An alternative to the new minimal SM

P. Ko (KIAS)
with S. Baek and W.I. Park (in preparation)

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Contents

- Brief review of new minimal SM
- Hidden sector CDM models w/ Higgs portal
- Higgs Inflation
- Our proposal (Model, and particle physics and cosmological aspects thereof)

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Experiments
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Why New Physics ?

- SM : very successful but has to be extended
- Neutrino masses and mixings
- Baryogenesis
- Nonbaryonic CDM
- Inflation
- What would be the simplest NP model ??

New minimal SM

(Davoudiasl, Kitano, Li,Murayama)
hep-ph/0405097

SM Lagrangian

$$
\begin{aligned}
\mathcal{L}_{MSM} = & -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\
& -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\
& +|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i \\
& +\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\
& -\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right). (1)
\end{aligned}
$$

Scalar CDM

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

Neutrino mass and Leptogenesis

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

Inflation

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

Interactions

$$\begin{aligned} V_{RH} &= \mu_1 \varphi |H|^2 + \mu_2 \varphi S^2 + \kappa_H \varphi^2 |H|^2 + \kappa_S \varphi^2 S^2 \\ &\quad + (y_N^{\alpha\beta} \varphi N_\alpha N_\beta + c.c.). \end{aligned}$$

inflation model [18]. Current data prefer the quadratic term to drive inflation [19, 20] with $m \simeq 1.8 \times 10^{13}$ GeV [21], while $\mu \lesssim 10^6$ GeV and $\kappa \lesssim 10^{-14}$.[32]

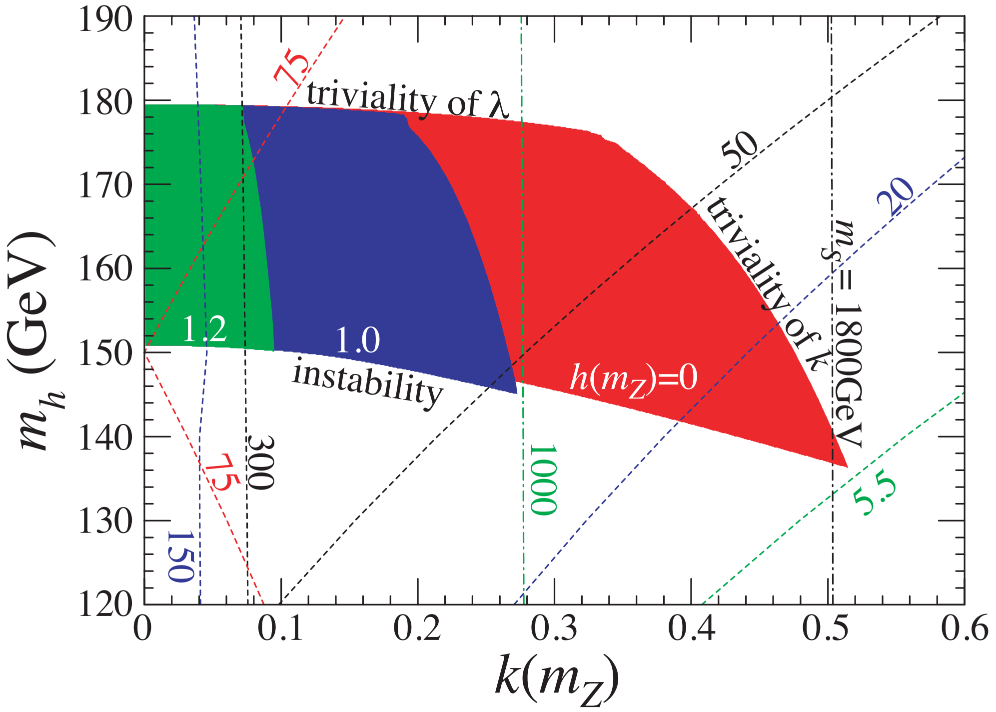


FIG. 1: The region of the NMSM parameter space $(k(m_Z), m_h)$ that satisfies the stability and triviality bounds, for $h(m_Z) = 0$, 1.0, and 1.2. Also the preferred values from the cosmic abundance $\Omega_S h^2 = 0.11$ are shown for various m_S. We used $y(m_Z) = 1.0$.

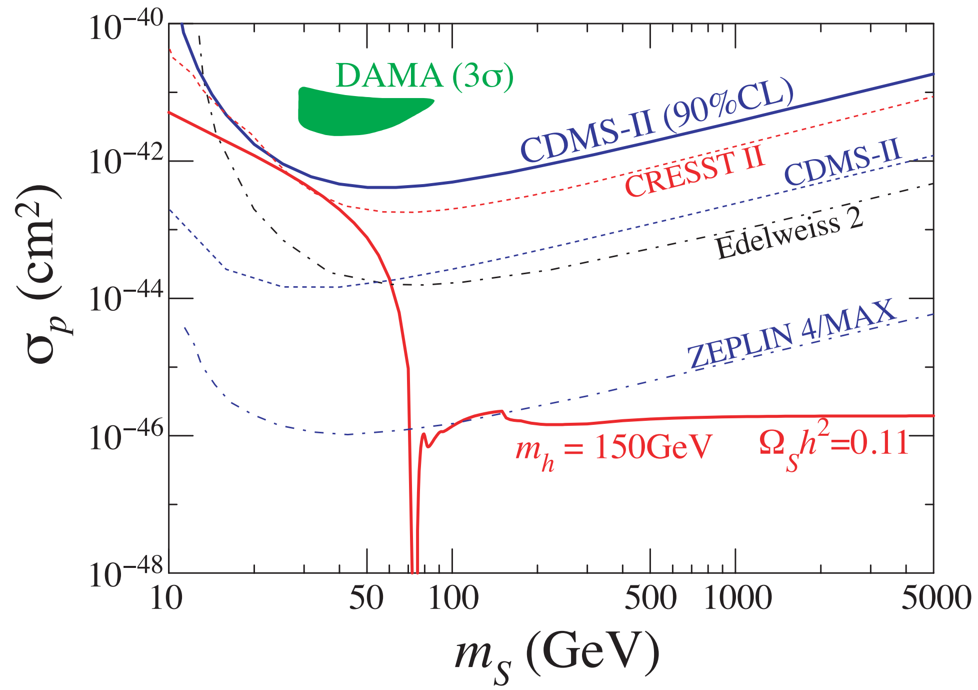


FIG. 2: The elastic scattering cross section of Dark Matter from nucleons in NMSM, as a function of the Dark Matter particle mass m_S for $m_h = 150$ GeV. Note that the region $m_S \gtrsim 1.8$ TeV is disallowed by the triviality bound on k. Also shown are the experimental bounds from CDMS-II [25] and DAMA [26], as well as improved sensitivities expected in the future [27].

Our Proposal For a New Model:

S, N, Inflaton → N, X, psi, X_mu

Implement Z2 to unbroken local dark symmetry

Main Issues

- Origin of Z_2 for dark matter stability ? Is it global or local Z_2 symmetry ?
- Global sym is expected to be broken at least by Planck scale suppressed higher dim operators. Then Z_2 should be local discrete gauge symmetry : Model becomes more complicated than the usual scalar DM model (in preparation)
- What is the nature of inflaton after all ?

Our Basic Assumptions

- Local Dark Gauge Symmetry guarantees DM stability
- DM in a hidden sector
- Singlet Portal to the hidden sector
- Higgs inflation (Shaposhinikov et al.)

Why is the DM stable?

- Stability is guaranteed by a symmetry.
- If it is a global symmetry, it can be broken by gravitational effect, and there can be

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

Too short life-time unless kinematically forbidden

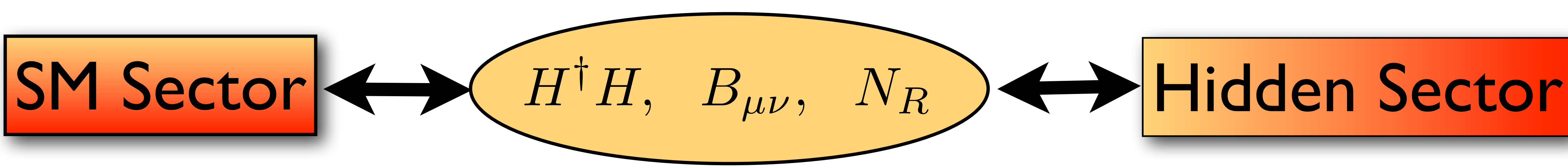
So I assume a local symmetry for DM stability

Hidden Sector

- Less constrained by EWPT and CKMology
- Generic in many BSMs including SUSY or Superstring models
- Natural setting for nonbaryonic CDMs
- A few generic aspects can be derived without knowing the details of the hidden sector (gauge group, matter contents etc)

Singlet Portal

- If there is a hidden sector, then we need a portal to it in order not to overclose the universe
- There are only three unique gauge singlets in the SM + RH neutrinos



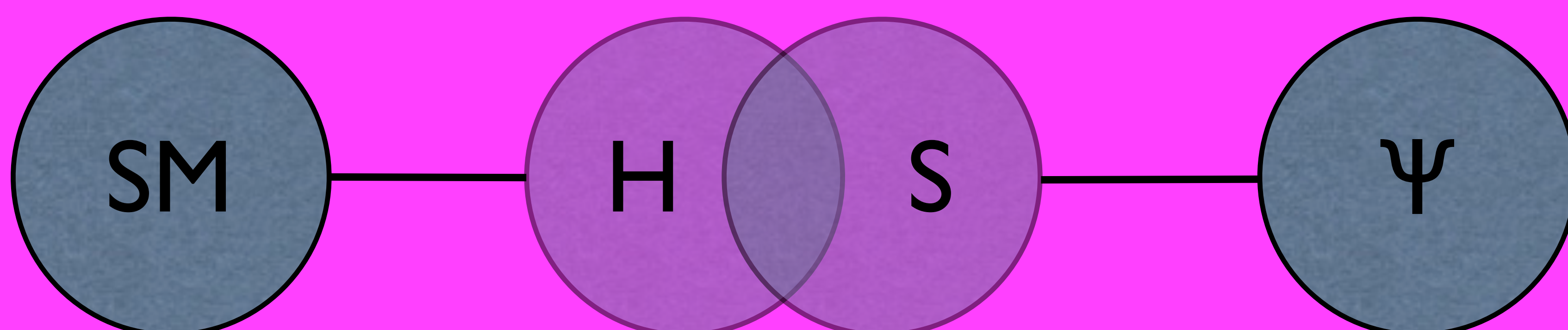
Ratiocination

- A scenario of a singlet fermion dark matter with global U(1) for dark matter

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ &\quad + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4 \\ &\quad + \overline{\psi}(i \not\partial - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi\end{aligned}$$

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

Ratiocination

- Mixing and Eigenstates of Higgs-like bosons

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2}\lambda_{HS} v_S^2,$$
$$m_S^2 = -\frac{\mu_S^3}{v_S} - \mu'_S v_S - \lambda_S v_S^2 - \frac{\mu_{HS} v_H^2}{2 v_S} - \frac{1}{2}\lambda_{HS} v_H^2,$$

at vacuum

$$M^2_{\rm Higgs} \equiv \begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_1 = h\cos\alpha - s\sin\alpha,$$
$$H_2 = h\sin\alpha + s\cos\alpha.$$

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$r_i = \frac{\sigma_i \, \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \, \mathrm{Br}(h \to \mathrm{SM})}$$

$$r_1 = \frac{\cos^4\alpha \, \Gamma^{\mathrm{SM}}_{H_1}}{\cos^2\alpha \, \Gamma^{\mathrm{SM}}_{H_1} + \sin^2\alpha \, \Gamma^{\mathrm{hid}}_{H_1}}$$

$$r_2 = \frac{\sin^4\alpha \, \Gamma^{\mathrm{SM}}_{H_2}}{\sin^2\alpha \, \Gamma^{\mathrm{SM}}_{H_2} + \cos^2\alpha \, \Gamma^{\mathrm{hid}}_{H_2} + \Gamma_{H_2 \to H_1 H_1}}$$

$0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1$

Invisible decay mode is not necessary!

If r_i > 1 for any single channel,
this model will be excluded !!

Constraints

EW precision observables

Peskin & Takeuchi, Phys.Rev.Lett.65,964(1990)

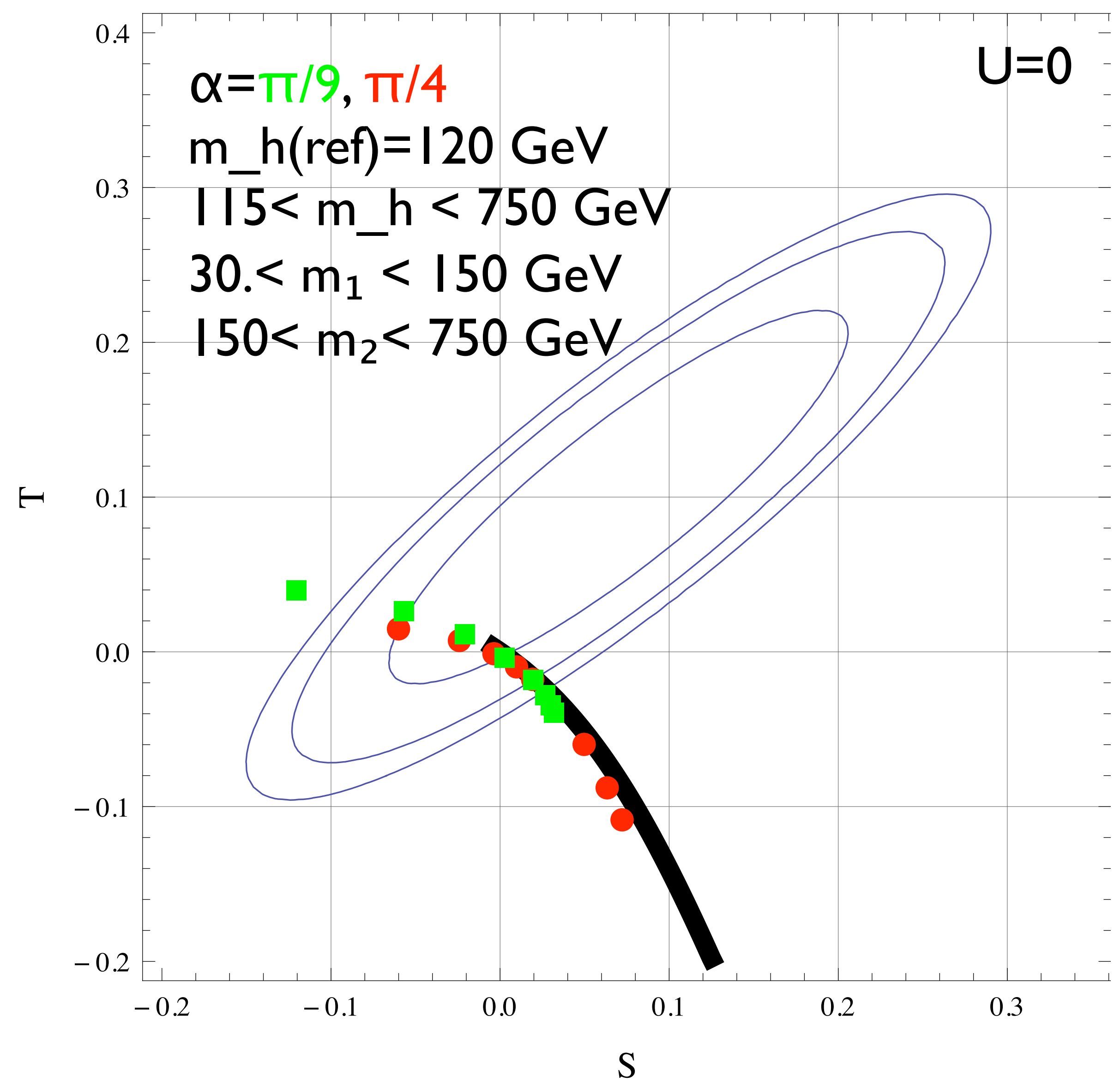
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2}\right]$$

$$\alpha_{\rm em} T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha_{\rm em} U = 4 s_W^2 \left[\frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2}\right]$$

$$S = \cos^2\alpha \; S(m_1) + \sin^2\alpha \; S(m_2)$$

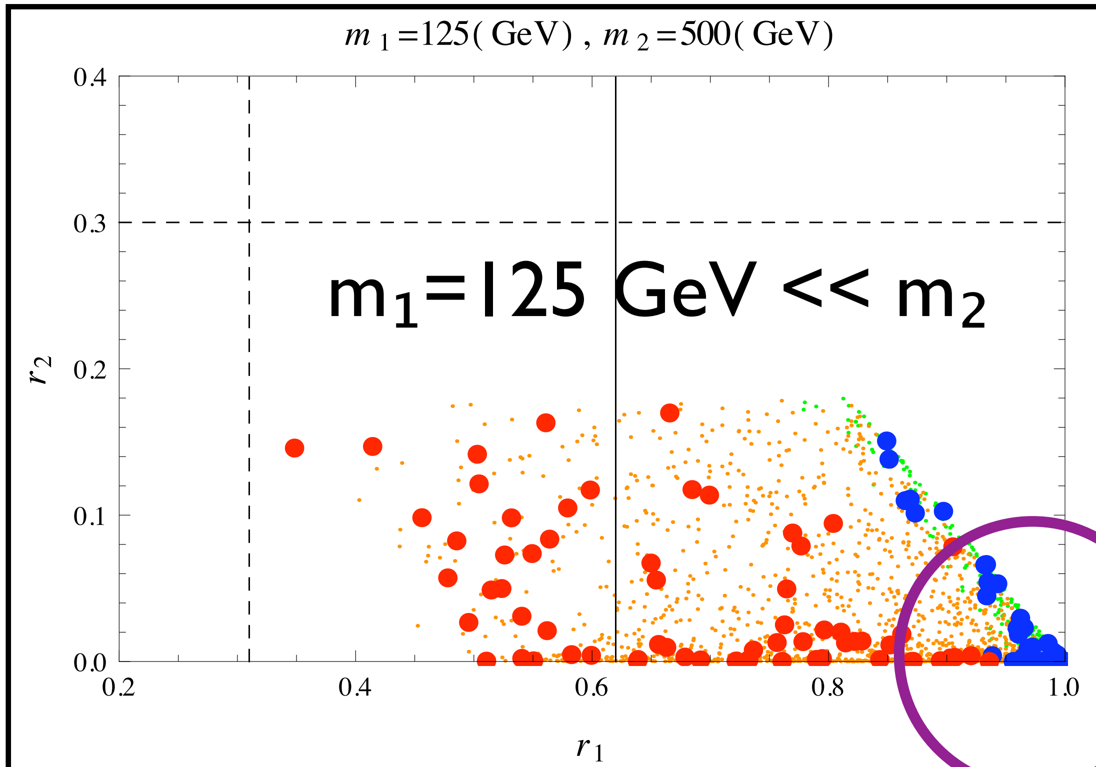
Same for T and U

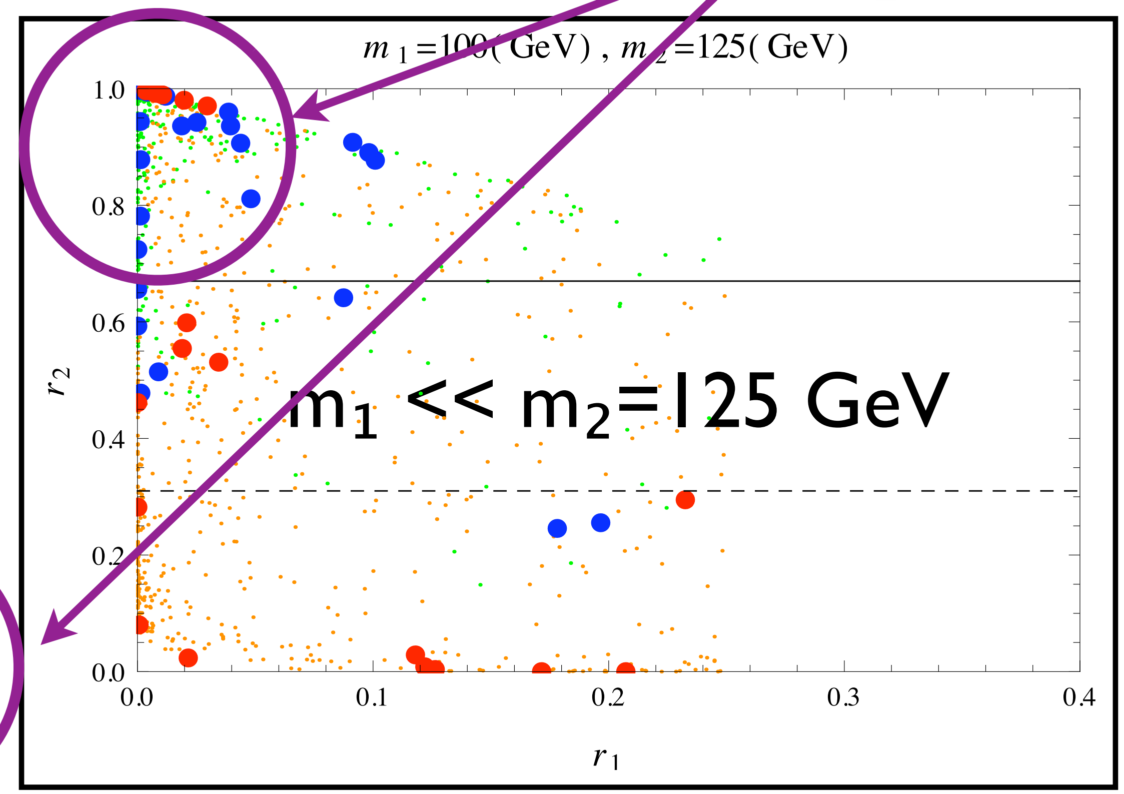


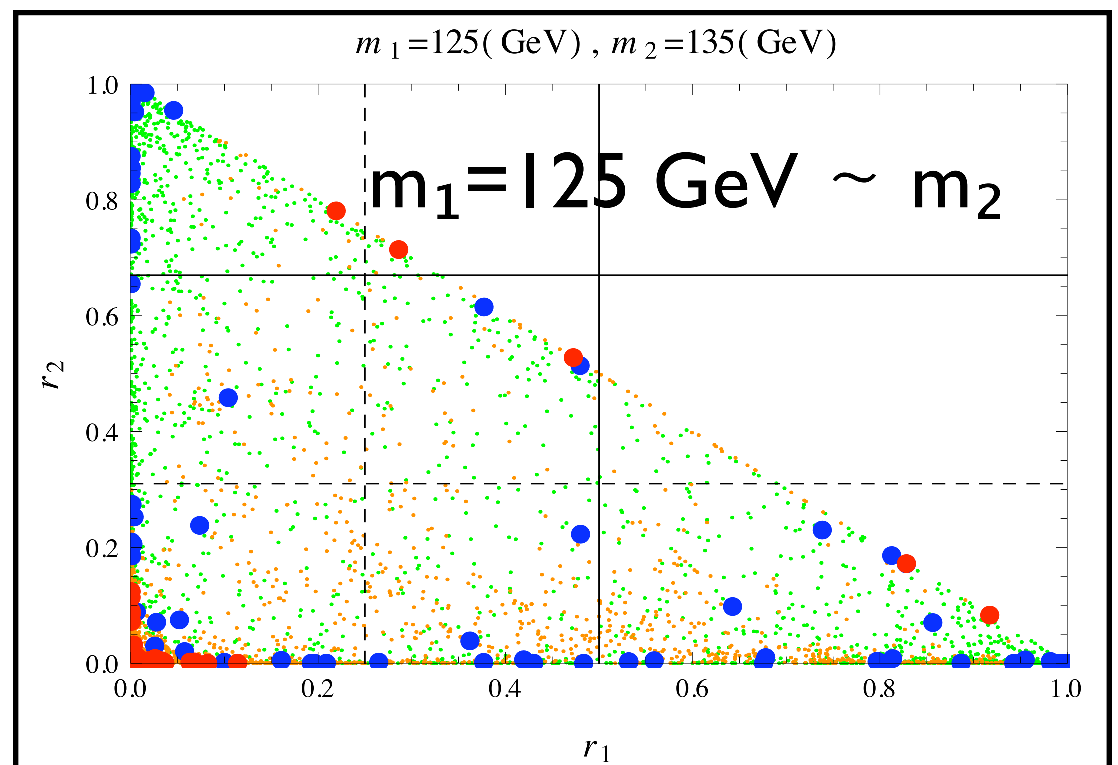
Discovery possibility

- Signal strength (r_2 vs r_1)

LHC data for 125 GeV resonance







: L= 5 fb^{-1} for 3σ Sig.
: L=10 fb^{-1} for 3σ Sig.

: Ω(x),σ_p(x)
: Ω(x),σ_p(o)
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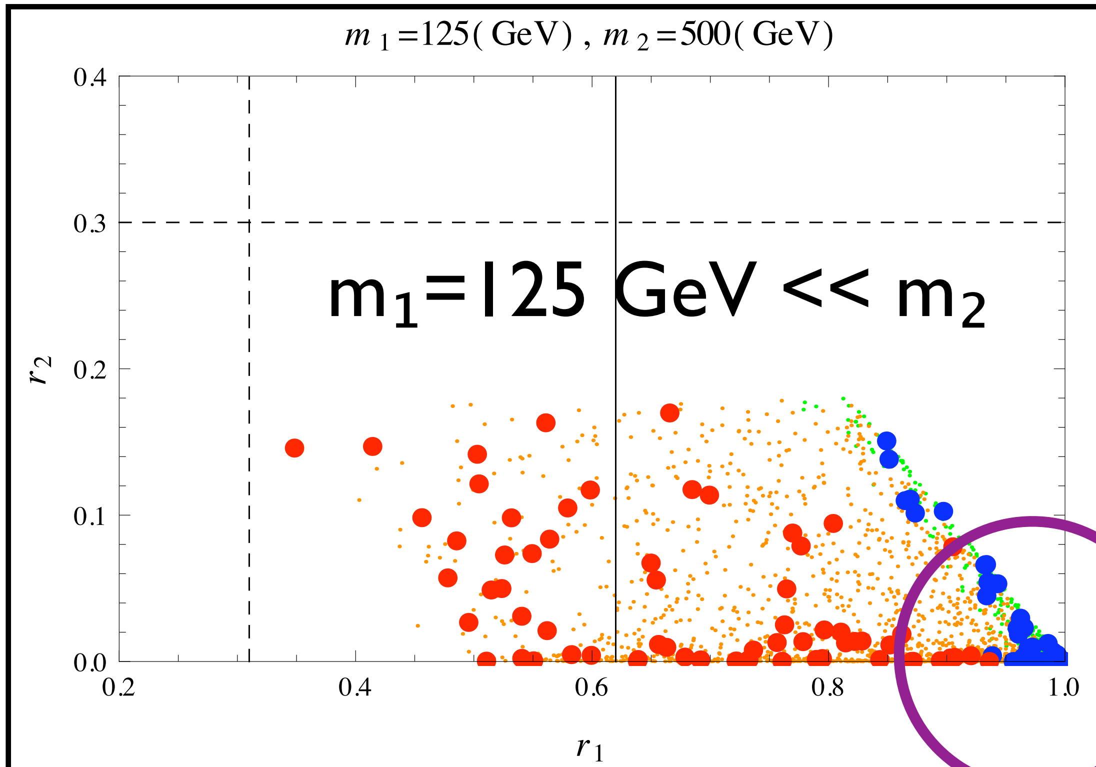

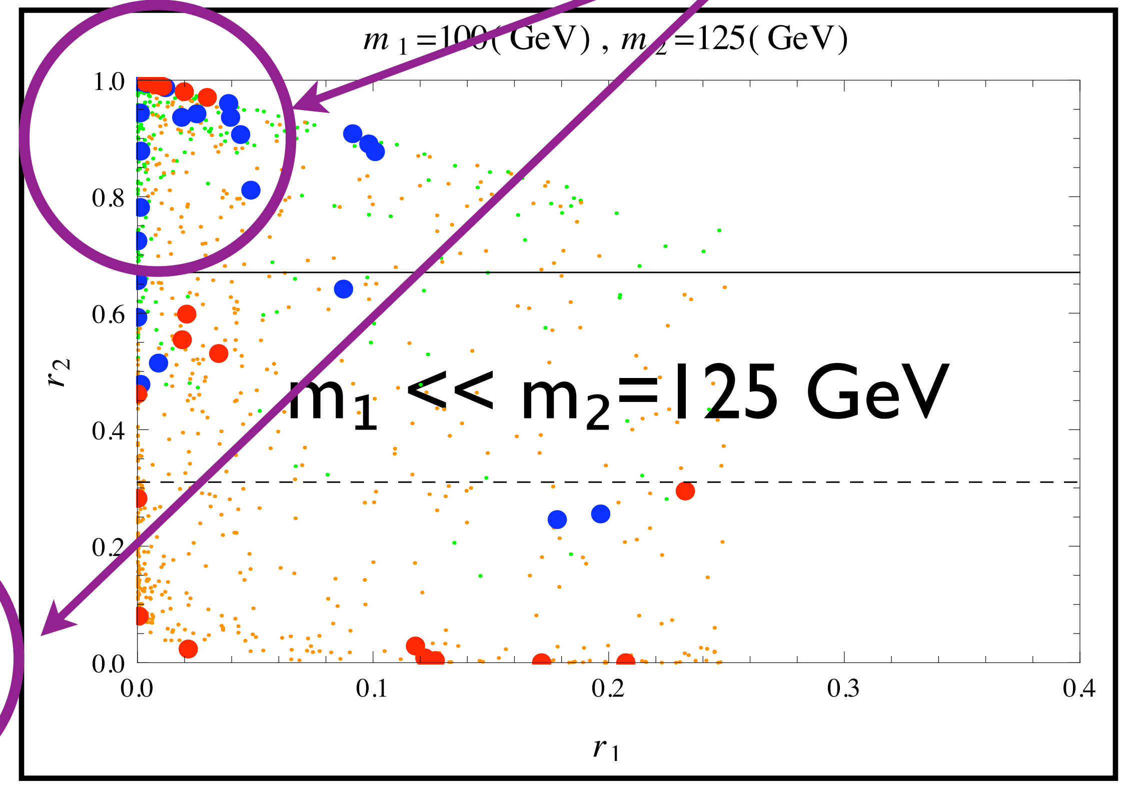

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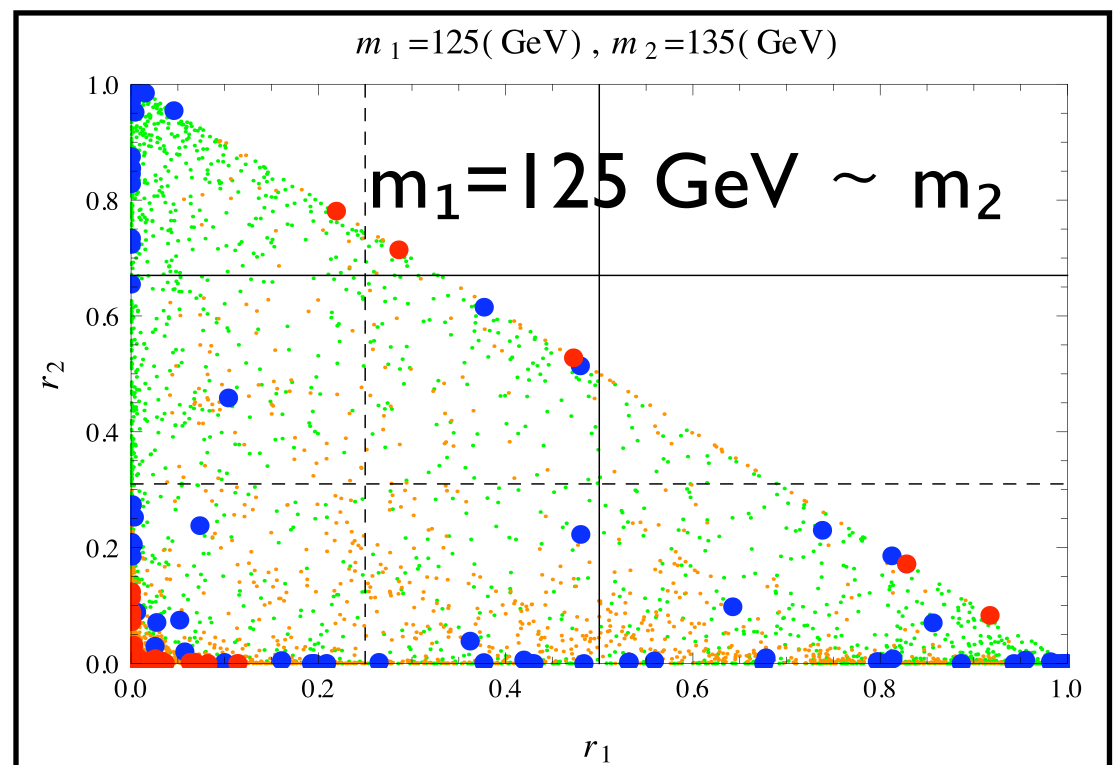

: Ω(x),σ_p(x)
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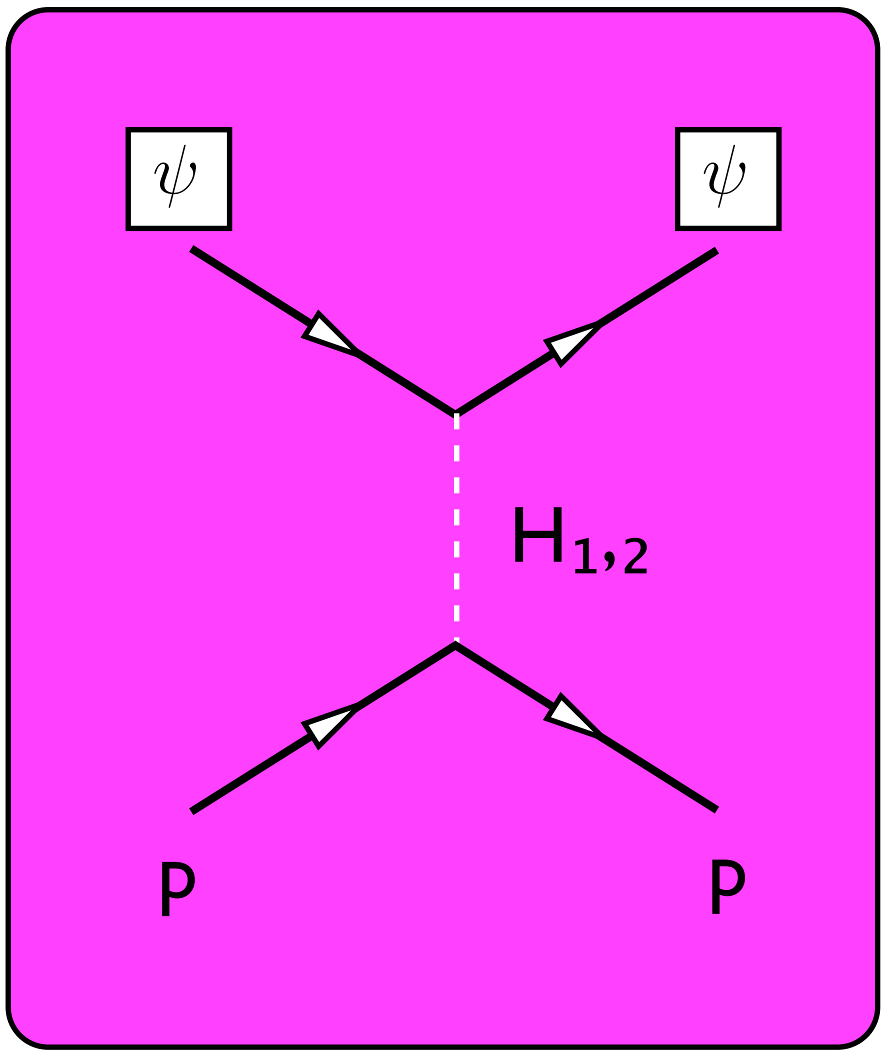
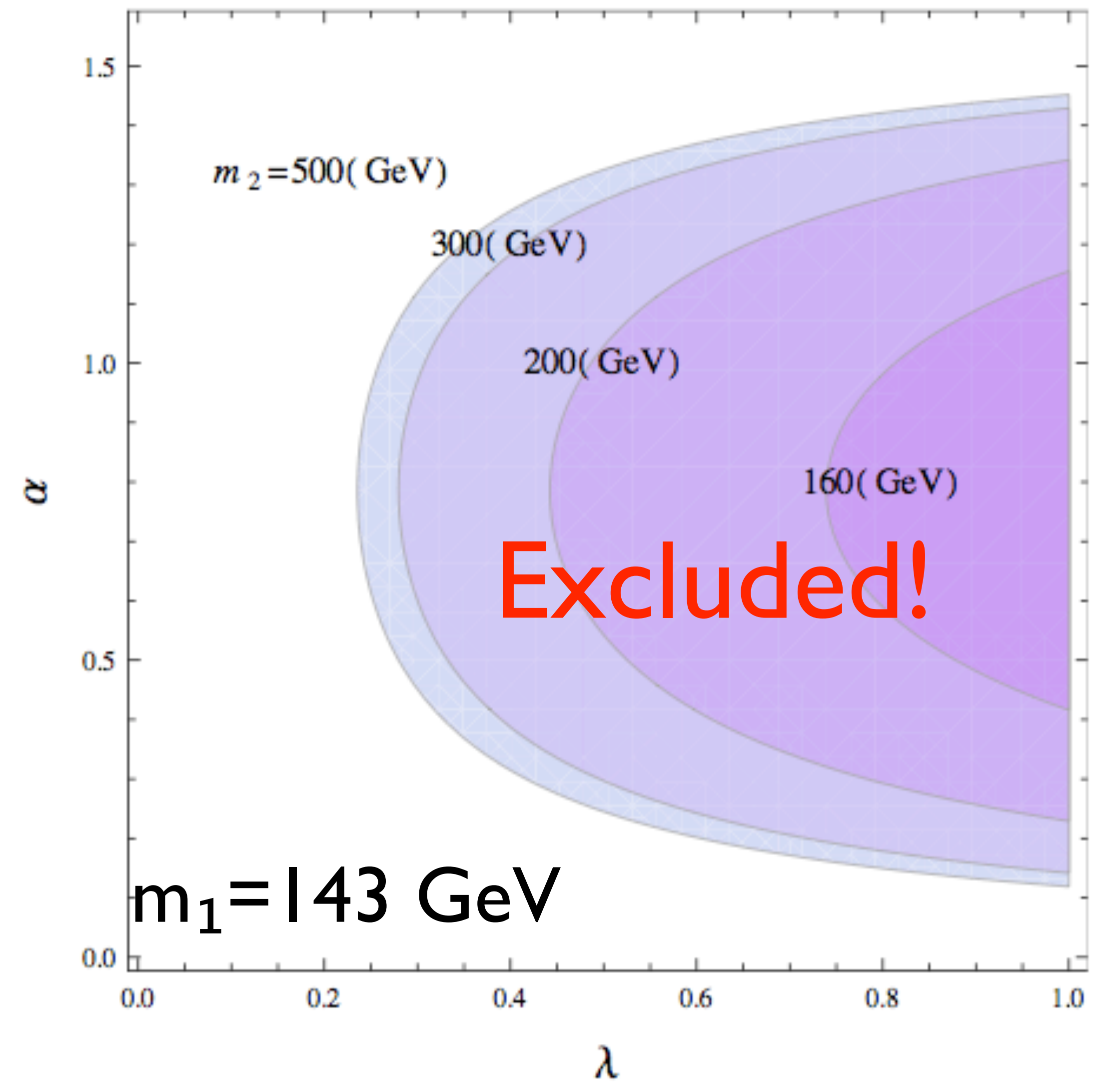
Constraints

- Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi}\mu^2\lambda_p^2 \simeq 2.7\times 10^{-2}\frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda\sin\alpha\cos\alpha\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)\right|^2$$





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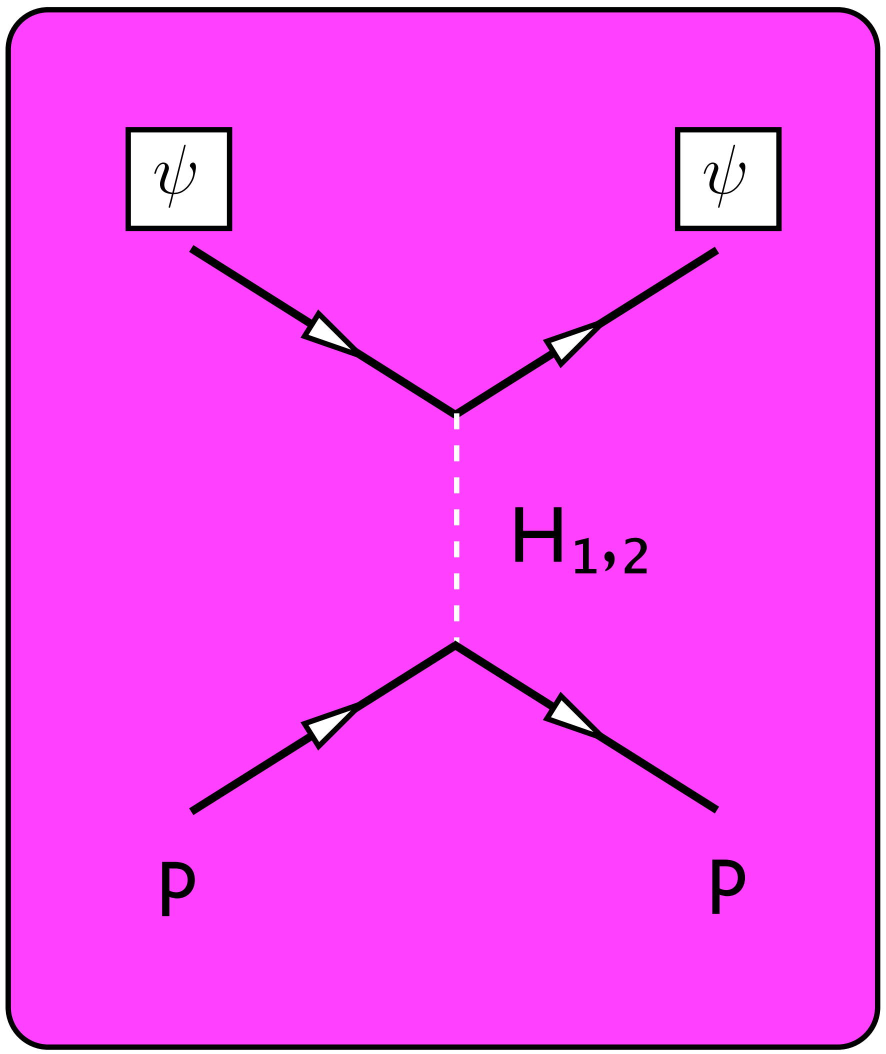
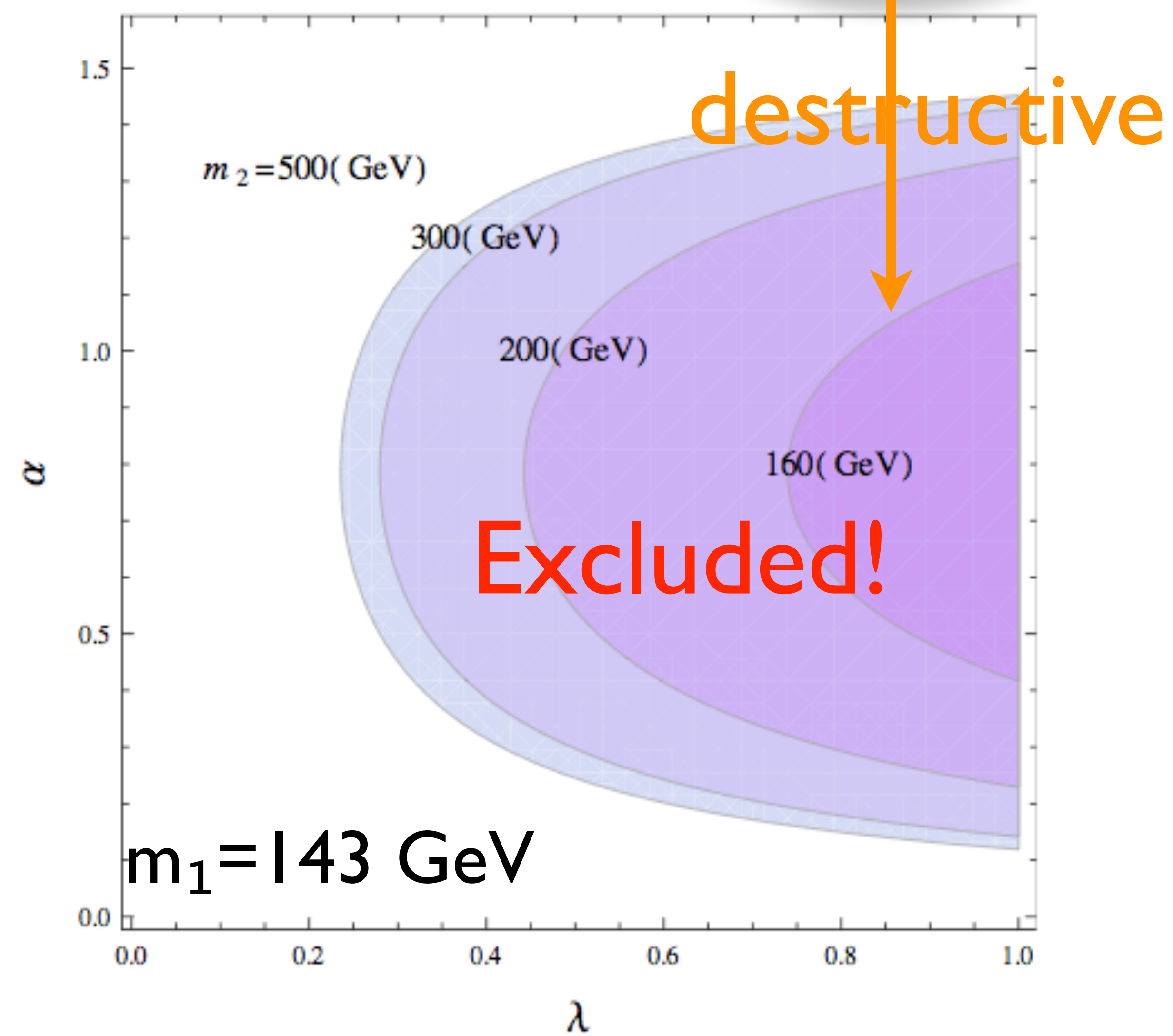




- We don’t use the effective lagrangian approach (nonrenormalizable interactions), since we don’t know the mass scale related with the CDM

$$\mathcal{L}_{\rm eff} = \overline{\psi}\left(m_0 + \frac{H^\dagger H}{\Lambda}\right)\psi.$$

- Only one Higgs boson (alpha = 0)

- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Similar for Higgs portal Vector DM

$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- A complete model should be something like this:

$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \frac{\lambda_\Phi}{4}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2$$
$$-\lambda_{H\Phi}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right) ,$$

$$\langle 0|\phi_X|0\rangle = v_X + h_X(x)$$

- There appear a new singlet scalar h_X from phi_X , which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model
- Important to consider a minimal renormalizable model to discuss physics correctly
- Baek, Ko, Park and Senaha, arXiv:1212.2131

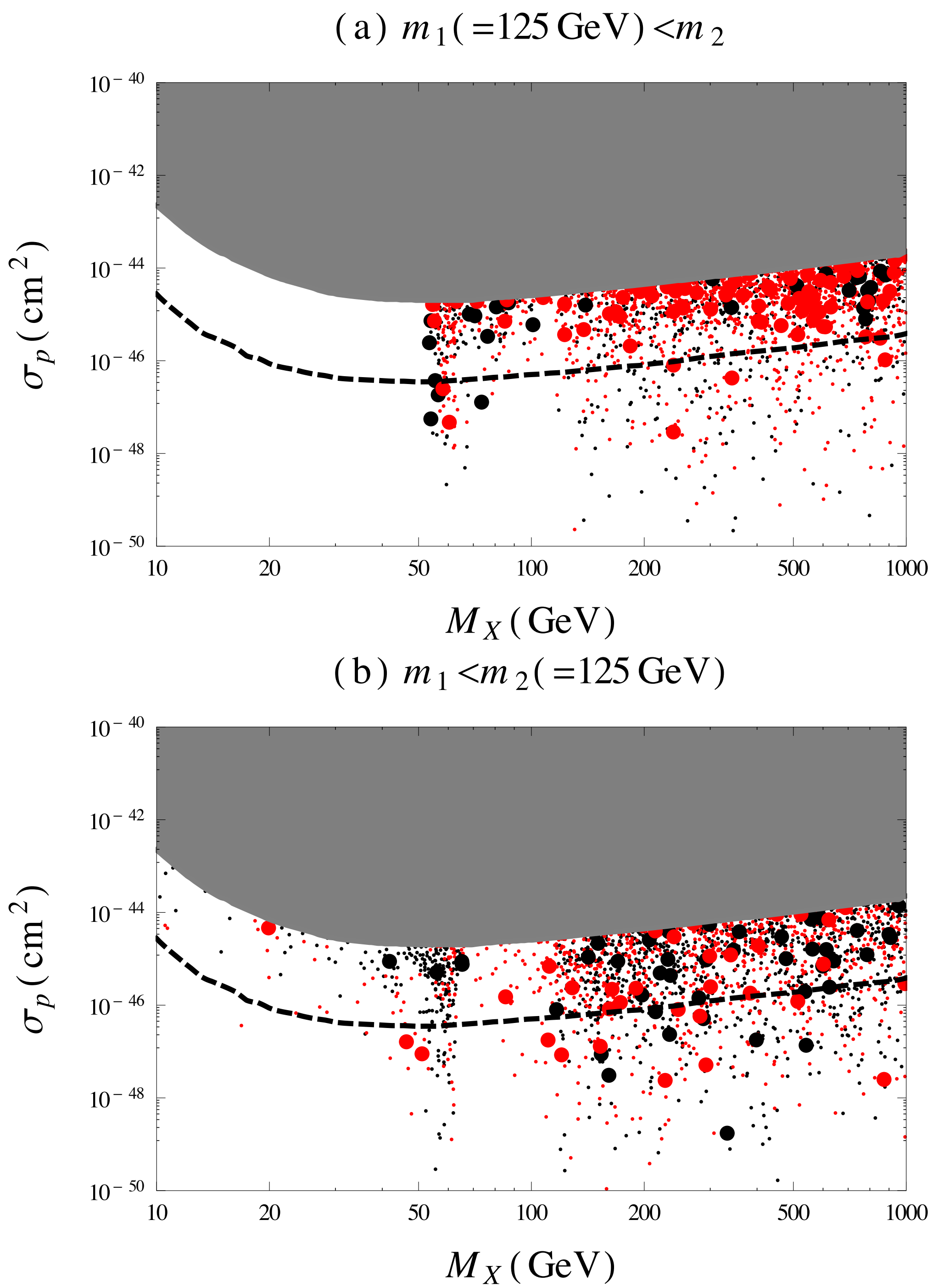


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity of the next XENON experiment, XENON1T.

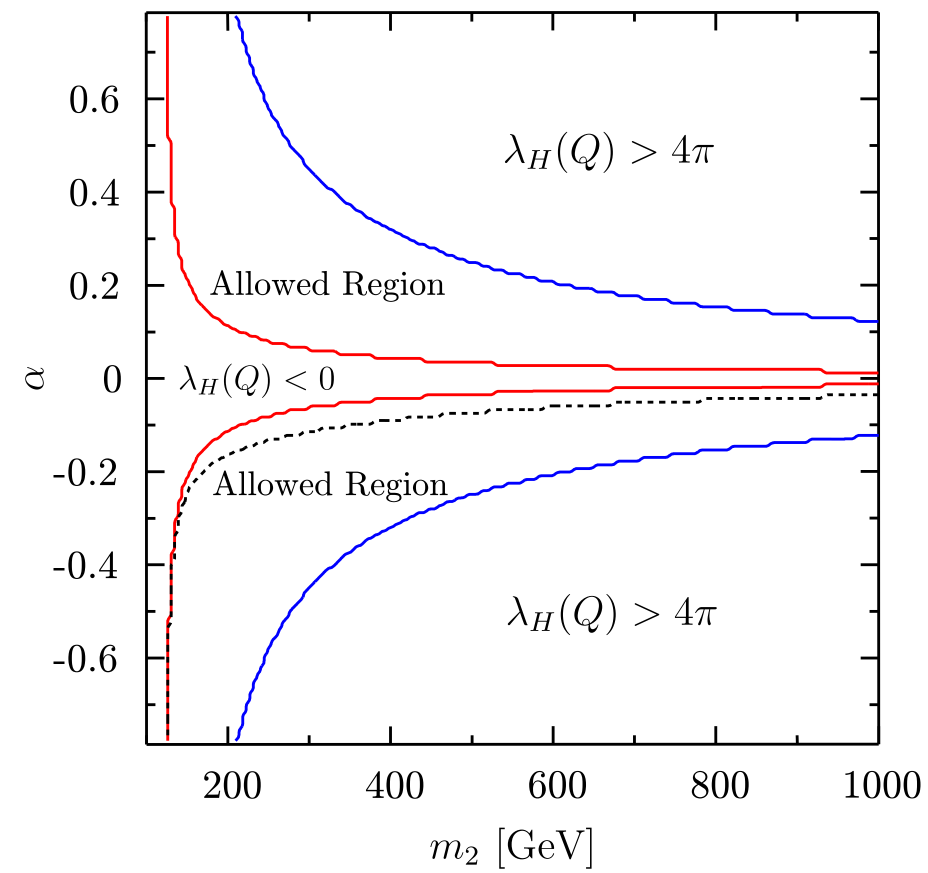


Figure 7. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Comparison with the EFT approach

- SFDM scenario is ruled out in the EFT
- We may lose imformation in DM pheno.

A. Djouadi, et.al. 2011

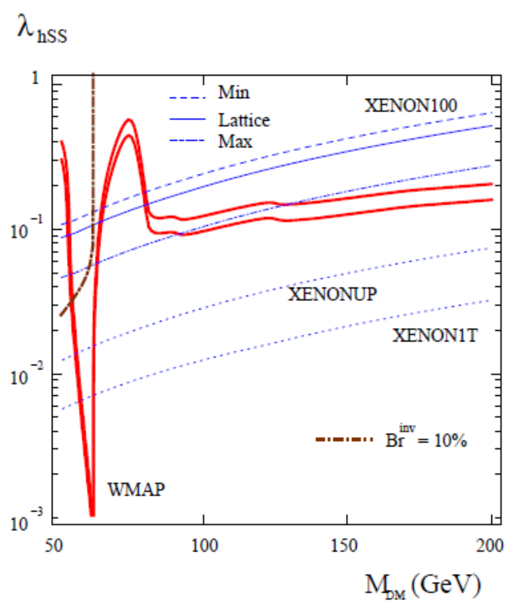


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

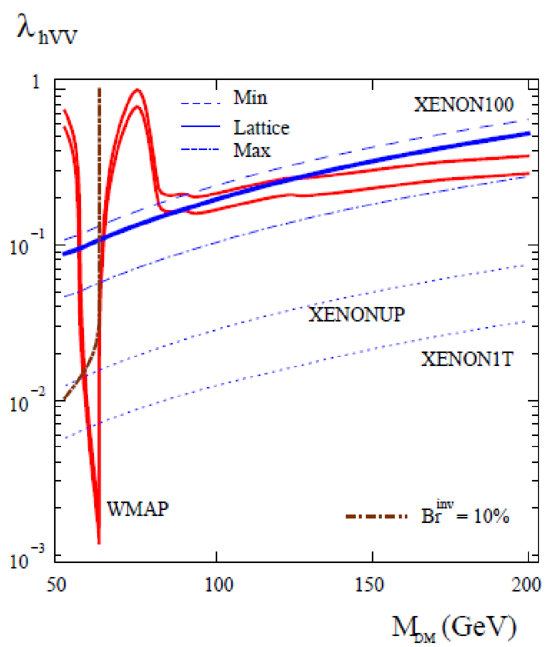


FIG. 2. Same as Fig. 1 for vector DM particles.

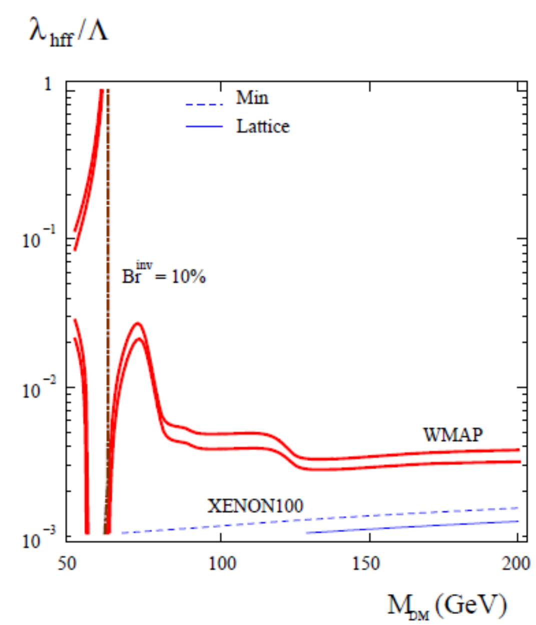
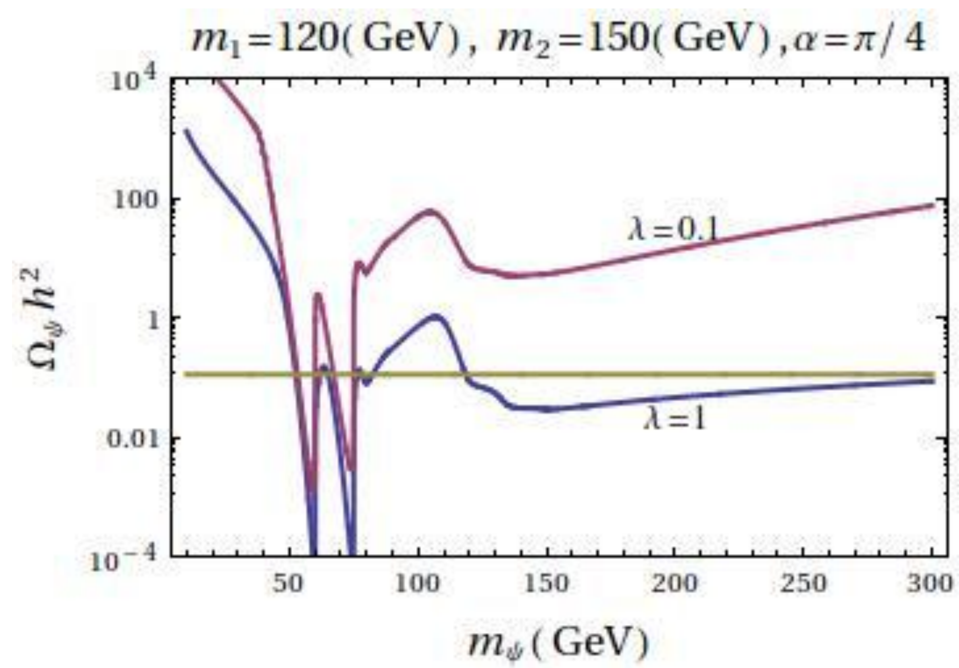


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian, we get different results !

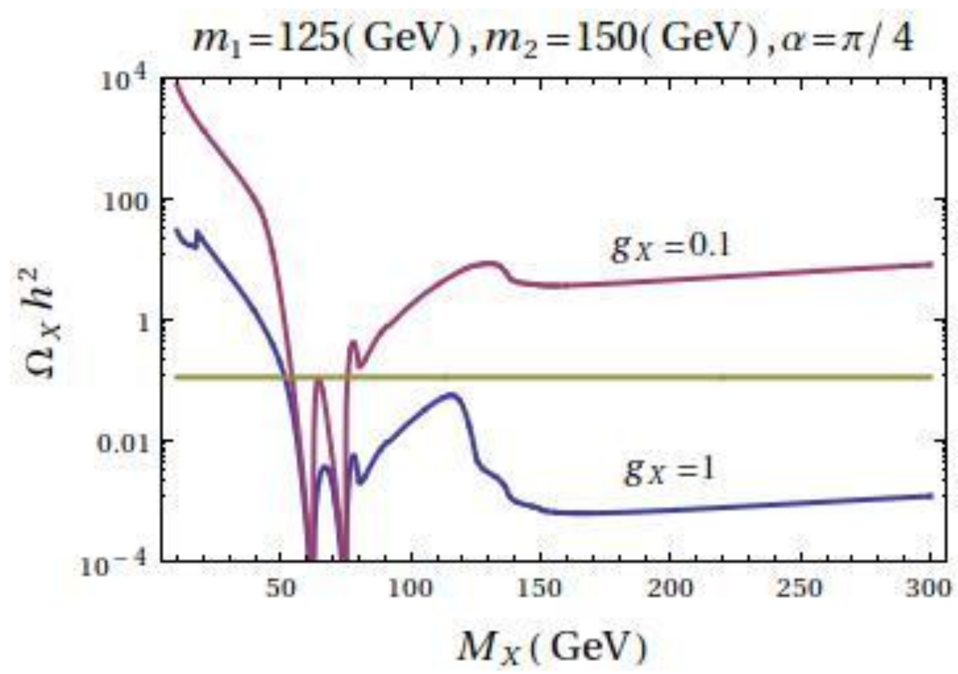
DM relic density

SFDM



P-wave annihilation

VDM



S-wave annihilation

Higgs-DM couplings less constrined due to the GIM-like cancellation mechansim

General Aspects of Higgs portal to a hidden sector

- A singlet acalar S and/or scalar ϕ_X charged under hidden sector gauge group can appear with the couplings with the SM $H^\dagger H$ operators:

$$H^\dagger H S, H^\dagger H S^2, H^\dagger H \phi_X^\dagger \phi_X, S\phi_X^\dagger \phi_X, S^2 \phi_X^\dagger \phi_X$$

- Both S and ϕ_X can develop nonzero VEV's: v_S and v_ϕ, and the fluctuations around these vacuum will be additional real singlet scalars from the viewpoint of SM gauge interactions.

- There will be generic mixings among h_{SM}, s and ϕ_X, resulting a number of neutral scalar bosons. Only h_{SM} couples to the SM fermions and the weak gauge bosons

- More than one neutral scalar bosons with reduced couplings to the SM fermions and weak gauge bosons
- No extra charged scalar bosons
- Invisible Higgs (or scalar boson) decays

Let us consider the mixing between $h_\alpha \equiv (h, s, \phi_{\alpha=1,\dots,n})$. The mass eigenstates $h_i \equiv (h_1, h_2, ..., h_{n+2})$ will be linear combinations of h_α in terms of $SO(n+2)$ matrix O: $h_i = O_i{}^\alpha h_\alpha$ with $OO^T = O^T O = 1$. Then the couplings between h_i and the SM fermions $f\bar{f}$ and the SM weak gauge boson $V = W, Z^0$ are given by

$$G_{if\bar{f}} = \frac{m_f}{v} O_{1j}, \tag{6}$$

$$G_{iVV} = g_V \frac{m_V^2}{v} O_{1j}. \tag{7}$$

$$G_{i\psi_X\overline{\psi_X}} = \lambda_X O_{2i}$$

Then, DM-N scattering amplitude behaves as

$$\text{amp} \sim \lambda_X \sum_i O_{1i} \frac{1}{t - m_i^2} O_{2i} \simeq -\lambda_X \sum_i O_{1i} \frac{1}{m_i^2} O_{i2}^T$$

$$\to -\frac{1}{m^2} \sum_i \left(O_{1i} O_{i2}^T = (OO^T)_{12} = 0 \right)$$

- The cancellation in the DD scattering cross section in the degenerate H_i's is generic (at tree level)
- Similar to the GIM cancellation
- It cannot be seen if we included only the SM Higgs
- This would be also true for other Higgs portal models
- No spin-dependent DD cross section
- If there are new gauge interactions, this conclusion may be not true, because there would be extra contributions from new gauge bosons

General Remarks

- Sometimes we need new fields beyond the SM ones and the CDM, in order to make DM models realistic and theoretically consistent
- If there are light fields in addition to the CDM, the usual Eff. Lag. with SM+CDM would not work
- Better to work with minimal renormalizable model
- See papers by Ko, Omura, Yu on the top FB asym with leptophobic Z' coupling to the RH up-type quarks only : new Higgs doublets coupled to Z' are mandatory in order to make a realistic model

Higgs Inflation

- Higgs can be an inflaton (Shaposhnikov et al) with a large nonminimal coupling

$$L_{\rm tot} = L_{\rm SM} - \frac{M^2}{2} R - \xi H^\dagger H R \,,$$

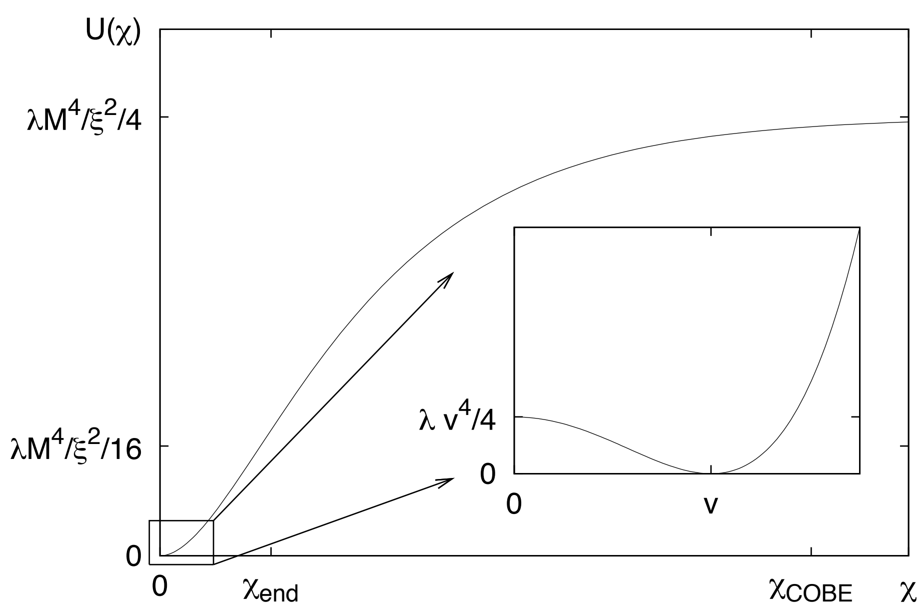


Fig. 1. Effective potential in the Einstein frame.

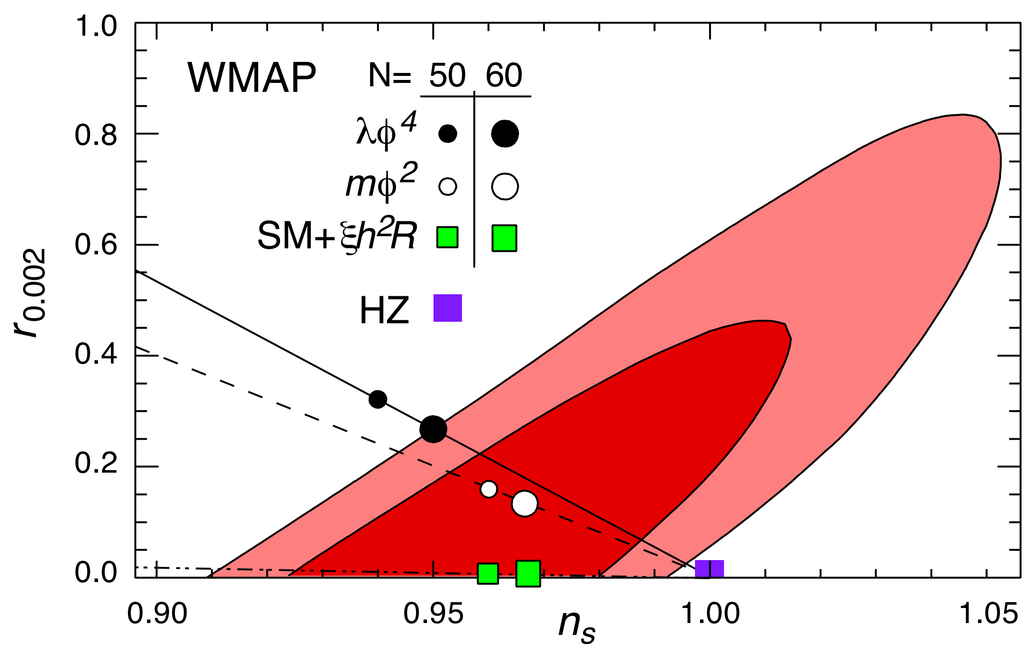


Fig. 2. The allowed WMAP region for inflationary parameters (r, n). The green boxes are our predictions supposing 50 and 60 e–foldings of inflation. Black and white dots are predictions of usual chaotic inflation with $\lambda\phi^4$ and $m^2\phi^2$ potentials, HZ is the Harrison-Zeldovich spectrum.

Higgs Inflation possible, if

$$m_{\min} < m_H < m_{\max} ,$$

$$m_{\min} = [136.7 + (m_t - 171.2) \times 1.95]\,\mathrm{GeV} ,$$

$$m_{\max} = [184.5 + (m_t - 171.2) \times 0.5]\,\mathrm{GeV} .$$

Current LHC data on Higgs mass excludes the Higgs inflation scenario.

However, this could be cured if there are extra scalars such as singlet scalar DM, as in our model

Our proposal

- An alternative new minimal model
- Constraints
- Inflation
- Lepto/darkogenesis
- Conclusion

A new minimal model

- Symmetry

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

(SM fields are neutral under U(1)_X, and vice versa)

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

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

$$\mathcal{L}_{\rm Kinetic} = \bar{\psi}(i\not{D} - m_\psi)\psi + |D_\mu X|^2 - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}B^{\mu\nu}$$

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

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

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

Constraints

Our model is a very simple extension of the SM+RH neutrinos, and can address

* Vacuum stability of Higgs potential (Positive scalar loop correction) (λ_{hx})
* Small scale structure problem (Dark matter self-interaction) (α_X, m_X)
* CDM relic density (Unbroken dark U(1)$_X$) (λ_{hx}, m_X, ε)
* Dark radiation (Massless photon)(ε)
* Lepto/darkogenesis (Asymmetric 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.

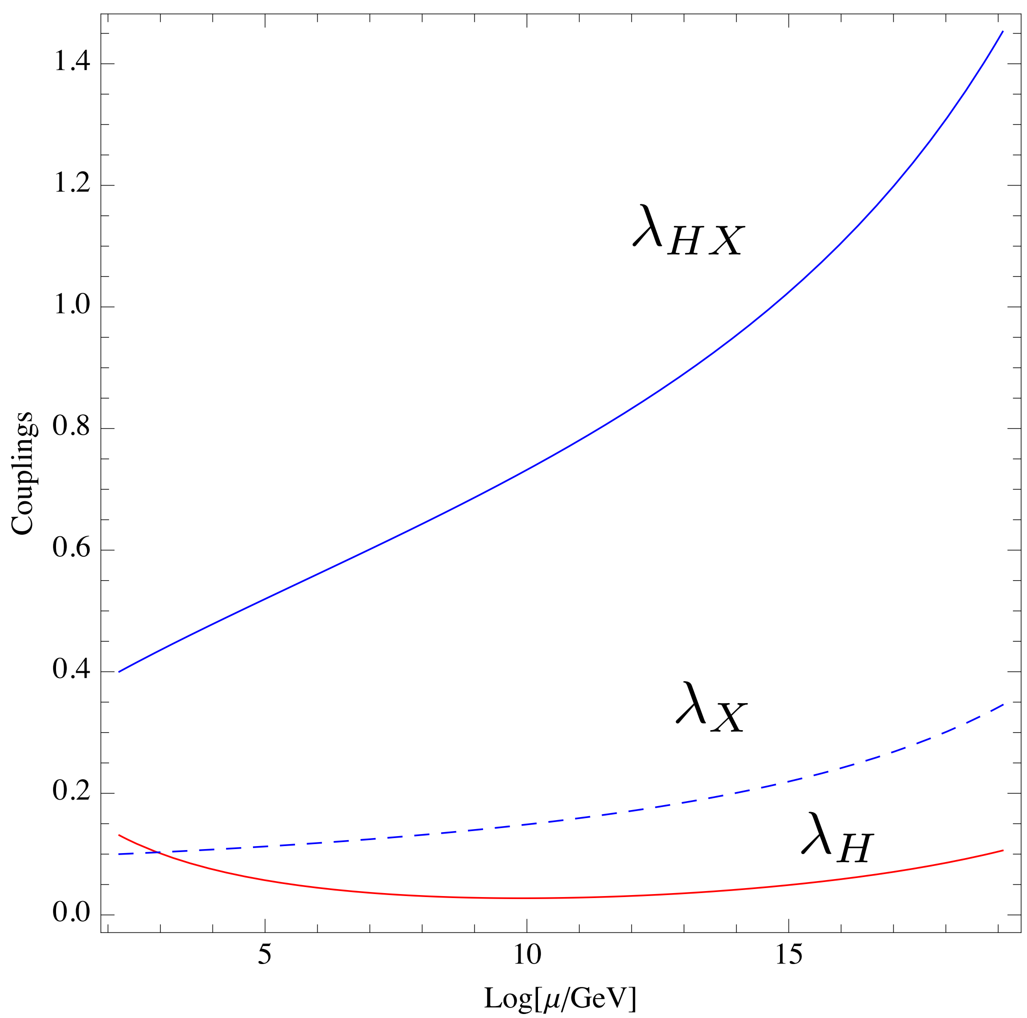
- # Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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

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

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

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

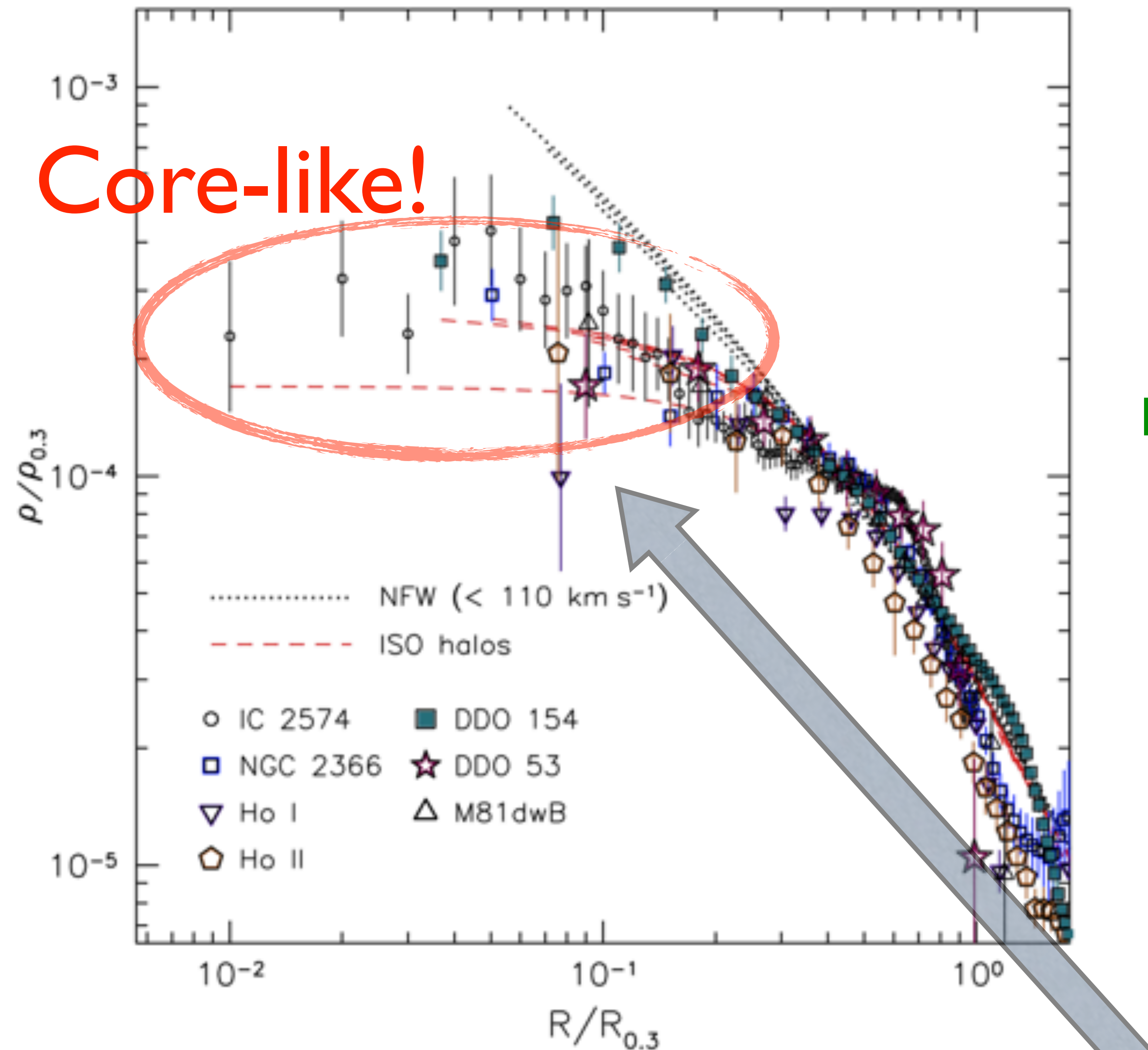


Perturbativitiy

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

vacuum stability Perturbativitiy

- Small scale structure (α_X, m_X)



[S-E. Oh et al., 1011.0899]

Dark matter density profiles of the 7 THINGS dwarf galaxies

- due to massive baryonic outflows from supernovae?

[S-E. Oh et at., 1011.2777; A. Pontzen & F. Governato, 1106.0499; F. Governato et al., 1202.0554]

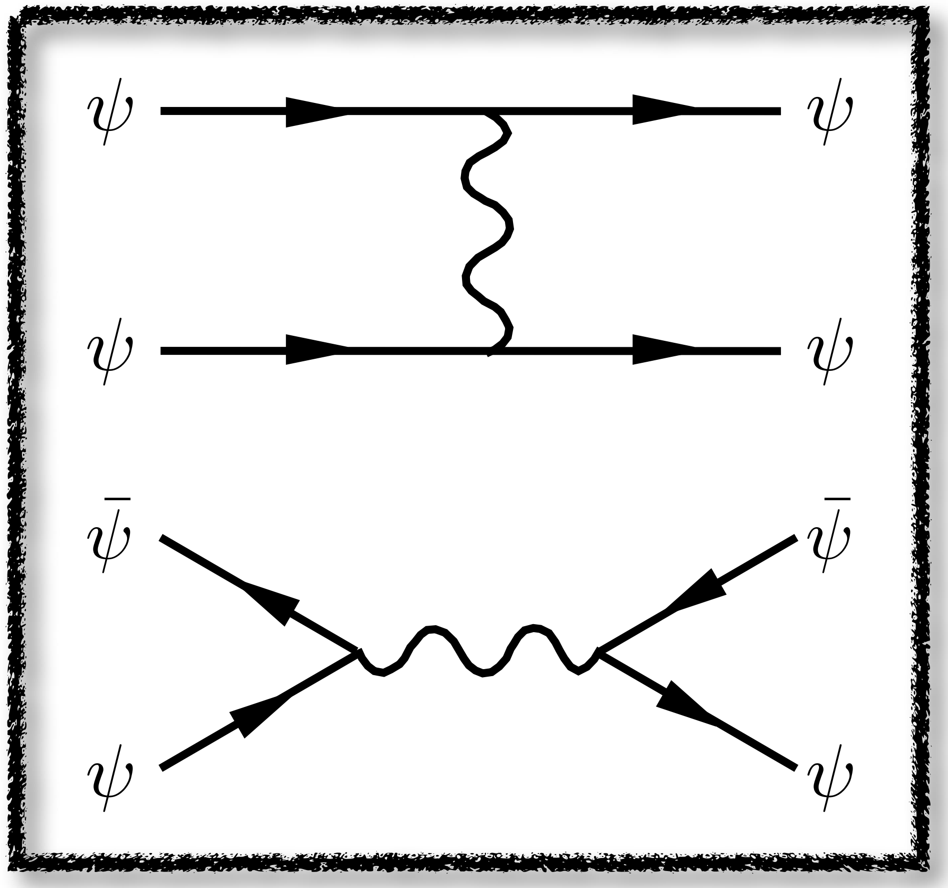
- dark matter self-interaction?

[M. Vogelsberger et al., 1201.5892; M. Rocha et al., 1208.3025; A. H. G. Peter et al., 1208.3026]

self-interacting rate

$$\boxed{\sigma_T \sim 2 \times 10^{-21}\mathrm{cm}^2 \left(\frac{m_{\rm dm}}{100\mathrm{GeV}}\right)}$$

Dark matter self-interaction



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

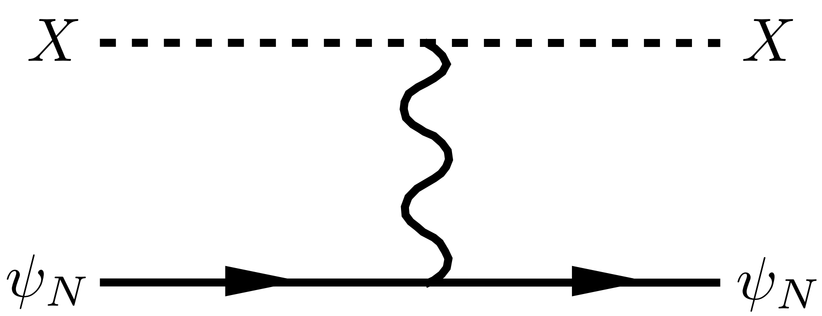
$$\Rightarrow \boxed{\alpha_X \lesssim 6\times10^{-6}\left(\frac{m_\psi}{1\mathrm{TeV}}\right)^{3/2}}$$

$$\Omega_\psi \gtrsim 10^2\left(\frac{1\mathrm{TeV}}{m_\psi}\right)$$

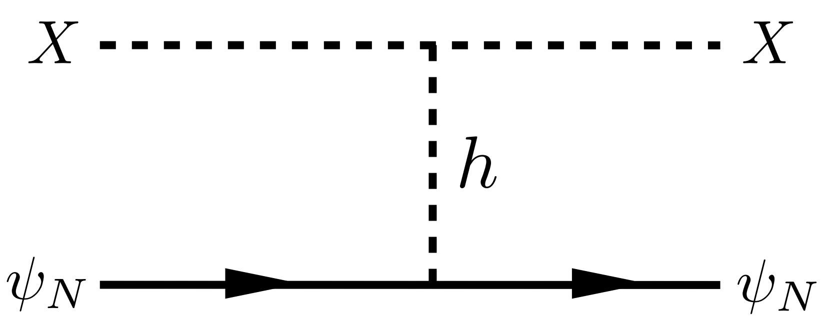
Too much!

- Ψ_X Should be able to decay $\Rightarrow$ $m_\Psi > m_X$
- Ψ_X Should decay before the thermal freeze-out of X or non-thermal freeze-out when it decay is necessary.
- 'X' can form a symmetric DM, having asymmetric origin.

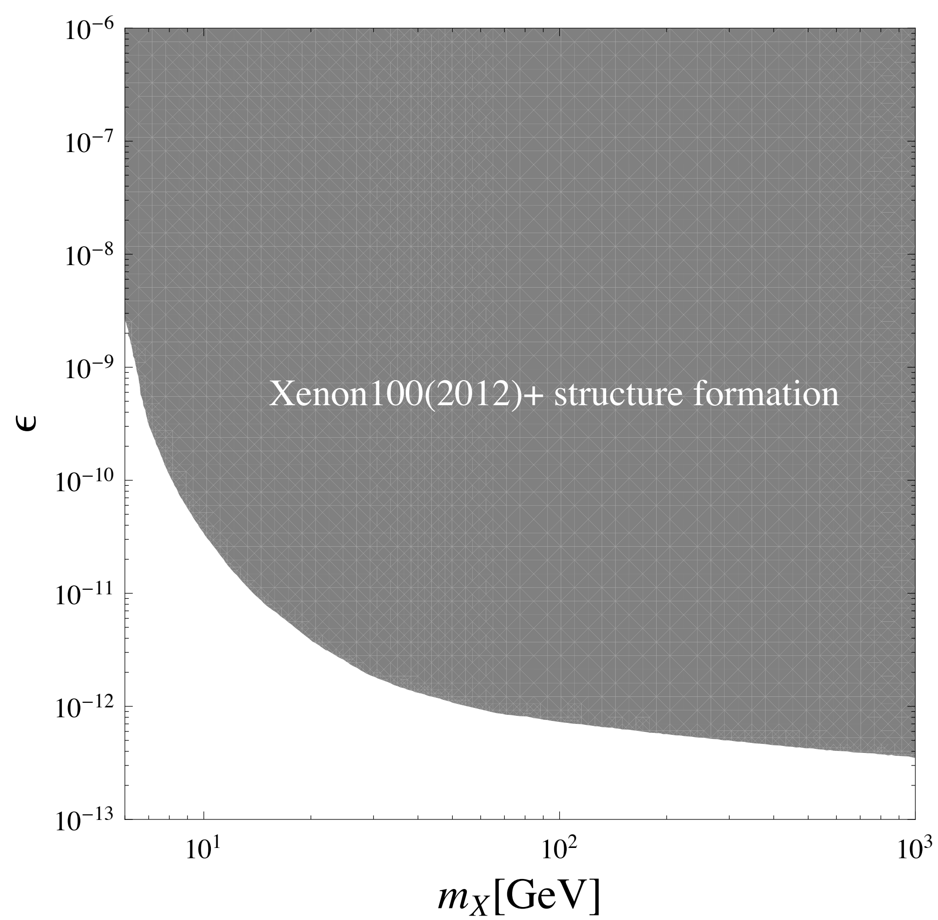
• DM direct search (ε, λ_{hx}, m_X)

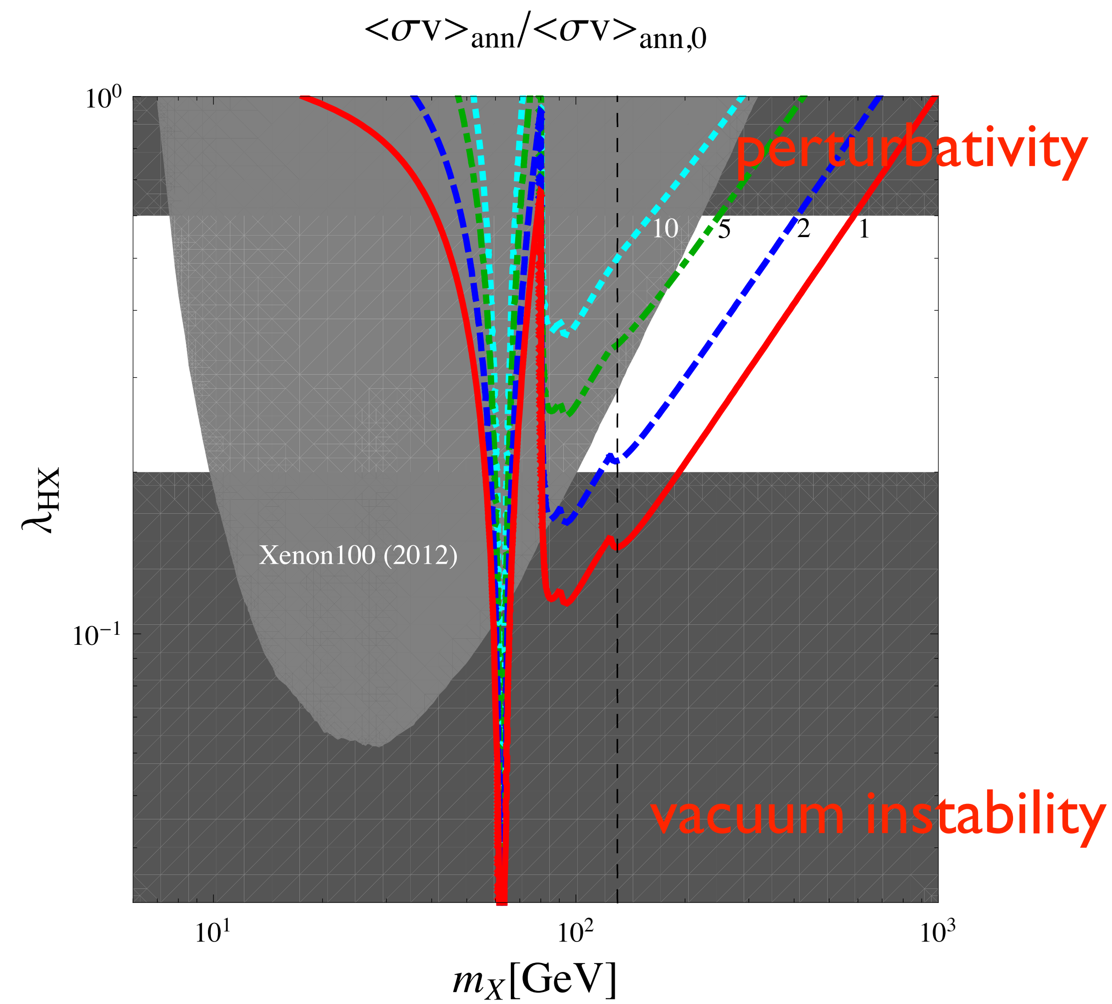


$$\sigma^{\rm SI}_{\mathcal{N},\gamma'} = \frac{4\alpha_X \alpha_{\rm em} c_W^2 s_\epsilon^2}{\pi} \frac{1}{m_{\rm r}^2} \frac{1}{v^4} \ln\left(\frac{2}{\theta_{\rm min}}\right)$$



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

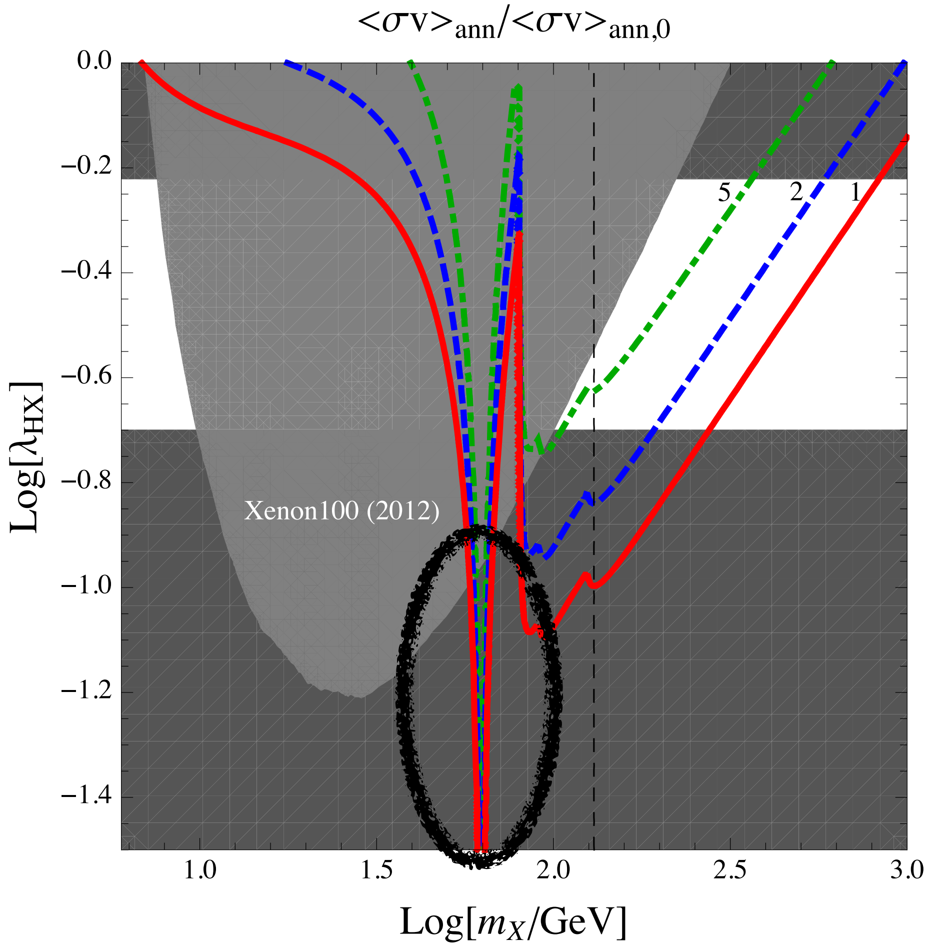




- Collider phenomenology (λ_{hx}, m_X)

Invisible decay rate of Higgs is

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



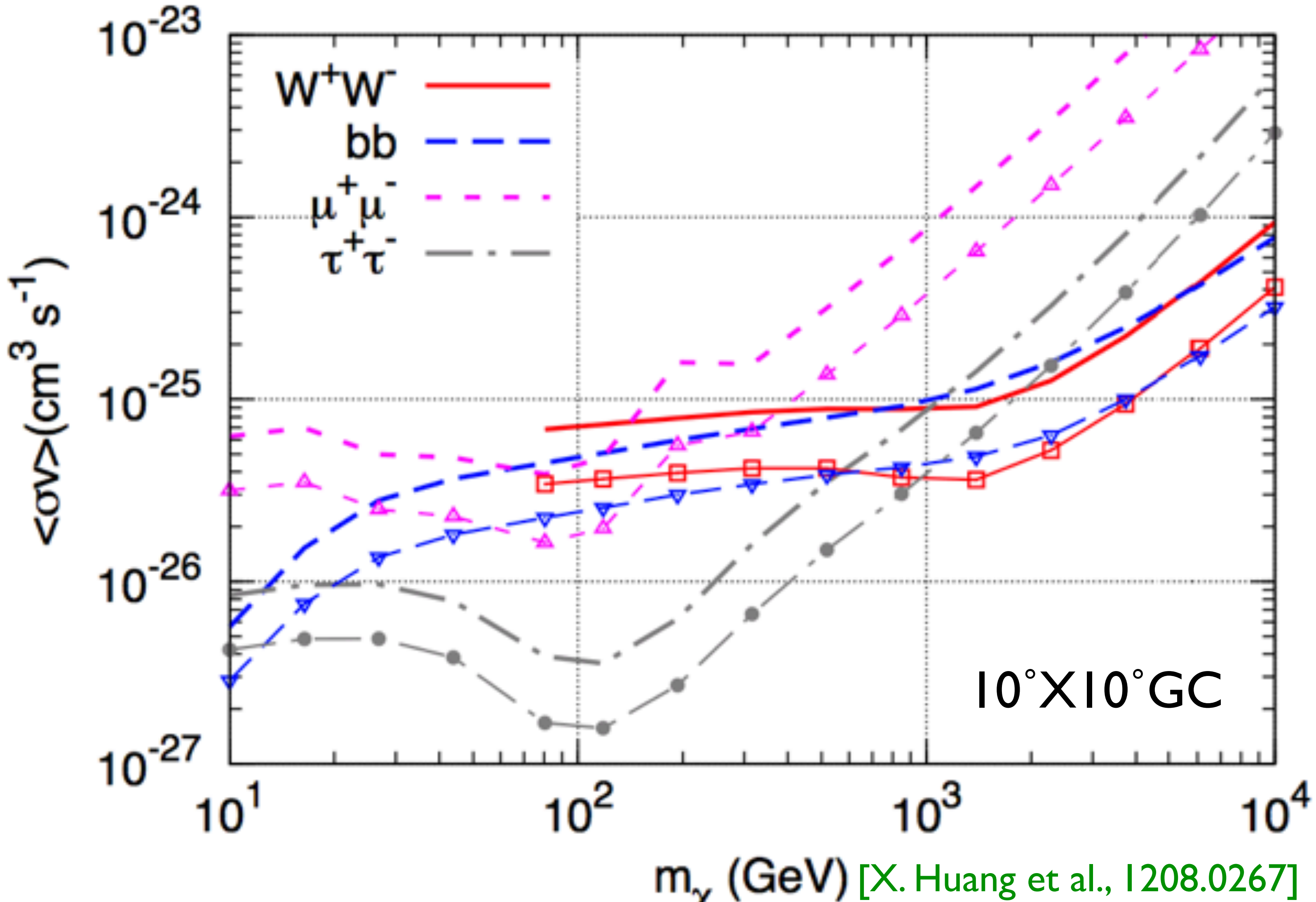
$\mathrm{Br}(h \to XX^\dagger) \ll \mathcal{O}(10)\%$ requires

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

or kinematically forbidden

- 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]

$$\Rightarrow \boxed{1 \leq \langle\sigma v\rangle^{\rm tot}_{\rm ann}/\langle\sigma v\rangle^{\rm th}_{\rm ann} \lesssim 10}$$

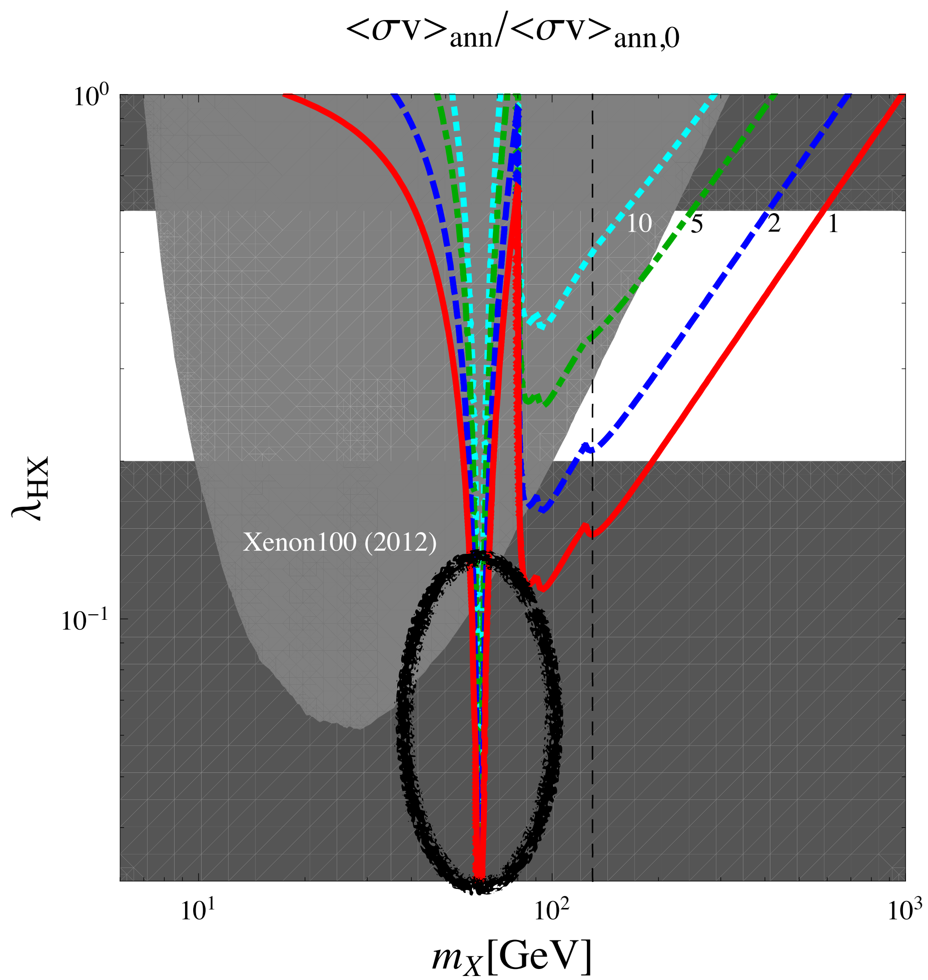
$$\Rightarrow \langle\sigma v\rangle^{\gamma\gamma}_{\rm ann} \sim 10^{-4}\langle\sigma v\rangle^{\rm tot}_{\rm ann} \sim 10^{-29}{\rm cm}^2/{\rm sec}$$

Fermi-LAT 130 GeV line is difficult to be explained.

- Collider phenomenology (λ_{hx}, m_X)

Invisible decay rate of Higgs is

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



$\mathrm{Br}(h\to XX^\dagger) \ll \mathcal{O}(10)\%$ requires

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

or kinematically forbidden

- # Dark radiation (ε) -1/2

Diagonalization of kinetic term

$$\begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix}$$ ➡ X_μ does not couple SM particles.

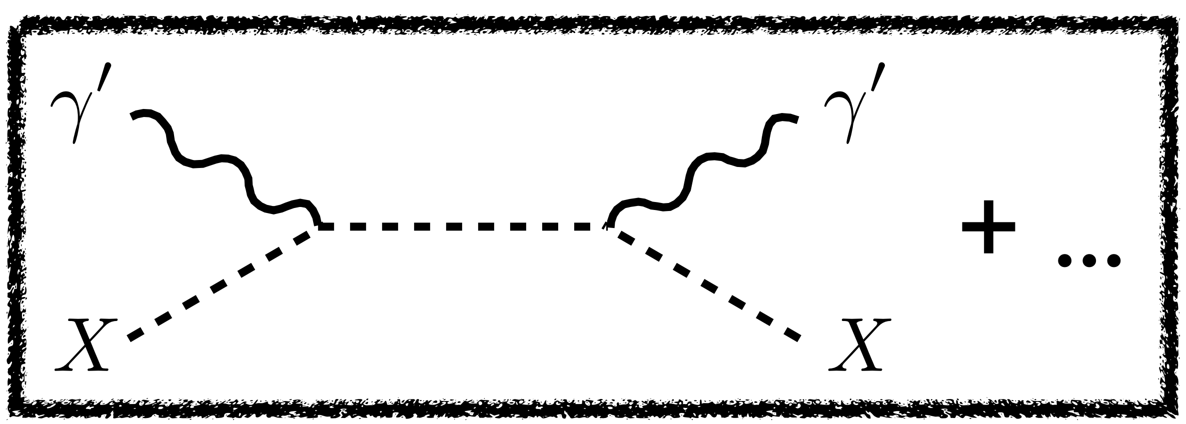
Diagonalizing mass term results in interactions between DS and SM,

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

$$(\ \sin\theta_W = e/g,\ \ \cos\theta_W = e\cos\epsilon/g'\ )$$

➡ Ψ and X are mini-charged under electromagnetism.

Decoupling of X_μ



➡ $$\begin{cases} \sigma_T \simeq \dfrac{8}{3}\dfrac{\pi\alpha_X^2}{m_X^2} \ \text{for}\ T \ll m_X \\ T_{\mathrm{dec},X_\mu} \gg T_{\mathrm{fz}} \sim \text{few GeV} \end{cases}$$

- # Dark radiation (ε)-2/2

# of extra relativistic degree of freedom

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

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

$\Delta N_{\rm eff}^{CMB} = 0.26 \pm 0.35$ [G. Hinshaw et al., arXiv:1212.5226]

Large scale structure constrains $\alpha_X \ll \alpha_{EW}$. As the result,

$$\boxed{T_{{\rm dec},X_\mu} \gg 0.1{\rm GeV} \Rightarrow \Delta N_{\rm eff} = \frac{2}{2\frac{7}{8}}\left(\frac{11}{4}\right)^{4/3}\left(\frac{g_{*S}(T_{\gamma,0})}{g_{*S}(T_{{\rm dec},X_\mu})}\right)^{4/3} \sim 0.06}$$

- # Summary of constraint

Vacuum stability + perturbativity

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

$$\Rightarrow \quad 100\mathrm{GeV} \lesssim m_X \lesssim 1\mathrm{TeV}$$

Small scale structure + CDM

$$\alpha_X \lesssim 2 \times 10^{-4} \left(\frac{m_{\psi(X)}}{1\mathrm{TeV}}\right)^{3/2}$$
$$\lambda_1^2 \, m_\psi \gtrsim 4\mathrm{TeV}$$

Direct search

$$\epsilon \lesssim 10^{-9}$$

Indirect search

$$1 \leq \langle\sigma v\rangle_{\mathrm{ann}}^{\mathrm{tot}} / \langle\sigma v\rangle_{\mathrm{ann}}^{\mathrm{th}} \lesssim 10$$

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 $\xi_h, \xi_x \gg 1.$

Conformal transformation

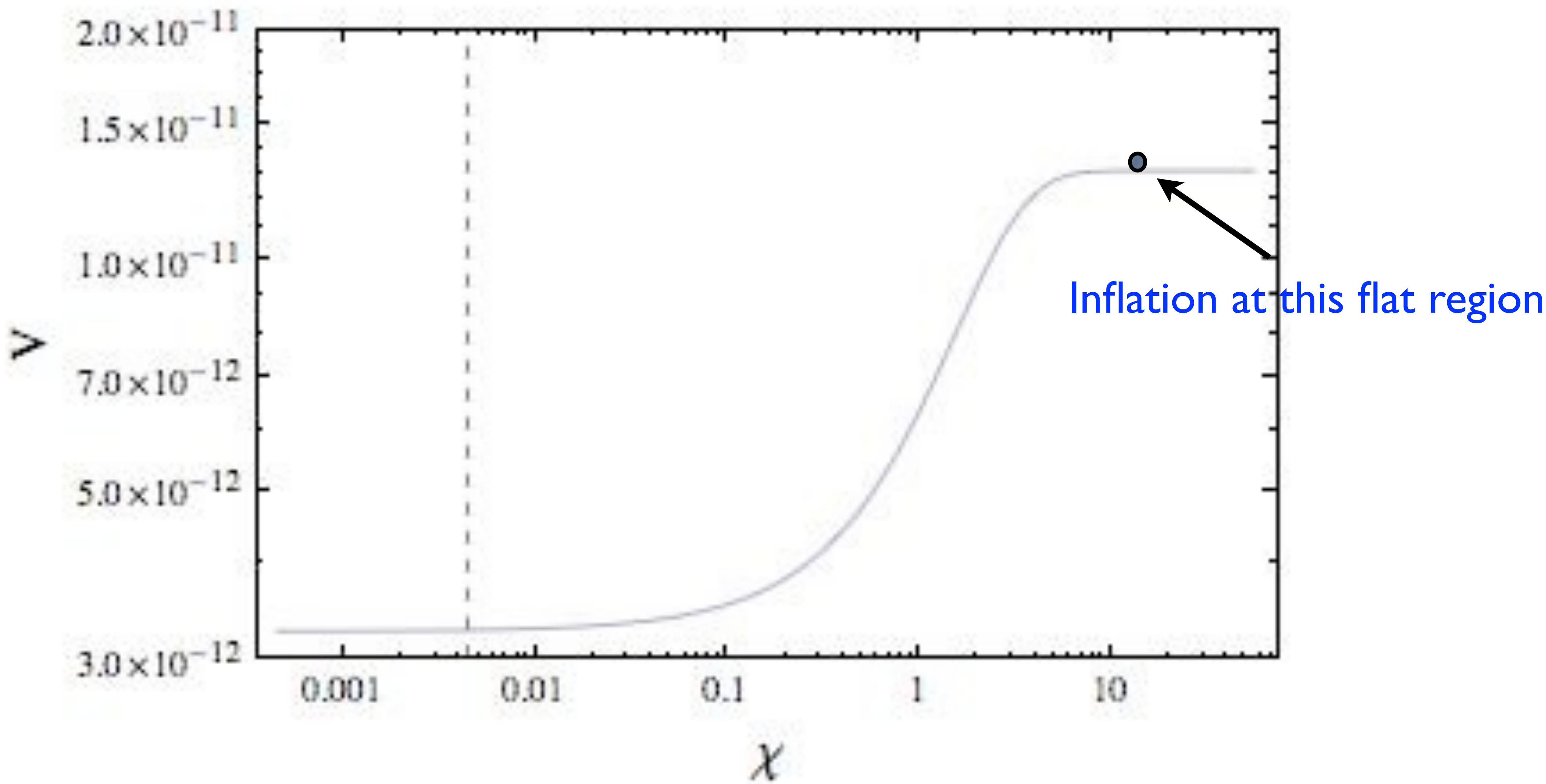
$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad \Omega^2 = 1 + \frac{\xi_h h^2 + \xi_x x^2}{M_{\rm P}^2}$$

Potential at large field limit of the canonical field □

$$U(\chi) = \frac{1}{4}\frac{\lambda_{\rm eff}}{\xi_h^2}\left[1 + \exp\left(-\sqrt{\frac{2}{3}}\chi\right)\right]^{-2}, \quad \lambda_{\rm eff} = \begin{cases} \lambda_h & \text{H.I.} \\ \lambda_s \left(\frac{\xi_h}{\xi_x}\right)^2 & \text{S.I.} \\ \ldots & \text{M.I} \end{cases}$$

12년 12월 28일 금

Inflaton(Higgs) potential



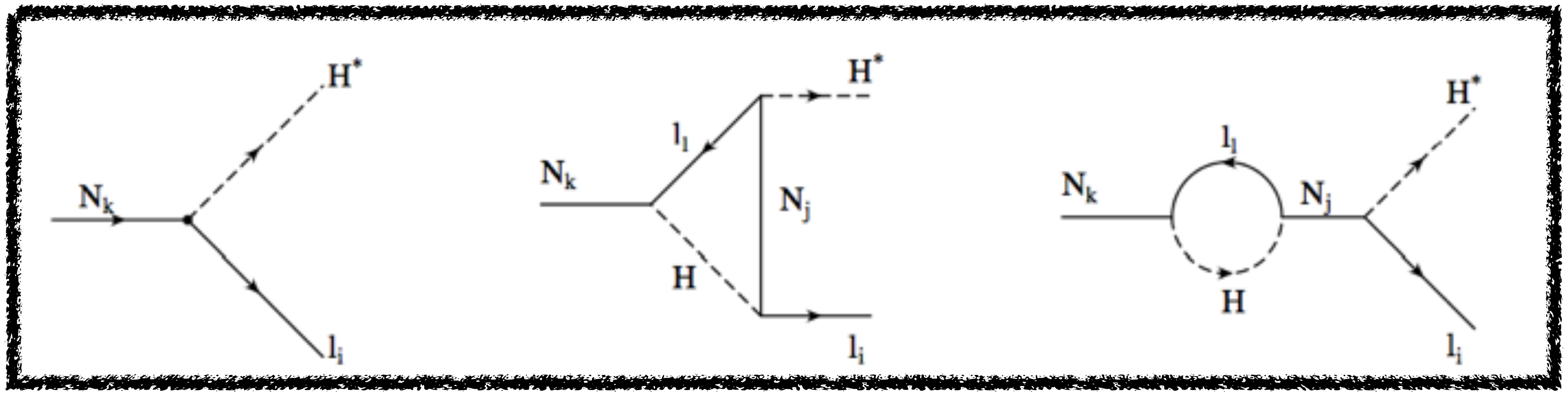
$$\lambda_X \lesssim 0.23$$

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

12년 12월 28일 금

Lepto/darkogenesis

- Lepto/darkogenesis from the decay of RHN



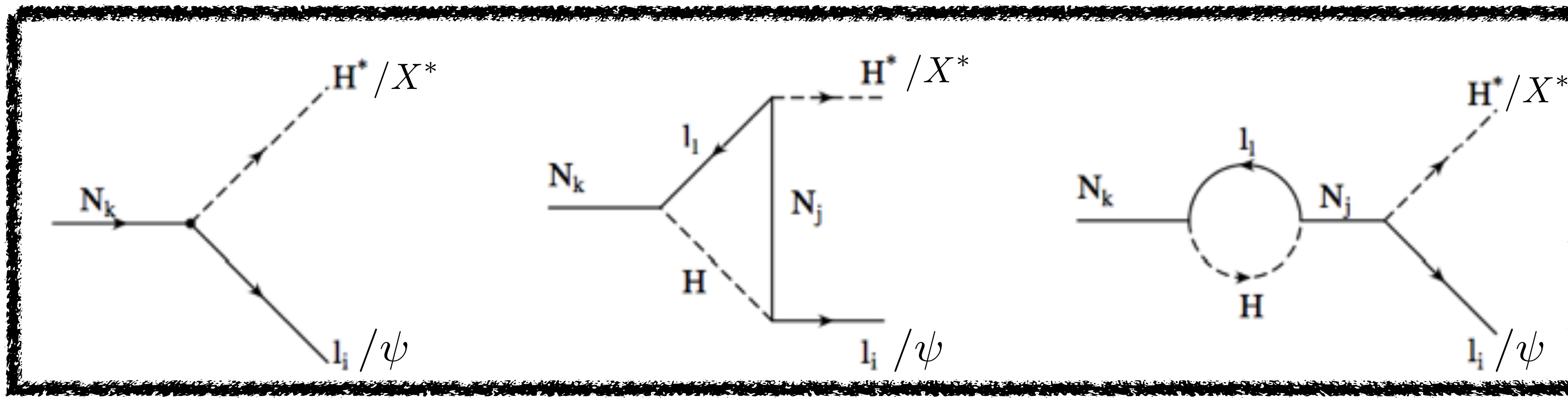
$$\epsilon_L \simeq \frac{M_1}{8\pi} \frac{\mathrm{Im}\left[\left(3Y_\nu^* Y_\nu^T + \lambda^*\lambda\right)\mathbb{M}^{-1} Y_\nu Y_\nu^\dagger\right]_{11}}{\left[2Y_\nu Y_\nu^\dagger + \lambda\lambda^*\right]_{11}}$$

$$\epsilon_\psi \simeq \frac{M_1}{8\pi} \frac{\mathrm{Im}\left[\left(Y_\nu^* Y_\nu^T + \lambda^*\lambda\right)\mathbb{M}^{-1} \lambda\lambda^*\right]_{11}}{\left[2Y_\nu Y_\nu^\dagger + \lambda\lambda^*\right]_{11}}$$

$$\epsilon_L \leq \frac{3M_1 m_\nu^{\max}}{16\pi v^2} \times \begin{cases} 1 & \text{for} \quad \mathrm{Br}_L \gg \mathrm{Br}_\chi \\ \sqrt{\lambda_2^2 M_1/\lambda_1^2 M_2} & \text{for} \quad \mathrm{Br}_L \ll \mathrm{Br}_\chi \end{cases}$$

Lepto/darkogenesis

- Lepto/darkogenesis from the decay of RHN



$$\epsilon_L \simeq \frac{M_1}{8\pi} \frac{\mathrm{Im}\left[\left(3Y_\nu^* Y_\nu^T + \lambda^* \lambda\right) \mathbb{M}^{-1} Y_\nu Y_\nu^\dagger\right]_{11}}{\left[2Y_\nu Y_\nu^\dagger + \lambda\lambda^*\right]_{11}}$$

$$\epsilon_\psi \simeq \frac{M_1}{8\pi} \frac{\mathrm{Im}\left[\left(Y_\nu^* Y_\nu^T + \lambda^* \lambda\right) \mathbb{M}^{-1} \lambda\lambda^*\right]_{11}}{\left[2Y_\nu Y_\nu^\dagger + \lambda\lambda^*\right]_{11}}$$

$$\epsilon_L \leq \frac{3M_1 m_\nu^{\max}}{16\pi v^2} \times \begin{cases} 1 & \text{for} \quad \mathrm{Br}_L \gg \mathrm{Br}_\chi \\ \sqrt{\lambda_2^2 M_1 / \lambda_1^2 M_2} & \text{for} \quad \mathrm{Br}_L \ll \mathrm{Br}_\chi \end{cases}$$

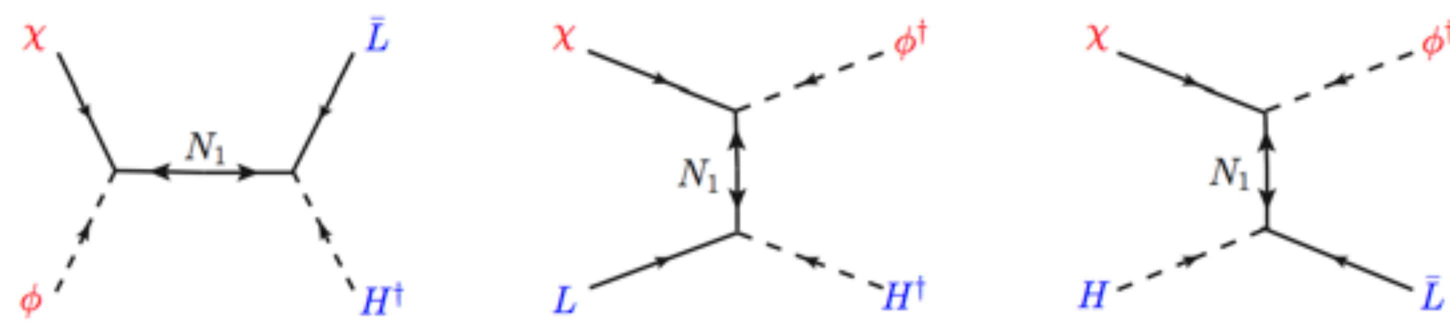
- Boltzman equations

$$\frac{sH_1}{z}Y_1' = -\gamma_D\left(\frac{Y_1}{Y_1^{\rm eq}}-1\right)+(2\leftrightarrow 2)\,,\quad \gamma_D = \frac{M_1^3K_1(z)}{\pi^2 z}\Gamma_1$$

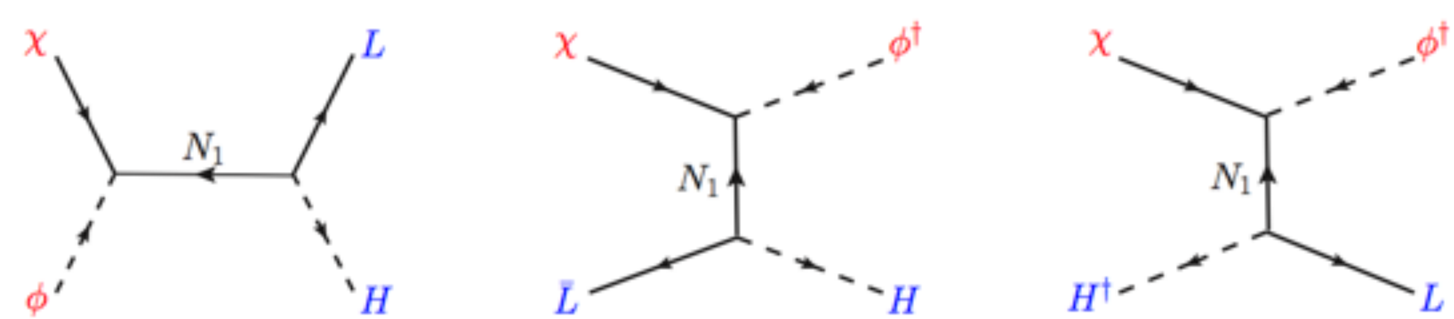
$$\frac{sH_1}{z}Y_{\Delta\psi}' = \gamma_D\left[\epsilon_\psi\left(\frac{Y_1}{Y_1^{\rm eq}}\right)-\frac{Y_{\Delta\psi}}{2Y_\psi^{\rm eq}}{\rm Br}_\psi\right]+(2\leftrightarrow 2{\rm washout}+{\rm transfer})$$

$$\frac{sH_1}{z}Y_{\Delta\ell}' = \gamma_D\left[\epsilon_\ell\left(\frac{Y_1}{Y_1^{\rm eq}}\right)-\frac{Y_{\Delta\ell}}{2Y_\ell^{\rm eq}}{\rm Br}_\ell\right]+(2\leftrightarrow 2{\rm washout}+{\rm transfer})$$

wash-out: $\Delta L = 2$



transfer: $\Delta L = 0$

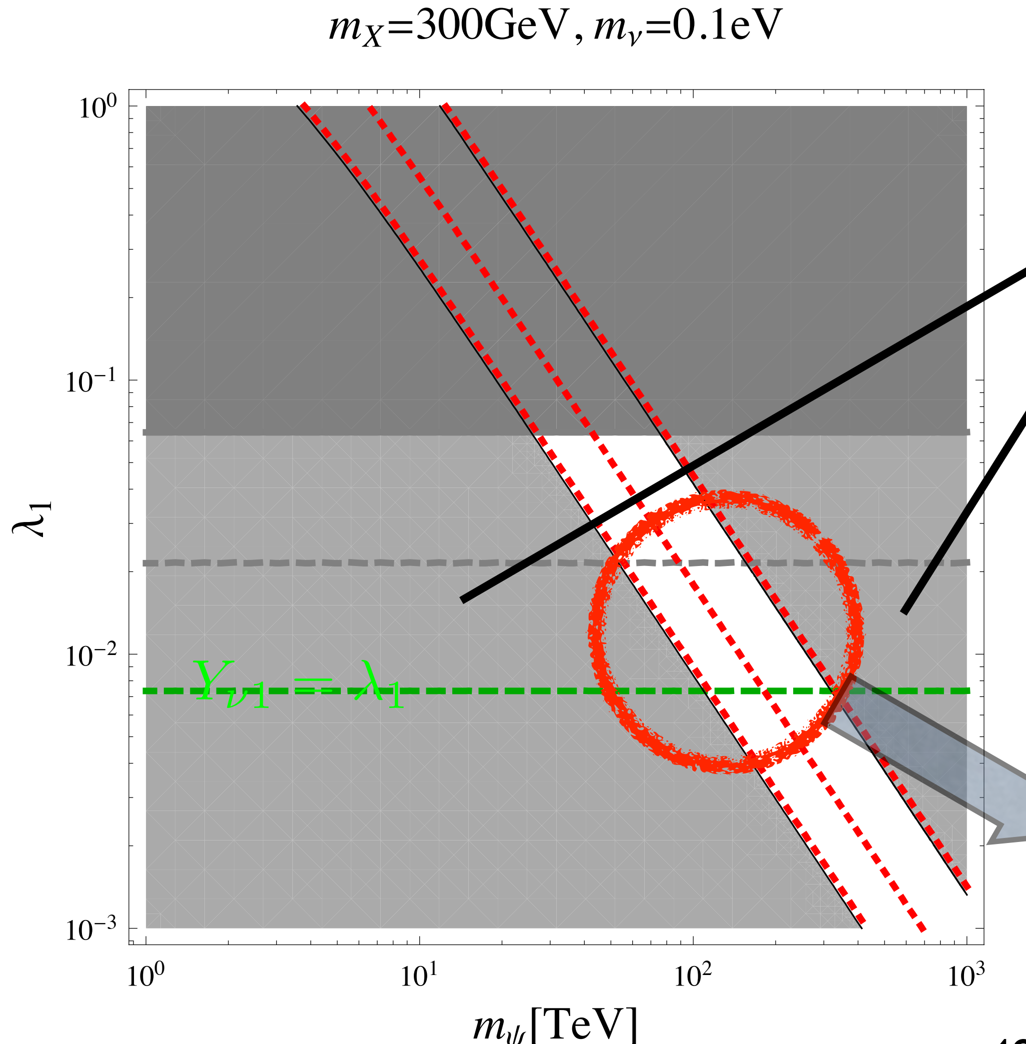


- Lepton/darkon number asymmetry

$$Y_{\Delta L} = \epsilon_L \eta_L Y_1^{\rm eq}(0) \simeq 2.6 \times 10^{-10}$$
$$Y_{\Delta\psi} = \epsilon_\psi \eta_\psi Y_1^{\rm eq}(0) \simeq 2 \times 10^{-12} \left(\frac{100\,\mathrm{GeV}}{m_X}\right)$$

Narrow-width approx.

$$\Gamma_1/M_1 \ll 1,\ \Gamma_1^2/M_1 H_1 \ll 1$$



Light gray: narrow width regime

White between black lines:

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

Red lines:

$T_{{\rm d},\psi} = 1, 2, 5\mathrm{GeV}$ (from left)

Correct BAU and CDM relic can be obtained.

Some Variations

- If we consider a scenario w/o psi_X, then we have thermal relic hidden scalar CDM with the same dark radiation, and Higgs inflation
- If we consider a scenario w/o X, then we need to introduce a singlet scalar messenger to achieve the correct relic density. ==> 2 scalar bosons with $r<1$ (universal suppressions), the same dark radiation and higgs inflation
- Our model with RH neutrino portal is unique and interesting

Higher Dim Op's

- Since our model has neither Landau pole nor the vacuum instability below Planck scale, we can assume that the NP scale of higher dim op's is Planck scale
- Since the local dark sym is unbroken, the DM is stable even in the presence of higher dim op's
- This is not possible if dark sym is global or spontaneously broken (DM should decay in these cases)

Summary

- We assume that CDM is stable due to a local symmetry
- The simplest extension of SM with a local U(1) has a unique renormalizable interactions
- The model can address following issues

*Vacuum stability of Higgs potential
* Small scale structure problem
* CDM relic density (thermal or non-thermal via asymmetric generation)
* Dark radiation
* Lepto/darkogenesis
* Inflation (Higgs inflation type)

Nontrivial at all

- Dark matter physics is also determined by local gauge principle associated with conserved dark charges
- Power of local gauge symmetry may work for dark matter sector, too
- Whether dark symmetry is spontaneously broken or not can be tested by Higgs signal strengths
- If $r < 1$ for all decay channels, dark symmetry can be spontanesouly broken
- If $r=1$, dark symmetry is unbroken with dark radiation

To Do List

- Role of Higgs and extra scalar fields in cosmology (Inflation, non Gaussianity, etc)
- Broken U(1)x with massive dark photon
- Nonabelian hidden (dark) gauge symmetry
- D.W. Jung, Hur, Ko and Lee, PLB; Hur and Ko, PRL (2011)
- 2 Higgs Doublets Portals
- SUSY extension