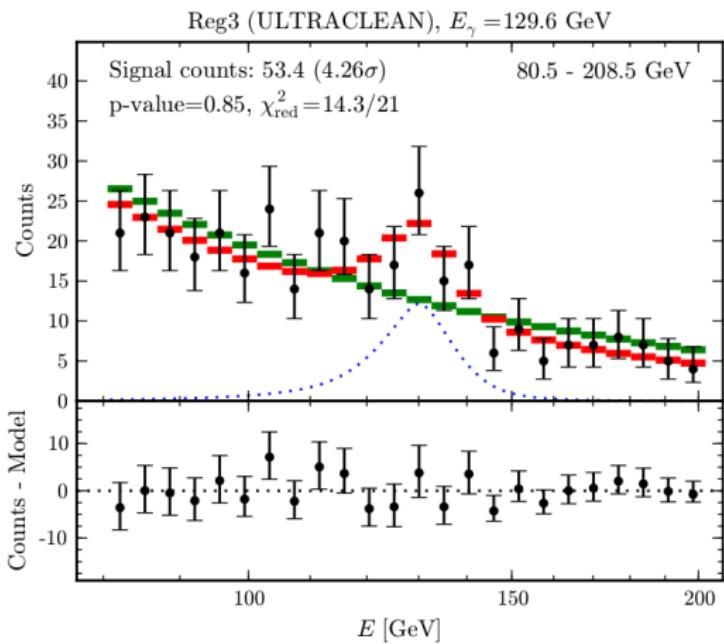
# The little story of a little light ray

[Dudas et al., 2012]



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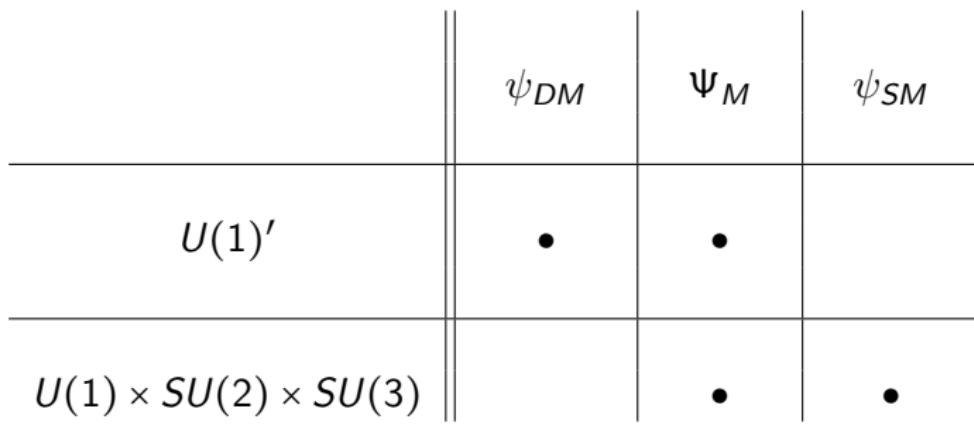
[Weniger, 2012]



## End of the story?...

- ↪ detected in other regions of the sky
  
- ↪ detector effects suspected...

# Introduction : The model



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## Initial lagrangian

$$\begin{aligned}\mathcal{L} = & \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu a_X - M_{Z'} Z'_\mu)^2 - \frac{1}{4}F_{\mu\nu}^X F^{X\mu\nu} \\ & + \bar{\Psi}_L^i \left( i\gamma^\mu D_\mu + \frac{g_X}{2} X_L^i \gamma^\mu Z'_\mu \right) \Psi_L^i + \bar{\Psi}_R^i \left( i\gamma^\mu D_\mu + \frac{g_X}{2} X_R^i \gamma^\mu Z'_\mu \right) \Psi_R^i \\ & - \left( \bar{\Psi}_L^i M_{ij} e^{\frac{i a_X (X_L^i - X_R^j)}{V}} \Psi_R^j + \text{h.c.} \right)\end{aligned}\quad (1.2)$$

where  $M_{Z'} \equiv g_X \frac{V}{2}$ . (1.3)

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- ↪  $\mathcal{L}$  anomaly-free &  $\mathcal{L}_{SM}$  neutral under  $U(1)'$   $\Rightarrow \Psi_M$  set anomaly-free

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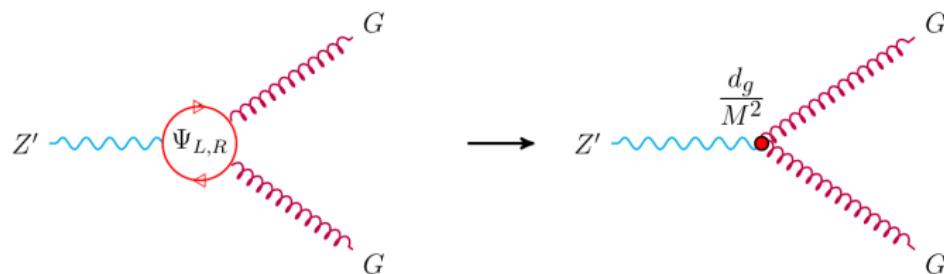
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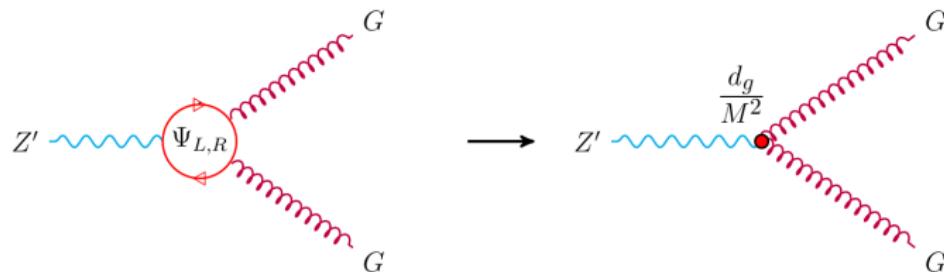
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- $\mathcal{L}$  anomaly-free &  $\mathcal{L}_{SM}$  neutral under  $U(1)'$   $\Rightarrow \Psi_M$  set anomaly-free
- Kinetic mixing term  $\frac{\delta}{2} F_X^{\mu\nu} F_{\mu\nu}^Y$  is neglected Why?...

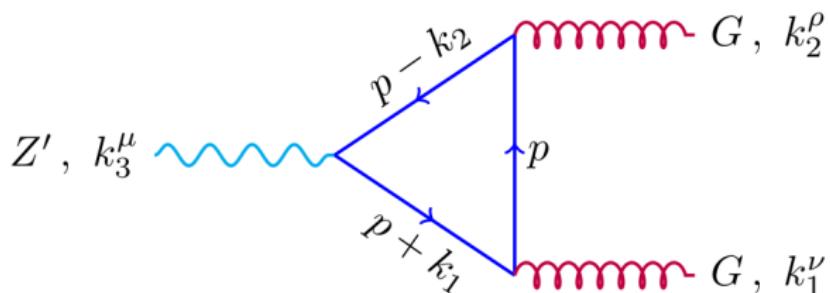
# Effective couplings

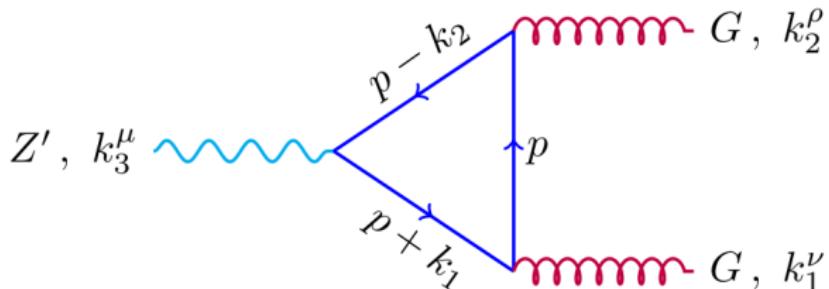


# Effective couplings



$$\begin{aligned}
 \mathcal{L}_{\text{CP even}}^{(6)} &= \frac{1}{M^2} \left\{ d_g \partial^\mu D_\mu \theta_X \text{Tr}(G \tilde{G}) + d'_g \partial^\mu D^\nu \theta_X \text{Tr}(G_{\mu\rho} \tilde{G}_\nu^\rho) \right. \\
 &+ e_g D^\mu \theta_X \text{Tr}(G_{\nu\rho} D_\mu \tilde{G}^{\rho\nu}) + e'_g D_\mu \theta_X \text{Tr}(G_{\alpha\nu} D^\nu \tilde{G}^{\mu\alpha}) \Big\} \\
 &+ \frac{1}{M^2} \left\{ D^\mu \theta_X \left[ i(D^\nu H)^\dagger (c_1 \tilde{F}_{\mu\nu}^Y + 2c_2 \tilde{F}_{\mu\nu}^W) H + h.c. \right] \right. \\
 &+ \partial^m D_m \theta_X (d_1 \text{Tr}(F^Y \tilde{F}^Y) + 2d_2 \text{Tr}(F^W \tilde{F}^W)) \\
 &+ d'_{ew} \partial^\mu D^\nu \theta_X \text{Tr}(F_{\mu\rho} \tilde{F}_\nu^\rho) \\
 &\left. + e_{ew} D^\mu \theta_X \text{Tr}(F_{\nu\rho} D_\mu \tilde{F}^{\rho\nu}) + e'_{ew} D_\mu \theta_X \text{Tr}(F_{\alpha\nu} D^\nu \tilde{F}^{\mu\alpha}) \right\} , \quad (1.4)
 \end{aligned}$$





$$\begin{aligned}
 \mathcal{O} = & \frac{g_3^2}{24\pi^2} \sum_i \text{Tr} \left( \frac{(X_L - X_R) T_a T_a}{M^2} \right)_i \\
 & \times \left[ \partial^\mu D_\mu \theta_X \text{Tr}(G \tilde{G}) - 2 D_\mu \theta_X \text{Tr}(G_{\alpha\nu} \mathcal{D}^\nu \tilde{G}^{\mu\alpha}) \right]. \quad (1.5)
 \end{aligned}$$

# DM annihilation into Gluons

couplings

$$\begin{aligned} \mathcal{L}_{CP \text{ even}} = & \frac{1}{M^2} \left\{ d_g \partial^\mu D_\mu \theta_X \text{Tr}(G \tilde{G}) + \cancel{d'_g \partial^\mu D^\nu \theta_X \text{Tr}(G_{\mu\rho} \tilde{G}_\nu^\rho)} \right. \\ & \left. + \cancel{e_g D^\mu \theta_X \text{Tr}(G_{\nu\rho} D_\mu \tilde{G}^{\rho\nu})} + e'_g D_\mu \theta_X \text{Tr}(G_{\alpha\nu} D^\nu \tilde{G}^{\mu\alpha}) \right\} \quad (2.1) \end{aligned}$$

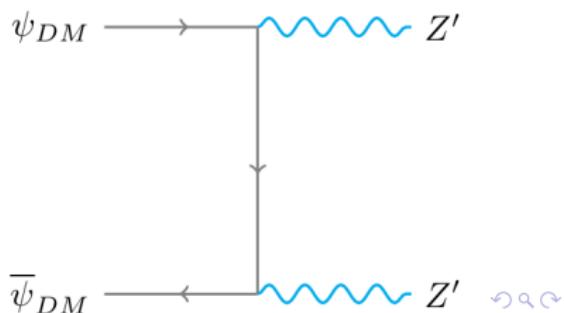
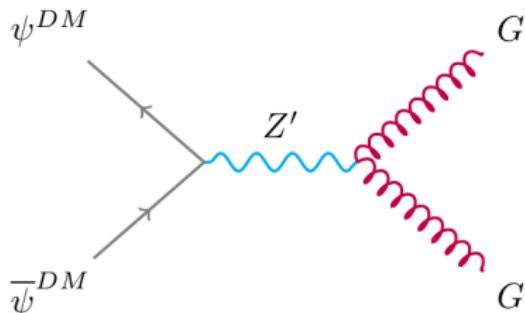
$$\mathcal{L}_{DM} = \bar{\psi}_L^{DM} \frac{1}{2} g_X X_L^{DM} \gamma^\mu Z'_\mu \psi_L^{DM} + \bar{\psi}_R^{DM} \frac{1}{2} g_X X_R^{DM} \gamma^\mu Z'_\mu \psi_R^{DM} \quad (2.2)$$

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# Experimental constraints

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

↪ need to be constrained !

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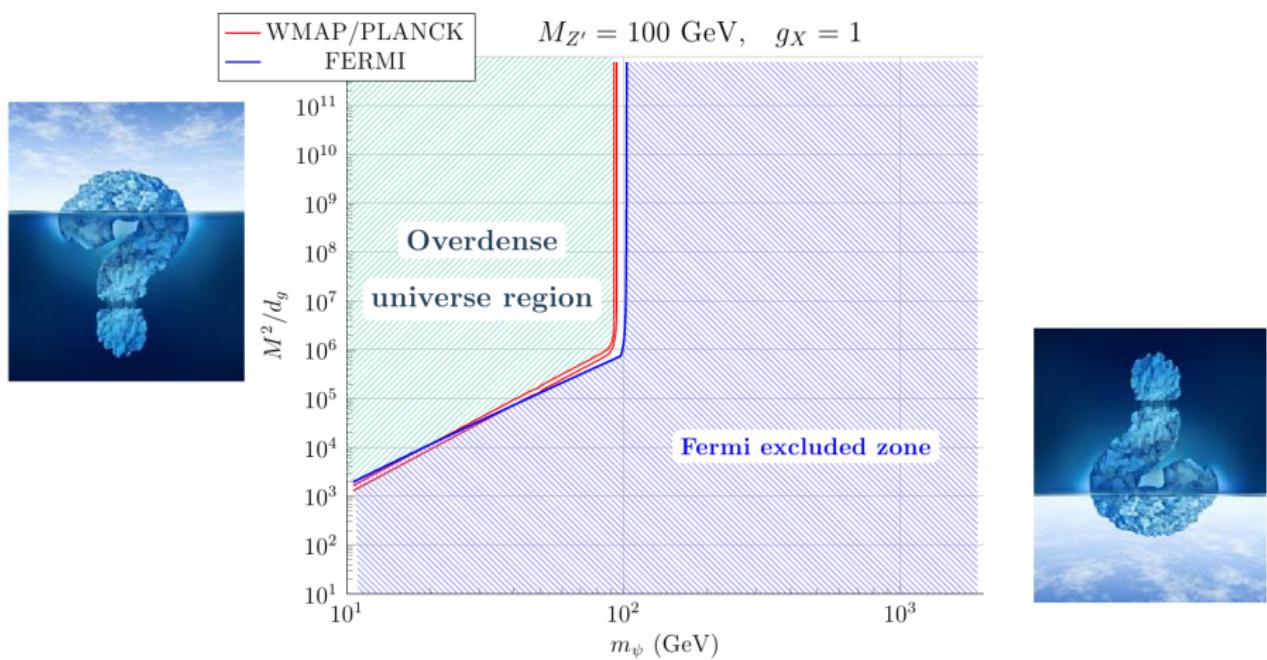
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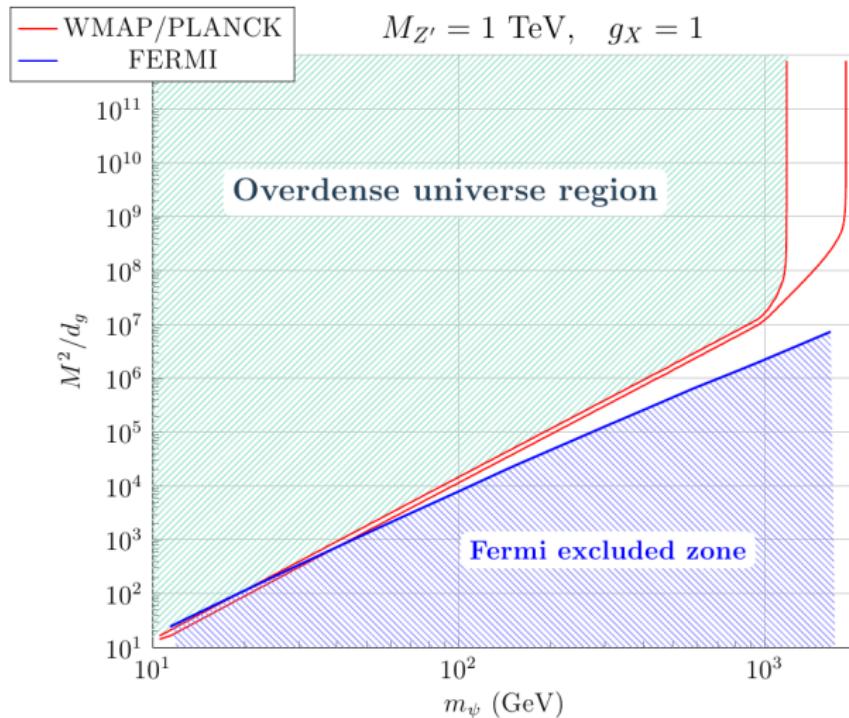
- Relic abundance
- Indirect detection
- LHC mono-jets events

# Relic abundance and indirect detection



Other curves

# Relic abundance and indirect detection

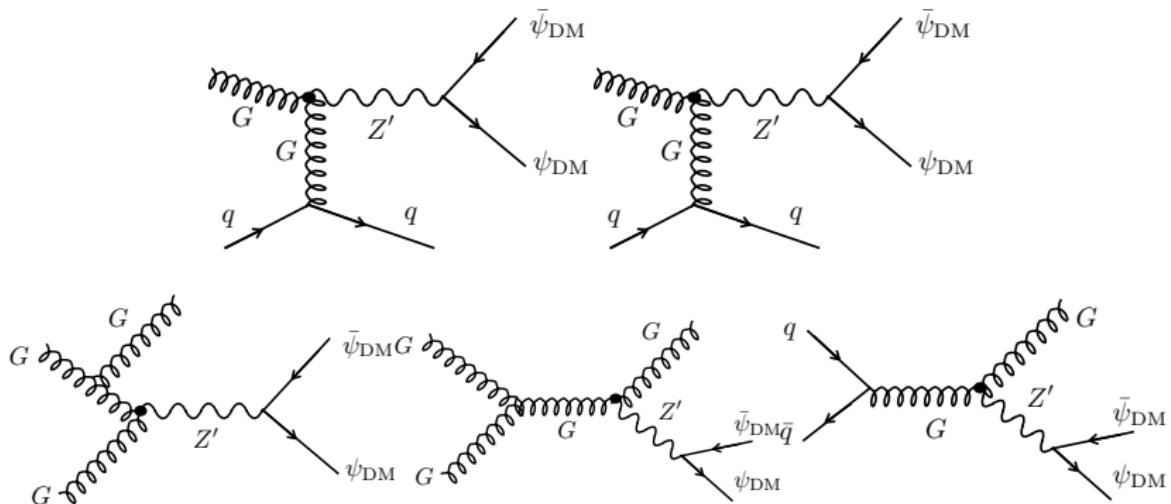


Other curves

# LHC constraints

1 jet + missing  $E_T$

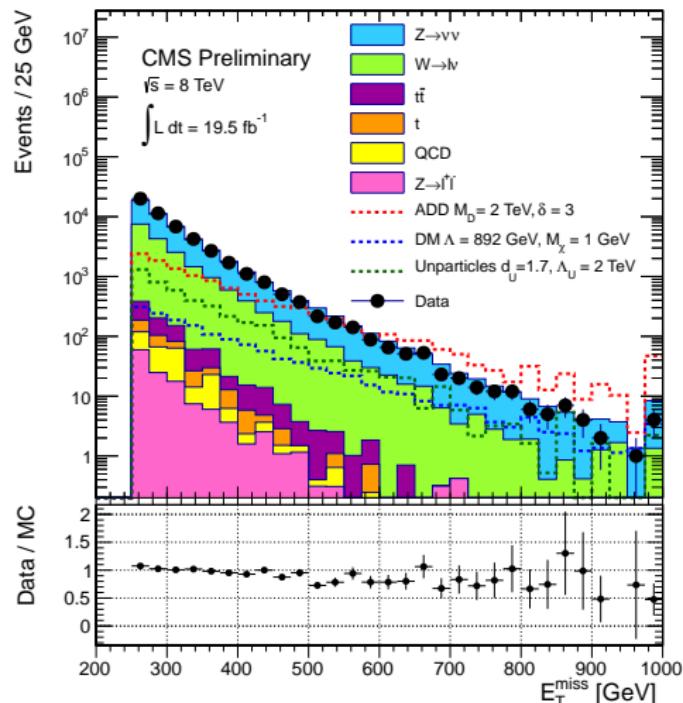
Possible mono-jets final states :



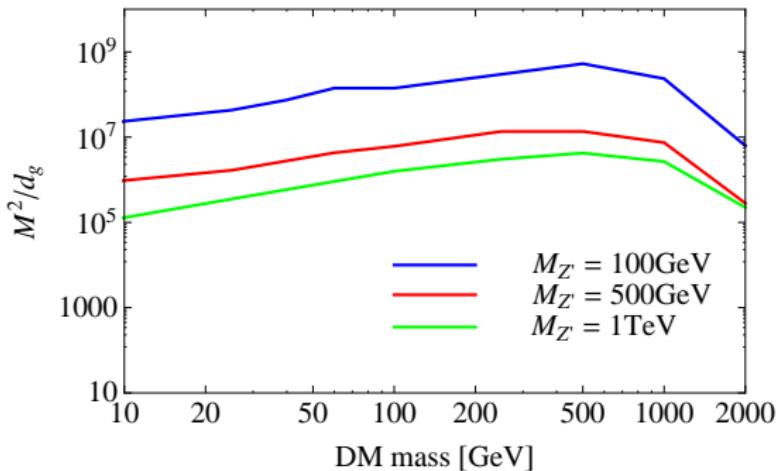
**Figure:** Dark matter production processes at the LHC (at partonic level), in association with 1 jet :  $p\ p \rightarrow j \bar{\psi}_{\text{DM}} \psi_{\text{DM}}$ .

# LHC constraints

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

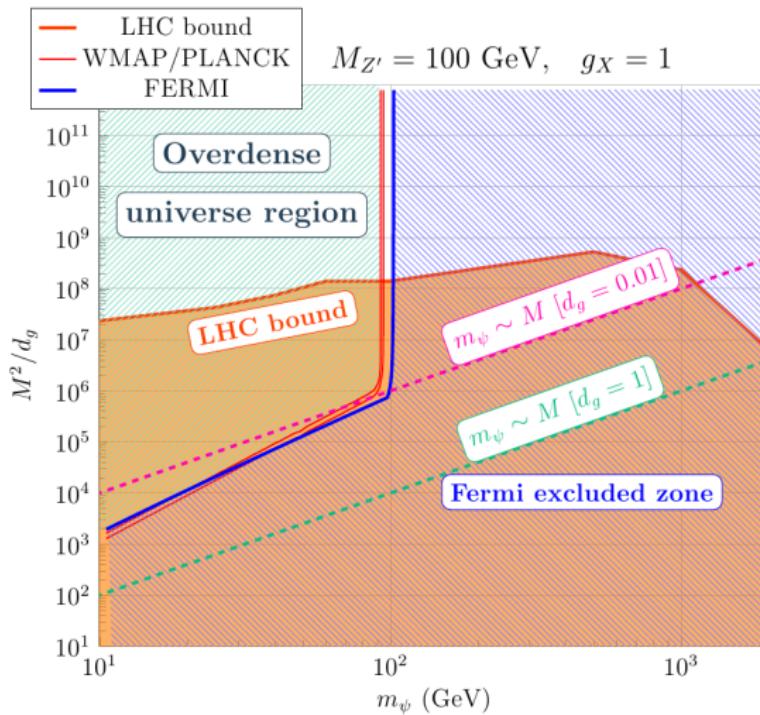


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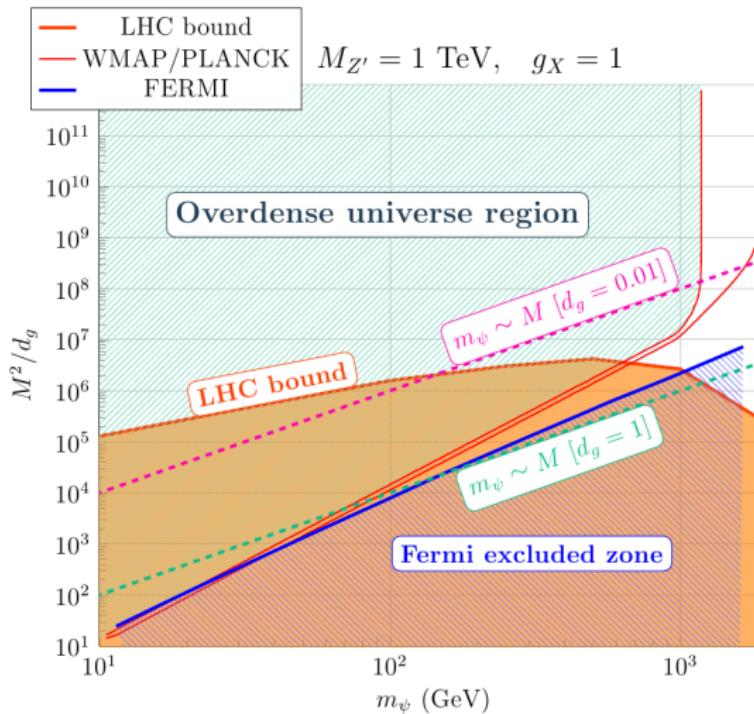
**Figure:** 90% CL lower bounds on the quantity  $M^2/d_g$  as a function of the dark matter mass, for  $M_{Z'} = 100$  GeV (blue), 500 GeV (red) and 1 TeV (green). Based on the CMS analysis with collected data using a center-of-mass energy of 8 TeV and a luminosity of 19.5/fb.

# Synthesis



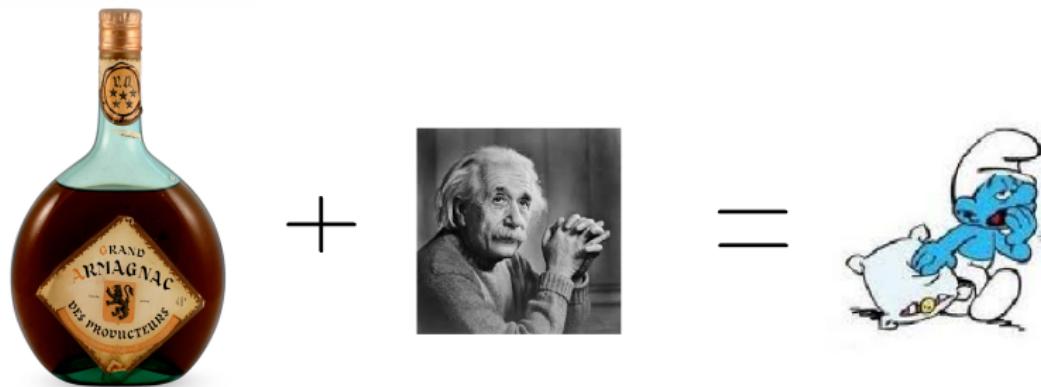
Other curves

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Other curves

# Conclusions and outlooks



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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

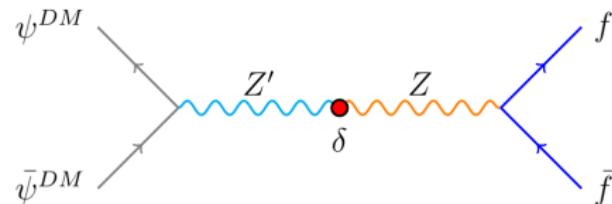
# The End

Thanks !

*Applaud...*

# Constraints on kinetic mixing

If not neglected → new diagrams



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

→ [X. Chu, Y. Mambrini, J. Quevillon and B. Zaldivar, arXiv :1306.4677 [hep-ph]]

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

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

# Constraints on kinetic mixing

Kinetic mixing competes with other effective operators if

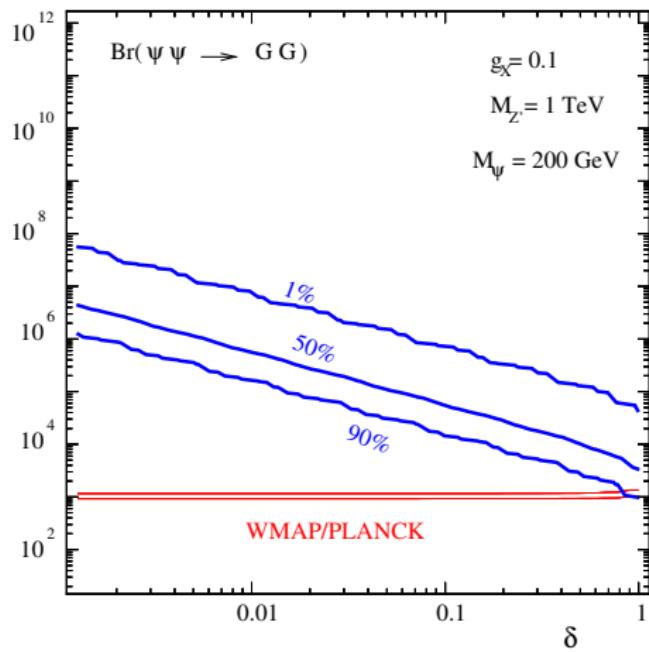
$$\delta \gtrsim \frac{d_g}{M^2} \frac{g_X}{2\sqrt{2}g} m_\psi^2 \quad , \quad m_\psi < M_Z$$

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

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

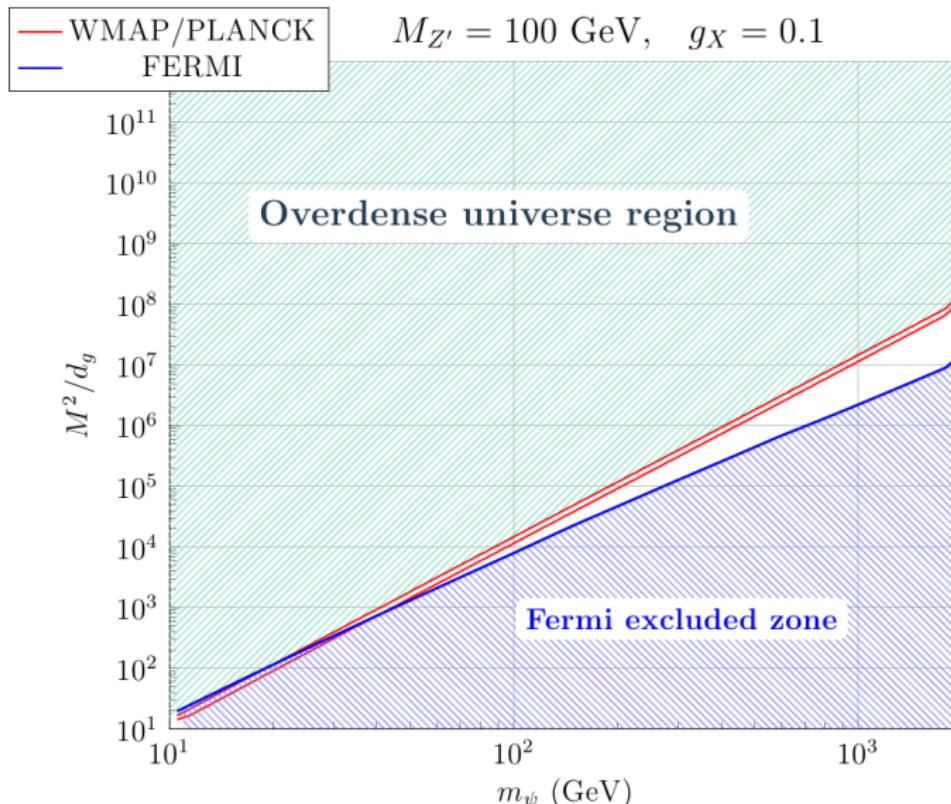
# Constraints on kinetic mixing

$$M^2/dg$$

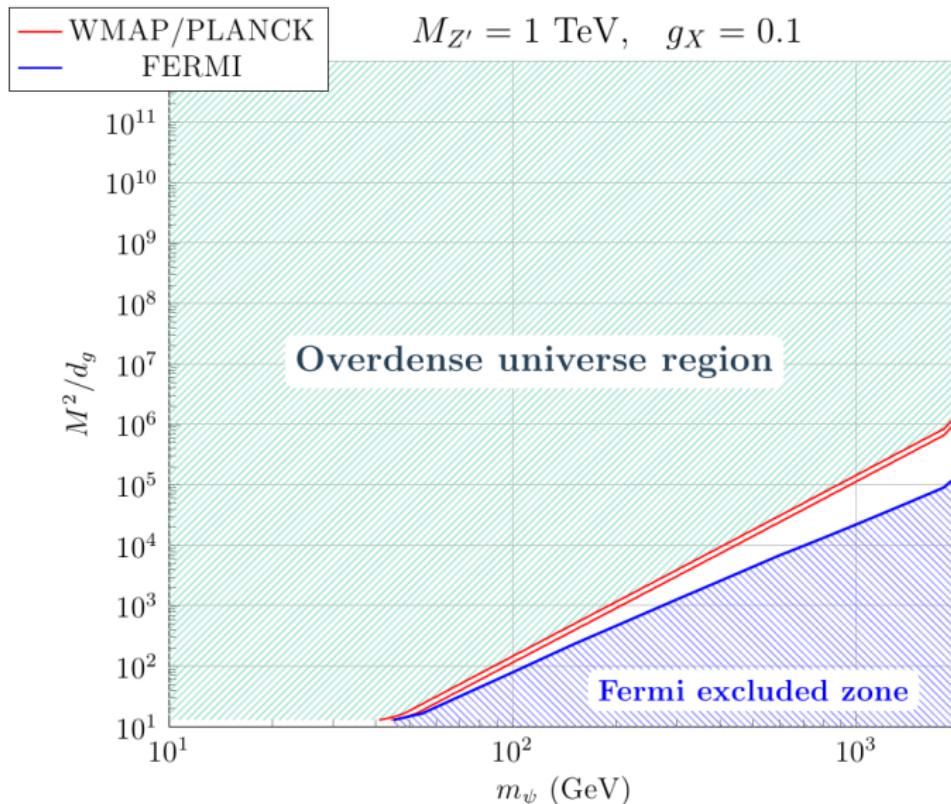


↪  $\delta \gtrsim 0.8$  excluded by LEP experiments...

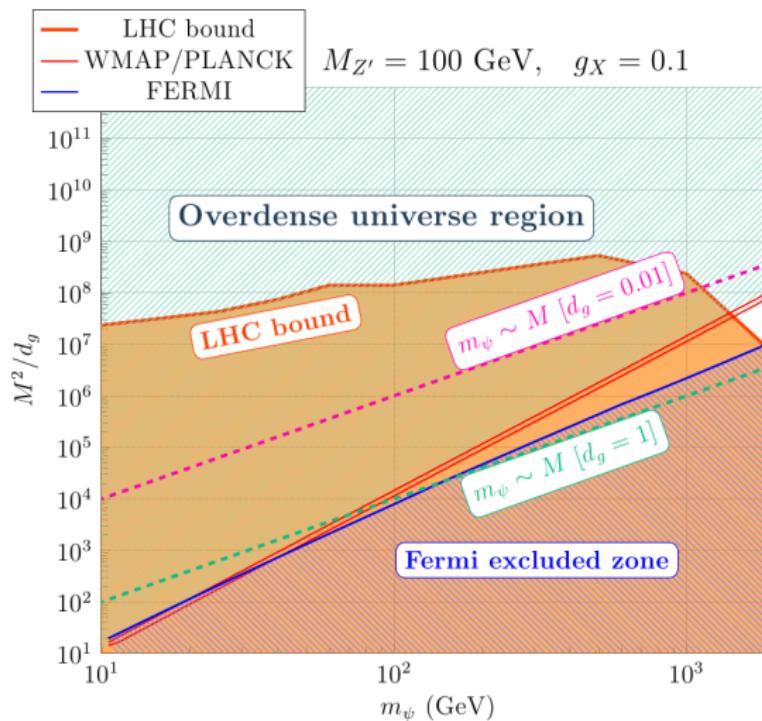
# Relic abundance and indirect detection



# Relic abundance and indirect detection



# Synthesis



# Synthesis

