Title: Dark Sector Theory 2

Date: Jul 16, 2018 04:30 PM

URL: http://pirsa.org/18070035

Abstract:

Lecture 2.

Different types of Dark matter models. Dark matter models based on Higgs portal.

1

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 $J_\mu^{\,i} A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^{\,i} A_\mu$ 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

……….

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

2

DM classification

At some early cosmological epoch of hot Universe, with temperature T >> 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 --> SM of order ~ 1 pbn, 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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WIMP (= DM freeze-out) mechanism

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2

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DM - χ

$$\frac{1}{a^3}\frac{d}{dt}\left(a^3 n_{DM}\right) =$$

$$= \langle \sigma_{\chi\chi\to SM}\, v \rangle \left(n_{eq}^2 - n^2\right)$$

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4

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$$\xrightarrow[T<m]{}$$

4

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4

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4

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

$$Y = n$$

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$$Y = n_{DM}/s \qquad \left(s = \frac{2\pi^2}{45} g_{*s} T^3\right)$$

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4

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

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$$T < m \qquad g_i\left(\frac{\;}{2\pi}\right) \; e$$

4

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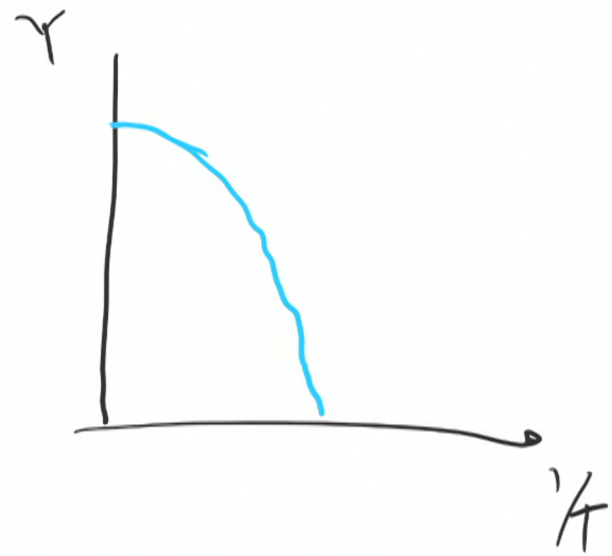

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Weakly interacting massive particles, WIMPs

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$T < m \qquad g_i\left(\frac{\cdots}{2\pi}\right) \cdots e$

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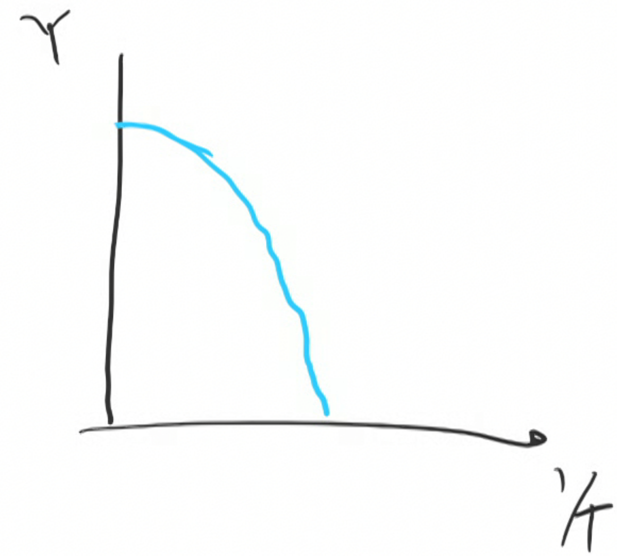

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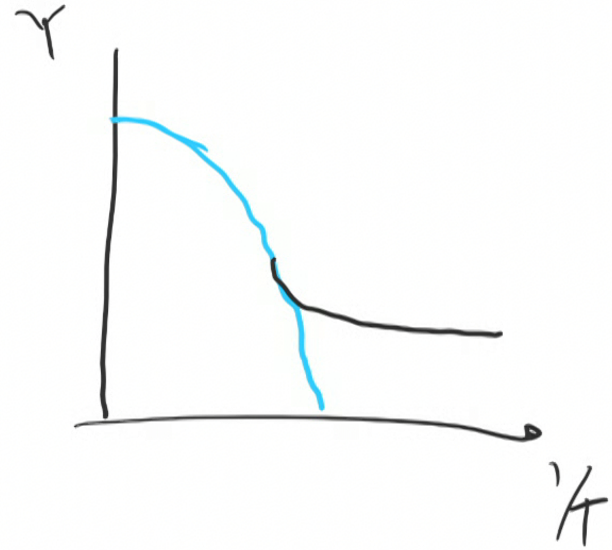

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Weakly interacting massive particles, WIMPs

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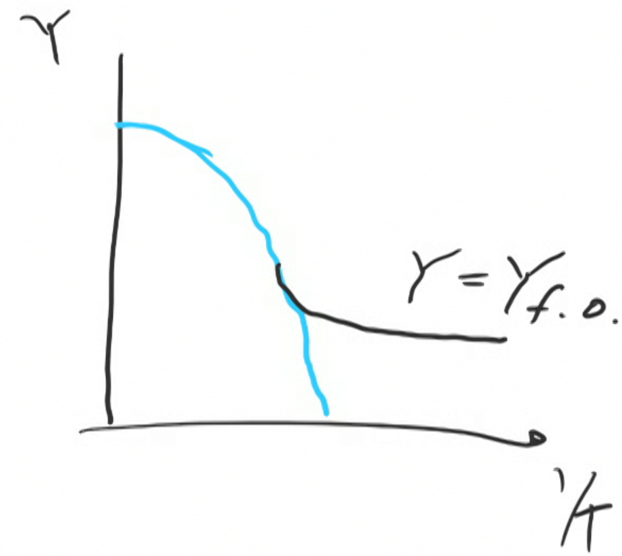

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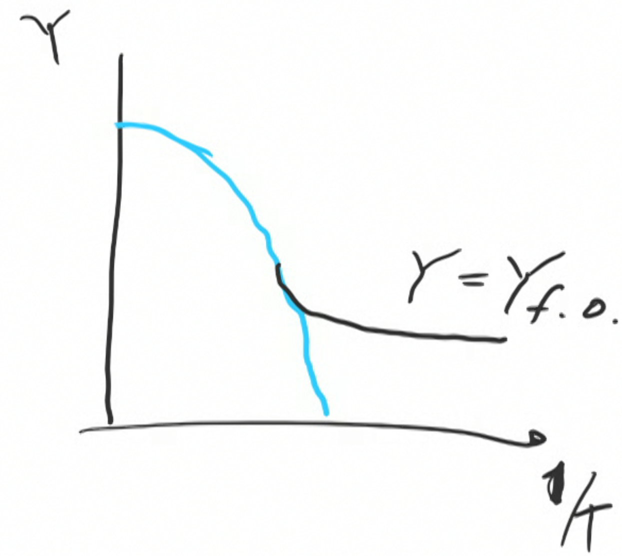

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Weakly interacting massive particles, WIMPs

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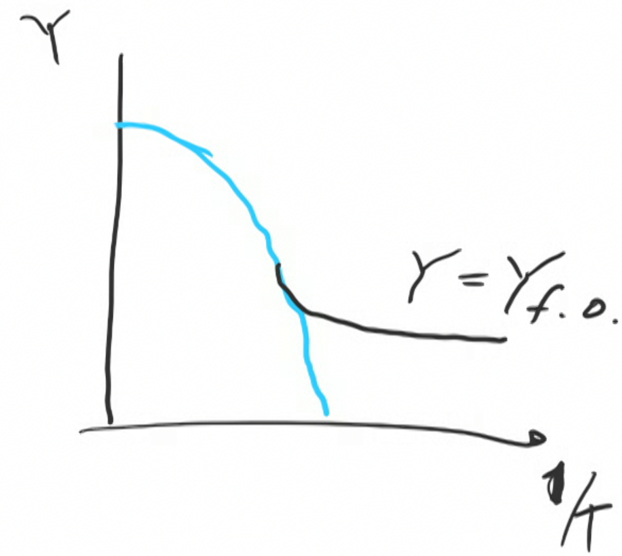

$$\Omega_{DM} h^2 \simeq \frac{10^9 x_f}{g_*^{1/2}}$$

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Weakly interacting massive particles, WIMPs

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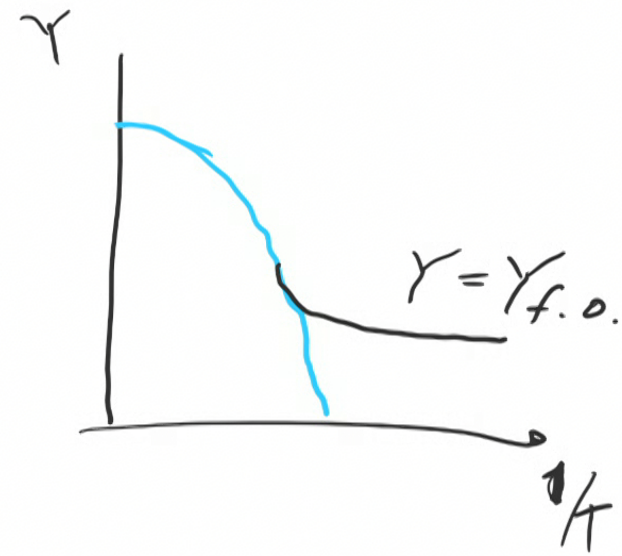

Weakly interacting massive particles, WIMPs

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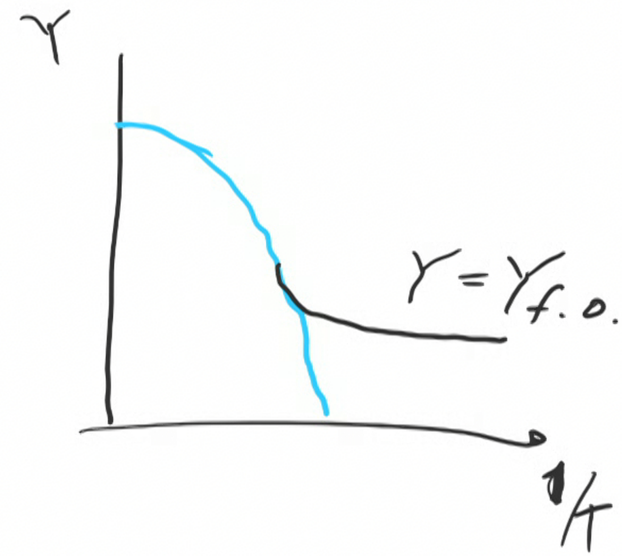

$$\Omega_{DM} h^2 \simeq \frac{10^9\, x_f}{g_*^{1/2} \cdot M_{pl} \cdot \text{GeV} \langle\sigma v\rangle}$$

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Weakly interacting massive particles, WIMPs

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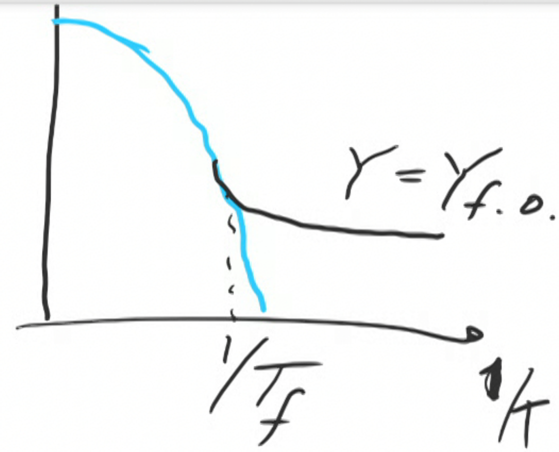

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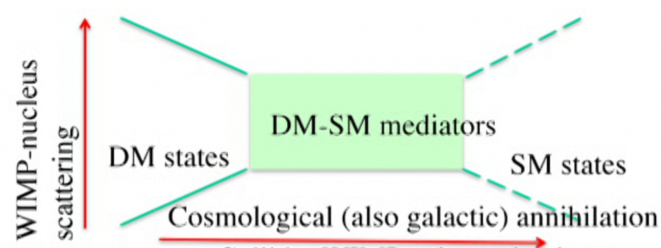
$(x_f =$

Weakly interacting massive particles, WIMPs



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$$dt \quad \ldots \quad (Y_{eq} \ldots)$$

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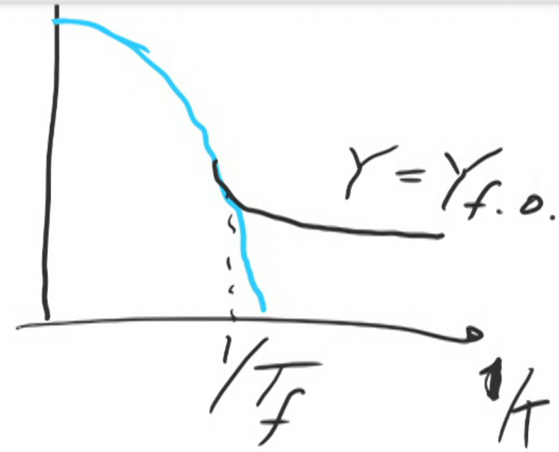

$$\Omega_{DM} h^2 \simeq \frac{10^9 x_f}{g_{*s}^{1/2} \cdot M_{pl} \cdot \text{GeV} \langle \sigma v \rangle}$$

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

Weakly interacting massive particles, WIMPs

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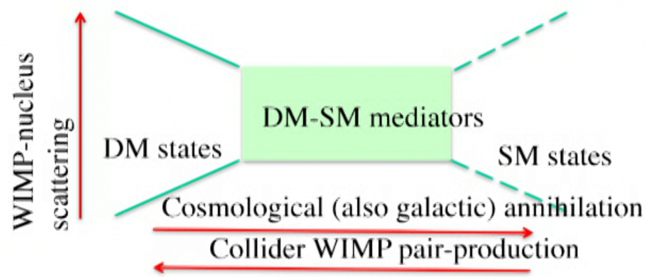

$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

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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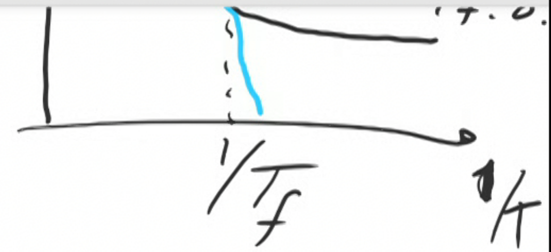

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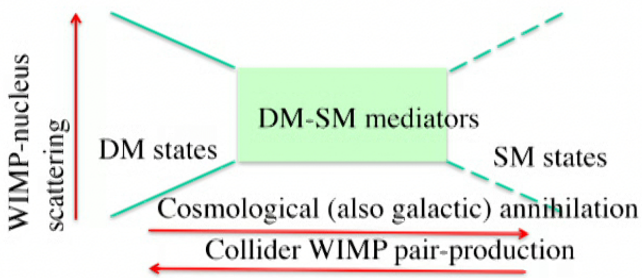
Number of thermally excited degrees of freedom

Weakly interacting massive particles, WIMPs



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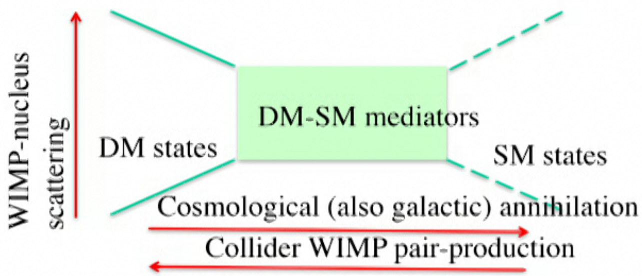
Number of thermally excited degrees of freedom

Correct DM abundance

Weakly interacting massive particles, WIMPs



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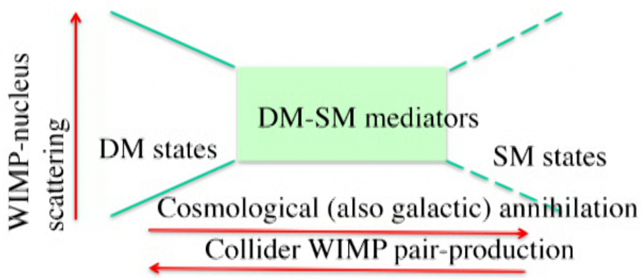
Weakly interacting massive particles, WIMPs

Number of thermally excited degrees of freedom



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

Correct DM abundance is achieved at $\langle \sigma v \rangle \sim 10^{-36}\,\mathrm{cm}^2$

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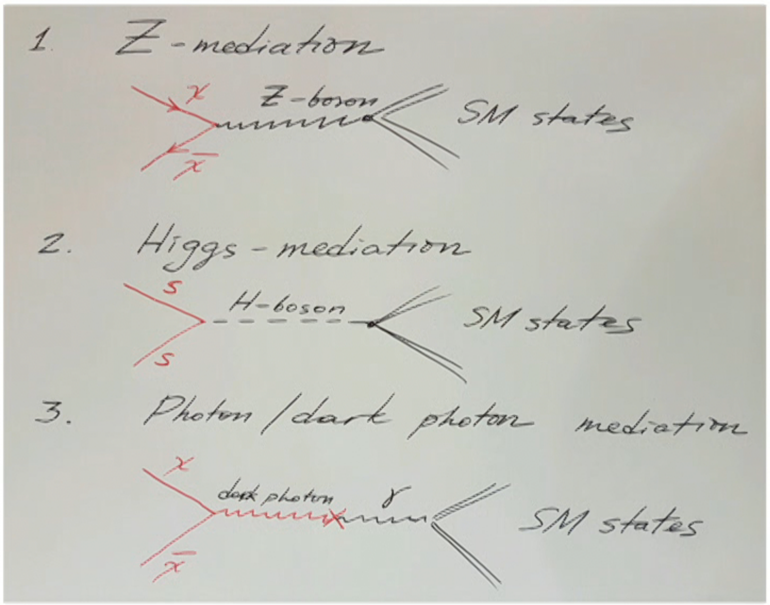
rate and collider DM production?

Examples of DM-SM mediation



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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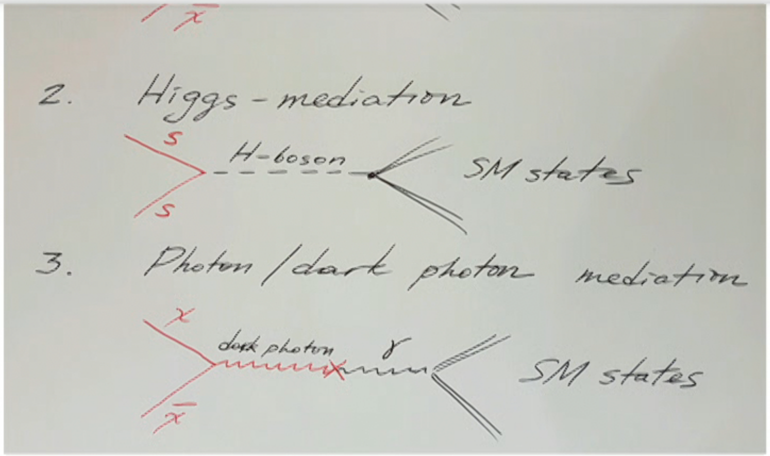

Very economical extensions
DM particles themselves + 1
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If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to-10000 GeV (Lee, Weinberg) 7

Bosonic super-cold DM (``initial displacement” mechanism)

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(becomes a specific example of $J_\mu^i A_\mu$ extension)

LHN neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ 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

……….

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

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Super-WIMP (=DM freeze-in) mechanism

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Super-WIMP (=DM freeze-in) mechanism

$$SM + SM \rightarrow DS$$

$$\Gamma \ll \text{Hubble rate}$$

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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)

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

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Bosonic super-cold DM (``initial displacement” mechanism)

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

$$H(T)$$

8

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)

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

$$H(T)$$

8

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

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

$$H(T) >$$

8

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)

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

φ

$$H(T) > m_\varphi$$

8

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displacement” mechanism)

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

$$H(T) > m_\varphi$$

$$\varphi_{in} \simeq const$$

8

Super-WIMP (=DM freeze-in) mechanism

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displacement" mechanism)

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

$$H(T) > m_\varphi$$

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

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

8

Super-WIMP (=DM freeze-in) mechanism

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displacement" mechanism)

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

$$H(T) > m_\varphi$$

$$\varphi_{in} \simeq const$$

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

8

$$\varphi \sim \left(\frac{a_{in}}{a}\right)^{3/2} \cos(m_\varphi t)$$

Super-WIMP (=DM freeze-in) mechanism

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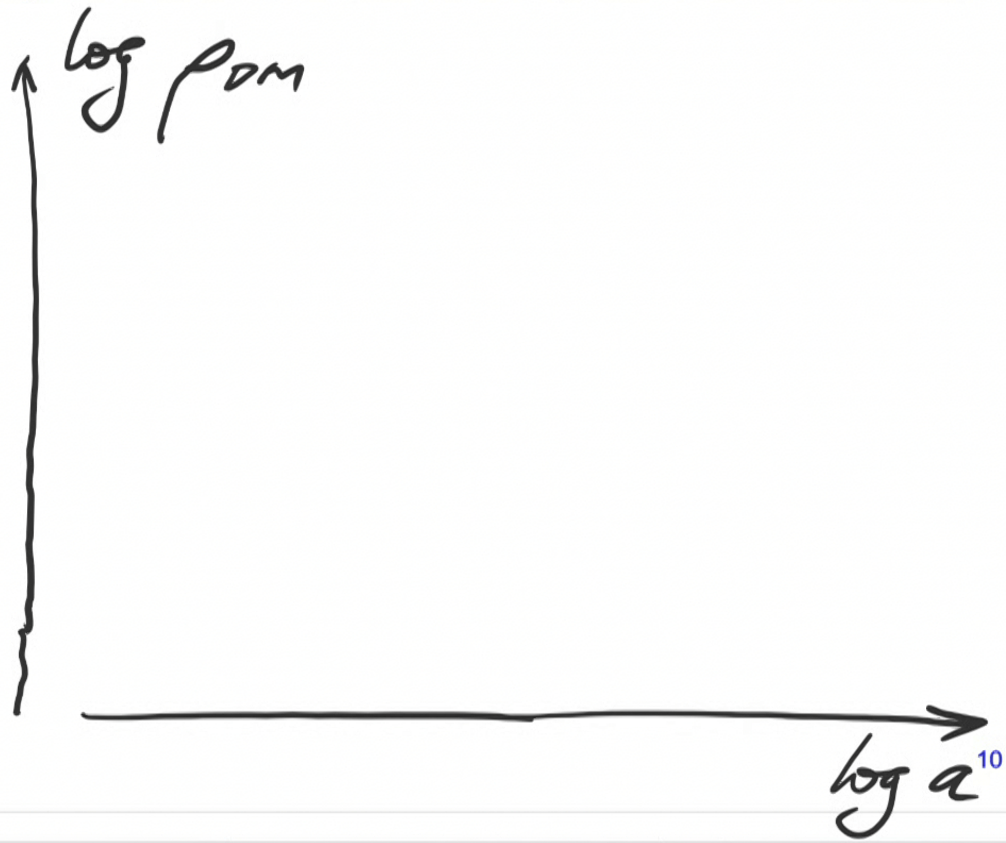
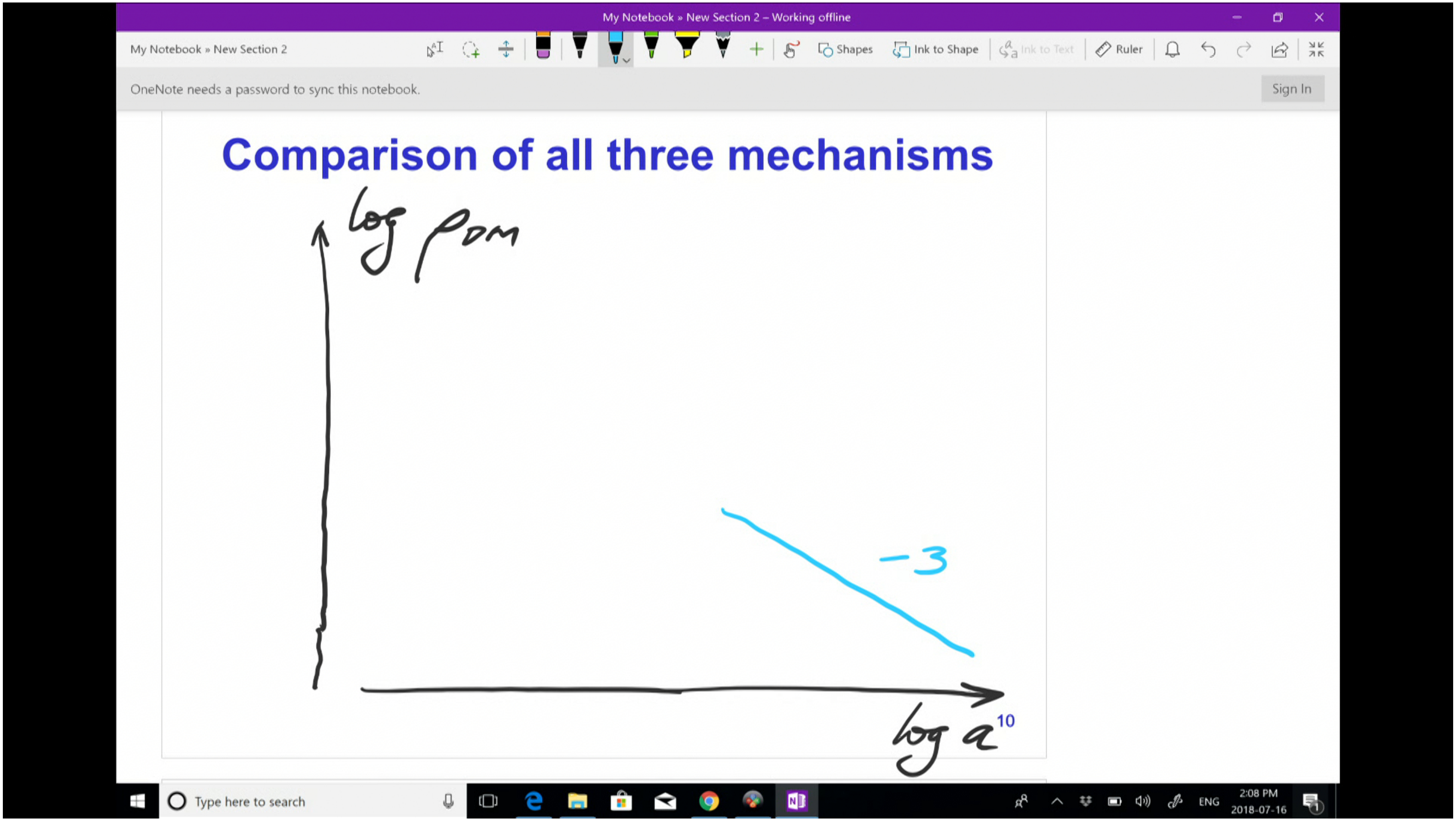
Comparison of all three mechanisms

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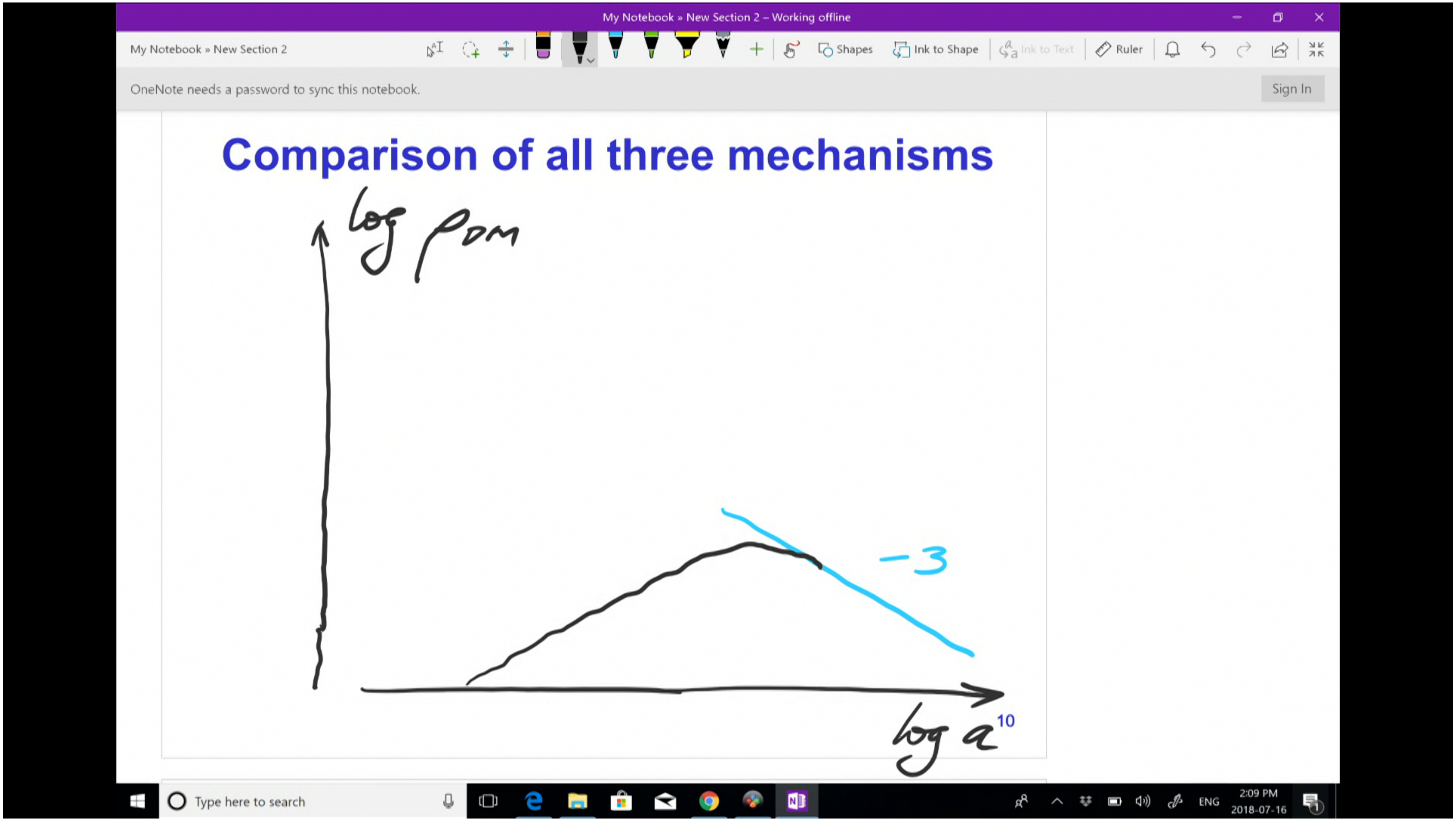
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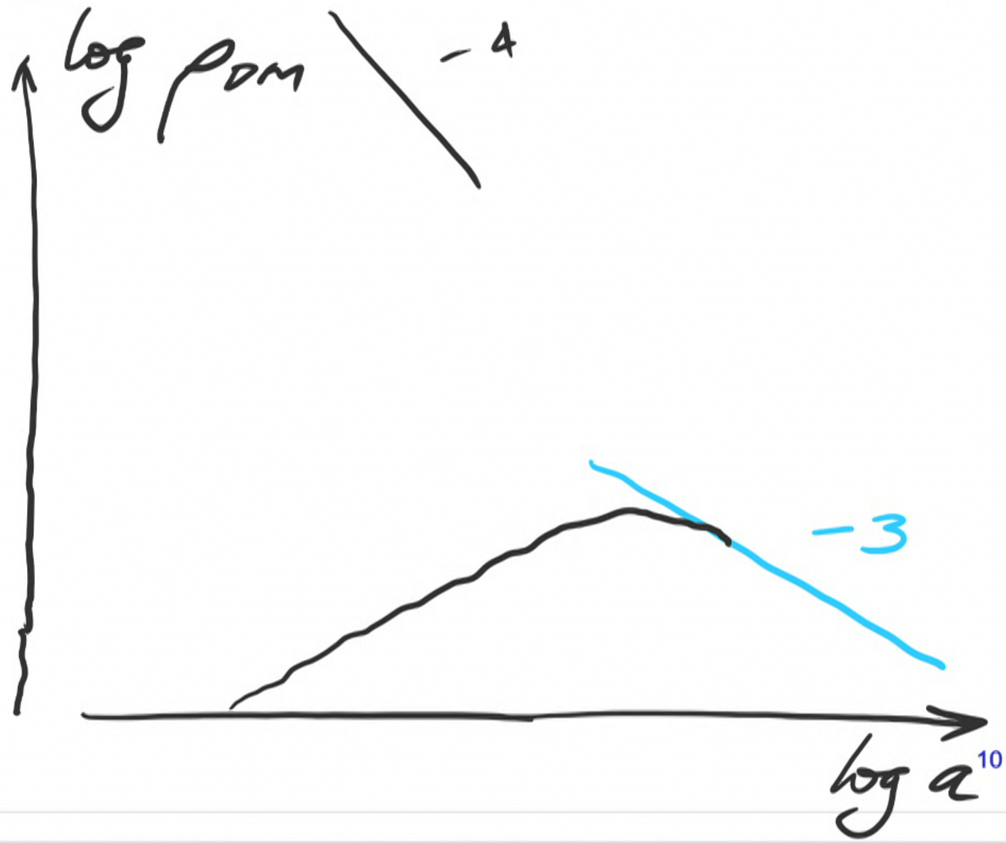
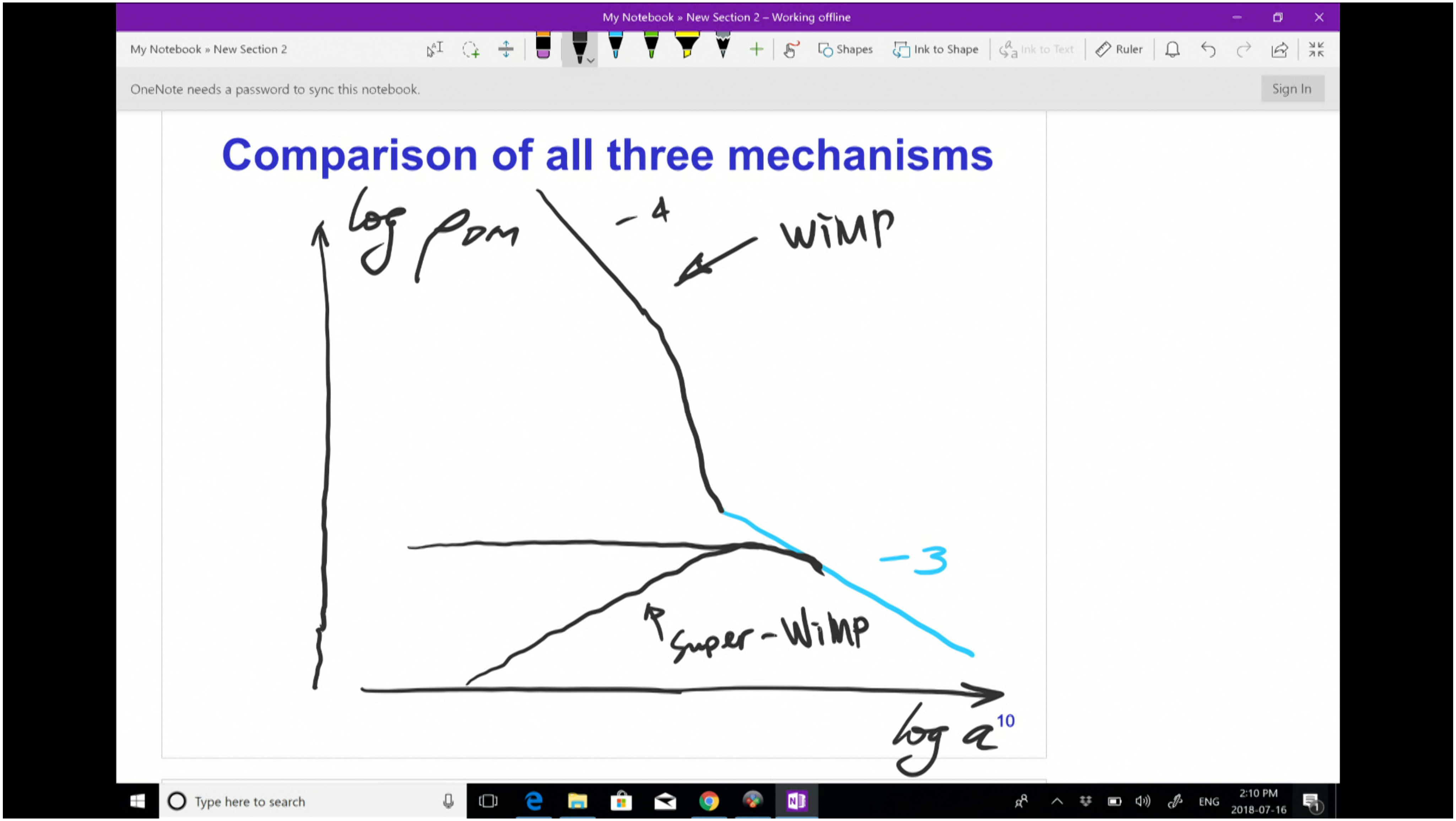
Comparison of all three mechanisms



Comparison of all three mechanisms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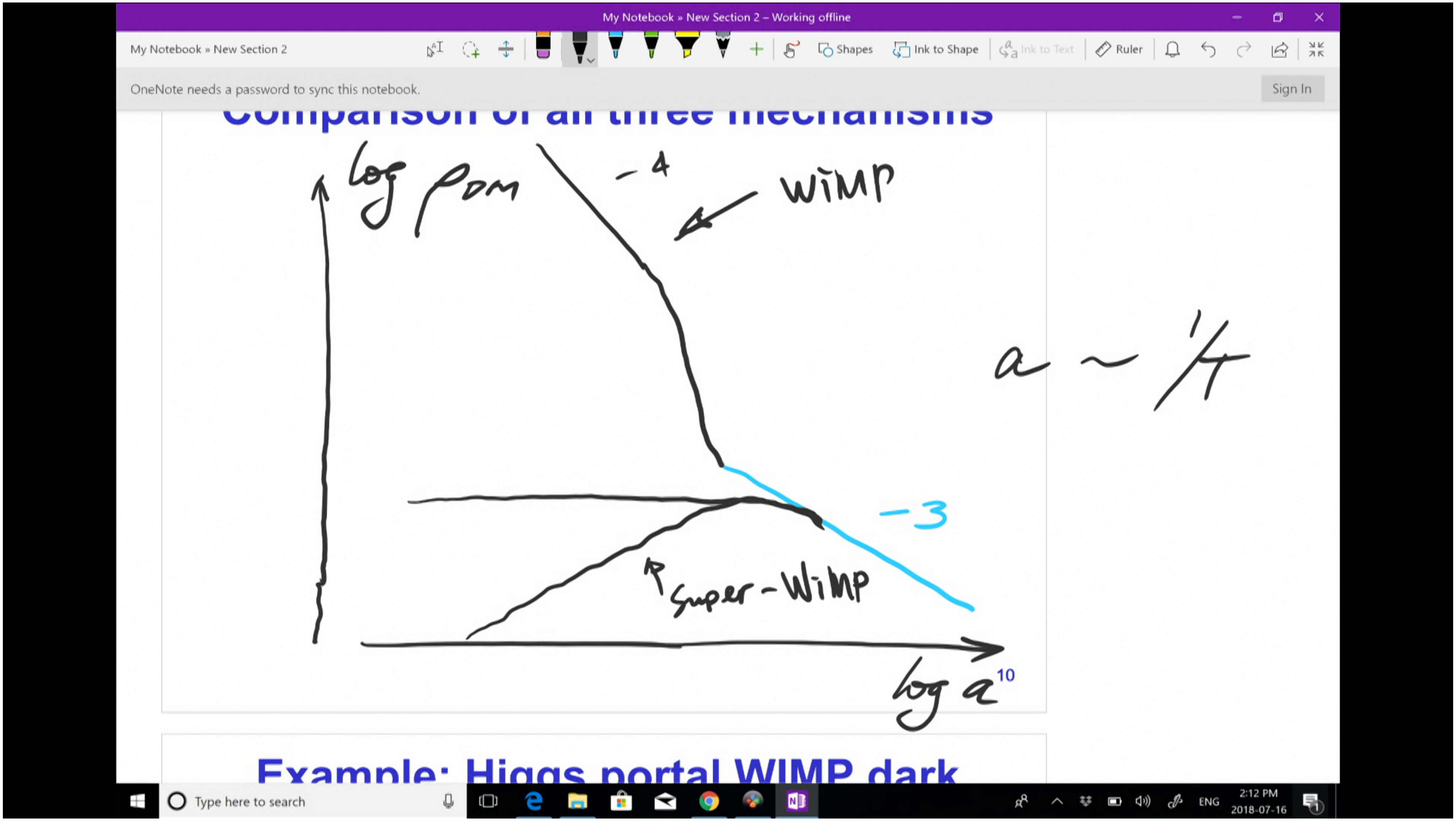
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Example: Higgs portal WIMP dark
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Example: Higgs portal WIMP dark matter

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Example: Higgs portal WIMP dark matter

SM +1 singlet scalar S

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

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

$S \to -S$

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

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

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

$S \to -S$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + \left(-\frac{1}{2} m_0 S^2\right) + \lambda (H^\dagger H) S^2 + \cancel{A \cdot S H^\dagger H} \to 0$$

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

$S \to -S$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + \left(-\frac{1}{2} m_0 S^2\right) + \lambda (H^\dagger H) S^2 + \cancelto{0}{A \cdot S H^\dagger H}$$

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

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Example: Higgs portal WIMP dark matter

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

$v = 246\ \text{GeV}$

11

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

$S \to -S$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + \left(-\frac{1}{2} m_0 S^2\right) + \lambda (H^\dagger H) S^2 + \cancel{A \cdot S H^\dagger H}\ 0$$

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$v = 246\,\text{GeV}$

h = "125 GeV"

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$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + \left(-\frac{1}{2} m_0 S^2\right) + \lambda (H^\dagger H) S^2 + \cancel{A \cdot S H^\dagger H} \rightarrow 0$$

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

$v = 246\,\mathrm{GeV}$

$h = $ "125 guy"

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

$S \to -S$

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

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

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

$v = 246\,\text{GeV}$

$h =$ „125 guy"

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

Annihilation rate

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Example: Higgs portal WIMP dark matter

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

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Annihilation rate

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SM +1 singlet scalar S

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

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

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

$v = 246\,\text{GeV}$

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Annihilation rate

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

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$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 + \left(-\frac{1}{2} m_0 S^2\right) - \lambda (H^\dagger H) S^2 + \cancel{A \cdot S H^\dagger H} \to 0 = \dots - \frac{1}{2} S^2 (m_0^2 + v^2 \lambda) - \lambda h v S^2$$

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

$v = 246\,\text{GeV}$

$h =$ "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

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

$v = 246\,\text{GeV}$

$h =$ „125 guy"

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

Annihilation rate

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

Annihilation rate

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

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Example: Higgs portal WIMP dark matter

SM +1 singlet scalar S

$S \to -S$

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

$$+ \left(-\tfrac{1}{2} m_0 S^2\right) - \lambda (H^\dagger H) S^2 + \cancel{A \cdot S H^\dagger H}^{\,0} = \ldots -\tfrac{1}{2} S^2 (m_0^2 + v^2 \lambda) - \lambda h v S^2 - \lambda h^2 S^2/2$$

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

$v = 246\,\text{GeV}$

$h =$ „125 guy"

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

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

Annihilation rate

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

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Example: Higgs portal WIMP dark matter

SM + 1 singlet scalar S

$S \to -S$

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

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

$v = 246\,\text{GeV}$

$h = $ „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

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$$+\left(-\tfrac{1}{2} m_0 S^2\right) - \lambda (H^\dagger H) S^2 + \cancel{A \cdot S H^\dagger H} = \ldots - \lambda h v S^2$$

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

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

$v = 246\,\text{GeV}$

$h =$ „125 guy"

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

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

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

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

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

$v = 246$ GeV

$h =$ „125 guy"

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 $m_S \gtrsim$ TeV

$m_S < m_h/2$

Large m_S

$S S \to$ 4 scalar fields of H

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

$v = 246\,\text{GeV}$

$h =$ "125 guy"

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

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

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

Annihilation rate

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

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

$m_S < m_h/2$

Large m_S

$S, S \to$ 4 scalar fields of H

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

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Annihilation rate

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

Two specific cases $\quad m_s \gtrsim \text{TeV}$

$m_s < m_h/2$

Large m_s

4 scalar fields of H

12

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

$$M = \lambda$$

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Scattering on nuclei

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Annihilation rate

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

Two specific cases $\quad m_s \gtrsim \text{TeV}$

$m_s < m_h/2$

Large m_s

4 scalar fields of H

12

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

$$M = 2\lambda$$

13

Scattering on nuclei

Annihilation rate

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

12

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

$$M = 2\lambda$$

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

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Scattering on nuclei

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Annihilation rate

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

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

$$M = 2\lambda$$

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

13

Scattering on nuclei

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

Two specific cases $\quad m_s \gtrsim \text{TeV}$

$m_s < m_h/2$

Large m_s

4 scalar fields of H

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

$$M = 2\lambda$$

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

$$4(2\lambda)^2$$

12

13

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$s^2\lambda$

12

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

$$M = 2\lambda$$

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

$$4(2\lambda)^2$$

$$t = t_0 - 4p_1p_3\sin^2(\theta/2)$$

13

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14

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13

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

$$M = 2\lambda$$

$$\frac{d\sigma}{dt} = \frac{1}{64\pi(2m_s)^2}\cdot\frac{1}{|\frac{m}{2}\cdot v_{rel}|^2}\,4(2\lambda)^2$$

$m_s\frac{v}{2}$ m_s

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

$$\sigma_{ann} =$$

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$$M = 2\lambda$$

13

Scattering on nuclei

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

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

$$4(2\lambda)^2$$

$m_s\frac{v}{2}$ m_s

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

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

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Scattering on nuclei

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

$$M = 2\lambda$$

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

$$4(2\lambda)^2$$

$$m_s\frac{v}{2} \qquad m_s$$

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

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

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

$$M = 2\lambda$$

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

$$4(2\lambda)^2$$

$$m_s\frac{v}{2} \qquad m_s$$

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

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

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

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

$$M = 2\lambda$$

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

$$4(2\lambda)^2 =$$

$$t = t_0 - 4\overset{m_s\frac{v}{2}}{\vec{P}_1}\,\overset{m_s}{|\vec{P}_3|}\sin^2(\theta/2)$$

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

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

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

$$4(2\lambda)^2 =$$

$m_s \frac{v}{2}$ $\quad m_s$

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

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

$$4\cdot 4\lambda^2\,\frac{1}{\left|\frac{m}{2}v_{rel}\right|^2}$$

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Scattering on nuclei

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

$$4(2\lambda)^2 =$$

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

$m_s \frac{v}{2}$ m_s

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

$$4 \cdot 4\lambda^2 \frac{1}{|m/2\, v_{rel}|^2}$$

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

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

$$4(2\lambda)^2 = \qquad m_s \frac{v}{2} \qquad m_s$$

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

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

$$4 \cdot 4\lambda^2 \frac{1}{\left|\frac{m}{2} v_{rel}\right|^2}$$

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

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$$dt \qquad 64\pi(2m_s)^2 \qquad \left|\frac{m}{2}\cdot v_{rel}\right|^2$$

$$4(2\lambda)^2 =$$

$m_s \frac{v}{2}$ $\quad m_s$

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

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

$$4\cdot 4\lambda^2\frac{1}{|m/2\, v_{rel}|^2}$$

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

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

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2\, v_{rel}|^2}$$

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

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

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2\, v_{rel}|^2}$$

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

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Scattering on nuclei

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

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2 \, v_{rel}|^2}$$

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

$$\lesssim$$

$$\gtrsim 1 \text{ pbn} \quad \text{OK}$$

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

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2 \, v_{rel}|^2}$$

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

$\lesssim$ not ok !

$\gtrsim$ 1 pbn ok

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2\, v_{rel}|^2}$$

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

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

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2\, v_{rel}|^2}$$

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

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

Compare to 1/pb.

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2 \, v_{rel}|^2}$$

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

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

Compare to 1 pbn.

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

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

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

$$4 \cdot 4 \lambda^2 \frac{1}{|m/2\, v_{rel}|^2}$$

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

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

Compare to 1 pbn.

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

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

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

Compare to 1 pbn.

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

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

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

15

16

Higgs decay to light scalar DM

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

Compare to 1 pbn.

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

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

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

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

15

16

Higgs decay to light scalar DM

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Higgs decay to light scalar DM

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

Compare to 1 pbn.

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

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

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

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

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15

16

Higgs decay to light scalar DM

17

Comparison with data

$$\lambda \sim \sqrt{2\pi}\, m \cdot 1\,\mathrm{pbn}$$

$$\sim 2.5 \cdot m_{TeV} \cdot 10^{-18}\,\mathrm{cm} \cdot \mathrm{TeV}$$

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

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

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

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$$\lambda \sim \sqrt{2\pi}\; m \cdot 1\,\mathrm{pbn}$$

$$\sim 2.5 \cdot m_{TeV} \cdot 10^{-18}\,\mathrm{cm}\cdot \mathrm{TeV}$$

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

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

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

At $m \sim 10$ TeV

$$\lambda \sim O(1)$$

Higgs decay to light scalar DM

Comparison with data

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17

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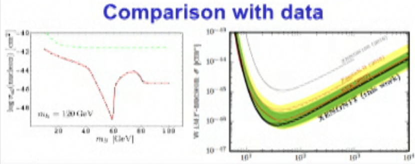

$$\lambda \sim \sqrt{2\pi\, m^2 \cdot 1\,\text{pbn}}$$

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

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

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

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

At $m \sim 10$ TeV

$\lambda \sim O(1)$

Conclusion: DM has to be lighter than few 10 TeV

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Scattering on nuclei

$m_s < m_h/2$

Large m_s

4 scalar fields of H

λ

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

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$$4(2\lambda)^2 \Rightarrow$$

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

$m_s\frac{v}{2}$ m_s

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

$$4\cdot 4\lambda^2\frac{1}{|m/2\, v_{rel}|^2}$$

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

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

Compare to 1 pbn.

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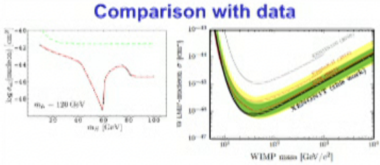
Higgs decay to light scalar DM

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*

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

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

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

$10^{-13}\,\mathrm{cm} \cdot 0.2\,\mathrm{GeV}$

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

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

At $m \sim 10$ TeV

$\lambda \sim O(1)$

Conclusion: DM has to be lighter than few 10 TeV

$m_S < m_h/2$

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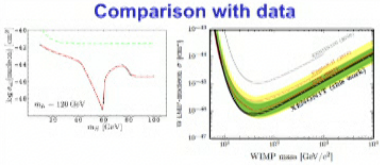
Higgs decay to light scalar DM

Comparison with data



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

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

10^{-13} cm $\cdot$ 0.2 GeV

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

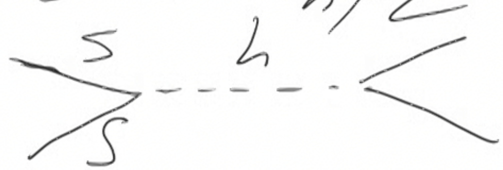
$\simeq 12.5 \times 10^{-2}\, m_{TeV}$

At $m \sim 10$ TeV

$\lambda \sim O(1)$

Conclusion: DM has to be lighter than few 10 TeV

$m_S < m_h/2$



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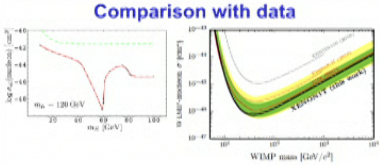
Higgs decay to light scalar DM

Comparison with data



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$10^{-13}\,\text{cm} \cdot 0.2\,\text{GeV}$

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

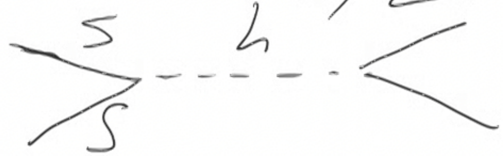
$\simeq 12.5 \times 10^{-2}\, m_{TeV}$

At $m \sim 10$ TeV

$\lambda \sim O(1)$

Conclusion: DM has to be lighter than few 10 TeV

$2m_b < m_s < m_h/2$



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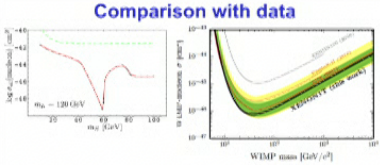
Higgs decay to light scalar DM

17

Comparison with data



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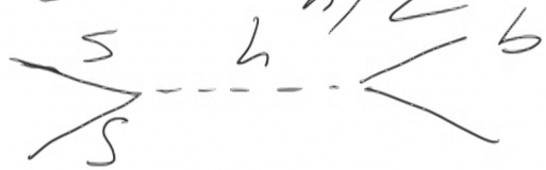

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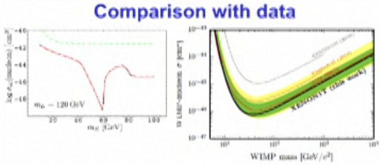

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TeV

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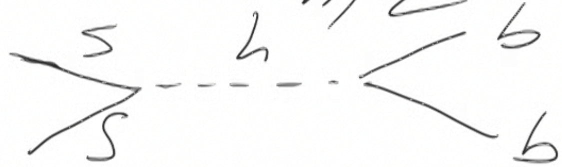

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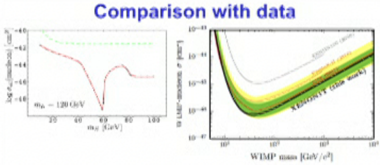

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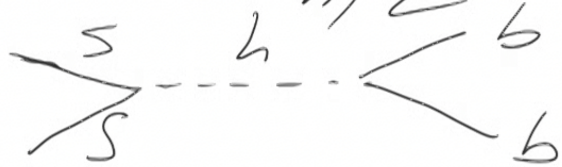

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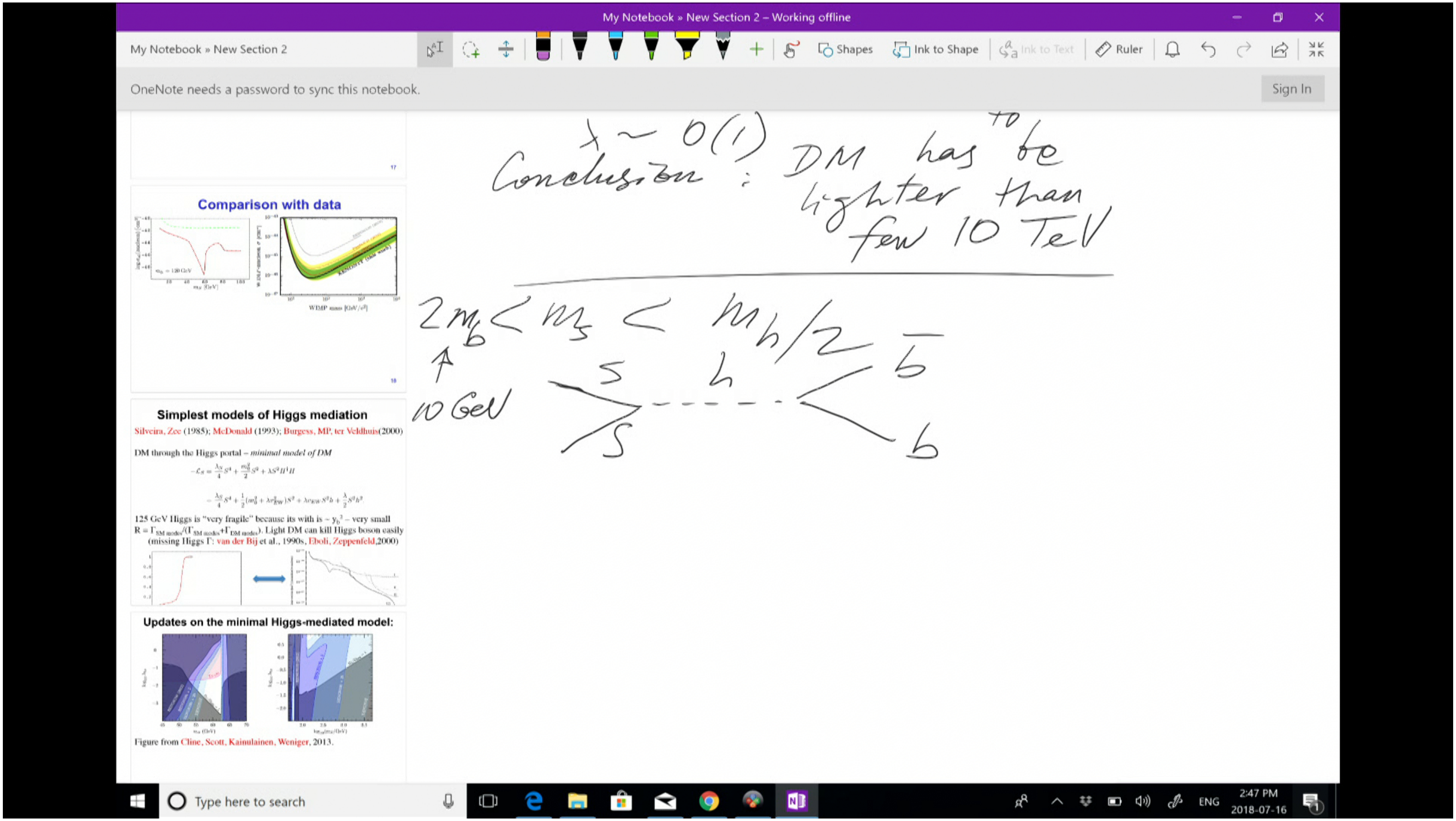
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10 GeV
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Annihilation rate

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

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

$$M = 2\lambda$$

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

$$4(2\lambda)^2 \Rightarrow$$

$m_s \frac{v}{2}$ m_s

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

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

$$4\cdot 4\lambda^2\frac{1}{|m/2\, v_{rel}|^2}$$

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

Scattering on nuclei

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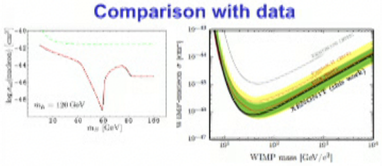

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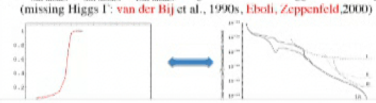

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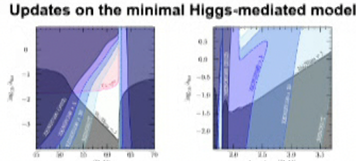

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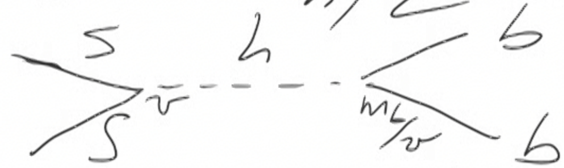
10 GeV



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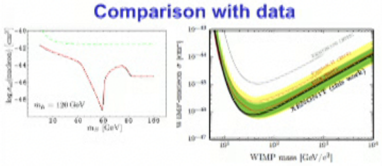

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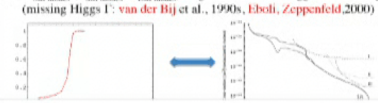

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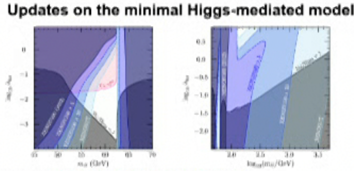

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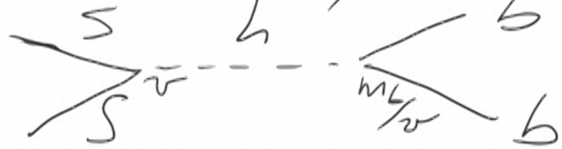

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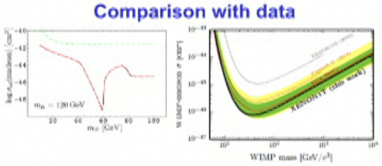

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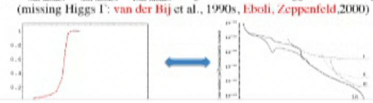

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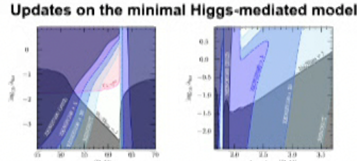

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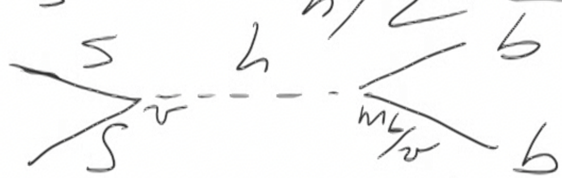

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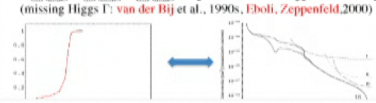

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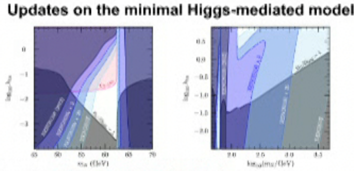

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20

Conclusion on minimal Higgs portal model of DM

21

Light WIMPs due to light mediators direct production/detection

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

WIMP paradigm: $\sigma_{annih}(v/c) \sim 1$ pbn $\Longrightarrow \Omega_{DM} \simeq 0.25$.

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

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

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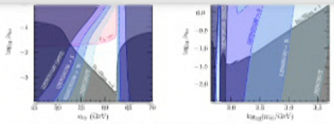

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$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for } m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for } m_\chi \gg m_W. \end{cases} \Longrightarrow \text{few GeV} < m_\chi < \text{few TeV}$$

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

22

"Simplified models" for light DM

some examples

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

$$\frac{\ \ }{(4m_s^2 - m_h^2)^2} \qquad (p_4 - m_b))$$

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

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

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"Simplified models" for light DM
some examples

Two different types of annihilation

Important consequence of secluded dark matter mechanism

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

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

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

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10 GeV

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

$$\sum_{b,\text{pol}} |M|^2 = (2\lambda)^2 \frac{m_b^2}{(4m_s^2 - m_h^2)^2} \mathrm{Tr}\left((p_3 + m_b)(p_4 - m_b)\right)$$

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$m_s = 20$ GeV (example)

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What does it imply for the Higgs boson? $h \to SS$