A portal extension of SM with an unbroken dark U(1)

(based on "arXiv: 1303.4280" with Seungwon Baek and Pyungwon Ko)

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Why is the DM stable?

- Stability is guaranteed by a symmetry.
  e.g: Z_2, R-parity, Topology

- A global symmetry is broken by gravitational effects, allowing interactions like

$$-\mathcal{L}_{\rm int} = \begin{cases} \lambda \frac{\phi}{M_{\rm P}} F_{\mu\nu} F \mu\nu & \text{for boson} \\ \lambda \frac{1}{M_{\rm P}} \bar{\psi} \gamma^\mu D_\mu \ell_{Li} H^\dagger & \text{for fermion} \end{cases}$$

Observation requires [M. Ackermann et al. (LAT Collaboration), PRD 86, 022002 (2012)]

$$\tau_{\rm DM} \gtrsim 10^{26-30}{\rm sec} \Rightarrow \begin{cases} m_\phi \lesssim \mathcal{O}(10){\rm keV} \\ m_\psi \lesssim \mathcal{O}(1){\rm GeV} \end{cases}$$

- Weak scale DM requires a local symmetry.

Discrete or continuous?

- Discrete symmetry

  - The symmetry may be originated from a spontaneously broken continuous symmetry (e.g: local Z_2-symmetry).
  - Dark matter should have nothing to do with the symmetry breaking.
  - It should be the lightest odd particle.

- Continuous symmetry

  - It may be from a large gauge group in a UV theory (e.g: SO(32) or $E_8 \times E_8' \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times G_{DS}$?).
  - Dark matter should be the lightest charged particle.

Unbroken local U(1)x

- DM self-interaction

It may solve some puzzles of the collisionless CDM.

- core/cusp problem:
  simulated cusp of DM density profile contrary to the cored one found in the obvserved LSB galaxies and dSphs

- "too big to fail" problem:
  simulated high internal density concentration of the subhalos in the MW-sized halos contrary to the observed brightest MW satellites

- Massless dark photon

Contributes to the radiation energy in addition to the one from SM.

$$N_{\rm eff}^{\rm obs} = 3.30 \pm 0.27 \text{ at } 68\% \text{ (cf., } N_{\rm eff}^{\rm SM} = 3.04)$$

$\Rightarrow$ Fractional contribution of dark photon is still allowed.

SM-DM communication

- Kinetic mixing

There could be the kinetic mixing between $U(1)_X$ and $U(1)_Y$ of the SM.

⇒ DM becomes mini-charged under the electromagnetic interaction.

$$\mathcal{L} \supset -\frac{1}{2} \sin\epsilon X_{\mu\nu} B^{\mu\nu} \Rightarrow q_{\rm em} = -q_X \frac{g_X}{e} \cos W \tan\epsilon$$

⇒ This opens a direct detection channel.

- Gauge-singlets

$$H^\dagger H, \quad \ell_i H^\dagger, \quad N$$

Higgs portal ($H^\dagger H$)

may cause efficient annihilations

provides a direct detection channel

Right-handed neutrino portal (N)

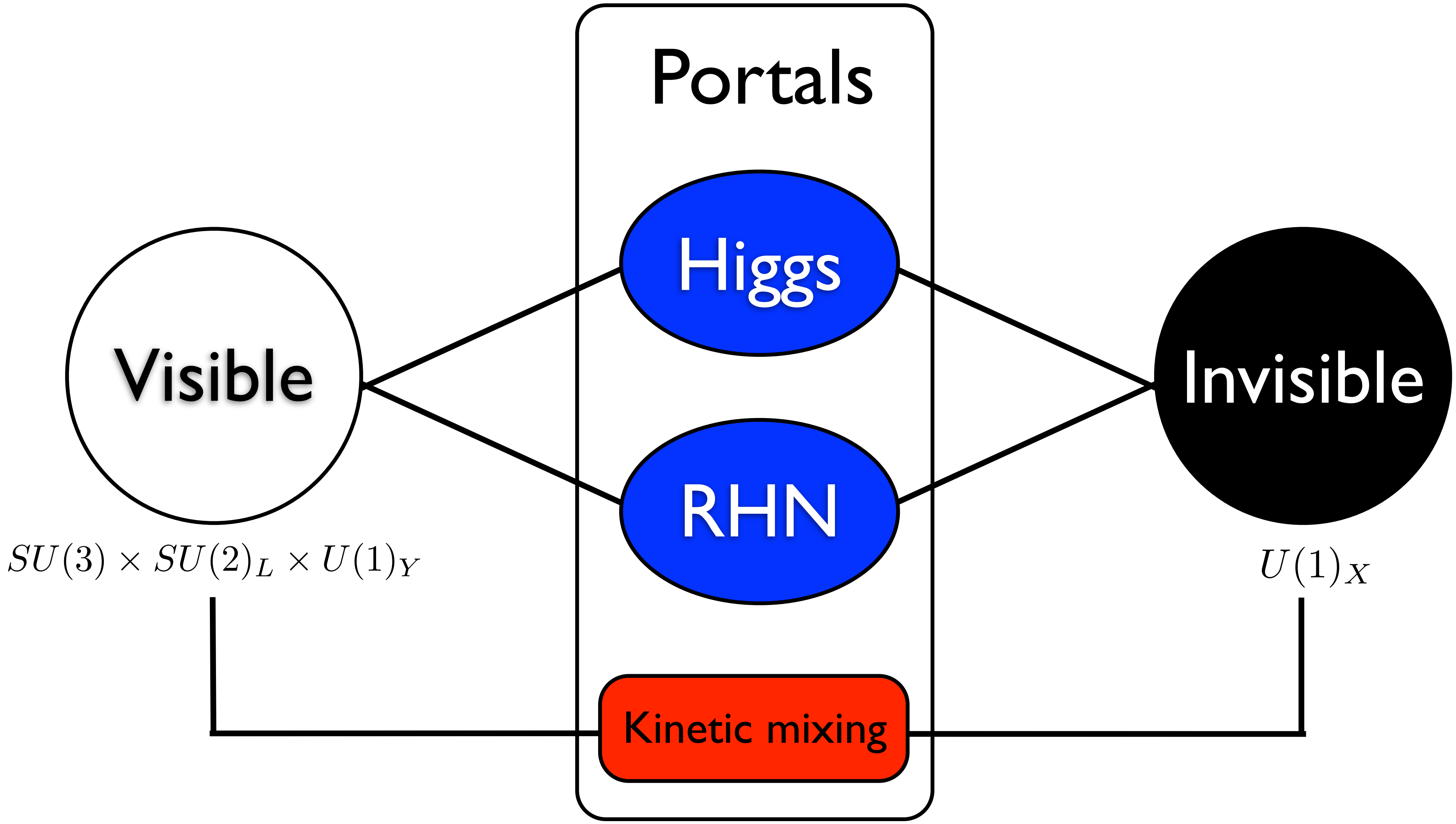
Leptogenesis and asymmetric DM?

Anything else?

$\ell_i H^\dagger$: does not allow renormalizable interactions for a gauge-charged DM

A minimal(?) model

- The structure of the model



- # Symmetry

$$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$$

(SM is neutral under U(1)_X)

[See also A. Falkowski, J.T. Ruderman & T.Volansky, JHEP1105.016]

- # Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm Kinetic} + \mathcal{L}_{\rm H-portal} + \mathcal{L}_{\rm RHN-portal} + \mathcal{L}_{\rm DS}$$

$$\mathcal{L}_{\rm Kinetic} = i\bar{\psi}\gamma^\mu D_\mu \psi + |D_\mu X|^2 - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}B^{\mu\nu}$$

$$-\mathcal{L}_{\rm H-portal} = \frac{1}{2}\lambda_{HX}|X|^2 H^\dagger H$$

$$-\mathcal{L}_{\rm RHN-portal} = \frac{1}{2}M_i \bar{N}_{Ri}^C N_{Ri} + [Y_\nu^{ij}\bar{N}_{Ri}\ell_{Lj}H^\dagger + \lambda^i \bar{N}_{Ri}\psi X^\dagger + {\rm H.c.}]$$

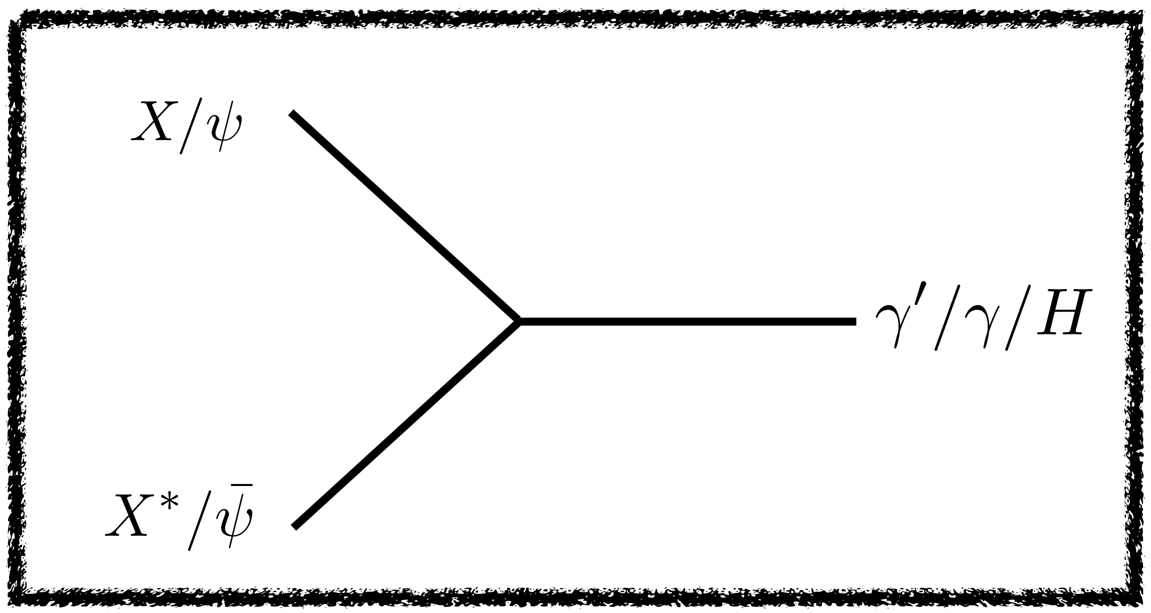
$$-\mathcal{L}_{\rm DS} = m_\psi \bar{\psi}\psi + m_X^2|X|^2 + \frac{1}{4}\lambda_X |X|^4$$

$$(q_L, q_X): \;\; N = (1,0), \;\; \psi = (1,1), \;\; X = (0,1)$$

• Interaction vertices of dark particles (X, ψ)

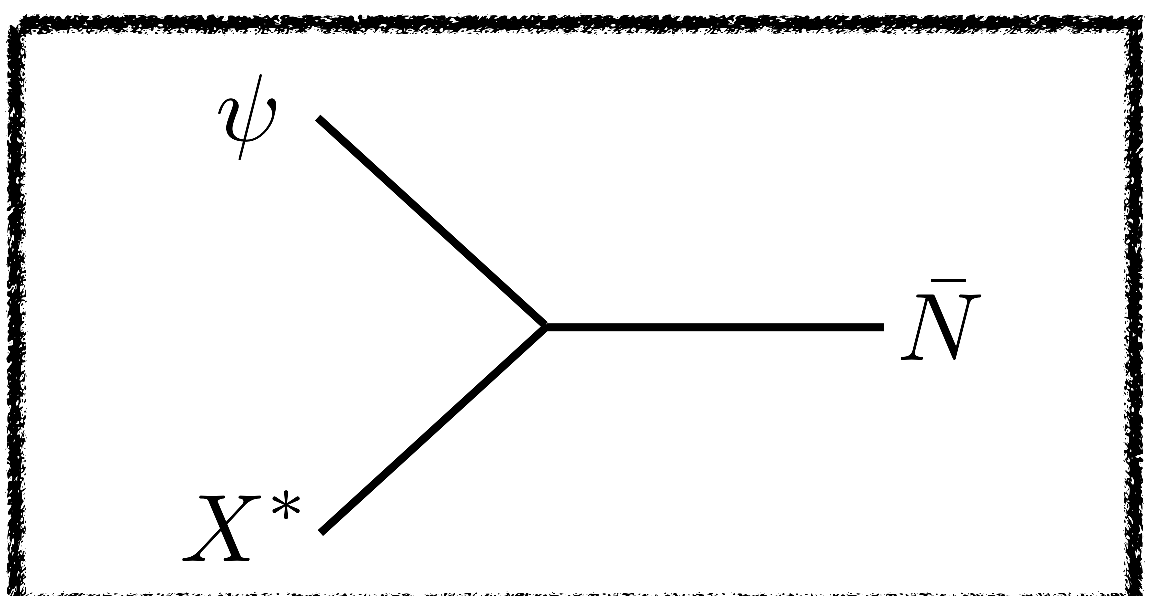
Kinetic term diagonalization: $\begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix}$

$$\Longrightarrow \mathcal{L}_{\rm DS-SM} = g_X q_X t_\epsilon \bar{\psi}\gamma^\mu\psi\left(c_W A_\mu - s_W Z_\mu\right) + \left|\left[\partial_\mu - i g_X q_X t_\epsilon\left(c_W A_\mu - s_W Z_\mu\right)\right] X\right|^2$$



Annihilation
or
scattering

(⇒ Relic density, direct/indirect searches)



Decay of ψ or X

(⇒ Lepto/darkogenesis?)

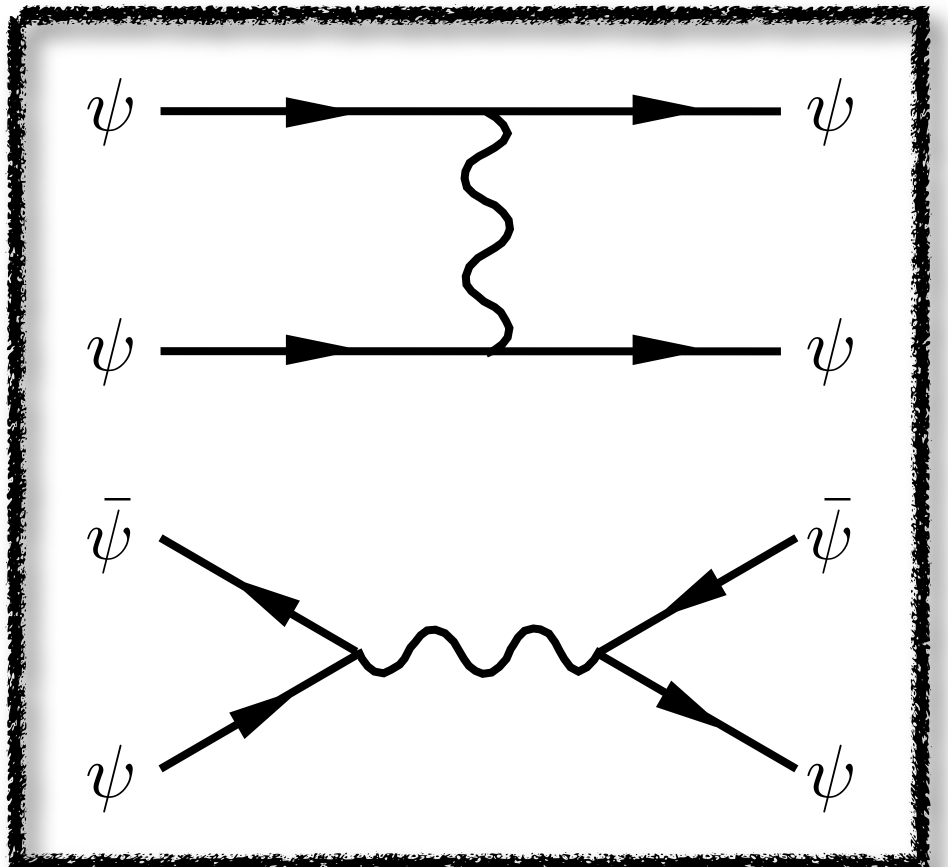
Constraints

Our model can address

* Some small scale puzzles of CDM (Dark matter self-interaction) (α_X, m_X)
* CDM relic density (Unbroken dark $U(1)_X$) (λ, λ_{hx}, m_X,)
* Vacuum stability of Higgs potential (Positive scalar loop correction) (λ_{hx})
* Direct detection (Photon and Higgs exchange)(ε, λ_{hx})
* Dark radiation (Massless photon)(α_X)
* Lepto/darkogenesis (Asymmetric origin of dark matter) (Y_ν, λ, M_1, m_X)
* Inflation (Higgs inflation type) (λ_{hx}, λ_X)

In other words, the model is highly constrained.

- # Constraints on dark gauge coupling



$$\Rightarrow \quad \sigma_T \sim \frac{16\pi\alpha_X^2}{m_{X(\psi)}^2}\frac{1}{v^4}\ln\left[\frac{m_{X(\psi)}^2 v^3}{\sqrt{4\pi\rho_{X(\psi)}\alpha_X^3}}\right]$$

From inner structure and kinematics of dwarf galaxies,

$$\sigma_T^{\max}/m_{\rm dm} \lesssim 35\ {\rm cm}^2/{\rm g}$$

[Vogelsberger, Zavala and Leb, 1201.5892]

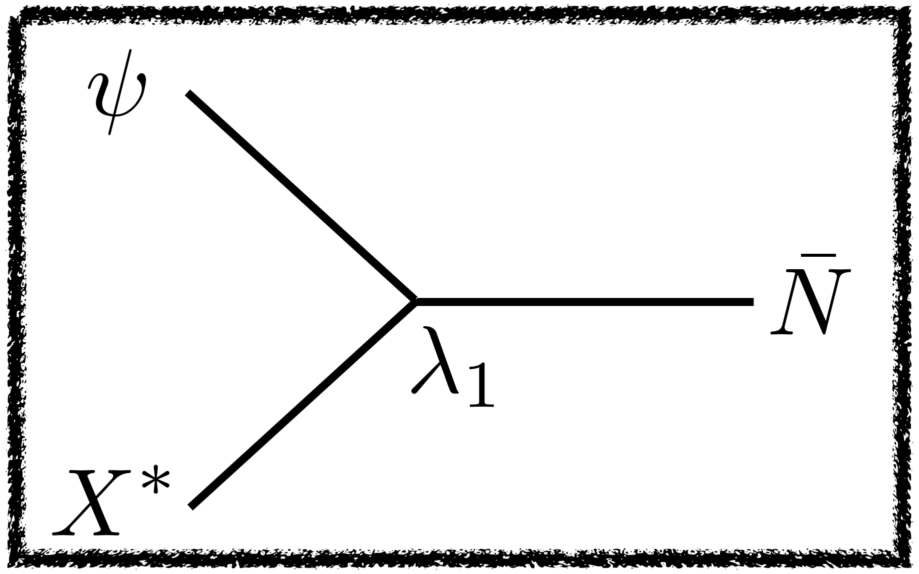
$$\alpha_X \lesssim 5\times 10^{-5}\left(\frac{m_{X(\psi)}}{300{\rm GeV}}\right)^{3/2}$$

If stable, $\Omega_\psi \sim 10^4\left(\frac{300{\rm GeV}}{m_\psi}\right)$. It is too much for CDM relic density at present.
Therefore, Ψ should be able to decay ⇒ $m_\Psi > m_X$

"X" is responsible for the present CDM relic density.
For α_X close to its upper bound, X-X* can explain some puzzles of collisionless CDM:

(i) cored profile of dwarf galaxies.
(ii) low concentration of LSB galaxies and dwarf galaxies. [Vogelsberger, Zavala and Leb, 1201.5892]

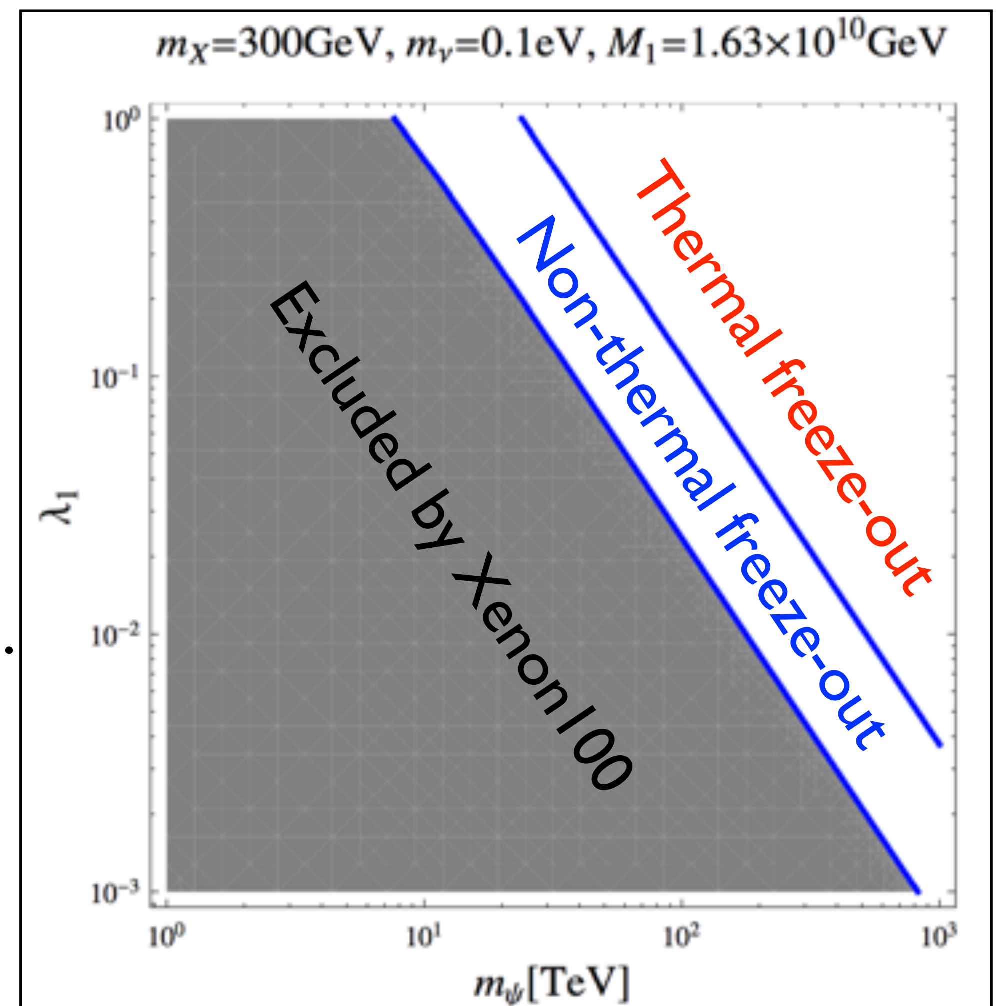
- CDM relic density



The late-time decay of ψ

(Non-) thermal freeze-out of X via Higgs portal

$$\lambda_1^2 \simeq 58.5 \left(\frac{0.1\,\mathrm{eV}}{\tilde{m}_\nu}\right)\left(\frac{M_1}{10^9\,\mathrm{GeV}}\right)\left(\frac{1\,\mathrm{TeV}}{m_\psi}\right)\left(1-\frac{m_X^2}{m_\psi^2}\right)^{-2}\left[1+\frac{1}{48\pi^2}\left(\frac{m_\psi}{v_H}\right)^2\right]^{-1}\left(\frac{m_X}{300\,\mathrm{GeV}}\right)^2\left(\frac{\langle\sigma v\rangle_{\mathrm{ann}}^{\mathrm{th}}}{\langle\sigma v\rangle_{\mathrm{ann,d}}^{X}}\right)^2$$



* Relic density constrains λ_1.

* X forms a symmetric DM
(although it might be asymmetric before ψ decays).

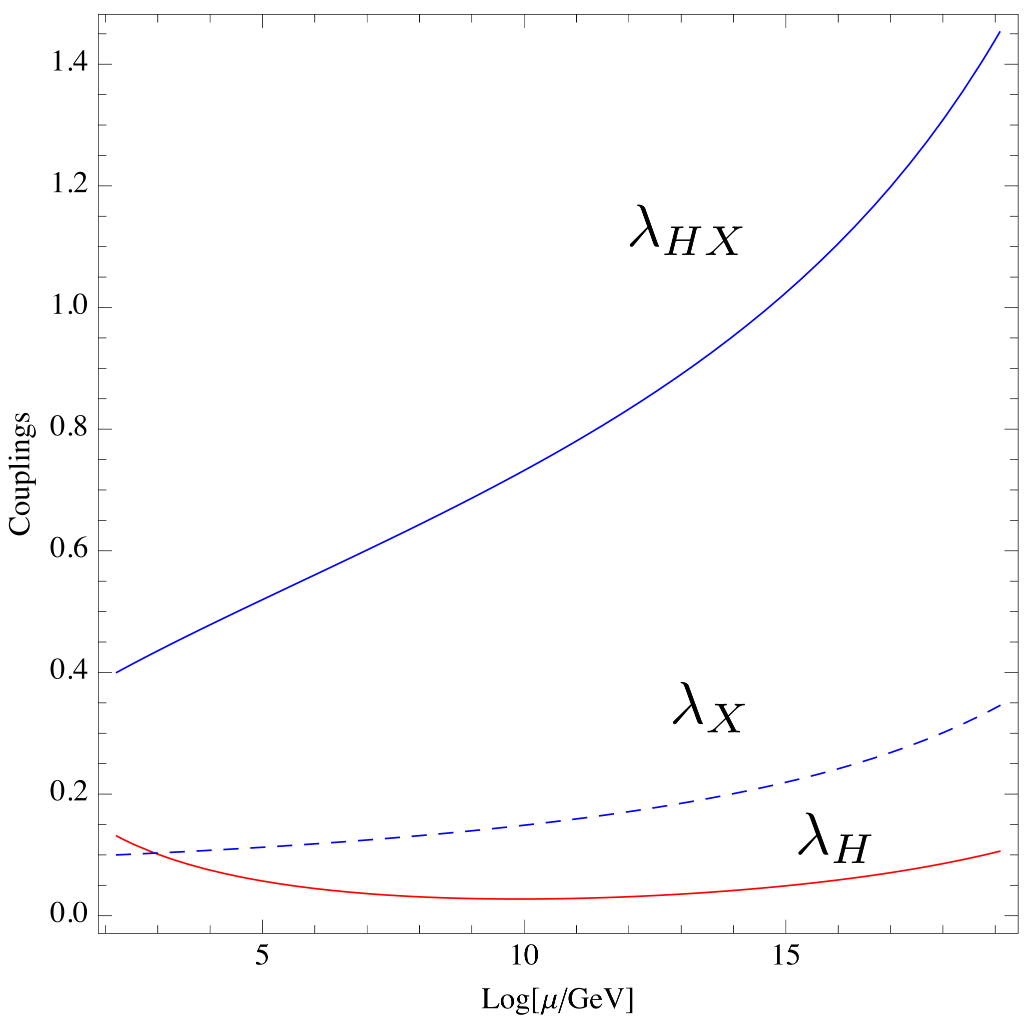
- # Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

$$\beta^{(1)}_{\lambda_H} = \frac{1}{16\pi^2}\left[24\lambda_H^2 + 12\lambda_H\lambda_t^2 - 6\lambda_t^4 - 3\lambda_H\left(3g_2^2+g_1^2\right) + \frac{3}{8}\left(2g_2^4 + \left(g_2^2+g_1^2\right)^2\right) + \frac{1}{2}\lambda_{HS}^2\right]$$

$$\beta^{(1)}_{\lambda_{HS}} = \frac{\lambda_{HS}}{16\pi^2}\left[2\left(6\lambda_H + 3\lambda_S + 2\lambda_{HS}\right) - \left(\frac{3}{2}\lambda_H\left(3g_2^2+g_1^2\right) - 6\lambda_t^2 - \cancel{4\lambda^2}\right)\right],$$

$$\beta^{(1)}_{\lambda_S} = \frac{1}{16\pi^2}\left[2\lambda_{HS}^2 + 18\lambda_S^2 + 8\cancel{\lambda_S}\lambda^2 - \cancel{8\lambda^4}\right],$$

with $\lambda_{HS} \to \lambda_{HX}/2$ and $\lambda_S \to \lambda_X$



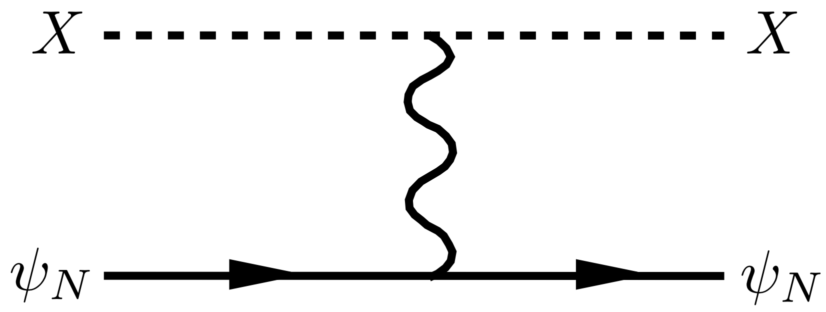
Perturbativitiy

$$\lambda_X \lesssim 0.23$$

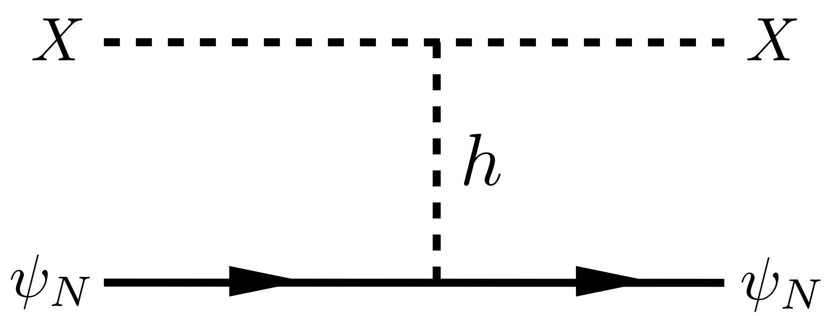
$$0.2 \lesssim \lambda_{HX} \lesssim 0.6$$

vacuum stability　　Perturbativitiy

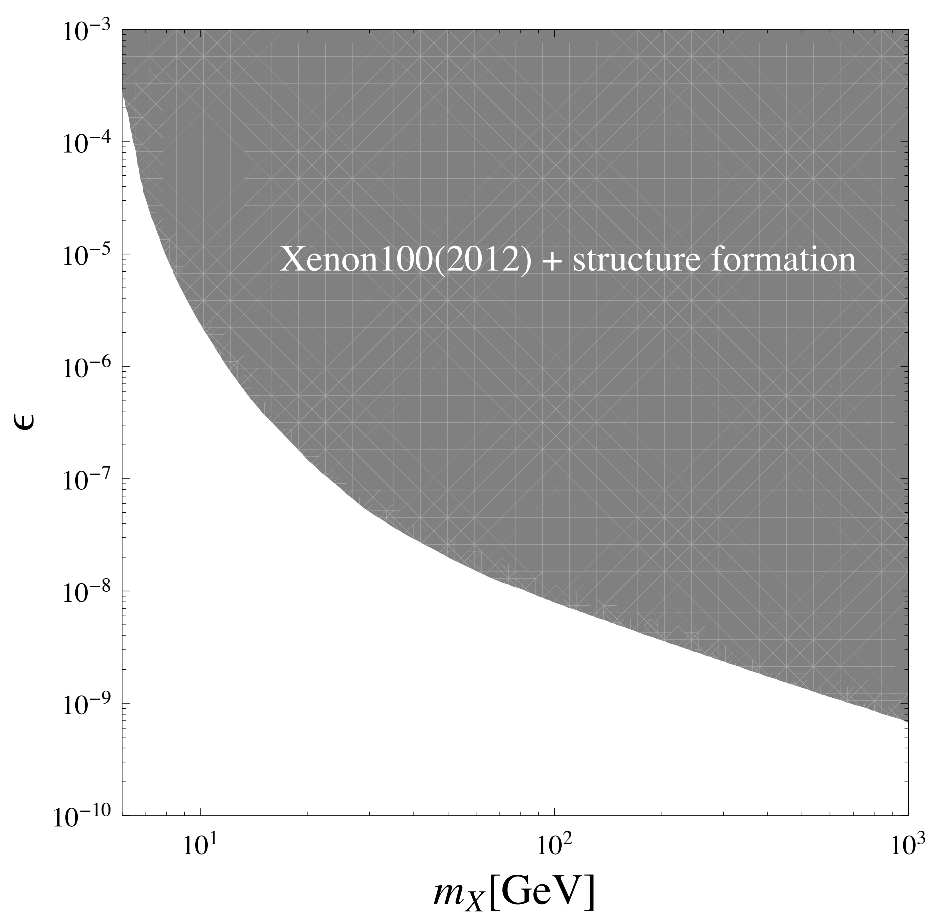
• DM direct search (ϵ, λ_{hx}, m_X)

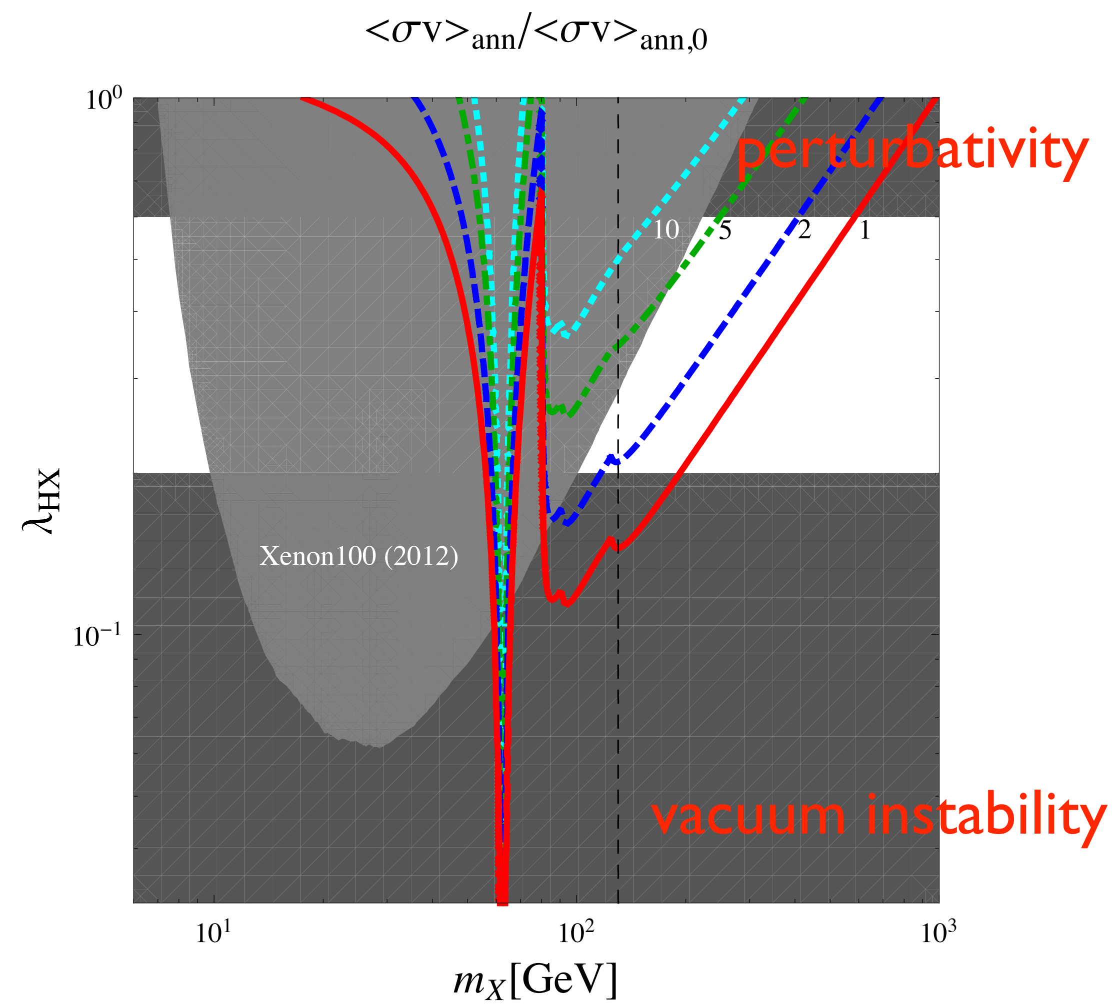


$$\frac{d\sigma_A}{dE_r} = \frac{2\pi\epsilon_e^2\alpha_{em}^2 Z^2}{m_A E_r^2 v^2}\mathcal{F}_A^2(qr_A)$$



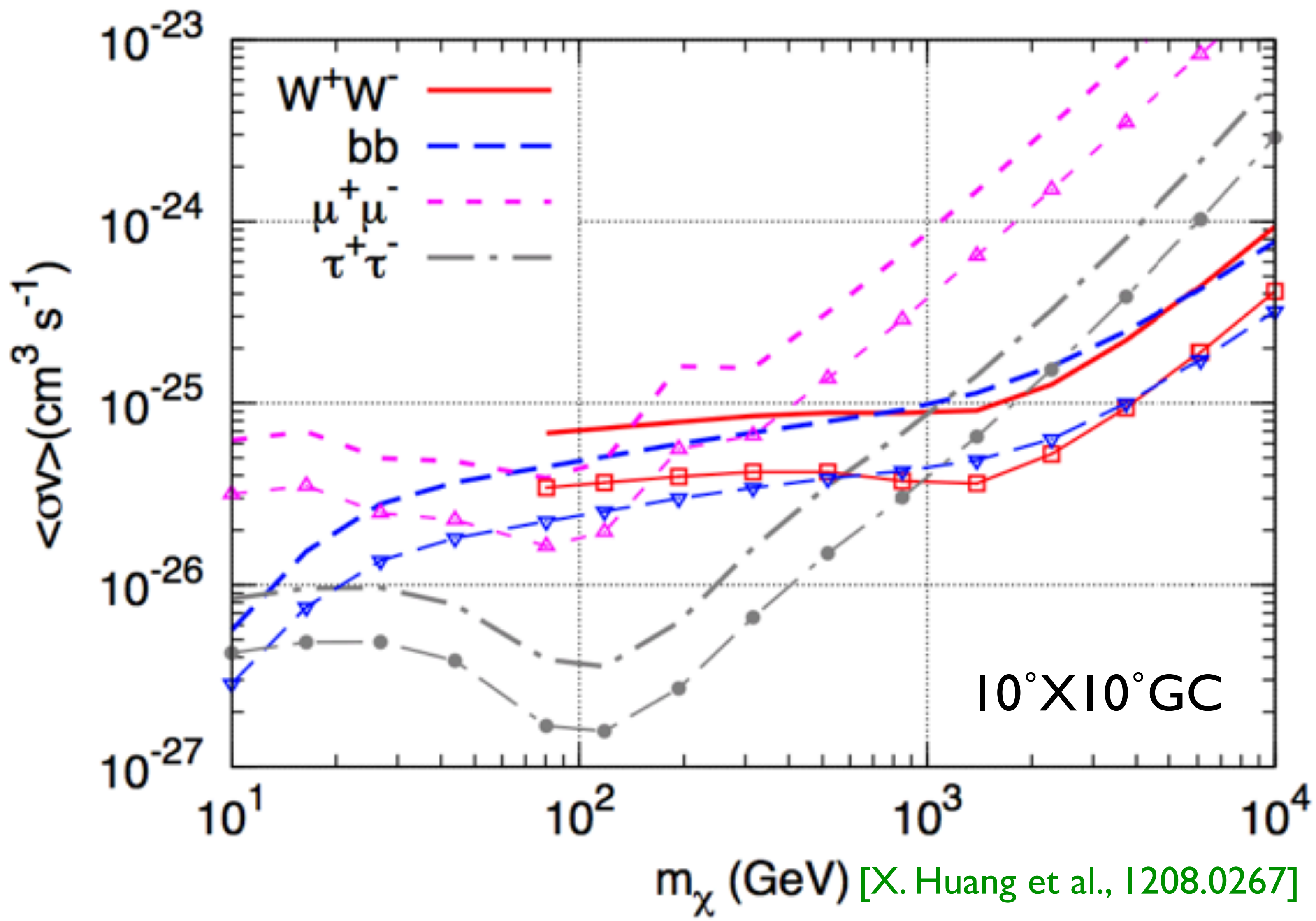
$$\sigma^{SI}_{\mathcal{N},h} = \frac{\lambda_{HX}^2}{64\pi}\frac{m_r^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$





• Indirect search (λ_{hx}, m_X)

- DM annihilation via Higgs produces a continum spectrum of γ-rays
- Fermi-LAT γ-ray search data poses a constraint



[X. Huang et al., 1208.0267]

In our model,

$$\langle \sigma v \rangle^{\rm obs}_{XX^\dagger \to W^+W^-} \lesssim 2 \times 7.4 \times 10^{-26} {\rm cm}^3/{\rm sec}$$

$$\Rightarrow \langle \sigma v \rangle^X_{\rm ann} \lesssim \frac{2 \times 7.4 \times 10^{-26} {\rm cm}^3/{\rm sec}}{{\rm Br}(XX^\dagger \to W^+W^-)}$$

$$1 \leq \frac{\langle \sigma v \rangle^X_{\rm ann}}{\langle \sigma v \rangle^{\rm th}_{\rm ann}} \lesssim 5$$

* Monochromatic γ-ray spectrum?

$$\langle \sigma v \rangle^{\gamma\gamma}_{\rm ann} \sim 10^{-4} \langle \sigma v \rangle^X_{\rm ann} \lesssim 10^{-29} {\rm cm}^3/{\rm sec}$$

Too weak to be seen!

- # Collider phenomenology (λ_{hx}, m_X)

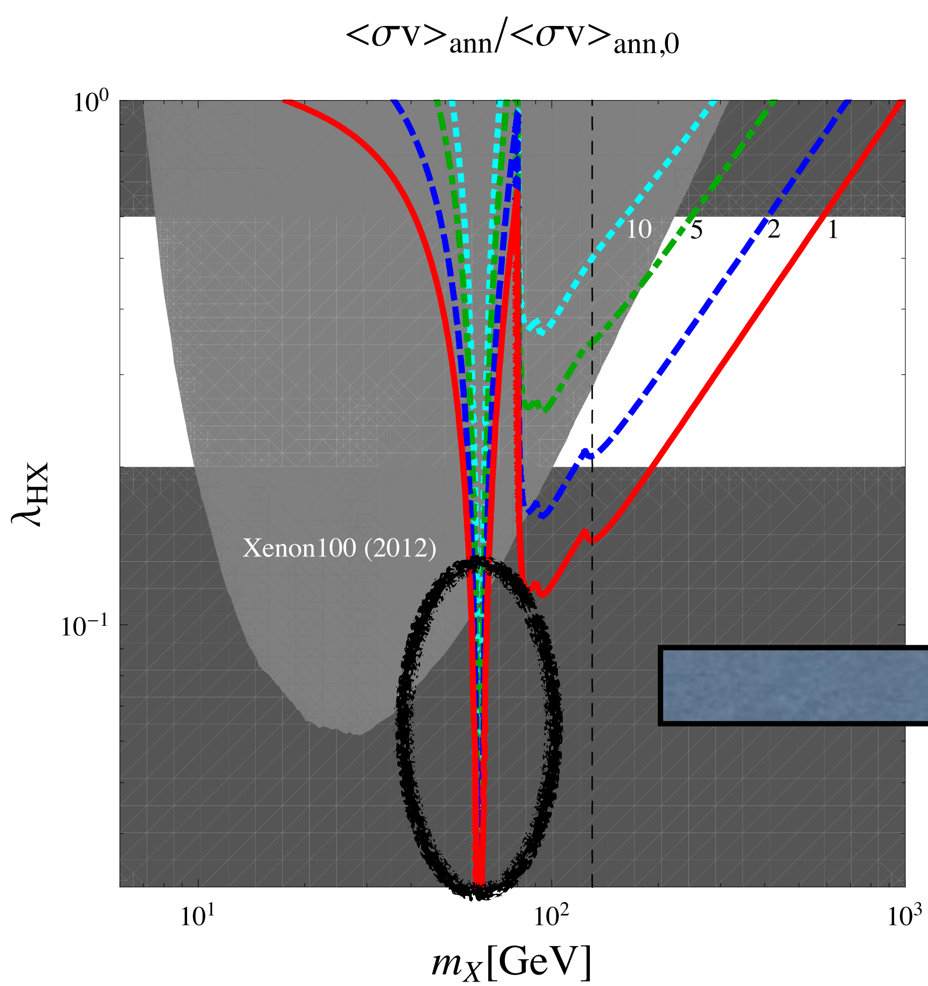
Invisible decay rate of Higgs is

$$\Gamma_{h\to XX^\dagger} = \frac{\lambda_{HX}^2}{128\pi}\frac{v^2}{m_h}\left(1-\frac{4m_X^2}{m_h^2}\right)^{1/2}$$

SM signal strength at collider is

$$\mu = 1 - \frac{\Gamma_{h\to XX^\dagger}}{\Gamma_h^{\rm tot}}$$

(cf., $\mu_{\rm ATLAS} = 1.43 \pm 0.21$ for $m_h = 125.5\,{\rm GeV}$
$\mu_{\rm CMS} = 0.8 \pm 0.14$ for $m_h = 125.7\,{\rm GeV}$)



We may need $\mathrm{Br}(h\to XX^\dagger) \ll \mathcal{O}(10)\%$, i.e.,

$\lambda_{HX} \ll 0.1$

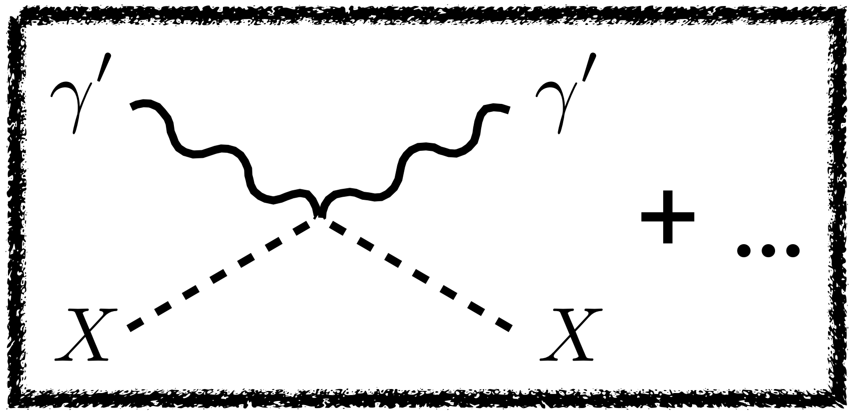
or

$m_h - 2m_X \lesssim 0.5\mathrm{GeV}$

or kinematically forbidden

- # Dark radiation

Decoupling of dark photon



$$\left\{ \begin{array}{l} \Gamma(T_{\gamma'}) = \dfrac{32\pi^3 \alpha_X^2 T_{\gamma'}^4}{45 m_X^3} \Rightarrow T_{\mathrm{dec},\gamma'-X} \gtrsim 16\mathrm{MeV} \\ \\ T_{\mathrm{dec},X-\mathrm{SM}} \sim 1\mathrm{GeV} \Rightarrow T_{\mathrm{dec},\gamma'-\mathrm{SM}} \sim 1\mathrm{GeV} \end{array} \right.$$

# of extra relativistic degree of freedom

$$\Delta N_{\mathrm{eff}} = \frac{\rho_{\gamma'}}{\rho_\nu} = \frac{g_{\gamma'}}{g_\nu} \left(\frac{T_{\gamma,0}}{T_{\nu,0}}\right)^4 \left(\frac{T_{\gamma',\mathrm{dec}}}{T_{\gamma,\mathrm{dec}}}\right)^4 \left(\frac{g_{*S}(T_{\gamma,0})}{g_{*S}(T_{\gamma,\mathrm{dec}})}\right)^{4/3}$$

$$\frac{T_{\nu,0}}{T_{\gamma,0}} = \left\{ \begin{array}{lll} \left(\frac{4}{11}\right)^{1/3} & \mathrm{for} & T_{\mathrm{dec}} \gtrsim 1\mathrm{MeV} \\ 1 & \mathrm{for} & T_{\mathrm{dec}} \lesssim 1\mathrm{MeV} \end{array} \right.$$

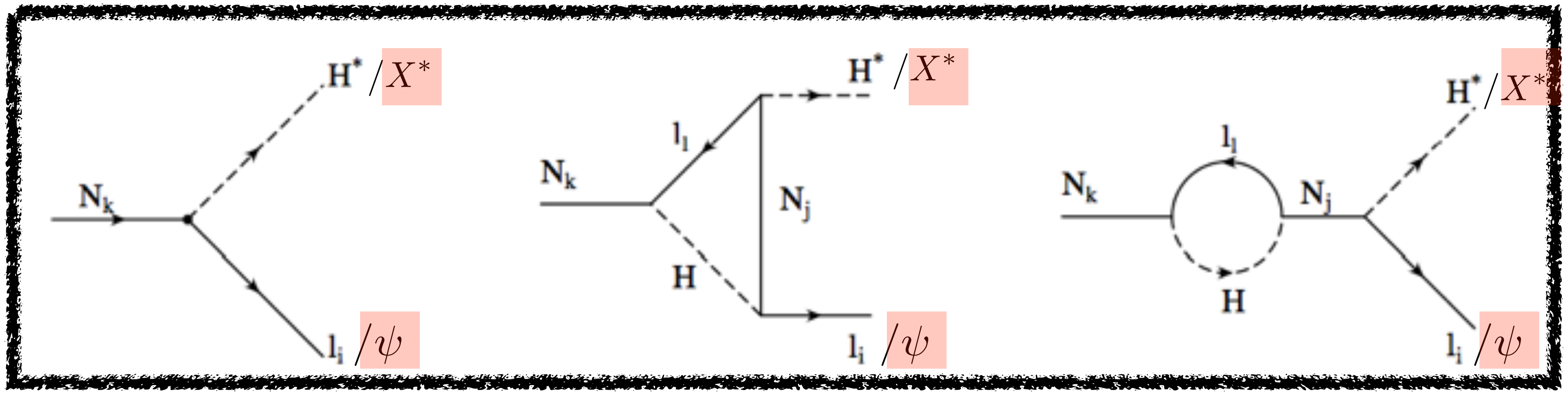
$\Delta N_{\mathrm{eff}} = 0.474^{+0.48}_{-0.45}$ at 95% CL (Planck+WP+highL+H_0+BAO)

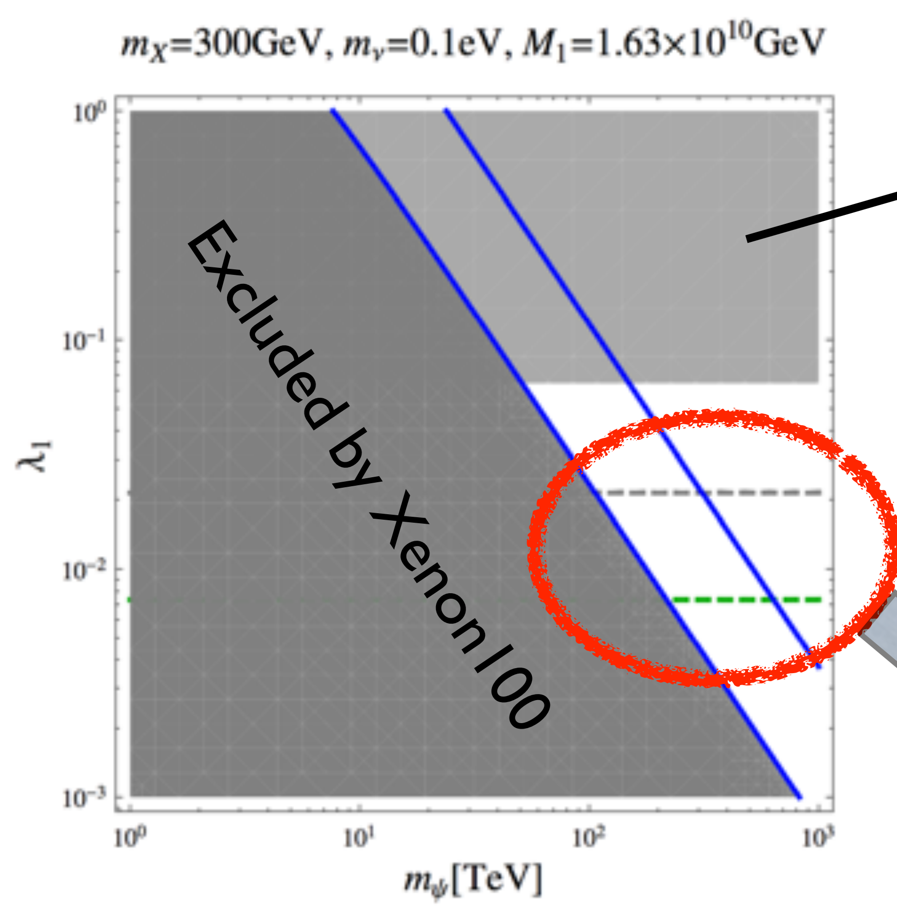
[Planck Collaboration, arXiv:1303.5076]

$$T_{\mathrm{dec},\gamma'-\mathrm{SM}} \sim 1\mathrm{GeV} \;\Rightarrow\; \Delta N_{\mathrm{eff}} = \frac{2}{2\frac{7}{8}} \left(\frac{11}{4}\right)^{4/3} \left(\frac{g_{*S}(T_{\gamma,0})}{g_{*S}(T_{\mathrm{dec},X_\mu})}\right)^{4/3} \sim 0.06$$

Lepto/darkogenesis

- Lepto/darkogenesis from the decay of RHN





Light gray: narrow width approx. is invalid

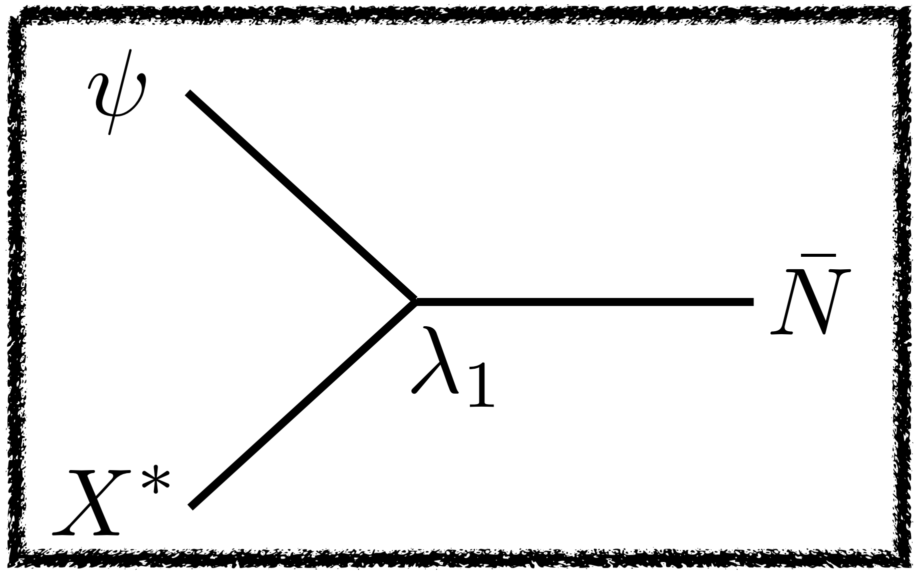
White between blue lines:

$$1 \leq \langle \sigma v \rangle_{\rm ann}^{\rm tot} / \langle \sigma v \rangle_{\rm ann}^{\rm th} \lesssim 5$$

Green lines: $Y_{\nu 1} = \lambda_1$

Correct BAU and CDM relic can be obtained.

- Leptogenesis from the late-time decay of ψ &ψ-bar



Late-time decay → No wash-out!

$$\Delta(Y_{\Delta L}) = 2\epsilon_L Y_\psi(T_{\rm fz}^\psi)$$

$$Y_\psi(T_{\rm fz}^\psi) = \frac{3.79\left(\sqrt{8\pi}\right)^{-1} g_*^{1/2}/g_{*S}x_{\rm fz}^\psi}{m_\psi M_{\rm P}\langle\sigma v\rangle_{\rm ann}^\psi} \simeq 0.05\frac{x_{\rm fz}^\psi}{\alpha_X^2}\frac{m_\psi}{M_{\rm P}}$$

$$\frac{\Delta(Y_{\Delta L})}{Y_{\Delta L}} \simeq 2\times 10^7 \frac{x_{\rm fz}^\psi}{\alpha_X^2}\frac{m_\psi}{M_{\rm P}}\frac{M_1 m_\nu^{\rm max}}{v_H^2} \times \begin{cases} 1 & \text{for } {\rm Br}_L \gg {\rm Br}_\psi \\ \sqrt{\lambda_2^2 M_1/\lambda_1^2 M_2} & \text{for } {\rm Br}_L \ll {\rm Br}_\psi \end{cases}$$

$$\left({\rm e.g}: \epsilon_L \sim 10^{-7}, \alpha_X \sim 10^{-5}, m_\psi \sim 10^3{\rm TeV} \to \frac{\Delta(Y_{\Delta L})}{Y_{\Delta L}} \sim 0.3\ \right)$$

* Late-time decays of symmetric ψ and ψ-bar can generate a sizable amount of lepton number asymmetry.

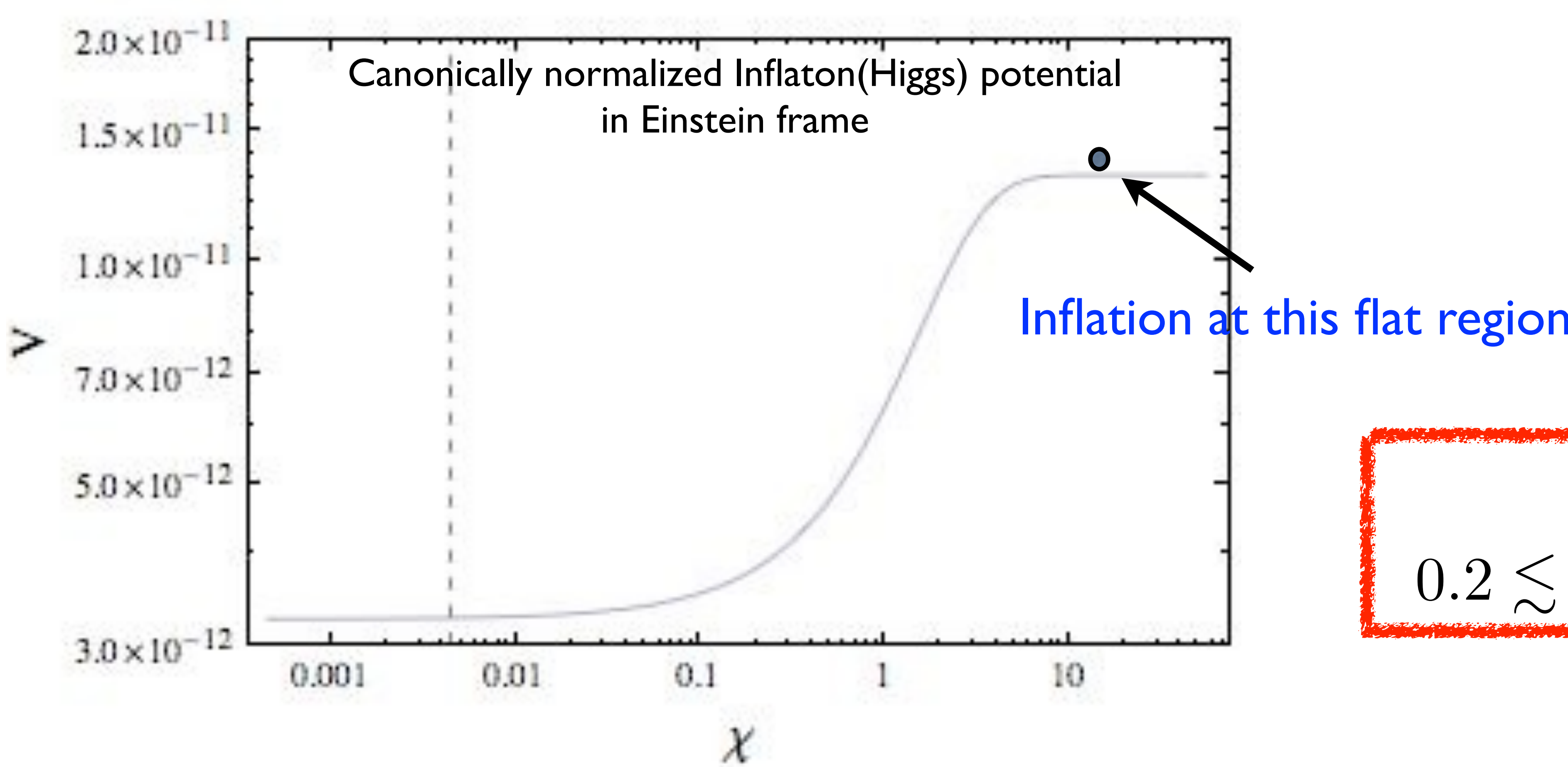
Inflation

- Higgs inflation in Higgs-singlet system

[Lebedev,1203.0156]

$$\frac{\mathcal{L}_{\rm scalar}}{\sqrt{-g}} = -\frac{1}{2}M_{\rm P}^2 R - \frac{1}{2}\left(\xi_h h^2 + \xi_x x^2\right) R + \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu x)^2 - V(h,x)$$

where $\xi_h,\ \xi_x \gg 1$



$$\lambda_X \lesssim 0.23$$

$$0.2 \lesssim \lambda_{HX} \lesssim 0.6$$

- Summary of main constraints

Small scale structure + CDM

$$\alpha_X \lesssim 4 \times 10^{-5} \left(\frac{m_{\psi(X)}}{300\mathrm{GeV}} \right)^{3/2}$$

$$\lambda_1^2 \simeq 58.5 \left(\frac{0.1\,\mathrm{eV}}{\tilde{m}_\nu} \right) \left(\frac{M_1}{10^9\,\mathrm{GeV}} \right) \left(\frac{1\,\mathrm{TeV}}{m_\psi} \right) \left(1 - \frac{m_X^2}{m_\psi^2} \right)^{-2} \left[1 + \frac{1}{48\pi^2} \left(\frac{m_\psi}{v_H} \right)^2 \right]^{-1} \left(\frac{m_X}{300\,\mathrm{GeV}} \right)^2 \left(\frac{\langle \sigma v \rangle_{\mathrm{ann}}^{\mathrm{th}}}{\langle \sigma v \rangle_{\mathrm{ann,d}}^{X}} \right)^2$$

Vacuum stability + perturbativity

$$\lambda_X \lesssim 0.23$$
$$0.2 \lesssim \lambda_{HX} \lesssim 0.6$$

⇒

$$100\mathrm{GeV} \lesssim m_X \lesssim 600\mathrm{GeV}$$

Direct search

$$\epsilon \lesssim 10^{-9} - 10^{-4}, \quad 1 \leq \langle \sigma v \rangle_{\mathrm{ann}}^{\mathrm{tot}} / \langle \sigma v \rangle_{\mathrm{ann}}^{\mathrm{th}} \lesssim 5$$

- Variations of the model

Signal strength

Assume the decay of Higgs to DMs is forbidden.

Dark sector fields	$U(1)_X$	Messenger	DM	Extra DR	μ_i
$\hat{B}'_\mu, X, \psi_X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X	~ 0.06	$1\ (i=1)$
$\hat{B}'_\mu, X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0.06	$1\ (i=1)$
$\hat{B}'_\mu, \psi_X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ_X	~ 0.06	$<1\ (i=1,2)$
$\hat{B}'_\mu, X, \psi_X, \phi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X or ψ_X	~ 0	$<1\ (i=1,2)$
$\hat{B}'_\mu, X, \phi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0	$<1\ (i=1,2)$
$\hat{B}'_\mu, \psi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ_X	~ 0	$<1\ (i=1,2,3)$

○ = a singlet real scalar

because of mixing in Higgs sector

* Unbroken $U(1)_X$ allows a sizable contribution to the extra radiation.
* Broken $U(1)_X$ or the case of fermion dark matter results in "$\mu_i<1$".

Summary

- Stability of weak scale dark matter requires a local symmetry.
- The simplest extension of SM with a local U(1) has a unique set of renormalizable interactions.
- The model can address following issues.

  * Some small scale puzzles of standard CDM scenario
  * Vacuum stability of Higgs potential
  * CDM relic density (thermal or non-thermal)
  * Dark radiation
  * Lepto/darkogenesis
  * Inflation (Higgs inflation type)