# *H* portal to fermionic Dark Matter: from WIMP to FIMP

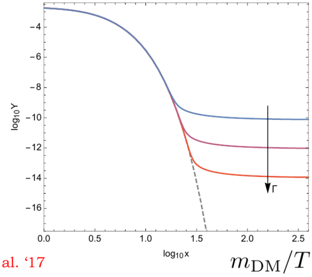
Laura Lopez Honorez

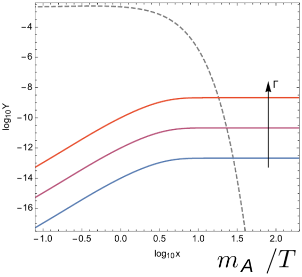
based on JHEP 1804 (2018) 011 & JHEP 1809 (2018) 037
in collaboration with L. Calibbi, S. Lowette, A. Mariotti, M. Tytgat, B. Zaldivar & P. Tziveloglou

Interdisciplinary approach to QCD-like composite dark matter,
ECT workshop - Trento, 1-5/10/18

# WIMP versus FIMP

DM abundance: Freeze-out versus Freeze-in (through decay)




Bernal et al. '17

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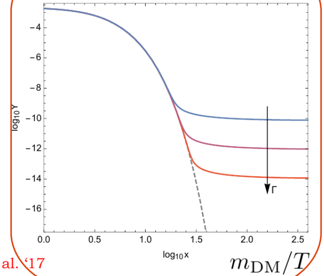


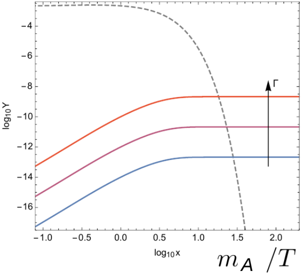


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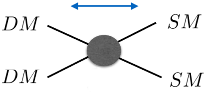


$$\Omega h^2 \sim 0.12 \times \frac{m_{DM}}{100\text{GeV}} \times \frac{0.2\text{pb}}{\langle \sigma v \rangle}$$

Typical cross-section probed by indirect detect° searches or CMB

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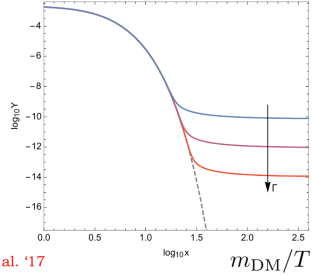
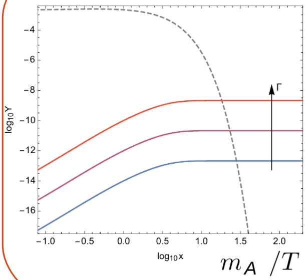
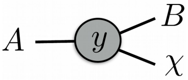



Bernal et al. '17

$$\Omega h^2 \sim 0.12 \left(\frac{\Gamma_A}{4\times 10^{-15}\ \text{GeV}}\right)\left(\frac{600\ \text{GeV}}{m_A}\right)^2\left(\frac{m_{DM}}{10\ \text{keV}}\right)$$



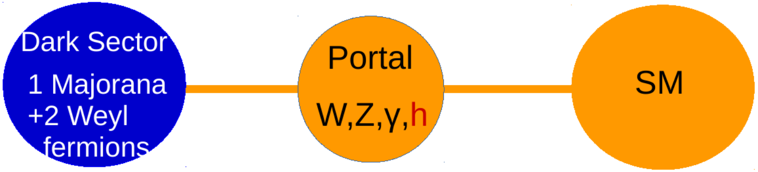

$y \sim 10^{-8}$ for $\Gamma_A \sim \frac{y^2}{8\pi} m_A$

$$c\tau_A = \frac{10^{-15}\ \text{GeV}}{\Gamma_A} \times 19\ \text{cm}$$

Long lived particle A probed at LHC with Displaced vertex

# H-coupled fermionic Dark Matter

see also [1M2D:Mahubani'05, D'Eramo'07, Enberg'07, Cohen'11,Clifford'14, Calibi'15; 3M2D: Dedes'14, Freitas'15; 3M4D: Tait'16, etc]




≡ Integrating the Higgs portal into fermionic MDM.

- SM + 3 dark $SU(2)_L$ $n-$plet $\rightsquigarrow$ $Z_2$ symmetry for DM stability
- Already well known examples in SUSY:
  $1_M 2_D \equiv$ bino-higgsino or $3_M 2_D \equiv$ wino-higgsino systems

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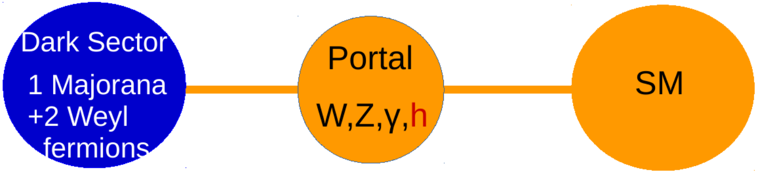


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- coupling to $H \rightsquigarrow \Delta n = 1$
- EW perturbativity till $M_{pl}$:

| Major./Dirac | 2 | 4 | 6 |
|---|---|---|---|
| 1 | ✓ | | |
| 3 | ✓ | ✓ | |
| 5 | | ✓ | ✘ |
| 7 | | | ✘ |

# Generic Mass Patterns

see also e.g. [Freitas'15, Tait'16]

$$\mathcal{L} \subset \mathcal{L}_{\rm K} - m_D \psi\tilde{\psi} - \frac{1}{2} m_M \chi\chi - (y_1 \psi\chi h^* + y_2 \tilde{\psi}\chi h + hc)$$

$\chi$ Majorana fermion, $\psi, \tilde{\psi}$ are Weyl fermions of representations $(n, 0)$ and $(n \pm 1, 1/2)$, $(n \pm 1, -1/2)$ of (SU(2), U(1)$_Y$) with $n$ odd.

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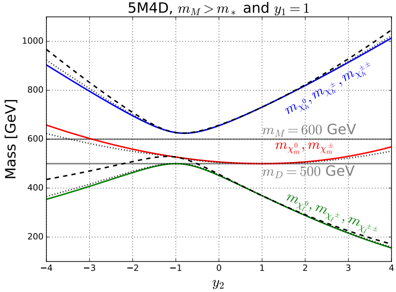
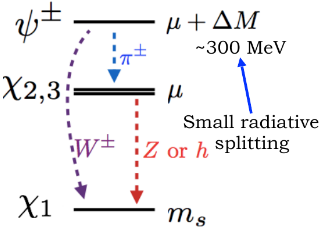
For $>$ 1M2D: Custodial sym. enforce $\chi_l^0$ degenerate with at least $\chi^\pm$




$\rightsquigarrow$ interesting WIMP pheno

In the limit $m_M \ll m_D$ 1M2D large mass splittings $\chi_l^0$-$\chi^\pm$



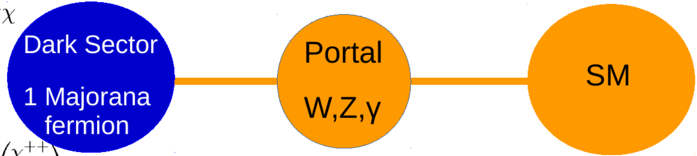

$\rightsquigarrow$ interesting FIMP pheno

# overview of WIMP H-coupled fermionic DM

# What about Gauge Portal only?

[Hisano'04,Hisano'06,Cirelli'07,Arkani-Hamed'08,Cohen'13, Cirelli'15,Garcia-Cely'15++,Asadi'16, Mitridate'17]

$-\frac{1}{2} m_M \chi\chi$




$$\chi_{(5,0)} = \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ \chi^{0} \\ \chi^{-} \\ \chi^{--} \end{pmatrix}$$

- SM + 1 single Majorana $n$plet of $SU(2)_L \rightsquigarrow$ 3-plet ($Z_2$) and 5-plet (stable) "Minimal Dark Matter" (MDM) $\rightsquigarrow m_3 = 2.4$ TeV and $m_5 = 4.4$ TeV

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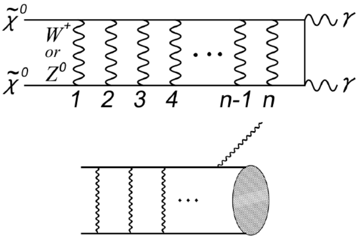


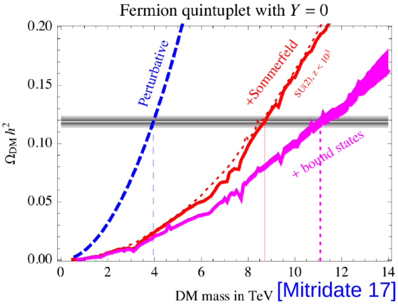


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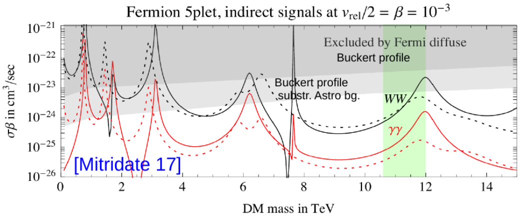


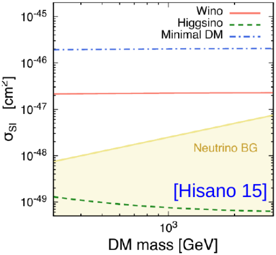


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- Gamma-ray/CR searches: MDM at the verge of discovery/exclusion if DM profile is cuspy, might evade constraints if the profile is cored

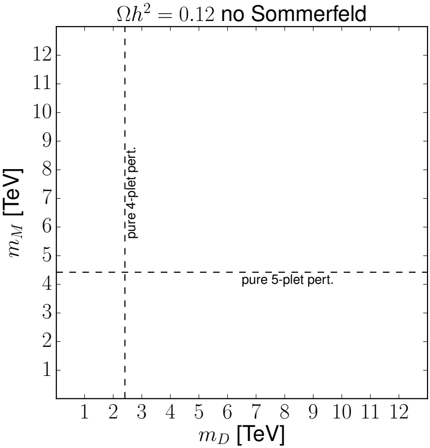
see [$\gamma$ rays:Rinchiuso ICRC'17 & '18 ; CR: Cuoco '17]

# $H$ & gauge portal: boundaries DM parameter space*

*perturbative level only!!

For one single multiplet:

$$\sigma v_{\mathrm{eff},n} \simeq \frac{\zeta}{n^2} \frac{\alpha_2^2 \mathcal{C}_n}{m_{DM}^2}$$



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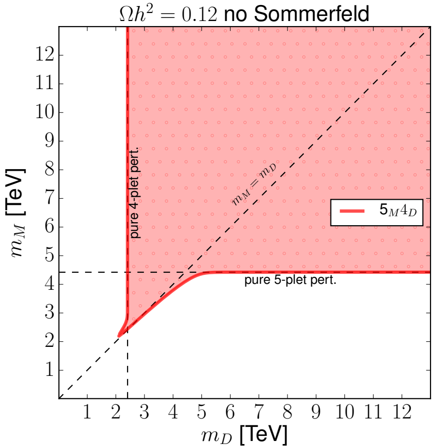

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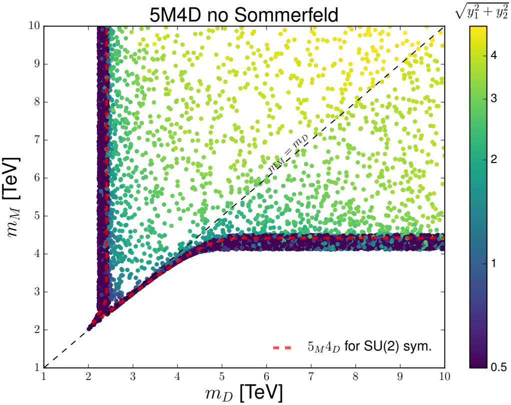


confirmed at perturbative level using `micrOMEGAs`

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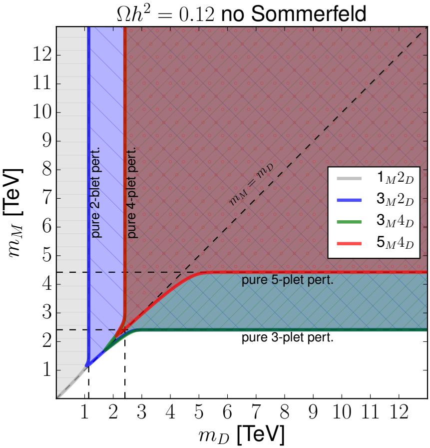

# Sommerfeld effect on HMDM Boundaries

[Hisano'04,Hisano'06,Cirelli'07,Arkani-Hamed'08,Cohen'13, Cirelli'15,Garcia-Cely'15++]

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| $n$ | $I_a$ | $\lambda_a$ | $S_{I_a}$ | $\sigma v_{I_a}^{\rm pert}$ | $m_{DM}^{\rm pert}$ [TeV] | $m_{DM}^{\rm Som}$ [TeV] |
|---|---|---|---|---|---|---|
| 2 | 0 | $\frac{3}{4}+\frac{1}{4}t_w^2$ | 1.5 | $\frac{3\pi\alpha_2^2}{8m_{DM}^2}$ | 1.1 | 1.1 |
| | 1 | $-\frac{1}{4}+\frac{1}{4}t_w^2$ | 0.9 | $\frac{25\pi\alpha_2^2}{16m_{DM}^2}$ | | |
| 3 | 0 | 2 | 2.3 | $\frac{4\pi\alpha_2^2}{m_{DM}^2}$ | 2.4 | 3. |
| | 1 | 1 | 1.6 | $\frac{25\pi\alpha_2^2}{4m_{DM}^2}$ | | |
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| 4 | 0 | $\frac{15}{4}+\frac{1}{4}t_w^2$ | 3.9 | $\frac{75\pi\alpha_2^2}{4m_{DM}^2}$ | 2.4 | 3.9 |
| | 1 | $\frac{11}{4}+\frac{1}{4}t_w^2$ | 3. | $\frac{125\pi\alpha_2^2}{8m_{DM}^2}$ | | |
| | 2 | $\frac{3}{4}+\frac{1}{4}t_w^2$ | 1.5 | $\frac{6\pi\alpha_2^2}{m_{DM}^2}$ | | |
| | 3 | $-\frac{9}{4}+\frac{1}{4}t_w^2$ | 0.3 | – | | |
| 5 | 0 | 6 | 5.9 | $\frac{60\pi\alpha_2^2}{m_{DM}^2}$ | 4.4 | 9.3 |
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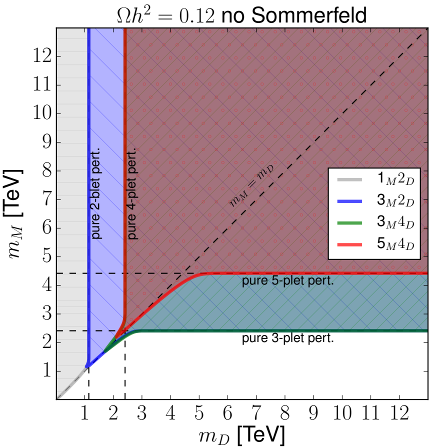

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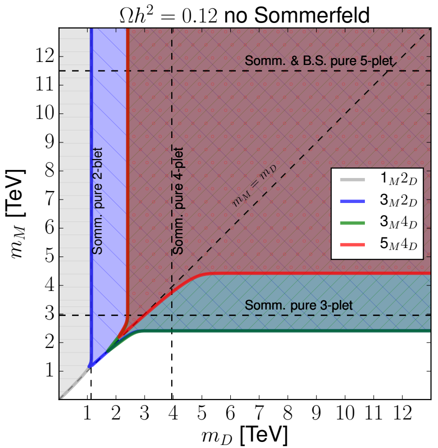

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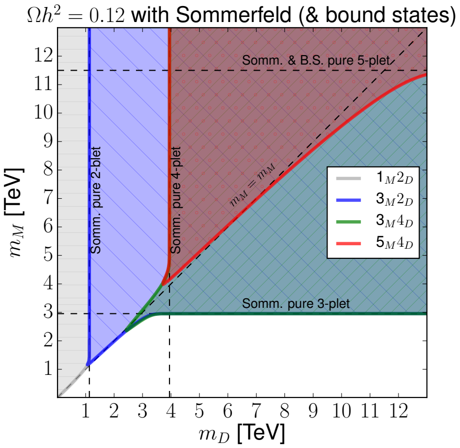
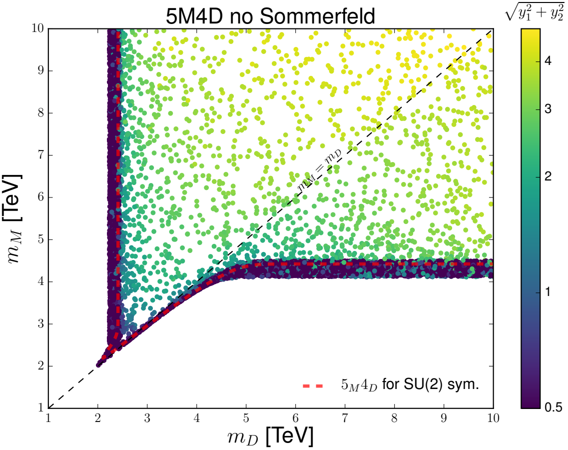
| | 3 | 0 | 1. | – | | |

$$\sigma v_{\rm eff} \simeq \frac{1}{g_{\rm eff}^2} \sum_{i=M,D} g_i^2 \sigma v^{\rm Som}_{{\rm DM},i}$$



# Pheno Hints - 5M4D: *perturbative* case

- Enveloppe for $y_1, y_2 < 1$ : $m_D = m_{4-\text{plet}}$, $m_M = m_{5-\text{plet}}$, $m_M = m_D$
- Need $y_1, y_2 \sim \mathcal{O}(1)$ to cover other possibilities



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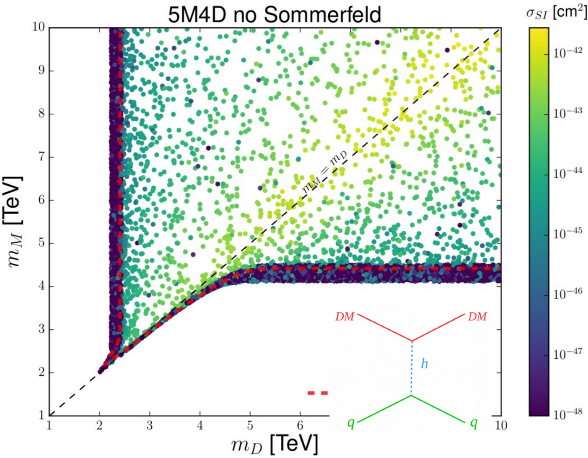
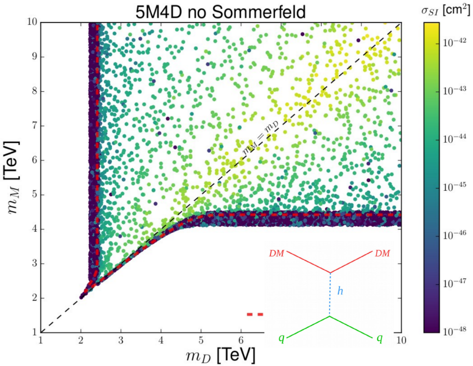
- Majorana nature of DM suppresses direct detection except for substantial $y_1, y_2$.
- $\sigma_{SI}$ is maximal for $m_M \simeq m_D$ where the coupling to $H$ is maximal, see also [Freitas'15] and $\sigma_{SI}$ is supressed for $y_1 \to -y_2$




$(\sigma_{SI}^{5-plet} = 2.4\,10^{-46}$ cm$^2$, & Xenon 1T reach $\sigma_{SI} > 10^{-44}$ cm$^2$)

# Prospects for DM detection

- Direct detection
  - Majorana nature of DM suppresses direct detection except for substantial $y_1, y_2$.
  - Increased sensitivity to HMDM than in MDM due to tree level $H$ exchange
  - Sommerfeld corrections shift to higher masses the allowed (tree-level) models.



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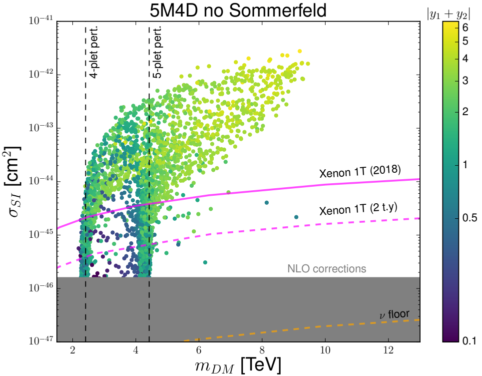

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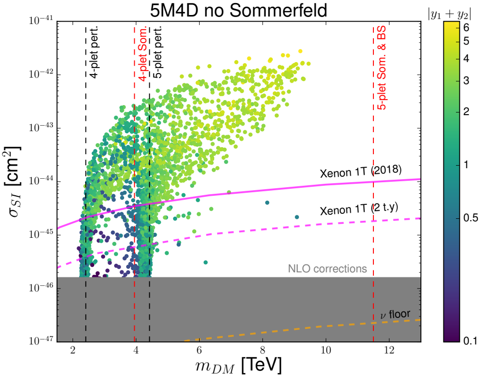



- Indirect detection: larger (tree-level) $\Delta m_{\chi^\pm \chi^0} \rightsquigarrow$ change the Sommerfeld effect and move the position of resonant peaks, see e.g. [Slatyer'09, Jin Chun'12] $\rightsquigarrow$ help to evade gamma-ray constraints (?)
- Colliders: disapearing tracks (up to multi TeV for 100 TeV collider); mono-X (up to multi TeV for 100 TeV collider); EWPT measurements and H-V modified couplings (up to $\sim$ TeV)

see [Ostdiek'15,Cirelli'14,Fedderke'15,Ismail'16,Cai'16,Voigt'17,Wang'17,Xiang'17]

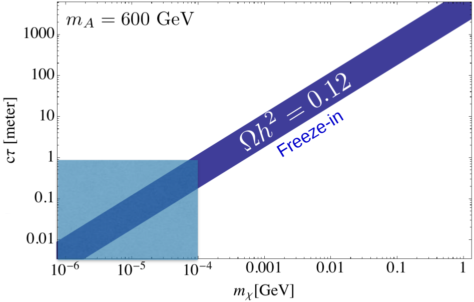
# FIMP H-coupled fermionic DM: The singlet doublet case

# FIMP: displaced vertices and cosmology interplay

see also e.g. [Hall'09, Co'15, Hessler'16, d'Eramo'17, Buchmueller'17, Heeck'17, Boulebnane'17, Brooijmans'18, Garny'18]

$$\Omega h^2 \sim 0.12 \left(\frac{5 \text{ cm}}{c\tau_A}\right) \left(\frac{600 \text{ GeV}}{m_A}\right)^2 \left(\frac{m_\chi}{10 \text{ keV}}\right)$$

Mediator mass range
reachable at colliders



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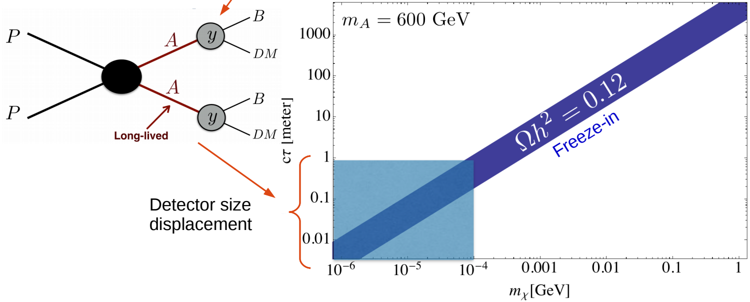

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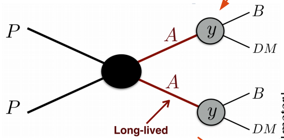
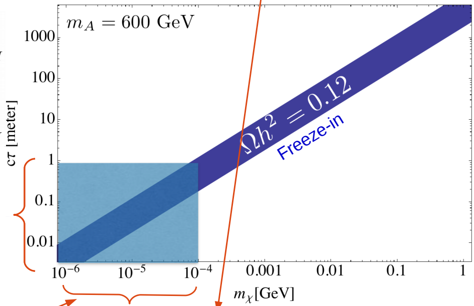
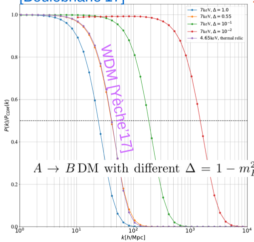



[Boulebnane’17]



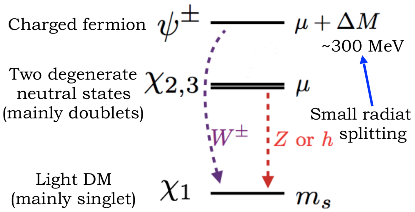

$A \to B\,\mathrm{DM}$ with different $\Delta = 1 - m_B^2/m_A^2$

Warm DM like signatures
Suppressing small scale structures

# Freeze-in from doublet decay in 1M2D

Freeze-in in the limit of $y_{1,2} \ll 1$ & $m_M = \mu \ll m_D = m_s$:

$$Y_{\chi_1} = \frac{270 M_{Pl}}{(1.66) 8\pi^3 g_*^{3/2}} \left( \sum_{B=Z,h} \frac{\Gamma[\chi_3 \to B\chi_1]}{m_{\chi_3}^2} + \sum_{B=Z,h} \frac{\Gamma[\chi_2 \to B\chi_1]}{m_{\chi_2}^2} + g_\psi \frac{\Gamma[\psi^+ \to W^+\chi_1]}{m_\psi^2} \right)$$



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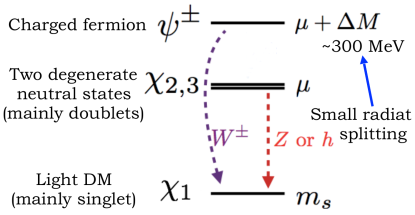
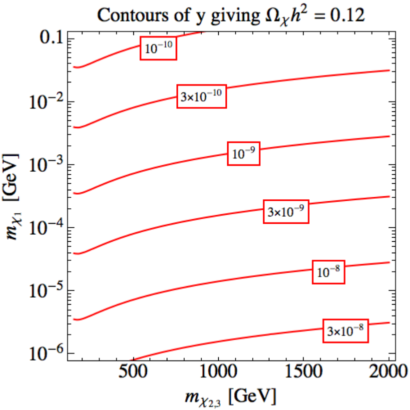


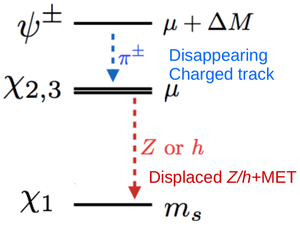

⇝ relevant $H$-coupling for freeze-in in 1M2D: $y < \mathcal{O}(10^{-8})$ for $m_{DM} >$ few keV

Results confirmed using micrOMEGAs5.0 [Belanger'18]

# Disapearing track or displaced h/Z+ MET

Copious production of $\chi_{2,3}, \psi^{\pm}$ at colliders through EW processes

- $\psi^{\pm} \to \pi^{\pm}\chi_{2,3}$
- $\chi_2\chi_3 \to ZZ/hh/Zh+$ MET



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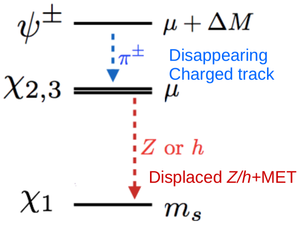


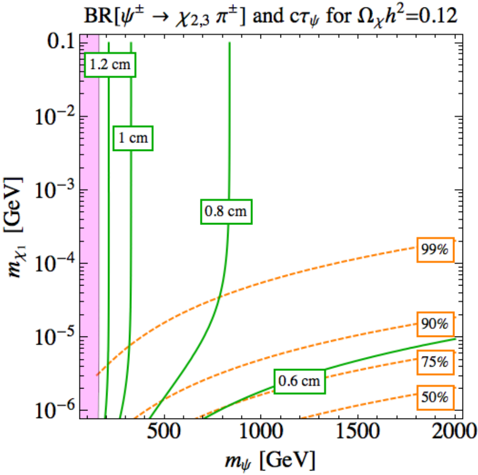

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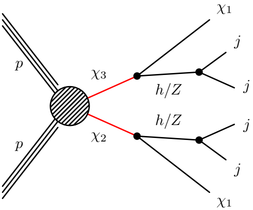
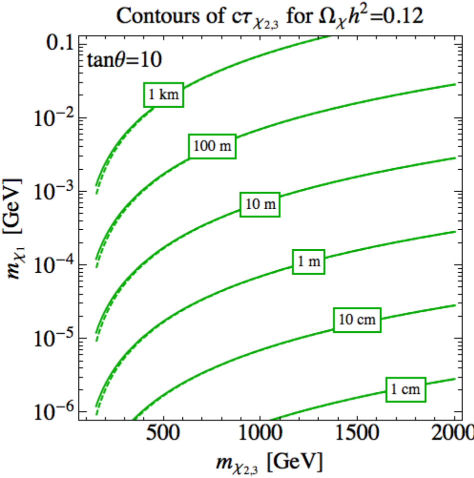
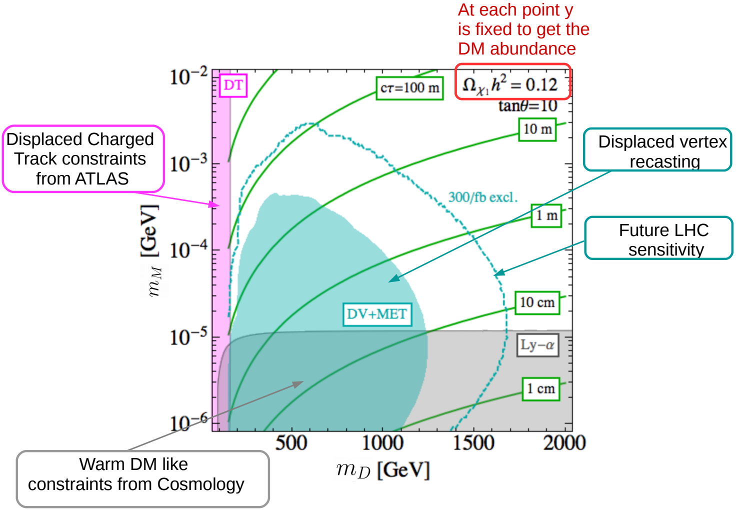
  $\rightsquigarrow$ displaced vertex with jet and MET with possibly $c\tau > \mathcal{O}(\text{ cm})$
  $\rightsquigarrow$ probe $m_D \leq 1.2$ TeV [ATLAS DV'17]

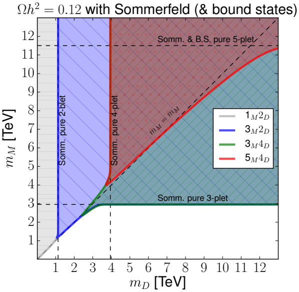


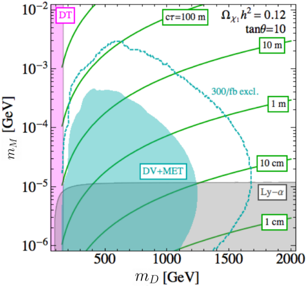



# LHC & Cosmology complementarity



# Conclusion




- H-coupled WIMP fermionic DM
  - Sommerfeld effect for H-coupled EW DM (computed in the SU(2) symmetric lim) $\rightsquigarrow$ boundaries of H-coupled EW WIMP parameter space.
  - constraints from direct searches and potentially evade indirect searches
- H-coupled FIMP fermionic DM: freeze-in through decays
  - small couplings $y \sim 10^{-8} - 10^{-9}$ $\rightsquigarrow$ long lived mediator at colliders tested with displaced vertices and dispearing charged track
  - complementary constraints from cosmology with WDM-like behaviour of light FIMP.

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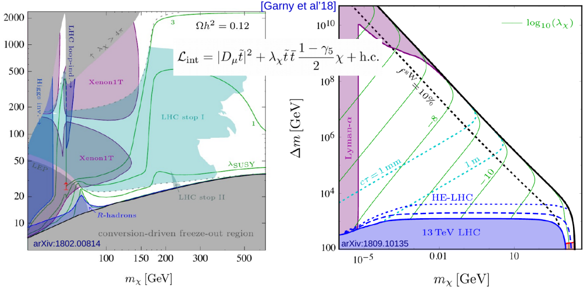


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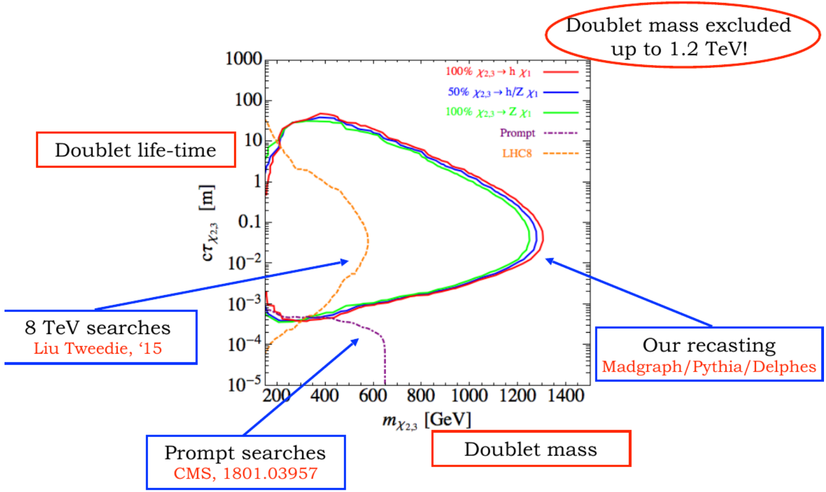
Thank you for your attention!

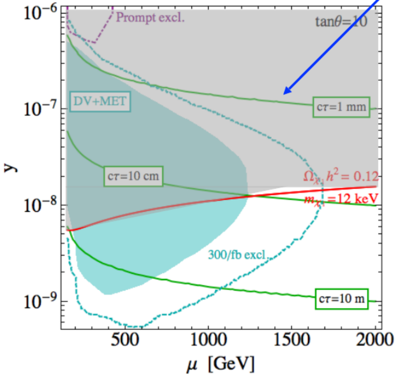
# Backup

# Recasting a DV+MET search by ATLAS

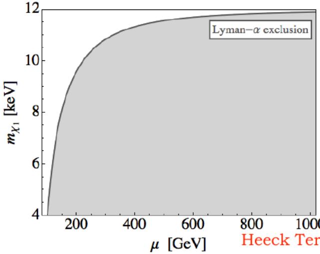



Rather general result: it also applies e.g. to Higgsino decaying to gravitino

Combined Lyman-alpha and relic density bound (assuming standard cosmology)




Bound from small structure formation (based on Lyman-alpha data):




Heeck Teresi '17

# Generic Mass Patterns

see also e.g. [Freitas'15, Tait'16]

- 4 free parameters: $m_M, m_D, y_1, y_2$

$$\mathcal{L} \subset \mathcal{L}_{\rm K} - m_D \psi \tilde{\psi} - \frac{1}{2} m_M \chi\chi - (y_1 \psi \chi h^* + y_2 \tilde{\psi} \chi h + hc)$$

$\chi$ Majorana fermion, $\psi, \tilde{\psi}$ are Weyl fermions of representations $(n, 0)$ and $(n \pm 1, 1/2), (n \pm 1, -1/2)$ of (SU(2), U(1)$_Y$) with $n$ odd.

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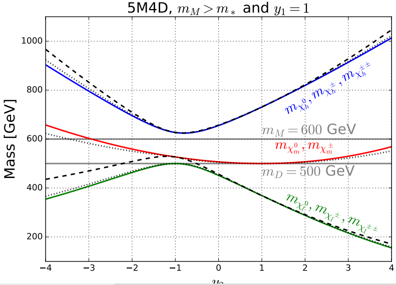
- Two Generic Mass Patterns after EWSB at tree-level:
  - Custodial sym. limit ($y_1 = \pm y_2$): $\chi_l^0$ degenerate with at least $\chi^\pm$ (except for $1_M 2_D$)
  - Beyond custodial sym. $\chi_l^0$ is the lightest with compressed spectra $\Delta m_{\chi^0\chi^\pm} \propto y^2 v^2/m_M$ or $\propto y^4 v^4/m_D^3$

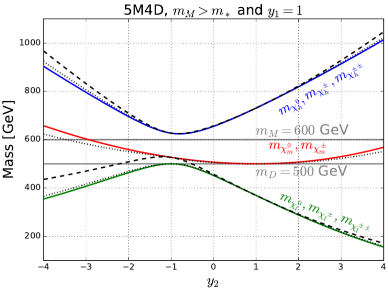


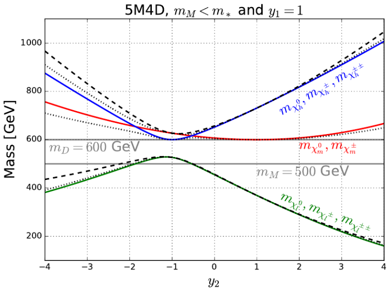

Loop corrections might give $m_{\chi^\pm} < m_{\chi^0}$ [Tait'16]

# Generic Mass Patterns

For $y_1 = \pm y_2$ , the Majorana and two Weyl states mix and neutral and charged particles combine to form Majorana SU(2) multiplets:

| M-D system | $m_M < m_* \sim m_D$ | $m_M > m_* \sim m_D$ |
|---|---|---|
| $1_M 2_D \sim 1_M 1_M 3_M$ | $\chi_l^0 \sim 1_M$ | $\chi_l^0 \subset \begin{cases} 3_M \text{ at } y_1 = -y_2 \\ 1_M \text{ at } y_1 = y_2 \end{cases}$ |
| $3_M 2_D \sim 1_M 3_M 3_M$ | $\chi_l^0 \subset 3_M$ | $1_M \quad y_1 = -y_2$<br>$3_M \quad y_1 = y_2$ |
| $3_M 4_D \sim 3_M 3_M 5_M$ | $3_M$ | $5_M \quad y_1 = -y_2$<br>$3_M \quad y_1 = y_2$ |
| $5_M 4_D \sim 3_M 5_M 5_M$ | $5_M$ | $3_M \quad y_1 = -y_2$<br>$5_M \quad y_1 = y_2$ |



# Fermionic Dark Matter: Gauge Portal

see e.g. [Cirelli et al'05-15, Hisano et al '04-15, Cohen'13, Garcia-Cely et al '15, Lefranc'15,...]

*Pure* gauge portal: Minimal DM (MDM) scenarios [Cirelli et al'05]

$$\mathcal{L} \subset \bar{\chi}(\not{D} - m_M)\chi$$

- SM + 1 single Majorana $n$plet of SU$(2)_L$
  $\rightsquigarrow$ 3-plet ($Z_2$) and 5-plet (stable)
  minimal fermionic WIMP DM
- loop corrections $\rightsquigarrow M_\chi^\pm - M_\chi^0 \sim 100$'s MeV
  $\rightsquigarrow$ the neutral $\chi^0$ is the lightest
- Gauge interactions only $\sigma v \propto \alpha_W^2/M^2$, $\Omega h^2 = 0.12$

$\rightsquigarrow M_{0,3} = 2.4$ TeV and $M_{0,5} = 4.4$ TeV (at first sight!!)

$$\chi_{(3,0)} = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix}$$

$$\chi_{(5,0)} = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \\ \chi^- \\ \chi^{--} \end{pmatrix}.$$

# Sommerfeld effect in SU(2) symmetric limit

- $m_{DM} \sim$ MultiTeV $\rightsquigarrow$ f.o. SU(2) symmetric limit
- In this limit, non-abelian Sommerfeld effect can be reduced to a combination of abelian-like Sommerfeld corrections, using group theory decompositions [Strumia'08].

  Potential between particles of repres. $R_i$ and $R_j \equiv V_{I_a} = V_{I_a}^{SU(2)} + V^{U(1)}$:

$$V_{I_a}^{SU(2)}(r) = \frac{\alpha_2}{r}\frac{1}{2}\left(C_a - C_i - C_j\right); \quad V^{U(1)} = \frac{-\alpha_2 t_w^2 Y^2}{r}$$

  and $R_i \otimes R_j = \sum_{k=1}^{N'} R_k$ with $C_l$ the quadratic Casimir of $R_l$

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- For $\Omega_{\rm DM} h^2 \propto 1/\sigma v_{\mathit{eff}}$, $\sigma v_{\mathit{eff}} = \sum_{ij} g_i g_j / g_{\mathit{eff}} \sigma v_{ij}$ becomes

$$\sigma v_{\mathit{eff}} = \frac{1}{(2I_X+1)^2}\left(\sum_I (2I+1) S_I \sigma v_I^{\rm pert} + S_{I=1}\,\sigma v_{gg'}^{\rm pert} + S_{I=0}\,\sigma v_{g'}^{\rm pert}\right),$$

$\sigma v_I$: pure $SU(2)$, Clebsh-Gordan relate $|ij\rangle$ to $|I\rangle$,

$\sigma v_{gg'}$ and $\sigma v_{g'}$: involves U(1) gauge boson

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- Multi-TeV DM $\rightsquigarrow$ compute annihilations in SU(2) symmetric limit
  $\rightsquigarrow$ Isospin is conserved in annihilations
- Decompose the product of initial states as a sum of 2-particle states of definite isospin $I$: $R_i \otimes R_j = \sum_I \mathcal{R}_I$ [Strumia'08]
  Associated an abelian-like Sommerfeld correction with $a_I = v/(2\alpha)$

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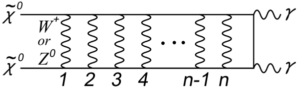
$\sigma v_{gg'}$ and $\sigma v_{g'}$: involves U(1) gauge boson
see also [Garcia-Cely'15] and [Mitridate'17]

# Sommerfeld effect and bound state formation

[Hisano'04,Hisano'06,Cirelli'07,Arkani-Hamed'08,Cohen'13, Cirelli'15,Garcia-Cely'15++]

- The Sommerfeld effect is caused by distortion of the 2bdy wave function due to long range potential.

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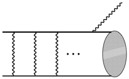
- Formation of bound states from 2 DM particle can provide an extra enhancement [Asadi'16, Mitridate'17]



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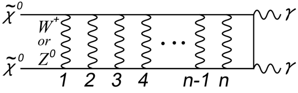


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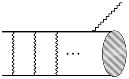
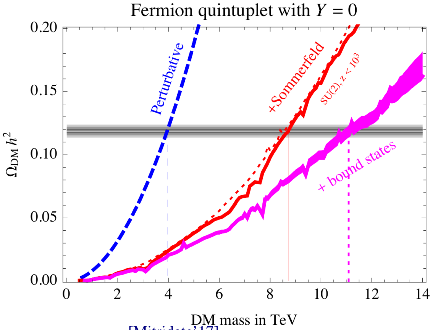


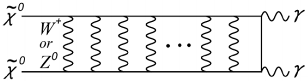


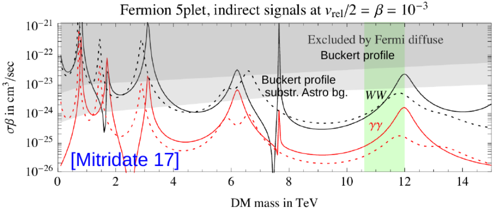

[Mitridate'17]

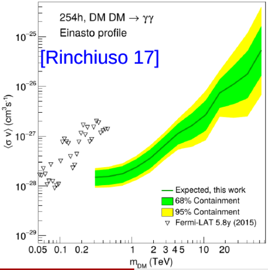
$\rightsquigarrow M_{0,3} = 3$ TeV & $M_{0,5} = 11.5$ TeV

# Minimal Dark matter: at the verge of discovery/exclusion

Indirect Detection

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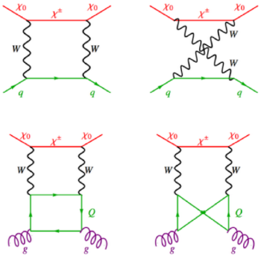


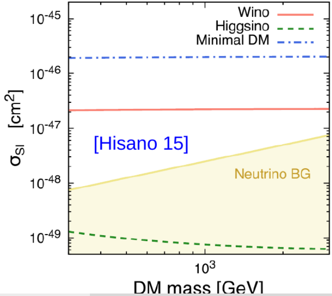

# H-coupled Minimal Dark Matter

see also [1M2D:Mahubani'05, D'Eramo'07, Enberg'07, Cohen'11,Clifford'14, Calibi'15; 3M2D: Dedes'14, Freitas'15; 3M4D: Tait'16, etc]

$\equiv$ Integrating the Higgs portal into fermionic MDM.

- SM + 3 dark SU(2)$_L$ $n-$plet $\rightsquigarrow$ $Z_2$ symmetry for DM stability
- Already well known examples in SUSY:
  $1_M 2_D \equiv$ bino-higgsino or $3_M 2_D \equiv$ wino-higgsino systems

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Are the possibilities infinite?

- coupling to $H \rightsquigarrow \Delta n = 1$
- EW perturbativity till $M_{pl}$:

| *Major./Dirac* | **2** | **4** | **6** |
|---|---|---|---|
| **1** | ✓ | | |
| **3** | ✓ | ✓ | |
| **5** | | ✓ | ✘ |
| **7** | | | ✘ |

What are the generic features?

# (Minimal Dark Matter)$^2$: the general setup

- 4 free parameters: $m_M = m_\chi, m_D = m_\psi, y_1, y_2$

$$\mathcal{L}_{\rm DARK} = \mathcal{L}_{\rm K} - m_\psi \psi\tilde{\psi} - \frac{1}{2} m_\chi \chi\chi - (y_1 \psi\chi h^* + y_2 \tilde{\psi}\chi h + hc)$$

$\chi$ and $\psi, \tilde{\psi}$ are Weyl fermions of representations $(n, 0)$ and $(n \pm 1, 1/2), (n \pm 1, -1/2)$ of (SU(2), U(1)$_Y$) with $n$ odd.

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- After EWSB, the fermions of charge $Q = T_3 + Y$ in the bases $\{\chi^Q, \psi^Q, \tilde{\psi}^Q\}$ have mass matrices of the form:

$$M_Q^{3\times3} = (-1)^Q \begin{pmatrix} m_\chi & a_Q\, y_1 v & \tilde{a}_Q\, y_2 v \\ \tilde{a}_Q\, y_1 v & 0 & m_\psi \\ a_Q\, y_2 v & m_\psi & 0 \end{pmatrix},$$

$$M_Q^{2\times2} = (-1)^Q \begin{pmatrix} m_\chi & y_1 v \\ y_2 v & m_\psi \end{pmatrix}, \quad M_Q^{1\times1} = (-1)^Q m_\psi \,.$$

# Custodial symmetry $y1 = \pm y2$

$$m_1 = \frac{1}{2}(m_M + m_D + \Delta m_\eta)$$
$$m_2 = m_D$$
$$m_3 = \frac{1}{2}(m_M + m_D - \Delta m_\eta)$$

$$\Delta m_\eta = \sqrt{(m_D - m_M)^2 + 8(\eta y v/\sqrt{2})^2}$$

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \end{pmatrix} = \begin{pmatrix} c_\eta & s_\eta/\sqrt{2} & s_\eta/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \\ -s_\eta & c_\eta/\sqrt{2} & c_\eta/\sqrt{2} \end{pmatrix} \begin{pmatrix} \chi_0 \\ \psi_0 \\ \tilde{\psi}_0 \end{pmatrix}$$

$$\sin^2\theta_\eta = \frac{1}{2}\left(1 + \frac{m_D - m_M}{\Delta m_\eta}\right)$$

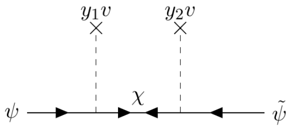
$$\mathcal{L} = -\frac{g}{2}(\psi_0^\dagger \bar{\sigma}^\mu \psi_0 - \tilde{\psi}_0^\dagger \bar{\sigma}^\mu \tilde{\psi}_0) Z_\mu - y\eta(\tilde{\psi}_0 - \psi_0)\chi_0\, h$$

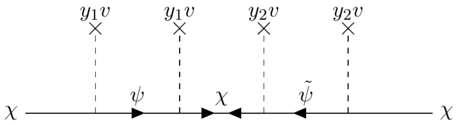
$$\mathcal{L} = \frac{g}{2}\chi_2^{0*}\bar{\sigma}^\mu(s_\eta \chi_1^0 + c_\eta \chi_3^0) Z_\mu + h.c.$$
$$-\frac{y\eta}{2\sqrt{2}}\left(s_{2\eta}(\chi_1^0\chi_1^0 - \chi_3^0\chi_3^0) + 2c_{2\eta}\chi_1^0\chi_3^0\right) h + h.c.$$

# Generic Mass Patterns

| M-D system | $m_M < m_* \sim m_D$ | $m_M > m_* \sim m_D$ |
|---|---|---|
| $1_M 2_D \sim 1_M 1_M 3_M$ | $\chi_l^0 \sim 1_M$ | $\chi_l^0 \subset \begin{cases} 3_M \text{ at } y_1 = -y_2 \\ 1_M \text{ at } y_1 = y_2 \end{cases}$ |
| $3_M 2_D \sim 1_M 3_M 3_M$ | $\chi_l^0 \subset 3_M$ | $1_M \quad y_1 = -y_2$<br>$3_M \quad y_1 = y_2$ |
| $3_M 4_D \sim 3_M 3_M 5_M$ | $3_M$ | $5_M \quad y_1 = -y_2$<br>$3_M \quad y_1 = y_2$ |
| $5_M 4_D \sim 3_M 5_M 5_M$ | $5_M$ | $3_M \quad y_1 = -y_2$<br>$5_M \quad y_1 = y_2$ |

# Generic Mass Patterns



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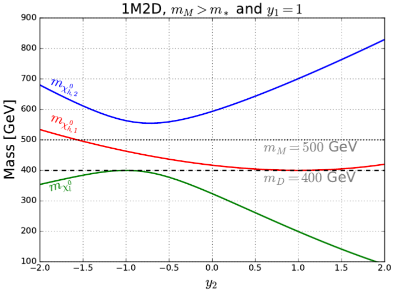


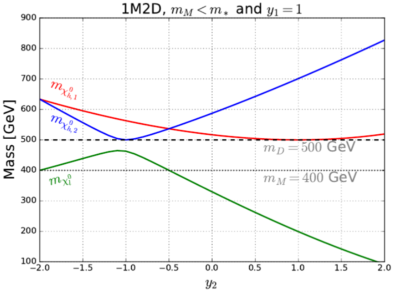

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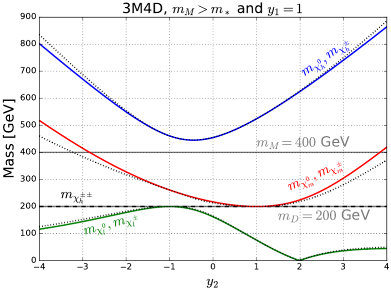


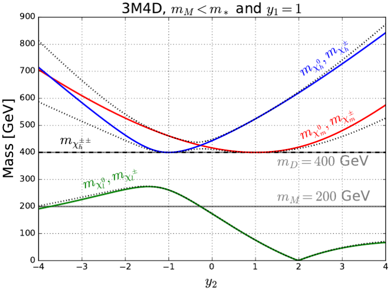

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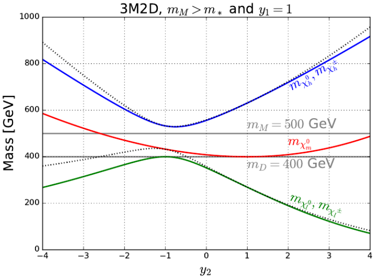


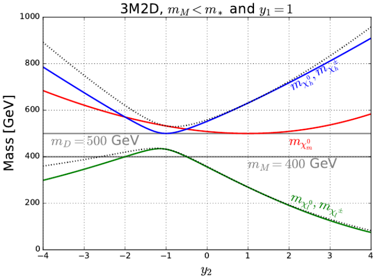

# Generic Mass Patterns

For $y_1 = \pm y_2$ , the Majorana and two Weyl states mix and neutral and charged particles combine to form Majorana SU(2) multiplets:

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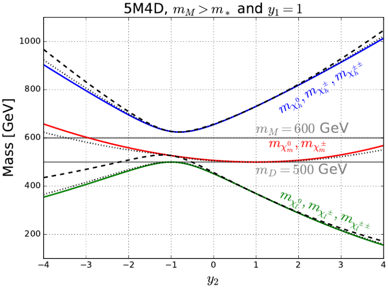


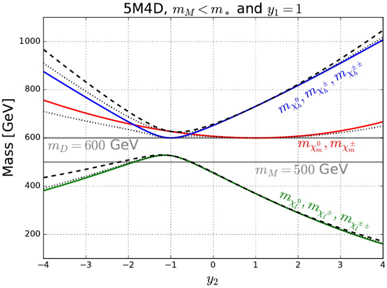

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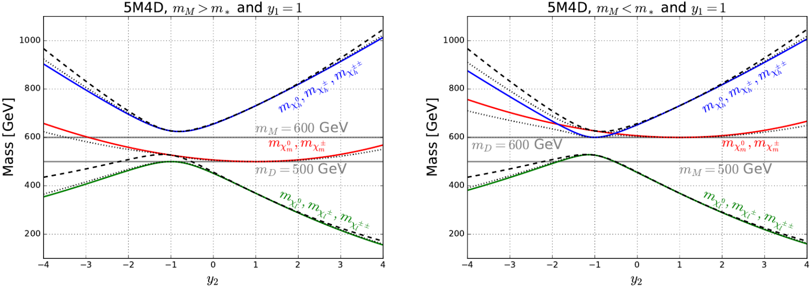

# SU(2) unbroken Sommerfeld on pure 4-plet

$$\psi = \begin{pmatrix} \psi^{++} \\ \psi^{+} \\ \psi^{0} \\ \psi^{-} \end{pmatrix}, \quad \tilde{\psi} = \begin{pmatrix} \tilde{\psi}^{+} \\ \tilde{\psi}^{0} \\ \tilde{\psi}^{-} \\ \tilde{\psi}^{--} \end{pmatrix},$$

• $4 \otimes \bar{4} = 1 \oplus 3 \oplus 5 \oplus 7 = \sum_{a=1}^{N'} \mathcal{R}_a$
with $I_a = \{0, 1, 2, 3\}$ and
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- From charge to Isospin e.g. $\sigma v_{I=2}/2 = \sigma v_{\chi_1^+ \chi_2^+ \to WW}$

$$\sigma v_{eff} = \frac{1}{16}\left(S_{I=0}\sigma v_{I=0} + S_{I=1}3\sigma v_{I=1} + S_{I=2}5\sigma v_{I=2} + S_{I=0}\sigma v_{g'} + S_{I=1}\sigma v_{g'g}\right)$$

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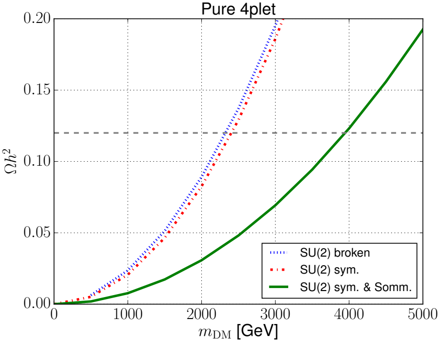


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Perturb: $M_{DM} = 2.4$ TeV while w/ Sommerfeld $M_{DM} = 3.9$ TeV

# Quadruplet $\sigma v_{eff}$ contribs

$$\sigma v_0 = \frac{75}{4}\frac{\alpha_2^2\pi}{M_{DM}^2}, \quad \sigma v_1 = \frac{125}{8}\frac{\alpha_2^2\pi}{M_{DM}^2}, \quad \sigma v_2 = 6\frac{\alpha_2^2\pi}{M_{DM}^2}$$

$$\sigma v_{g'g} = \frac{15}{2}\, t_w^2\, \frac{\alpha_2^2\pi}{M_{DM}^2}$$

$$\sigma v_{g'} = \frac{43}{8}\, t_w^4\, \frac{\alpha_2^2\pi}{M_{DM}^2}$$

# Quadruplet $\sigma v_{ij}$ total contribs

$$Q_{tot} = 0$$

$$\sigma v_{0,\bar{0}} = \frac{\alpha_2^2 \pi}{32\, c_w^4\, M_{DM}^2}(223 - 442 s_w^2 + 262 s_w^4) = \sigma v_{1,-1}$$

$$\sigma v_{2,-2} = \frac{\alpha_2^2 \pi}{32\, c_w^4\, M_{DM}^2}(423 - 810 sw^2 + 430 sw^4) = \sigma v_{-1,1}$$

$$Q_{tot} = 1$$

$$\sigma v_{2,-1} = \frac{3\, \alpha_2^2 \pi}{16\, c_w^4\, M_{DM}^2}(41 - 37 sw^2) = \sigma v_{0,1}$$

$$\sigma v_{1,\bar{0}} = \frac{\alpha_2^2 \pi}{4\, c_w^4\, M_{DM}^2}(25 - 21 sw^2)$$

$$Q_{tot} = 2$$

$$\sigma v_{2,\bar{0}} = \frac{3\, \alpha_2^2 \pi}{M_{DM}^2} = \sigma v_{1,1}$$

# Quadruplet $\sigma v_I$ contribs (SU(2) only)

$$Q_{tot} = 0$$

$$\begin{aligned} \sigma v_{0,\bar{0}} &= \sigma v_{I=0}/4 + \sigma v_{I=2}/4 + \sigma v_{I=1}/20 = \sigma v_{1,-1} \\ \sigma v_{2,-2} &= \sigma v_{I=0}/4 + \sigma v_{I=2}/4 + 9\sigma v_{I=1}/20 = \sigma v_{-1,1} \end{aligned}$$

$$Q_{tot} = 1$$

$$\begin{aligned} \sigma v_{2,-1} &= \sigma v_{I=2}/2 + 3\sigma v_{I=1}/10 = \sigma v_{0,1} \\ \sigma v_{1,\bar{0}} &= 2/5\sigma v_{I=1} \end{aligned}$$

$$Q_{tot} = 2$$

$$\sigma v_{2,\bar{0}} = \sigma v_{I=2}/2 = \sigma v_{1,1}$$

# Sommerfeld effect and bound state formation

The Sommerfeld effect $\equiv$ NR QM effect. It is caused by the distortion of the wave function describing the relative motion of annihilating particles through the exchange of light mediators

$\rightsquigarrow$ significant enhancement or suppresion of DM scattering by Coulomb like forces when $M_{med} < \alpha M_{DM}$

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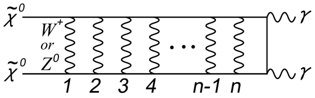
- smoking gun signatures like

  $\chi_0\chi_0 \to \gamma\gamma$ [Hisano'04]

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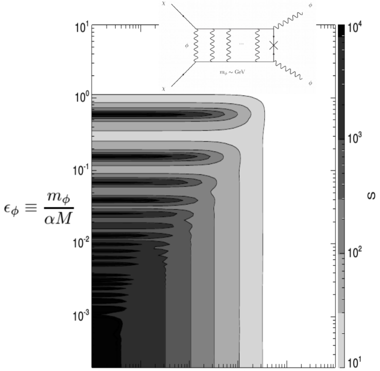
Example: DM= $\chi$ & mediator= $\phi$

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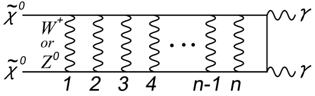


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# Fermionic Minimal Dark Matter: multi-TeV EWDM

[Cirelli et al'05]

- SM +1 single $n$plet of $SU(2)_L$
- $n$plet $\supset$ a neutral component $\equiv$ DM
  $\rightsquigarrow$ $Y$ is fixed for given $n$, e.g. $n = 3, Y = 0, 1/2$
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$$\chi_{(3,0)} = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix}$$

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- loop corrections $\rightsquigarrow M_\chi^\pm - M_\chi^0 \sim 100$'s MeV
  $\rightsquigarrow$ the neutral $\chi^0$ is the lightest
- Gauge interactions only $\sigma v \propto \alpha_W^2/M^2$, $\Omega h^2 = 0.12$

$\rightsquigarrow M_{0,3} = 2.4$ TeV and $M_{0,5} = 4.3$ TeV (at first sight)

$$\chi_{(3,0)} = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix} \qquad \chi_{(5,0)} = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \\ \chi^- \\ \chi^{--} \end{pmatrix}.$$

# Sommerfeld effect

The Sommerfeld effect $\equiv$ NR QM effect. It is caused by the distortion of the wave function describing the relative motion of annihilating particles through the exchange of light mediators.

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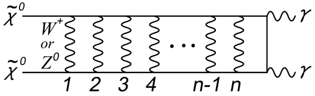
For EWDM $\chi_0$, at low $v$ and $M_{\chi_0}$ large:

- smoking gun signatures like

  $\chi_0\chi_0 \to \gamma\gamma$ [Hisano'04]

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[Hisano'04'06, Cirelli'07]

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Example: DM= $\chi$ & mediator= $\phi$

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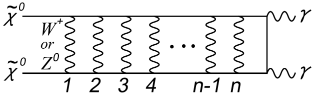


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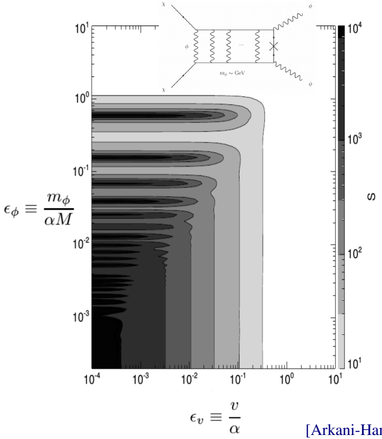


[Arkani-Hamed'08]

# Sommerfeld effect: Evaluation for EWDM freeze-out

- Very degenerate mass spectra $\rightsquigarrow$ all $n$-plets components play into the game!
  - Need the NR EW potentials associated to $\mathcal{V} = W, Z, \gamma$ exchange
    $$V_{\alpha,\beta} = c_{\alpha,\beta} \frac{e^{-M_{\mathcal{V}} r}}{r}$$
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- Evolve $N$ initial pairs $\rightsquigarrow$ $N$ coupled diff. eqs.:

$$\sigma v_\alpha = \sum_{\beta\beta'} \mathcal{S}^*{}_{\alpha\beta} \Gamma_{\beta\beta'} \mathcal{S}_{\beta'\alpha}\ ,$$

$\mathcal{S}_{\alpha\beta}$ depends on $V_{\alpha'\beta'}$ and $M_{\rm DM} v^2$;

[Hisano'04,Hisano'06,Cirelli'07,Cohen'13, Cirelli'15,Garcia-Cely'15++]

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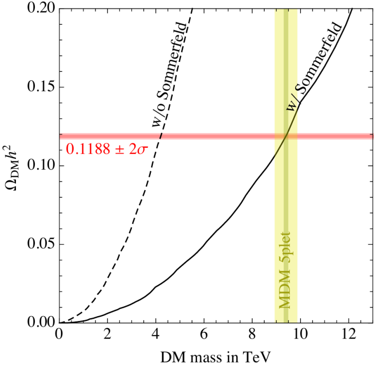
$\rightsquigarrow$ $M_{0,3} = 2.7$ TeV & $M_{0,5} = 9.4$ TeV



[Cirelli'15]

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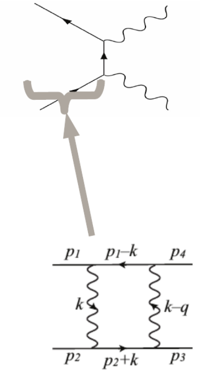
# Sommerfeld $e^+e^-$

Related to e+e- → γ γ hep-ph/0412403




→ diverges at low v

$$\mathcal{A}_n \propto \alpha(\alpha/v)^n$$

If v<α → Non perturbative, the ladder diagrams **have to be resummed**.

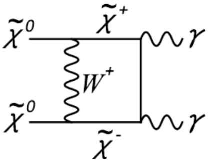
NB: v<α → The coulomb potential is larger than the kinetic energy of the incident particles.

The NR incident pair of electron has its **plane wave deformed by the coulomb potential.**

→ Need an improved calculation [Sommerfeld 1931]

# Sommerfeld EWDM

For EWIMP hep-ph/0412403



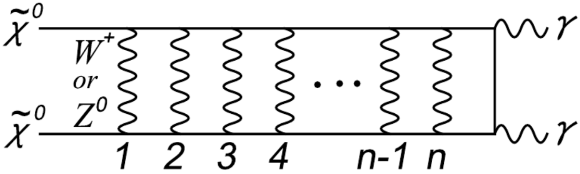

$$\sigma v \sim \frac{\alpha^2 \alpha_2^2}{m_W^2}$$

Unitary limit

$$\sigma v < \frac{4\pi}{v m^2}$$

Bound exceeded for heavy m or low v

→ Higher order corr. to be included




$$\mathcal{A}_n \simeq \alpha \left( \frac{\alpha_2 m}{m_W} \right)^n$$

→ Higher order corrections increasingly important for $\alpha_2 m \gtrsim m_W$

→ non perturbative regime

→ resum the ladder diag.

# Sommerfeld single mediator -theory

ArXiv:0810.0713 : Single mediator

Sommerfeld enhancement is an elementary effect in NR QM: The potential may significantly distort the wave function of describing the relative motion of the initial pair of particles:

$$-\frac{1}{2M}\nabla^2\psi_k + V(r)\psi_k = \frac{k^2}{2M}\psi_k$$

$$\sigma = \sigma_0 S_k \qquad S_k = \frac{|\psi_k(0)|^2}{|\psi_k^{(0)}(0)|^2}$$

wave fn at the origin, no V

Coulomb case

$$V(r) = -\frac{\alpha}{2r} \qquad S_k = \left|\frac{\frac{\pi}{\epsilon_v}}{1-e^{-\frac{\pi}{\epsilon_v}}}\right| \qquad \epsilon_v \equiv \frac{v}{\alpha}$$

$$S_k \to \frac{\pi\alpha}{v}$$

At small v

The Sommerfeld effect **is caused by the distortion of the plane wave describing the relative motion of the ann. pair through the exchange of light mediators**

# Sommerfeld single mediator -results

<u>Yukaka case</u>

$$V(r) = -\frac{\alpha}{2r} e^{-m_\phi r}$$

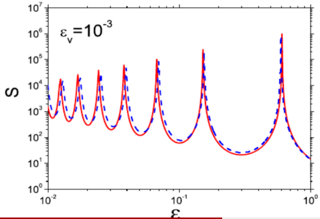
$$S = \frac{\pi}{\epsilon_v} \frac{\sinh\left(\frac{2\pi\epsilon_v}{\pi^2\epsilon_\phi/6}\right)}{\cosh\left(\frac{2\pi\epsilon_v}{\pi^2\epsilon_\phi/6}\right) - \cos\left(2\pi\sqrt{\frac{1}{\pi^2\epsilon_\phi/6} - \frac{\epsilon_v^2}{(\pi^2\epsilon_\phi/6)^2}}\right)}$$

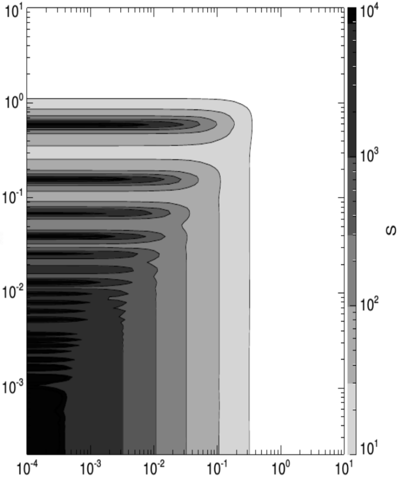
Resonant behaviour at:

$$m_\phi \simeq \frac{6\alpha_X m_X}{\pi^2 n^2} \;, \quad n = 1, 2, 3 \ldots$$

$$S \simeq \frac{\pi^2 \alpha_X m_\phi}{6 m_X v^2}$$

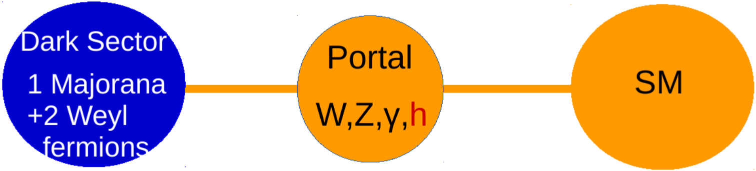
$$\epsilon_\phi \equiv \frac{m_\phi}{\alpha M}$$




$$\epsilon_v \equiv \frac{v}{\alpha}$$

# Take Home Message




- We extend the Standard Model portal to include the Higgs
- Still $\chi_0\epsilon$ Majorana-like multiplet of $SU(2)$, ie with compressed spectra ( $\Delta m \sim$ up to GeV $\ll$ $m_{DM} \sim$ multiTeV )
- Careful : Sommerfeld effects affect the boundaries of the parameter space especially for large representations!!
- Something like a 5-plet or 3-plet Majorana DM candidate might not be fully excluded yet and could be tested by direct DM searches

Now you can sleep until the conclusions ;)

# bla

# This is really the end