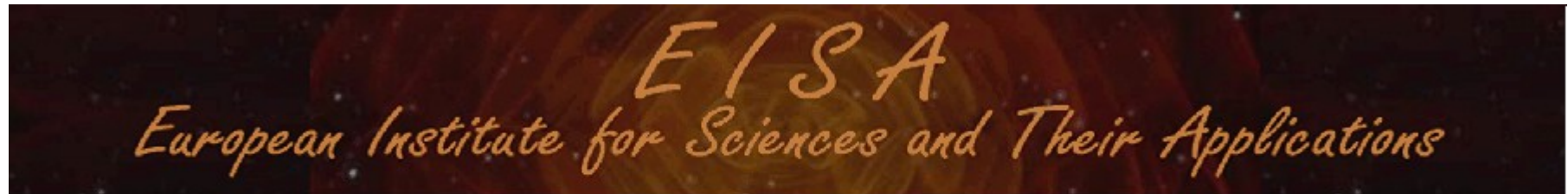


Minimal Consistent Fermion Dark Matter



Connecting Insights in Fundamental Physics: Standard Model
and Beyond
9th Sept 2019

Daniel Locke

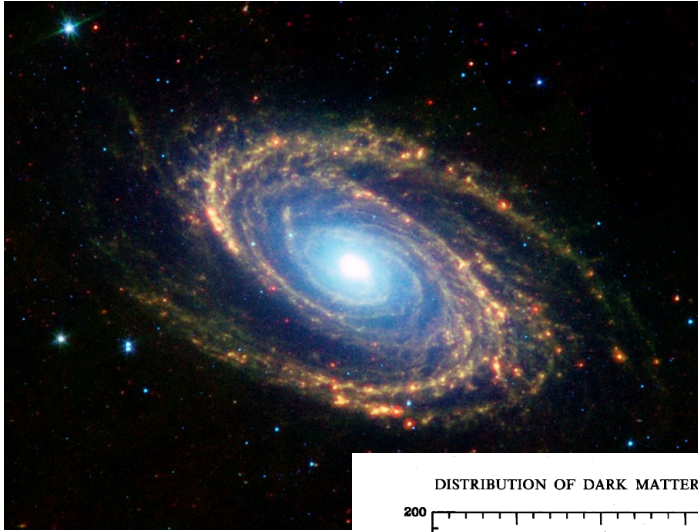
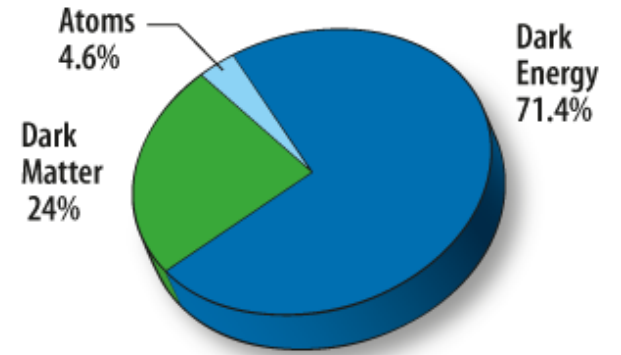


In collaboration with A.Belyaev, G.Cacciapaglia

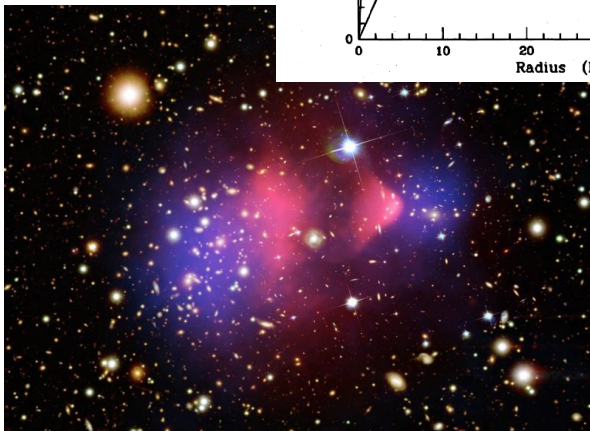
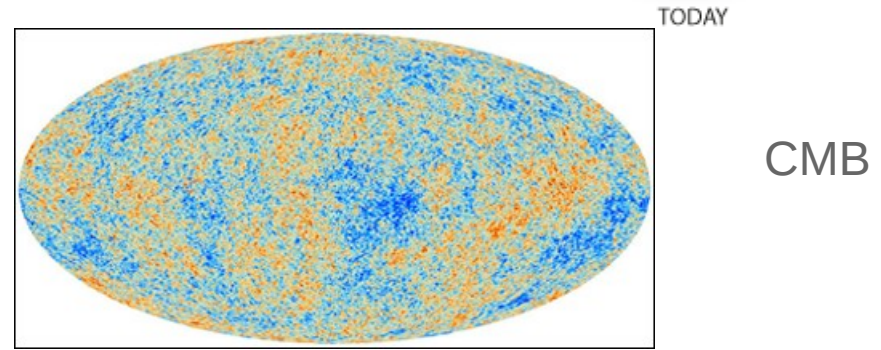
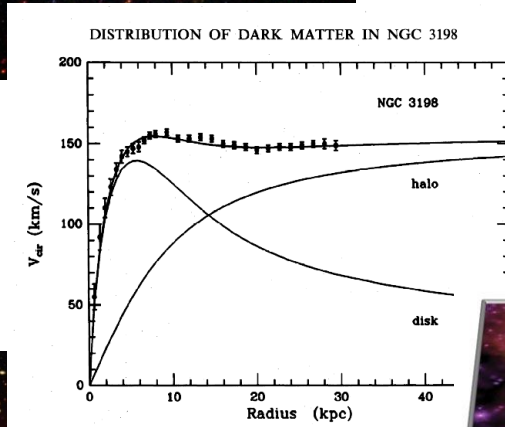
Outline

- 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

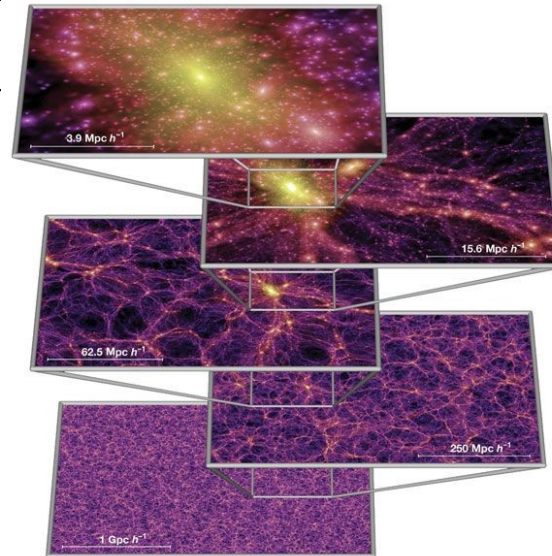
Why DM?



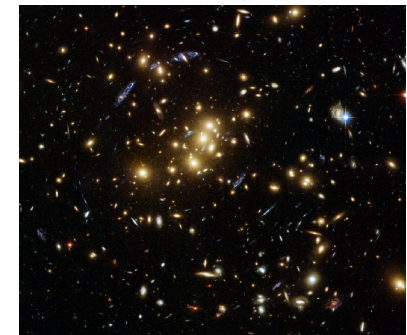
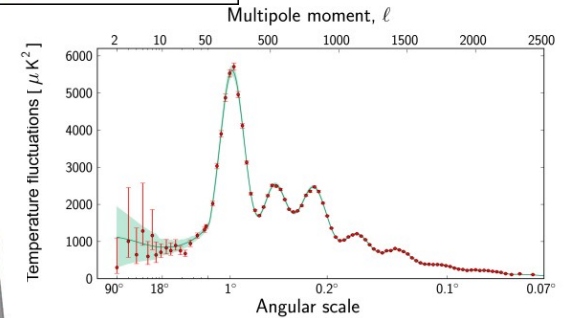
Galaxy rotation curves



Bullet cluster

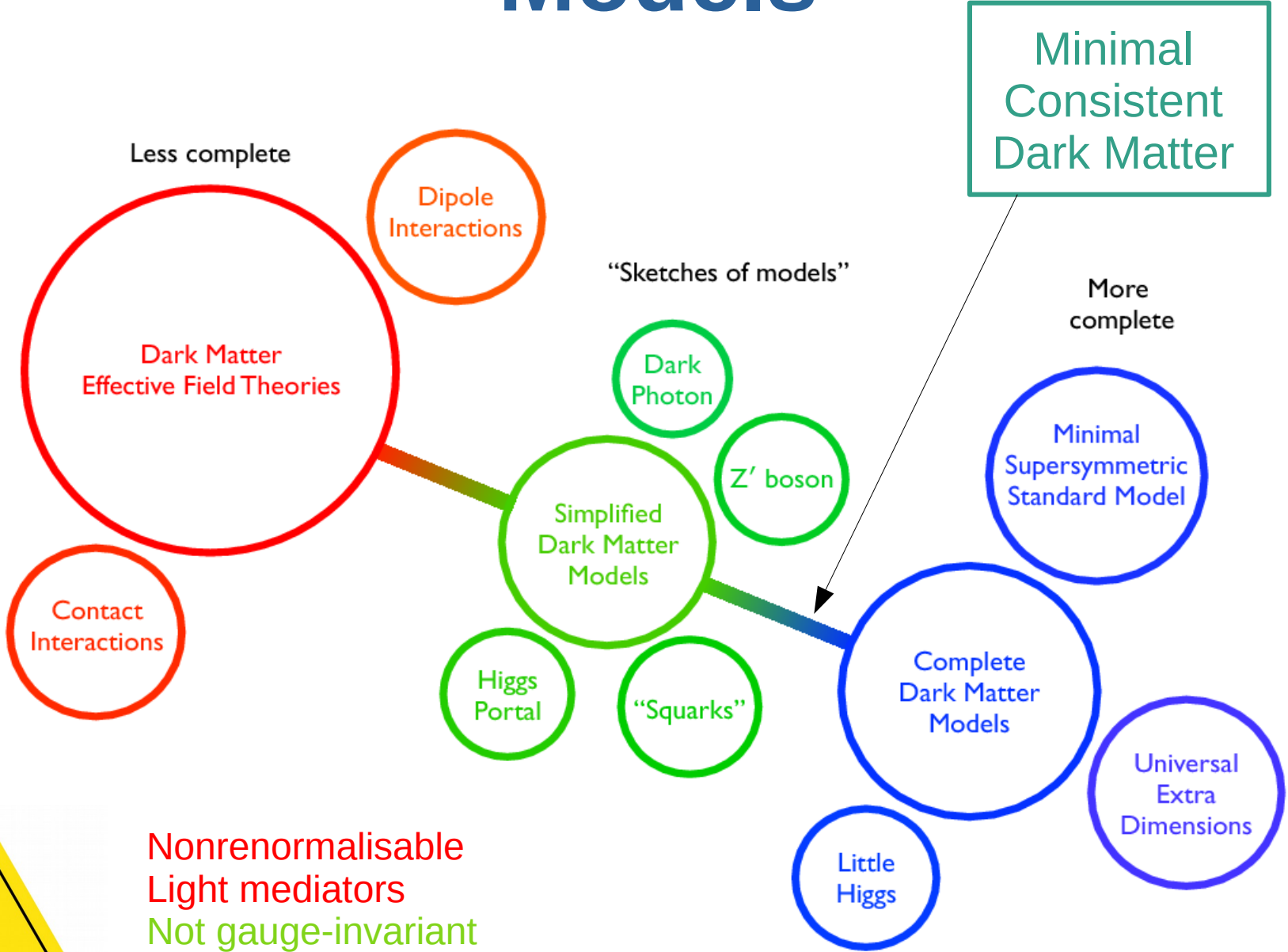


Large Scale Structure



Gravitational lensing

Models



Nonrenormalisable
Light mediators
Not gauge-invariant
May have anomalies



Why MCDM?

- EFT

- Not valid at LHC if light mediators present

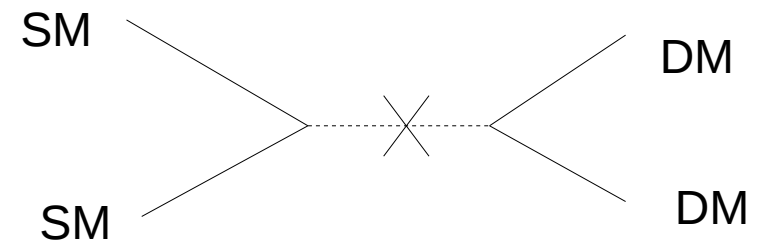
$$\frac{g_{\chi} g_{SM}}{M_{med}^2} \sim \frac{1}{\Lambda^2}$$

- 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

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

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

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

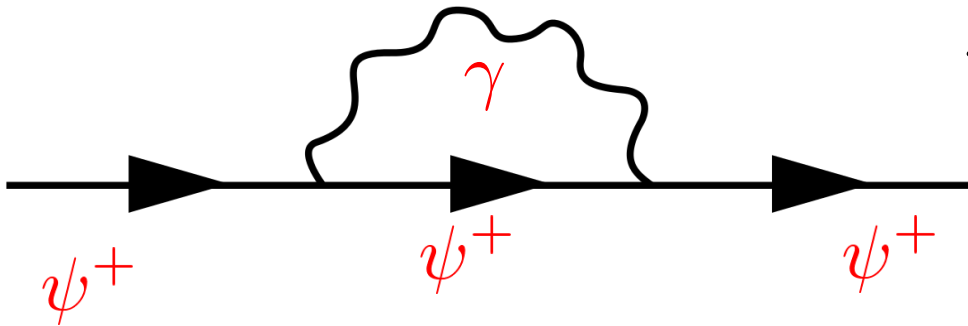
- Introduce **non-chiral** Dirac multiplet
- $\{I, Y\} = \{0, 0\}, \{1/2, 1/2\}, \{1, 0\}$ may have yukawa to SM leptons
 - **forbid these couplings by imposing Z_2**
- $\{0, 0\}$ has no gauge-interactions – invisible to direct detection and collider but over(under) abundant if thermal(non-thermal)

Radiative Mass split

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

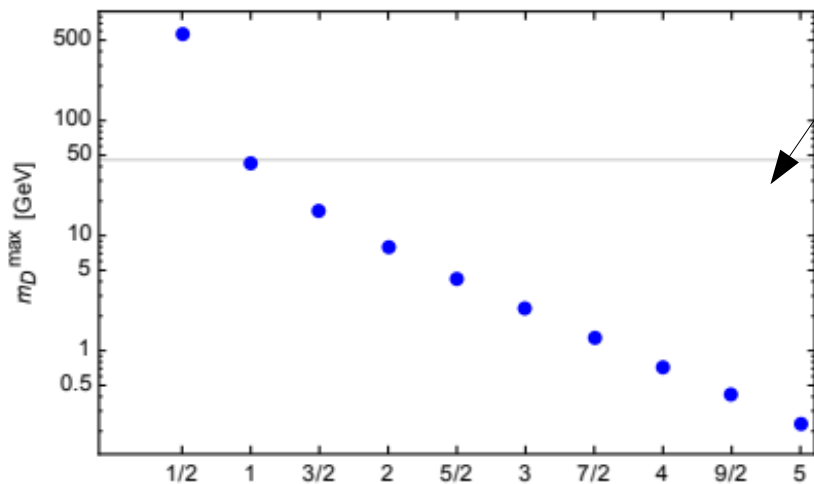
$$M_Q - M_{Q'} = \frac{M_D g^2}{16\pi^2} (Q - Q') \left[(Q + Q' - 2Y)(f_W - f_Z) + (Q + Q')(f_Z - f_\gamma) s_w^2 \right]$$

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

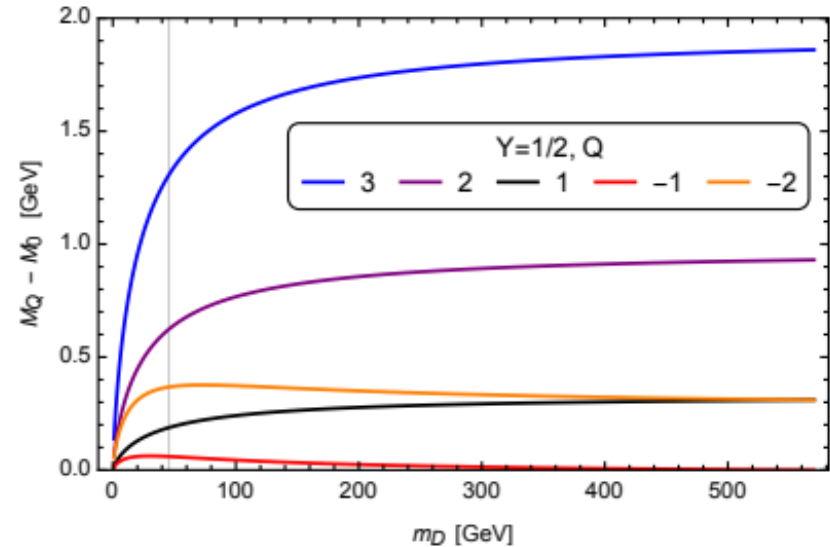


Excluded from Z decays

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



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

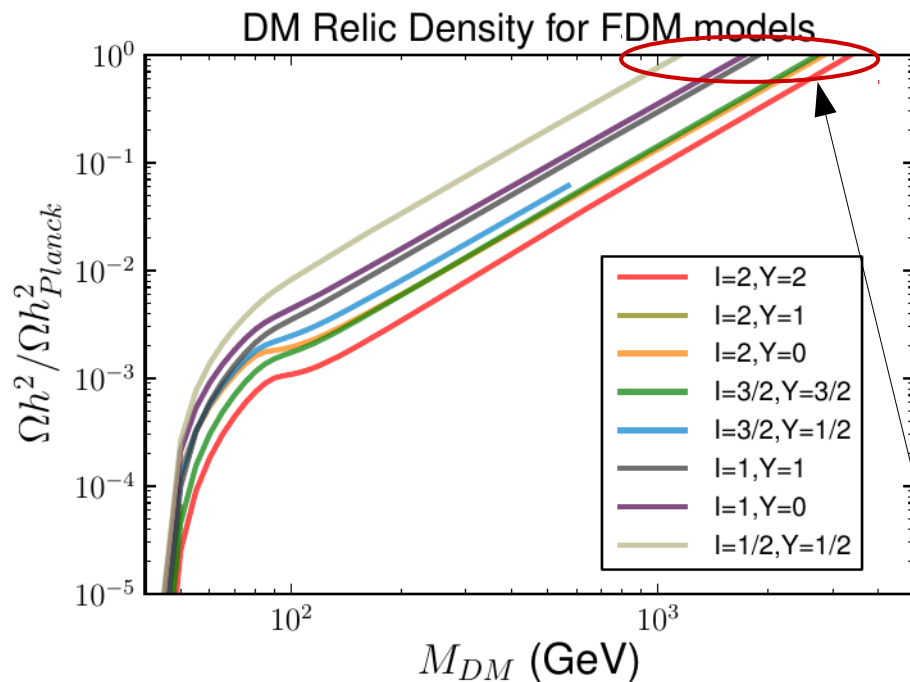


Relic abundance

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

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

$\sim Y^2$



Dominates, driven by small mass split but also CC coupling

Note: lines end when neutral state no longer lightest state

$$\Omega h^2 \approx \Omega h^2_{Planck} = 0.1188 \pm 0.0010 \quad \text{at } M_{DM} \sim \text{few TeV}^9$$

Colliders

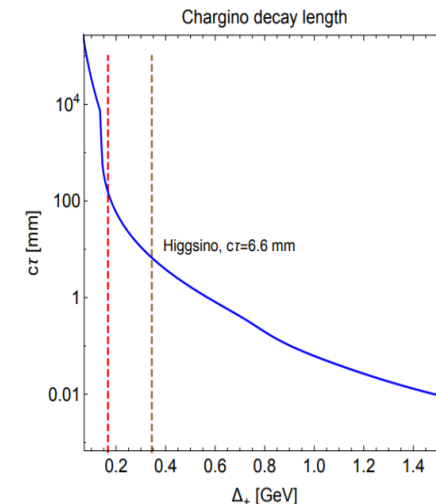
- LEP (209 GeV) constraint on charged particles

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

- Non-prompt searches for compressed spectra

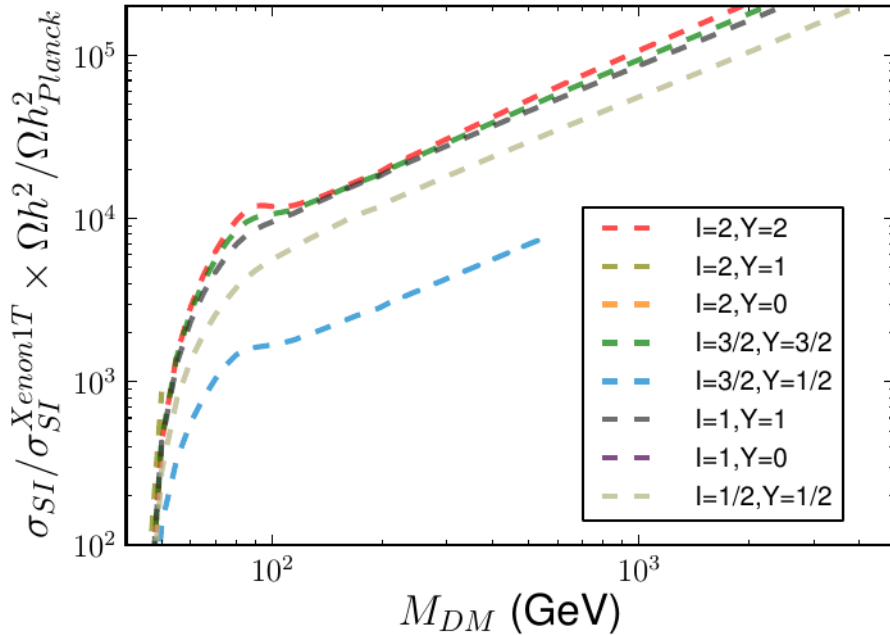
$$\Gamma(\chi^- \rightarrow \chi_0 f \bar{f}) = \frac{2N_C G_F^2 \Delta_+^5}{15\pi^3} \quad (\Delta_+ \gg m_f)$$

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



Direct detection

Direct Detection rates for FDM models

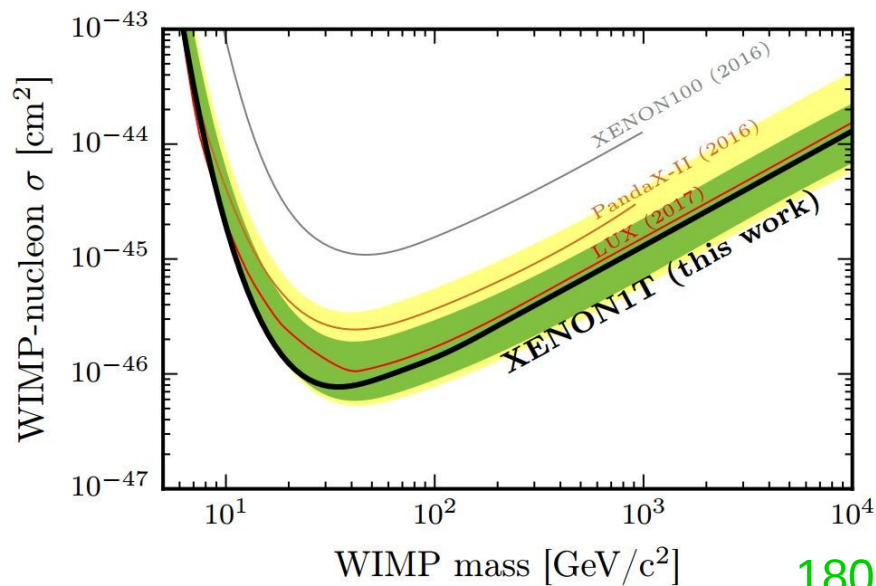


$Y \neq 0$

Excluded by DD

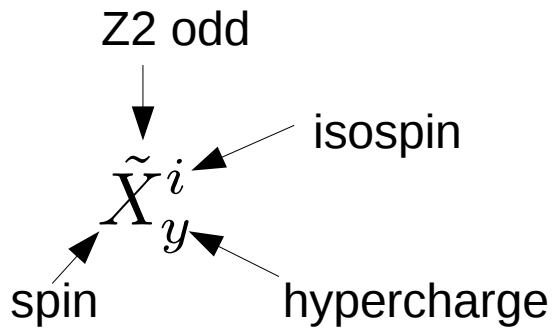
$Y = 0$

loop suppressed
nucleon scattering –
close to DD bounds



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

+Mediator



Spin of Dark Matter \ Spin of Mediator	0	1/2	1
spin 0 even mediator	$\tilde{S}_Y^I S_{Y'}^{I'}$	$\tilde{F}_Y^I S_0^{I'}$	$\tilde{V}_Y^I S_{Y'}^{I'}$
spin 0 odd mediator	$\tilde{S}_Y^I \tilde{S}_{Y'}^{I'}$	$\tilde{F}_Y^I \tilde{S}_{Y'}^{I'}$ $\tilde{F}_Y^I \tilde{S}_{Y'}^{I'c}$	$\tilde{V}_Y^I \tilde{S}_{Y'}^{I'}$
spin 1/2 even mediator			
spin 1/2 odd mediator	$\tilde{S}_Y^I \tilde{F}_{Y'}^{I'}$ $\tilde{S}_Y^I \tilde{F}_{Y'}^{I'c}$	$\tilde{F}_Y^I \tilde{F}_{Y \pm 1/2}^{I \pm 1/2}$	$\tilde{V}_Y^I \tilde{F}_{Y'}^{I'}$ $\tilde{V}_Y^I \tilde{F}_{Y'}^{I'c}$
spin 1 even mediator	$\tilde{S}_Y^I V_0^{I'}$	$\tilde{F}_Y^I V_0^{I'}$	$\tilde{V}_Y^I V_{Y'}^{I'}$
spin 1 odd mediator	$\tilde{S}_Y^I \tilde{V}_{Y'}^{I'}$	$\tilde{F}_Y^I \tilde{V}_{Y'}^{I'}$ $\tilde{F}_Y^I \tilde{V}_{Y'}^{I'c}$	$\tilde{V}_Y^I \tilde{V}_{Y'}^{I'}$

$\tilde{F}_Y^I S_{Y'}^{I'}$

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

$$I' = 0, \dots, 2I$$

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

Real CP-odd scalar

$$Y' = 2Y$$

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

Real CP-even scalar

$$I' = 0, \dots, 2I$$

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

CP-odd scalar

Even scalar mediator

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

$$S_0^0 \Rightarrow V_{\text{linear}} = -\mu \Phi \phi_H^\dagger \phi_H, \quad (\text{CP-even});$$

$$S_0^1 \Rightarrow V_{\text{linear}} = -\mu \Phi^a \phi_H^\dagger \tau^a \phi_H, \quad (\text{CP-even});$$

$$S_1^1 \Rightarrow V_{\text{linear}} = -\mu \Phi^a \phi_H^\dagger \tau^a \phi_H^\dagger + \text{h.c.}$$

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

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

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:

$$S_2^0 \Rightarrow V_{\text{ferm.}} = -y_s \Phi \bar{e}_R^c e_R$$

$$S_1^1 \Rightarrow V_{\text{ferm.}} = -y_s \Phi^a \bar{l}_L^c \tau^a l_L$$

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

Important cases

- **Linear couplings present** $\Phi\phi_H^2$
 - generated by Φ VEV \rightarrow 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 \rightarrow scalar not a direct mediator
 - Φ may be accidentally stable \rightarrow 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}_Y^0 $Y \lesssim 10^{-8}$ ψ *FIMP*
 $\Phi\psi$ only couple through Y . $Y \sim 1$ ψ *WIMP*

– $m_{\Phi} > 2m_{\psi}$ & \tilde{F}_Y^0 $Y \lesssim 10^{-10}$ ψ *superWIMP*
 ψ will not thermalise, Φ obtains thermal relic which decays into ψ after freeze-out $Y \sim 1$ $\Omega_{\Phi} \sim 0$

Two-component DM model

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

$\tilde{F}_0^0 S_0^0 (CP - odd)$

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

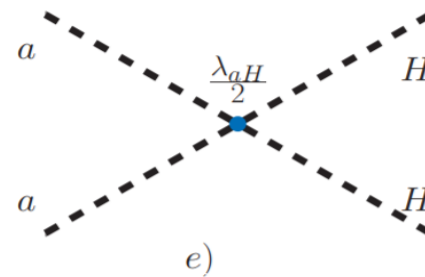
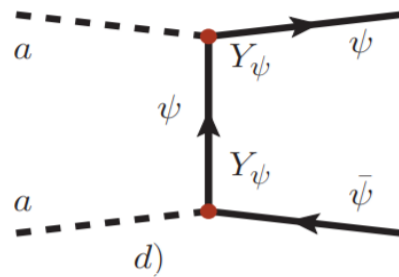
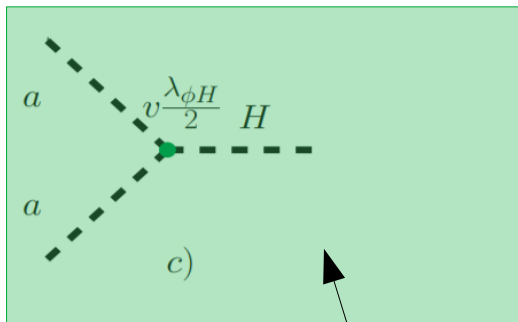
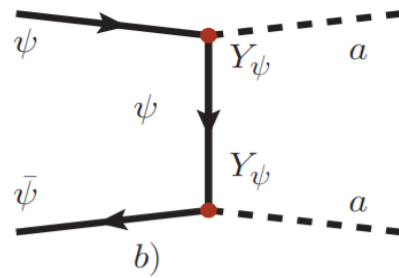
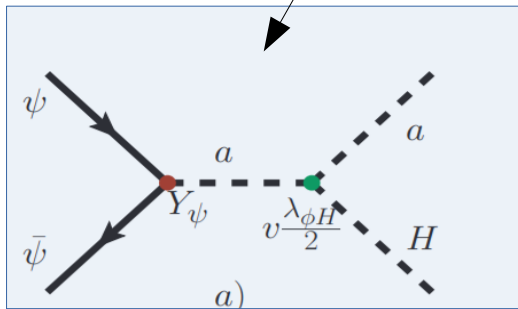
- a does not acquire VEV \rightarrow no linear coupling to Higgs
- $m_a < 2m_\psi \rightarrow$ “secluded DM”
- Model implemented in **LanHEP**, and numerical scan performed using **micrOMEGAs**.

4 relevant parameters:

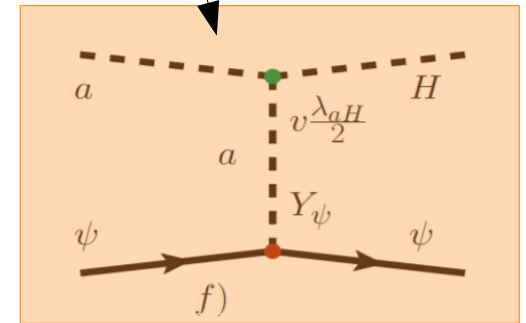
$$m_\psi, Y_\psi, m_a, \lambda_{aH}$$

(co)Annihilation channels

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



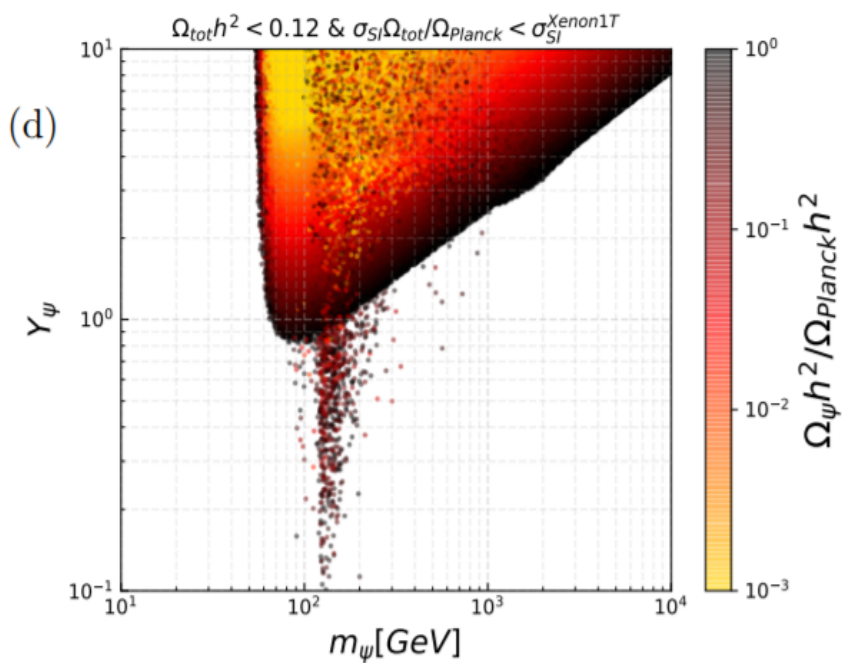
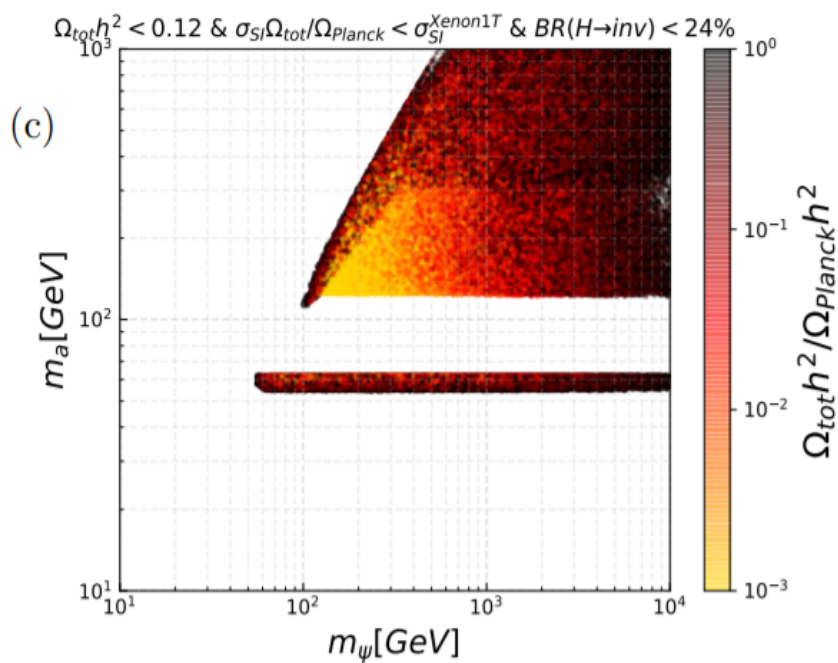
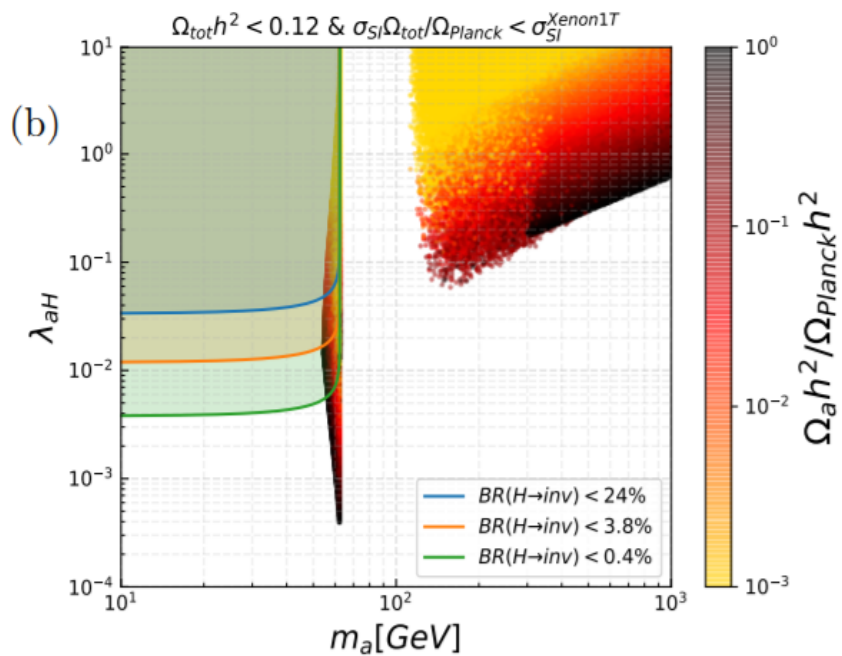
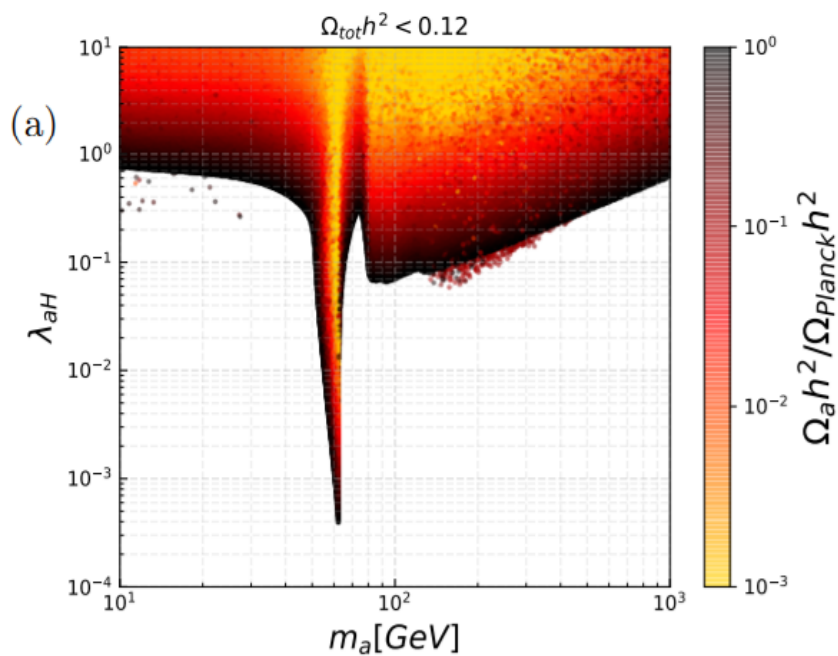
$$m_a \sim m_\psi \gtrsim m_H$$



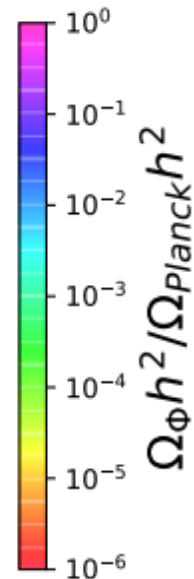
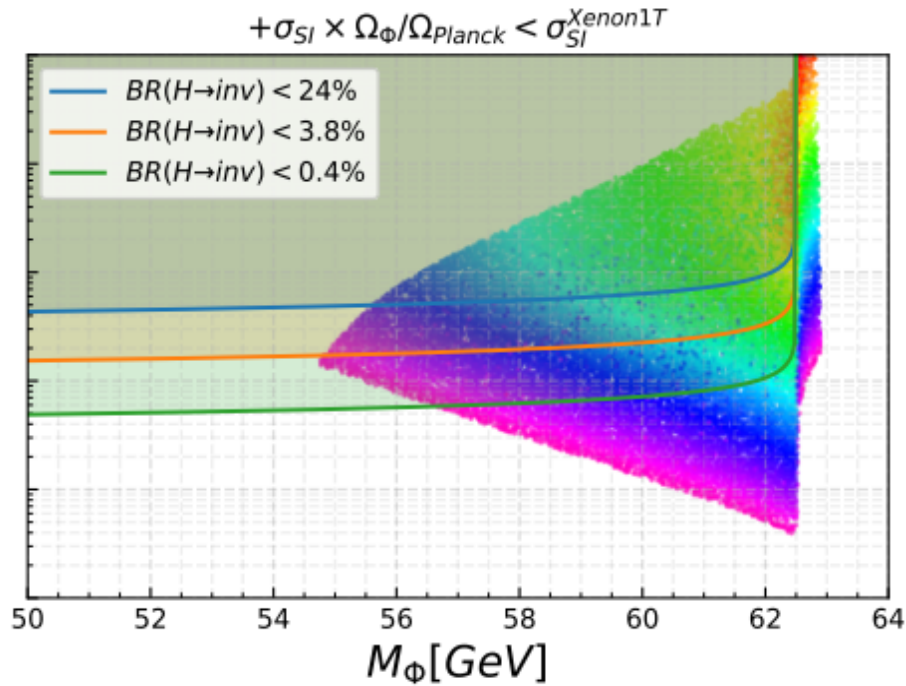
$$\sigma_{aa \rightarrow ff}^{ann} \sim \frac{\lambda^2 m_f^2}{(4m_a^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$aa \rightarrow WW$
 $aa \rightarrow ZZ$
 $aa \rightarrow tt$

$m_a > 80\text{GeV}$
 $m_a > 90\text{GeV}$
 $m_a > 173\text{GeV}$

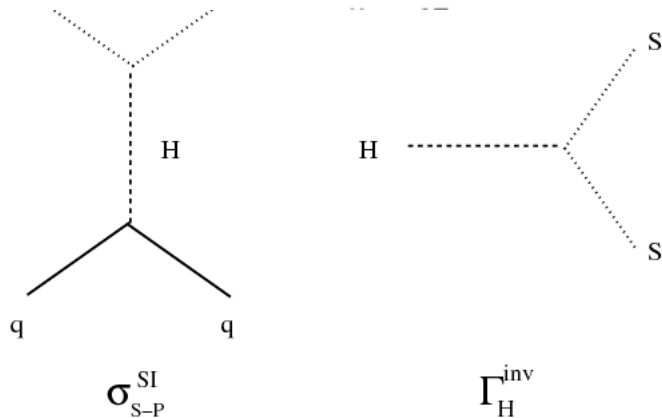


Direct Detection



$$\sigma_{SI}(aN \rightarrow aN) \sim \frac{\lambda_{aH}^2 f_N^2 A^2 m_N^4}{m_H^4 m_a^2}$$

$$\approx 3 \times 10^{-7} \frac{\lambda_{aH}^2}{m_a^2}$$



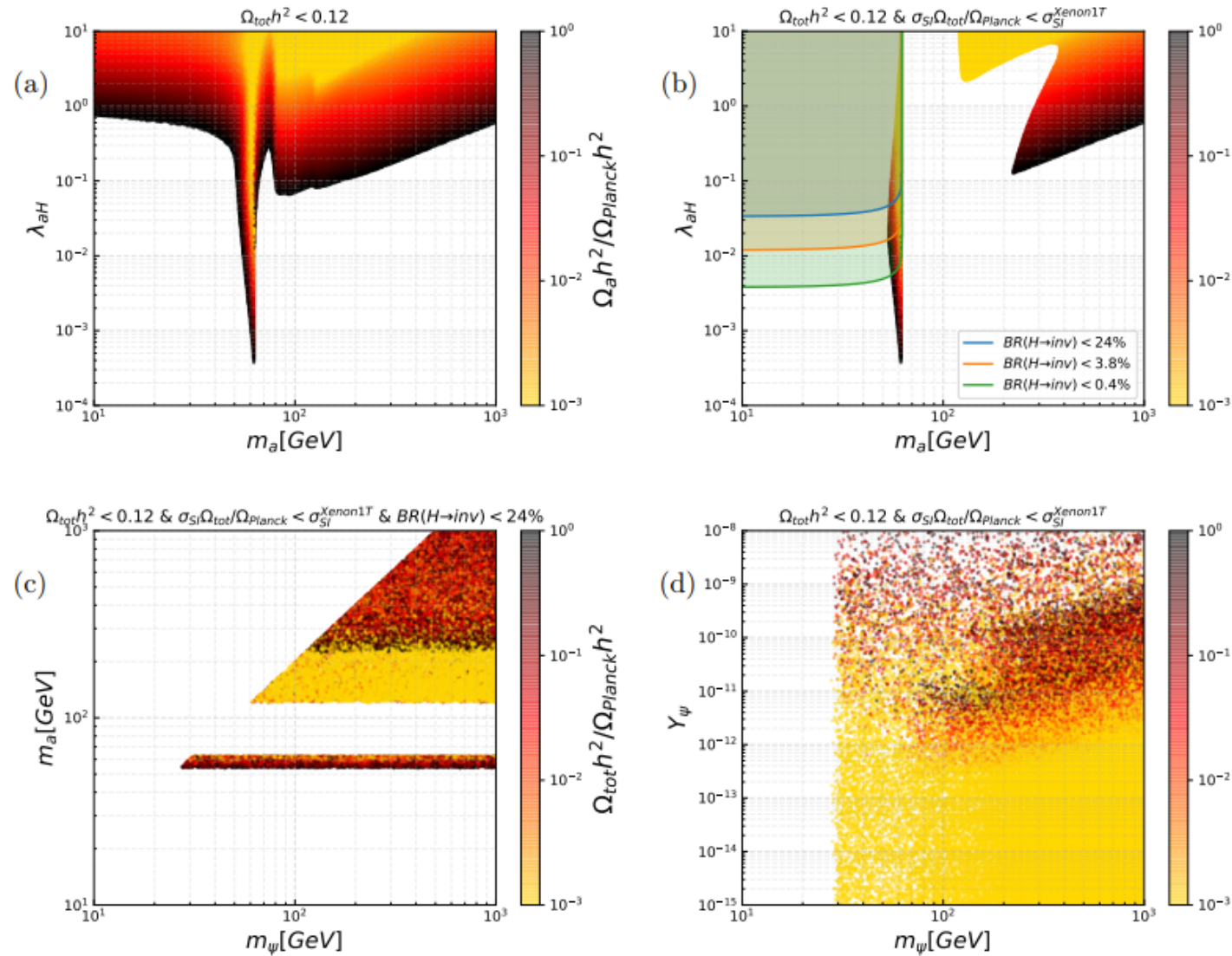
$$\Gamma_{H \rightarrow aa} = \frac{\lambda_{aH}^2 v^2}{128\pi m_H} \sqrt{1 - \frac{4m_a^2}{m_H^2}}$$

Metastable a

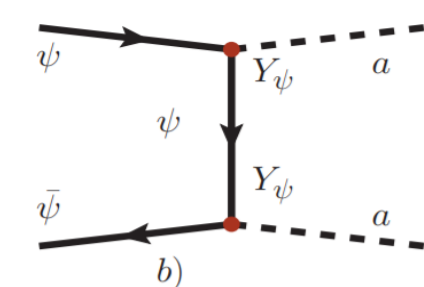
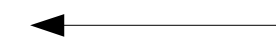
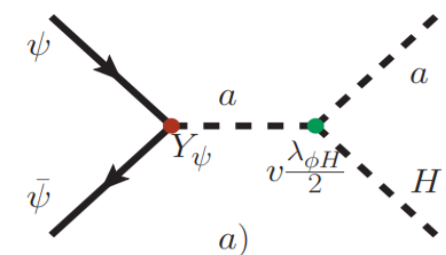
$$\Gamma(a \rightarrow \bar{\psi}\psi) = \frac{Y_\psi^2}{4\pi} m_a \left(1 - \frac{4m_\psi^2}{m_a^2} \right)^{\frac{3}{2}}$$

- 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 \rightarrow 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 et al. [hep-ph/0603067](https://arxiv.org/abs/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