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

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Based on arXiv:1310.6256 in collaboration with Alejandro Ibarra and Emiliano Molinaro

Outline

- Motivation
- Description of the Model
- Dark Matter Production
- Constraints from Direct Detection Experiments
- Goldstone Bosons as Dark Radiation
- Conclusions

Motivation

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- 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.

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- Could these Golstone bosons be Dark Radiation? Weinberg 2013

What is Dark Radiation?

Radiation Density of the Universe

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

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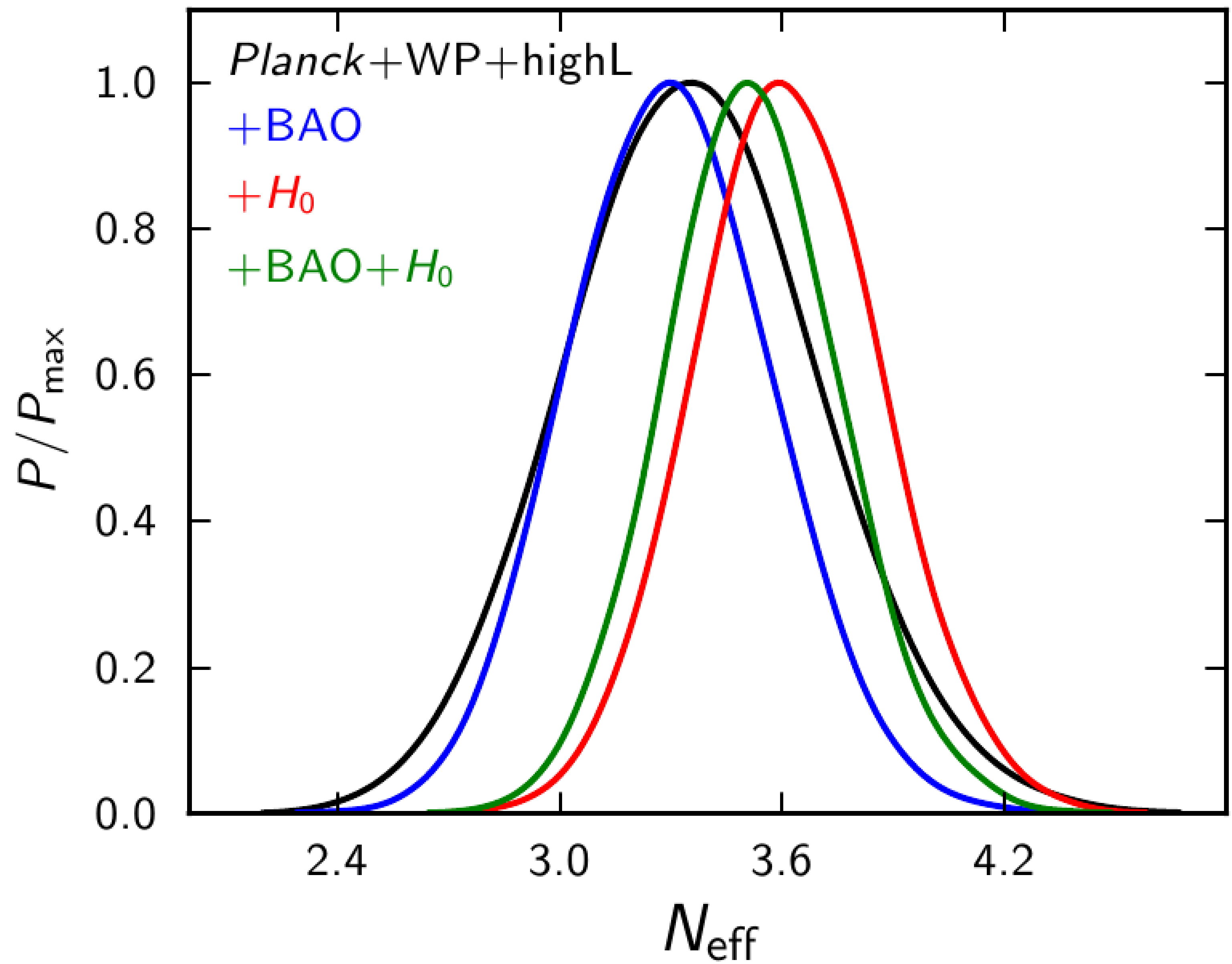
$$\rho_R = \frac{\pi^2}{30}\left(2 \cdot (T_\gamma^0)^4 + 2 \cdot \frac{7}{8} \cdot N_{eff} (T_\nu^0)^4\right)$$

$$N_{eff} = 3 + \frac{4}{7}\left(\frac{T_\eta^0}{T_\nu^0}\right)^4$$



Planck Collaboration 2013

What happens if the Goldstones decouple before muon annihilation?

$$\gamma \; e^{\pm} \; \mu^{\pm} \; \nu \; \overline{\nu} \; \eta$$

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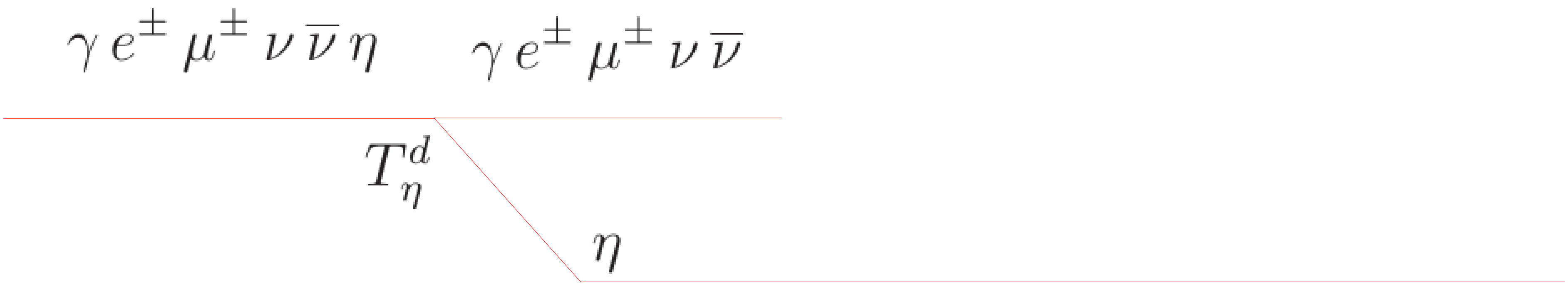

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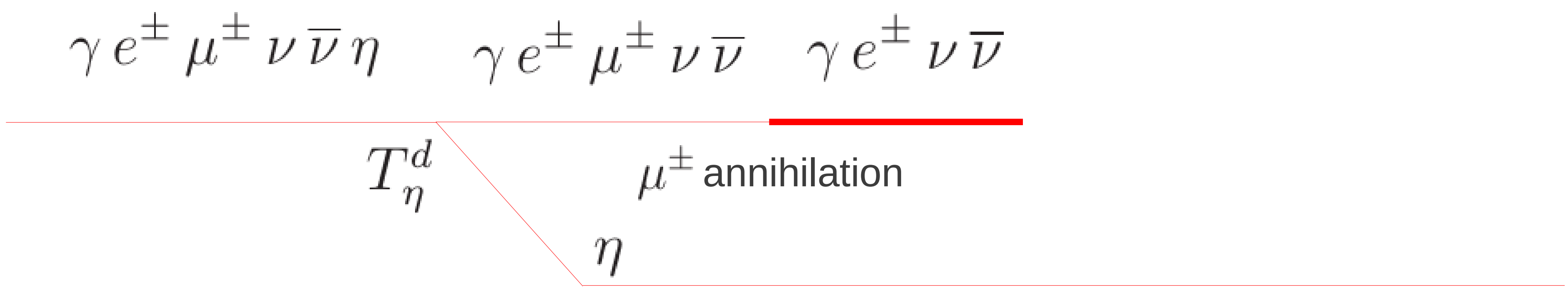

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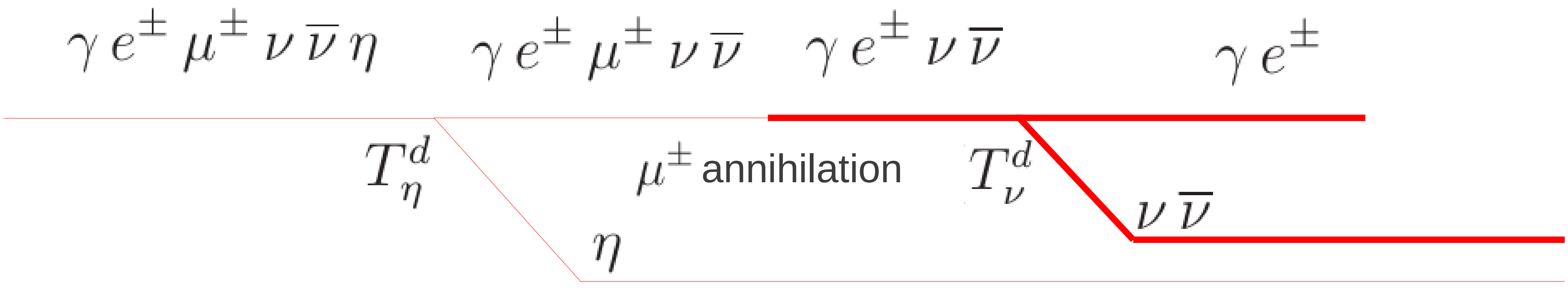

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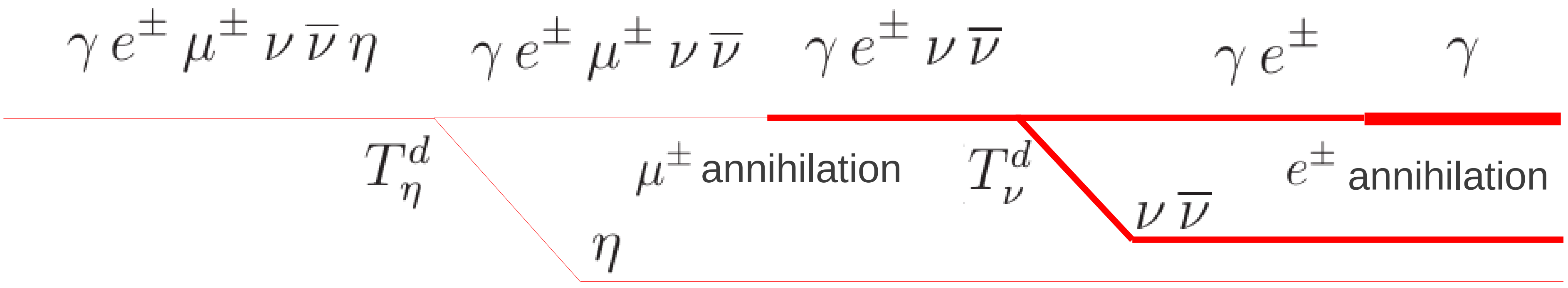

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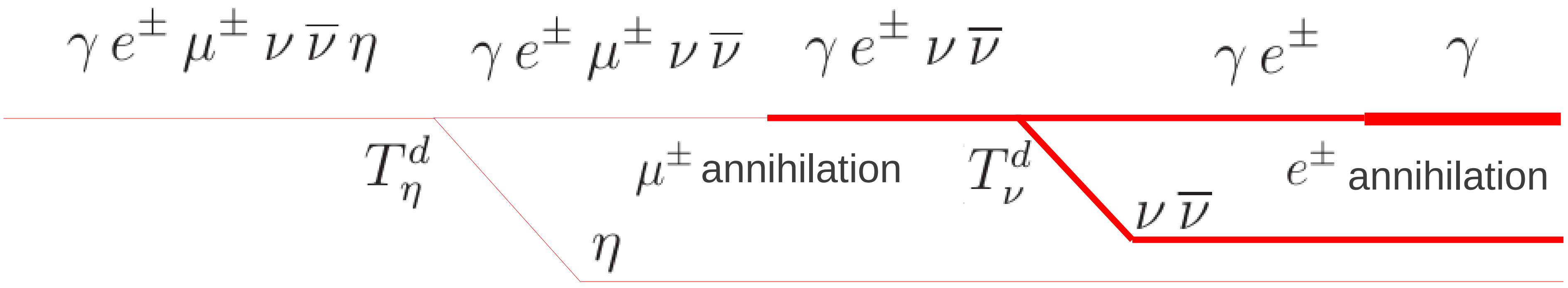

Entropy conservation per unit of comoving volume

$$s \propto g_* T^3$$

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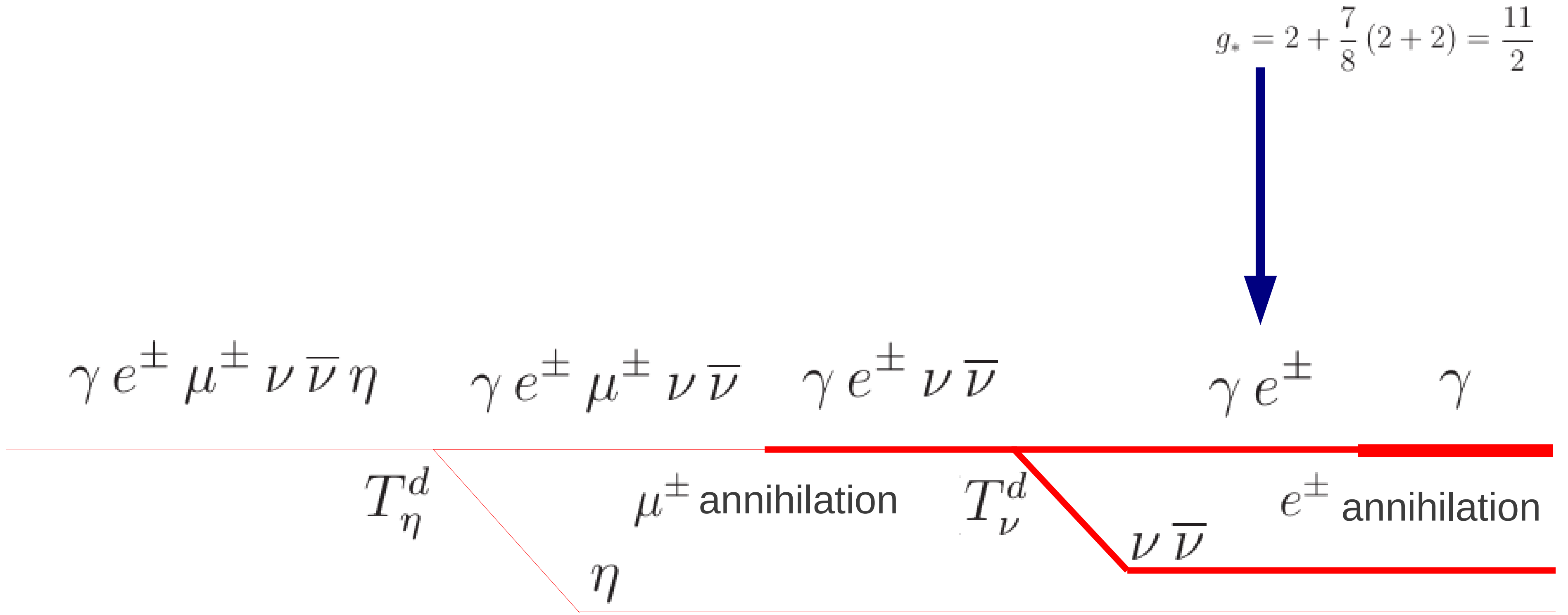

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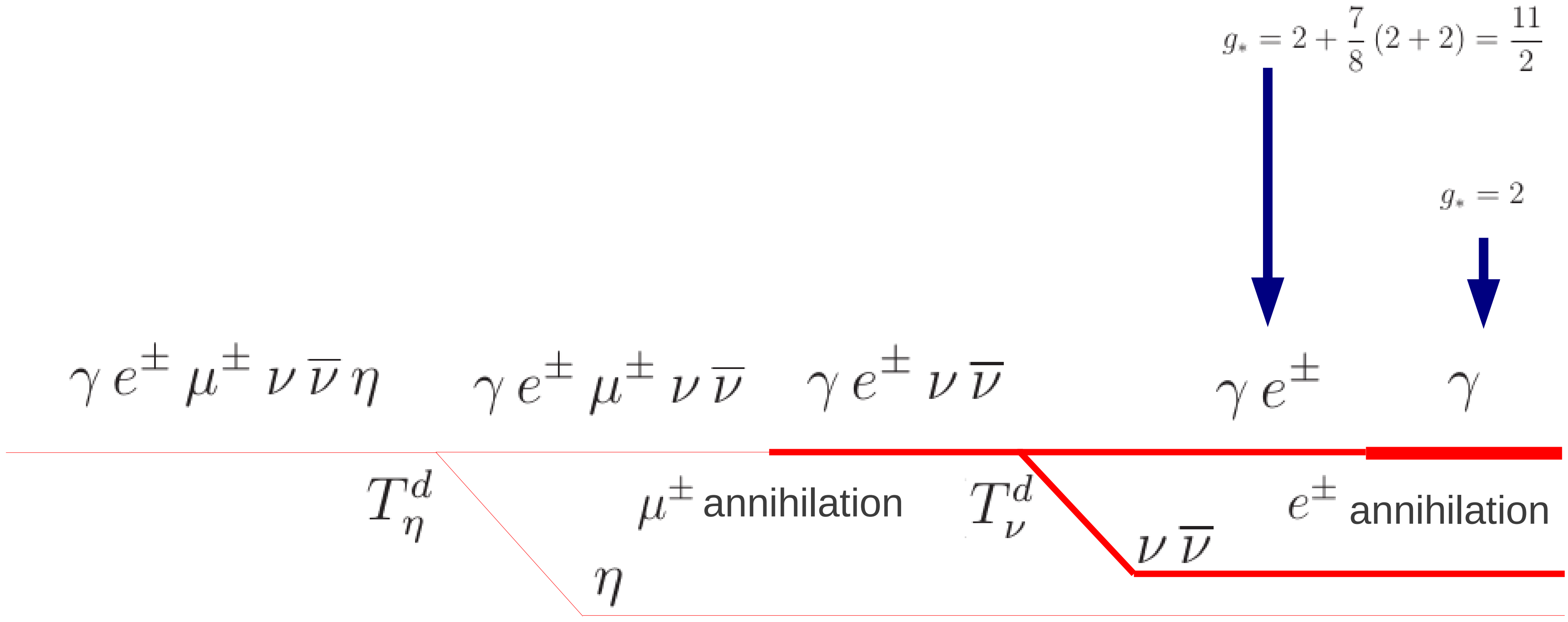

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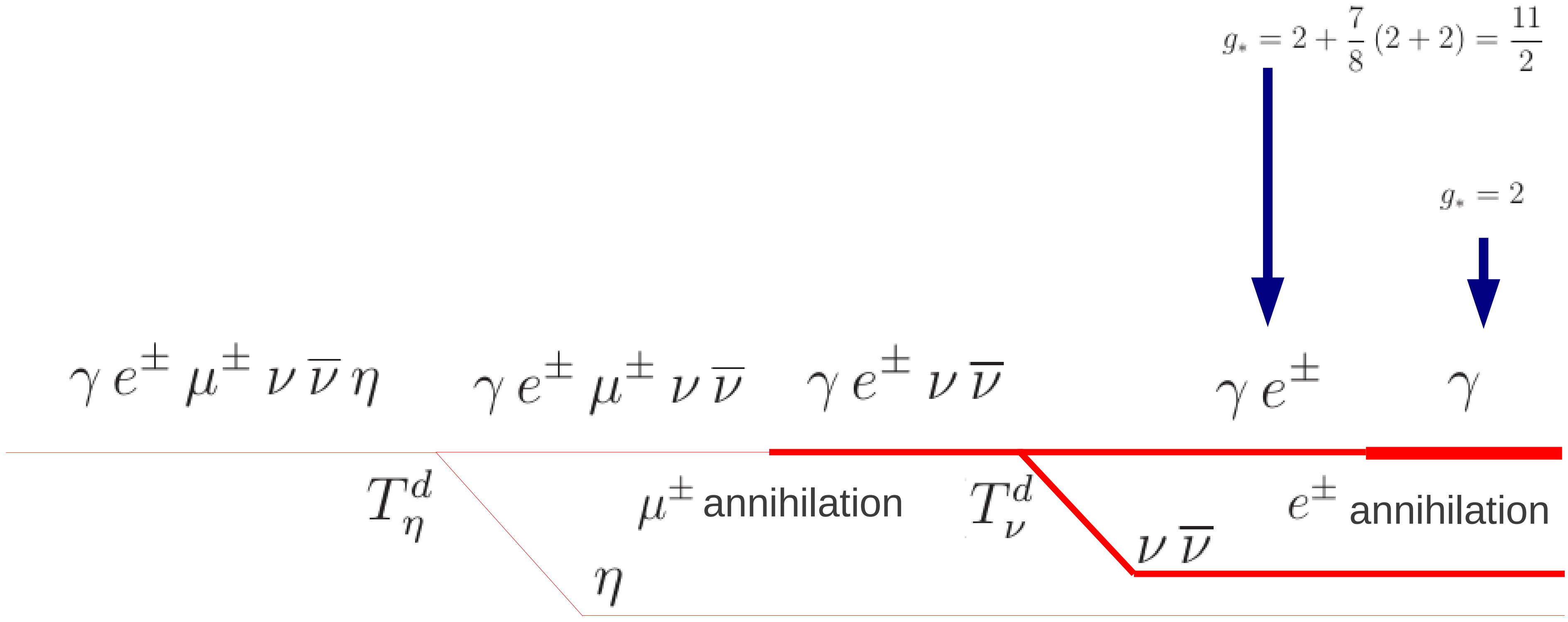

$$\frac{T_\nu^0}{T_\gamma^0} = \left(\frac{g_*^{\rm after}}{g_*^{\rm before}}\right)^{1/3} = \left(\frac{4}{11}\right)^{1/3}$$

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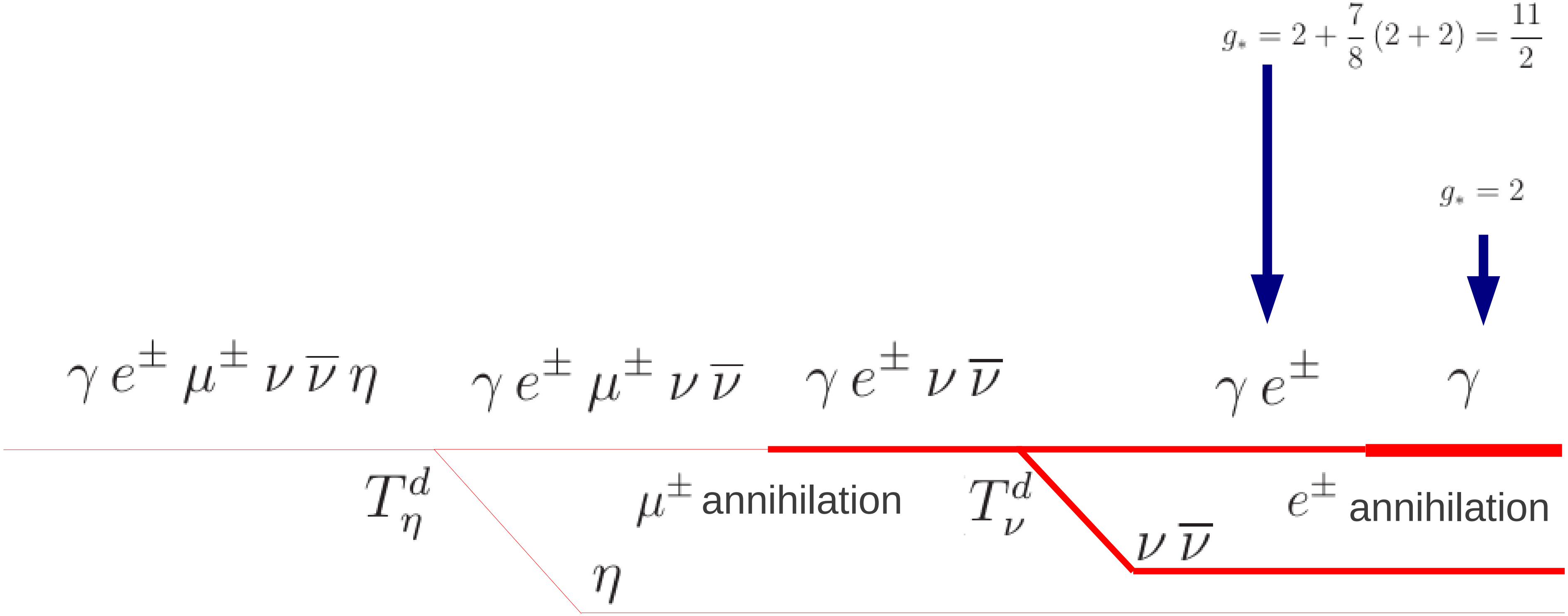

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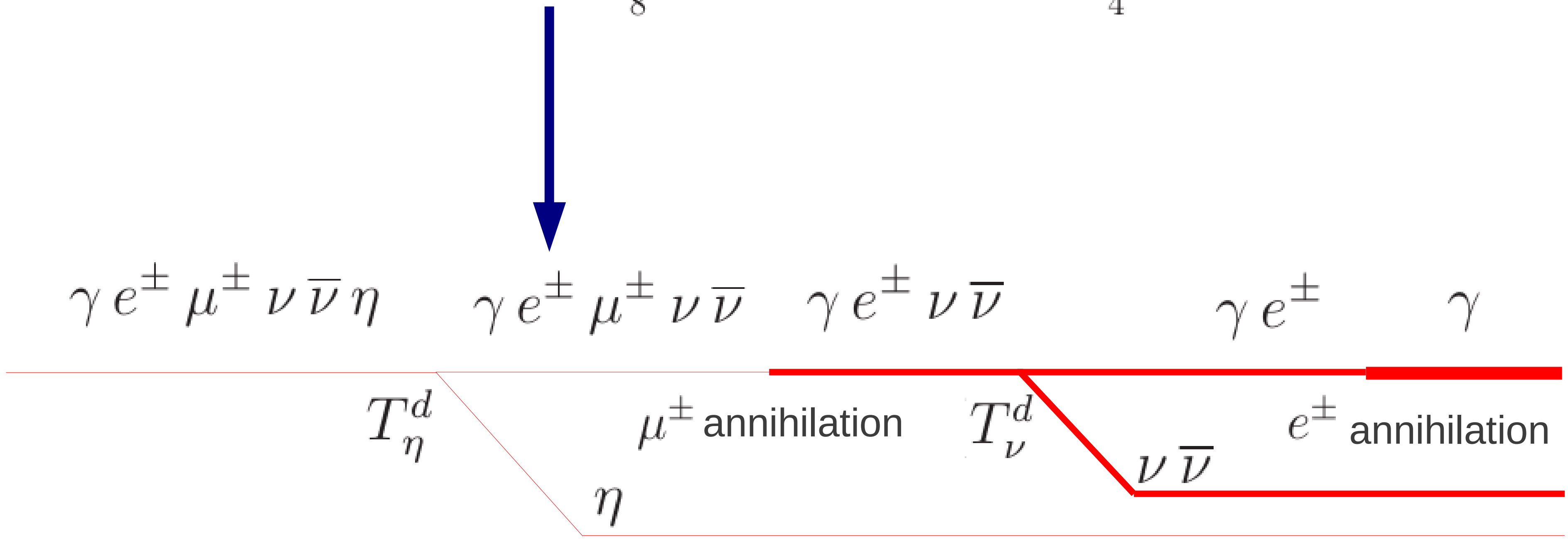
$$g_* = 2 + \frac{7}{8}(2+2+2+2+3(1+1)) = \frac{57}{4}$$



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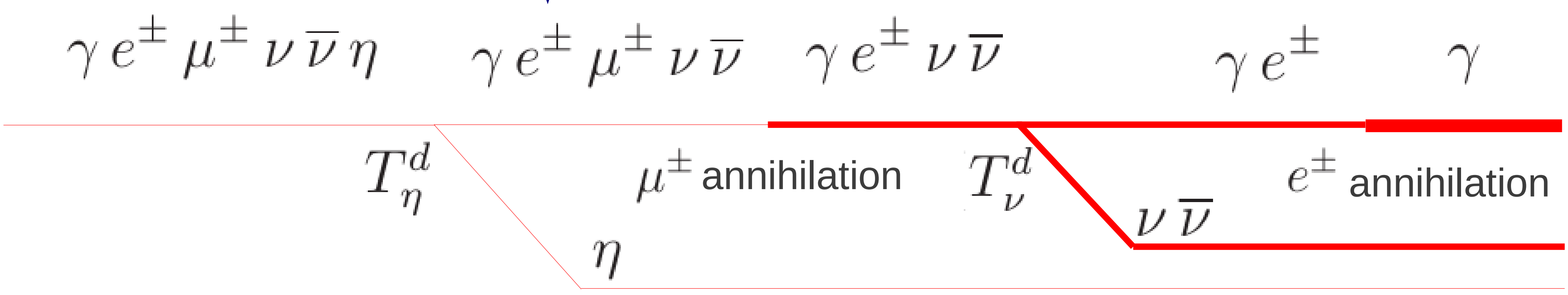

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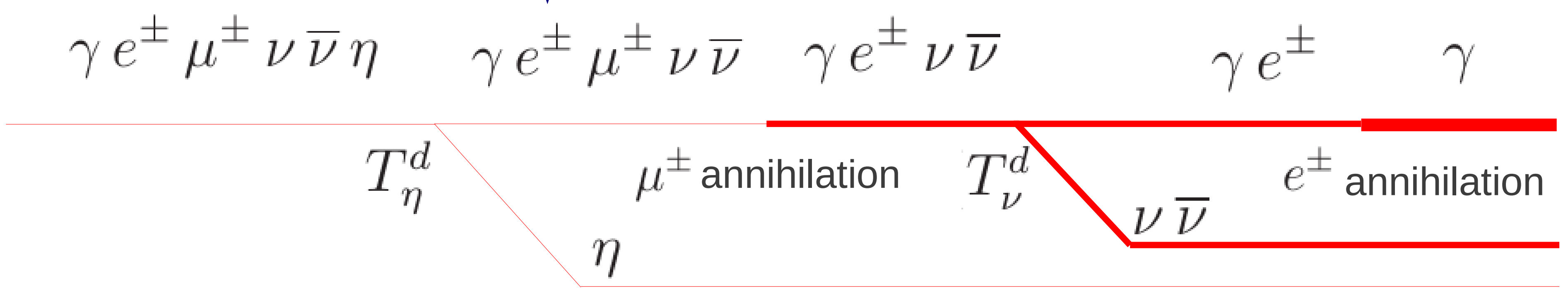

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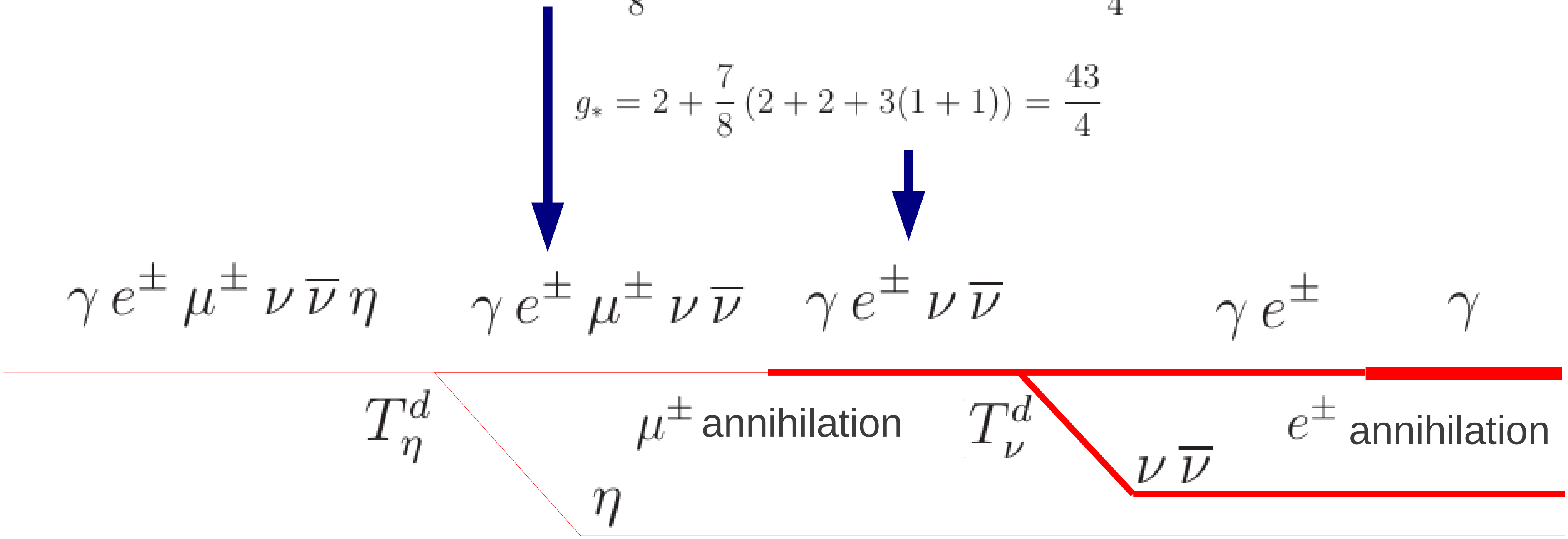

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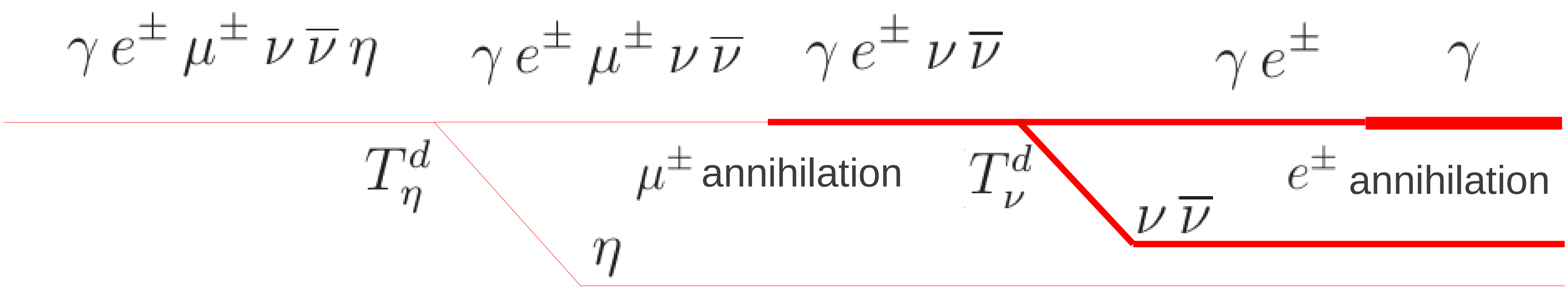

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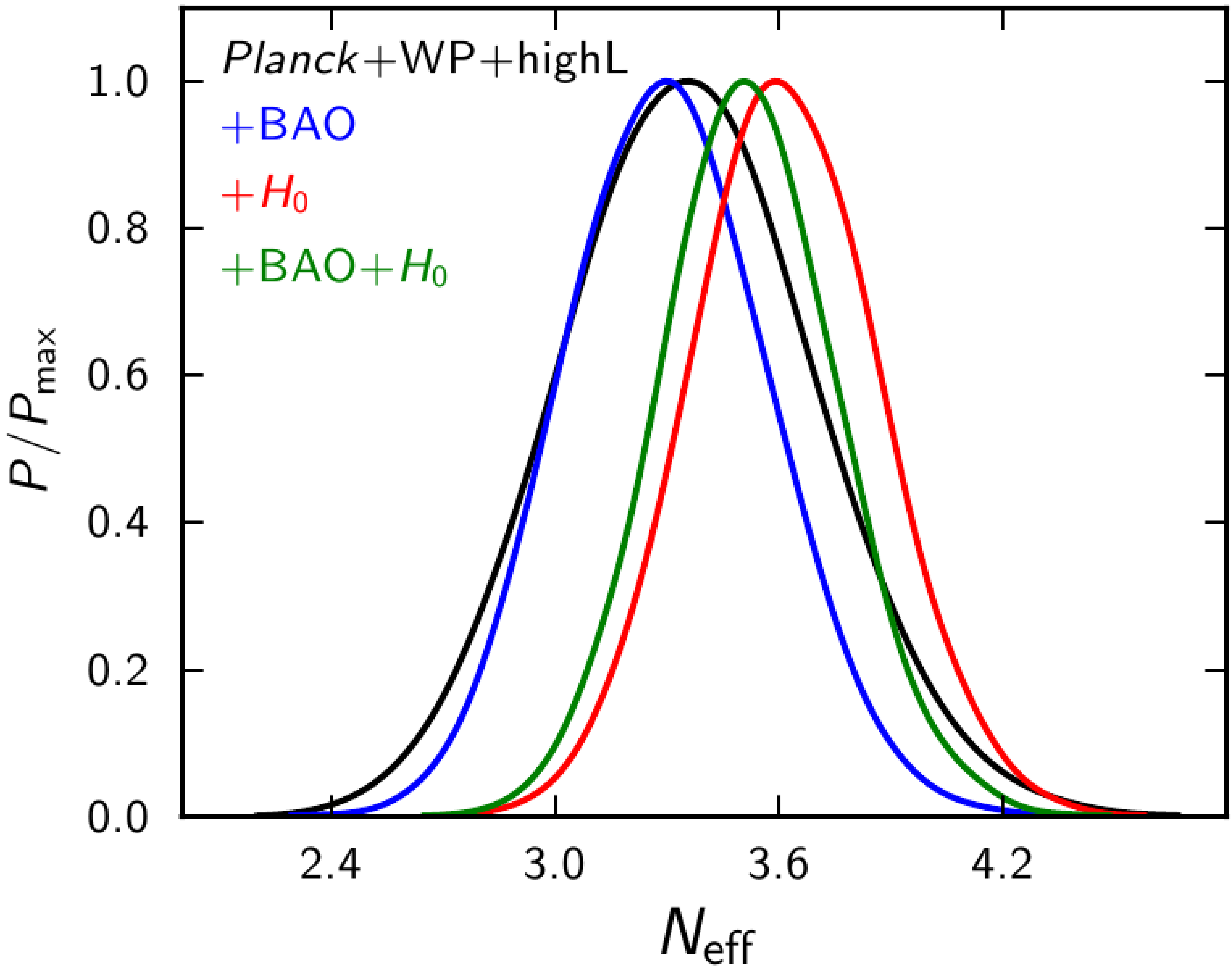
Weinberg 2013

$$T_\eta^0 = 1.771\, K \qquad N_{eff} - 3 = \frac{4}{7}\left(\frac{43}{57}\right)^{4/3} \simeq 0.39$$



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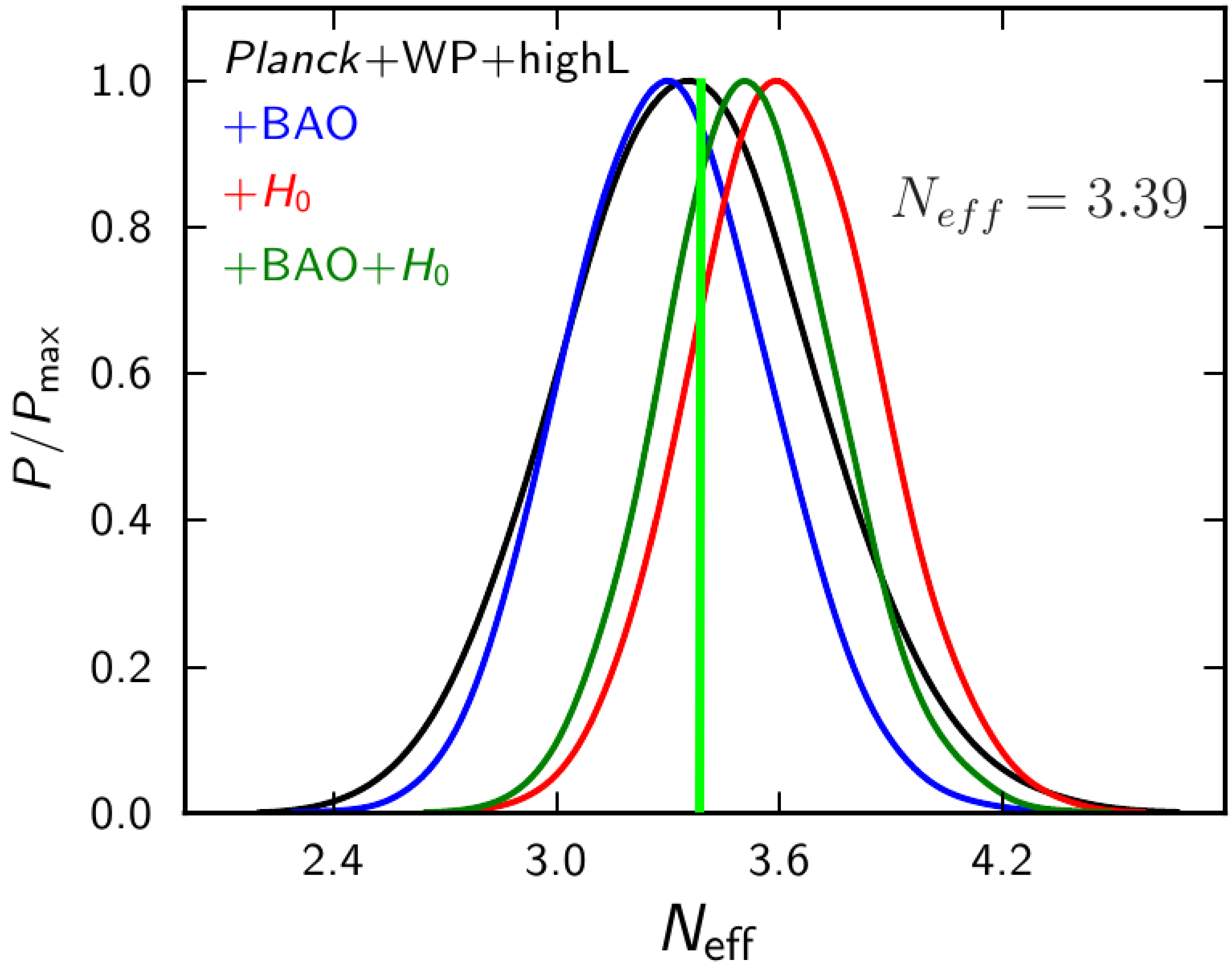

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Description of the Model

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Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{\mathrm{DM}}$
ϕ	1	1	0	2
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$$\mathcal{L}_{\mathrm{DM}} = i\overline{\psi}\gamma^\mu \partial_\mu \psi - M\overline{\psi}\psi - \left(\frac{f}{\sqrt{2}}\phi\overline{\psi}\psi^c + h.c.\right)$$

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After symmetry breaking in the scalar sector

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

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

$$\begin{aligned} m_h^2 &= 2\,\lambda_H\, v_H^2\, \cos^2\theta + 2\,\lambda_\phi\, v_\phi^2\, \sin^2\theta - \kappa\, v_H\, v_\phi\, \sin 2\theta \\ m_\rho^2 &= 2\,\lambda_H\, v_H^2\, \sin^2\theta + 2\,\lambda_\phi\, v_\phi^2\, \cos^2\theta + \kappa\, v_H\, v_\phi\, \sin 2\theta \end{aligned}$$

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Brout-Englert-Higgs Boson $m_h = 125$ GeV

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The field η corresponds to the Goldstone boson that arises from the spontaneous breaking of the global $U(1)_{\rm DM}$ symmetry.

After symmetry breaking in the fermionic sector

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

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}\left(i\overline{\psi_+}\gamma^\mu\partial_\mu\psi_+ + i\overline{\psi_-}\gamma^\mu\partial_\mu\psi_- - M_+\overline{\psi_+}\psi_+ - M_-\overline{\psi_-}\psi_-\right) \\ &\quad - \frac{f}{2}\left((-\sin\theta\, h + \cos\theta\,\rho)(\overline{\psi_+}\psi_+ - \overline{\psi_-}\psi_-) + \eta\,(\overline{\psi_+}\psi_- + \overline{\psi_-}\psi_+)\right)\end{aligned}$$

$$M_\pm = |M \pm f v_\phi|$$

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Invariance under the Z_2 transformation $\psi_\pm \to -\psi_\pm$

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The lightest Majorana fermion is stable and, consequently, a dark matter candidate

Constraints from Invisible Higgs Decays

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$$\Downarrow$$

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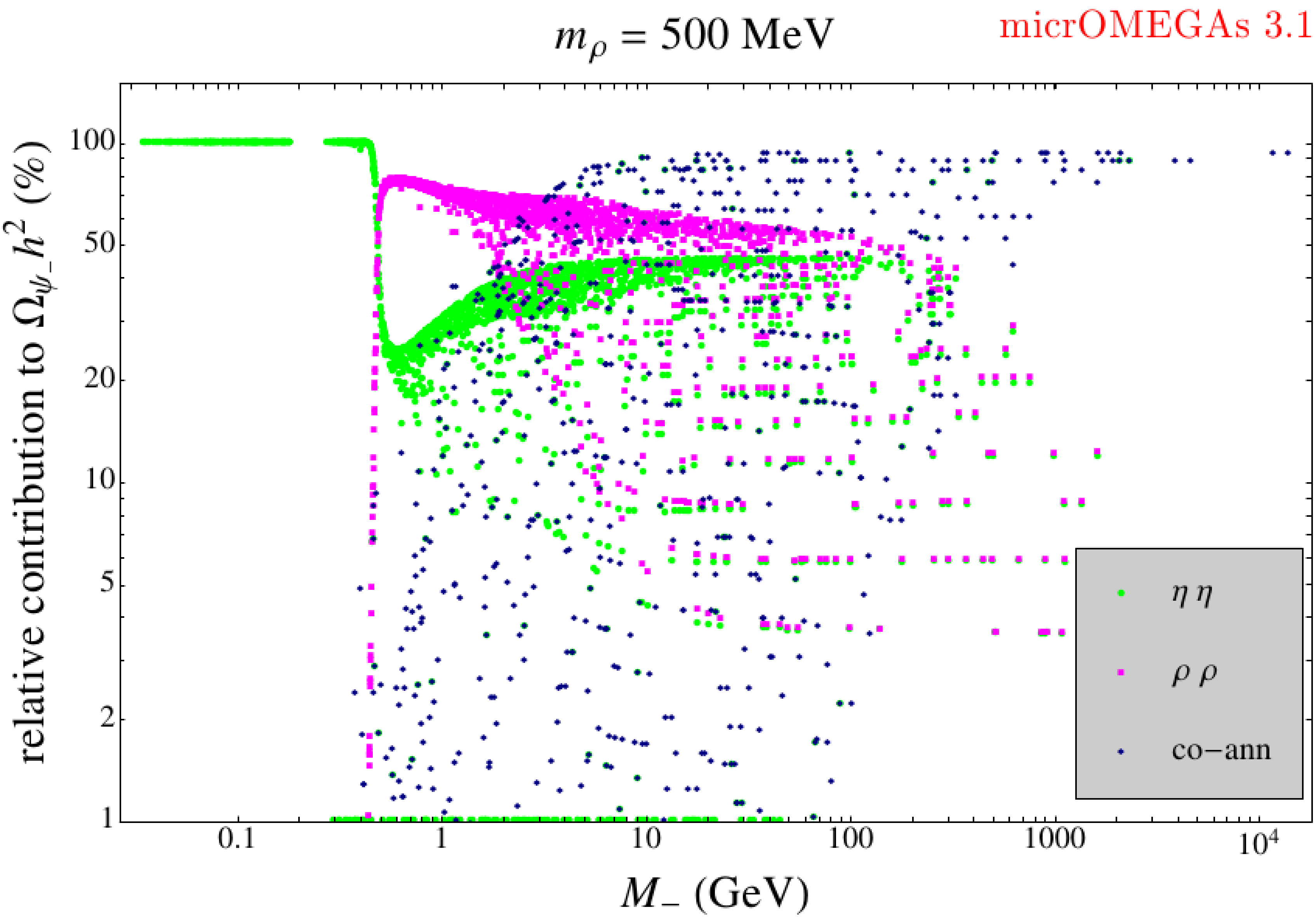
$$|\tan\theta| \;\lesssim\; 2.2\times 10^{-3}\left(\frac{v_\phi}{10\,\mathrm{GeV}}\right)$$

Weinberg 2013

Dark Matter Production

Contribution from the different channels



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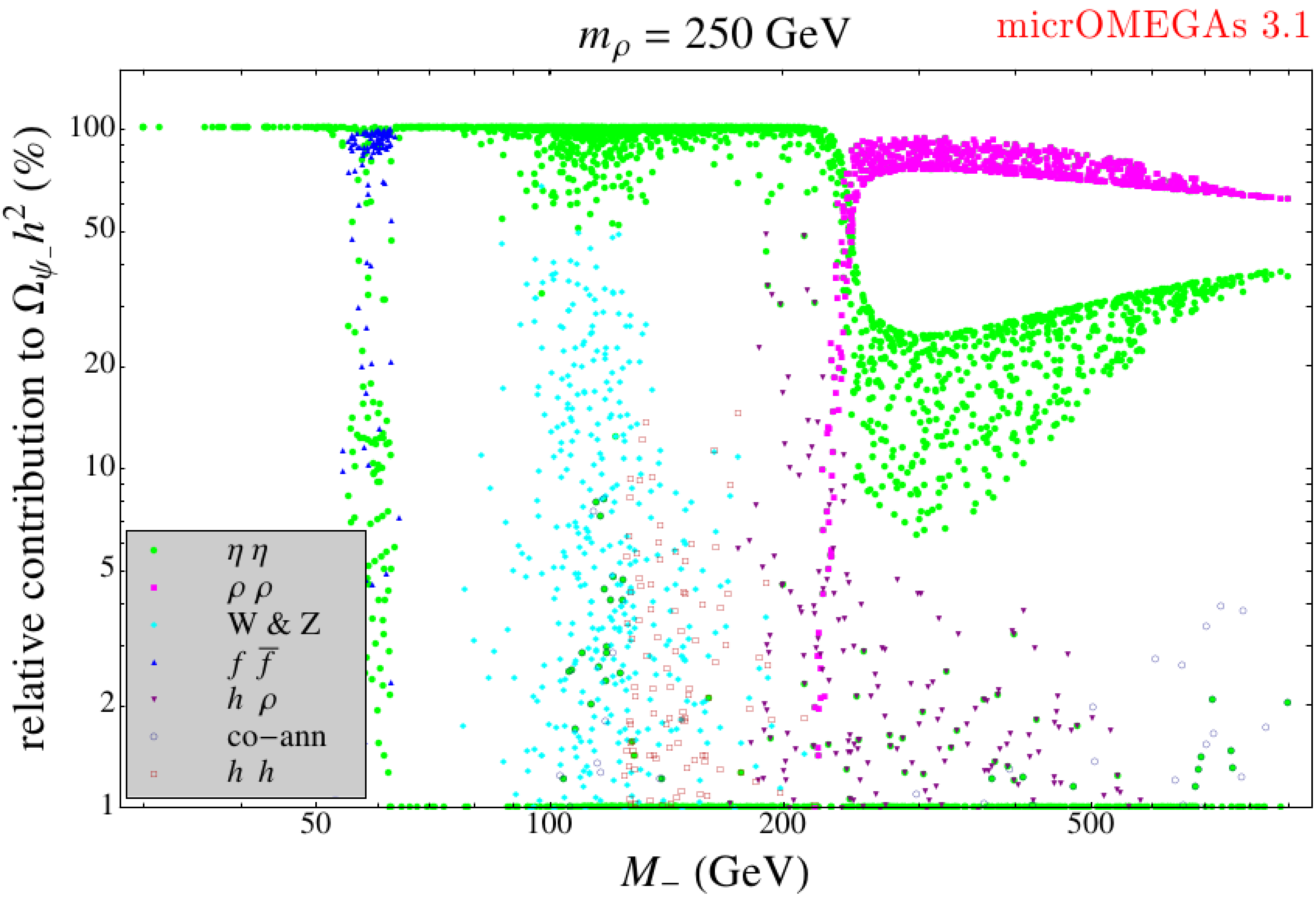
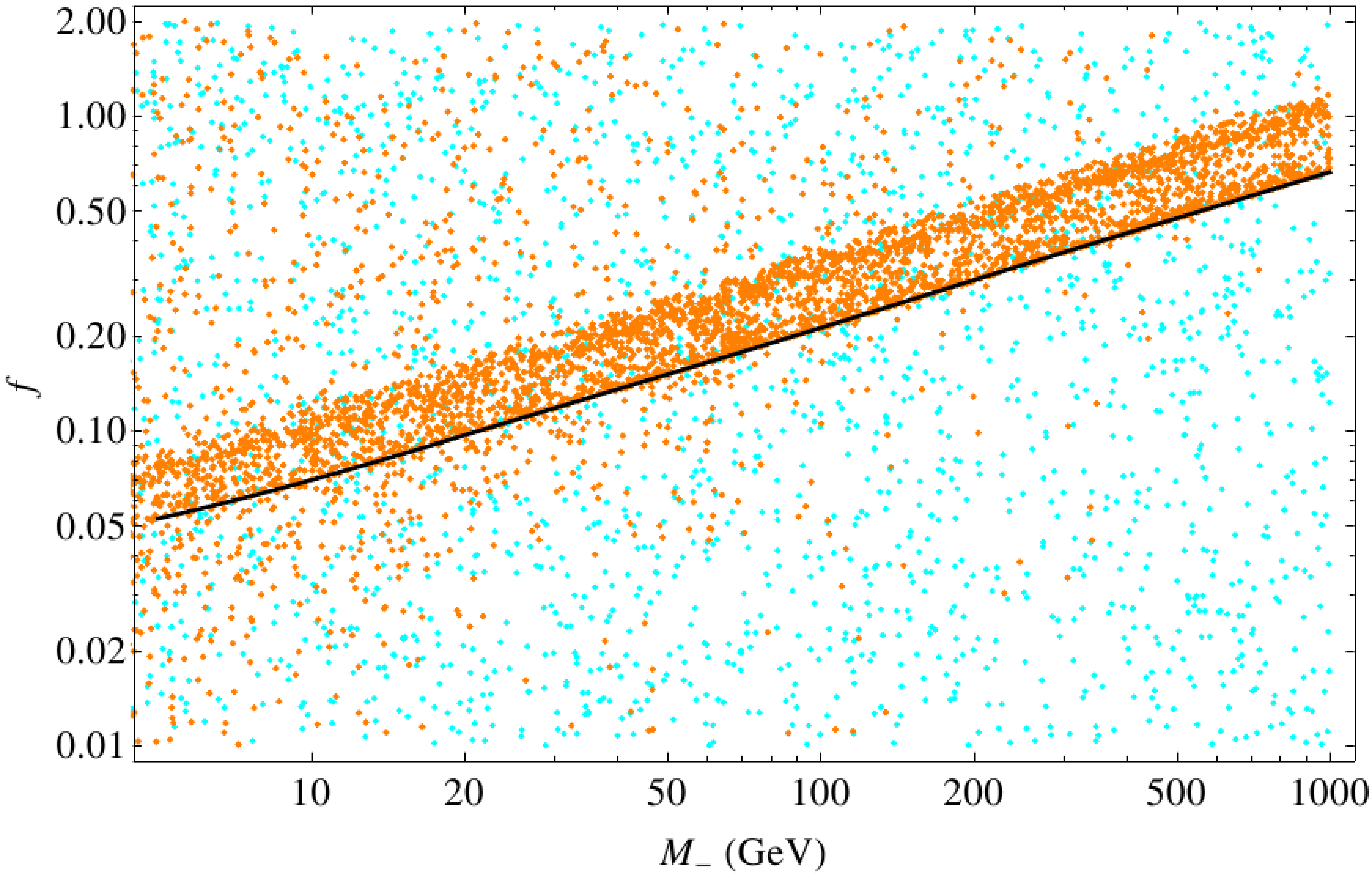
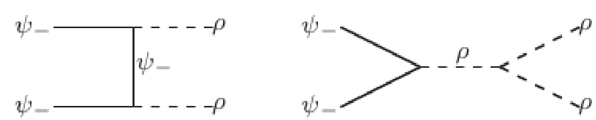
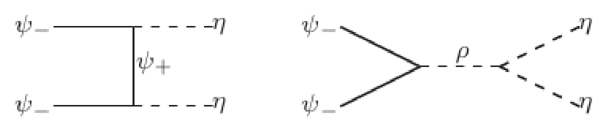
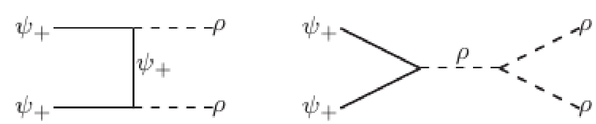
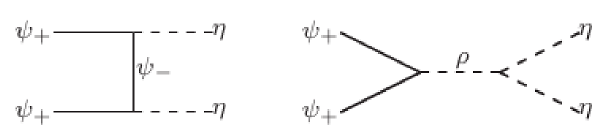
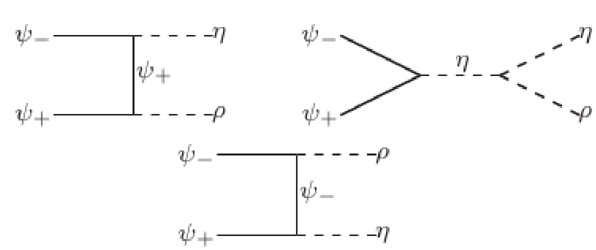


Dark Matter Coupling



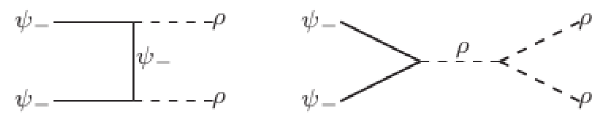
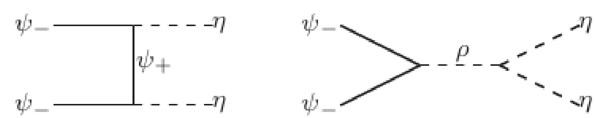
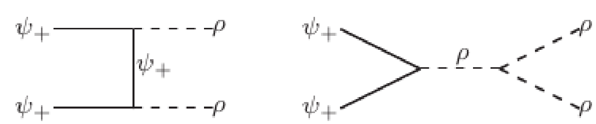
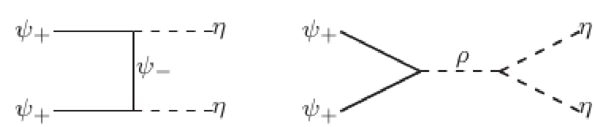
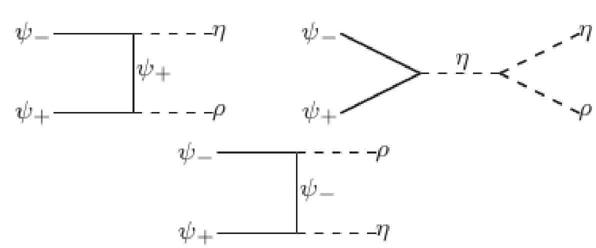
Case $\theta \ll 1$

Process	
Annihilation $\psi_-\psi_- \to \rho\rho$ 	
Annihilation $\psi_-\psi_- \to \eta\eta$ 	
Annihilation $\psi_+\psi_+ \to \rho\rho$ 	
Annihilation $\psi_+\psi_+ \to \eta\eta$ 	
Coannihilation $\psi_-\psi_+ \to \rho\eta$ 	

Case $\theta \ll 1$

Threshold Effects

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

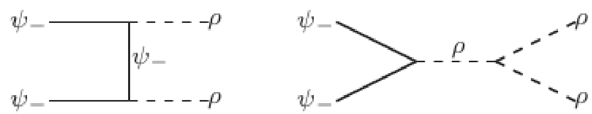
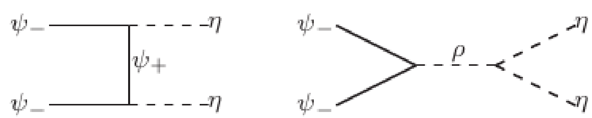
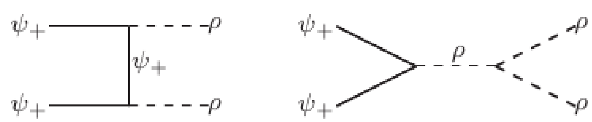
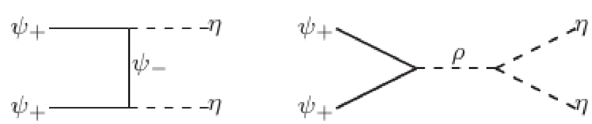
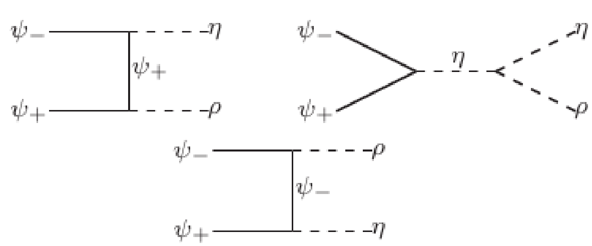
Process	
Annihilation $\psi_-\psi_- \to \rho\rho$ 	Open if $m_\rho < M_-$ or equivalently if $r < 1$
Annihilation $\psi_-\psi_- \to \eta\eta$ 	
Annihilation $\psi_+\psi_+ \to \rho\rho$ 	Open if $m_\rho < M_+$ or equivalently if $r < z$
Annihilation $\psi_+\psi_+ \to \eta\eta$ 	
Coannihilation $\psi_-\psi_+ \to \rho\eta$ 	Open if $m_\rho < (M_- + M_+)$ or equivalently if $r < 1 + z$

Case $\theta \ll 1$

Threshold Effects

Resonances

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

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

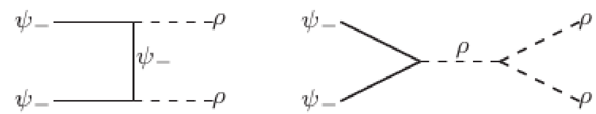
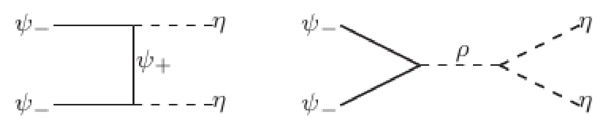
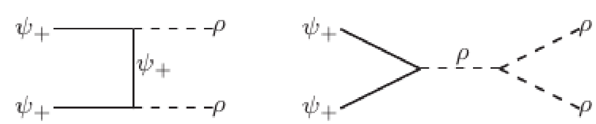
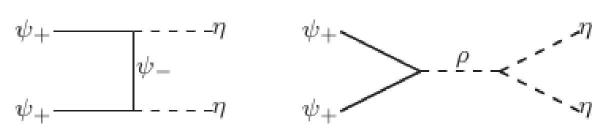
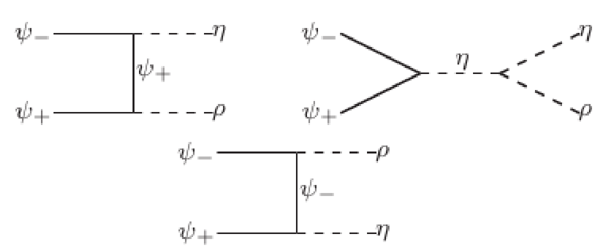
Case $\theta \ll 1$

Threshold Effects

Resonances

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

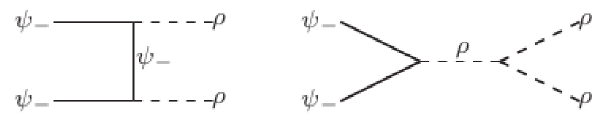
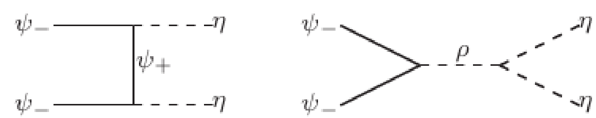
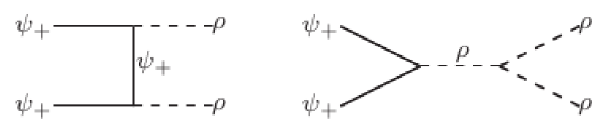
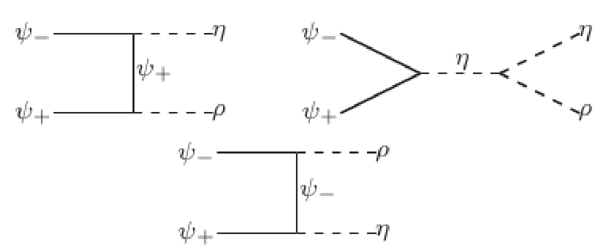
We can avoid this for $r \lesssim 0.8$

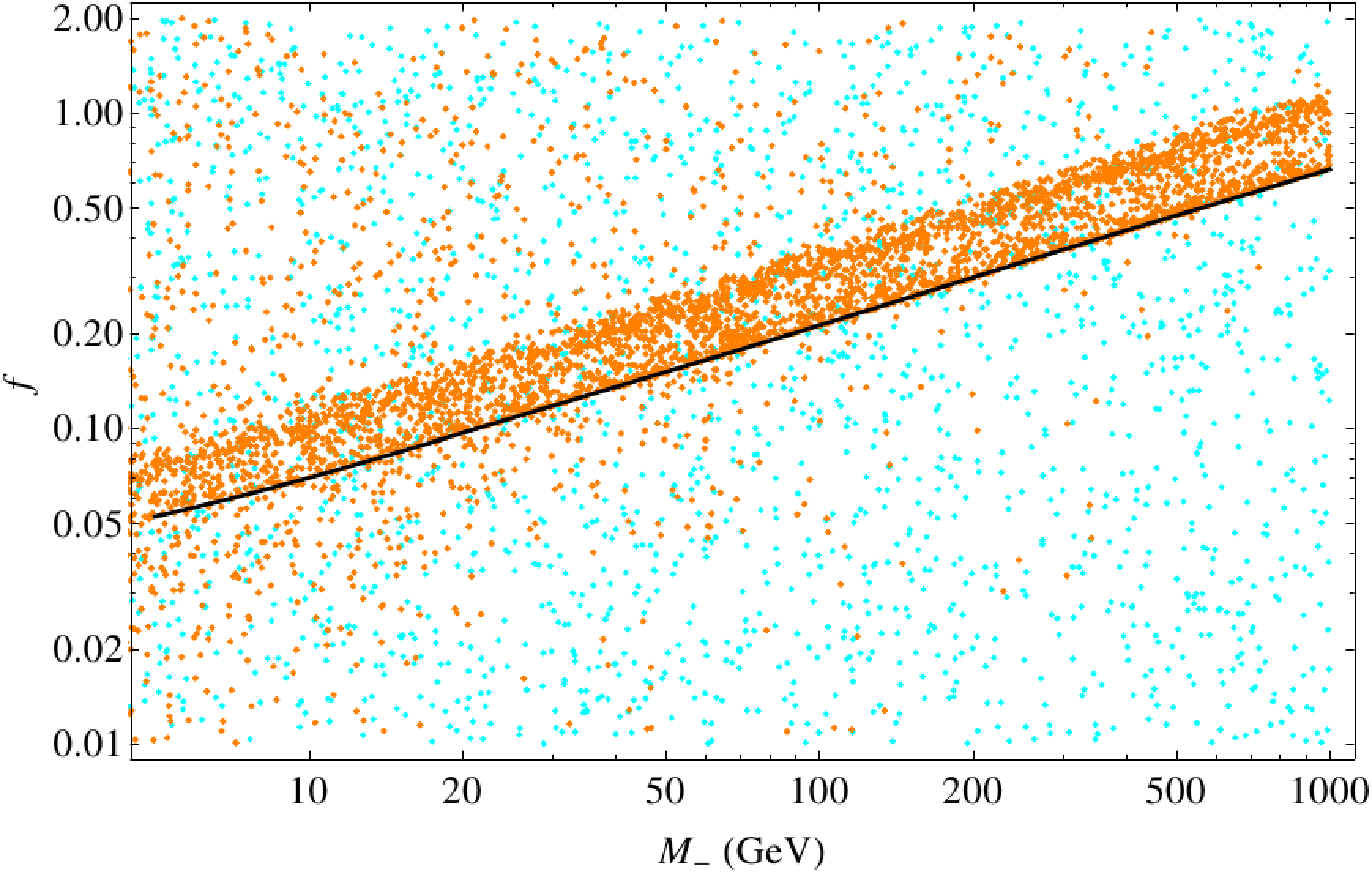
Process	
Annihilation $\psi_-\psi_- \to \rho\rho$ 	Open if $m_\rho < M_-$ or equivalently if $r < 1$
Annihilation $\psi_-\psi_- \to \eta\eta$ 	Always open, resonantly enhanced $r \gtrsim 2$
Annihilation $\psi_+\psi_+ \to \rho\rho$ 	Open if $m_\rho < M_+$ or equivalently if $r < z$
Annihilation $\psi_+\psi_+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

Case $\theta \ll 1$

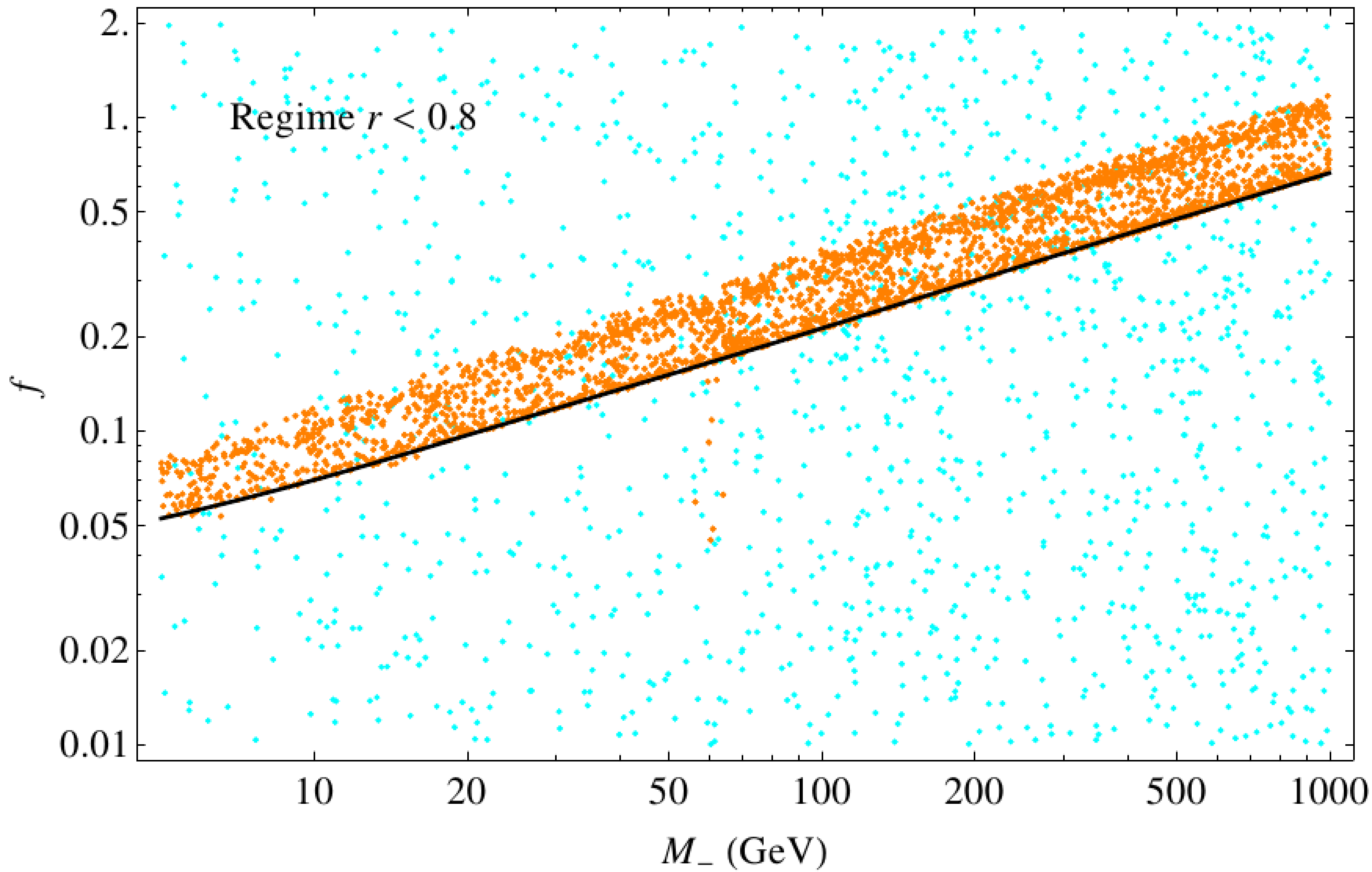
p-waves

s-wave

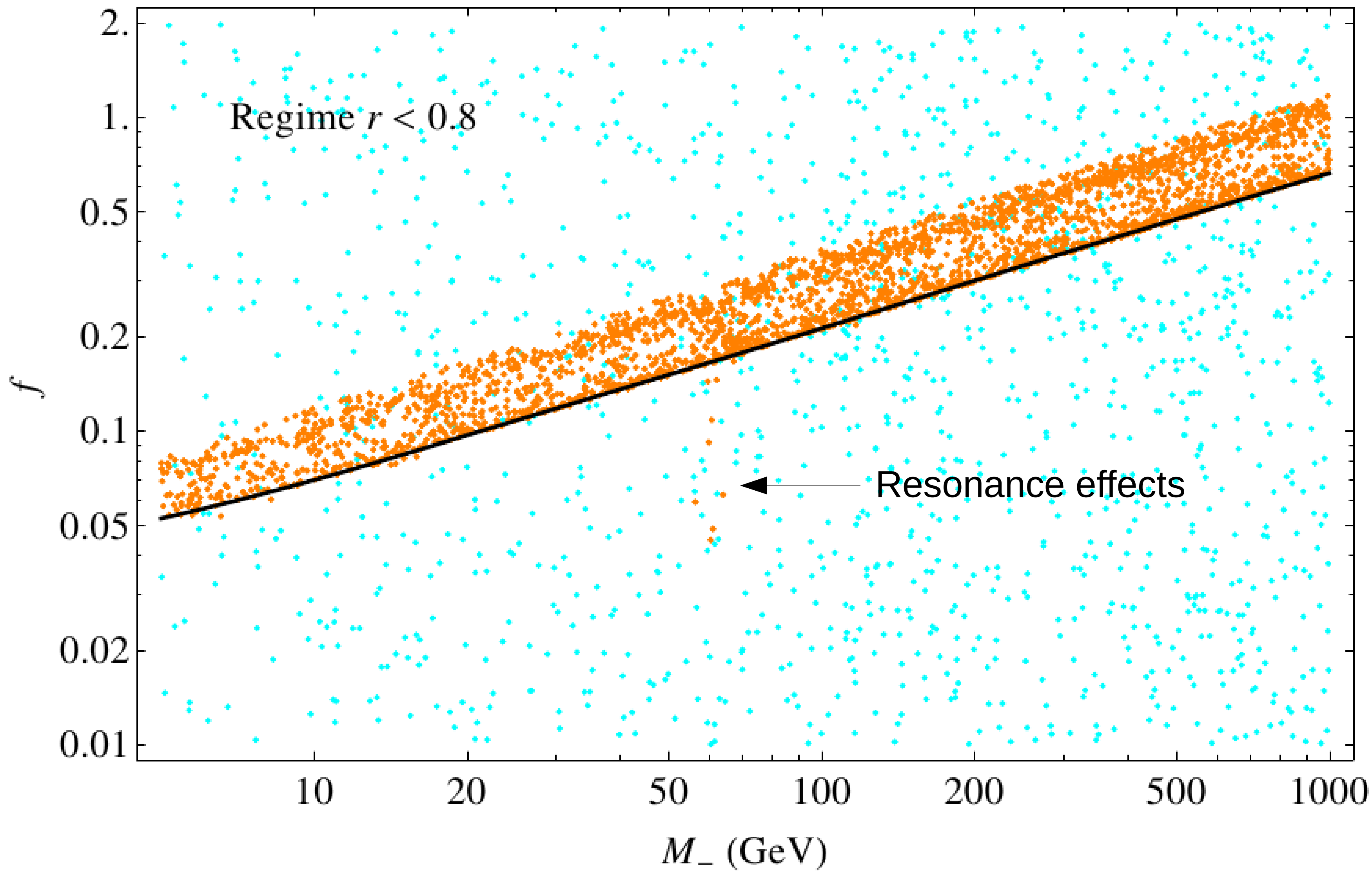
Process	
Annihilation $\psi_-\psi_- \to \rho\rho$ 	Open if $m_\rho < M_-$ or equivalently if $r < 1$
Annihilation $\psi_-\psi_- \to \eta\eta$ 	Always open, resonantly enhanced $r \gtrsim 2$
Annihilation $\psi_+\psi_+ \to \rho\rho$ 	Open if $m_\rho < M_+$ or equivalently if $r < z$
Annihilation $\psi_+\psi_+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



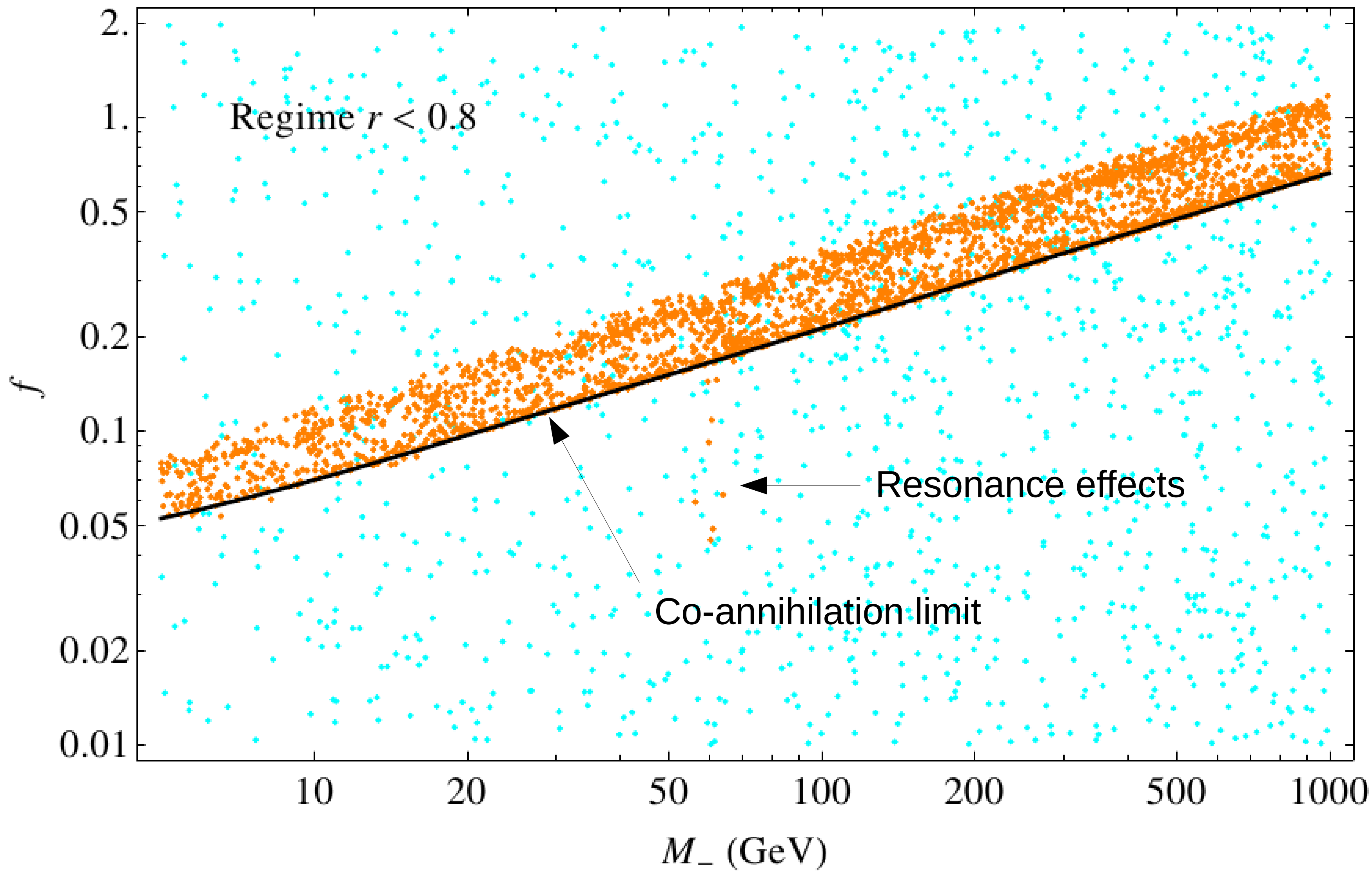
2.00
1.00
0.50
0.20
0.10
0.05
0.02
0.01
f
10
20
50
100
200
500
1000
M_ (GeV)



Regime $r < 0.8$
2.
1.
0.5
0.2
0.1
0.05
0.02
0.01
f
10
20
50
100
200
500
1000
M_- (GeV)



Regime $r < 0.8$
Resonance effects
f
2.
1.
0.5
0.2
0.1
0.05
0.02
0.01
10
20
50
100
200
500
1000
M_- (GeV)



Annihilations proceed via p-waves $\longrightarrow$ Large f

Co-annihilations proceed via s-waves $\longrightarrow$ Small f

$$f\Big|_{z\to 1} \simeq \left(\frac{1.07\times 10^{11}\,\mathrm{GeV}^{-1}\,x_f}{g_*(x_f)^{1/2}\,m_{\rm Pl}\,\Omega_{\rm DM}h^2}\right)^{1/4} M_-^{1/2}$$

CP Analysis of Annihilations

$$\psi_-\psi_- \to \rho\rho \text{ and } \psi_-\psi_- \to \eta\eta$$

CP Analysis of Annihilations

$$\psi_-\psi_- \to \rho\rho \text{ and } \psi_-\psi_- \to \eta\eta$$

Initial State

$CP \qquad (-1)^{L+1}$

CP Analysis of Annihilations

$$\psi_- \psi_- \to \rho\rho \text{ and } \psi_- \psi_- \to \eta\eta$$

	Initial State	Final State
CP	$(-1)^{L+1}$	$(-1)^{L_f} = (-1)^J$

CP Analysis of Annihilations

$$\psi_-\psi_- \to \rho\rho \text{ and } \psi_-\psi_- \to \eta\eta$$

	Initial State	Final State
CP	$(-1)^{L+1}$	$(-1)^{L_f} = (-1)^J$

$$\Downarrow$$

$$|J - L| = 1, 3, 5...$$

CP Analysis of Annihilations

$$\psi_-\psi_- \to \rho\rho \text{ and } \psi_-\psi_- \to \eta\eta$$

	Initial State	Final State
CP	$(-1)^{L+1}$	$(-1)^{L_f} = (-1)^J$

$$|J - L| = 1, 3, 5...$$

If $L = 0$ then $S = J = 1$. Symmetric initial state!!!

CP Analysis of Annihilations

$$\psi_-\psi_- \to \rho\rho \text{ and } \psi_-\psi_- \to \eta\eta$$

	Initial State	Final State
CP	$(-1)^{L+1}$	$(-1)^{L_f} = (-1)^J$

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CP Analysis of Annihilations

$$\psi_- \psi_- \rightarrow \rho\rho \text{ and } \psi_- \psi_- \rightarrow \eta\eta$$

	Initial State	Final State
CP	$(-1)^{L+1}$	$(-1)^{L_f} = (-1)^J$

$$|J - L| = 1, 3, 5...$$

If $L = 0$ then $S = J = 1$. Symmetric initial state!!! $\times$

$$L > 0$$

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	$(-1)^L$	$(-1)^{L_f+1} = (-1)^{J+1}$

CP Analysis of Co-annihilations

$$\psi_-\psi_+ \rightarrow \eta\rho$$

	Initial State	Final State
CP	$(-1)^L$	$(-1)^{L_f+1} = (-1)^{J+1}$

$$\Downarrow$$

$$|J - L| = 1, 3, 5 \ldots$$

CP Analysis of Co-annihilations

$$\psi_- \psi_+ \to \eta \rho$$

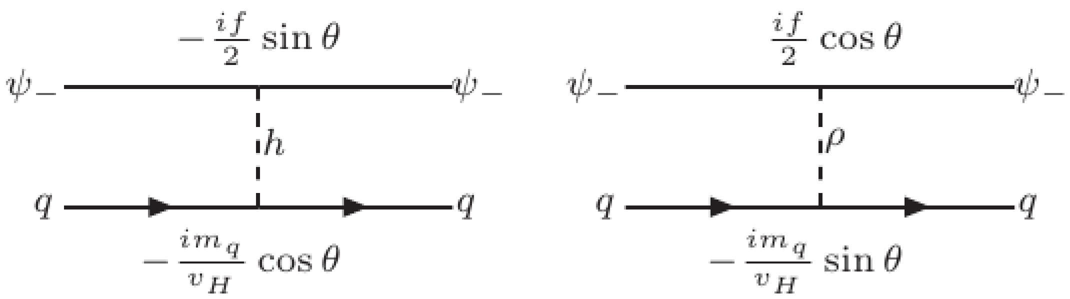
	Initial State	Final State
CP	$(-1)^L$	$(-1)^{L_f+1} = (-1)^{J+1}$

$$|J - L| = 1, 3, 5...$$

If $L = 0$ then $J = S = 1$. No problem! s-waves are possible

Constraints from Direct Detection Experiments

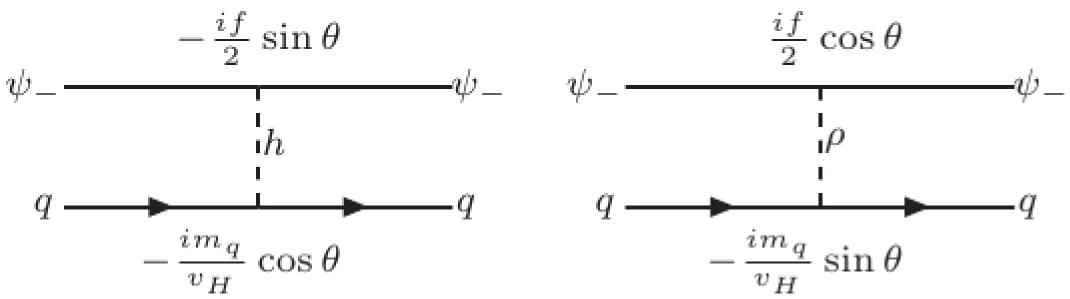
Constraints from Direct Detection Experiments



Relevant Feynman diagrams for dark matter direct detection experiments.

$$\sigma_{\psi_- N} \quad = \quad C^2 \frac{m_N^4 \, M_-^2}{4\pi \, v_H^2 \, (M_- + m_N)^2} \left(\frac{1}{m_h^2} - \frac{1}{m_\rho^2} \right)^2 (f \sin 2\theta)^2$$

Constraints from Direct Detection Experiments



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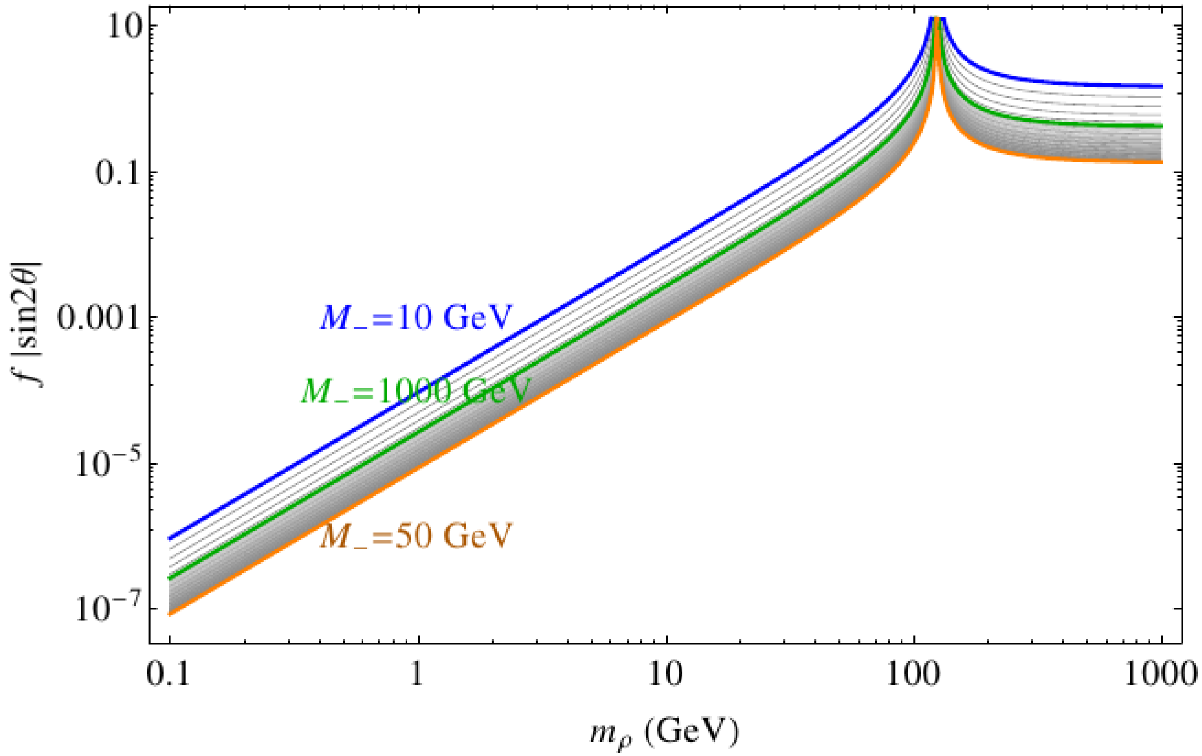
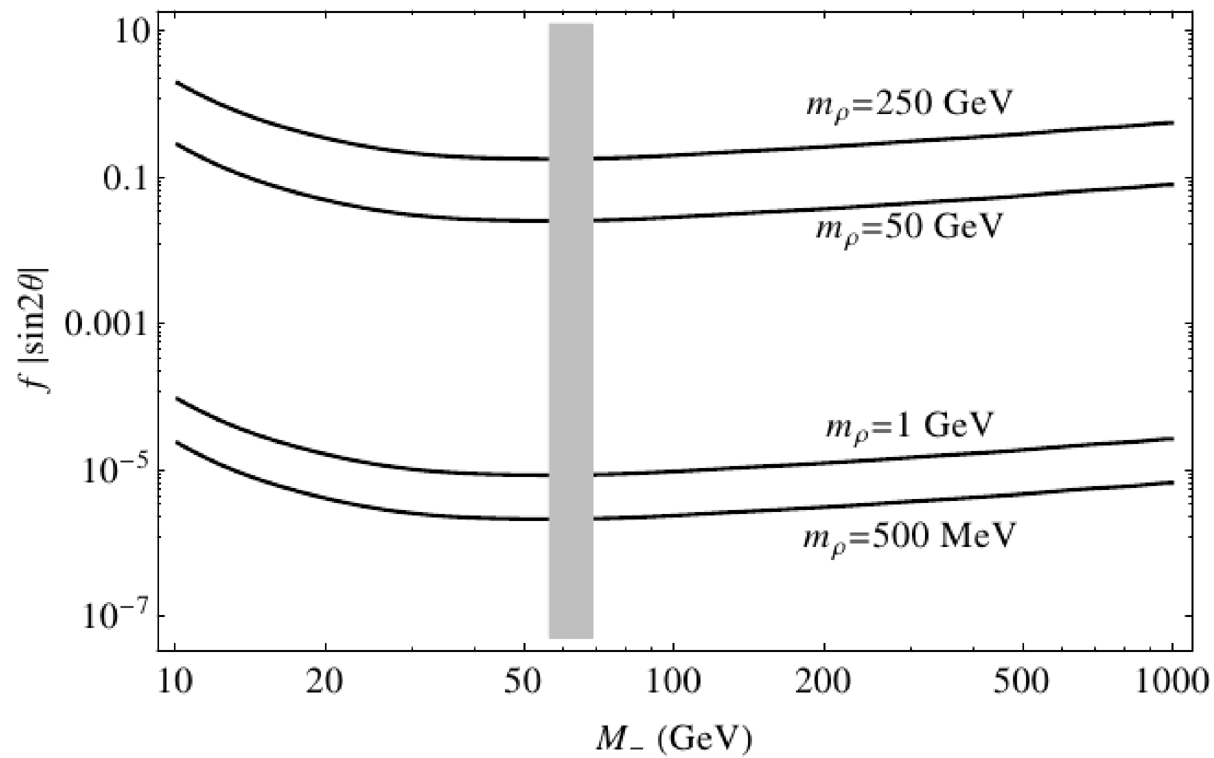
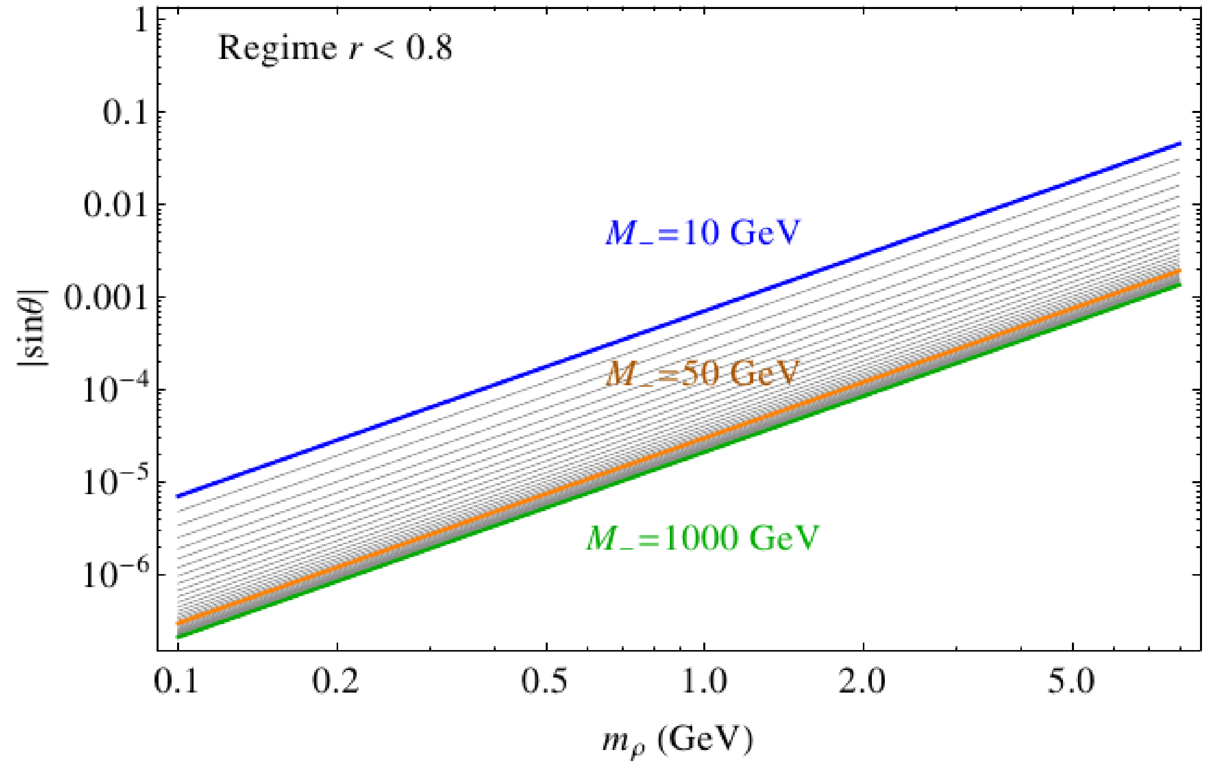
XENON100 limits

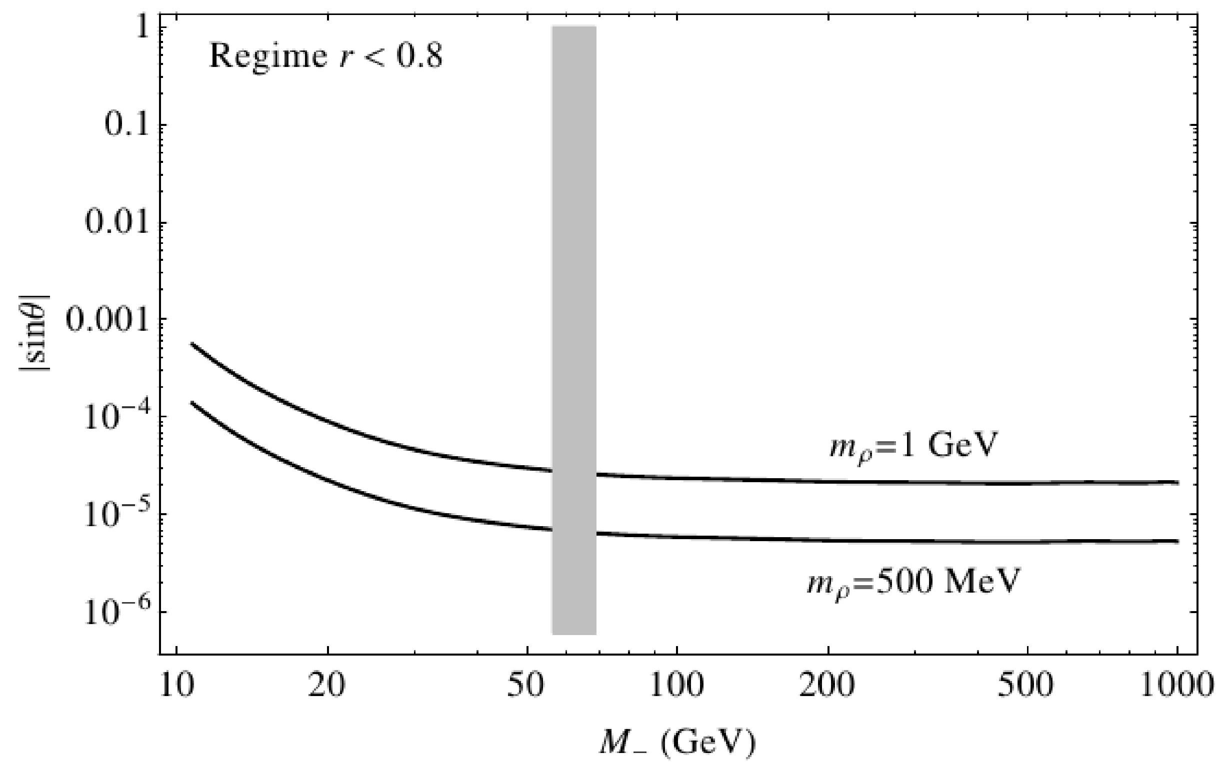




XENON100 limits



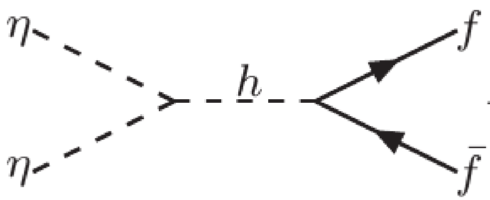
Using the co-annihilation limit!



Goldstone Bosons as Dark Radiation

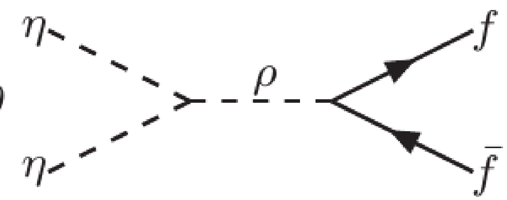
Analysis of the decoupling of the Goldstone Bosons

$\frac{i m_h^2}{2 v_\phi} \sin\theta$



$-\frac{i m_f}{v_H} \cos\theta$

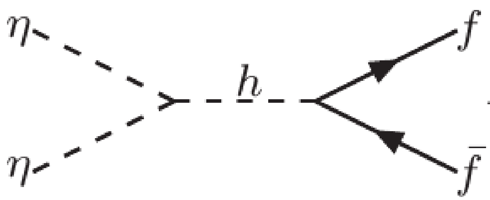
$-\frac{i m_\rho^2}{2 v_\phi} \cos\theta$



$-\frac{i m_f}{v_H} \sin\theta$

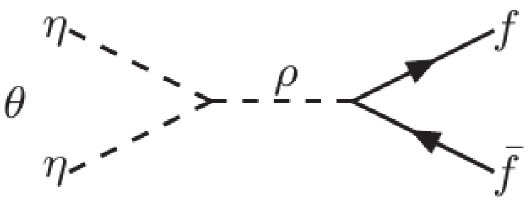
Analysis of the decoupling of the Goldstone Bosons

$\frac{im_h^2}{2v_\phi}\sin\theta$



$-\frac{im_f}{v_H}\cos\theta$

$-\frac{im_\rho^2}{2v_\phi}\cos\theta$



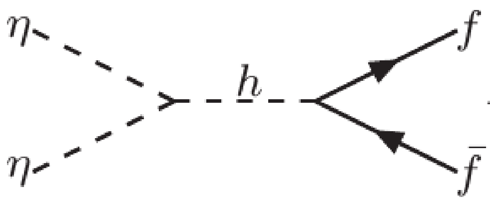
$-\frac{im_f}{v_H}\sin\theta$

The decoupling takes place when

$$\left.\frac{n_\eta^{eq}\ \sum_f\langle\sigma v\rangle_{\eta\eta\to f\bar{f}}}{H}\right|_{T=T_\eta^d} = 1$$

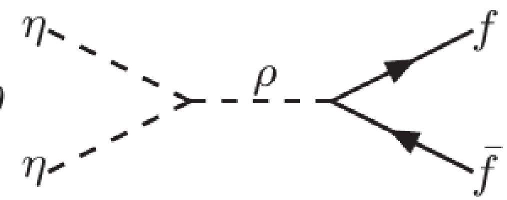
Analysis of the decoupling of the Goldstone Bosons

$\frac{im_h^2}{2v_\phi}\sin\theta$



$-\frac{im_f}{v_H}\cos\theta$

$-\frac{im_\rho^2}{2v_\phi}\cos\theta$

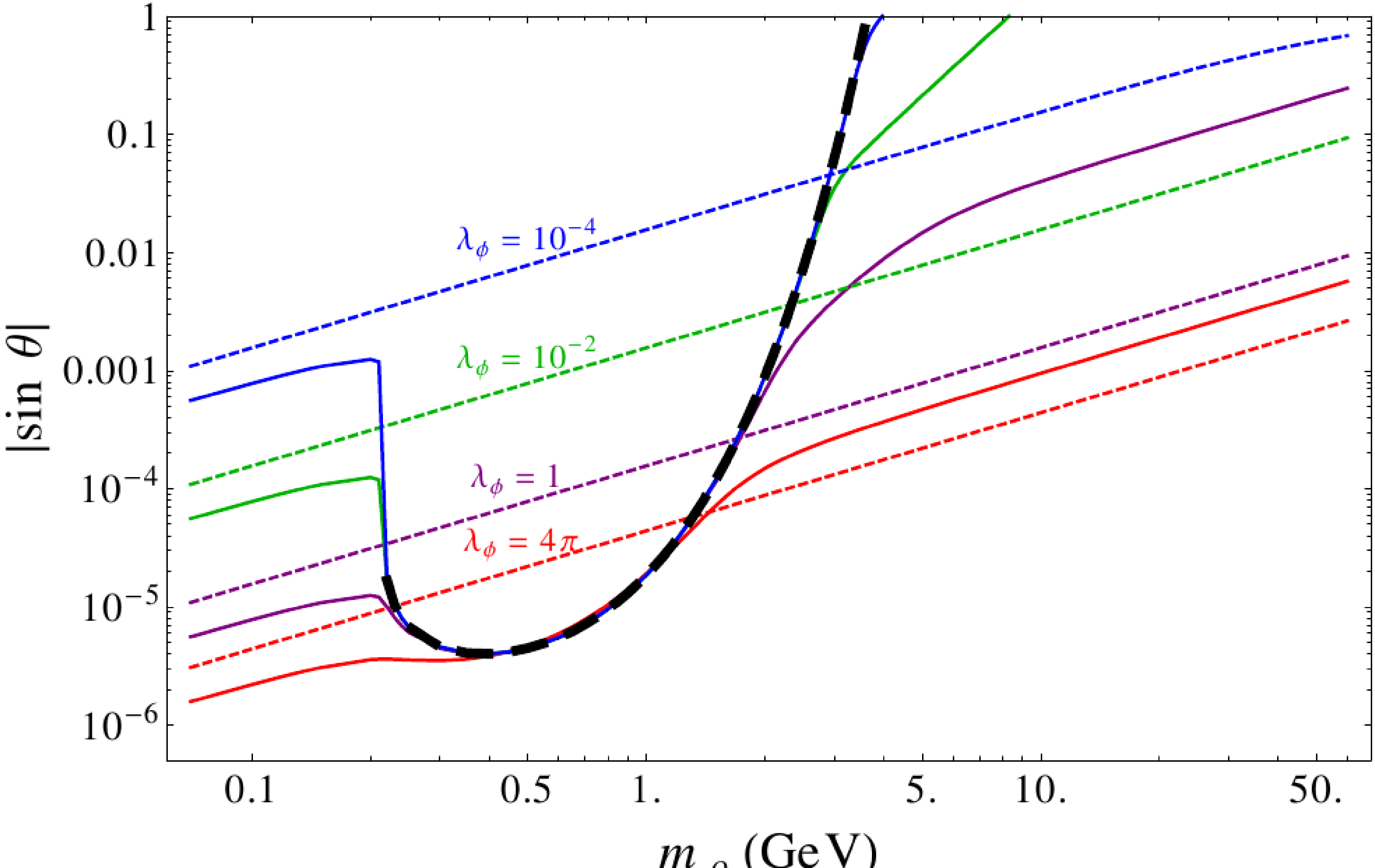


$-\frac{im_f}{v_H}\sin\theta$

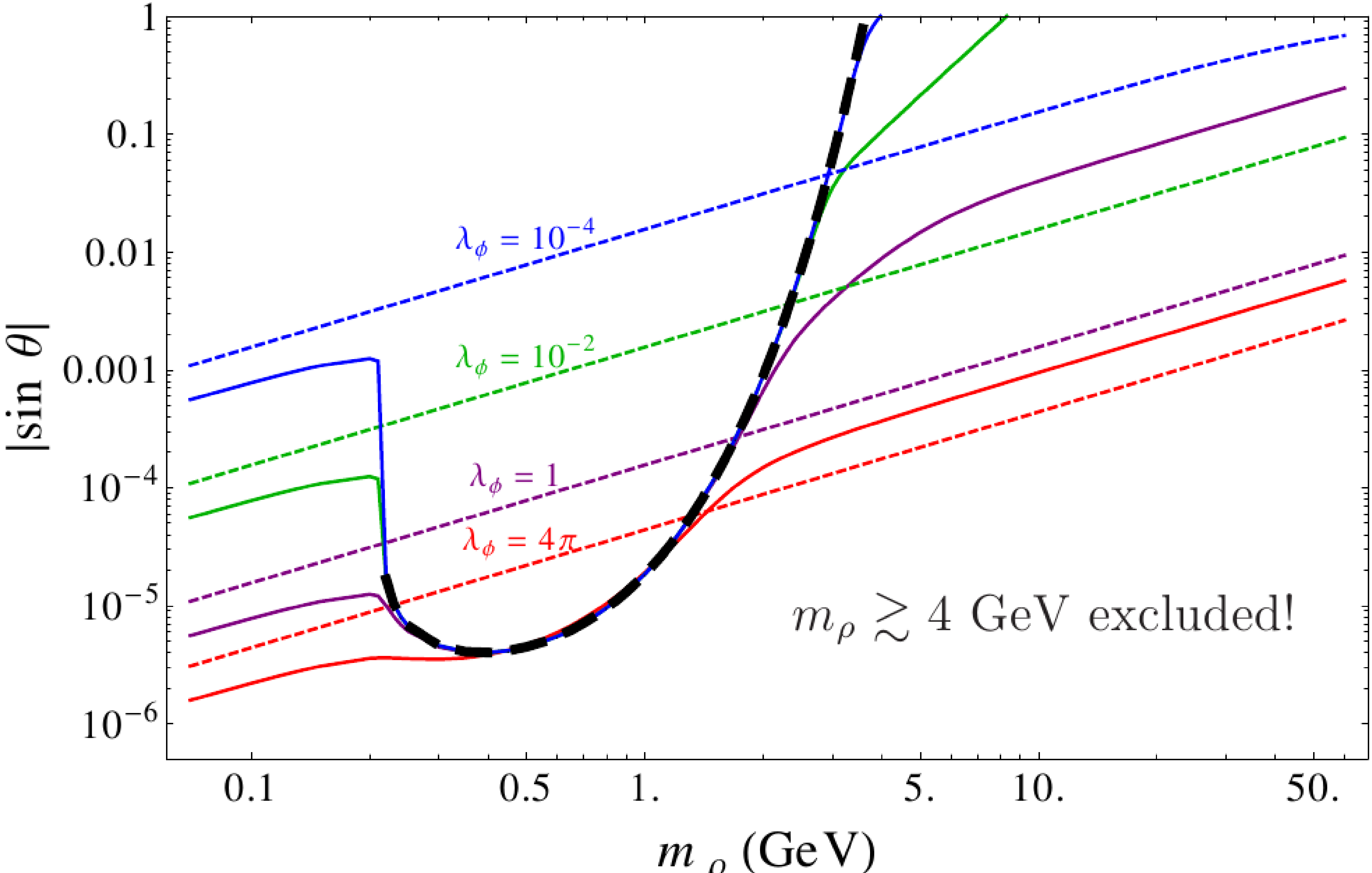
The decoupling takes place when

$$\left.\frac{n_\eta^{eq}\ \sum_f \langle\sigma v\rangle_{\eta\eta\to f\bar{f}}}{H}\right|_{T=T_\eta^d} = 1$$

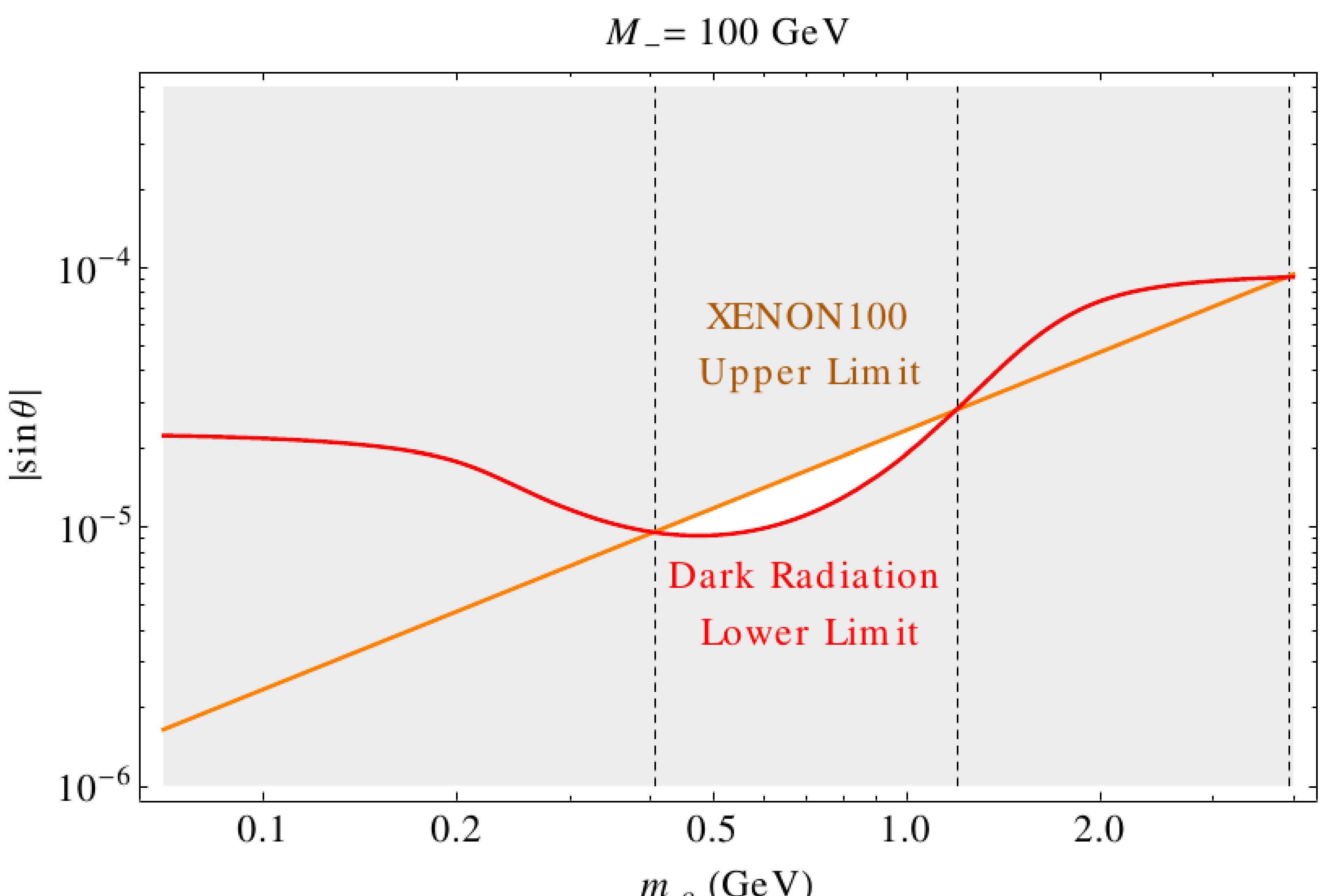
Our goal is to calculate the values of $|\sin\theta|$ for which $T_\eta^d \approx m_\mu$



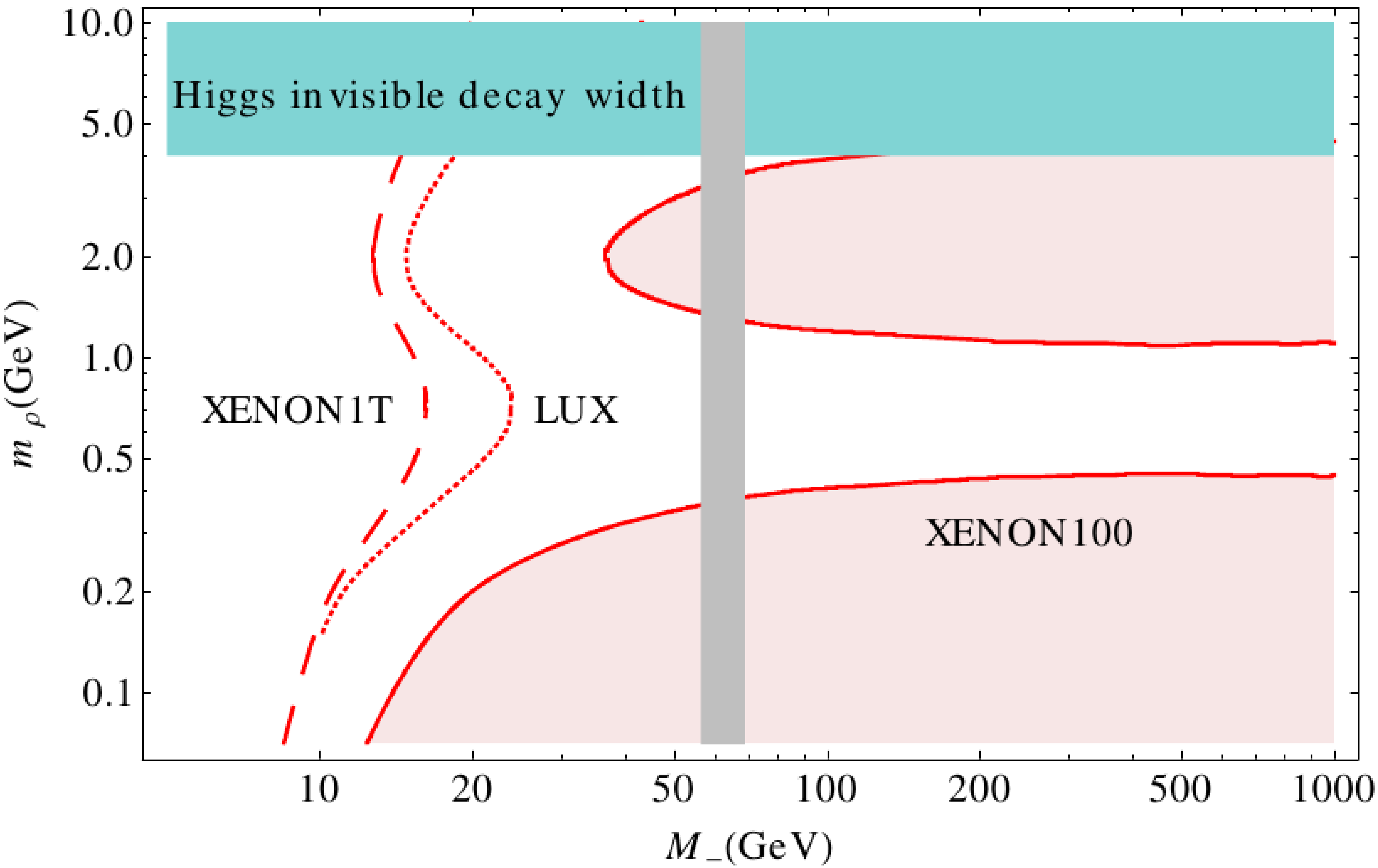
1
0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
$|\sin\theta|$
0.1
0.5
1.
5.
10.
50.
m_ρ (GeV)
$\lambda_\phi = 10^{-4}$
$\lambda_\phi = 10^{-2}$
$\lambda_\phi = 1$
$\lambda_\phi = 4\pi$



$|\sin\,\theta|$
1
0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
$\lambda_\phi = 10^{-4}$
$\lambda_\phi = 10^{-2}$
$\lambda_\phi = 1$
$\lambda_\phi = 4\pi$
$m_\rho \gtrsim 4$ GeV excluded!
0.1
0.5
1.
5.
10.
50.
m_ρ (GeV)



M_{-}= 100 GeV
$|\sin\theta|$
10^{-4}
10^{-5}
10^{-6}
0.1
0.2
0.5
1.0
2.0
m_{ρ} (GeV)
XENON100
Upper Limit
Dark Radiation
Lower Limit



Higgs invisible decay width
XENON1T
LUX
XENON100
10.0
5.0
2.0
1.0
0.5
0.2
0.1
10
20
50
100
200
500
1000
m_ρ(GeV)
M_-(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 ~ 25 GeV.