DM, DR and Higgs phenomenology in hidden sector DM models

Pyungwon Ko (KIAS)

The 5th Capri workshop
May 23-25 (2014)

SM Chapter is being closed

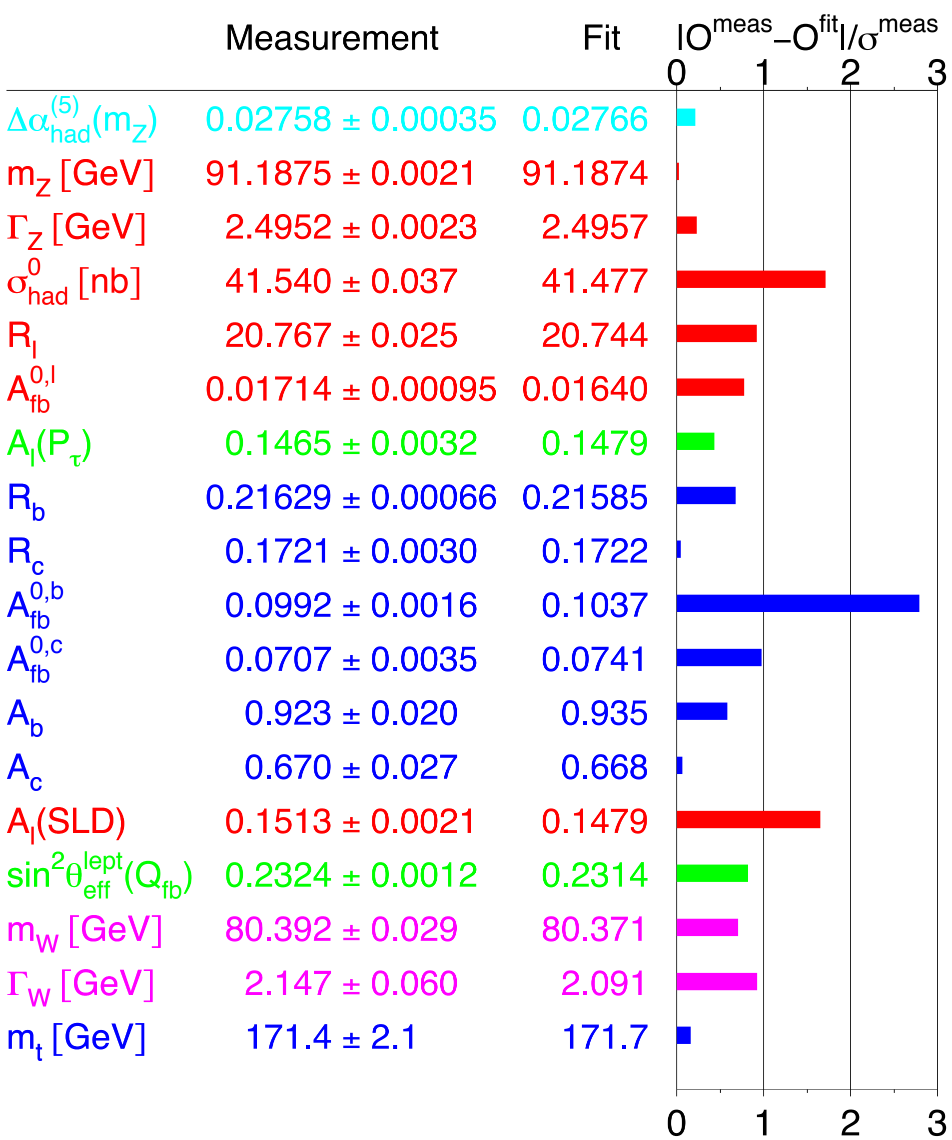
- SM has been tested at quantum level
  - EWPT favors light Higgs boson
  - CKM paradigm is working very well so far
  - LHC found a SM-Higgs like boson around 125 GeV
- No smoking gun for new physics at LHC so far

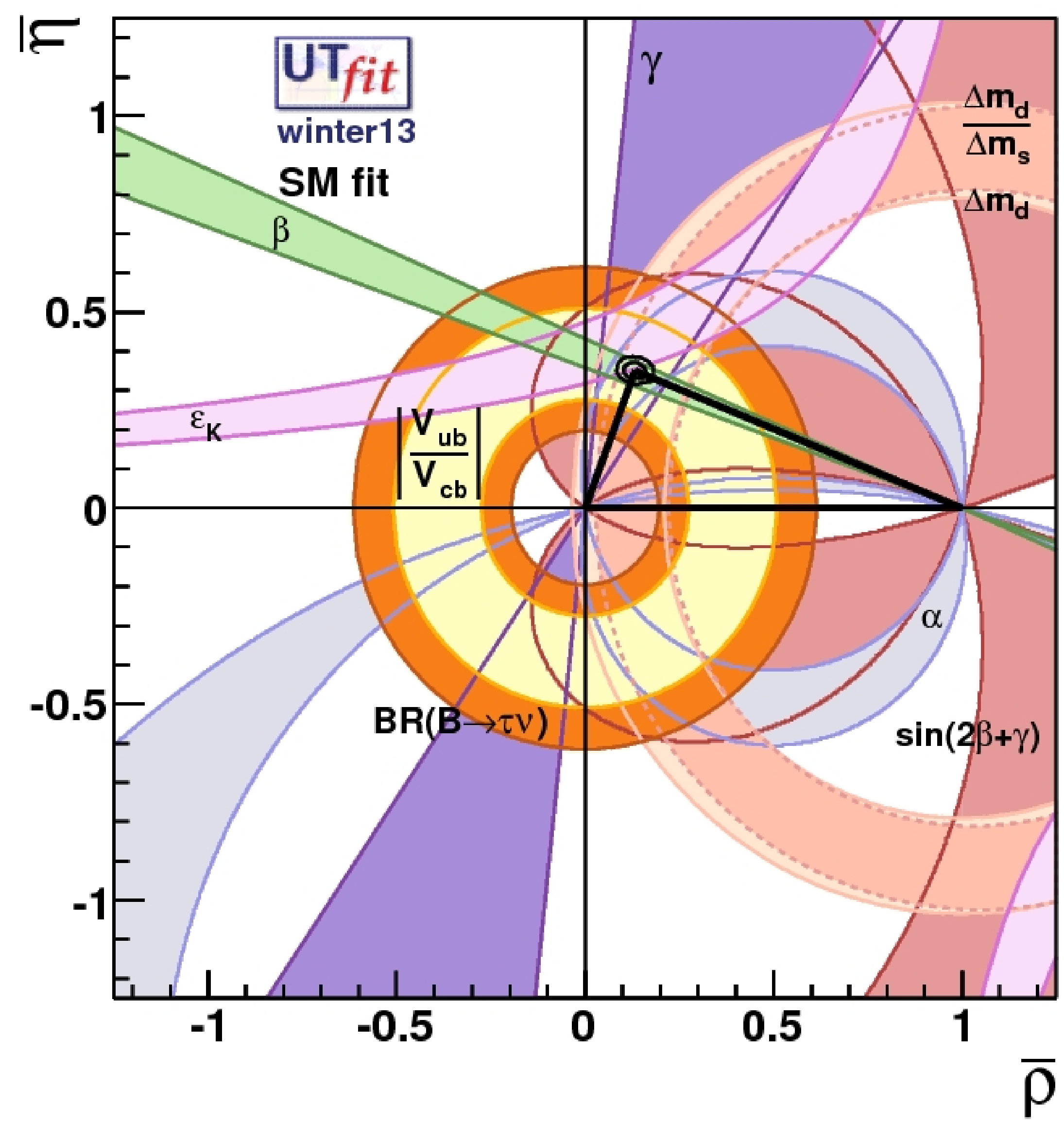
SM Lagrangian

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

Based on local gauge principle

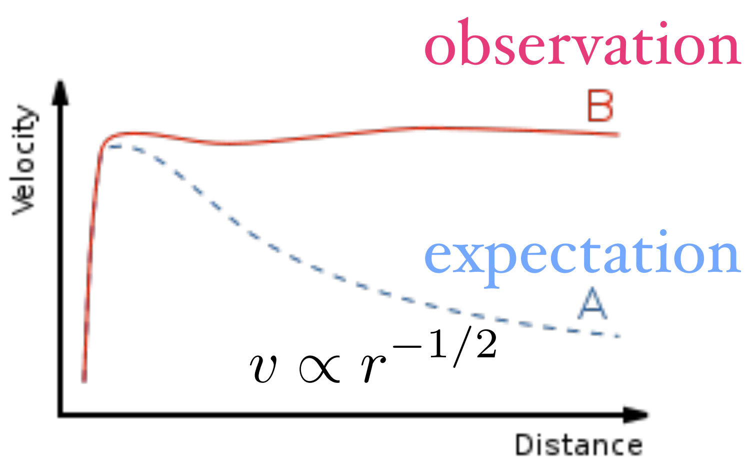
EWPT & CKM





Almost Perfect !

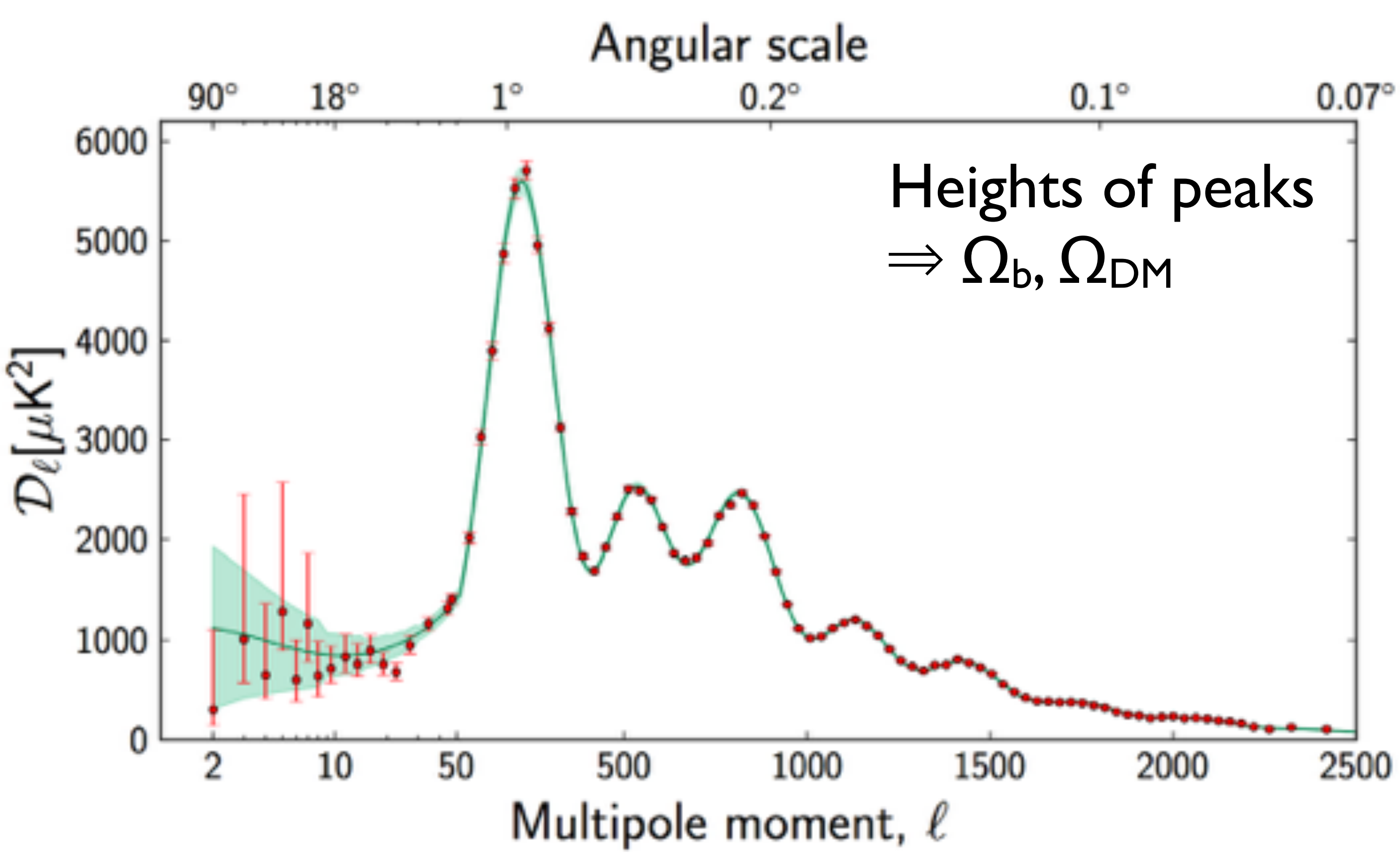
- Dark & visible matter and dark energy, neutrinos



Jan Oort (1932), Fritz Zwicky (1933)

Bullet cluster

Strong gravitational lensing in Abell 1689

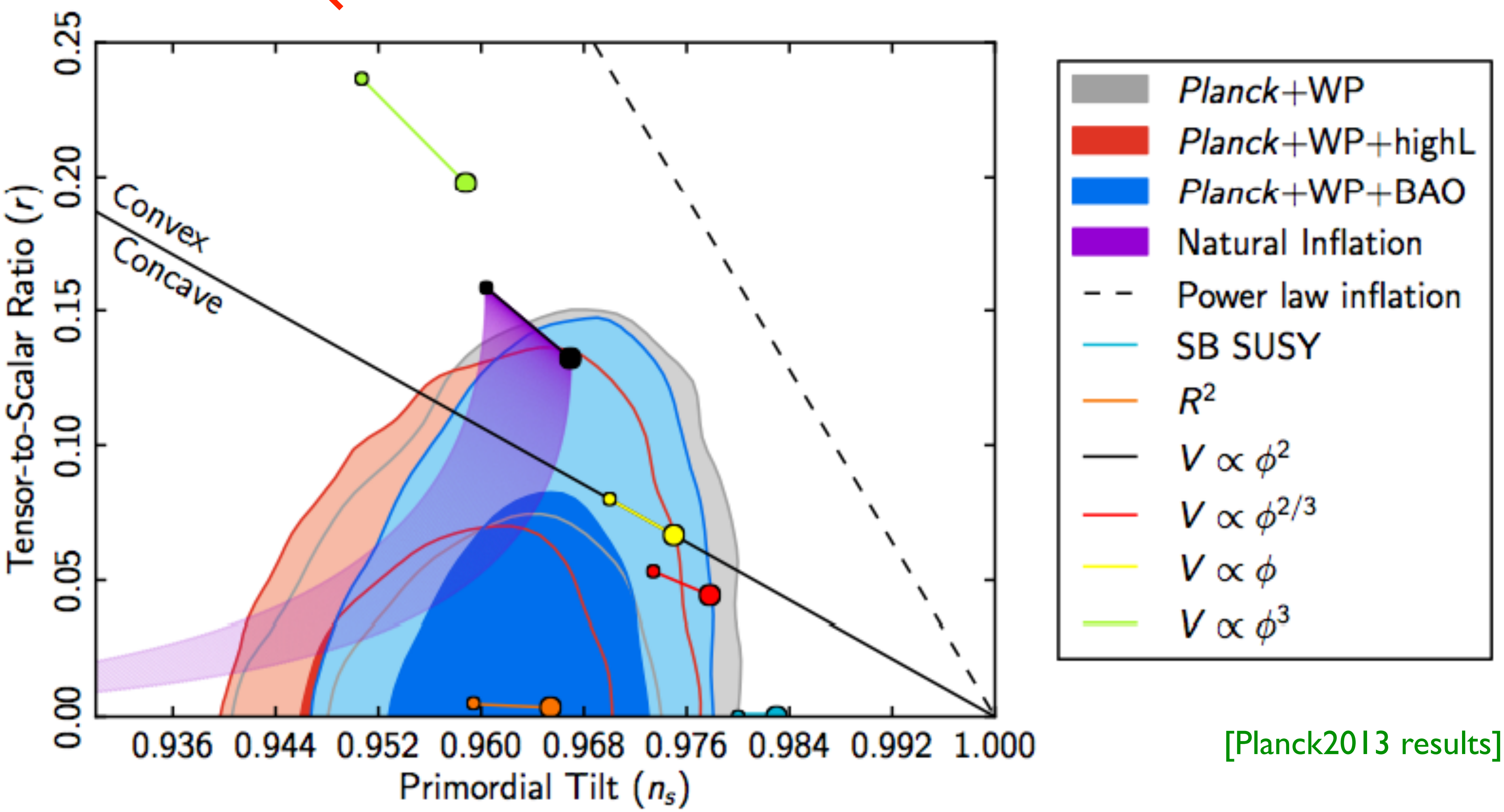


$$\Omega_{\rm b} \simeq 0.048$$
$$\Omega_{\rm DM} \simeq 0.259$$
$$\Omega_\Lambda \simeq 0.691$$

(Planck+WP+highL+BAO)

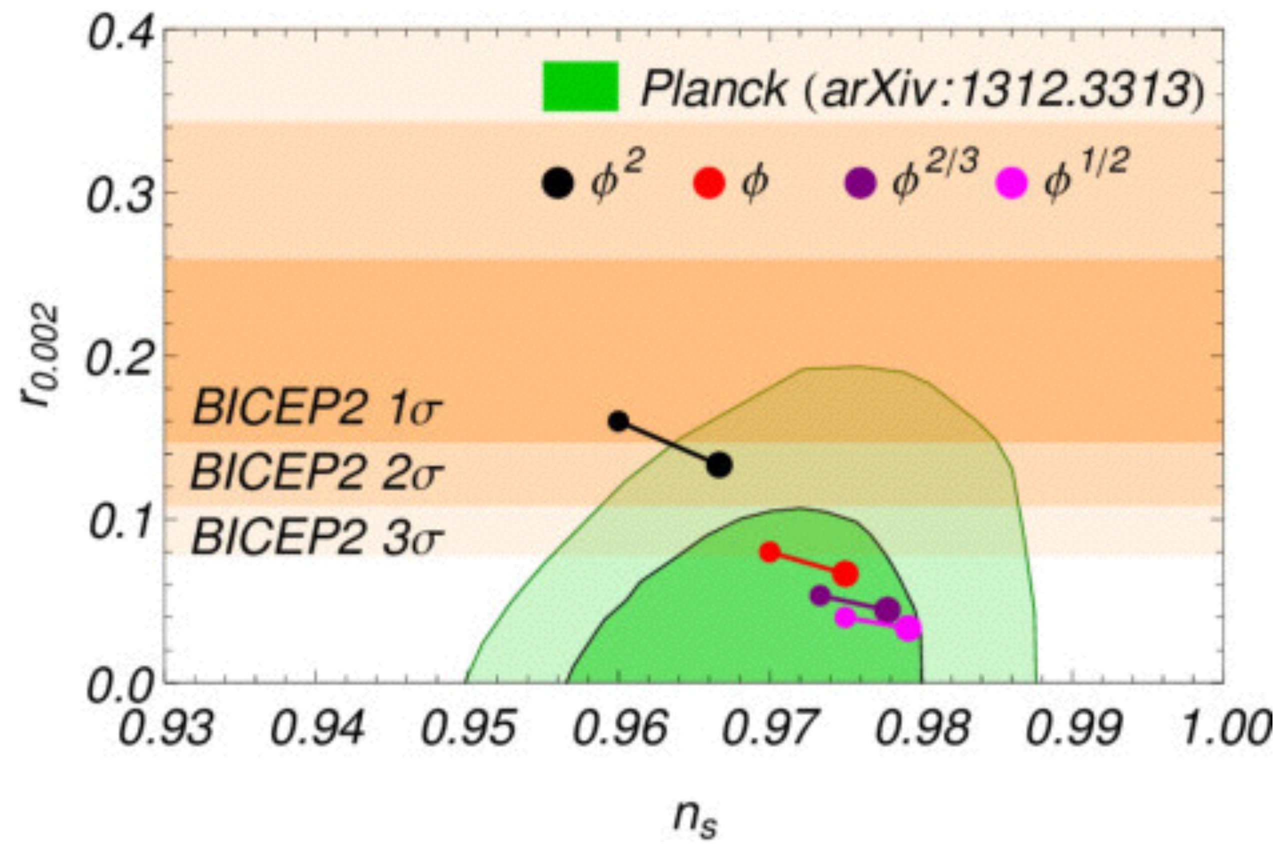
Inflation models in light of Planck2013 data

$V \propto \phi^4$



[Planck2013 results]

Inflation in light of BICEP2



Original Higgs inflation and Starobinsky model is now strongly disfavored (premature?)

Maybe it is right time to think about what LHC and Planck data tells us about New Physics@EW scale

Building Blocks of SM

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

Lessons from SM

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- One may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

(3,2,1) or SU(3)cXU(1)em ?

- Well below the EW sym breaking scale, it may be fine to impose SU(3)c X U(1)em
- At EW scale, better to impose (3,2,1) which gives better description in general after all
- Majorana neutrino mass is a good example
- For example, in the Higgs + dilaton (radion) system, and you get different results
- Singlet mixing with SM Higgs

Issue here is whether we use

$$\mathcal{L}_{\rm int} \simeq -\frac{\phi}{f_\phi}\, T^\mu_{\ \mu} = -\frac{\phi}{f_\phi}\left[m_H^2 H^\dagger H - 2 m_W^2 W^+ W^- - m_Z^2 Z_\mu Z^\mu + \sum_f m_f \bar{f} f + \sum_G \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu} \right], \tag{1}$$

OR

$$T^\mu_{\ \mu}({\rm SM}) = 2\mu_H^2 H^\dagger H + \sum_G \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu}.$$

arXiv:1401.5586 with D.W.Jung
Phys.Lett. B (2014)

In the usual earlier approach, one has

$$\mathcal{L}(f, \bar{f}, \phi) = -\frac{m_f}{f_\phi}\bar{f}f\phi\, \mathrm{e}^{-\bar{\phi}/f_\phi}.$$

In the new approach, one has

$$\mathcal{L}(f, \bar{f}, H_{i=1,2}) = -\frac{m_f}{v}\overline{f}fh = -\frac{m_f}{v}\overline{f}f(H_1 c_\alpha + H_2 s_\alpha),$$

These two lead to very different predictiontions for the Higgs phenomenology at the LHC, especially for H to diphoton, and gg fusion for H productions (see the paper for the details)

Contents

- Underlying Principles : Hidden Sector DM, Singlet Portals, Renormalizability, Local Dark Gauge Symmetry
- Scale Inv Extension of the SM with strongly Interacting Hidden Sector : EWSB and CDM from hQCD; All Masses including DM mass from Dim Transmutation in hQCD
- (un)broken $U(1)_X$: Singlet Portal and Dark Radiation
- Higgs Phenomenology & Dark Radiation : Universal Suppression of Higgs signal strength and extra neutral scalar, dark radiation, etc.

Based on the works

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

- Strongly interacting hidden sector (0709.1218 PLB, 1103.2571 PRL)
- Light DM in leptophobic Z' model (1106.0885 PRD)
- 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 Monopole, VDM and DR (1311.1035)
- Self-interacting scalar DM with local Z3 symmetry (1402.6449)
- And a few more, including Higgs-portal assisted Higgs inflation, Higgs portal VDM for gamma ray excess from GC, and DM-sterile nu's etc.

Main Motivations

- Understanding DM Stability or Longevity ?
- Origin of Mass (including DM, RHN) ?
- Assume the standard seesaw for neutrino masses and mixings, and leptogenesis for baryon number asymmetry of the universe
- Assume minimal inflation models : Higgs(+singlet scalar) inflation, Starobinsky inflation

Questions about DM

- Electric Charge/Color neutral
- How many DM species are there ?
- Their masses and spins ?
- Are they absolutely stable or very long lived ?
- How do they interact with themselves and with the SM particles ?
- Where do their masses come from ? Another (Dark) Higgs mechanism ? Dynamical SB ?
- How to observe them ?

Origin of Mass

- Massive SM particles get their masses from Higgs mechanism or confinement in QCD
- How about DM particles ? Where do their masses come from ?
- SM Higgs ? SUSY Breaking ? Extra Dim ?
- Can we generate all the masses as in proton mass from dim transmutation in QCD ? (proton mass in massless QCD)

Underlying Principles

- Hidden Sector CDM thermalized by
- Singlet Portals (including Higgs portal)
- Renormalizability (with some caveats)
- Local Dark Gauge Symmetry (unbroken or spontaneously broken) : Dark matter feels gauge force like most of other particles & DM is stable for the same reason as electron is stable

(Alternative models by Asaka, Shaposhnikov et al.)

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
- E8 X E8' : natural setting for SM X Hidden
- SO(32) may be broken into G_{SM} X G_h

Hidden Sector

- Hidden sector gauge symmetry can stabilize hidden DM
- There could be some contributions to the dark radiation (dark photon or sterile neutrinos)
- Consistent with GUT in a broader sense
- 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

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 and dark radiation

Known facts for hCDM

- Strongly interacting hidden sector
  - CDM : composite h-mesons and h-baryons
  - All the mass scales can be generated from hidden sector
  - No long range dark force
  - CDM can be absolutely stable or long lived

T. Hur, D. -W. Jung, P. Ko and J. Y. Lee, Phys. Lett. B **696**, 262 (2011) [arXiv:0709.1218 [hep-ph]]; T. Hur and P. Ko, Phys. Rev. Lett. **106**, 141802 (2011) [arXiv:1103.2571 [hep-ph]].

P. Ko, Int. J. Mod. Phys. A **23**, 3348 (2008) [arXiv:0801.4284 [hep-ph]]; P. Ko, AIP Conf. Proc. **1178**, 37 (2009); P. Ko, PoS ICHEP **2010**, 436 (2010) [arXiv:1012.0103 [hep-ph]]; P. Ko, AIP Conf. Proc. **1467**, 219 (2012).

- Weakly interacting hidden sector
  - Long range dark force if Gh is unbroken
  - If Gh is unbroken and CDM is DM, then no extra scalar boson is necessary (*)
  - If Gh is broken, hDM can be still stable or decay, depending on Gh charge assignments
- More than one neutral scalar bosons with signal strength = 1 or smaller (indep. of decays) except for the case (*)
- Vacuum is stable up to Planck scale

S.Baek, P.Ko, W.I.Park, E.Senaha, JHEP (2012)

Higgs signal strength/Dark radiation/DM

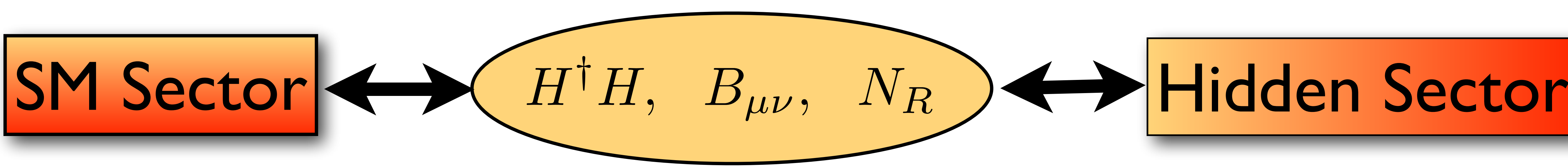
in preparation with Baek and W.I. Park

Models	Unbroken U(1)X	Local Z2	Unbroken SU(N)	Unbroken SU(N) (confining)
Scalar DM	1 0.08 complex scalar	<1 ~0 real scalar	1 ~0.08*# complex scalar	1 ~0 composite hadrons
Fermion DM	<1 0.08 Dirac fermion	<1 ~0 Majorana	<1 ~0.08*# Dirac fermion	<1 ~0 composite hadrons

: The number of massless gauge bosons

Singlet Portal

- If there is a hidden sector and DM is thermal, then we need a portal to it
- 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

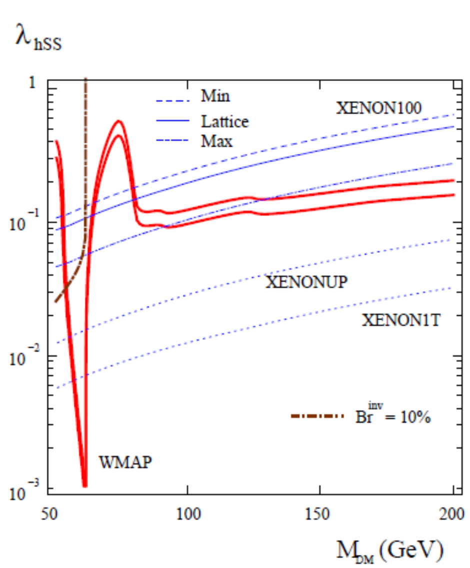


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

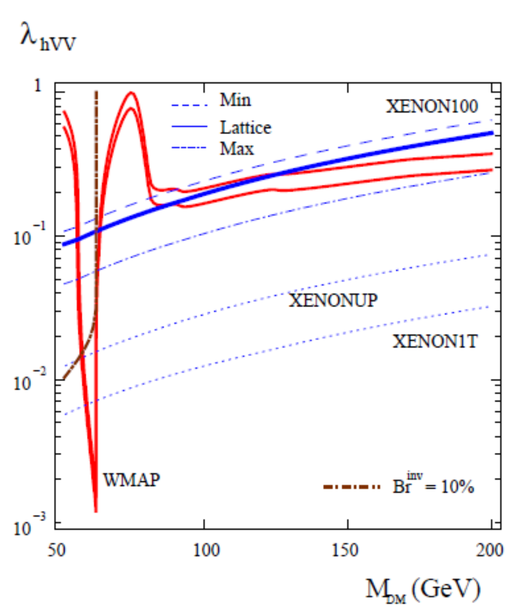


FIG. 2. Same as Fig. 1 for vector DM particles.

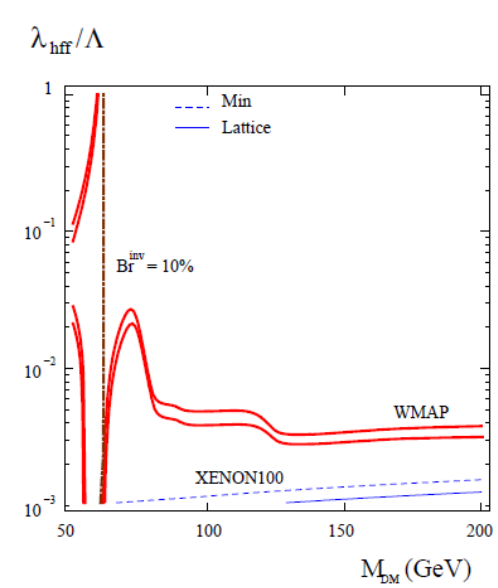


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$
$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma \cdot \partial - m_\psi \right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$
$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

- 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

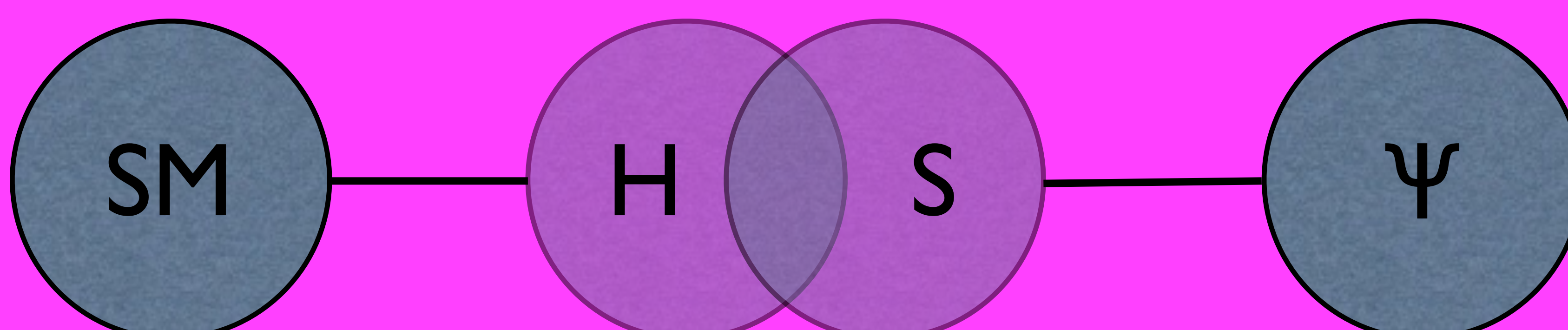
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

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

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

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

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$
\begin{aligned}
r_i &= \frac{\sigma_i \ \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \ \mathrm{Br}(h \to \mathrm{SM})} \\
r_1 &= \frac{\cos^4\alpha \ \Gamma^{\mathrm{SM}}_{H_1}}{\cos^2\alpha \ \Gamma^{\mathrm{SM}}_{H_1} + \sin^2\alpha \ \Gamma^{\mathrm{hid}}_{H_1}} \\
r_2 &= \frac{\sin^4\alpha \ \Gamma^{\mathrm{SM}}_{H_2}}{\sin^2\alpha \ \Gamma^{\mathrm{SM}}_{H_2} + \cos^2\alpha \ \Gamma^{\mathrm{hid}}_{H_2} + \Gamma_{H_2 \to H_1 H_1}}
\end{aligned}
$$

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

Invisible decay mode is not necessary!

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

Constraints

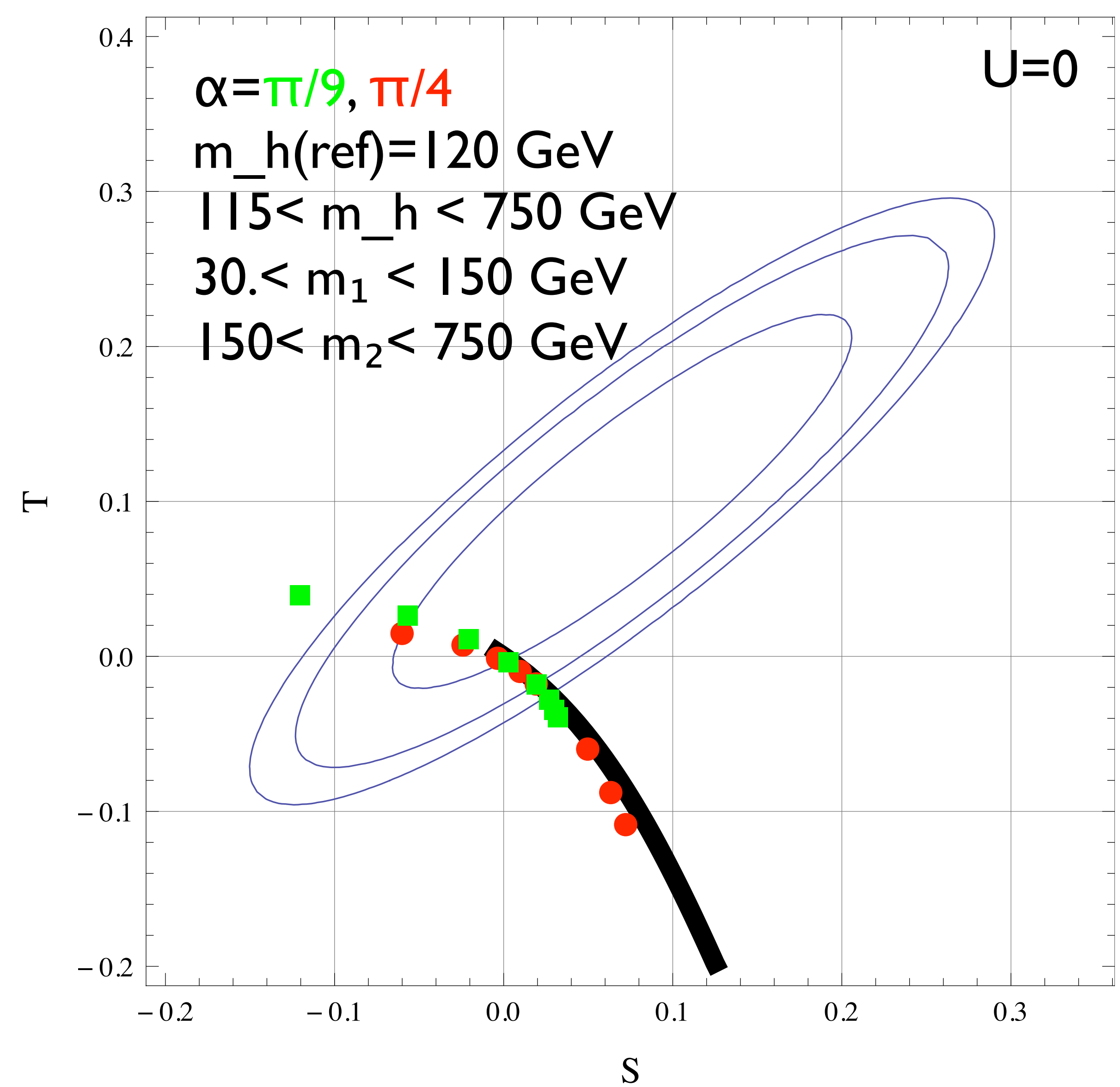
EW precision observables

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

$$
\begin{aligned}
\alpha_{\rm em} S &= 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2}\right] \\
\alpha_{\rm em} T &= \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} \\
\alpha_{\rm em} U &= 4 s_W^2 \left[\frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2}\right]
\end{aligned}
$$

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

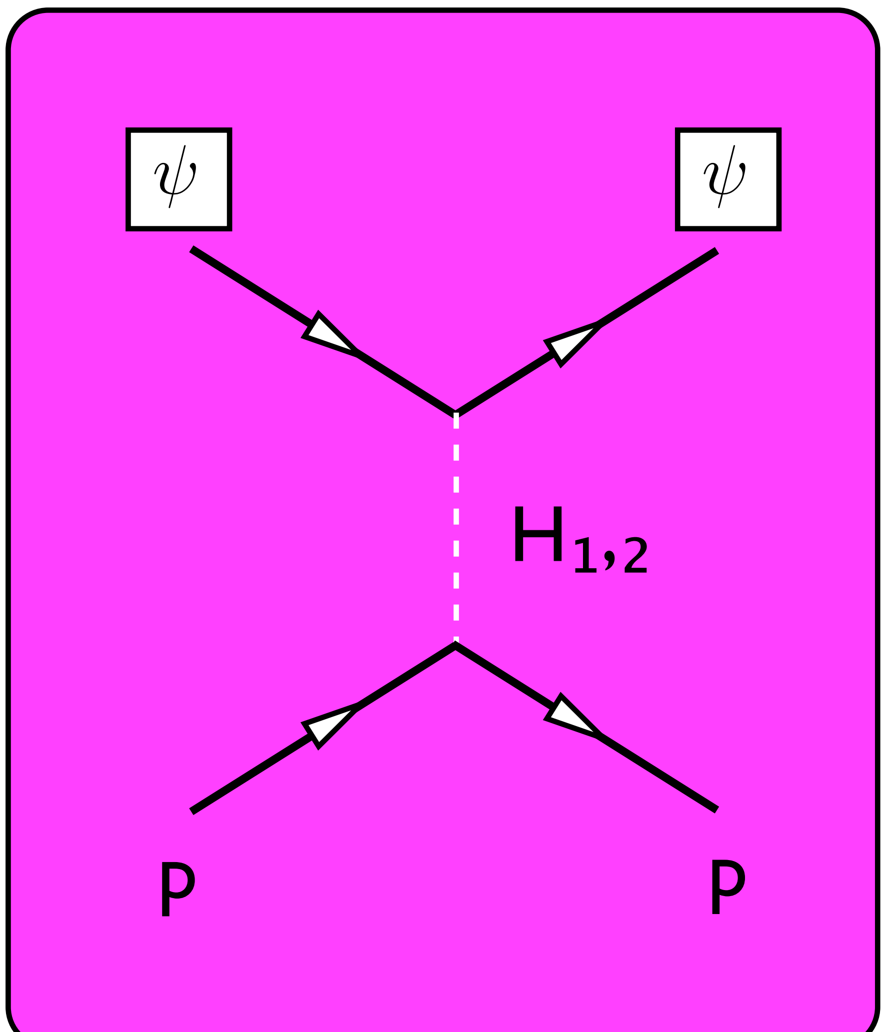
Same for T and U

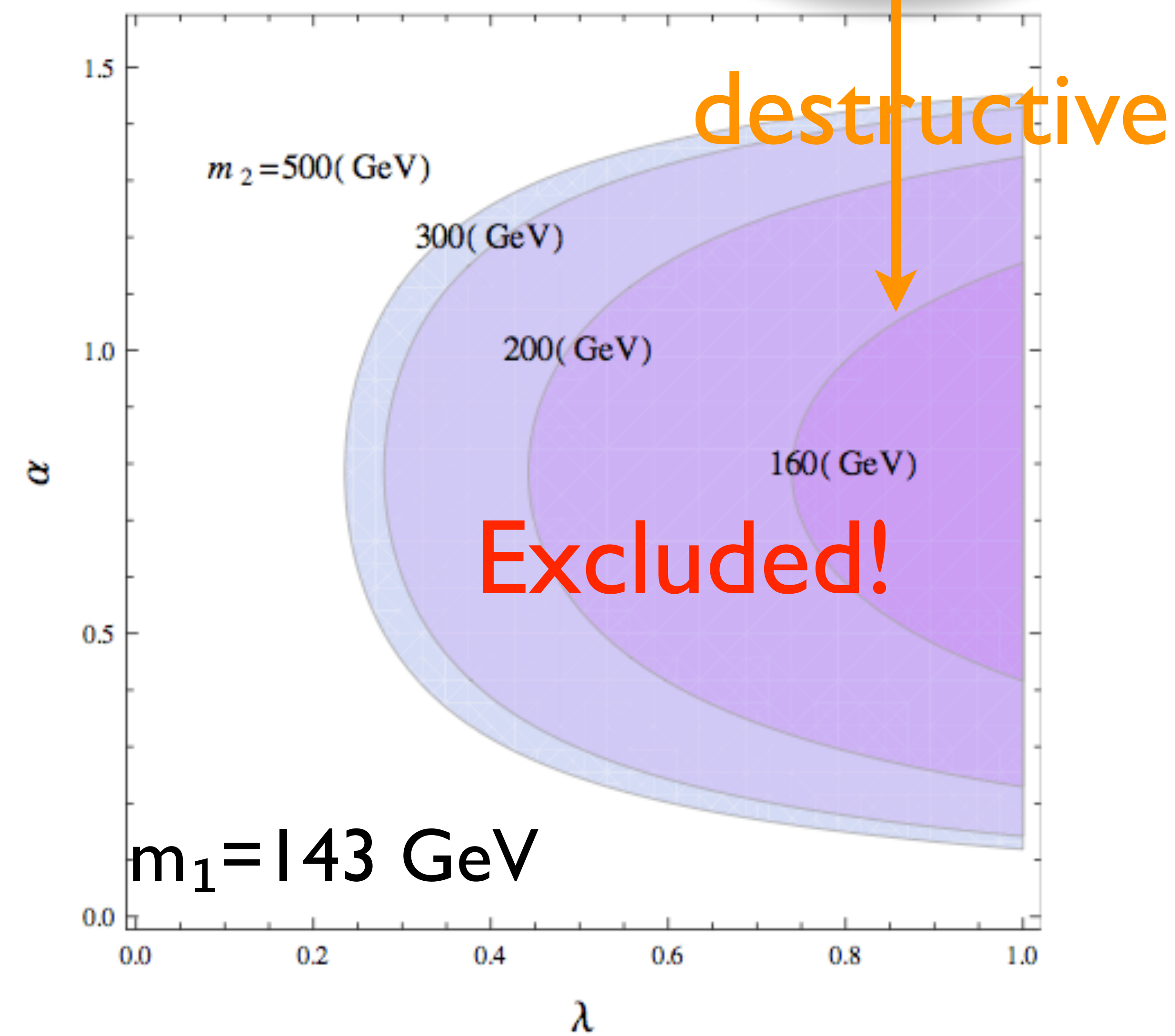


Constraints

- Dark matter to nucleon cross section (constraint)

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





Invisible Higgs decay vs DD x-section

(Baek, Ko, Park, arXiv:1405.3530)

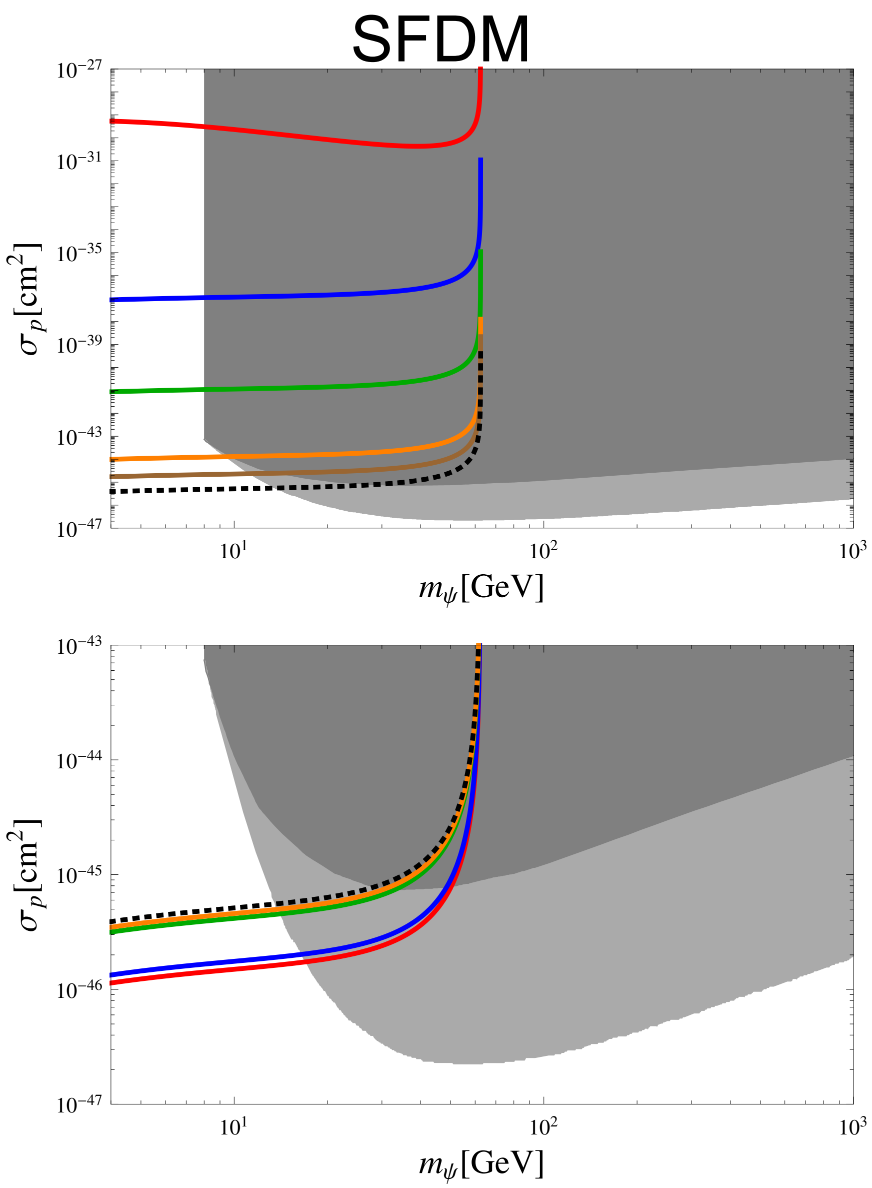


FIG. 1: σ_p^{SI} as a function of the mass of dark matter for SFDM for a mixing angle $\alpha = 0.2$ Upper panel: $m_2 = 10^{-2}, 1, 10, 50, 70\,\mathrm{GeV}$ for solid lines from top to bottom. Lower panel: $m_2 = 100, 200, 500, 1000\,\mathrm{GeV}$ for dashed lines from bottom to top. The balck dotted line is EFT prediction. Dark-gray and gray region are the exclusion regions of LUX [10] and projected XENON1T (gray) [11].

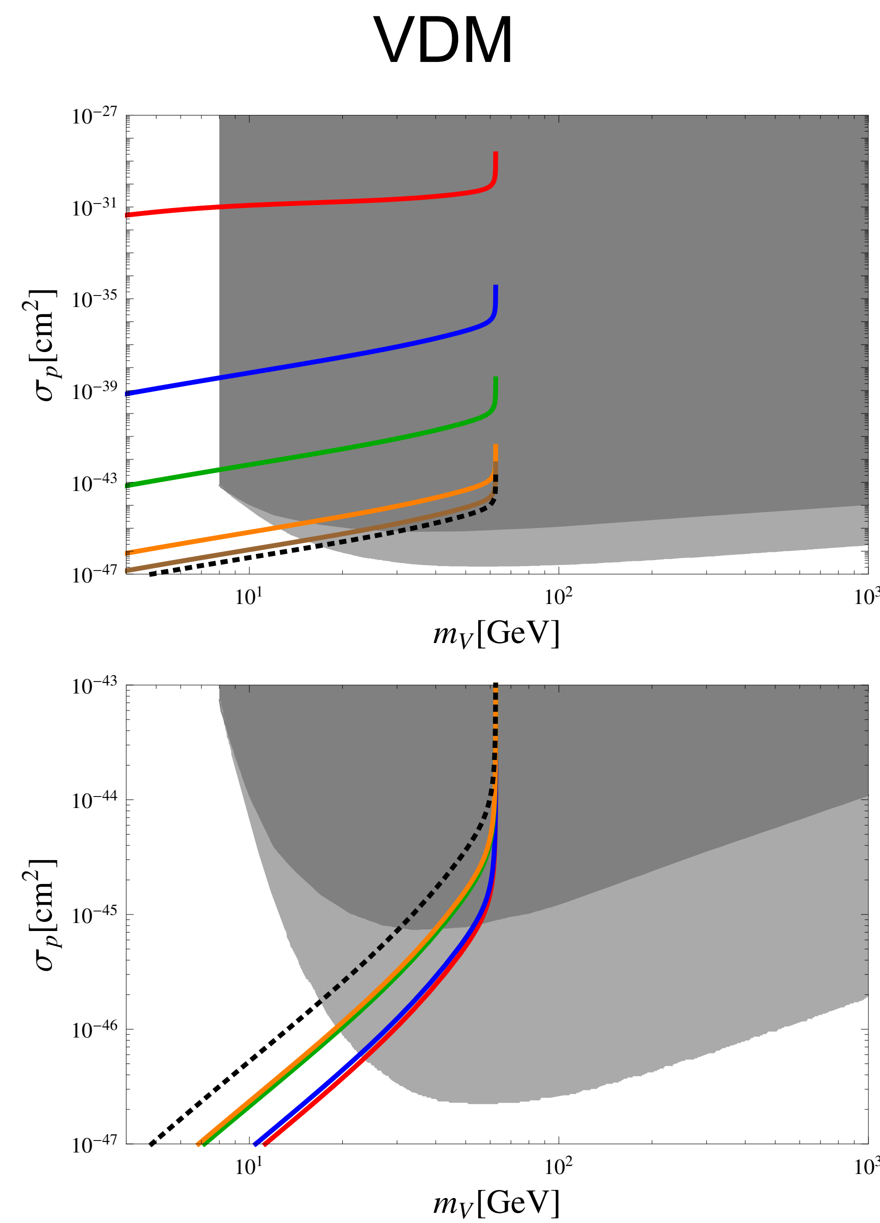


FIG. 2: σ_p^{SI} as a function of the mass of dark matter for SVDM for a mixing angle $\alpha = 0.2$ Same color and line scheme as Fig. 1.

Invisible Higgs decay vs DD x-section

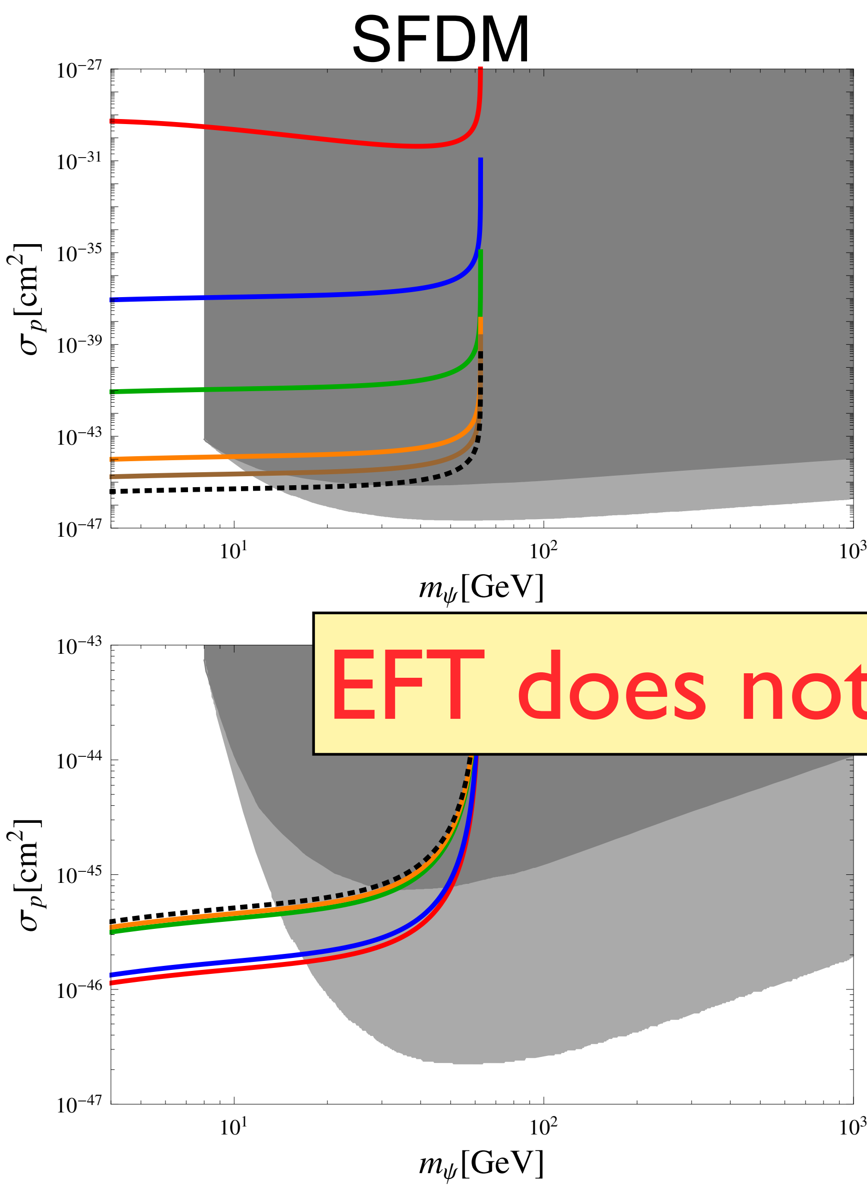


FIG. 1: σ_p^{SI} as a function of the mass of dark matter for SFDM for a mixing angle $\alpha = 0.2$ Upper panel: $m_2 = 10^{-2}, 1, 10, 50, 70\,\mathrm{GeV}$ for solid lines from top to bottom. Lower panel: $m_2 = 100, 200, 500, 1000\,\mathrm{GeV}$ for dashed lines from bottom to top. The balck dotted line is EFT prediction. Dark-gray and gray region are the exclusion regions of LUX [10] and projected XENON1T (gray) [11].

EFT does not give a good description

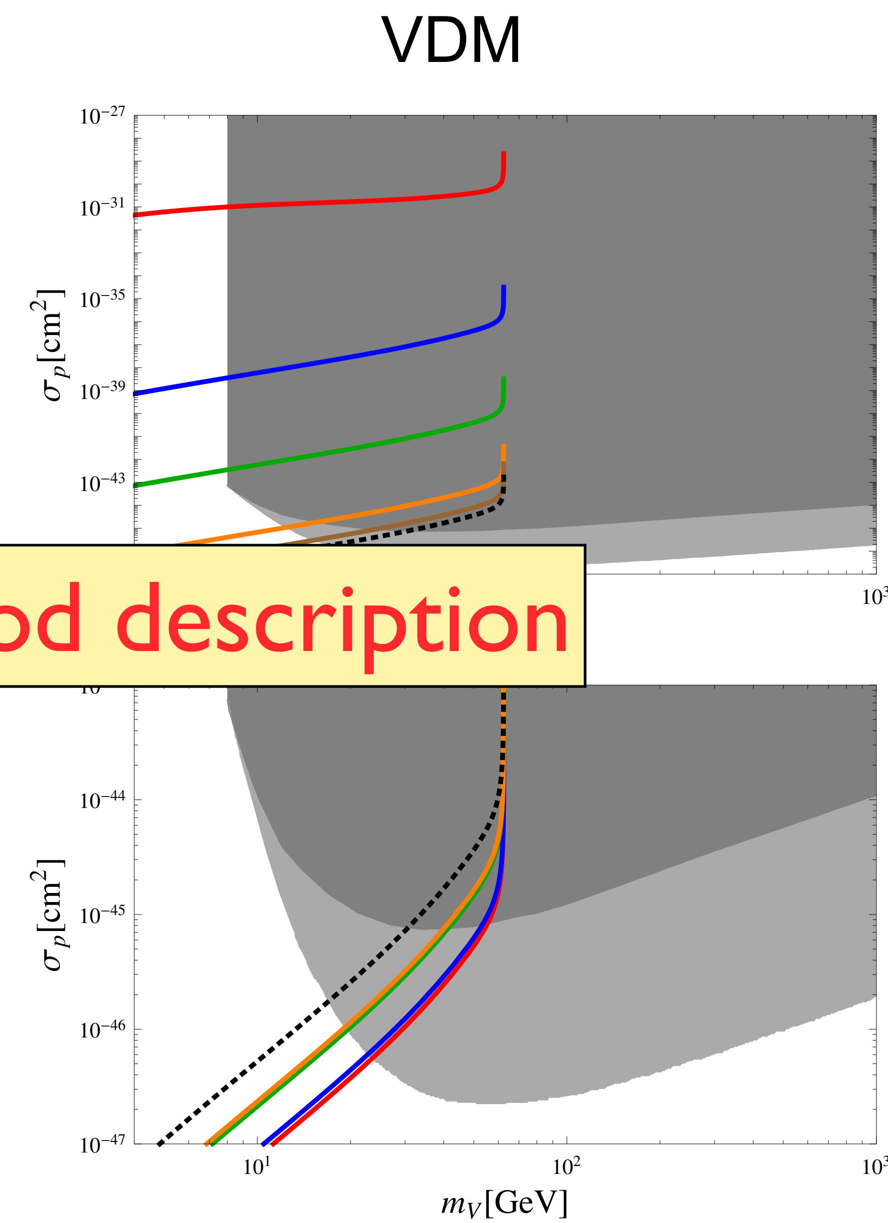


FIG. 2: σ_p^{SI} as a function of the mass of dark matter for SVDM for a mixing angle $\alpha = 0.2$ Same color and line scheme as Fig. 1.

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

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

Breaks SM gauge sym

- Only one Higgs boson (alpha = 0)

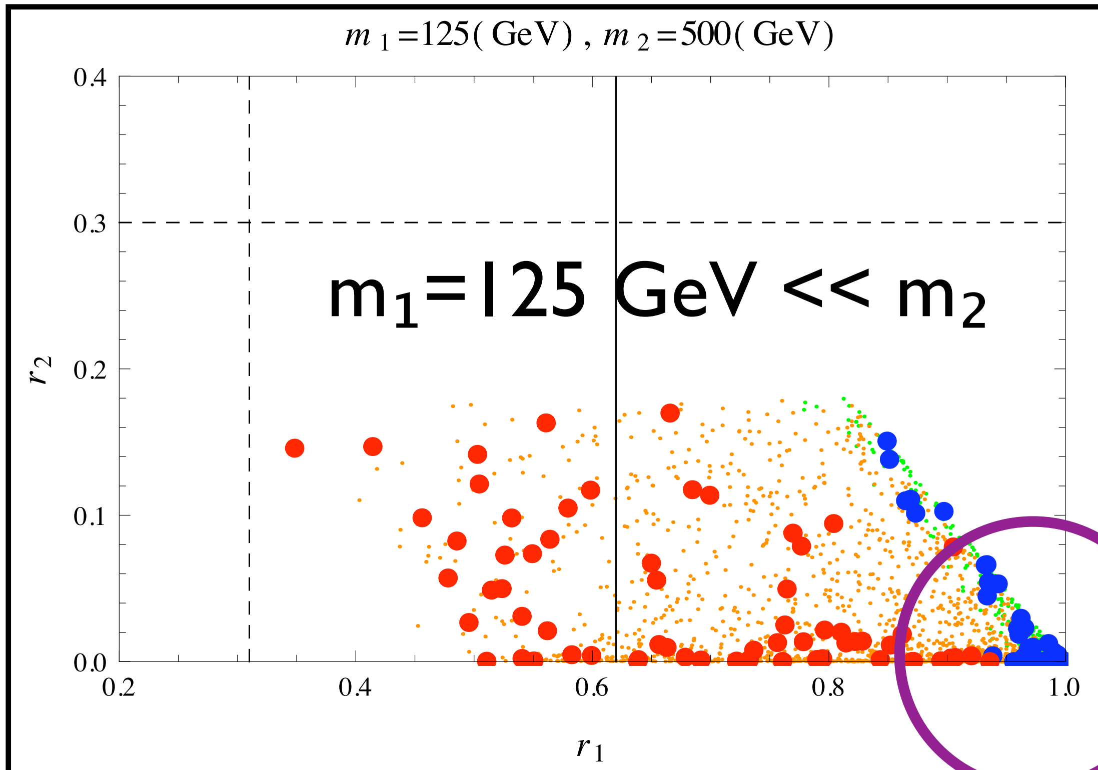
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

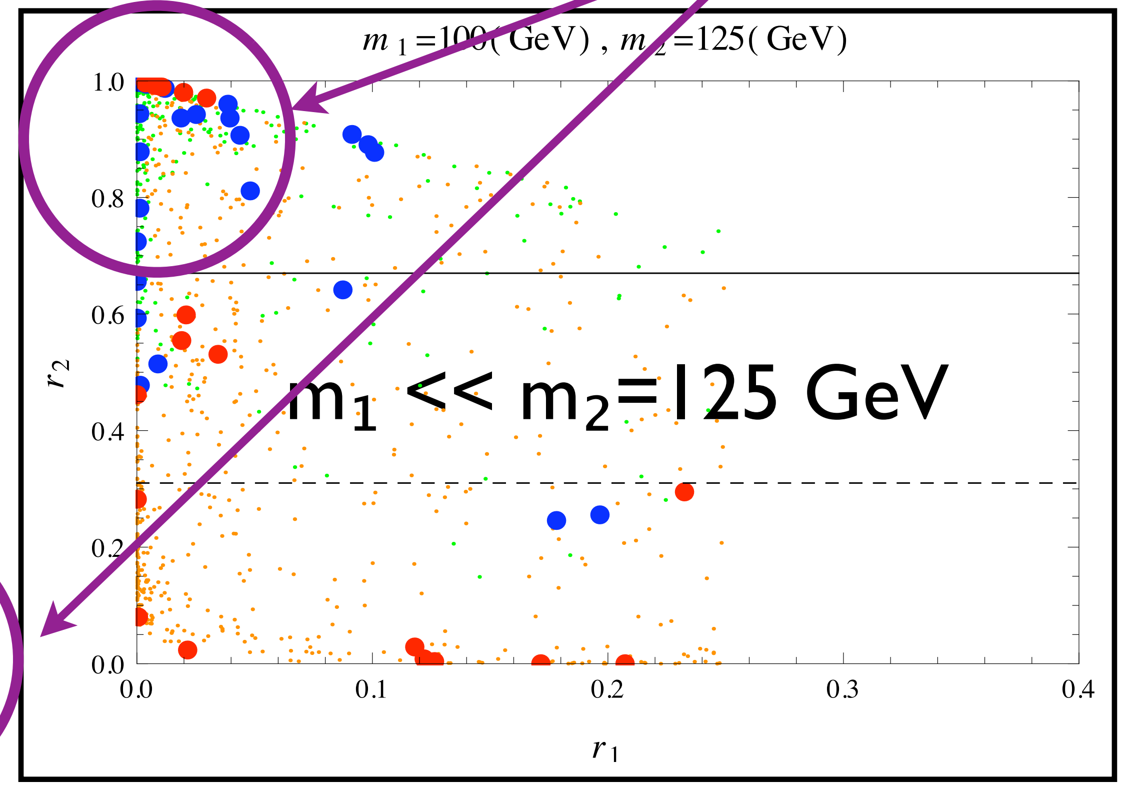
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Discovery possibility

- Signal strength (r_2 vs r_1)

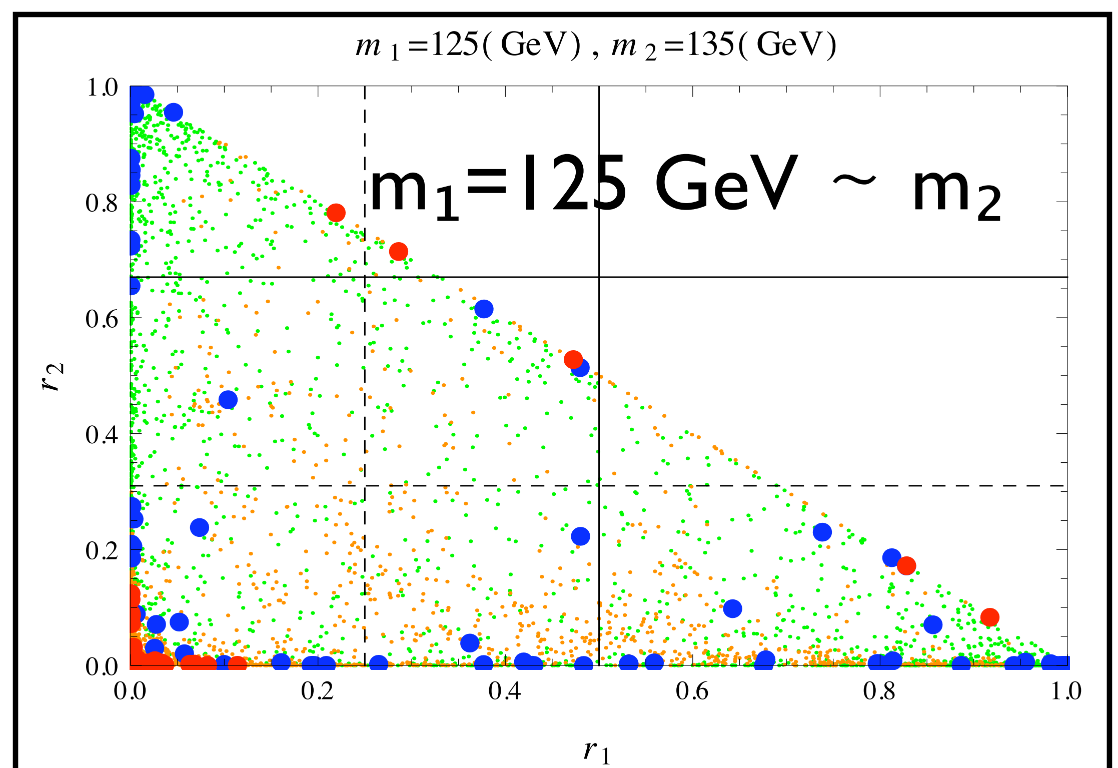
LHC data for 125 GeV resonance





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.

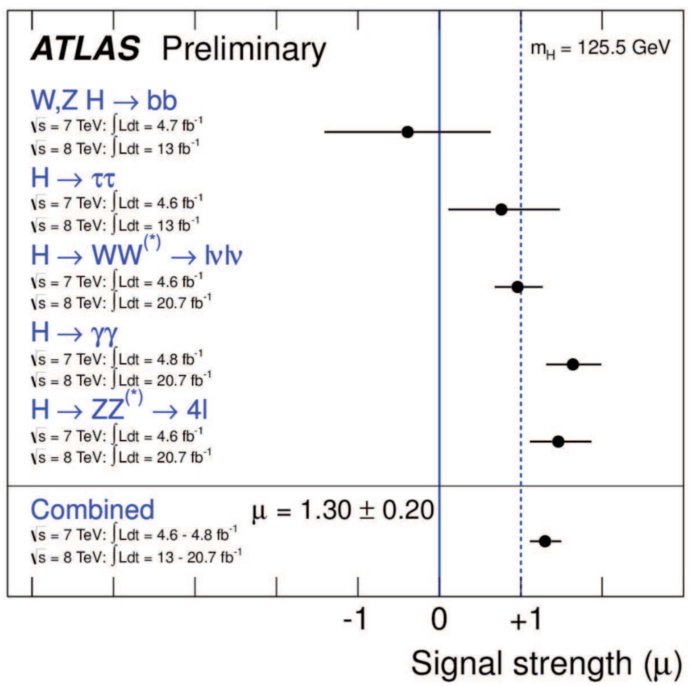


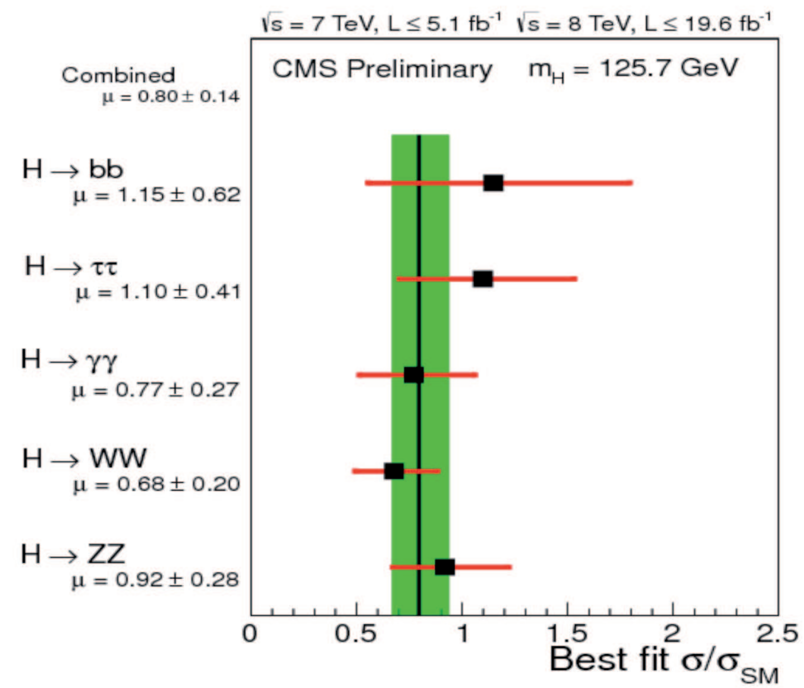
- (green): Ω(x),σ_p(x)
- (orange): Ω(x),σ_p(o)
- (blue): Ω(o),σ_p(x)
- (red): Ω(o),σ_p(o)

Updates@LHCP

Signal Strengths

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



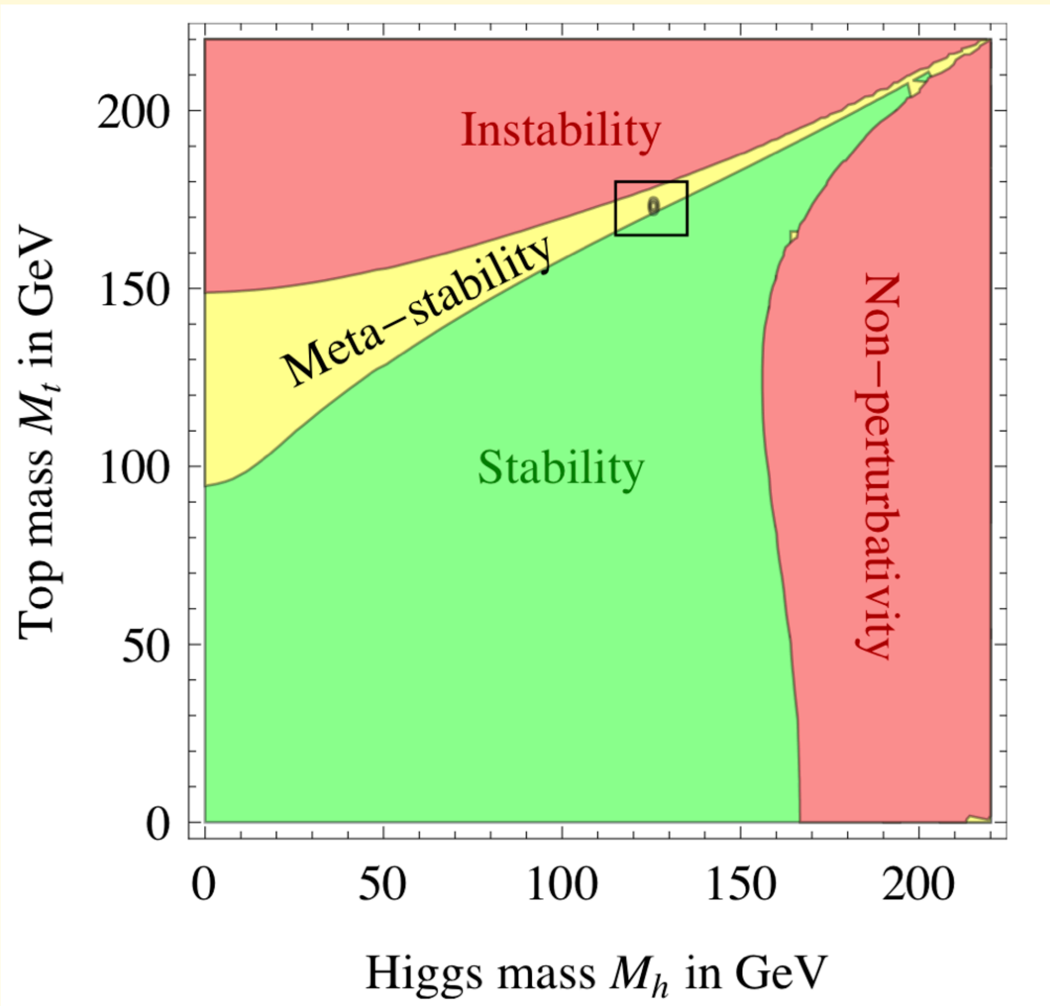


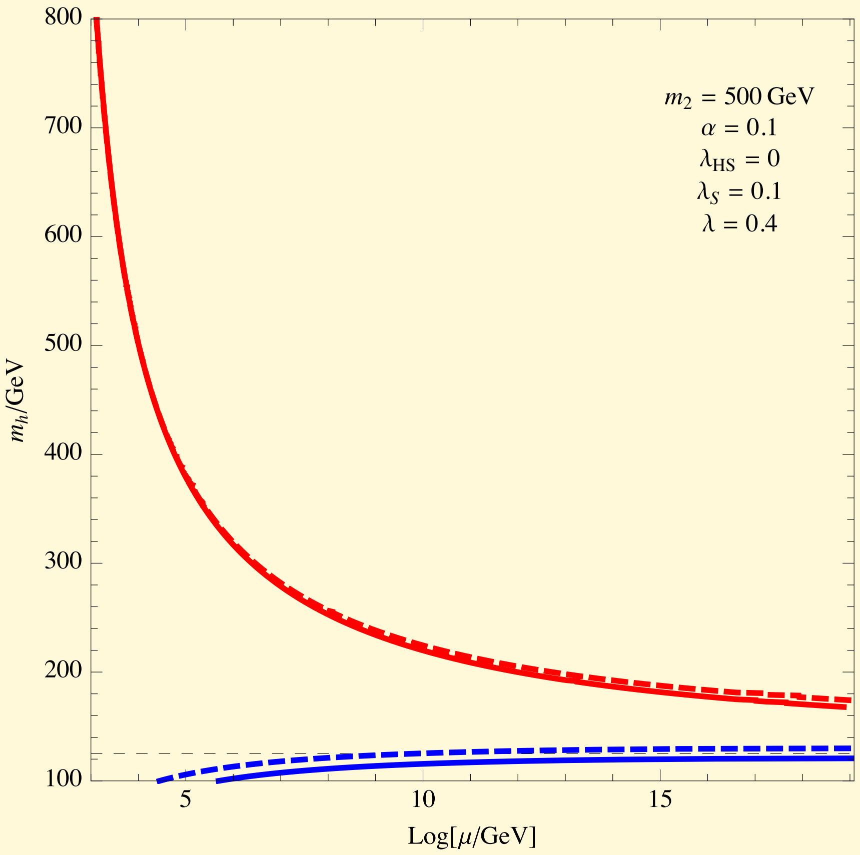
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

Getting smaller

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
- Stueckelberg mechanism ?? (work in progress)
- 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

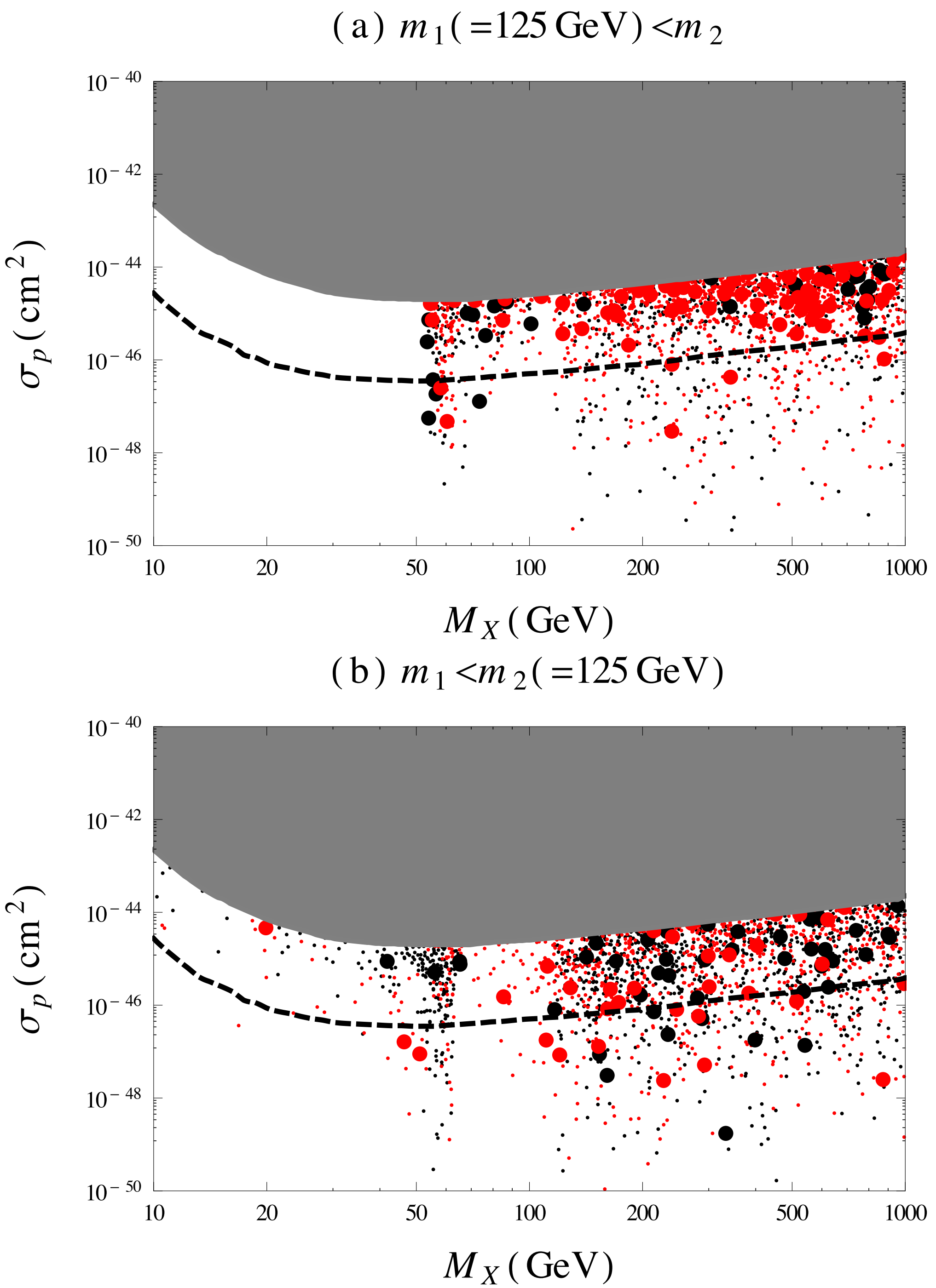


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

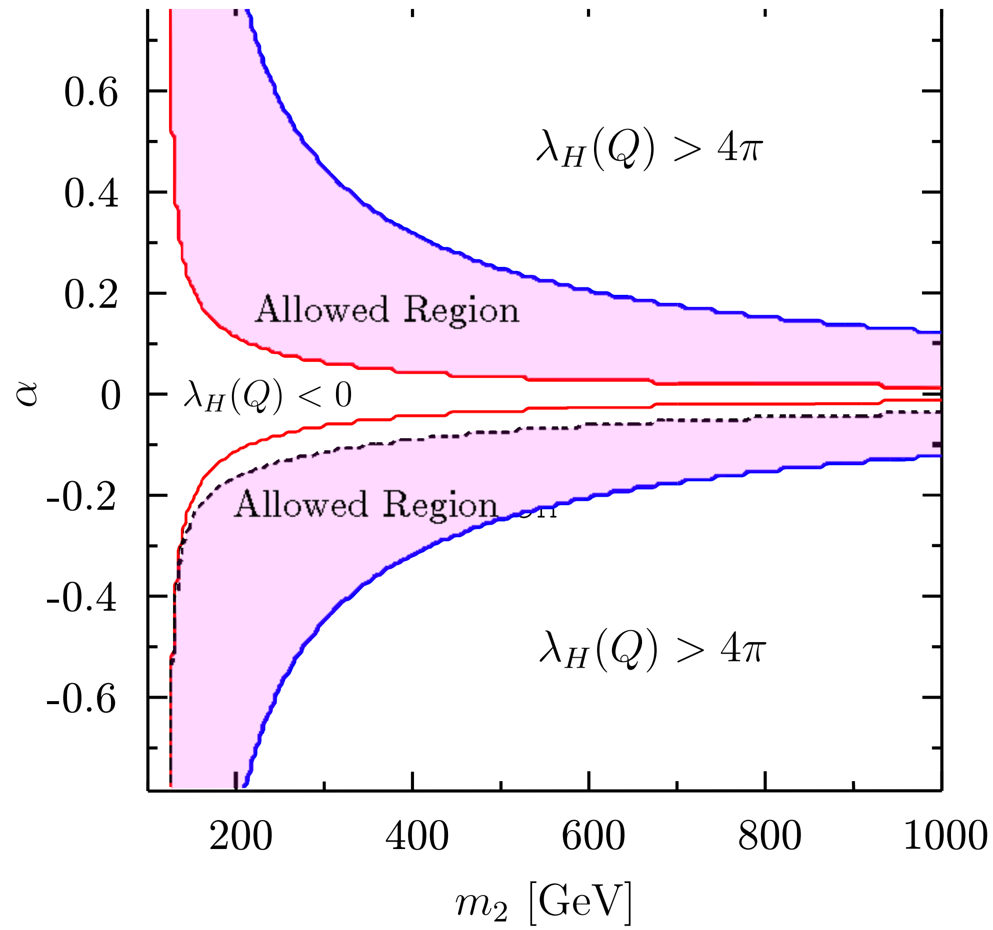


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

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

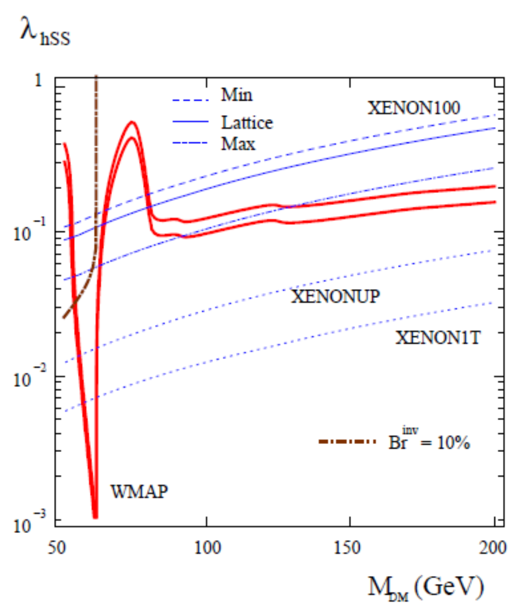


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

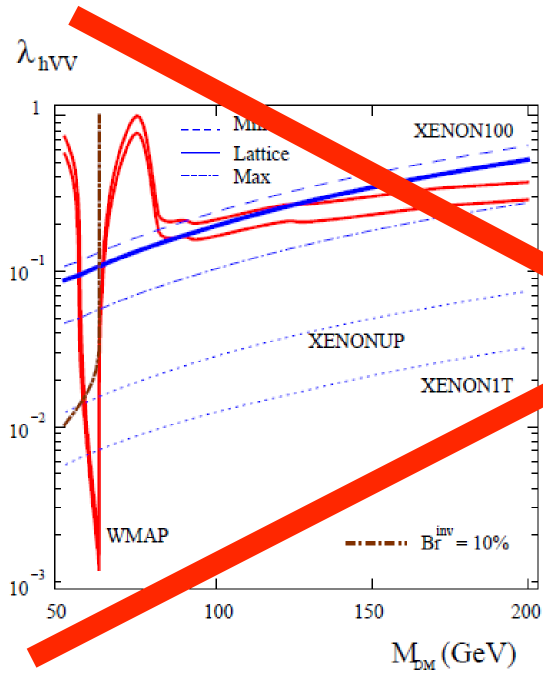


FIG. 2. Same as Fig. 1 for vector DM particles.

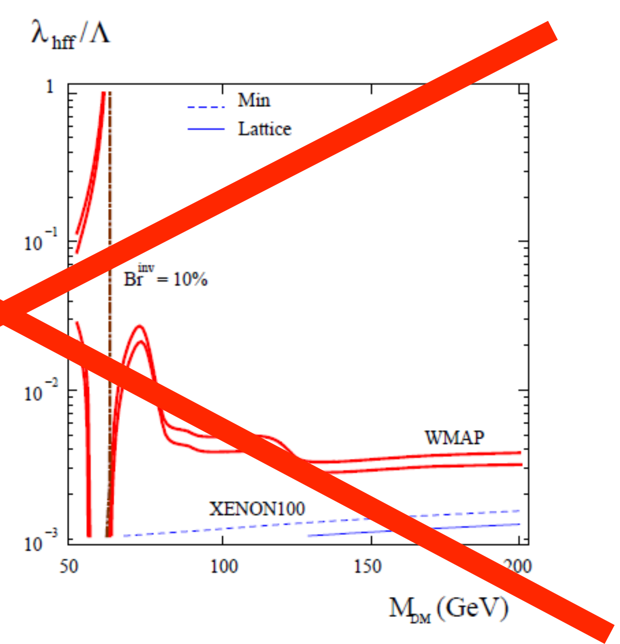
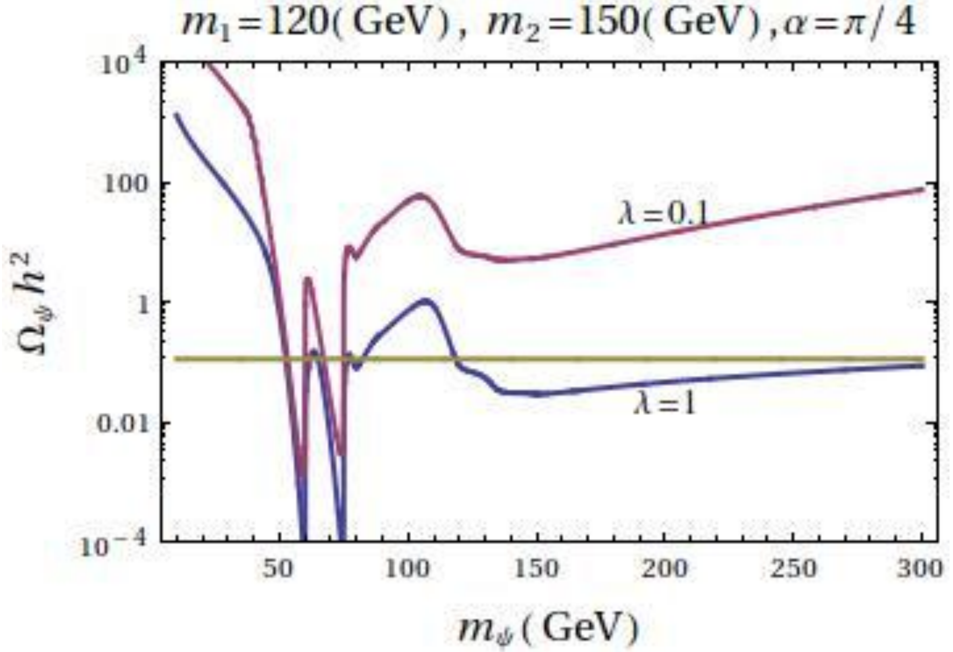


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian,
we get different results !

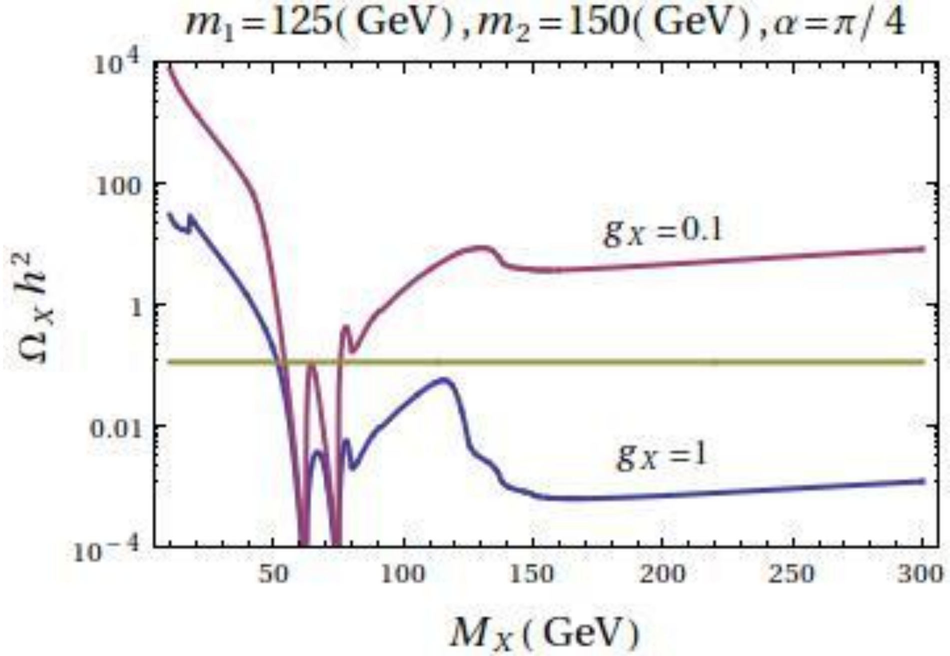
DM relic density

SFDM



P-wave annihilation

VDM



S-wave annihilation

Higgs-DM couplings less constrained due to the GIM-like cancellation mechanism

Higgs Inflation in SM

(before BICEP2)

$$\epsilon = \frac{M_P^2}{2}\left(\frac{dU/d\chi}{U}\right)^2 \simeq \frac{4M_P^4}{3\xi^2 h^4}$$

$$\eta = M_P^2 \frac{d^2U/d\chi^2}{U} \simeq -\frac{4M_P^2}{3\xi h^2},$$

$$\Rightarrow \epsilon \simeq \frac{3}{4}\eta^2$$

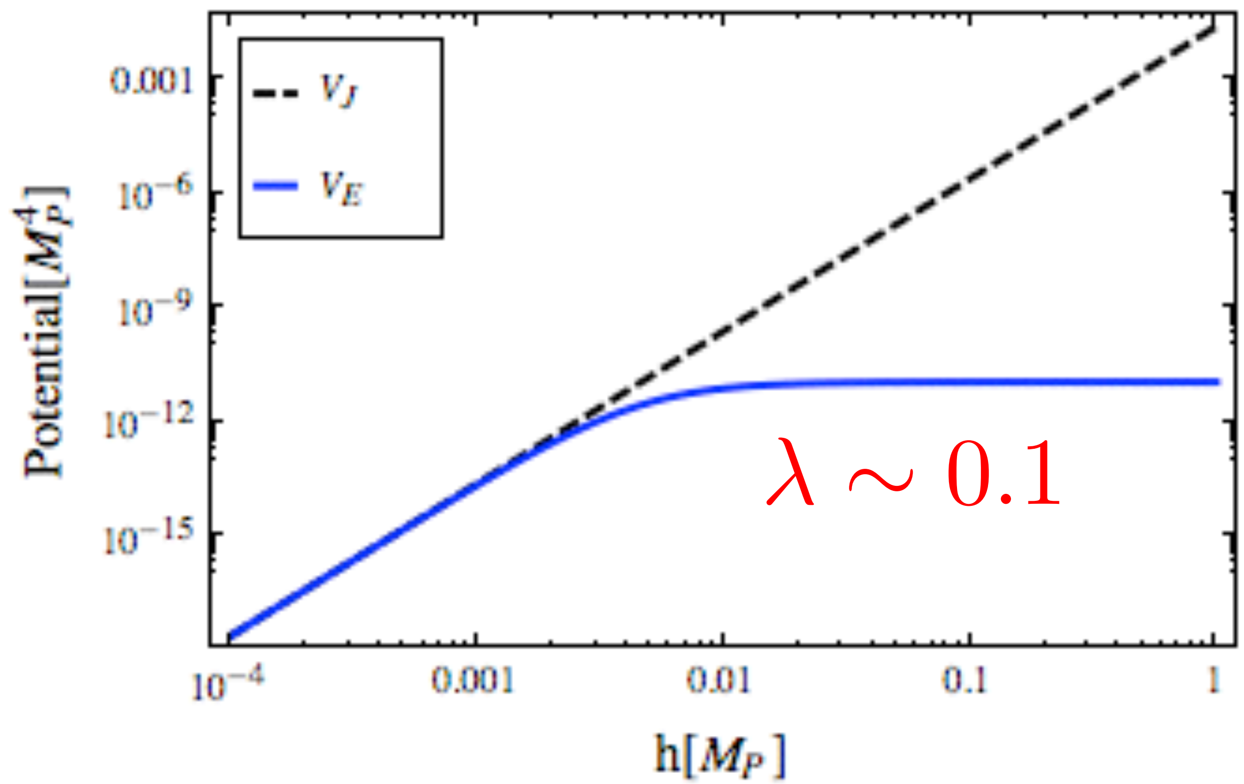
$$n_s = 1 - 6\epsilon + 2\eta \sim 0.96$$

$$\Rightarrow \eta \simeq \frac{1}{2}(n_s - 1)$$

$$\Rightarrow \epsilon \simeq \frac{3}{16}(n_s - 1)^2$$

$$\boxed{\Rightarrow r \simeq 16\epsilon \simeq 3(n_s - 1)^2 \sim 5 \times 10^{-3}}$$

$$U(\chi) = \frac{1}{\Omega(\chi)^4}\frac{\lambda}{4}\left(h(\chi)^2 - v^2\right)^2$$



$\lambda \sim 0.1$

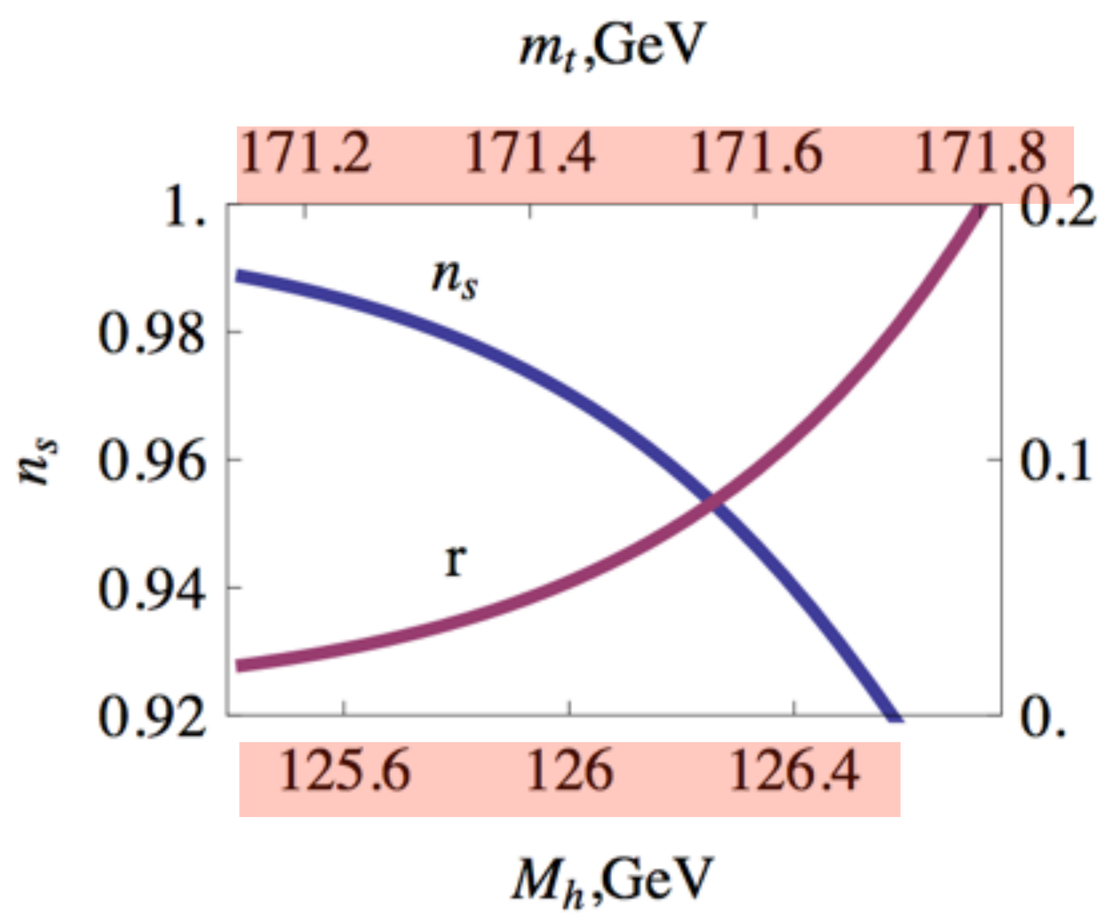
Higgs Inflation in SM

(after BICEP2)

$r_{\text{BICEP2}} \sim 0.1$ ⇨ Is Higgs inflation ruled out? No!

$$U(h) = \frac{\lambda}{4\Omega^4}\left(h^2 - v_H^2\right) \to \frac{\lambda(\mu)}{4\Omega^4}\left(h^2 - v_H^2\right)$$

[Hamda, Kawai, Oda and Park, 1403.5043; Bezrukov and Shposhnikov, 1403.6078]



However m_t and M_h are tightly constrained!

Higgs portal interaction

$$V \supset \lambda_{\Phi H} |\Phi|^2 H^\dagger H \Rightarrow \boxed{\lambda_H = \left[1 - \left(1 - \frac{m_\phi^2}{m_h^2}\right) \sin^2\alpha\right] \lambda_H^{\rm SM}}$$

Scalar mixing

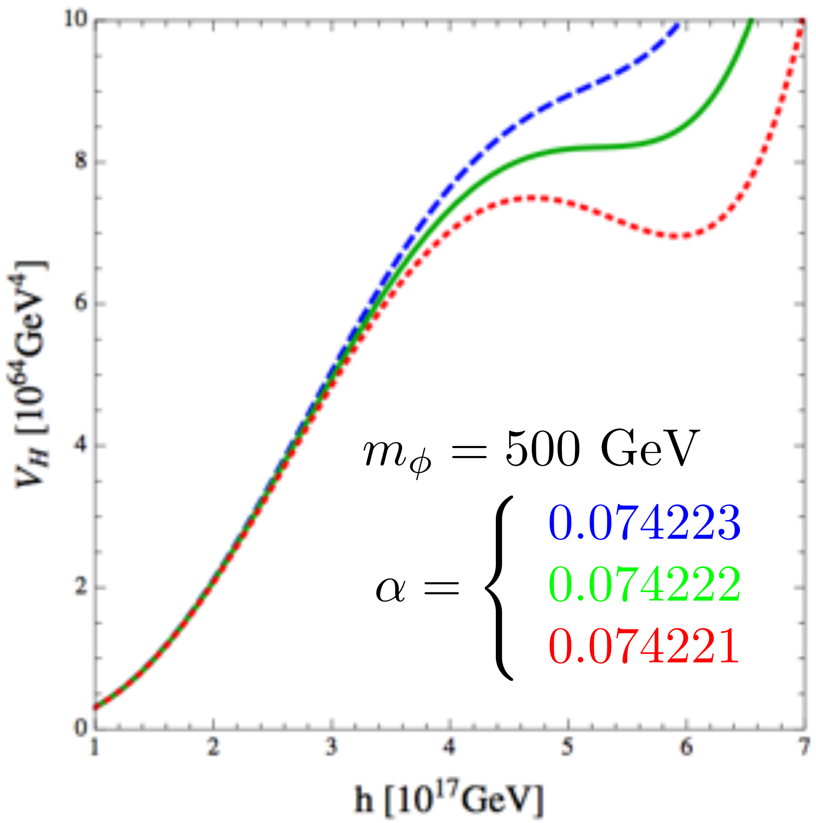
⇨ $\lambda_H > \lambda_H^{\rm SM}$ for $m_\phi > m_h$ & $\alpha \neq 0$

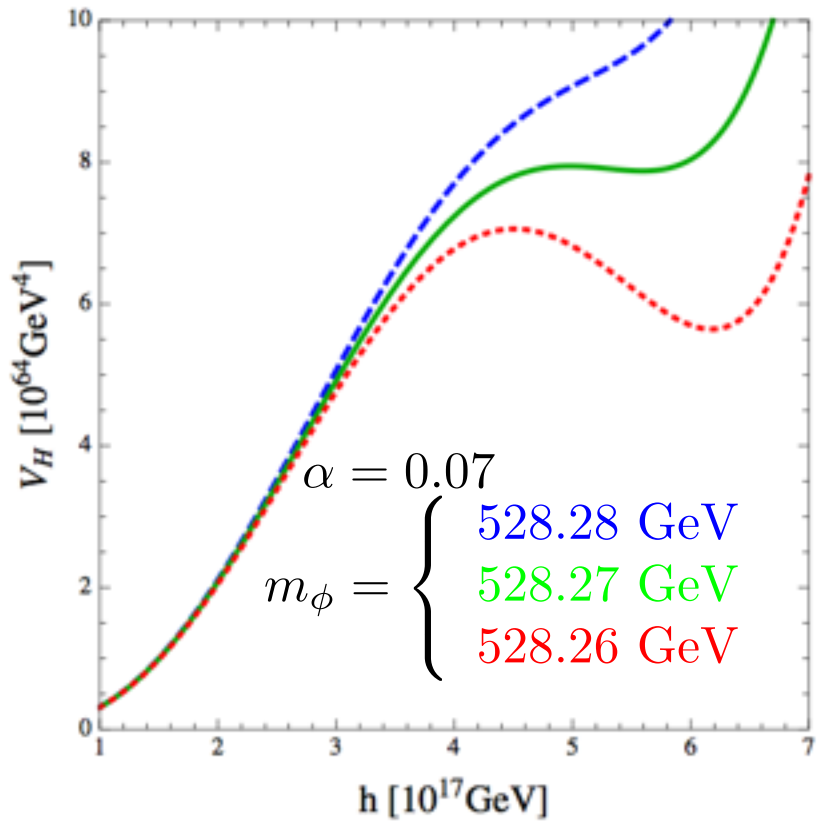
⇨ Vacuum instability is easily improved

⇨ Higgs inflation consistent with BICEP2 is possible for a wider range of m_t and M_h

Higgs portal interaction disconnects m_t and M_h from inflationary observables.

Higgs portal Higgs inflation





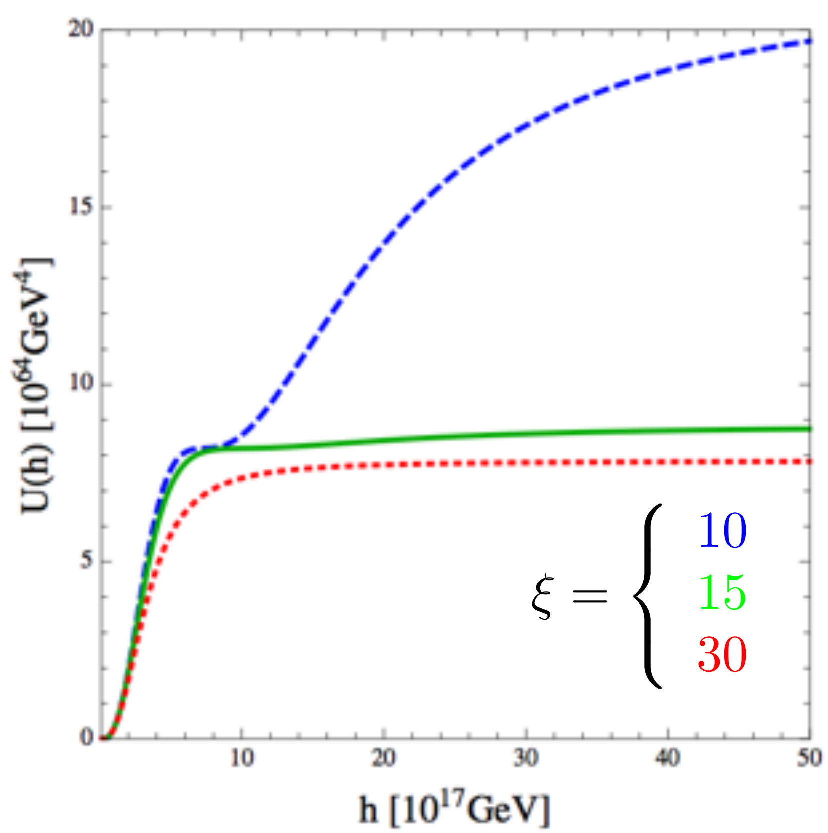
$m_t = 173.2$ GeV

$M_h = 125.5$ GeV

Ko, Park arXiv: 1405.1635

* Inflection point control

$(\alpha, m_\phi)\ \ \&\ \lambda_{\Phi H}$



Result of numerical analysis

$k_* \times$ Mpc	N_e	$h_*/M_{\rm Pl}$	ϵ_*	η_*	$10^9 P_S$	n_s	r
0.002	59	0.83	0.00448	−0.02465	2.2639	0.9238	0.0717
0.05	56	0.72	0.00525	−0.0019	2.1777	0.9647	0.084

- Result depends very sensitively on α, m_ϕ and $\lambda_{\Phi H}$ -

H.P.H.I allows Higgs inflation matching to BICEP2 result without resorting to m_t and M_h.

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

DM is stable because...

- Symmetries
  - (ad hoc) Z_2 symmetry
  - R-parity
  - Topology (from a broken sym.)

- Very small mass and weak coupling

  e.g: QCD-axion ($m_a \sim \Lambda_{QCD}^2/f_a$; $f_a \sim 10^{9\text{-}12}$ GeV)

$$\Rightarrow \quad \Gamma_a \sim \mathcal{O}(10^{-5}) \frac{m_a^3}{f_a^2} \ll H_0 \sim 10^{-42}\mathrm{GeV}$$

But for WIMP ...

- Global sym. is not enough since

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

Observation requires [M. Ackermann et al. (LAT Collaboration), PRD 86, 022002 (2012)]

$$\tau_{\text{DM}} \gtrsim 10^{26-30} \text{sec} \Rightarrow \begin{cases} m_{\phi} \lesssim \mathcal{O}(10)\text{keV} \\ m_{\psi} \lesssim \mathcal{O}(1)\text{GeV} \end{cases}$$

$\Rightarrow$ WIMP is unlikely to be stable

- SM is guided by gauge principle

It looks natural and may need to consider a gauge symmetry in dark sector, too.

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) if dark sym is spontaneously broken

Higgs can be harmful to weak scale 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

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

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 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)
- See a paper by Ko and Tang on local Z3 scalar DM, and another by Ko, Omura and Yu on inert 2HDM with local U(1)_H

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

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

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)

Scalar DM with local Z_3 sym

P, Ko, YT, arXiv:1402.6449

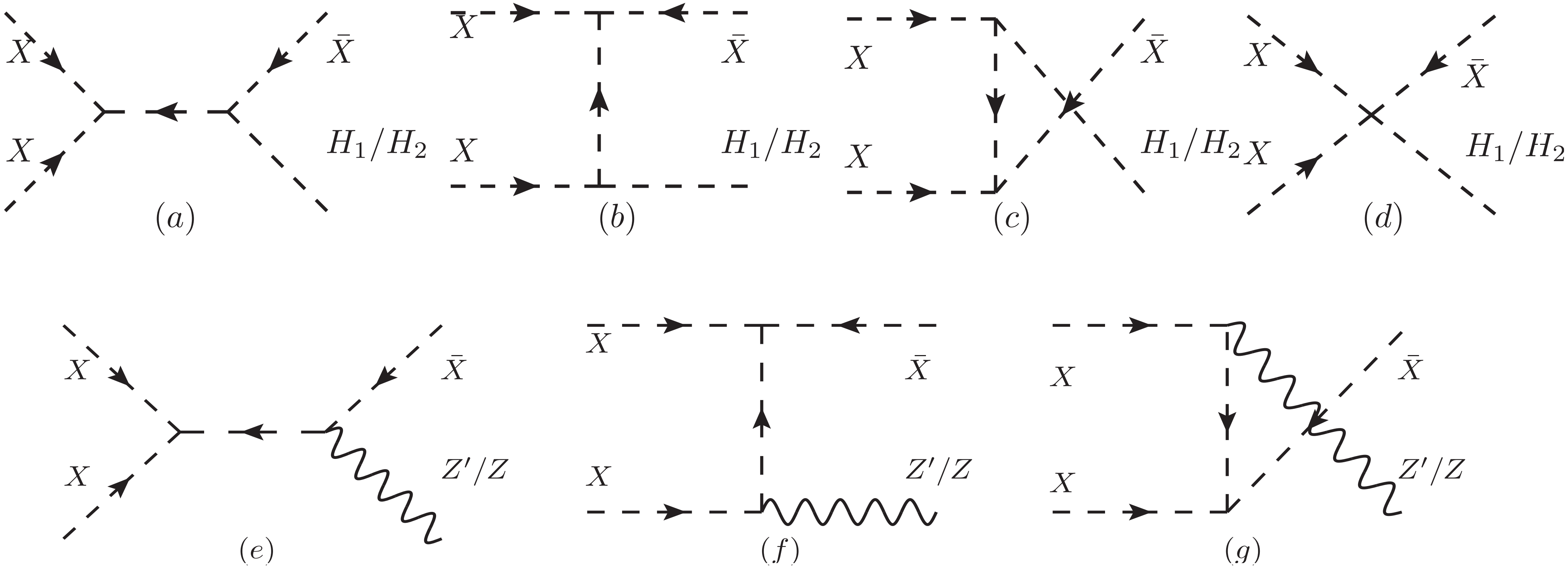
Again an extra $U(1)_X$ gauge symmetry is introduced, with scalar DM X and dark higgs with charges 1 and 3, respectively.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \tilde{X}_{\mu\nu}\tilde{B}^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X + D_\mu X^\dagger D^\mu X - V$$

$$V = -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 - \mu_\phi^2 \phi_X^\dagger \phi_X + \lambda_\phi \left(\phi_X^\dagger \phi_X\right)^2 + \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2$$
$$+ \lambda_{\phi H}\phi_X^\dagger\phi_X H^\dagger H + \lambda_{\phi X} X^\dagger X \phi_X^\dagger \phi_X + \lambda_{HX} X^\dagger X H^\dagger H + \left(\lambda_3 X^3 \phi_X^\dagger + H.c.\right)$$

cf) Z_2 model in preparation
with S. Baek and W.I. Park

Semi-annihilation



$$\frac{dn_X}{dt} = -v\sigma^{XX^*\to YY}\left(n_X^2 - n_{X\,\mathrm{eq}}^2\right) - \frac{1}{2}v\sigma^{XX\to X^*Y}\left(n_X^2 - n_X n_{X\,\mathrm{eq}}\right) - 3Hn_X,$$

$$r \equiv \frac{1}{2}\frac{v\sigma^{XX\to X^*Y}}{v\sigma^{XX^*\to YY} + \frac{1}{2}v\sigma^{XX\to X^*Y}}.$$

micrOMEGAs

Comparison with global Z3

$$V_{\rm eff} \simeq - \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2 + \lambda_{HX} X^\dagger X H^\dagger H + \mu_3 X^3 \\ + \text{higher order terms} + H.c,$$

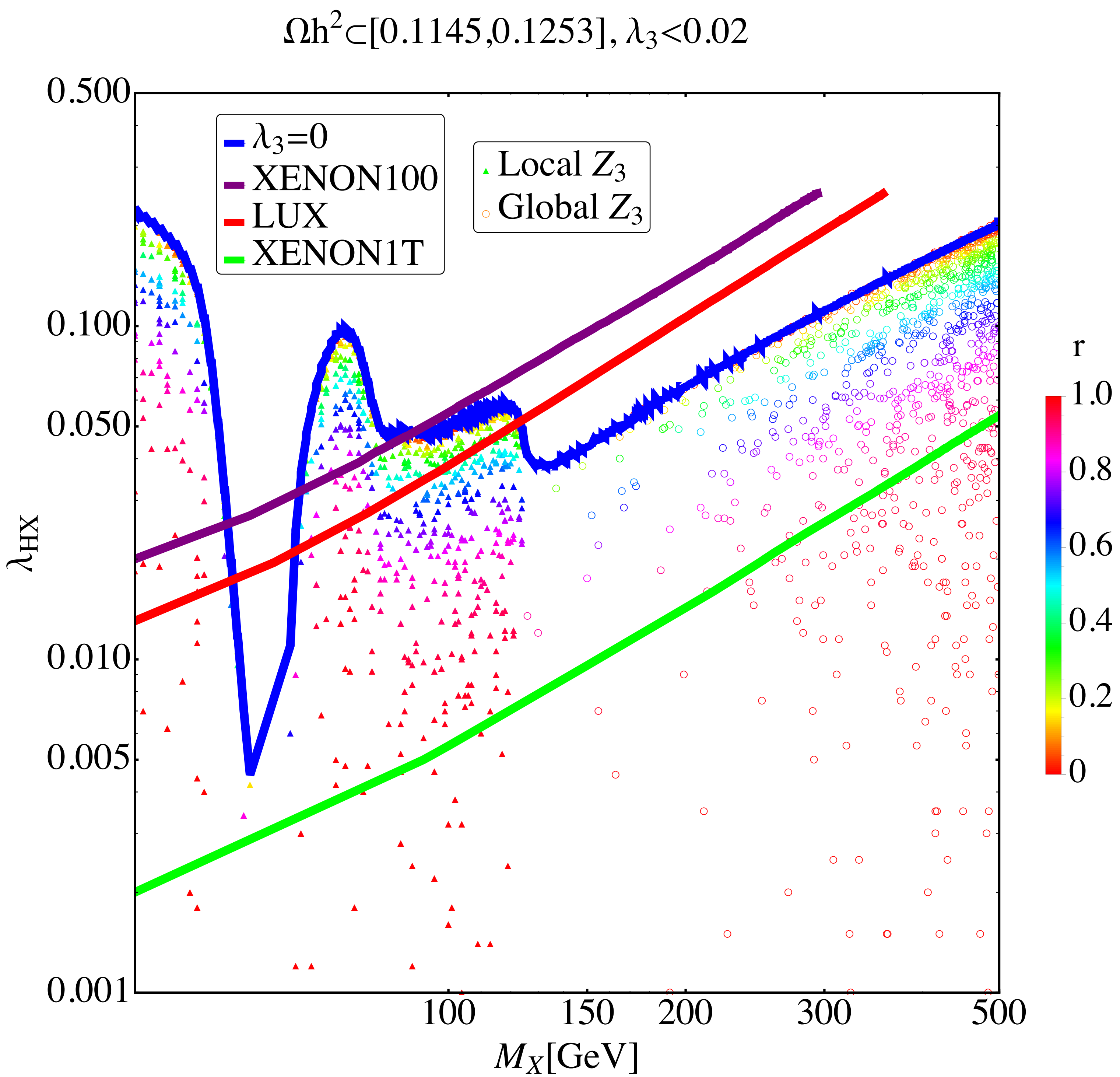
- However global symmetry can be broken by gravity induced nonrenormalizable op's:

$$\frac{1}{\Lambda} X F_{\mu\nu} F^{\mu\nu}$$

Global Z_3 "X" will decay immediately and can not be a DM

- Also particle contents different : Z' and H_2
- DM & H phenomenology change a lot

Relic density and Direct Search



- Blue band marks the upper bound,
- All points are allowed in our local Z3 model, 1402.6449
- only circles are allowed in global Z3 model,1211.1014

Comparison with EFT

$$U(1)_X \text{ sym}: \quad X^\dagger X H^\dagger H,\ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(H^\dagger D^\mu H\right),\ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(\overline{f}\gamma^\mu f\right),\ etc. \tag{4.3}$$

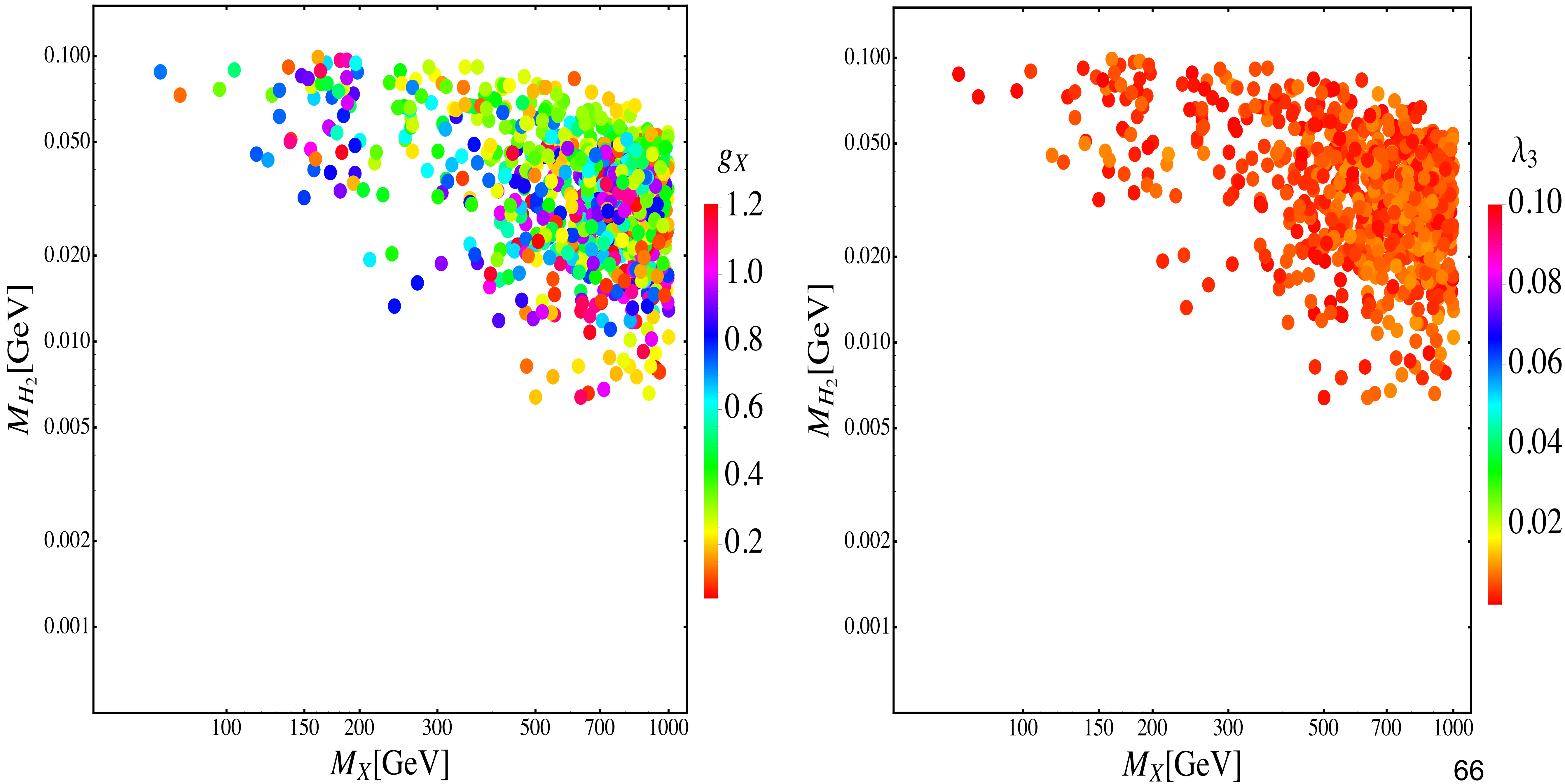
$$Z_3 \text{ sym}: \quad \frac{1}{\Lambda}X^3 H^\dagger H,\quad \frac{1}{\Lambda^2}X^3\overline{f}f,\ etc. \tag{4.4}$$

$$\left(\text{or } \frac{1}{\Lambda^3}X^3\overline{f_L}Hf_R, \text{if we imposed the full SM gauge symmetry}\right) \tag{4.5}$$

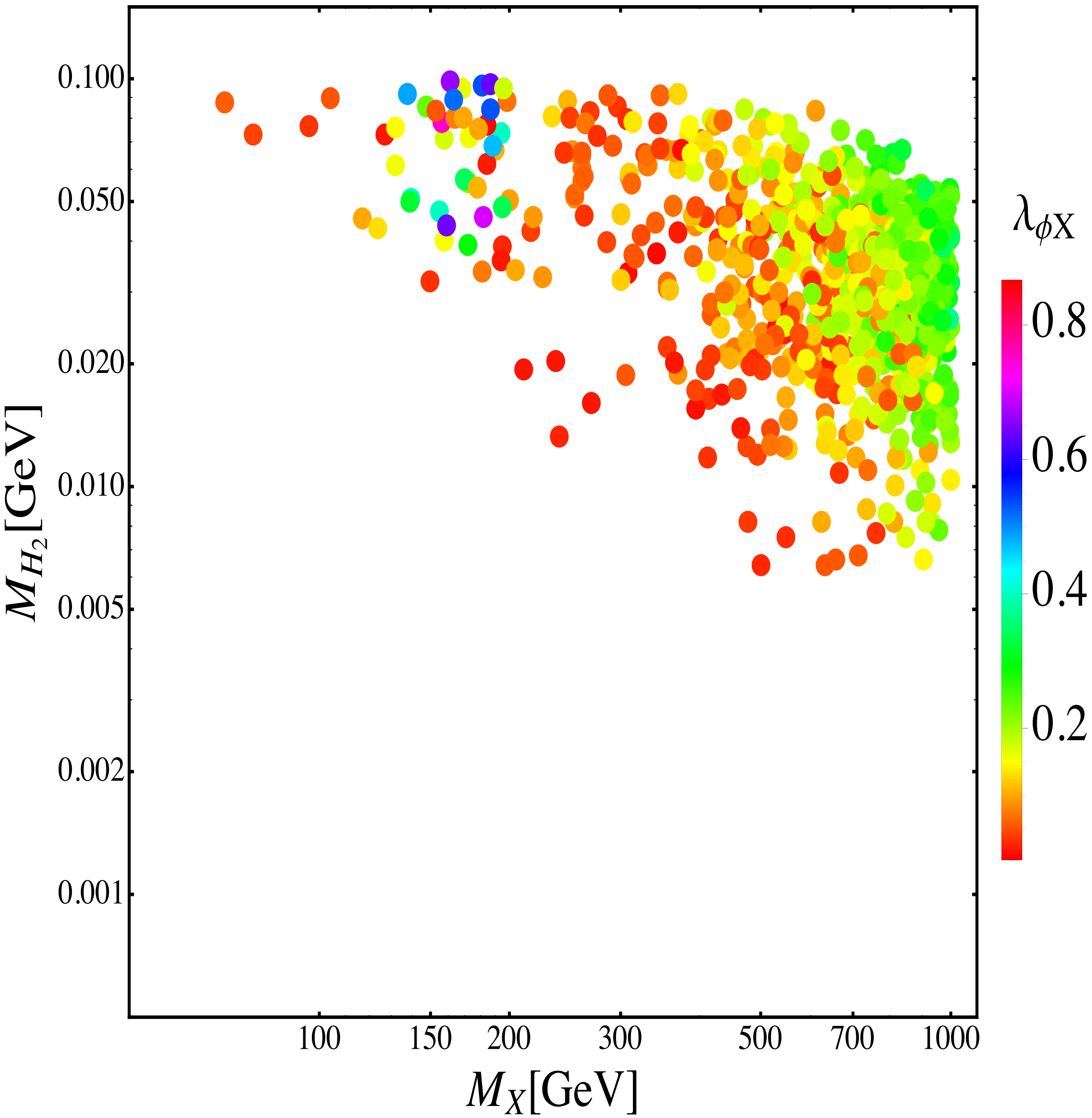
- There is no Z', H2 in the EFT, and so indirect detection or thermal relic density calculations can be completely different
- Complementarity breaks down : (4.3) cannot capture semi-annihilation

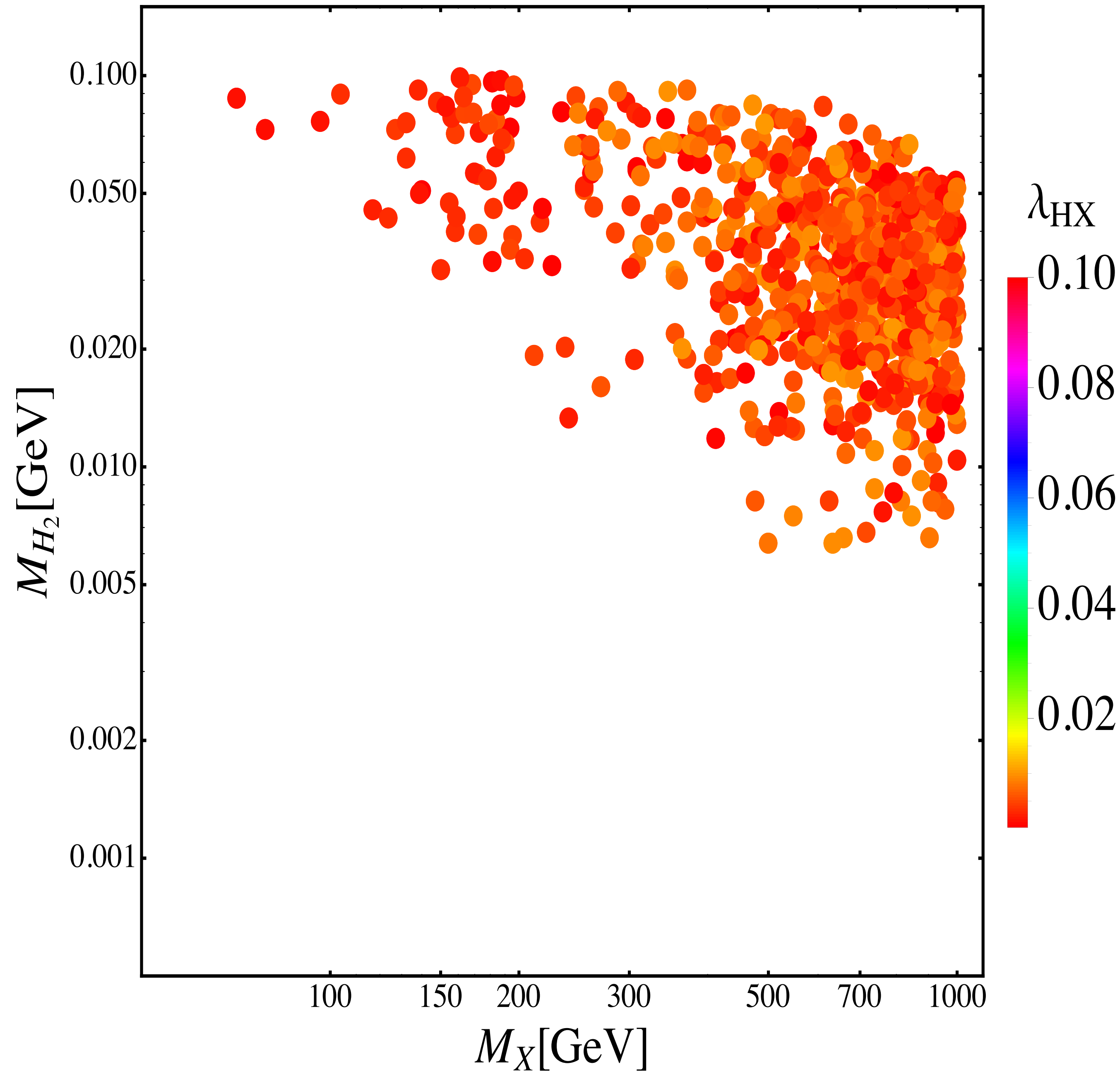
illustrations

We expect light bosons (H2 and/or Zx)
Can we find them experimentally ?



illustrations

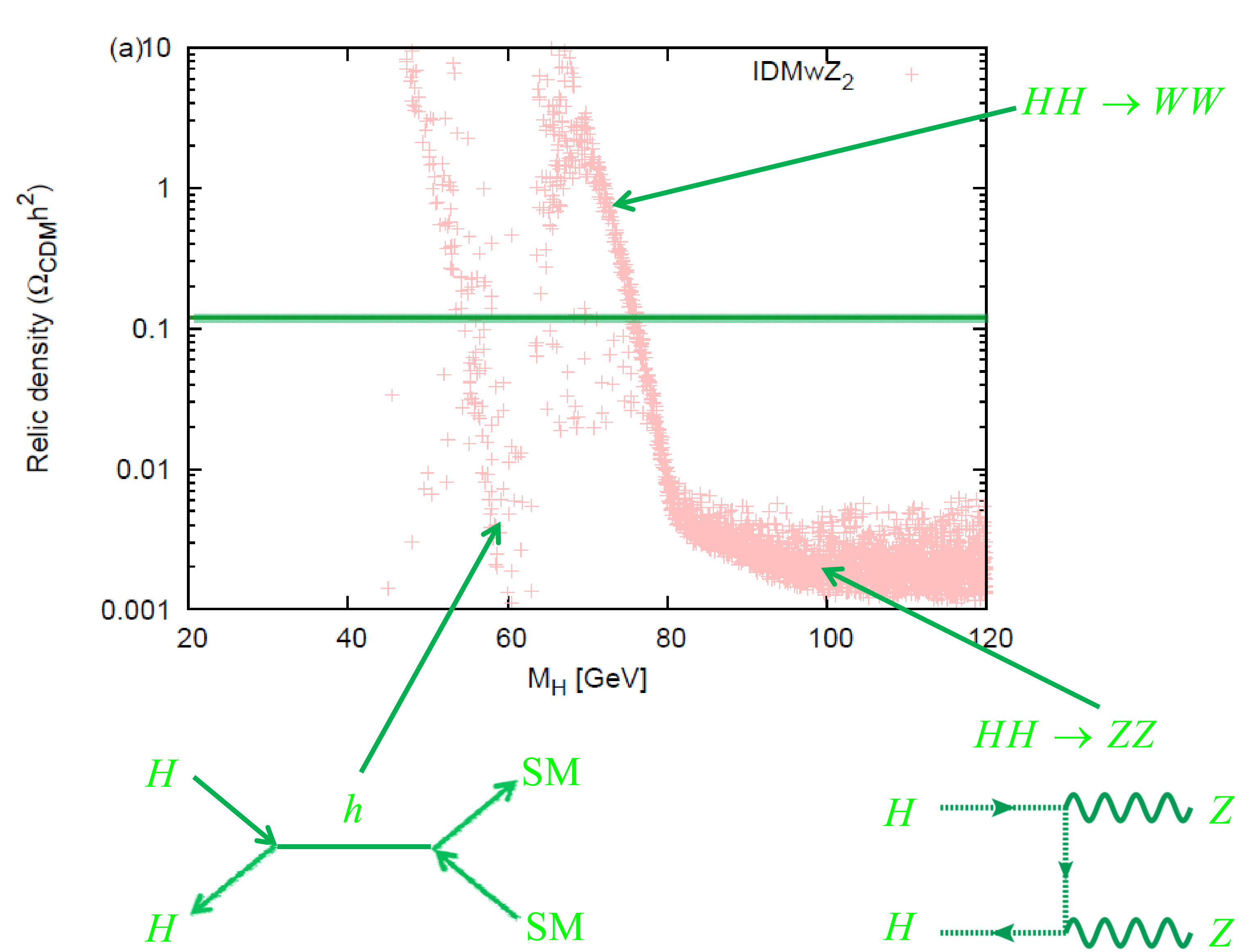




Inert 2HDM model

Relic density (low mass)

$$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$$



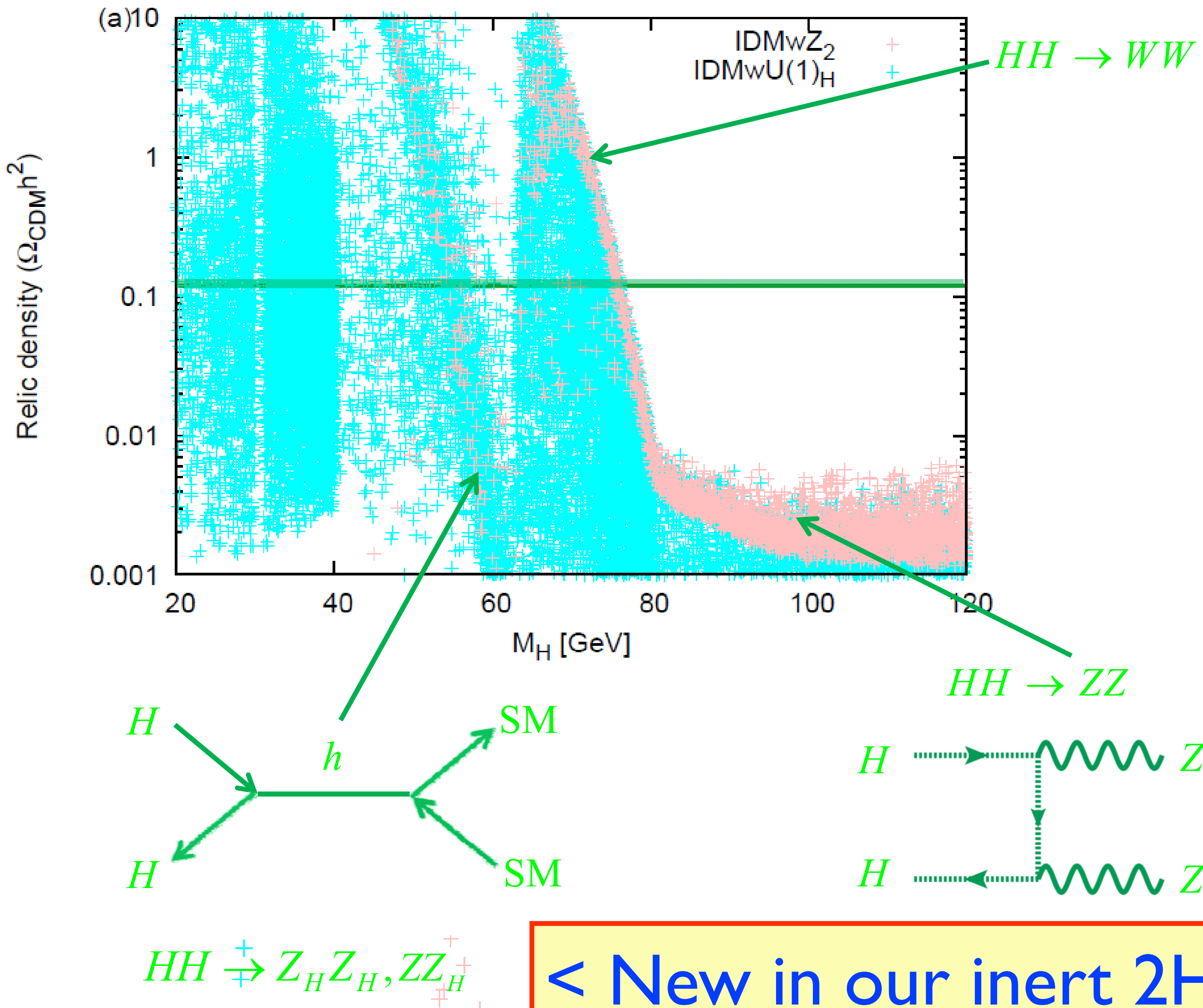
+ IDMwZ$_2$

LUX bound is satisfied.

Inert 2HDM with U(1)H gauge symmetry

Relic density (low mass)

$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$



+ IDMwZ_2
+ IDMwU(1)$_H$

LUX bound is satisfied.

Ko, Omura, Yu
arXiv:1405.2138

< New in our inert 2HDM with U(1)$_H$ gauge sym

DM + Dark gauge sym

- DM stability dynamically guaranteed as in QED
- Higgs portal can thermalize the hidden sector DM efficiently
- Dark radiation
- Higgs signal strength : universally less than 1
- Additional singlet scalar, (light) dark photon
- DM & H phenomenology changes a lot !

Basic Picture : SM Higgs + “S”

Suyong Choi, Sunghoon Jung and P. Ko, arXiv:1307.3948, JHEP (2013)

Important to seek for

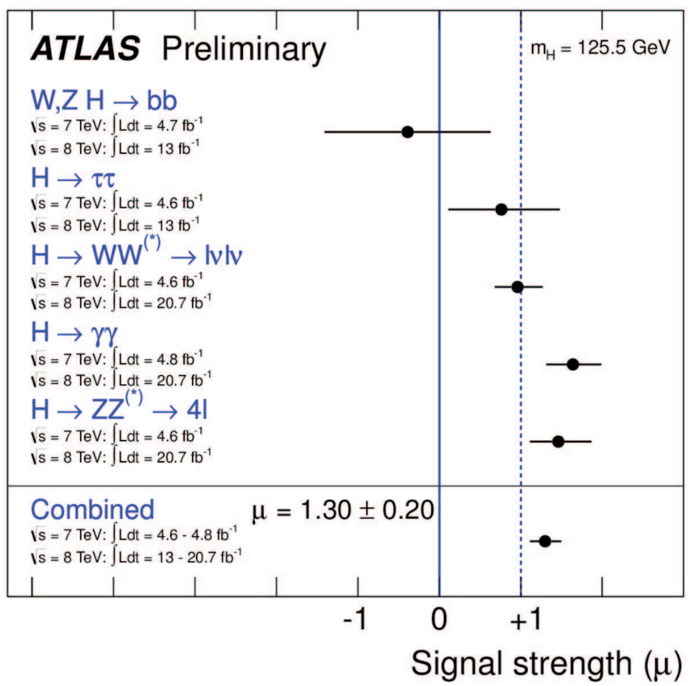
- The 2nd singlet-like scalar boson (which might couple to the DM)
- This scalar is very generic in any DM models with hidden sector (with local dark gauge symmetries)
- And can solve some puzzles in CDM models with DM self-interaction from light mediator (2nd scalar or dark gauge boson)

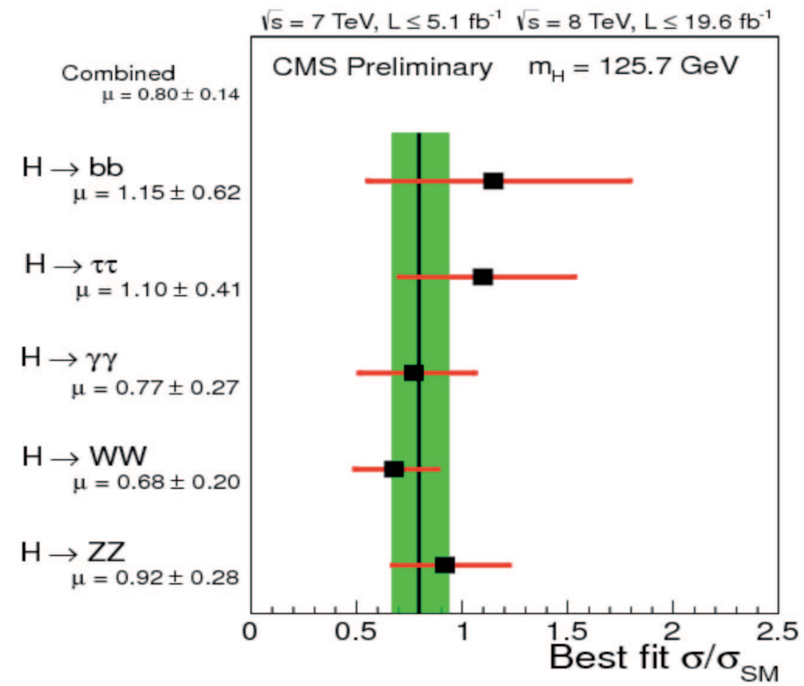
And measure the Higgs signal strengths as precisely as possible

Updates@LHCP by Pich

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

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

Higgs signal strength/Dark radiation/DM

in preparation with Baek and W.I. Park

Models	Unbroken U(1)X	Local Z2	Unbroken SU(N)	Unbroken SU(N) (confining)
Scalar DM	1 0.08 complex scalar	<1 ~0 real scalar	1 ~0.08*# complex scalar	1 ~0 composite hadrons
Fermion DM	<1 0.08 Dirac fermion	<1 ~0 Majorana	<1 ~0.08*# Dirac fermion	<1 ~0 composite hadrons

: The number of massless gauge bosons

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics, and CDM long lived by accidental sym

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Nicety of QCD

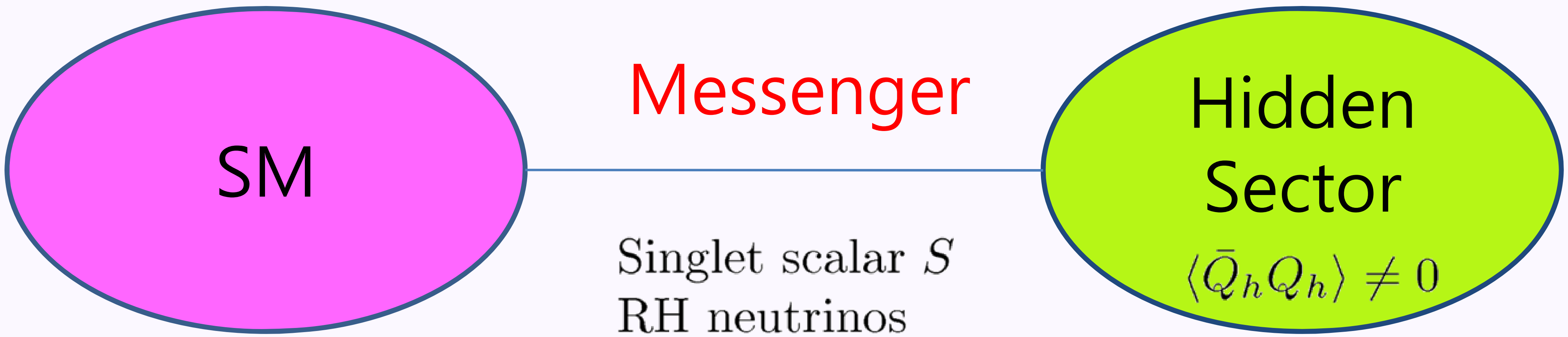
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

(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

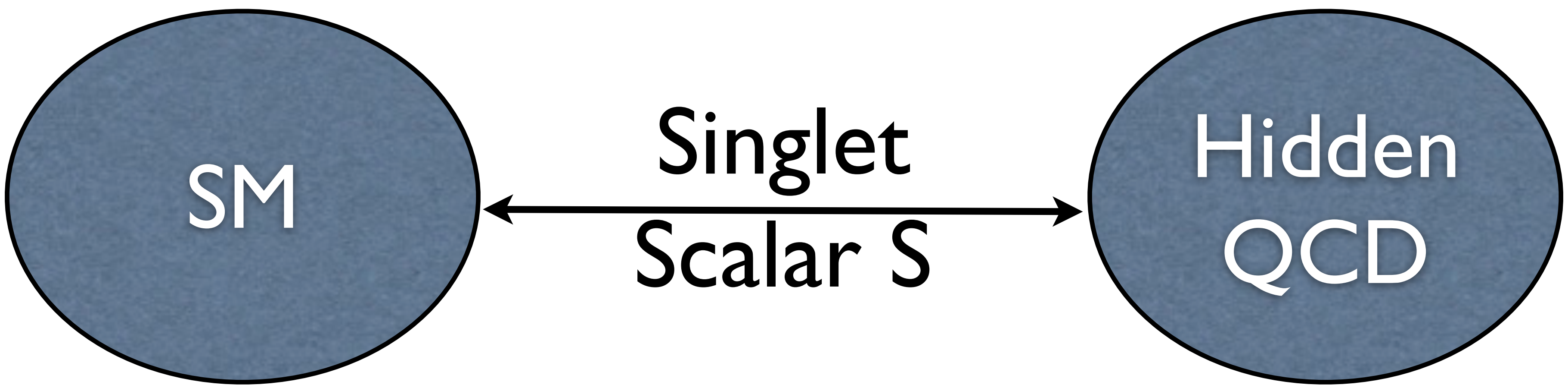
Similar to ordinary QCD

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector QCD

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- 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"

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

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

Hidden sector lagrangian with new strong interaction

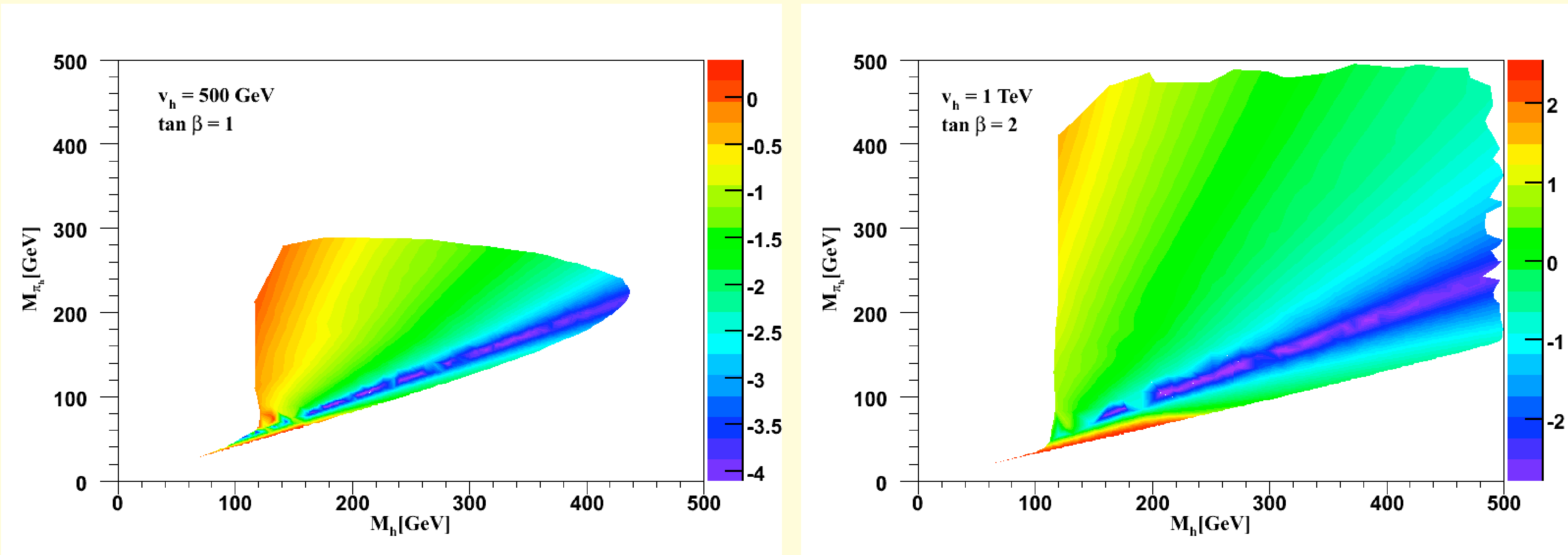
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

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

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

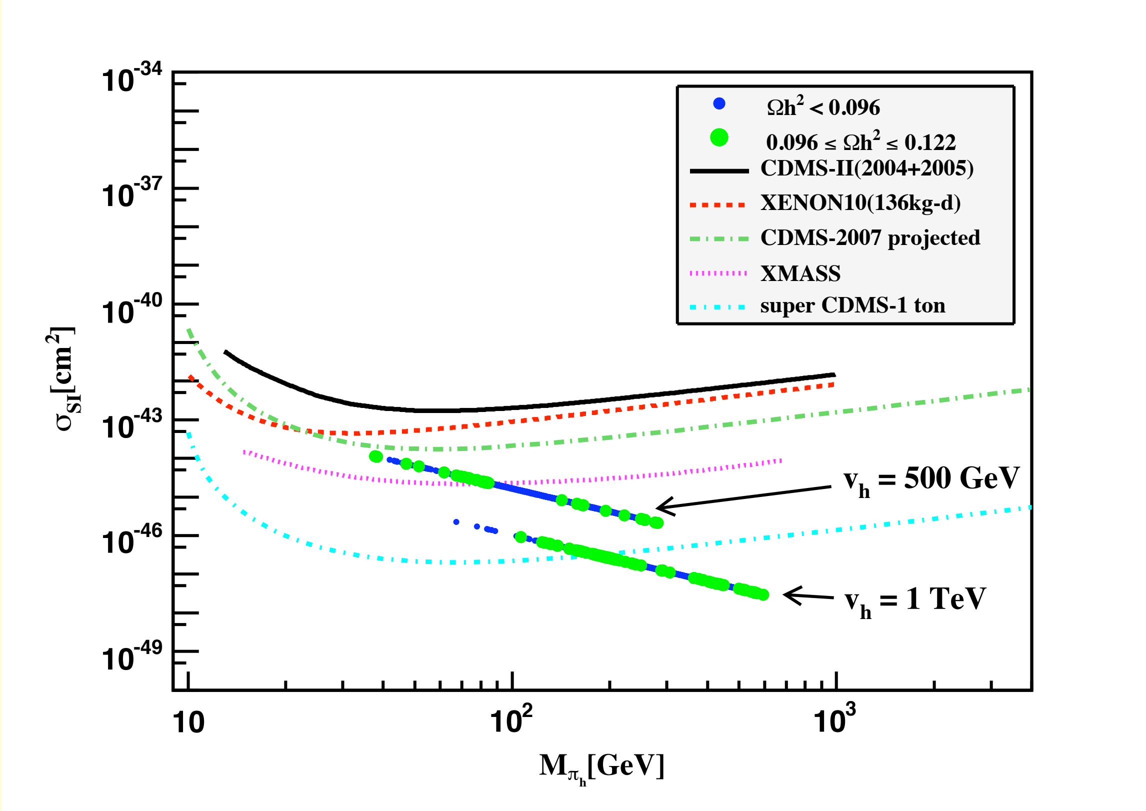
Relic density



$\Omega_{\pi_h} h^2$ 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 w/ other model

- Dark gauge symmetry is unbroken (DM is absolutely stable), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Similar to the massless QCD with the physical proton mass without finetuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example
- Could consider SUSY version of it

More issues to study

- DM : strongly interacting composite hadrons in the hidden sector >> self-interacting DM >> can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations
- Better approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach)

Conclusion

- Renomalizable model (with some caveat) is important for DM phenomenology
- Hidden sector DM with Dark Gauge Sym is well motivated, can guarantee DM stability, solves some puzzles in CDM paradigm, and open a new window in DM models
- Especially a wider region of DM mass is allowed due to new open channels

- Additional singlet-like scalar “S” : generic, improves EW vac stability, helps Higgs inflation with larger tensor/scalar ratio >> Should be actively searched for

- Invisible Higgs decay into a pair of DM

- Non Standard Higgs decays into a pair of light dark Higgs bosons, or dark gauge bosons, etc.

- Some constraints already from B factories, and LHC, and More data in new channels are welcome

Backup

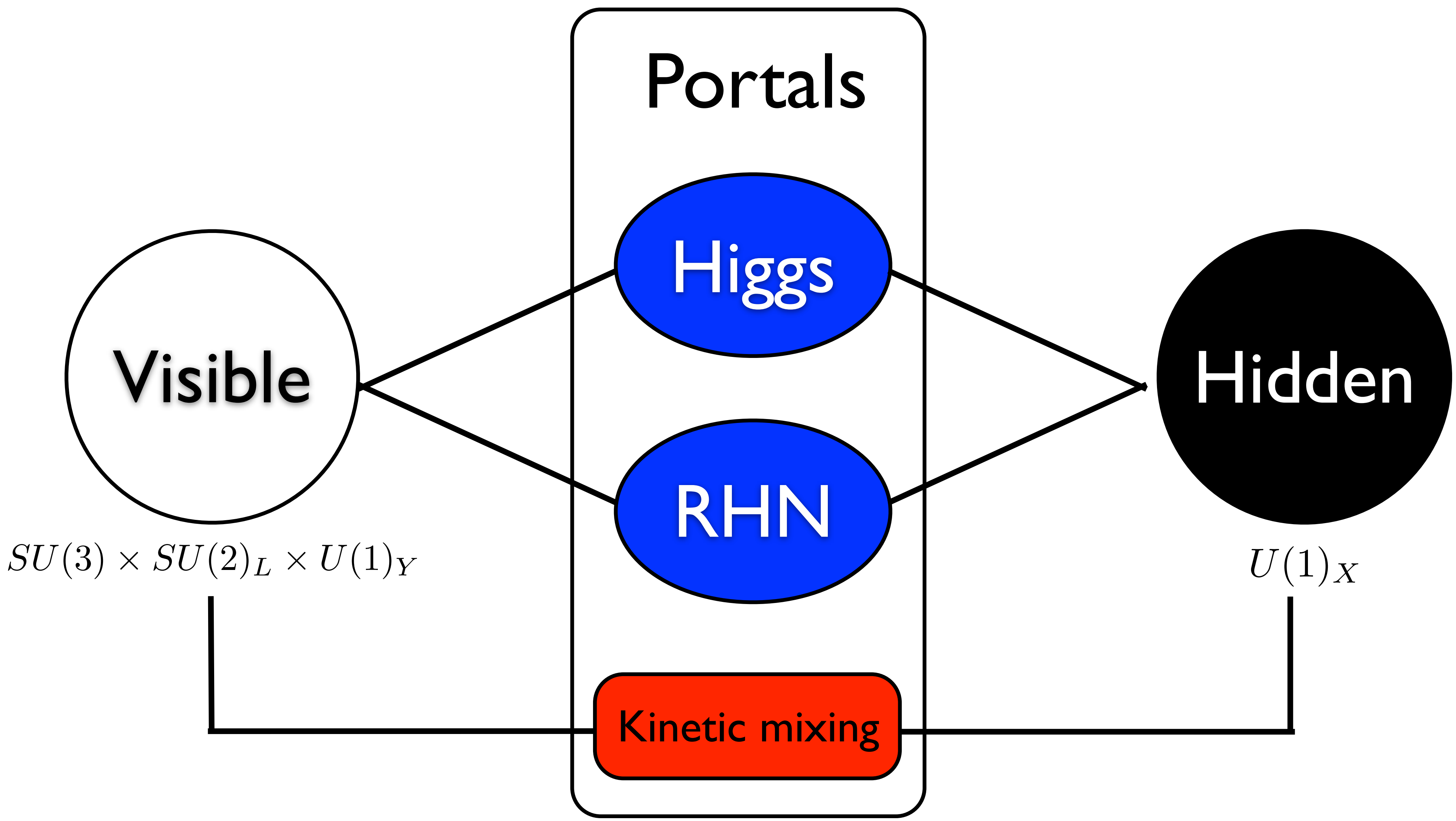
Singlet Portal Extension of the Standard Seesaw Model with Unbroken Dark Sym

An Alternative to the new minimal SM

(based on a work with S. Baek, P. Ko, 1303.4280, JHEP)

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)

- **Lagrangian**

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

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

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

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

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

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

G. Shiu et al. arXiv:1302.5471, PRL for millicharged DM from string theory

Constraints

Our model can address

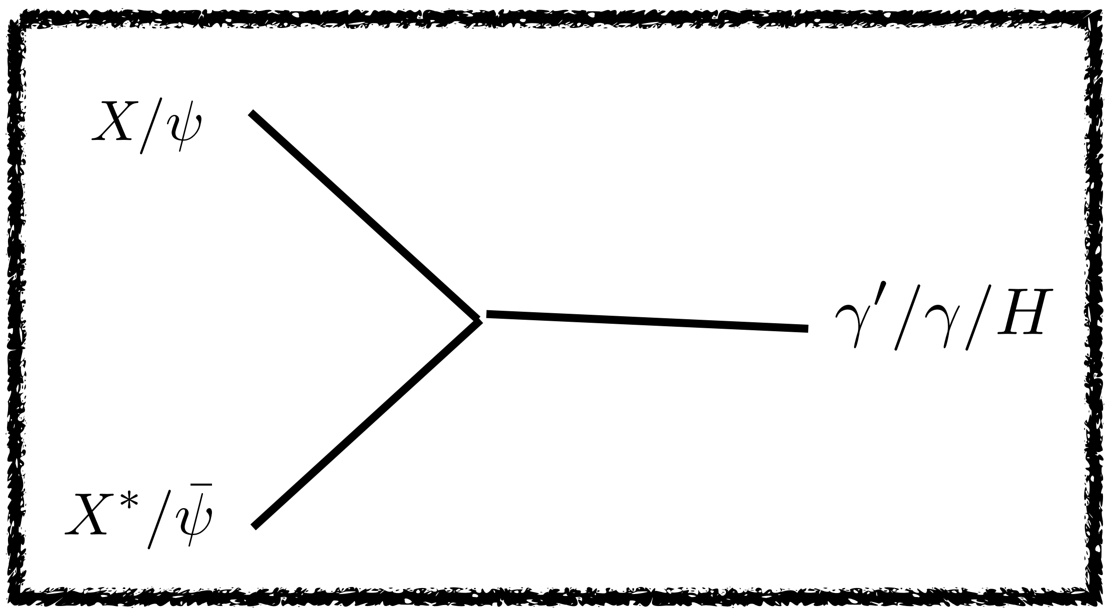
* Some small scale puzzles of CDM (Dark matter self-interaction) (α_X, m_X)
* CDM relic density (Unbroken dark $U(1)_X$) (λ, λ_{hx}, m_X,)
* Vacuum stability of Higgs potential (Positive scalar loop correction) (λ_{hx})
* Direct detection (Photon and Higgs exchange)(ε, λ_{hx})
* Dark radiation (Massless photon)(α_X)
* Lepto/darkogenesis (Asymmetric origin of dark matter) (Y_ν, λ, M_1, m_X)
* Inflation (Higgs inflation type) (λ_{hx}, λ_X)

In other words, the model is highly constrained.

• Interaction vertices of dark particles (X, ψ)

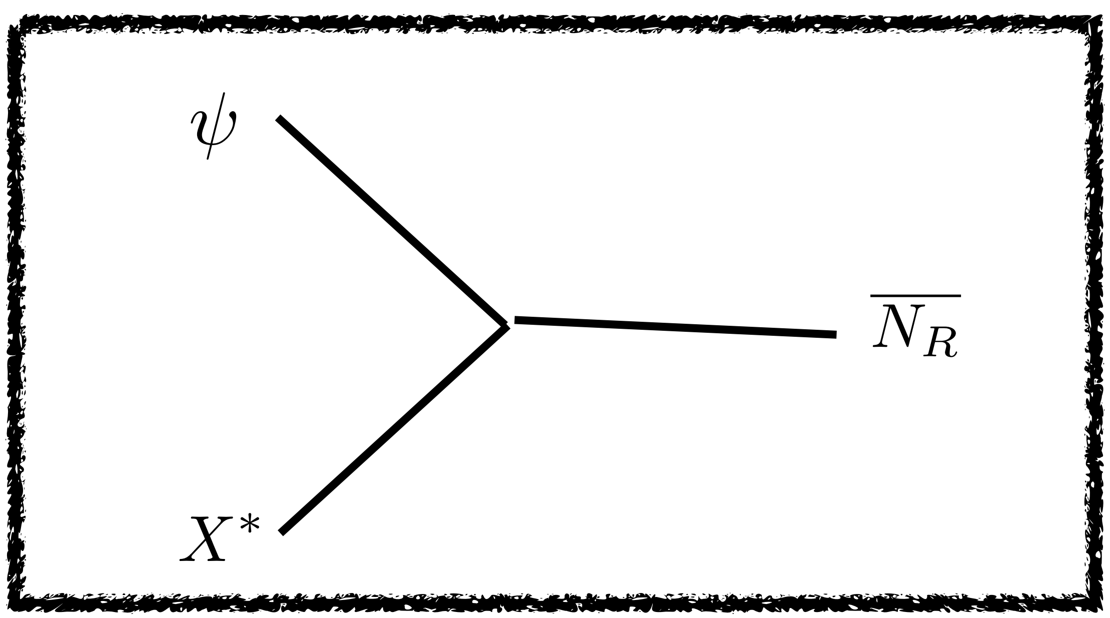
Kinetic term diagonalization: $\begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix}$

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



Annihilation
or
scattering

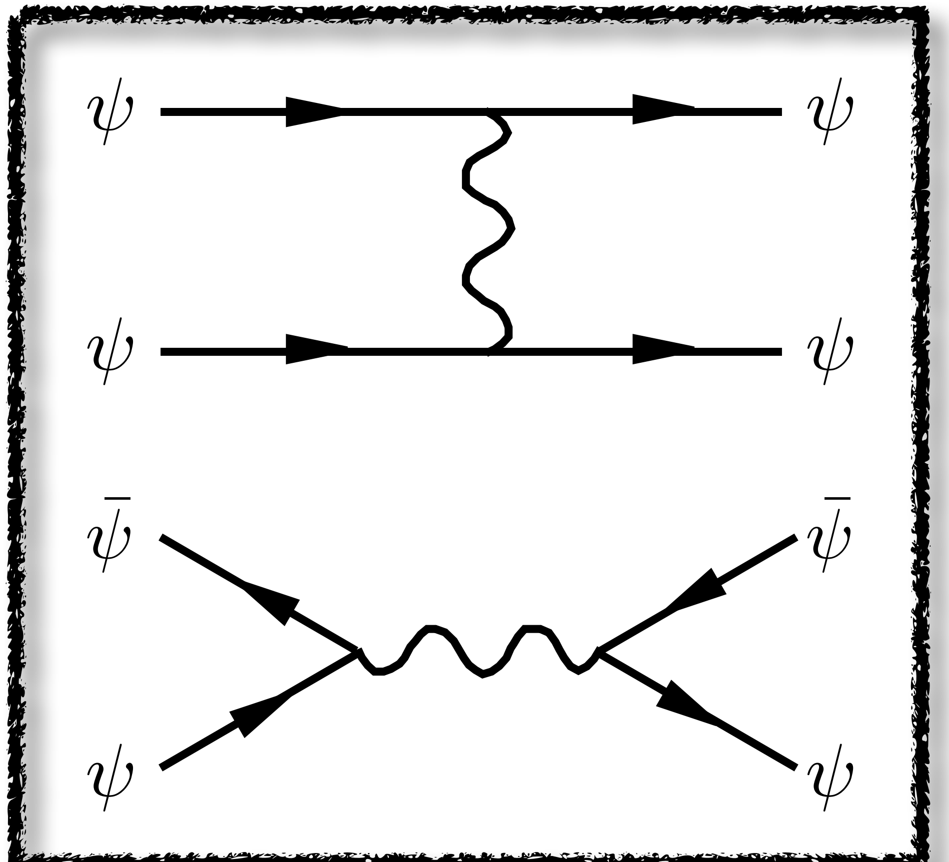
(⇒ Relic density, direct/indirect searches)



Decay of N_R and ψ or X

(⇒ Lepto/darkogenesis?)

- # Constraints on dark gauge coupling



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

From inner structure and kinematics of dwarf galaxies,

$$\sigma_T^{\max}/m_{\rm dm} \lesssim 35\ {\rm cm}^2/{\rm g}$$

[Vogelsberger, Zavala and Leb, 1201.5892]

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

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

“$m_\Psi > m_X$” $\Rightarrow$ Ψ decays.

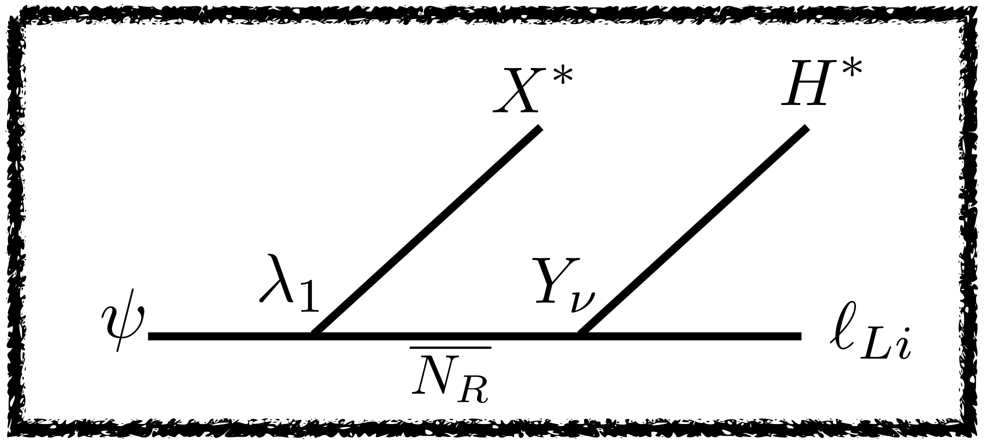
“X”(the scalar dark field) = CDM

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

(i) cored profile of dwarf galaxies.

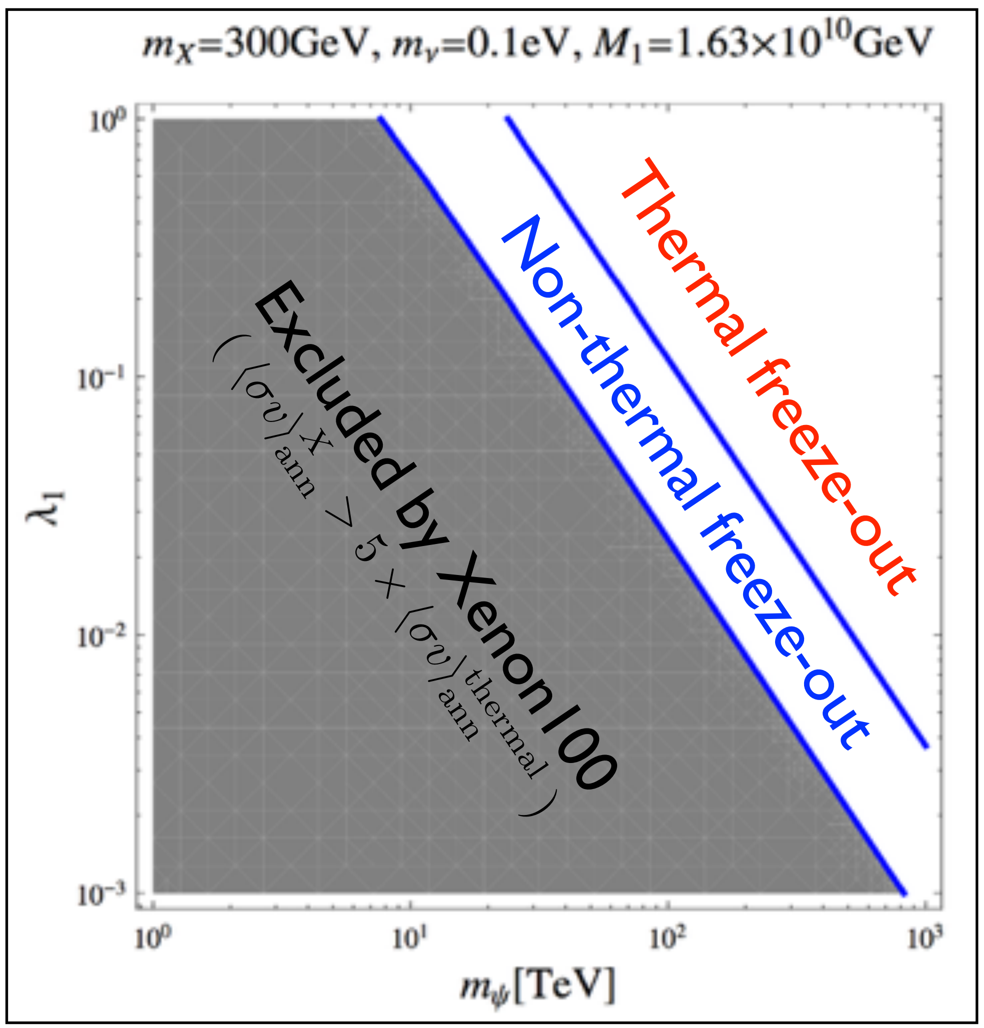
(ii) low concentration of LSB galaxies and dwarf galaxies. [Vogelsberger, Zavala and Leb, 1201.5892]

- CDM relic density



The late-time decay of ψ

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



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

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

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

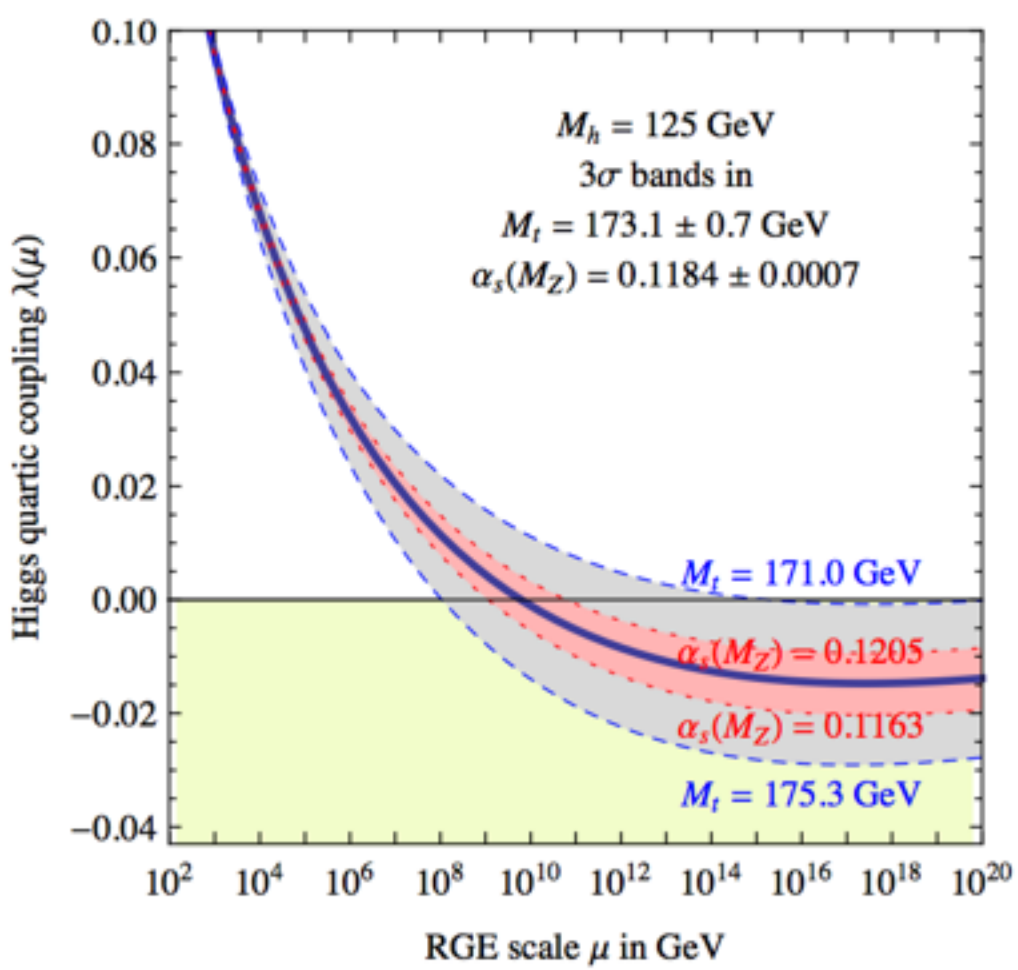
• Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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

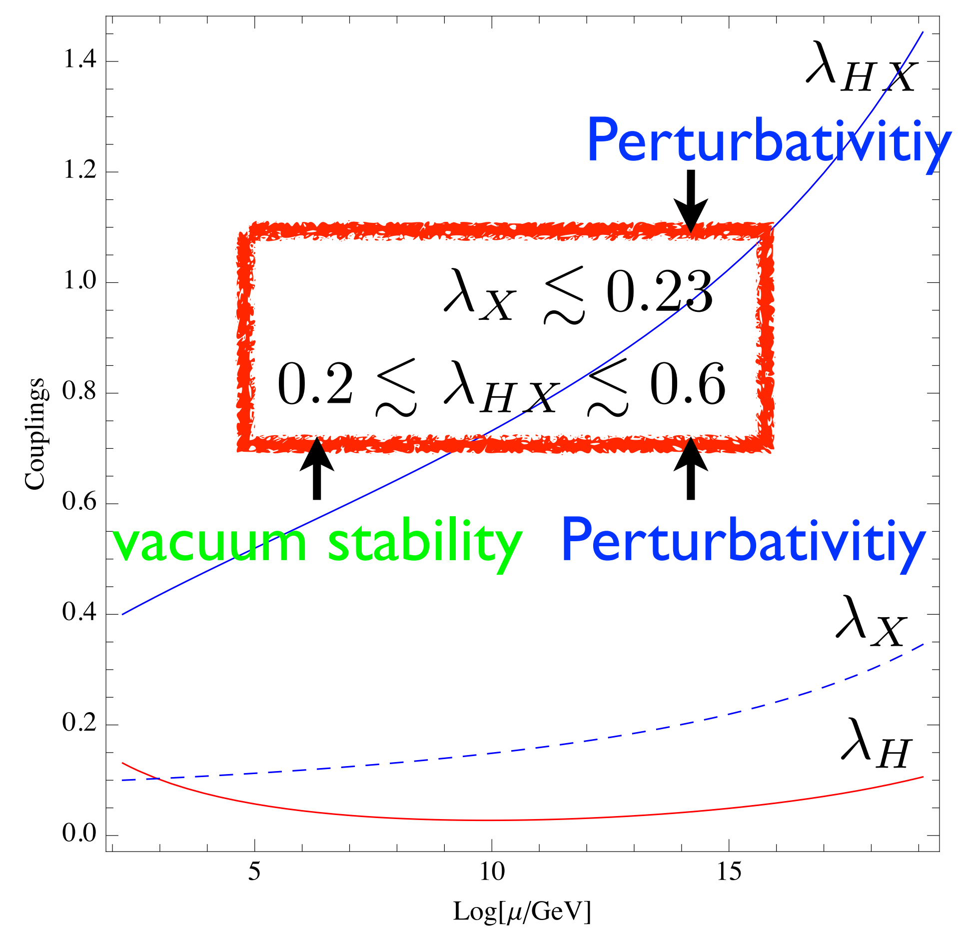
$$\beta^{(1)}_{\lambda_{HS}} = \frac{\lambda_{HS}}{16\pi^2}\left[2\left(6\lambda_H + 3\lambda_S + 2\lambda_{HS}\right) - \left(\frac{3}{2}\lambda_H\left(3g_2^2+g_1^2\right) - 6\lambda_t^2 - \cancel{4X^2}\right)\right],$$

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

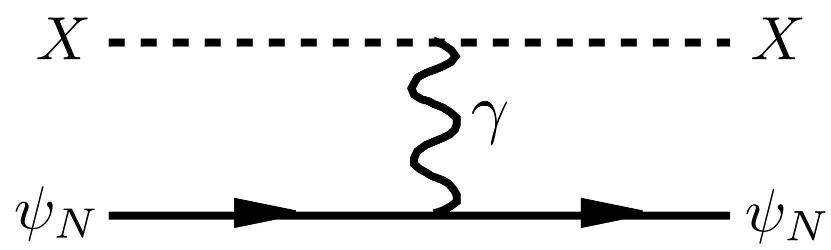
with $\lambda_{HS} \to \lambda_{HX}/2$ and $\lambda_S \to \lambda_X$



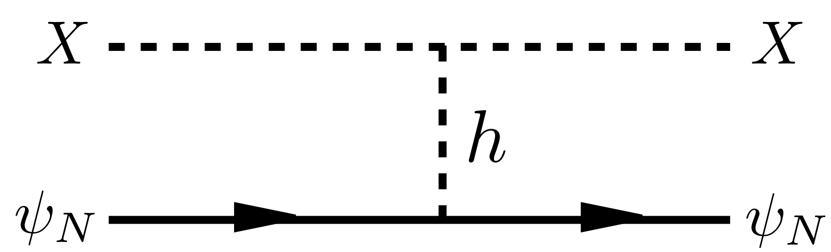
[G. Degrassi et al., 1205.6497]



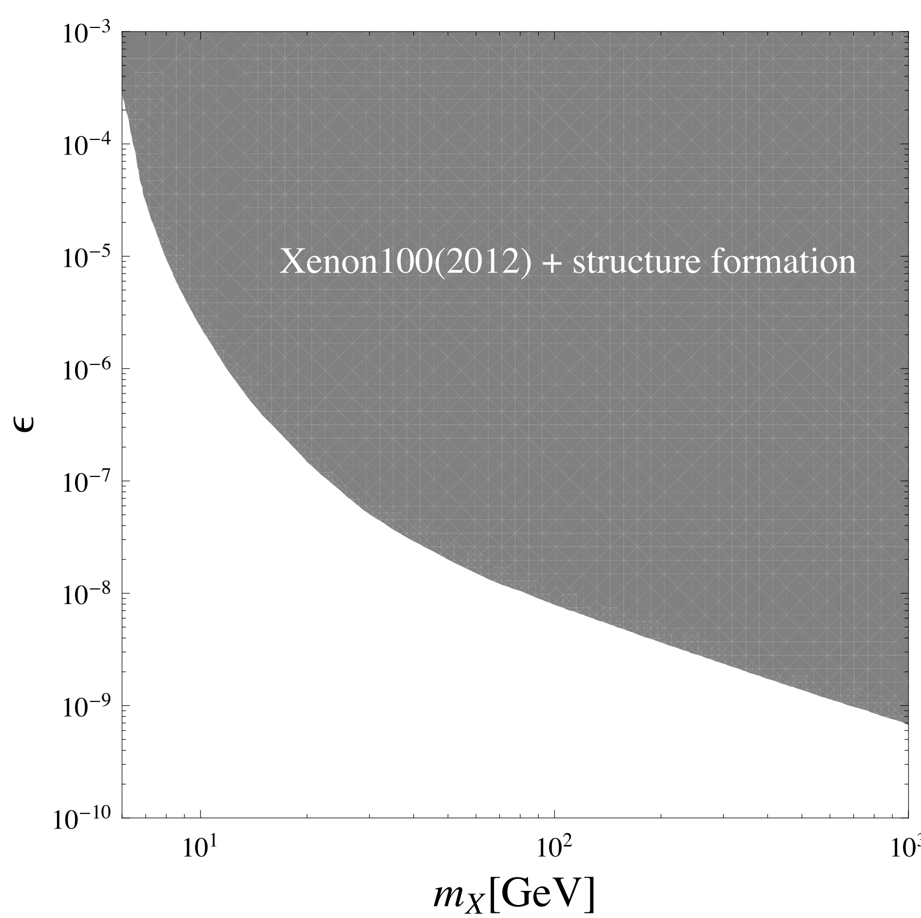
- DM direct search (ϵ, λ_{hx}, m_X)

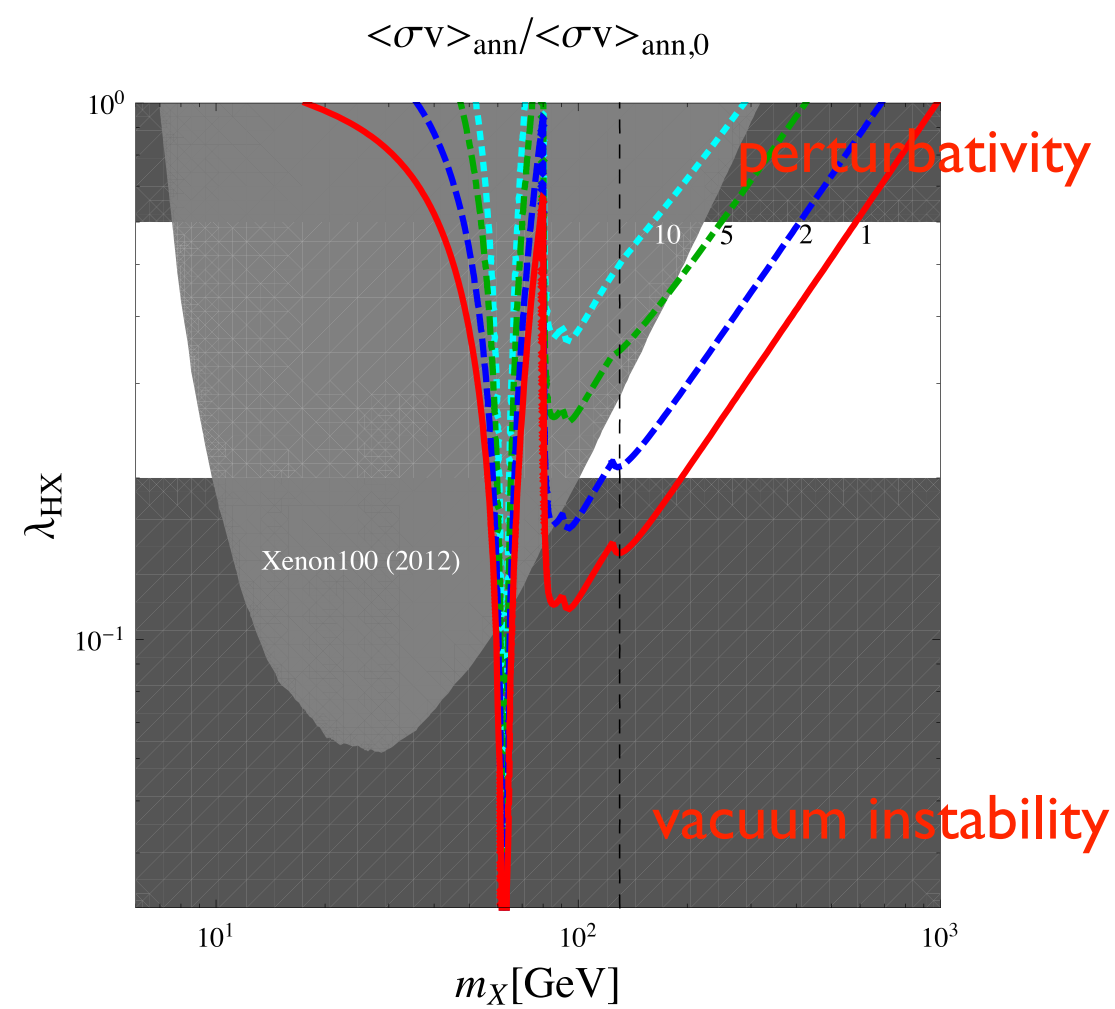


$$\frac{d\sigma_A}{dE_r} = \frac{2\pi\epsilon_e^2\alpha_{em}^2 Z^2}{m_A E_r^2 v^2}\mathcal{F}_A^2(qr_A)$$



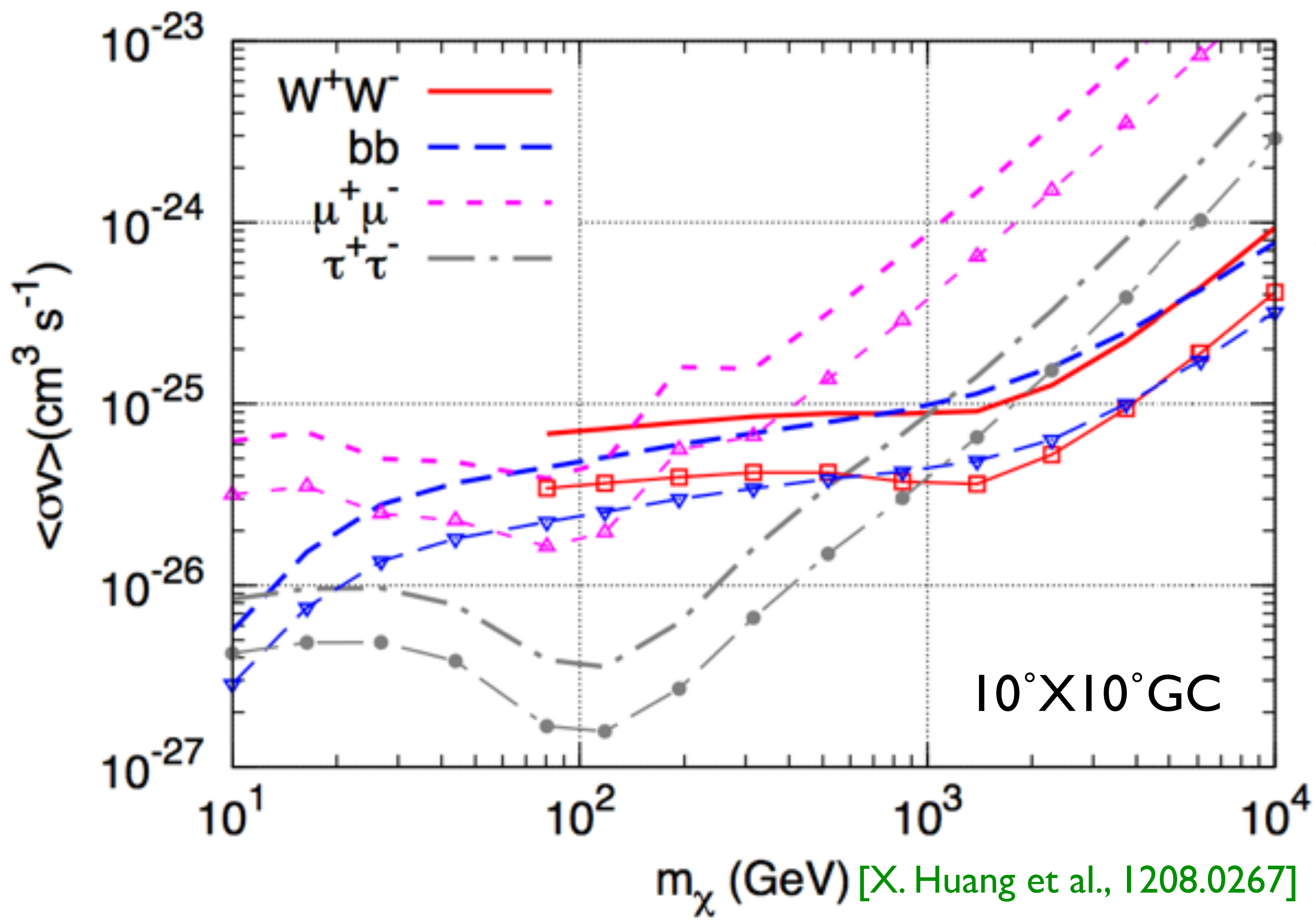
$$\sigma^{SI}_{\mathcal{N},h} = \frac{\lambda_{HX}^2}{64\pi}\frac{m_r^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$





• Indirect search (λ_{hx}, m_X)

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



[X. Huang et al., 1208.0267]

In our model,

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

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

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

☛ Monochromatic γ-ray spectrum?

$$\langle \sigma v \rangle^{\gamma\gamma}_{\rm ann} \sim 10^{-4} \langle \sigma v \rangle^X_{\rm ann} \lesssim 10^{-29} {\rm cm}^3/{\rm sec}$$

Too weak to be seen!

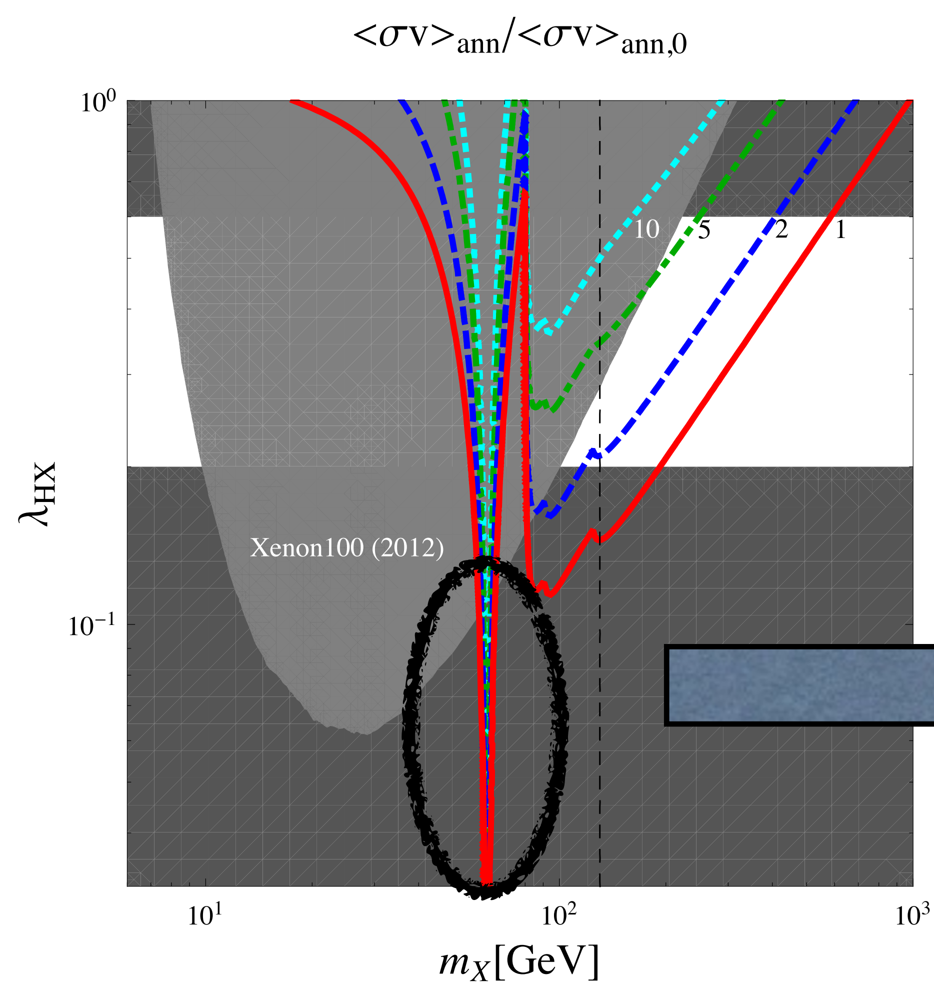
- Collider phenomenology (λ_{hx}, m_X)

Invisible decay rate of Higgs is

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

SM signal strength at collider is

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



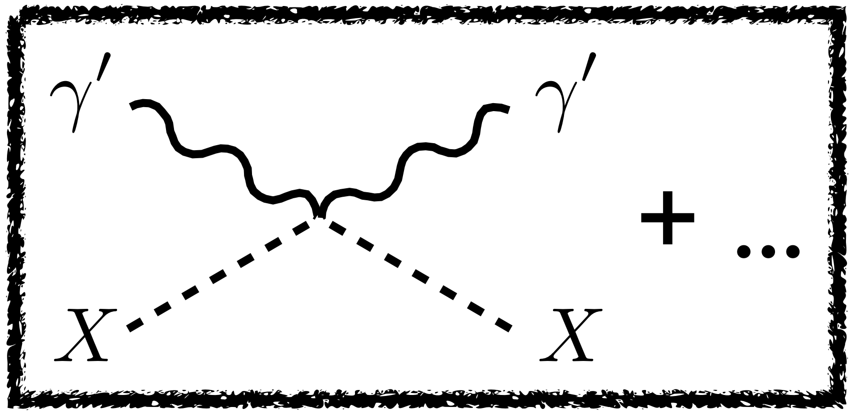
We may need $\mathrm{Br}(h \to XX^\dagger) \ll \mathcal{O}(10)\%$, i.e.,

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

or kinematically forbidden

- # Dark radiation

Decoupling of dark photon



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

# of extra relativistic degree of freedom

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

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

$\Delta N_{\mathrm{eff}} = 0.474^{+0.48}_{-0.45}$ at 95% CL (Planck+WP+highL+H_0+BAO)
[Planck Collaboration, arXiv:1303.5076]

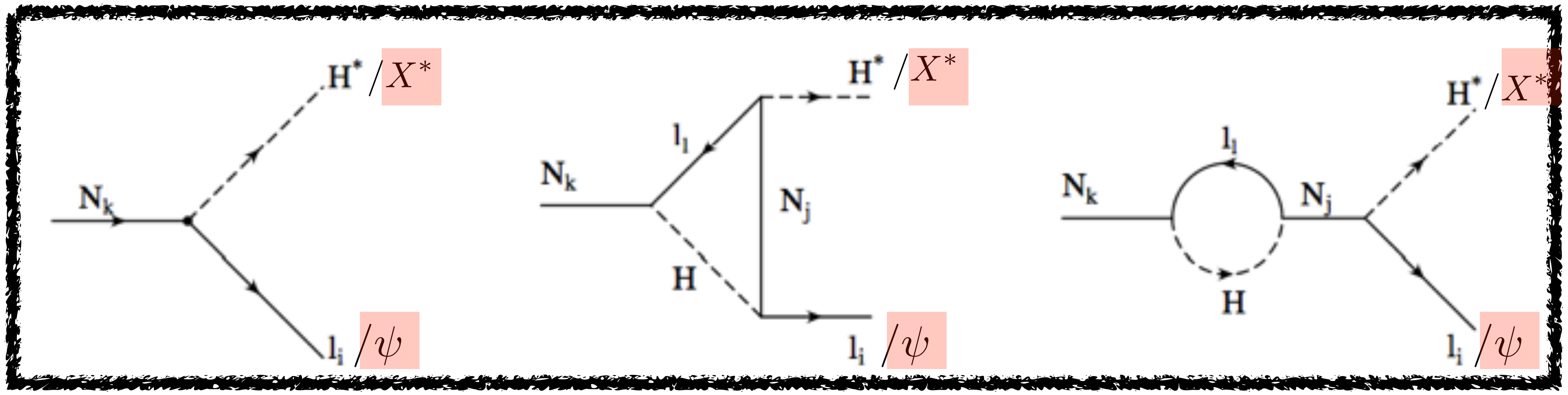
Unbroken SU(N) dark sym

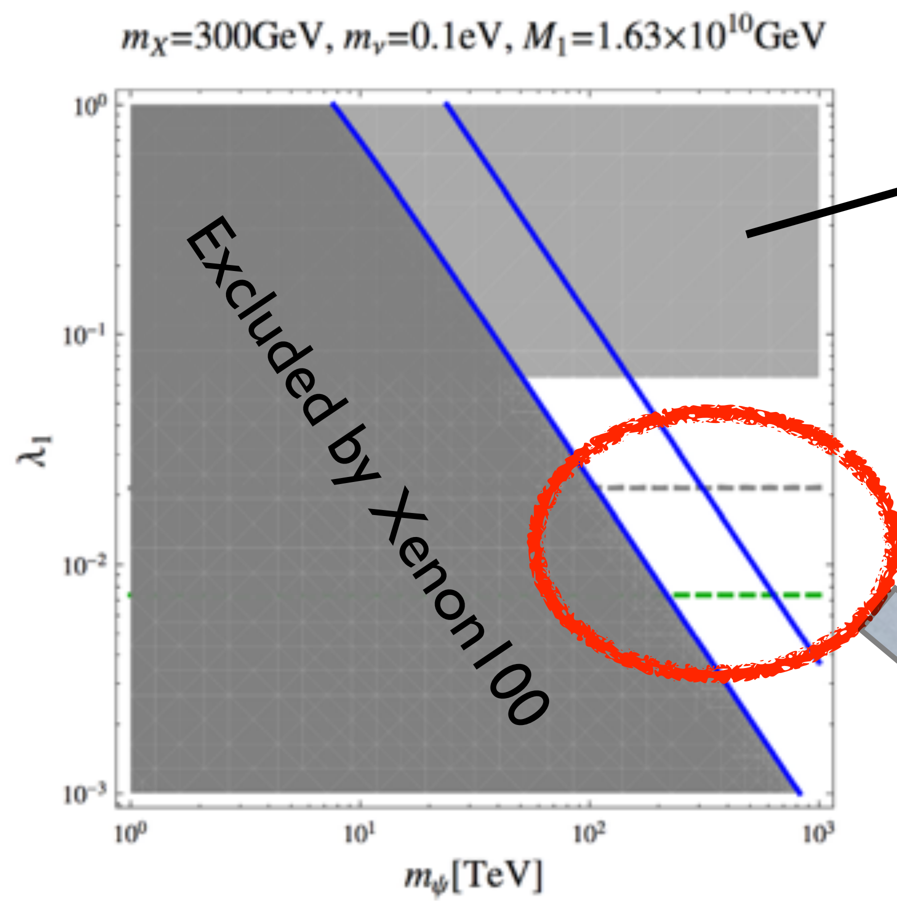
$$\Delta N_{\mathrm{eff}}(N=2) = 0.253,$$
$$\Delta N_{\mathrm{eff}}(N=3) = 0.675,$$
$$\Delta N_{\mathrm{eff}}(N=4) = 1.265.$$

(In preparation)

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

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





Light gray: narrow width approx. is invalid

White between blue lines:

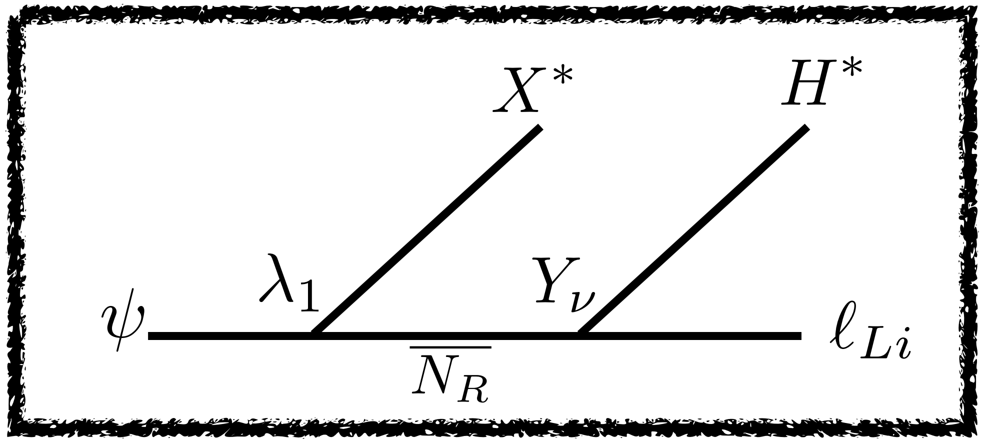
$$1 \leq \langle \sigma v \rangle^{\rm tot}_{\rm ann} / \langle \sigma v \rangle^{\rm th}_{\rm ann} \lesssim 5$$

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

Correct BAU and CDM relic can be obtained.

- # Lepto/darkogenesis (2/2)

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



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

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

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

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

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

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

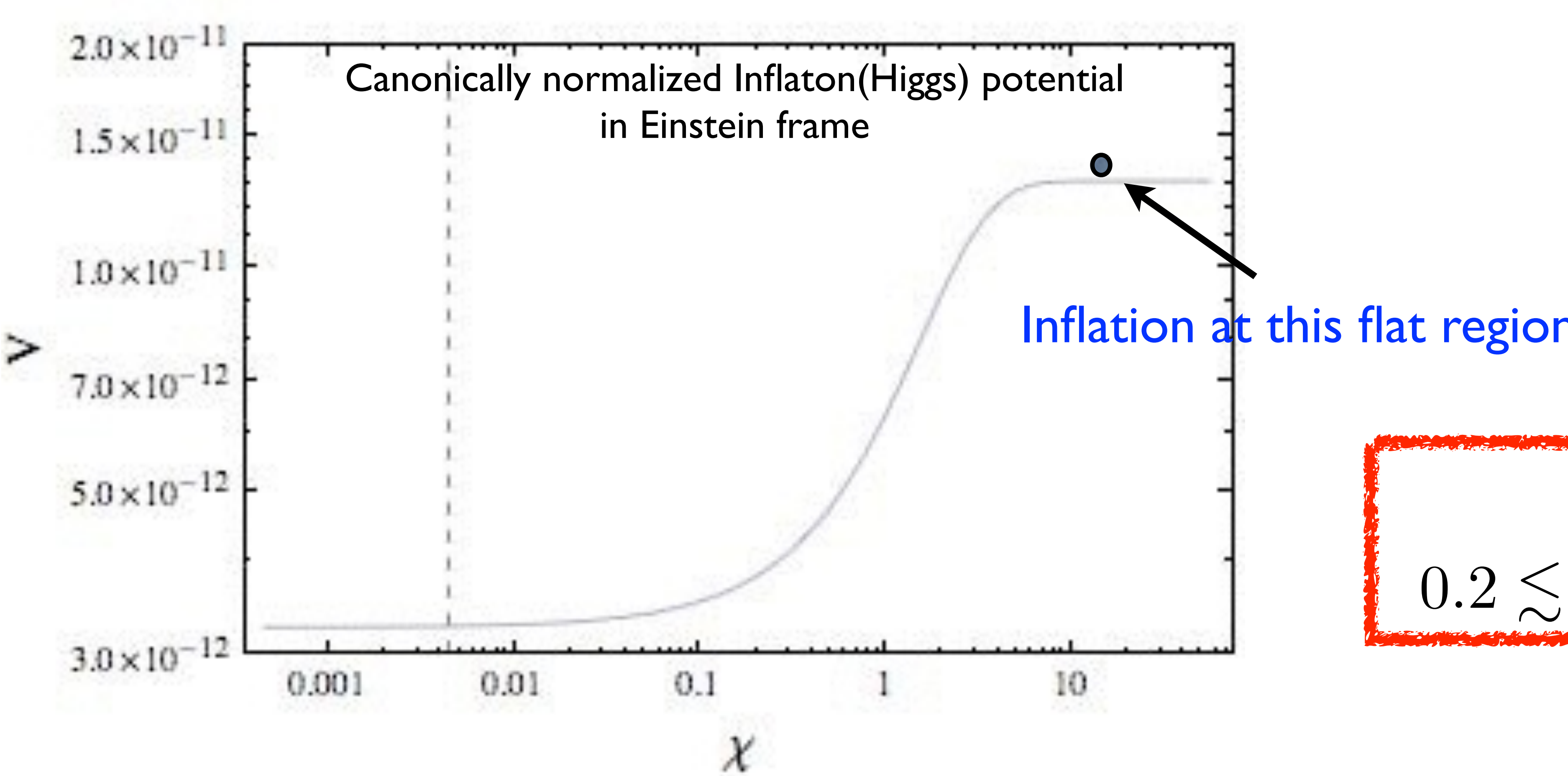
* Late-time decays of symmetric ψ and ψ-bar can generate a sizable amount of lepton number asymmetry.

- # Higgs inflation in Higgs-singlet system

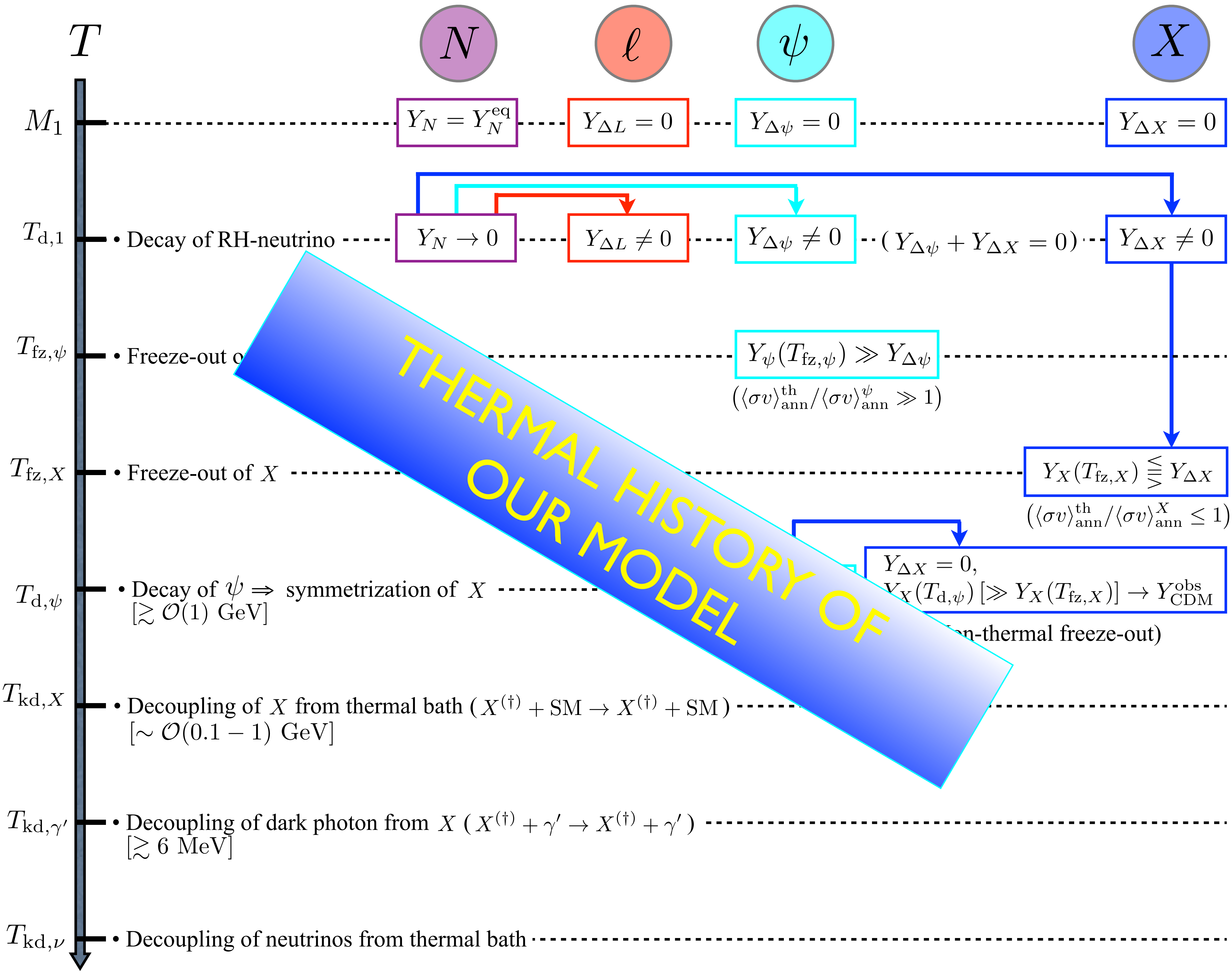
[Lebedev,1203.0156]

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

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



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



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 o
$Y_\psi(T_{fz,\psi}) \gg Y_{\Delta\psi}$
$(\langle\sigma v\rangle^{th}_{ann}/\langle\sigma v\rangle^{\psi}_{ann} \gg 1)$
$T_{fz,X}$
• Freeze-out of X
$Y_X(T_{fz,X}) \lesseqgtr Y_{\Delta X}$
$(\langle\sigma v\rangle^{th}_{ann}/\langle\sigma v\rangle^{X}_{ann} \leq 1)$
$T_{d,\psi}$
• Decay of $\psi \Rightarrow$ symmetrization of X
$[\gtrsim \mathcal{O}(1)\ \mathrm{GeV}]$
$Y_{\Delta X} = 0,$
$Y_X(T_{d,\psi})\ [\gg Y_X(T_{fz,X})] \to Y^{obs}_{CDM}$
n-thermal freeze-out)
$T_{kd,X}$
• Decoupling of X from thermal bath $(X^{(\dagger)} + \mathrm{SM} \to X^{(\dagger)} + \mathrm{SM})$
$[\sim \mathcal{O}(0.1-1)\ \mathrm{GeV}]$
$T_{kd,\gamma'}$
• Decoupling of dark photon from X $(X^{(\dagger)} + \gamma' \to X^{(\dagger)} + \gamma')$
$[\gtrsim 6\ \mathrm{MeV}]$
$T_{kd,\nu}$
• Decoupling of neutrinos from thermal bath
THERMAL HISTORY OF OUR MODEL

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

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.

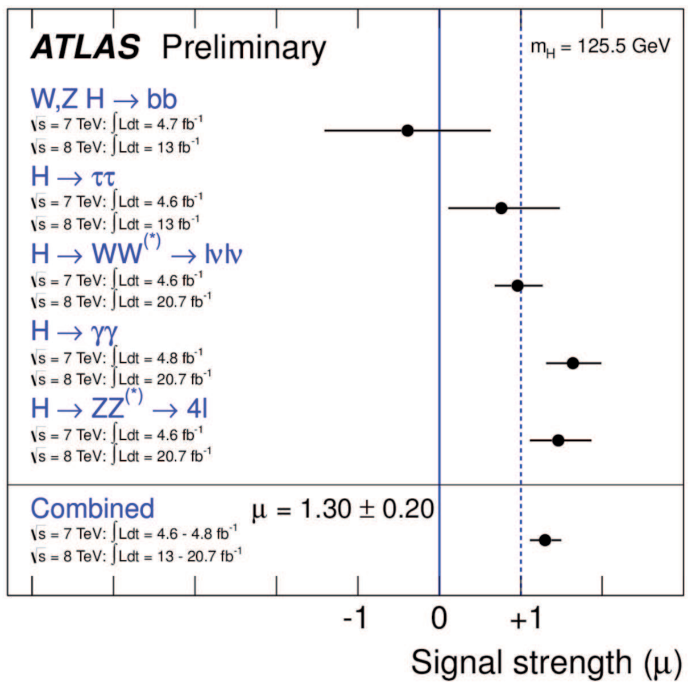
Note that "mu < 1" if CDM is fermion, whether U(1)x is broken or not

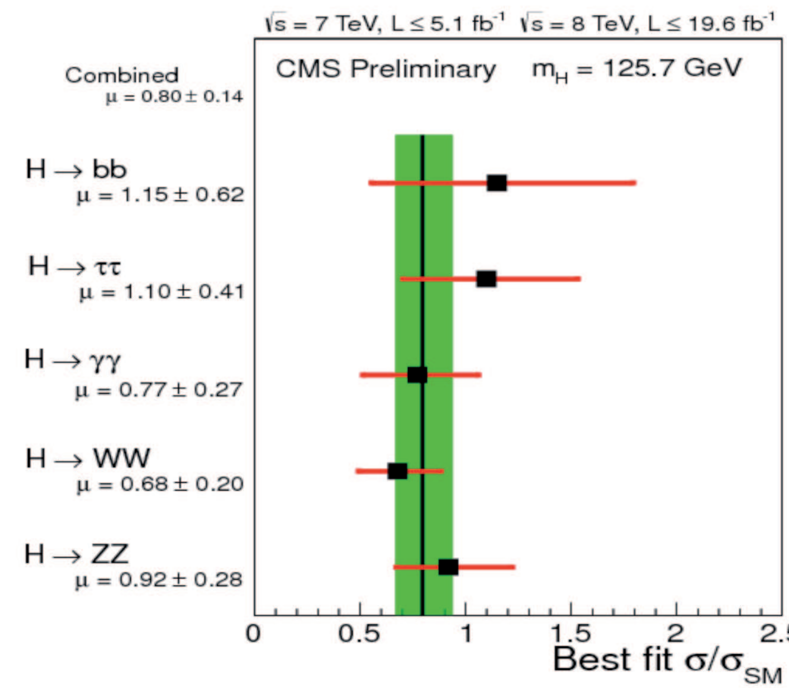
And Universal Suppression

Updates@LHCP

Signal Strengths

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





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

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

Summary of the 2nd part

- 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)

Conclusion

- Two examples of hidden sector DM models with local DM symmetry
- Strongly Interacting Case : EWSB and CDM mass from dim transmutation in hidden sector
- Weakly Interacting Case : Dark Radiation Constrained by Planck
- In either case, the Higgs signal strengths are universally suppressed

- Stability or longevity of a hCDM is closely related with the SM Higgs sector (amusing !)
- Whatever you do for CDM stabilization or longevity, 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

- The signal strength of Higgs boson is universally reduced from “one”If dark sym is unbroken and DM is scalar, there could be only one SM Higgs boson with signal strengths = ONE (and dark radiation)

- LHC Higgs data probes the hidden sector DM

- Dark radiation begins to constrain the number of massless dark gauge bosons that stabilize the EW scale DM

- The 2nd scalar is very very elusive
- Small mixing limit is the interesting region
- How can we find the 2nd scalar at experiments ?
- We will see if this class of DM can survive the LHC Higgs data in the coming years

Higgs signal strength/Dark radiation/DM

in preparation with Baek and W.I. Park

Models	Unbroken U(1)X	Local Z2	Unbroken SU(N)	Unbroken SU(N) (confining)
Scalar DM	1 0.08 complex scalar	<1 ~0 real scalar	1 ~0.08*# complex scalar	1 ~0 composite hadrons
Fermion DM	<1 0.08 Dirac fermion	<1 ~0 Majorana	<1 ~0.08*# Dirac fermion	<1 ~0 composite hadrons

: The number of massless gauge bosons

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
  - New chiral Gauge Sym needs new Higgs Doublets

Model 2 : vΛMDM

P. Ko, Y.Tang, 1404.0236

We introduce two right-handed gauge singlets, a dark sector with an extra U(1)X gauge symmetry,

$$
\begin{aligned}
\mathcal{L} =& \mathcal{L}_{\rm SM} + \bar{N}_i i\partial\!\!\!/ N_i - \left(\frac{1}{2} m^R_{ij} \bar{N}^c_i N_j + y_{\alpha i} \bar{L}_\alpha H N_i + h.c\right) - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu} \\
& + \bar{\chi}\left(i D\!\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(i D\!\!\!\!/ - m_\psi\right)\psi + D^\dagger_\mu \phi^\dagger_X D^\mu \phi_X - \left(f_i \phi^\dagger_X \bar{N}^c_i \psi + g_i \phi_X \bar{\psi} N_i + h.c\right) \\
& - \lambda_\phi \left[\phi^\dagger_X \phi_X - \frac{v^2_\phi}{2}\right]^2 - \lambda_{\phi H}\left[\phi^\dagger_X \phi_X - \frac{v^2_\phi}{2}\right]\left[H^\dagger H - \frac{v^2_h}{2}\right],
\end{aligned}
$$

$v_\phi \sim \mathcal{O}\left(\mathrm{MeV}\right)$ for our interest

Various Mixing

- Kinetic mixing term $\frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$ leads to three physical neutral gauge boson mixing,
- Scalar interaction term $\lambda_{\phi H}\left[\phi_X^\dagger \phi_X - \frac{v_\phi^2}{2}\right]\left[H^\dagger H - \frac{v_h^2}{2}\right]$ leads to Higgs mixing,
- $y_{\alpha i}\bar{L}_\alpha H N_i,\ f_i \phi_X^\dagger \bar{N}_i \psi,\ g_i \phi_X \bar{\psi} N_i$ give rise to neutrino mixing.

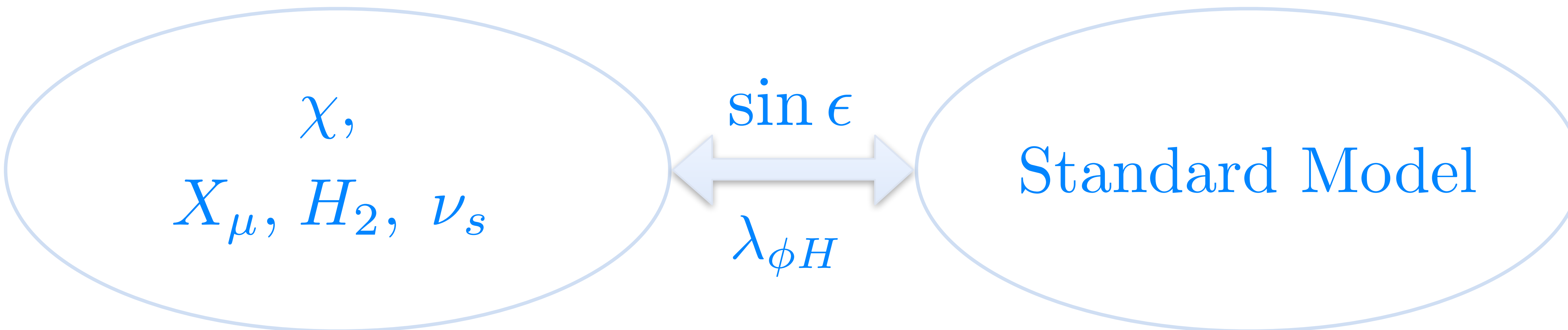
Physical Spectrum

- Dark Matter, dark gauge boson, dark Higgs, and 4 sterile neutrinos,

$\chi,$
$X_\mu,\ H_2,\ \nu_s$

Standard Model

Thermal History



- DM decoupled, determining its relic density,
- Then the whole dark sector decoupled from SM thermal bath, and entropy is conserved separately. Effective number of neutrinos can be calculated.

$\Delta N_{\rm eff}$(BBN)

When only sterile neutrinos are relativistic at the time just before BBN epoch, we have

$$\Delta N_{\rm eff}(T) = 4 \times \frac{T_{\nu_s}^4}{T_{\nu_a}^4} = 4 \times \left[\frac{g_{*s}(T)}{g_{*s}^x(T)} \times \frac{g_{*s}^x(T)\,T_{\nu_s}^3}{g_{*s}(T)\,T_{\nu_a}^3}\right]^{\frac{4}{3}}$$

$$= 4 \times \left[\frac{g_{*s}(T)}{g_{*s}^x(T)} \times \frac{g_{*s}^x\left(T_x^{\rm dec}\right)}{g_{*s}\left(T_x^{\rm dec}\right)}\right]^{\frac{4}{3}},$$

and

$$g_{*s}^x\left(T_x^{\rm dec}\right) = 3 + 1 + \frac{7}{8} \times (4 \times 2) = 11,$$

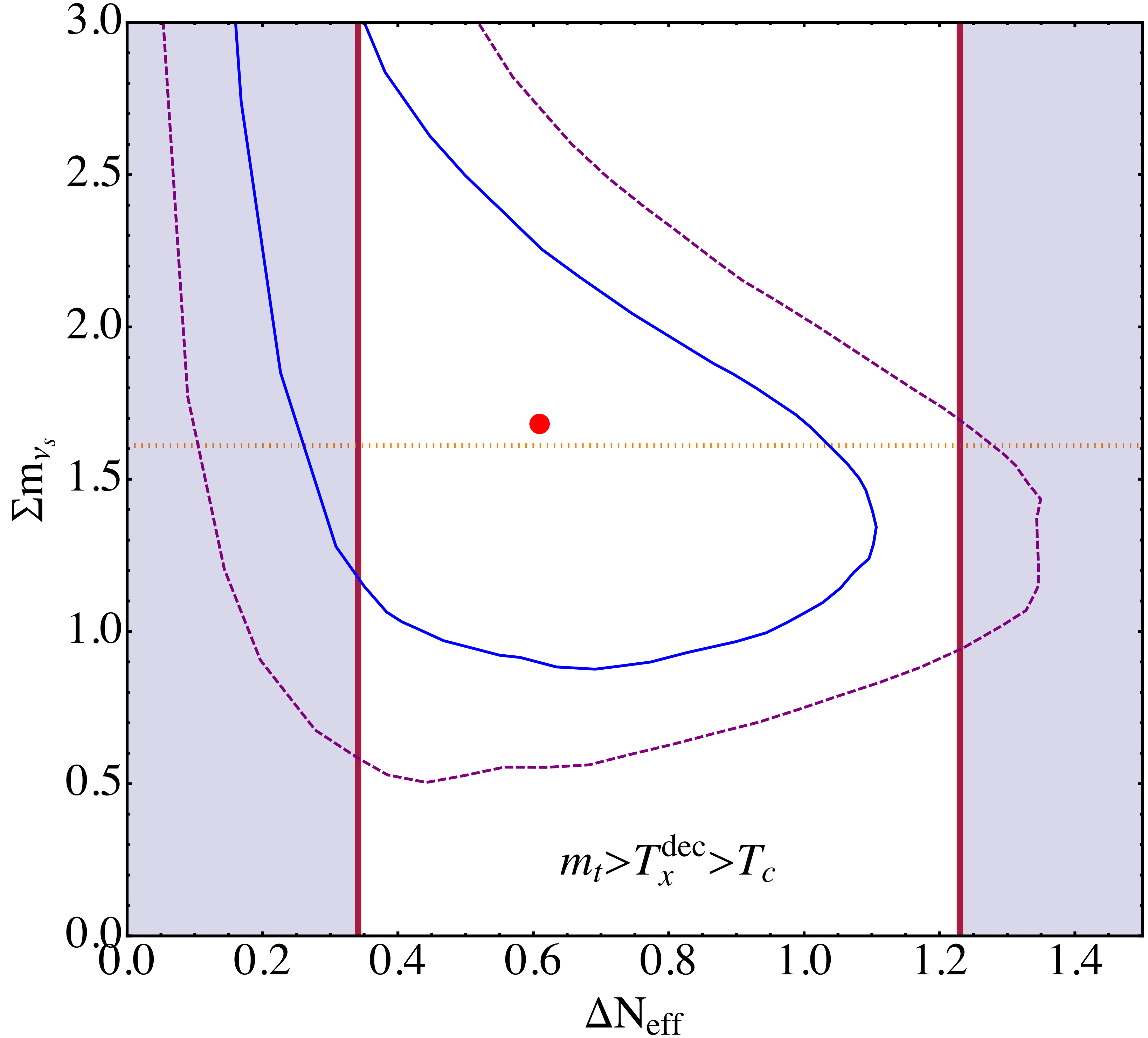
$$g_{*s}^x\left(T_{\rm bbn}\right) = \frac{7}{8} \times (4 \times 2) = 7.$$

$$g_{*s}\left(T_x^{\rm dec}\right) \simeq 72 \text{ for } m_c < T_x^{\rm dec} < m_\tau.$$

It gives

$$\Delta N_{\rm eff} = 4 \times \left[\frac{\frac{43}{4} \times 11}{7 \times 72}\right]^{\frac{4}{3}} \simeq 0.579.$$

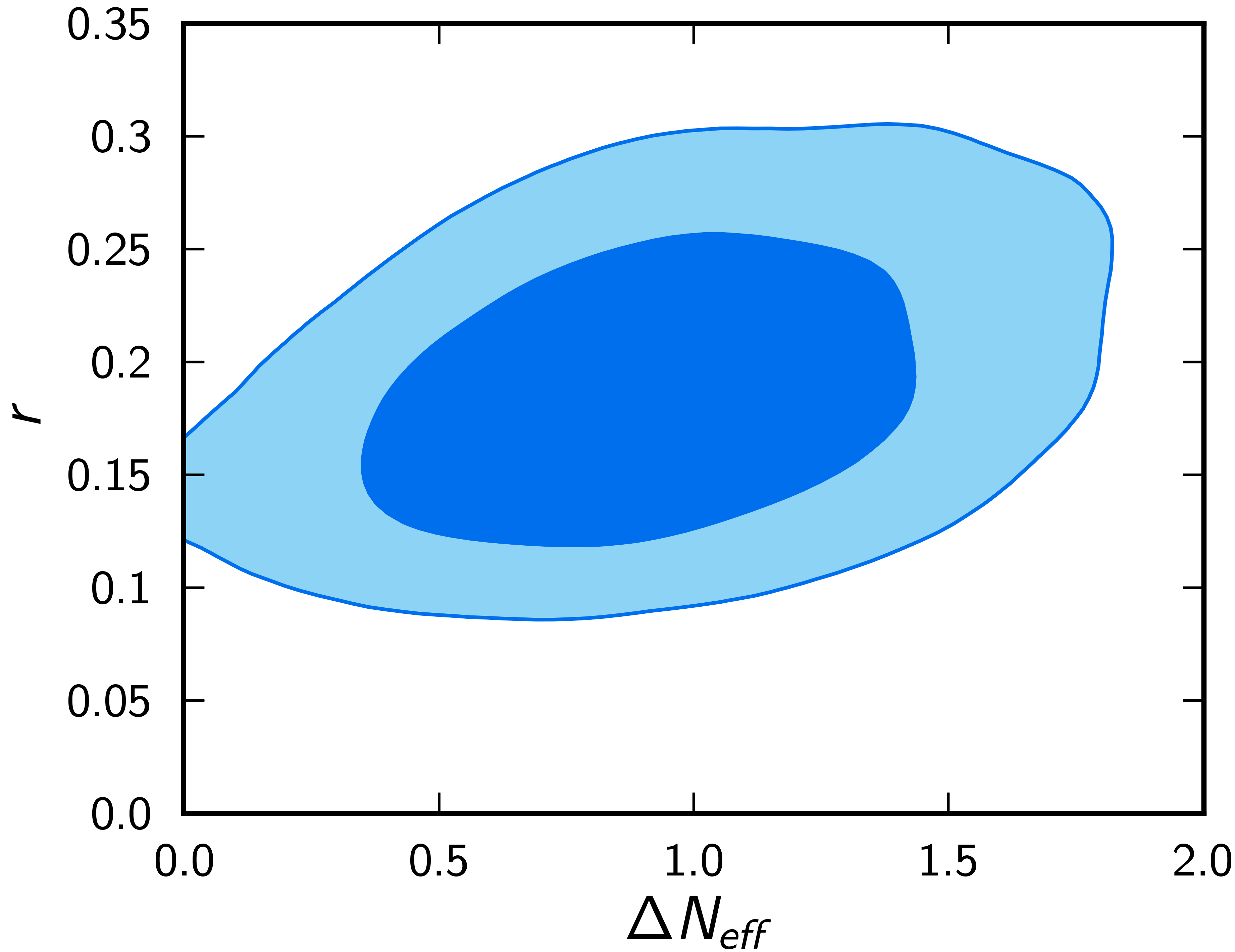
ΔN_{eff}(CMB) and m_{ν_s}



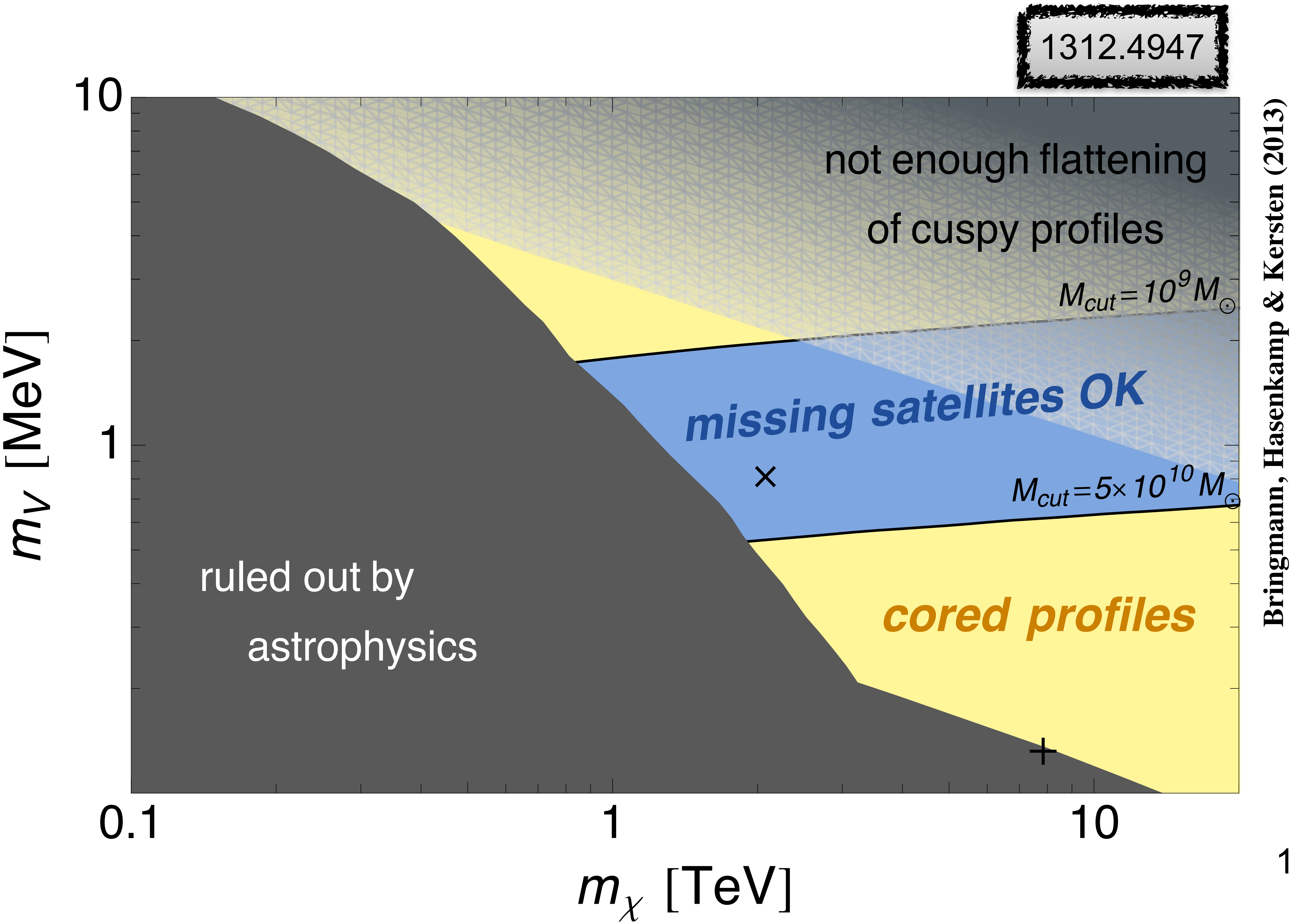
Contours for CMB data, *1308.3255*

Dot line marks the centre value for 3+2 scenario for neutrino

ΔN_{eff} helps reconcile Planck and BICEP2



How?


1312.4947
not enough flattening
of cuspy profiles
$M_{cut}=10^9 M_\odot$
missing satellites OK
$M_{cut}=5\times 10^{10} M_\odot$
ruled out by
astrophysics
cored profiles
m_V [MeV]
m_χ [TeV]
10
1
0.1
1
10
Bringmann, Hasenkamp & Kersten (2013)

Tight bond between sterile neutrinos and DM (Bringmann, Hasenkamp, Kersten)

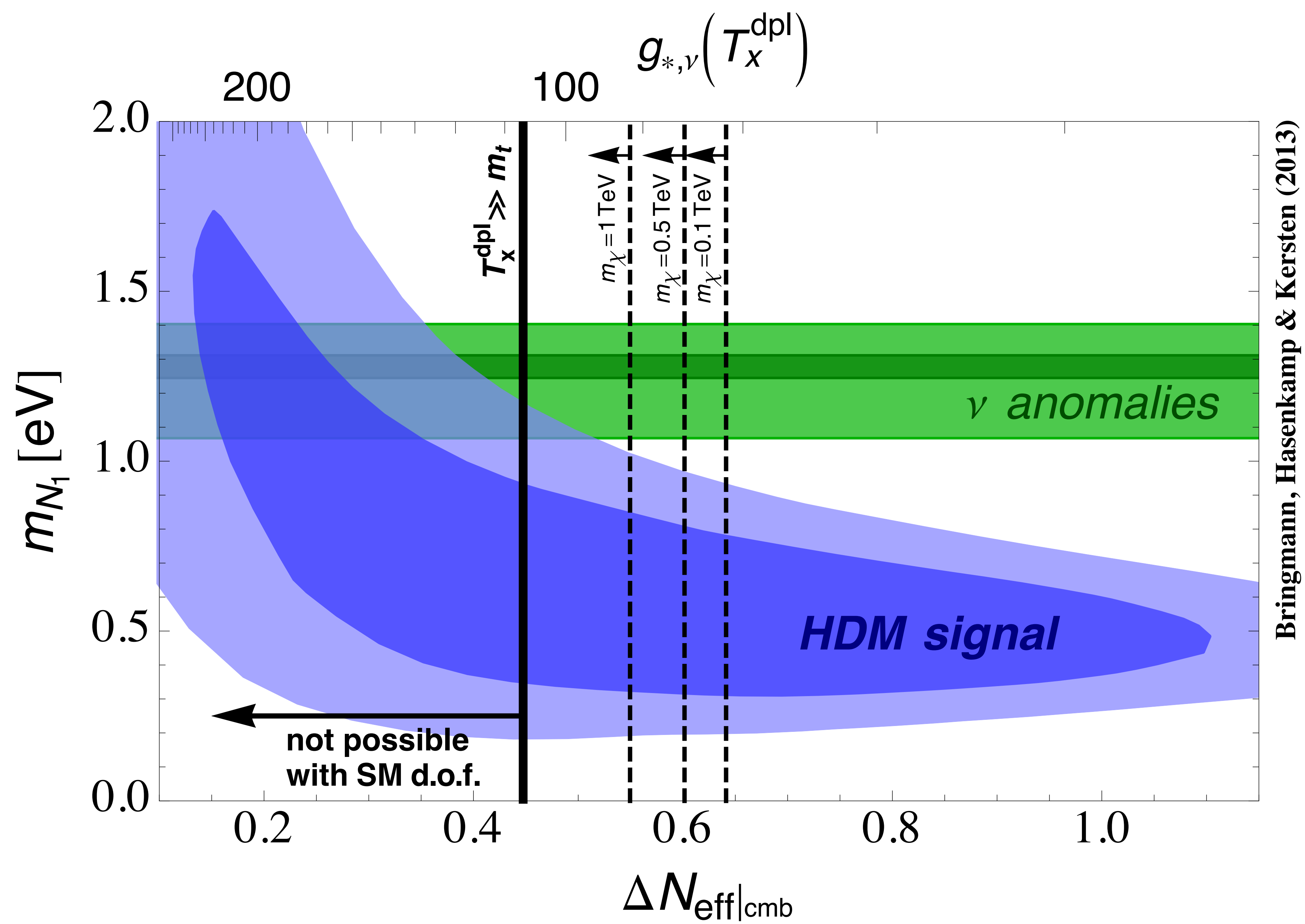
$$\mathcal{L}_R \supset -\frac{1}{2}\overline{\nu^c_{R_1}} M_1 \nu_{R_1} - \frac{1}{2}\overline{\nu^c_{R_2}} M_2 \nu_{R_2} - \overline{\nu^c_{R_1}} M_{RR} \nu_{R_2} - \overline{\nu_L} M_{LR} \nu_{R_1} + \text{h.c.}\,, \qquad (3)$$

from dim-5 operator

$$\mathcal{L}_x = \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \frac{1}{4}F^x_{\mu\nu}F^{x\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu - g_X V_\mu \left(X_{\nu_R}\overline{\nu_R}_1 \gamma^\mu \nu_{R_1} - X_{\nu_R}\overline{\nu_R}_2 \gamma^\mu \nu_{R_2} + \bar{\chi}\gamma^\mu\chi\right), \qquad (4)$$

Based on local gauge symmetry:
$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

Tight bond between sterile neutrinos and DM (Bringmann, Hasenkamp, Kersten)



Features

- Ultraviolet complete theory for CDM and sterile neutrinos that can accommodate both cosmological data and neutrino oscillation experiments within 1σ level
- DM's self-scattering and scattering-off sterile neutrinos can resolve three controversies for cold DM on small cosmological scales, cusp vs. core,too-big-to-fail and missing satellites problems
- eV sterile neutrinos can fit some neutrino oscillation anomalies, contribute to dark radiation and also reconcile the tension between the data by Planck and BICEP2 on the tensor-to-scalar ratio
- Local Dark Symmetry plays a key role !

- There is a singlet scalar with a small mixing with the SM Higgs boson
- Universal suppression of Higgs signal strengths for both neutral scalars
- No charged scalar bosons
- There could be a light vector boson (dark photon if dark gauge symmetry is U(1) Abelian) weakly coupled to the SM fields
- “How to find them” is an important question for experimentalists