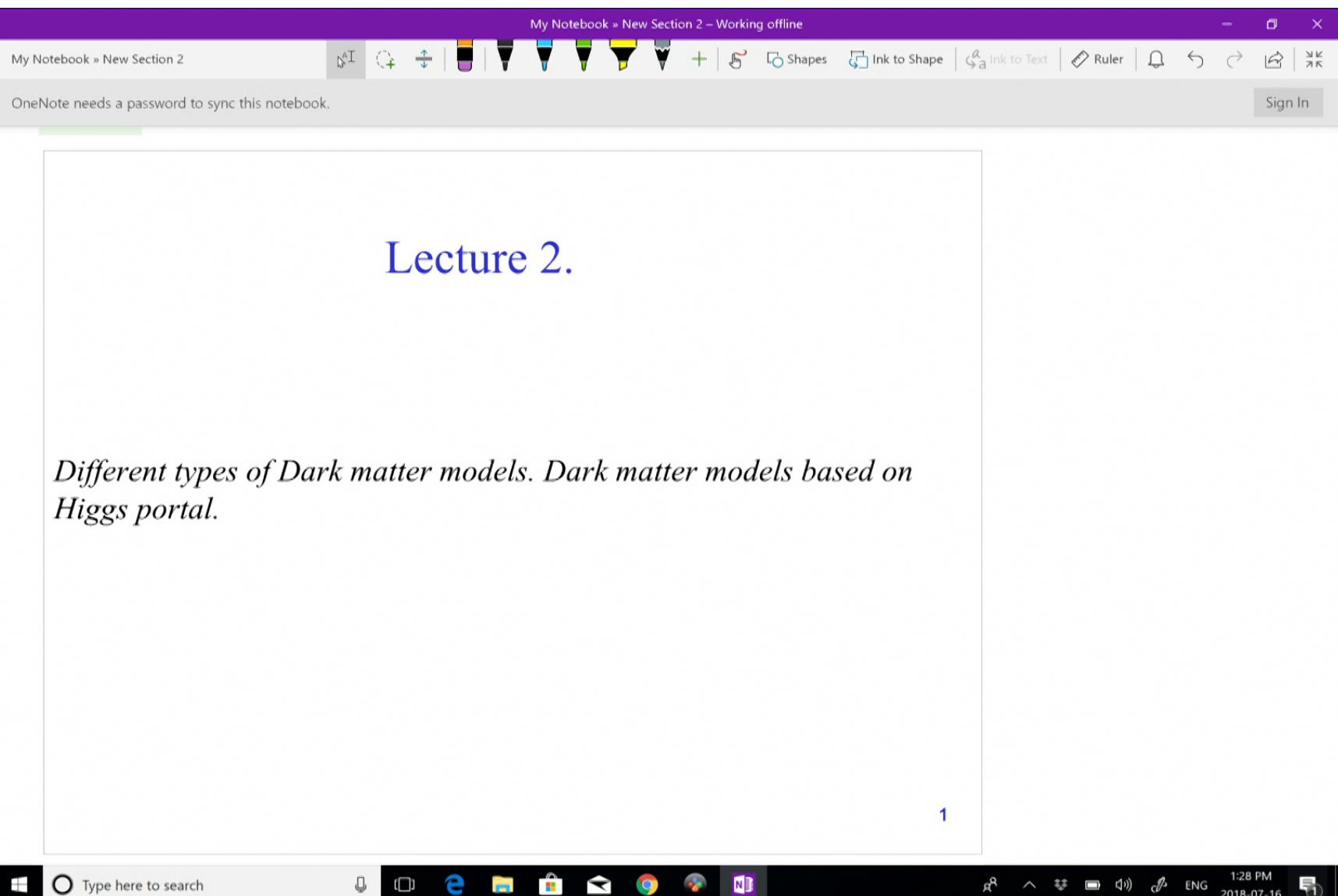


Title: Dark Sector Theory 2

Date: Jul 16, 2018 04:30 PM

URL: <http://pirsa.org/18070035>

Abstract:



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Neutral “portals” to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H(\lambda S^2 + A S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu}V_{\mu\nu}$ “Kinetic mixing” with additional U(1)' group
(becomes a specific example of $J_\mu^i A_\mu^i$ extension)

LHN neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu^i$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that
Nature may have used the *LHN* portal...

Dim>4

$J_\mu^A \partial_\mu a/f$ axionic portal

.....

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

2

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DM classification

At some early cosmological epoch of hot Universe, with temperature $T \gg DM$ mass, the abundance of these particles relative to a species of SM (e.g. photons) was

Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for $DM \rightarrow SM$ of order ~ 1 pb, which points towards weak scale. These are **WIMPs**. Asymmetric DM is also in this category.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other “feeble” creatures – call them **superweakly interacting MPs**]

Huge: Almost non-interacting light, $m < eV$, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. “Super-cool DM”. Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

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Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma \gg 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM \rightarrow SM of order ~ 1 pb, which points towards weak scale supersymmetry.

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WIMP (= DM freeze-out) mechanism



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scalar portals to the SM

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$$\frac{d}{dt} \left(\frac{a^3 n_{DM}}{a^3} \right) =$$
$$= \langle \sigma_{xx} v_{sm} \rangle (n_{eq}^2 - n^2)$$

4

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$\frac{dM}{dt} = \frac{d}{dt} (a^3 n_{DM}) =$

$= \langle \sigma_{xx} v_{sm} \rangle (n_{eq}^2 - n^2)$

$n_{eq} = g_i \int \frac{dP}{(2\pi)^3} \frac{1}{e^{E(P)/T} \pm 1}$

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$\overrightarrow{T < m}$

4

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$\rightarrow T < m \quad g_i \cdot \left(\frac{mT}{2\pi}\right)^3 h e^{-mT}$

4

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$n_g = g_i \int \frac{d^3p}{(2\pi)^3} e^{-E(p)/T} \pm 1$

$\rightarrow T < m \quad g_i \cdot \left(\frac{mT}{2\pi}\right)^3 h e^{-mT}$

4

$\frac{dY}{dT} = \beta \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = n$

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$n_g = g_i \int \frac{dp}{(2\pi)^3} e^{\frac{E(p)}{kT}} \pm 1$

$\rightarrow T < m \quad g_i \cdot \left(\frac{mT}{2\pi}\right)^3 h e^{-mT}$

$\frac{dY}{dT} = -s \langle ov \rangle (Y_{eq}^2 - Y^2)$

$Y = n_{DM}/s \quad (s = \frac{2\pi^2}{45} g_{xs} T^3)$

4

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$\frac{dY}{dt} = \beta \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = \frac{\text{mom}}{\beta} \quad (\beta = \frac{2\pi^2}{45} g \times T^3)$

$a \sim t^k ; H = \frac{1}{2t} \approx \text{const} T^{-2}$

$\frac{d}{dT} = - H(t) T \frac{d}{dT}$

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$T < m \quad f\left(\frac{m}{2\pi}\right) - e$

4

$\frac{dY}{dt} = \beta \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = \frac{n_{DM}}{\beta} \quad (\beta = \frac{2\pi^2}{45} g_{us} T^3)$

$a \sim t^{1/2} ; H = \frac{1}{2t} \simeq \text{const} T^{-2}$

$\frac{d}{dt} = - H(t) T \frac{d}{dT}$

5

Y

t

Weakly interacting massive particles, WIMPs

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$T \ll m \quad f\left(\frac{v}{2\pi}\right) \sim e^{-v^2/2\pi^2}$

4

$\frac{dY}{dt} = \beta \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = n_{DM}/\beta \quad (\beta = \frac{2\pi^2}{45} g_{us} T^3)$

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5

Y

t

Weakly interacting massive particles, WIMPs

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$T \ll m \quad f\left(\frac{v}{2\pi}\right) \approx e^{-\frac{mv^2}{2kT}}$

4

$\frac{dY}{dt} = \beta \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = n_{DM}/\beta \quad (\beta = \frac{2\pi^2}{45} g_{us} T^3)$

$a \sim t^{1/2} ; H = \frac{1}{2t} \approx \text{const} T^{-2}$

$\frac{d}{dt} = -H(t)T \frac{d}{dT}$

5

Y

t

Weakly interacting massive particles, WIMPs

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$T < m \quad f_i(\frac{m}{2\pi})^{-e}$

4

$\frac{dY}{dt} = s \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = n_{DM}/s \quad (s = \frac{2\pi^2}{45} g_{us} T^3)$

$a \sim t^{1/2} ; H = \frac{1}{2t} \simeq \text{const} T^{-2}$

$\frac{d}{dt} = -H(t)T \frac{d}{dT}$

5

$Y = Y_{f.o.}$

t

Weakly interacting massive particles, WIMPs

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$T \ll m$ $\mathcal{J}(\frac{\omega}{2\pi}) \sim e^{-i\omega t}$

4

$\frac{dY}{dt} = \beta \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = n_{DM}/s \quad (\beta = \frac{2\pi^2}{45} g_{us} T^3)$

$a \sim t^{1/2} ; H = \frac{1}{2t} \sim \text{const} T^{-2}$

$\frac{d}{dt} = -H(t)T \frac{d}{dT}$

5

γ

$Y = Y_{f.o.}$

T

Weakly interacting massive particles, WIMPs

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$T < m \quad f(\frac{m}{2\pi})^{-e}$

$\frac{dY}{dt} = s \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

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$\frac{d}{dt} = -H(t)T \frac{d}{dT}$

$R_{DM} h^2 \simeq \frac{10^9 x_f}{g_*^{1/2}}$

$Y = Y_{f.o.}$

Weakly interacting massive particles, WIMPs

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$T < m \quad f(\frac{m}{2\pi})^{-e}$

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$R_{DM} h^2 \simeq \frac{10^9 x_f}{g_*^{1/2} \cdot M_p}$

$Y = Y_{f.o.}$

Weakly interacting massive particles, WIMPs

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$T < m \quad f\left(\frac{m}{2\pi}\right) = e^{-\frac{m^2}{4\pi}}$

$\frac{dY}{dt} = \beta \langle \sigma v \rangle (Y_{eq}^2 - Y^2)$

$Y = n_{DM}/\beta \quad (\beta = \frac{2\pi^2}{45} g_{us} T^3)$

$a \sim t^{1/2}; \quad H = \frac{1}{2t} \simeq \text{const} T^{-2}$

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$R_{DM} h^2 \simeq \frac{10^9 x_f}{g_{us}^{1/2} \cdot M_p \cdot GeV \langle \sigma v \rangle}$

Weakly interacting massive particles, WIMPs

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$\frac{dt}{Y} = \frac{n_{DM}}{\beta} \quad (\beta = \frac{2\pi^2}{45} g_{*S} T^3)$

$a \sim t^{1/2}; H = \frac{1}{2t} = \text{const} T^{-2}$

$\frac{d}{dT} = -H(T)T \frac{d}{dT}$

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$(x_f =$

Weakly interacting massive particles, WIMPs

WIMP-nucleus scattering

DM states

SM states

Cosmological (also galactic) annihilation

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$\frac{dt}{Y} = \frac{n_{DM}}{\beta} \quad (\beta = \frac{2\pi^2}{45} g_{*S} T^3)$

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$Y = Y_{f.o.}$

$\frac{1}{T_f} \quad \frac{1}{T}$

Weakly interacting massive particles, WIMPs

WIMP-nucleus scattering

DM states

DM-SM mediators

SM states

Cosmological (also galactic) annihilation

Galactic WIMP pair production

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$(x_f = \frac{m}{T_f})$
 $\sim 15-20$

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$\sigma_{DM} \approx g_x^{1/2} \cdot M_p \cdot GeV \langle \sigma v \rangle$

$(x_f = \frac{m}{T_f}) \sim 15 - 20$

Weakly interacting massive particles, WIMPs

WIMP-nucleus scattering

DM states

SM states

Cosmological (also galactic) annihilation

Collider WIMP pair-production

$$\langle \sigma_{ann} v \rangle \approx 1 \text{ pbn} \times c$$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production?

Examples of DM-SM mediation

1. Z -mediation

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$a \sim T^{-\gamma}; H = \frac{c}{2T} \approx \text{const}$

$$\frac{d}{dT} = -H(T)T \frac{d}{dT}$$

$$R_{DM} h^2 \approx \frac{10^9 x_f}{g_{x_5^{1/2}}^{1/2} \cdot M_p \cdot \text{GeV} \langle \sigma v \rangle}$$

$$(x_f = \frac{m}{T_F})$$

$$\sim 15-20$$

Weakly interacting massive particles, WIMPs

$\langle \sigma_{ann} v \rangle \approx 1 \text{pb} \times c$

Number of thermally excited degrees of freedom

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$R_{DM} h^2 \approx \frac{10^9 x_f}{g_x^{1/2} \cdot M_p \cdot GeV \langle \sigma v \rangle}$

$(x_f = \frac{m}{T_f}) \sim 15 - 20$

Weakly interacting massive particles, WIMPs

The diagram illustrates the interactions of WIMPs with the Standard Model (SM). A central green box labeled "DM-SM mediators" contains "DM states" on the left and "SM states" on the right. Four arrows point from this box to external regions: a red arrow labeled "WIMP-nucleus scattering" points upwards; a blue arrow labeled "Cosmological (also galactic) annihilation" points downwards; a red arrow labeled "Collider WIMP pair-production" points to the right; and a blue arrow labeled "WIMP-nucleus scattering" points to the left. Below the diagram, the formula $\langle \sigma_{ann} v \rangle \approx 1 \text{ pb} \times c$ is given.

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

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Number of thermally excited degrees of freedom
Correct DM abundance

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$R_{DM} h^2 \approx \frac{10^9 x_f}{g_x^{1/2} \cdot M_p \cdot GeV \langle \sigma v \rangle}$

$(x_f = \frac{m}{T_f}) \sim 15-20$

Weakly interacting massive particles, WIMPs

The diagram illustrates the interaction of WIMP-nucleus scattering with DM states, SM states, and mediators. A central green box labeled "DM-SM mediators" contains "DM states" on the left and "SM states" on the right. Two dashed green arrows point from the top and bottom towards this central box. A solid red arrow points from the left towards the central box, labeled "WIMP-nucleus scattering". Another solid red arrow points from the central box towards the right, labeled "Cosmological (also galactic) annihilation". A third solid red arrow points from the central box towards the bottom, labeled "Collider WIMP pair-production".

$\langle \sigma_{ann} v \rangle \approx 1 \text{ pb} \times c$

1. What is inside this green box? I.e. what forces mediate WIMP-SM interaction?

2. Do sizable annihilation cross section always imply sizable scattering rate and collider DM production?

Number of thermally excited degrees of freedom
Correct DM abundance is achieved at $\langle \sigma v \rangle \sim 10^{-36} \text{ cm}^2$

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rate and consider DM production!

1. Z -mediation

$\chi \chi \rightarrow Z$ -boson \rightarrow SM states

2. Higgs-mediation

$\chi \chi \rightarrow H$ -boson \rightarrow SM states

3. Photon/dark photon mediation

$\chi \chi \rightarrow$ dark photon \rightarrow SM states

Very economical extensions of the SM.
DM particles themselves + may be extra mediator force. Can be very predictive.

If dark matter annihilation is mediated by weak scale particles, the mass

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Very economical extensions
DM particles themselves + 1 extra mediator force. Can be predictive.

2. Higgs - mediation

3. Photon / dark photon mediation

If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to–10000 GeV (Lee, Weinberg)⁷

Bosonic super-cold DM ('`initial displacement" mechanism)

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1

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Dim>4

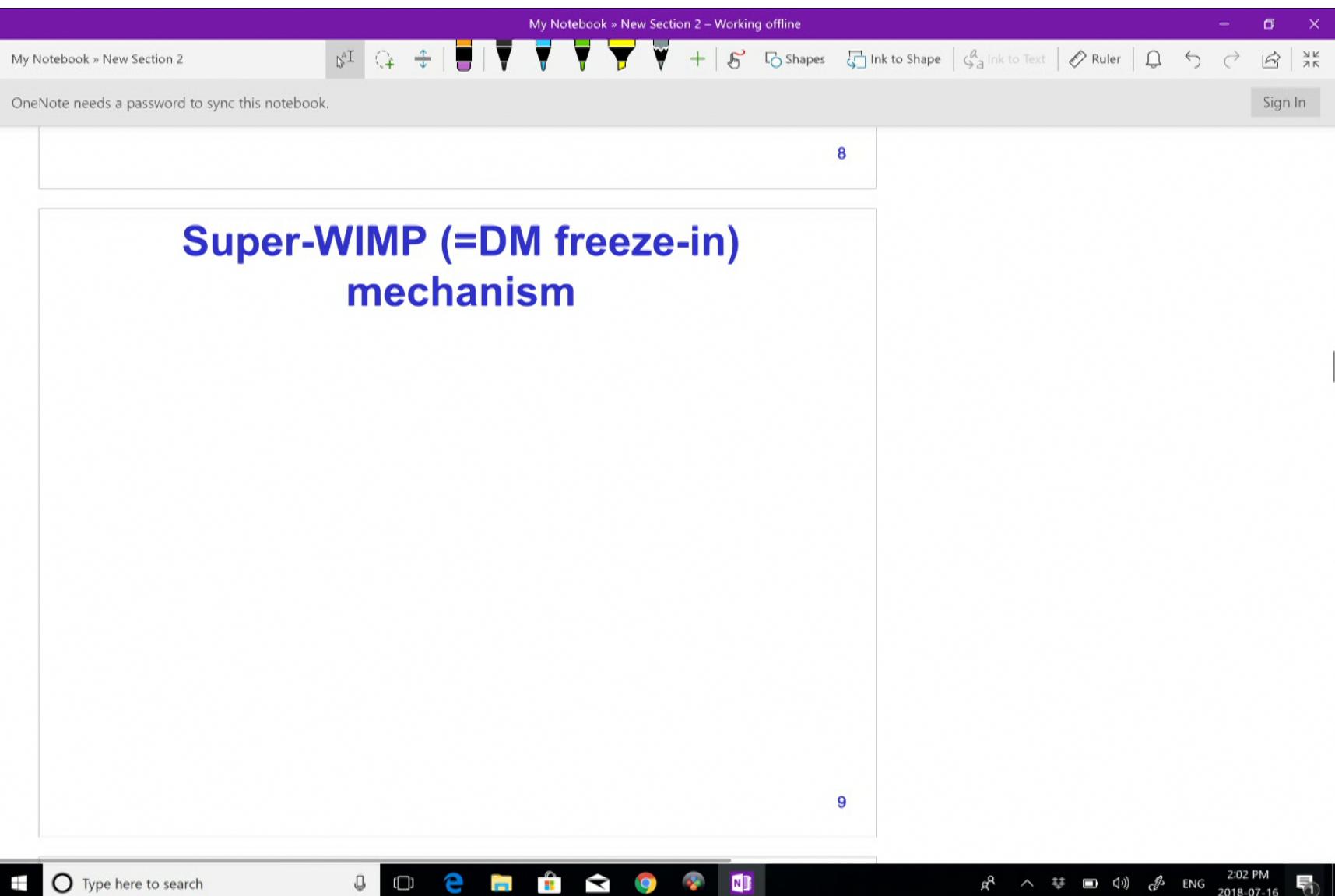
$J_\mu^A \partial_\mu a/f$ axionic portal

.....

$$\mathcal{L}_{\text{mediation}} = \sum_{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

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Super-WIMP (=DM freeze-in) mechanism

$$SM + SM \rightarrow DS$$
$$\Gamma \ll \text{Hubble rate}$$

9

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If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to– 10000 GeV (Lee, Weinberg)⁷

Bosonic super-cold DM ('`initial displacement" mechanism)

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If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to– 10000 GeV (Lee, Weinberg)⁷

Bosonic super-cold DM ('`initial displacement" mechanism)

$$V(a) \approx \frac{1}{2} m^2 a^2$$

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Bosonic super-cold DM ('`initial displacement" mechanism)

$$V(a) \approx \frac{1}{2} m^2 a^2$$


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8

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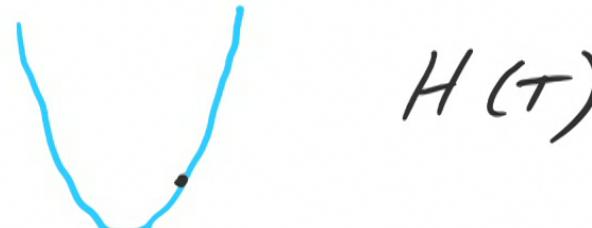
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If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to–10000 GeV (Lee, Weinberg)⁷

Bosonic super-cold DM ('`initial displacement" mechanism)

$$V(a) \approx \frac{1}{2} m_a^2 a^2$$


$H(\tau)$

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If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to– 10000 GeV (Lee, Weinberg)⁷

Bosonic super-cold DM ('`initial displacement" mechanism)

$$V(\varphi) \approx \frac{1}{2} m_a^2 \varphi^2$$


$H(\tau)$

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Bosonic super-cold DM ('`initial displacement" mechanism)

$$V(\varphi) \approx \frac{1}{2} m_\chi^2 \varphi^2$$

$H(\tau) >$

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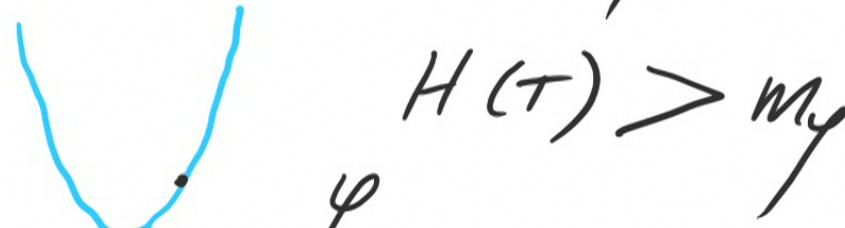
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If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to–10000 GeV (Lee, Weinberg)⁷

Bosonic super-cold DM ('`initial displacement" mechanism)

$$V(\varphi) \approx \frac{1}{2} m_\gamma^2 \varphi^2$$

$$H(\tau) > m_\gamma$$

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displacement" mechanism)

$$V(\varphi) \approx \frac{1}{2} m_\varphi^2 \varphi^2$$

$$H(\tau) > m_\varphi$$
$$\varphi_{in} \approx \text{const}$$

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Super-WIMP (=DM freeze-in) mechanism

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displacement" mechanism)

$V(\varphi) \approx \frac{1}{2} m_\varphi^2 \dot{\varphi}^2$

$H(\tau) > m_\varphi$

$\varphi_{in} \approx \text{const}$

$\frac{d^2\varphi}{dt^2} + 3H \cdot \dot{\varphi} + m_\varphi^2 \varphi = 0$

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Super-WIMP (=DM freeze-in)
mechanism

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displacement" mechanism)

$V(\varphi) \approx \frac{1}{2} m_\varphi^2 \varphi^2$



$H(\tau) > m_\varphi$

$\varphi_{in} \approx \text{const}$

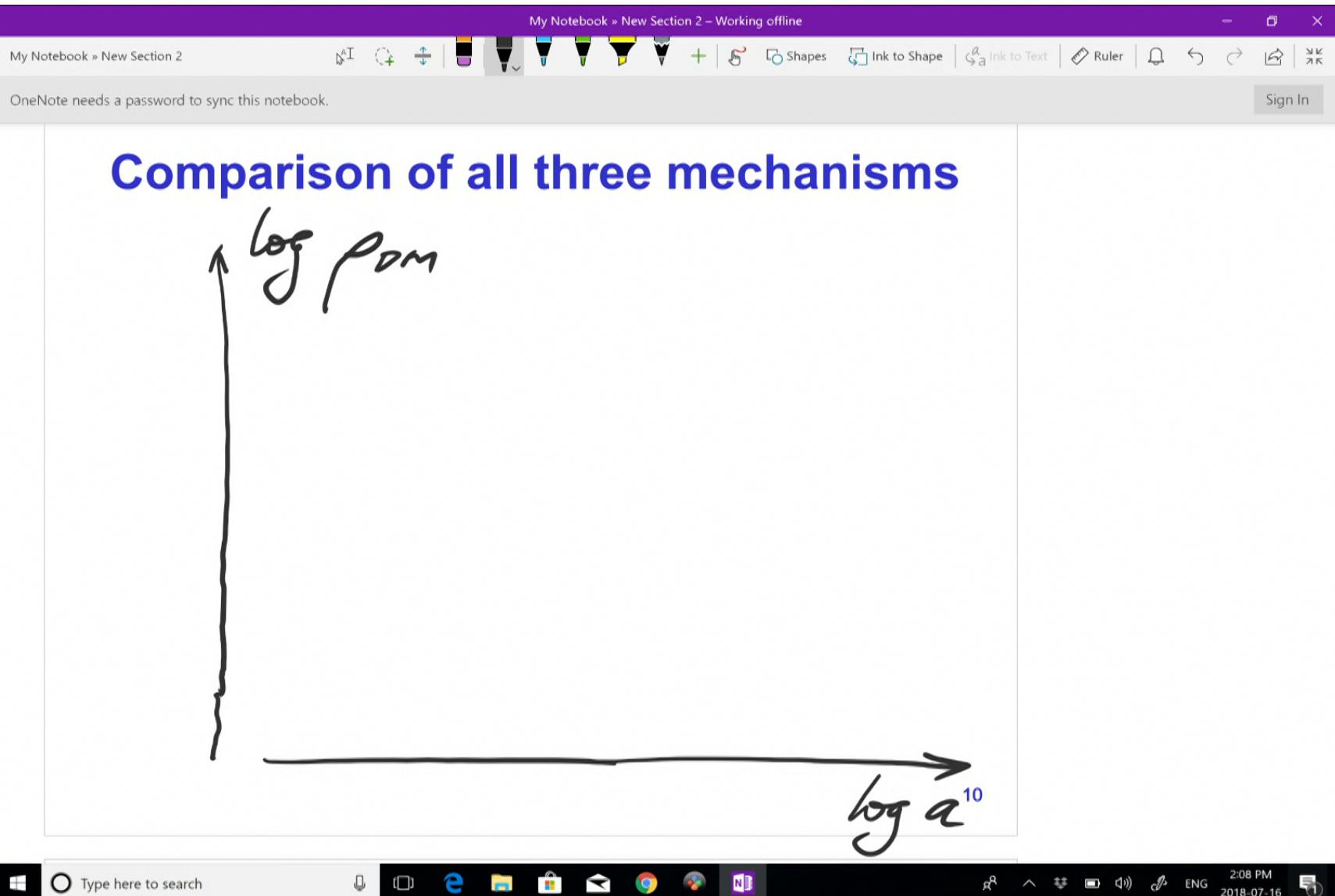
$\frac{d^2\varphi}{dt^2} + 3H \cdot \dot{\varphi} + m_\varphi^2 \varphi = 0$

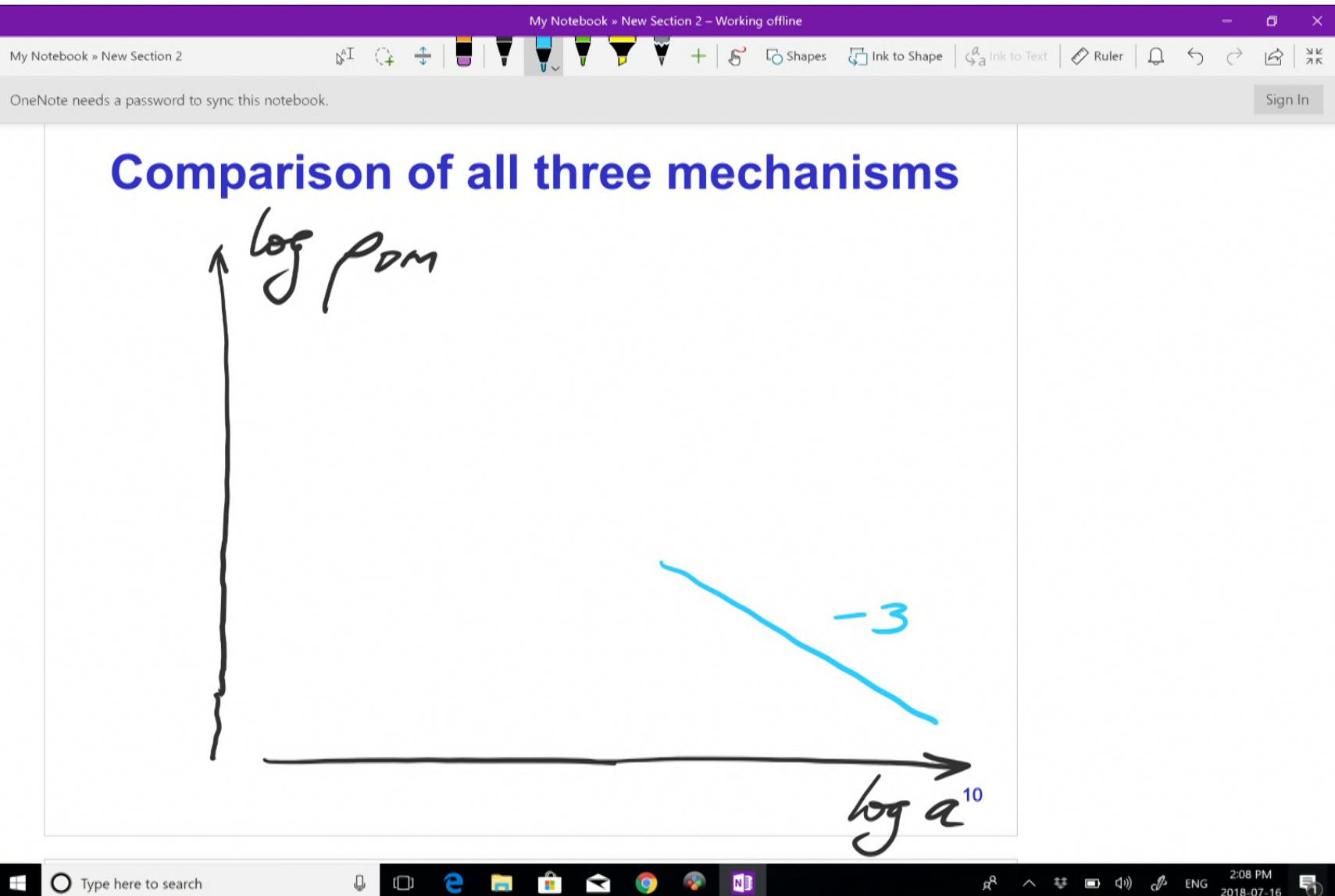
$\varphi \sim (\frac{a_m}{a})^{3/2} \cos(m_\varphi t)$

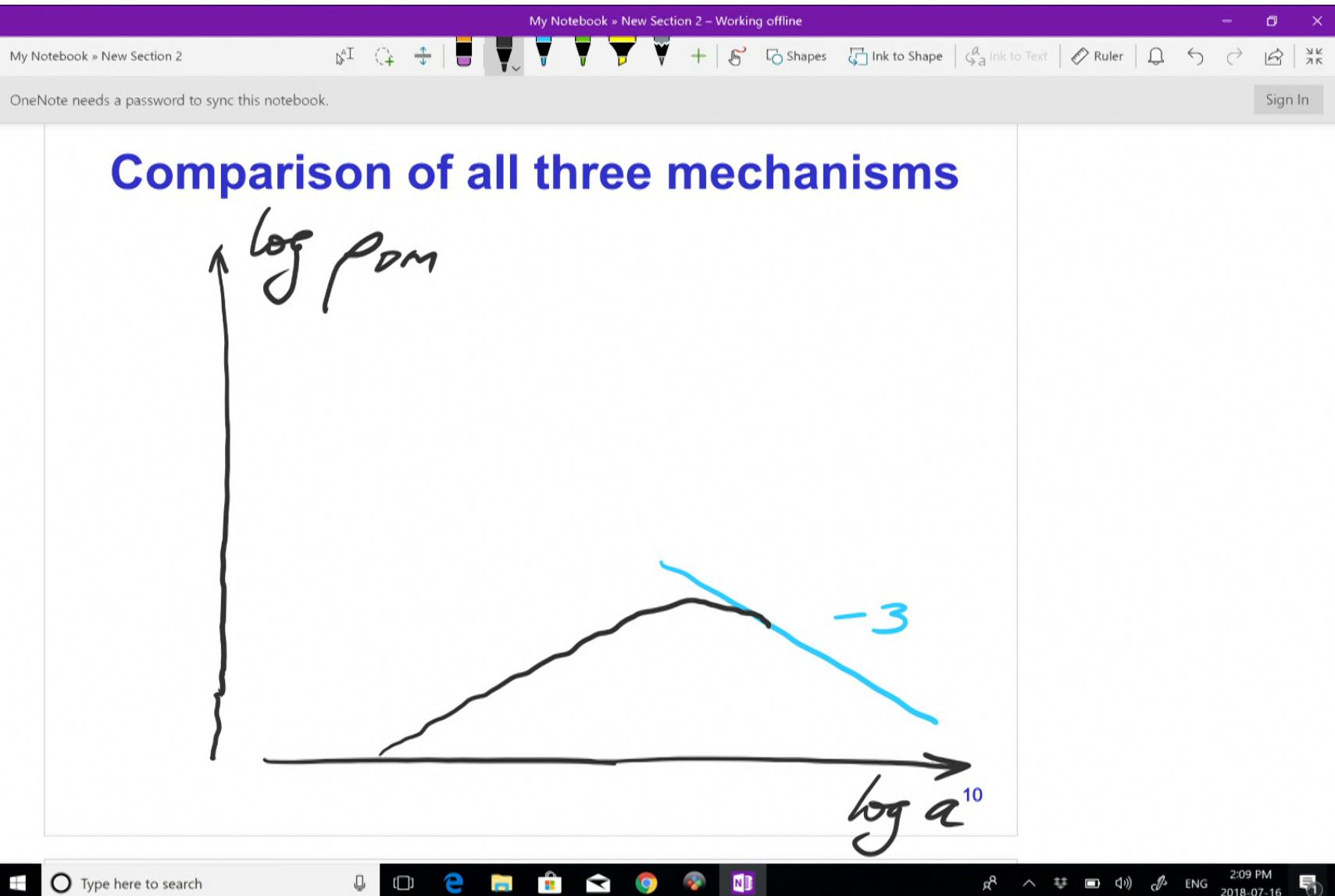
Super-WIMP (=DM freeze-in) mechanism

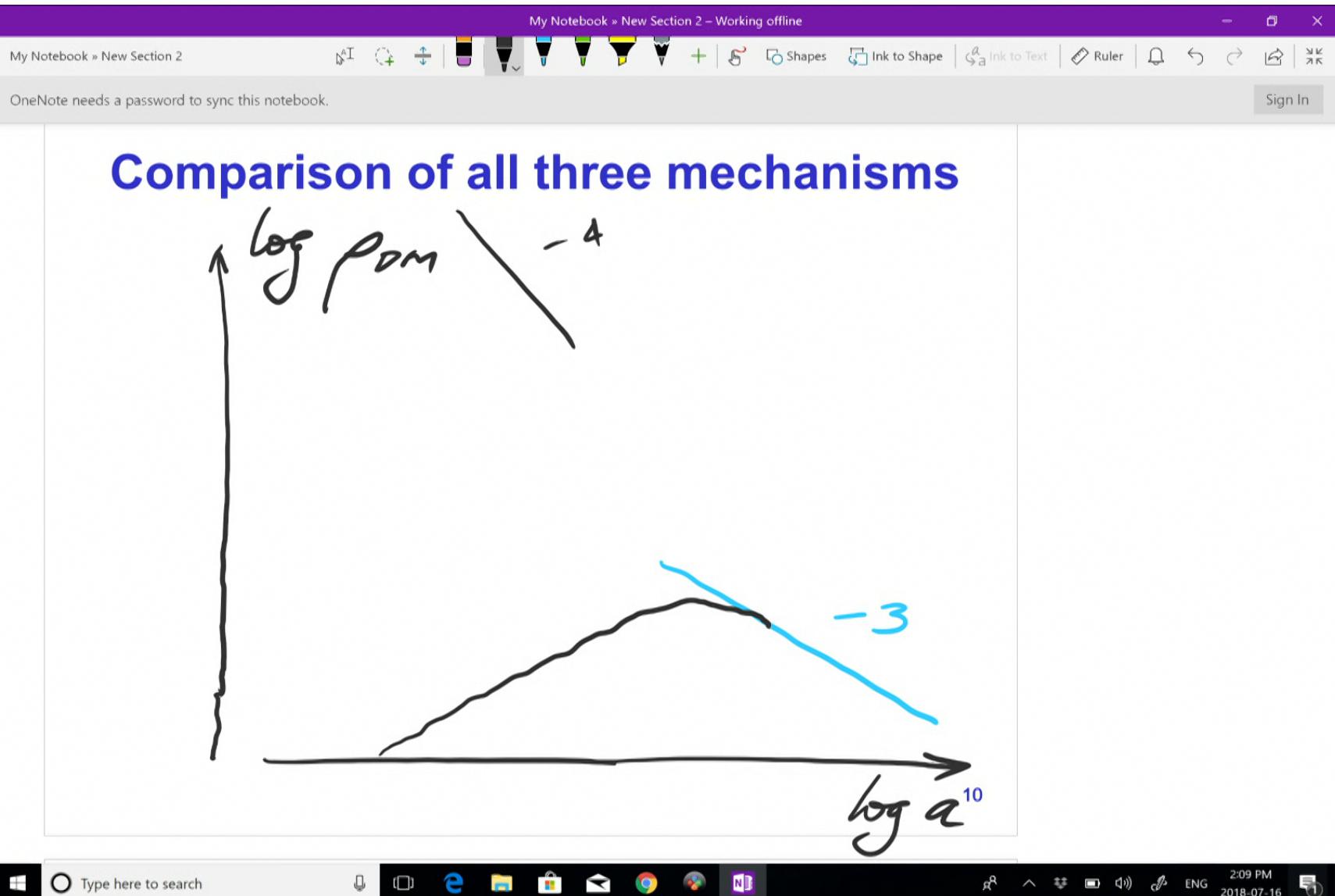
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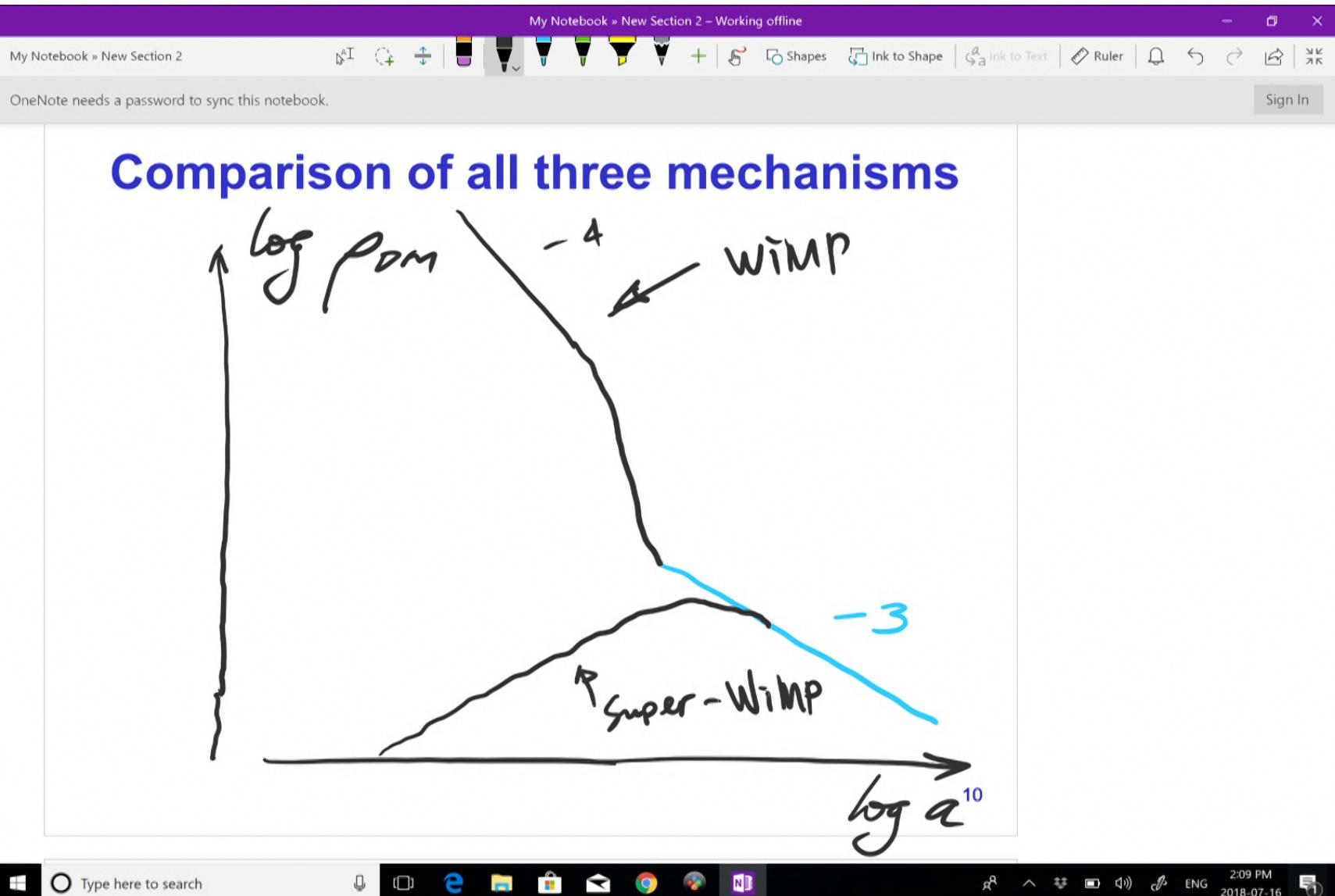
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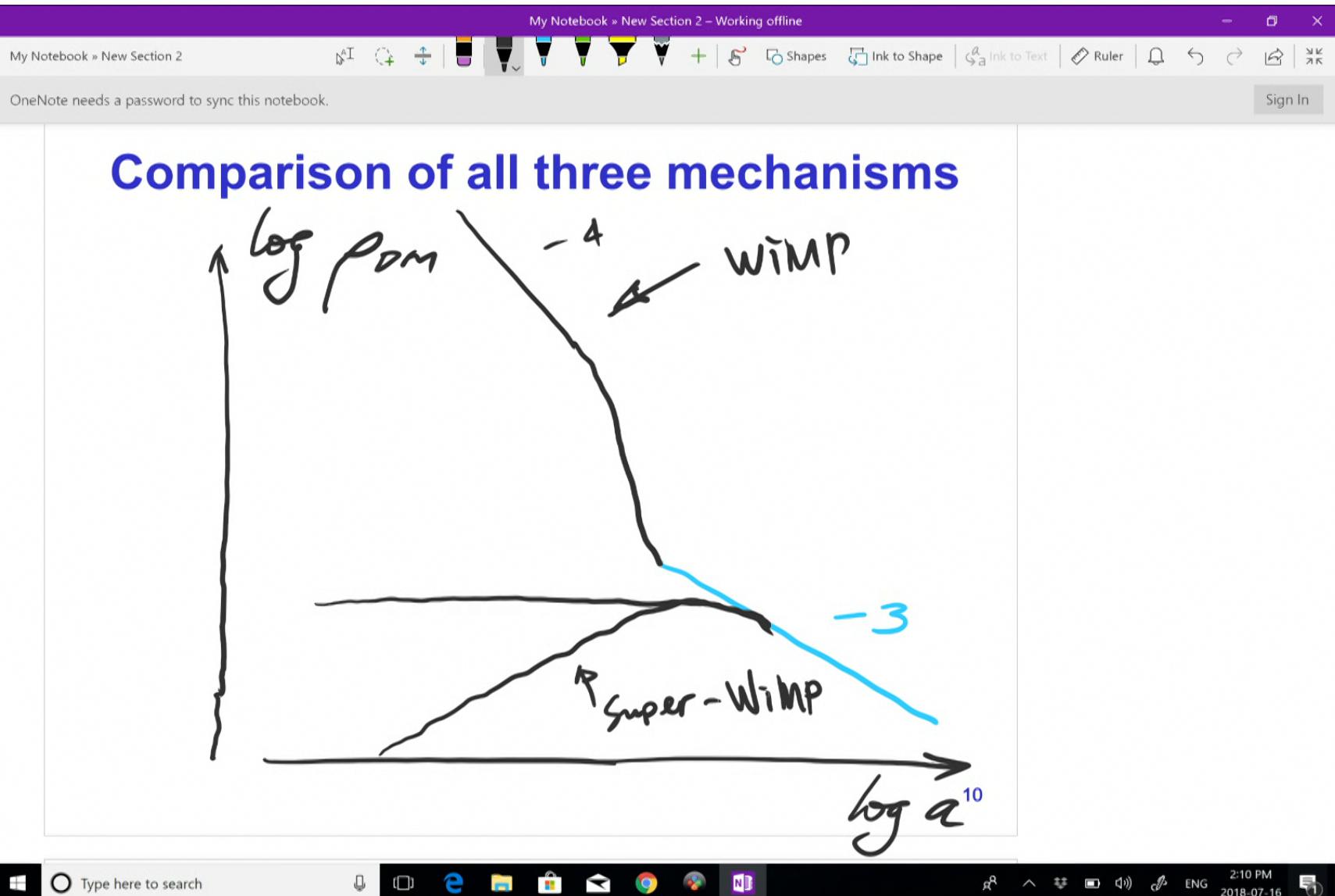


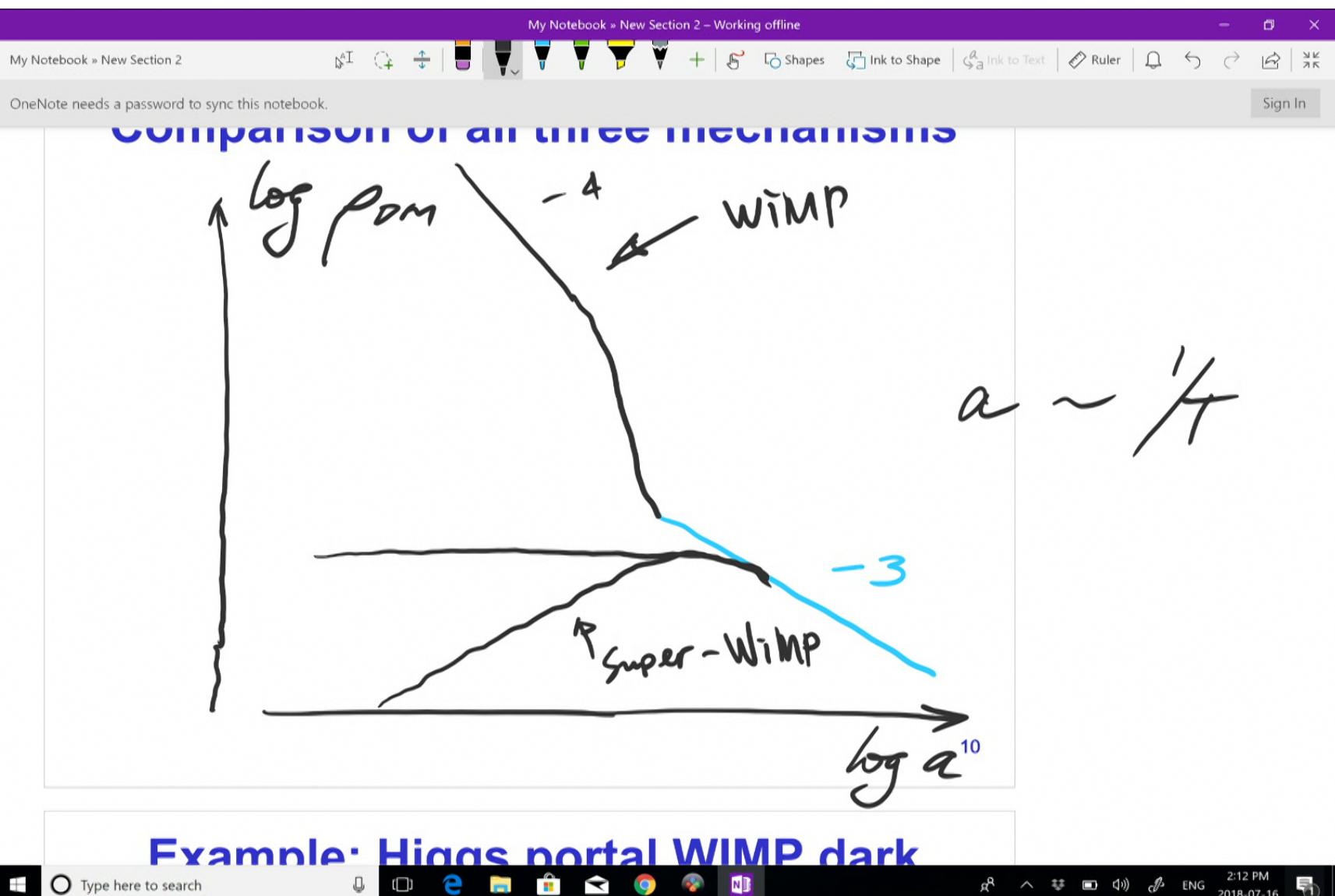


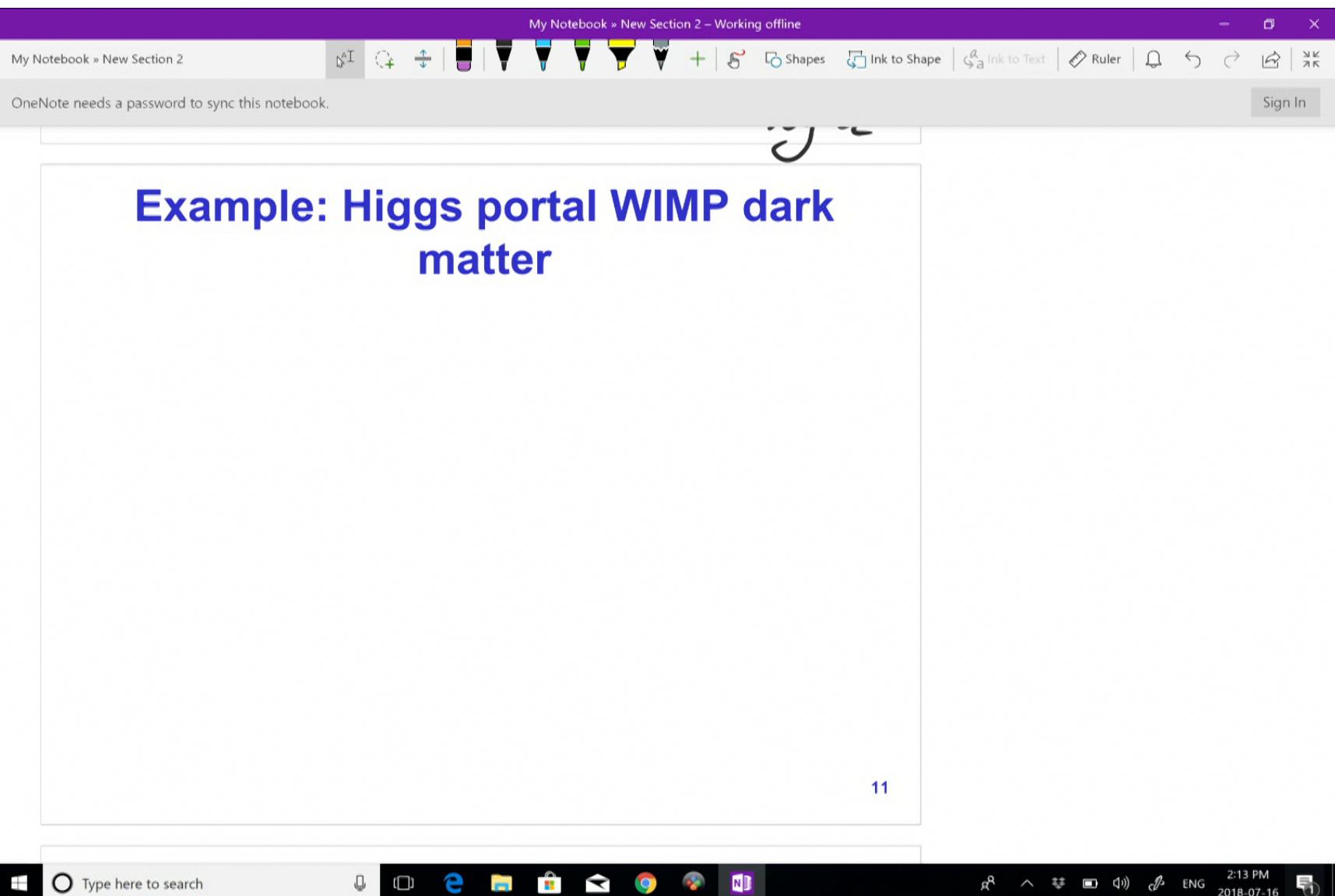












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Example: Higgs portal WIMP dark matter

$SM + 1 \text{ singlet scalar } S'$

$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2$

$+ \left(-\frac{1}{2} m_0 S^2 \right) + \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H$

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$S \rightarrow -S$

Example: Higgs portal WIMP dark matter

$SM + 1 \text{ singlet scalar } S'$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2 + \left(-\frac{1}{2} m_0 S^2 \right) + \lambda (H^\dagger H) S^2 + A S H^\dagger H$$

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Example: Higgs portal WIMP dark matter

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Example: Higgs portal WIMP dark matter

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$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2 + \left(-\frac{1}{2} m_0 S^2 \right) + \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H$$

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{q_1+iq_2}{\sqrt{2}} \end{pmatrix}$$

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$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + (-\frac{1}{2} m_0 S^2) + \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{q_1 + i q_2}{\sqrt{2}} \end{pmatrix}$

$v = 246 \text{ GeV}$

$S \rightarrow -S$

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$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + (-\frac{1}{2} m_0 S^2) + \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{q_1 + i q_2}{\sqrt{2}} \end{pmatrix}$

$v = 246 \text{ GeV}$

$h = \text{"125 GeV"}$

$S \rightarrow -S$

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$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2 + (-\frac{1}{2} m_0 S^2) + \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{\varphi_1 + i \varphi_2}{\sqrt{2}} \end{pmatrix}$

$v = 246 \text{ GeV}$
 $h = \text{"125 GeV"}$

Unitary gauge $H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$

Annihilation rate

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Example: Higgs portal WIMP dark matter

$S \rightarrow -S$

$SM + 1 \text{ singlet scalar } S'$

$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2$

$+ \left(-\frac{1}{2} m_0 S^2\right) \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H = \dots$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{g_1 + ig_2}{\sqrt{2}} \end{pmatrix}$

$v = 246 \text{ GeV}$

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Unitary gauge $H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$

Annihilation rate

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Example: Higgs portal WIMP dark matter

$S \rightarrow -S$

$SM + 1 \text{ singlet scalar } S'$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2 + (-\frac{1}{2} m_0 S^2) - \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H = \dots$$

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{g_1 + ig_2}{\sqrt{2}} \end{pmatrix}$$

$v = 246 \text{ GeV}$

$h = \text{"125 GeV"}$

Unitary gauge $H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$

Annihilation rate

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S'

$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + (-\frac{1}{2}m_S^2)S^2 - \lambda(H^\dagger H)S^2 + A \cdot S H^\dagger H = \dots$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{y_1 + i y_2}{\sqrt{2}} \end{pmatrix}$

Unitary gauge $H = \begin{pmatrix} v+h \\ 0 \end{pmatrix}$

$S \rightarrow -S$

$v = 246 \text{ GeV}$
 $h = \text{"125 GeV"}$

Annihilation rate

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S'

$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + (-\frac{1}{2}m_0 S^2) - \lambda (H^\dagger H)S^2 + A \cdot S H^\dagger H = \dots - \lambda h v S^2$

$S \rightarrow -S$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{y_1 + i y_2}{\sqrt{2}} \end{pmatrix}$

Unitary gauge $H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$

$v = 246 \text{ GeV}$
 $h = \text{"125 GeV"}$

Annihilation rate

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$\log \alpha$

Example: Higgs portal WIMP dark matter

$SM + 1 \text{ singlet scalar } S'$

$L = L_{SM} + \frac{1}{2} (\partial_\mu S)^2$

$+ (-\frac{1}{2} m_0 S^2) - \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{y_1 + i y_2}{\sqrt{2}} \end{pmatrix}$

Unitary gauge $H = \begin{pmatrix} v+h \\ 0 \end{pmatrix}$

$S \rightarrow -S$

$- \frac{1}{2} S^2 (m_0^2 + v^2)$

$- \lambda h v S^2$

$- \lambda h^2 S^2 / 2$

$v = 246 \text{ GeV}$

$h = \text{"125 GeV"}$

Annihilation rate

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Unitary gauge $H = \left(\frac{v+h}{\sqrt{2}} \right)$

Annihilation rate

Assume $\lambda > 10^{-7}$, thermal equilibrium

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2$$

$$+ \left(-\frac{1}{2}m_S^2\right) - \lambda (H^\dagger H)S^2 + A \cdot S H^\dagger H = \dots$$

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{g_1 + ig_2}{\sqrt{2}} \end{pmatrix}$$

$$\text{'mixing gauge'} \quad H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$$

Assume Annihilation rate $\lambda > 10^{-7}$, thermal equilibrium

$S \rightarrow -S$

$$\begin{aligned} -\frac{1}{2}S^2(m_S^2 + v^2) \\ - \lambda h v S^2 \\ - \lambda h^2 S^2 / 2 \\ V(S) = \frac{1}{2}m_S^2 S^2 \\ + \lambda_S S^4 + \dots \end{aligned}$$

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + (-\frac{1}{2}m_0 S^2) - \lambda (HH)S^2 + A \cdot S H^\dagger H$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{q_1 + iq_2}{\sqrt{2}} \end{pmatrix}$

Unitary gauge $H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$

$S \rightarrow -S$

$- \frac{1}{2}S^2(m_0^2 + v^2\lambda) - \lambda hvS^2 - \lambda h^2 S^2/2$

$V(S) = \frac{1}{2}m_0^2 S^2 + \lambda_S S^4 + \dots$

Annihilation rate

Assume $\lambda > 10^{-7}$, thermal equilibrium

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$\tilde{t} \left(-\frac{1}{2} m_0 s^2 \right) - \lambda \tilde{H} H S^2 + A \cdot \cancel{S H^2 H} = \dots \rightarrow \lambda h \bar{v} S^2$

$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{\alpha}{\sqrt{2}} \\ \frac{q_1 + i q_2}{\sqrt{2}} \end{pmatrix}$

$v = 246 \text{ GeV}$

$h = \text{"125 GeV"}$

Unitary gauge $H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$

$V(S) = \frac{1}{2} m_0^2 S^2 + \lambda_S S^4 + \dots$

Annihilation rate

Assume $\lambda > 10^{-7}$, thermal equilibrium

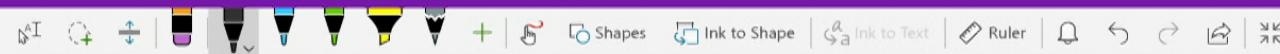
Two specific cases $m_S \gtrsim \text{TeV}$

$m_S < m_h/2$

12

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$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2} (\partial_\mu S)^2$$

$$+ \left(-\frac{1}{2} m_0 S^2 \right) - \lambda (H^\dagger H) S^2 + A \cdot S H^\dagger H$$

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{a}{\sqrt{2}} \\ \frac{y_1 + i y_2}{\sqrt{2}} \end{pmatrix}$$

$$\text{Unitary gauge } H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ 0 \end{pmatrix}$$

$$-\frac{1}{2} S^2 (m_0^2 + v^2)$$

$$- \lambda h v S^2$$

$$- \lambda h^2 S^2 / 2$$

$$V(S) = \frac{1}{2} m_0^2 S^2 + \lambda_S S^4 + \dots$$

Annihilation rateAssume $\lambda > 10^{-7}$, thermal equilibrium

Two specific cases

$$m_S \gtrsim \text{TeV}$$

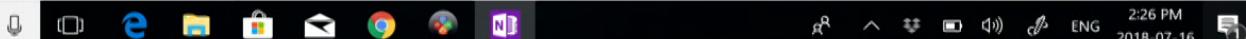
$$m_S < M_h/2$$

Large m_S $S \gg \dots$ 4 scalar fields of H

12



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$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(v+h) + i \frac{a}{\sqrt{2}} \\ \frac{y_1 + iy_2}{\sqrt{2}} \end{pmatrix}$

$v = 246 \text{ GeV}$

$h = "125 \text{ GeV}"$

$\text{Unitary gauge } H = \begin{pmatrix} v+h \\ 0 \end{pmatrix}$

$V(s) = -\lambda h^5/2 + \lambda_s s^4 + \dots$

Annihilation rate

Assume $\lambda > 10^{-7}$, thermal equilibrium

Two specific cases $m_S \gtrsim \text{TeV}$

$m_S < m_h/2$

Large m_S

$s \gg 4 \text{ scalar fields of } H$

$\frac{ds}{dt} = \frac{1}{64\pi s} \frac{1}{|P_{cm}|^2} \cdot |M|^2$

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Assume $\lambda > 10^{-7}$, thermal equilibrium
Two specific cases $m_S \gtrsim \text{TeV}$
 $m_S < m_h/2$

Large m_S

\rightarrow 4 scalar fields of H

$$\frac{d\sigma}{dT} = \frac{1}{64\pi s} \frac{1}{|TP_{cm}|^2} \cdot |M|^2$$

$$M = \lambda$$

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Scattering on nuclei





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Assume $\lambda > 10^{-7}$, thermal equilibrium
Two specific cases $m_S \gtrsim \text{TeV}$
 $m_S < m_h/2$

Large m_S

\rightarrow 4 scalar fields of H

\rightarrow

$$\frac{d\sigma}{dT} = \frac{1}{64\pi s} \frac{1}{|TP_{cm}|^2} \cdot |M|^2$$

$$M = 2\lambda$$

13

Scattering on nuclei





13

Scattering on nuclei





Assume $\lambda > 10^{-7}$, thermal equilibrium

Two specific cases $m_S \gtrsim \text{TeV}$

$$m_S < m_h/2$$

Large m_S

∴ 4 scalar fields of H

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$$M = 2\lambda$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_S)^2} \cdot \frac{1}{|\frac{m}{2} \cdot v_{rel}|^2}$$

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Scattering on nuclei





Scattering on nuclei



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$\sigma \propto \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$

$M = 2\lambda$

$\frac{d\sigma}{dt} = \frac{1}{64\pi(2m_s)^2} \cdot \frac{1}{|\frac{m}{2} \cdot v_{rel}|^2}$

$t = t_0 - 4P_1 P_3 \sin^2(\theta/2)$

Scattering on nuclei

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$\sigma \propto \lambda^2$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$$M = 2\lambda$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_s)^2} \cdot \frac{1}{|\frac{m \cdot v_{rel}}{2}|^2}$$

$$t = t_0 - 4 \frac{(2\lambda)^2}{\vec{P}_1 \cdot \vec{P}_3 / \sin^2(\theta/2)}$$

$$\sigma_{ann} =$$

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$\sigma \propto \lambda^2$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$$M = 2\lambda$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_s)^2} \cdot \frac{1}{|\frac{m \cdot v_{rel}}{2}|^2}$$

$$t = t_0 - 4 \frac{(2\lambda)^2}{\vec{P}_1 \cdot \vec{P}_3 / \sin^2(\theta/2)}$$

$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2}$$

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$\sigma \propto \lambda^2$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$$M = 2\lambda$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_s)^2} \cdot \frac{1}{|\frac{m \cdot v_{rel}}{2}|^2}$$

$$t = t_0 - \frac{4(2\lambda)^2}{4\vec{P}_1 \cdot \vec{P}_3 / sm^2(\theta/2)}$$

$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{v}{2} \right)$$

Scattering on nuclei

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$\sigma \propto \lambda^4$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$$M = 2\lambda$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_s)^2} \cdot \frac{1}{|\frac{m \cdot v_{rel}}{2}|^2}$$

$$t = t_0 - 4 \frac{\vec{p}_1 \cdot \vec{p}_3}{s m^2} \sin^2(\theta/2)$$

$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{v}{2} \right)^2 m_s$$

$$4 \cdot 4 \lambda^2$$

Scattering on nuclei

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$\sigma \propto \lambda^2$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$M = 2\lambda$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_s)^2} \cdot \frac{1}{|\frac{m_s v_{rel}}{2}|^2} \times$$

$$t = t_0 - 4 \frac{\vec{p}_1 \cdot \vec{p}_3}{s m^2} \sin^2(\theta/2)$$

$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(\frac{m_s v}{2} \right) m_s$$

$$4 \cdot 4 \lambda^2 -$$

Scattering on nuclei

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Scattering on nuclei

$\sqrt{t} = \frac{64\pi(2m_s)}{\lambda^2} \frac{1}{m_s v_{rel}/2}$

$t = t_0 - \frac{4\lambda^2}{P_1/P_3} \frac{m_s v^2}{sm^2(\theta/2)}$

$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(\frac{m_s v}{2} \right)^2 m_s$

$4 \cdot 4 \lambda^2 \frac{1}{m_s v_{rel}/2}$

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Scattering on nuclei

$\frac{dt}{d\Omega} = \frac{64\pi(2m_s)}{\lambda^2} \frac{1}{\frac{m}{2}v_{rel}} \frac{1}{r^2}$

$t = t_0 - \frac{4\lambda^2}{P_1/P_3} \frac{1}{sm^2(\theta/2)}$

$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(\frac{m_s}{2} \right)^2 m_s$

$= \frac{4 \cdot 4 \lambda^2}{16 \frac{1}{m_s^2 v_{rel}^2}}$

$= \frac{\lambda^2}{m^2}$

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Scattering on nuclei

$\frac{dt}{d\Omega} = \frac{64\pi(2m_s)^2}{\lambda^2} \frac{1}{m_s v_{rel}/2}$

$t = t_0 - \frac{4(2\lambda)^2}{P_1/P_3} \frac{1}{sm^2(\theta/2)}$

$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{v_{rel}}{2} \right) m_s$

$= \frac{4 \cdot 4 \lambda^2}{m^2} \frac{1}{(m_s v_{rel})^2}$

$= \frac{\lambda^2}{m^2} \cdot \frac{1}{v_{rel}} \cdot \frac{1}{\pi}$

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Scattering on nuclei

$\frac{dt}{d\Omega} = \frac{64\pi(2m_s)}{\lambda^2} \frac{1}{m_s v_{rel}/2} \frac{1}{\sin^2(\theta/2)}$

$t = t_0 - \frac{4P_1/P_3}{\lambda^2} \frac{1}{m_s^2} m_s$

$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(\frac{m_s v_{rel}}{2} \right) m_s$

$= \frac{4 \cdot 4 \lambda^2}{m^2} \frac{1}{(m_s v_{rel})^2}$

$= \frac{\lambda^2}{m^2} \cdot \frac{1}{v_{rel}} \cdot \frac{1}{2\pi}$

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Scattering on nuclei

$t = t_0 - \frac{4 \vec{p}_1 \cdot \vec{p}_3}{m_s^2} \sin^2(\theta/2)$

$$\sigma_{\text{ann}} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\nu_{\text{rel}}}{2} \right) m_s$$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\nu_{\text{rel}}} \cdot \frac{2}{\pi}$$

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Scattering on nuclei

$t = t_0 - \frac{4 \vec{p}_1 \cdot \vec{p}_3}{m_s^2} \sin^2(\theta/2)$

$$\sigma_{\text{ann}} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\omega_{\text{rel}}}{2} \right) m_s$$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\omega_{\text{rel}}} \cdot \frac{1}{2\pi}$$

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Scattering on nuclei

$t = t_0 - \frac{4 \tilde{P}_1 / \tilde{P}_3}{\sin^2(\theta/2)}$

$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\nu_{rel}}{2} \right) m_s$$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\nu_{rel}} \cdot \frac{1}{2\pi}$$
 \leq
 $\gtrsim 1 \text{ pbn} \quad \text{OK}$

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Scattering on nuclei

$t = t_0 - \frac{4 \tilde{P}_1 / \tilde{P}_3}{\sin^2(\theta/2)}$

$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\nu_{rel}}{2} \right) m_s$$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\nu_{rel}} \cdot \frac{1}{2\pi}$$

\leq not ok!

$\gtrsim 1 \text{ pbn}$ ok

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$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\nu_{rel}}{2} \right)^2 m_s$$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\nu_{rel}} \cdot \frac{1}{2\pi}$$

$$\sigma V = \frac{\lambda^2}{m^2} \cdot \frac{1}{2\pi}$$

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$\sigma_{\text{ann}} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\nu_{\text{rel}}}{2} \right)^2 m_s$

$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\nu_{\text{rel}}} \cdot \frac{1}{2\pi}$

$\sigma V = \frac{\lambda^2}{m^2} \cdot \frac{1}{2\pi}$

Compare to / plan.

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$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\nu_{rel}}{2} \right)^2 m_s$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\nu_{rel}} \cdot \frac{1}{2\pi}$$

$$\sigma V = \frac{\lambda^2}{m^2} \cdot \frac{1}{2\pi} = pbm$$

Compare to 1 pbm .

$$\lambda \sim \sqrt{2\pi m^2 \cdot 1 \text{ pbm}}$$

$$\sim 2.5 \cdot m \cdot \cdot$$

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$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\nu_{rel}}{2} \right)^2 m_s$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\nu_{rel}} \cdot \frac{1}{2\pi}$$

$$\sigma V = \frac{\lambda^2}{m^2} \cdot \frac{1}{2\pi} = pbm$$

Compare to 1 pbm .

$$\lambda \sim \sqrt{2\pi m^2 \cdot 1 \text{ pbm}}$$

$$\sim 2.5 \cdot m \cdot 10^{-18} \text{ cm}$$

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$\sigma V = \frac{\lambda}{m^2} \cdot \frac{1}{2\pi} = \text{pbn}$

Compare to 1 pbn .

$\lambda \sim \sqrt{2\pi m^2 \cdot 1 \text{ pbn}}$

$\sim 2.5 \cdot \frac{m_{\text{TeV}}}{10^{-18} \text{ cm}} \cdot \text{TeV}$

$\sim 2.5 m_{\text{TeV}} \cdot \frac{10^{-18} \text{ cm} \cdot \text{TeV}}{10^{13} \text{ cm} \cdot 0.2 \text{ GeV}}$

Higgs decay to light scalar DM

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$\sigma V = \frac{\lambda}{m^2} \cdot \frac{1}{2\pi} = \text{pbn}$

Compare to 1 pbn .

$$\lambda \sim \sqrt{2\pi m^2 \cdot 1 \text{ pbn}}$$

$$\sim 2.5 \cdot \frac{m_{\text{TeV}}}{10^{-18} \text{ cm}} \cdot \text{TeV}$$

$$\sim 2.5 m_{\text{TeV}} \cdot \frac{10^{-18} \text{ cm} \cdot \text{TeV}}{10^{13} \text{ cm} \cdot 0.2 \text{ GeV}}$$

$$\sim 2.5 m_{\text{TeV}} \cdot 10^{-5}$$

Higgs decay to light scalar DM

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$\sigma V = \frac{\lambda}{m^2} \cdot \frac{1}{2\pi} = \text{pbn}$

Compare to 1 pbn .

$$\lambda \sim \sqrt{2\pi m^2 \cdot 1 \text{ pbn}}$$

$$\sim 2.5 \cdot \frac{m_{\text{TeV}}}{10^{-18} \text{ cm}} \cdot \text{TeV}$$

$$\sim 2.5 m_{\text{TeV}} \cdot \frac{10^{-18} \text{ cm} \cdot \text{TeV}}{10^{13} \text{ cm} \cdot 0.2 \text{ GeV}}$$

$$\sim 2.5 m_{\text{TeV}} \cdot 10^{-5} \times 5 \times 10^3$$

Higgs decay to light scalar DM

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$\lambda \sim \sqrt{2\pi} m^{-1} \text{pbm}$

$$\sim 2.5 \cdot m_{\text{TeV}}^{-1} \cdot 10^{-18} \text{cm} \cdot \text{TeV}$$

$$\sim 2.5 m_{\text{TeV}} \cdot \frac{10^{-18} \text{cm} \cdot \text{TeV}}{10^{13} \text{cm} \cdot 0.2 \text{GeV}}$$

$$\sim 2.5 m_{\text{TeV}} \cdot 10^{-5} \times 5 \times 10^3$$

$$\simeq 12.5 \times 10^{-2} m_{\text{TeV}}$$

Higgs decay to light scalar DM

Comparison with data

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$\lambda \sim \sqrt{2\pi} m^{-1} \text{pb}\cdot\text{fm}$

$$\sim 2.5 \cdot m_{\text{TeV}}^{-1} \cdot 10^{-18} \text{cm} \cdot \text{TeV}$$

$$\sim 2.5 m_{\text{TeV}} \cdot \frac{10^{-18} \text{cm} \cdot \text{TeV}}{10^{13} \text{cm} \cdot 0.2 \text{GeV}}$$

$$\sim 2.5 m_{\text{TeV}} \cdot 10^{-5} \times 5 \times 10^3$$

$$\simeq 12.5 \times 10^{-2} m_{\text{TeV}}$$

At $m \sim 10 \text{ TeV}$

$$\lambda \sim 0(1)$$

Higgs decay to light scalar DM

Comparison with data

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$\lambda \sim \sqrt{2\pi m^2 \cdot 1 \text{ pb}} \sim 2.5 \cdot m_{\text{TeV}} \cdot 10^{-18} \text{ cm} \cdot \text{TeV} \sim 2.5 m_{\text{TeV}} \cdot \frac{10^{-18} \text{ cm} \cdot \text{TeV}}{10^{13} \text{ cm} \cdot 0.2 \text{ GeV}} \sim 2.5 m_{\text{TeV}} \cdot 10^{-5} \times 5 \times 10^3 \simeq 12.5 \times 10^{-2} m_{\text{TeV}}$

At $m \sim 10 \text{ TeV}$

$\lambda \sim 0(1)$

Conclusion: DM has to be lighter than few 10 TeV

Higgs decay to light scalar DM

Comparison with data

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Large m_s

$m_s < M_h/2$

$s \gg \lambda$: 4 scalar fields of H

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$M = 2\lambda$

$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_s)^2} \cdot \frac{1}{|\frac{m}{2}\vec{v}_{rel}|^2} \times$

$4(2\lambda)^2 \Rightarrow \frac{m_s^2}{2} \frac{m_s}{m}$

$t = t_0 - 4\vec{p}_1 \cdot \vec{p}_2 / |\vec{p}_1|^2 \sin^2(\theta/2)$

$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{\vec{v}_{rel}}{2} \right) m_s$

$4 \cdot 4 \lambda^2 \frac{1}{|\frac{m}{2}\vec{v}_{rel}|^2}$

$= \frac{\lambda^2}{m^2} \cdot \frac{1}{\vec{v}_{rel}} \cdot \frac{1}{2\pi}$

$\sigma V = \frac{\lambda^2}{m^2} \cdot \frac{1}{2\pi} = \text{pbn}$

Compare to $/ \text{pbn}$

Scattering on nuclei

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Higgs decay to light scalar DM

Comparison with data

$m_h = 120 \text{ GeV}$

$\sim 2.5 M_{\text{TeV}} \cdot 10^{-5} \times 5 \times 10^3$

$\simeq 12.5 \times 10^{-2} M_{\text{TeV}}$

At $M \sim 10 \text{ TeV}$

Conclusion: $\lambda \sim 0(1)$ DM has to be lighter than few 10 TeV

$m_s < m_h/2$

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis (2000)

DM through the Higgs portal – minimal model of DM

$$\begin{aligned} -\mathcal{L}_H &= \frac{\lambda_0}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H \\ &= \frac{\lambda_0}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2) S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2} S^2 h^2 \end{aligned}$$

125 GeV Higgs is "very fragile" because its width is $\sim y_b^{-2}$ – very small
 $R = \Gamma_{\text{SM mode}} / (\Gamma_{\text{SM mode}} + \Gamma_{\text{DM mode}})$. Light DM can kill Higgs boson easily
 (missing Higgs I: van der Bij et al., 1990s, Elloli, Zeppenfeld, 2000)

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Higgs decay to light scalar DM

Comparison with data

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125 GeV Higgs is "very fragile" because its width is $\sim y_b^{-2}$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily
 (missing Higgs I: van der Bij et al., 1990s, Ebell, Zeppenfeld, 2000)

$m_S < m_h/2$

$S \quad h \quad h$

$10^{13} \text{ cm} \cdot 0.2 \text{ GeV}$
 $\sim 2.5 M_{\text{TeV}} \cdot 10^{-5} \times 5 \times 10^3$
 $\simeq 12.5 \times 10^{-2} M_{\text{TeV}}$

At $m \sim 10 \text{ TeV}$

Conclusion: DM has to be lighter than few 10 TeV

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Higgs decay to light scalar DM

Comparison with data

$m_h = 120 \text{ GeV}$

At $m \sim 10 \text{ TeV}$

$\lambda \sim 0(1)$

Conclusion: DM has to be lighter than few 10 TeV

$2m_b < m_S < m_h/2$

$S \quad h$

m_b

m_S

m_h

m_{DM}

DM through the Higgs portal – minimal model of DM

$$\mathcal{L}_H = \frac{\lambda_0}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H$$

$$= \frac{\lambda_0}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2} S^2 h^2$$

125 GeV Higgs is "very fragile" because its width is $\sim y_b^{-2}$ – very small
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 (missing Higgs I: van der Bij et al., 1990s, Ebell, Zeppenfeld, 2000)

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Higgs decay to light scalar DM

Comparison with data

Simplest models of Higgs mediation
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125 GeV Higgs is "very fragile" because its width is $\sim y_b^{-2}$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily
 (missing Higgs I: van der Bij et al., 1990s, Ebell, Zeppenfeld, 2000)

$m_b < m_S < m_h/2$

m_b
 m_S
 m_h
 m_b

At $m \sim 10 \text{ TeV}$
 $\lambda \sim 0(1)$
 Conclusion: DM has to be lighter than few 10 TeV

10 GeV

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Higgs decay to light scalar DM

Comparison with data

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis (2000)

DM through the Higgs portal – minimal model of DM

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125 GeV Higgs is "very fragile" because its width is $\sim y_b^{-2}$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily
 (missing Higgs I: van der Bij et al., 1990s, Ebell, Zeppenfeld, 2000)

$m_h^{13} \text{ cm} \cdot 0.2 \text{ GeV}$

$\sim 2.5 M_{\text{TeV}} \cdot 10^{-5} \times 5 \times 10^3$

$\simeq 12.5 \times 10^{-2} M_{\text{TeV}}$

At $M \sim 10 \text{ TeV}$

Conclusion: $\lambda \sim 0(1)$ DM has to be lighter than few 10 TeV

$2m_b < m_S < m_h/2$

$m_h/2$

m_b

m_S

m_h

m_b

m_S

m_b

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Higgs decay to light scalar DM

Comparison with data

Simplest models of Higgs mediation
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$$\begin{aligned} \mathcal{L}_H &= \frac{\lambda_0}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H \\ &= \frac{\lambda_0}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2} S^2 h^2 \end{aligned}$$

125 GeV Higgs is "very fragile" because its width is $\sim y_b^{-2}$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily
 (missing Higgs I: van der Bij et al., 1990s, Elloli, Zeppenfeld, 2000)

$m_b < m_S < m_h/2$

m_b m_S $m_h/2$
 \uparrow \searrow \swarrow
 10 GeV S h b

10 13 cm - 0.2 GeV
 $\sim 2.5 M_{TeV} \cdot 10^{-5} \times 5 \times 10^3$
 $\simeq 12.5 \times 10^{-2} M_{TeV}$

At $m \sim 10 \text{ TeV}$

Conclusion: DM has to be lighter than few 10 TeV

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Conclusion: $\lambda \sim O(1)$ DM has to be lighter than few 10 TeV

Comparison with data

Simplest models of Higgs mediation
Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis (2000)

DM through the Higgs portal – minimal model of DM

$$-\mathcal{L}_A = \frac{\lambda_S}{4} S^4 + \frac{m_S^2}{2} S^2 + \lambda S^2 H^\dagger H$$

$$= \frac{\lambda_S}{4} S^4 + \frac{1}{2}(m_b^2 + \lambda v_{EW}^2) S^2 + \lambda v_{EW} S^2 b + \frac{\lambda}{2} S^2 b^2$$

125 GeV Higgs is "very fragile" because its width is $-y_t^2$ – very small
 $R = \Gamma_{SM\text{ mode}} / (\Gamma_{SM\text{ mode}} + \Gamma_{DM\text{ mode}})$. Light DM can kill Higgs boson easily (missing Higgs Γ ; van der Bij et al., 1990s; Eboli, Zeppenfeld, 2000)

Updates on the minimal Higgs-mediated model:

Figure from Cline, Scott, Kainulainen, Weniger, 2013.

2 m_b < m_S < m_h / 2

10 GeV S h b b

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Assume $\lambda > 10^{-7}$, thermal equilibrium.

Two specific cases $m_s \gtrsim \text{TeV}$
 $m_s < m_h/2$

Large m_s

4 scalar fields of H

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s} \frac{1}{|\vec{P}_{cm}|^2} \cdot |M|^2$$

$$M = 2\lambda$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi (2m_s)^2} \cdot \frac{1}{|\vec{m} \cdot \vec{v}_{rel}|^2} \times$$

$$t = t_0 - 4\vec{p}_1 \cdot \vec{p}_3 / |\vec{s}|^2 \sin^2(\theta/2)$$

$$\sigma_{ann} = \frac{1}{64\pi} \frac{1}{4m_s^2} 4 \left(m_s \frac{v_{rel}}{2} \right) m_s$$

$$= \frac{4 \lambda^2}{m^2} \frac{1}{|v_{rel}|^2}$$

$$= \frac{\lambda^2}{m^2} \cdot \frac{1}{v_{rel}} \cdot \frac{1}{2\pi}$$

Scattering on nuclei

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Conclusion: $\lambda \sim O(1)$ DM has to be lighter than few 10 TeV

Comparison with data

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis (2000)

DM through the Higgs portal – minimal model of DM

$$\mathcal{L}_S = \frac{\Lambda_S}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H$$

$$= \frac{\Lambda_S}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda g_{HW}^2) S^2 + \lambda g_{HW} S^2 h + \frac{\lambda}{2} S^2 h^2$$

125 GeV Higgs is "very fragile" because its width is $\sim y_h^2$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily (missing Higgs Γ ; van der Bij et al., 1990s; Ehsoli, Zeppenfeld, 2000)

Updates on the minimal Higgs-mediated model:

Figure from Cline, Scott, Kainulainen, Weniger, 2013.

$2m_b < m_S < m_h/2$

$m_h/2 \bar{b}$

$m_b \bar{b}$

$M = 2\lambda v \frac{1}{(2m_S)^2 - m_h^2} \cdot \frac{m_b}{v} \bar{b} b$

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Conclusion: $\lambda \sim O(1)$ DM has to be lighter than few 10 TeV

Comparison with data

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis (2000)

DM through the Higgs portal – minimal model of DM

$$\begin{aligned} -\mathcal{L}_S &= \frac{\Lambda_S}{4} S^4 + \frac{m_H^2}{2} S^2 + \lambda S^2 H^\dagger H \\ &= \frac{\Lambda_S}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda g_{HWW}^2) S^2 + \lambda g_{HWW} S^2 h + \frac{\lambda}{2} S^2 h^2 \end{aligned}$$

125 GeV Higgs is "very fragile" because its width is $\sim y_t^{-2}$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily
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Updates on the minimal Higgs-mediated model:

Figure from Cline, Scott, Kainulainen, Weniger, 2013.

$2m_b < m_S < m_h/2$

m_h

m_b

$M = 2\lambda v \frac{1}{(2m_S)^2 - m_h^2} \cdot \frac{m_b}{v} \bar{b}b$

$\sum |M|^2 = (2\lambda)^2 \frac{m_b^2}{(4m_S^2 - m_h^2)^2}$

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Conclusion: $\lambda \sim O(1)$ DM has to be lighter than few 10 TeV

Comparison with data

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis (2000)

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$$\begin{aligned} -\mathcal{L}_S &= \frac{\Lambda_S}{4} S^4 + \frac{m_0^2}{2} S^2 + \lambda S^2 H^\dagger H \\ &= \frac{\Lambda_S}{4} S^4 + \frac{1}{2}(m_0^2 + \lambda g_{HW}^2) S^2 + \lambda g_{HW} S^2 h + \frac{\lambda}{2} S^2 h^2 \end{aligned}$$

125 GeV Higgs is "very fragile" because its width is $\sim y_t^2$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily
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$$M = 2\lambda v \frac{1}{(2m_S)^2 - m_h^2} \cdot \frac{m_b}{v} \bar{b}b$$

Updates on the minimal Higgs-mediated model:

Figure from Cline, Scott, Kainulainen, Weniger, 2013.

$\sum |M|^2 = (2\lambda)^2 \frac{m_b^2}{(4m_S^2 - m_h^2)^2} \cdot \text{Tr} \left(\frac{(p_3 + m_b)}{(p_4 - m_b)} \right)$

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$$-\mathcal{L}_H = \frac{\lambda_S}{4} S^4 + \frac{m_H^2}{2} S^2 + \lambda S^2 H^\dagger H$$

$$= \frac{\lambda_S}{4} S^4 + \frac{1}{2} (m_0^2 + \lambda v_{EW}^2) S^2 + \lambda v_{EW} S^2 b + \frac{\lambda}{2} S^2 b^2$$

125 GeV Higgs is "very fragile" because its width is $\sim y_t^{-2}$ – very small
 $R = \Gamma_{SM \text{ mode}} / (\Gamma_{SM \text{ mode}} + \Gamma_{DM \text{ mode}})$. Light DM can kill Higgs boson easily
 (missing Higgs Γ ; van der Bij et al., 1990s; Eboli, Zeppenfeld, 2000)

Updates on the minimal Higgs-mediated model:

Figure from Cline, Scott, Kainulainen, Weniger, 2013.

Conclusion on minimal Higgs portal model of DM

Light WIMPs due to light mediators direct production/detection

Light dark matter is not ruled out if one adds a light mediator.
 WIMP paradigm: $\sigma_{\text{annals}}(v/c) \sim 1 \text{ pbm} \implies \Omega_{\text{DM}} \approx 0.25$,
 Electroweak mediators lead to the so-called Lee-Weinberg window,

$$M = 2\lambda v \frac{1}{(2m_S)^2 - m_h^2} \cdot \frac{m_b}{v} bb$$

$$\sum |M|^2 = (2\lambda)^2 \frac{m_b^2}{(4m_S^2 - m_h^2)^2} \cdot \frac{tr((P_3 + m_b)(P_4 - m_b))}{4(P_3 P_4 - m_b^2)}$$

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$b, \beta_0 l$

Figure from Cline, Scott, Kainulainen, Weniger, 2013.

Conclusion on minimal Higgs portal model of DM

Light WIMPs due to light mediators direct production/detection

Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $\sigma_{\text{ann}} v / c \approx 1 \text{ pbn} \implies \Omega_{\text{DM}} \approx 0.25$.

Electroweak mediators lead to the so-called Lee-Weinberg window,

$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for } m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for } m_\chi \gg m_W, \end{cases} \implies \text{few GeV} < m_\chi < \text{few TeV}$$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as $\sim \text{MeV}$ (and not ruled out by the CMB if it is a scalar).

"Simplified models" for light DM some examples

- Scalar dark matter talking to the SM via a dark photon (variants: $L_{\text{int}} - L_{\text{int}}$ etc gauge bosons). With $2m_{\text{DM}} < m_{\text{mediator}}$.

$$= (2\lambda)^2 \cdot \frac{m_b^2}{(4m_S^2 - m_h^2)^2} \cdot 4(P_3 P_4 - m_b^2)$$

$$P_3 P_4 = \frac{1}{2} ((P_3 + P_4)^2 - 2m_b^2) =$$

$$= \frac{1}{2} ((P_1 + P_2)^2 - 2m_b^2)$$

$$= \frac{1}{2} (4m_S^2 - 2m_L^2)$$

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Figure from Clew, Scott, Kesteloot, Weigert, 2013.

Conclusion on minimal Higgs portal model of DM

Light WIMPs due to light mediators direct production/detection

Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $\sigma_{\text{ann}}(v/c) \sim 1 \text{ pb} \rightarrow \Omega_{\text{DM}} \approx 0.25$.

Electronless mediators lead to the so-called Lee-Wenberg window:

$$\sigma_{\text{ann}}(v) = \begin{cases} \frac{G_F m_{\chi}^2}{16 \pi v^2} & m_{\chi} < m_h \\ 0 & m_h < m_{\chi} < m_B \end{cases} \quad \text{low GeV} < m_{\chi} < \text{few TeV}$$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as $\sim \text{MeV}$ (and not ruled out by the CMB if it is a scalar).

$$= (2\lambda)^2 \cdot \frac{\tilde{m}_b^2}{(4m_s^2 - m_h^2)^2} \cdot 4(P_3 P_4 - \tilde{m}_b^2)$$

$$P_3 P_4 = \frac{1}{2}((P_3 + P_4)^2 - 2m_b^2) =$$

$$= \frac{1}{2}((P_1 + P_2)^2 - 2m_b^2)$$

$$= \frac{1}{2}(4m_s^2 - 2\tilde{m}_b^2)$$

$$/M^2 = (2\lambda)^2 \frac{\tilde{m}_b^2 (2m_s^2 - \tilde{m}_b^2)}{(4m_s^2 - m_h^2)^2}$$

"Simplified models" for light DM some examples

- Scalar dark matter talking to the SM via a dark photon (constant $A_{\mu\chi}$, $L_{\mu\chi}$, etc gauge bosons). With $2m_{\chi} < m_{\text{center}}$

$$\mathcal{L} = [D_\mu \chi]^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} F_\mu^2 + \frac{1}{2} m_H^2 V^2 - \frac{1}{2} V_\mu F_\mu$$

- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $2m_{\chi} > m_{\text{center}}$

$$\mathcal{L} = \bar{\chi} (\partial_\mu \gamma_\mu - m_{\chi} \chi + A \chi \delta^A_\mu) + \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \lambda S (H^\dagger H)$$

After EW symmetry breaking S mixes with physical h , and can be light and weakly coupled provided that coupling A is small. Let's call it a dark Higgs.

Two different types of annihilation

- Model 1: one step process

$$\chi \chi \rightarrow \text{off shell dark photon} \rightarrow e^+ e^-$$

- Model 2: two-step process: annihilation to mediators with subsequent decay

$$\chi \chi \rightarrow S + S \rightarrow \dots \rightarrow (e^+ e^-) + (e^+ e^-)$$

In both cases, the annihilation process is ρ wave, and is very suppressed at the recombination time \rightarrow no CMB constraints. Thus, the MeV – to – GeV range is not excluded by cosmology.

Important consequence of secluded dark matter mechanism

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Figure from Clew, Scott, Kesteloot, Weigert, 2013.

Conclusion on minimal Higgs portal model of DM

Light WIMPs due to light mediators direct production/detection

Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $\sigma_{\text{ann}}(v/c) \sim 1 \text{ pb} \rightarrow \Omega_{\text{DM}} \approx 0.25$.

Electronless mediators lead to the so-called Lee-Wenberg mechanism:

$$\sigma(v/c) = \begin{cases} \frac{G_F m_e^2}{16\pi v^2} & \text{for } m_e \ll m_\phi \\ 0 & \text{for } m_e \gg m_\phi \end{cases} \quad \text{low TeV} < m_\phi < \text{few TeV}$$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as $\sim \text{MeV}$ (and not ruled out by the CMB if it is a scalar).

$$= (2\lambda)^2 \cdot \frac{\tilde{m}_b^2}{(4m_s^2 - m_h^2)^2} \cdot 4(P_3 P_4 - \tilde{m}_b^2)$$

$$P_3 P_4 = \frac{1}{2}((P_3 + P_4)^2 - 2m_b^2) =$$

$$= \frac{1}{2}((P_1 + P_2)^2 - 2m_b^2)$$

$$= \frac{1}{2}(4m_s^2 - 2\tilde{m}_b^2)$$

$$/M^2 = (2\lambda)^2 \frac{\tilde{m}_b^2 (2m_s^2 - \tilde{m}_b^2)}{(4m_s^2 - m_h^2)^2}$$

"Simplified models" for light DM some examples

- Scalar dark matter coupling to the SM via a dark photon (coupling Γ_{SM} , Γ_{dark} , etc gauge bosons). With $2m_{\text{DM}} < M_{\text{center}}$

$$\mathcal{L} = [D_S \chi^2 - m_\chi^2 \chi^2] - \frac{1}{2} \bar{F}_\mu^2 + \frac{1}{2} m_H^2 F_\mu^2 - \frac{1}{3} \bar{V}_\mu V_\mu$$

- Fermionic dark matter coupling to the SM via a "dark scalar" that mixes with the Higgs. With $2m_{\text{DM}} > M_{\text{center}}$

$$\mathcal{L} = \bar{\chi} (\partial_\mu \gamma_\mu - m_\chi \chi + \lambda \chi \delta^2) + \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_H^2 S^2 - \lambda S (\delta^2 H^\dagger H)$$

After EW symmetry breaking S mixes with physical h , and can be light and weakly coupled provided that coupling λ is small. Let's call it a dark Higgs.

Two different types of annihilation

- Model 1: one step process

$$\chi \chi^* \rightarrow \text{off shell dark photon} \rightarrow e^+ e^-$$

- Model 2: two-step process: annihilation to mediators with subsequent decay

$$\chi \chi^* \rightarrow S + S \rightarrow \dots \rightarrow (e^+ e^-) + (e^+ e^-)$$

In both cases, the annihilation process is ρ wave, and is very suppressed at the recombination time \rightarrow no CMB constraints. Thus, the MeV – to – GeV range is not excluded by cosmology.

Important consequence of secluded dark matter mechanism

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Figure from Cline, Srost, Kehdman, Weigert, 2013.

Conclusion on minimal Higgs portal model of DM

Light WIMPs due to light mediators direct production/detection

Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $\sigma_{\text{ann}} v / \pi \sim 1 \text{ pb} \rightarrow \Omega_{\text{DM}} \approx 0.25$.

Electronless mediators lead to the so-called Lee-Wenberg window:

$$\sigma_{\text{ann}} v / \pi = \begin{cases} 0 & m_1 < m_2 \\ 1/m_2^2 & m_1 > m_2 \end{cases} \quad \text{for } 10 \text{ GeV} < m_1 < 100 \text{ GeV}$$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as $\sim 1 \text{ MeV}$ (and not ruled out by the CMB if it is a scalar).

$\langle \sigma v \rangle = \frac{(2\lambda)^2}{M^2} \frac{\tilde{m}_b^2}{(4m_s^2 - m_h^2)^2} \frac{4(P_3 P_4 - \tilde{m}_b^2)}{m_b^2 (2m_s^2 - \tilde{m}_b^2)}$

"Simplified models" for light DM some examples

- Scalar dark matter (coupling to the SM via a dark photon, constants L_{int} , L_{kin} , etc gauge bosons). With $2m_{\text{DM}} < M_{\text{center}}$

$$\mathcal{L} = [D_S \chi^2 - m_S^2 \chi]^2 - \frac{1}{4} D_\mu^2 + \frac{1}{2} m_H^2 V^2 - \frac{1}{2} V_{\mu} F_{\mu}$$

- Fermionic dark matter (coupling to the SM via a "dark scalar" that mixes with the Higgs. With $2m_{\text{DM}} > M_{\text{center}}$)

$$\mathcal{L} = Y(\partial_\mu \chi_L - m_{\chi} \chi_L + \lambda \chi \phi) + \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \lambda S(H^\dagger H)$$

After EW symmetry breaking S mixes with physical h , and can be light and weakly coupled provided that coupling λ is small. Let's do call it a dark Higgs

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- Model 1: one step process

$$\chi \bar{\chi} \rightarrow \text{off shell dark photon} \rightarrow e^+ e^-$$

- Model 2: two-step process: annihilation to mediators with subsequent decay

$$\chi \bar{\chi} \rightarrow S + S \rightarrow \dots \rightarrow (e^+ e^-) + (e^+ e^-)$$

In both cases, the annihilation process is ρ -invariant, and is very suppressed at the recombination time \rightarrow no CMB constraints. Thus, the $10 \text{ MeV} - 10 \text{ GeV}$ range is not excluded by cosmology.

Important consequence of secluded dark matter mechanism

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Figure from Cleo, Scott, Komatsu, Weinger, 2013.

Conclusion on minimal Higgs portal model of DM

Light WIMPs due to light mediators direct production/detection

Light dark matter is not ruled out if one adds a light mediator.
WIMP paradigm: $\sigma_{\text{ann}} v / (4 \pi) \sim 1 \text{ pb} \rightarrow 12 \text{ GeV} \approx 9.25$.
Electroweak mediators lead to the so-called Lee-Watabe model.

$\sigma_{\text{ann}} v = \frac{1}{2} \left(\frac{\alpha_s}{m_1 m_2} \right)^2 \left(\frac{m_1^2 + m_2^2}{m_1 m_2} \right) \sim 10^{-26} \text{ cm}^3 \text{s}^{-1}$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as ~ MeV (and not ruled out by the CMB if it is a scalar).

"Simplified models" for light DM

• Scalar dark matter takes to the SM via a scalar photon
coupling: $I_{\text{int}} = I_{\text{int}}(\text{SM gauge bosons}) + 2 \Phi \partial_\mu \Phi - \frac{1}{2} m_\phi^2 \Phi^2 - \frac{1}{2} V_{\text{eff}}$

$\mathcal{L} = [D_\mu \Phi]^2 - m_\phi^2 \Phi^2 - \frac{1}{2} \partial_\mu^2 \Phi^2 + \frac{1}{2} m_\phi^2 \Phi^2 - \frac{1}{2} V_{\text{eff}}$

• Fermionic dark matter takes to the SM via a "dark scalar"
that mixes with the Higgs. With Higgs: I_{int}

$\mathcal{L} = \chi (\partial_\mu \chi - m_\chi) \chi + \lambda \chi \phi + \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \mathcal{L}_{\text{Higgs}}$

After EW symmetry breaking 5 massless bosons (with physical b , and can be light and weakly coupled provided that coupling λ is small. Let's call it a dark Higgs.

Two different types of annihilation

- Model 1: one step process
- $\chi \bar{\chi} \rightarrow \text{off shell dark photon} \rightarrow e^+ e^-$
- Model 2: two step process: annihilation to mediators with subsequent decay
- $\chi \bar{\chi} \rightarrow S + S \rightarrow \dots \rightarrow (e^+ e^-) + (e^+ e^-)$

In both cases, the annihilation proceeds in p conserving, and is very suppressed at the recombination time \rightarrow no CMB constraints. Thus, three MeV \rightarrow 10 GeV range is not excluded by cosmology.

Important consequence of secluded dark matter mechanism

$$= (2\lambda)^2 \cdot \frac{m_b^2}{(4m_s^2 - m_h^2)^2} \cdot 4(P_3 P_4 - \tilde{m}_b^2)$$

$$P_3 P_4 = \frac{1}{2} ((P_3 + P_4)^2 - 2m_b^2) =$$

$$= \frac{1}{2} ((P_1 + P_2)^2 - 2m_b^2)$$

$$= \frac{1}{2} (4m_s^2 - 2m_b^2)$$

$$/M^2 = (2\lambda)^2 \frac{m_b^2}{(4m_s^2 - m_h^2)^2} \frac{(2m_s^2 - m_b^2)}{(2m_s^2 - m_b^2)}$$

$$\langle \sigma v \rangle = \frac{\lambda^2}{m_s^2} \frac{1}{2\pi} \frac{m_b^2 (2m_s^2 - m_b^2)}{(4m_s^2 - m_h^2)^2}$$

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Figure from Chack, Scott, Komatsu, Weinger, 2013.

Conclusion on minimal Higgs portal model of DM

Light WIMPs due to light mediators direct production/detection

Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $m_{\text{DM}} \ll m_h \sim 1 \text{ pb} \rightarrow \Omega_{\text{DM}} \approx 0.25$.

Electroweak mediators lead to the so-called Lee-Watabe model.

atmos $\int d^3 p \approx m_s \cdot m_b \cdot m_b \rightarrow \text{few GeV} < m_s < \text{few TeV}$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as ~ MeV (and not ruled out by the CMB if it is a scalar).

"Simplified models" for light DM

• Scalar dark matter takes to the SM via a scalar photon (coupling $\Gamma_{\phi\gamma\gamma}$, $\Gamma_{\phi\gamma\gamma}$, etc gauge bosons). With $2m_{\text{DM}} < m_{\text{scalar}}$

$$\mathcal{L} = [D_\mu \phi]^2 - m_\phi^2 \phi^2 - \frac{1}{4} F_{\mu\nu}^2 + \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2} V_{\phi\phi}$$

• Fermionic dark matter takes to the SM via a "dark scalar" that mixes with the Higgs. With $m_{\text{Higgs}} > m_{\text{scalar}}$

$$\mathcal{L} = \chi (\partial_\mu \chi - m_\chi) \chi + \lambda \chi \phi + \frac{1}{2} (\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - \Lambda R(H^2) H$$

After EW symmetry breaking 5 times as physical δ , and can be light and weakly coupled provided that coupling Λ is small. Let's call it a dark Higgs.

Two different types of annihilation

- Model 1: one step process
- $\chi^0 \rightarrow \text{off shell dark photon} \rightarrow e^+ e^-$
- Model 2: two step process: annihilation to mediates with subsequent decay
- $\chi\bar{\chi} \rightarrow S + S \rightarrow \dots \rightarrow (e^+ e^-) + (e^+ e^-)$

In both cases, the annihilation proceeds in p conserving, and is very suppressed at the recombination time \rightarrow no CMB constraints. Thus, three MeV \rightarrow ~ GeV range is not excluded by cosmology.

Important consequence of secluded dark matter mechanism

$$= (2\lambda)^2 \cdot \frac{m_b}{(4m_s^2 - m_h^2)^2} \cdot 4(P_3 P_4 - \tilde{m}_b^2)$$

$$P_3 P_4 = \frac{1}{2} ((P_3 + P_4)^2 - 2m_b^2) =$$

$$= \frac{1}{2} ((P_1 + P_2)^2 - 2m_b^2)$$

$$= \frac{1}{2} (4m_s^2 - 2m_b^2)$$

$$/M^2 = (2\lambda)^2 \frac{m_b^2 (2m_s^2 - m_b^2)}{(4m_s^2 - m_h^2)^2}$$

$$\langle \sigma v \rangle = \frac{\lambda^2}{m_s^2} \frac{1}{2\pi \cdot 4} \frac{m_b^2 (2m_s^2 - m_b^2)}{(4m_s^2 - m_h^2)^2}$$

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$\frac{b}{10 \text{ GeV}} \rightarrow \frac{b}{\sqrt{\lambda}} \rightarrow \frac{b}{\sqrt{(2m_s)^2 - m_b^2}} \rightarrow \frac{m_b}{\sqrt{2}} \bar{b}b$

$$M = 2\lambda \sqrt{\frac{1}{(2m_s)^2 - m_b^2}} \cdot \frac{m_b}{\sqrt{2}} \bar{b}b$$

$$\frac{1}{M^2} = \frac{(2\lambda)^2}{(4m_s^2 - m_b^2)^2} \cdot \frac{\text{Tr}((\bar{b}b + M))}{(p_3 - m_b)}$$

$$= (2\lambda)^2 \cdot \frac{m_b^2}{(4m_s^2 - m_b^2)^2} \cdot 4(p_3 p_4 - m_b^2)$$

$$p_3 p_4 = \frac{1}{2}((p_3 + p_4)^2 - 2m_b^2) =$$

$$= \frac{1}{2}((p_1 + p_2)^2 - 2m_b^2)$$

$$= \frac{1}{2}(4m_s^2 - 2m_b^2)$$

$$\frac{1}{M^2} = (2\lambda)^2 \frac{m_b^2}{(4m_s^2 - m_b^2)^2} \frac{(2m_s^2 - m_b^2)}{(2m_s^2 - m_b^2)}$$

$$\langle \bar{b}b \rangle = \frac{\lambda^2}{m_s^2} \frac{1}{2\pi \cdot 4} \frac{m_b^2 (2m_s^2 - m_b^2)}{(4m_s^2 - m_b^2)^2}$$

$$m_s = 20 \text{ GeV} \text{ (example)}$$

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Light WIMPs due to light mediators direct production/selection

Light dark matter is an idea of two additional light mediators. WIMP partner: $m_{\text{WIMP}} = 1 \text{ GeV} \rightarrow m_h = 0.25$. Electromagnetic mediators lead to the so-called Lee-Wickling selection. It removes the contributions coming from a focus center with light mass. One has to go to light as a WIMP does not radiate one by the CMB if it is a center.

Simplified models* for light DM

- Scalar dark matter interacting to the DM via a dark photon (massless) $\chi \rightarrow \chi + \gamma$ (page 2000). With $m_\chi = 0.25$.
- Photino dark matter interacting to the DM via a "dark scalar" that mixes with the Higgs. With $m_\chi = 0.25$.

After LHC symmetry breaking 2 states with physical m_χ and can be light or heavy. Lightest might provide the coupling to the CMB. Lightest χ does not have.

Two different types of annihilation

- Model 1: one step process: $\chi^+ \chi^- \rightarrow \text{off shell dark photon} \rightarrow e^+ e^-$
- Model 2: two step process: annihilation to an intermediate state with the Higgs. With $m_H = 125$.

In both cases, the annihilation process is very rare, and is only suppressed by the transmission factor $\propto \text{GeV}^2$ (CMB constraint). Thus, low M_{DM} (~ 100 GeV) range is not excluded by constraints.

Important consequence of excluded dark matter mechanism

$m_\chi = 20 \text{ GeV}$ (example) ?
 ↳ ← inferred from abundance.

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Light WIMPs due to light mediators direct production/selection

Light dark matter is an other sort of massless light mediator. WIMP partner $m_{\text{partner}} = 1 \text{ GeV} \rightarrow m_h = 0.5 \text{ GeV}$. Electromagnetic mediators lead to the so-called Lee-Wickling violation. It is assumed the contributions come from a focus center with light mass. DM can be as light as $\sim 10^3$ GeV and not ruled out by the CMB if it is a scalar.

Simplified models* for light DM

- Scalar dark matter filling in the DM as a dark photon. Masses $m_1 = m_2$, one page beyond. WIMPs & R-symmetries
- $\delta = m_1 c^2 - m_2^2 c^2 = \sqrt{4m_1^2 - m_2^2} c^2 / [2m_1]$
- Pointlike dark matter filling in the DM as a "dark scalar" that mixes with the Higgs. With mass m_h . Masses
- $\delta = 1000 \text{ GeV} - m_h \text{ GeV} + 1000 \times \sqrt{4m_1^2 - m_2^2} \text{ GeV} - 1000 \text{ GeV}$

After LHC symmetry breaking 2 states with physical m_i and m_h have been coupled due to mixing. A small Δm^2 could not have

Two different types of annihilation

- Model 1: one loop process
- $\chi^0 \rightarrow \text{off shell dark photon} \rightarrow e^+ e^-$
- Model 2: two step process: annihilation to an intermediate state with the Higgs. With mass m_h .

In both cases, the contribution present is very small and is only suppressed by the nonrelativistic term $\propto m_h^2$ (CMB constraint). Thus, the $M_{\text{DM}} = 10^3$ GeV range is not excluded by constraints

Important consequence of excluded dark matter mechanism

$m_2 = 20 \text{ GeV} \text{ (example)}$?

↳ inferred from abundance.

What does it imply for the Higgs boson $h \rightarrow S S$

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