Dark Matter Production from Goldstone Boson Interactions and Implications for Direct Searches and Dark Radiation

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Outline

• Motivation
• Description of the Model
• Dark Matter Production
• Constraints from Direct Detection Experiments
• Goldstone Bosons as Dark Radiation
• Conclusions
Motivation
• Numerous observations support the hypothesis that the 85% of the matter content of the Universe is in the form of a new particle.
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\[ \text{Dark} \quad \text{Stable} \quad \overset{\rightarrow}{\text{Z}_2 \text{ Symmetry?}} \]
• Numerous observations support the hypothesis that the 85% of the matter content of the Universe is in the form of a new particle.

\[ \text{Dark} \quad \text{Stable} \quad \leftarrow Z_2 \text{ Symmetry?} \]

• If a global $U(1)$ symmetry is spontaneously broken by a scalar field with charge 2 under that symmetry, a discrete $Z_2$ symmetry automatically arises in the Lagrangian.

\[
\begin{align*}
U(1) & \longrightarrow Z_2 \\
\text{Odd Charge} & \quad -1 \\
\text{Even Charge} & \quad +1
\end{align*}
\]

Krauss and Wilczek 1989
• Numerous observations support the hypothesis that the 85% of the matter content of the Universe is in the form of a new particle.

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– Krauss and Wilczek 1989

• The spontaneous breaking of a global continuous symmetry, as is well known, gives rise to massless Goldstone bosons in the spectrum.

• Could these Goldstone bosons be Dark Radiation? Weinberg 2013
What is Dark Radiation?

Radiation Density of the Universe

$$\rho_R = \frac{\pi^2}{30} \left( 2 \cdot (T_\gamma^0)^4 + 2 \cdot \frac{7}{8} \cdot N_\nu (T_\nu^0)^4 + (T_\eta^0)^4 \right)$$
What is Dark Radiation?

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Two polarization states
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Number of neutrinos.
In our case \( N_\nu = 3 \)

Two polarization states

Fermi-Dirac distribution
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Two polarization states

Fermi-Dirac distribution

Number of neutrinos. In our case \( N_\nu = 3 \)

Dark Radiation?

\[ \rho_R = \frac{\pi^2}{30} \left( 2 \cdot \left( T_\gamma^0 \right)^4 + 2 \cdot \frac{7}{8} \cdot N_{eff} \left( T_\nu^0 \right)^4 \right) \]

\[ N_{eff} = 3 + \frac{4}{7} \left( \frac{T_\eta^0}{T_\nu^0} \right)^4 \]
$P/P_{\text{max}}$ vs $N_{\text{eff}}$

- Planck + WP + highL
- +BAO
- $+H_0$
- $+\text{BAO} + H_0$

Planck Collaboration 2013
What happens if the Goldstones decouple before muon annihilation?

\[ \gamma e^\pm \mu^\pm \nu \bar{\nu} \eta \]
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\[
\gamma e^\pm \mu^\pm \nu \bar{\nu} \eta \quad \gamma e^\pm \mu^\pm \nu \bar{\nu} \\
T^d_\eta \quad \eta
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\[ T^d_\eta \]

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Entropy conservation per unit of comoving volume

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\[ g_* = 2 \]

\[ \gamma e^\pm \mu^\pm \nu \bar{\nu} \eta \quad \gamma e^\pm \mu^\pm \nu \bar{\nu} \quad \gamma e^\pm \nu \bar{\nu} \quad \gamma e^\pm \gamma \]

\[ T^d_{\eta} \quad \mu^\pm \text{annihilation} \quad T^d_{\nu} \quad \nu \bar{\nu} \quad e^\pm \text{annihilation} \]

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\[ \gamma \]

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\[ \frac{T^0_\nu}{T^0_\gamma} = \left( \frac{g^\text{after}_*}{g^\text{before}_*} \right)^{1/3} = \left( \frac{4}{11} \right)^{1/3} \]

Entropy conservation per unit of comoving volume

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\mu^\pm \text{annihilation} & \quad T^d_{\eta} \\
\text{Entropy conservation per} & \quad T^d_{\nu} \\
\text{unit of comoving volume} & \quad \nu \bar{\nu} \\
\end{align*}
\]

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\[
T^0_{\nu} = 1.945 \text{ } K
\]

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What happens if the Goldstones decouple before muon annihilation?

\[ g_* = 2 + \frac{7}{8}(2 + 2 + 2 + 2 + 3(1 + 1)) = \frac{57}{4} \]

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\[ T_\eta^d \quad \mu^\pm \text{annihilation} \quad T_\nu^d \quad \nu \bar{\nu} \quad e^\pm \text{annihilation} \]

Entropy conservation per unit of comoving volume

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\[ T^d_\eta \]

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What happens if the Goldstones decouple before muon annihilation?

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Entropy conservation per unit of comoving volume

\[ s \propto g_\ast T^3 \]

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\[ \left( \frac{T_\eta}{T_\nu} \right)_{T^d_\nu} = \left( \frac{g_\ast \text{after}}{g_\ast \text{before}} \right)^{1/3} = \left( \frac{43}{57} \right)^{1/3} \]

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\[ T_\nu^0 = 1.945 \, K \]

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\[ T^0_\eta = 1.771 \, K \]

\[ N_{\text{eff}} - 3 = \frac{4}{7} \left( \frac{43}{57} \right)^{4/3} \approx 0.39 \]

Weinberg 2013
Planck, + WP, + high L, + BAO, + $H_0$, + BAO + $H_0$.
$N_{eff} = 3.39$
Description of the Model
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| Field | $SU(3)$ | $SU(2)$ | $U(1)_Y$ | $U(1)_{DM}$ |
|-------|---------|---------|----------|-------------|
| $\phi$ | 1       | 1       | 0        | 2           |
| $\psi$ | 1       | 1       | 0        | 1           |
| $H$    | 1       | 2       | $\frac{1}{2}$ | 0           |
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\[
\mathcal{L} = (D_\mu H)\dagger (D^\mu H) + \mu_H^2 H\dagger H - \lambda_H (H\dagger H)^2 \\
+ \partial_\mu \phi^* \partial^\mu \phi + \mu_\phi \phi^* \phi - \lambda_\phi (\phi^* \phi)^2 - \kappa (H\dagger H) (\phi^* \phi) + \mathcal{L}_{DM}
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\[ \mathcal{L}_{DM} = i\bar{\psi} \gamma^\mu \partial_\mu \psi - M\bar{\psi} \psi - \left( \frac{f}{\sqrt{2}} \phi \bar{\psi} \psi^c + \text{h.c.} \right) \]

Weinberg 2013
After symmetry breaking in the scalar sector

\[
H = \left( \begin{array}{c} G^+ \\ \frac{v_H + \tilde{h} + iG^0}{\sqrt{2}} \end{array} \right), \\
v_H \simeq 246 \text{ GeV}
\]

\[
\phi = \frac{v_\phi + \tilde{\rho} + i\eta}{\sqrt{2}}
\]
After symmetry breaking in the scalar sector

\[ H = \begin{pmatrix} \frac{G^+}{\sqrt{2}} \\ \frac{v_H + \tilde{h} + iG^0}{\sqrt{2}} \end{pmatrix}, \quad \phi = \frac{v_\phi + \tilde{\rho} + i\eta}{\sqrt{2}} \]

\[ v_H \simeq 246 \text{ GeV} \]

\[
\begin{pmatrix} \tilde{h} \\ \tilde{\rho} \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ \rho \end{pmatrix}
\]

\[ m_h^2 = 2 \lambda_H v_H^2 \cos^2 \theta + 2 \lambda_\phi v_\phi^2 \sin^2 \theta - \kappa v_H v_\phi \sin 2\theta \]

\[ m_\rho^2 = 2 \lambda_H v_H^2 \sin^2 \theta + 2 \lambda_\phi v_\phi^2 \cos^2 \theta + \kappa v_H v_\phi \sin 2\theta \]
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Brout-Englert-Higgs Boson \( m_h = 125 \text{ GeV} \)
After symmetry breaking in the scalar sector

\[ H = \left( \frac{G^+}{\sqrt{2}} \right) \]

\[ v_H \simeq 246 \text{ GeV} \]

\[
\begin{pmatrix}
\tilde{h} \\
\tilde{\rho}
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
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h \\
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\]

Brout-Englert-Higgs Boson \( m_h = 125 \text{ GeV} \)

The field \( \eta \) corresponds to the Goldstone boson that arises from the spontaneous breaking of the global \( U(1)_{DM} \) symmetry.
After symmetry breaking in the fermionic sector

$$\psi_+ = \frac{\psi + \psi^c}{\sqrt{2}}, \quad \psi_- = \frac{\psi - \psi^c}{\sqrt{2i}}$$

$$\mathcal{L} = \frac{1}{2} \left( i\bar{\psi}_+ \gamma^\mu \partial_\mu \psi_+ + i\bar{\psi}_- \gamma^\mu \partial_\mu \psi_- - M_+ \bar{\psi}_+ \psi_+ - M_- \bar{\psi}_- \psi_- \right)$$

$$- \frac{f}{2} \left( (-\sin \theta \, h + \cos \theta \, \rho)(\bar{\psi}_+ \psi_+ - \bar{\psi}_- \psi_-) + \eta (\bar{\psi}_+ \psi_- + \bar{\psi}_- \psi_+) \right)$$

$$M_\pm = |M \pm f \nu_\phi|$$
After symmetry breaking in the fermionic sector

\[ \psi_+ = \frac{\psi + \psi^c}{\sqrt{2}}, \quad \psi_- = \frac{\psi - \psi^c}{\sqrt{2i}} \]

\[ \mathcal{L} = \frac{1}{2} \left( i \bar{\psi_+} \gamma^\mu \partial_\mu \psi_+ + i \bar{\psi_-} \gamma^\mu \partial_\mu \psi_- - M_+ \bar{\psi_+} \psi_+ - M_- \bar{\psi_-} \psi_- \right) \]

\[ - \frac{f}{2} \left( (- \sin \theta \ h + \cos \theta \ \rho)(\bar{\psi_+} \psi_+ - \bar{\psi_-} \psi_-) + \eta \ (\bar{\psi_+} \psi_- + \bar{\psi_-} \psi_+) \right) \]

\[ M_\pm = |M \pm f \nu_\phi| \]

Invariance under the \( Z_2 \) transformation \( \psi_\pm \rightarrow -\psi_\pm \)
After symmetry breaking in the fermionic sector

\[ \psi_+ = \frac{\psi + \psi^c}{\sqrt{2}} , \quad \psi_- = \frac{\psi - \psi^c}{\sqrt{2i}} \]

\[ \mathcal{L} = \frac{1}{2} \left( i \bar{\psi}_+ \gamma^\mu \partial_\mu \psi_+ + i \bar{\psi}_- \gamma^\mu \partial_\mu \psi_- - M_+ \bar{\psi}_+ \psi_+ - M_- \bar{\psi}_- \psi_- \right) \]

\[ - \frac{f}{2} \left( (- \sin \theta \, h + \cos \theta \, \rho) (\bar{\psi}_+ \psi_+ - \bar{\psi}_- \psi_-) + \eta (\bar{\psi}_+ \psi_- + \bar{\psi}_- \psi_+) \right) \]

\[ M_\pm = |M \pm f \nu_\phi| \]

Invariance under the \( Z_2 \) transformation \( \psi_\pm \to -\psi_\pm \)

The lightest Majorana fermion is stable and, consequently, a dark matter candidate
Constraints from Invisible Higgs Decays

\[ \Gamma_{h}^{\text{tot}} = \cos^2 \theta \Gamma_{h}^{\text{SM}} + \Gamma (h \rightarrow \eta \eta) \]
Constraints from Invisible Higgs Decays

\[ \Gamma_{h}^{\text{tot}} = \cos^2 \theta \, \Gamma_{h}^{\text{SM}} + \Gamma (h \rightarrow \eta \eta) \]

\[ B_{\text{inv}} \approx 20\% \quad \Gamma_{h}^{\text{SM}} \approx 4 \text{ MeV} \]
Constraints from Invisible Higgs Decays

\[ \Gamma_{h}^{\text{tot}} = \cos^2 \theta \Gamma_h^{\text{SM}} + \Gamma (h \rightarrow \eta \eta) \]

\[ B_{\text{inv}} \simeq 20\% \quad \Gamma_h^{\text{SM}} \simeq 4 \text{ MeV} \]

\[ |\tan \theta| \lesssim 2.2 \times 10^{-3} \left( \frac{v_\phi}{10 \text{ GeV}} \right) \]

Weinberg 2013
Dark Matter Production
Contribution from the different channels

\[ m_\rho = 500 \text{ MeV} \]
Contribution from the different channels

$m_\rho = 250$ GeV

micrOMEGAs 3.1
Dark Matter Coupling

![Graph showing the relationship between $f$ and $M_\pi$ (GeV)].
### Process

| Process          | Diagram |
|------------------|---------|
| Annihilation $\psi_+ \psi_- \rightarrow \rho \rho$ | ![Diagram](image) |
| Annihilation $\psi_- \psi_- \rightarrow \eta \eta$ | ![Diagram](image) |
| Annihilation $\psi_- \psi_+ \rightarrow \rho \rho$ | ![Diagram](image) |
| Annihilation $\psi_+ \psi_+ \rightarrow \eta \eta$ | ![Diagram](image) |
| Coannihilation $\psi_- \psi_+ \rightarrow \rho \eta$ | ![Diagram](image) |

**Case $\theta \ll 1$**
### Case $\theta \ll 1$

| Process | Diagram | Condition |
|---------|---------|-----------|
| Annihilation $\psi_-\psi_- \rightarrow \rho\rho$ | ![Diagram](image1) | Open if $m_{\rho} < M_-$ or equivalently if $r < 1$ |
| Annihilation $\psi_-\psi_- \rightarrow \eta\eta$ | ![Diagram](image2) | |
| Annihilation $\psi_+\psi_+ \rightarrow \rho\rho$ | ![Diagram](image3) | Open if $m_{\rho} < M_+$ or equivalently if $r < z$ |
| Annihilation $\psi_+\psi_+ \rightarrow \eta\eta$ | ![Diagram](image4) | |
| Coannihilation $\psi_-\psi_+ \rightarrow \rho\eta$ | ![Diagram](image5) | Open if $m_\rho < (M_- + M_+)$ or equivalently if $r < 1 + z$ |

\[ r = \frac{m_{\rho}}{M_-} \quad z = \frac{M_+}{M_-} \]
### Threshold Effects

#### Resonances

\[
r = \frac{m_{\rho}}{M_-} \quad z = \frac{M_+}{M_-}
\]

| Process | Condition |
|---------|-----------|
| Annihilation $\psi_-\psi_- \rightarrow \rho\rho$ | Open if $m_{\rho} < M_-$ or equivalently if $r < 1$ |
| Annihilation $\psi_-\psi_- \rightarrow \eta\eta$ | Always open, resonantly enhanced $r \gtrsim 2$ |
| Annihilation $\psi_+\psi_+ \rightarrow \rho\rho$ | Open if $m_{\rho} < M_+$ or equivalently if $r < z$ |
| Annihilation $\psi_+\psi_+ \rightarrow \eta\eta$ | Always open, resonantly enhanced $r \gtrsim 2z$ |
| Coannihilation $\psi_-\psi_+ \rightarrow \rho\eta$ | Open if $m_{\rho} < (M_- + M_+)$ or equivalently if $r < 1 + z$ |
**Case $\theta \ll 1$**

### Threshold Effects

Resonances

$$r = \frac{m_\rho}{M_-} \quad z = \frac{M_+}{M_-}$$

We can avoid this for $r \lesssim 0.8$

| Process | Description |
|---------|-------------|
| **Annihilation $\psi^- \psi^- \rightarrow \rho \rho$** | Open if $m_\rho < M_-$ or equivalently if $r < 1$ |
| ![Diagram](image1) | |
| **Annihilation $\psi^- \psi^- \rightarrow \eta \eta$** | Always open, resonantly enhanced $r \gtrsim 2$ |
| ![Diagram](image2) | |
| **Annihilation $\psi^+ \psi^+ \rightarrow \rho \rho$** | Open if $m_\rho < M_+$ or equivalently if $r < z$ |
| ![Diagram](image3) | |
| **Annihilation $\psi^+ \psi^+ \rightarrow \eta \eta$** | Always open, resonantly enhanced $r \gtrsim 2z$ |
| ![Diagram](image4) | |
| **Coannihilation $\psi^- \psi^+ \rightarrow \rho \eta$** | Open if $m_\rho < (M_- + M_+)$ or equivalently if $r < 1 + z$ |
| ![Diagram](image5) | |
### Case $\theta \ll 1$

| Process                        | Condition                                      |
|--------------------------------|------------------------------------------------|
| Annihilation $\psi_- \psi_- \rightarrow \rho \rho$ | $m_\rho < M_-$ or equivalently if $r < 1$         |
| Annihilation $\psi_- \psi_- \rightarrow \eta \eta$ | Always open, resonantly enhanced $r \gtrsim 2$ |
| Annihilation $\psi_+ \psi_+ \rightarrow \rho \rho$ | Open if $m_\rho < M_+$ or equivalently if $r < z$ |
| Annihilation $\psi_+ \psi_+ \rightarrow \eta \eta$ | Always open, resonantly enhanced $r \gtrsim 2z$ |
| Coannihilation $\psi_- \psi_+ \rightarrow \rho \eta$ | Open if $m_\rho < (M_- + M_+)$ or equivalently if $r < 1 + z$ |

- **p-waves**
- **s-wave**
Regime $r < 0.8$
Resonance effects

Regime $r < 0.8$
Resonance effects
Co-annihilation limit

Regime \( r < 0.8 \)

Annihilations proceed via p-waves → Large \( f \)
Co-annihilations proceed via s-waves → Small \( f \)

\[
f \bigg|_{z \to 1} \approx \left( \frac{1.07 \times 10^{11} \text{ GeV}^{-1} x_f}{g_*(x_f)^{1/2} m_{\text{Pl}} \Omega_{\text{DM}} h^2} \right)^{1/4} M_-^{1/2}
\]
CP Analysis of Annihilations

\[ \psi_+ \psi_+ \rightarrow \rho \rho \text{ and } \psi_- \psi_- \rightarrow \eta \eta \]
CP Analysis of Annihilations

\[ \psi^- \psi^- \rightarrow \rho \rho \text{ and } \psi^- \psi^- \rightarrow \eta \eta \]

Initial State

\[ CP \quad (-1)^{L+1} \]
CP Analysis of Annihilations

\[ \psi_+ \psi_+ \rightarrow \rho \rho \text{ and } \psi_- \psi_- \rightarrow \eta \eta \]

Initial State  Final State

\[ CP \quad (-1)^{L+1} \quad (-1)^{L_f} = (-1)^J \]
CP Analysis of Annihilations

\[ \psi_- \psi_- \rightarrow \rho \rho \text{ and } \psi_- \psi_- \rightarrow \eta \eta \]

Initial State \hspace{1cm} Final State

\[ CP \quad (-1)^{L+1} \quad (-1)^{L_f} = (-1)^J \]

\[ |J - L| = 1, 3, 5... \]
CP Analysis of Annihilations

\[ \psi_- \psi_- \rightarrow \rho \rho \text{ and } \psi_- \psi_- \rightarrow \eta \eta \]

Initial State \hspace{1cm} Final State

\[ CP \quad (-1)^{L+1} \quad (-1)^{L_f} = (-1)^J \]

\[ |J - L| = 1, 3, 5... \]

If \( L = 0 \) then \( S = J = 1 \). Symmetric initial state!!!
CP Analysis of Annihilations

\[ \psi_- \psi_- \rightarrow \rho \rho \text{ and } \psi_- \psi_- \rightarrow \eta \eta \]

Initial State \quad Final State

\[ CP \quad (-1)^{L+1} \quad (-1)^{L_f} = (-1)^J \]

\[ |J - L| = 1, 3, 5... \]

If \( L = 0 \) then \( S = J = 1 \). Symmetric initial state!!!
CP Analysis of Annihilations

\[ \psi_+ \psi_- \rightarrow \rho \rho \text{ and } \psi_+ \psi_- \rightarrow \eta \eta \]

**Initial State | Final State**

\[ CP \quad (-1)^{L+1} \quad (-1)^{L_f} = (-1)^J \]

\[ |J - L| = 1, 3, 5... \]

If \( L = 0 \) then \( S = J = 1 \). Symmetric initial state!!!

\[ L > 0 \]
CP Analysis of Co-annihilations

\[ \psi_- \psi_+ \rightarrow \eta \rho \]
CP Analysis of Co-annihilations

\[ \psi_- \psi_+ \rightarrow \eta \rho \]

Initial State

\[ CP \quad (-1)^L \]
CP Analysis of Co-annihilations

\[ \psi_- \psi_+ \rightarrow \eta \rho \]

Initial State       Final State

\[ CP \quad (-1)^L \quad (-1)^{L_f+1} = (-1)^{J+1} \]
CP Analysis of Co-annihilations

\[ \psi_- \psi_+ \rightarrow \eta \rho \]

Initial State \hspace{1cm} Final State

\[ CP \hspace{1cm} (-1)^L \hspace{1cm} (-1)^{L_f+1} = (-1)^{J+1} \]

\[ |J - L| = 1, 3, 5... \]
CP Analysis of Co-annihilations

\[ \psi_- \psi_+ \rightarrow \eta \rho \]

**Initial State** \hspace{1cm} **Final State**

**CP** \hspace{1cm} \((-1)^L\) \hspace{1cm} \((-1)^{L_f+1} = (-1)^{J+1}\)

\[ |J - L| = 1, 3, 5... \]

If \( L = 0 \) then \( J = S = 1 \). No problem! s-waves are possible
Constraints from Direct Detection Experiments
Constraints from Direct Detection Experiments

Relevant Feynman diagrams for dark matter direct detection experiments.

\[
\sigma_{\psi_- N} = C^2 \frac{m_N^4 M_-^2}{4\pi v_H^2 (M_- + m_N)^2} \left( \frac{1}{m_h^2} - \frac{1}{m_\rho^2} \right)^2 (f \sin 2\theta)^2
\]
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Relevant Feynman diagrams for dark matter direct detection experiments.

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\]
XENON100 limits
XENON100 limits

Using the co-annihilation limit!
Goldstone Bosons as Dark Radiation
Analysis of the decoupling of the Goldstone Bosons
The decoupling takes place when

\[ \frac{n_{\eta}^{eq} \sum_f \langle \sigma v \rangle_{\eta \rightarrow f \bar{f}}}{H} \bigg|_{T=T_{\eta}^d} = 1 \]
Analysis of the decoupling of the Goldstone Bosons

\[ \frac{\text{i}m^2_h}{2v_\phi} \sin \theta \quad \eta \quad \rightarrow \quad h \quad \rightarrow \quad f \quad \bar{f} \quad - \quad \frac{\text{i}m_f}{v_H} \cos \theta \]

\[ - \quad \frac{\text{i}m^2_\rho}{2v_\phi} \cos \theta \quad \eta \quad \rightarrow \quad \rho \quad \rightarrow \quad f \quad \bar{f} \quad - \quad \frac{\text{i}m_f}{v_H} \sin \theta \]

The decoupling takes place when

\[ \eta^e_q \sum_f \langle \sigma v \rangle_{\eta \rightarrow ff} \quad \frac{n_H}{H} \quad \bigg|_{T=T^d_\eta} = 1 \]

Our goal is to calculate the values of \( |\sin \theta| \) for which \( T^d_\eta \approx m_\mu \).
$m_\rho \gtrsim 4$ GeV excluded!
$M_- = 100$ GeV

![Graph showing $|\sin\theta|$ vs. $m_\rho$ (GeV) with XENON100 Upper Limit and Dark Radiation Lower Limit indicated.]
Higgs invisible decay width

$m_\rho$(GeV)

$M_\rho$(GeV)
Conclusions

• The stability of the dark matter particle could be attributed to the remnant $Z_2$ symmetry that arises from the spontaneous breaking of a global $U(1)$ symmetry.

• This plausible scenario contains a Goldstone boson which is a strong candidate for dark radiation.

• This Goldstone boson, together with the $CP$-even scalar associated to the spontaneous breaking of the global $U(1)$ symmetry, plays a central role in the dark matter production.

• The mixing of the $CP$-even scalar with the Brout-Englert-Higgs boson leads to novel decay channels and to interactions with nucleons, thus opening the possibility of probing this scenario at the LHC and in direct dark matter search experiments.

• There are good prospects to observe a signal at the future experiments LUX and XENON1T provided the dark matter particle was produced thermally and has a mass larger than $\sim 25$ GeV.