New minimal SM?

[Davoudiasl, Kitano, Li and Murayama, PLB 609 (2005) 117]

New minimal(?) SM (NMSM)

- Lagrangian

[Davoudiasl, Kitano, Li and Murayama, PLB 609 (2005) 117]

$$\mathcal{L}_{\rm NMSM} = \mathcal{L}_{\rm MSM} + \mathcal{L}_S + \mathcal{L}_\Lambda + \mathcal{L}_N + \mathcal{L}_\varphi - V_{\rm RH}$$

Dark matter ⇨
$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4$$

Cosmological constant ⇨
$$\mathcal{L}_\Lambda = (2.3 \times 10^{-3}\ {\rm eV})^4$$

Neutrino mass, Leptogenesis ⇨
$$\mathcal{L}_N = \bar{N}_\alpha i \partial\!\!\!/ N_\alpha - \left(\frac{M_\alpha}{2} N_\alpha N_\alpha + h_\nu^{\alpha i} N_\alpha L_i \tilde{H} + {\rm c.c.} \right)$$

Inflation ⇨
$$\mathcal{L}_\varphi = \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{\mu}{3!}\varphi^3 - \frac{\kappa}{4!}\varphi^4$$

⇦
$$m \simeq 1.8 \times 10^{13} {\rm GeV}$$
$$\mu \lesssim 10^6 {\rm GeV}$$
$$\kappa \lesssim 10^{-14}$$

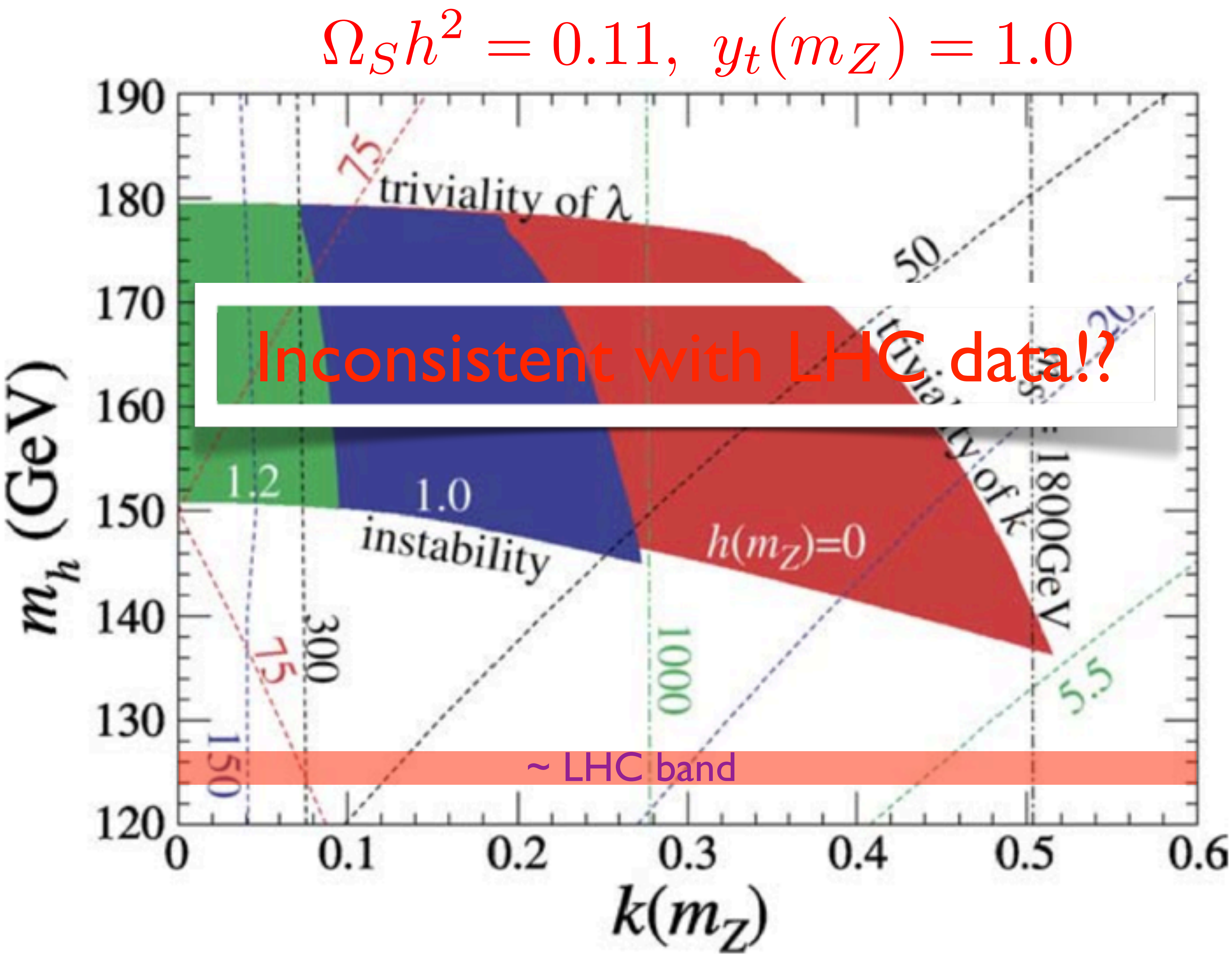
Reheating ⇨
$$V_{\rm RH} = \mu_1 \varphi |H|^2 + \mu_2 \varphi S^2 + \kappa_H \varphi^2 |H|^2 + \kappa_S \varphi^2 S^2 + (y_N^{\alpha\beta} \varphi N_\alpha N_\beta + {\rm c.c.}).$$

- Organizing principle
  - minimal particle content
  - the most general renormalizable Lagrangian

- DM stability

  assumed by ad hoc. Z_2-parity (where is this from?)

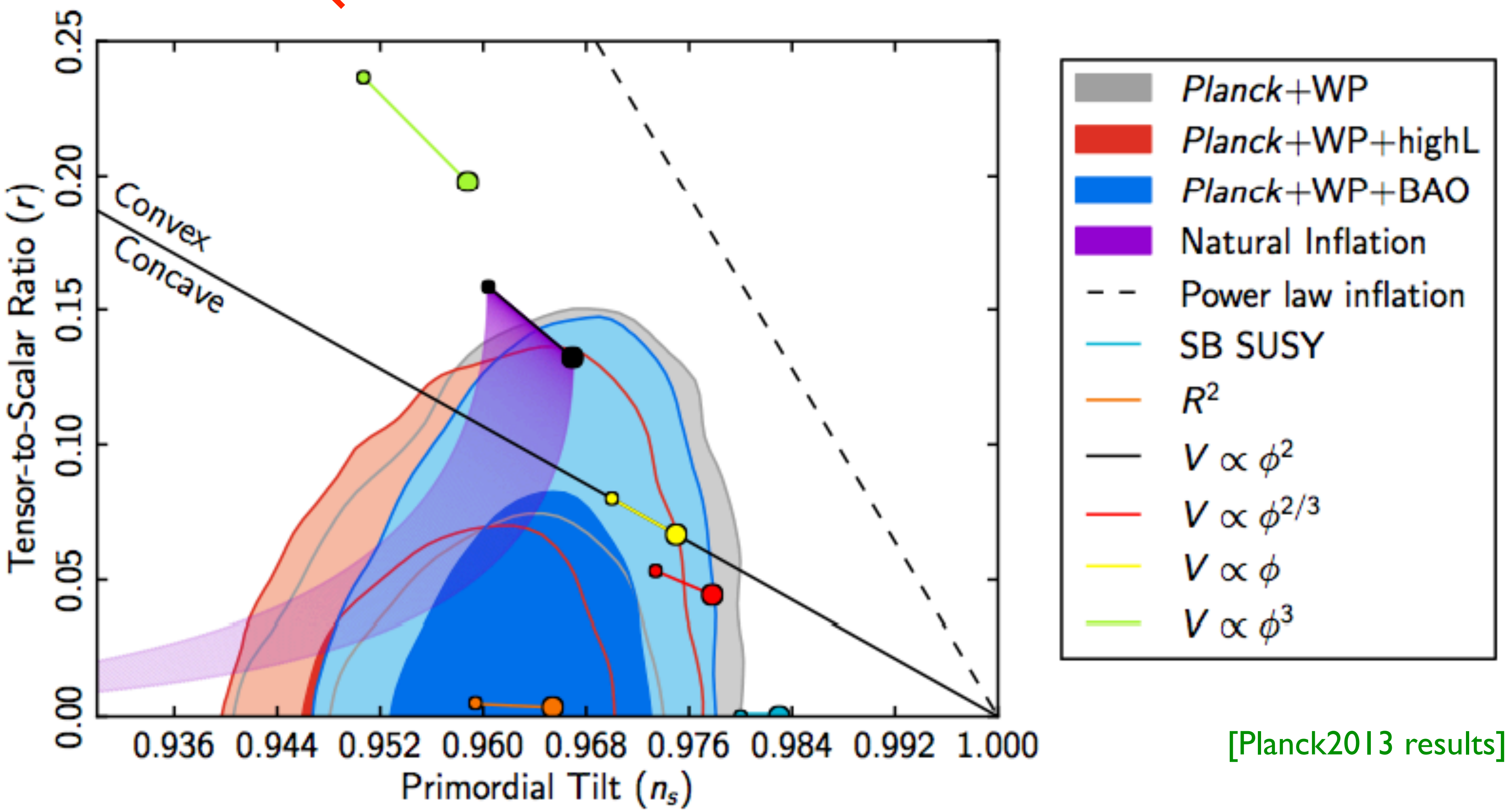
- NMSM parameter space



□= quartic coupling of Higgs, □= quartic coupling of S (DM)
□= mixed quartic coupling of Higgs and DM

Inflation models in light of Planck2013 data

$$V \propto \phi^4$$



[Planck2013 results]

New Minimal SM

☞ Simple addition of unrelated things
(cf. SM was guided by gauge principle)

☞ Z_2 does not guarantee the stability of DM

☞ Inconsistent with present data

Any Alternatives ??

Alternative(s) to NMSM

[from "Seungwon Baek, P.Ko and Wan-IlPark, arXiv: 1303.4280 (accepted for JHEP)"]

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.

⇒ 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

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

Higgs portal

may lead efficient annihilations

provides a direct detection channel

Right-handed neutrino portal

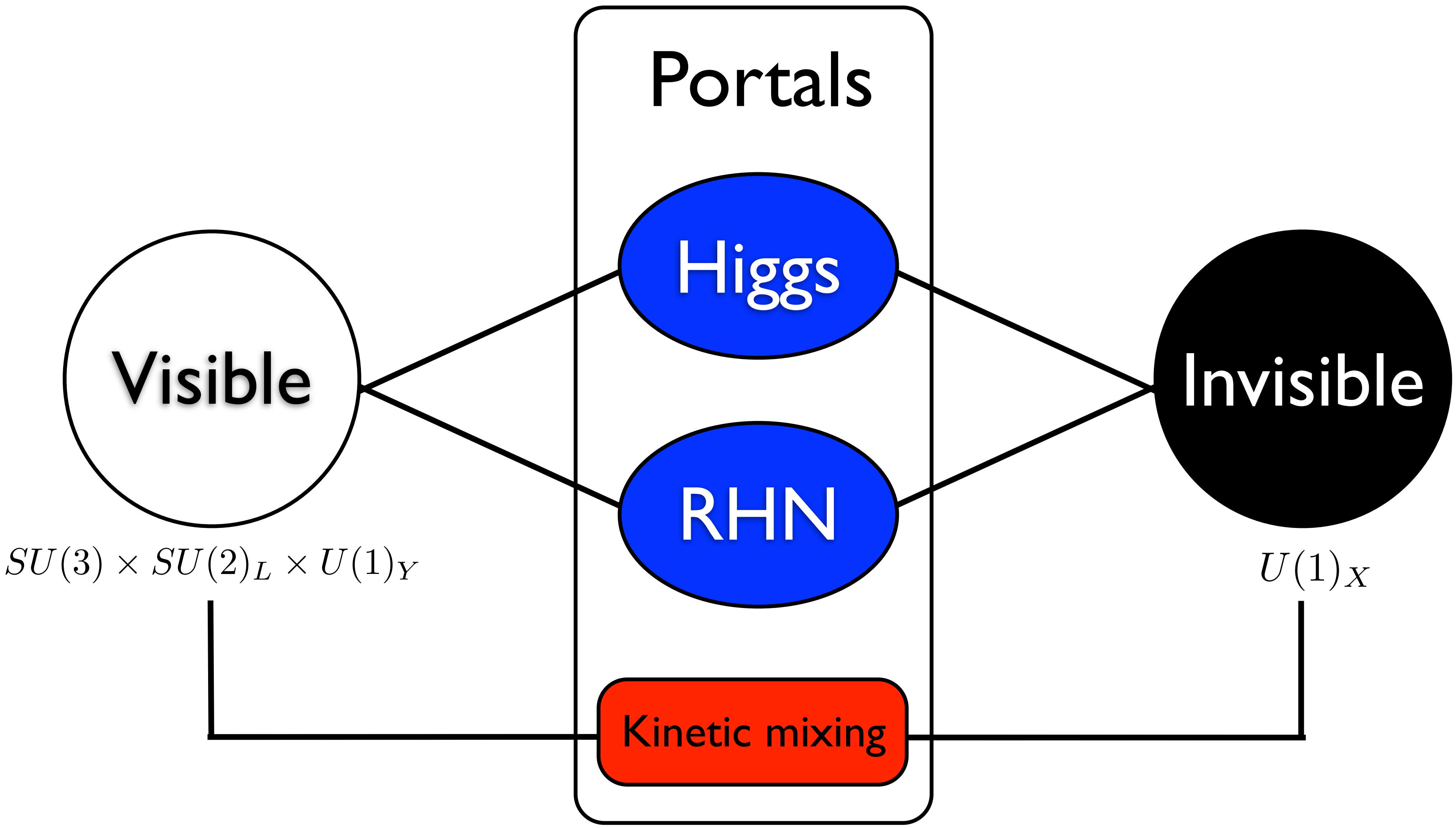
Leptogenesis and asymmetric DM?

Anything else?

does not allow renormalizable interactions for a gauge-charged DM

A minimal(?) model

- The structure of the model



- **Symmetry**

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

(SM is neutral under U(1)_X)

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

- **Lagrangian**

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

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

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

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

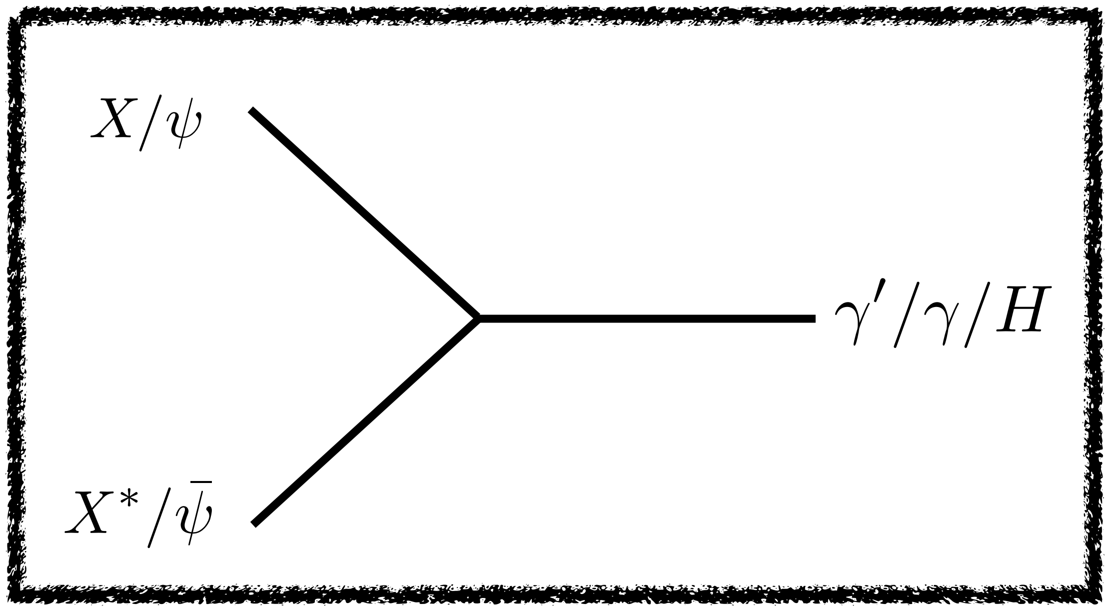
$$-\mathcal{L}_{\rm DS} = m_\psi \bar{\psi}\psi + m_X^2 |X|^2 + \frac{1}{4}\lambda_X |X|^4$$

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

• Interaction vertices of dark particles (X, ψ)

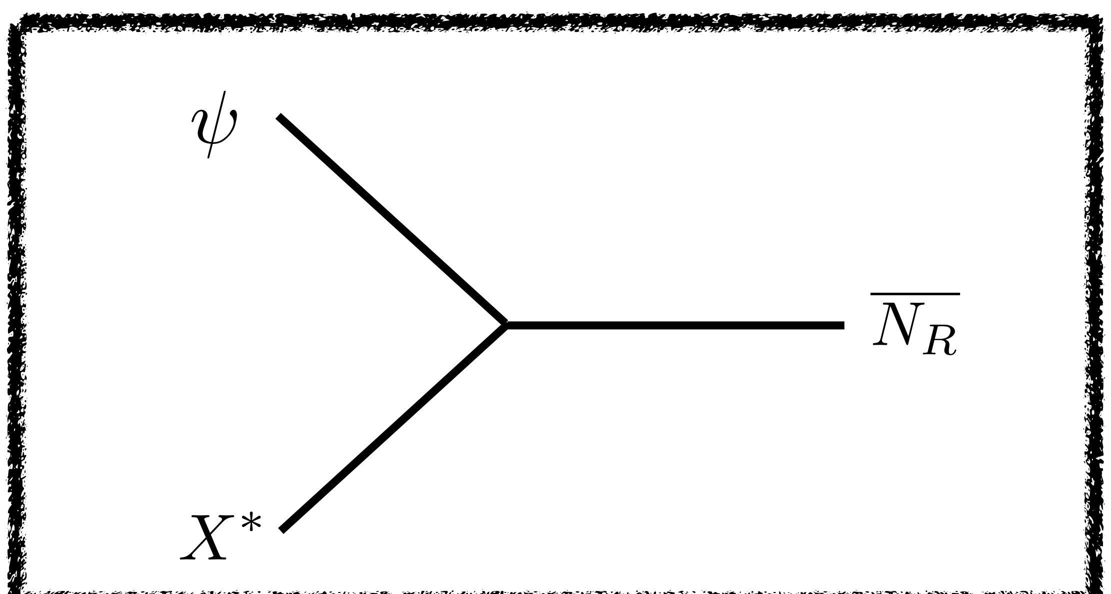
Kinetic term diagonalization: $\begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix}$

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



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})

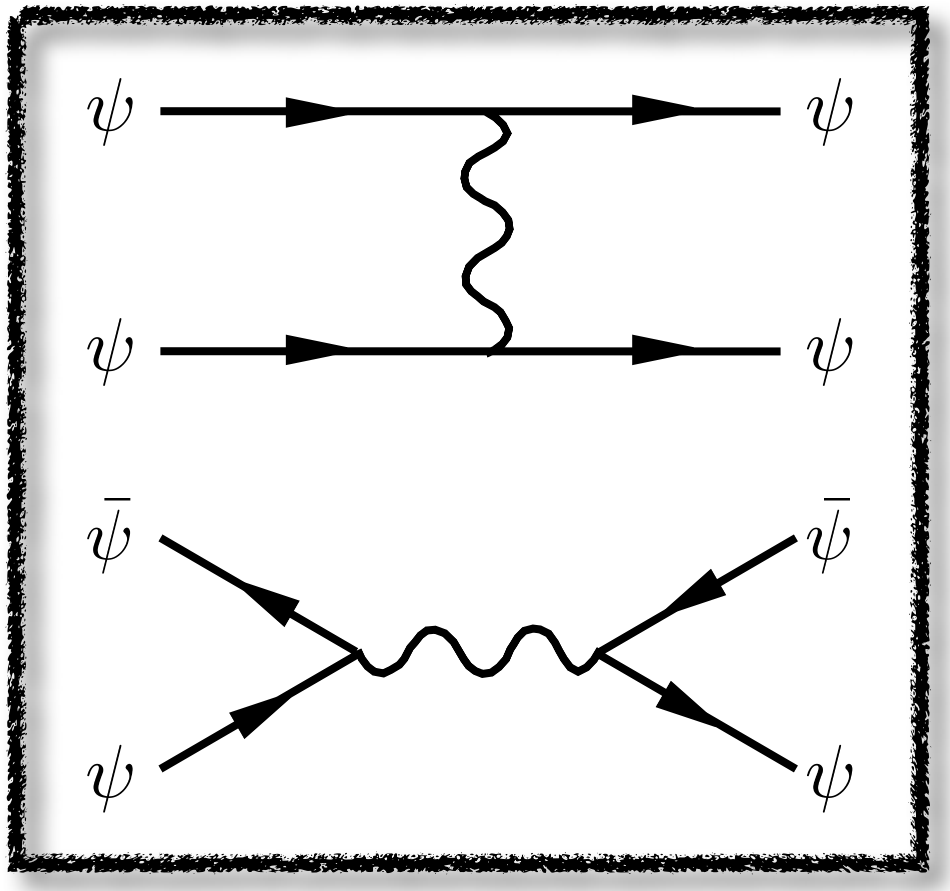
* Dark radiation (Massless photon)(α_X)

* Lepto/darkogenesis (Asymmetric origin of dark matter) (Y_ν, λ, M_I, 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.

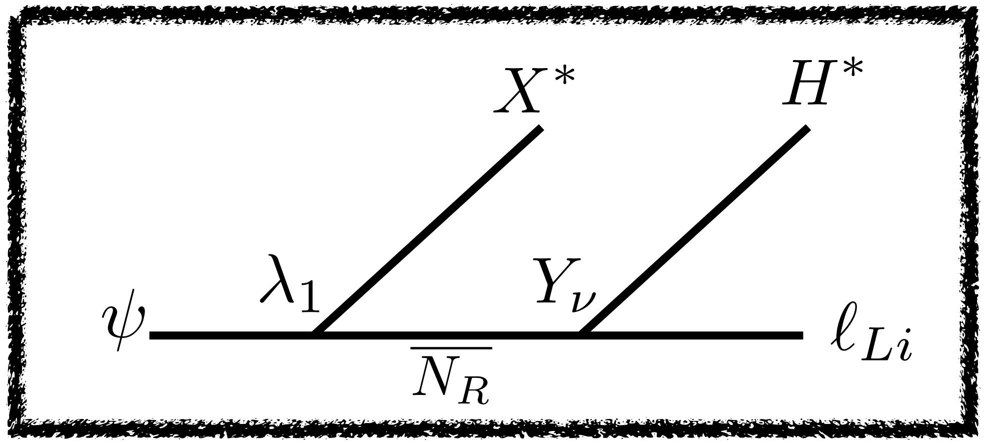
"X"(the scalar dark field) = CDM

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

(i) cored profile of dwarf galaxies.

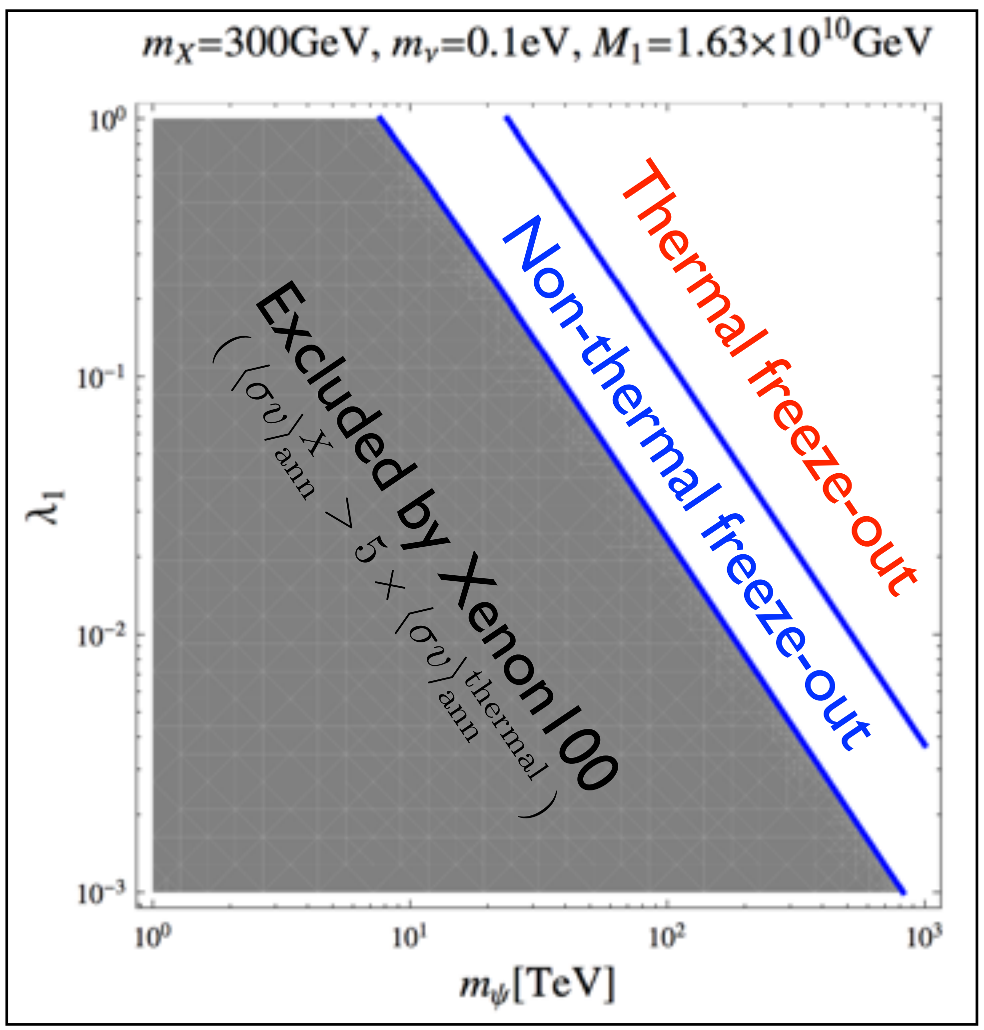
(ii) low concentration of LSB galaxies and dwarf galaxies. [Vogelsberger, Zavala and Leb, 1201.5892]

- # CDM relic density



The late-time decay of ψ

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



$$\mathrm{Thermal}(T^\psi_{\rm d} > T^X_{\rm fz}):\ \langle\sigma v\rangle^X_{\rm ann} = \langle\sigma v\rangle^{\rm thermal}_{\rm ann}$$

$$\mathrm{Nonthermal}(T^\psi_{\rm d} < T^X_{\rm fz}):\ \langle\sigma v\rangle^X_{\rm ann} \sim \Gamma^\psi_{\rm d}/n^{\rm obs}_X$$

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

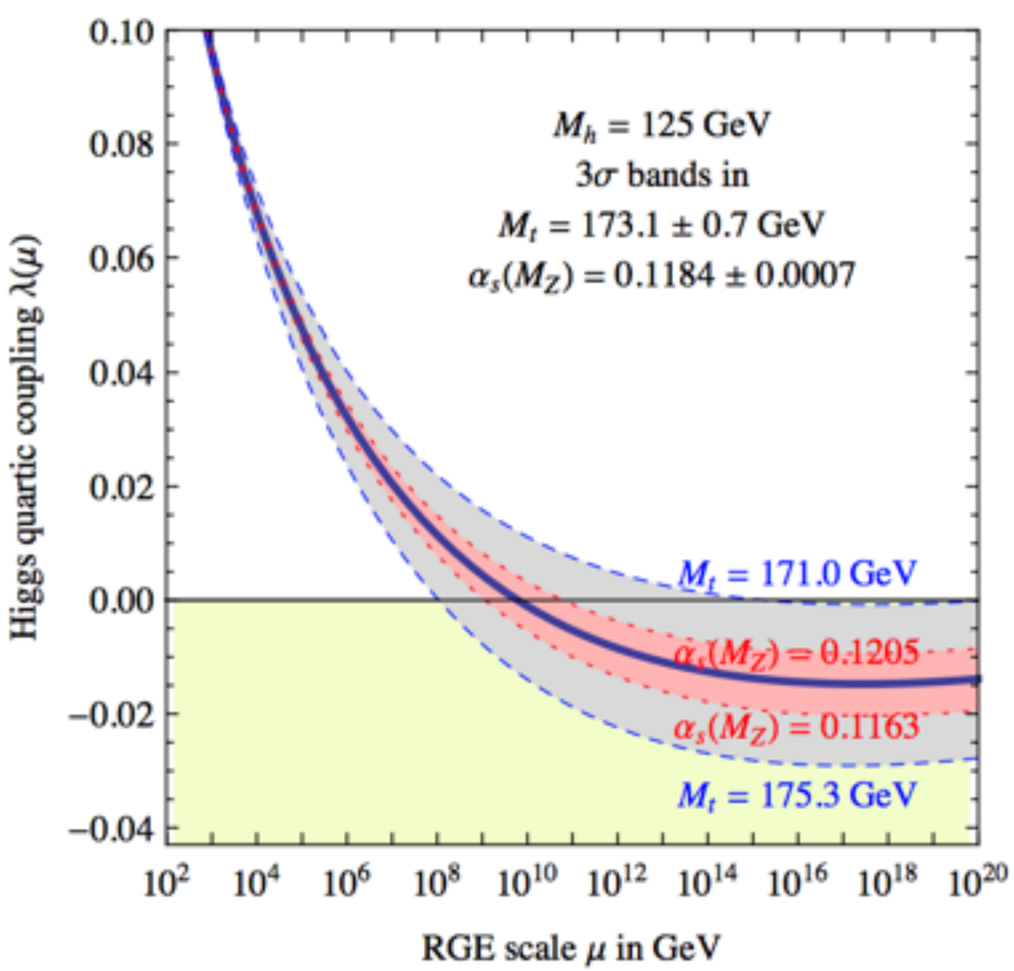
- Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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

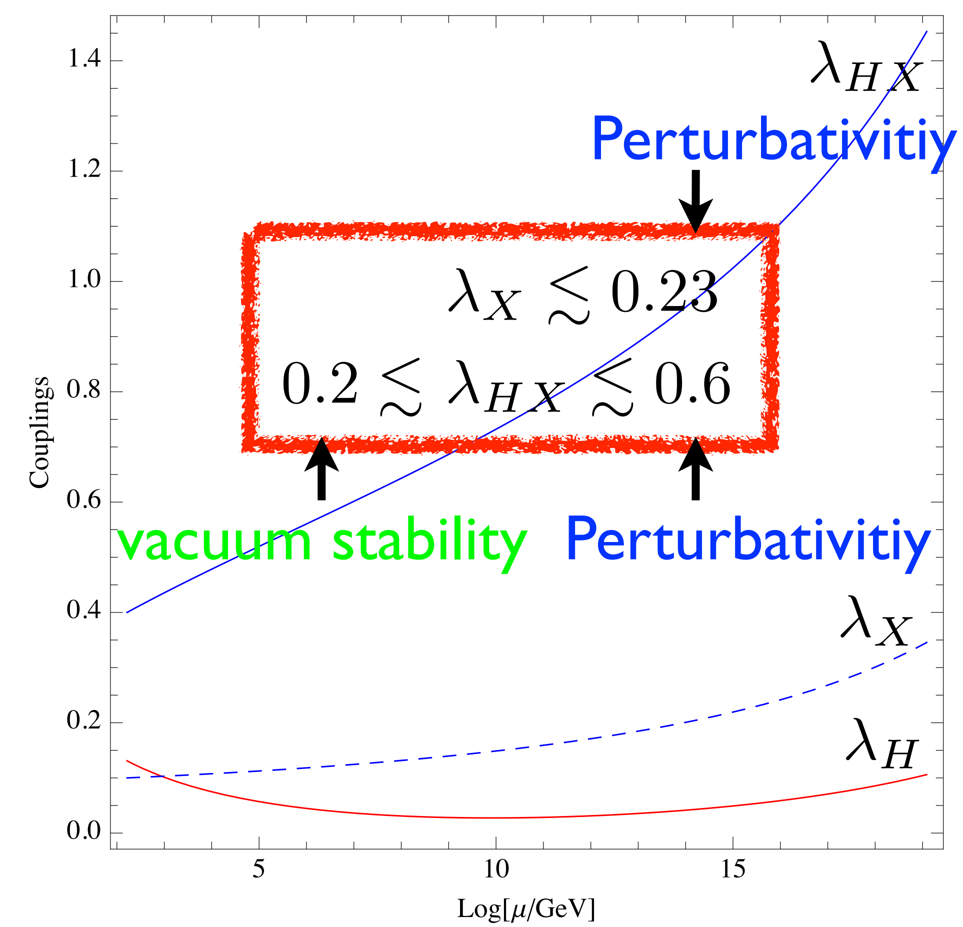
$$\beta^{(1)}_{\lambda_{HS}} = \frac{\lambda_{HS}}{16\pi^2}\left[2\left(6\lambda_H + 3\lambda_S + 2\lambda_{HS}\right) - \left(\frac{3}{2}\lambda_H\left(3g_2^2+g_1^2\right) - 6\lambda_t^2 - \cancel{4\lambda^2}\right)\right],$$

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

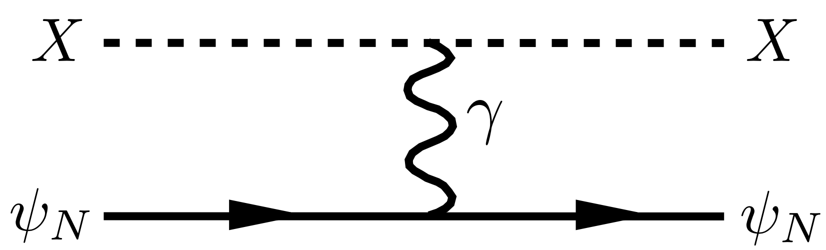
with $\lambda_{HS} \to \lambda_{HX}/2$ and $\lambda_S \to \lambda_X$



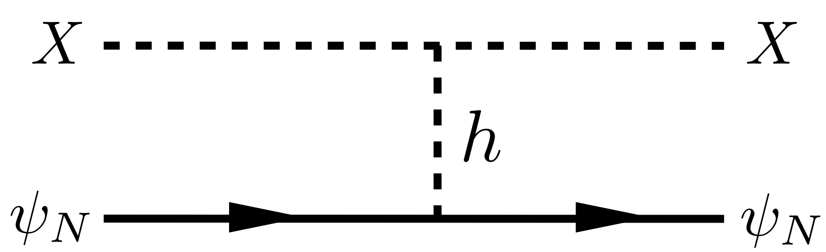
[G. Degrassi et al., 1205.6497]



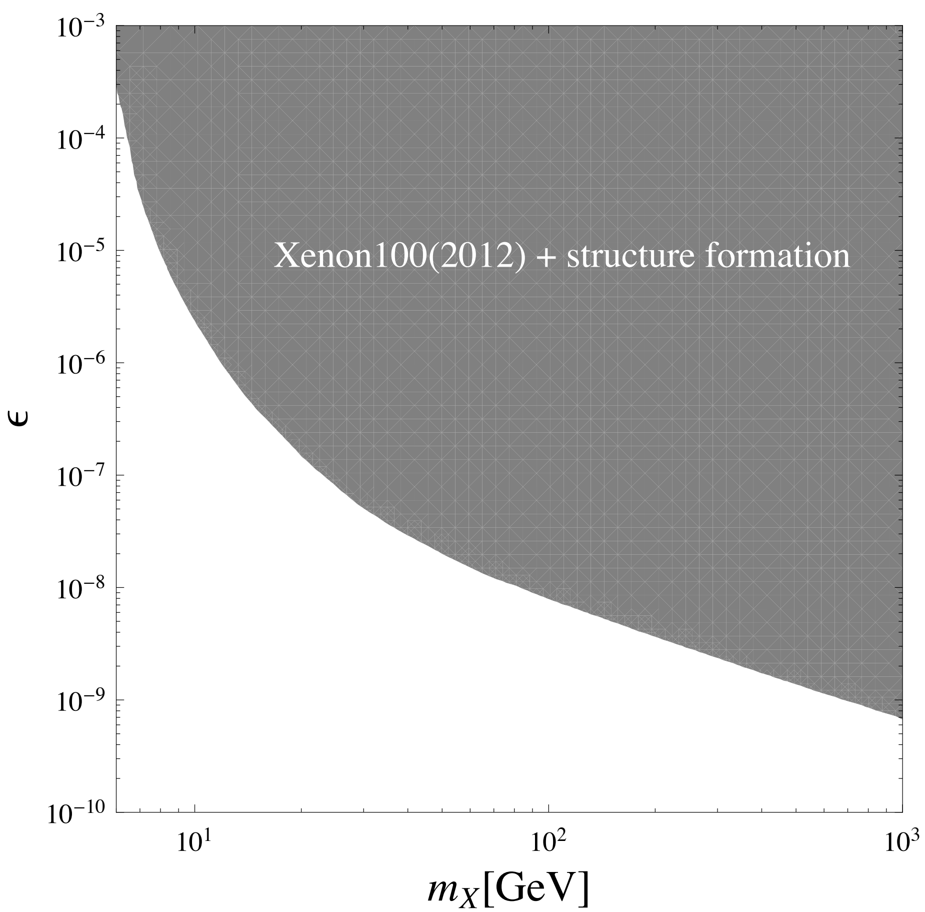
• DM direct search (ε, λ_{hx}, m_X)

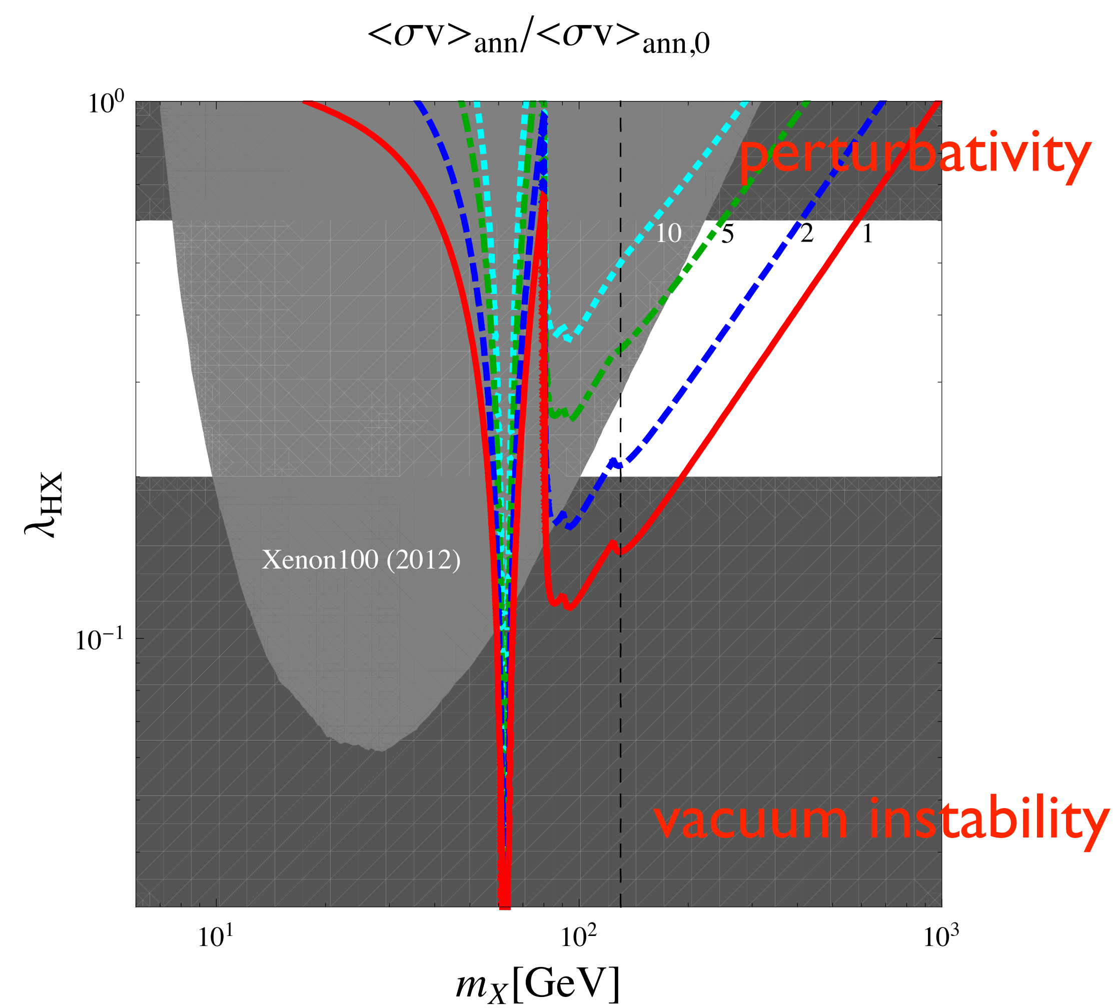


$$\frac{d\sigma_A}{dE_r} = \frac{2\pi\epsilon_e^2\alpha_{em}^2 Z^2}{m_A E_r^2 v^2}\mathcal{F}_A^2(qr_A)$$



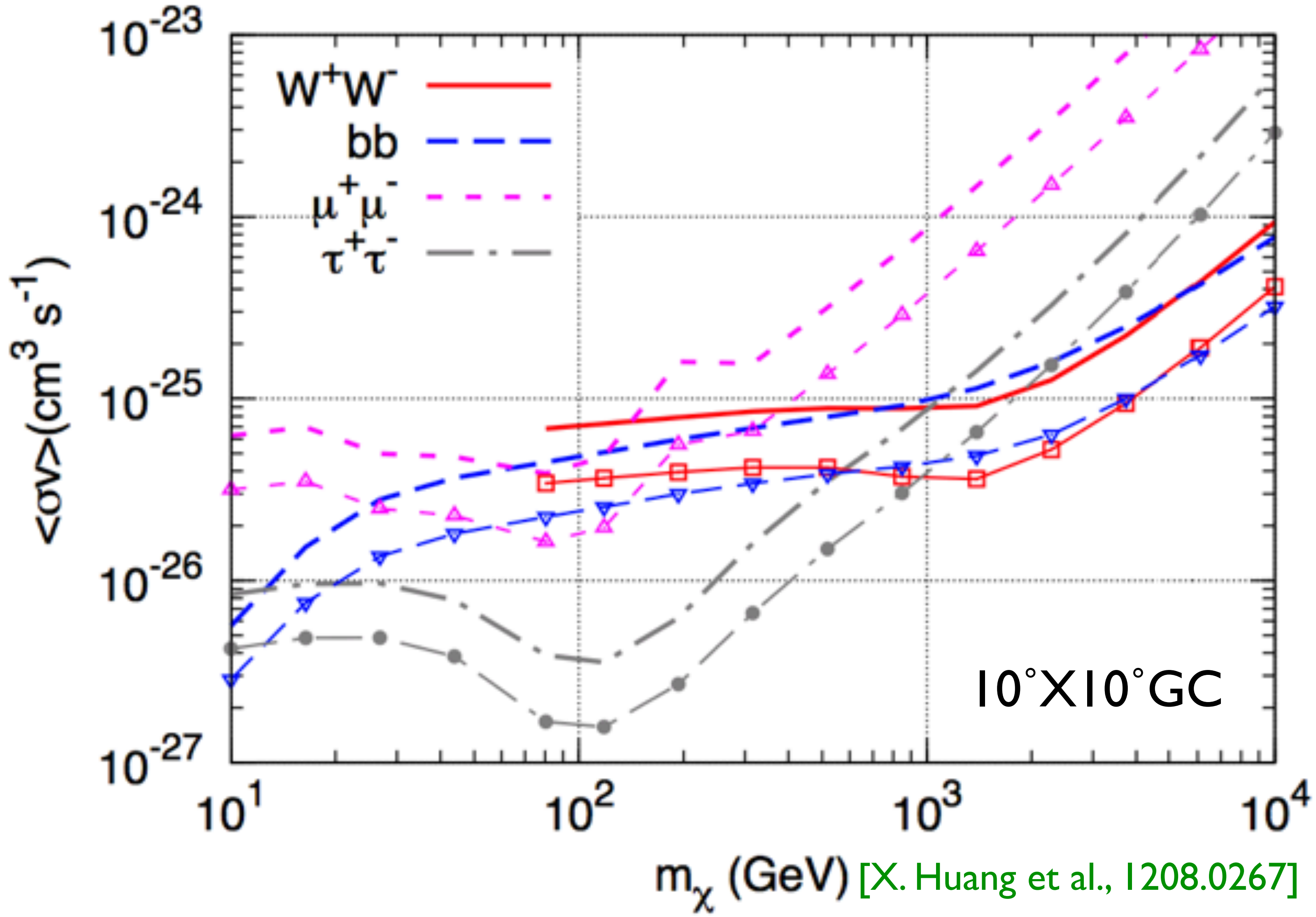
$$\sigma_{\mathcal{N},h}^{\mathrm{SI}} = \frac{\lambda_{HX}^2}{64\pi}\frac{m_r^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$





- 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,

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

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

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

☛ 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!

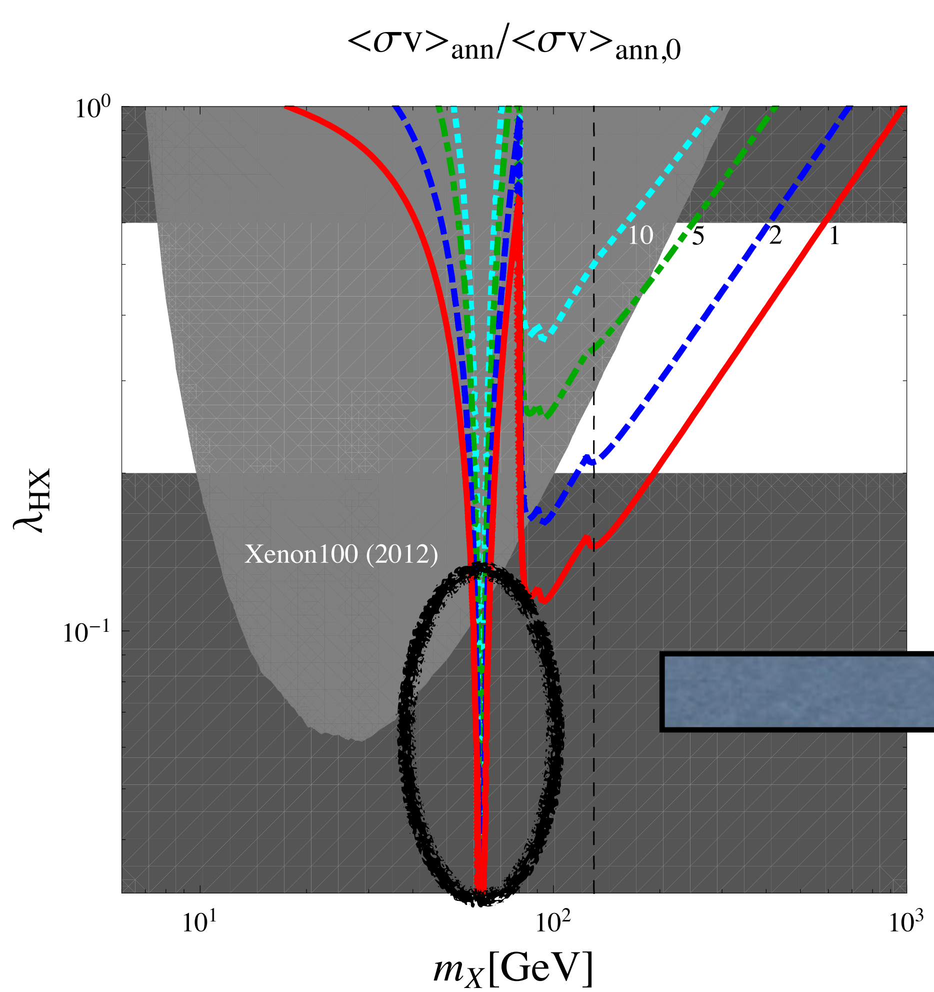
- # Collider phenomenology (λ_{hx}, m_X)

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

$$\mu = 1 - \frac{\Gamma_{h\to XX^\dagger}}{\Gamma_h^{\rm tot}} \qquad \left(\begin{array}{ll} \text{cf., } \mu_{\rm ATLAS} = 1.43 \pm 0.21 & \text{for } m_h = 125.5\,{\rm GeV} \\ \mu_{\rm CMS} = 0.8 \pm 0.14 & \text{for } m_h = 125.7\,{\rm GeV} \end{array}\right)$$



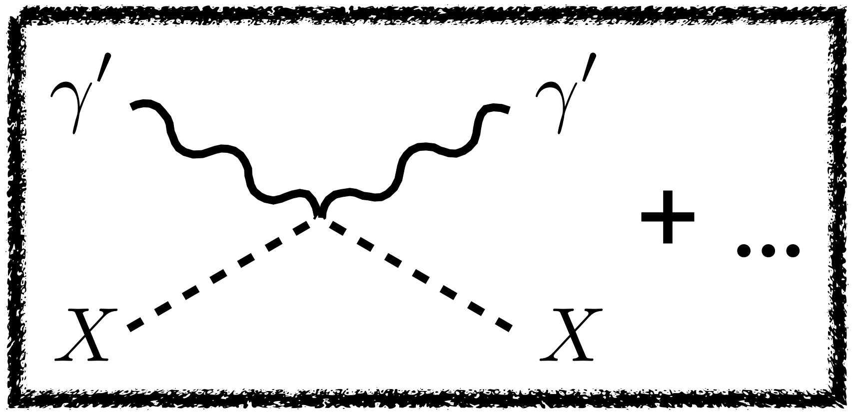
We may need $\mathrm{Br}(h\to XX^\dagger) \ll \mathcal{O}(10)\%$, i.e.,

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

or kinematically forbidden

- # Dark radiation

Decoupling of dark photon



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

# of extra relativistic degree of freedom

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

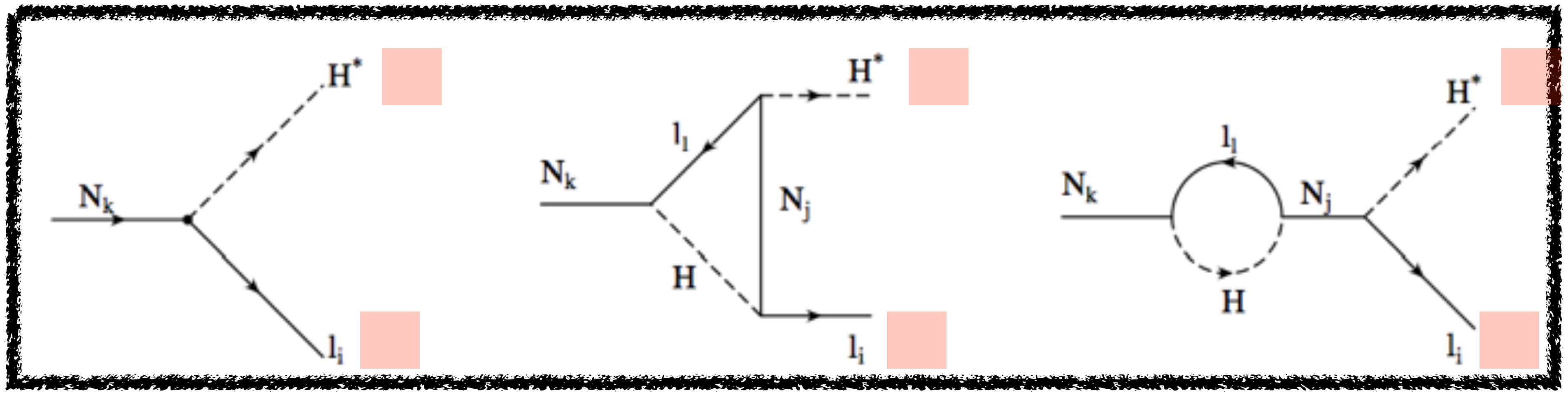
$$\frac{T_{\nu,0}}{T_{\gamma,0}} = \begin{cases} \left(\frac{4}{11}\right)^{1/3} & \text{for} \quad T_{\mathrm{dec}} \gtrsim 1\mathrm{MeV} \\ 1 & \text{for} \quad T_{\mathrm{dec}} \lesssim 1\mathrm{MeV} \end{cases}$$

$\Delta N_{\mathrm{eff}} = 0.474^{+0.48}_{-0.45}$ **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)



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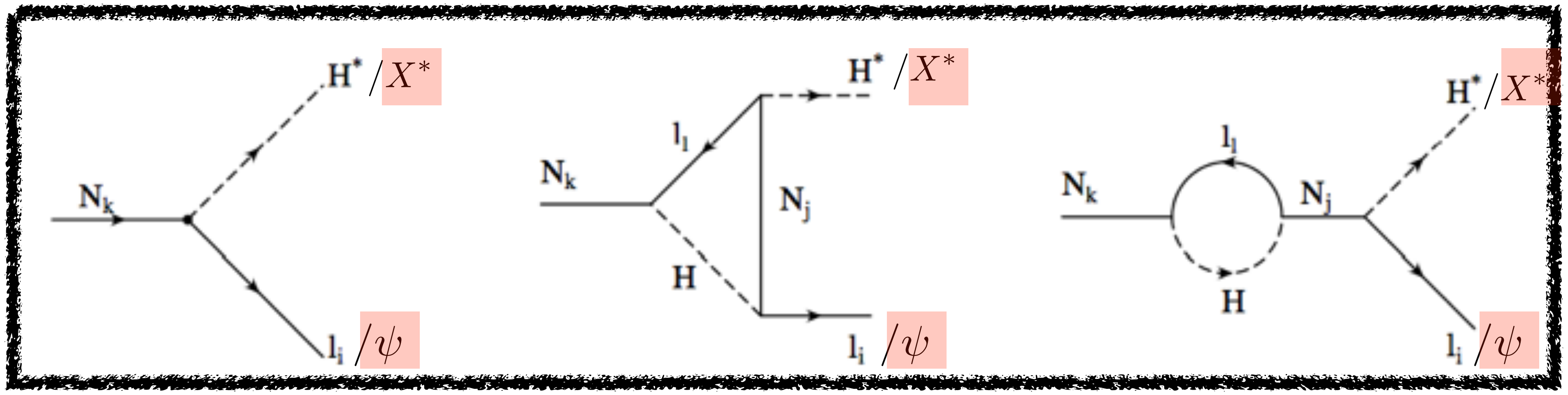

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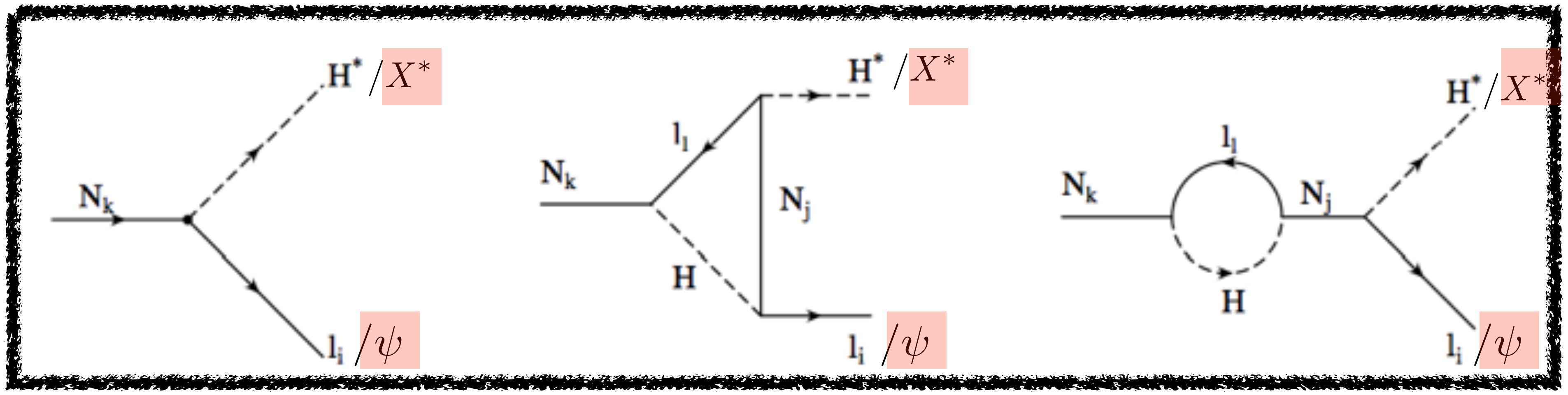
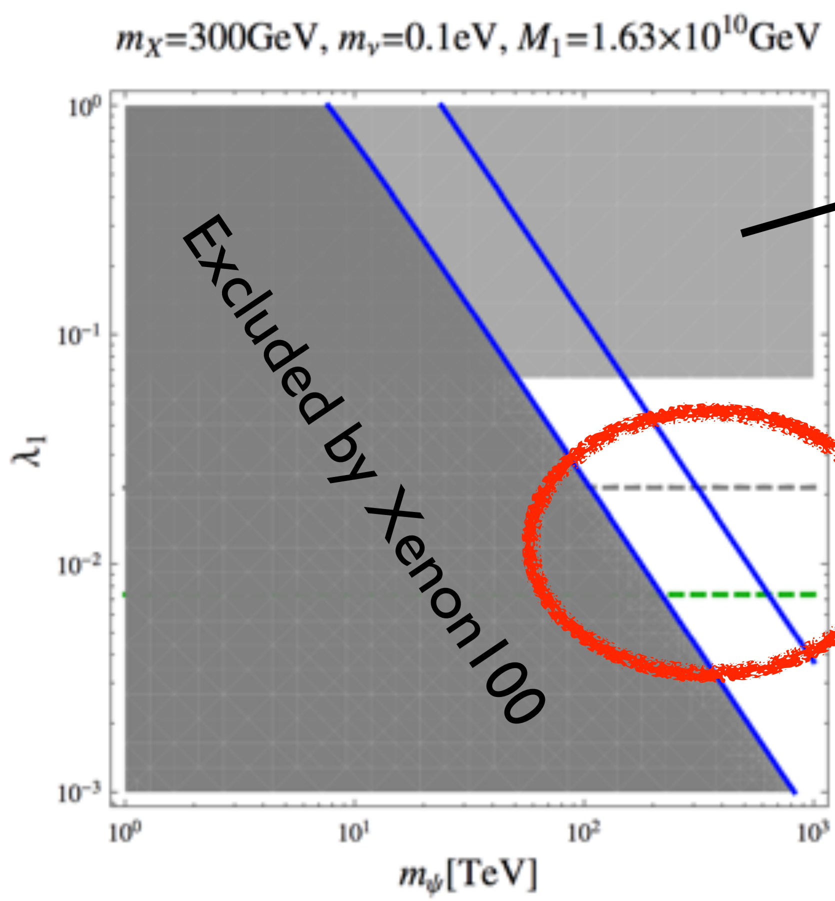




Light gray: narrow width approx. is invalid

White between blue lines:

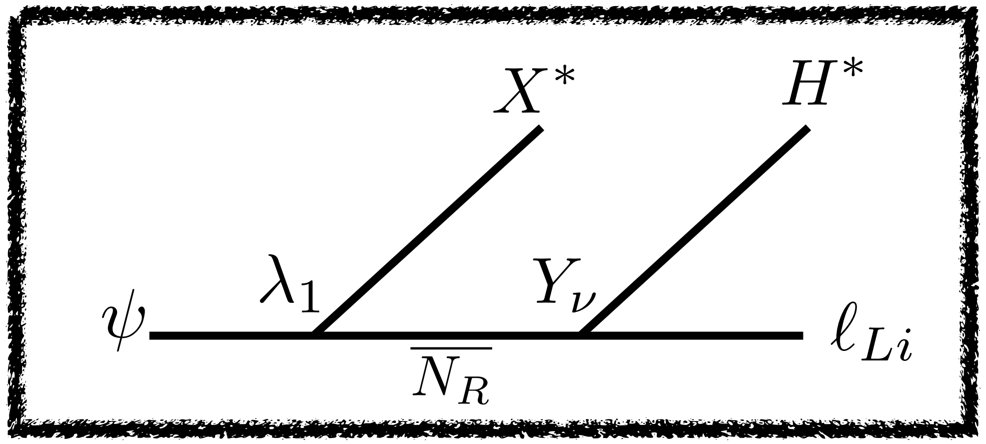
$$1 \leq \langle\sigma v\rangle^{\rm tot}_{\rm ann}/\langle\sigma v\rangle^{\rm th}_{\rm ann} \lesssim 5$$

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!

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

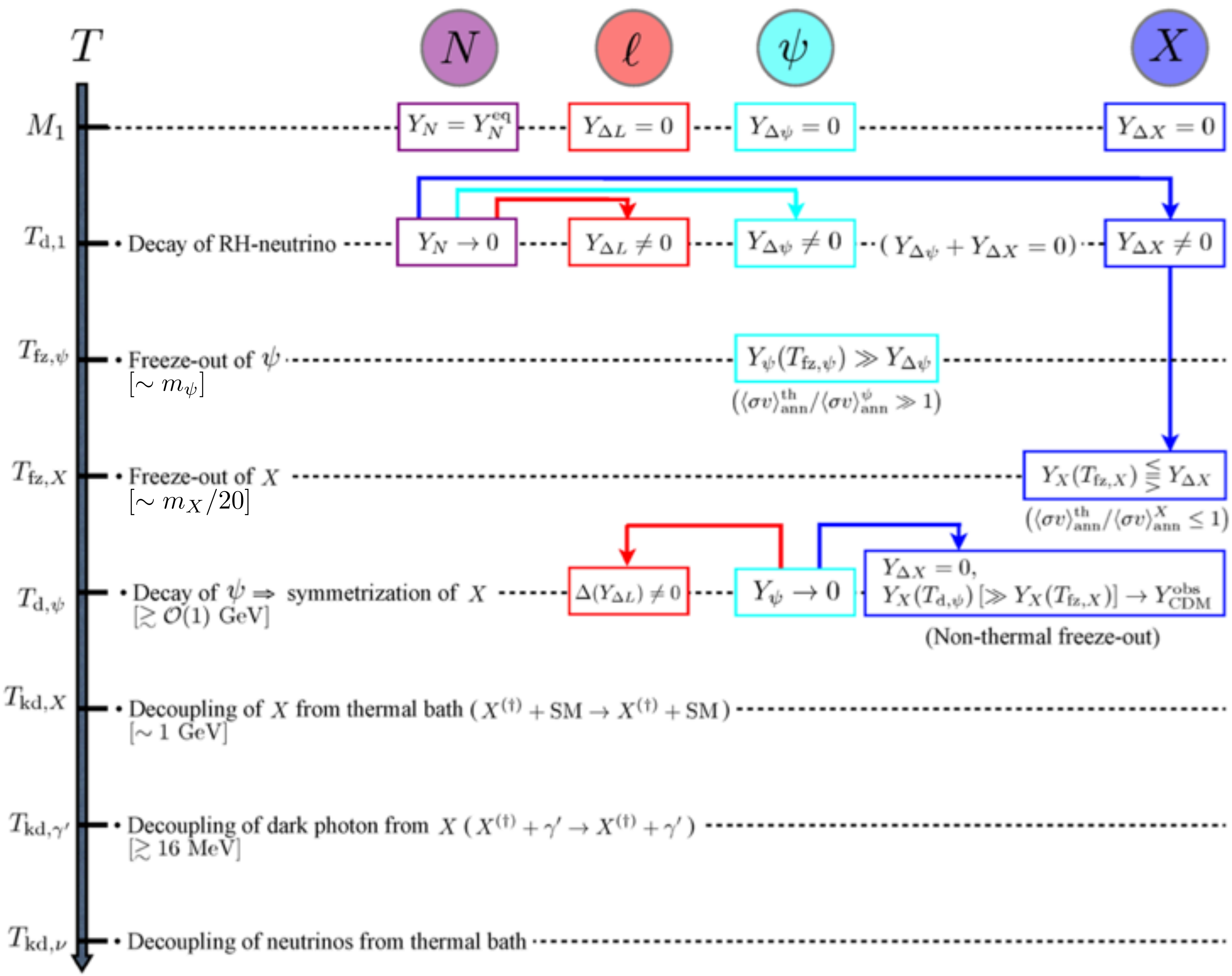
$$Y_\psi(T_{\rm fz}^{\psi}) = \frac{3.79\left(\sqrt{8\pi}\right)^{-1} g_*^{1/2}/g_{*S}\, x_{\rm fz}^{\psi}}{m_\psi M_{\rm P} \langle \sigma v\rangle_{\rm ann}^{\psi}} \simeq 0.05\, \frac{x_{\rm fz}^{\psi}}{\alpha_X^2}\frac{m_\psi}{M_{\rm P}}$$

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

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

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

Thermal history
(leptogenesis and DM production)

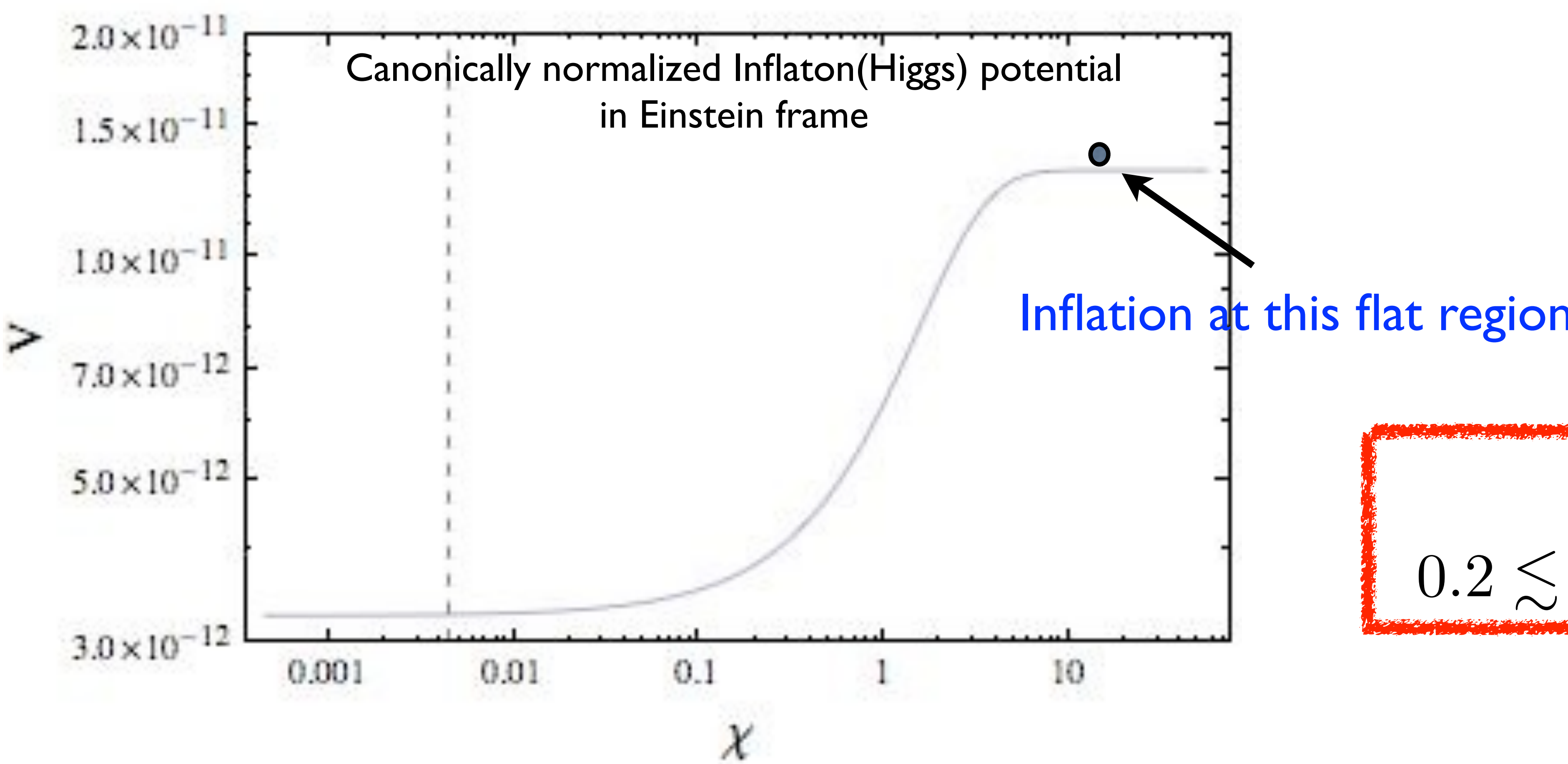


Higgs inflation in Higgs-singlet system

[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 $\xi_h,\ \xi_x \gg 1$



$$\boxed{\begin{array}{r} \lambda_X \lesssim 0.23 \\ 0.2 \lesssim \lambda_{HX} \lesssim 0.6 \end{array}}$$

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

* Fermion dark matter requires a real scalar mediator which is mixed with SM Higgs.

* Unbroken U(1)$_X$ allows a sizable contribution to the extra radiation.

Note that "mu < 1" if CDM is fermion, whether U(1)x is broken or not

And Universal Suppression

Local Gauge Principle
Enforced to DM Physics
in the models presented

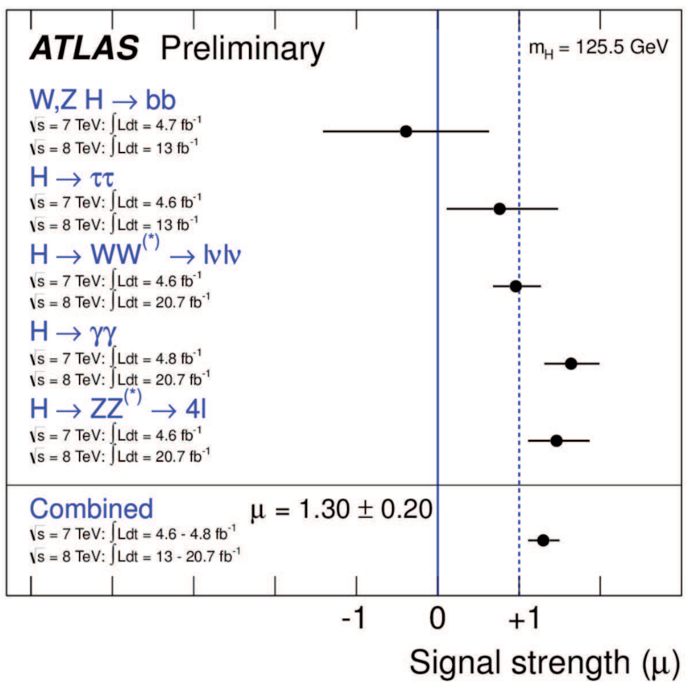
We got a set of predictions
consistent with all the
observations available so far

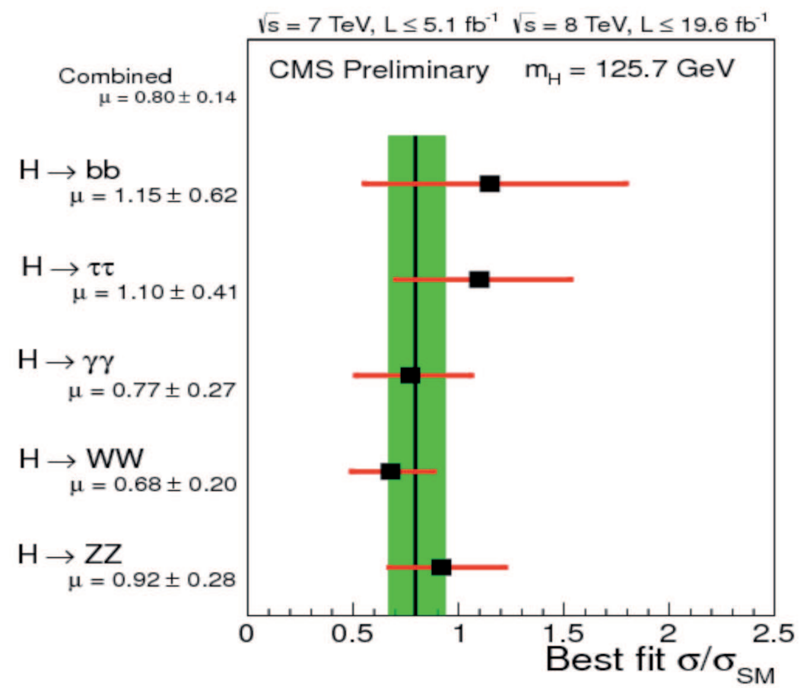
Nontrivial and Interesting possibility

Updates@LHCP

Signal Strengths

$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$





Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = \mathbf{0.96 \pm 0.12}$$

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 be an alternative of NMSM, 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)