Minimal Consistent Fermion Dark Matter

NeXT Spring Workshop 2020

Daniel Locke
D.Locke@soton.ac.uk

In collaboration with A.Belyaev, G.Cacciapaglia

Outline

1) Why particle DM?

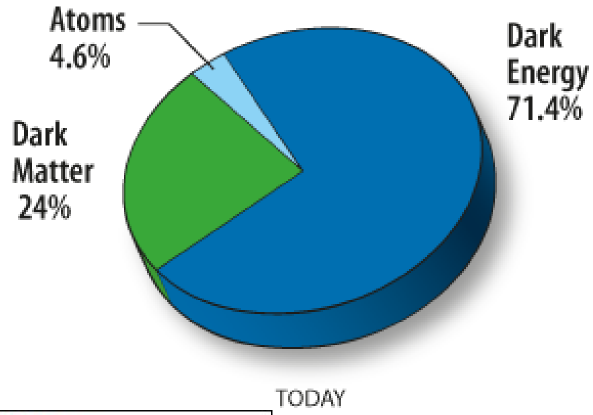
2) What are MCDM models?

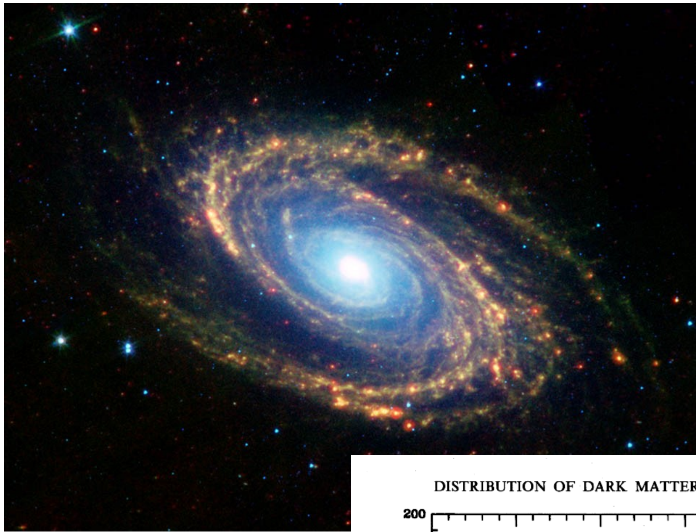
- Single DM multiplet case
- Adding mediator multiplets

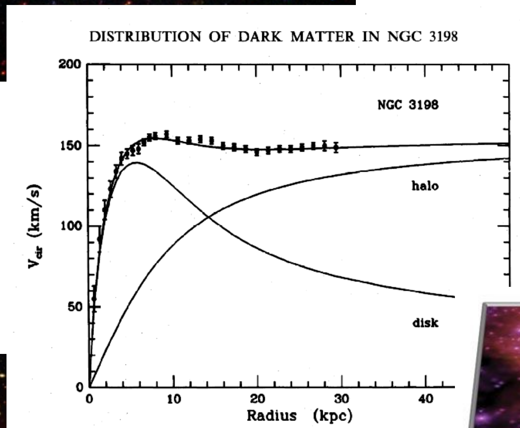
3) Exploring a two-component DM model - accidentally stable mediators

4) Conclusions & Outlook

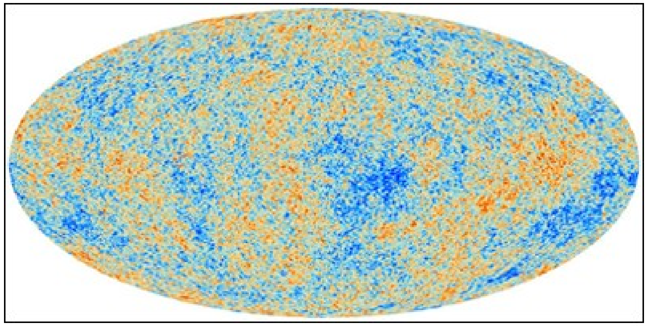
Why DM?



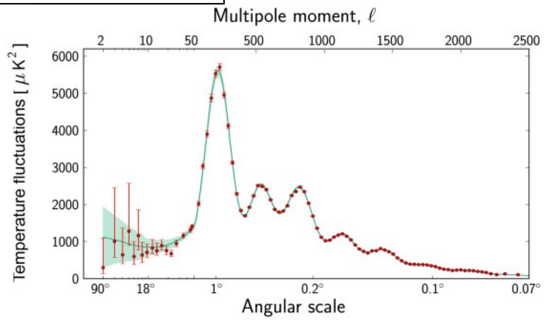


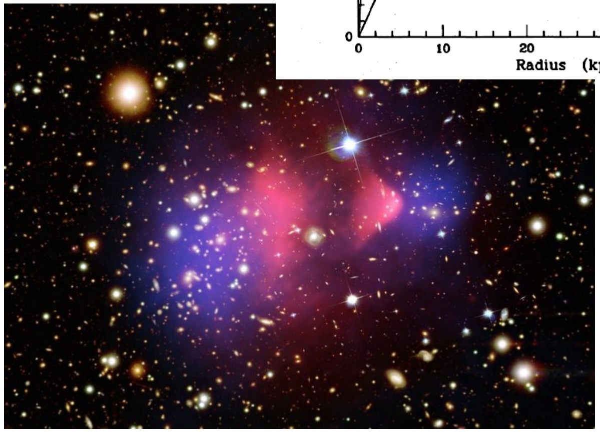


Galaxy rotation curves

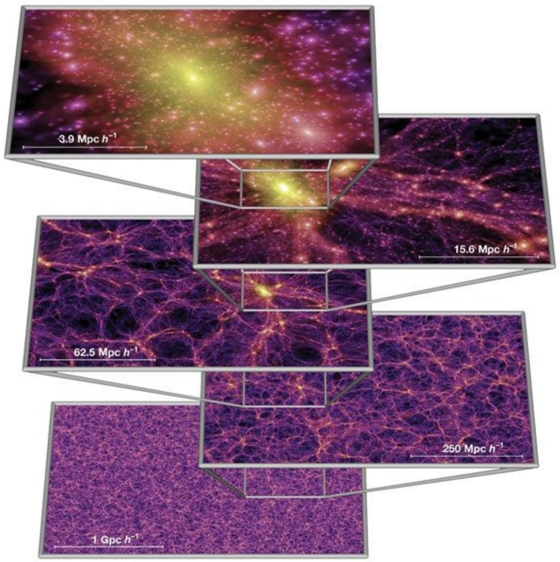


CMB

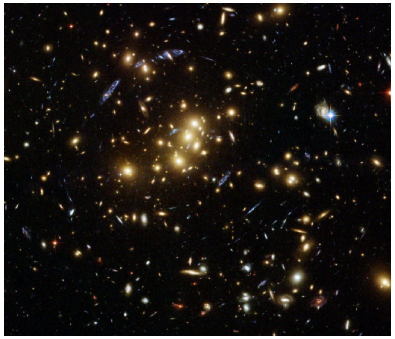




Bullet cluster



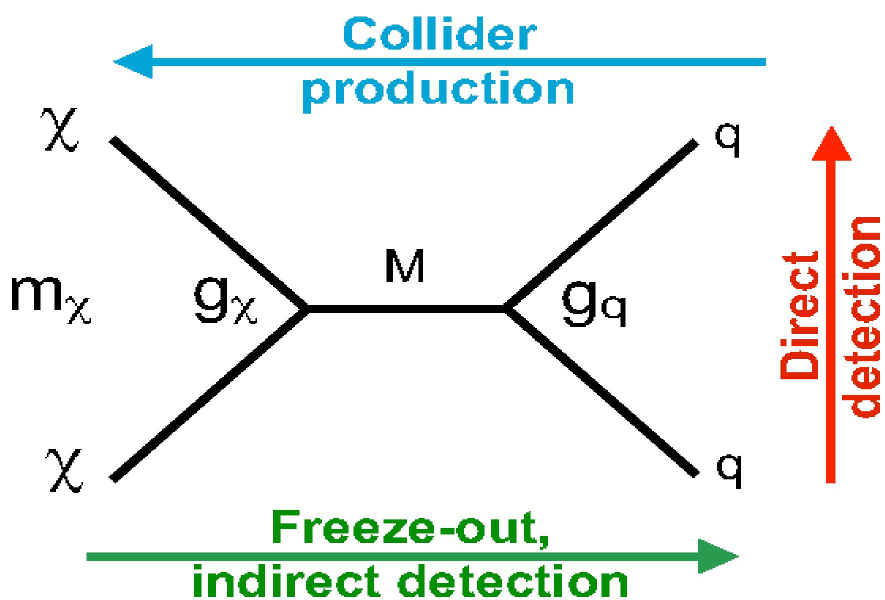
Large
Scale Structure

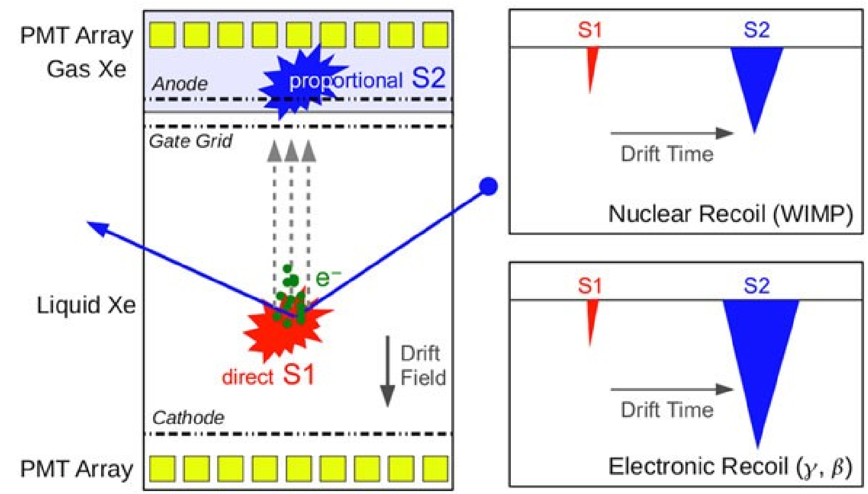


Gravitational lensing

Experimental complementarity

mono-X+MET, multilepton+MET, multijet+MET, non-prompt searches.





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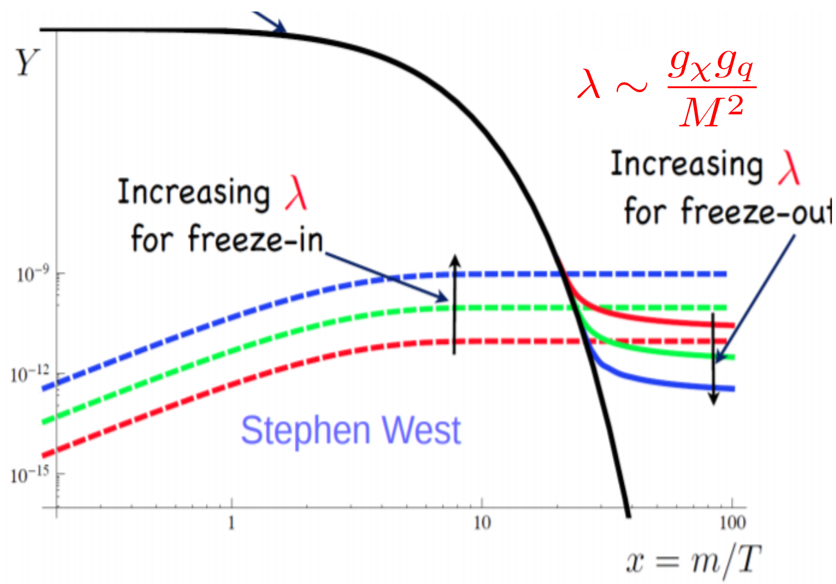
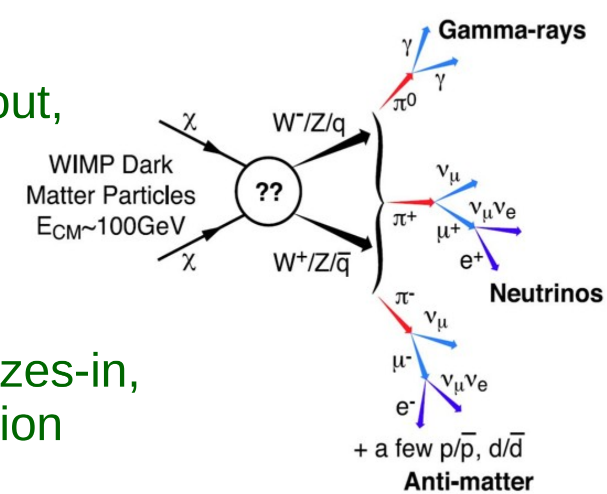


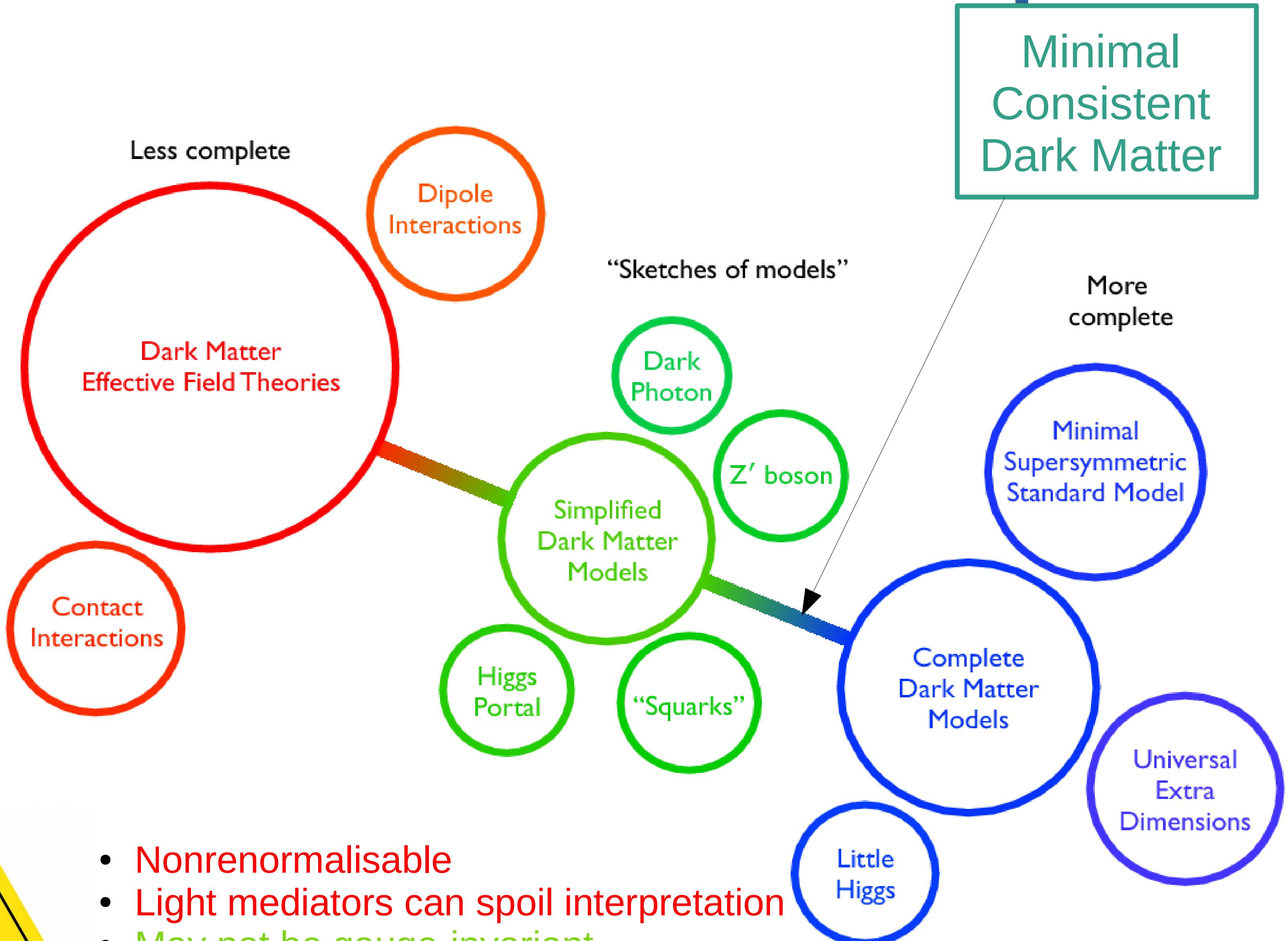
WIMP:
thermalised DM freezes out, requiring (co)annihilation channel(s)s

FIMP:
Non-thermalised DM freezes-in, requiring (feeble) production channel(s).



0912.3828

The model landscape



- Nonrenormalisable
- Light mediators can spoil interpretation
- May not be gauge-invariant
- May have anomalies

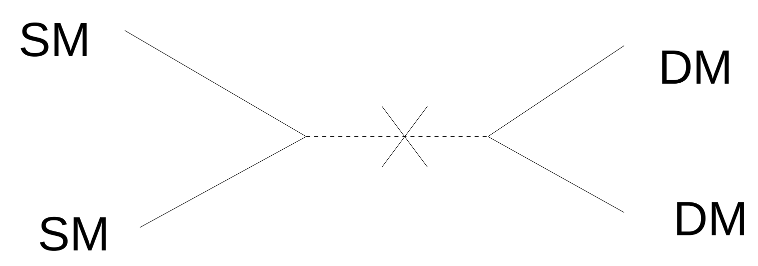
T.Tait 1506.03116

Why MCDM?

- EFT
  - Not valid at LHC if light mediators present

$$\frac{g_\chi g_{SM}}{M_{med}^2} \sim \frac{1}{\Lambda^2}$$

- Simplified models
  - Not always gauge-invariant, particles often treated as singlets
  - DM and/or mediator charged partners important for LHC phenomenology, coannihilation channels in early universe.
- MCDM
  - gauge-invariant, renormalisable and anomaly-free
  - Indirect mediators e.g higgs-portals, dark sectors
  - MFV only



Single multiplet

Y=0 $m_M \bar{\psi}^c \psi$

$$\Psi_L = \begin{pmatrix} \chi^{n+} \\ \vdots \\ \chi^+ \\ \chi_0 \\ (\chi^+)^C \\ \vdots \\ (\chi^{n+})^C \end{pmatrix}$$

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi - m_D \bar{\psi}\psi$$

$$\psi = \begin{pmatrix} \psi^{n+} \\ \vdots \\ \psi^+ \\ \psi_0 \\ \psi^- \\ \vdots \\ \psi^{m-} \end{pmatrix}$$

- Introduce non-chiral (vector-like) multiplet
- {I,Y}={0,0}, {½,½}, {1,0} may have yukawa to SM leptons
  - forbid these couplings by imposing Z_2
- {0,0} has no gauge-interactions – invisible to direct detection and collider but over(under) abundant if thermal(non-thermal)

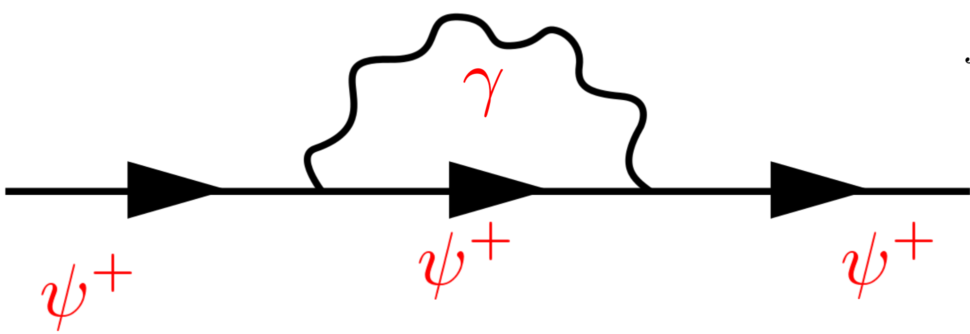
Cirelli et al. hep-ph/0512090

Radiative Mass split

Phenomenology highly sensitive to the mass split between components of a multiplet

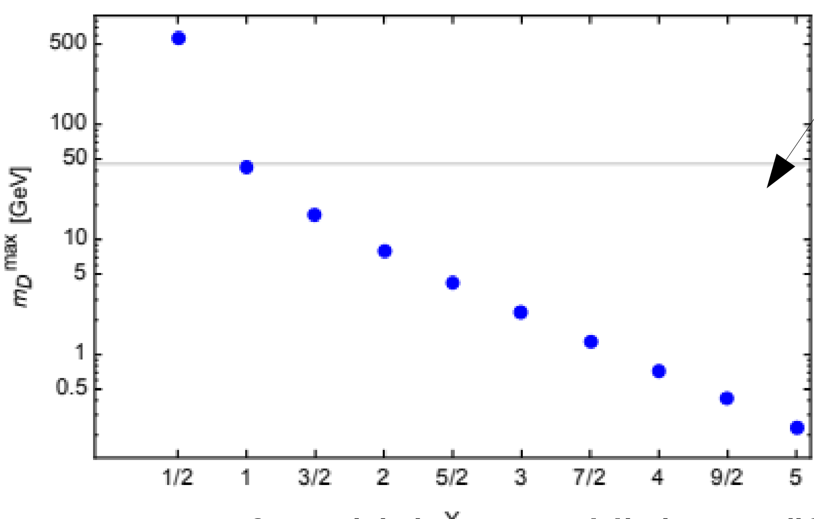
$$M_Q - M_{Q'} = \frac{M_D g^2}{16\pi^2}(Q - Q')\left[(Q + Q' - 2Y)(f_W - f_Z) + (Q + Q')(f_Z - f_\gamma)s_w^2\right]$$

$$f_a = \frac{r}{2}\left[2r^3\log(r) - 2r + \sqrt{r^2-4}\,(r^2+2)\log(A)\right] - 4$$

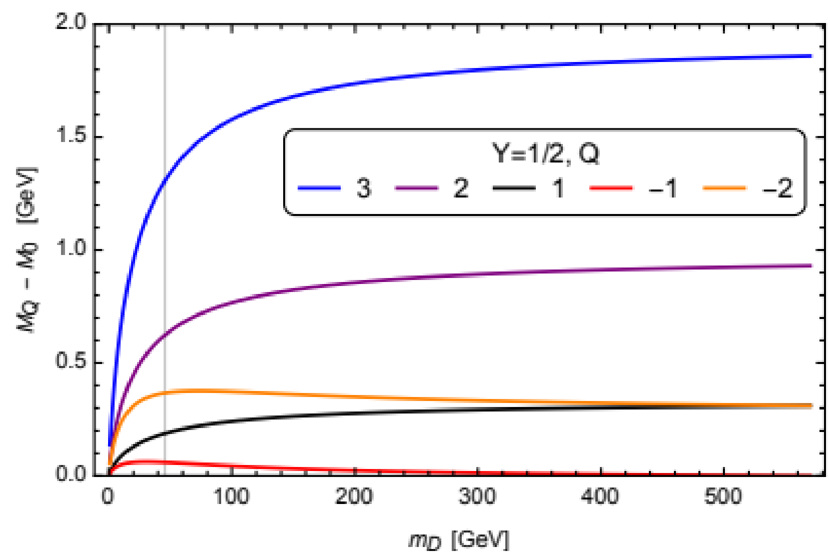


$$r = \frac{m_a}{M}$$

Excluded from Z decays



Max M for which neutral lightest (if Q=-1 present; I>Y)



Collider bounds

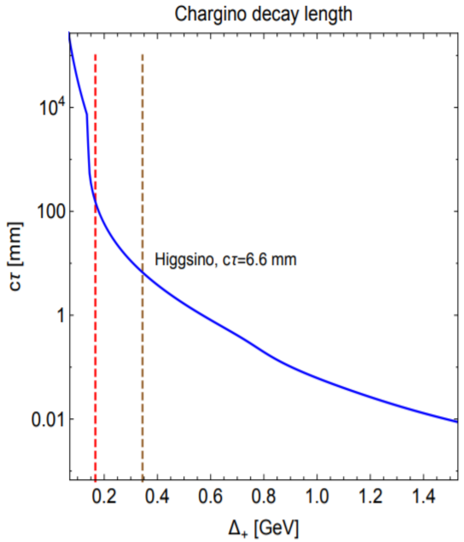
- LEP (209 GeV) constraint on charged particles

$$m_\psi^+ \gtrsim 100 GeV \quad \rightarrow \quad m_\psi^0 \gtrsim 100 GeV \quad (I \neq 0)$$

- Non-prompt searches for compressed spectra

$$\Gamma(\chi^- \rightarrow \chi_0 f \bar{f}) = \frac{2 N_C G_F^2 \Delta_+^5}{15\pi^3} \qquad (\Delta_+ \gg m_f)$$

$$\Gamma(\chi^- \rightarrow \chi^0 \pi^-) = \frac{2 G_F^2 f_\pi^2 cos^2(\theta_C)}{\pi} \Delta_+^3 \qquad (\Delta_+ \gg m_\pi^-)$$



Zurita et al. 1703.05327

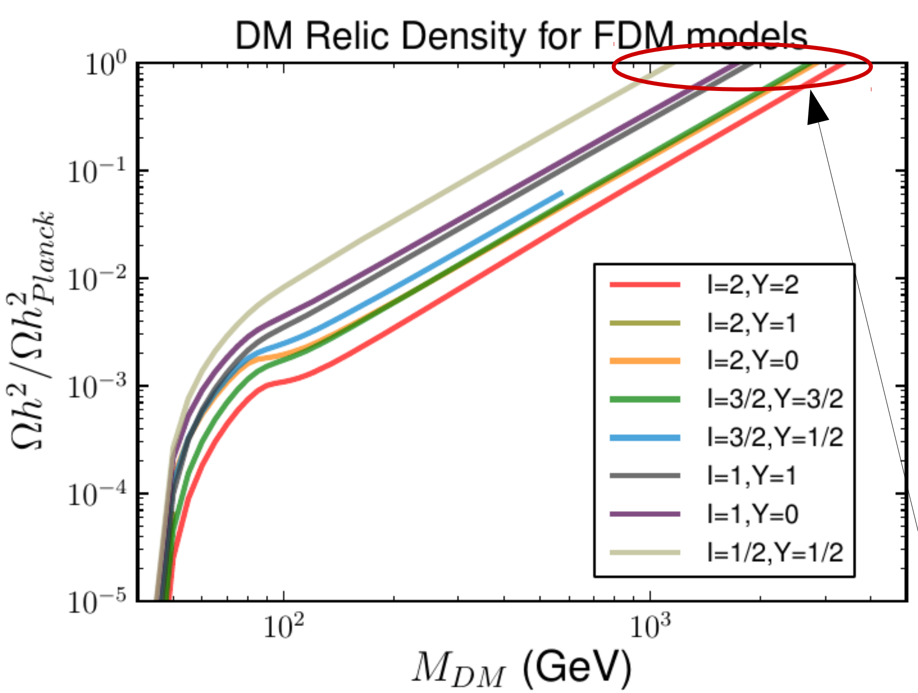
Chen, Drees, Gunion: hep-ph/951230, 9607421, 9902302.

Relic abundance

- Annihilation through Z, coannihilation with charged partners through W.

~Y²

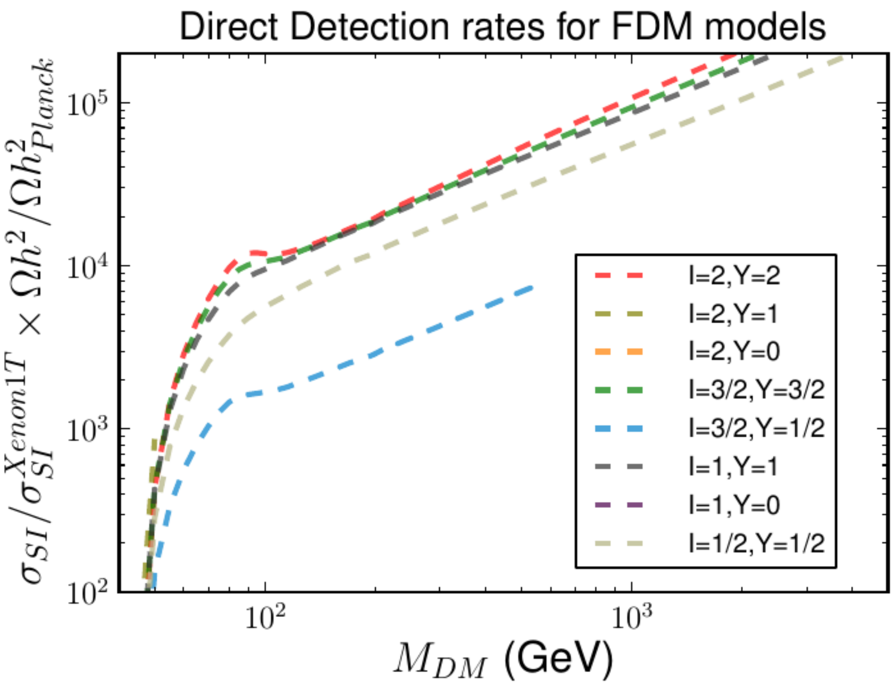
$$\dot{n}_1(t) + 3H(t)n_1(t) \approx -\left[< \sigma_{\chi_1\chi_1} v > + < \sigma_{\chi_1\chi_2} v > \frac{g_2}{g_1}\left(1+\frac{\Delta m_\chi}{m_{\chi_1}}\right)^{3/2} e^{-\Delta m_\chi/T} \right] (n_1(t)^2 - n_{1,eq}(t)^2)$$

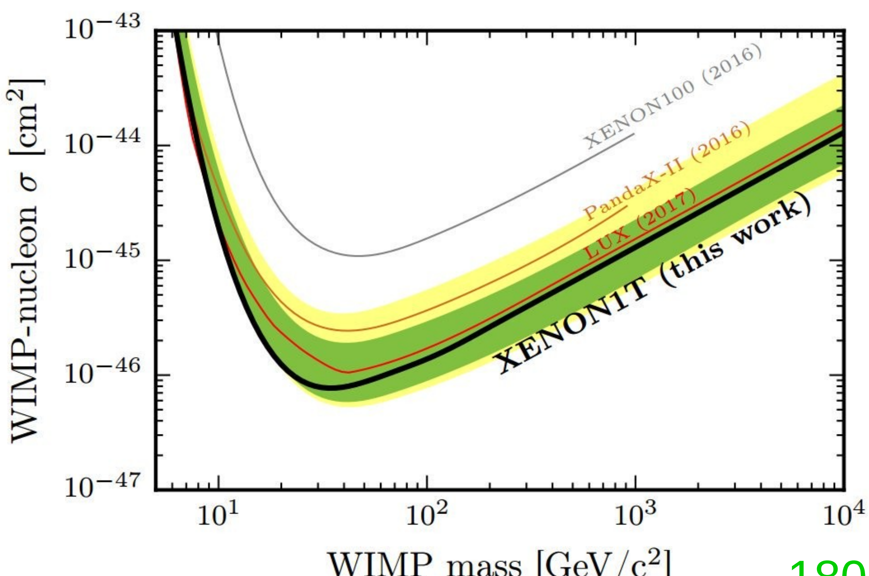


Dominates, driven by small mass split but also CC coupling

$$\Omega h^2 \approx \Omega h^2_{Planck} = 0.1188 \pm 0.0010 \quad at\ M_{DM} \sim \ few\ TeV$$

Direct detection





$Y \neq 0$
Excluded by DD

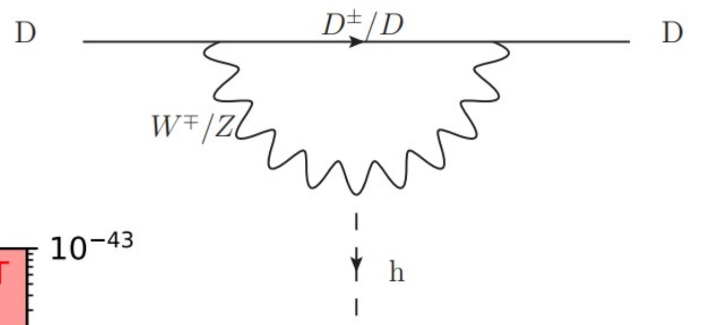
$Y = 0$
loop suppressed nucleon scattering – close to DD bounds

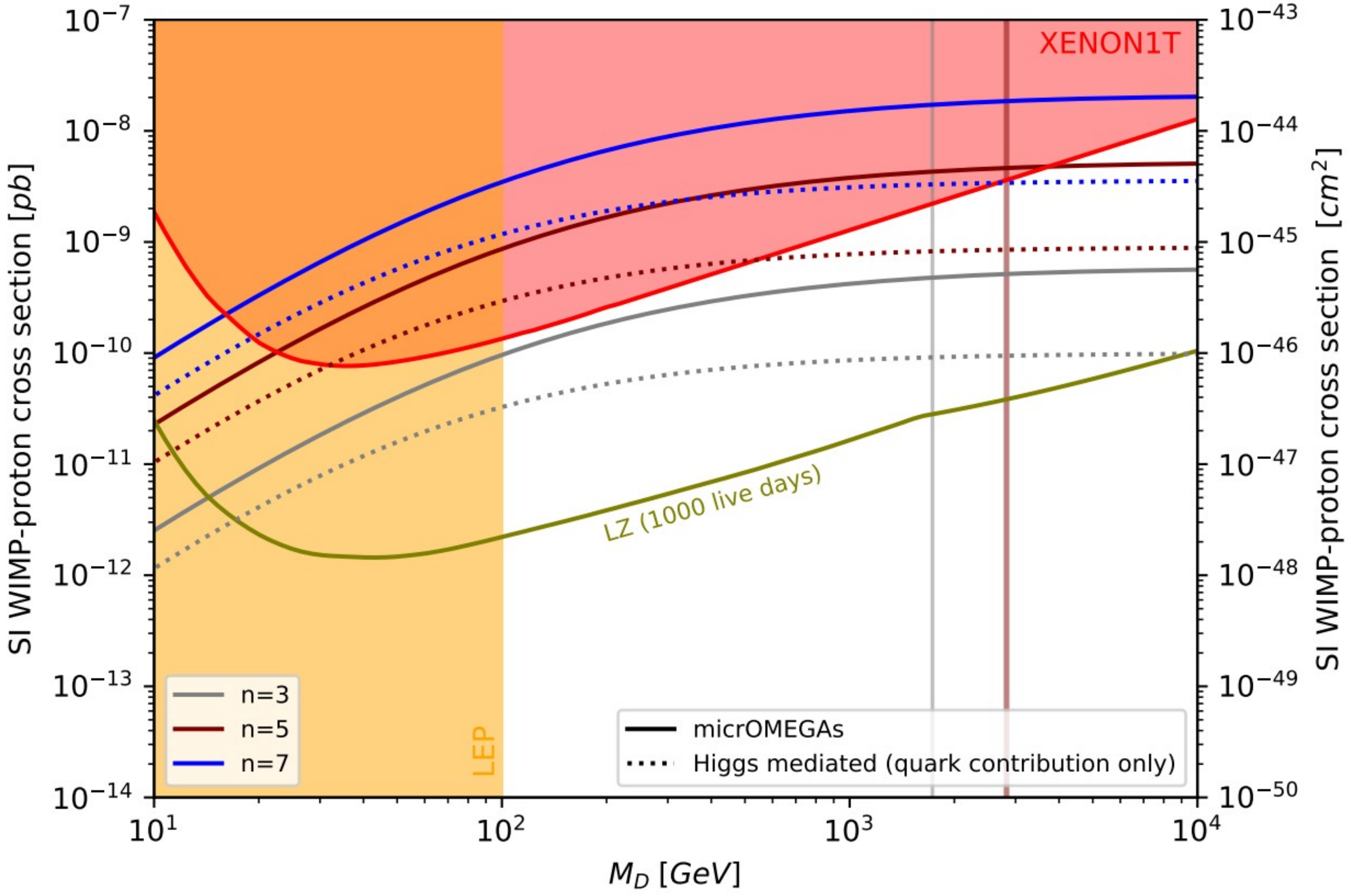
If mass split < 100KeV, may also have inelastic scatterings. But this would require masses below nuclear threshold (Y=0) if only from radiative split.

1805.12562

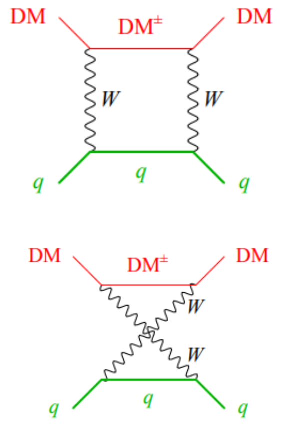
Direct detection loops

Y=0 minimal candidates (which are sizable piece of relic abundance) may be discovered or ruled out at next generation of DD experiments





+ box (WIP), expected to be O(triangle) in large MD limit



Dim-5 couplings to higgs?

Dim-5 operators generated by e.g Dirac mediator multiplet

$$\mathcal{L}_{\text{dim}--5} \supset -\frac{\kappa}{\Lambda}\,\phi_H^\dagger T^a_{1/2}\phi_H\;\bar{\Psi}T^a_I\Psi - \frac{\kappa'}{\Lambda}\,\phi_H^\dagger\phi_H\;\bar{\Psi}\Psi\,,$$

can be tuned to cancel (mass split dependent) loop contribution to DD cross section!

$$m'_D = m_D + \kappa'\frac{v^2}{2\Lambda}\,, \qquad M_Q - M_{Q'}\big|_{\text{Higgs}} = \mu_D(Q-Q') \qquad \mu_D = -\tfrac{\kappa v^2}{4\Lambda}$$

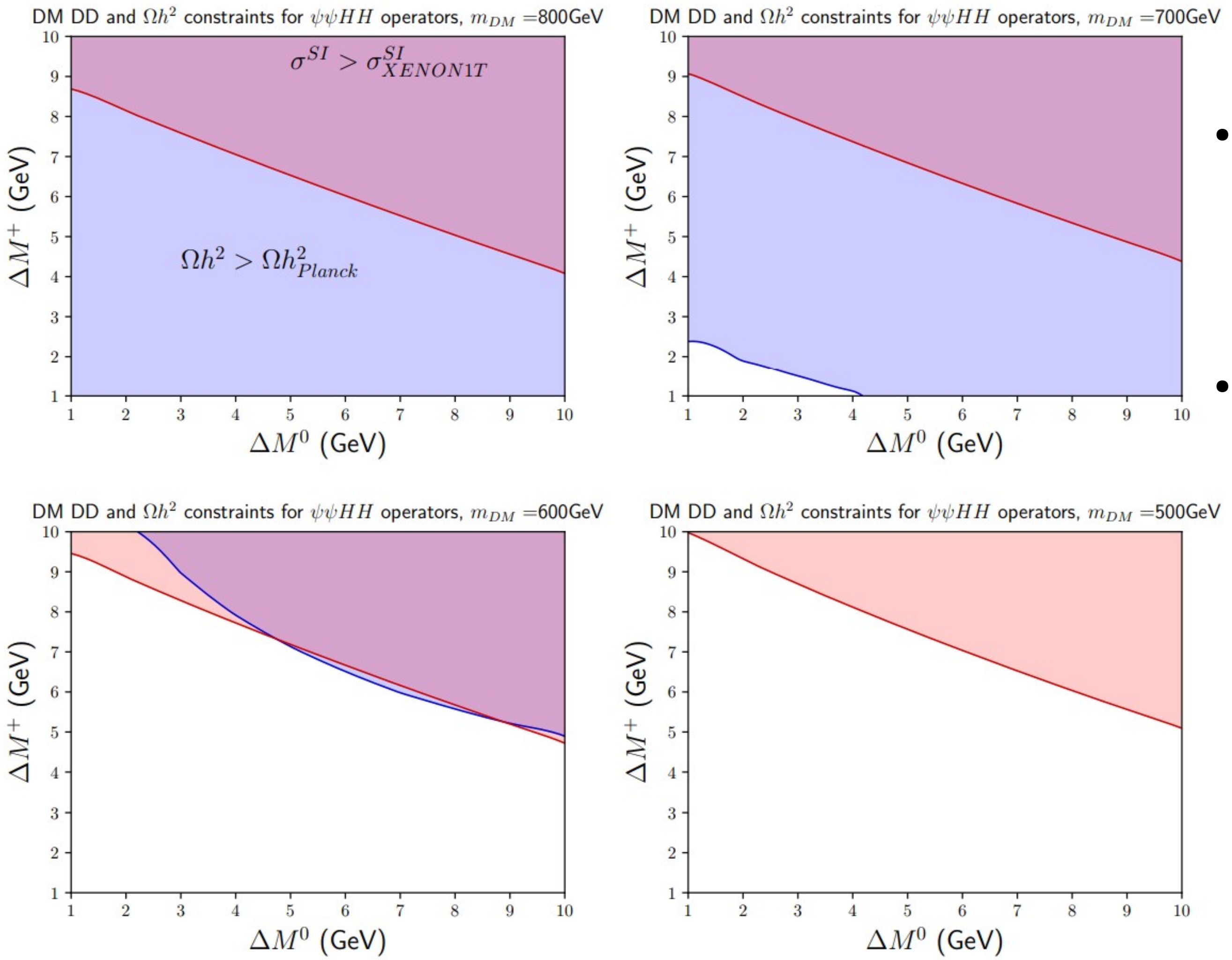
Special case – Y=1/2:

$$\Delta\mathcal{L}_{dim5} = -\frac{1}{2}\frac{\kappa_M}{\Lambda}\;\phi_H T^a_{1/2}\phi_H\;\bar{\Psi}T^a_I\Psi^C + \text{h.c.}$$

$$m^0_{1/2} = m_D - \frac{1}{2}\mu_D \pm c_{I+1/2}\mu_M\,, \qquad c_{I+1/2} = I + 1/2\,.$$

$$\mu_M = \tfrac{\kappa_M v^2}{4\Lambda}$$

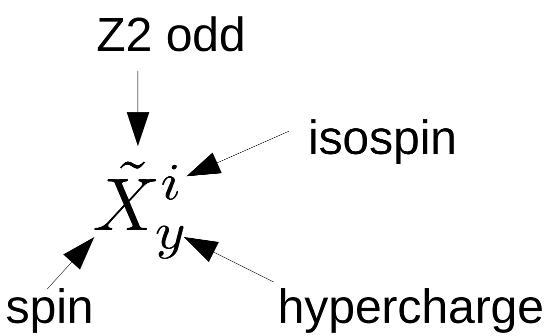
Dim-5 couplings to Higgs?



- Larger mass splits → larger dim5 couplings → larger DD signals

- NOTE: loops not included here, this example is **Y=1/2, I=1/2**

+Mediator



Spin of Dark Matter / Spin of Mediator	0	1/2	1
spin 0 even mediator	$\tilde{S}^I_Y S^{I'}_{Y'}$	$\tilde{F}^I_Y S^{I'}_0$	$\tilde{V}^I_Y S^{I'}_{Y'}$
spin 0 odd mediator	$\tilde{S}^I_Y \tilde{S}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{S}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{S}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{S}^{I'}_{Y'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\tilde{S}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{S}^I_Y \tilde{F}^{I'c}_{Y'}$	$\tilde{F}^I_Y \tilde{F}^{I\pm1/2}_{Y\pm1/2}$	$\tilde{V}^I_Y \tilde{F}^{I'}_{Y'}$ $\tilde{V}^I_Y \tilde{F}^{I'c}_{Y'}$
spin 1 even mediator	$\tilde{S}^I_Y V^{I'}_0$	$\tilde{F}^I_Y V^{I'}_0$	$\tilde{V}^I_Y V^{I'}_{Y'}$
spin 1 odd mediator	$\tilde{S}^I_Y \tilde{V}^{I'}_{Y'}$	$\tilde{F}^I_Y \tilde{V}^{I'}_{Y'}$ $\tilde{F}^I_Y \tilde{V}^{I'c}_{Y'}$	$\tilde{V}^I_Y \tilde{V}^{I'}_{Y'}$

$\tilde{F}^I_Y S^{I'}_{Y'}$

Even scalar mediator

$$\Delta\mathcal{L}_{\text{real}} = \frac{1}{2}(D_\mu\Phi)^2 - V(\Phi) - \frac{1}{2}\lambda\,(\Phi^2)(\phi_H^\dagger\phi_H) + V_{\text{linear}}$$

$$\Delta\mathcal{L}_{\text{com.}} = |D_\mu\Phi|^2 - V(\Phi) - \lambda\,(\Phi^\dagger\Phi)(\phi_H^\dagger\phi_H) - \lambda'\,(\Phi^\dagger T^a\Phi)(\phi_H^\dagger\tau^a\phi_H) + V_{\text{linear}}$$

$$Y' = 0$$

$$\Delta\mathcal{L}_{D1} = -y_1\Phi\bar{\psi}\psi$$ Real CP-even scalar

$$\Delta\mathcal{L}_{D2} = -iy_2\Phi\bar{\psi}\gamma^5\psi$$ Real CP-odd scalar

$$I' = 0, ..., 2I$$

$$Y' = 2Y$$

$$\Delta\mathcal{L}_{D3} = -y_3\Phi\bar{\psi}^c\psi + h.c.$$ Real CP-even scalar

$$\Delta\mathcal{L}_{D4} = -iy_4\Phi\bar{\psi}^c\gamma^5\psi + h.c.$$ CP-odd scalar

$$I' = 0, ..., 2I$$

Majorana DM: Y=0; LD2, LD4 vanish and LD1 & LD3 coincide by Majorana condition.

Even scalar mediator

If Φ acquires VEV there are eventual linear couplings of Φ to Higgs doublet, possible only in 3 cases:

$$\mathrm{S}_0^0 \Rightarrow V_{\text{linear}} = -\mu\ \Phi\ \phi_H^\dagger \phi_H\ , \quad (\text{CP-even})\,;$$

$$\mathrm{S}_0^1 \Rightarrow V_{\text{linear}} = -\mu\ \Phi^a\ \phi_H^\dagger \tau^a \phi_H\ , \quad (\text{CP-even})\,;$$

$$\mathrm{S}_1^1 \Rightarrow V_{\text{linear}} = -\mu\ \Phi^a\ \phi_H^\dagger \tau^a \phi_H^\dagger + \text{h.c.}\,.$$

Higgs portal interactions if CP-even – present if VEV induced for scalar → dangerous for rho parameter

$$\rho = \frac{m_W^2}{m_z^2 cos^2(\theta_w)} \sim 1 \rightarrow \frac{\Sigma_i 4 Y_i^2 v_i^2}{\Sigma_i (I_i(I_i+1) - Y_i(Y_i-1)) v_i^2} \sim 1$$

If scalar mixes with Higgs, SM-like Higgs couplings modified → couplings to SM fermions must be small. There are exceptions to this, where direct couplings can exist:

$$\mathrm{S}_2^0 \Rightarrow V_{\text{ferm.}} = -y_s\ \Phi\ \bar{e}_R^c e_R$$
$$\mathrm{S}_1^1 \Rightarrow V_{\text{ferm.}} = -y_s\ \Phi^a\ \bar{l}_L^c \tau^a l_L$$

← Type-II see saw like, breaks lepton number conservation

Important cases

- Linear couplings present $\Phi\phi_H^2$
  - generated by Φ VEV → mixes with Higgs (Higgs portal)
  - Experiment strongly limits size of VEV through rho parameter
- Bi-linear couplings only $\Phi^2\phi_H^2$
  - Φ VEV forbidden → scalar not a direct mediator
  - Φ may be accidentally stable → 2-component DM
- Lepton couplings
  - allowed in 2 special cases

$$S_2^0, \quad S_1^1$$

Two component models

- If only bilinear couplings of mediator to SM:

$m_\Phi < 2m_\psi$

Φ accidentally stable

- $m_\Phi < 2m_\psi$ & $\tilde{F}^0_Y$ $\quad Y \lesssim 10^{-8}$ $\psi\, FIMP$

$\Phi\,\psi$ only couple through Y. $\quad Y \sim 1$ $\psi\, WIMP$

- $m_\Phi > 2m_\psi$ & $\tilde{F}^0_Y$ $\quad Y \lesssim 10^{-10}$ $\psi\, superWIMP$

ψ will not thermalise, Φ obtains thermal relic which decays into ψ after freeze-out $\quad Y \sim 1$ $\quad \Omega_\Phi \sim 0$

Two-component DM model

- We explore a minimal model with accidentally stable pseudo-scalar mediator, with interesting interplays

$$\tilde{F}^0_0 S^0_0 (CP - odd)$$

$$\mathcal{L} \supset iY_\psi a \bar{\psi} \gamma^5 \psi - \frac{\lambda_{aH}}{4} |a|^2 \phi^\dagger_H \phi_H$$

- a does not acquire VEV → no linear coupling to Higgs
- $m_a < 2m_\psi$ → “secluded DM”
- Model implemented in LanHEP, and numerical scan performed using micrOMEGAs.

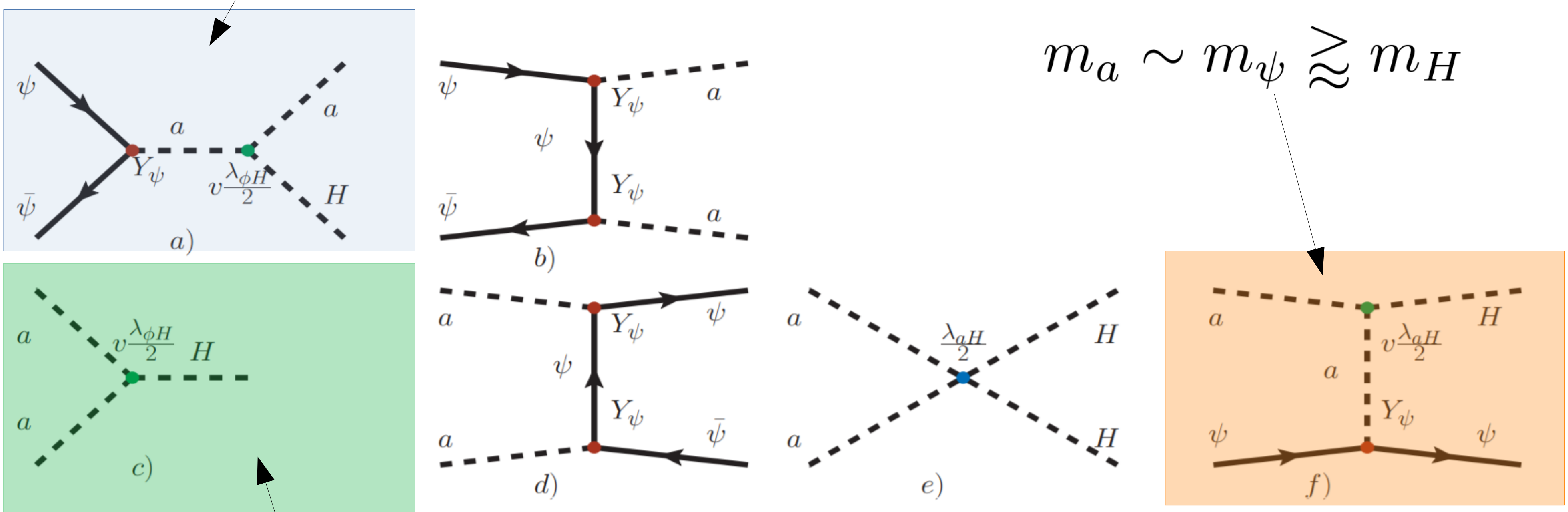
4 relevant parameters:

$$m_\psi, \; Y_\psi, \; m_a, \; \lambda_{aH}$$

(co)Annihilation channels

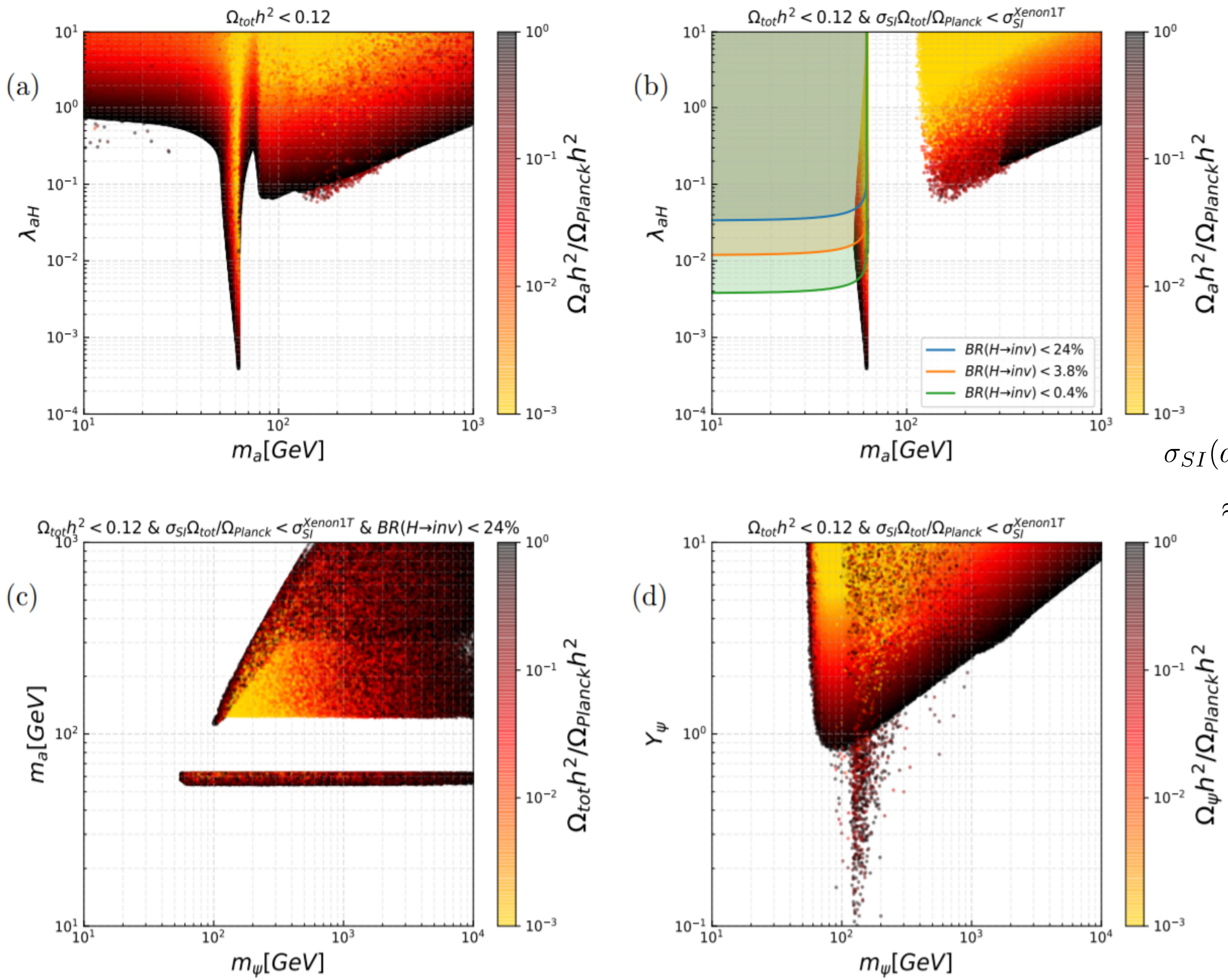
$$m_\psi \gtrapprox \frac{m_a + m_h}{2} \gtrapprox \frac{3m_H}{4} \sim 90GeV$$

$$m_a \sim m_\psi \gtrapprox m_H$$

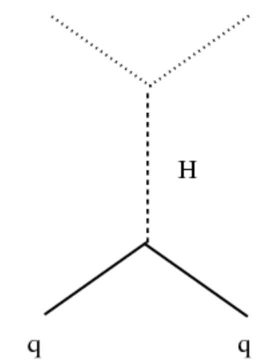


$$\sigma^{ann}_{aa\to ff} v \sim \frac{\lambda^2 m_f^2}{(4m_a^2 - m_H^2)^2 + m_H^2 \Gamma_H^2)}$$

aa→WW	ma>80GeV
aa→ZZ	ma>90GeV
aa→tt	ma>173GeV



$$\sigma_{SI}(aN \to aN) \sim \frac{\lambda_{aH}^2 f_N^2 A^2 m_N^4}{m_H^4 m_a^2} \approx 3 \times 10^{-7} \frac{\lambda_{aH}^2}{m_a^2}$$

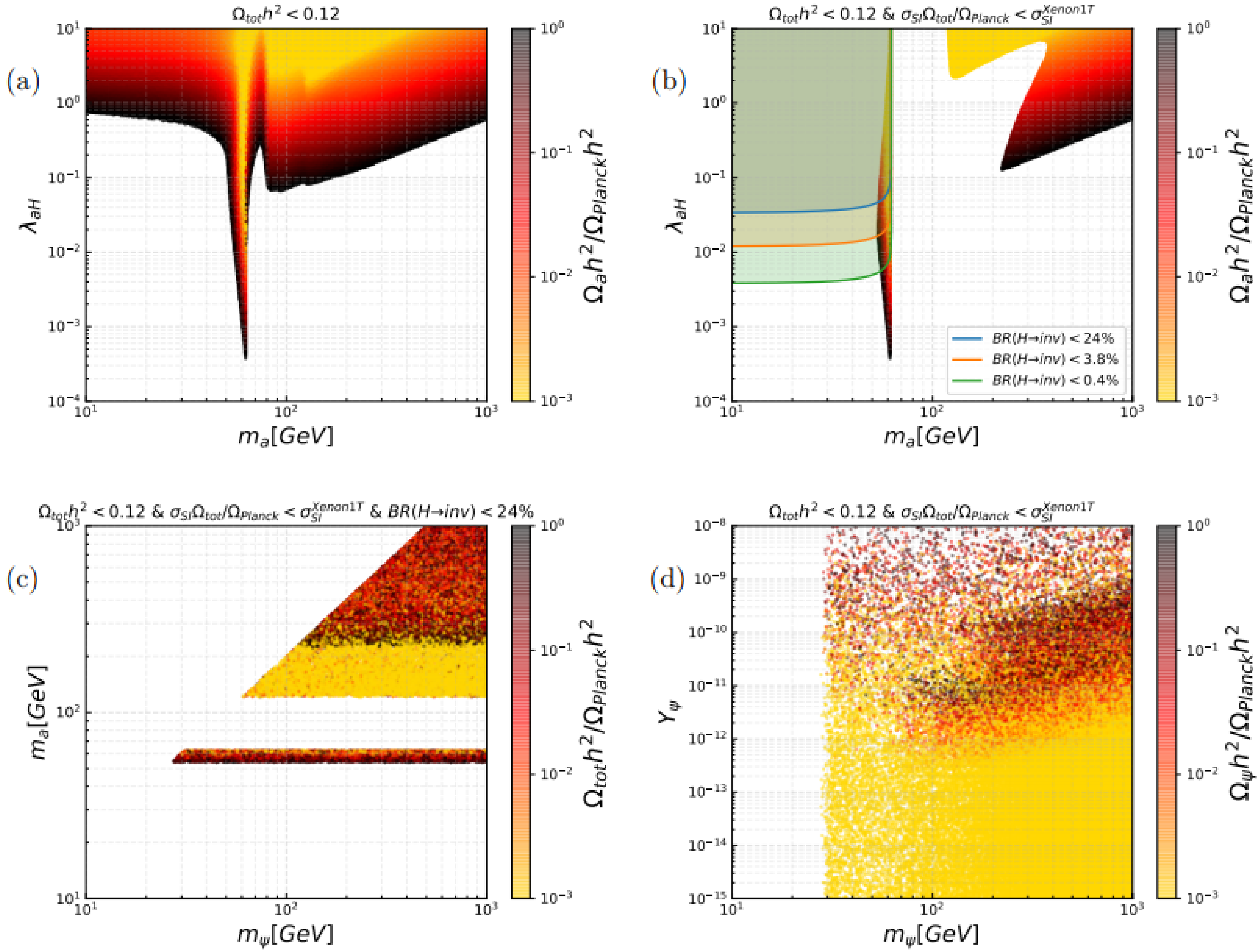


Metastable a

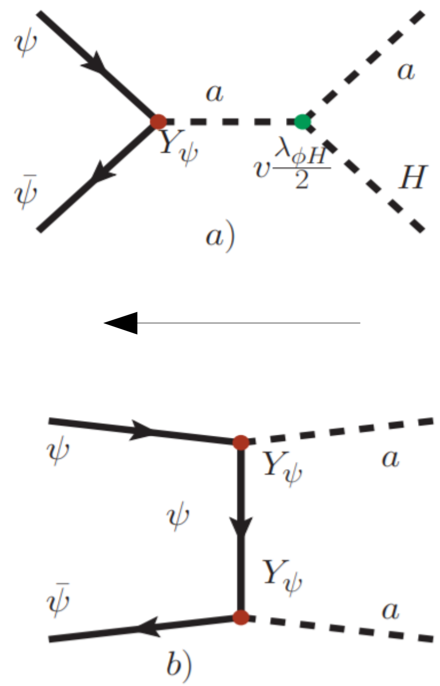
$$\Gamma(a \to \bar{\psi}\psi) = \frac{Y_\psi^2}{4\pi} m_a \left(1 - \frac{4m_\psi^2}{m_a^2}\right)^{\frac{3}{2}}$$

- Scalar **unstable** if $m_a > 2m_\psi$
- Can be **metastable** with width order of universe age – either fine tune mass or $Y_\psi \lesssim 10^{-12}$
- Can have DM mostly thermal a at freeze-out (DD visible), with small part non-thermal ψ (superWIMP)
- Decays to ψ make DM less visible to DD
- These decays to warm ψ can change velocity distributions of DM → mass ratio limited by LSS formation
- WIMPs predict overdense cores, order of magnitude more dwarf galaxies in local group than observed and disk galaxies with less angular momentum. Velocity and angular momentum of DM halos can increase naturally in superWIMP scenarios (J. Cembranos eta l. hep-ph/0603067)

Non-thermal ψ



$$m_a < 2m_\psi$$



Conclusions & Outlook

- Systematic classification of MCDM reveals interesting models even for simplest case: two component DM with **pseudoscalar** mediator
- **Y=0** minimal fermionic DM models not yet fully excluded by experiment - non-singlets can be probed via non prompt searches or SUSY-like cascades at colliders. Observables highly dependent on mass-split.
- Consistent models with additional mediators may have rich phenomenology. Interesting scenarios may arise even from very simple models, even singlet cases → Portals and dark sectors

Backup – loop details

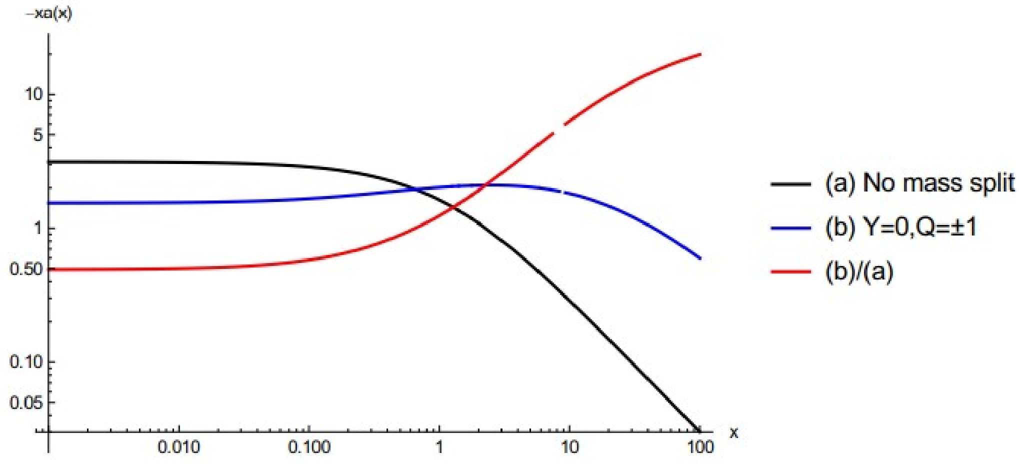


Figure 3. Triangle loop function -x.a(x,y) against x (inversely proportional to MDM)

$$a(x,y) = 2 + \left(y^2 - x^2\right)\log\left(\frac{x^2}{(y+1)^2}\right) + \frac{2\left(x^4 - 2x^2\left(y^2+y+1\right) + y^3(y+2) - 4y - 2\right)\log\left(\frac{x^2+\sqrt{(x-y-2)(x-y)(x+y)(x+y+2)}+y(y+2)}{2x(y+1)}\right)}{\sqrt{(x-y-2)(x-y)(x+y)(x+y+2)}} \tag{1.5}$$

Now notice that, in limit of zero mass split ($y = 0$), expanding around $x = 0$ - corresponding to $M_D >> M_W$:

$$\lim_{y\to 0} x.a(x,y)|_{x\approx 0} = -\pi + 3x - \frac{9\pi x^2}{8} + \mathcal{O}(x^2) \tag{1.6}$$

For the full scattering processs for DM and nucleon, $DN \to DN$, using $g_{hqq} = \frac{gM_q}{2M_W}$ and $\alpha_2 = \frac{g^2}{4\pi}$:

$$i\mathcal{M}_{2\to 2} = i\mathcal{M}_{DDh}.\frac{-igM_q}{2M_W}.\frac{i}{(k_1+k_2)^2 - M_h^2}\bar{u}(p_4)u(p_3) \tag{1.7}$$

$$= i\alpha_2^2\frac{M_q}{2M_W}\frac{1}{M_h^2}\left[\frac{Y^2}{c_W^3}x_Z a(x_Z, y_{D_2}) + \frac{x_W}{8}\left[(n^2-(1-2Y)^2)a(x_W,y_{D^+}) + (n^2-(1+2Y)^2)a(x_W,y_{D^-})\right]\right]\bar{u}(p_2)u(p_1)\bar{u}(p_4)u(p_3) \tag{1.8}$$

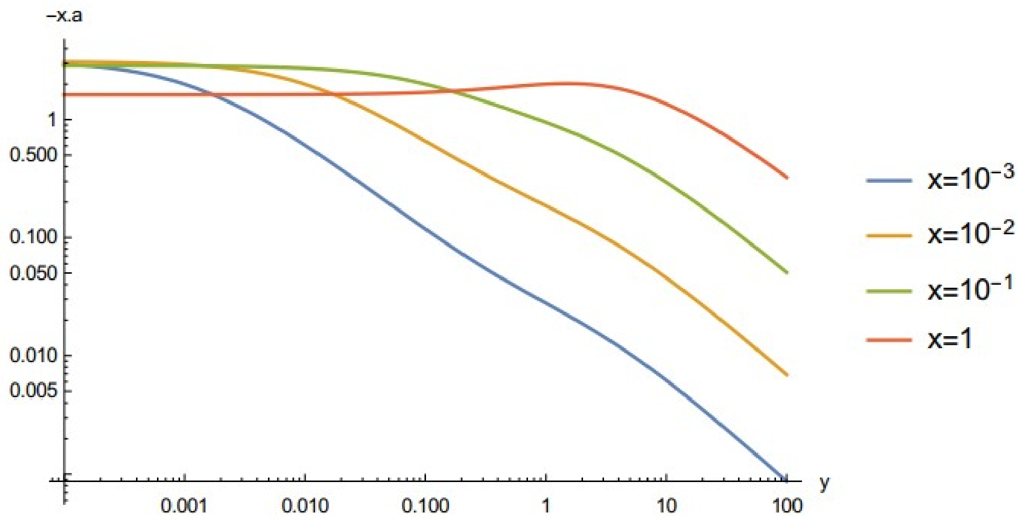
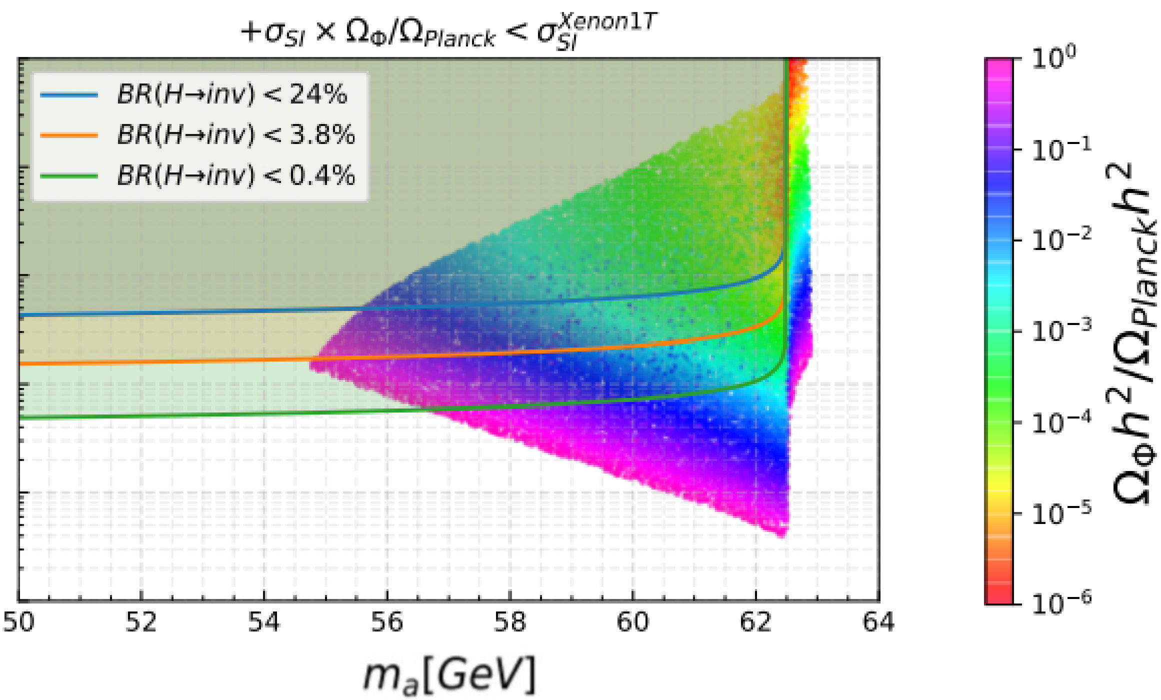


Figure 4. Triangle loop function -x.a(x,y) against y (mass split between MDM and fermion in loop / MDM)

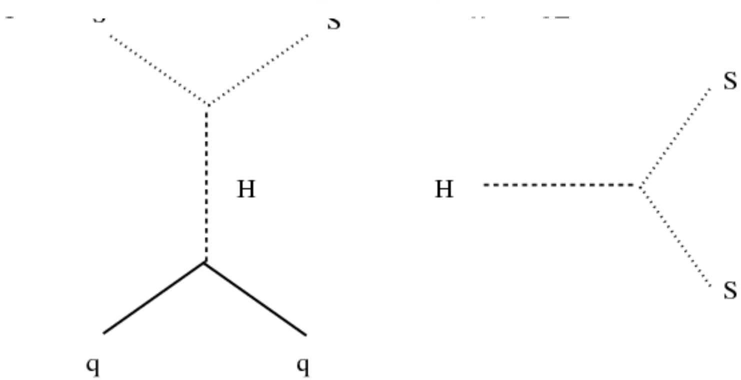
$$x_V = \frac{M_V}{M_D}$$

$$y_i = \frac{M_i - M_D}{M_D}$$

Direct Detection & Higgs invisible decays



$$\sigma_{SI}(aN \to aN) \sim \frac{\lambda_{aH}^2 f_N^2 A^2 m_N^4}{m_H^4 m_a^2}$$
$$\approx 3 \times 10^{-7} \frac{\lambda_{aH}^2}{m_a^2}$$



σ_{S-P}^{SI} Γ_H^{inv}

$$\Gamma_{H\to aa} = \frac{\lambda_{aH}^2 v^2}{128\pi m_H}\sqrt{1 - \frac{4m_a^2}{m_H^2}}$$