Higgs boson as a probe of dark sectors with dark gauge symmetries

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HPNP2013, Toyama, Japan, Feb. 13-16 (2013)

Higgs as a Probe of New Physics 2013

- What kind of new physics ?
  - Neutrino masses and mixings
  - Nonbaryonic Dark Matter
  - Matter-Antimatter Asymmetry
- Any relation with Higgs boson ? YES!

Many interesting talks on these issues @ this meeting

Contents

- Generalities on hCDM vs. Higgs Physics
  - Why Hidden Sector ?
  - Is CDM stable or not ? Local or Global Sym ?
  - EFT or Renormalizable Model ?
- Unbroken local dark symmetry : Singlet Portal extension of the Standard Seesaw Models

Based on the works

(with S.Baek, T. Hur, D.W.Jung, J.Y.Lee, W.I.Park, E.Senaha in various combinations)

(Some works in preparation)

- Strongly interacting hidden sector
- Singlet fermion dark matter
- Higgs portal vector dark matter
- Vacuum structure and stability issues
- Singlet portal extensions of the standard seesaw models with unbroken dark symmetry

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Hidden Sector

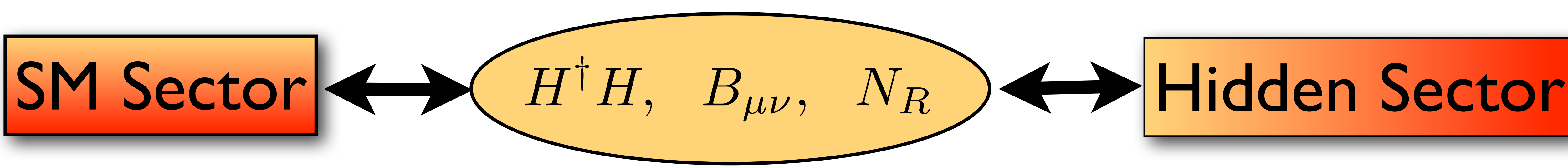
- Any NP @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM singlets, and less constrained, and could be CDM
- Generic in many BSM's including SUSY models
- Higgs fields are unique in that HH is gauge inv dim-2 operators
- RHN field (N): gauge singlet dim-3/2 operator
- HH and N can be portals to a hidden sector

How to specify hidden sector ?

- Gauge group (G_h) : Abelian or Nonabelian
- Strength of gauge coupling : strong or weak
- Matter contents : singlet, fundamental or higher dim representations of G_h
- All of these can be freely chosen at the moment : Any predictions possible ?
- But there are some generic testable features

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



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Why Dark Symmetry ?
Higgs is harmful to DM stability

- Is DM absolutely stable or very long lived ?
- If DM is absolutely stable, one can assume it carries a new conserved dark charge, associated with unbroken dark gauge sym
- DM can be long lived (lower bound on DM lifetime is much weaker than that on proton lifetime)

Fate of CDM with Z2 sym

- Global Z2 cannot save DM from decay with long enough lifetime

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\rm Planck}} S O_{\rm SM}$$

keeping dim-4 SM operators only

The lifetime of the Z_2 symmetric scalar CDM S is roughly given by

$$\Gamma(S) \sim \frac{m_S}{M^2_{\rm Planck}} \sim (\frac{m_S}{100{\rm GeV}})10^{-37} GeV$$

The lifetime is too short for 100 GeV DM

Fate of CDM with Z2 sym

- Spontaneously broken local U(1)x can do the job to some extent, but there is still a problem

Let us assume a local $U(1)_X$ is spontaneously broken by $\langle \phi_X \rangle \neq 0$ with

$$Q_X(\phi_X) = Q_X(X) = 1$$

Then, there are two types of dangerous operators:

$\phi_X^\dagger X H^\dagger H$, and $\phi_X^\dagger X O_{\rm SM}^{(dim-4)}$

Problematic !

Perfectly fine !

- These arguments will apply to all the CDM models based on ad hoc Z_2 symmetry, global or local it may be

- One way out is to implement Z_2 symmetry as local U(1) symmetry

- See the poster by Chaehyun Yu on 2HDM's with local U(1) for Higgs flavors

Fate of CDM with Z_2 sym

- Global Z2 cannot save DM from decay with long enough lifetime
- Spontaneously broken local $U(1)_X$ can do the job to some extent, but there is still a problem
- Let us talk with a Z2 scalar CDM which is a very popular model (the simplest extension of the SM with CDM in terms of # of new dof)
- Q: Lagrangian for the local Z_2 scalar CDM ?

$$Q_X(\phi) = 2, \quad Q_X(X) = 1$$

In preparation w/ WIPark and SBaek

$$\mathcal{L} = \mathcal{L}_{\rm SM} + -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2} \epsilon X_{\mu\nu} B^{\mu\nu} + D_\mu \phi_X^\dagger D^\mu \phi_X - \frac{\lambda_X}{4} \left(\phi_X^\dagger \phi_X - v_\phi^2 \right)^2 + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X$$
$$- \frac{\lambda_X}{4} \left(X^\dagger X \right)^2 - \left(\mu X^2 \phi^\dagger + H.c. \right) - \frac{\lambda_{XH}}{4} X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4} \phi_X^\dagger \phi_X H^\dagger H - \frac{\lambda_{XH}}{4} X^\dagger X \phi_X^\dagger \phi_X$$

The lagrangian is invariant under $X \to -X$ even after $U(1)_X$ symmetry breaking.

Unbroken Local Z2 symmetry

$X_R \to X_I \gamma_h^*$ followed by $\gamma_h^* \to \gamma \to e^+ e^-$ **etc.**

The heavier state decays into the lighter state

The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

Global dark symmetry ?

- global symmetry expected to be broken at least by quantum gravity effects (suppressed by Planck scale to some powers)
- Stability of CDM is not guaranteeed at all for global dark symmetry
- Scalar DM mixes with Higgs boson
- Fermion DM mixes with neutrinos
- Need to consider local dark symmetry, exact or spontaneously broken

Unbroken Local Dark Sym

- Dark charge is conserved if dark symmetry is unbroken (E. Noether's theorem)
- In this case, the Higgs sector needs not be extended
- Higgs phenomenology should be the same as the SM sector (modulo invisible H decay)
- Still the model could be OK until Planck scale for 125 GeV Higgs, since there could be other scalar fields (scalar CDM, for example)

Unbroken Local Dark Sym

- Local dark symmetry can be either confining (like QCD) or not
- For confining dark sym, gauge fields will confine and there is no long range dark force, and DM will be composite baryons/mesons in the hidden sector
- Otherwise, there could be a long range dark force that is constrained by large/small structures

Spon. Broken local dark sym

- If dark sym is spont. broken, DM will decay in general, if there is no discrete gauge symmetry
- There will be a singlet scalar after spontaneous breaking of dark gauge symmetry, which mixes with the SM Higgs boson
- There will be at least two neutral scalars (and no charged scalars) in this case
- Signal strengths universally reduced from ONE

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Why is this a problem at all ?

- Many studies on DM physics using EFT
- Very often one gets misleading results
- Better to work in a minimal renormalizable and anomly-free models in order not to reach wrong conclusions
- Explicit examples : singlet fermion Higgs portal DM, vector DM, Z2 scalar CDM

Usual approach (EFT)

All invariant under ad hoc Z2 symmetry

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma \cdot \partial - m_\psi \right] \psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \; \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

- Scalar CDM : looks OK, renorm. .. BUT .....
- Fermion CDM : nonrenormalizable
- Vector CDM : looks OK, but it has a number of problems (in fact, it is not renormalizable)

Usual story within EFT

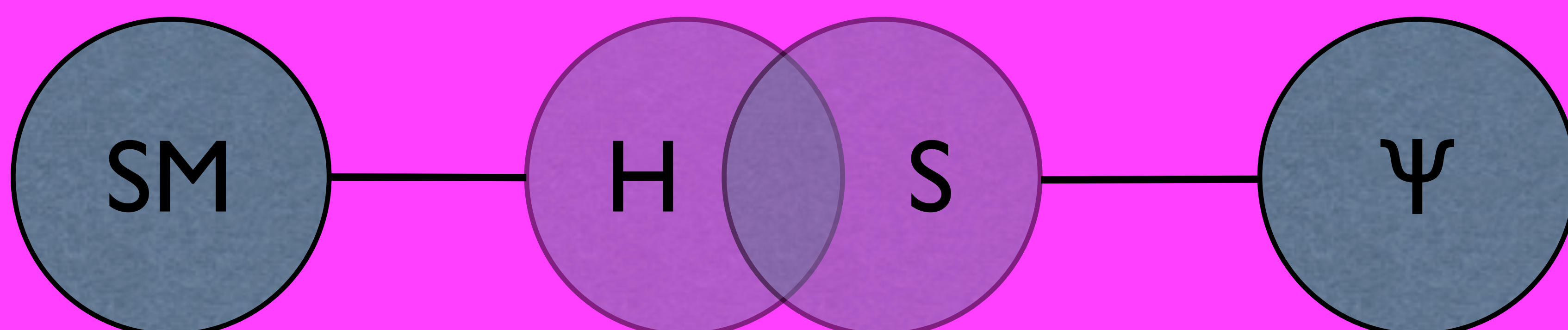
- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced in the full theories (renormalizable) however

Singlet fermion CDM

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

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)

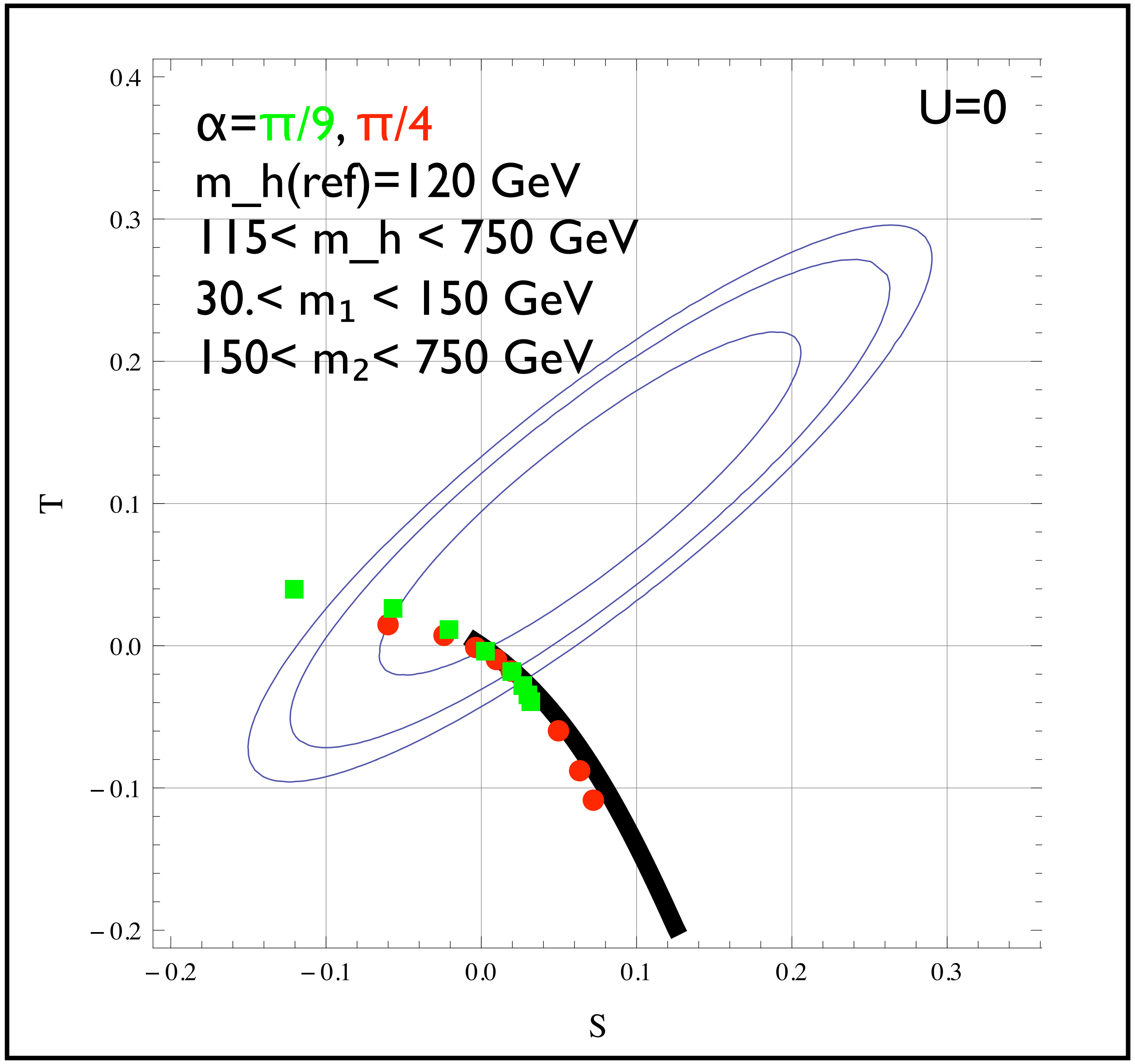
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right]$$

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

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

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

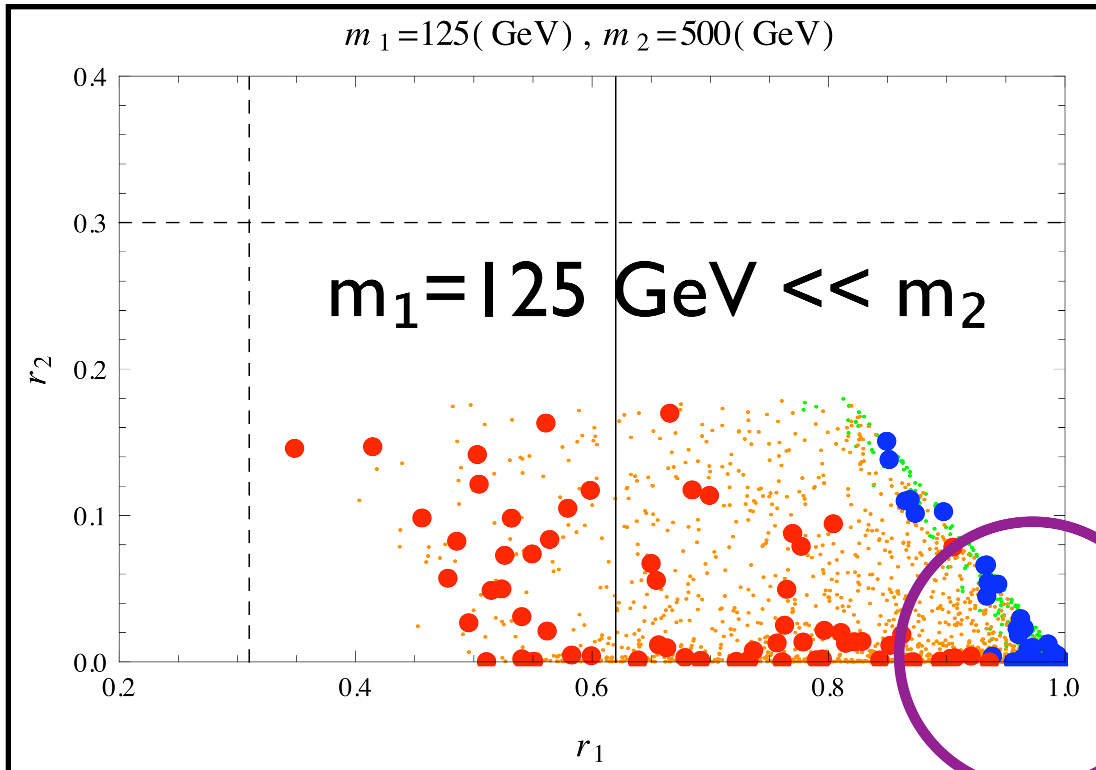
Same for T and U

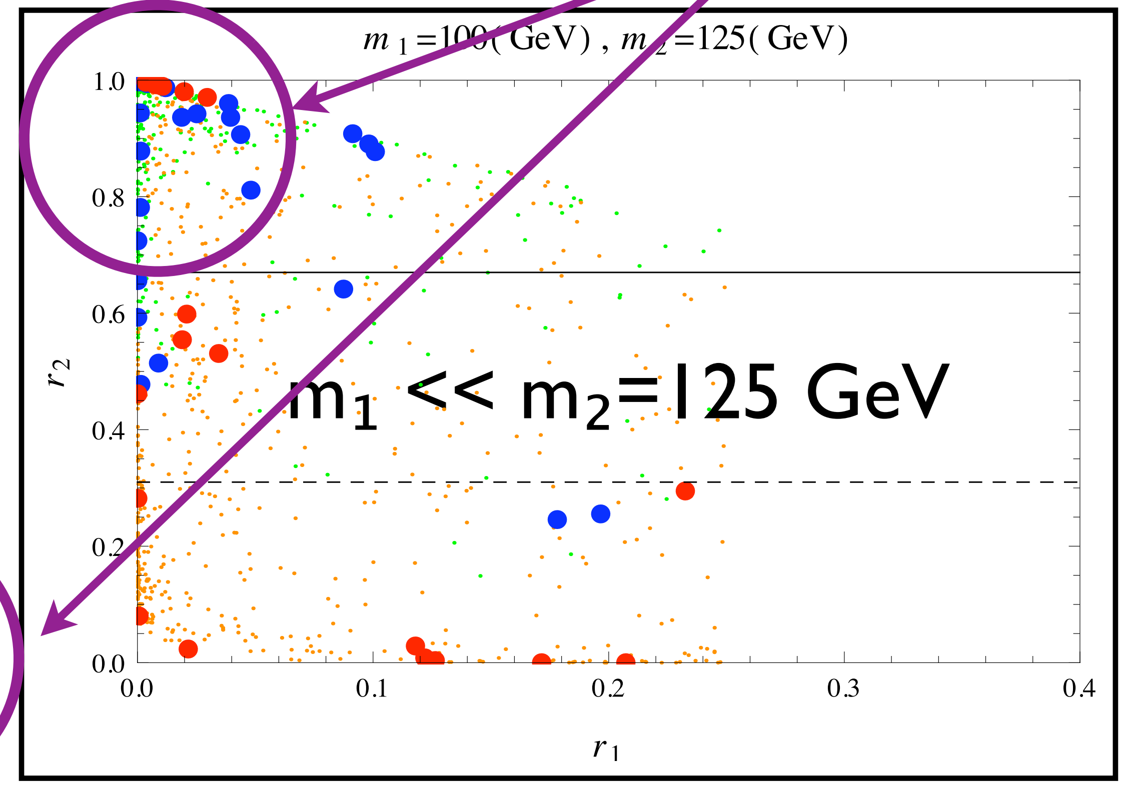


Discovery possibility

- Signal strength (r_2 vs r_1)

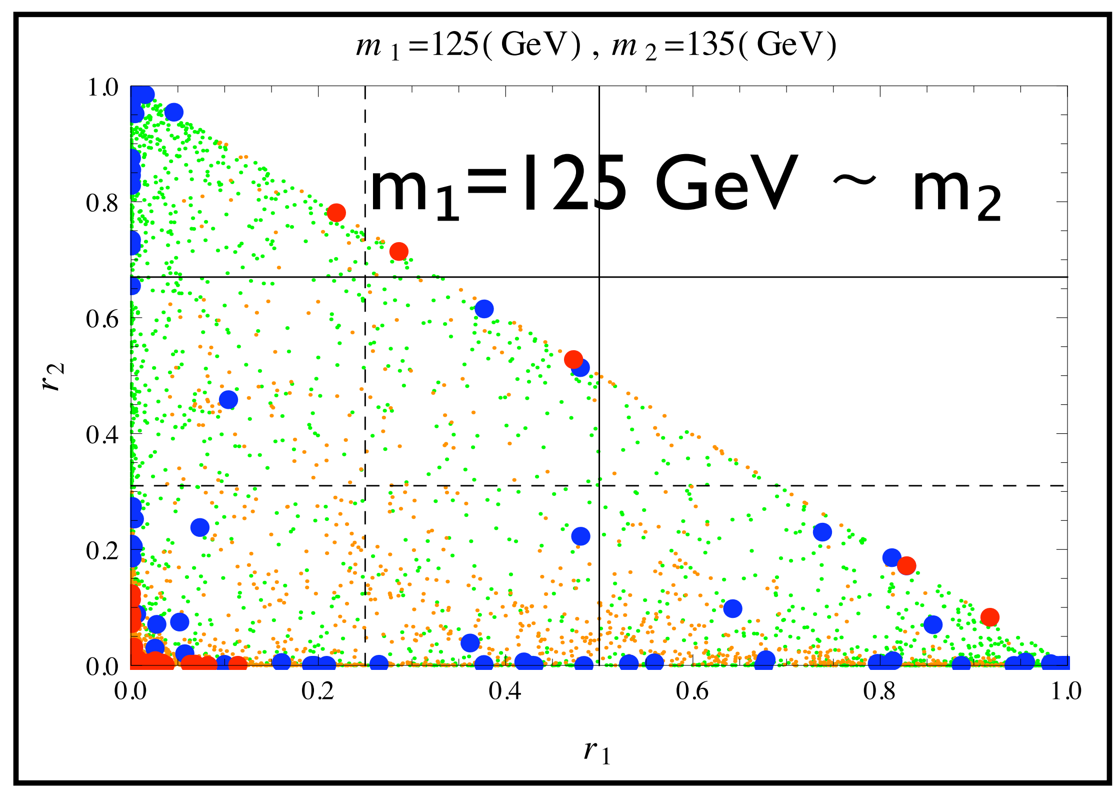
LHC data for 125 GeV resonance





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.



- (green): Ω(x),σ_p(x)
- (orange): Ω(x),σ_p(o)
- (blue): Ω(o),σ_p(x)
- (red): Ω(o),σ_p(o)

Discovery possibility

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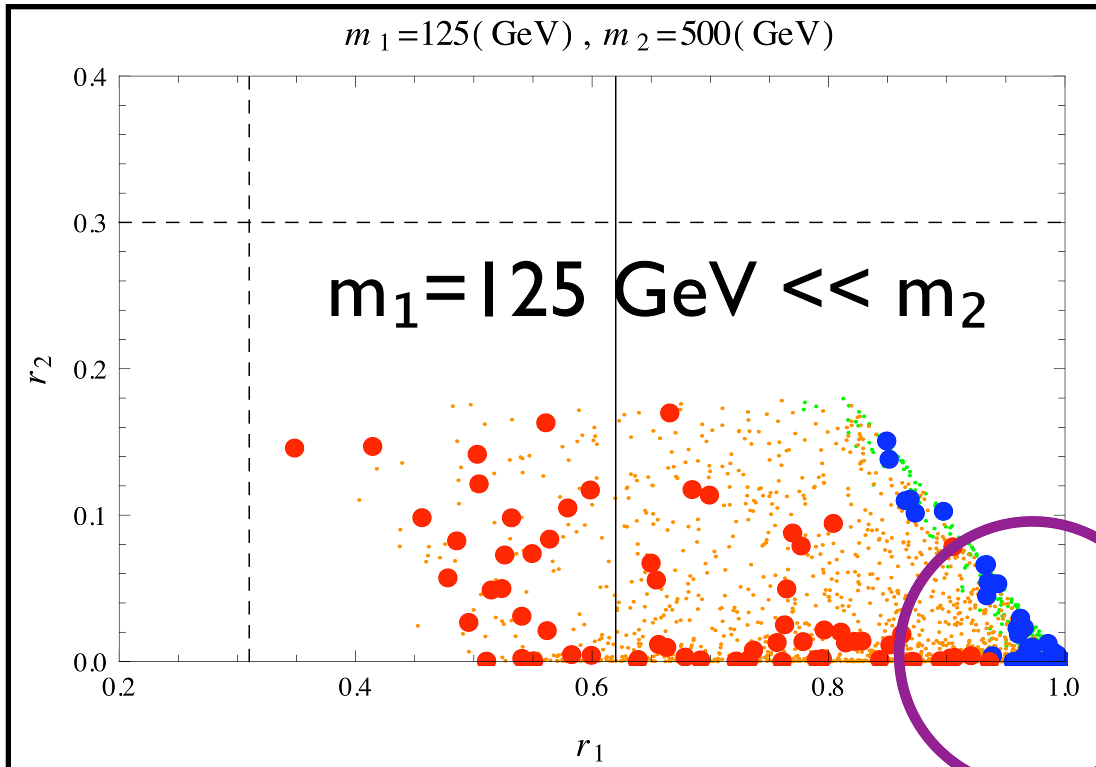

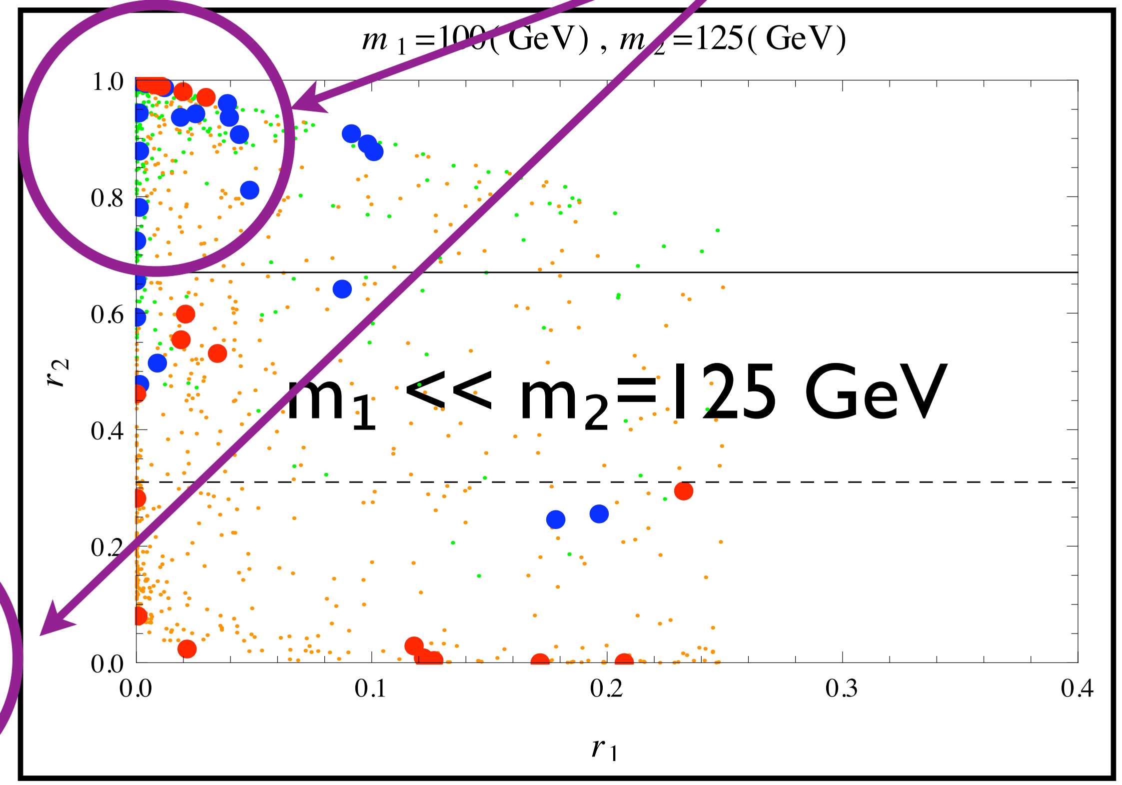

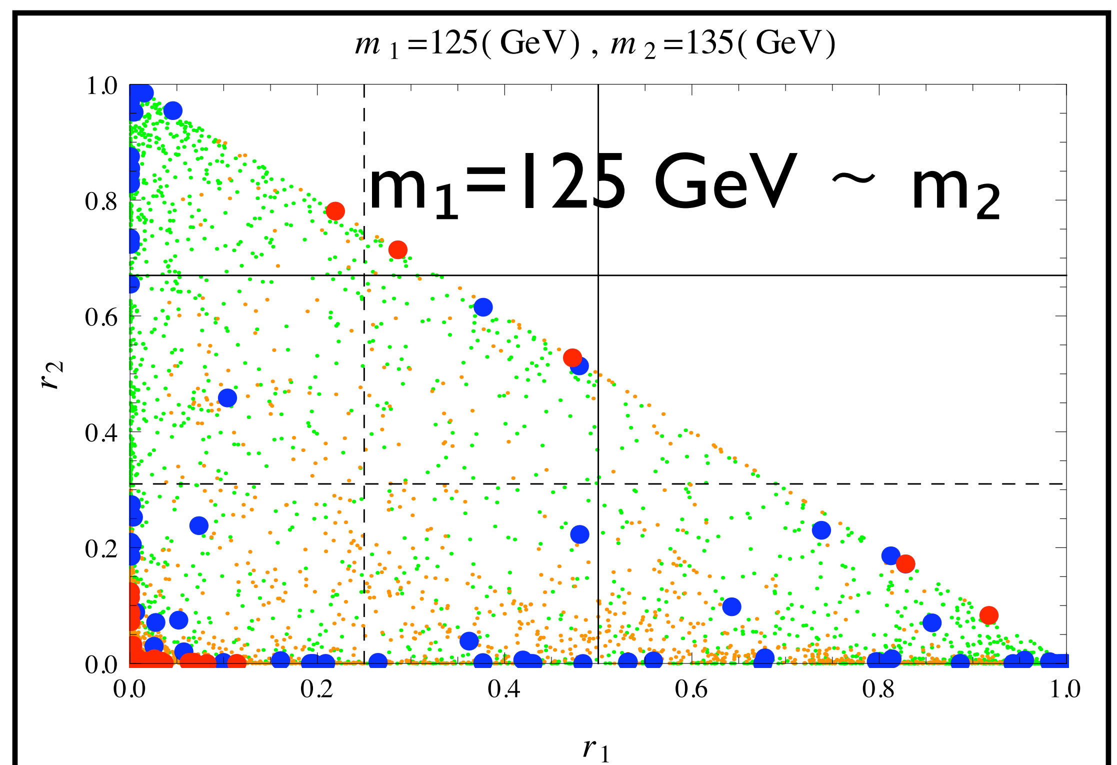

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- : Ω(x),σ_p(x)
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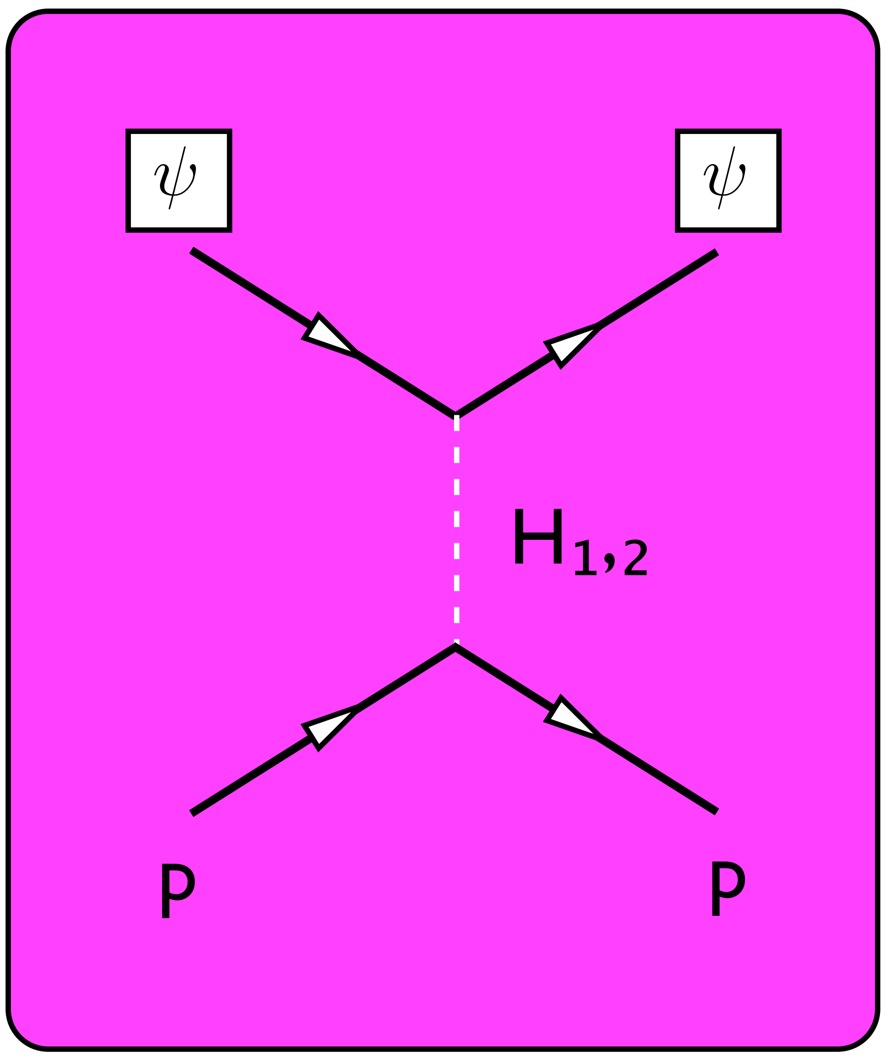
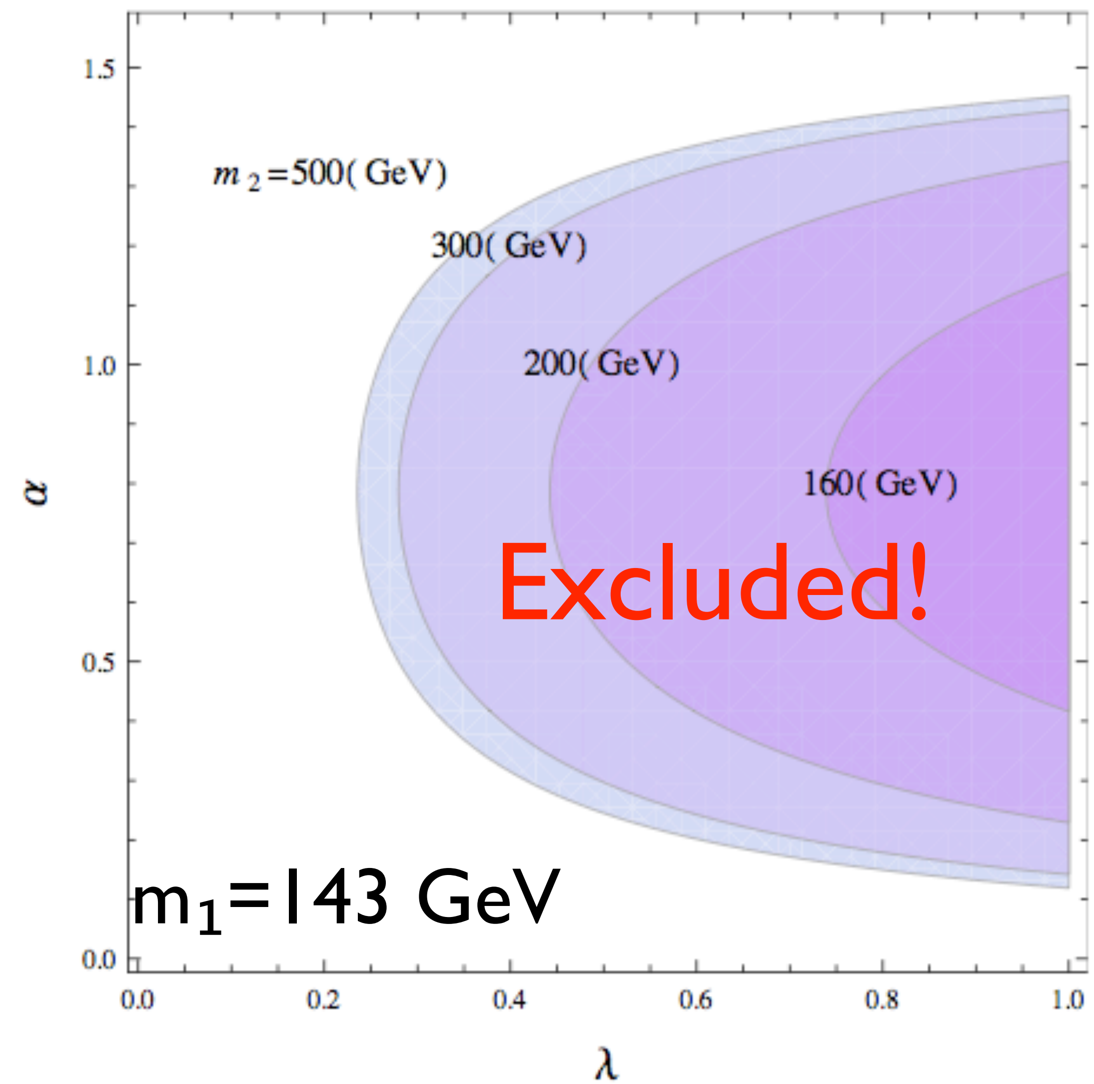
- : Ω(o),σ_p(x)
- : Ω(o),σ_p(o)

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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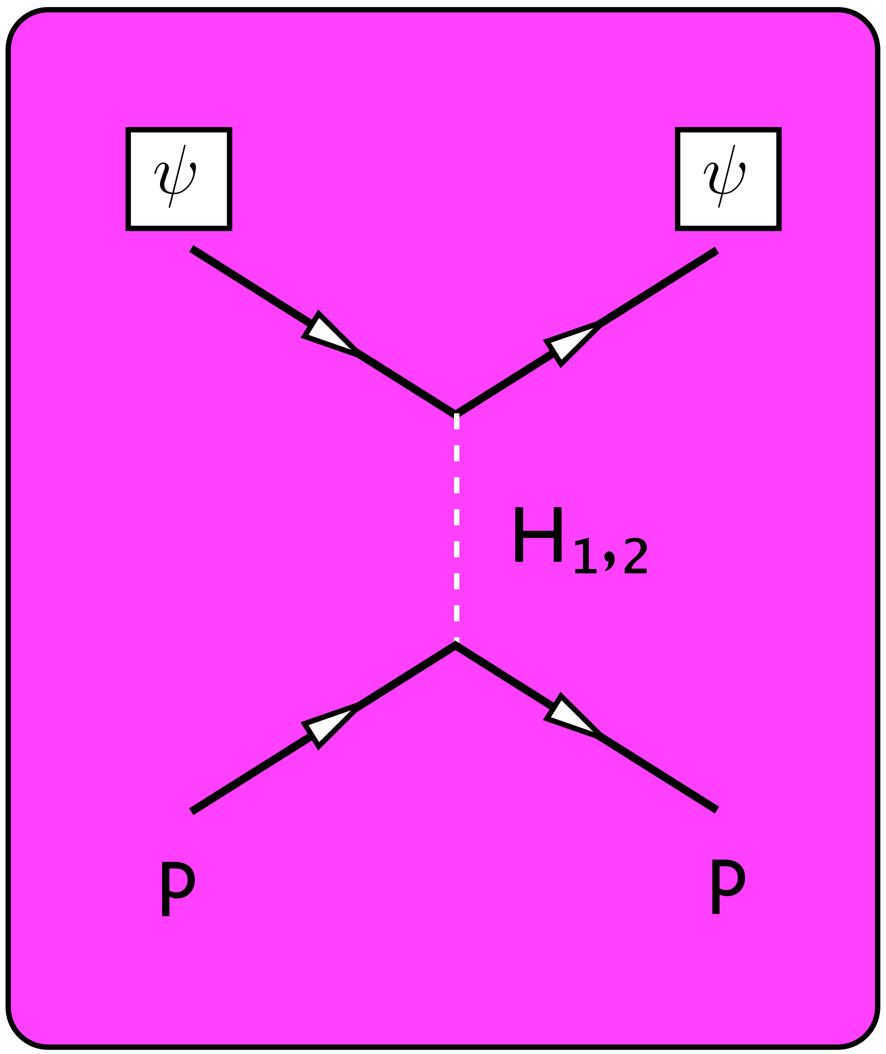
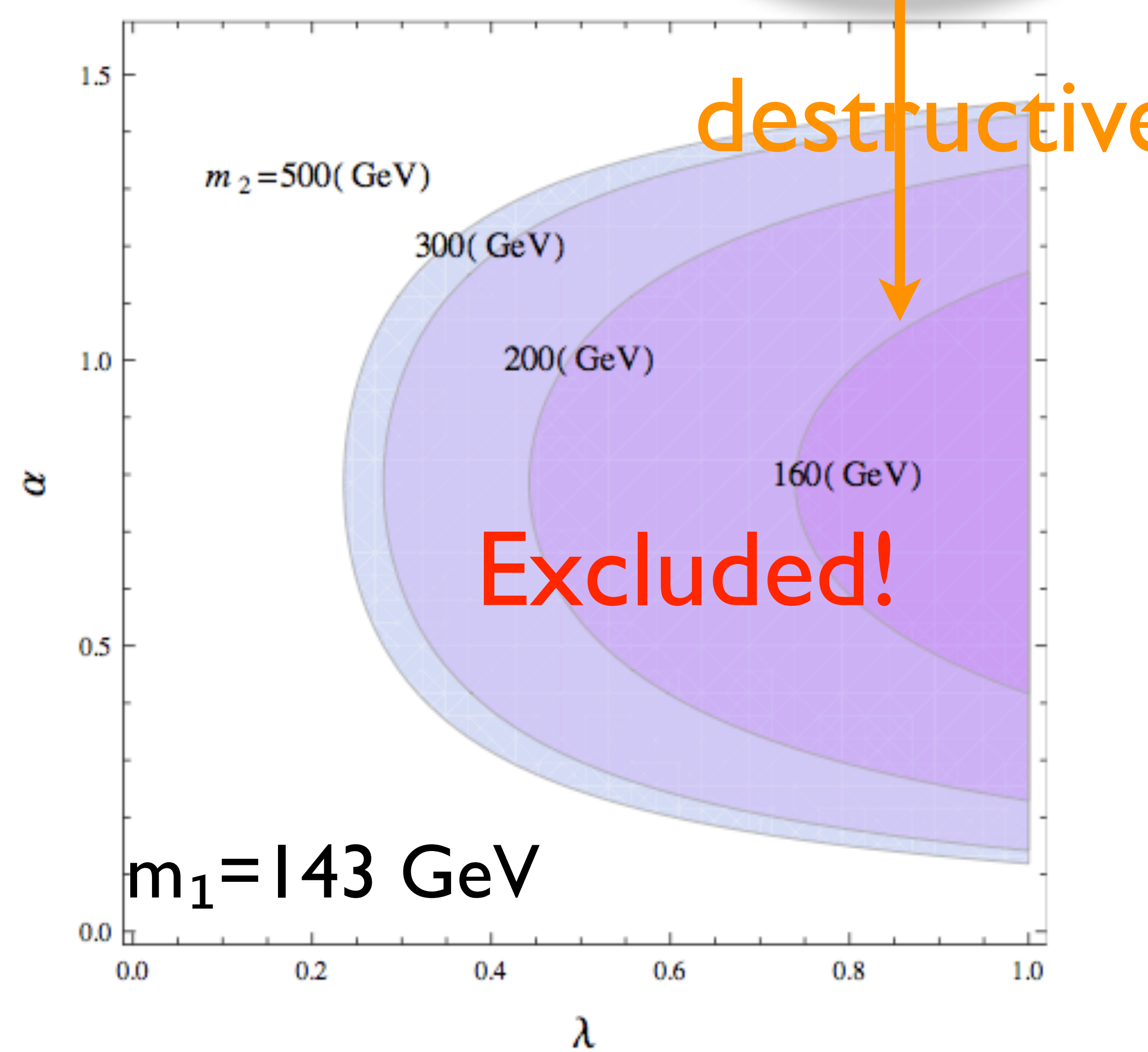




- We don't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

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

- 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

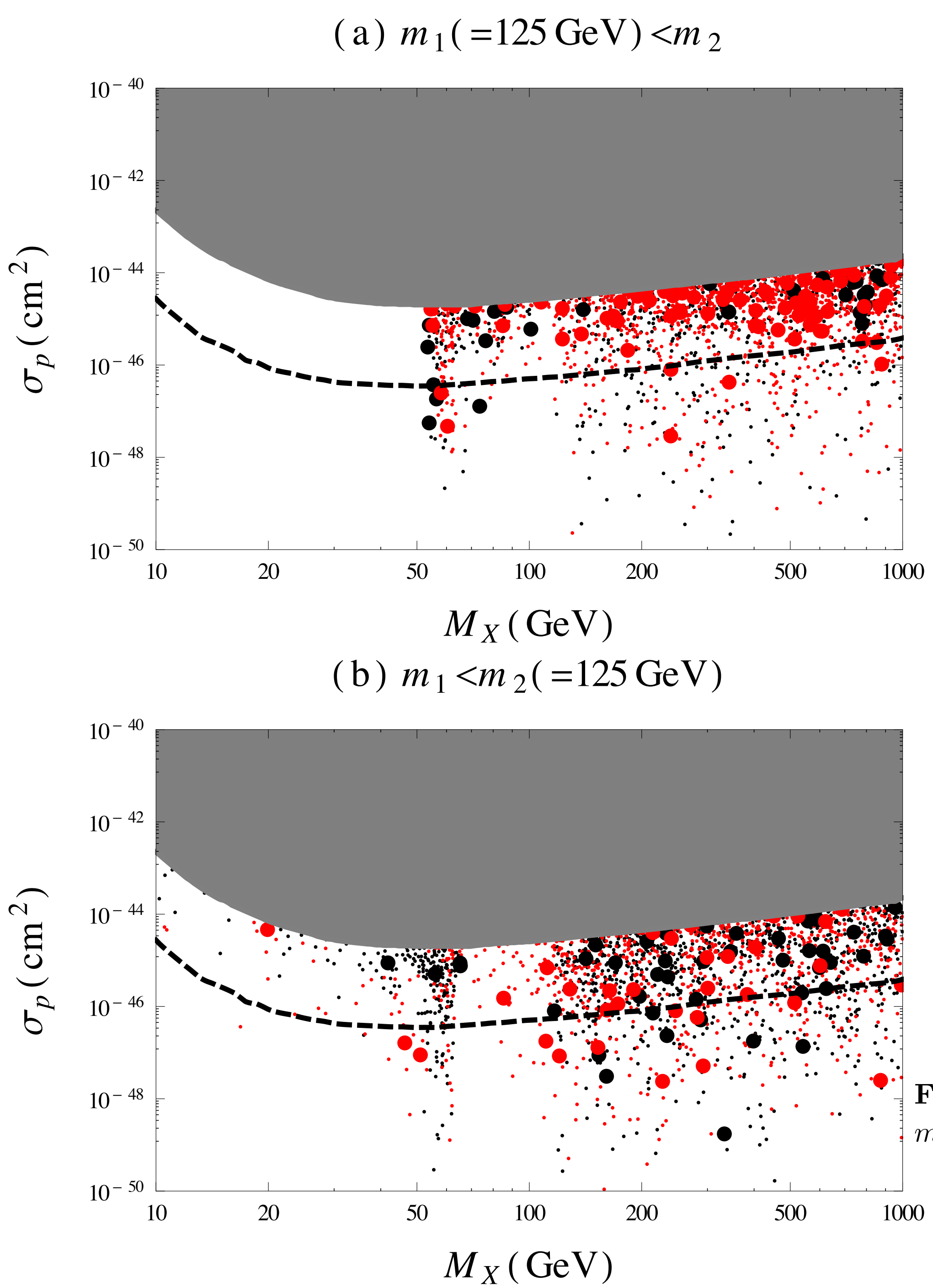
$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

- 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



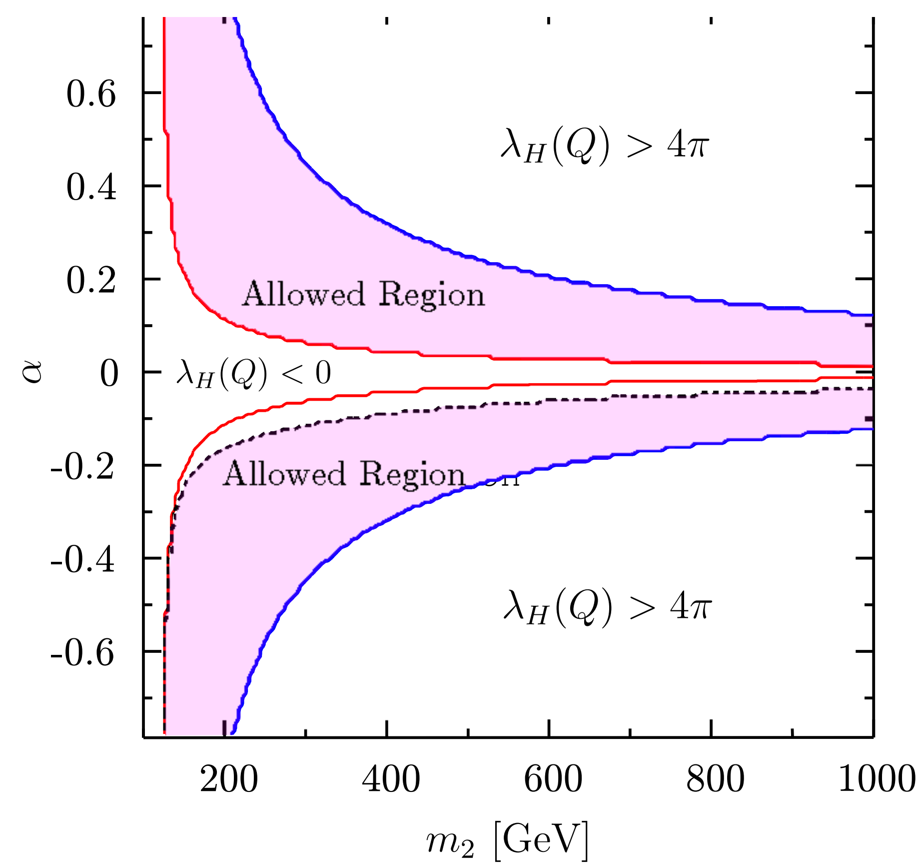


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

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.

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

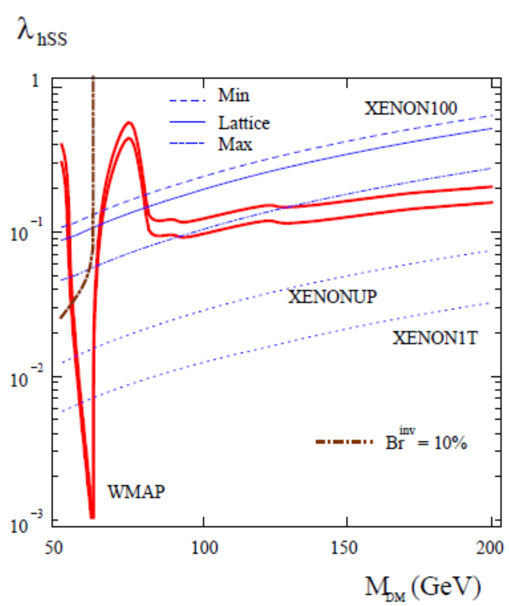


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

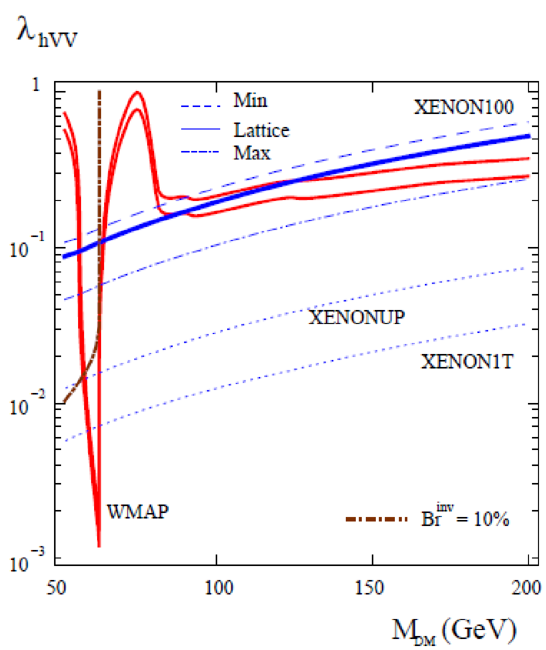


FIG. 2. Same as Fig. 1 for vector DM particles.

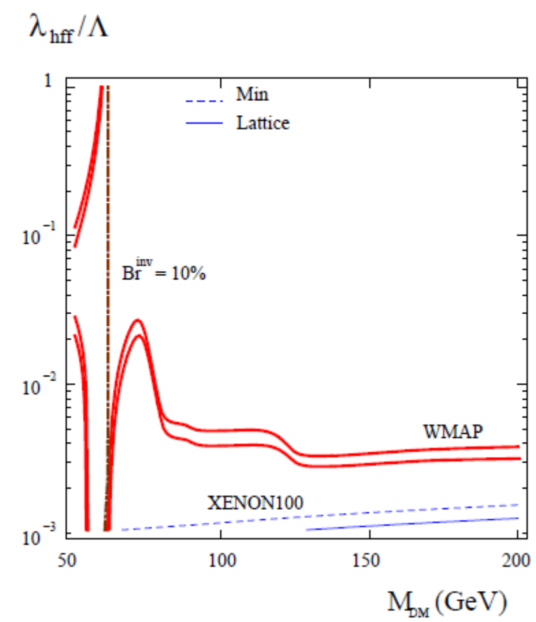
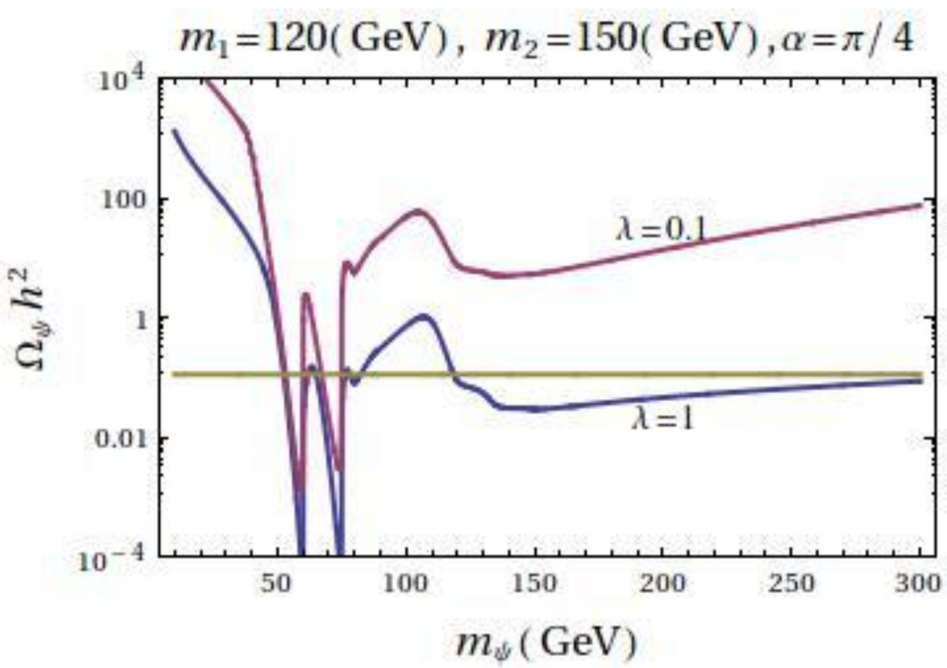


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian, we get different results !

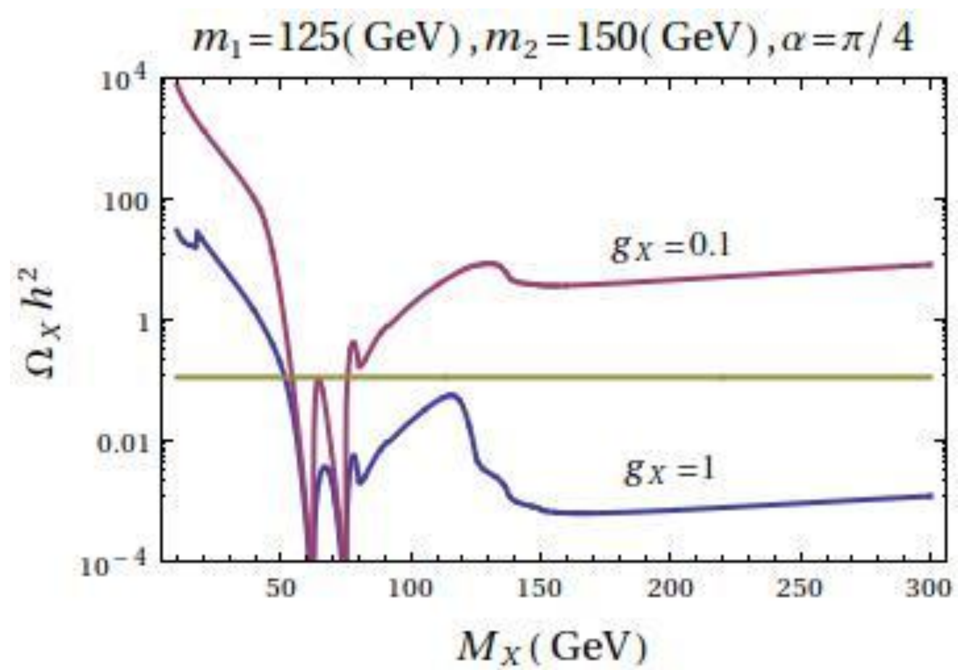
DM relic density

SFDM



P-wave annihilation

VDM



S-wave annihilation

Higgs-DM couplings less constrained 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:

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

- 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 $h_{\rm SM}$, s and ϕ_X, resulting a number of neutral scalar bosons. Only $h_{\rm SM}$ 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 $h_i \equiv (h_1, h_2, \dots, h_{n+2})$ 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

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

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

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

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

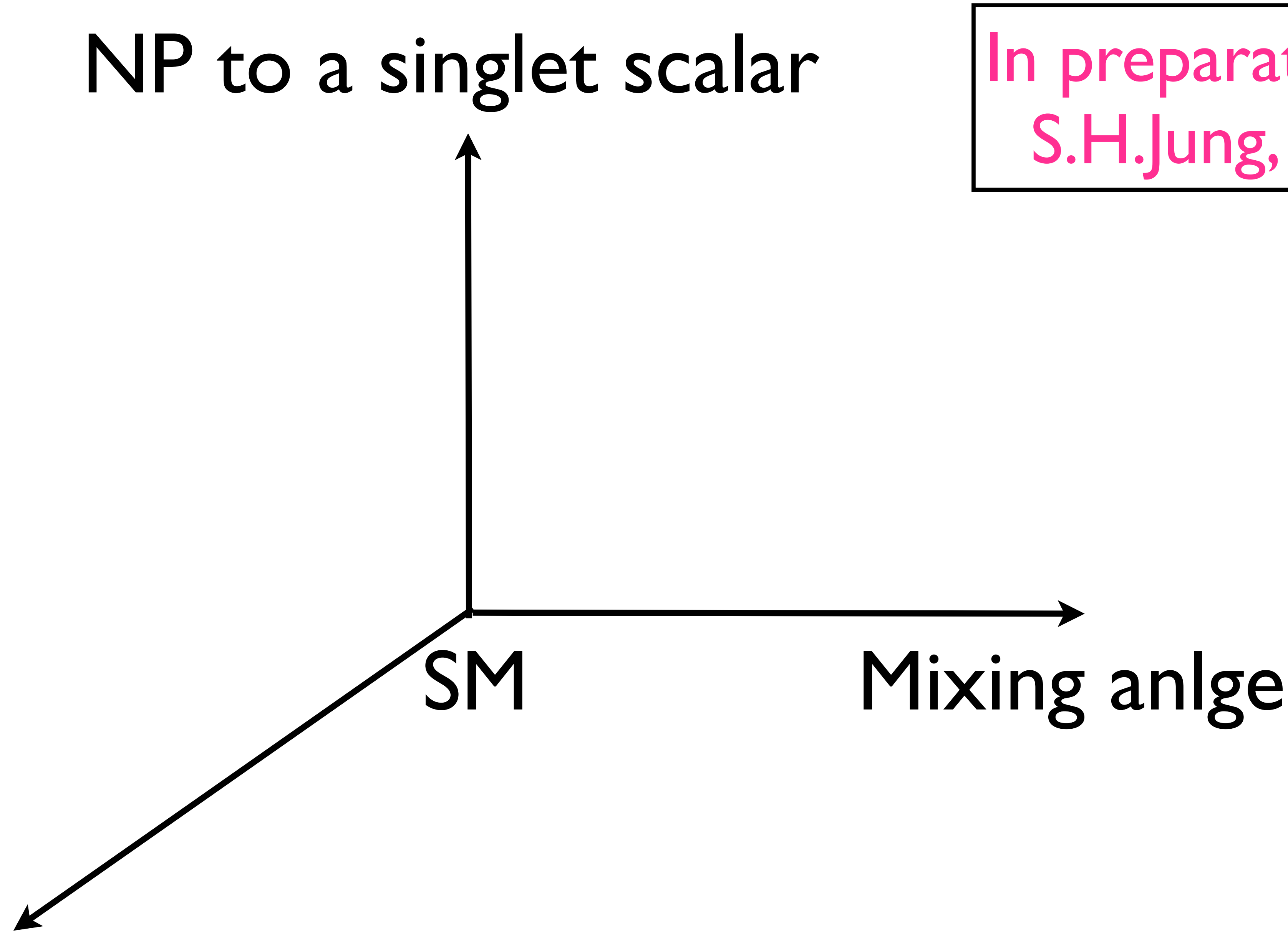
Reminder: An Old Lesson

- The SM with u,d,s quarks lead to too large FCNC in kaon physics, and is immediately ruled out
- This is cured by an additional quark "charm" (GIM mechanism)
- This problem could be absent from the beginning if we considered an anomaly free gauge theory : Important to work in models theoretically/mathematically consistent

Conclusion - I

- SM Higgs tends to make hCDM decay unless CDM carries local dark symmetry
- Whatever you do for CDM stabilization or longevity, Highly unlikely to avoid extra singlet scalar(s) which mix w/ the SM Higgs boson
- Universal suppressions of the signal strengths of Higgs productions/decays @ LHC
- Precise measurements of the signal strengths @ LHC can test the hCDM hypothesis

In preparation with
S.H.Jung, S. Choi



Talk by D.W.Jung on
Higgs-Dilaton Mixing

NP to the SM Higgs

Considered by the usual approaches
based on effective Lagrangian

Mixing with a singlet scalar

$$\mathcal{M}(H_1 F) = \mathcal{M}(hF)_{\rm SM} \times (b_F \cos\alpha - c_F \sin\alpha) \equiv \kappa_{1F} \mathcal{M}(hF)_{\rm SM}$$

$$\mathcal{M}(H_2 F) = \mathcal{M}(hF)_{\rm SM} \times (-b_F \sin\alpha + c_F \cos\alpha) \equiv \kappa_{2F} \mathcal{M}(hF)_{\rm SM}$$

Model	Nonzero c's
Pure Singlet Extension	c_{h^2}
Hidden Sector DM	c_χ
Dilaton	$c_{h^2}, c_g, c_W, c_Z, c_\gamma$
Vectorlike Quarks	c_g, c_γ
Vectorlike Leptons	c_γ
New Charged Vector bosons	c_γ

Other c's are all zeros !

I used the data compilation by Dobrescu and Lykken

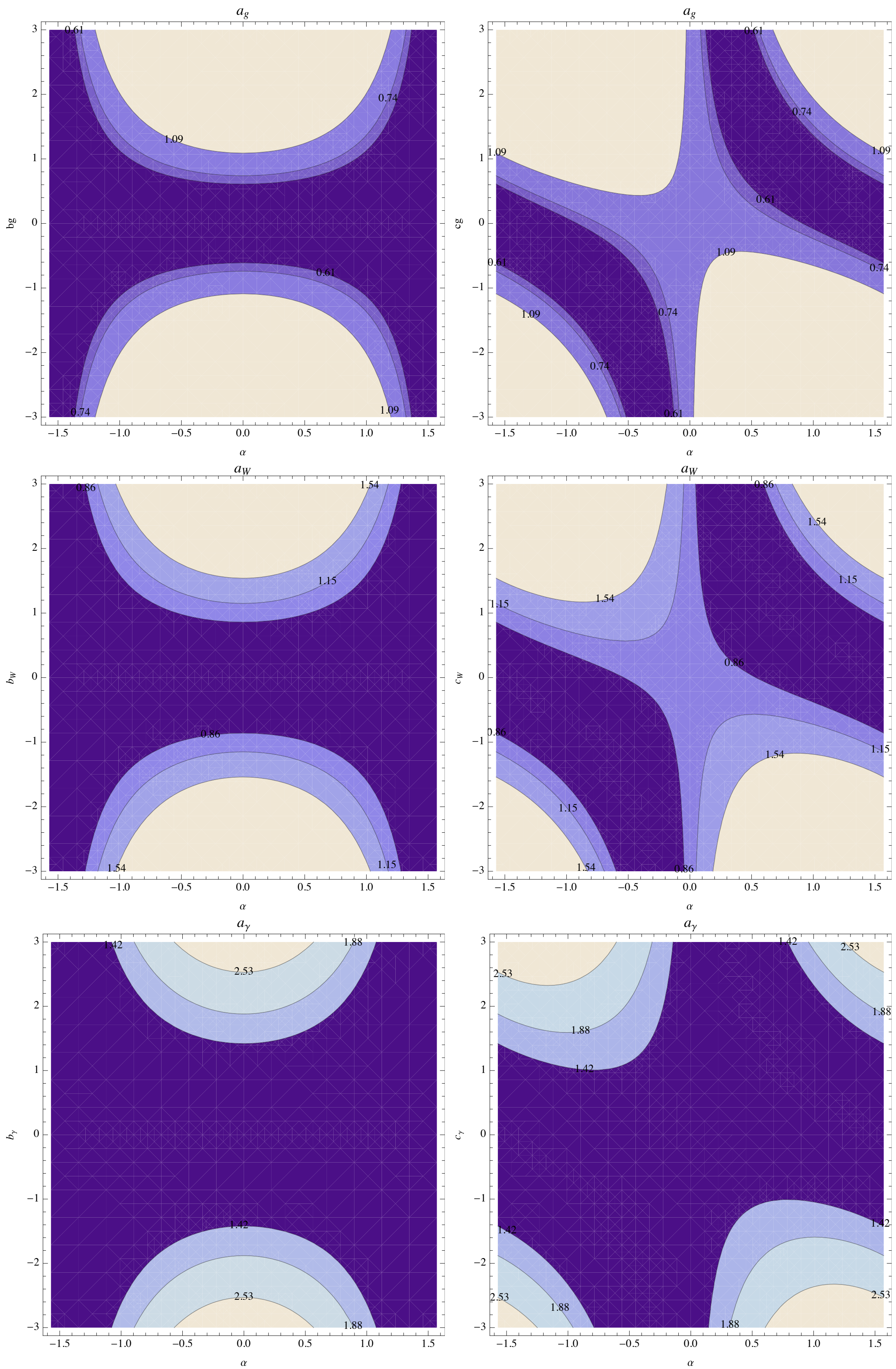


Figure 2. New physics contributions to the couplings between the Higgs boson and the SM bosons : b_F (left column) and c_F (right column) for $F = g, W, \gamma$.

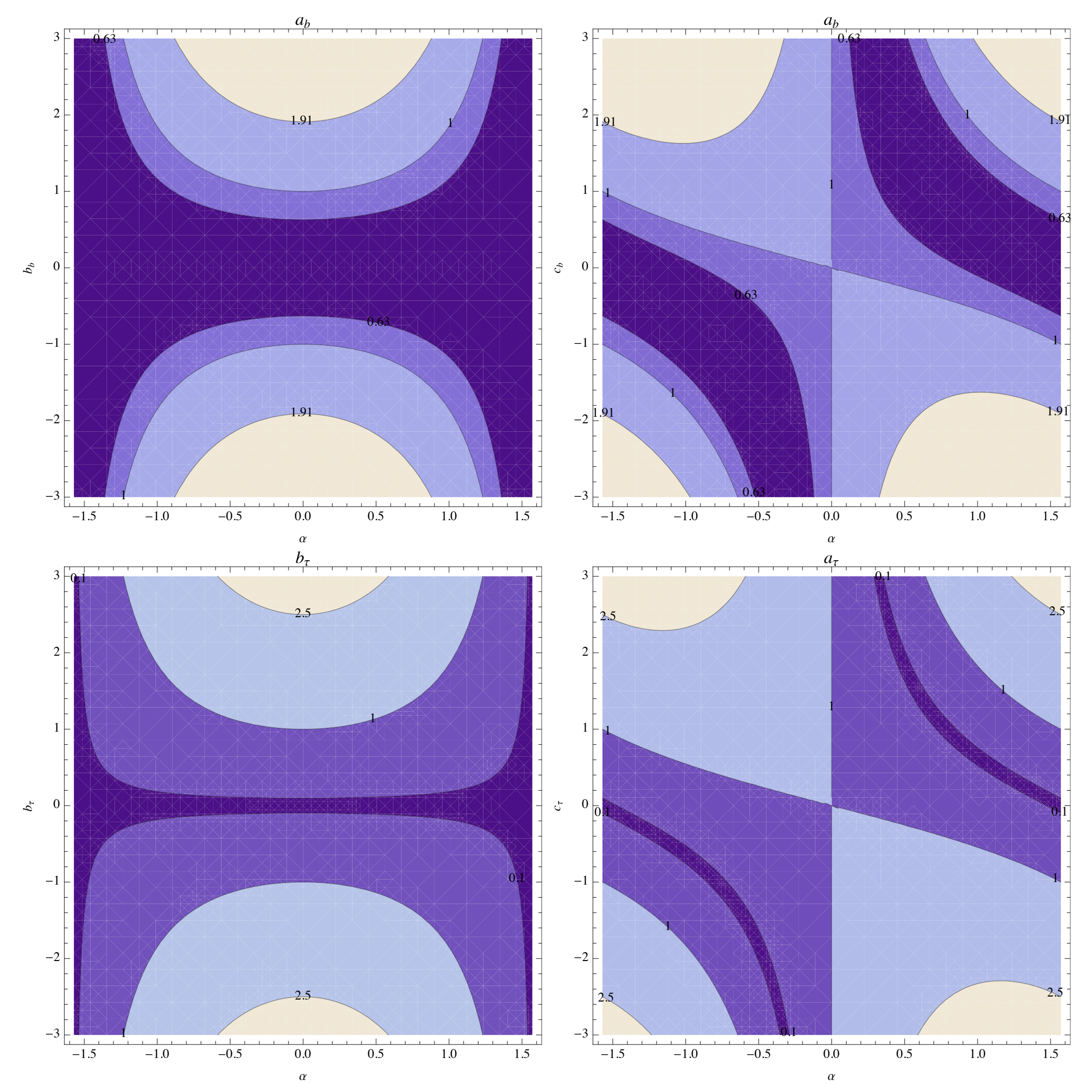


Figure 3. New physics contributions to the couplings between the Higgs boson and the SM fermions : b_F (left column) and c_F (right column) for $F = b, \tau$.

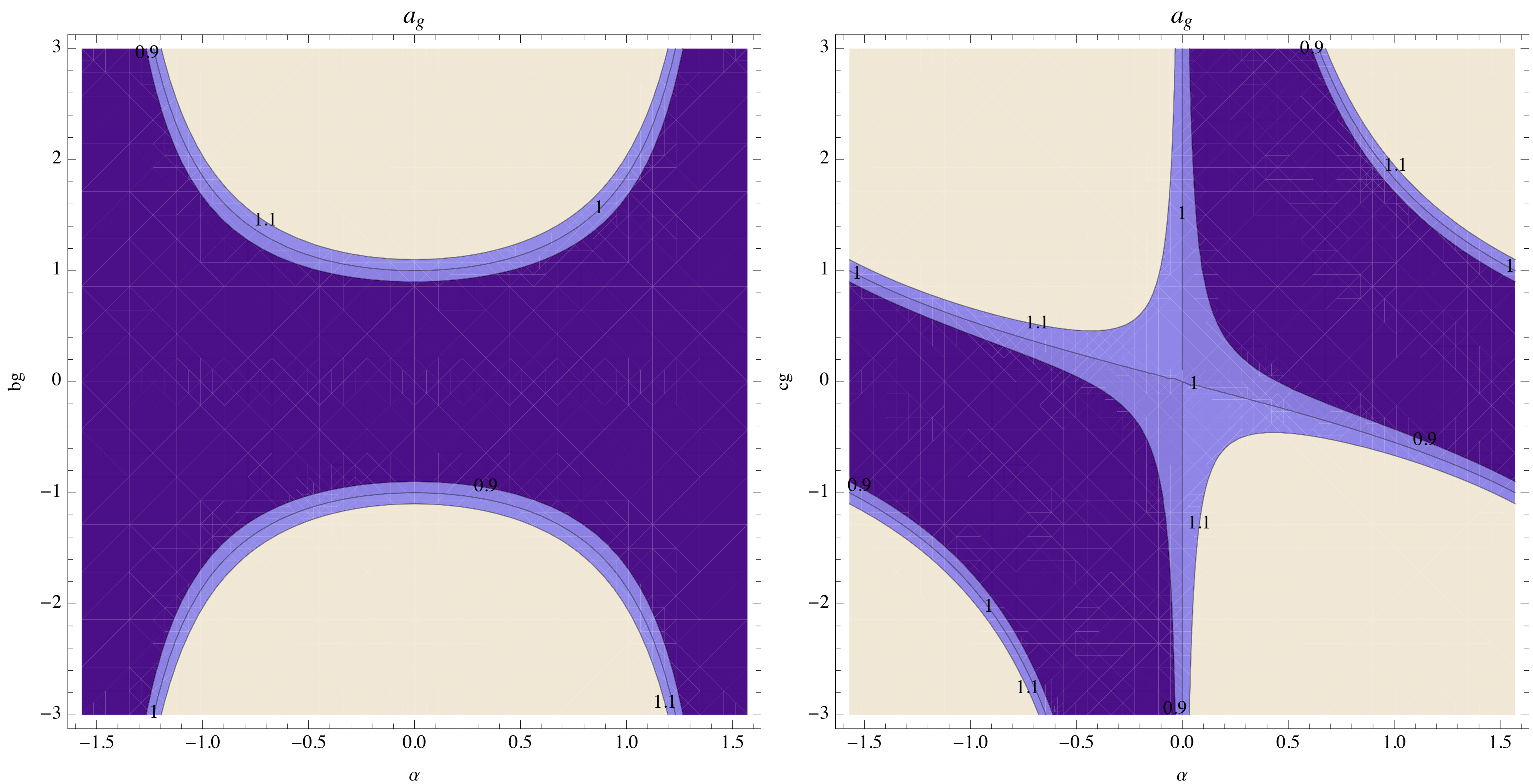


Figure 4. New physics contributions to the couplings between the Higgs boson and the SM bosons : b_F (left column) and c_F (right column) for $F = g, W, \gamma$.

1.0 +- 0.2

1.0 +- 0.1

Mixing angle is not so well constrained

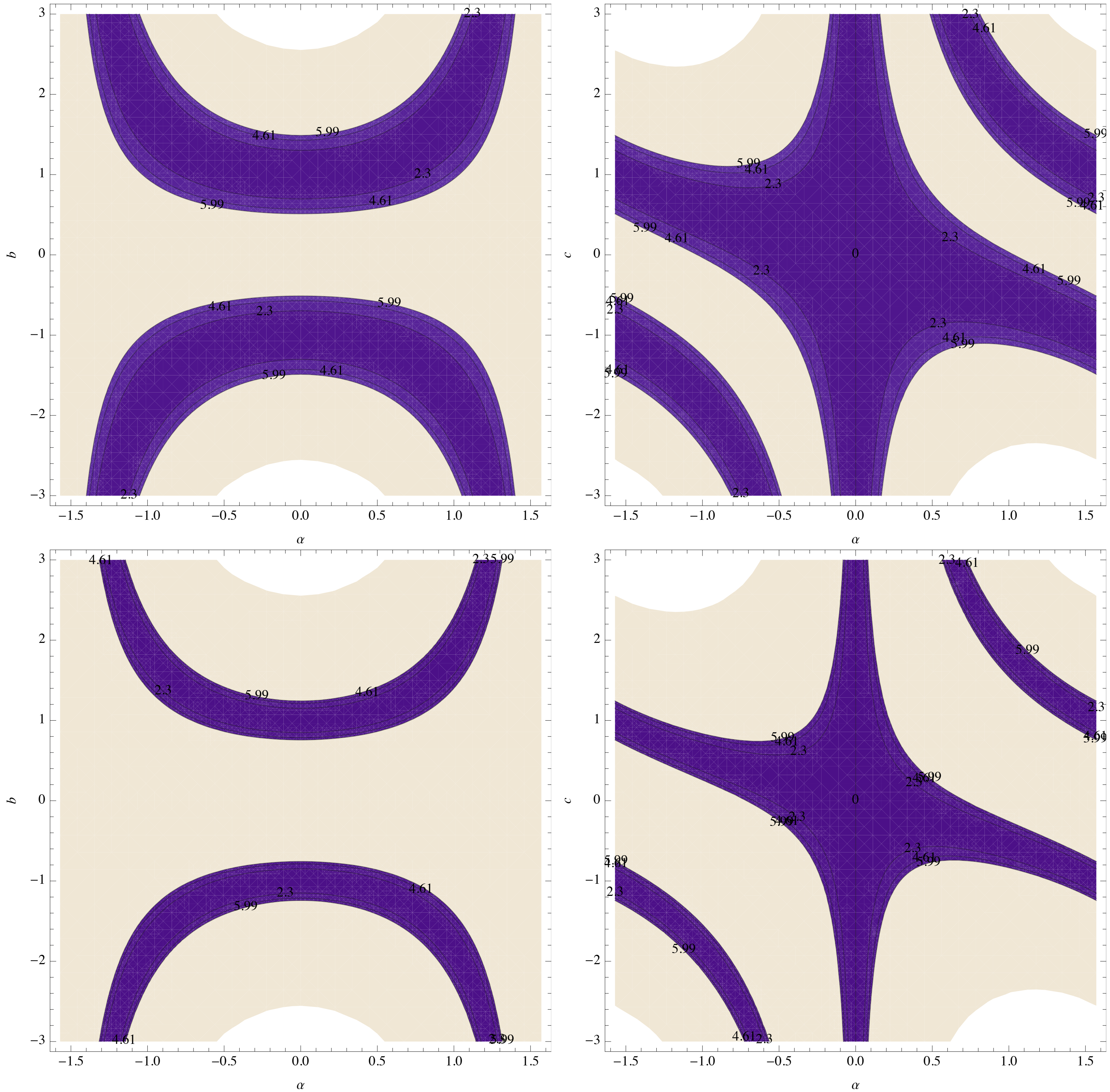


Figure 5. New physics contributions to the couplings between the Higgs boson and the SM bosons : b_F (left column) and c_F (right column) for $F = g, W, \gamma$.

- Higgs mixing with singlet scalars is not so well constrained, and not covered by the usual approaches based on effective lagrangian approach (see Ko et al in preparation, and also a recent paper by Zurek et al.)
- The 2nd scalar is very very elusive
- The signal strengths of H(125) give indirect informations on these scenarios w/ hCDM
- Better to work in a minimal complete model
- Some model dependence may be unavoidable

Contents

- Generalities on hCDM vs. Higgs Physics
  - Why Hidden Sector ?
  - Is CDM stable or not ?
  - Local or Global Sym ?
  - EFT or Renormalizable Model ?
- Unbroken local dark symmetry : Singlet Portal extension of the Standard Seesaw Models

An Alternative to the new minimal SM

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

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

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

Inflaton

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

Interactions

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

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]

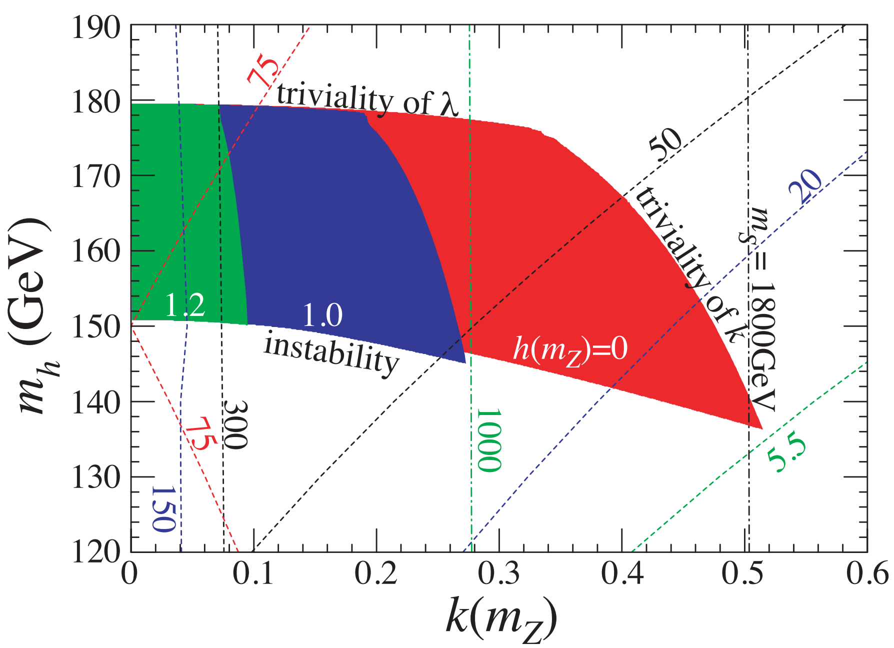


FIG. 1: The region of the NMSM parameter space $(k(m_Z), m_h)$ that satisfies the stability and triviality bounds, for $h(m_Z) = 0$, 1.0, and 1.2. Also the preferred values from the cosmic abundance $\Omega_S h^2 = 0.11$ are shown for various m_S. We used $y(m_Z) = 1.0$.

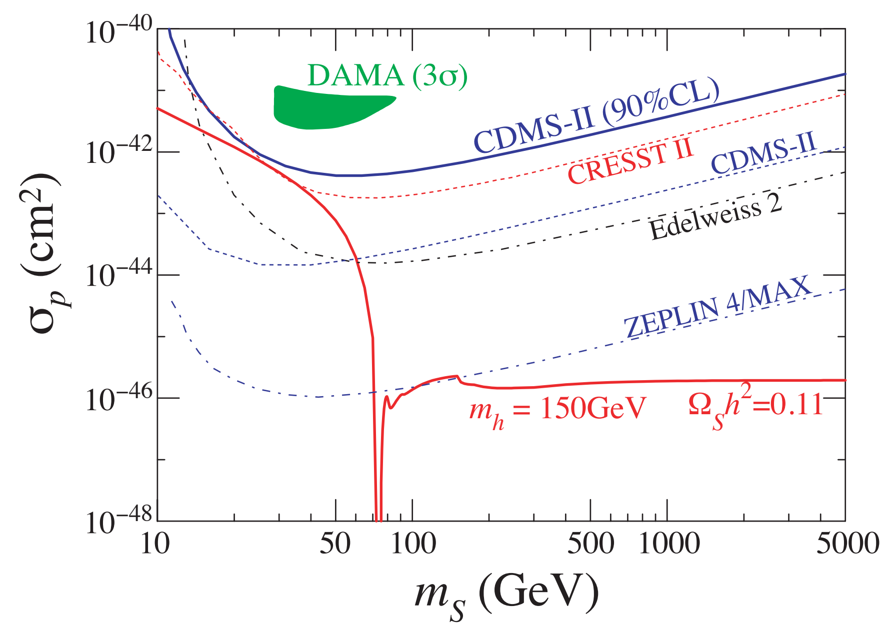


FIG. 2: The elastic scattering cross section of Dark Matter from nucleons in NMSM, as a function of the Dark Matter particle mass m_S for $m_h = 150$ GeV. Note that the region $m_S \gtrsim 1.8$ TeV is disallowed by the triviality bound on k. Also shown are the experimental bounds from CDMS-II [25] and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

Part 2.

Asymmetric dark matter & dark radiation

(based on a work with S. Baek, P. Ko, 1302.XXXX?)

Outline

- Stability of dark matter
- A (or the ?) minimal model
- Constraints
- Inflation
- Lepto/darkogenesis
- Conclusion

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

- The symmetry should be local.

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.)

A minimal 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 $\quad \text{New fields : } X_\mu,\ X,\ \psi$

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

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

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

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

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

Constraints

Our model 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.

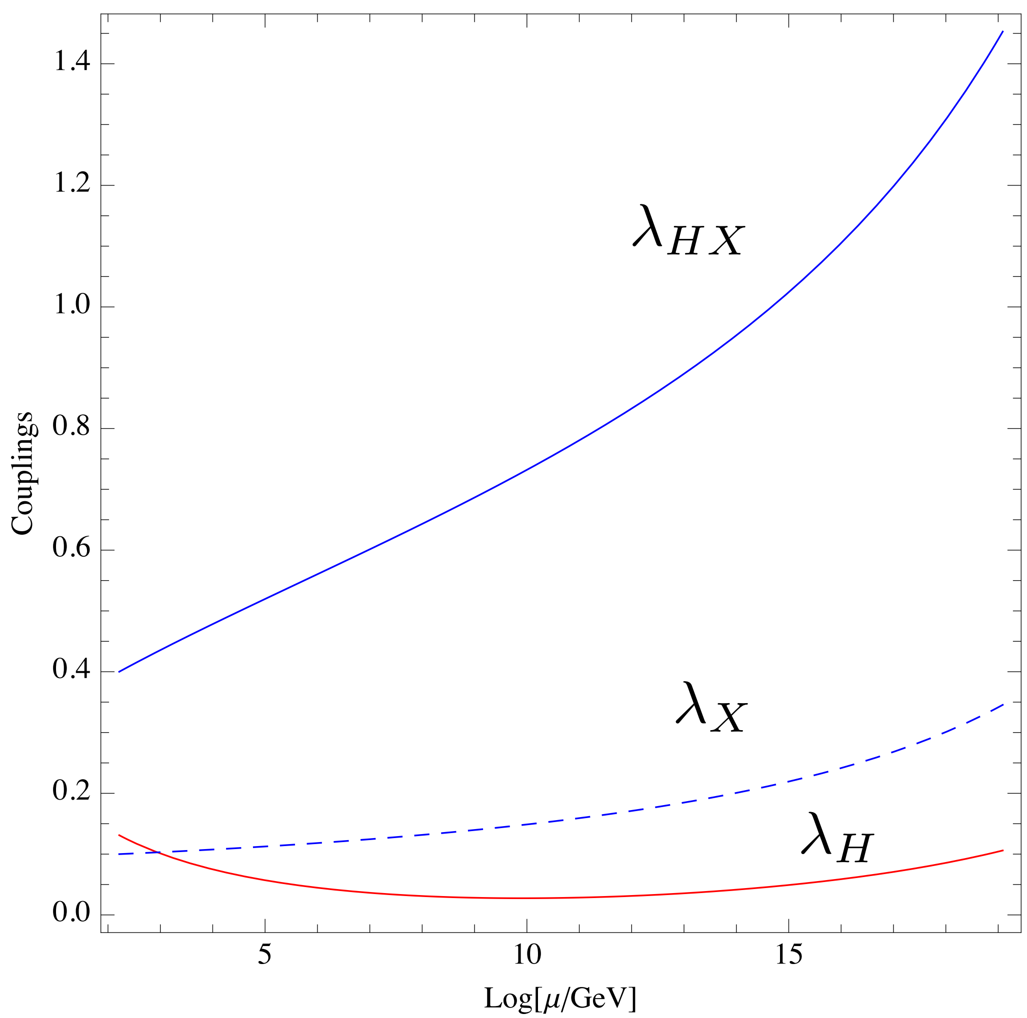
- # Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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

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

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

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



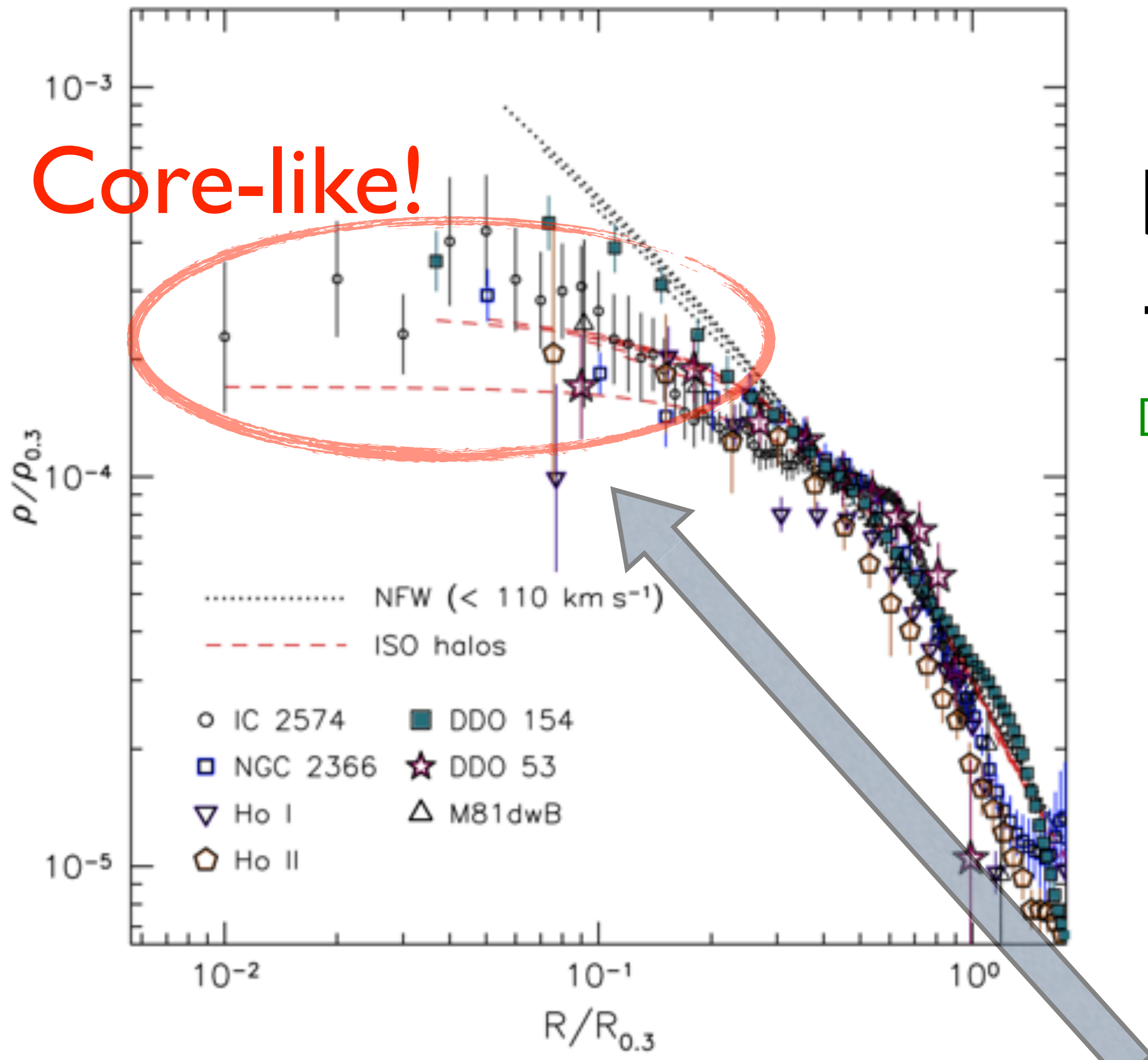
Perturbativitiy

$$\lambda_X \lesssim 0.23$$

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

vacuum stability   Perturbativitiy

- 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]

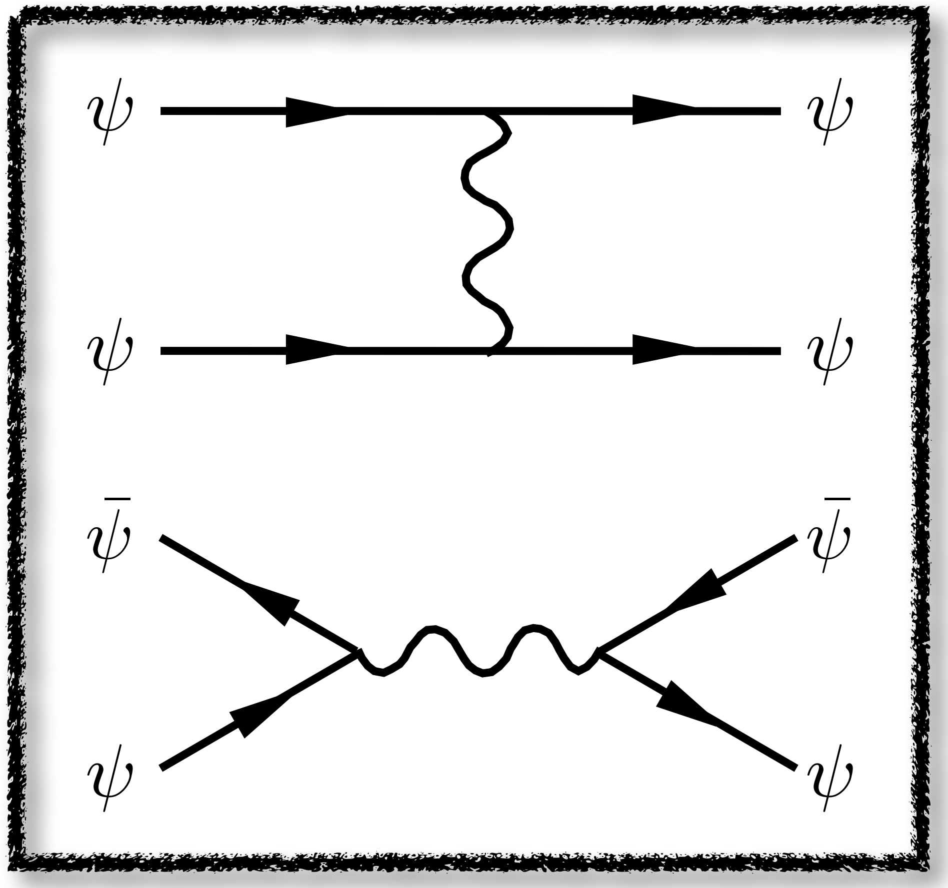
- dark matter self-interaction?

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

self-interacting rate

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

Dark matter self-interaction



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

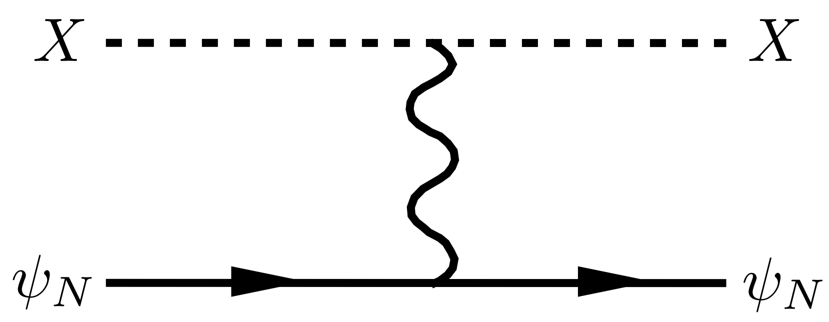
$$\Rightarrow \alpha_X \lesssim 6\times 10^{-6}\left(\frac{m_\psi}{1\mathrm{TeV}}\right)^{3/2}$$

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

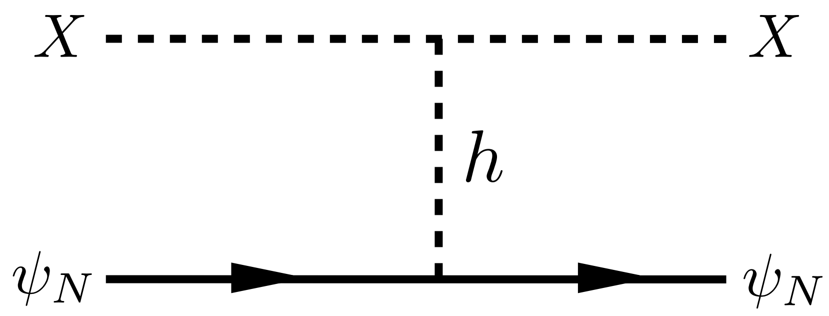
Too much!

- 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.

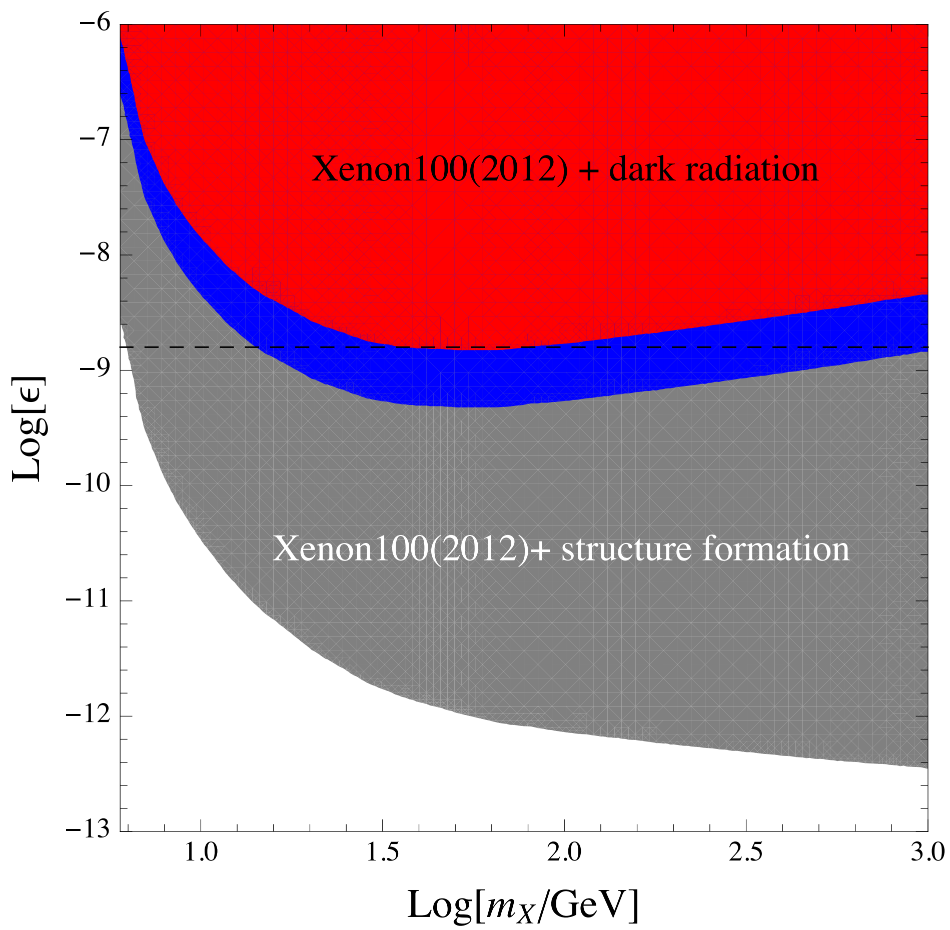
- DM direct search (ε, λ_{hx}, m_X)

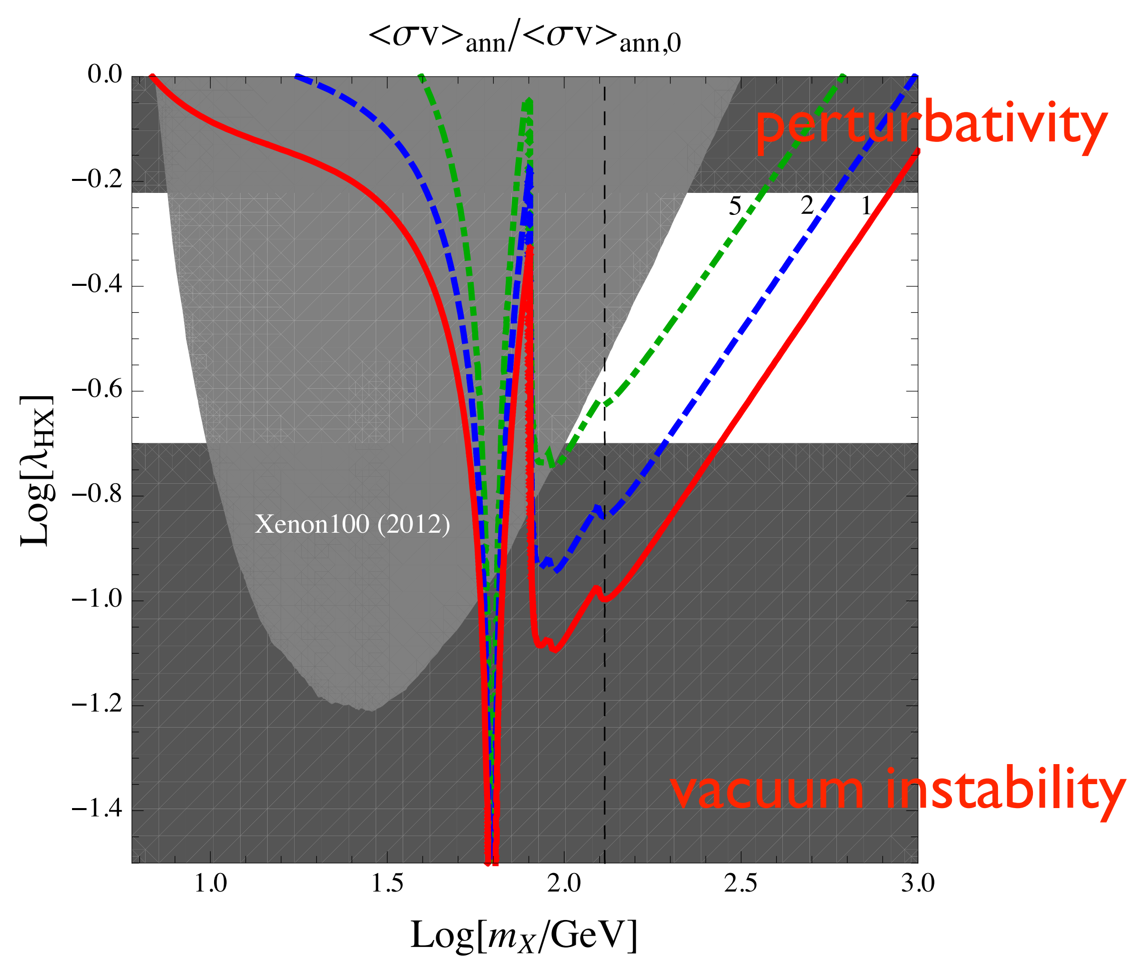


$$\sigma^{\rm SI}_{\mathcal{N},\gamma'} = \frac{4\alpha_X \alpha_{\rm em} c_W^2 s_\epsilon^2}{\pi} \frac{1}{m_{\rm r}^2} \frac{1}{v^4} \ln\left(\frac{2}{\theta_{\rm min}}\right)$$



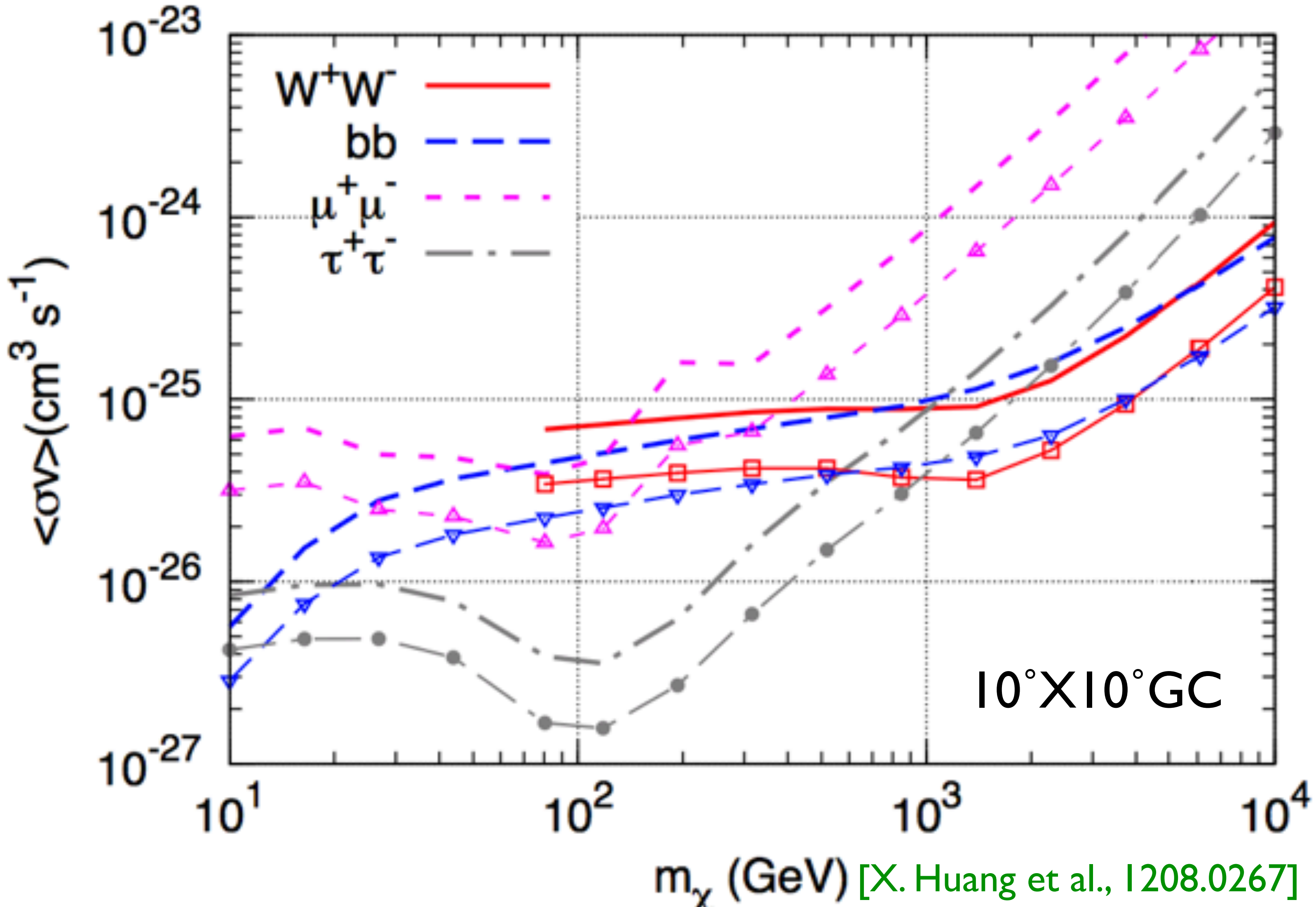
$$\sigma^{\rm SI}_{\mathcal{N},h} = \frac{\lambda_{HX}^2}{64\pi} \frac{m_{\rm r}^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$





- 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]

$$\langle\sigma v\rangle_{\rm ann}^{\rm tot} \lesssim 10^{-25}{\rm cm}^2/{\rm sec}$$

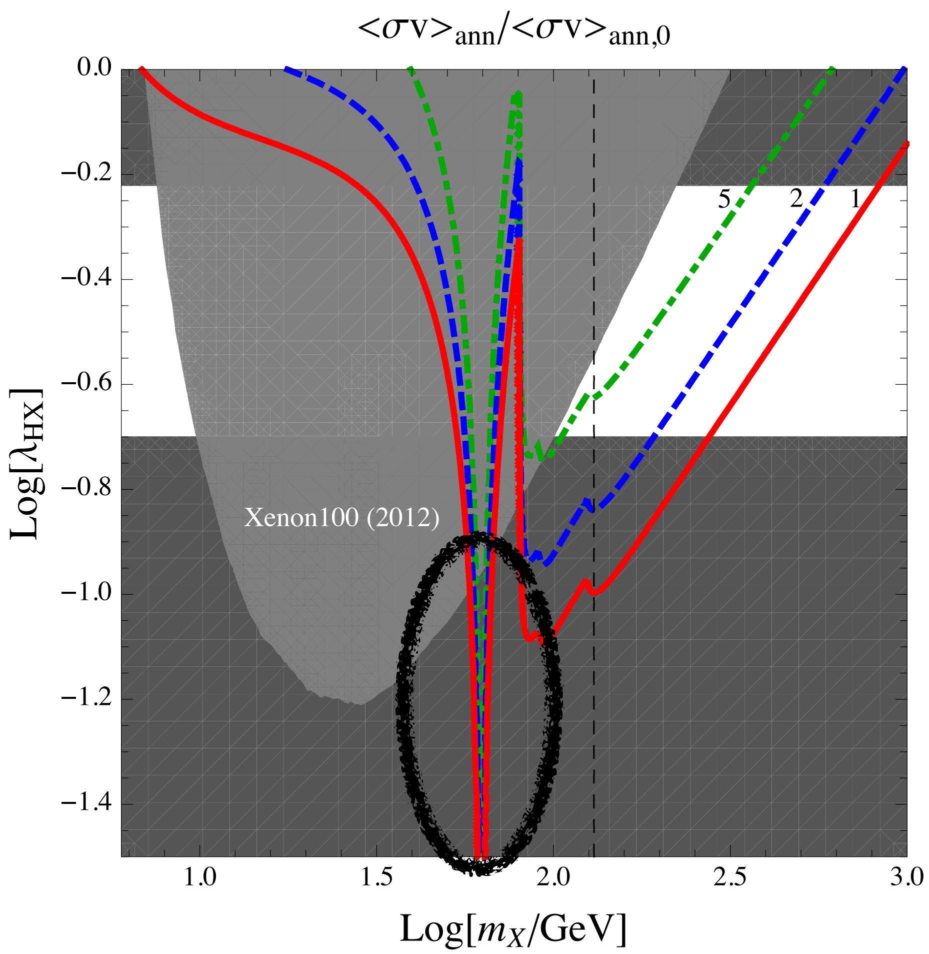
$$\Rightarrow \langle\sigma v\rangle_{\rm ann}^{\gamma\gamma} \sim 10^{-4}\langle\sigma v\rangle_{\rm ann}^{\rm tot} \sim 10^{-29}{\rm cm}^2/{\rm sec}$$

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

$$\lambda_{HX} \ll 0.1$$

or

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

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.

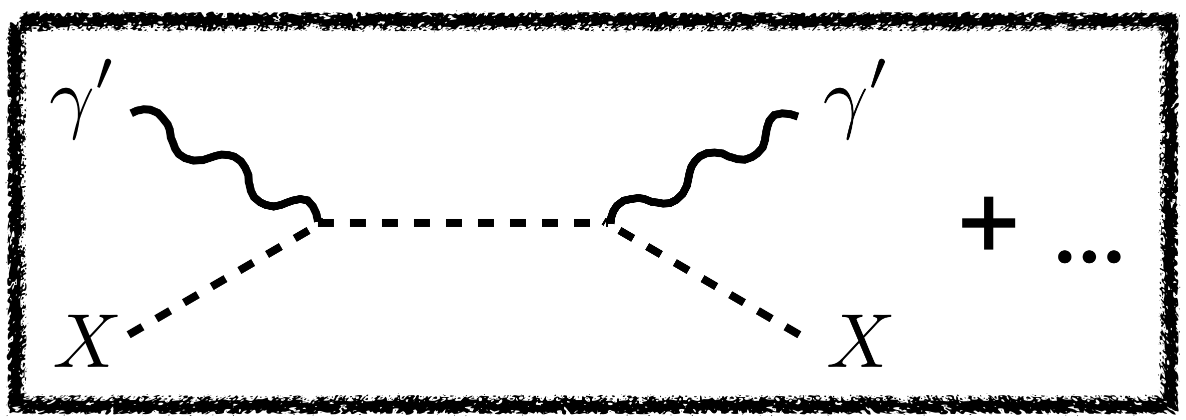
Diagonalizing mass term results in interactions between DS and SM,

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

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

⇨ Ψ and X are mini-charged under electromagnetism.

Decoupling of X_μ



⇨

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

• Dark radiation (ε)-2/2

of extra relativistic degree of freedom

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

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

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

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

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

- Summary of constraint

Vacuum stability + perturbativity

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

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

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 □

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

Higgs Inflation

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

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

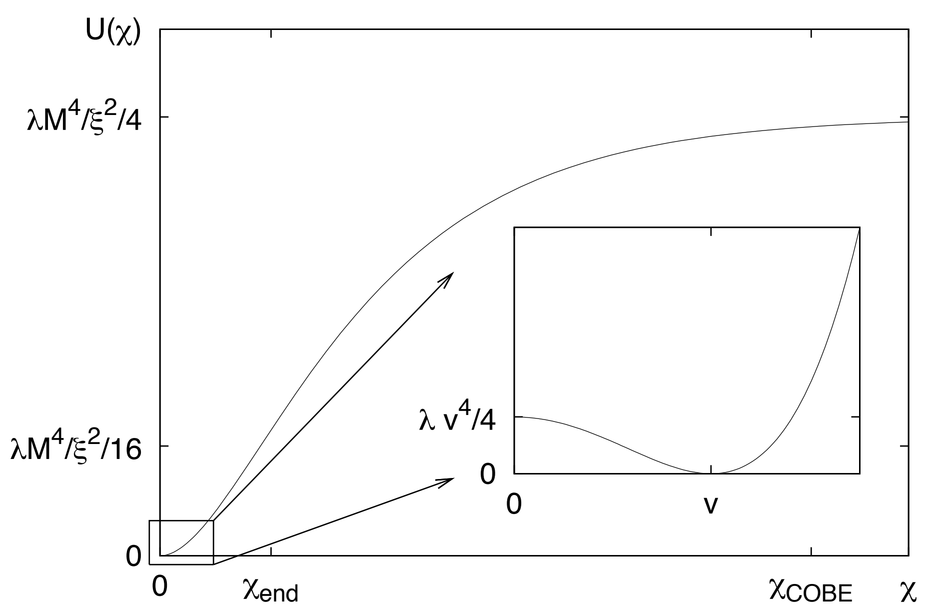


Fig. 1. Effective potential in the Einstein frame.

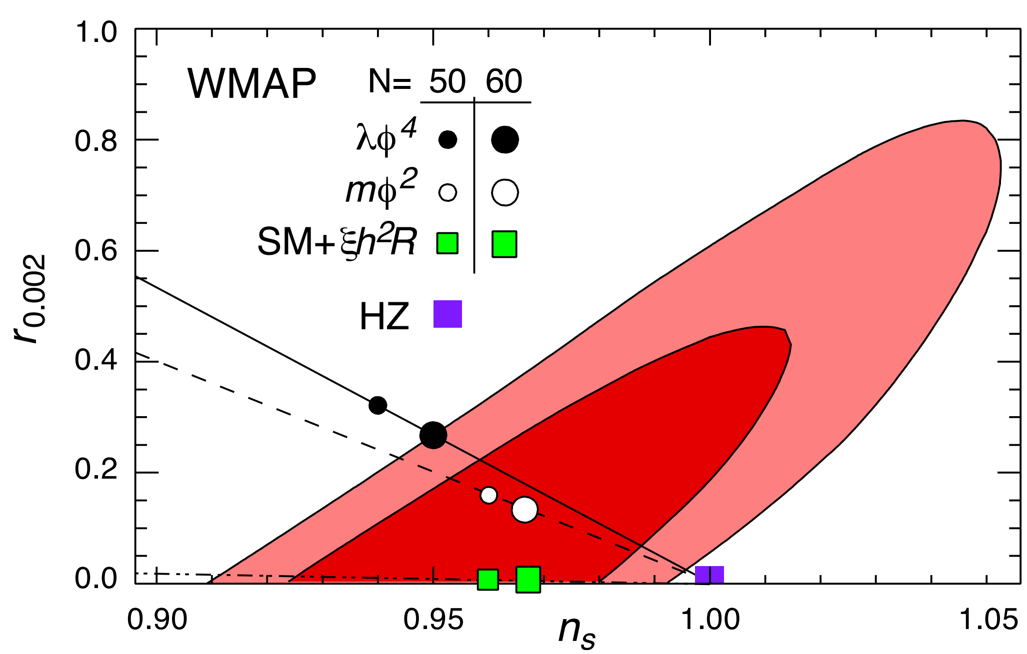


Fig. 2. The allowed WMAP region for inflationary parameters (r, n). The green boxes are our predictions supposing 50 and 60 e–foldings of inflation. Black and white dots are predictions of usual chaotic inflation with $\lambda\phi^4$ and $m^2\phi^2$ potentials, HZ is the Harrison-Zeldovich spectrum.

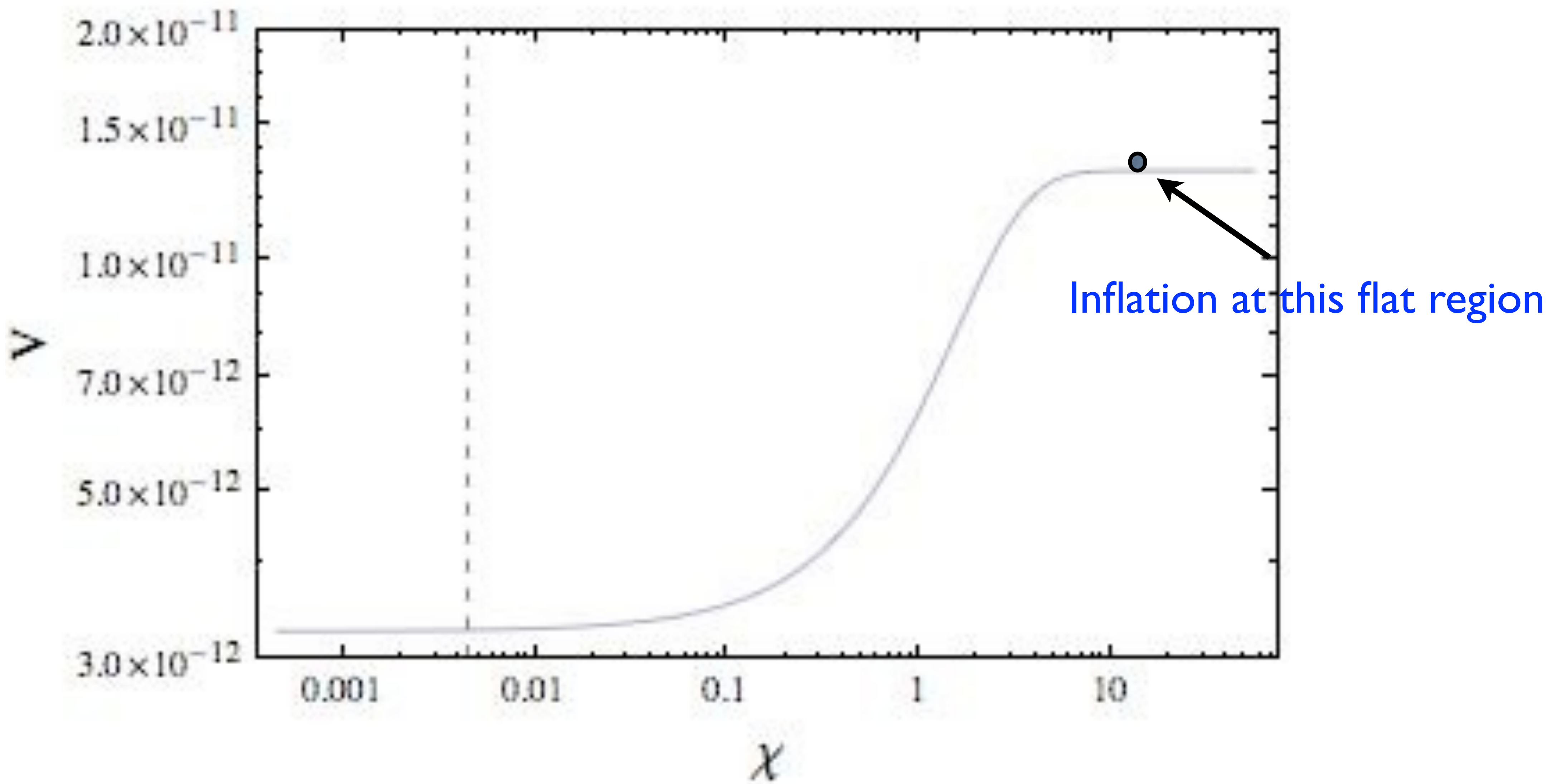
Higgs Inflation possible, if

$$m_{\rm min} < m_H < m_{\rm max} \ ,$$
$$m_{\rm min} = [136.7 + (m_t - 171.2) \times 1.95]\,{\rm GeV} \ ,$$
$$m_{\rm max} = [184.5 + (m_t - 171.2) \times 0.5]\,{\rm GeV} \ .$$

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

Inflaton(Higgs) potential

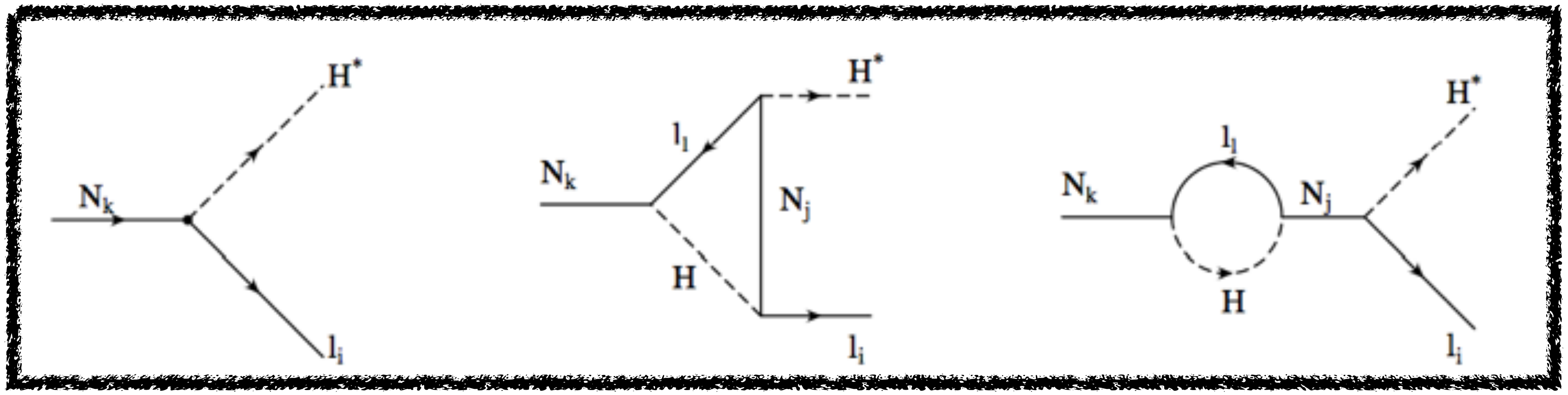


$$\lambda_X \lesssim 0.23$$

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

Lepto/darkogenesis

- Lepto/darkogenesis from the decay of RHN



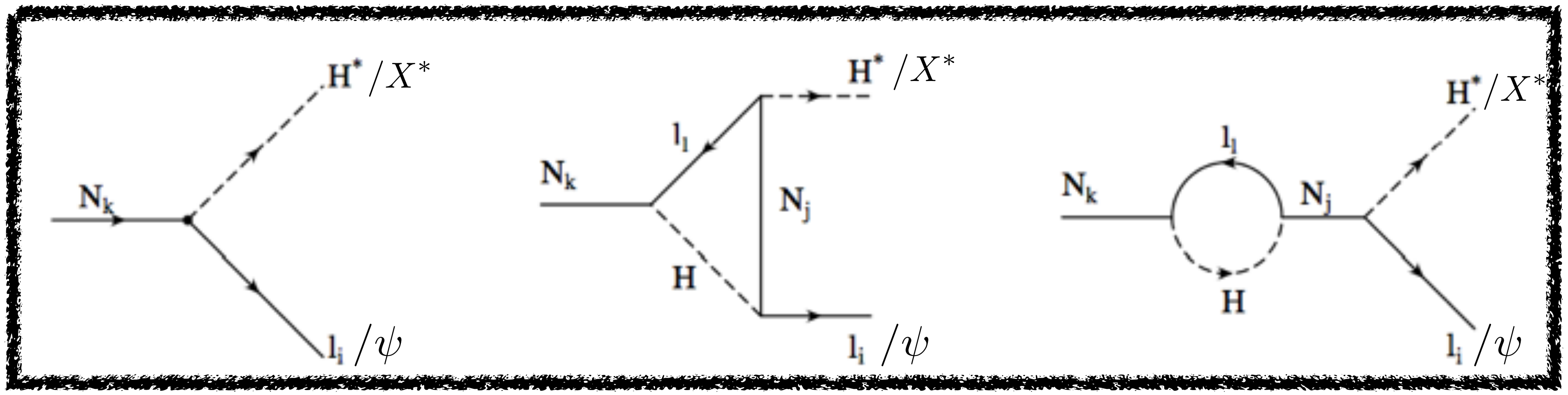
$$\epsilon_L \simeq \frac{M_1}{8\pi}\frac{\mathrm{Im}\left[\left(3Y_\nu^* Y_\nu^T + \lambda^*\lambda\right)\mathbb{M}^{-1} Y_\nu Y_\nu^\dagger\right]_{11}}{\left[2Y_\nu Y_\nu^\dagger + \lambda\lambda^*\right]_{11}}$$

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

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

Lepto/darkogenesis

- Lepto/darkogenesis from the decay of RHN



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

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

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

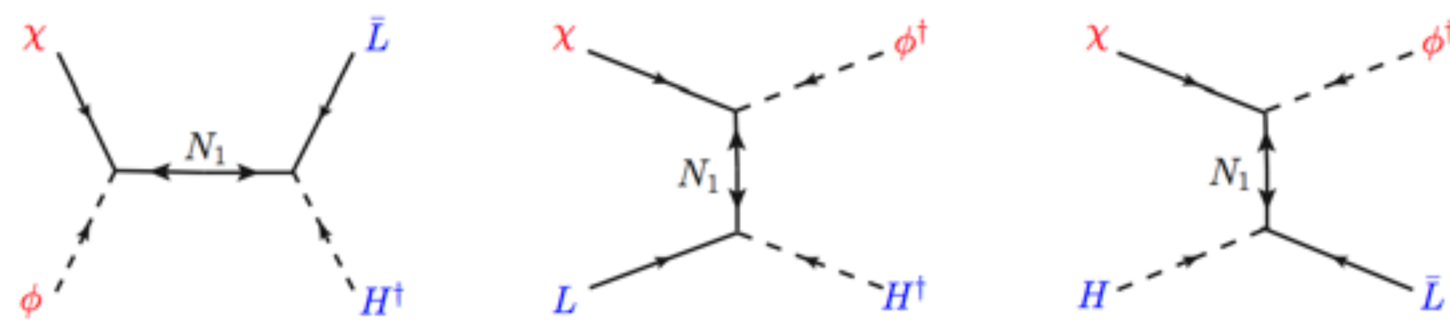
- Boltzman equations

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

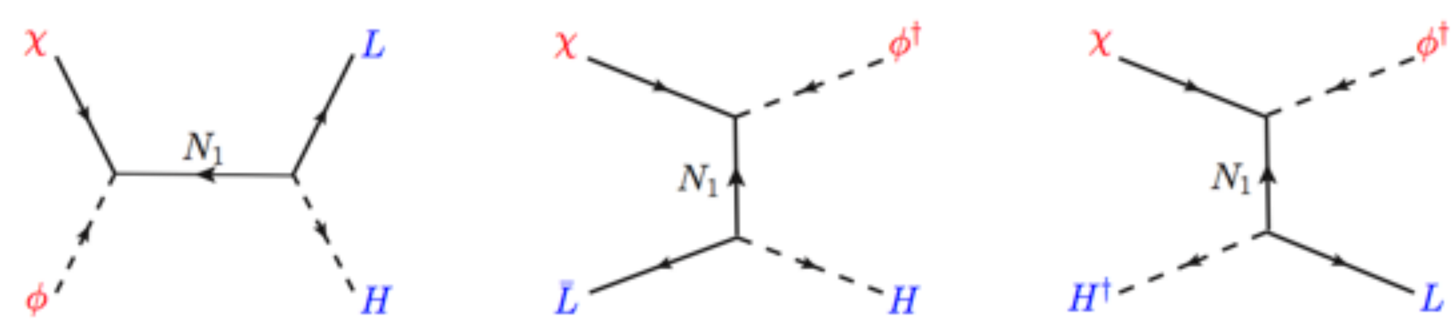
$$\frac{sH_1}{z}Y_{\Delta\psi}' = \gamma_D\left[\epsilon_\psi\left(\frac{Y_1}{Y_1^{\rm eq}}\right)-\frac{Y_{\Delta\psi}}{2Y_\psi^{\rm eq}}{\rm Br}_\psi\right]+(2\leftrightarrow 2\text{washout}+\text{transfer})$$

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

wash-out: $\Delta L = 2$



transfer: $\Delta L = 0$



- Lepton/darkon number asymmetry

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

Narrow-width approx.

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

Weak wash-out

$$m_\nu \sim 10^{-4}\,{\rm eV}\,, \quad \lambda_1 \sim 2-3\times 10^{-2}, \quad M_1 \sim 10^9\,{\rm GeV}$$

Matching observations

$$\left(\frac{\lambda_2^2 M_1}{\lambda_1^2 M_2}\right)^{1/2} \simeq 0.62, \ \lambda_1 \simeq 10^{-2}\left(\frac{M_1}{10^9\,{\rm GeV}}\right)\left(\frac{m_X}{1\,{\rm TeV}}\right)$$

Strong wash-out

$$10^{-3}\,{\rm eV} \lesssim m_\nu \lesssim 0.1\,{\rm eV}$$

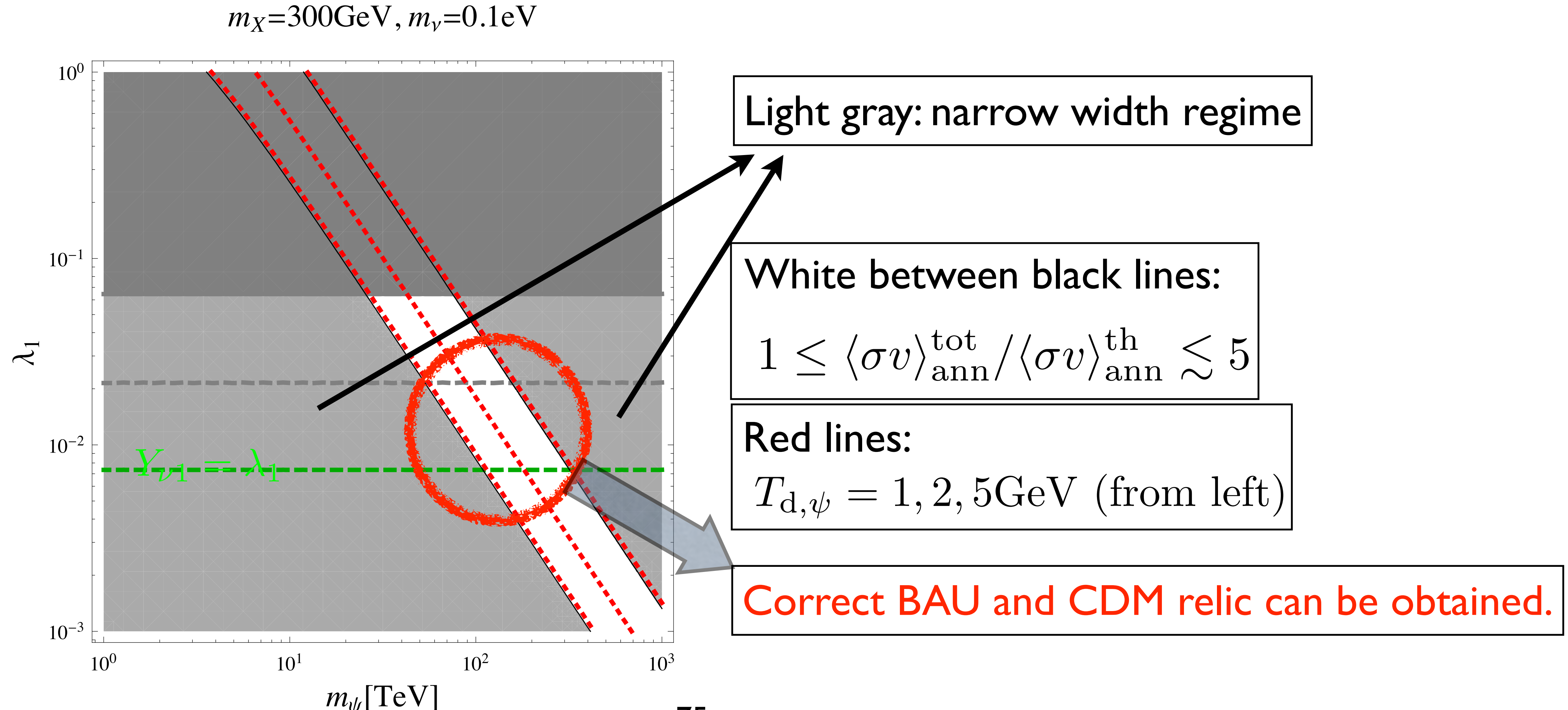
- Lepton/darkon number asymmetry

$$Y_{\Delta L} = \epsilon_L \eta_L Y_1^{\rm eq}(0) \simeq 2.6 \times 10^{-10}$$

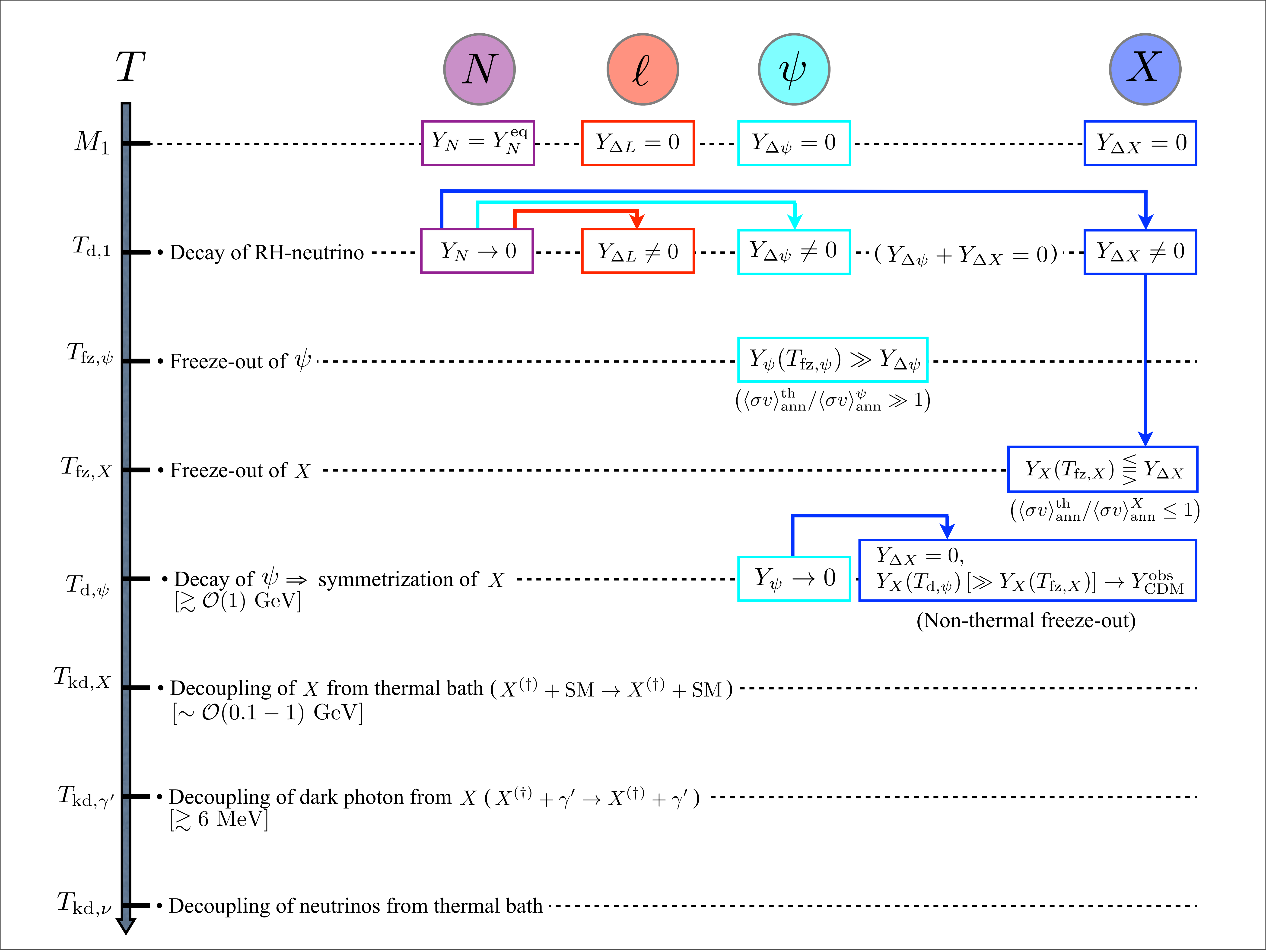
$$Y_{\Delta\psi} = \epsilon_\psi \eta_\psi Y_1^{\rm eq}(0) \simeq 2 \times 10^{-12} \left(\frac{100\,{\rm GeV}}{m_X}\right)$$

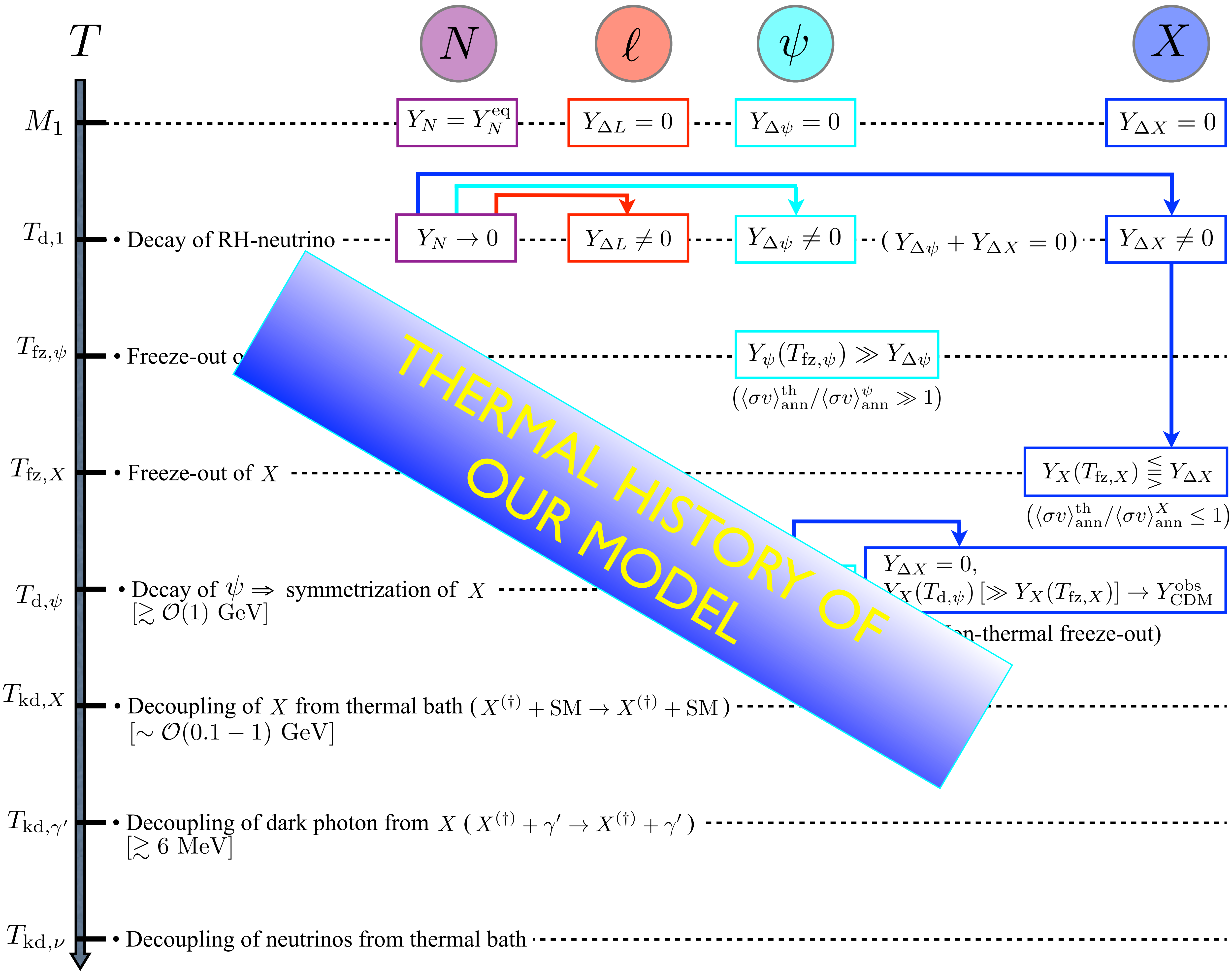
Narrow-width approx.

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



13년 2월 14일 목요일


T
N
ℓ
ψ
X
M_1
$Y_N = Y_N^{eq}$
$Y_{\Delta L} = 0$
$Y_{\Delta\psi} = 0$
$Y_{\Delta X} = 0$
$T_{d,1}$
• Decay of RH-neutrino
$Y_N \to 0$
$Y_{\Delta L} \neq 0$
$Y_{\Delta\psi} \neq 0$
$(Y_{\Delta\psi} + Y_{\Delta X} = 0)$
$Y_{\Delta X} \neq 0$
$T_{fz,\psi}$
• Freeze-out of ψ
$Y_\psi(T_{fz,\psi}) \gg Y_{\Delta\psi}$
$(\langle\sigma v\rangle_{ann}^{th}/\langle\sigma v\rangle_{ann}^{\psi} \gg 1)$
$T_{fz,X}$
• Freeze-out of X
$Y_X(T_{fz,X}) \lesseqgtr Y_{\Delta X}$
$(\langle\sigma v\rangle_{ann}^{th}/\langle\sigma v\rangle_{ann}^{X} \leq 1)$
$T_{d,\psi}$
• Decay of $\psi \Rightarrow$ symmetrization of X
$[\gtrsim \mathcal{O}(1)$ GeV$]$
$Y_\psi \to 0$
$Y_{\Delta X} = 0,$
$Y_X(T_{d,\psi})\,[\gg Y_X(T_{fz,X})] \to Y_{CDM}^{obs}$
(Non-thermal freeze-out)
$T_{kd,X}$
• Decoupling of X from thermal bath $(X^{(\dagger)} + \mathrm{SM} \to X^{(\dagger)} + \mathrm{SM})$
$[\sim \mathcal{O}(0.1-1)$ GeV$]$
$T_{kd,\gamma'}$
• Decoupling of dark photon from X $(X^{(\dagger)} + \gamma' \to X^{(\dagger)} + \gamma')$
$[\gtrsim 6$ MeV$]$
$T_{kd,\nu}$
• Decoupling of neutrinos from thermal bath



13년 2월 14일 목요일

Summary of this model

- Stability of dark matter requires 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)

Some Variations

- One can live with X only, and it can be thermal CDM. No longer RH neutrino portal. The same amount of dark radiation. Higgs inflation possible
- One can live without X. In this case, we need a singlet scalar messenger in order to thermalize the fermion dark matter. The same amount of dark radiation. But reduced signal strengths
- Broken $U(1)_X$ is OK, with reduced signal strengths, and no dark radiation

To Do List

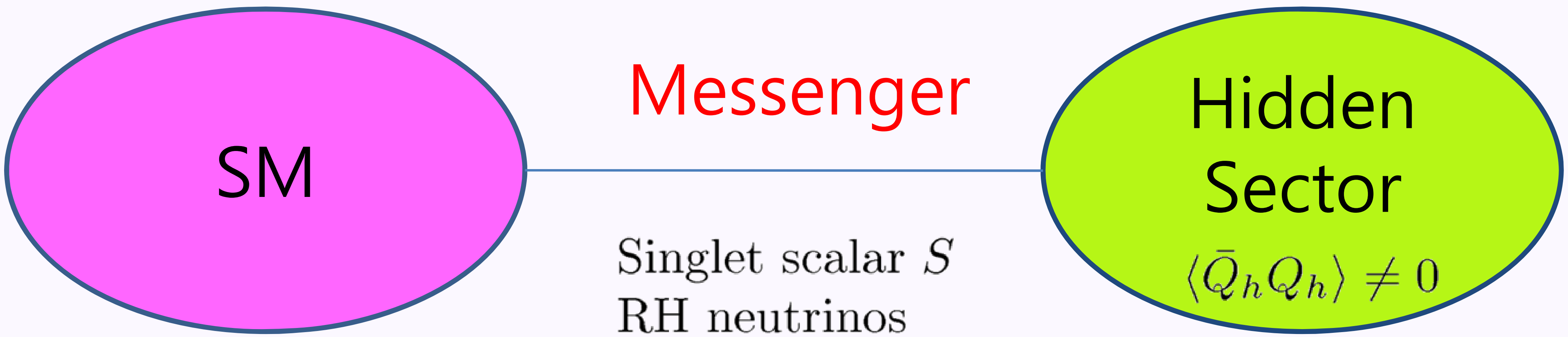
- Role of Higgs and extra scalar fields in cosmology (Structure formation and non Gaussianity, etc)
- Broken U(1)x with massive dark photon (Detailed study)
- Nonabelian hidden (dark) gauge symmetry
  - D.W.Jung, Hur, Ko and Lee, PLB; Hur and Ko, PRL (2011)
- SUSY extension ?

Strongly interacting hidden sector with unbroken non Abelian hidden gauge symmetry

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture



Singlet scalar S
RH neutrinos
etc.

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Warming up with a toy model

- Reinterpretation of 2 Higgs doublet model
- Consider a hidden sector with QCD like new strong interaction, with two light flavors
- Approximate SU(2)L X SU(2)R chiral symmetry, which is broken spontaneously
- Lightest meson π_h : Nambu-Goldstone boson -> Chiral lagrangian applicable
- Flavor conservation makes π_h stable -> CDM

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2)$$
$$+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{av_2^3}{2}\sigma_h$$

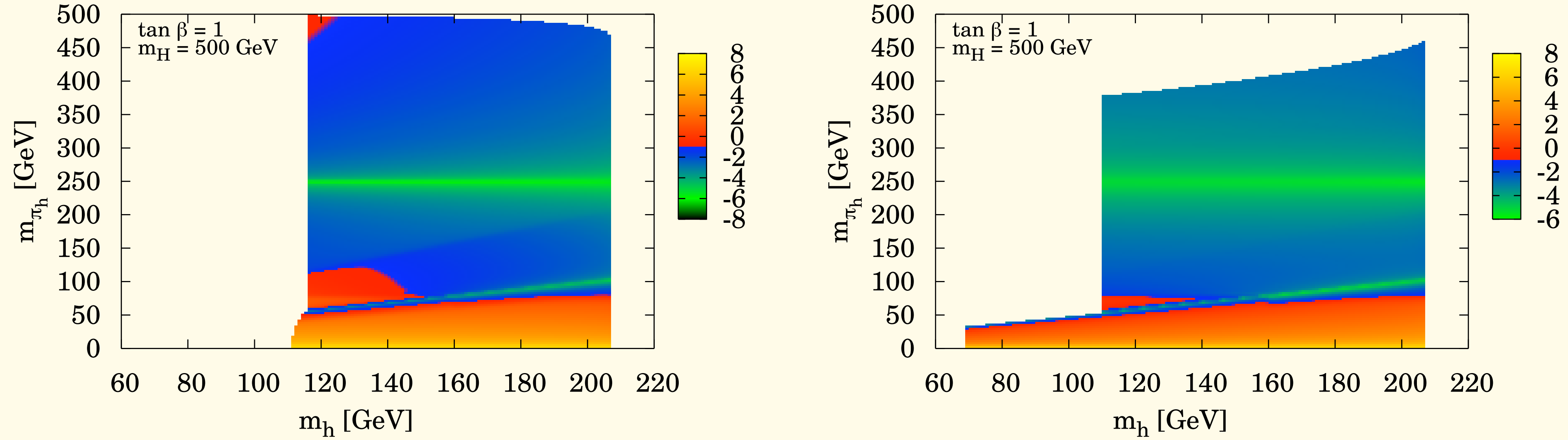
Not present in the two-Higgs Doublet model

- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \left(\begin{array}{c} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{array} \right), \qquad H_2 = \left(\begin{array}{c} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{array} \right)$$

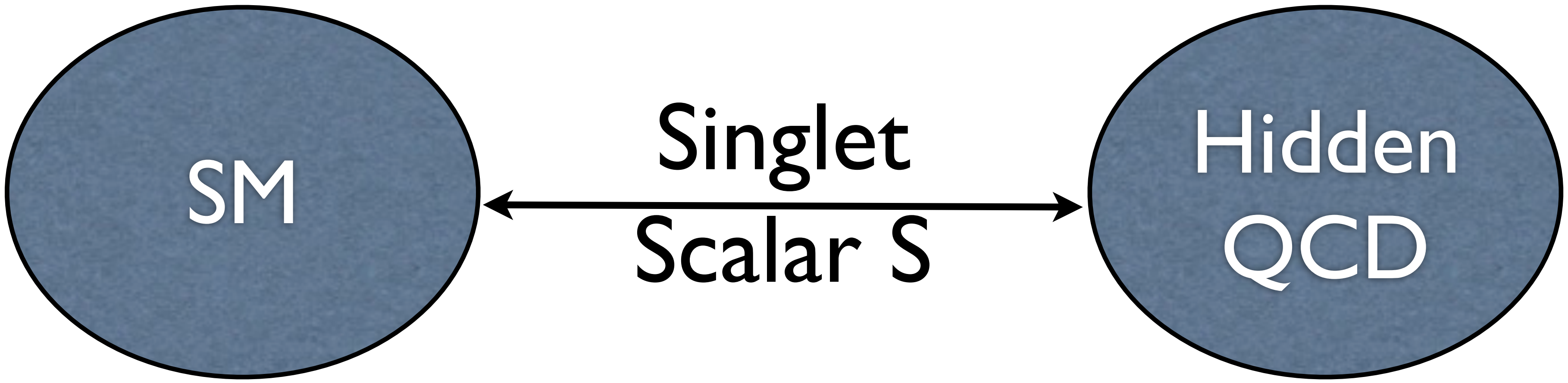
- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1\lambda_2' > \lambda_3^2$

Relic Density



- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Model I (Scalar Messenger)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by "S"

Modified SM with classical scale symmetry

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\ &+ \Big(\overline{Q}^i H Y^D_{ij} D^j + \overline{Q}^i \tilde{H} Y^U_{ij} U^j + \overline{L}^i H Y^E_{ij} E^j \\ &+ \overline{L}^i \tilde{H} Y^N_{ij} N^j + S N^{iT} C Y^M_{ij} N^j + h.c.\Big)\end{aligned}$$

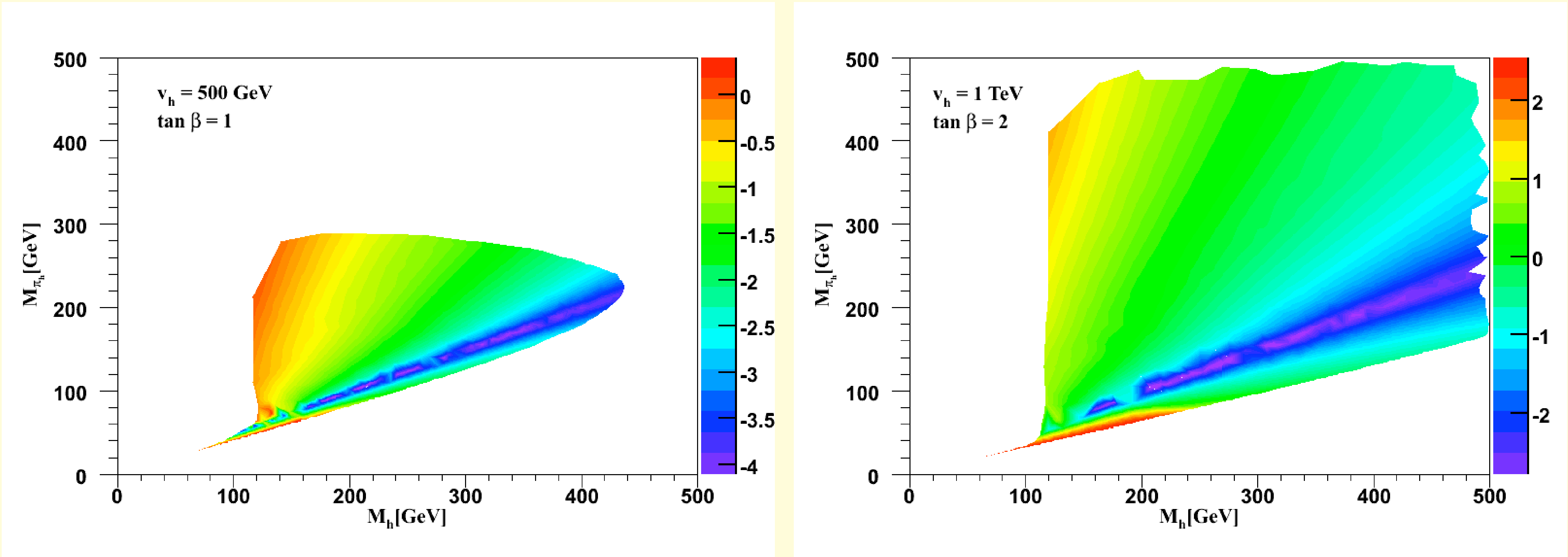
Hidden sector lagrangian with new strong interaction

$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}
$$

Relic density

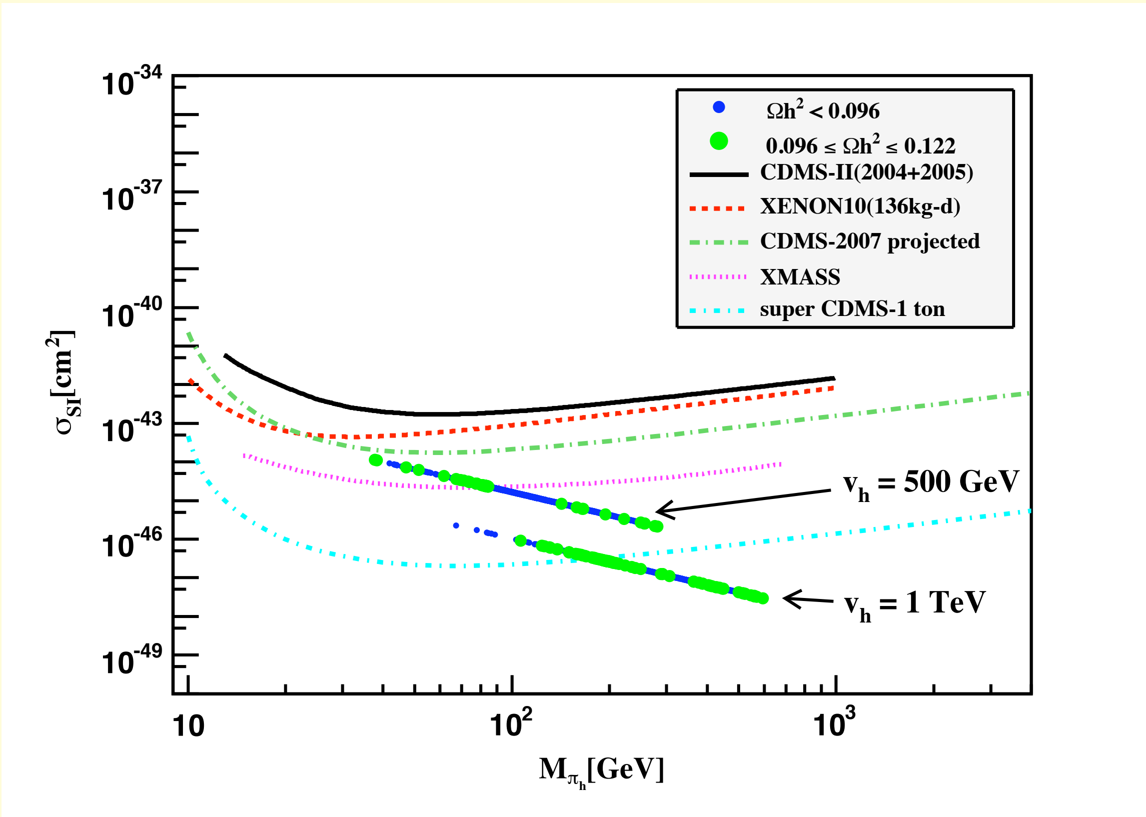


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.
the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Comparison with the previous model

- Dark gauge symmetry is unbroken (DM is absolutely stable), but confining like QCD (No long range dark force)
- DM : composite hidden hadrons
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- H Signal strengths : universally reduced from one

Generic Features

- Spontaneous breaking of dark symmetry requires extra Higgs fields that would mix with the SM Higgs after all
- Signal strength will be universally reduced from "one" for all the channels
- Easy to test this @ LHC in the near future
- Diphoton decay of H(125) will be precious information on this type of DM models

Conclusions - II

- Stability or longevity of a hCDM is closely related with the SM Higgs sector (amusing !)
- In general, a number of SM singlet scalar appear and they will mix with the SM Higgs boson
- The signal strength of Higgs boson is universally reduced from "one"
- If dark sym is unbroken, there will be only one SM Higgs boson with signal strengths = ONE
- LHC data will reveal the hidden sector DM

Loopholes & Ways Out

- DM could be very light and long lived (Totalitarian principle)
- More than one Higgs doublet playing the singlet portals to the hidden sector (against Occam's razor principle)
  - SUSY needs 2HDM's
  - Chiral Gauge Sym needs new Higgs Doublets (talk by Yuji Omura on this)