Singlet Portal Extensions of the Standard Seesaw Models to a Dark Sector with Local Dark Gauge Symmetry

Pyungwon Ko (KIAS)

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

The 9th PATRAS Workshop
Schloss Waldhausen, June 24-28 (2013)

Why BSM?

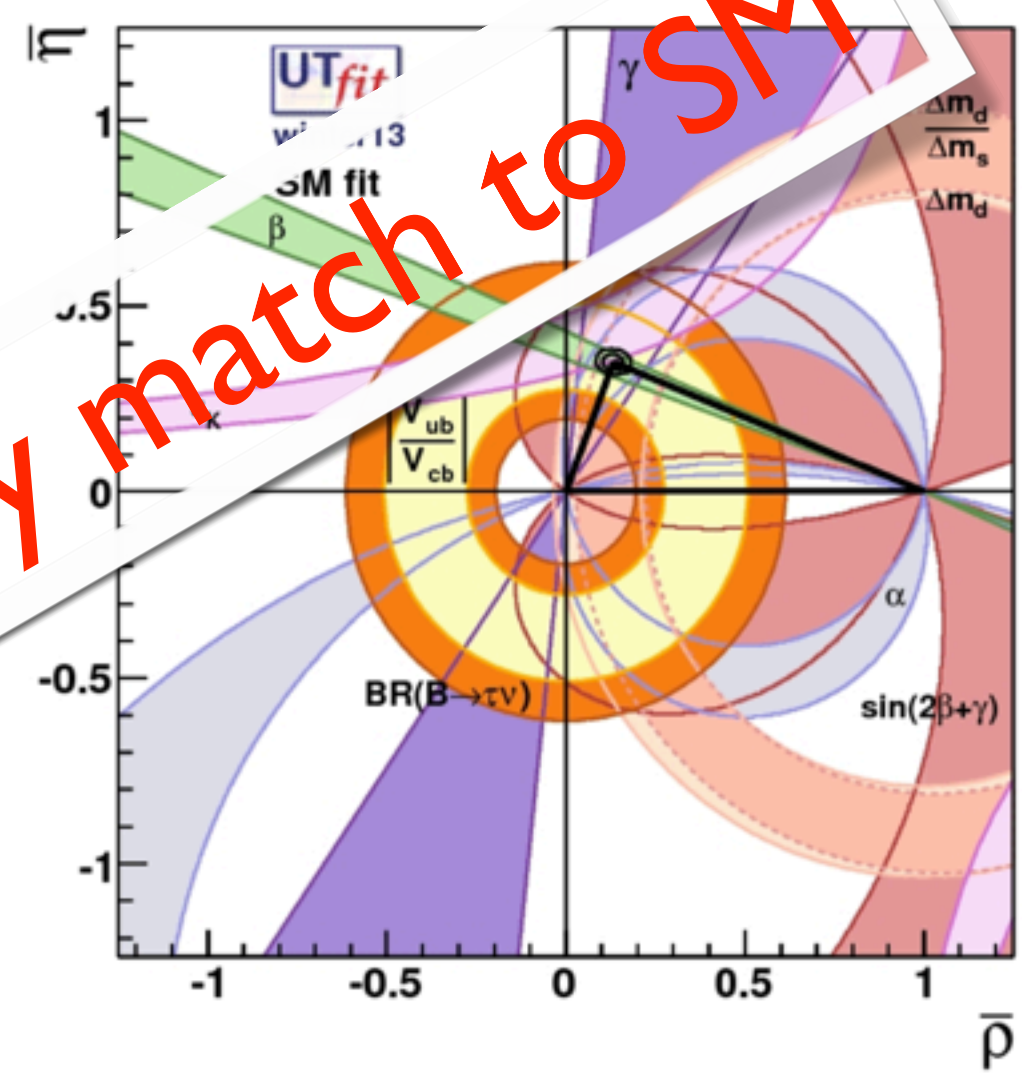
For subatomic world

- SM has been so successful.

EWPT

[LEPEWWG, Mar 2012]

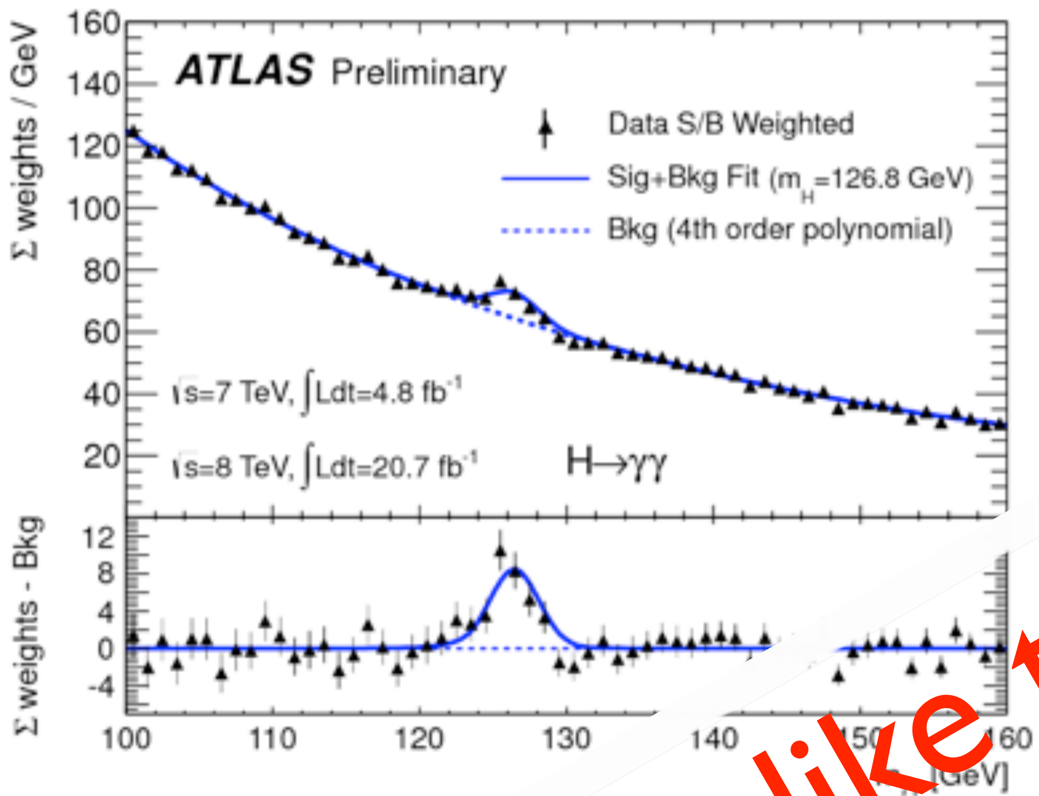
CKM

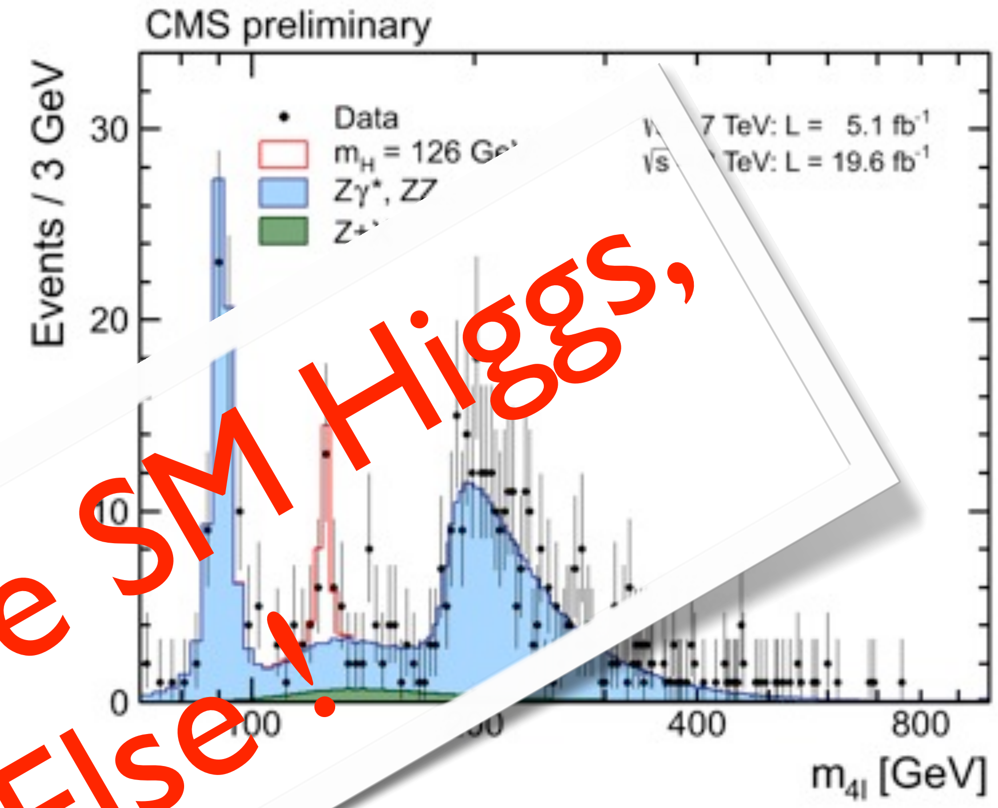


[Unitary Triangle fit]

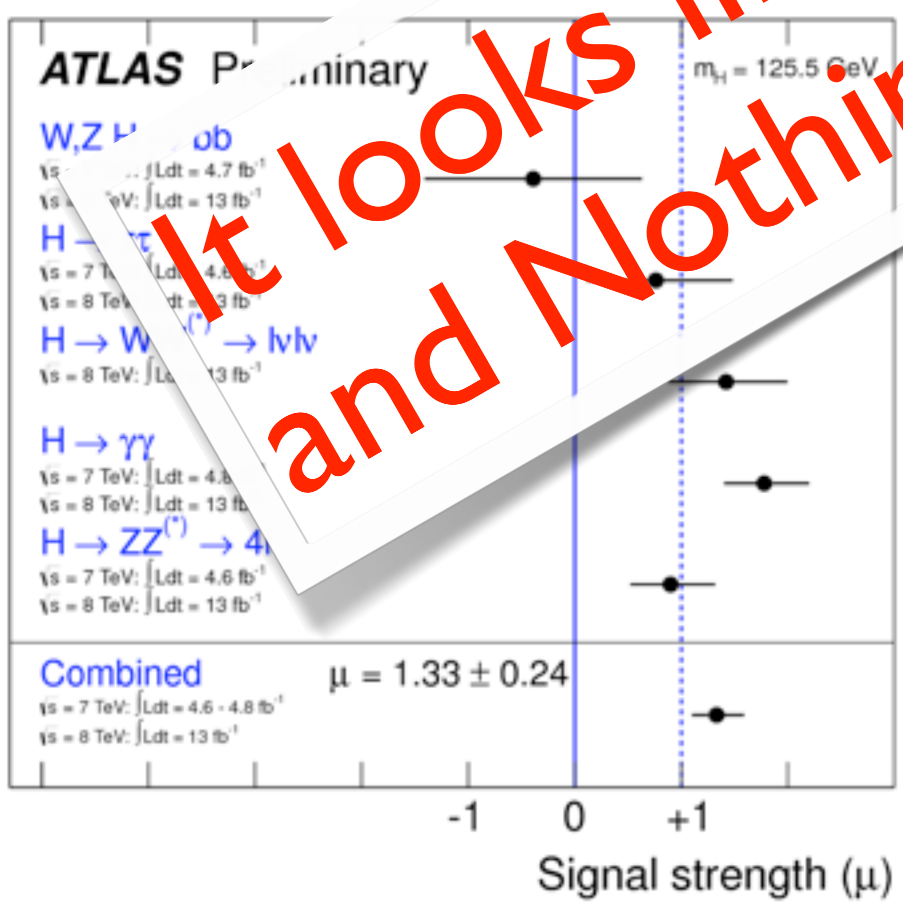
Almost perfectly match to SM

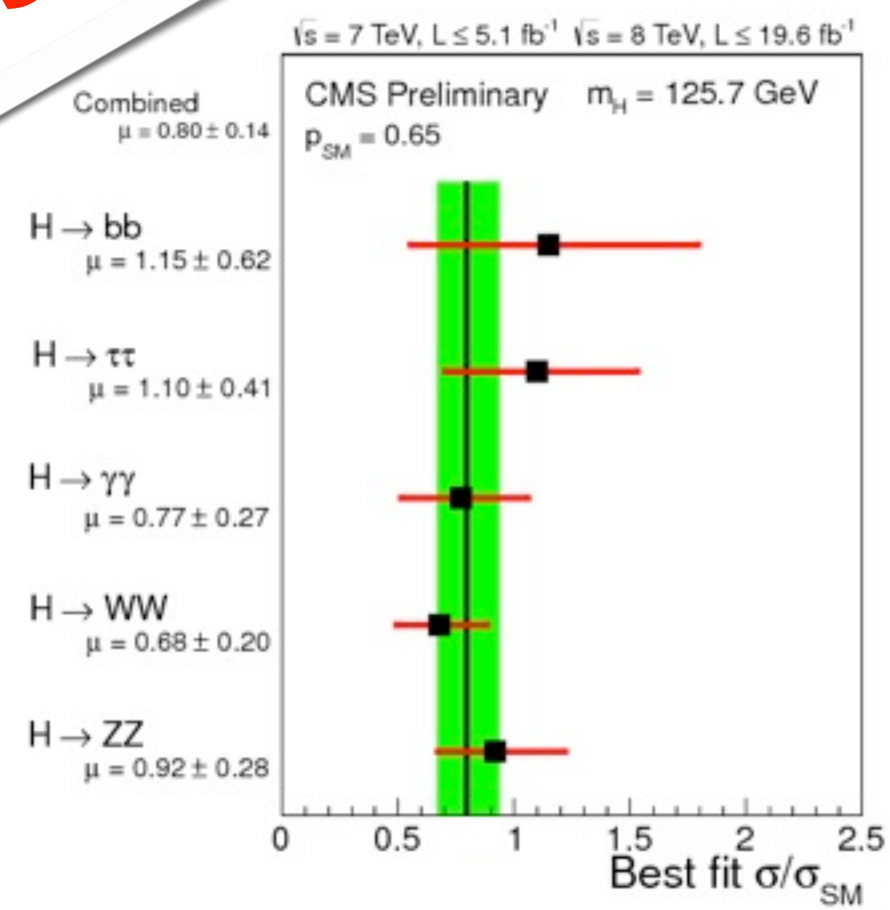
- The last SM chapter also looks correct.



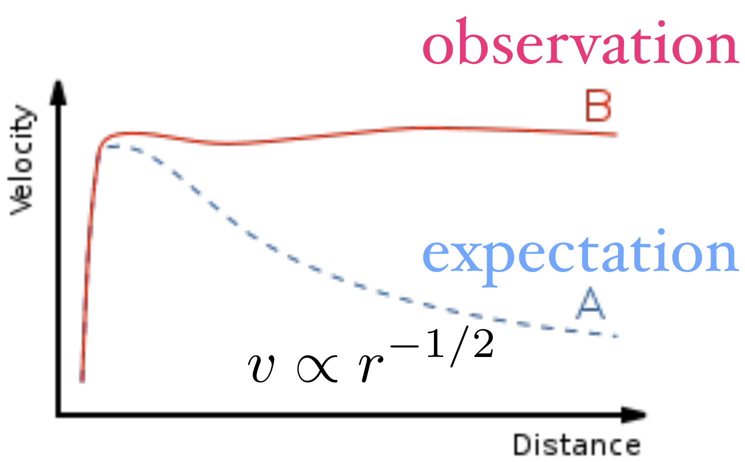


It looks like the SM Higgs,
and Nothing Else!





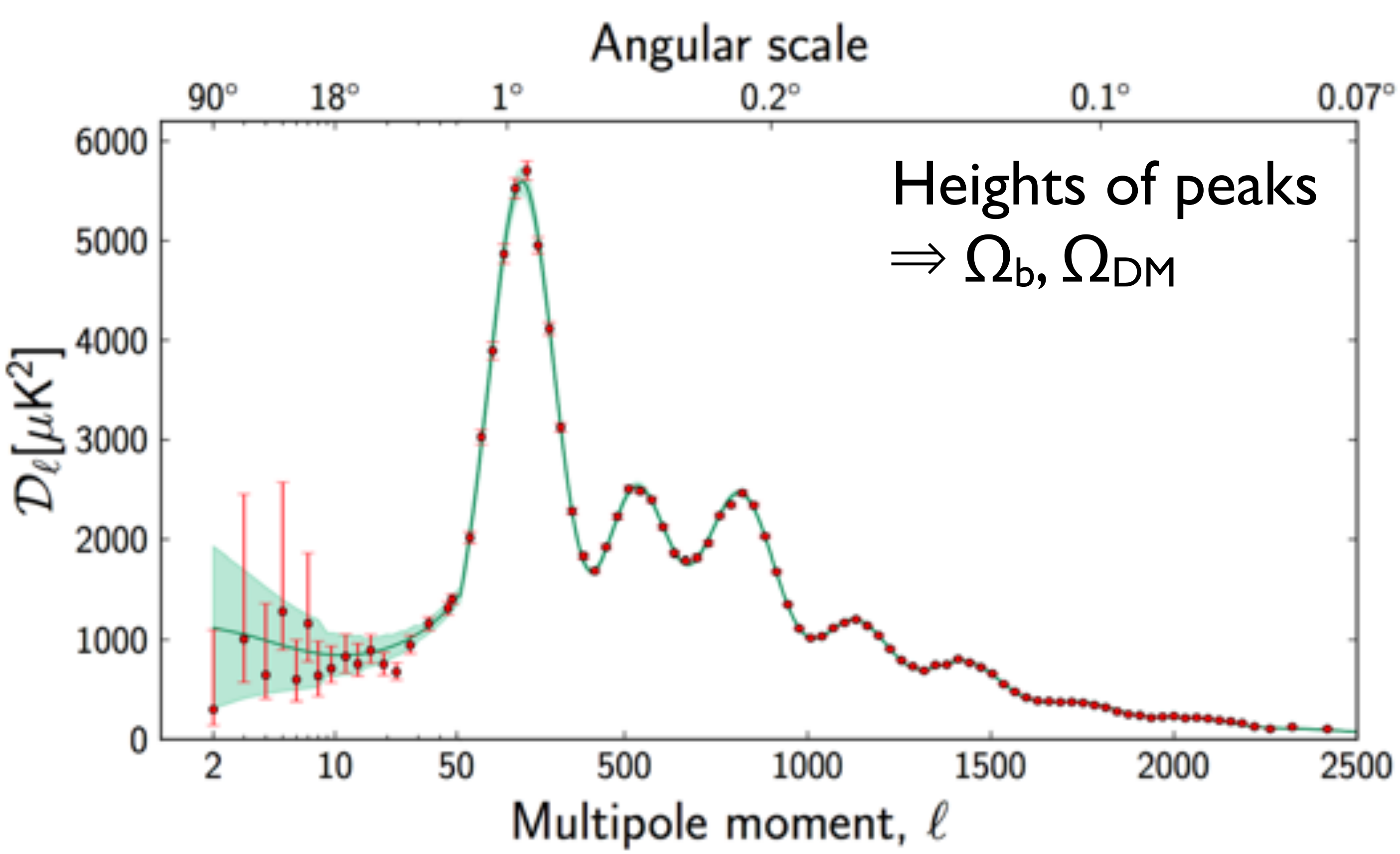
- Dark & visible matter and dark energy



Jan Oort (1932), Fritz Zwicky (1933)

Bullet cluster

Strong gravitational lensing in Abell 1689

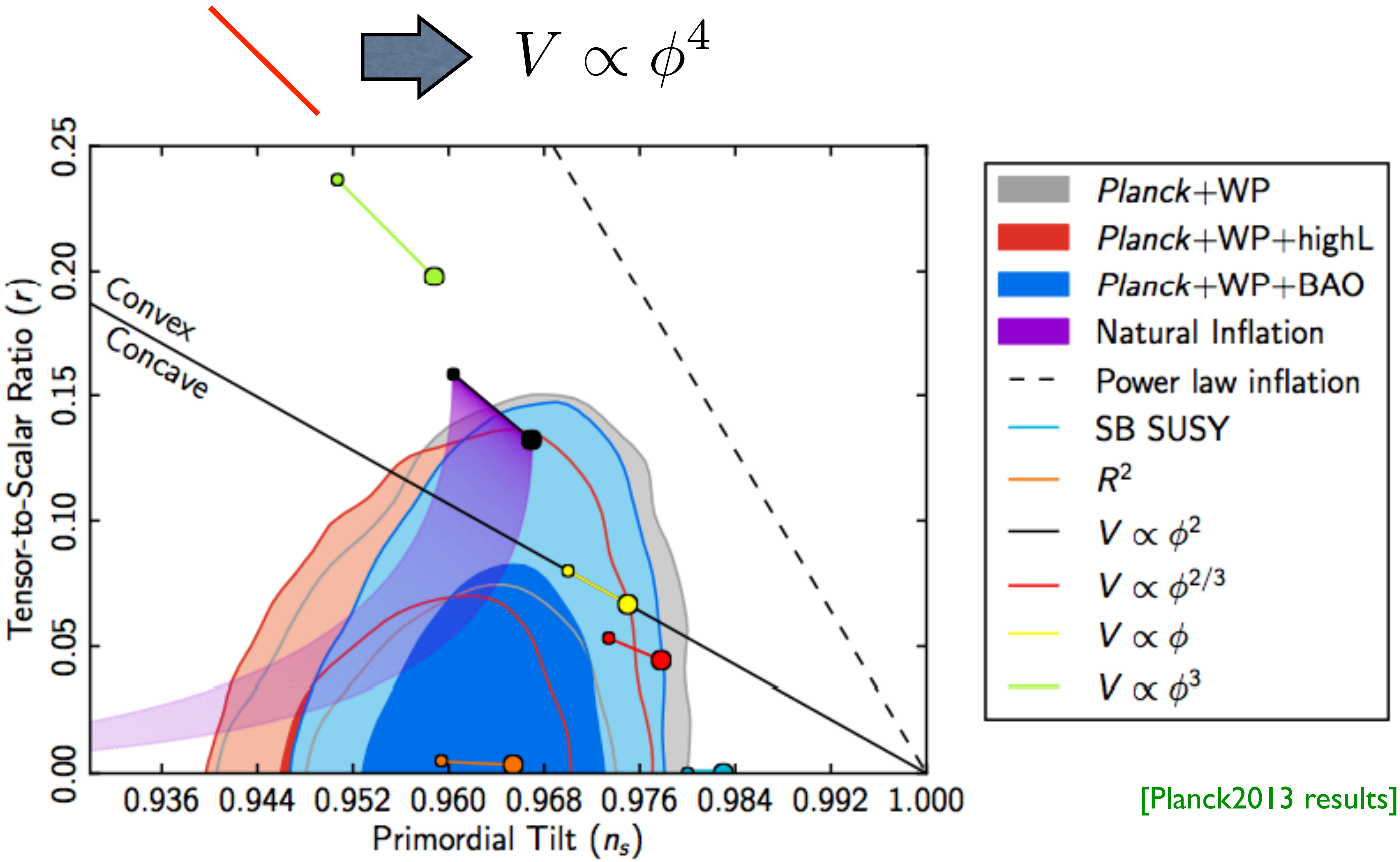


$$\Omega_b \simeq 0.048$$
$$\Omega_{DM} \simeq 0.259$$
$$\Omega_\Lambda \simeq 0.691$$

(Planck+WP+highL+BAO)

Inflation models in light of Planck2013 data

$V \propto \phi^4$



[Planck2013 results]

Shortcomings of SM

- Density perturbations
- Baryon number asymmetry
- Dark matter
- Dark energy
- Neutrino masses and mixing

No explanations to most of astrophysical and cosmological observations.

Contents

- Hidden Sector DM
- Higgs Portal
- Local vs. Global Dark Symmetry
- Models
- Implications for Higgs phenomenology

(see also talk by O. Lebedev)

Based on the works

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

(Some works in preparation)

- Strongly interacting hidden sector (0709.1218 PLB, 1103.2571 PRL)
- Singlet fermion dark matter (1112.1847 JHEP)
- Higgs portal vector dark matter (1212.2131 JHEP)
- Vacuum structure and stability issues (1209.4163 JHEP)
- Singlet portal extensions of the standard seesaw models with unbroken dark symmetry (1303.4280 JHEP)

Hidden Sector

- Any NP @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM singlets, and less constrained, and could make CDM
- Hidden gauge sym can stabilize CDM
- Generic in many BSM's including SUSY models
- Can address "QM generation of all the mass scales from strong dynamics in the hidden sector" (alternative to the Coleman-Weinberg) : Hur and Ko, PRL (2011) and earlier paper and proceedings

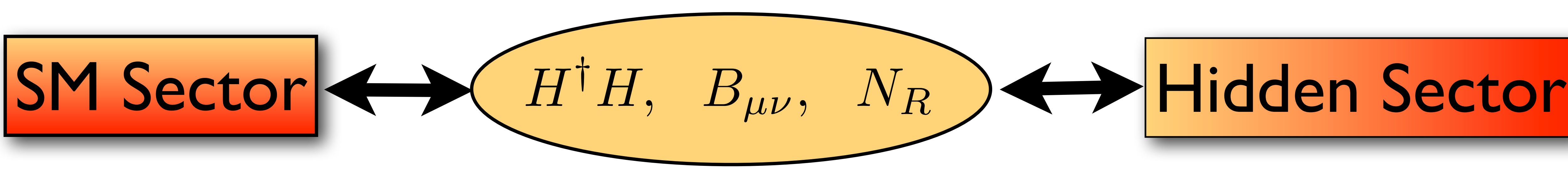
Talk @ 2th PATRAS, Mykonos

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 in Higgs phenomenology

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



$$\boxed{N_R \leftrightarrow \widetilde{H} l_L}$$

General Comments

- Many studies on DM physics using EFT
- However we don't know the mass scales of DM and the force mediator
- Sometimes one can get misleading results
- Better to work in a minimal renormalizable and anomaly-free models
- Explicit examples : singlet fermion Higgs portal DM, vector DM, Z2 scalar CDM

Higgs portal DM as examples

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

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

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

All invariant under ad hoc Z2 symmetry

A. Djouadi, et.al. 2011

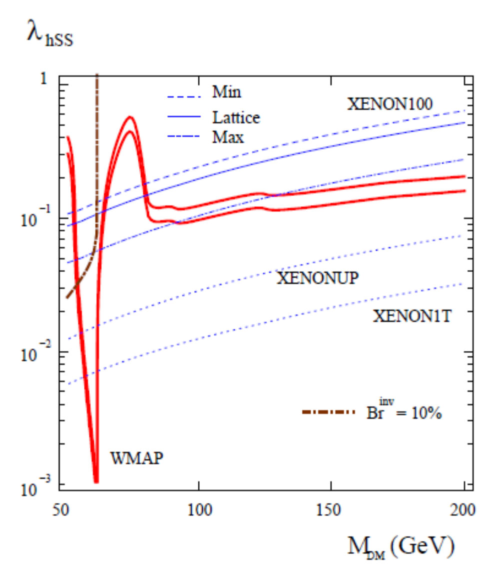


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

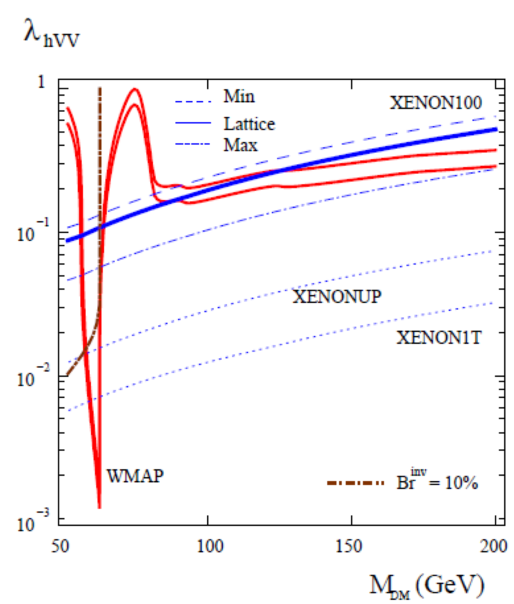


FIG. 2. Same as Fig. 1 for vector DM particles.

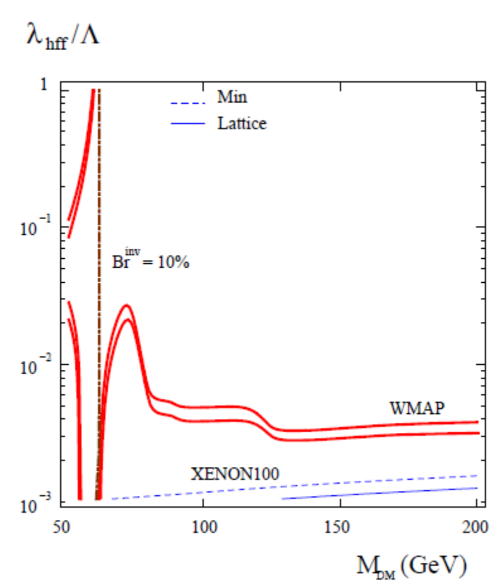


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

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All invariant under ad hoc Z2 symmetry

- 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

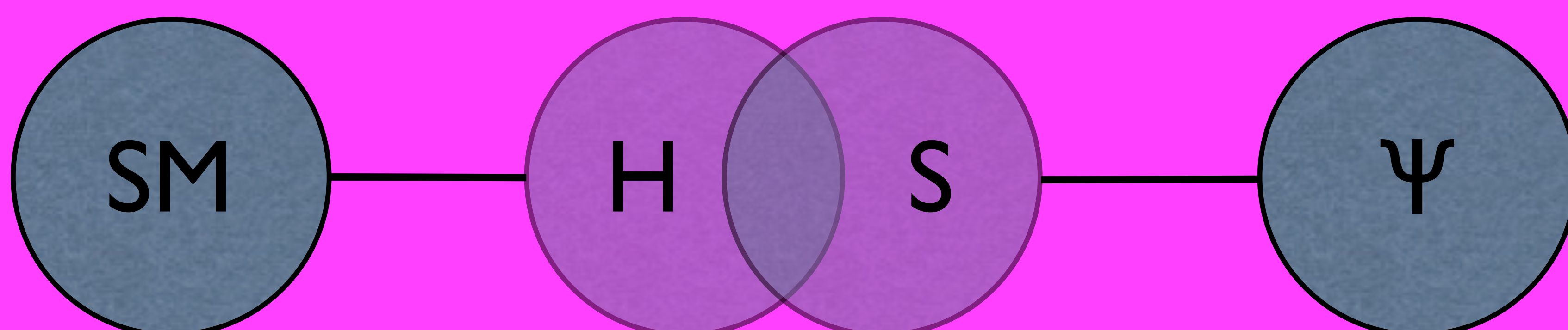
- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced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

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

at vacuum

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

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

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)

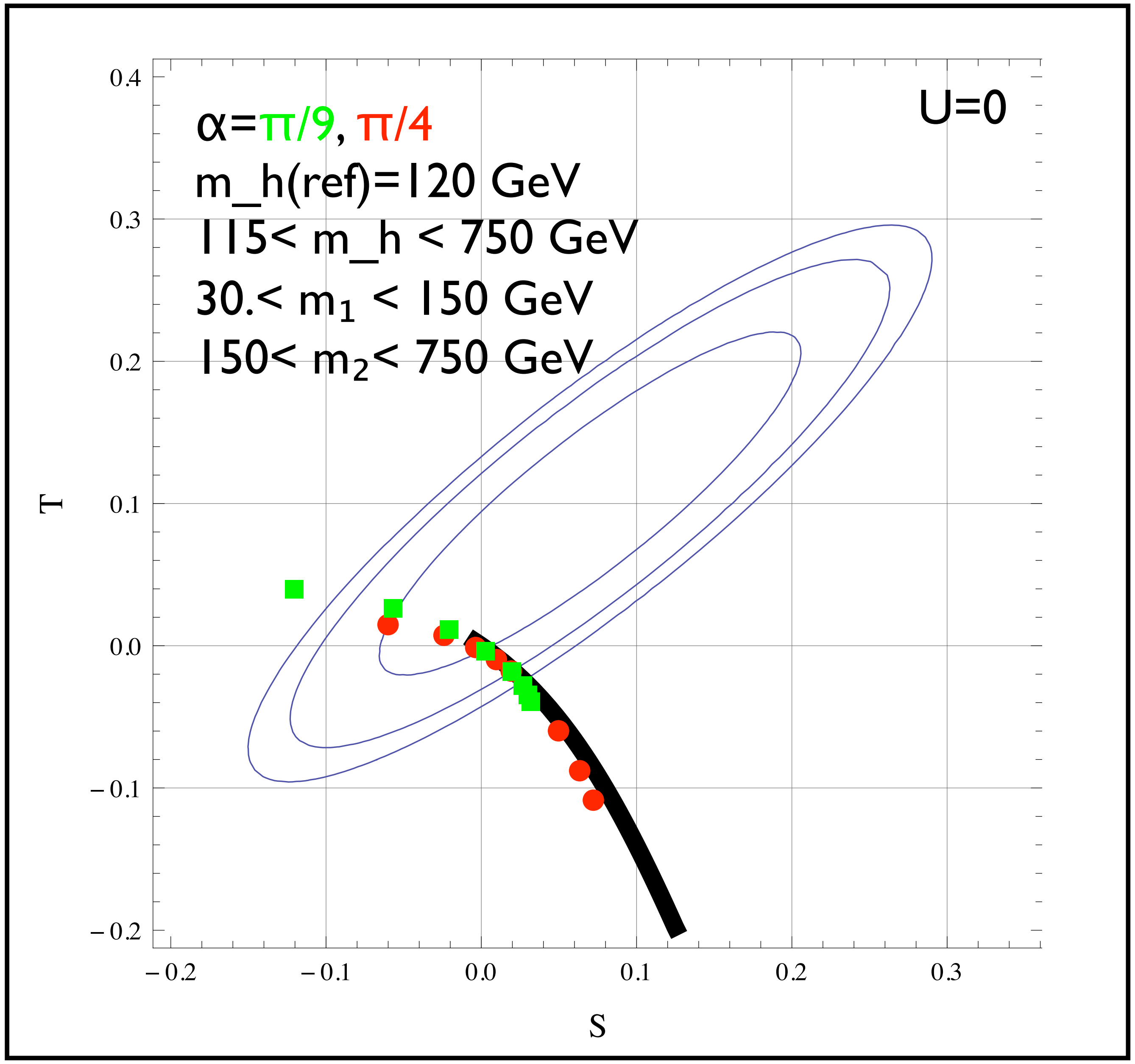
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right]$$

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

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

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

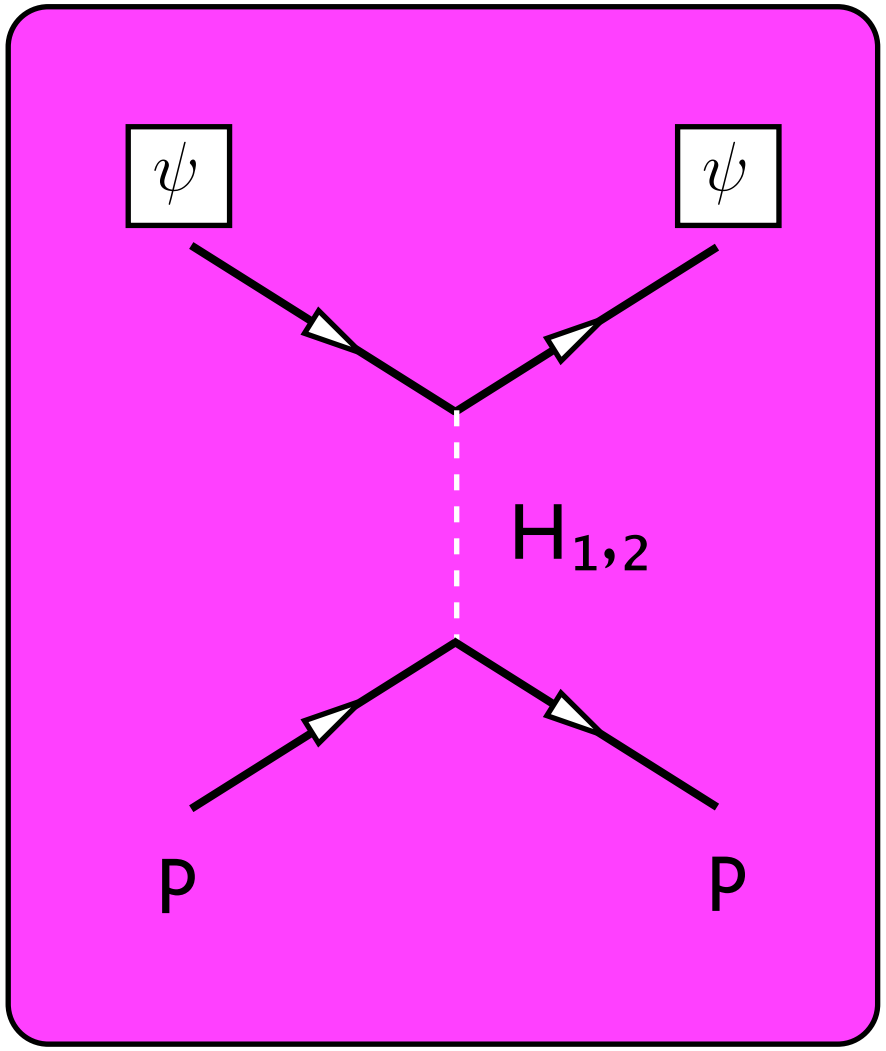
Same for T and U

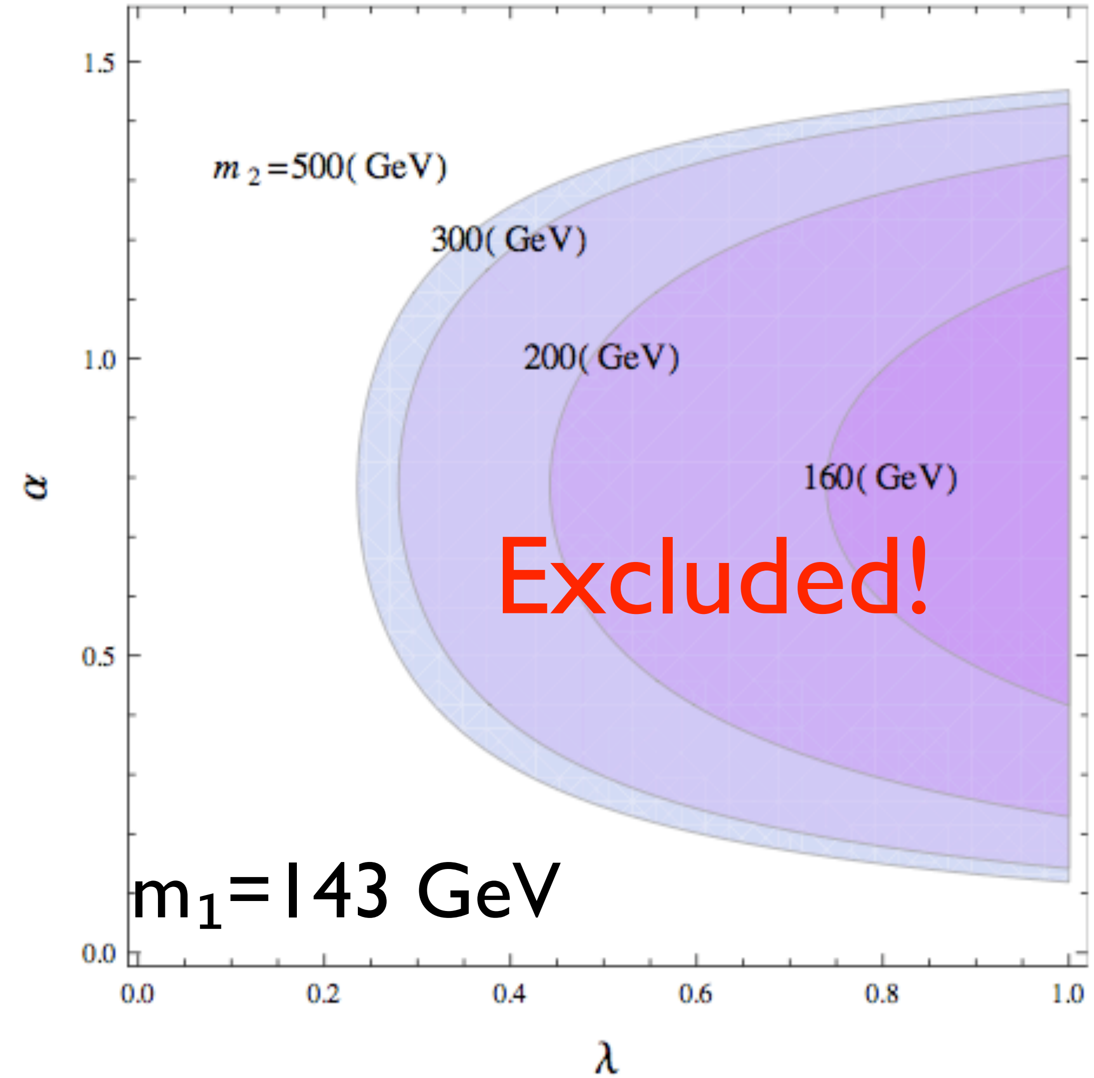


Constraints

- 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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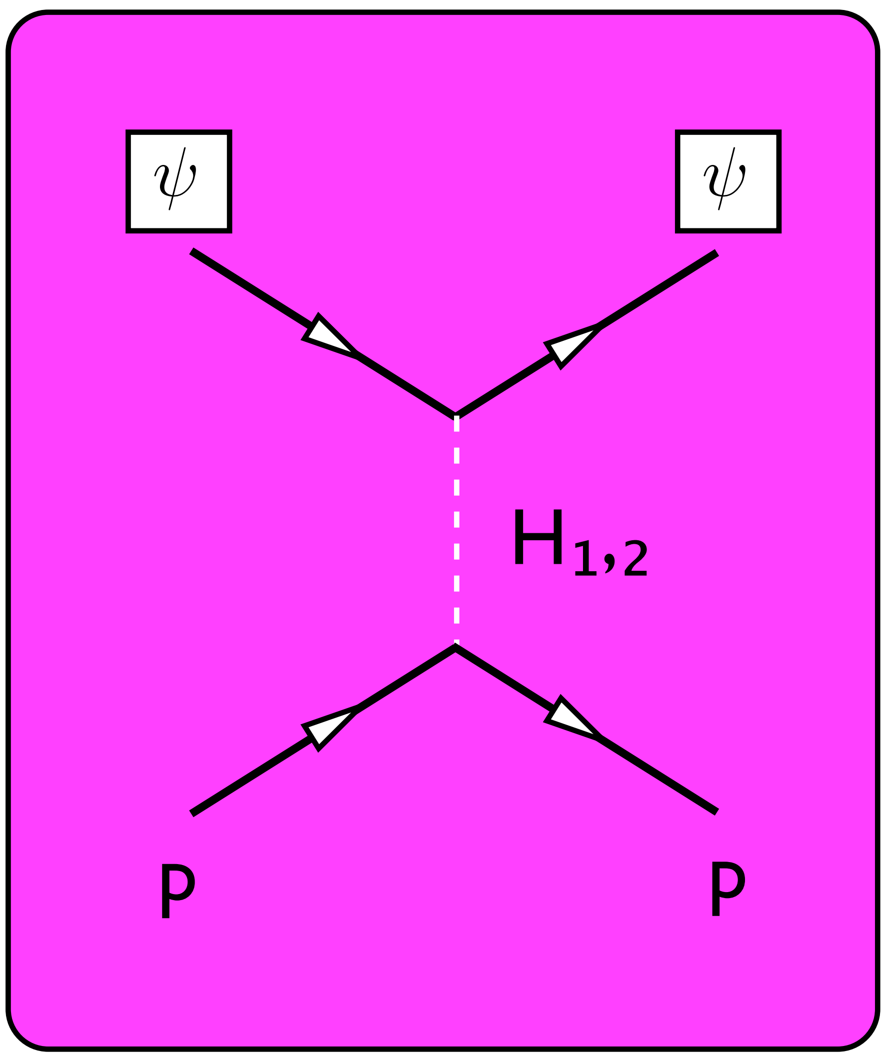
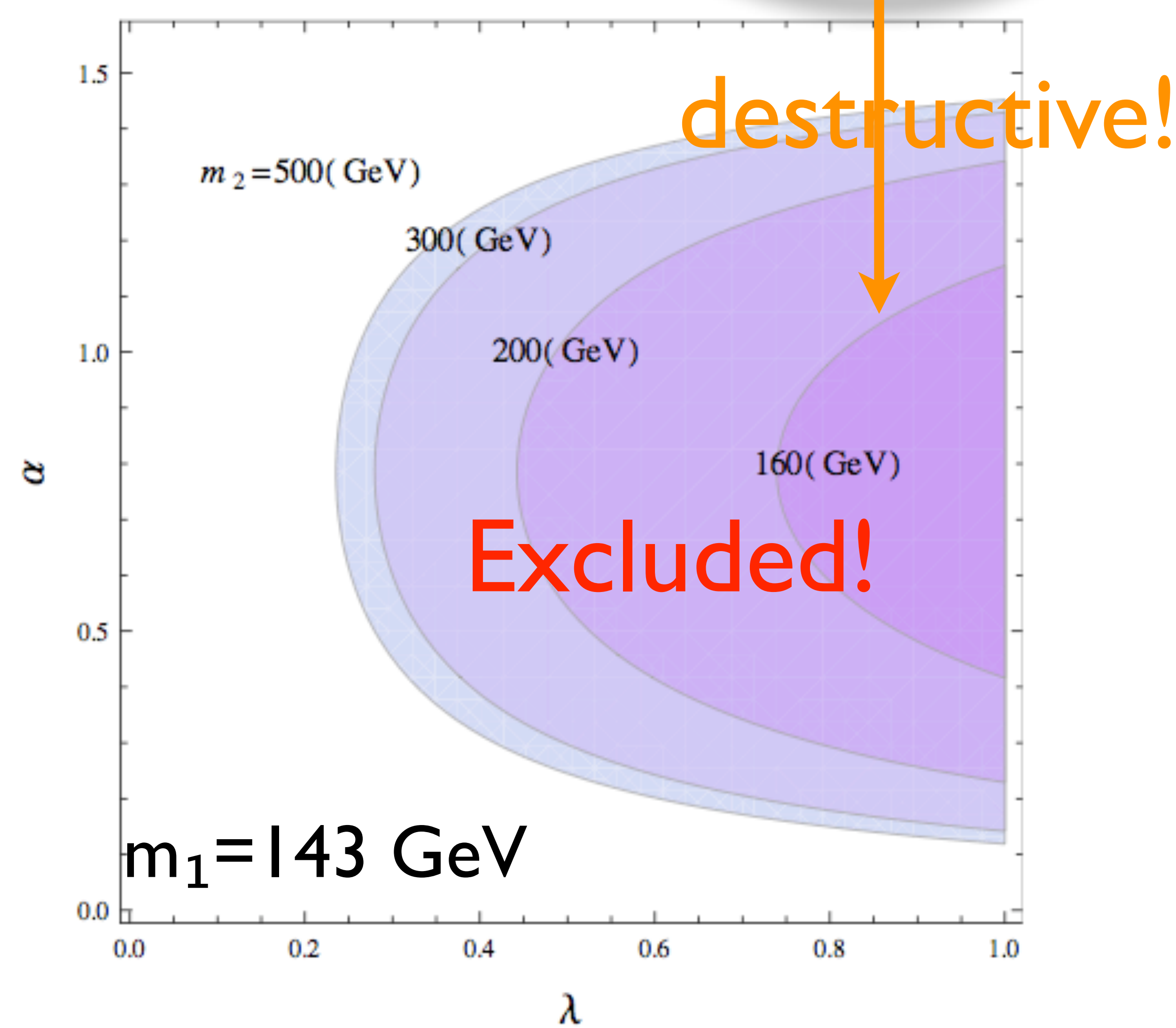




- We don't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

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

- Only one Higgs boson (alpha = 0)

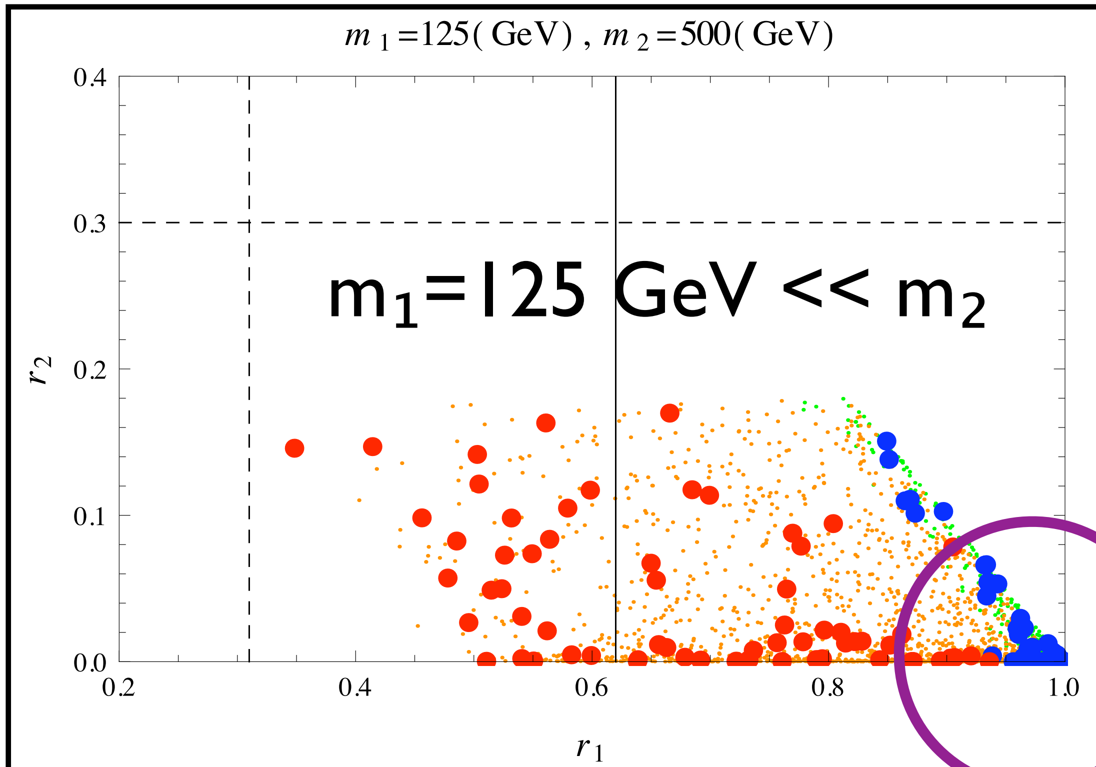
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

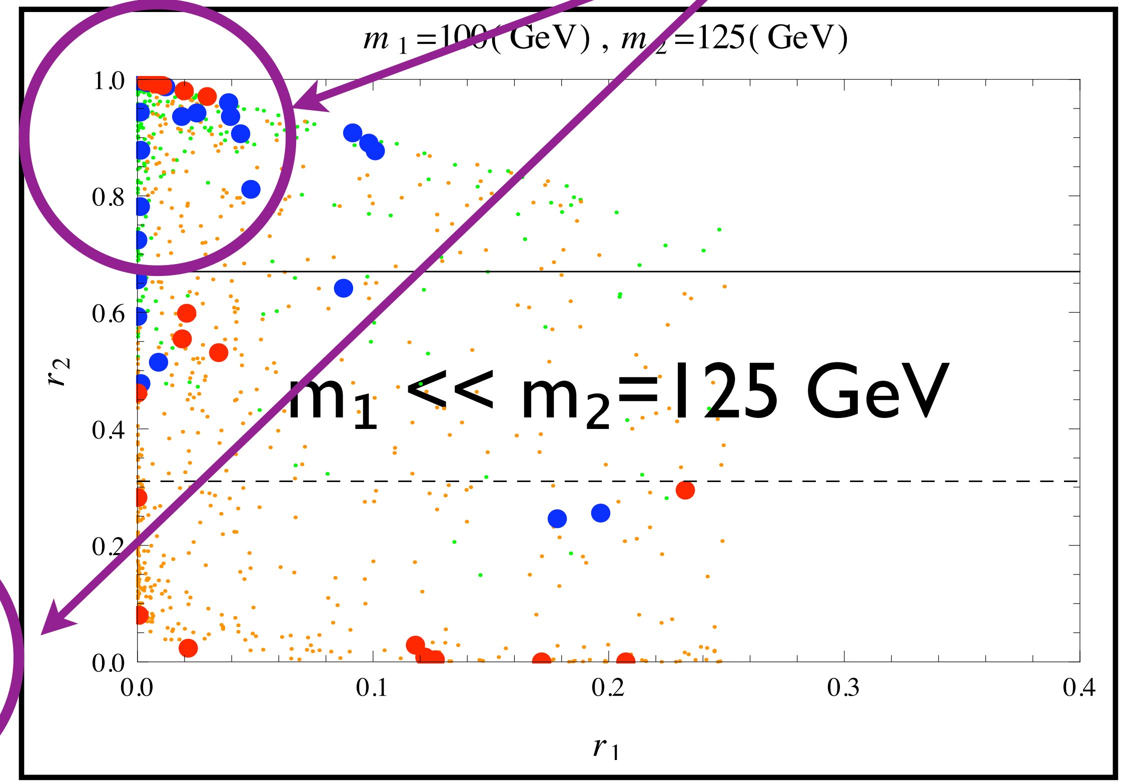
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Discovery possibility

- Signal strength (r_2 vs r_1)

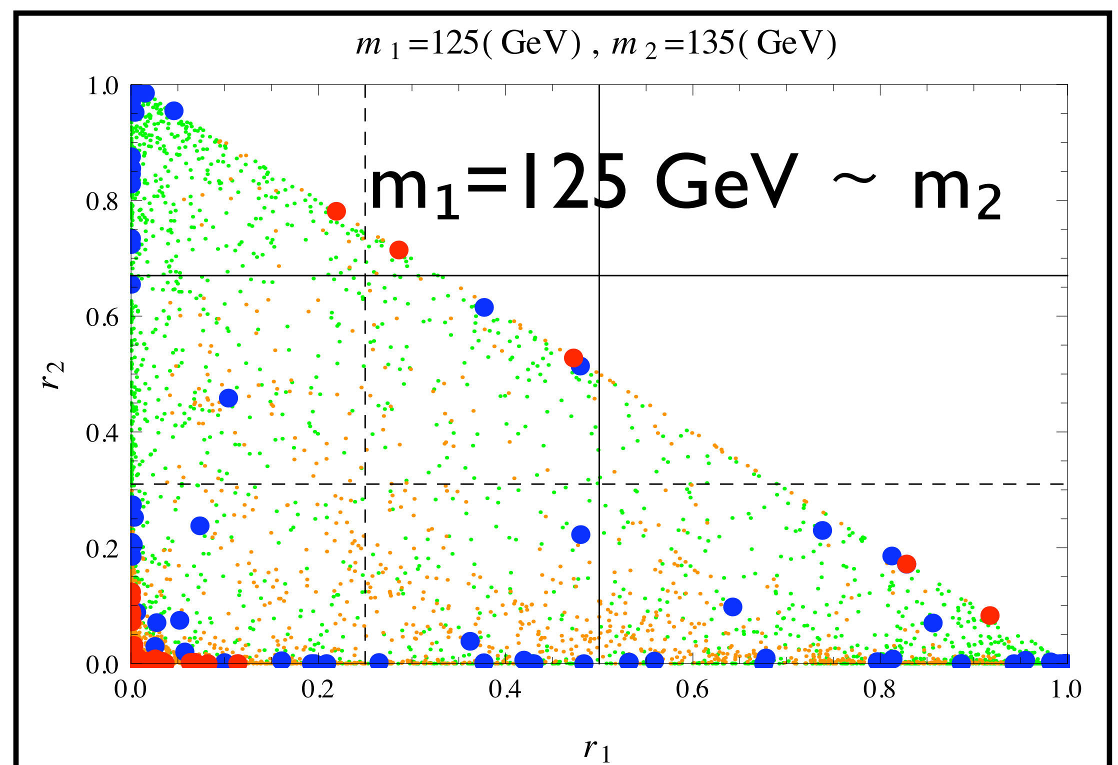
LHC data for 125 GeV resonance





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.



: Ω(x),σ_p(x)

: Ω(x),σ_p(o)

: Ω(o),σ_p(x)

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Discovery possibility

- Signal strength (r_2 vs r_1)

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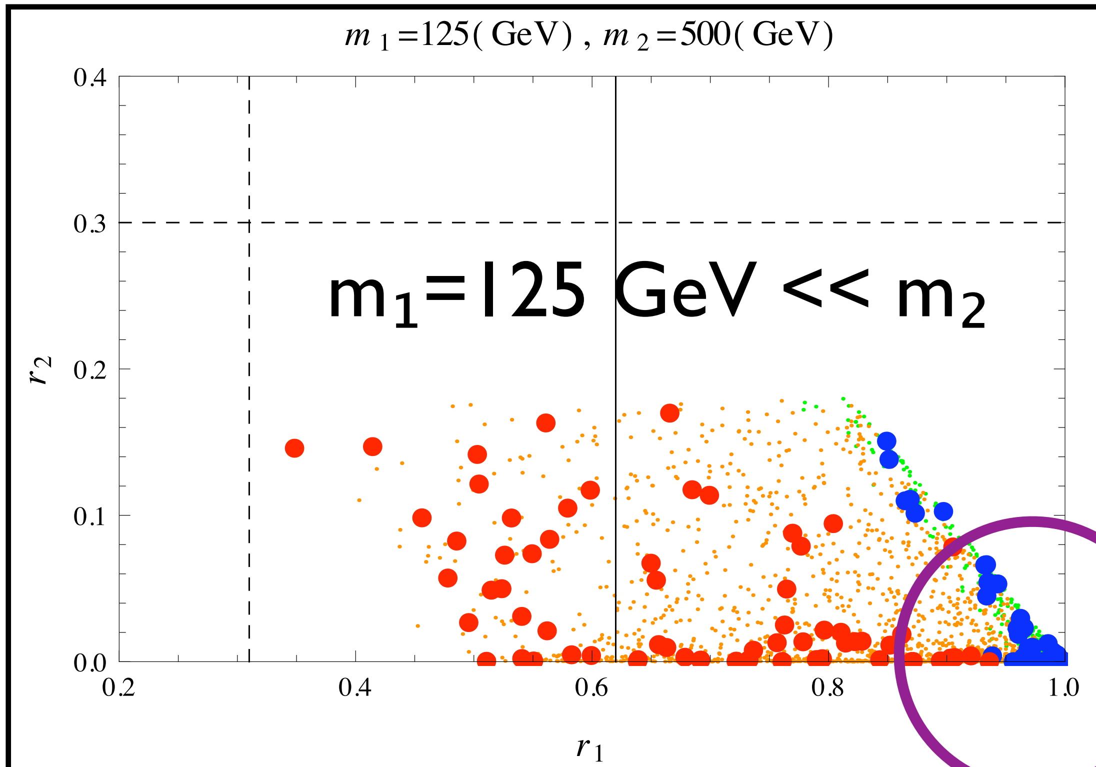

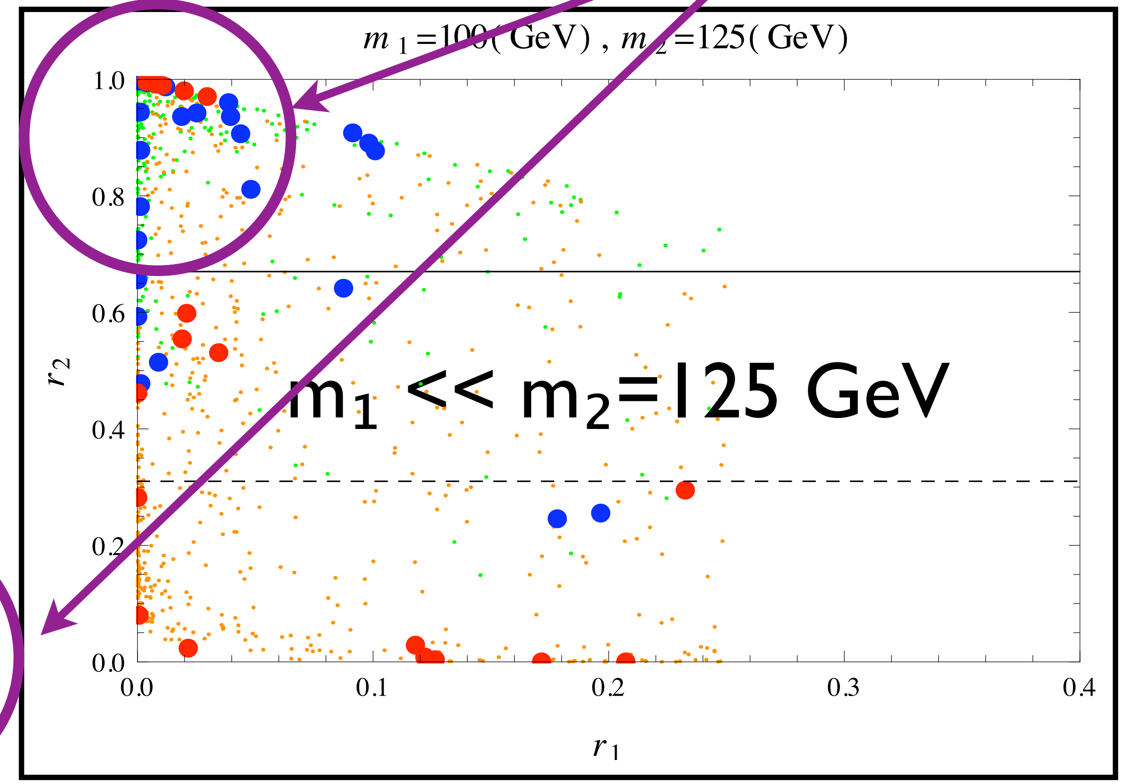

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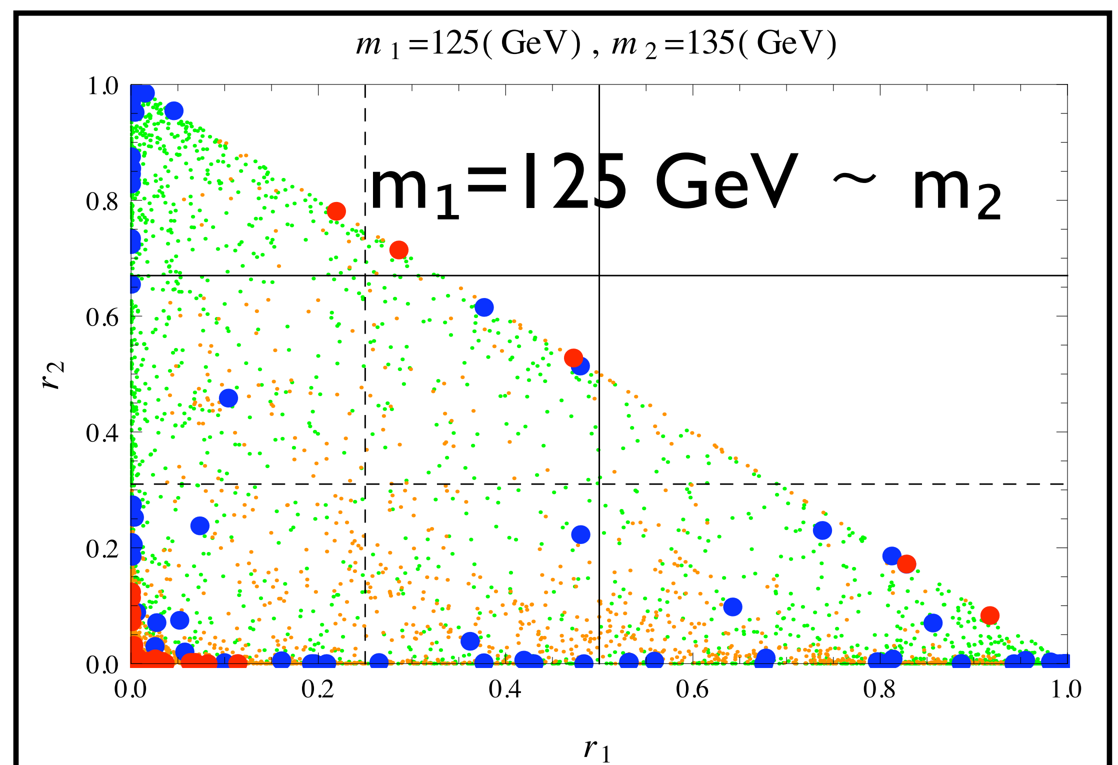

- : $\Omega(x), \sigma\_p(x)$
- : $\Omega(x), \sigma\_p(o)$
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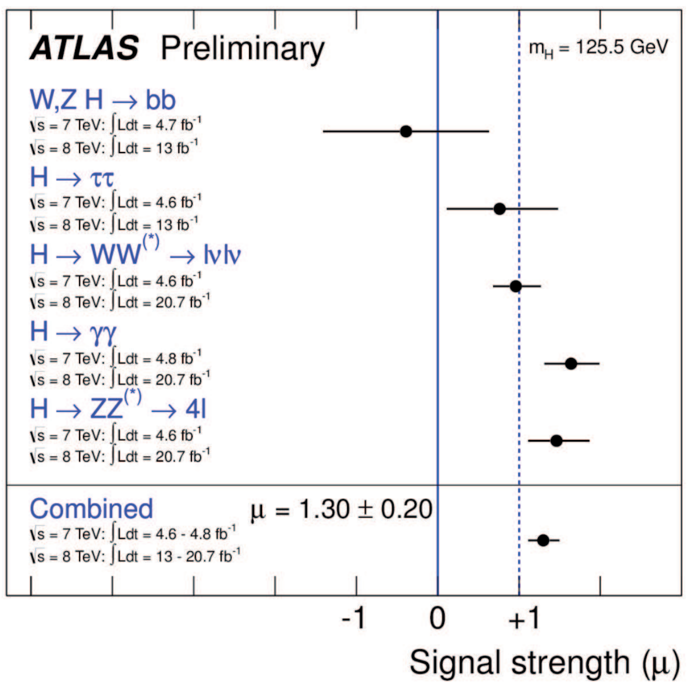
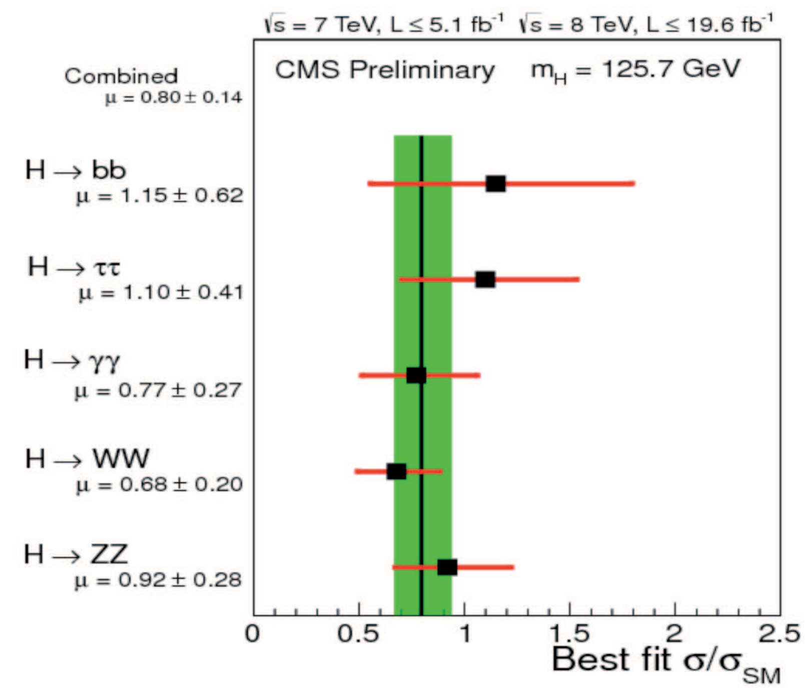
- : $\Omega(o), \sigma\_p(o)$

Updates@LHCP

Signal Strengths

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





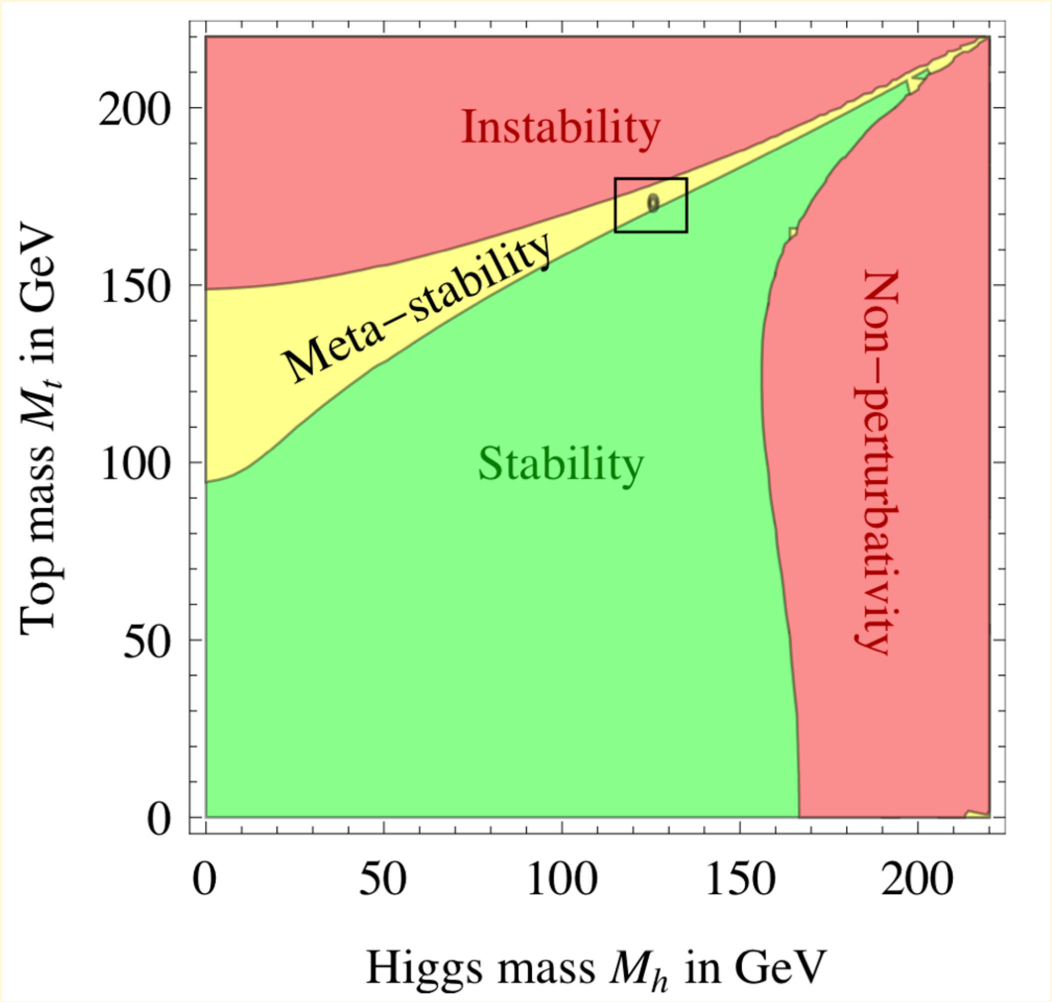
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

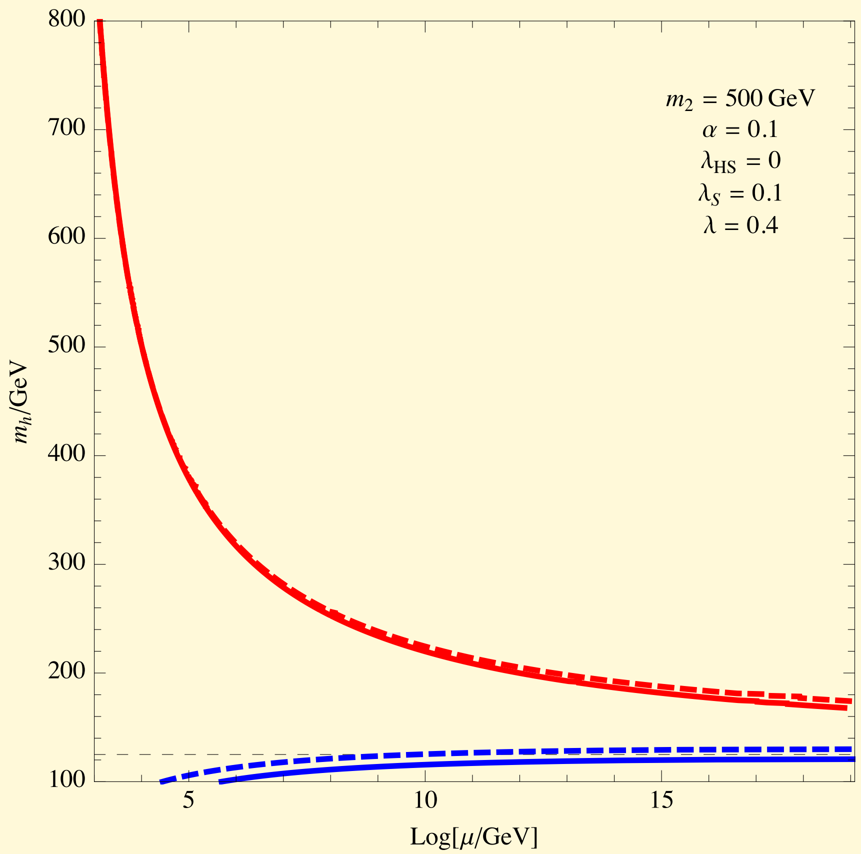
$$\langle \mu \rangle = \mathbf{0.96 \pm 0.12}$$

Getting smaller

13년 6월 27일 목요일

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

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 (JHEP)

New scalar improves EW vacuum stability

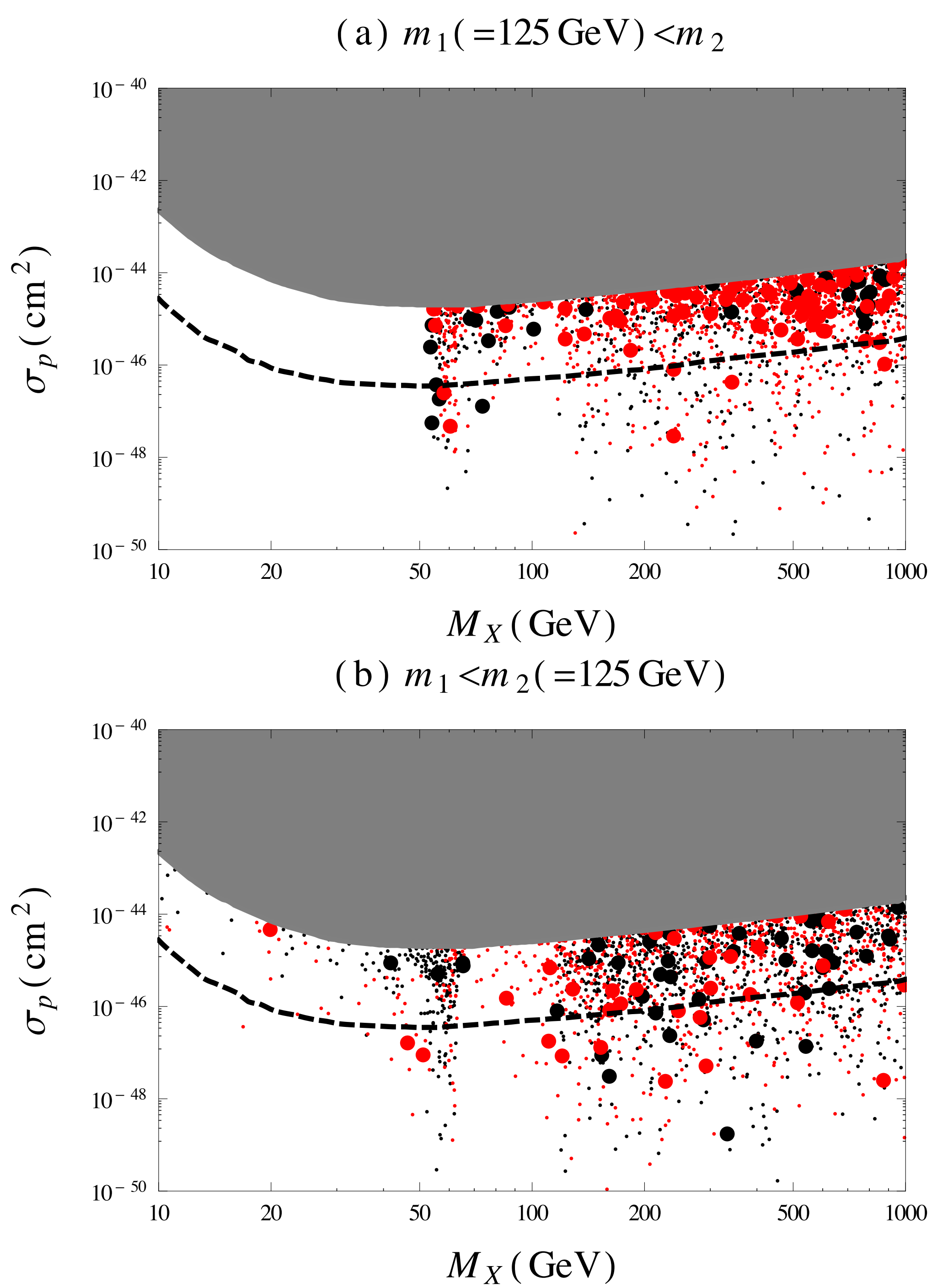


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

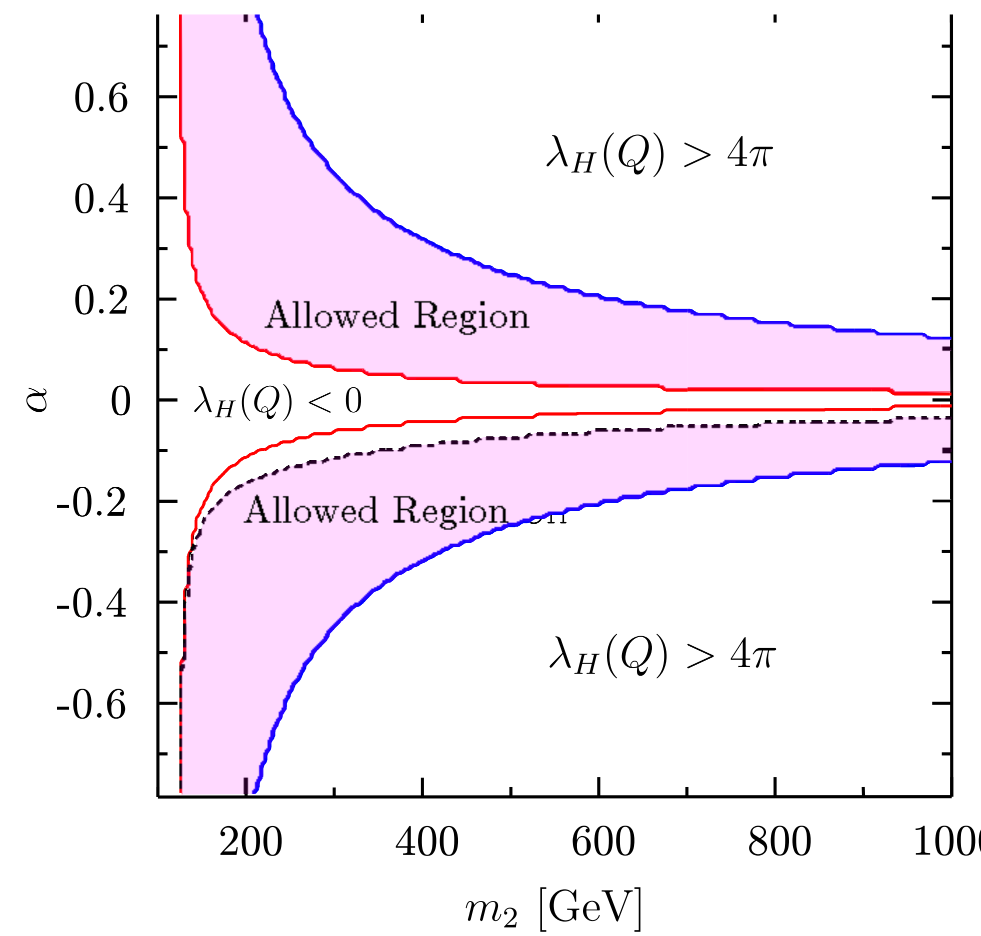
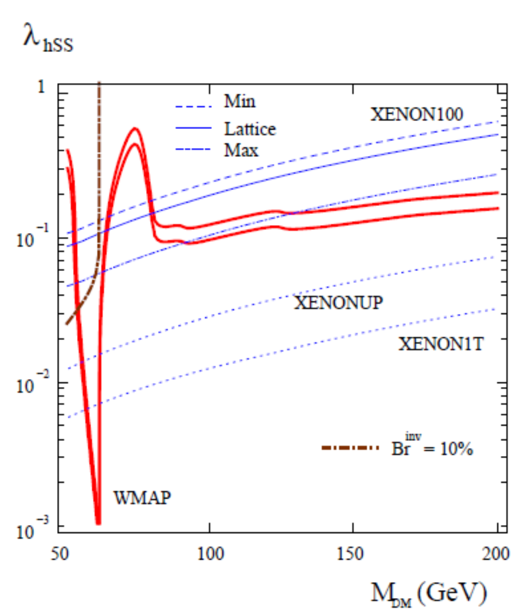


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

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



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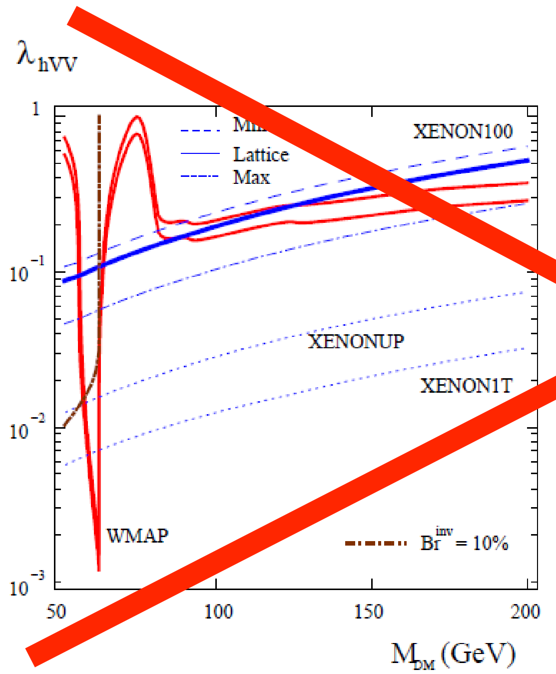


FIG. 2. Same as Fig. 1 for vector DM particles.

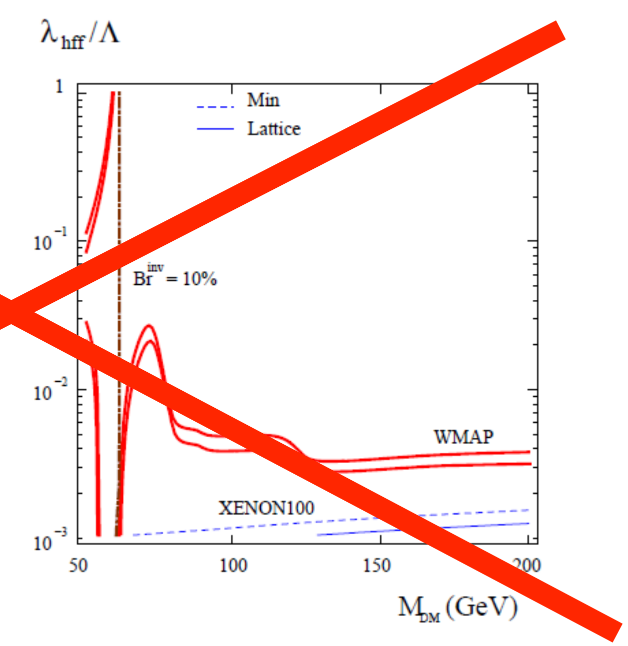


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian, we get different results !

Why Dark Symmetry ?

- 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)

Higgs is harmful to DM stability

Z2 sym scalar DM

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{SH}}{2} S^2 H^\dagger H.$$

- Very popular alternative to SUSY LSP
- Simplest in terms of the # of new dof's
- But, where does this Z2 symmetry come from ?
- Is it Global or Local ?

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

$$\Gamma(S) \sim \frac{m_S^3}{M_{\rm Planck}^2} \sim \left(\frac{m_S}{100{\rm GeV}}\right)^3 10^{-37} GeV$$

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 global Z_2 symmetry

- One way out is to implement Z_2 symmetry as local U(1) symmetry (Work in progress with Seungwon Baek and Wan-Il Park@ KIAS)

In preparation w/ WIPark and SBaek

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

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

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

Unbroken Local Z2 symmetry

$$X_R \to X_I\gamma_h^* \quad \text{followed by} \quad \gamma_h^* \to \gamma \to e^+e^- \qquad \text{etc.}$$

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)

13년 6월 27일 목요일

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 in the minimal version (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 symmetry, 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, and contributes to dark radiation

Spon. Broken local dark sym

- If dark sym is spont. broken, DM will decay in general, if there is no remaining (discrete) unbroken 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)
- Vacuum stability is improved by the new scalar
- Higgs Signal strengths universally reduced from "ONE"

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

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

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

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

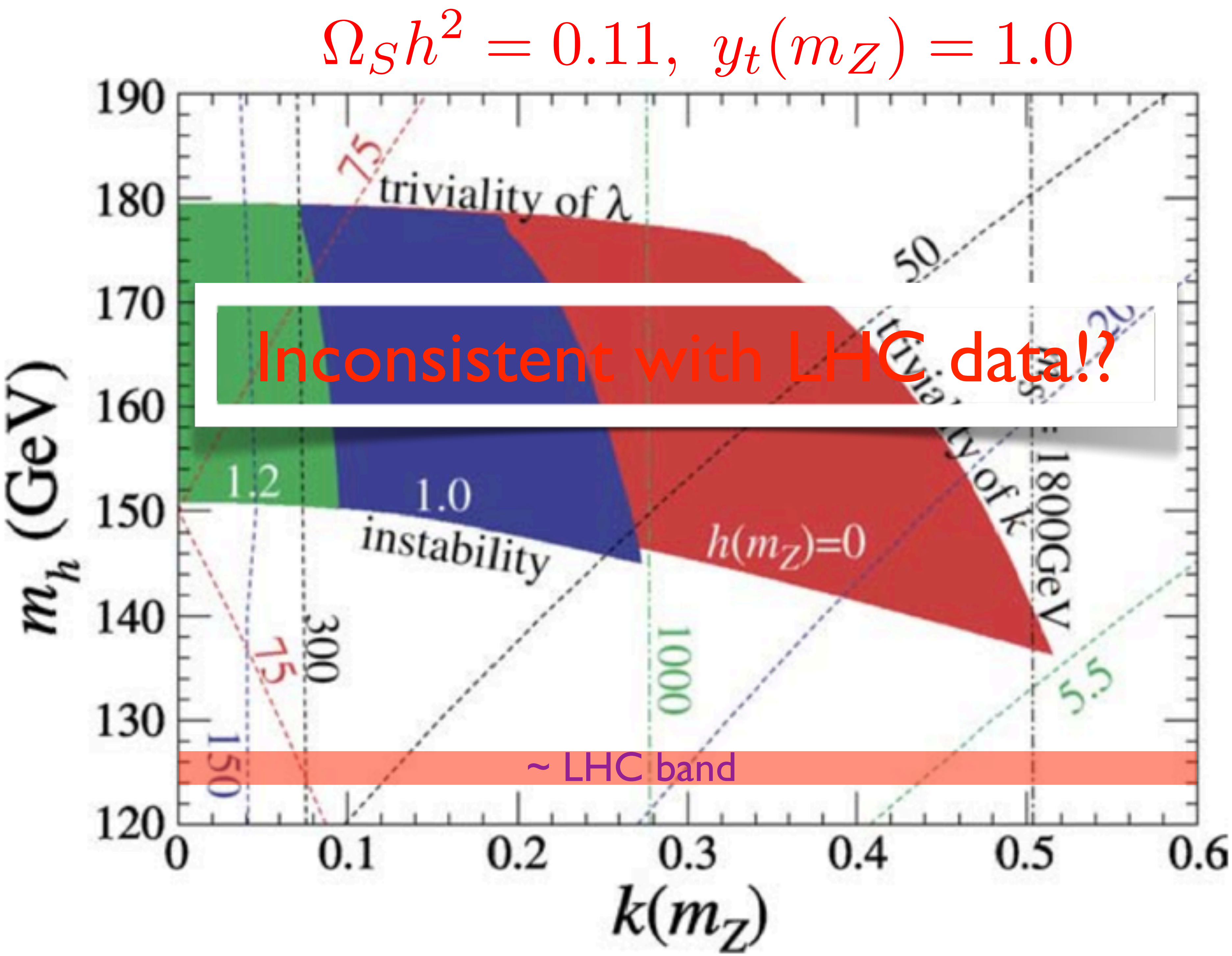
Reheating ⇨ $$V_{\rm RH} = \mu_1 \varphi |H|^2 + \mu_2 \varphi S^2 + \kappa_H \varphi^2 |H|^2 + \kappa_S \varphi^2 S^2 + (y_N^{\alpha\beta} \varphi N_\alpha N_\beta + \text{c.c.}).$$

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

- DM stability

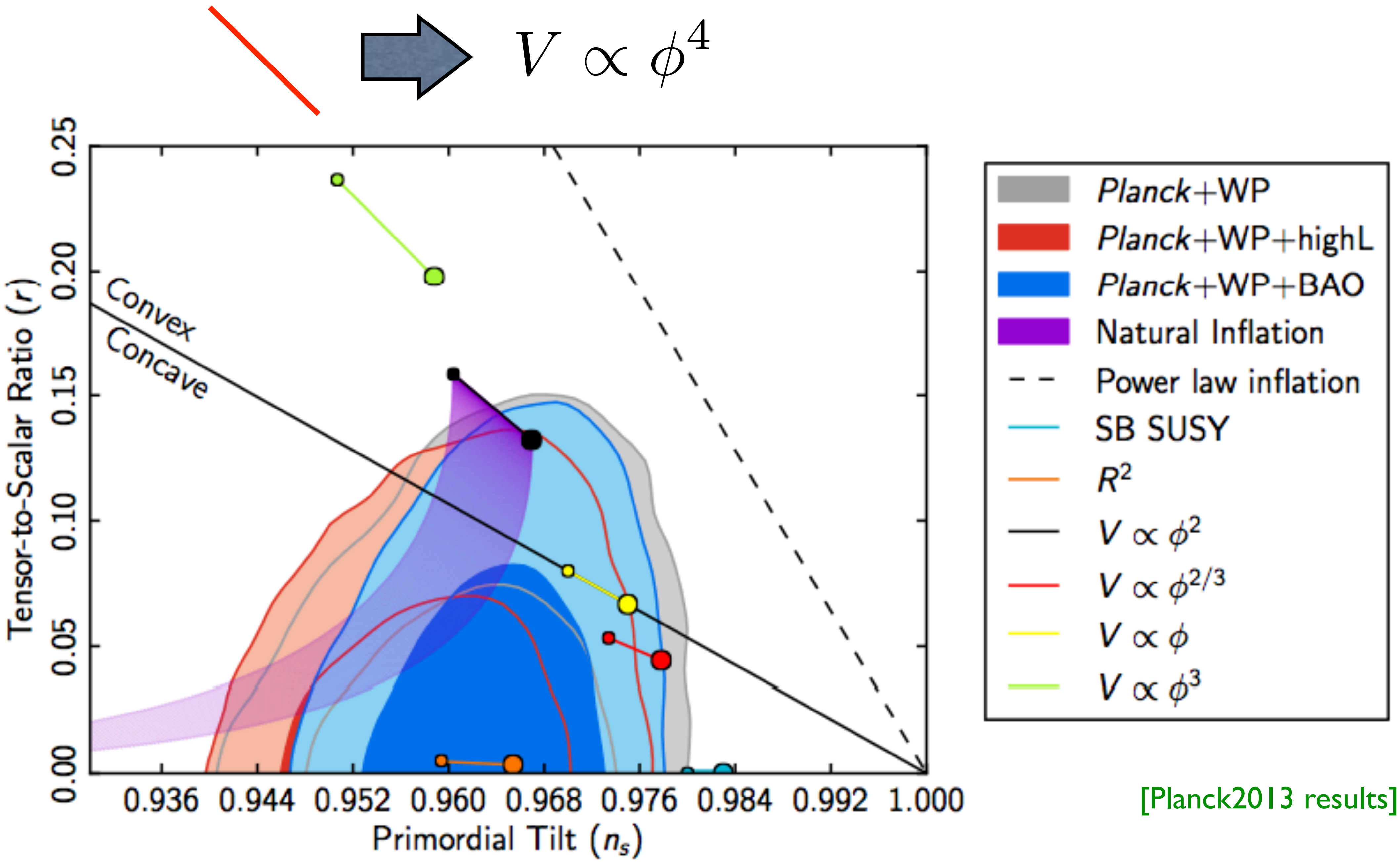
  assumed by ad hoc. Z_2-parity (where is this from?)

- NMSM parameter space



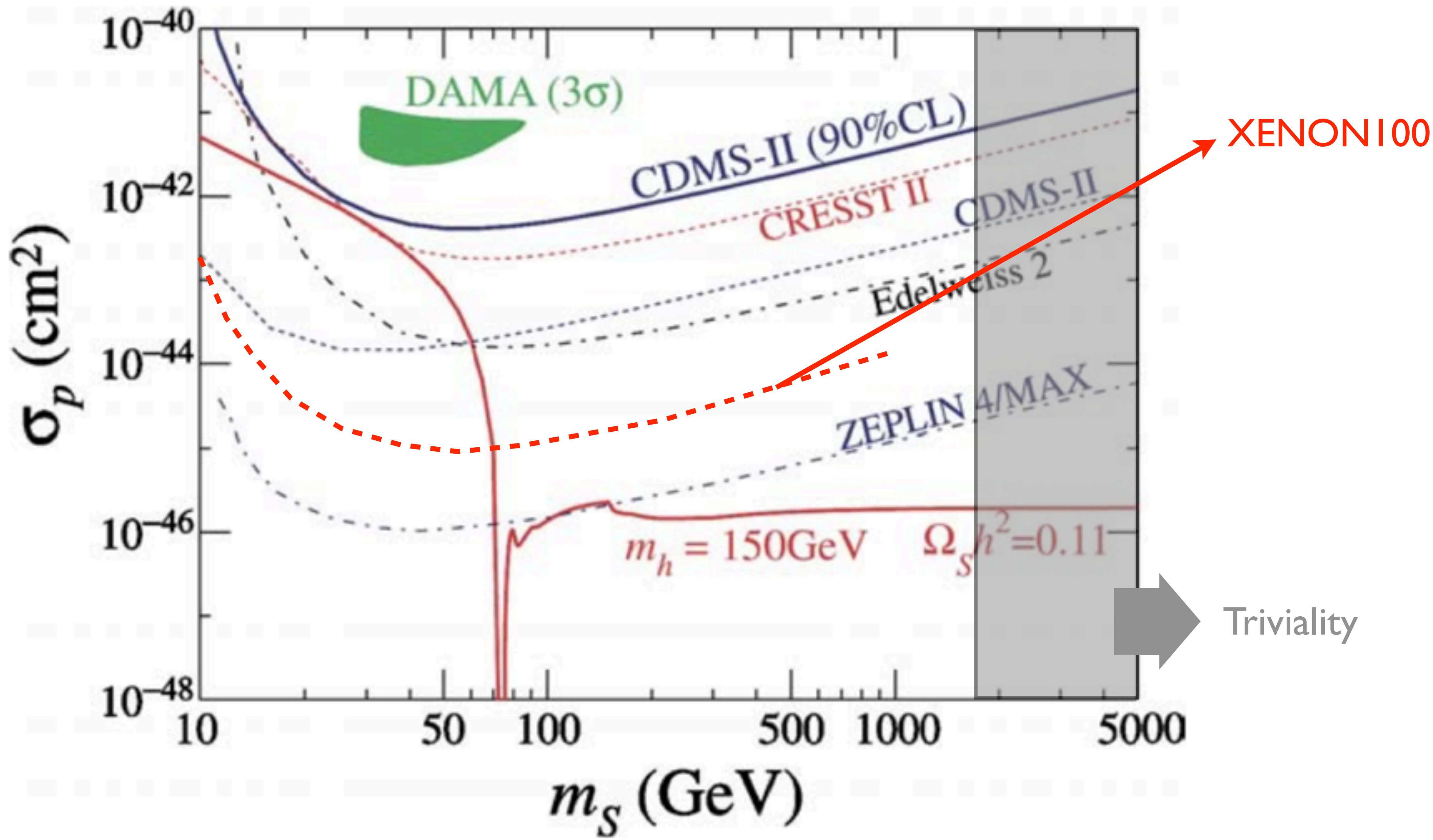
□= quartic coupling of Higgs, □= quartic coupling of S (DM)
□= mixed quartic coupling of Higgs and DM

Inflation models in light of Planck2013 data



[Planck2013 results]

- WIMP-nucleon scattering in New Minimal SM



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 $E_8 \times E_8' \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times G_{DS}$?).
  - Dark matter should be the lightest (dark) charged particle.

Unbroken local U(1)x

- DM self-interaction

It may solve some puzzles of the collisionless CDM.

- core/cusp problem: [S.-H Oh et al., arXiv:1011.0899]
simulated cusp of DM density profile contrary to the cored one found in the obvserved LSB galaxies and dSphs

- "too big to fail" problem: [M. Boylan-Kolchin et al., arXiv:1111.2048]
simulated high internal density concentration of the subhalos in the MW-sized halos contrary to the observed brightest MW satellites

- Massless dark photon

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

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

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

SM-DM communication

- Kinetic mixing

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

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

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

$\Rightarrow$ This opens a direct detection channel.

- Gauge-singlets

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

Higgs portal

may lead efficient annihilations

provides a direct detection channel

Right-handed neutrino portal

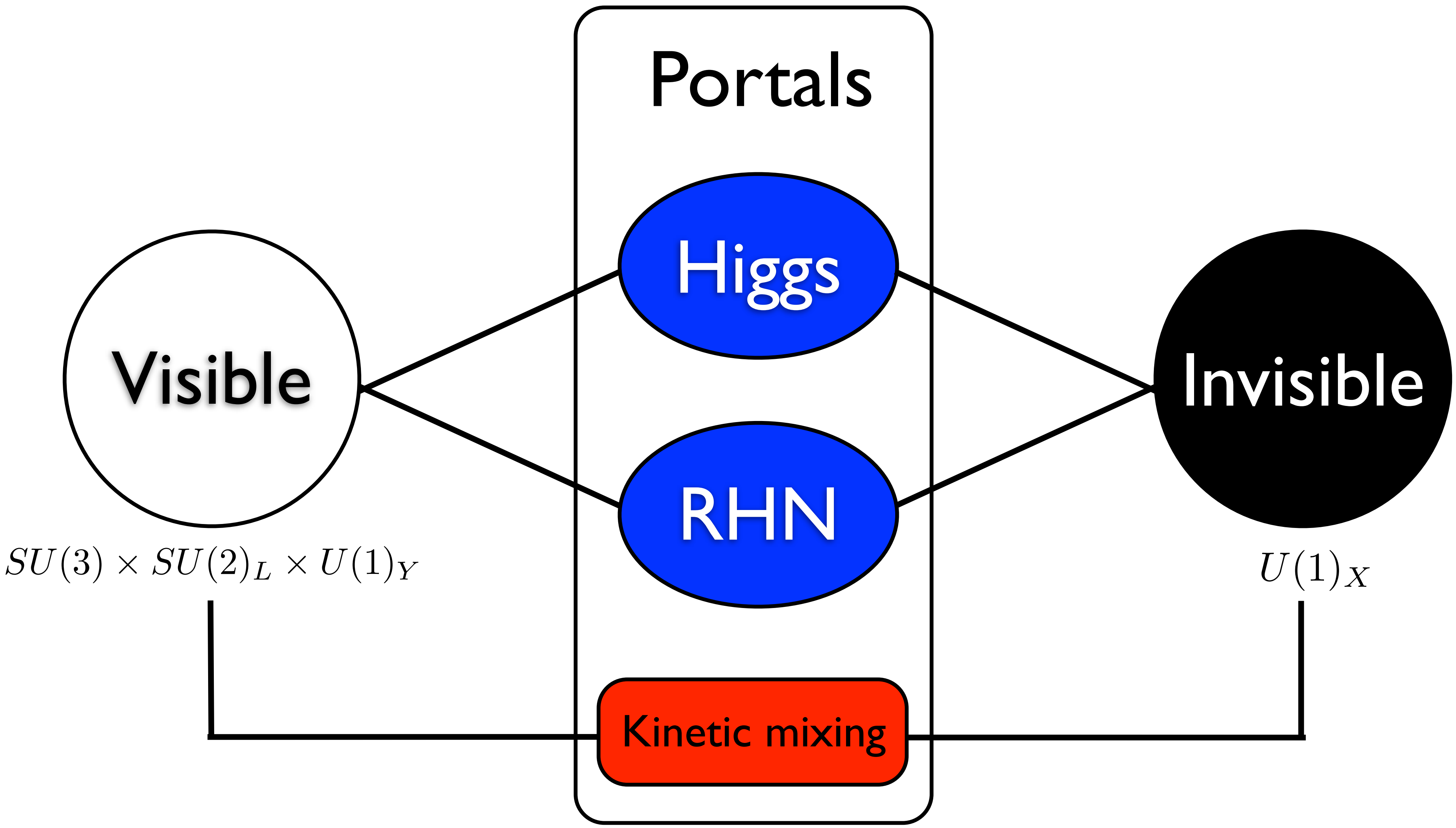
Leptogenesis and asymmetric DM?

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

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

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

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

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

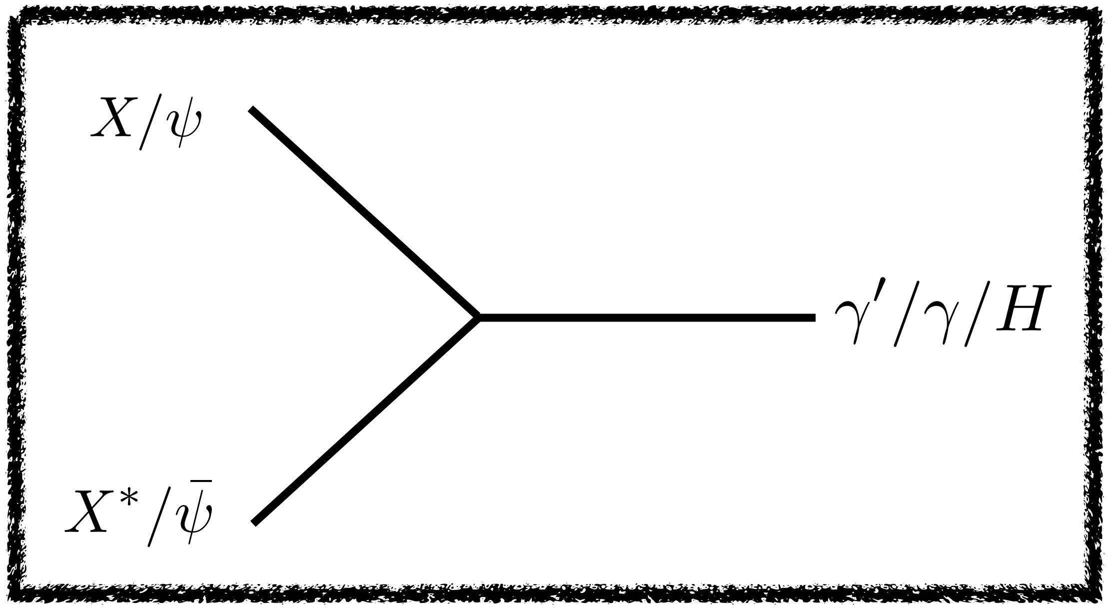
$$-\mathcal{L}_{\rm DS} = m_\psi \bar{\psi}\psi + m_X^2 |X|^2 + \frac{1}{4}\lambda_X |X|^4$$

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

• Interaction vertices of dark particles (X, ψ)

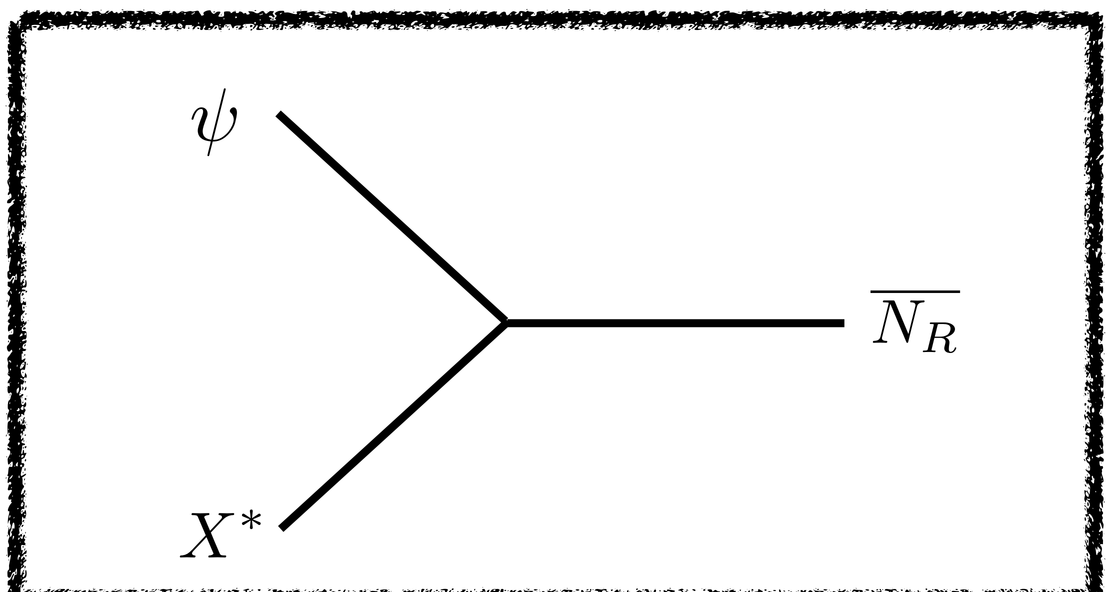
Kinetic term diagonalization: $\begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix}$

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



Annihilation
or
scattering

(⇒ Relic density, direct/indirect searches)



Decay of 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})

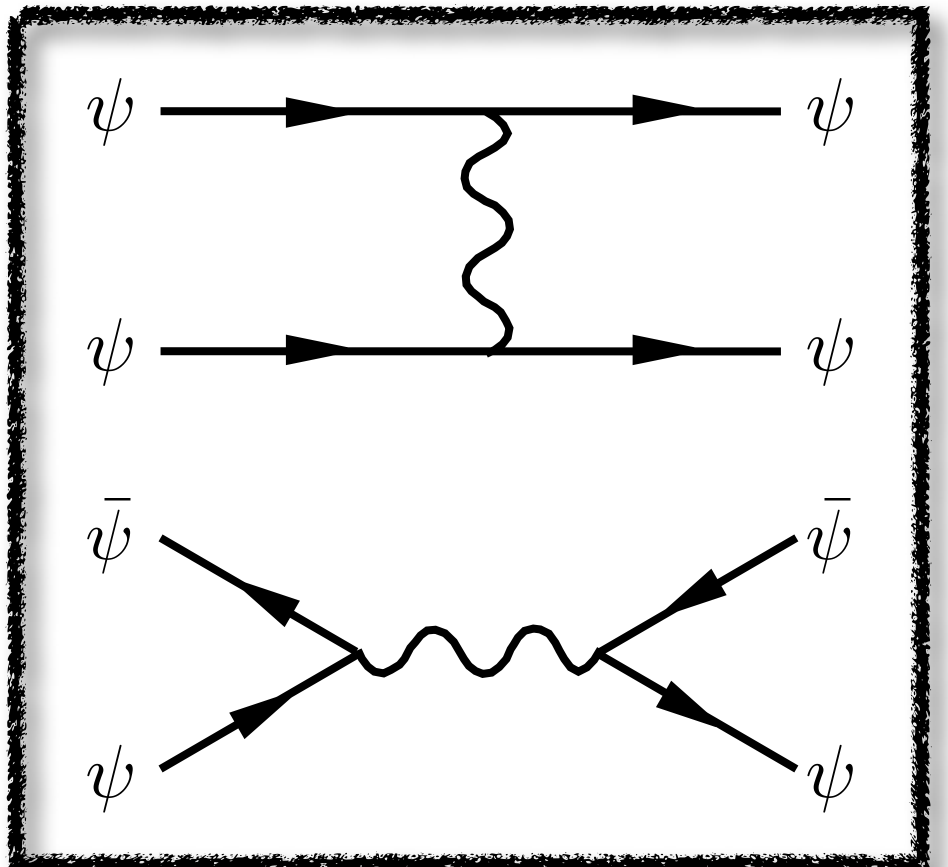
* Dark radiation (Massless photon)(α_X)

* 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]

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

☛ 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.

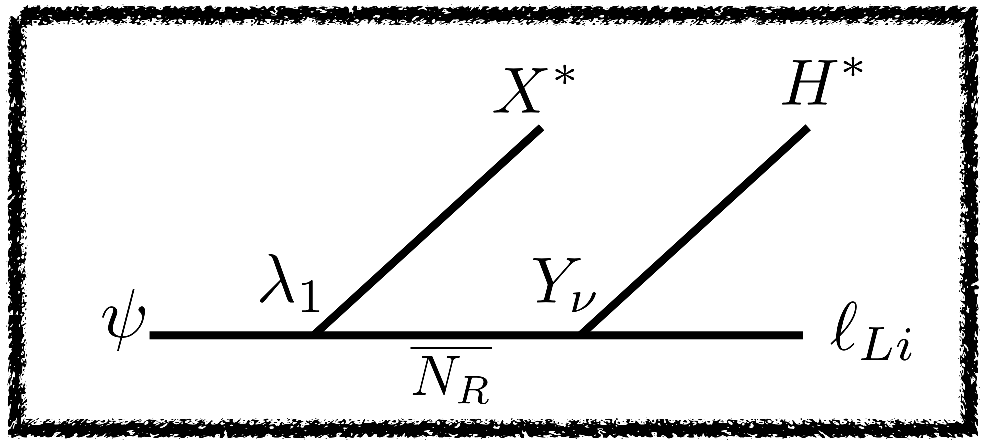
"X"(the scalar dark field) = CDM

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

(i) cored profile of dwarf galaxies.

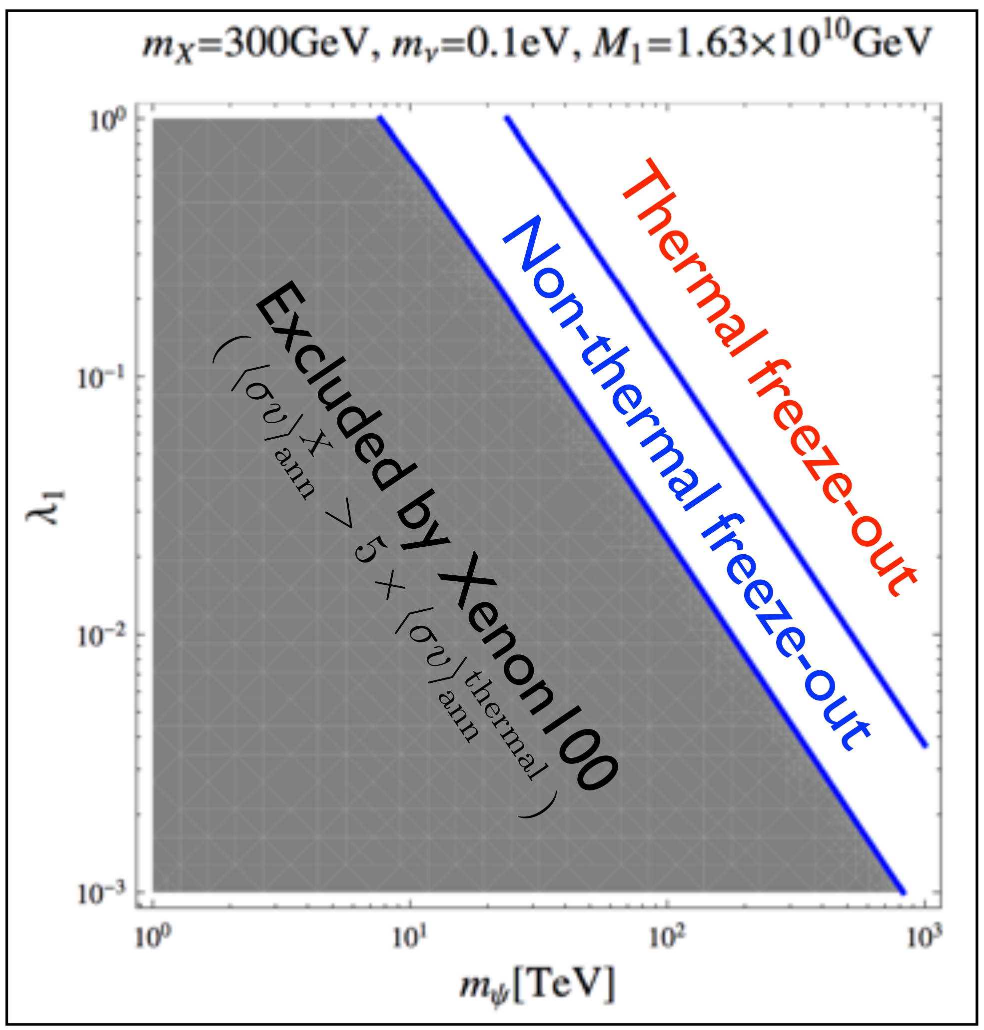
(ii) low concentration of LSB galaxies and dwarf galaxies. [Vogelsberger, Zavala and Leb, 1201.5892]

• CDM relic density



The late-time decay of ψ

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



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

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

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

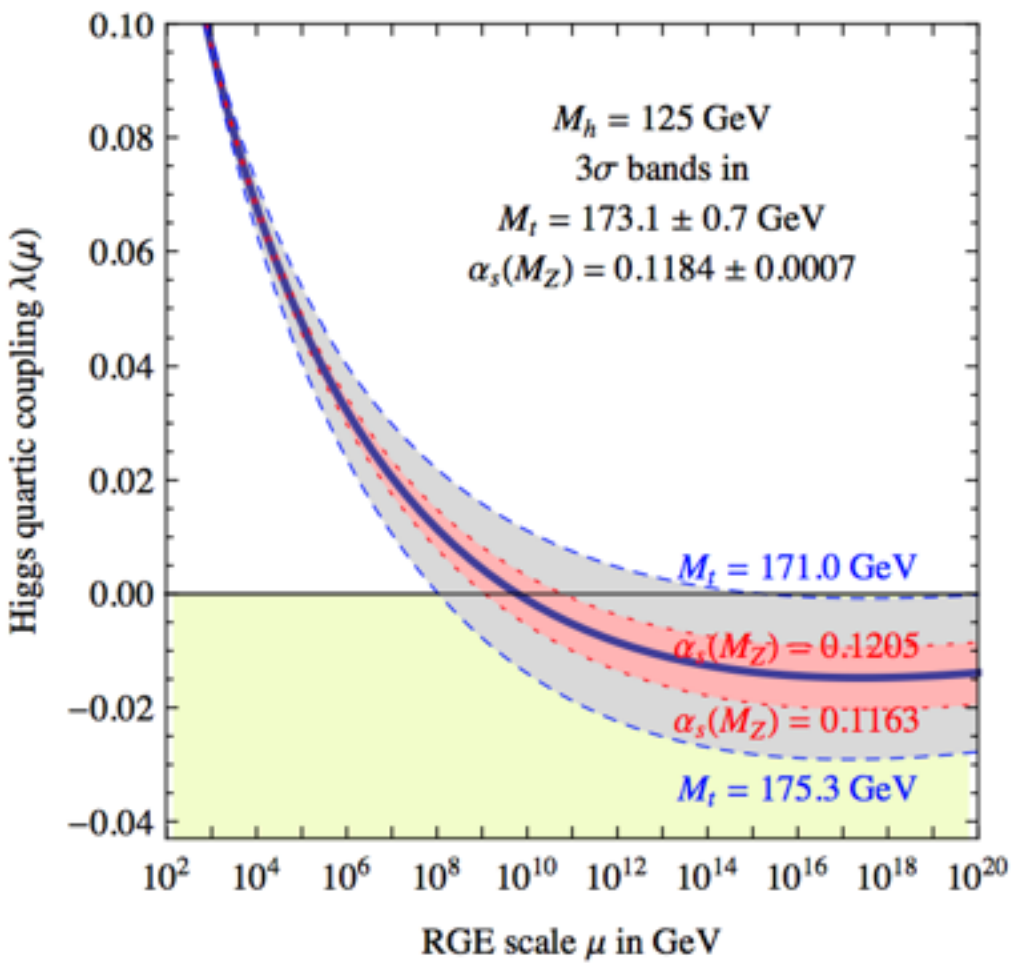
- Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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

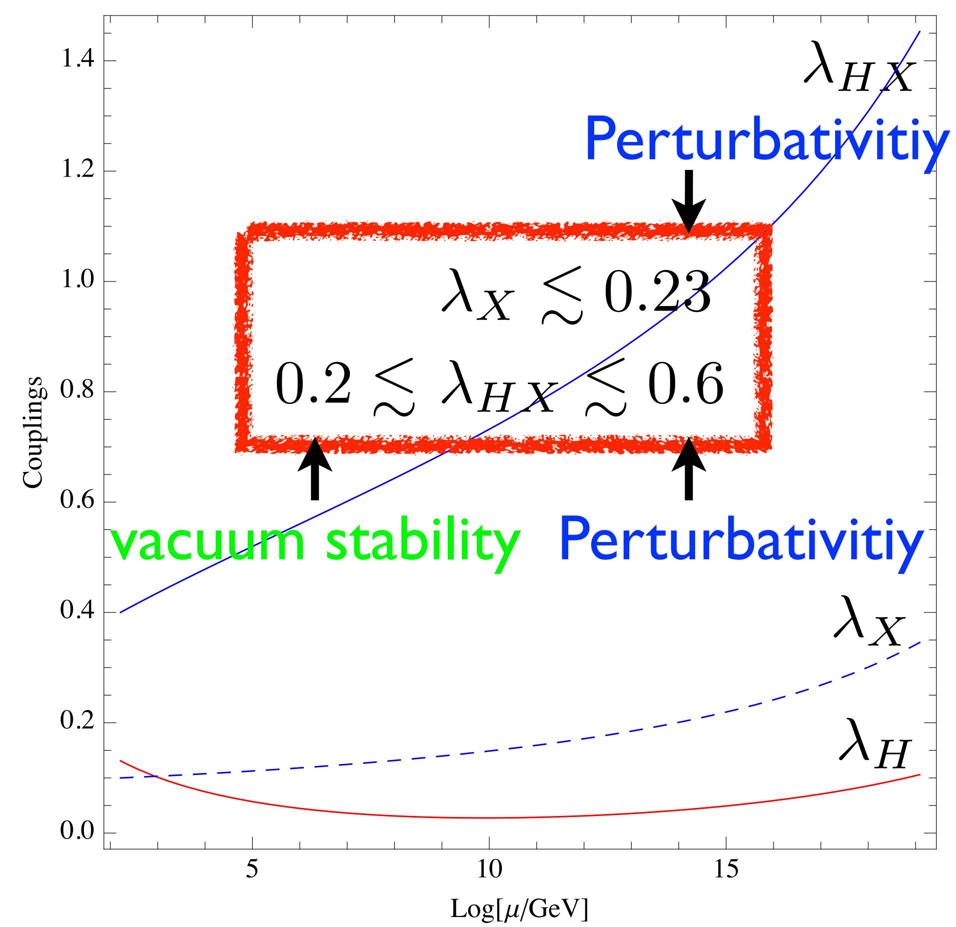
$$\beta^{(1)}_{\lambda_{HS}} = \frac{\lambda_{HS}}{16\pi^2}\left[2\left(6\lambda_H + 3\lambda_S + 2\lambda_{HS}\right) - \left(\frac{3}{2}\lambda_H\left(3g_2^2 + g_1^2\right) - 6\lambda_t^2 - 4\lambda^2\right)\right],$$

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

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

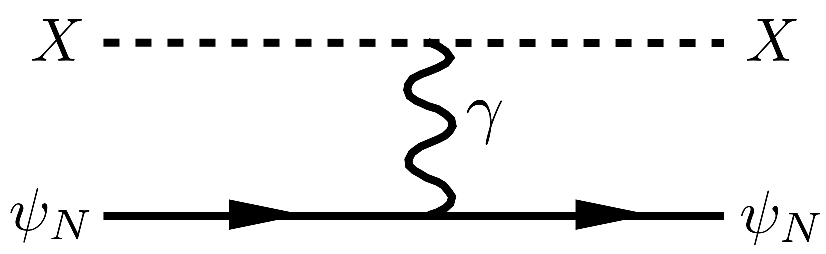


[G. Degrassi et al., 1205.6497]

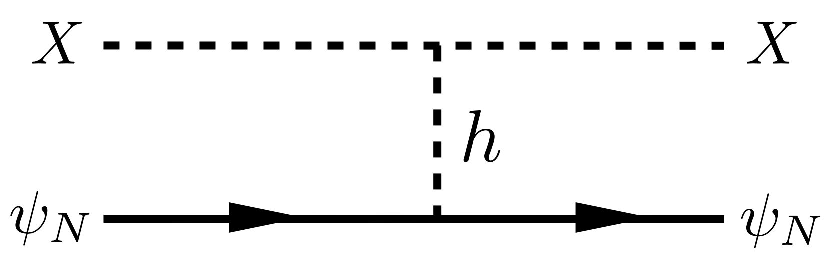


13년 6월 27일 목요일

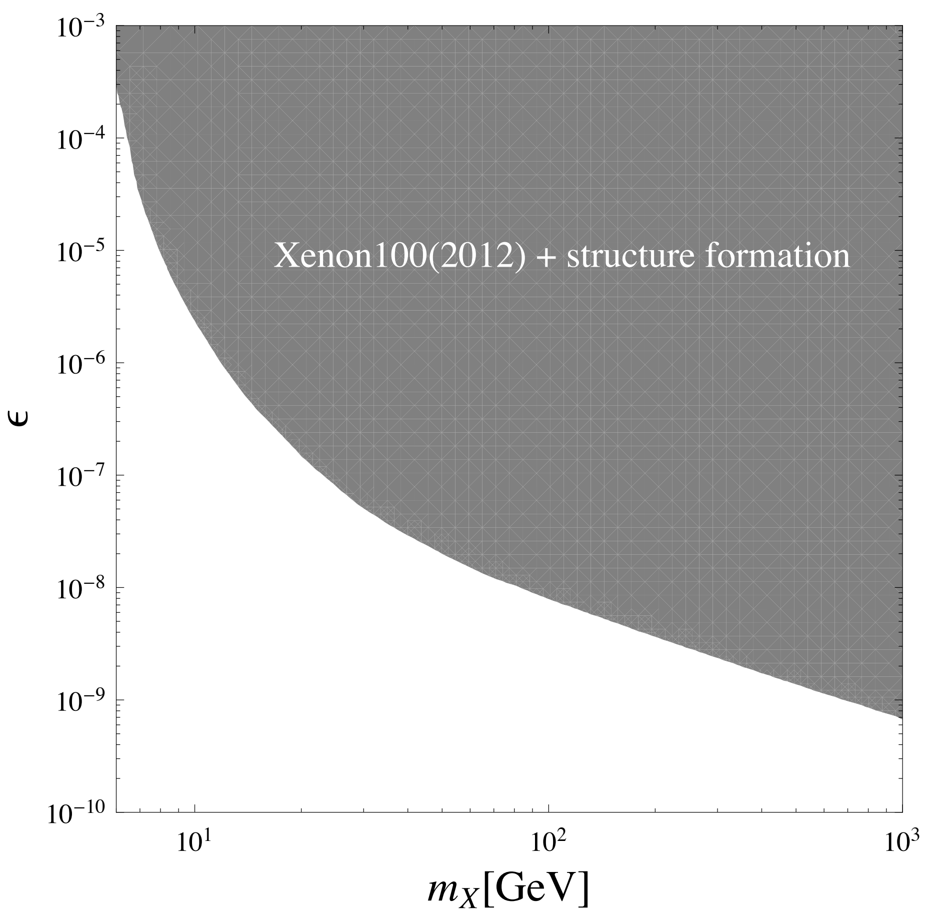
• DM direct search (ε, λ_{hx}, m_X)

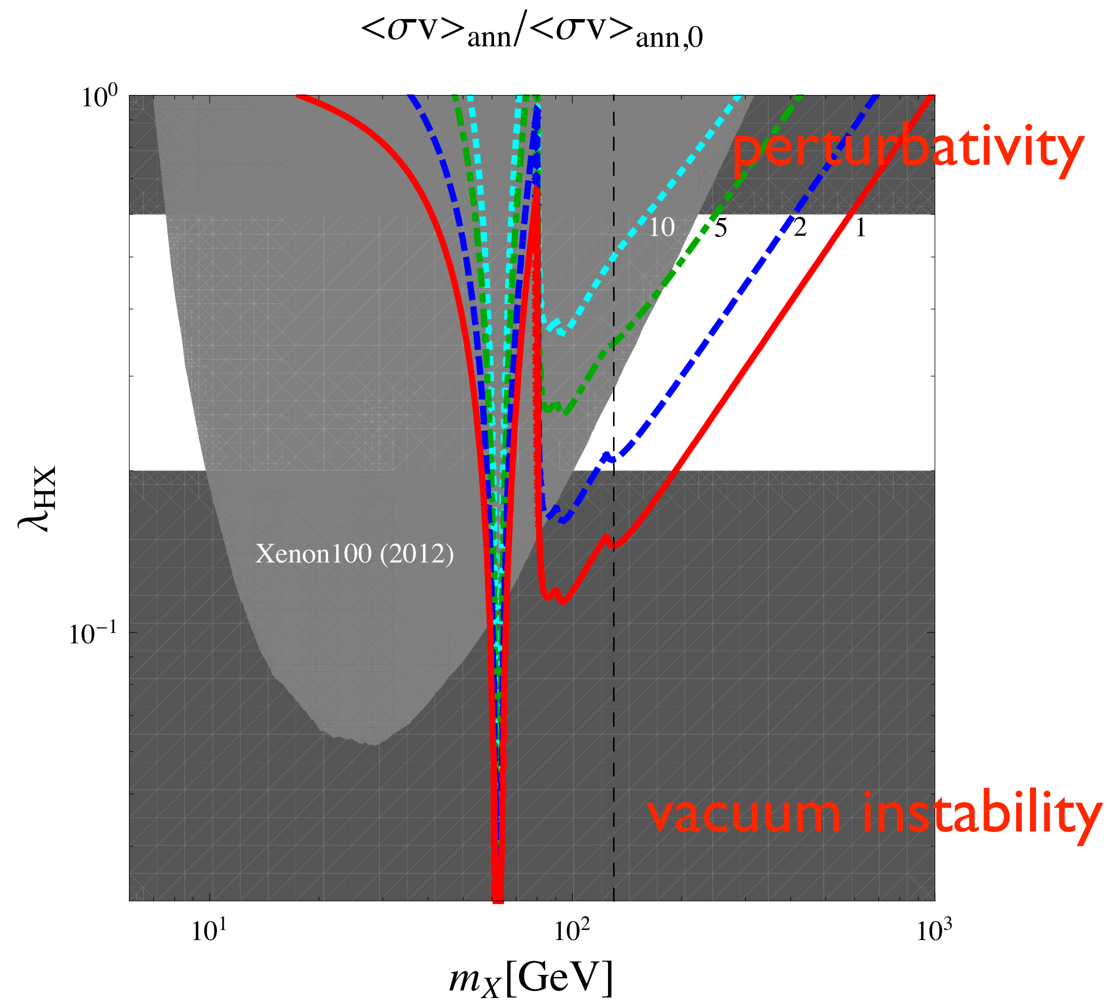


$$\frac{d\sigma_A}{dE_r} = \frac{2\pi\epsilon_e^2\alpha_{em}^2 Z^2}{m_A E_r^2 v^2}\mathcal{F}_A^2(qr_A)$$



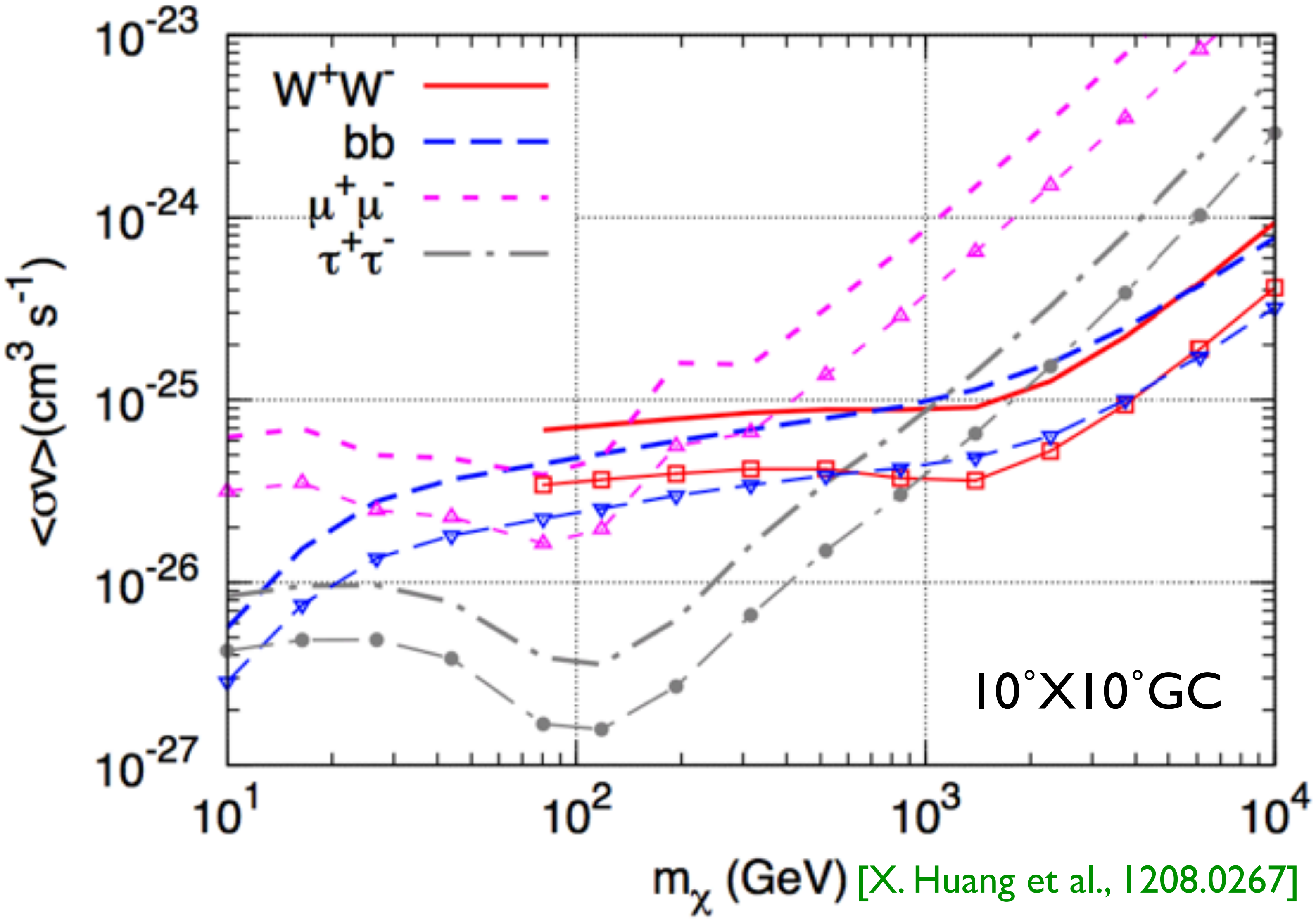
$$\sigma_{\mathcal{N},h}^{SI} = \frac{\lambda_{HX}^2}{64\pi}\frac{m_r^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$





- # Indirect search (λ_{hX}, m_X)

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



[X. Huang et al., 1208.0267]

In our model,

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

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

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

☛ 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!

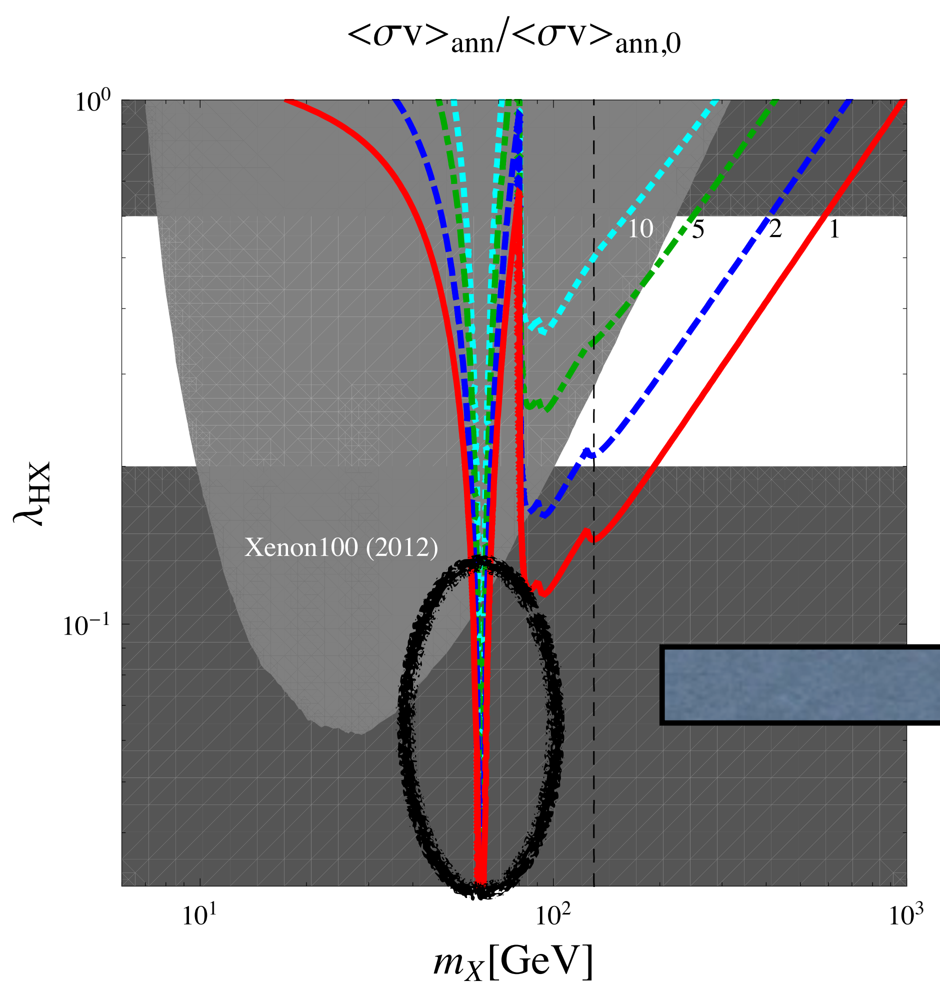
- # Collider phenomenology (λ_{hx}, m_X)

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

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



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

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

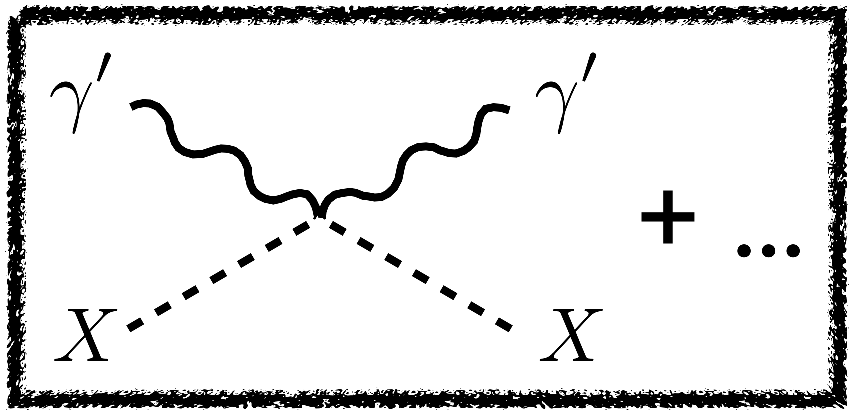
or

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

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

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

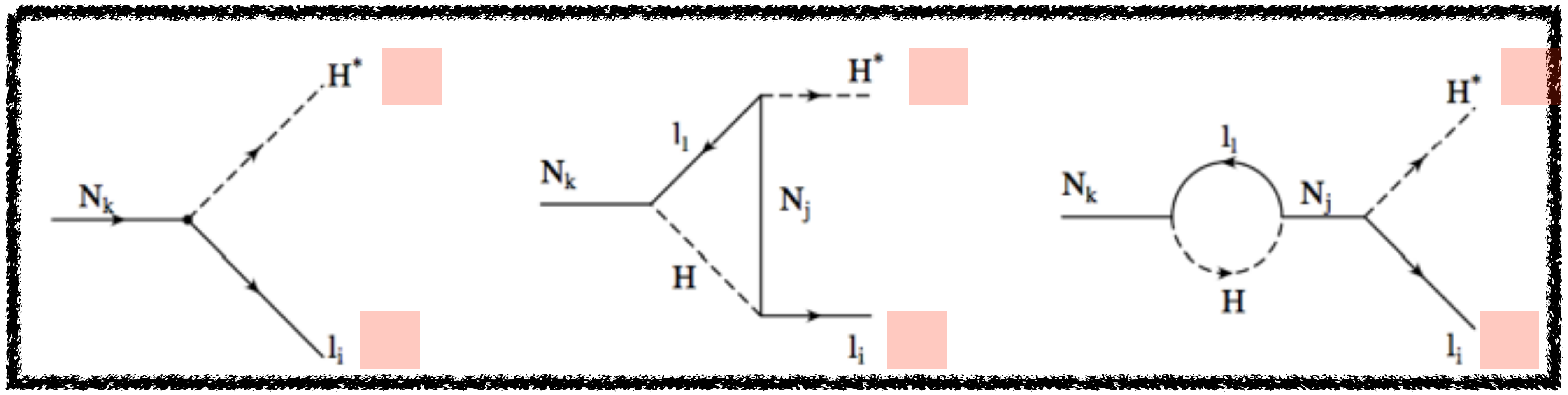
$$\frac{T_{\nu,0}}{T_{\gamma,0}} = \begin{cases} \left(\frac{4}{11}\right)^{1/3} & \text{for} \quad T_{\mathrm{dec}} \gtrsim 1\mathrm{MeV} \\ 1 & \text{for} \quad T_{\mathrm{dec}} \lesssim 1\mathrm{MeV} \end{cases}$$

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

[Planck Collaboration, arXiv:1303.5076]

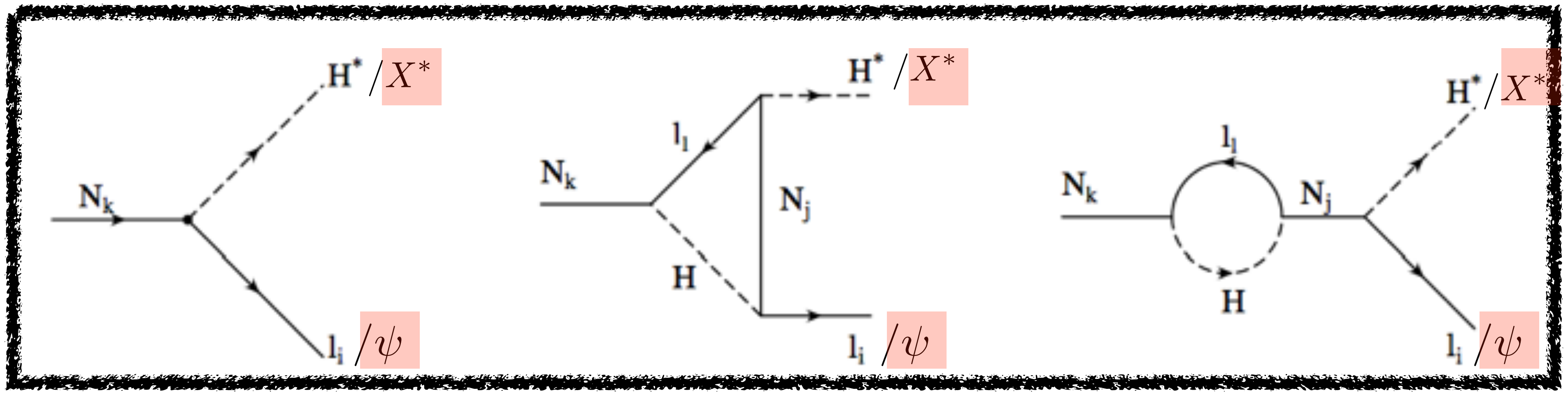
$$T_{\mathrm{dec},\gamma'-\mathrm{SM}} \sim 1\mathrm{GeV} \Rightarrow \Delta N_{\mathrm{eff}} = \frac{2}{2\frac{7}{8}}\left(\frac{11}{4}\right)^{4/3}\left(\frac{g_{*S}(T_{\gamma,0})}{g_{*S}(T_{\mathrm{dec},X_\mu})}\right)^{4/3} \sim 0.06$$

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



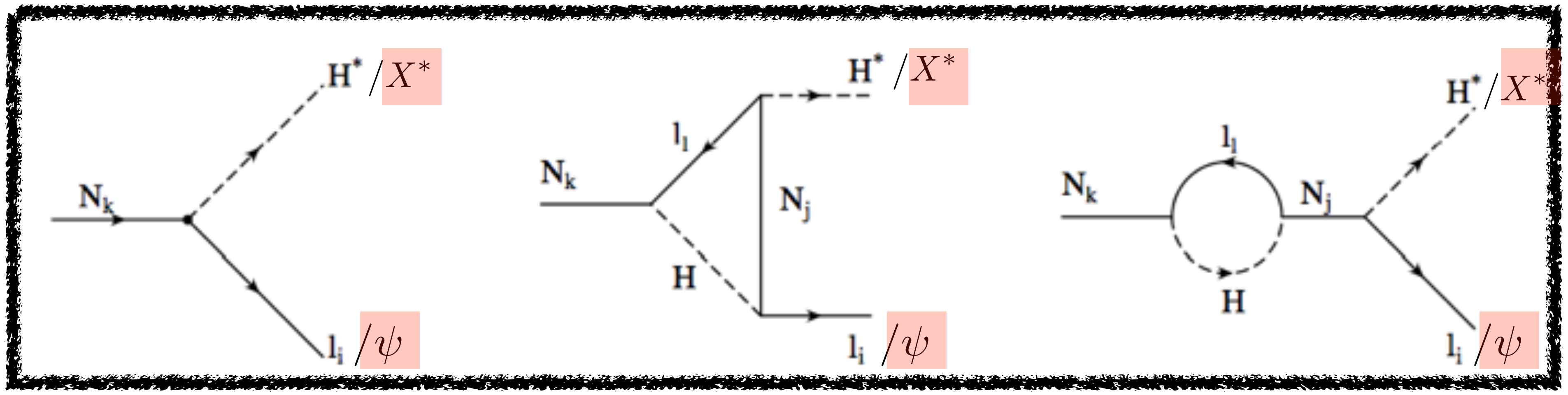
Lepto/darkogenesis (1/2)

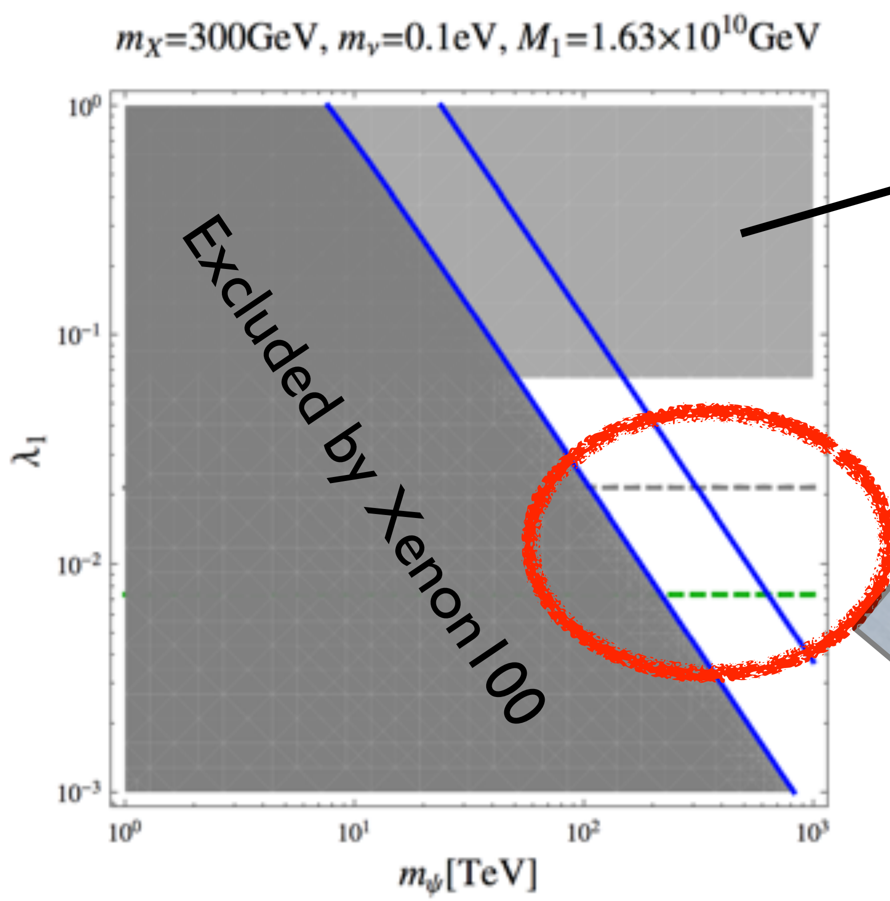
(Genesis from the decay of RHN)



• Lepto/darkogenesis (1/2)

(Genesis from the decay of RHN)





Light gray: narrow width approx. is invalid

White between blue lines:

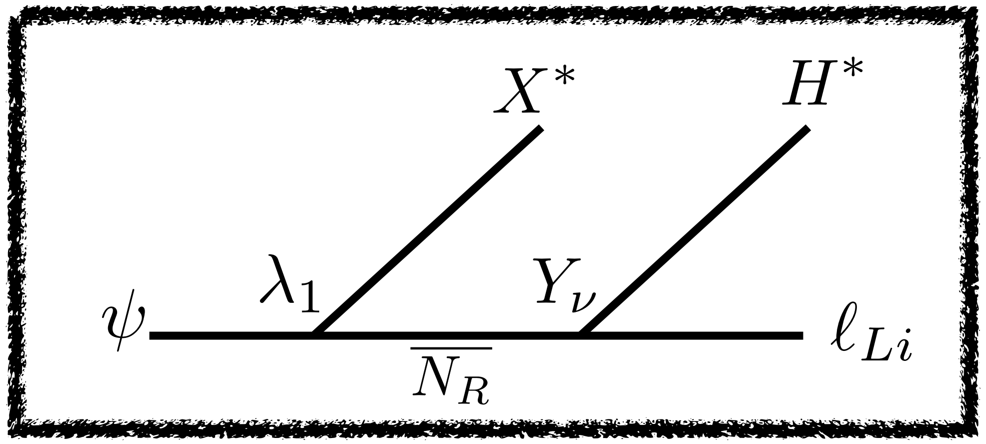
$$1 \leq \langle \sigma v \rangle_{\rm ann}^{\rm tot} / \langle \sigma v \rangle_{\rm ann}^{\rm th} \lesssim 5$$

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

Correct BAU and CDM relic can be obtained.

- # Lepto/darkogenesis (2/2)

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



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

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

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

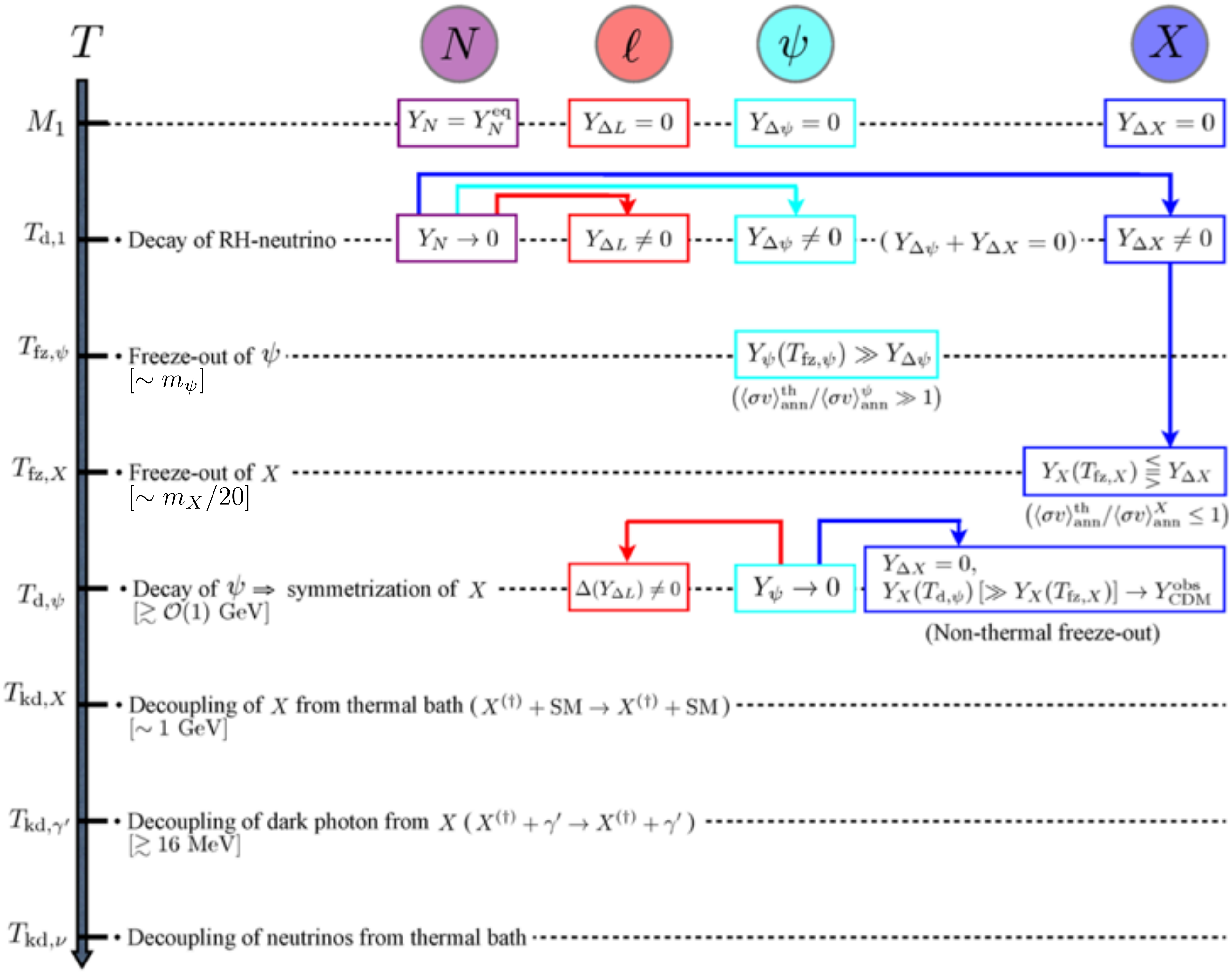
$$Y_\psi(T_{\rm fz}^{\psi}) = \frac{3.79\left(\sqrt{8\pi}\right)^{-1} g_*^{1/2}/g_{*S}\, x_{\rm fz}^{\psi}}{m_\psi M_{\rm P}\langle\sigma v\rangle_{\rm ann}^{\psi}} \simeq 0.05\frac{x_{\rm fz}^{\psi}}{\alpha_X^2}\frac{m_\psi}{M_{\rm P}}$$

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

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

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

Thermal history
(leptogenesis and DM production)



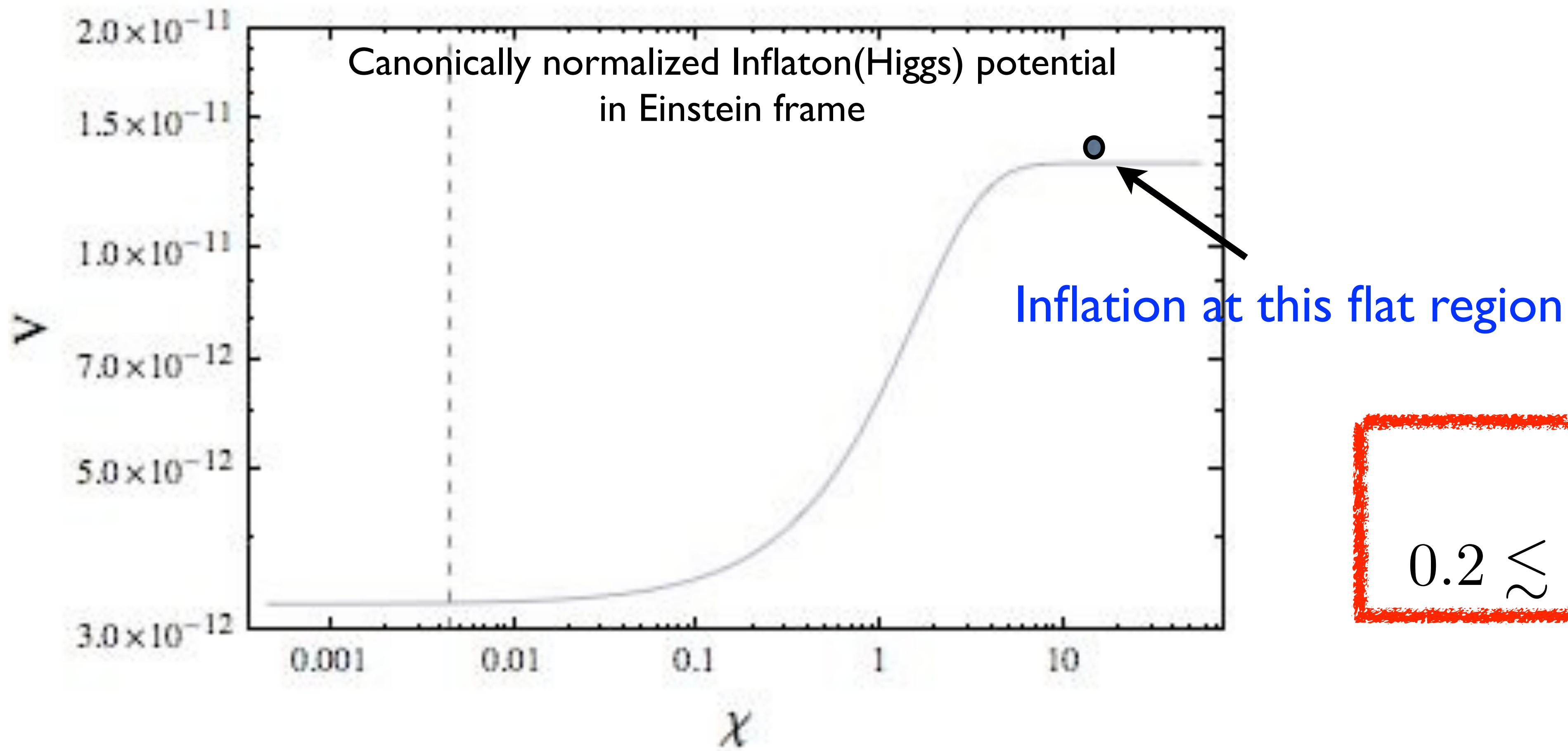
13년 6월 27일 목요일

- # Higgs inflation in Higgs-singlet system

[Lebedev, 1203.0156]

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

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



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

Variations

Assume the decay of Higgs to DMs is forbidden.

Signal strength

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

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)

Local Gauge Principle Enforced to DM Physics in the models presented

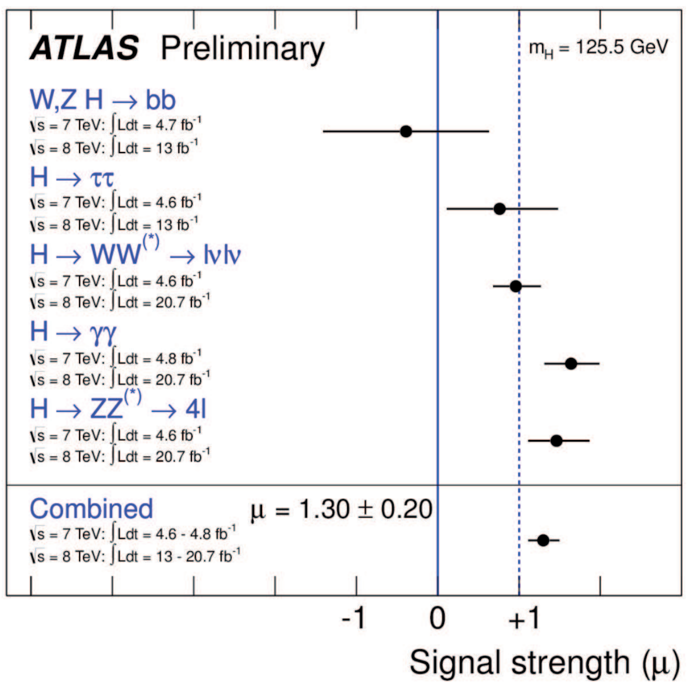
We got a set of predictions consistent with all the observations available so far

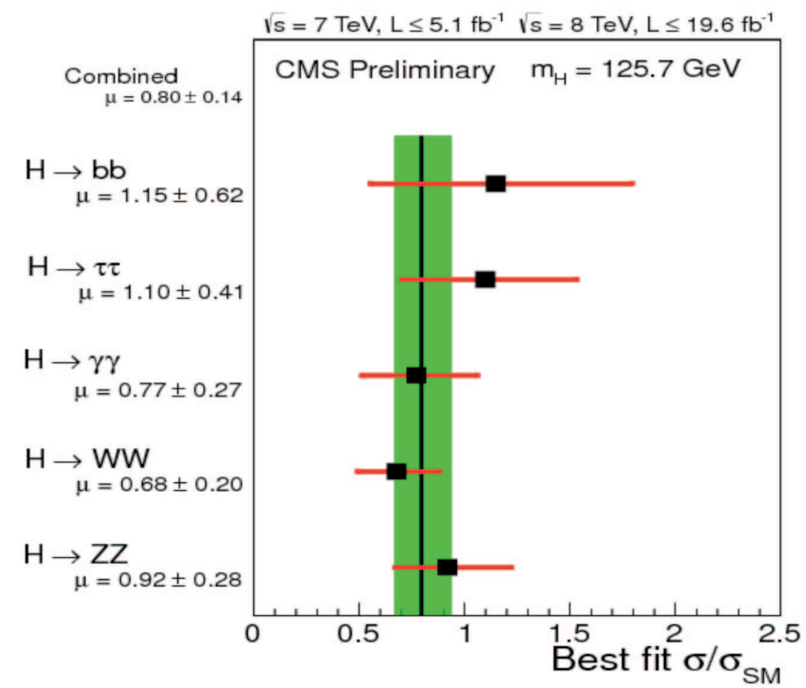
Nontrivial and Interesting possibility

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	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = 0.96 \pm 0.12$$