An unbroken dark U(1) and phenomenology

["arXiv: 1303.4280"(accepted for JHEP) collaborated 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 $E_8 \times E_8' \to SU(3)_c \times SU(2)_L \times U(1)_Y \times G_{DS}$?).
  - Dark matter should be the lightest (dark) charged particle.

Unbroken local U(1)x

- DM self-interaction

  It may solve some puzzles of the collisionless CDM.

  - core/cusp problem: [S.-H Oh et al., arXiv:1011.0899]

    simulated cusp of DM density profile contrary to the cored one found in the obvserved LSB galaxies and dSphs

  - "too big to fail" problem: [M. Boylan-Kolchin et al., arXiv:1111.2048]

    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.

$\Rightarrow$ DM becomes mini-charged under the electromagnetic interaction.

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

$\Rightarrow$ This opens a direct detection channel.

- Gauge-singlets

$$\boxed{H^\dagger H}, \ \ell_i H^\dagger, \ \boxed{N}$$

Higgs portal

may lead efficient annihilations

provides a direct detection channel

Right-handed neutrino portal

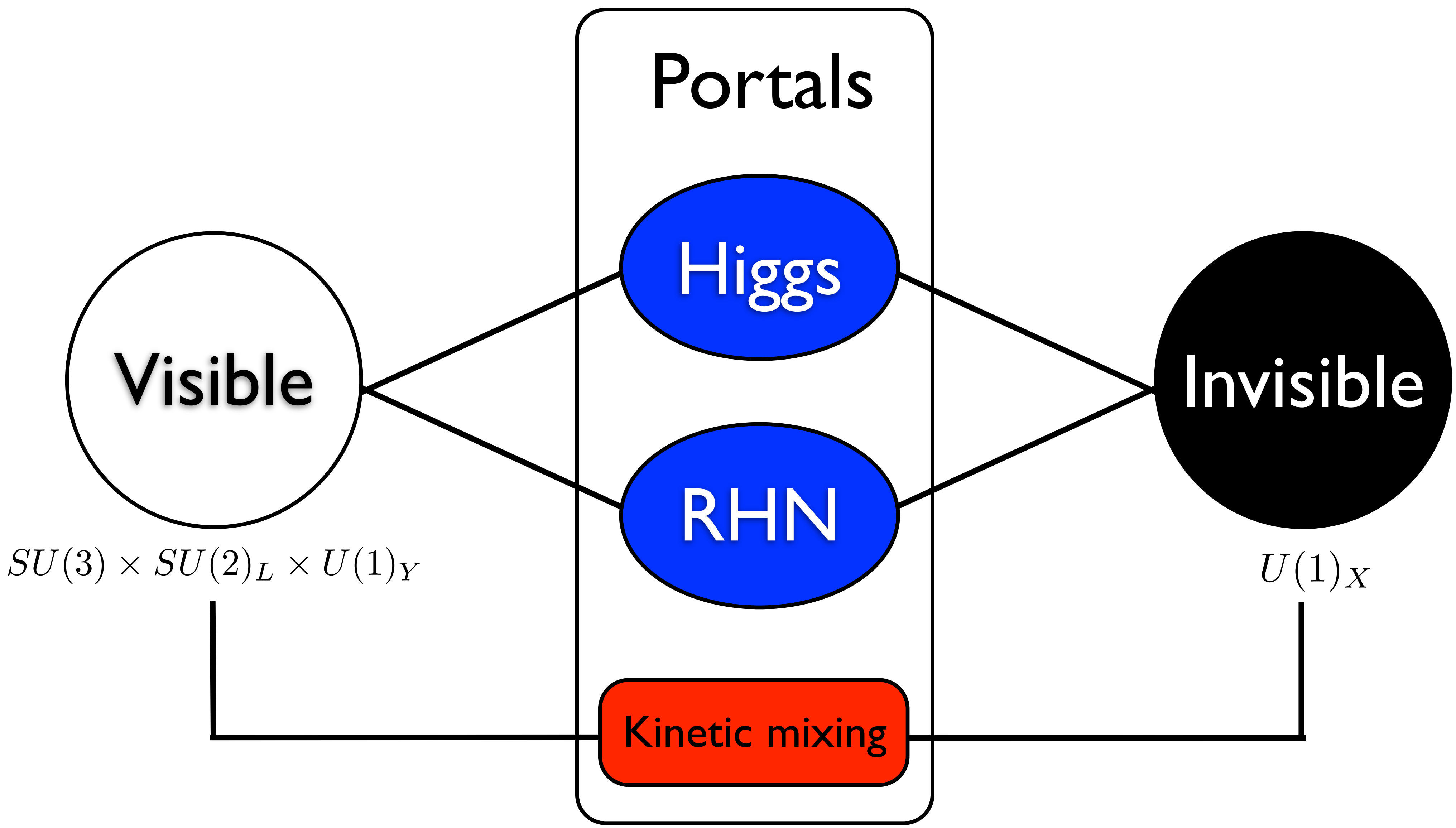
Leptogenesis and asymmetric DM?

Anything else?

does not allow renormalizable interactions for a gauge-charged DM

A minimal(?) model

- The structure of the model



- **Symmetry**

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

(SM is neutral under U(1)_X)

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

- **Lagrangian**

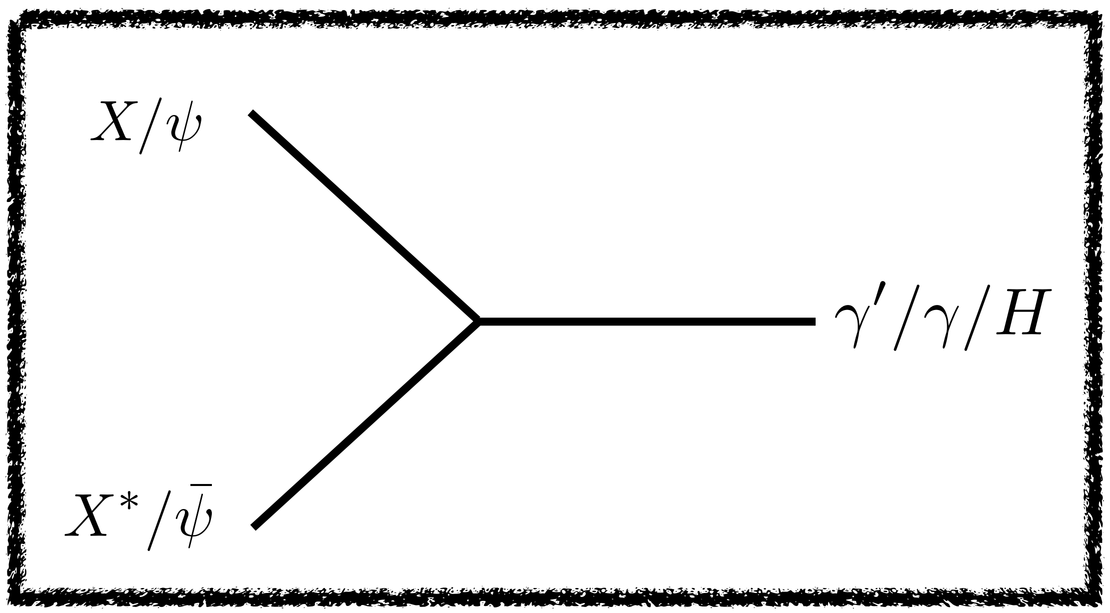
$$\boxed{\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\rm Kinetic} + \mathcal{L}_{\rm H-portal} + \mathcal{L}_{\rm RHN-portal} + \mathcal{L}_{\rm DS} \\
\mathcal{L}_{\rm Kinetic} &= i\bar{\psi}\gamma^\mu D_\mu \psi + |D_\mu X|^2 - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} \boxed{- \frac{1}{2}\sin\epsilon X_{\mu\nu}B^{\mu\nu}} \\
-\mathcal{L}_{\rm H-portal} &= \boxed{\frac{1}{2}\lambda_{HX}|X|^2 H^\dagger H} \\
-\mathcal{L}_{\rm RHN-portal} &= \frac{1}{2}M_i \bar{N_{Ri}^C} N_{Ri} + [Y_\nu^{ij}\bar{N_{Ri}}\ell_{Lj}H^\dagger + \boxed{\lambda^i \bar{N_{Ri}}\psi X^\dagger} + {\rm H.c.}] \\
-\mathcal{L}_{\rm DS} &= m_\psi \bar{\psi}\psi + m_X^2 |X|^2 + \frac{1}{4}\lambda_X |X|^4
\end{aligned}}$$

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

• Interaction vertices of dark particles (X, ψ)

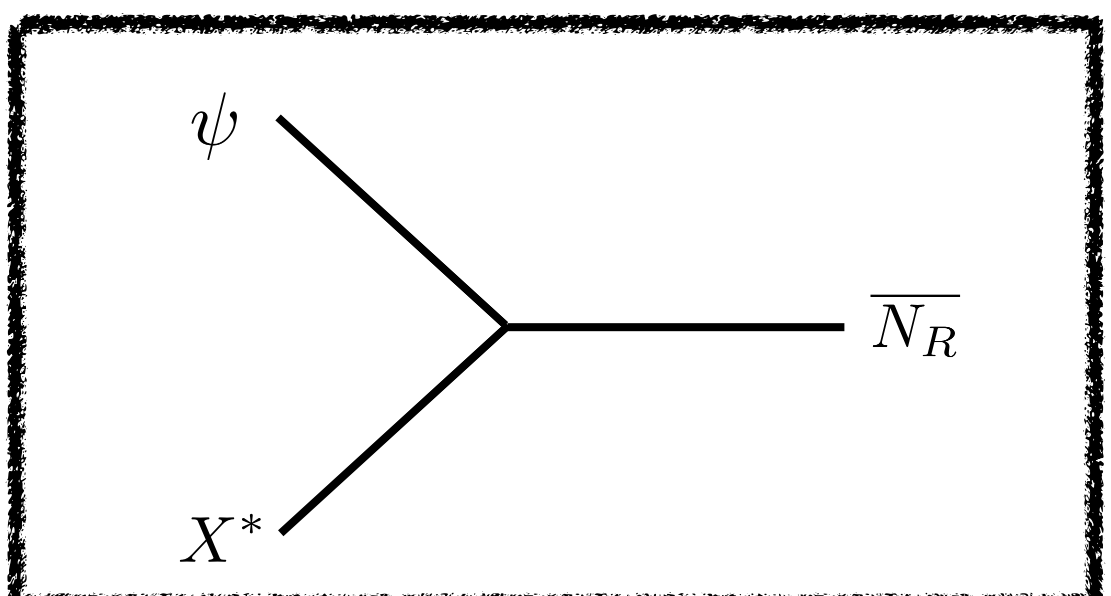
Kinetic term diagonalization: $\begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix}$

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



Annihilation
or
scattering

(⇒ Relic density, direct/indirect searches)



Decay of N_R and ψ or X

(⇒ Lepto/darkogenesis?)

Phenomenolgy (≈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})

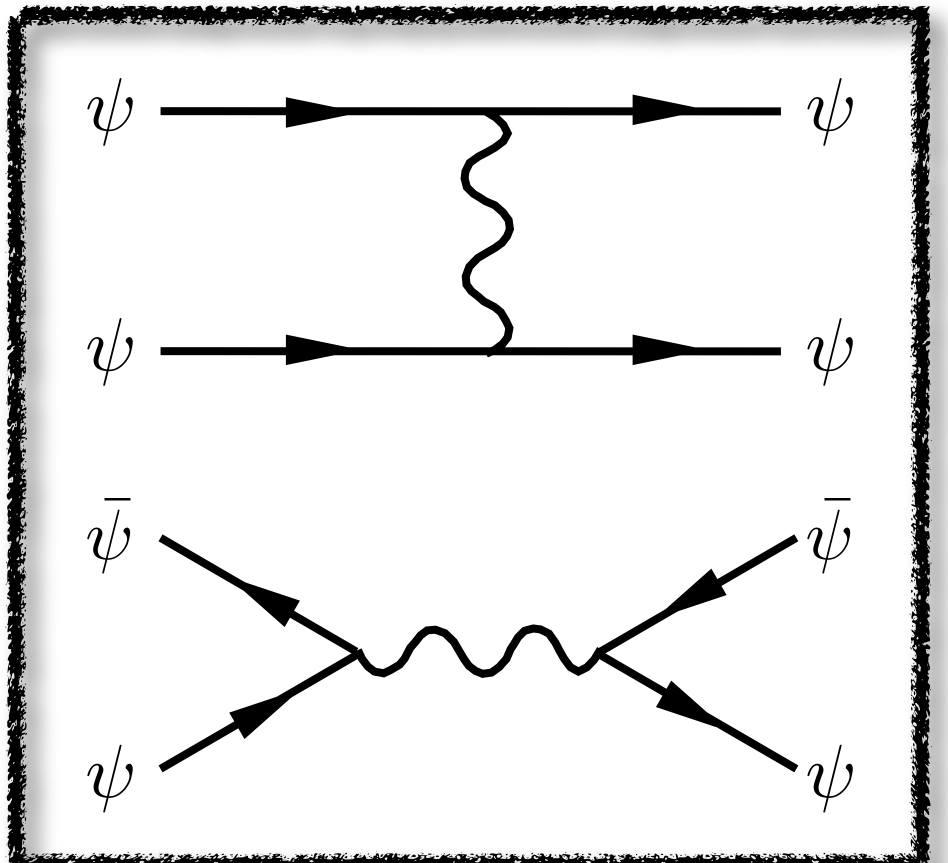
* Dark radiation (Massless photon)(α_X)

* 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



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

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]

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

☛ If stable, $\Omega_\psi \sim 10^4\,(300{\rm GeV}/m_\psi) \gg \Omega_{\rm CDM}^{\rm obs} \simeq 0.26$.

"$m_\Psi > m_X$" $\Rightarrow$ Ψ decays.

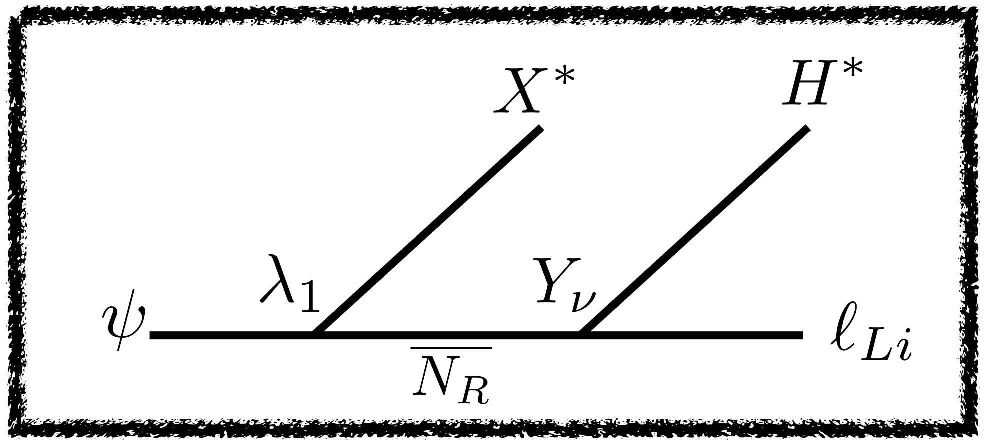
"X"(the scalar dark field) = CDM

☛ For α_X close to its upper bound, X-X* can explain some puzzles of collisionless CDM:

(i) cored profile of dwarf galaxies.

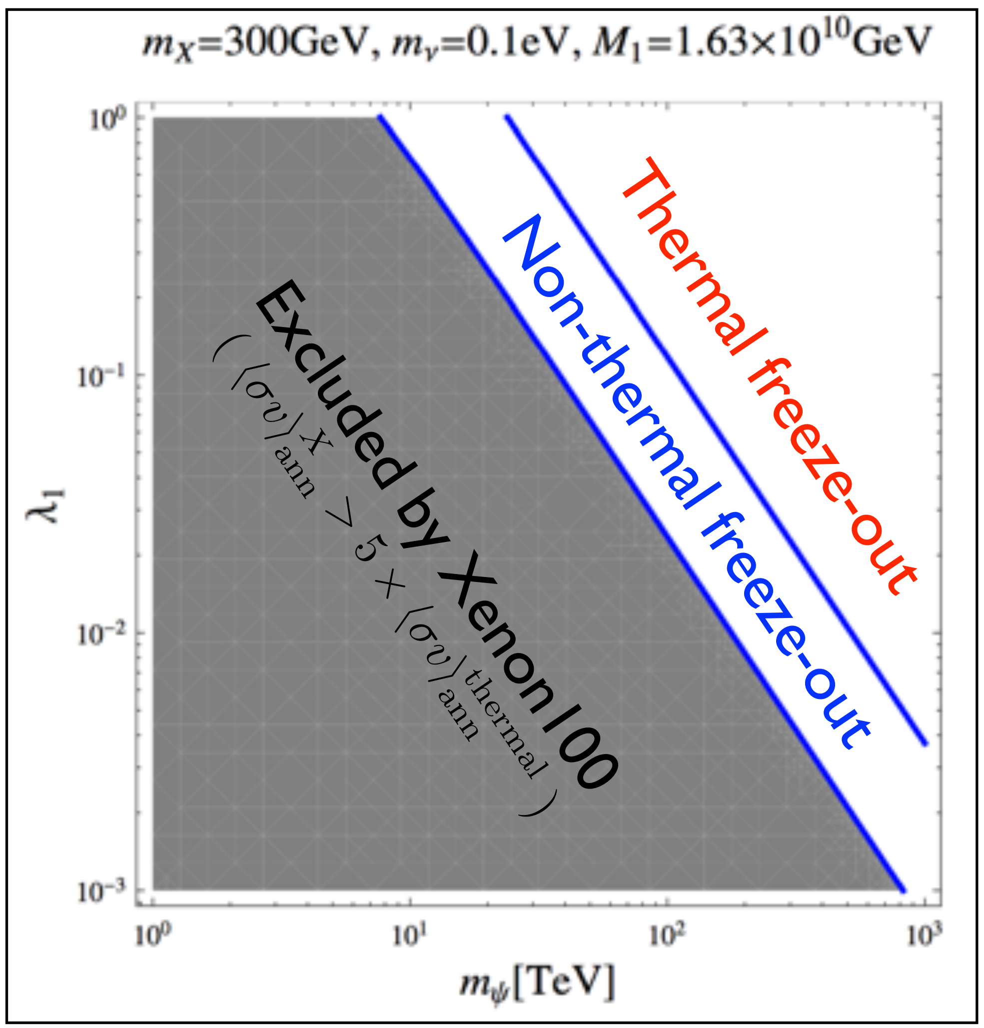
(ii) low concentration of LSB galaxies and dwarf galaxies. [Vogelsberger, Zavala and Leb, 1201.5892]

- # CDM relic density



The late-time decay of ψ

X forms a symmetric DM.
(Non-) thermal freeze-out of X via Higgs portal



$$\text{Thermal}(T_{\rm d}^\psi > T_{\rm fz}^X):\ \langle\sigma v\rangle^X_{\rm ann} = \langle\sigma v\rangle^{\rm thermal}_{\rm ann}$$

$$\text{Nonthermal}(T_{\rm d}^\psi < T_{\rm fz}^X):\ \langle\sigma v\rangle^X_{\rm ann} \sim \Gamma_{\rm d}^\psi / n_X^{\rm obs}$$

$$\boxed{\lambda_1 = \lambda_1(m_\psi, \langle\sigma v\rangle^X_{\rm ann}, \cdots)}$$

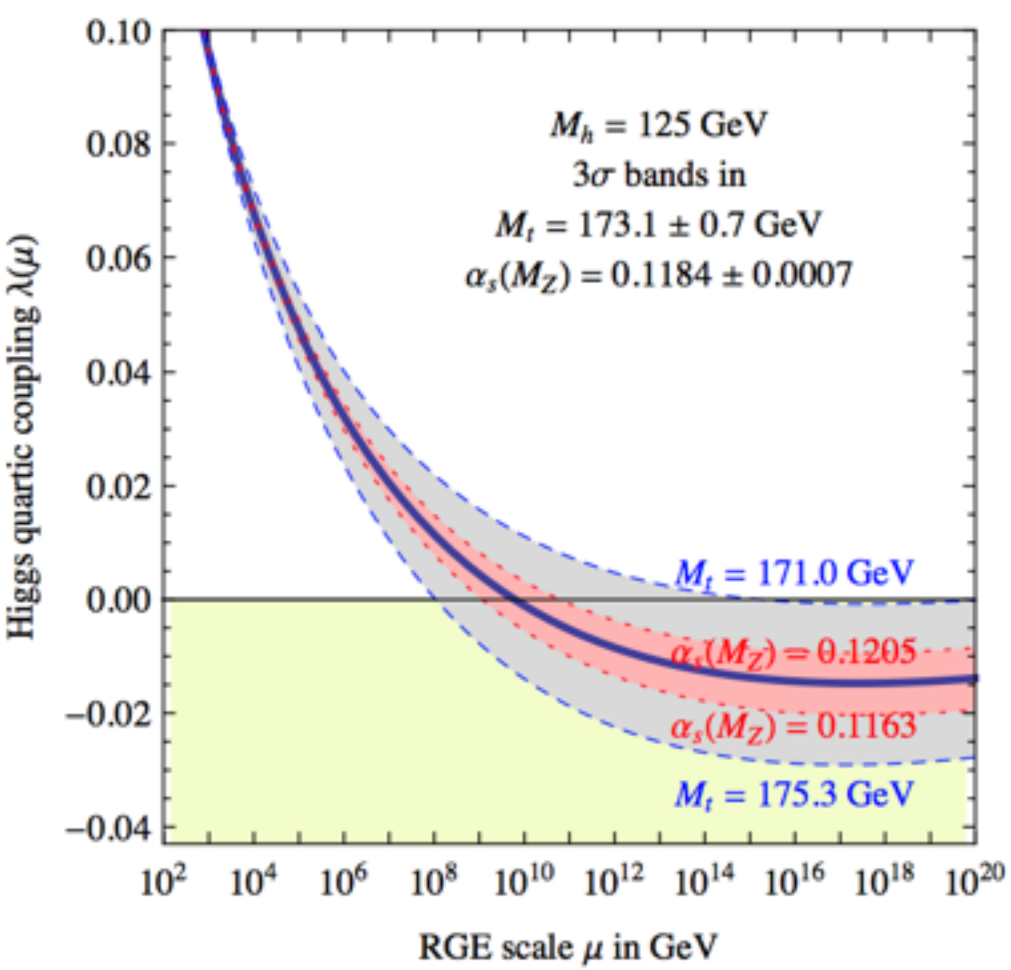
- # Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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

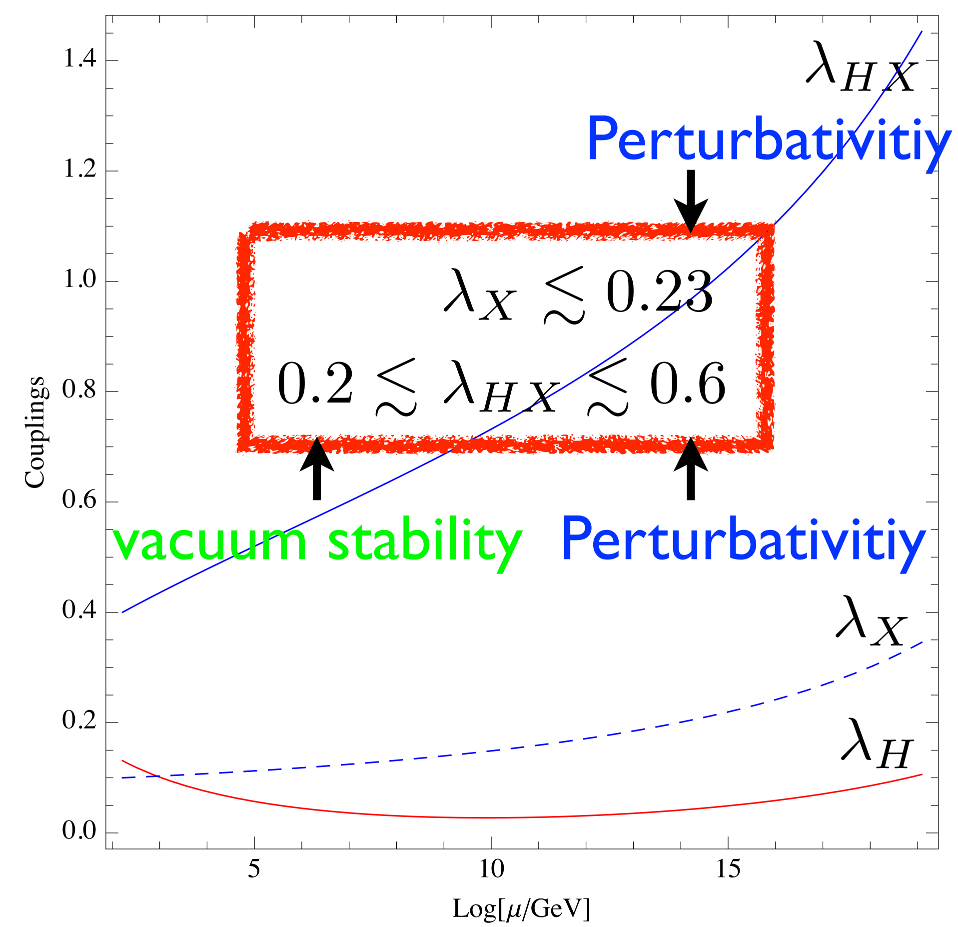
$$\beta^{(1)}_{\lambda_{HS}} = \frac{\lambda_{HS}}{16\pi^2}\left[2\left(6\lambda_H + 3\lambda_S + 2\lambda_{HS}\right) - \left(\frac{3}{2}\lambda_H\left(3g_2^2+g_1^2\right) - 6\lambda_t^2 - \cancel{4\lambda^2}\right)\right],$$

$$\beta^{(1)}_{\lambda_S} = \frac{1}{16\pi^2}\left[2\lambda_{HS}^2 + 18\lambda_S^2 + 8\cancel{\lambda_S}\lambda^2 - \cancel{3}\lambda^4\right],$$

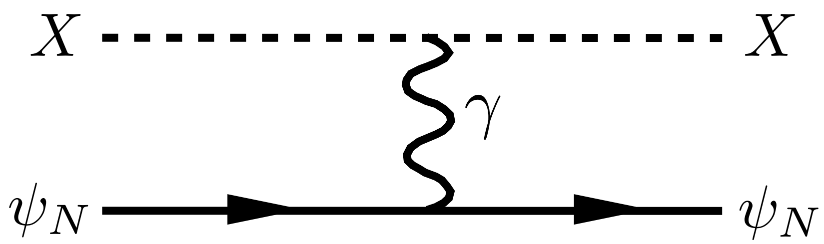
with $\lambda_{HS} \to \lambda_{HX}/2$ and $\lambda_S \to \lambda_X$



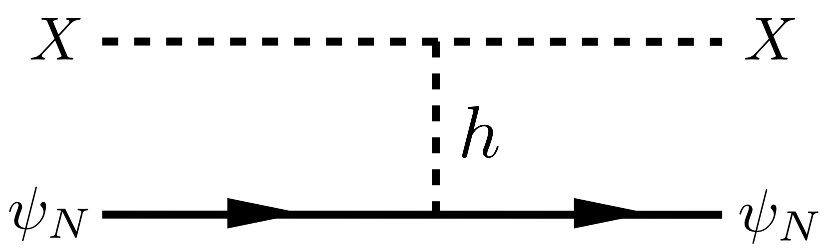
[G. Degrassi et al., 1205.6497]



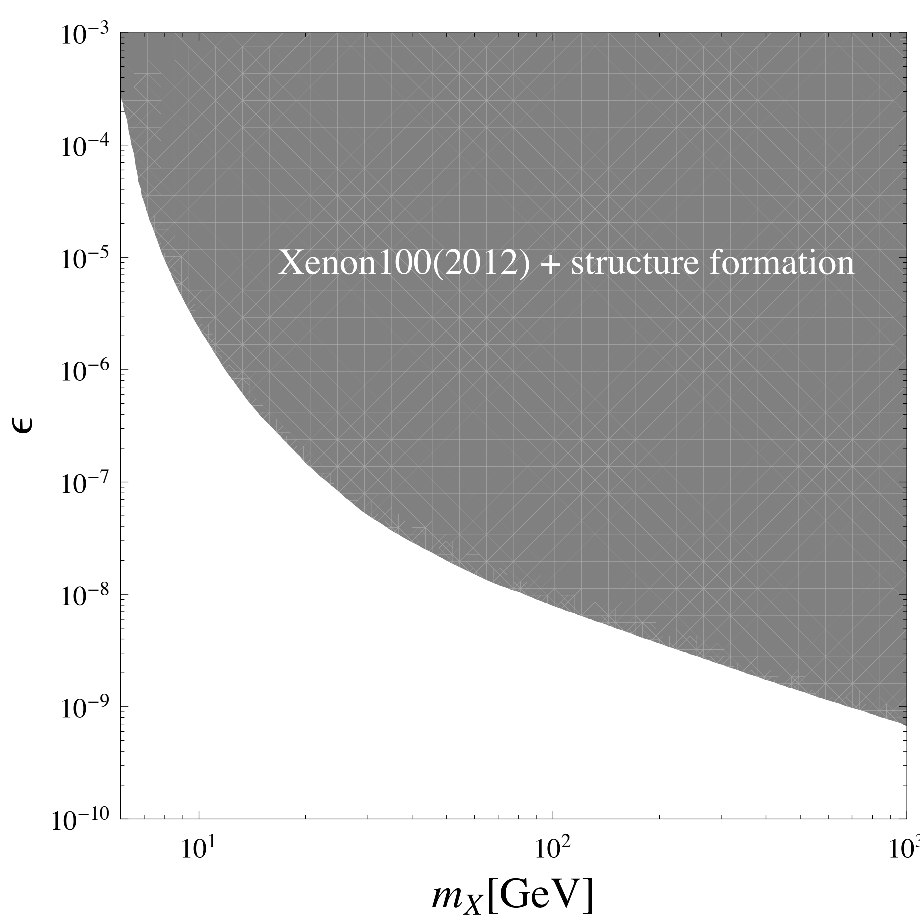
- DM direct search (ϵ, λ_{hx}, m_X)

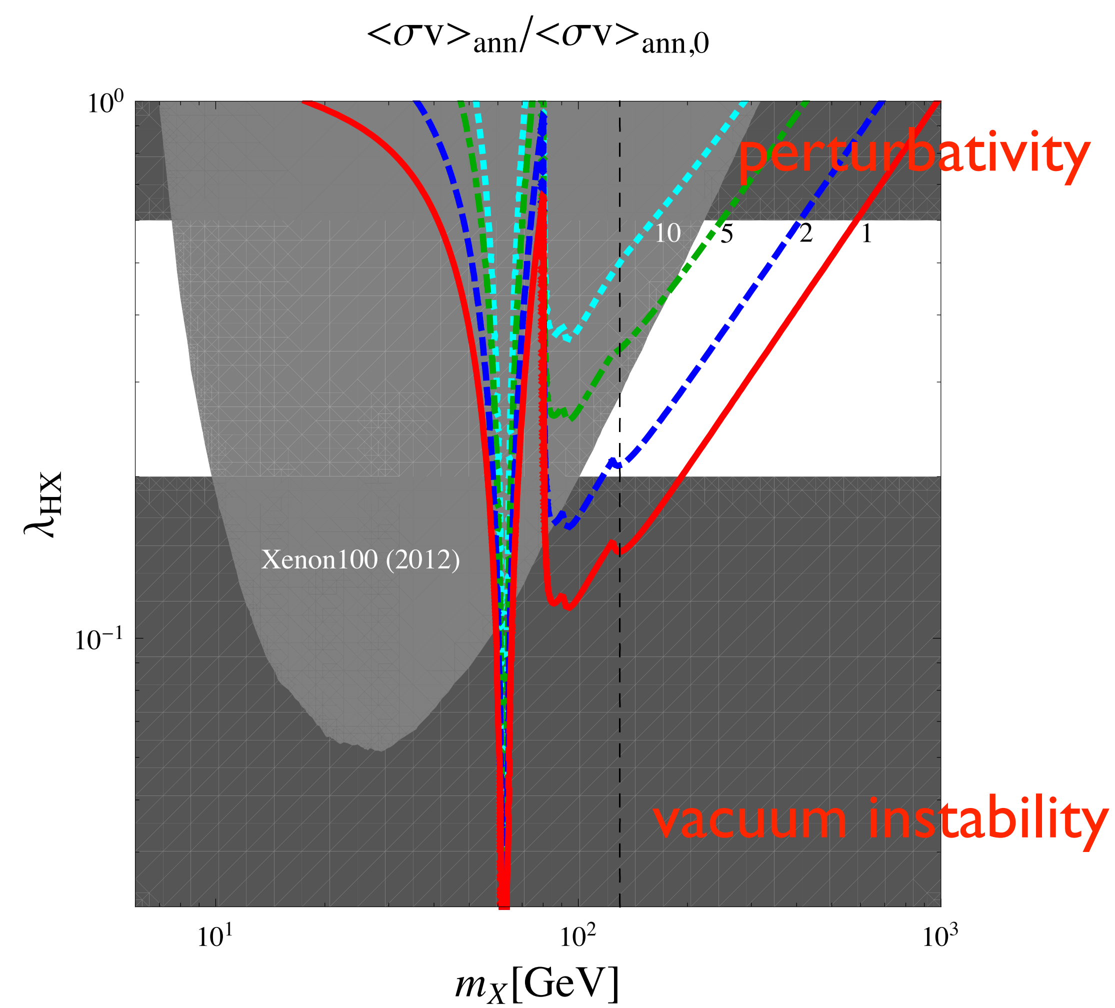


$$\frac{d\sigma_A}{dE_r} = \frac{2\pi\epsilon_e^2\alpha_{em}^2 Z^2}{m_A E_r^2 v^2}\mathcal{F}_A^2(qr_A)$$



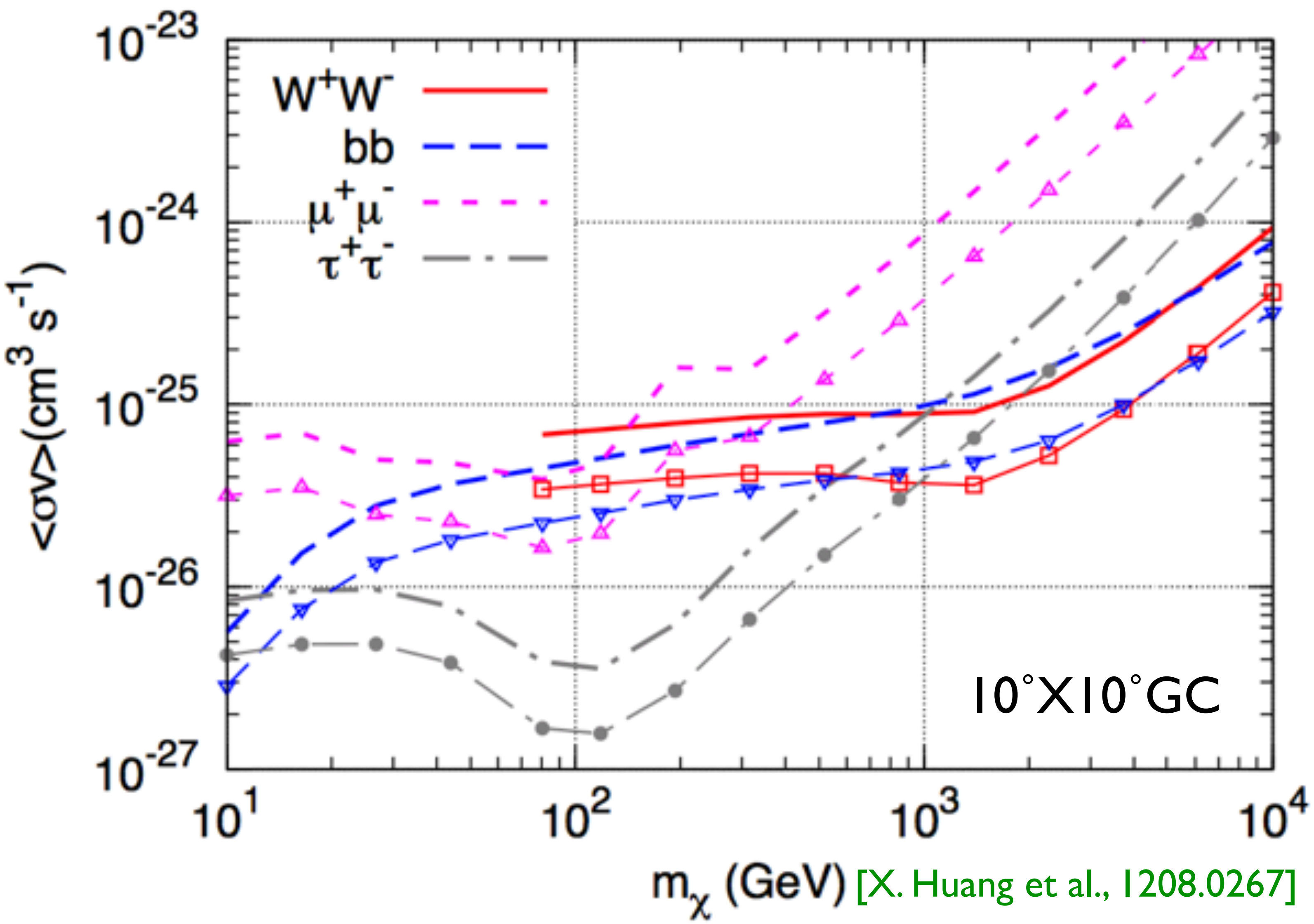
$$\sigma_{\mathcal{N},h}^{SI} = \frac{\lambda_{HX}^2}{64\pi}\frac{m_r^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$





• 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,

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

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

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

☛ 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)

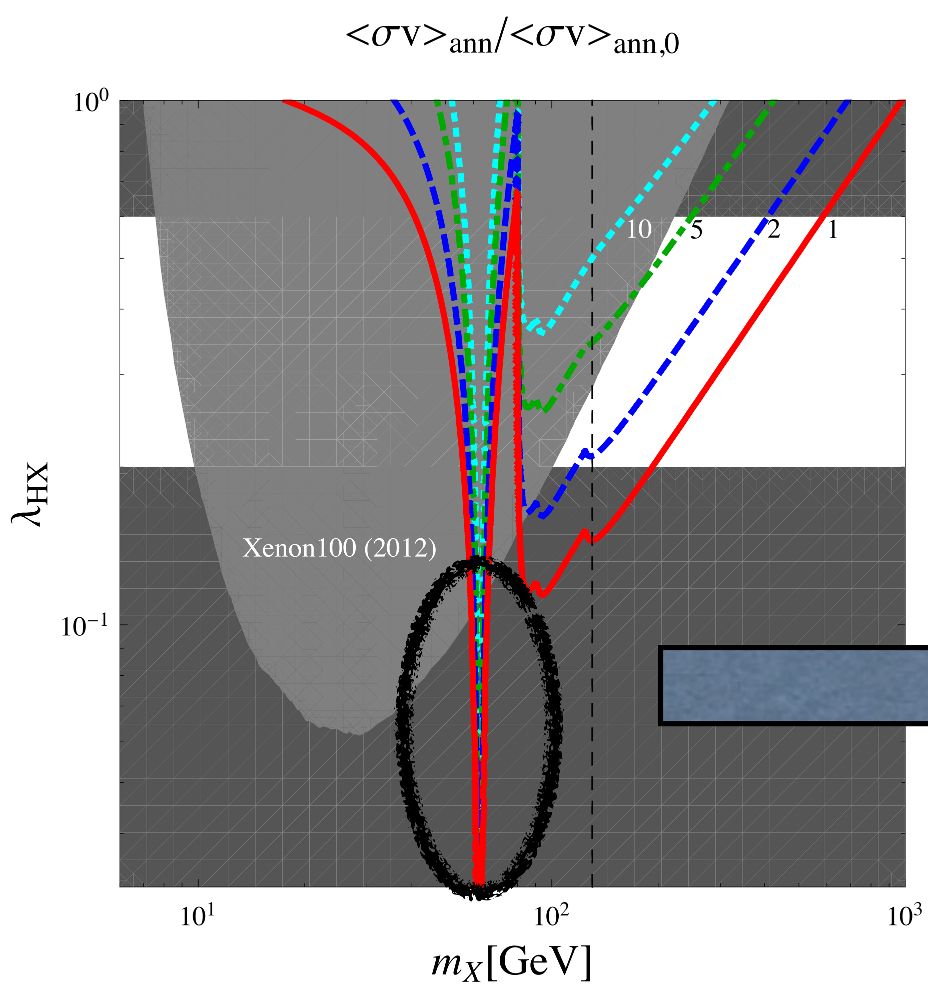
Invisible decay rate of Higgs is

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

SM signal strength at collider is

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

$$\left(\text{cf., } \begin{array}{ll} \mu_{\rm ATLAS} = 1.43\pm 0.21 & \text{for } m_h = 125.5\,\text{GeV} \\ \mu_{\rm CMS} = 0.8\pm 0.14 & \text{for } m_h = 125.7\,\text{GeV} \end{array}\right)$$



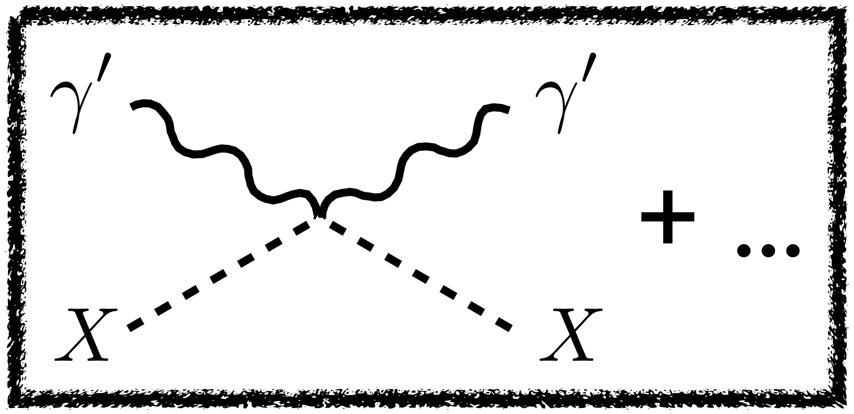
We may need $\text{Br}(h\to XX^\dagger) \ll \mathcal{O}(10)\%$, i.e.,

$$\boxed{\begin{array}{r} \lambda_{HX} \ll 0.1 \\ \text{or} \\ m_h - 2m_X \lesssim 0.5\text{GeV} \end{array}}$$

or kinematically forbidden

• Dark radiation

Decoupling of dark photon



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

# of extra relativistic degree of freedom

$$\Delta N_{\mathrm{eff}} = \frac{\rho_{\gamma'}}{\rho_\nu} = \frac{g_{\gamma'}}{(7/8)g_\nu}\left(\frac{T_{\gamma,0}}{T_{\nu,0}}\right)^4 \left(\frac{T_{\gamma',\mathrm{dec}}}{T_{\gamma,\mathrm{dec}}}\right)^4 \left(\frac{g_{*S}(T_{\gamma,0})}{g_{*S}(T_{\gamma,\mathrm{dec}})}\right)^{4/3}$$

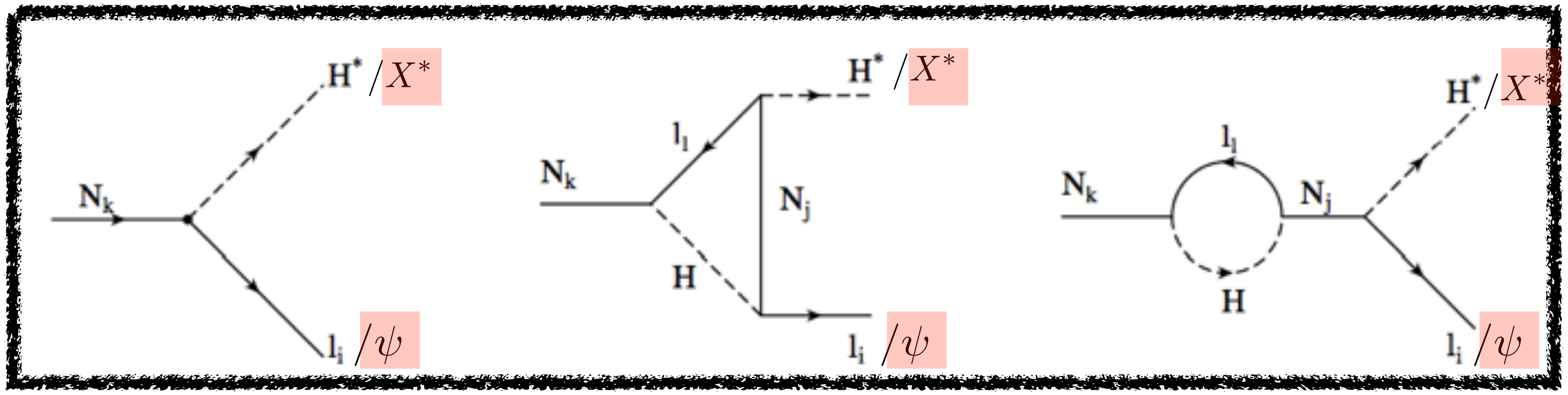
$$\frac{T_{\nu,0}}{T_{\gamma,0}} = \left\{ \begin{array}{lll} \left(\frac{4}{11}\right)^{1/3} & \text{for} & T_{\mathrm{dec}} \gtrsim 1\mathrm{MeV} \\ 1 & \text{for} & T_{\mathrm{dec}} \lesssim 1\mathrm{MeV} \end{array} \right.$$

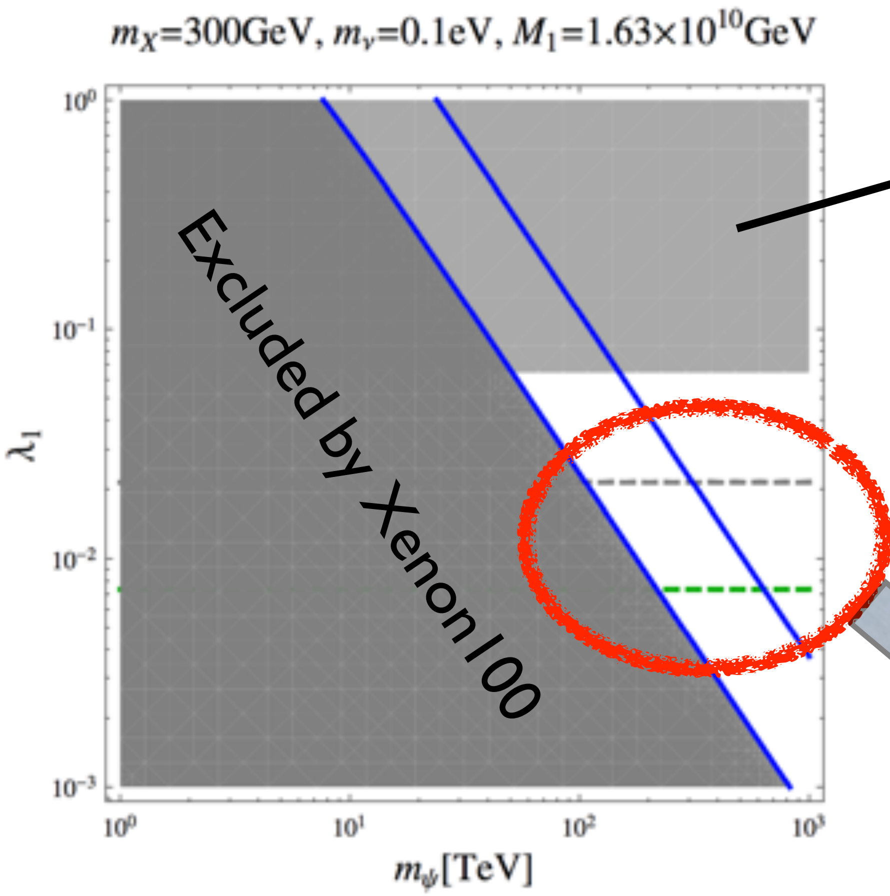
$\Delta N_{\mathrm{eff}} = 0.474^{+0.48}_{-0.45}$ at 95% CL (Planck+WP+highL+H_0+BAO)

[Planck Collaboration, arXiv:1303.5076]

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

- # Lepto/darkogenesis (1/2)
(Genesis from the decay of RHN)





Light gray: narrow width approx. is invalid

White between blue lines:

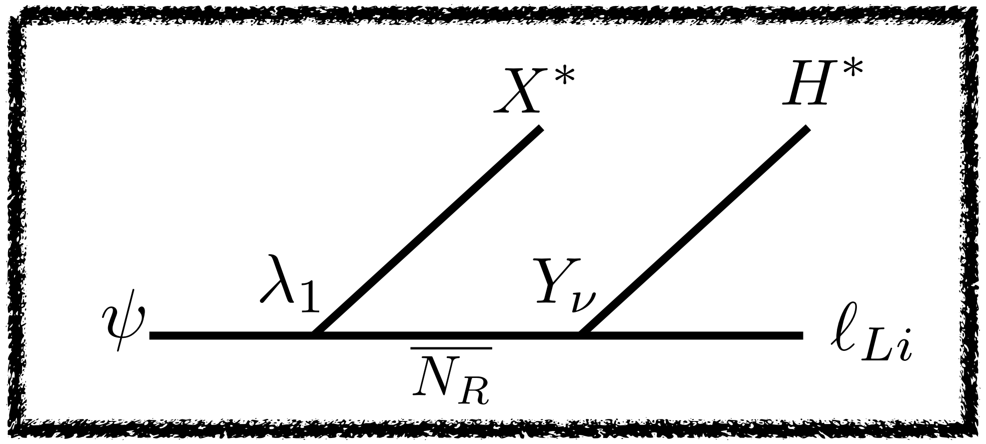
$$1 \leq \langle \sigma v \rangle^{\rm tot}_{\rm ann} / \langle \sigma v \rangle^{\rm th}_{\rm ann} \lesssim 5$$

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

Correct BAU and CDM relic can be obtained.

- # Lepto/darkogenesis (2/2)

(Genesis from the late-time decay of ψ &ψ-bar)



Late-time decay of ψ → $\Delta(Y_{\Delta L}) \neq 0$

$T_{\rm d}^{\psi} \ll m_\psi$ → No wash-out!

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

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

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

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

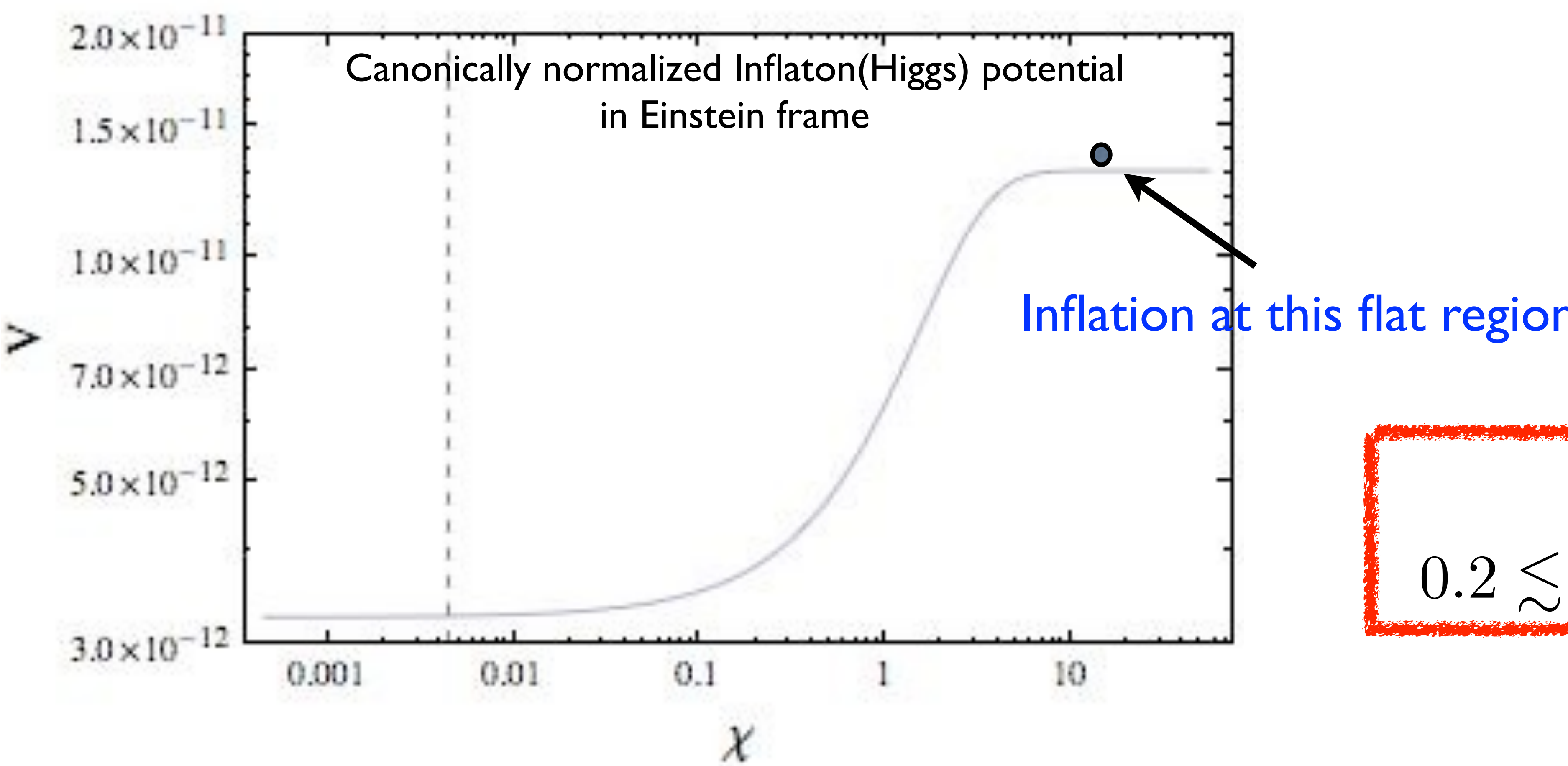
* Late-time decays of symmetric ψ and ψ-bar can generate a sizable amount of lepton number asymmetry.

- 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 $\xi_h,\ \xi_x \gg 1$



$$\boxed{\begin{aligned} \lambda_X &\lesssim 0.23 \\ 0.2 \lesssim \lambda_{HX} &\lesssim 0.6 \end{aligned}}$$

Variations

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	$<1\ (i=1,2,3)$

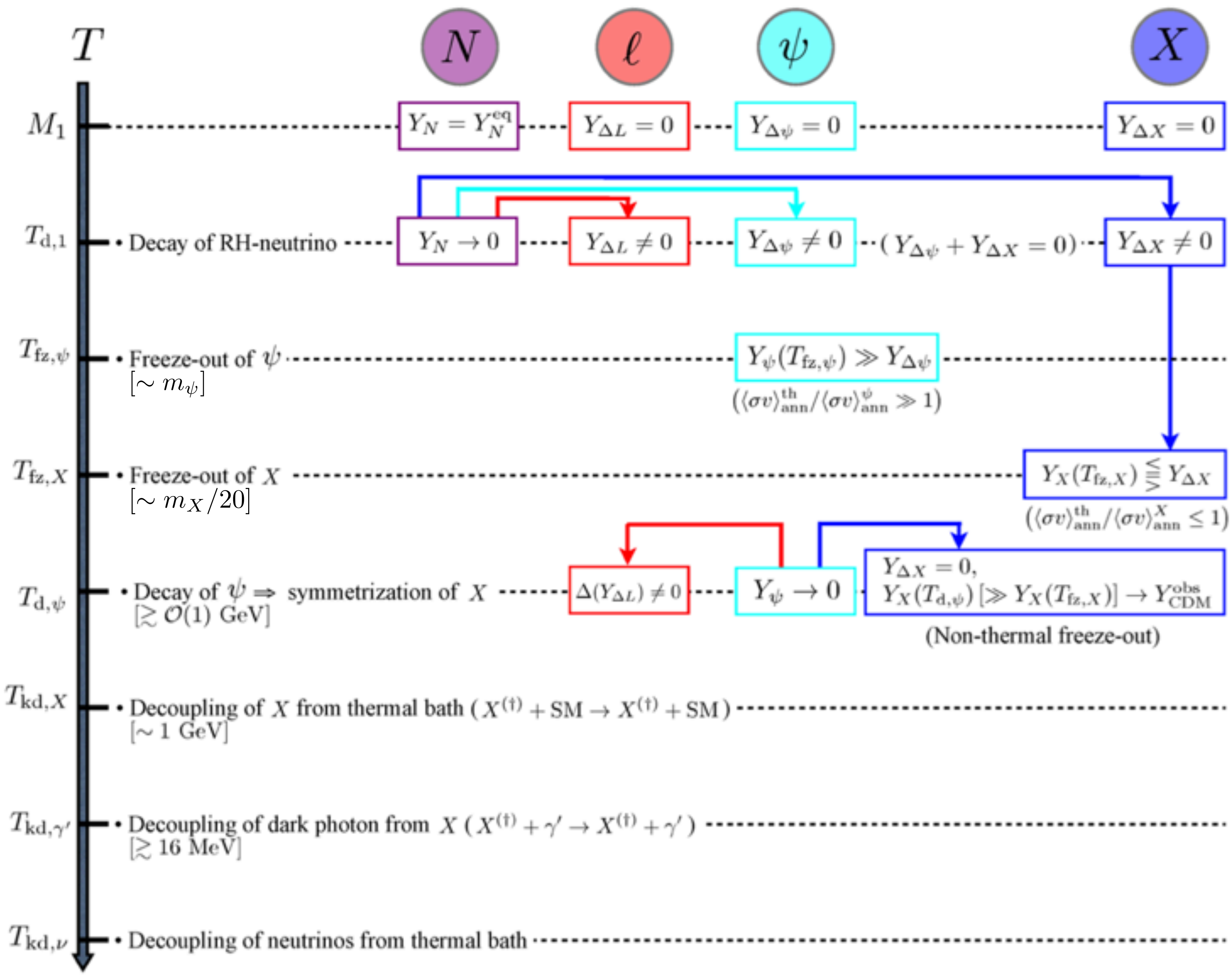
= a singlet real scalar

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 "μ_i<1".

Thermal history



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)