Thermal Dark Matter from Gauged Hidden Sectors

Pyungwon Ko (KIAS)

The 2nd NBIA-APCTP Workshop
Aug. 18-22 (2014)

Key Ideas

- Dark Matter Stability/Longevity
- Local Dark Gauge Symmetry
- Singlet Portals (including Higgs Portal)
- Connections between Higgs, DM and Higgs Inflation
- Related talks by JMCline, EJChun, KYChoi

SM Chapter is being closed

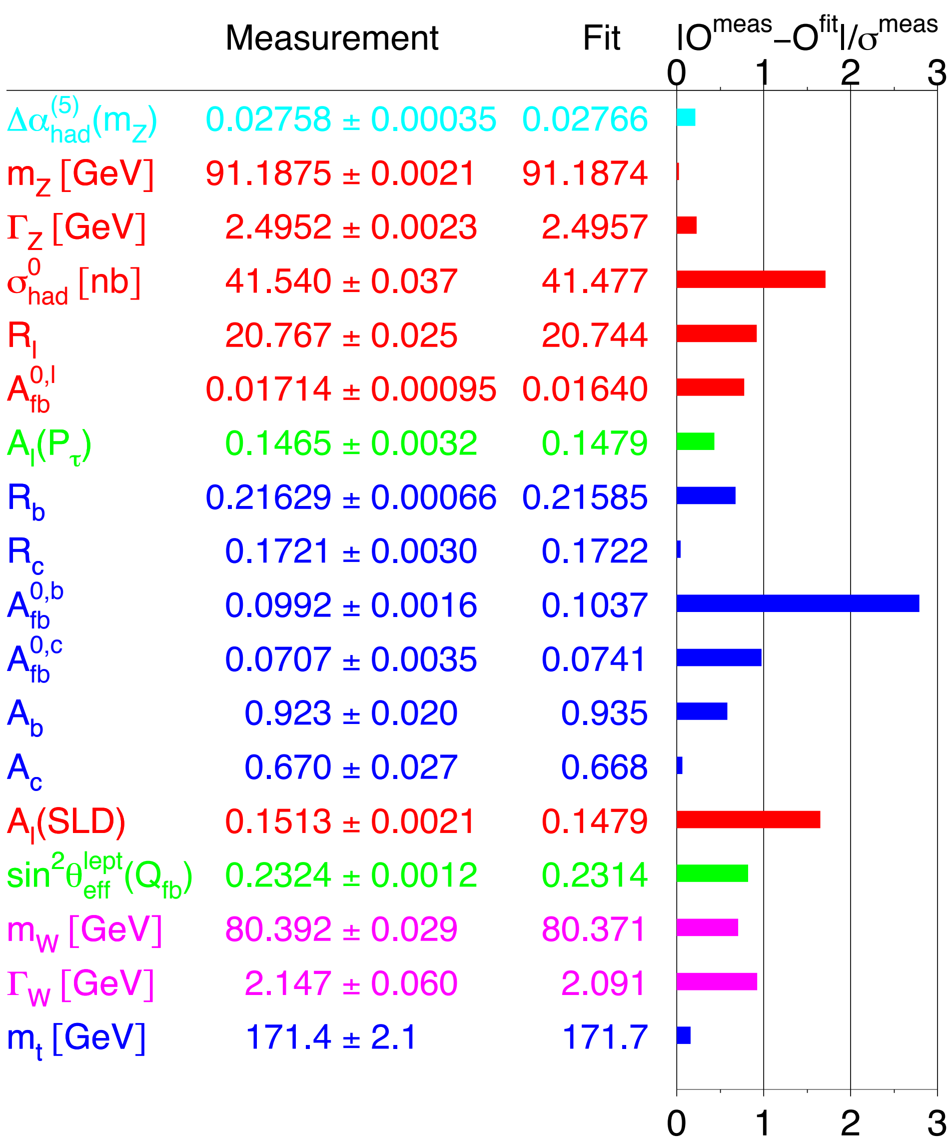
- SM has been tested at quantum level
    - EWPT favors light Higgs boson
    - CKM paradigm is working very well so far
    - LHC found a SM-Higgs like boson around 125 GeV
- No smoking gun for new physics at LHC so far

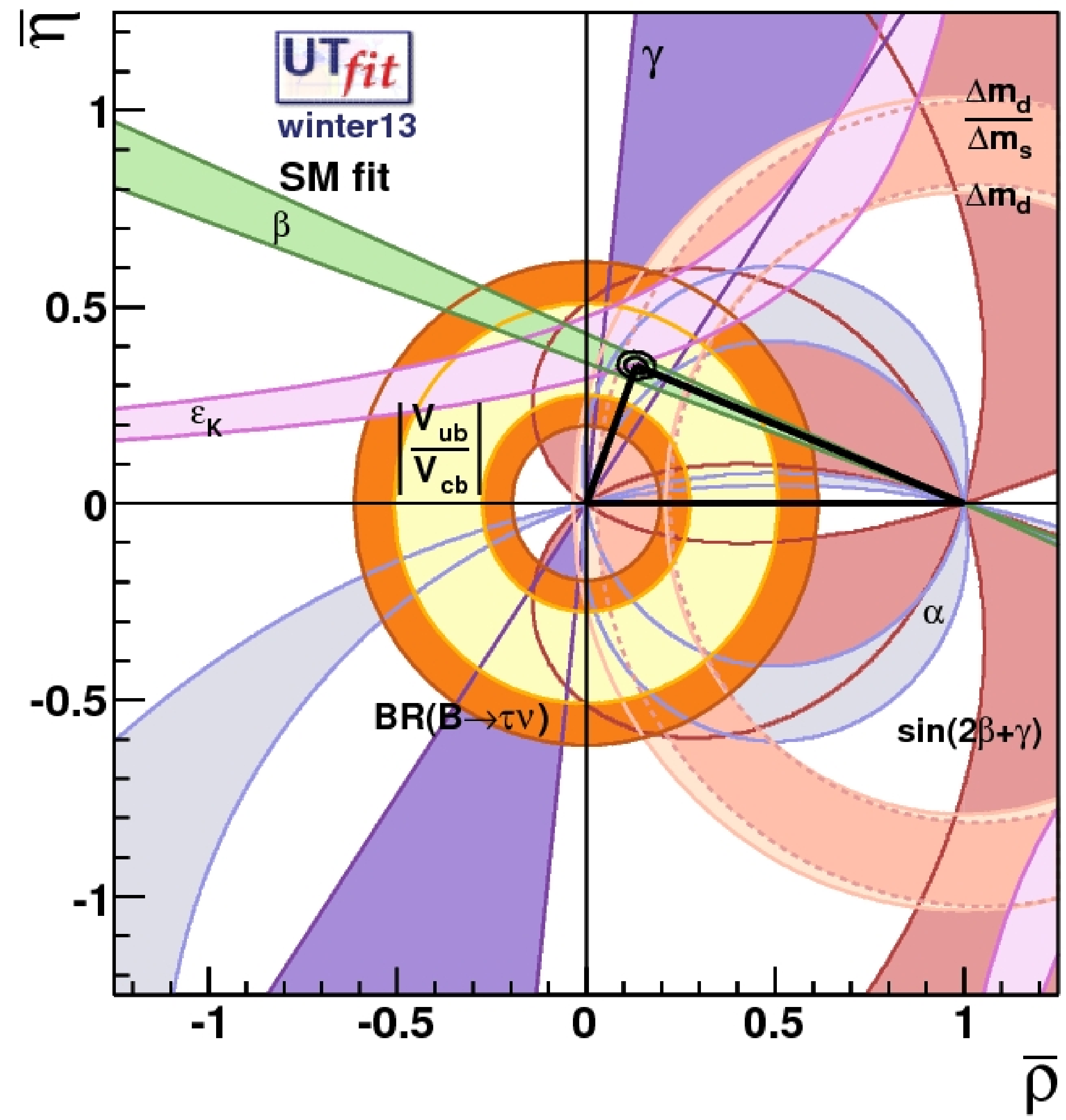
SM Lagrangian

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

Based on local gauge principle

EWPT & CKM



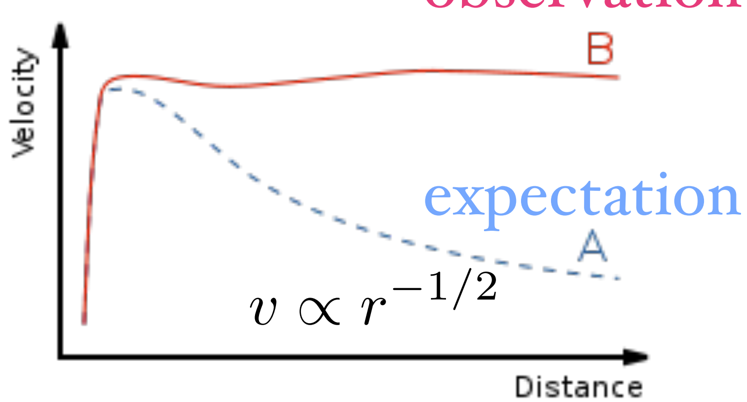


Almost Perfect !

Only Higgs (~SM) and Nothing Else So Far at the LHC &

Local Gauge Principle Works !

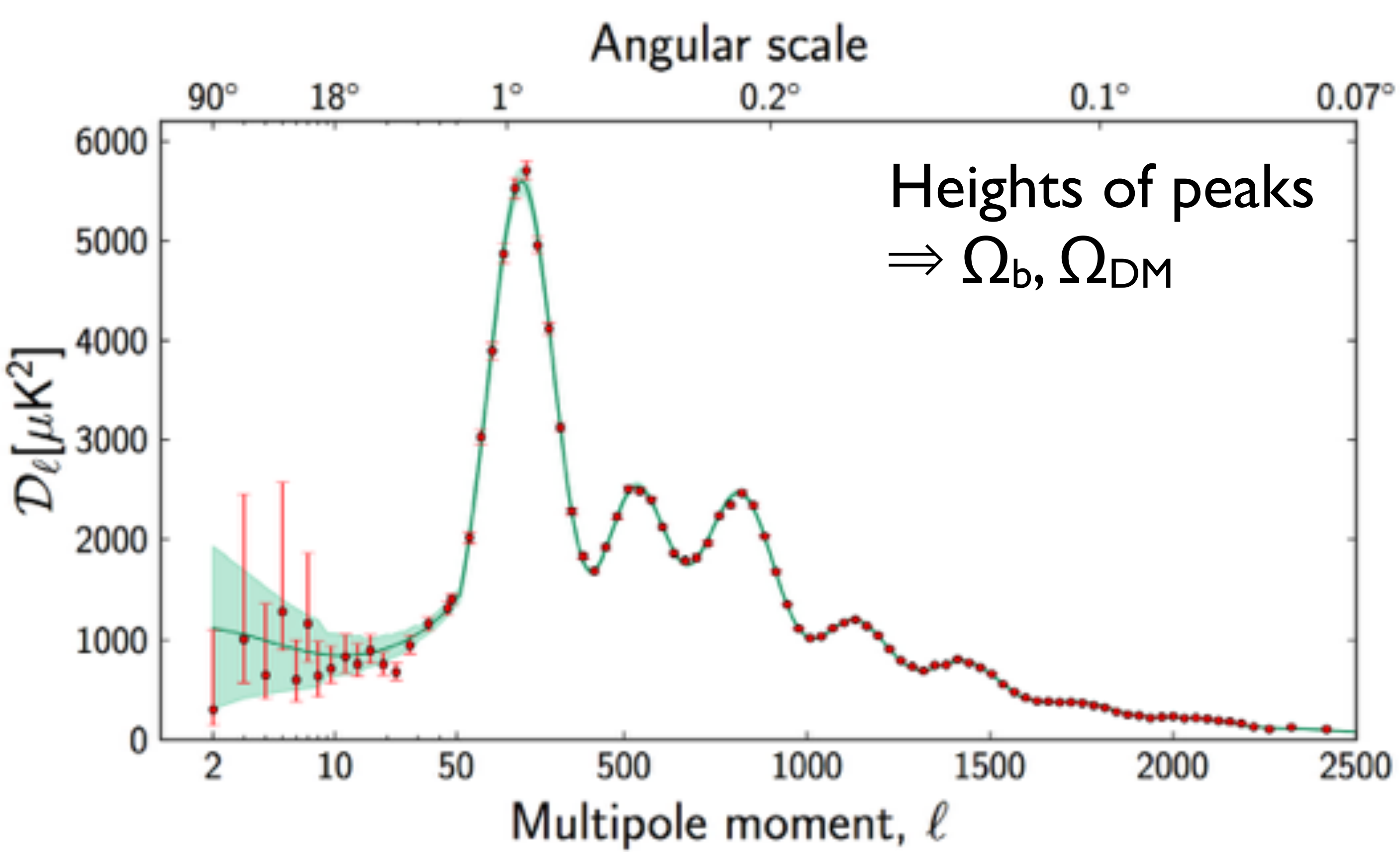
- Dark & visible matter and dark energy, neutrinos



Jan Oort (1932), Fritz Zwicky (1933)

Bullet cluster

Strong gravitational lensing in Abell 1689

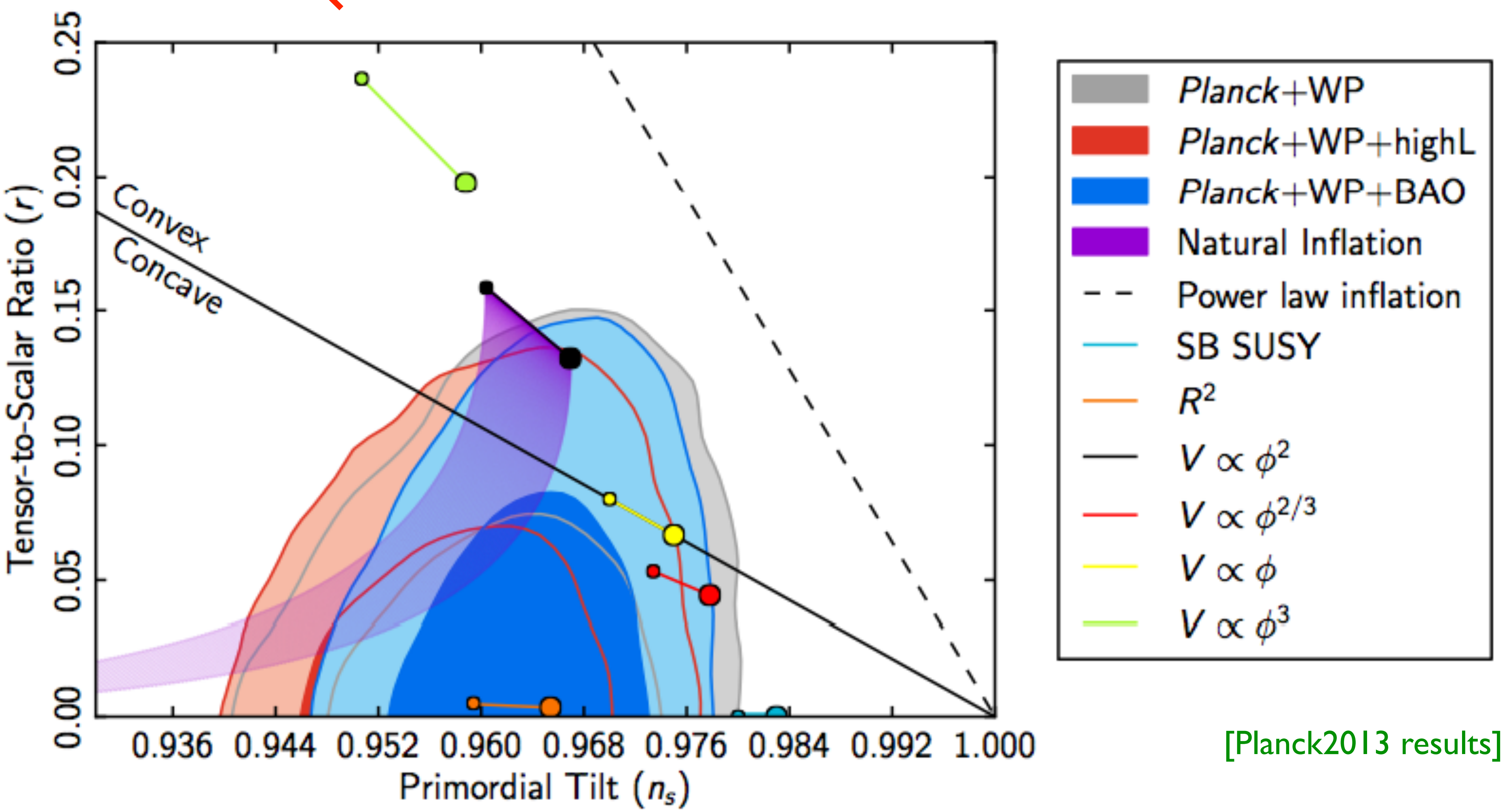


$$\Omega_b \simeq 0.048$$
$$\Omega_{DM} \simeq 0.259$$
$$\Omega_\Lambda \simeq 0.691$$

(Planck+WP+highL+BAO)

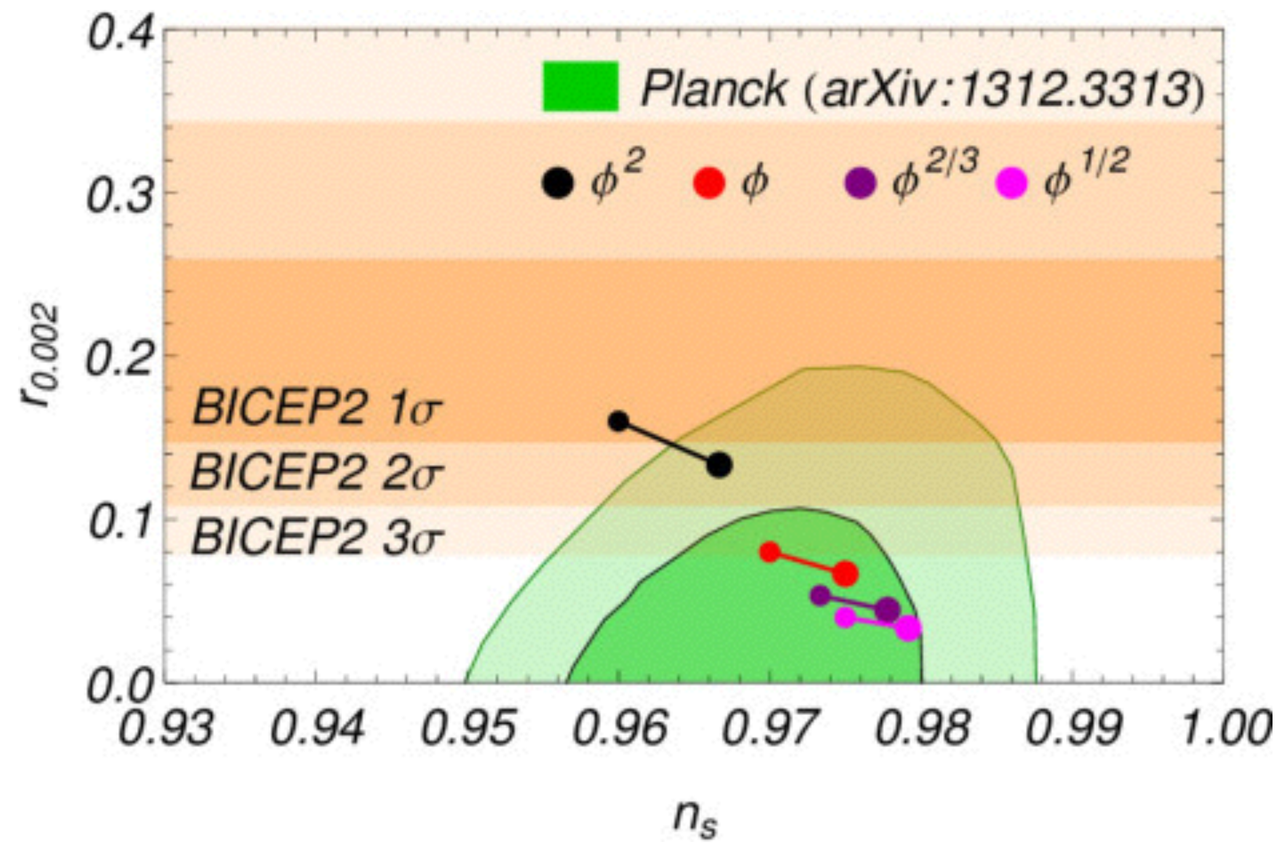
Inflation models in light of Planck2013 data

$V \propto \phi^4$



[Planck2013 results]

Inflation in light of BICEP2



Original Higgs inflation and Starobinsky models are strongly disfavored by BICEP2 (premature?)

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

Origin of EWSB ?

- LHC discovered a scalar ~ SM Higgs boson
- This answers the origin of EWSB within the SM in terms of the Higgs VEV, v
- Still we can ask the origin of the scale "v"
- Can we understand its origin by some strong dynamics similar to QCD or TC ?

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)

Motivations for BSM

- Neutrino masses and mixings
- Baryogenesis
- Inflation (inflaton)
- Nonbaryonic DM
- Origin of EWSB and Cosmological Const ?

Leptogenesis

Starobinsky ? Higgs Inflations

Many candidates

Can we attack these problems ?

New minimal SM (NMSM)

- Lagrangian

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

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

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

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

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

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

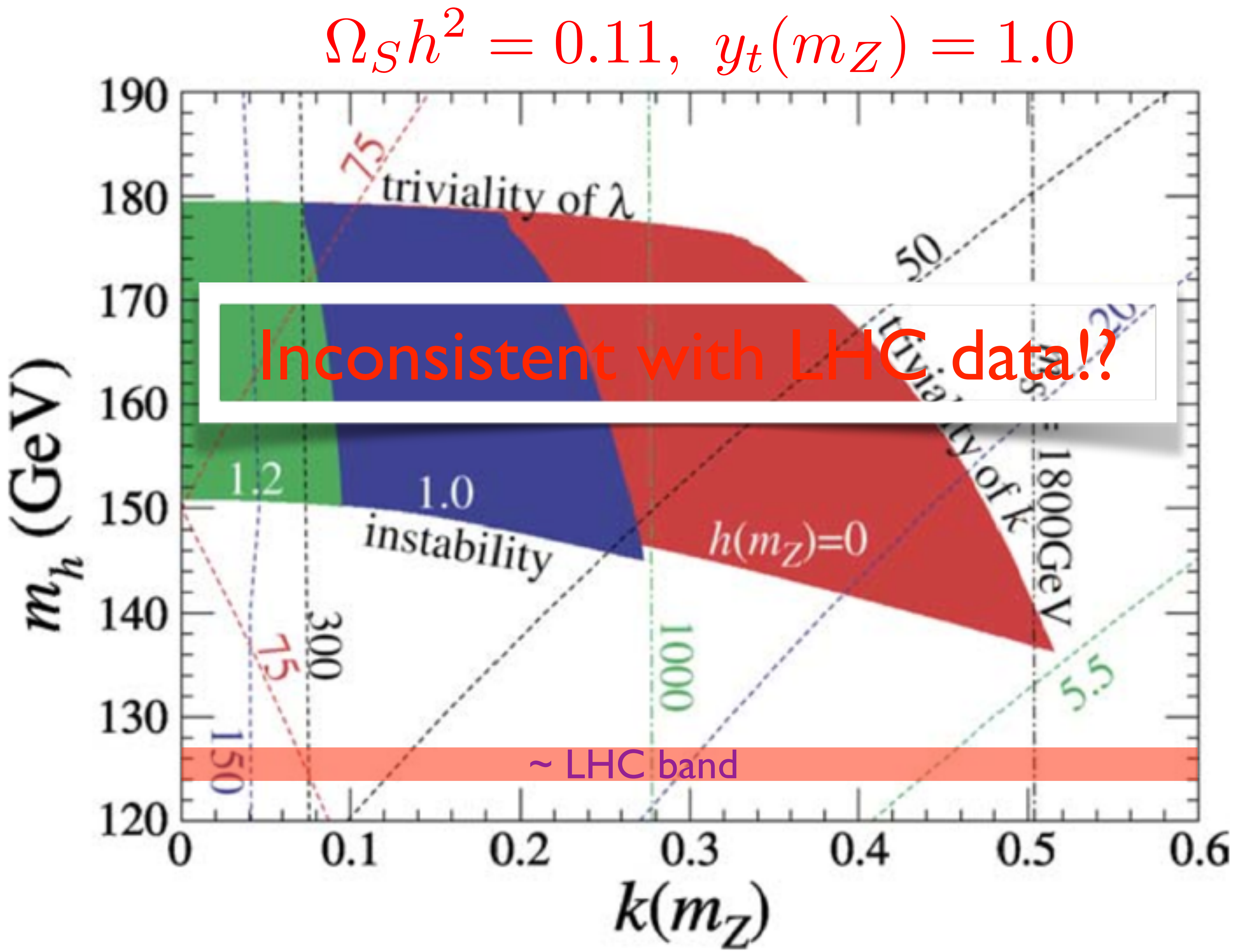
⇦
$m \simeq 1.8 \times 10^{13}{\rm GeV}$
$\mu \lesssim 10^6{\rm GeV}$
$\kappa \lesssim 10^{-14}$

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

- 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



$\boldsymbol{\lambda}$ = quartic coupling of Higgs, $\boldsymbol{h}$ = quartic coupling of S (DM)
$\boldsymbol{k}$ = mixed quartic coupling of Higgs and DM

New Minimal SM

☞ Without Gauge Principle in new terms
(cf. SM was guided by gauge principle)

☞ Z_2 does not guarantee the stability of DM

☞ Inconsistent with present data

Any Alternatives ??

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

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

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

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

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)

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

- Most studies on DM were driven by some anomalies: 511 keV gamma ray, PAMELA/ AMS02 positron excess, DAMA/CoGeNT, Fermi/LAT 135 GeV gamma ray, 3.5 keV Xray, Gamma ray excess from GC etc
- On the other hand, not so much attention given to DM stability/longevity in nonSUSY DM models
- I will be mainly concerned about DM stability/longevity, postponing the question of Naturalness Problem
- They are independent problems in principle

In QFT

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (hidden sector pions and baryons)
- I will mainly talk about local Z_2, Z_3 + EWSB & CDM from strongly interacting hidden sector, since other cases were discussed last year (backup slides FYI)

Contents

- Underlying Principles : Hidden Sector DM, Singlet Portals, Renormalizability, Local Dark Gauge Symmetry
- Scalar DM with local Z3, Z2 : comparison with global models, limitation of EFT approach, and phenomenology
- Scale Inv Extension of the SM with strongly Int. Hidden Sector : EWSB and CDM from hQCD; All Masses including DM mass from Dim Transmutation in hQCD, DM stable due to accidental sym
- Higgs Phenomenology & Higgs Inflation with extra singlet : Universal Suppression of Higgs signal strength and extra neutral scalar, Higgs inflation, etc.

see backup slides

- (un)broken $U(1)_X$: Singlet Portal and Dark Radiation; h-monopole
- Tight bond between DM-sterile nu's with $U(1)_X$: Dark Radiation

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 local 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.

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 ?

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.)

New Physics Scale ?

- No theory for predicting new physics scale, if our renormalizable model predictions agree well with the data
- Only data can tell where the NP scales are
- Given models working up to some energy scale, we can tell new physics scale if Unitarity is violated, or Landau pole or Vacuum Instability appears
- Otherwise we don't know for sure where is new physics scale

Neutral Kaon System

- Often said that the charm is predicted in order to solve the quadratic divergence in Delta MK
- This is not really true, since this comes from anomalous model (SM with three quarks and leptons are anomalous)
- If we imposed anomaly cancellation, we would have no quadratic div in Delta MK and no large FCNC from the beginning
- Important to work within theoretically consistent model Lagrangian to get correct phenomenology

Guiding Principles

- Data driven problems : New particles or new phenomena (DM, Neutrino masses and mixings, baryon # asymmetry, etc)

- Theoretical problems : Unitarity, Anomaly Cancellation, (Renormalizability) Very important to keep them

- Fine tuning problems : Higgs mass, Strong CP, Cosmological Constant, etc >> << Let me postpone considering these problems for the moment, since it does not violate any theoretical principles >> Anthropic principle (?) >><< We may miss some interesting possibilities if we stick to this principle too much in this era of LHC and many other expt's>>

Principles for DM Physics

- Local Gauge Symmetry for DM

  - can make DM absolutely stable

  - all the known particles feel gauge force

- Renormalizability with some caveat

  - does not miss physics which EFT can not catch.

- Singlet portals

  - allows communication of DS to SM (thermalization, detectability, ...)

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

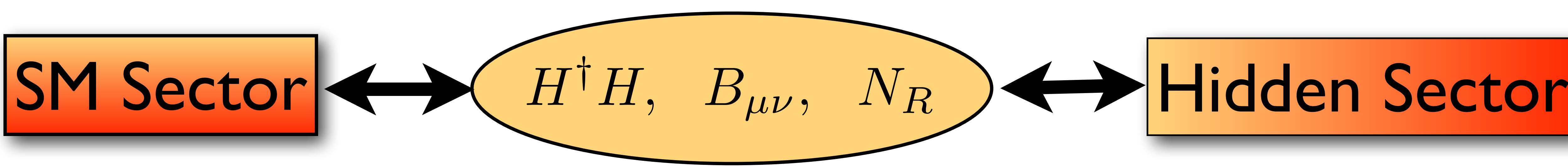
in preparation with Baek and W.I. Park

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



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

Generic Aspects

- Two types of force mediators :
  - Higgs-Dark Higgs portals (Higgs-singlet mixing)
  - Kinetic portal to dark photon for U(1) dark gauge sym (absent for non-Abelian dark gauge sym@renor. level)
  - Naturally there due to underlying dark gauge symmetry
- RH neutrino portal if it is a gauge singlet (not in the presence of U(1) B-L gauge sym)
- These (especially Higgs portal which has been often neglected) can thermalize CDM efficiently

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 Portals

- Singlets (up to dim=5) in EFTs

$$\text{Singlet Scalar}: S^n H^\dagger H \quad (n = 1-3)$$

$$\text{Singlet Fermion}: \frac{1}{\Lambda}\bar{\psi}(a + b\gamma_5)\psi H^\dagger H$$

$$\text{Singlet Vector}: V_\mu V^\mu H^\dagger H$$

Non-renormalizable
or
not gauge-invariant,
not unitary!

* A global Z_2 sym. could be imposed for DM, but gravity is expected to break the sym.

[See 1402.2115, Seungwon Baek, P. Ko, WIP and Yong Tang for example]

- Charged fields in renormalizable models

$$\text{Scalar}: \Phi^\dagger \Phi H^\dagger H \quad (\Phi \text{ can be a dark higgs})$$

$$\text{Fermion}: S\overline{\psi}(a + b\gamma_5)\psi + S^2 H^\dagger H$$

$$\text{Vector}: |D_\mu \Phi|^2 \to V_\mu V^\mu \Phi^\dagger \Phi$$

gauge-invariant and unitary!

A scalar is necessary to connect to SM

Higgs portal DM as examples

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

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

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

All invariant under ad hoc Z2 symmetry

A. Djouadi, et.al. 2011 de Simone, Giudice, Strumia (2014)

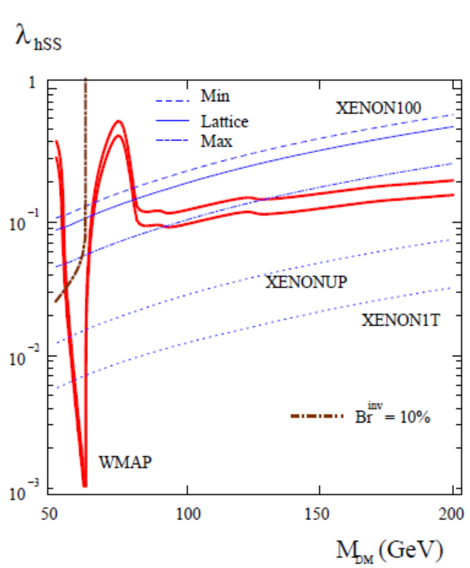


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

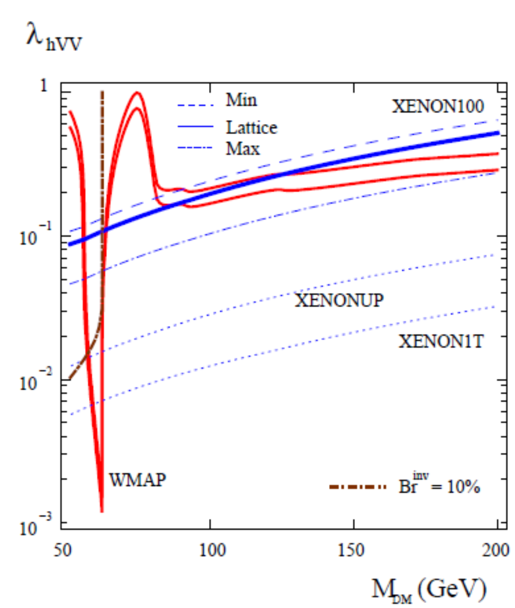


FIG. 2. Same as Fig. 1 for vector DM particles.

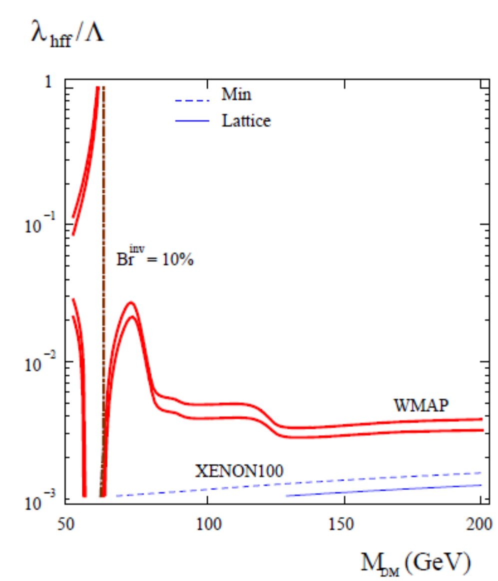


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

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

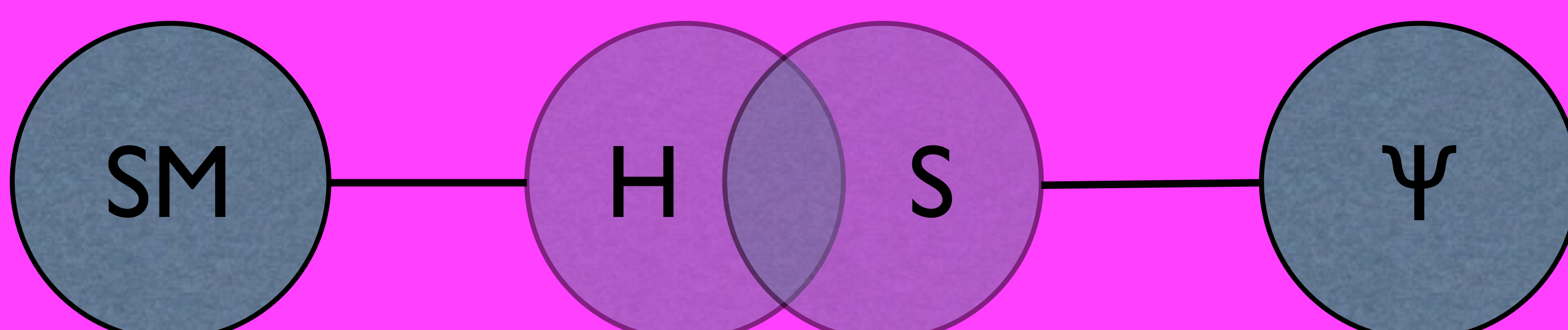
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

$\mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H$ → mixing

$\lambda S \overline{\psi}\psi$ → 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

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

$$H_1 = h\cos\alpha - s\sin\alpha,$$

$$H_2 = h\sin\alpha + s\cos\alpha.$$

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

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

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

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)

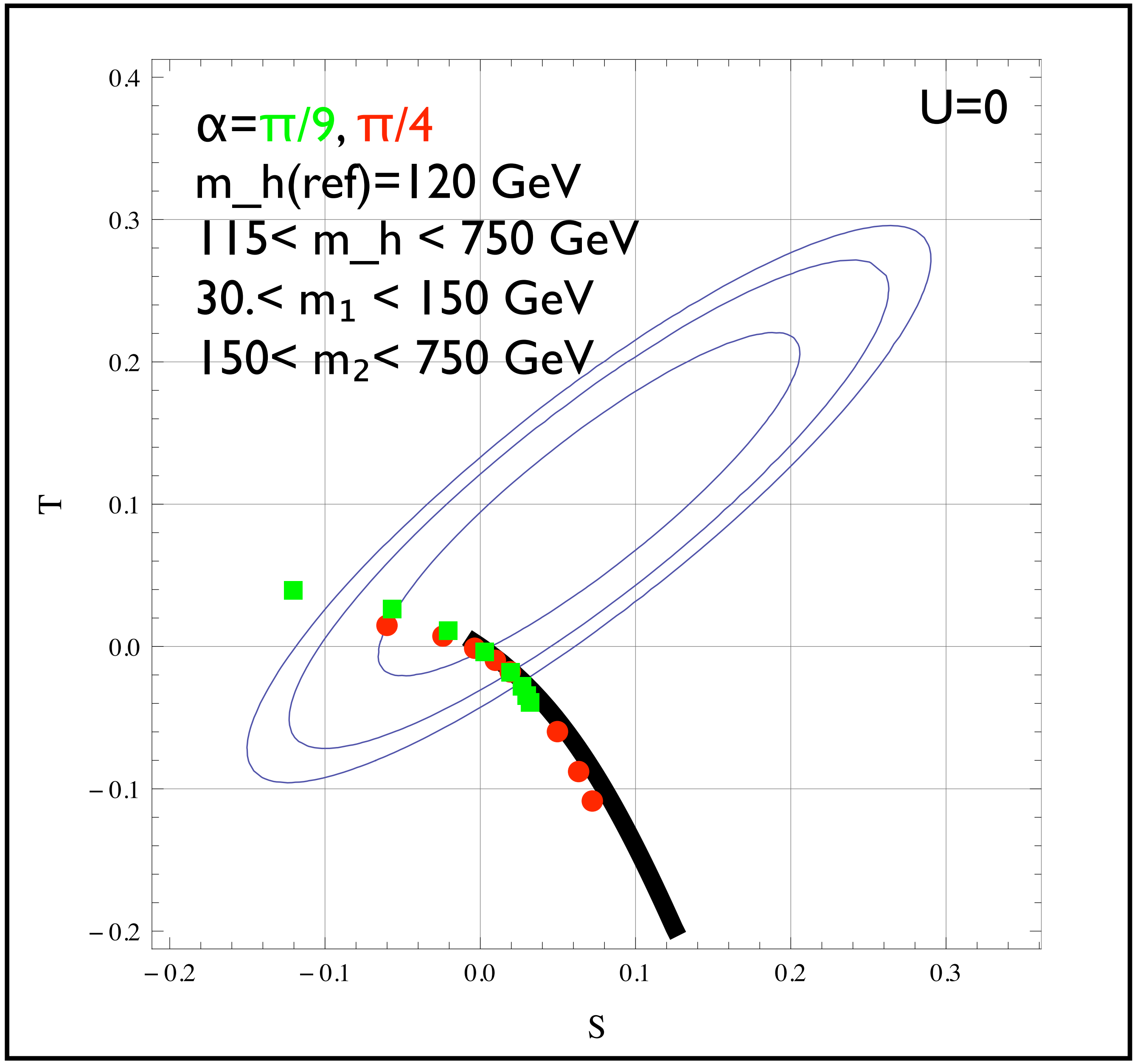
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right]$$

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

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

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

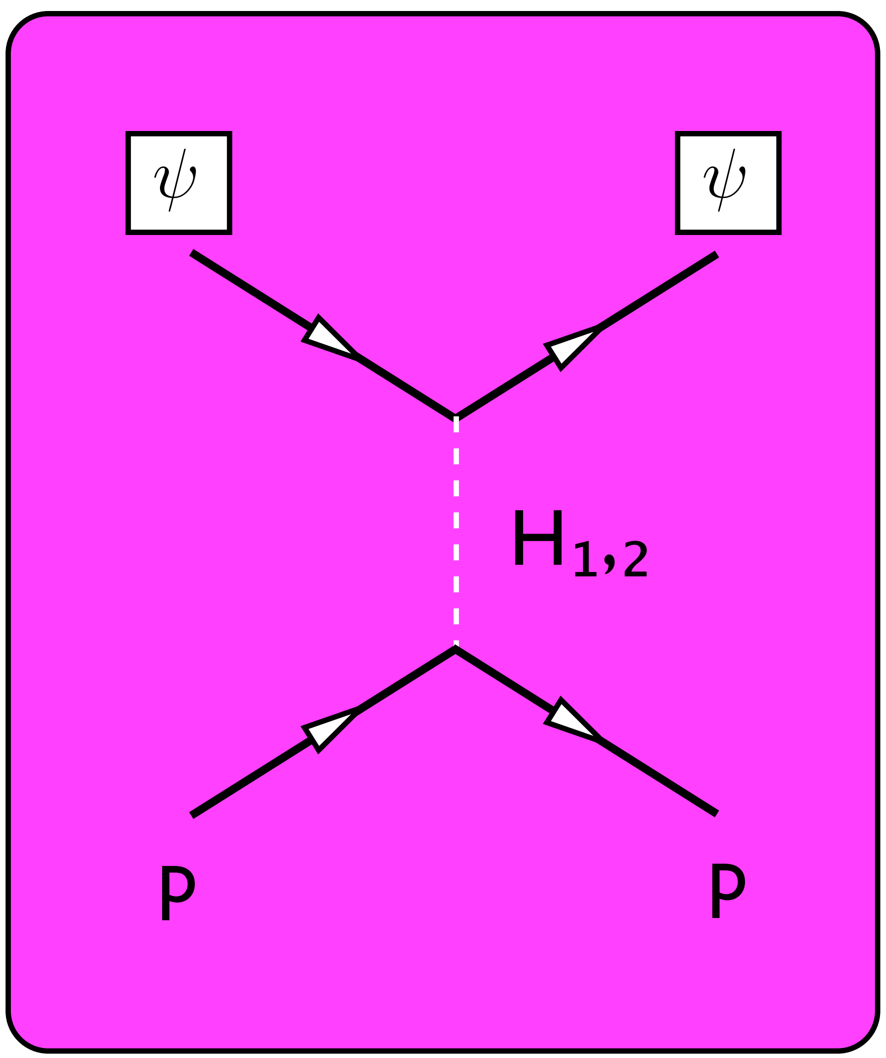
Same for T and U

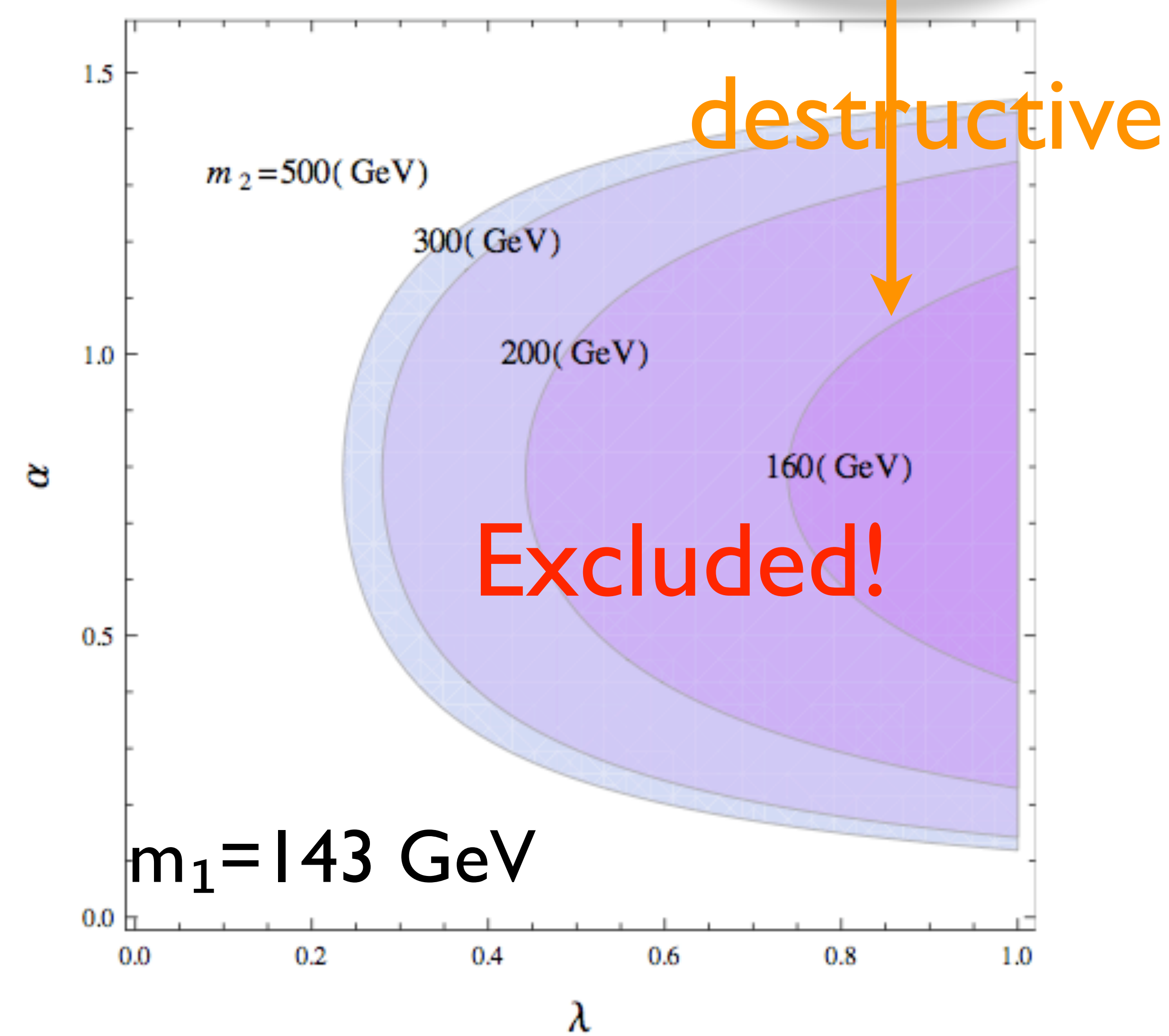


Constraints

- Dark matter to nucleon cross section (constraint)

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





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

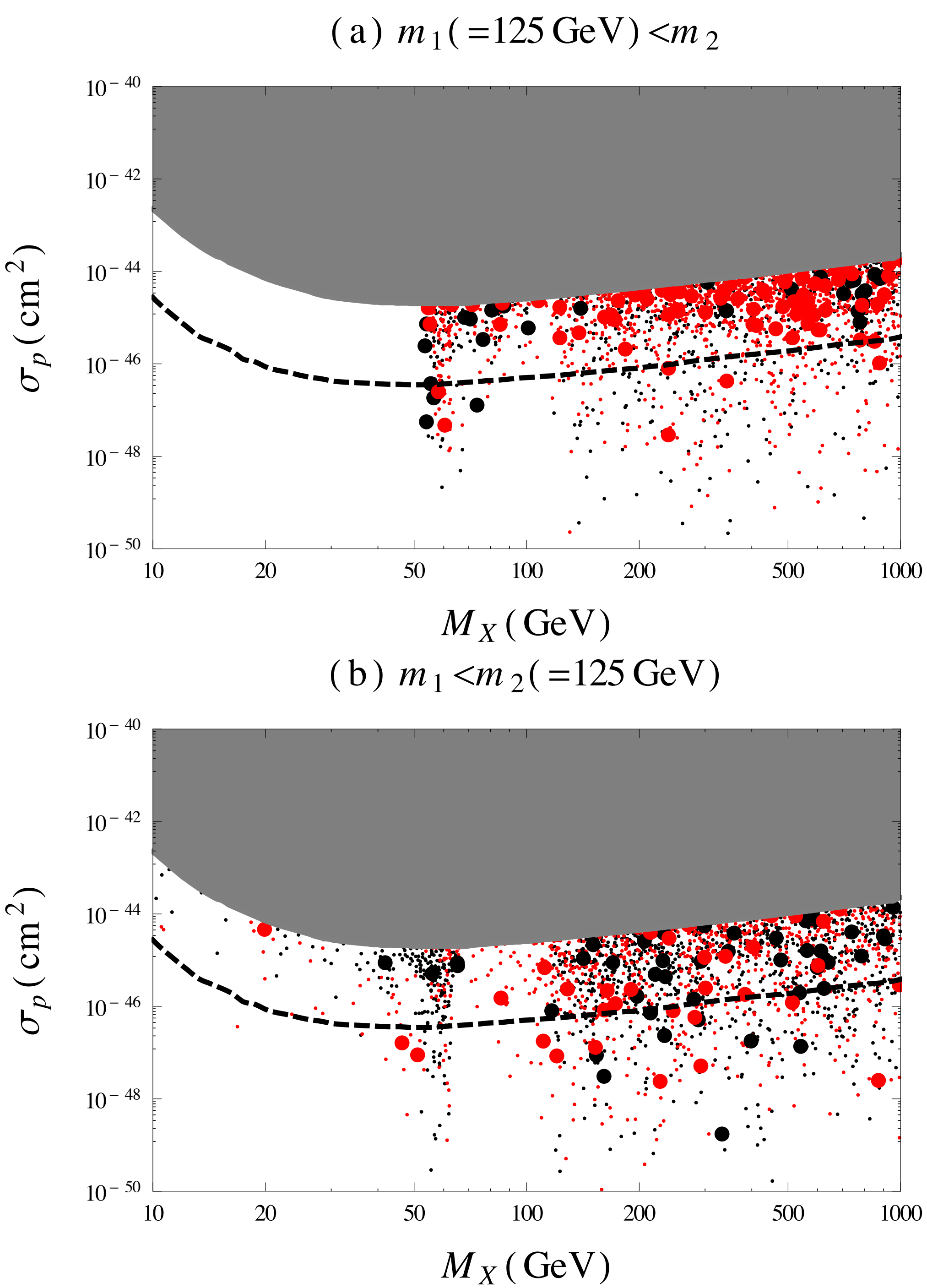


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

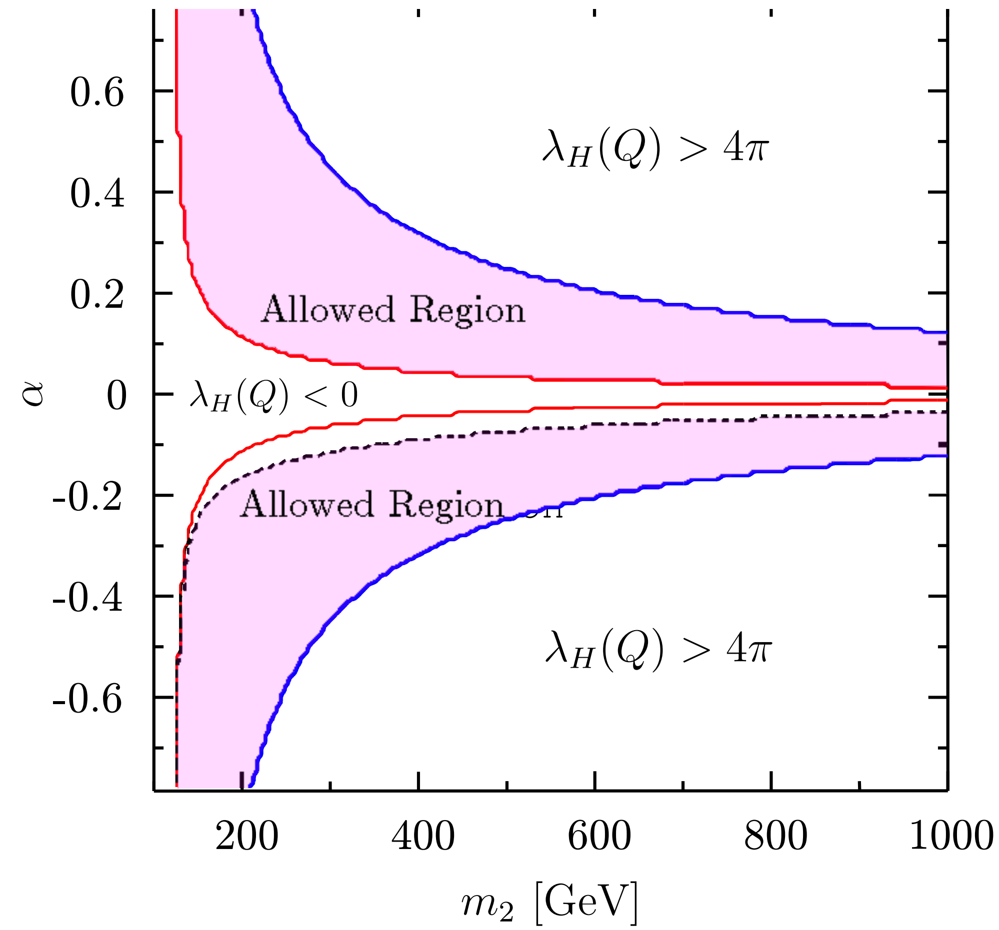


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

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 de Simone, Giudice, Strumia (2014)

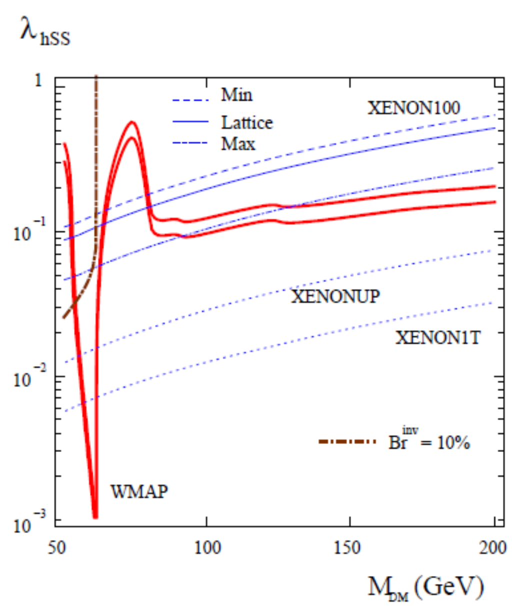


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

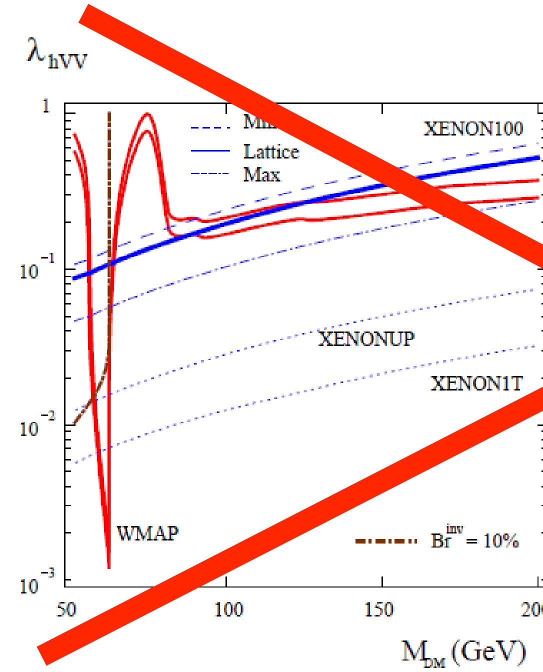


FIG. 2. Same as Fig. 1 for vector DM particles.

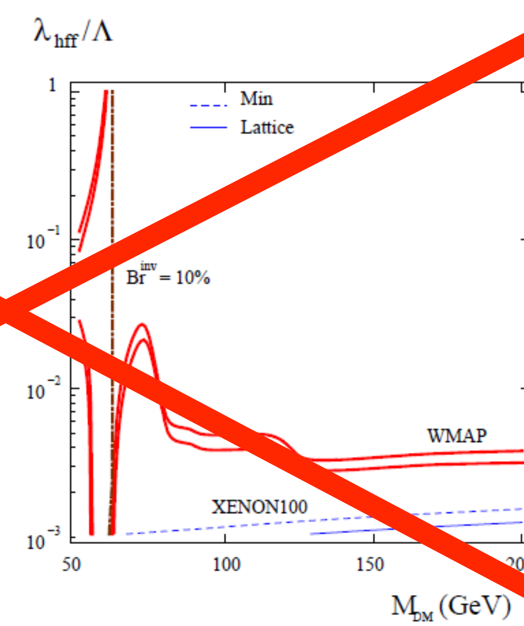
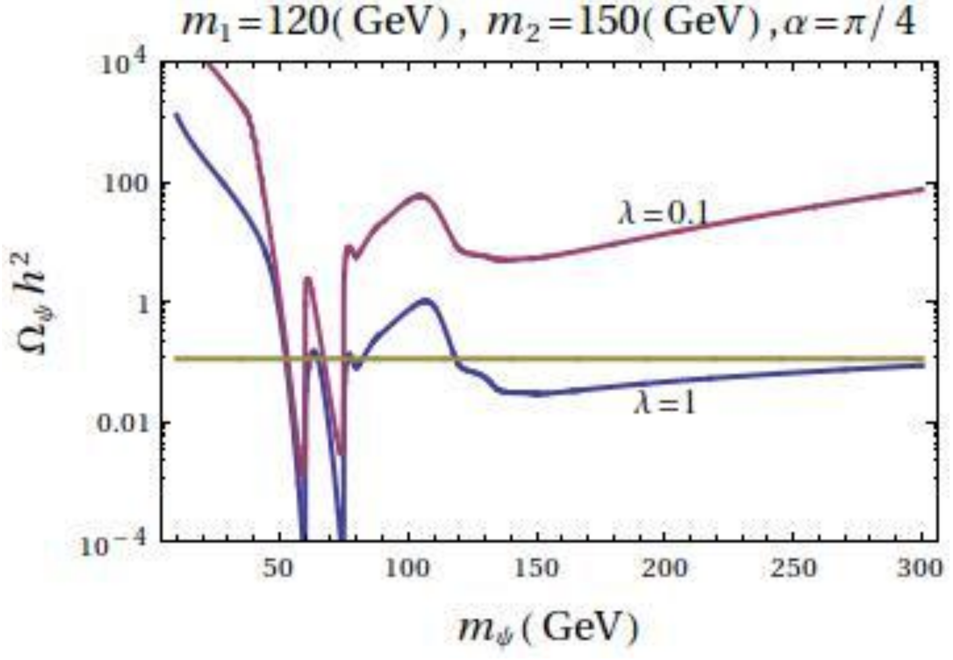


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian, we get different results !

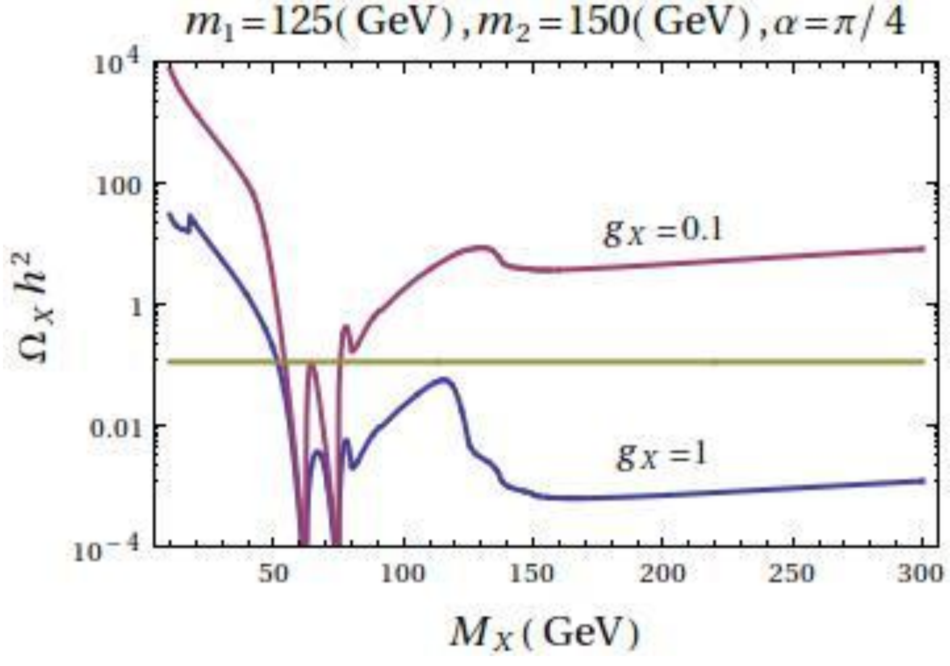
DM relic density

SFDM



P-wave annihilation

VDM



S-wave annihilation

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

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

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

Breaks SM gauge sym

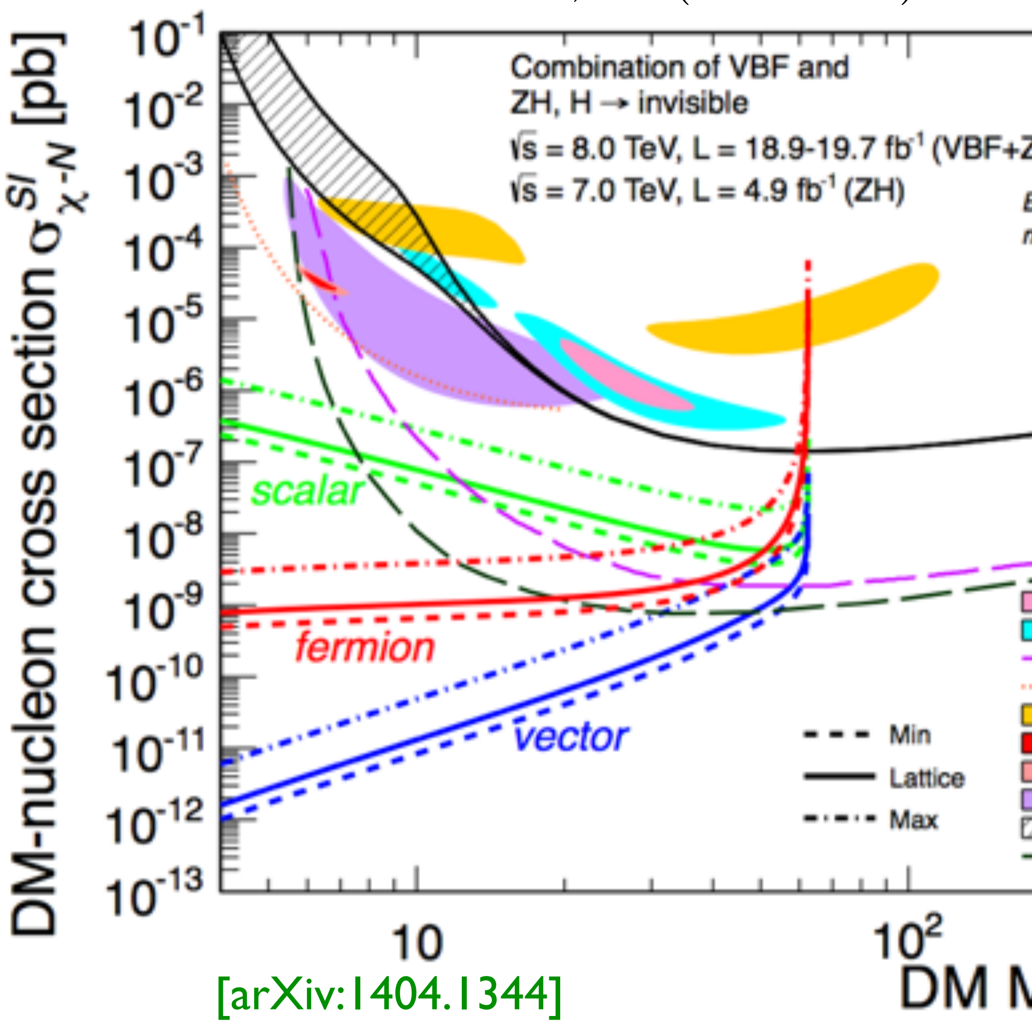
- Only one Higgs boson (alpha = 0)

- 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

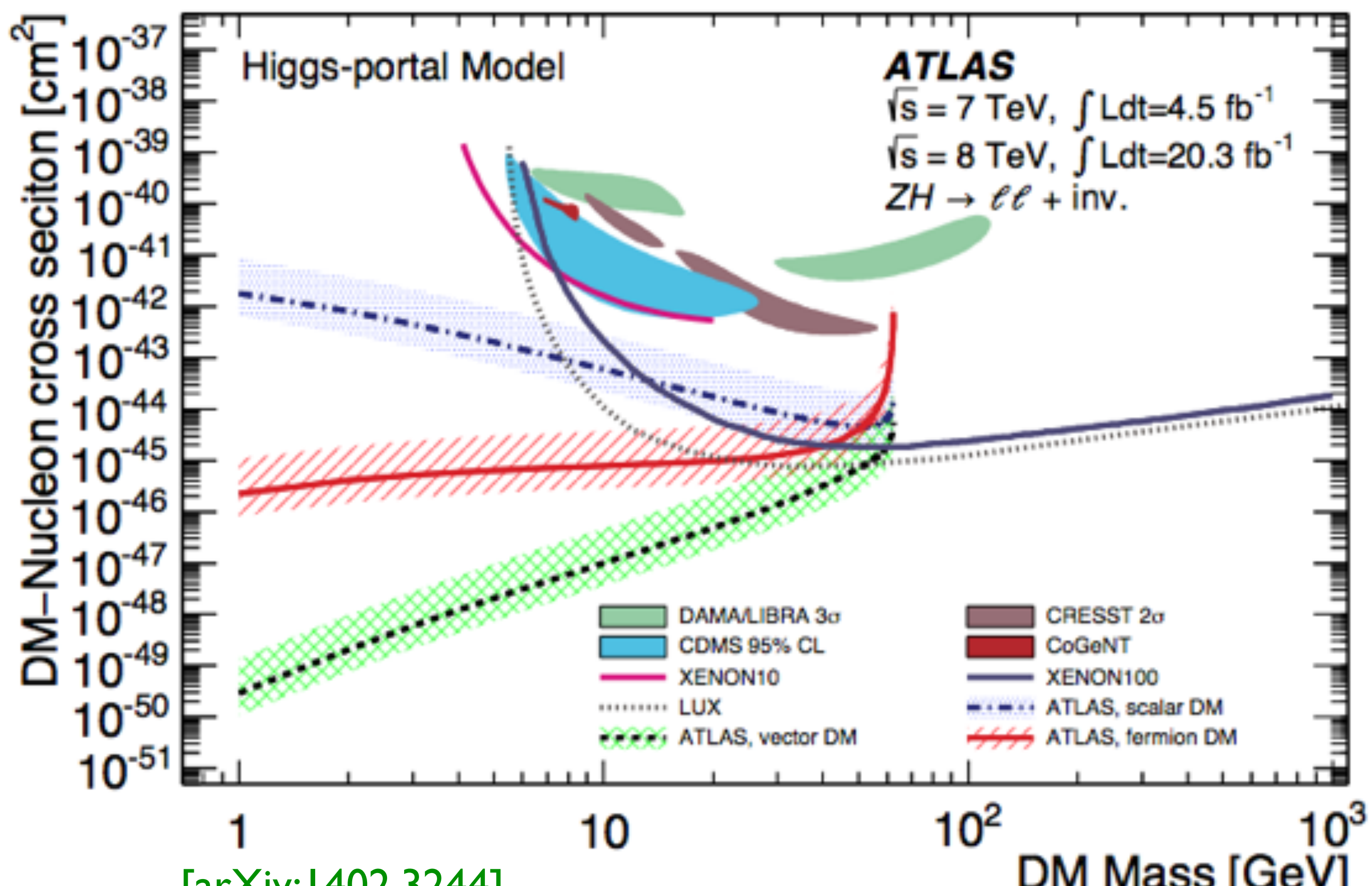
- DM-nucleon scattering in EFT Higgs portals

$m_h = 125\mathrm{GeV},\ \mathrm{Br}(H \to \mathrm{inv}) < 0.51$ at 90% CL



[arXiv:1404.1344]

$m_h = 125.5\mathrm{GeV},\ \mathrm{Br}(H \to \mathrm{inv}) < 0.52$ at 90% CL



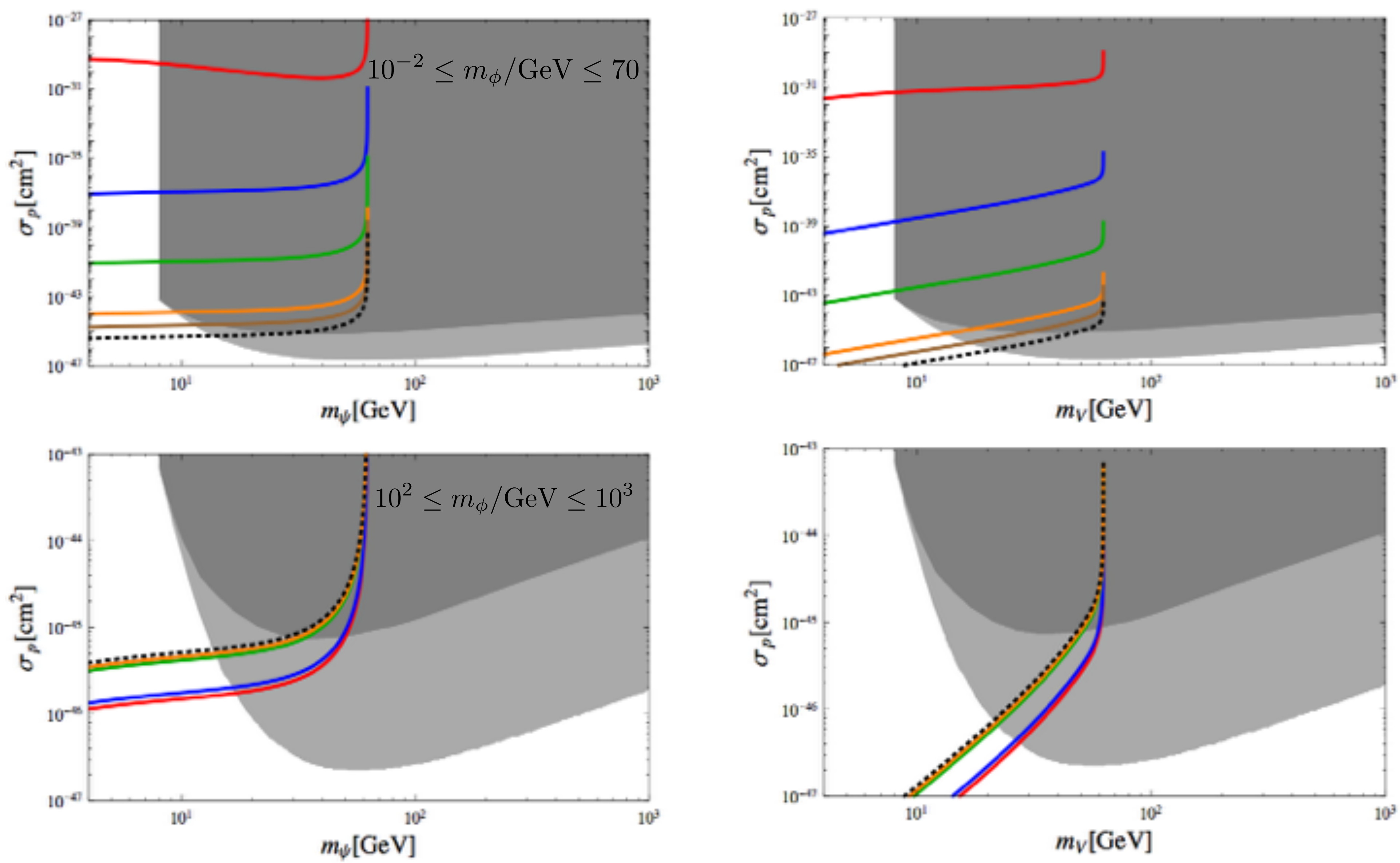
[arXiv:1402.3244]

- However, in renormalizable unitary models of Higgs portals, [arXiv: 1405.3530, Seungwon Baek, P. Ko & WIP]

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial\!\!\!/ - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4 .$$

$$\sigma_p^{\rm SI} \propto (s_\alpha c_\alpha)^2 \left(\frac{1}{m_\phi^2} - \frac{1}{m_h^2}\right)^2$$

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

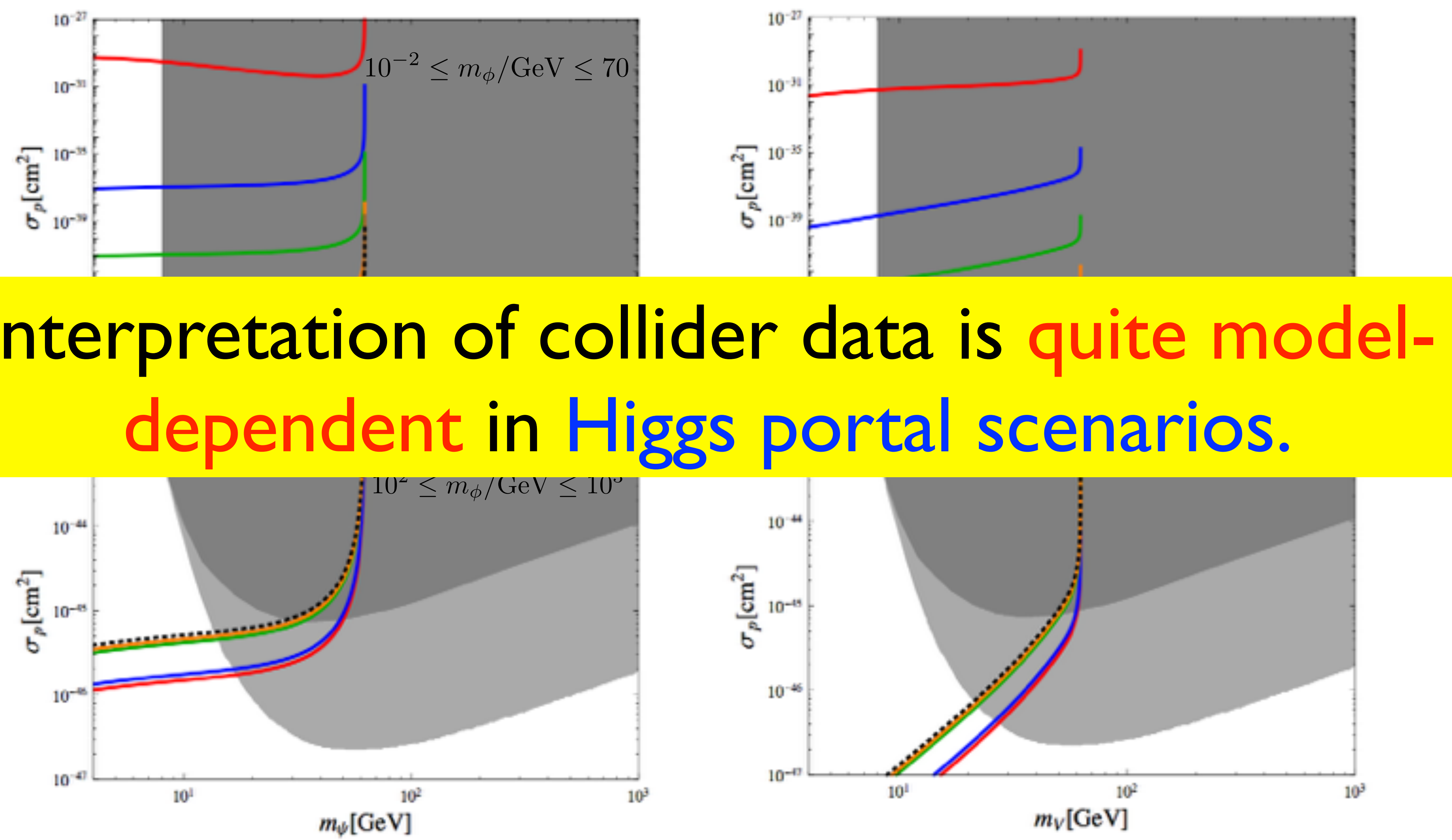


- However, in renormalizable unitary models of Higgs portals,

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\sigma_p^{\rm SI} \propto (s_\alpha c_\alpha)^2 \left(\frac{1}{m_\phi^2} - \frac{1}{m_h^2}\right)^2$$

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

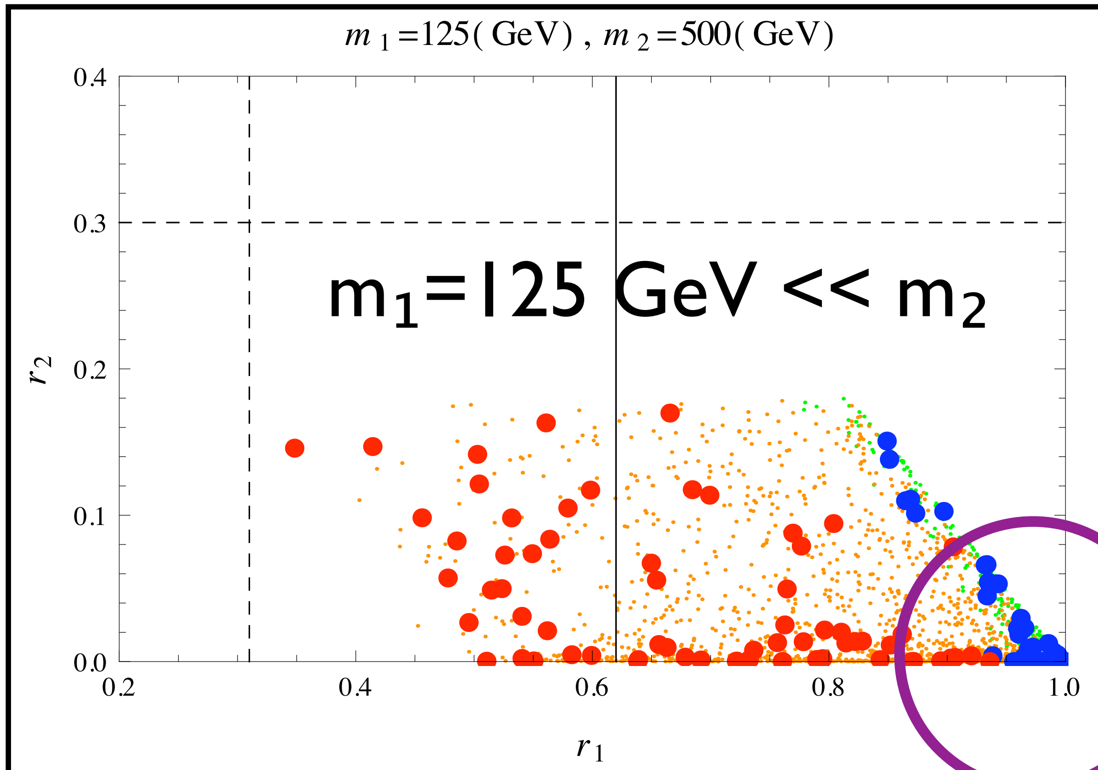


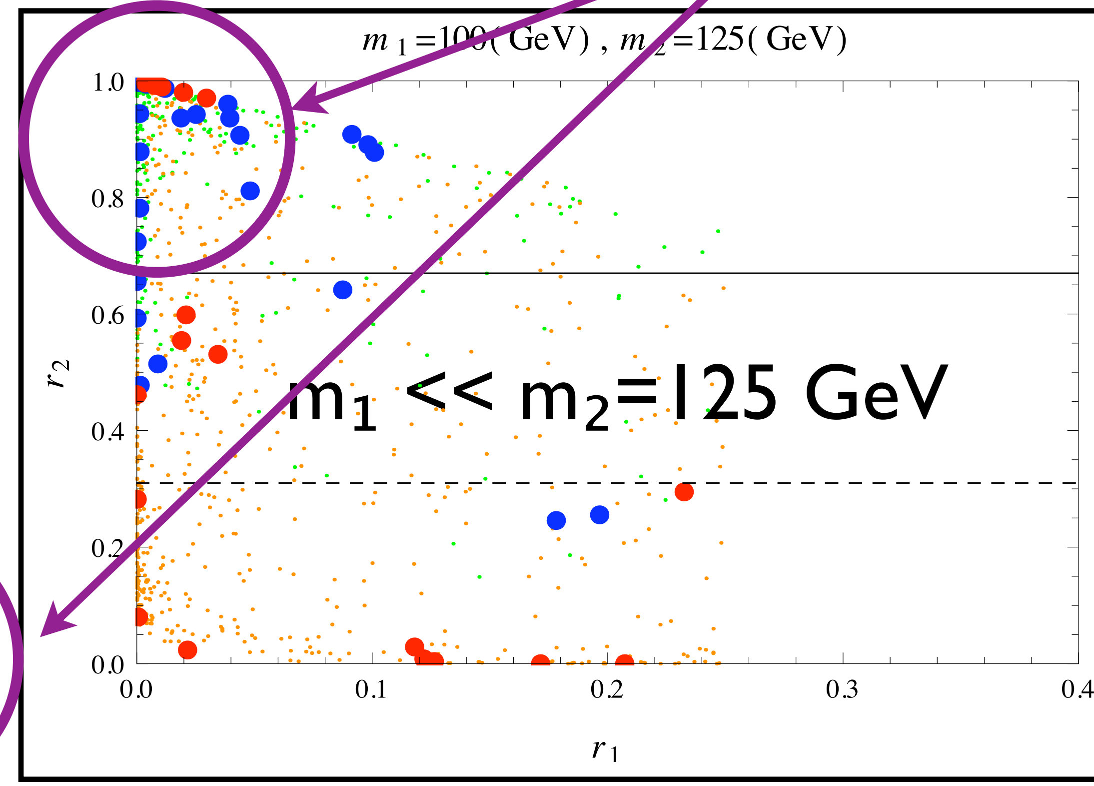
Interpretation of collider data is quite model-dependent in Higgs portal scenarios.

Discovery possibility

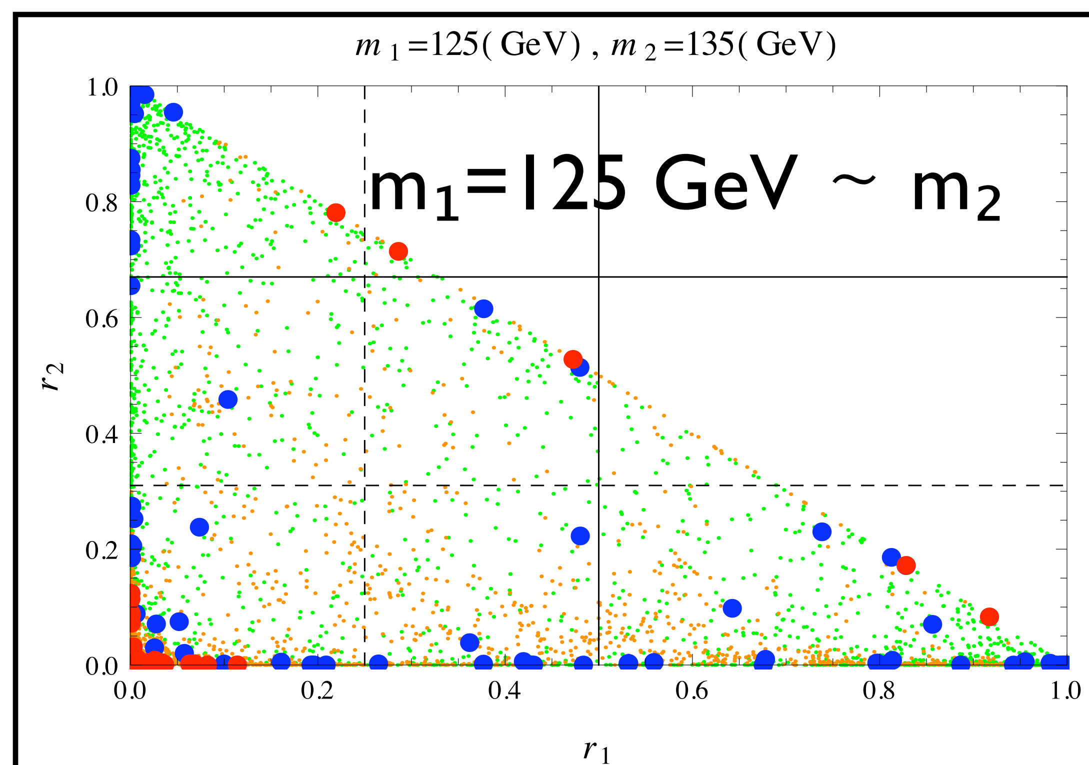
- Signal strength (r_2 vs r_1)

LHC data for 125 GeV resonance





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

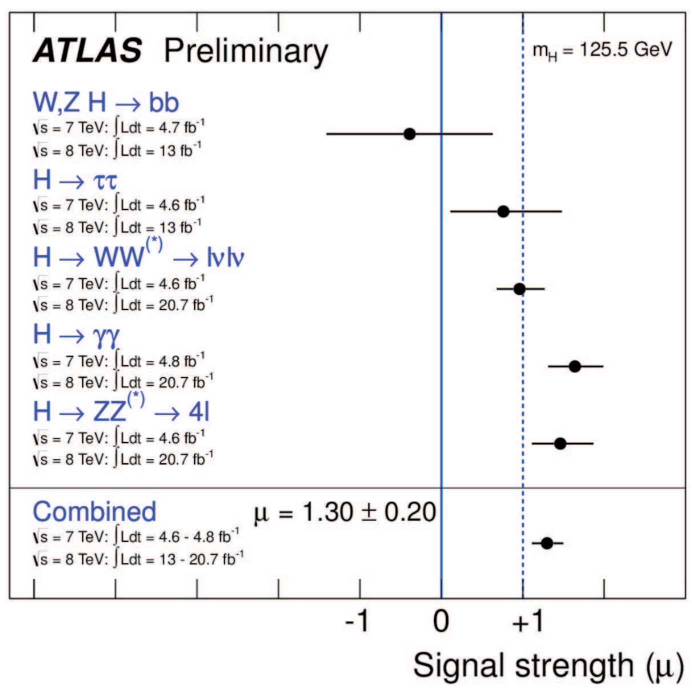


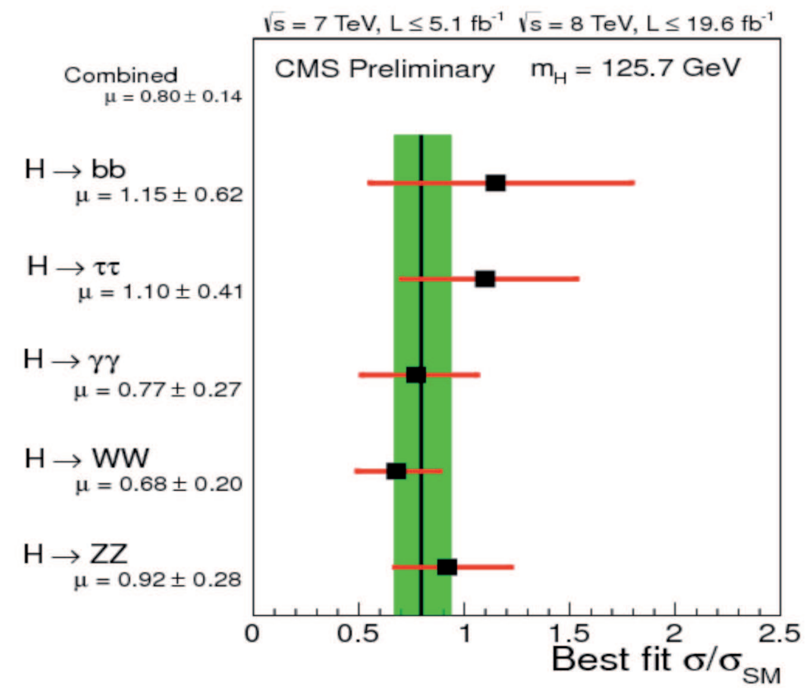
- (green) : Ω(x),σ_p(x)
- (orange) : Ω(x),σ_p(o)
- (blue) : Ω(o),σ_p(x)
- (red) : Ω(o),σ_p(o)

Updates@LHCP

Signal Strengths

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



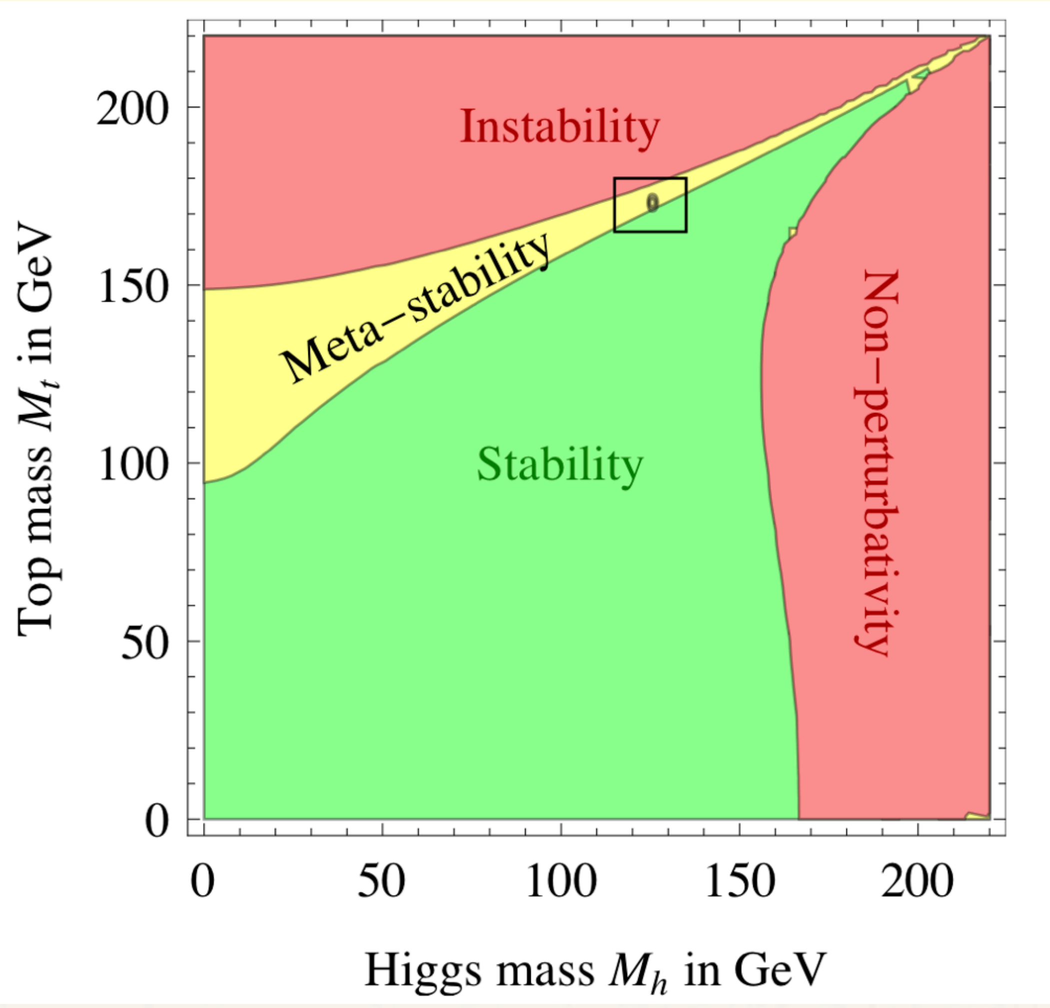


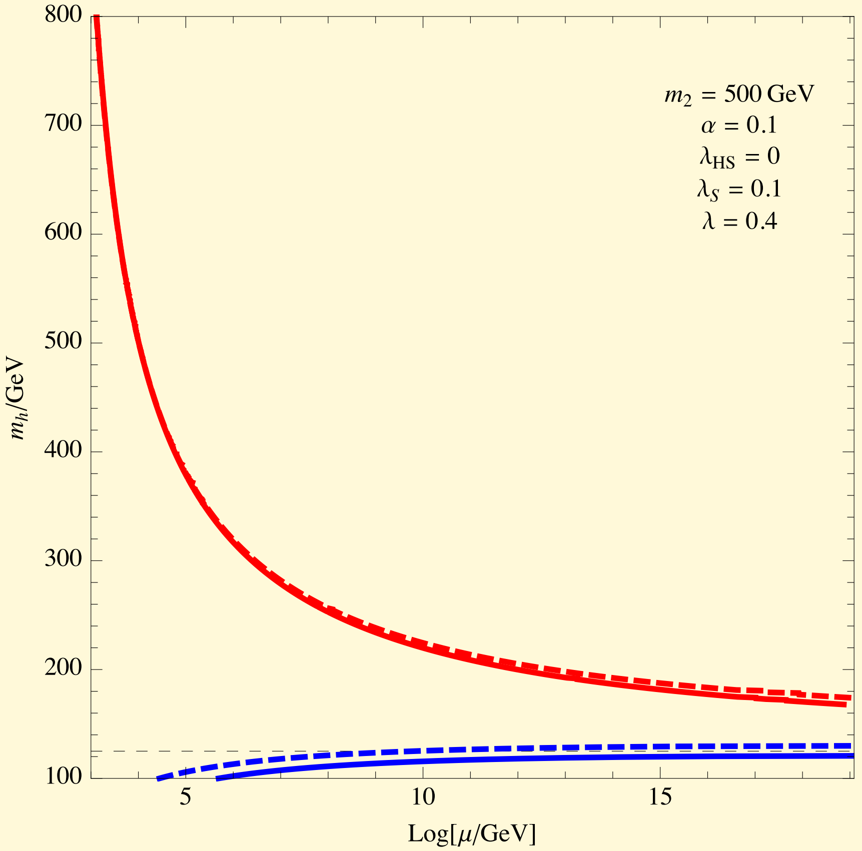
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

Getting smaller

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

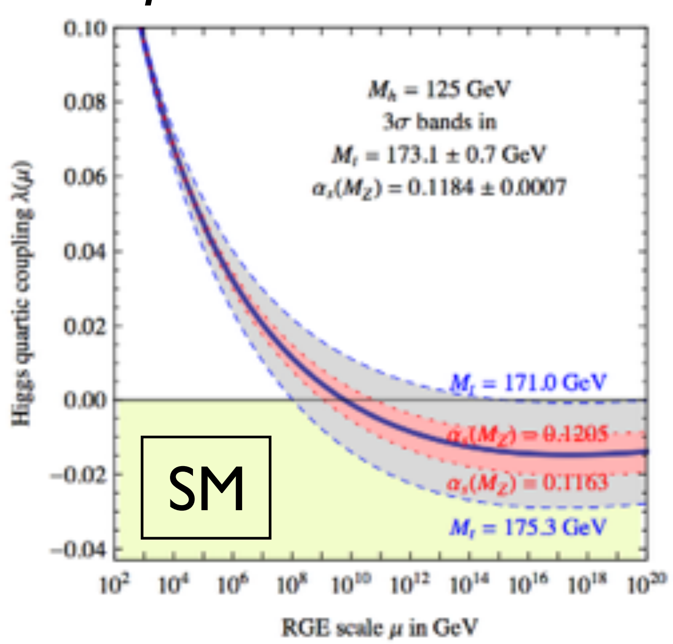
Baek, Ko, Park, Senaha (2012)

Low energy pheno.

- Universal suppression of collider SM signals [See 1112.1847, Seungwon Baek, P. Ko & WIP]
- If "$m_h > 2\ m_\phi$", non-SM Higgs decay!
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

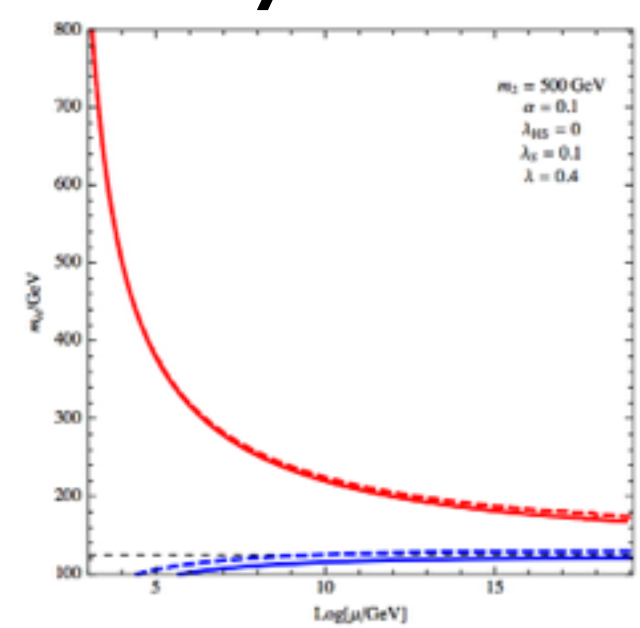
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{SM}$$

If "$m_\phi > m_h$", vacuum instability can be cured.



[G. Degrassi et al., 1205.6497]

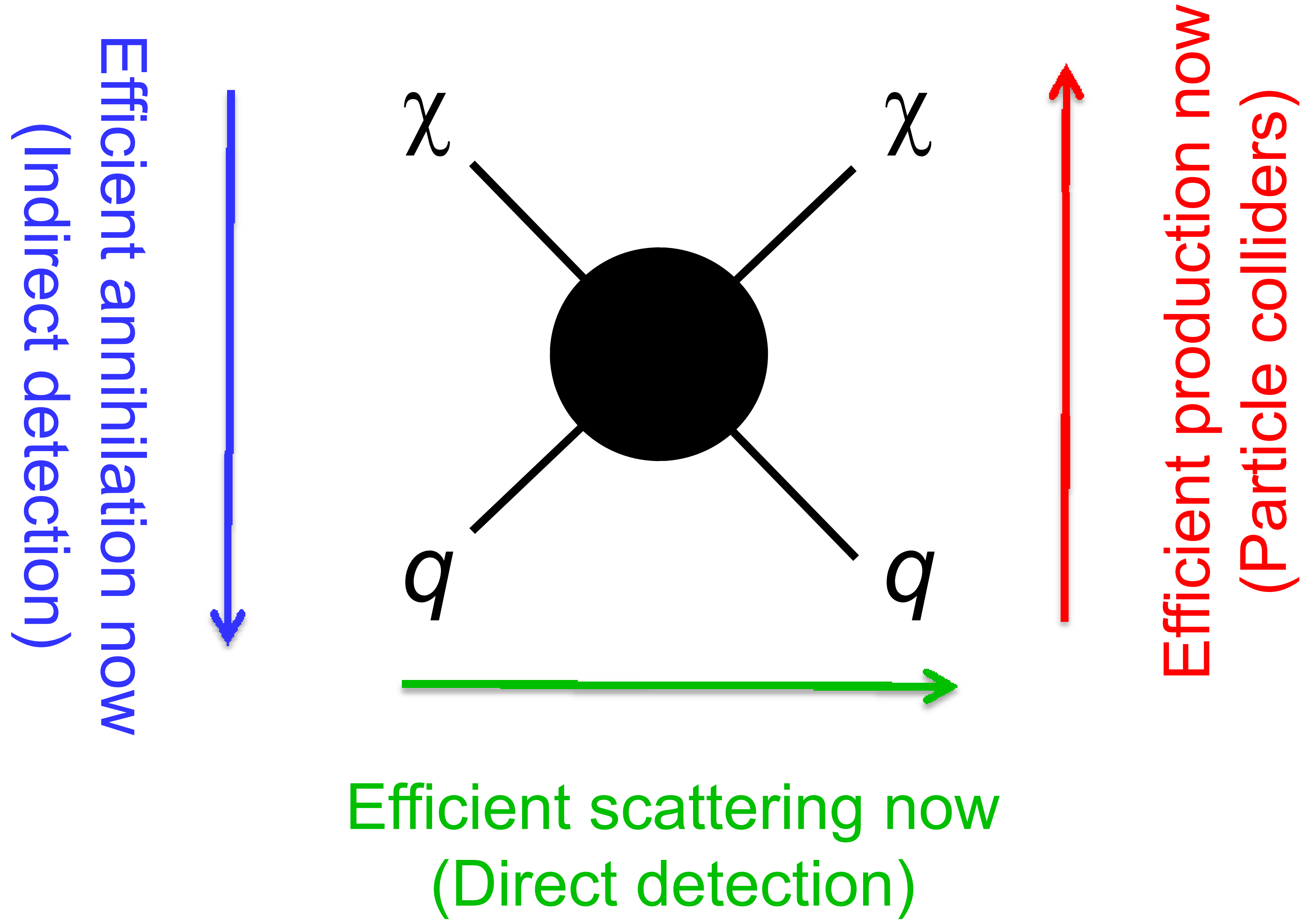
α



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

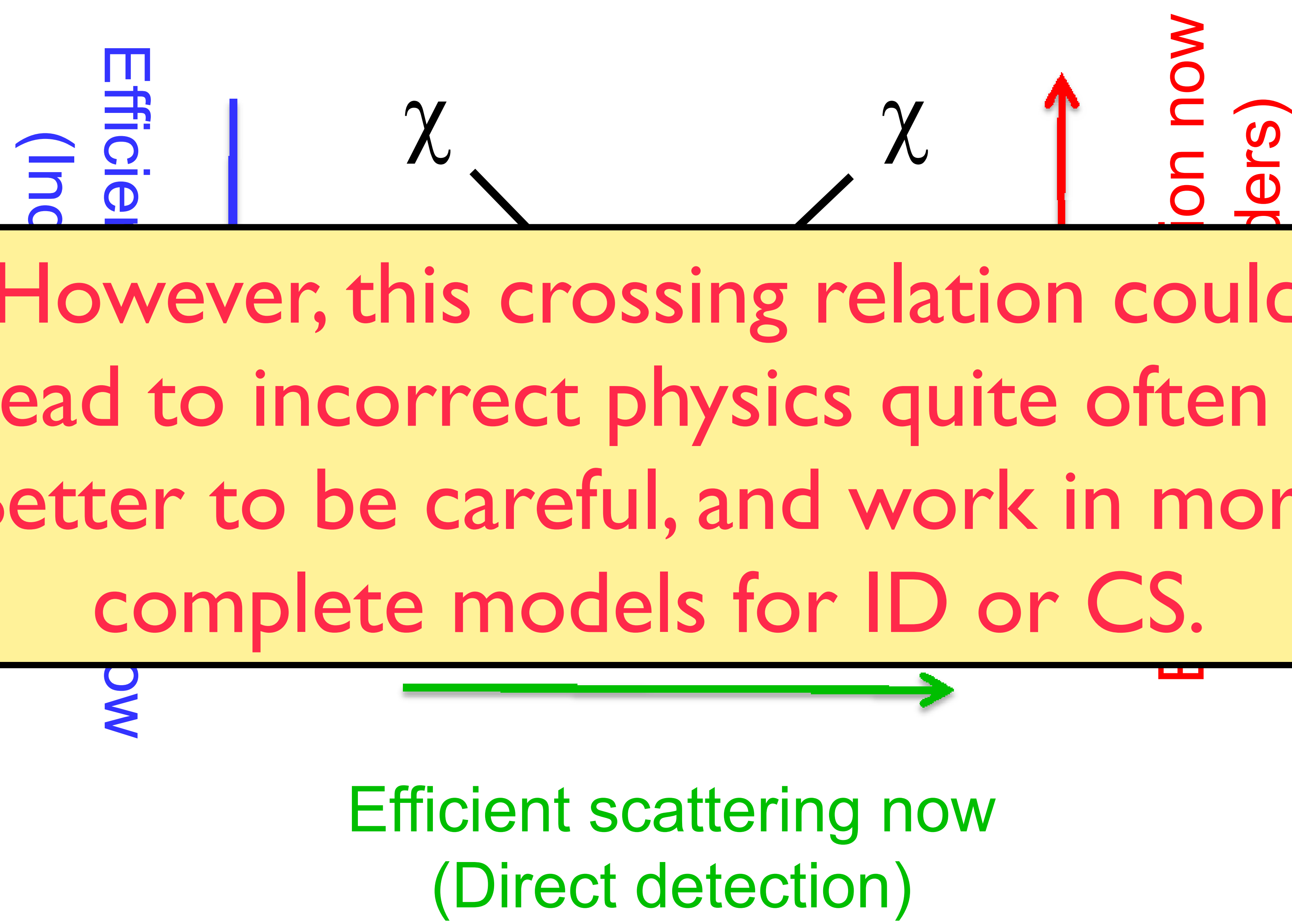
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then



However, this crossing relation could lead to incorrect physics quite often ! Better to be careful, and work in more complete models for ID or CS.

And this singlet scalar S modifies the Higgs inflation prediction with a larger “r”

(see the later part)

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

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

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

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

$\Rightarrow$ 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

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

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 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 Z_3 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

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

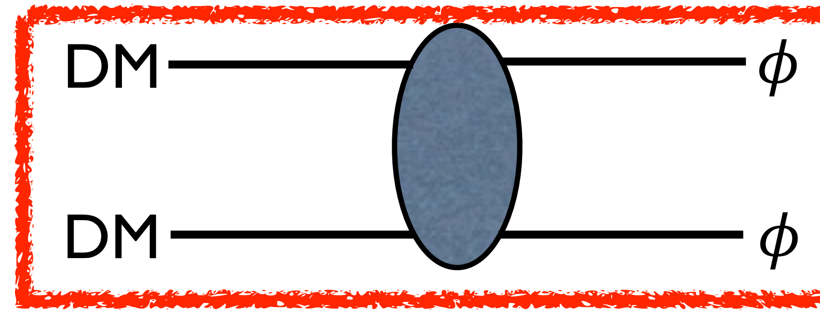
The heavier state decays into the lighter state

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

- Some DM models with Higgs portal

➢ Vector DM with Z2 [1404.5257, P. Ko, WIP & Y. Tang]

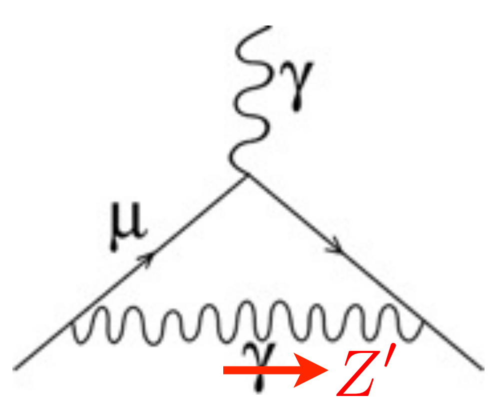
$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right),$$



➢ Scalar DM with local Z2 [1407.6588, Seungwon Baek, P. Ko & WIP]

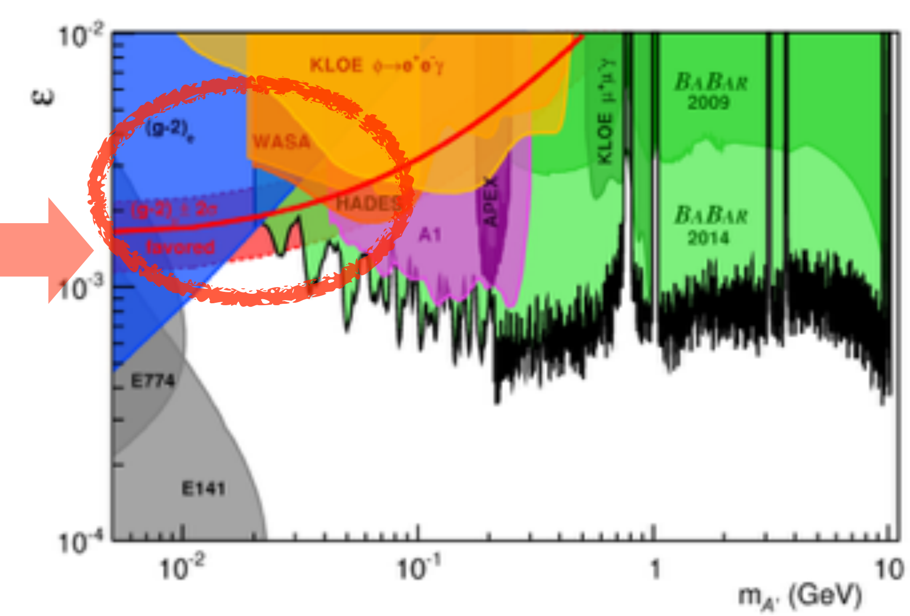
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi - \lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger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

- muon (g-2) as well as GeV scale gamma-ray excess explained
- natural realization of excited state
- free from direct detection constraint even for a light Z'



$$\Delta a_\mu \approx \frac{\alpha_{\rm em}\epsilon^2}{2\pi\cos\theta_W^2}$$

(for $m_{Z'} \lesssim m_\mu$)



[1406.2980, BaBar collaboration]

GC gamma ray in VDM

[1404.5257, P. Ko, WIP & Y. Tang]
To appear in JCAP (2014)

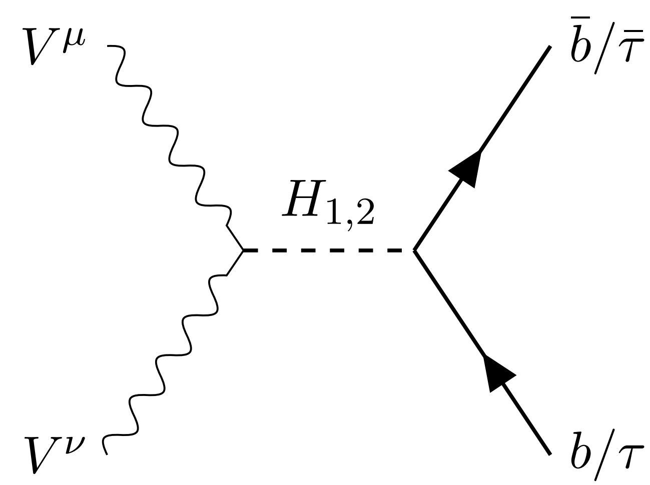


Figure 2. Dominant s channel $b + \bar{b}$ (and $\tau + \bar{\tau}$) production

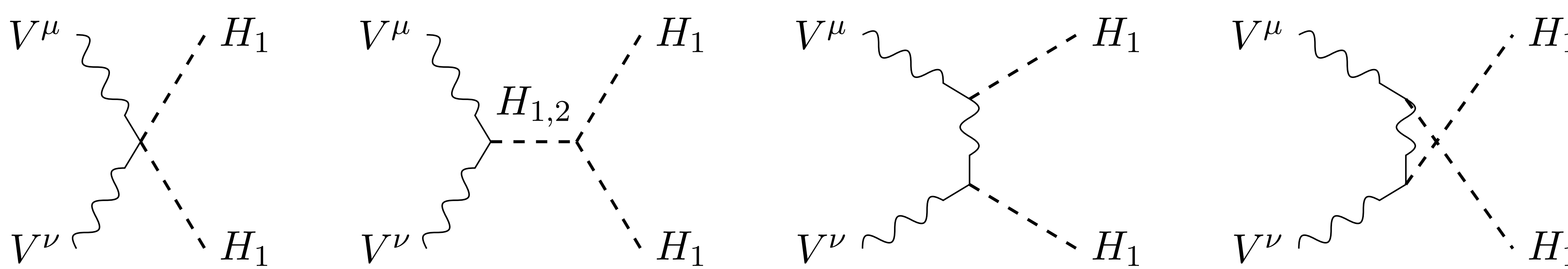


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of VDM with Dark Higgs

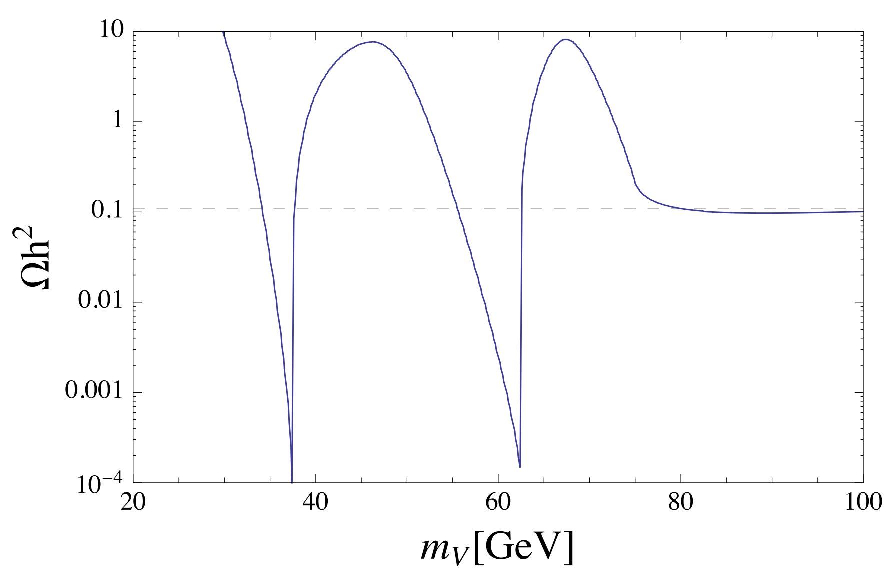


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\text{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

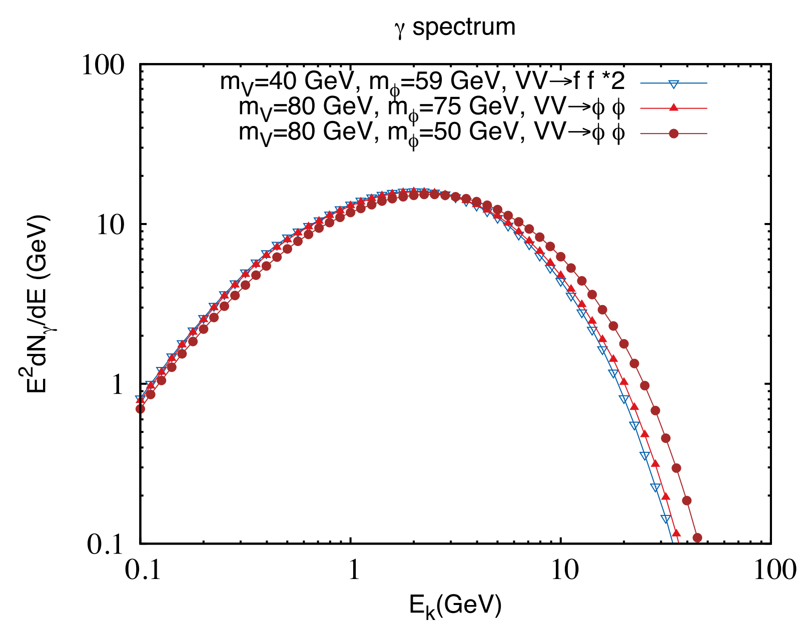


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

This mass range of VDM would have been impossible in the VDM model (EFT)

Main points

- Local Dark Gauge Symmetry can guarantee the DM stability (or longevity, see later discussion)
- Minimal models have new fields other than DM (Dark Higgs and Dark Gauge Bosons) for theoretical consistency
- Can solve many puzzles in CDM by large self-interactions, and also muon g-2, and also calculable amount of Dark Radiation

Scalar DM with Local Z3

P, Ko, Y.Tang, arXiv:1402.6449, JCAP (2014)

Scalar DM with local Z_3 sym

P, Ko, YTang, arXiv:1402.6449

Consider $U(1)_X$ dark gauge symmetry, with scalar DM X and dark higgs phi_X with charges 1 and 3, respectively.

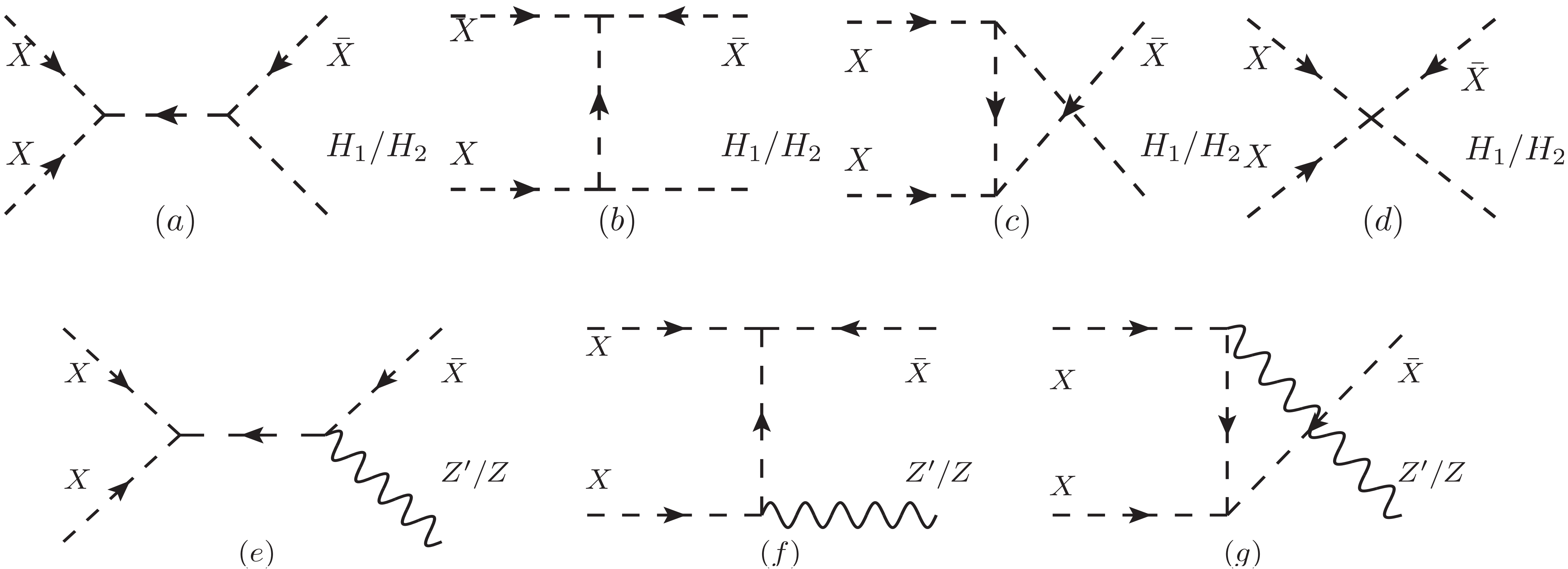
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\tilde{X}_{\mu\nu}\tilde{B}^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X + D_\mu X^\dagger D^\mu X - V$$

$$V = -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 - \mu_\phi^2\phi_X^\dagger\phi_X + \lambda_\phi\left(\phi_X^\dagger\phi_X\right)^2 + \mu_X^2 X^\dagger X + \lambda_X\left(X^\dagger X\right)^2$$

$$+ \lambda_{\phi H}\phi_X^\dagger\phi_X H^\dagger H + \lambda_{\phi X} X^\dagger X\phi_X^\dagger\phi_X + \lambda_{HX} X^\dagger X H^\dagger H + \left(\lambda_3 X^3\phi_X^\dagger + H.c.\right)$$

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

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

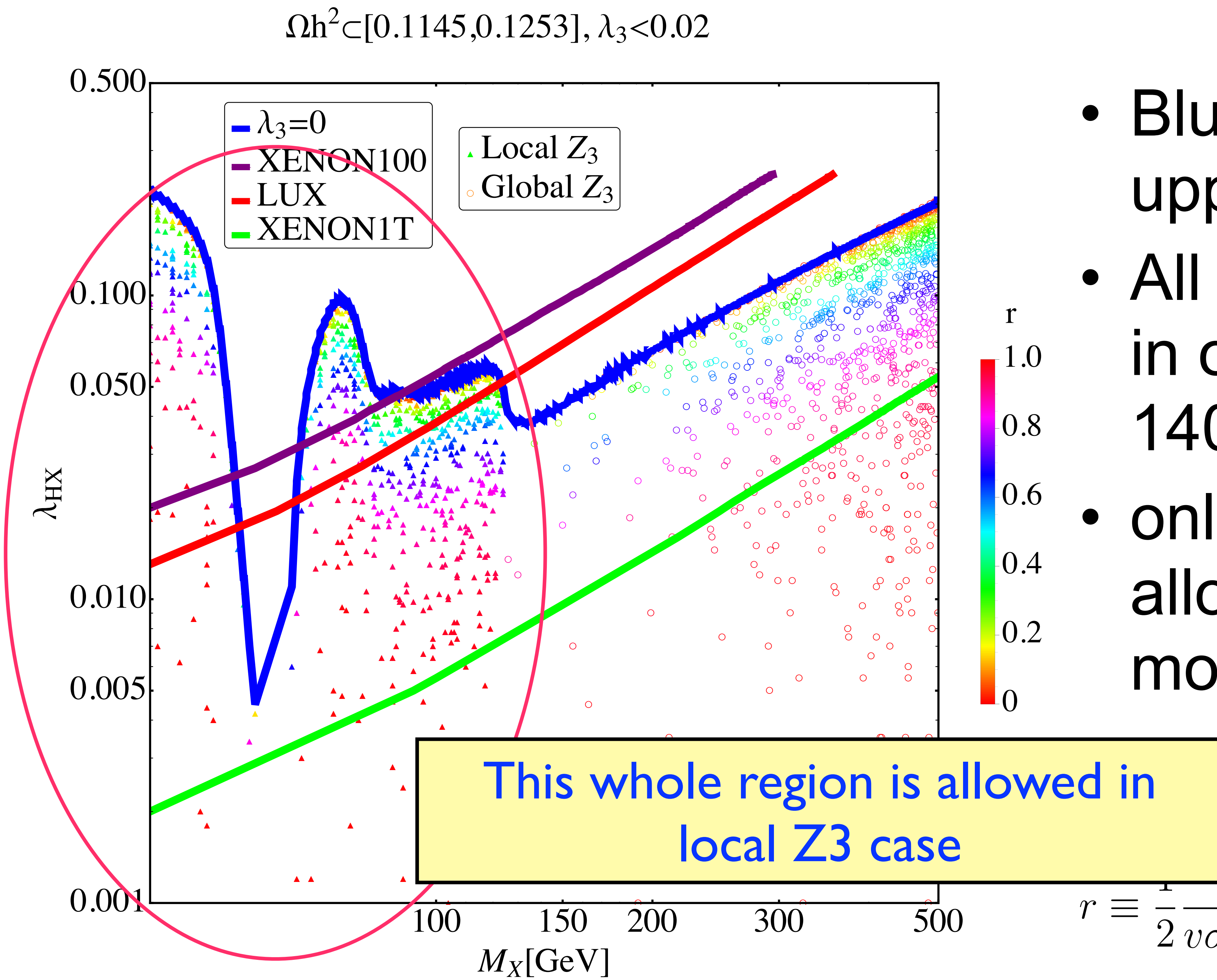
- However global symmetry can be broken by gravity induced nonrenormalizable op's:

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

Global Z3 "X" with EW scale mass will decay immediately and can not be a DM

- Also particle contents different : Z' and H2
- 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

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

Comparison with EFT

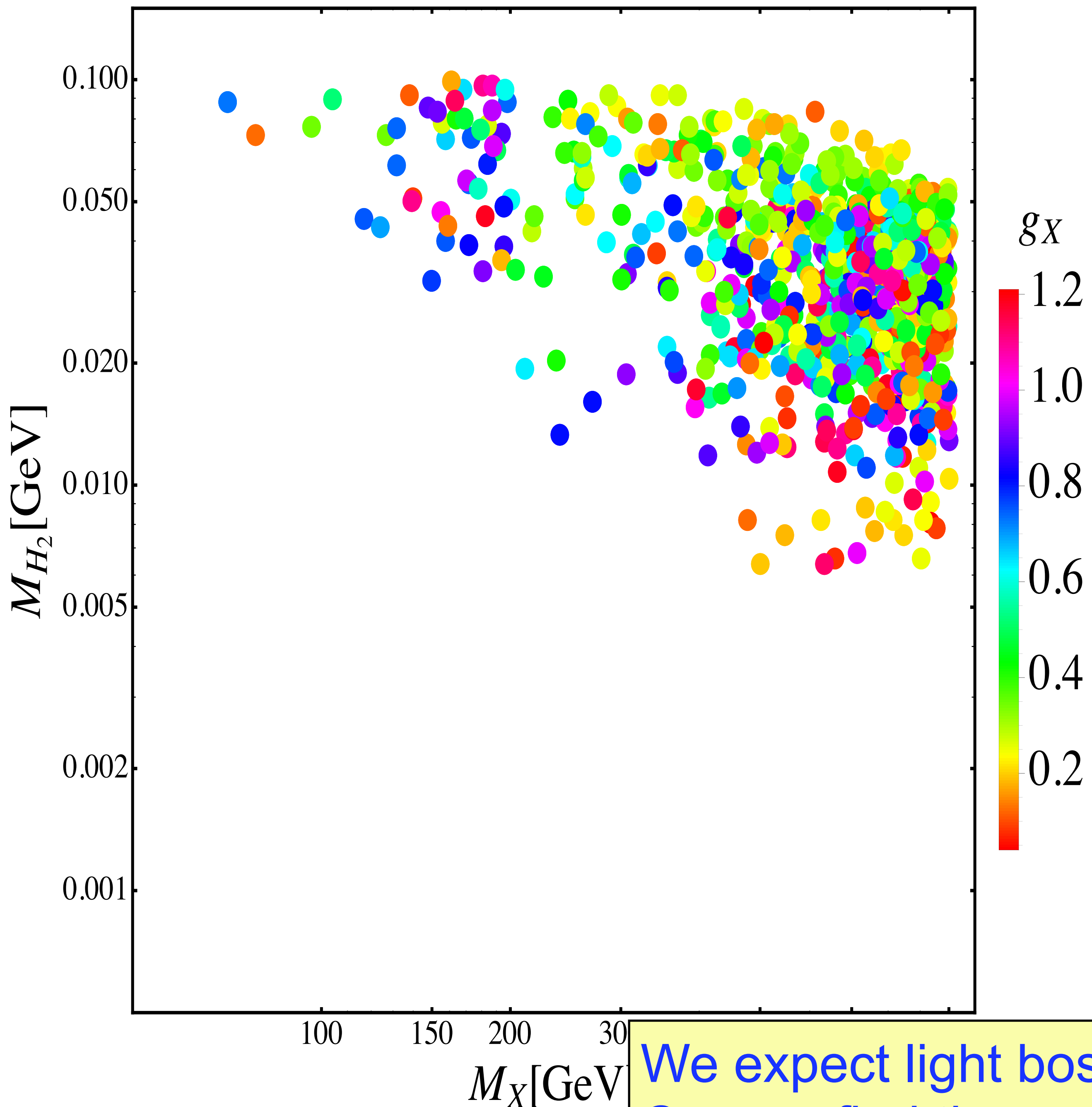
$$U(1)_X \text{ sym}: \quad X^\dagger X H^\dagger H,\ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(H^\dagger D^\mu H\right),\ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(\overline{f}\gamma^\mu f\right),\ etc. \quad (4.3)$$

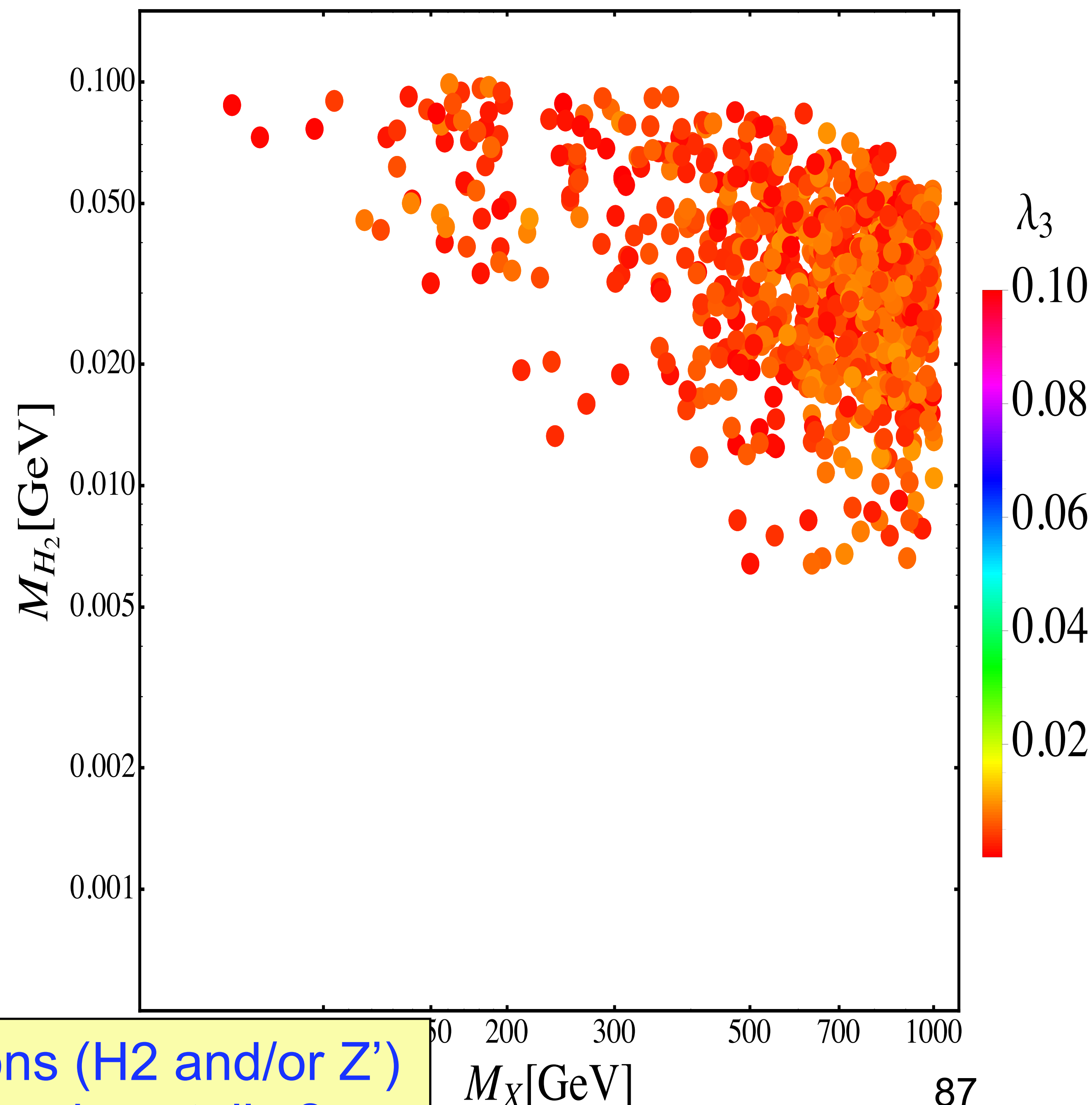
$$Z_3 \text{ sym}: \quad \frac{1}{\Lambda}X^3 H^\dagger H,\quad \frac{1}{\Lambda^2}X^3\overline{f}f,\ etc. \quad (4.4)$$

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

- 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

Strong DM self interaction from Light Mediators





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

Global Z3 (Belanger, Pukhov et al)

- SM + X
- DD & Thermal relic >> mX > 120 GeV
- Vacuum stability >> DD cross section within Xenon1T experiment
- No light mediators

Local Z3 (Ko, Yong Tang)

- SM + X , phi , Z'
- Additional Annihilation Channels open
- DD constraints relaxed
- Light mX allowed
- Light mediator phi : strong self interactions of X's

Gamma ray excess from GC

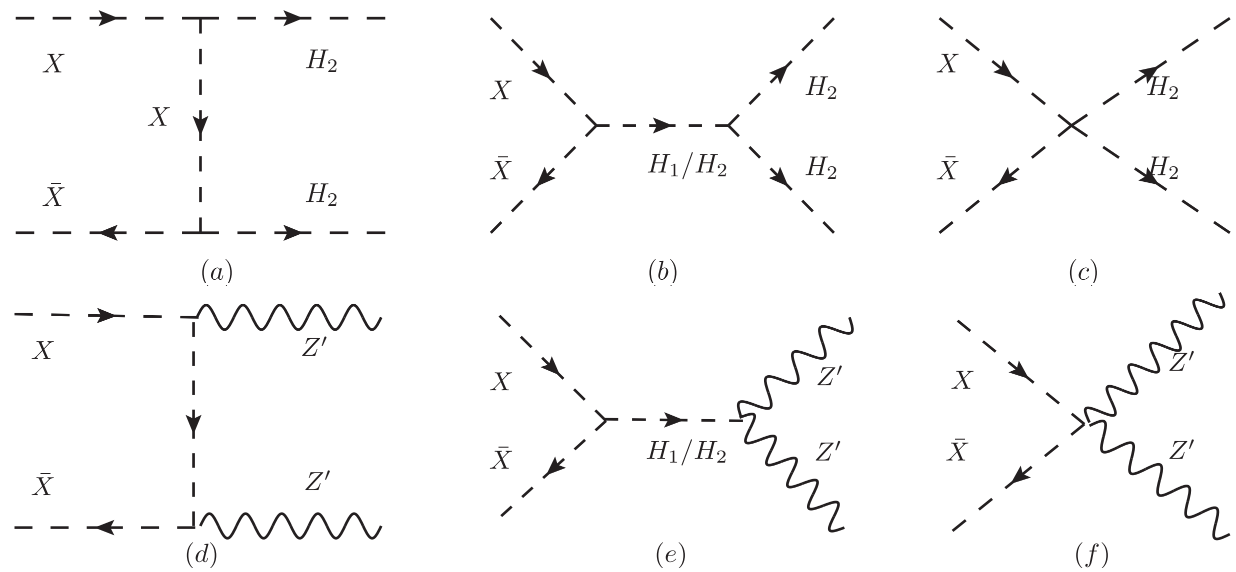


FIG. 1: Feynman diagrams for $X\bar{X}$ annihilation into H_2 and Z'.

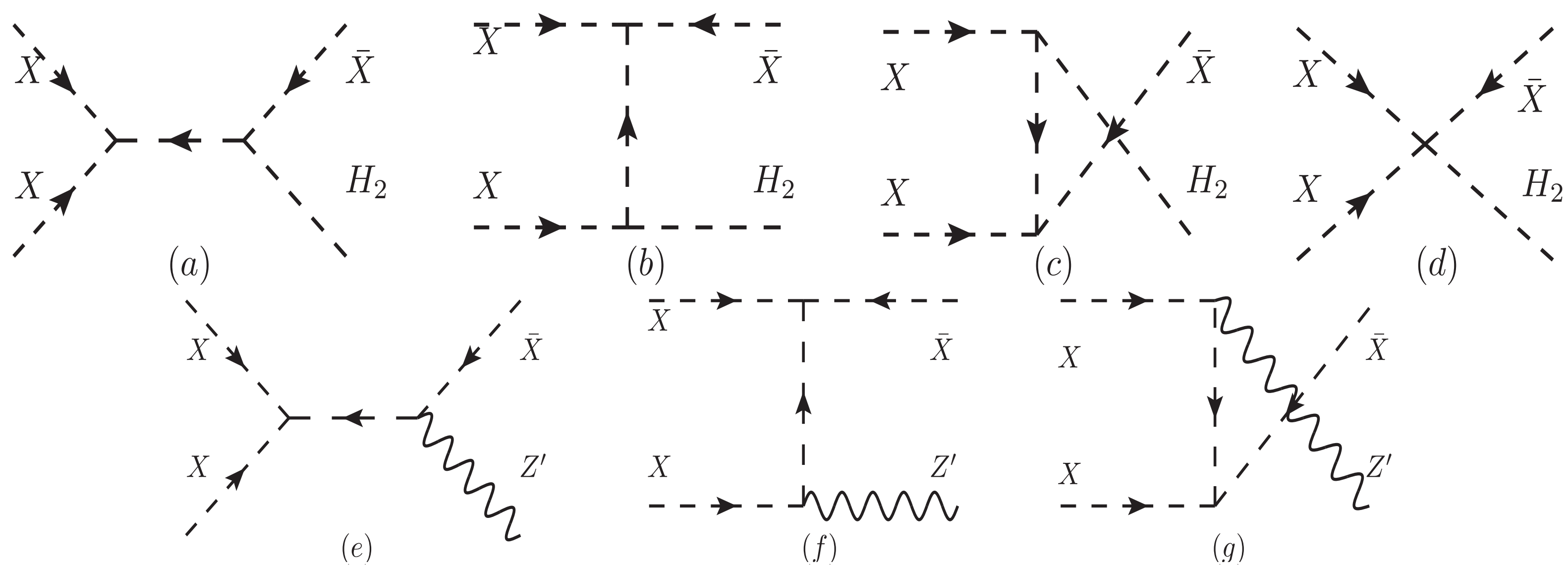


FIG. 2: Feynman diagrams for XX semi-annihilation into H_2 and Z'.

(arXiv:1407.5492 with Yong Tang)

Gamma ray excess from GC

(arXiv:1407.5492 with Yong Tang)

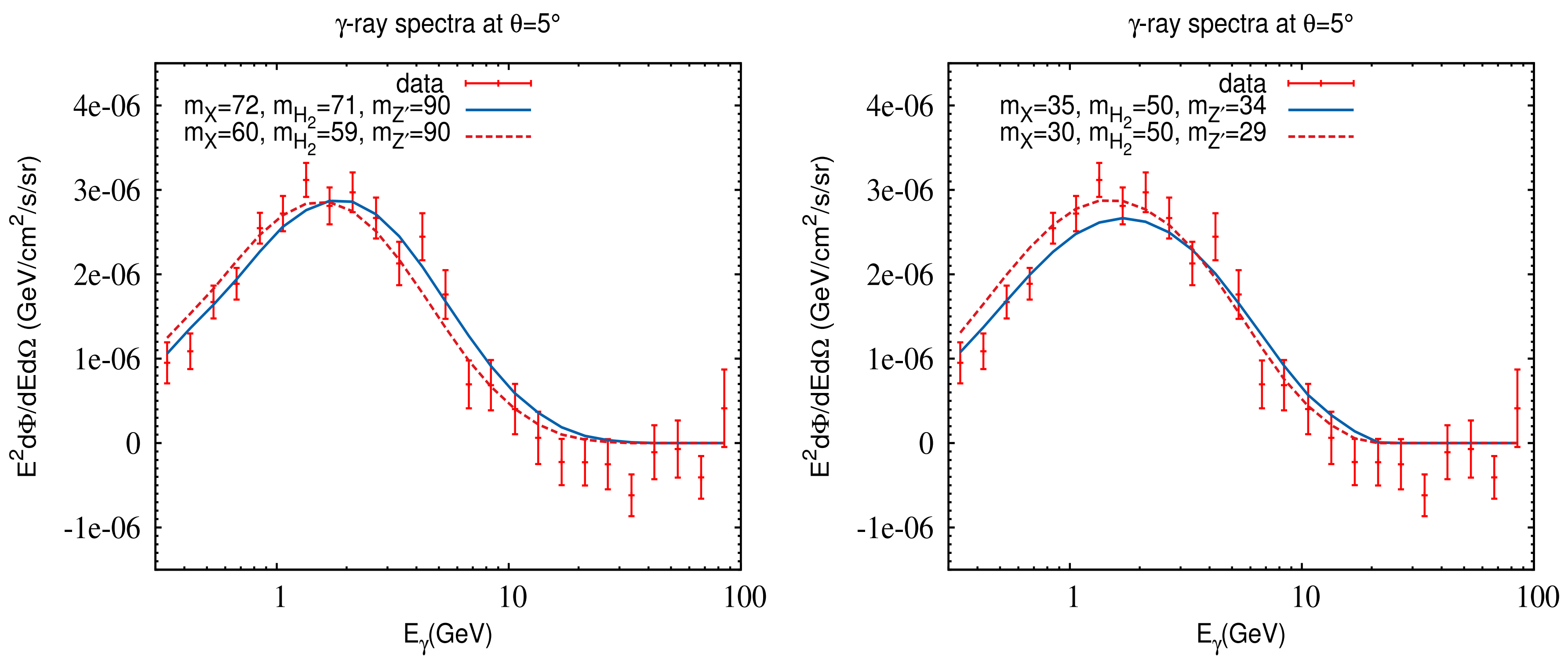


FIG. 4: γ-ray spectra from dark matter (semi-)annihilation with H_2(left) and Z'(right) as final states. In each case, mass of H_2 or Z' is chosen to be close to m_X to avoid large lorentz boost. Masses are in GeV unit. Data points at $\theta = 5$ degree are extracted from [1].

Possible only in local Z3, not in global Z3

Antiproton and positron

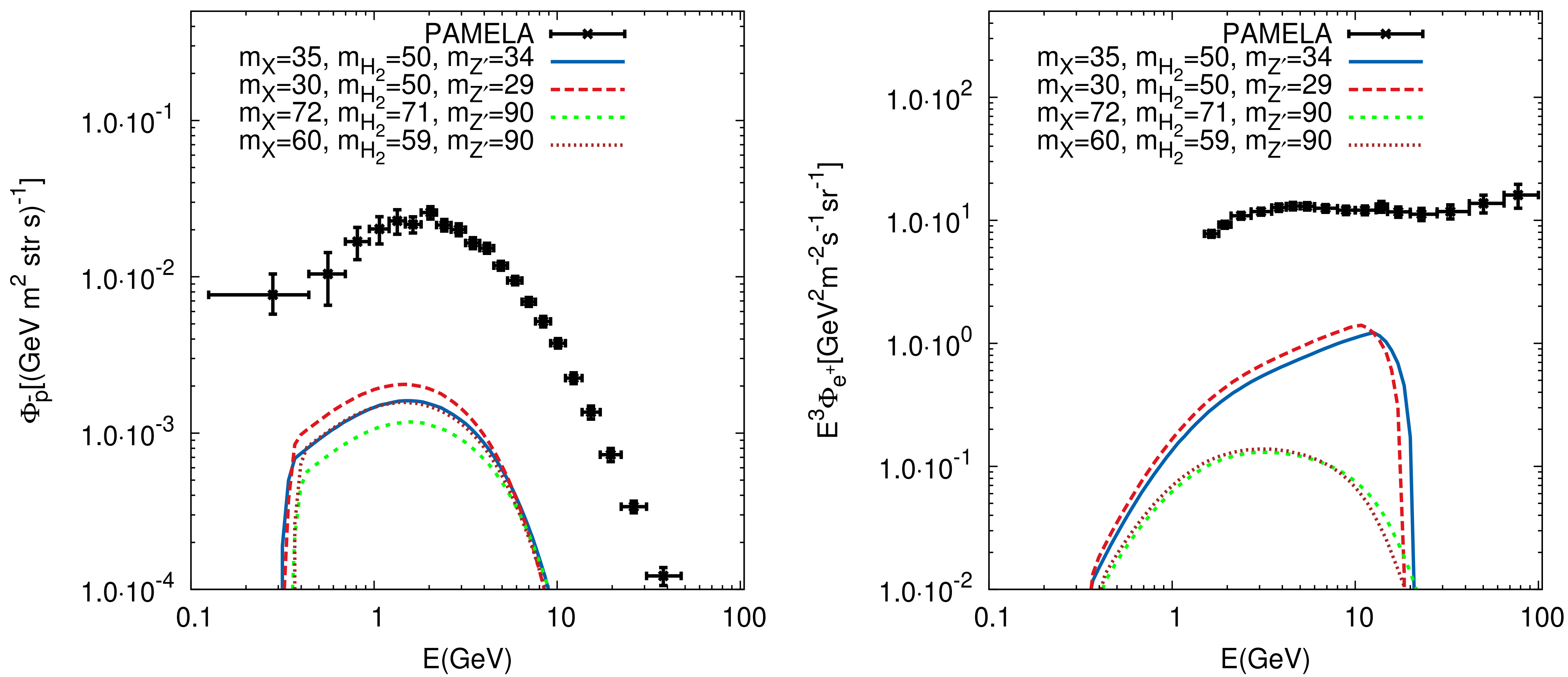


FIG. 5: $\bar{p}$ and e^+ spectra from dark matter (semi-)annihilation with H_2(left) and Z'(right) as final states. In each case, mass of H_2 or Z' is chosen to be close to m_X to avoid large lorentz boost. Masses are in GeV unit. $\langle\sigma v\rangle_{\rm ann} \simeq 6.8(4.4)\times10^{-26}{\rm cm}^3/{\rm s}$ for $H_2(Z')$ final states are assumed. Data point are taken from [53] for anti-proton and [54] for positron fluxes, using the database [55].

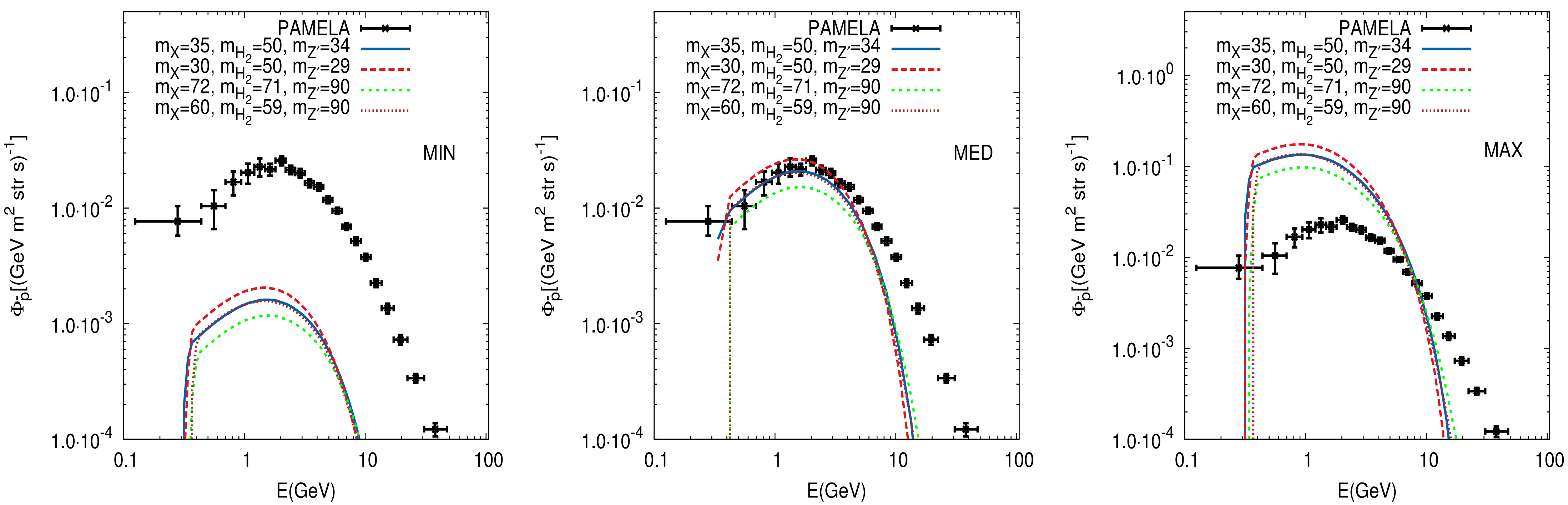
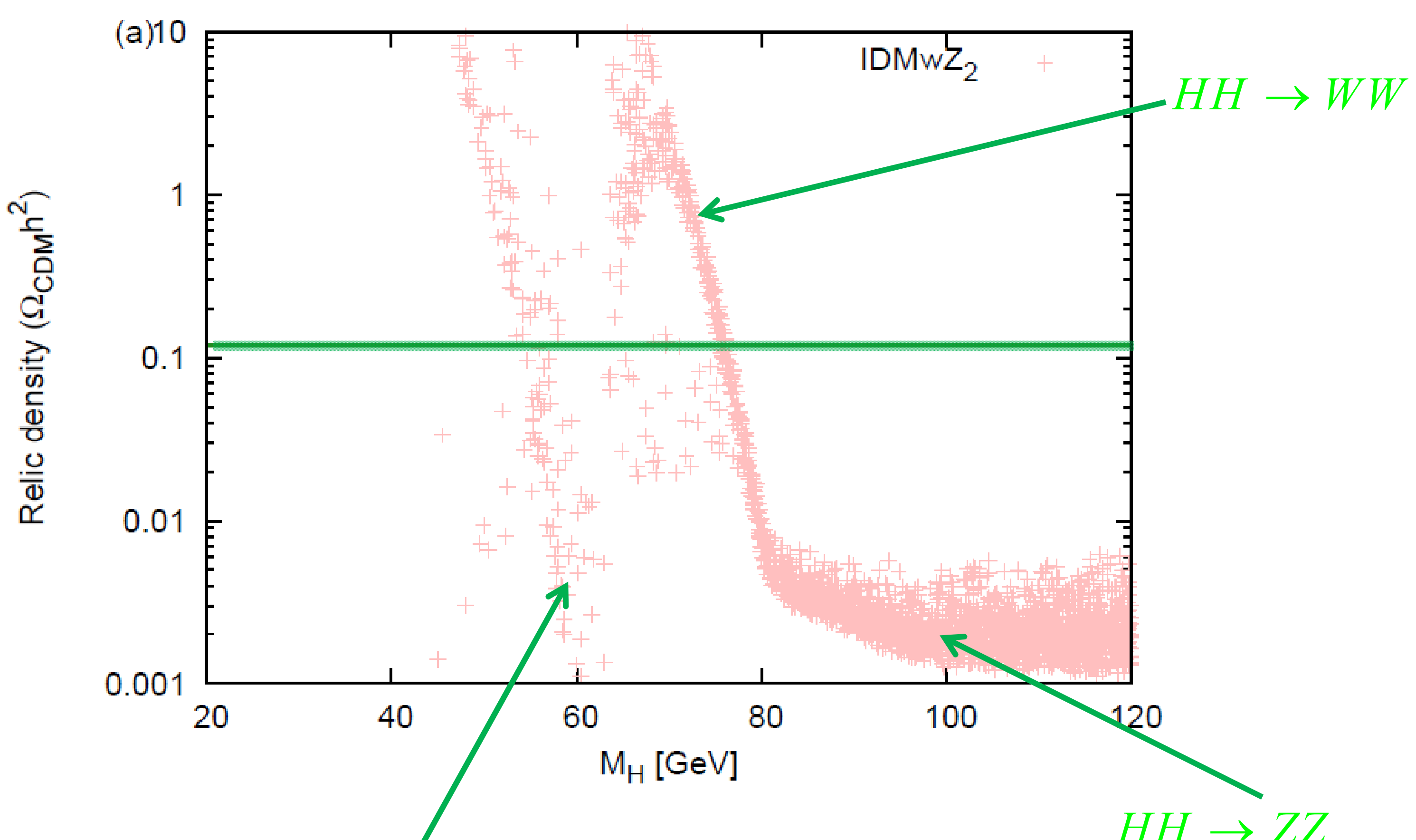


FIG. 6: Antiproton flux dependence on astrophysical parameters. From left to right, MIN, MED and MAX models are used respectively. See table. I for model parameters.

Inert 2HDM model

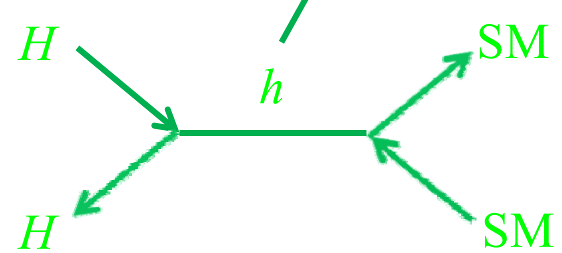
Relic density (low mass)

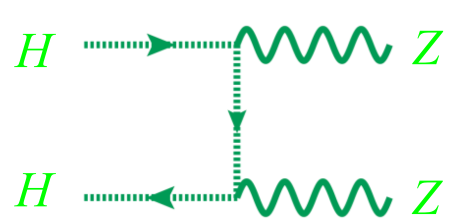
$\Omega_{CDM}h^2 = 0.1199 \pm 0.0027$



+ IDMwZ_2

LUX bound is satisfied.

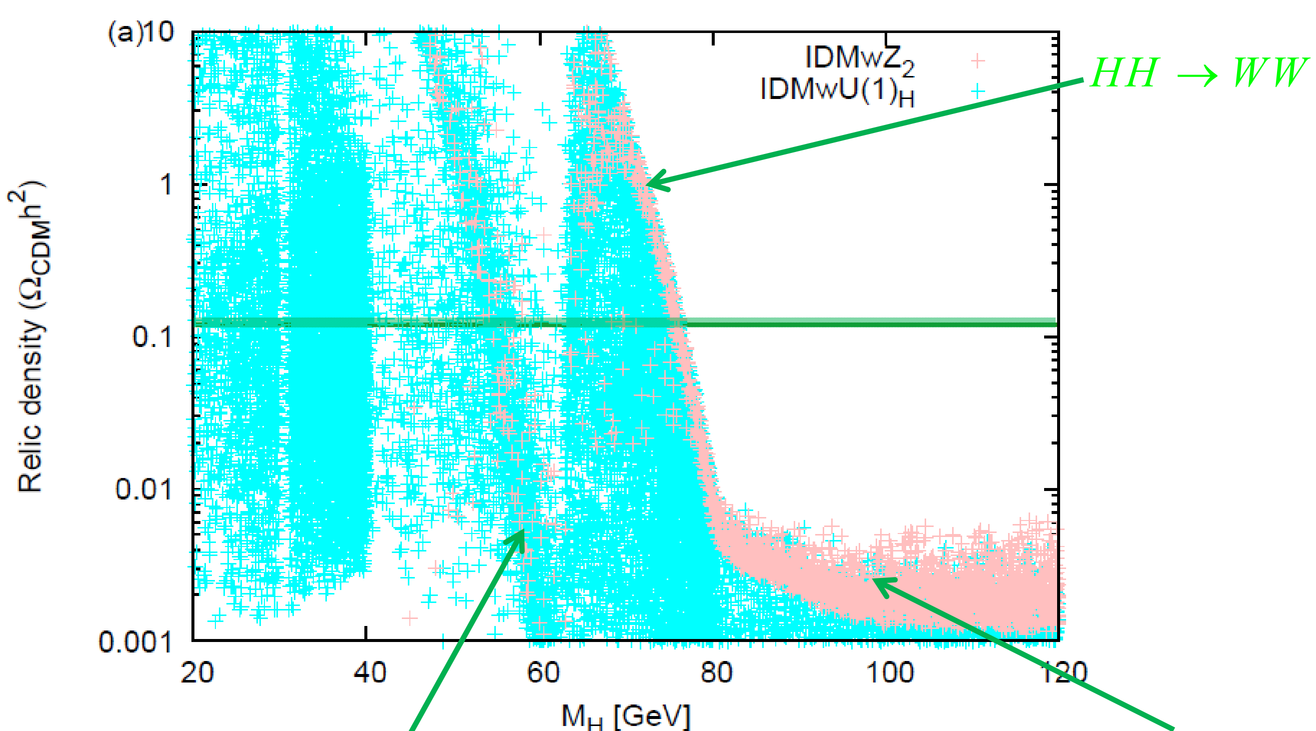




Inert 2HDM with U(1)H gauge symmetry

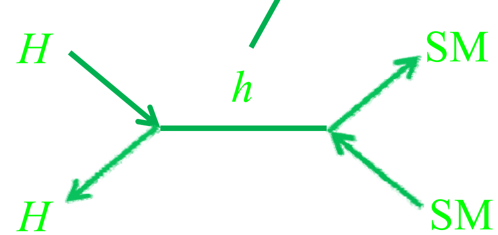
Relic density (low mass)

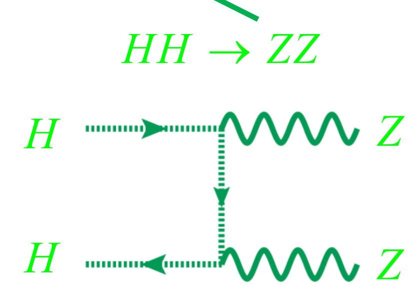
$\Omega_{\mathrm{CDM}}h^2 = 0.1199 \pm 0.0027$



+ $IDMwZ_2$
+ $IDMwU(1)_H$

LUX bound is satisfied.





$HH \to Z_H Z_H, Z Z_H$

Ko, Omura, Yu
arXiv:1405.2138

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

Scalar DM with Local Z2

[1407.6588, Seungwon Baek, P. Ko & WIP]

Model Lagrangian

$$q_X(X, \phi) = (1, 2)$$

[1407.6588, Seungwon Baek, P. Ko & WIP]

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

- X : scalar DM (XI and XR, excited DM)
- phi : Dark Higgs
- X_mu : Dark photon
- 3 more fields than Z2 scalar DM model
- Z2 Fermion DM can be worked out too

Gamma ray from GC

$$\frac{m_h}{2} < m_I \lesssim 80\,\mathrm{GeV}\,, \quad \frac{m_I - m_\phi}{m_I} \ll \mathcal{O}(0.1)$$

- Possible to satisfy thermal relic density, (in)direct detection constraints

- For light Z' with small kinetic mixing, muon g-2 can be accommodated

- Similar to the excited DM models by Weiner et al, etc. except for dark Higgs field

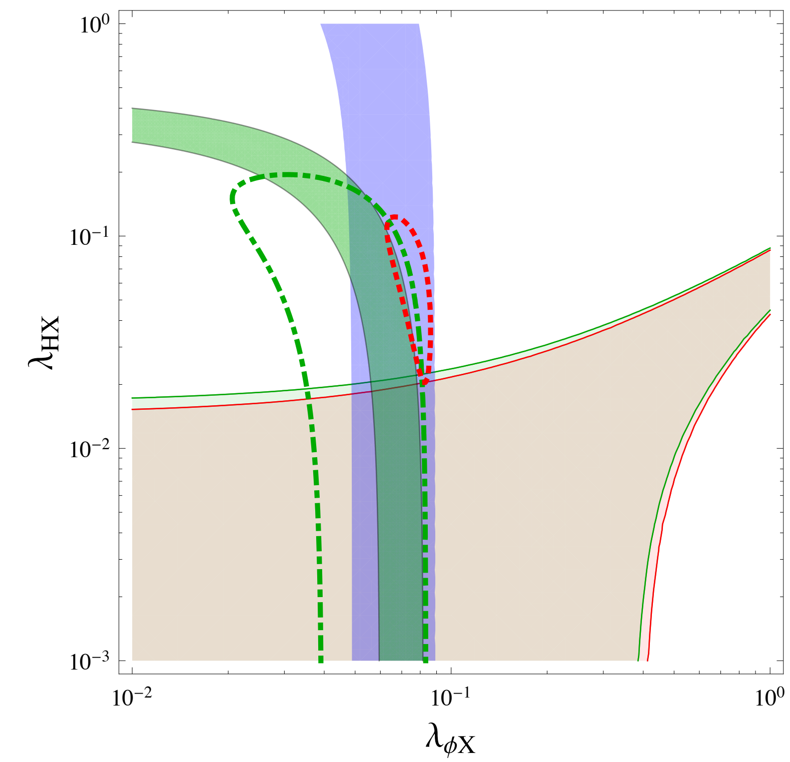


FIG. 3: Parameter space for $m_I = 80$, $m_\phi = 75\,\mathrm{GeV}$ with $\alpha = 0.1$, $v_\phi = 100\,\mathrm{GeV}$, satisfying constraints from LUX direct search experiment (Green region between thin green lines: $\mu = 5\,\mathrm{GeV}$. Red region between thin red lines: $\mu = 7\,\mathrm{GeV}$), $\langle\sigma v_{\rm rel}\rangle_{\rm tot}/\langle\sigma v_{\rm rel}\rangle_{26} = 1$ (Dot-dashed green line: $\mu = 5\,\mathrm{GeV}$. Dotted red line: $\mu = 7\,\mathrm{GeV}$), and $1/3 \le \langle\sigma v_{\rm rel}\rangle_{\phi\phi}/\langle\sigma v_{\rm rel}\rangle_{26} \le 1$ (Blue region). In the dark green region, $\langle\sigma v_{\rm rel}\rangle_{Z'Z'}/\langle\sigma v_{\rm rel}\rangle_{26} \le 0.1$, so the contribution of Z'-decay to GeV scale excess of γ-ray may be safely ignored.

Other possible phenomenology

- Another possibility was to use this model for 511 keV gamma ray and PAMELA/AMS2 positron excess (strong tension with CMB constraints, however)
- 3.55 keV Xray using endo(exo)thermic scattering (JMCline's talk) : for future work
- In any case, the local Z_2 model has new fields with interesting important own roles, and can modify phenomenology a lot

Hidden Sector Monopole, Stable VDM and Dark Radiation

$SU(2)_h \rightarrow U(1)_h$

+

Higgs portal

[S. Baek, P. Ko & WIP, arXiv:1311.1035]

Backup Slides

The Model

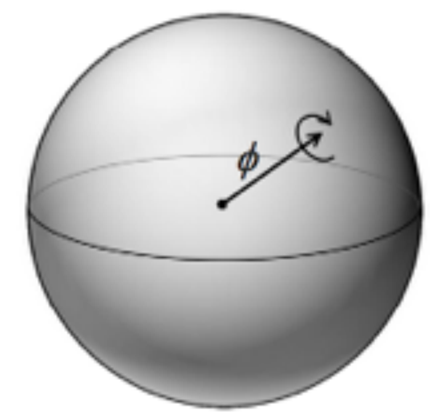
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V^a_{\mu\nu}V^{a\mu\nu} + \frac{1}{2}D_\mu\vec{\phi}\cdot D^\mu\vec{\phi} - \frac{\lambda_\phi}{4}\left(\vec{\phi}\cdot\vec{\phi} - v_\phi^2\right)^2 - \frac{\lambda_{\phi H}}{2}\vec{\phi}\cdot\vec{\phi}H^\dagger H$$

't Hooft-Polyakov monopole — Higgs portal

- Symmetry breaking

$$\phi^T = (0, 0, v_\phi) \Rightarrow SU(2) \to U(1)$$



- Particle spectra $\left(V^\pm \equiv \frac{1}{\sqrt{2}}(V_1 \mp iV_2),\ \gamma' \equiv V_3,\ H_1,\ H_2\right)$
  - VDM: $m_V = g_X v_\phi$
  - Monopole: $m_M = m_V/\alpha_X$
  - Higgses: $m_{1,2} = \frac{1}{2}\left[m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{\left(m_{hh}^2 - m_{\phi\phi}^2\right)^2 + 4m_{\phi h}^4}\right]$

Main Results

- h-Monopole is stable due to topological conservation
- h-VDM is stable due to the unbroken U(1) subgroup, even if we consider higher dim nonrenormalizable operators
- Massless h-photon contributes to the dark radiation at the level of 0.08-0.11
- Higgs portal plays an important role

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

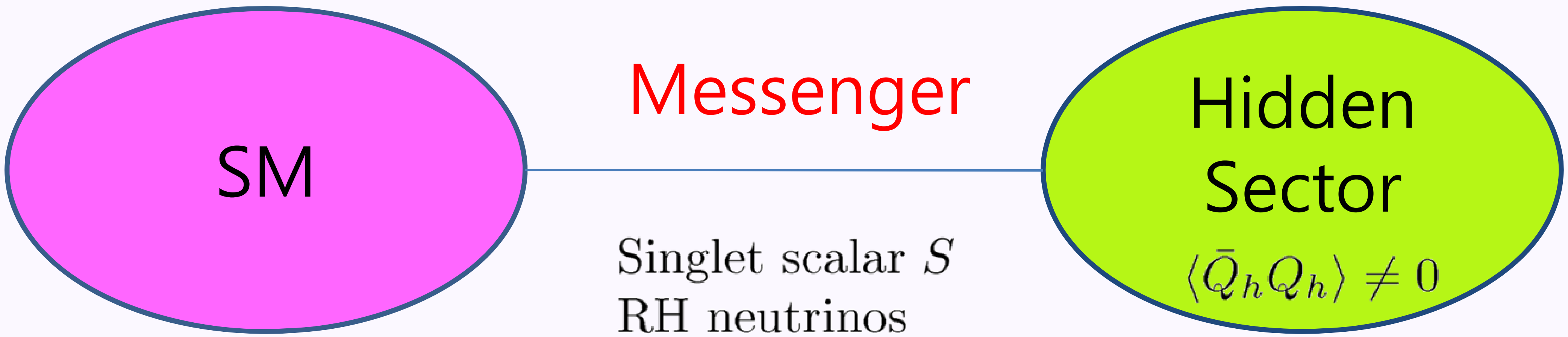
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 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

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2) + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

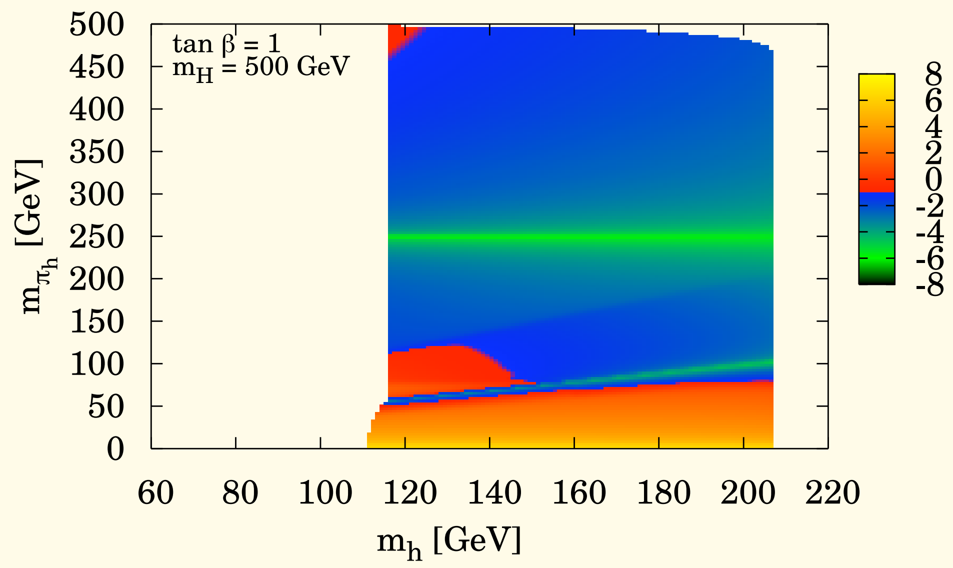
Not present in the two-Higgs Doublet model

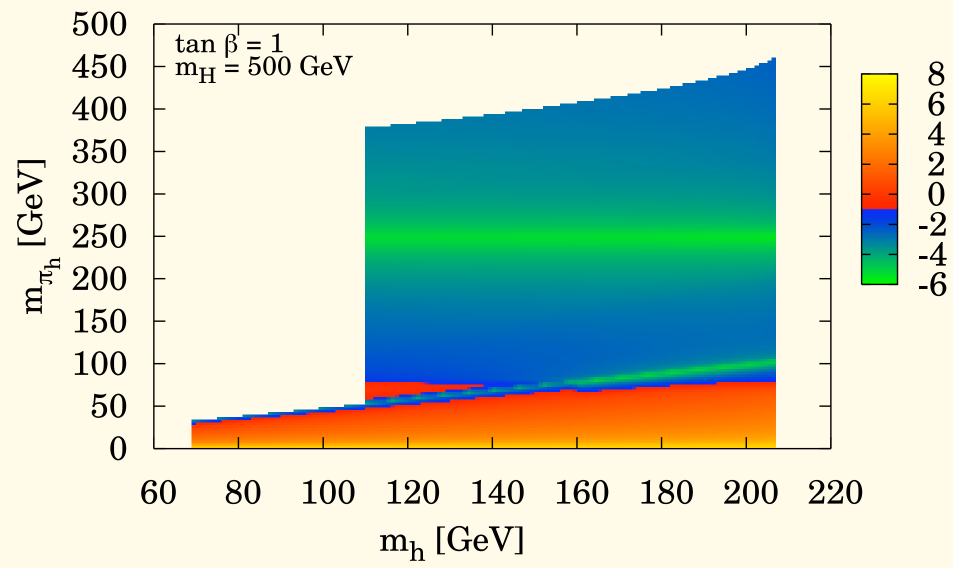
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

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

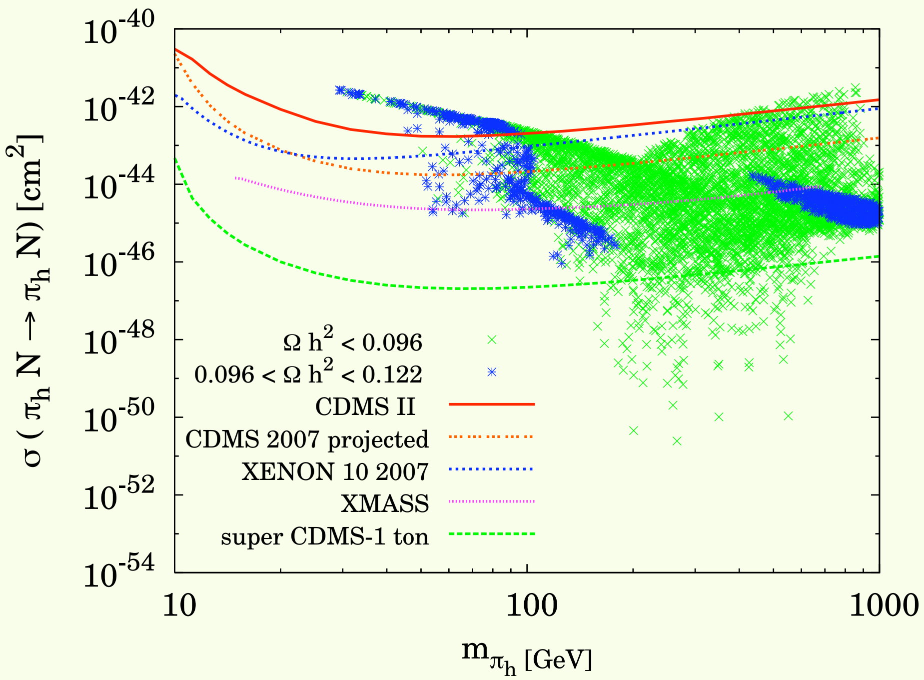
Relic Density

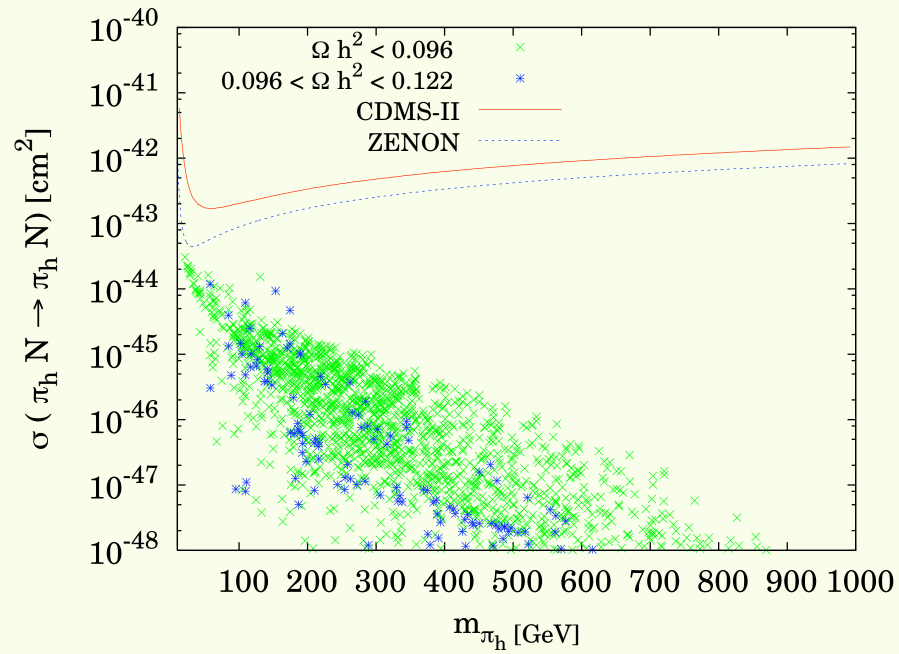




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate

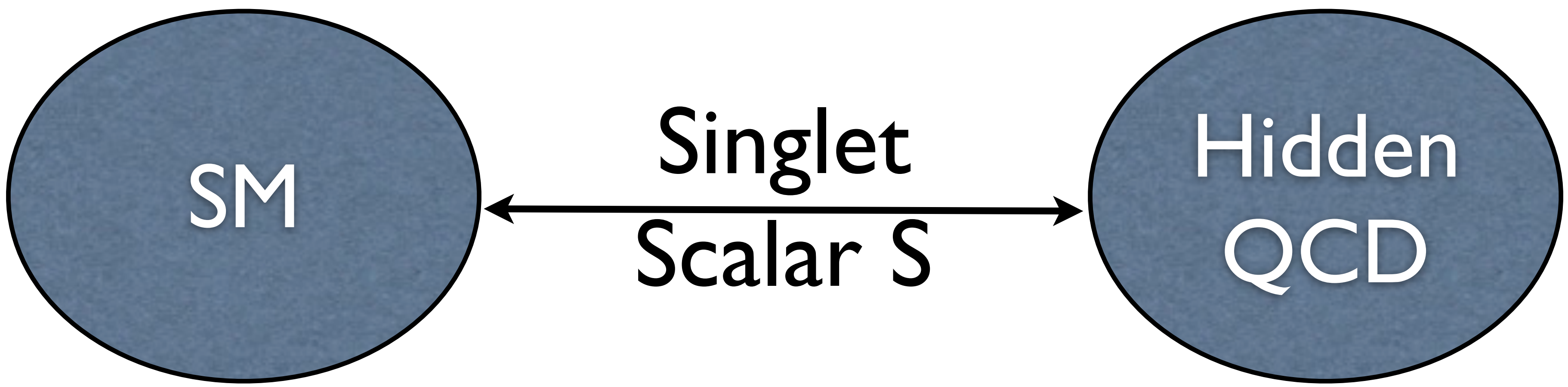




- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

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

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

Hidden sector lagrangian with new strong interaction

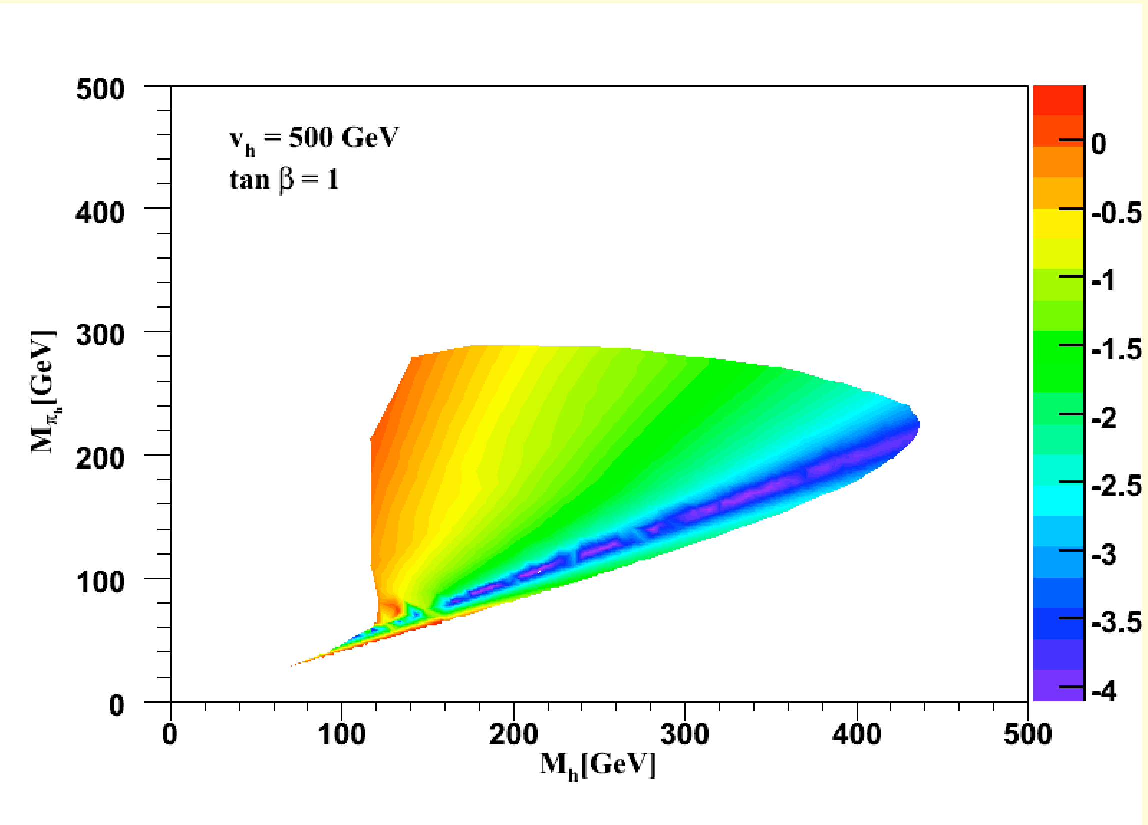
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

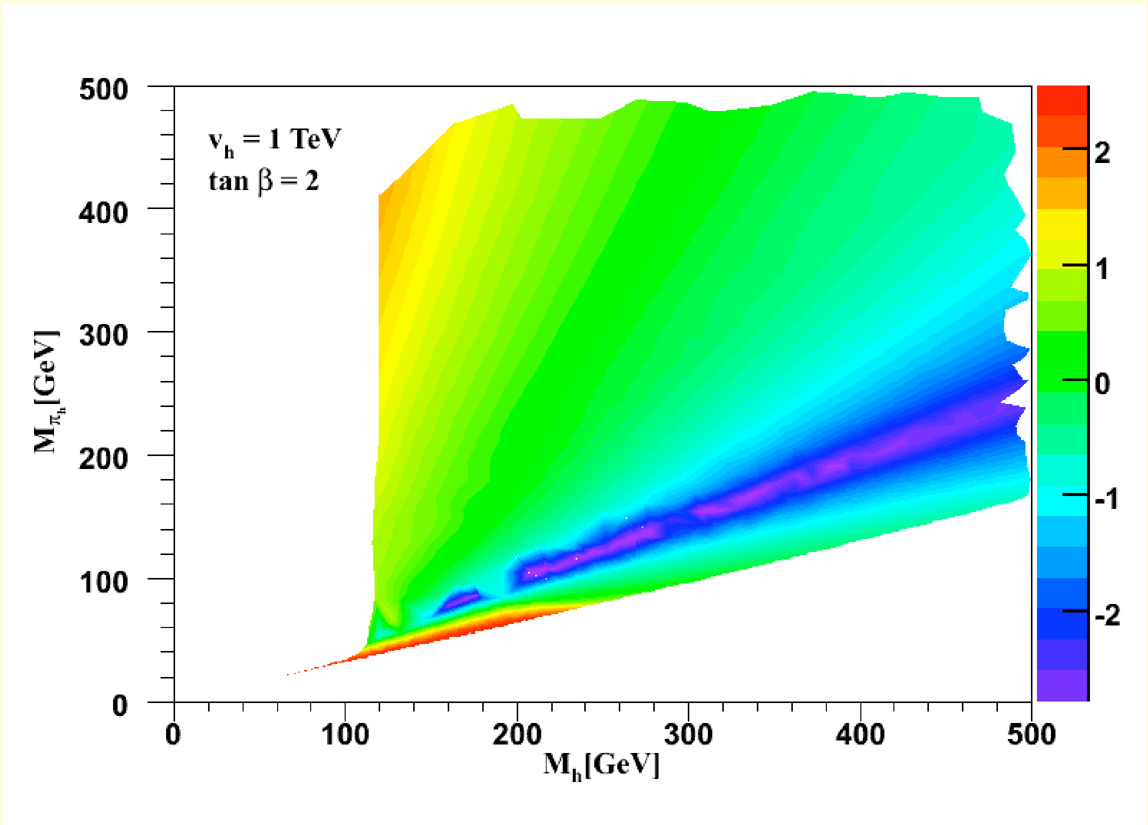
3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

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

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

Relic density



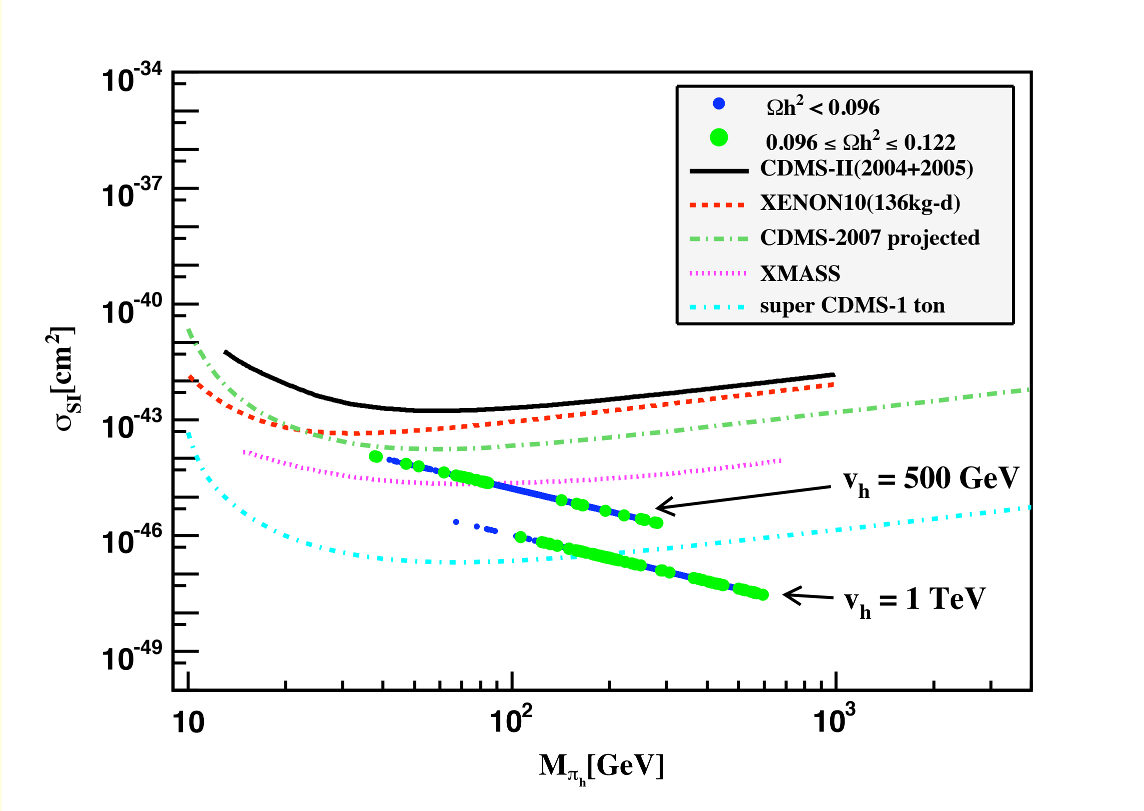


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

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

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

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

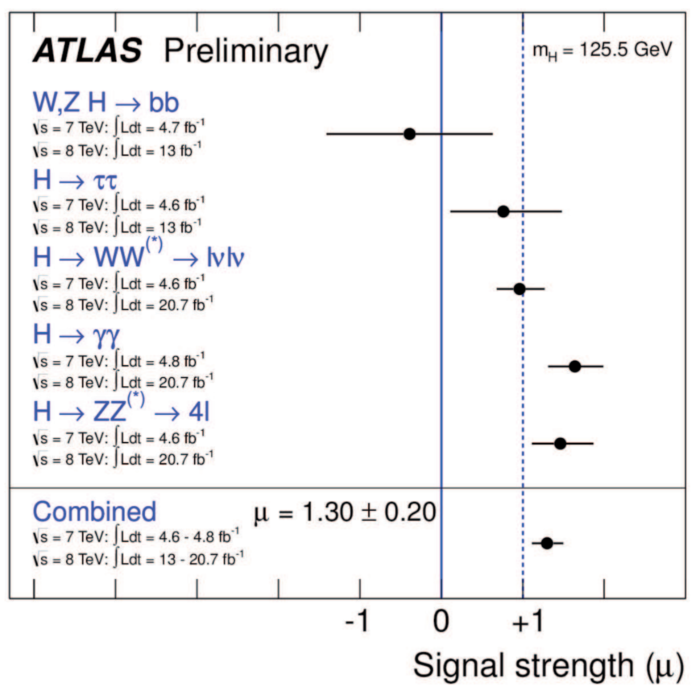
the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

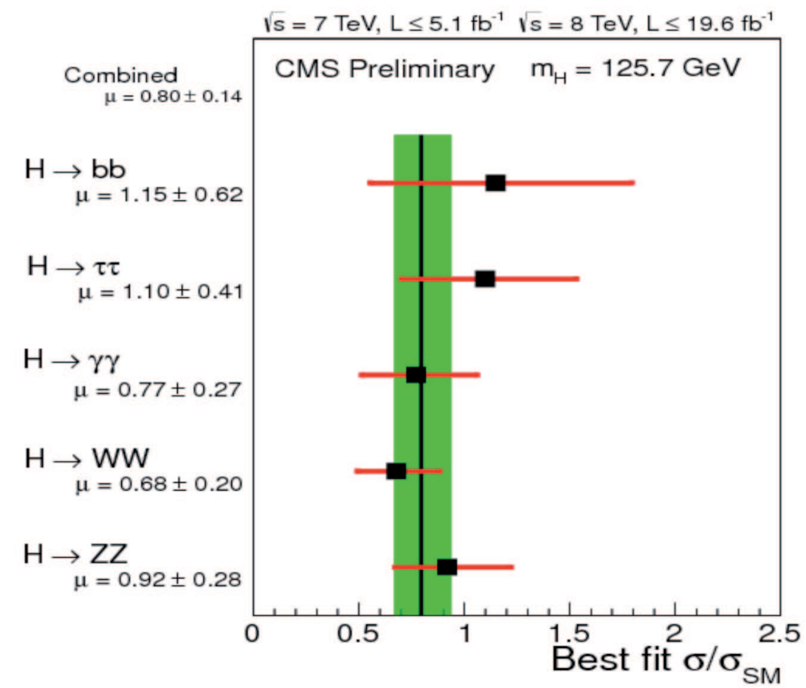
the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

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

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

Naturalness Problem ?

- Scale Symmetry is explicitly broken only by dim-4 operators (beta functions)
- Our model is renormalizable when dim regularization is used, and no quadratic divergence
- Logarithmic sensitivity to high energy scale
- OK up to Planck scale as long as no new particles at high energy scale

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)

Impact of dark higgs
-Cosmo.

(Higgs-portal assisted Higgs inflation)

[arXiv: 1405.1635, P. Ko & WIP]

Higgs Inflation in SM

(before BICEP2)

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2\kappa}\left(1+\xi\frac{h^2}{M_{\rm Pl}^2}\right)R + \mathcal{L}_h$$

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

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

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

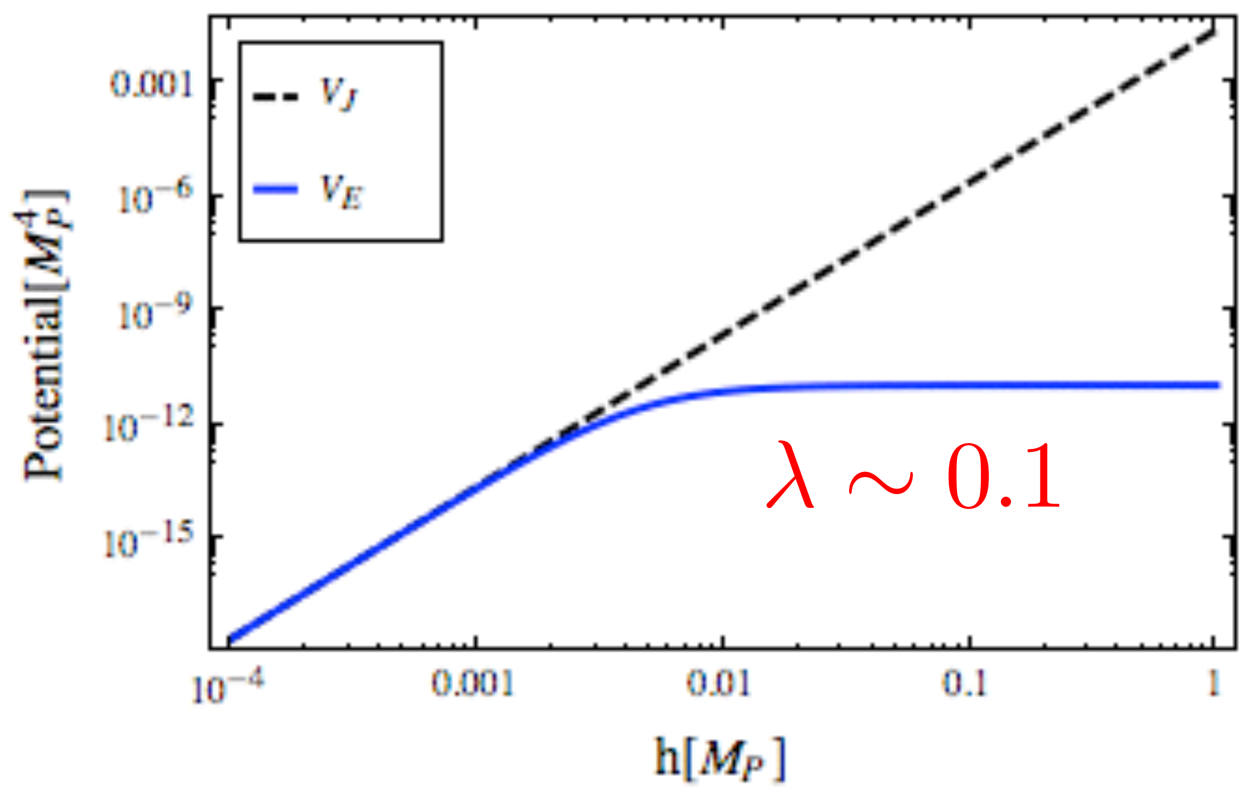
$$n_s = 1 - 6\epsilon + 2\eta \sim 0.96$$

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

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

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

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



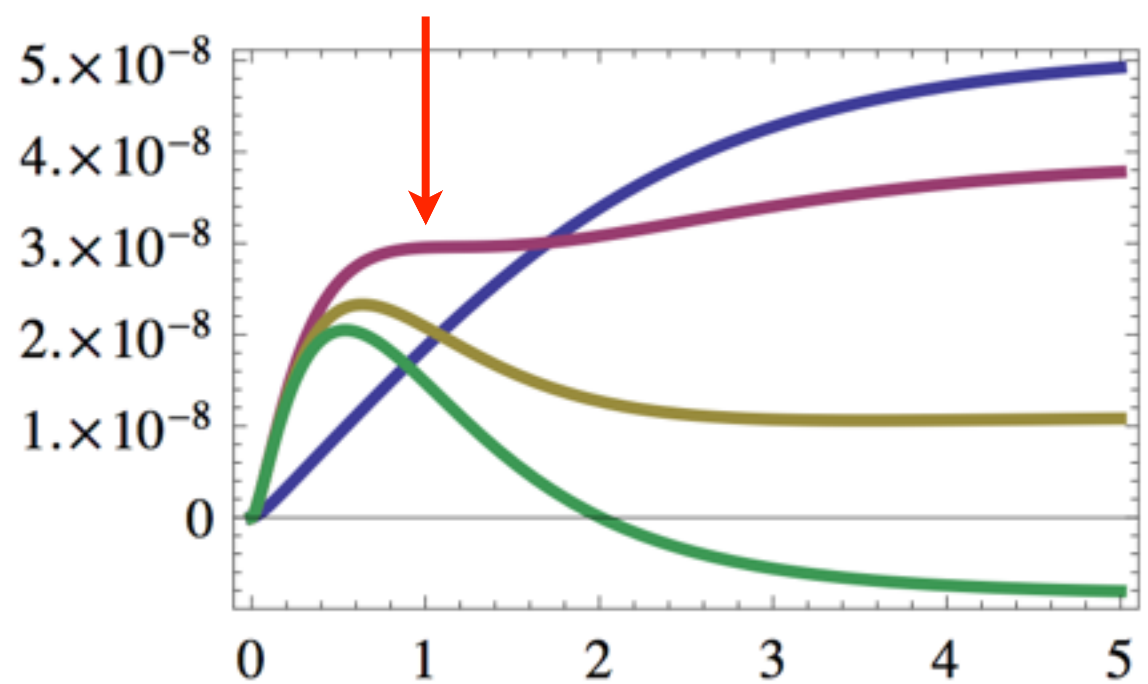
Higgs Inflation in SM

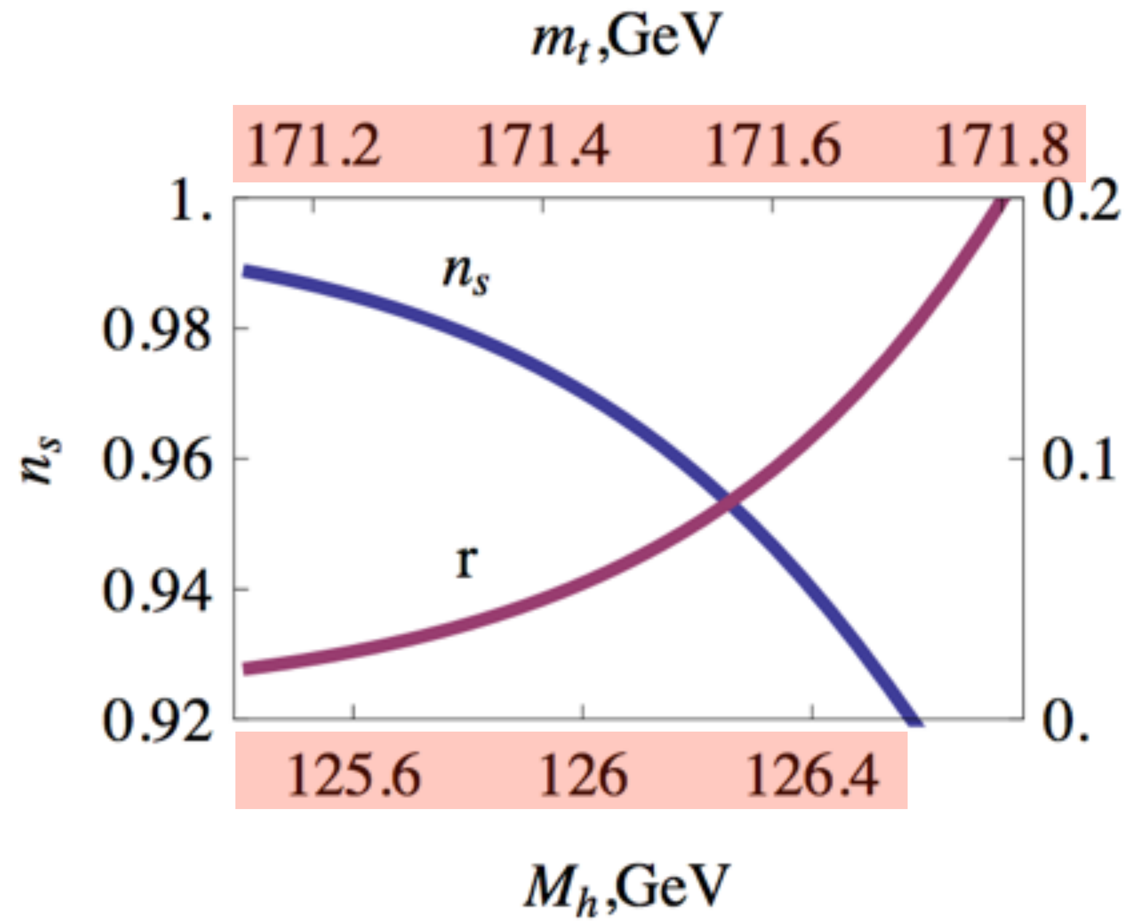
(after BICEP2)

$r_{\rm BICEP2} \sim 0.1$ ➡ 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]





Effects of running on slow-roll parameters

$$\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{dh}{d\chi}\frac{dU}{dh}\right)^2 = \frac{1}{2}\left(4+\frac{\beta_\lambda}{\lambda_H}\right)^2 \frac{M_{\rm Pl}^2/h^2}{\sqrt{\Omega^2+6\xi^2h^2/M_{\rm Pl}^2}} \approx \frac{1}{12}\left(4+\frac{\beta_\lambda}{\lambda_H}\right)^2\frac{M_{\rm Pl}^4}{\xi^2h^4} \qquad (17)$$

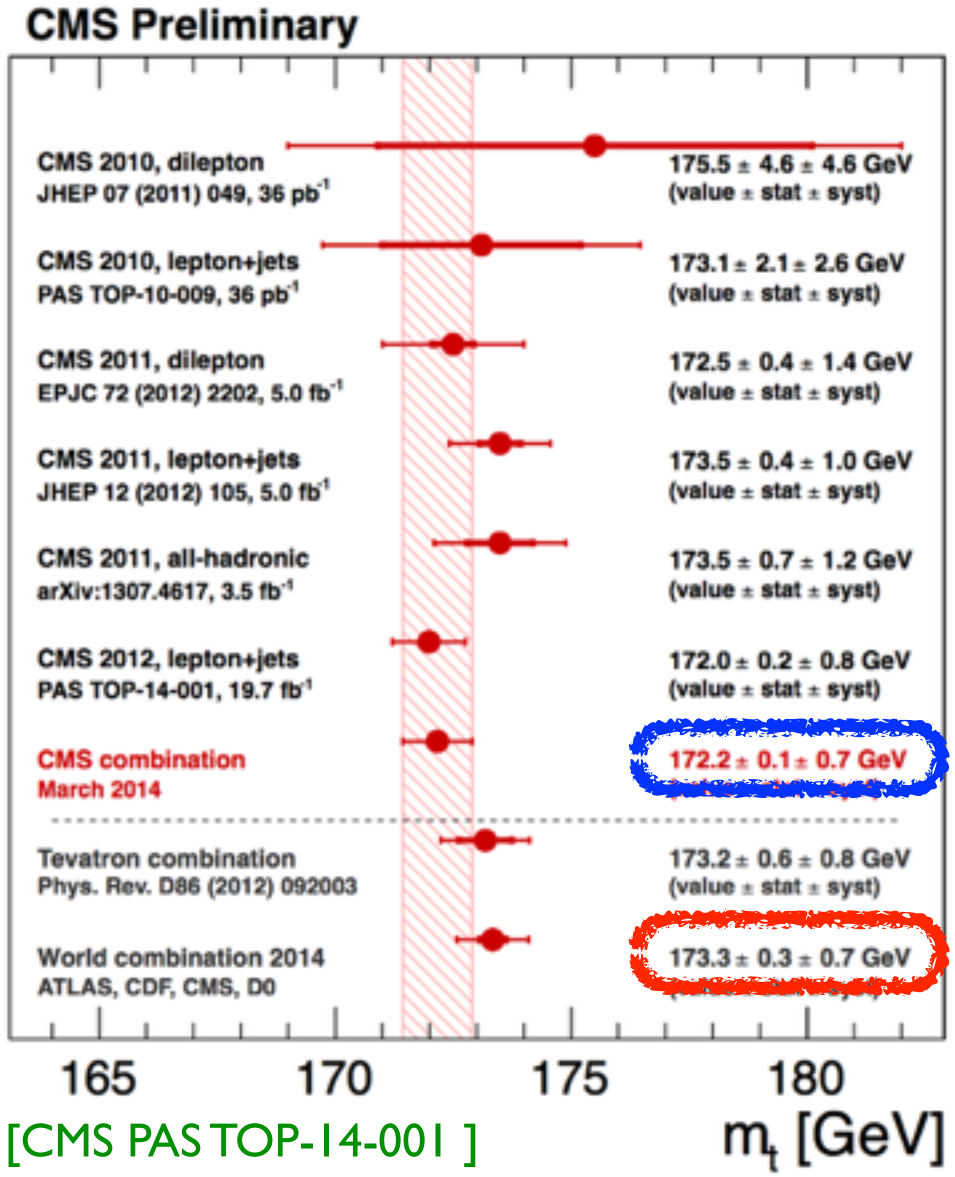
$$\eta = \frac{M_{\rm Pl}^2}{U}\frac{dh}{d\chi}\frac{d}{dh}\left(\frac{dh}{d\chi}\frac{dU}{dh}\right)$$

$$= \left(4+\frac{\beta_\lambda}{\lambda_H}\right)\frac{M_{\rm Pl}^2}{h^2}\frac{\Omega^2}{\Omega^2+6\xi^2h^2/M_{\rm Pl}^2}\left\{\frac{1}{\Omega^2}\frac{\beta_\lambda}{\lambda_H}\left[1+\frac{d\ln\left(\beta_\lambda/\lambda_H\right)/d\ln\varphi}{4+\beta_\lambda/\lambda_H}\right]+3-2\frac{d\ln\Omega^2}{d\ln h}-\frac{\xi\left(1+6\xi\right)h^2/M_{\rm Pl}^2}{1+\xi\left(1+6\xi\right)h^2/M_{\rm Pl}^2}\right\}$$

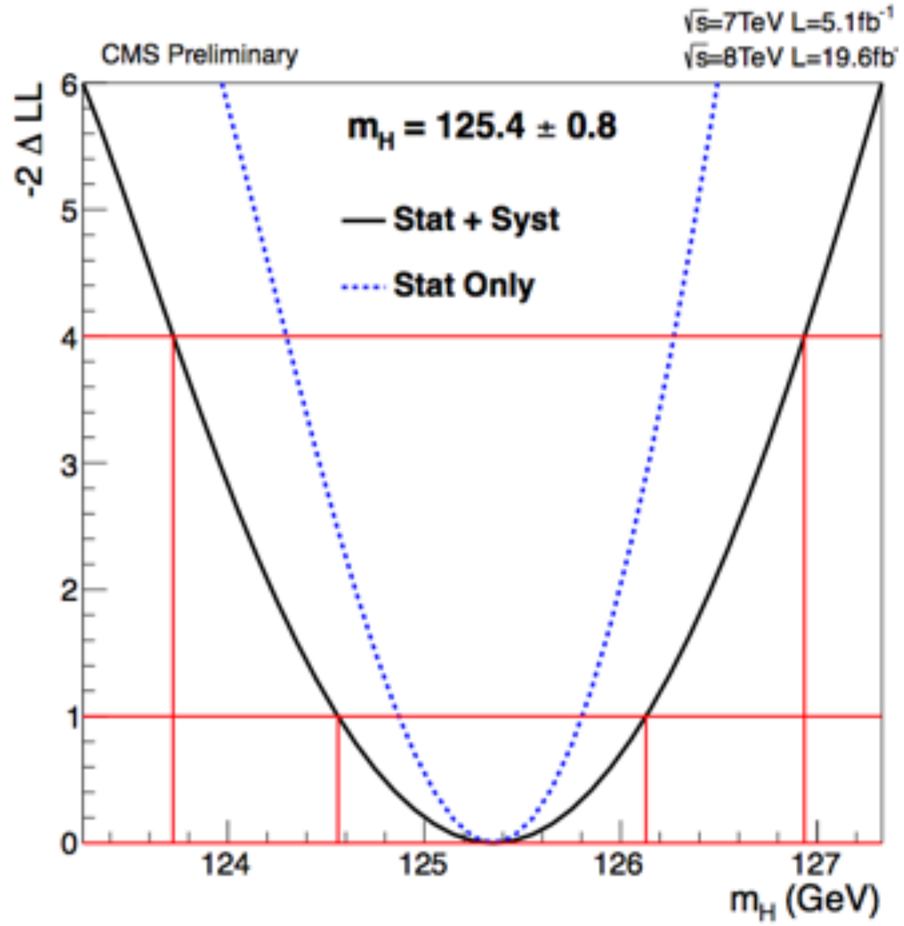
$$\simeq -\frac{1}{3}\left(4+\frac{\beta_\lambda}{\lambda_H}\right)\frac{M_{\rm Pl}^2}{\xi h^2}\left\{1-\frac{M_{\rm Pl}^2}{2\xi h^2}\frac{\beta_\lambda}{\lambda_H}\left[1+\frac{d\ln\beta_\lambda/d\ln\varphi-\beta_\lambda/\lambda_H}{4+\beta_\lambda/\lambda_H}\right]\right\} \qquad (18)$$

ϵ & η are independent

However m_t and M_h are tightly constrained!

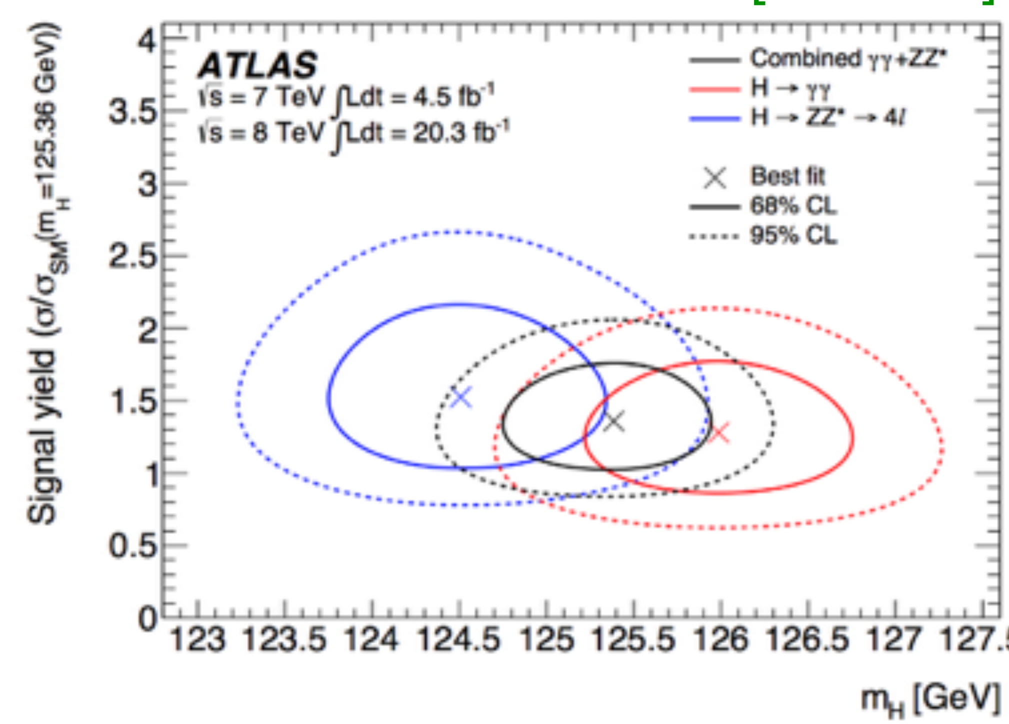


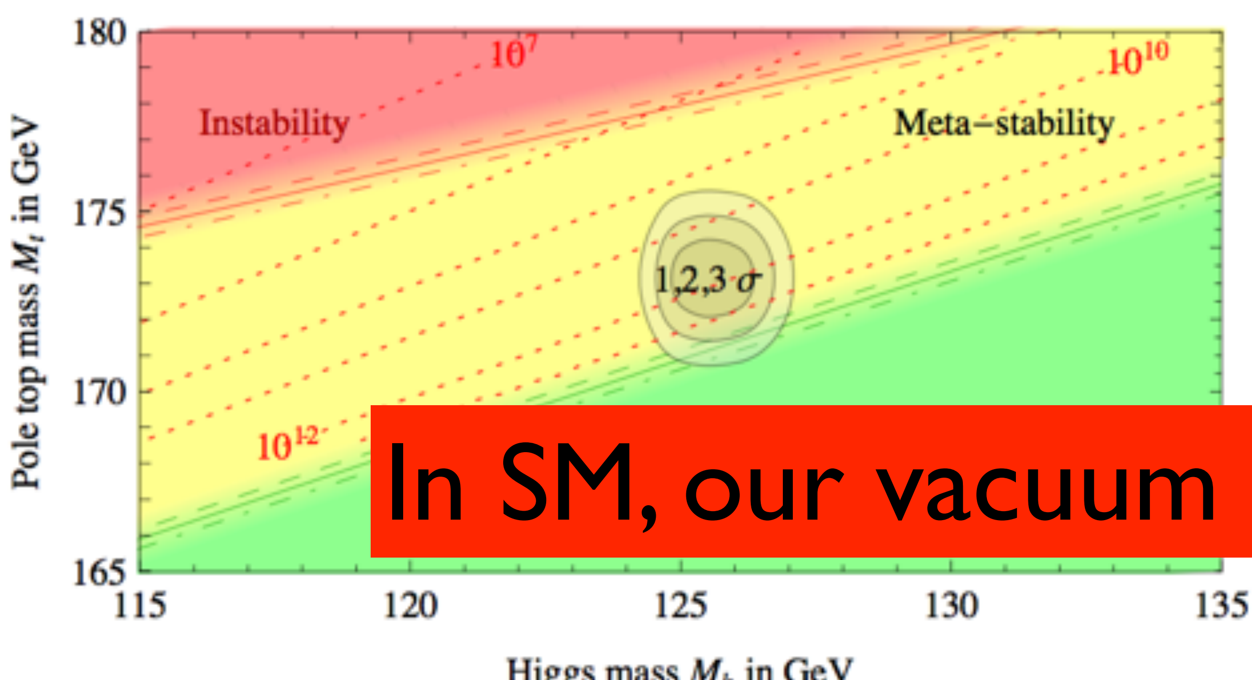
[CMS PAS TOP-14-001]



[CMS PAS HIG-13-001]

[1406.3827]





In SM, our vacuum is likely to be meta-stable.

Higgs portal interaction

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

Scalar mixing

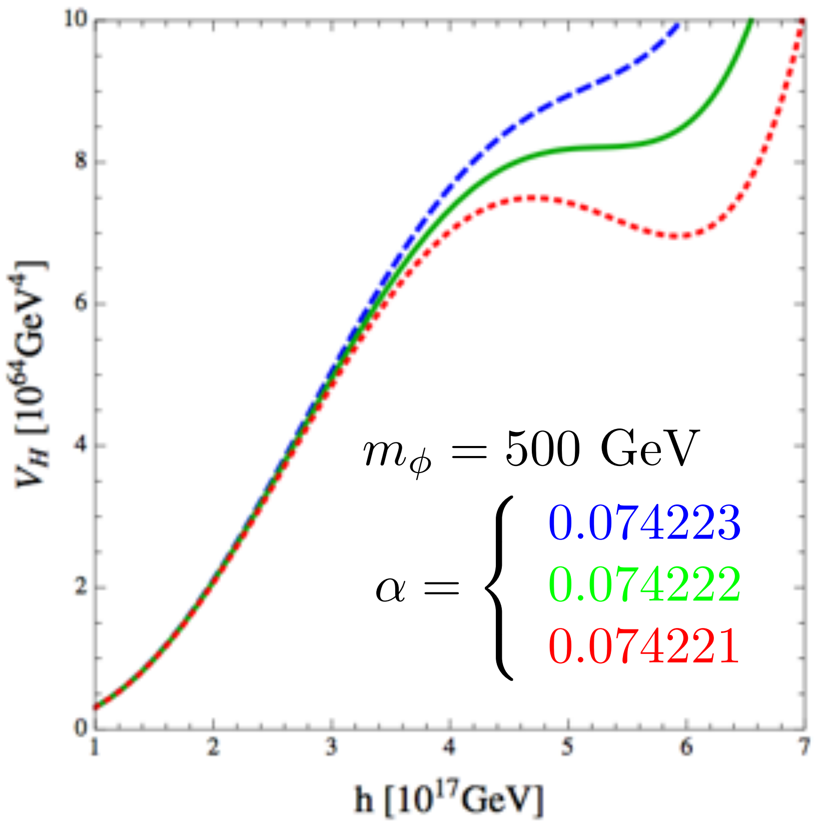
⇒ $\lambda_H > \lambda_H^{SM}$ for $m_\phi > m_h$ & $\alpha \neq 0$

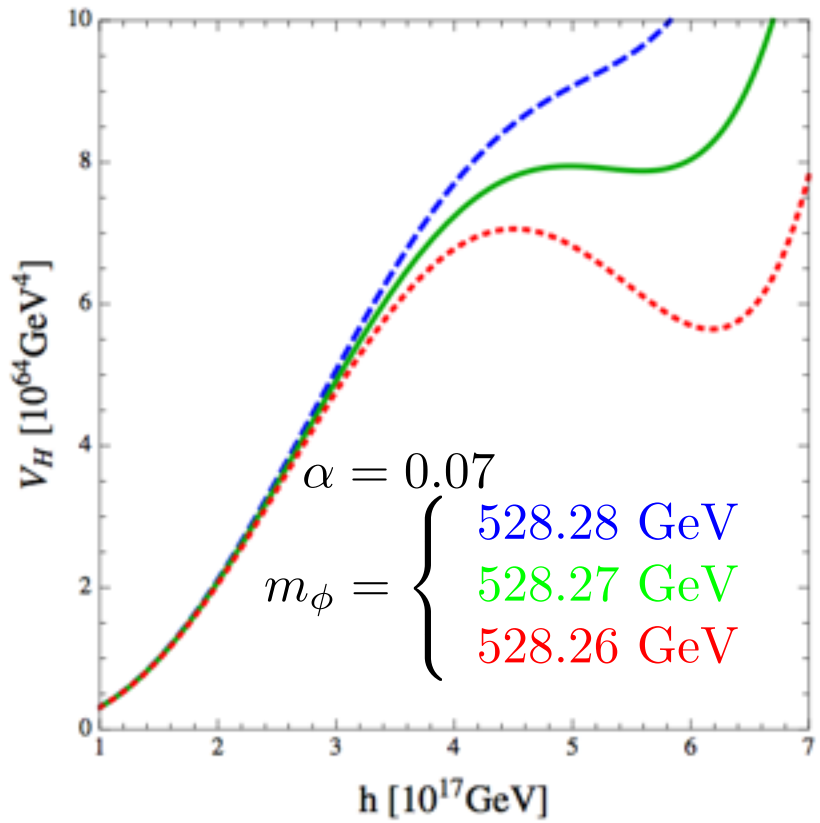
⇒ Vacuum instability is easily removed.

⇒ Higgs inflation consistent with BICET2 is possible for a wide range of m_t and M_h

Higgs portal interaction disconnect m_t and M_h from inflationary observables.

Higgs-portal Higgs inflation

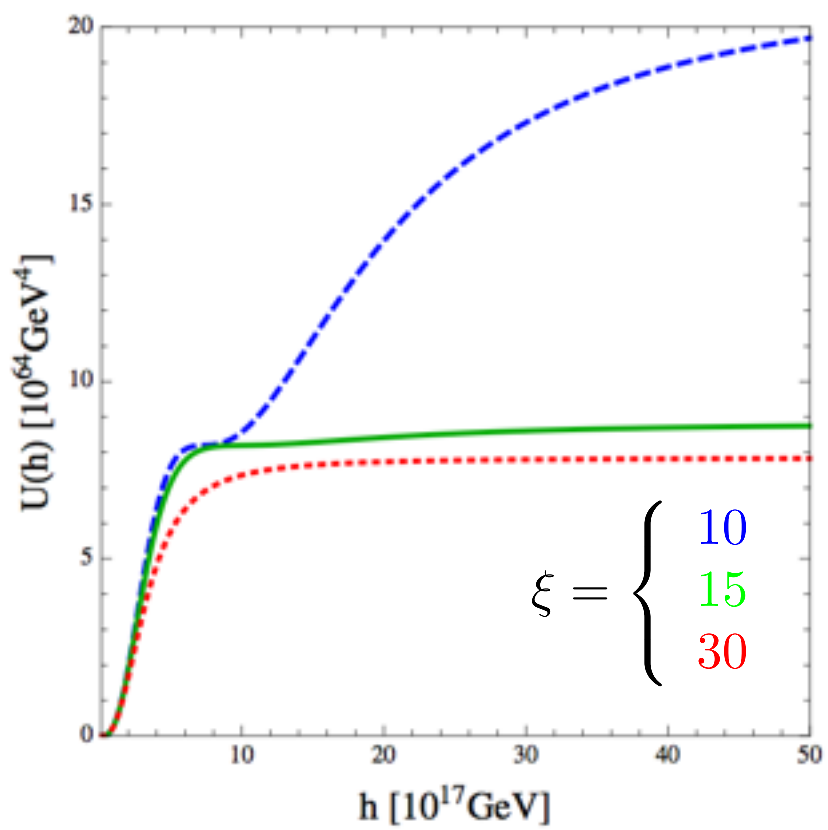




$m_t = 173.2$ GeV
$M_h = 125.5$ GeV

* Inflection point control

(α, m_ϕ) & $\lambda_{\Phi H}$



Result of numerical analysis

$k_* \times$ Mpc	N_e	h_*/M_{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	−0.00190	2.1777	0.9647	0.0840

- 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.

Conclusion

- Renormalizable and unitary 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.

- Searches @ LHC, CEPC, SPPC ???

Backup

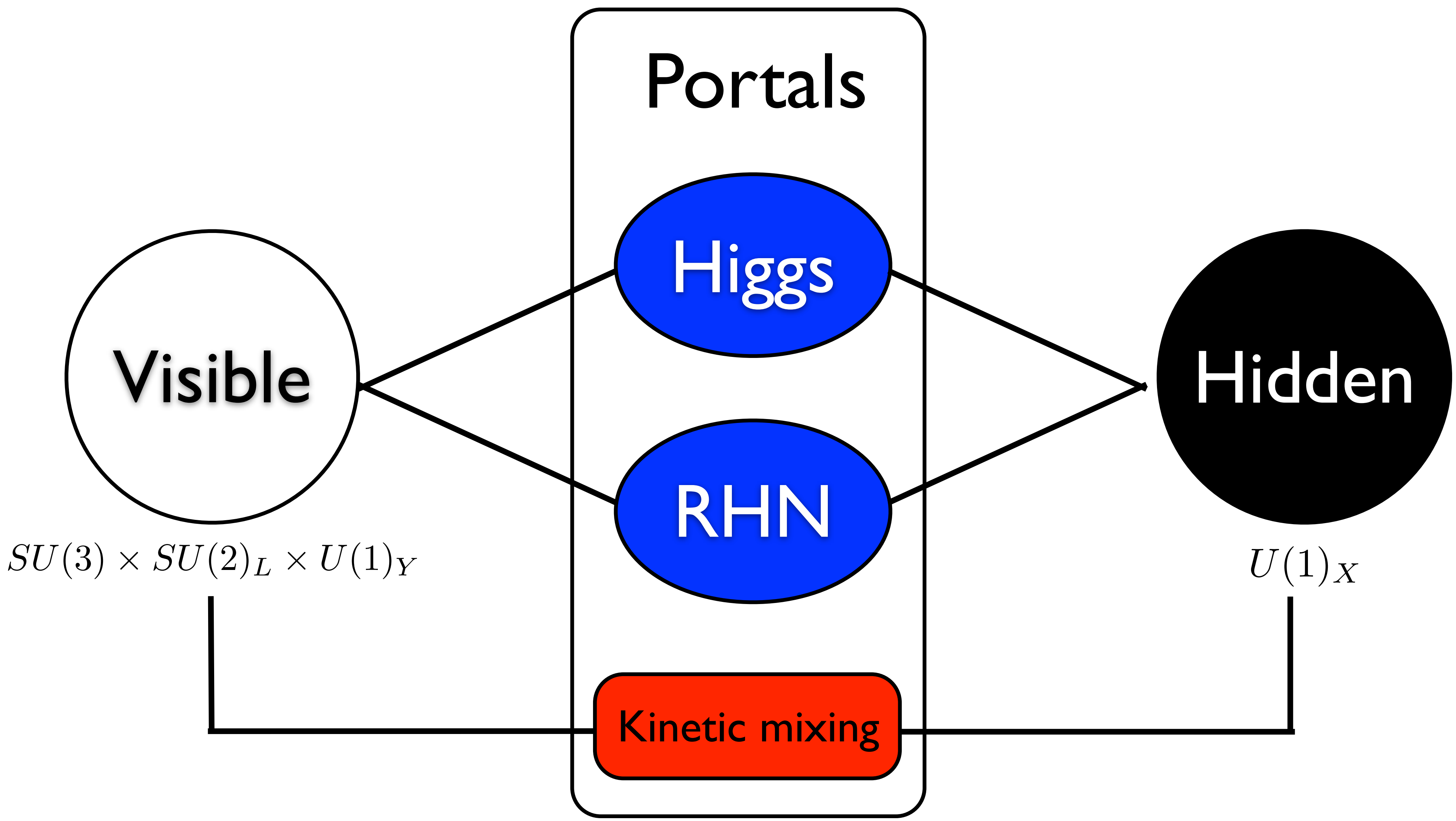
Singlet Portal Extension of the Standard Seesaw Model with Unbroken Dark Sym

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**

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

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

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

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

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

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

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

Constraints

Our model can address

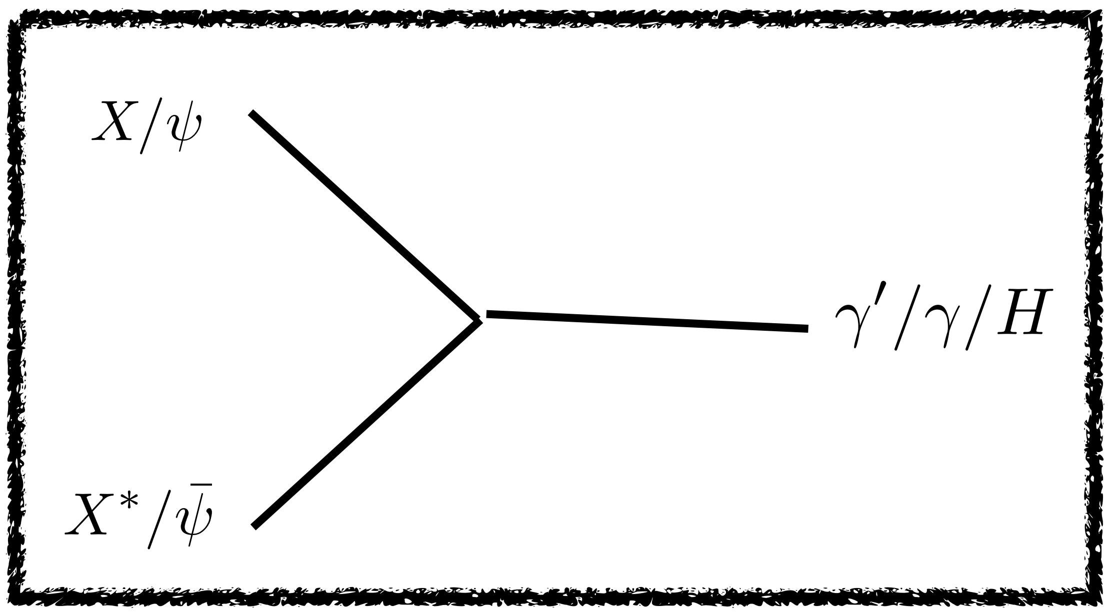
* Some small scale puzzles of CDM (Dark matter self-interaction) (α_X, m_X)
* CDM relic density (Unbroken dark $U(1)_X$) (λ, λ_{hx}, m_X,)
* Vacuum stability of Higgs potential (Positive scalar loop correction) (λ_{hx})
* Direct detection (Photon and Higgs exchange)(ε, λ_{hx})
* Dark radiation (Massless 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)

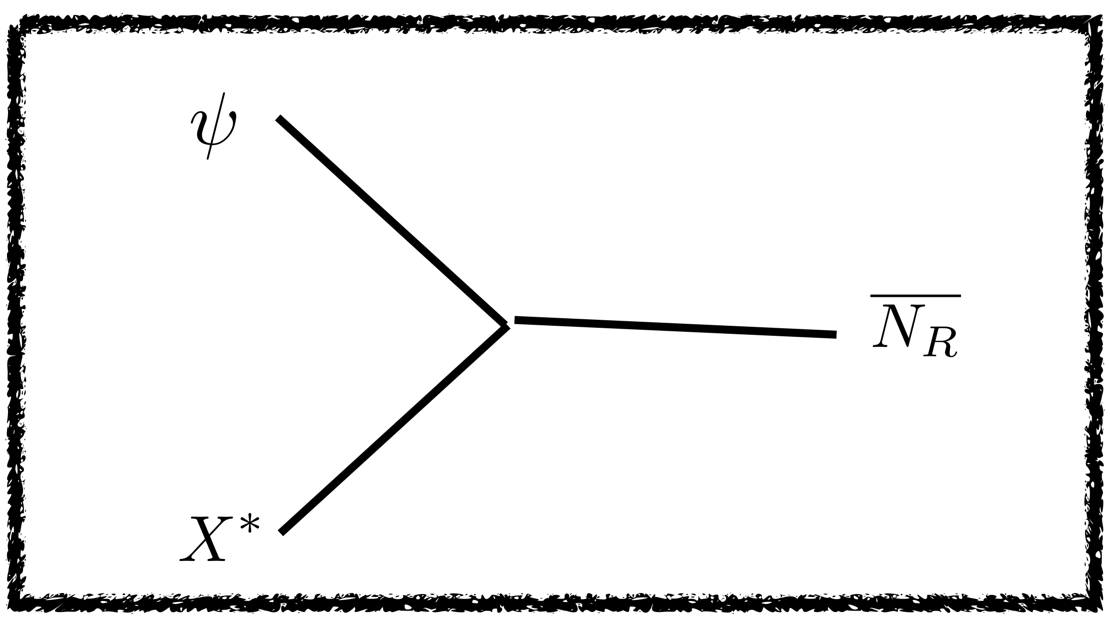
Kinetic term diagonalization: $\begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix}$

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



Annihilation
or
scattering

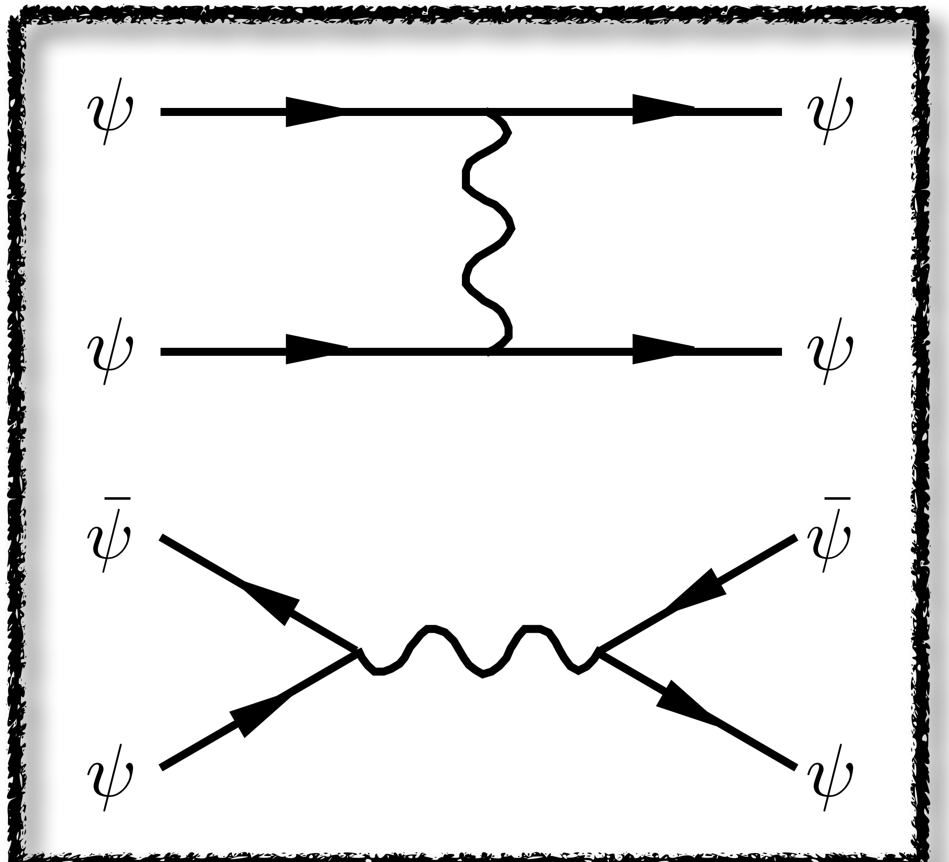
(⇒ Relic density, direct/indirect searches)



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,

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

[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.

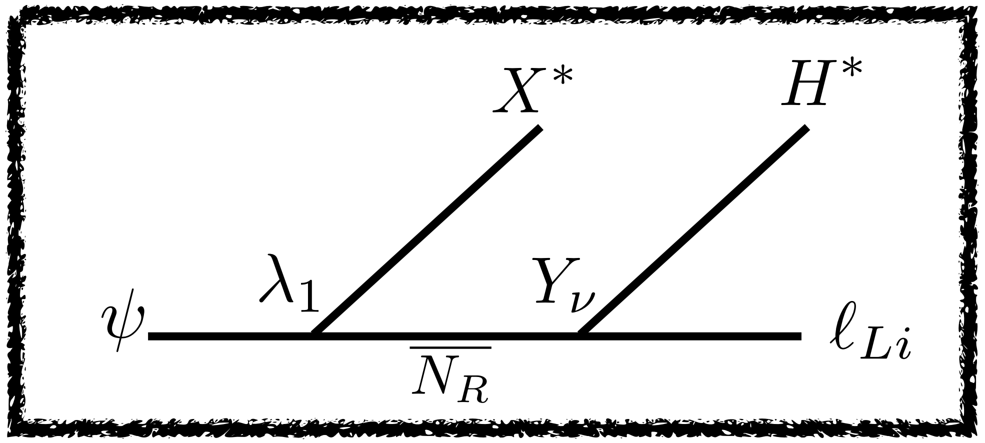
"X"(the scalar dark field) = CDM

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

(i) cored profile of dwarf galaxies.

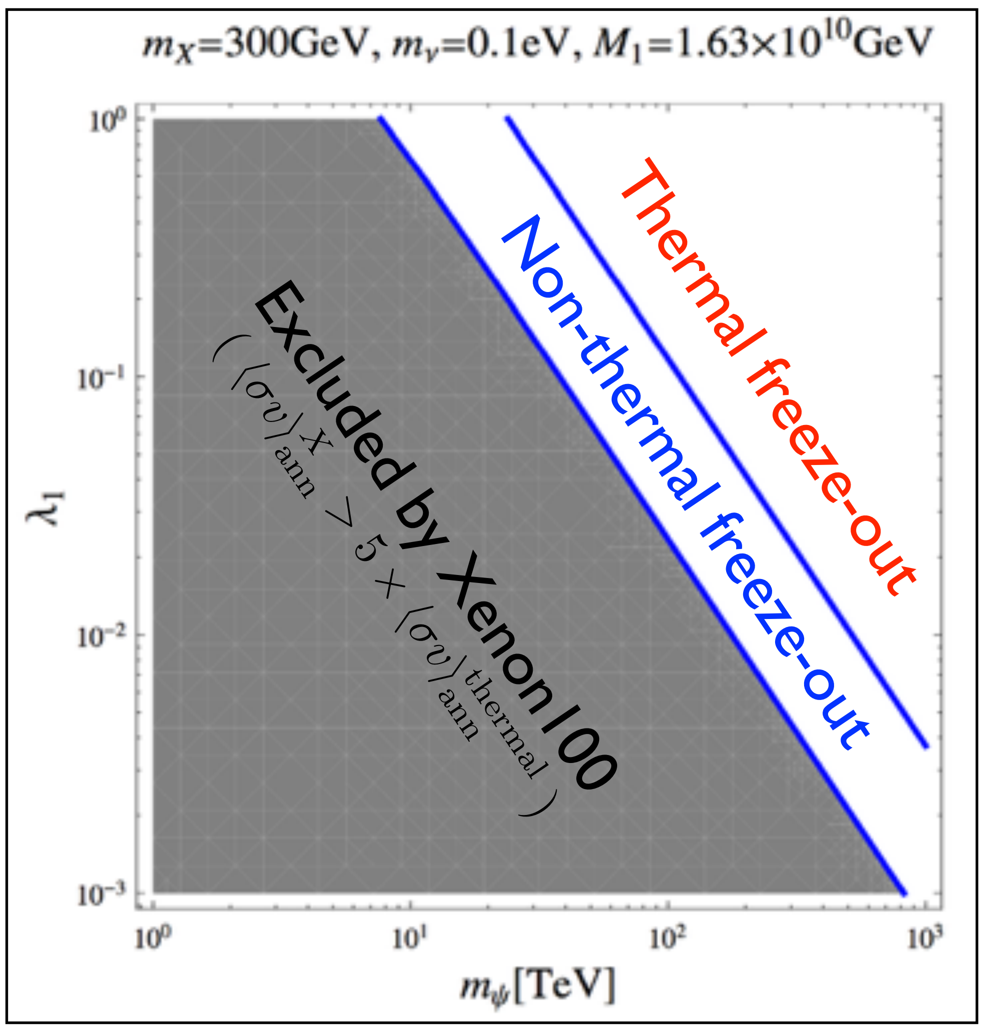
(ii) low concentration of LSB galaxies and dwarf galaxies. [Vogelsberger, Zavala and Leb, 1201.5892]

- # CDM relic density



The late-time decay of ψ

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



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

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

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

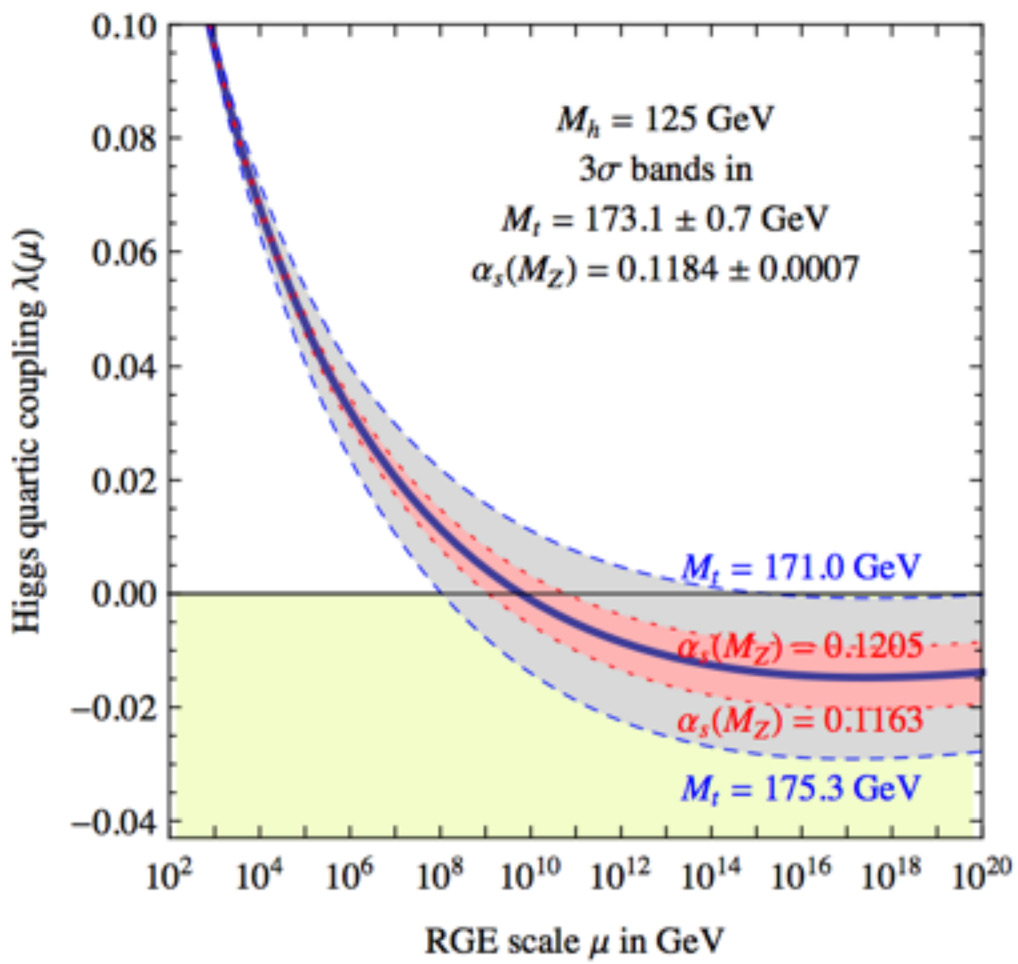
- # Vacuum stability (λ_{hx}) [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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

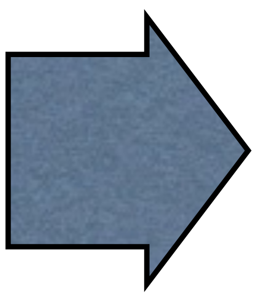
$$\beta^{(1)}_{\lambda_{HS}} = \frac{\lambda_{HS}}{16\pi^2}\left[2\left(6\lambda_H + 3\lambda_S + 2\lambda_{HS}\right) - \left(\frac{3}{2}\lambda_H\left(3g_2^2+g_1^2\right) - 6\lambda_t^2 - 4\kappa^2\right)\right],$$

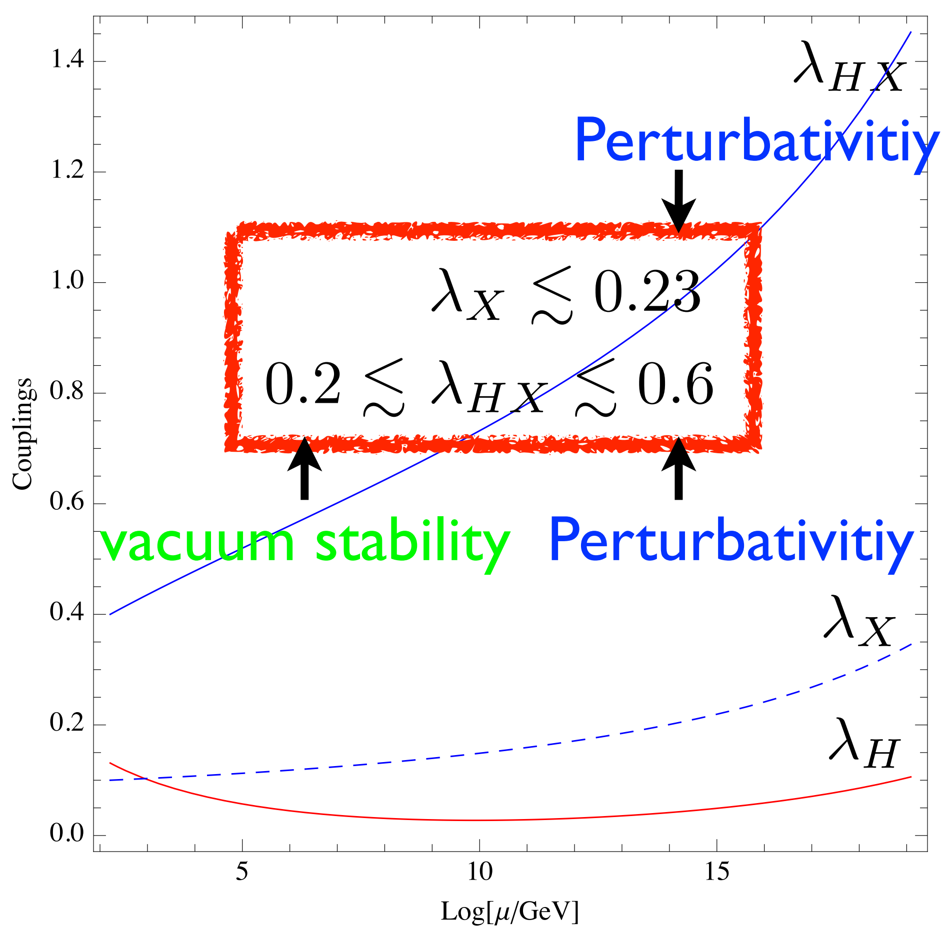
$$\beta^{(1)}_{\lambda_S} = \frac{1}{16\pi^2}\left[2\lambda_{HS}^2 + 18\lambda_S^2 + 8\lambda_S\kappa^2 - 8\kappa^4\right],$$

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

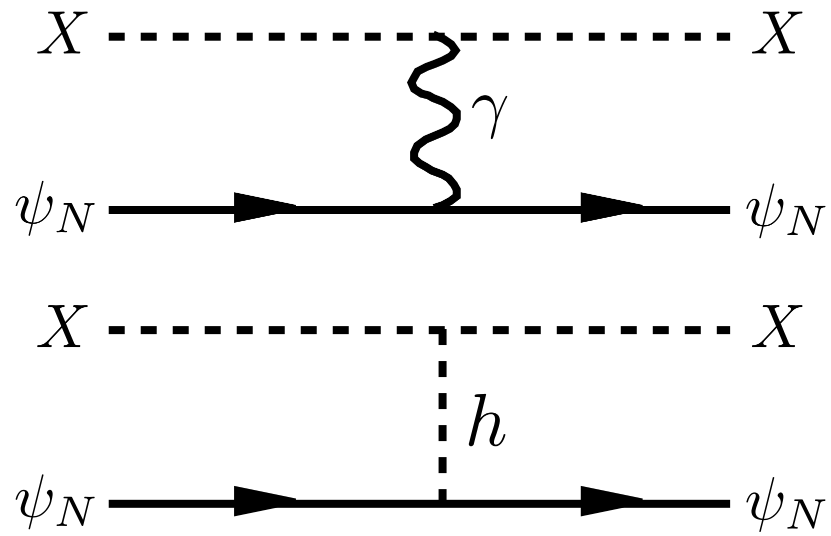


[G. Degrassi et al., 1205.6497]



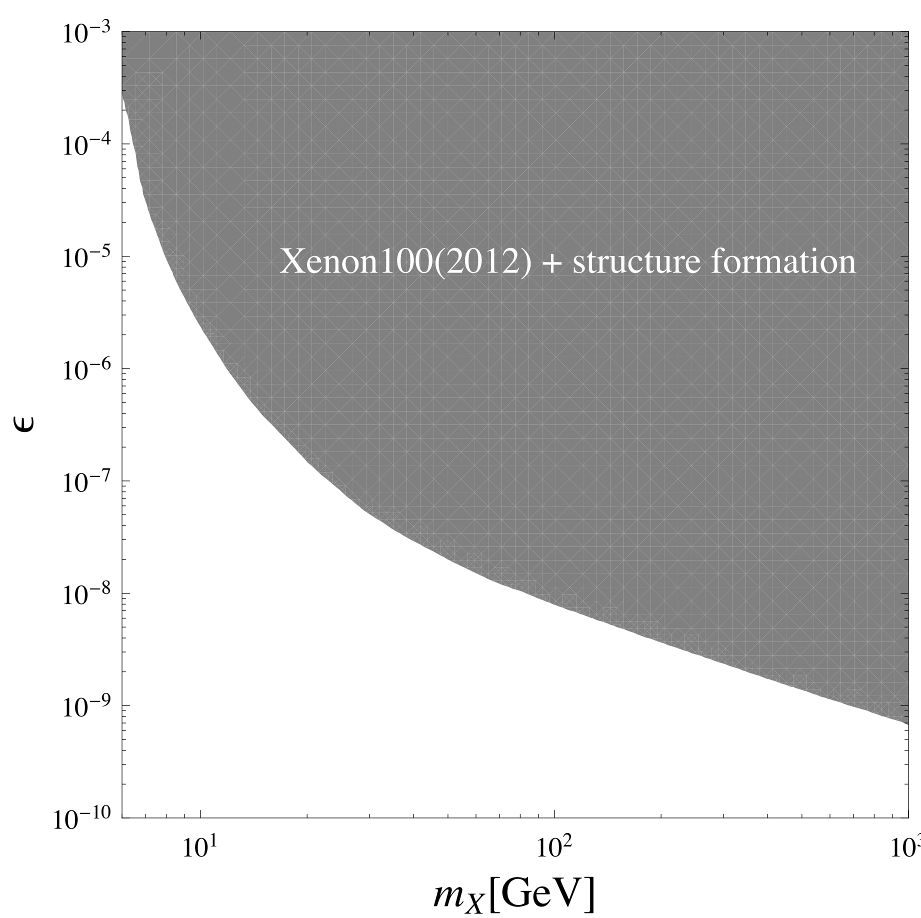


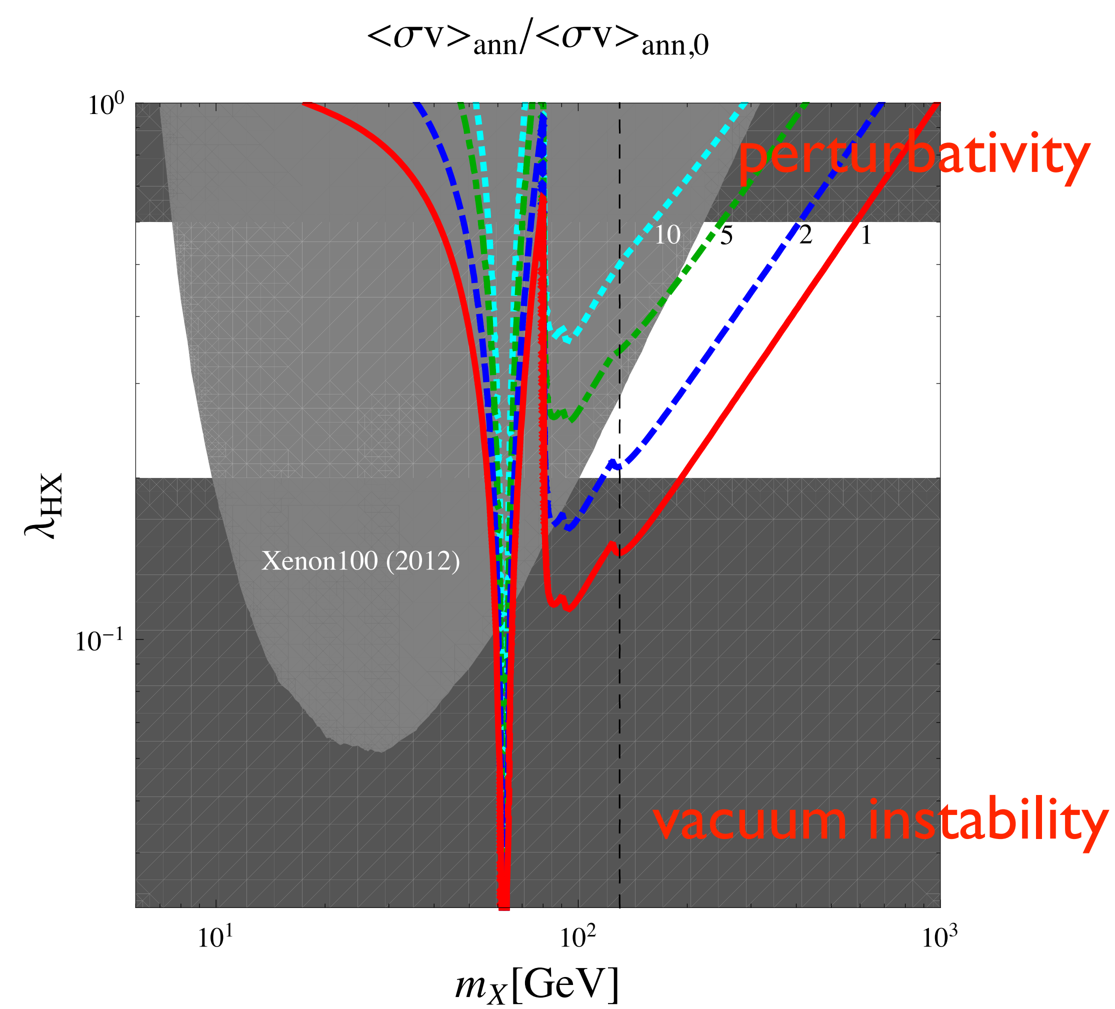
- DM direct search (ϵ, λ_{hx}, m_X)



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

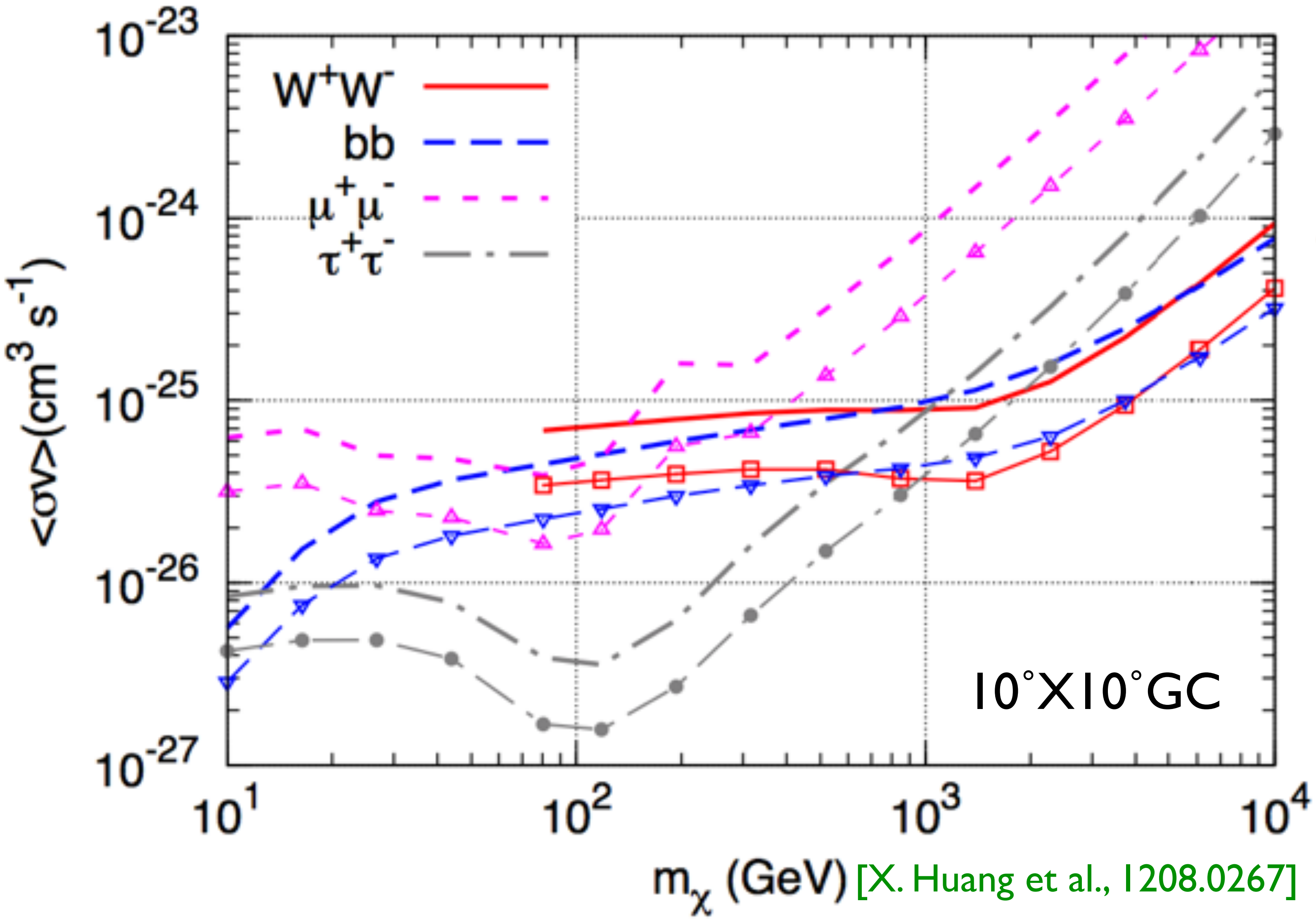
$$\sigma_{\mathcal{N},h}^{SI} = \frac{\lambda_{HX}^2}{64\pi}\frac{m_r^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$





• 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,

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

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

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

☛ 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)

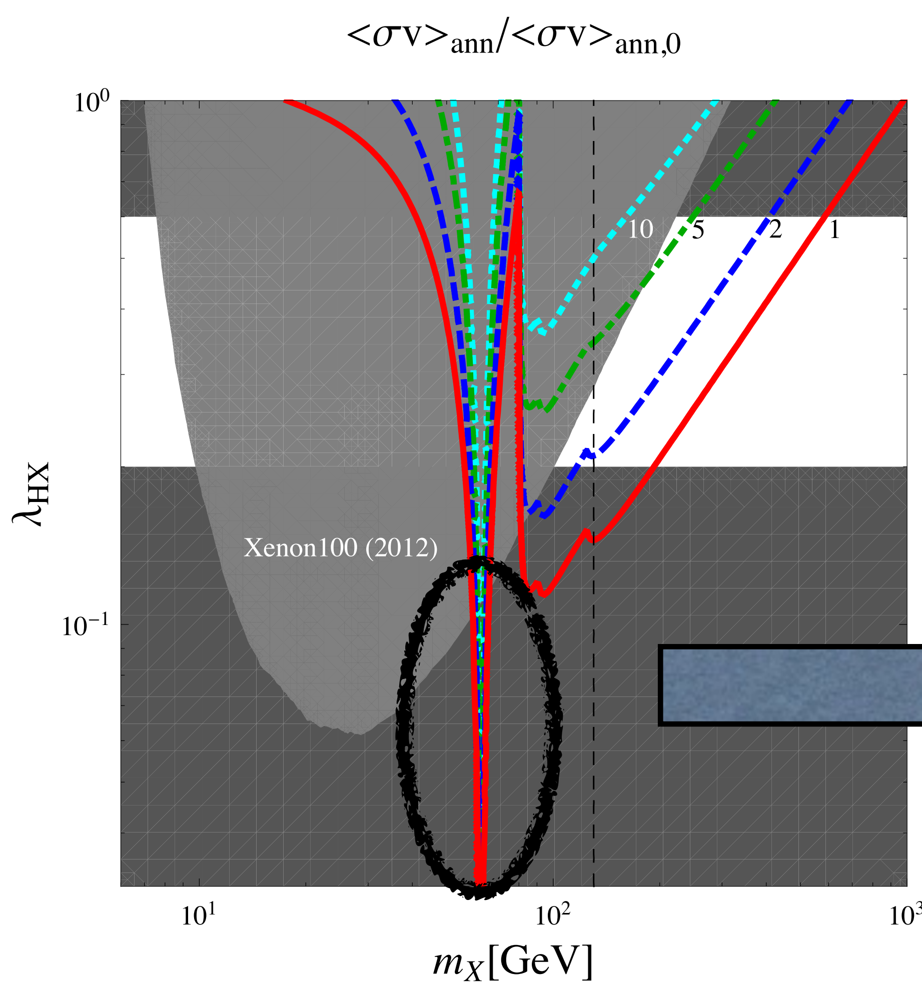
Invisible decay rate of Higgs is

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

SM signal strength at collider is

$$\mu = 1 - \frac{\Gamma_{h \to XX^\dagger}}{\Gamma_h^{\rm tot}}$$

$$\left(\text{cf., } \begin{array}{ll} \mu_{\rm ATLAS} = 1.43 \pm 0.21 & \text{for } m_h = 125.5\,\text{GeV} \\ \mu_{\rm CMS} = 0.8 \pm 0.14 & \text{for } m_h = 125.7\,\text{GeV} \end{array}\right)$$



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

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

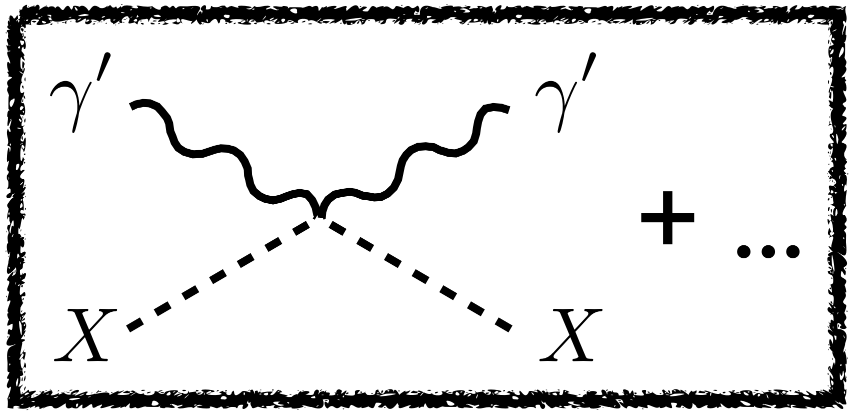
or

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

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]

Unbroken SU(N) dark sym

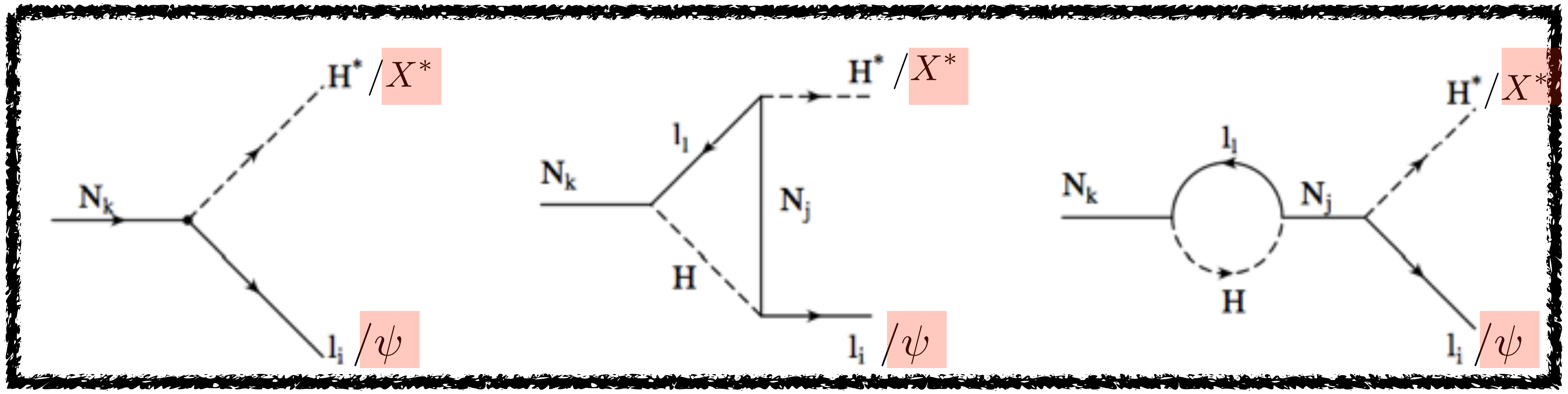
$$\Delta N_{\mathrm{eff}}(N=2) = 0.253,$$
$$\Delta N_{\mathrm{eff}}(N=3) = 0.675,$$
$$\Delta N_{\mathrm{eff}}(N=4) = 1.265.$$

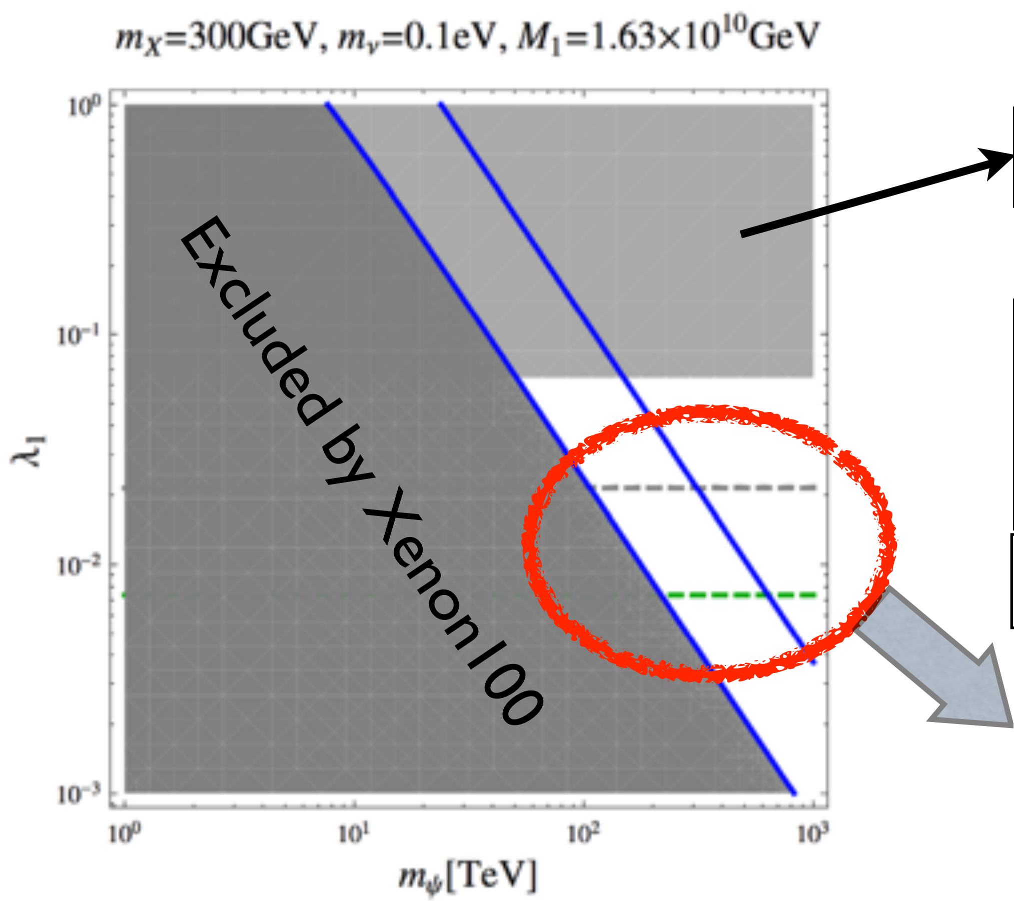
(In preparation)

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

- # Lepto/darkogenesis (1/2)

(Genesis from the decay of RHN)





Light gray: narrow width approx. is invalid

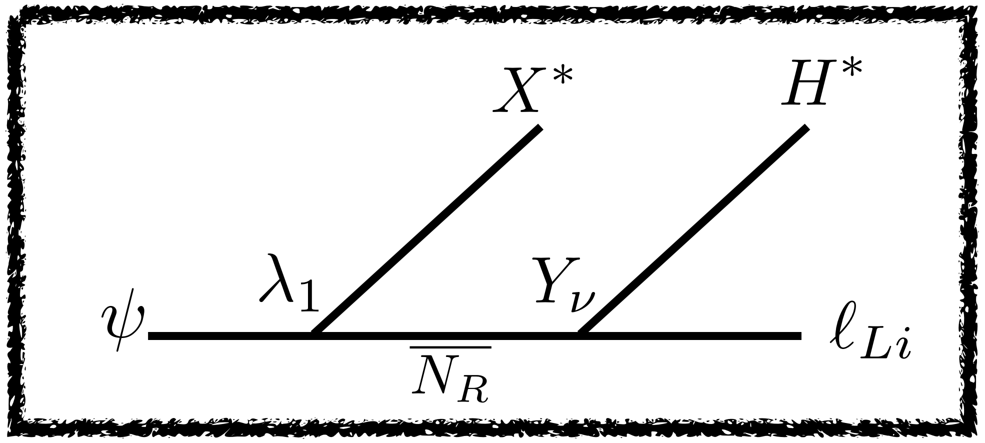
White between blue lines:

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

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!

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

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

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

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

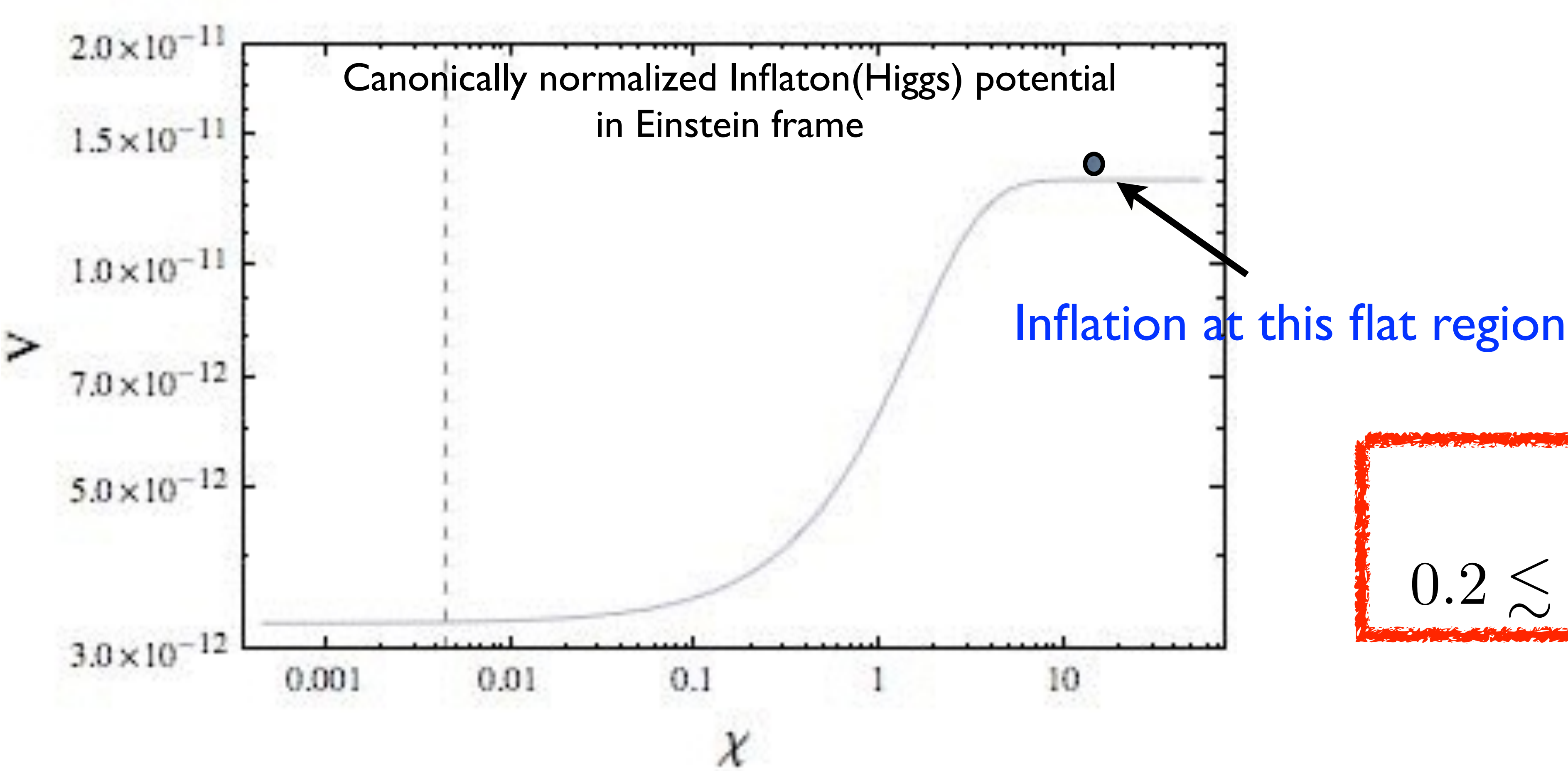
* Late-time decays of symmetric ψ and ψ-bar can generate a sizable amount of lepton number asymmetry.

- # Higgs inflation in Higgs-singlet system

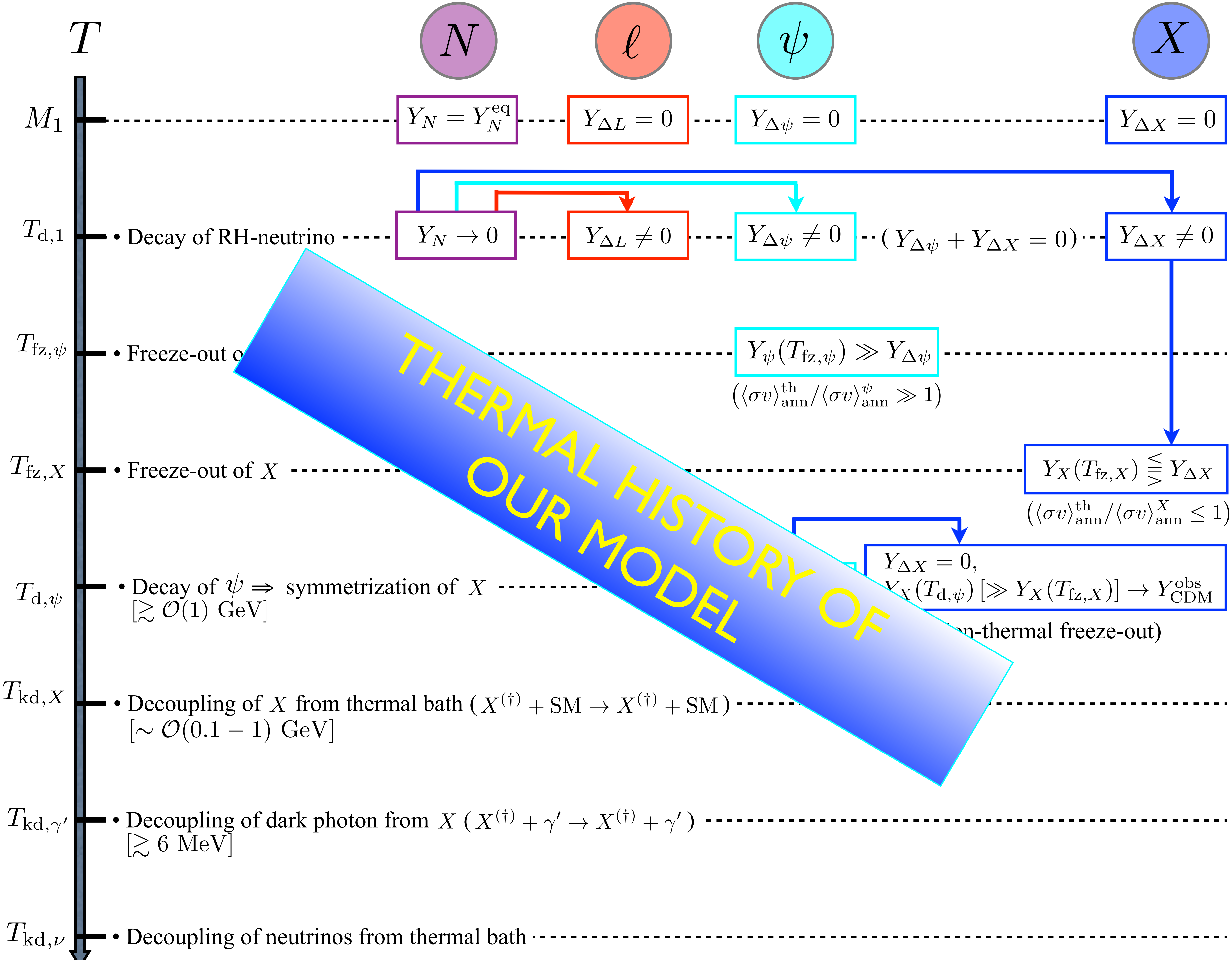
[Lebedev,1203.0156]

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

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



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



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

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

Signal strength

Assume the decay of Higgs to DMs is forbidden.

Dark sector fields	$U(1)_X$	Messenger	DM	Extra DR	μ_i
$\hat{B}'_\mu, X, \psi_X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X	~ 0.06	$1 \ (i=1)$
$\hat{B}'_\mu, X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0.06	$1 \ (i=1)$
$\hat{B}'_\mu, \psi_X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ_X	~ 0.06	$< 1 \ (i=1,2)$
$\hat{B}'_\mu, X, \psi_X, \phi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X or ψ_X	~ 0	$< 1 \ (i=1,2)$
$\hat{B}'_\mu, X, \phi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0	$< 1 \ (i=1,2)$
$\hat{B}'_\mu, \psi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ_X	~ 0	$< 1 \ (i=1,2,3)$

○ = a singlet real scalar

because of mixing in Higgs sector

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

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

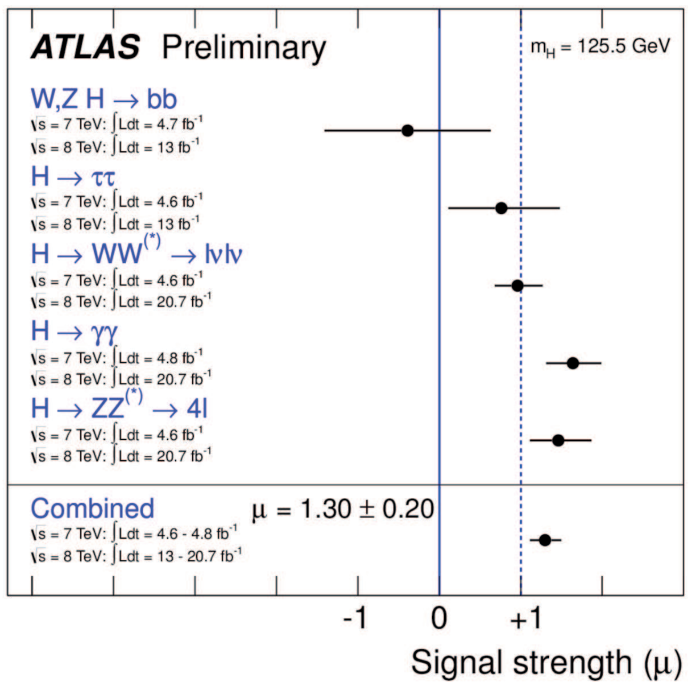
Note that "mu < 1" if CDM is fermion, whether U(1)x is broken or not

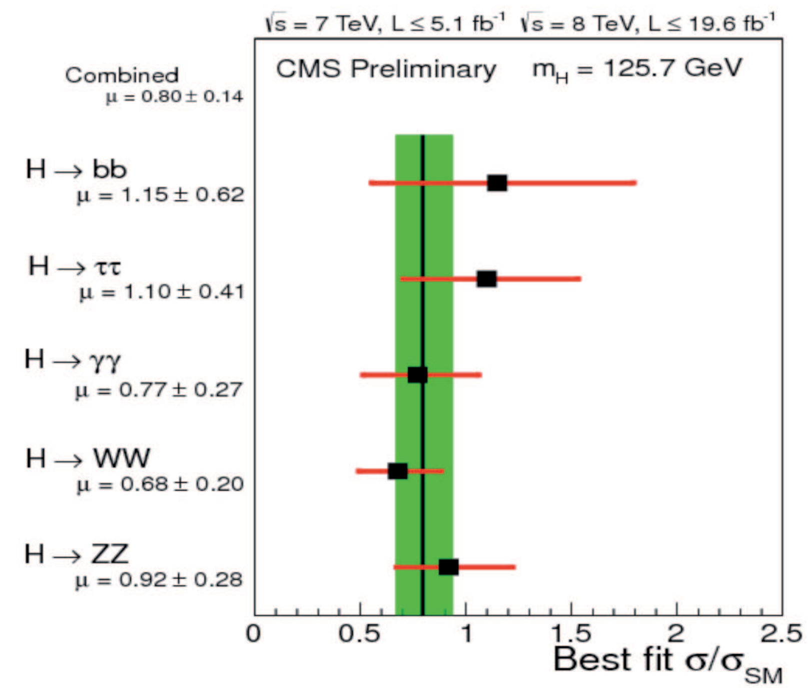
And Universal Suppression

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)

Crucial constraint

* DM annihilation is s-wave.
* Region of resonance is likely to be excluded.

⇨ CMB constraint on α_X is very strong.

$$\frac{\langle \sigma v \rangle_0}{\langle \sigma v \rangle_{26}} \lesssim \mathcal{O}(1-10) \times 10^{-5} \left(\frac{v_{\rm DM}}{10^{-11}} \right) \left(\frac{10^{-5}}{\alpha_X} \right) \left(\frac{m_{\rm DM}}{100 \rm GeV} \right)$$

$$\Longrightarrow \alpha_X \lesssim \mathcal{O}(10^{-10} - 10^{-9})$$

Phenomenology of $U(1)_h$

The model can address

* ~~Some small scale puzzles of CDM (Dark matter self interaction) (α_X, m_X)~~
* CDM relic density (Unbroken dark $U(1)_X$) ($\lambda, \lambda_{hx}, m_X,$)
* 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)~~
* Leptogenesis (from RHN & heavy dark fermion) (Y_ν, λ, M_1, m_X)
* Inflation (Higgs inflation) (λ_{hx}, λ_X)

It can be an alternative to the minimal SM.

See JHEP 1307 (2013) 013 for more details.

Variations

Signal strength

Assume the decay of Higgs to DMs is forbidden.

Dark sector fields	$U(1)_X$	Messenger	DM	Extra DR	μ_i
$\hat{B}'_\mu, X, \psi$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X	~~~ 0.08~~	$1\ (i=1)$
$\hat{B}'_\mu, X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~~~ 0.08~~	$1\ (i=1)$
$\hat{B}'_\mu, \psi$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ_X	~ 0.08	$< 1\ (i=1,2)$
$\hat{B}'_\mu, X, \psi, \phi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X or ψ	~ 0	$< 1\ (i=1,2)$
$\hat{B}'_\mu, X, \phi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0	$< 1\ (i=1,2)$
$\hat{B}'_\mu, \psi$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ	~ 0	$< 1\ (i=1,2,3)$

○ = a singlet real scalar

because of mixing in Higgs sector

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

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

Fermion dark matter ⇒ "$\mu_i < 1$".

(in both of broken and unbroken cases)

Summary of $U(1)_h$

- The simplest extension of SM with a local dark U(1) has a unique set of renormalizable interactions.
- The simple BSM model is valid up to M_P.
- It can be an alternative to the minimal standard model, addressing most of phenomenological shortcomings of SM.

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

Hidden Sector Monopole, Stable VDM and Dark Radiation

$SU(2)_h \rightarrow U(1)_h$

+

Higgs portal

[S. Baek, P. Ko & WIP, arXiv:1311.1035]

Backup Slides

The Model

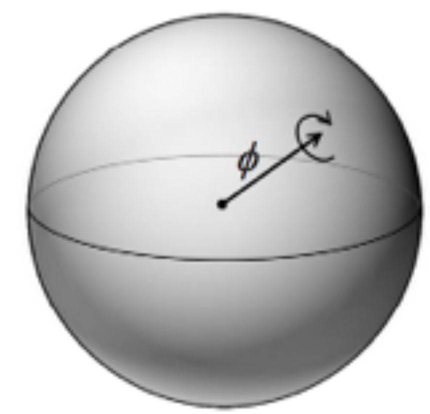
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V^a_{\mu\nu}V^{a\mu\nu} + \frac{1}{2}D_\mu\vec{\phi}\cdot D^\mu\vec{\phi} - \frac{\lambda_\phi}{4}\left(\vec{\phi}\cdot\vec{\phi} - v_\phi^2\right)^2 - \frac{\lambda_{\phi H}}{2}\vec{\phi}\cdot\vec{\phi}H^\dagger H$$

't Hooft-Polyakov monopole — Higgs portal

- Symmetry breaking

$$\phi^T = (0, 0, v_\phi) \Rightarrow SU(2) \to U(1)$$



- Particle spectra $\left(V^\pm \equiv \frac{1}{\sqrt{2}}(V_1 \mp iV_2),\ \gamma' \equiv V_3,\ H_1,\ H_2\right)$
  - VDM: $m_V = g_X v_\phi$
  - Monopole: $m_M = m_V/\alpha_X$
  - Higgses: $m_{1,2} = \frac{1}{2}\left[m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{\left(m_{hh}^2 - m_{\phi\phi}^2\right)^2 + 4m_{\phi h}^4}\right]$

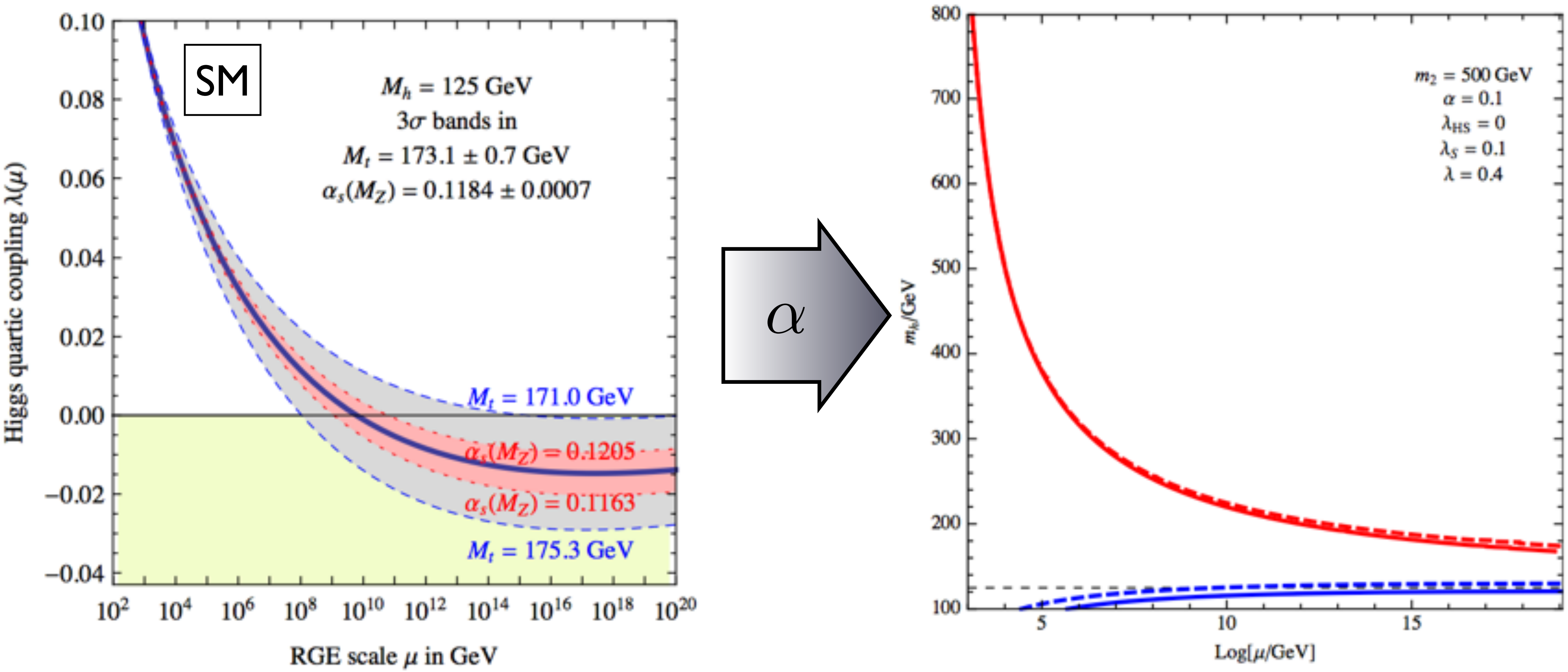
Main Results

- h-Monopole is stable due to topological conservation
- h-VDM is stable due to the unbroken U(1) subgroup, even if we consider higher dim nonrenormalizable operators
- Massless h-photon contributes to the dark radiation at the level of 0.08-0.11
- Higgs portal plays an important role

Low energy phenomenology

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

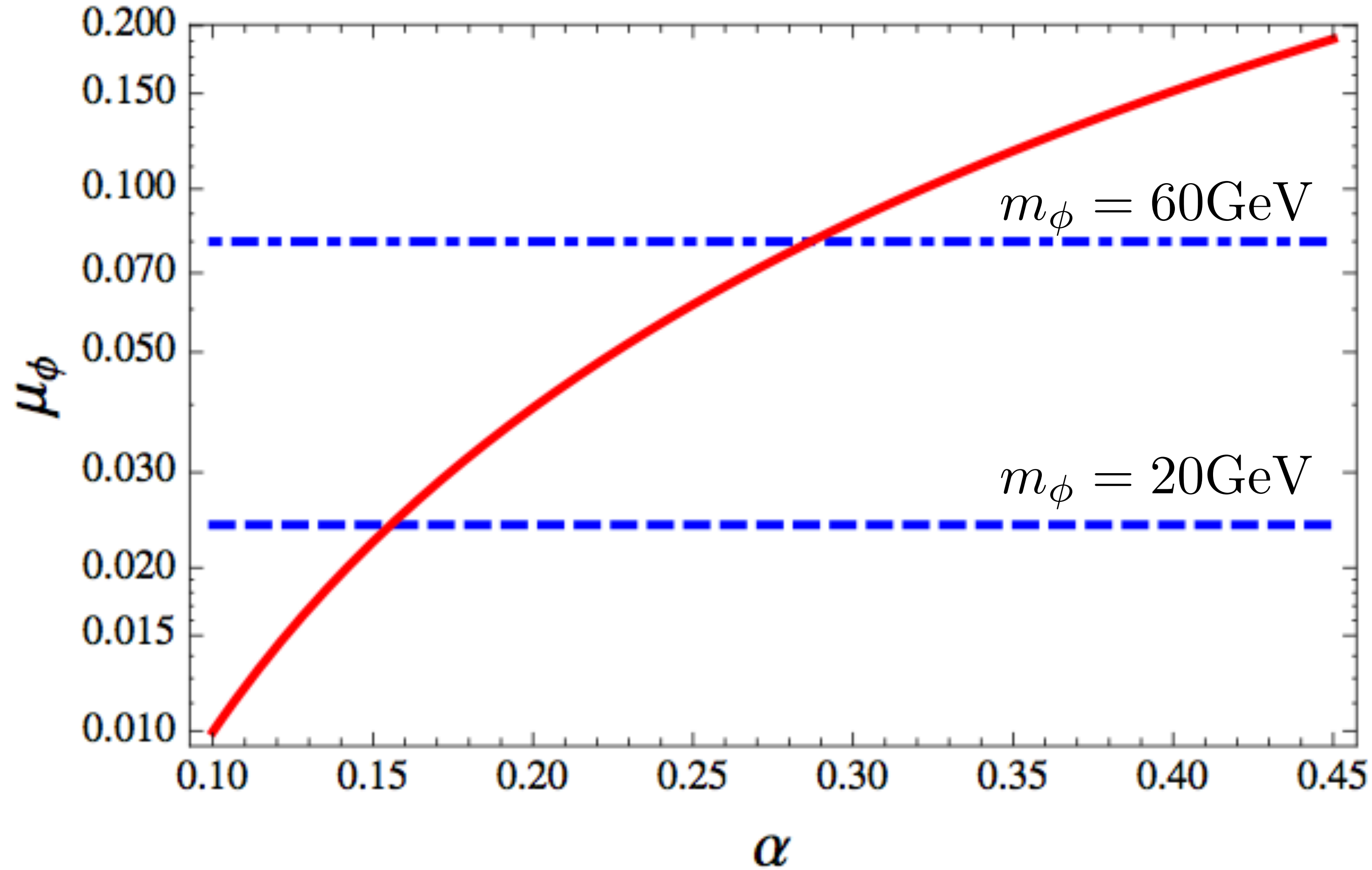
$$\lambda_H = \left[1 + \tan^2(\alpha)\frac{m_2^2}{m_1^2}\right]\cos^2(\alpha)\frac{m_1^2}{2v^2} \qquad (\Leftarrow \lambda_{\phi h})$$



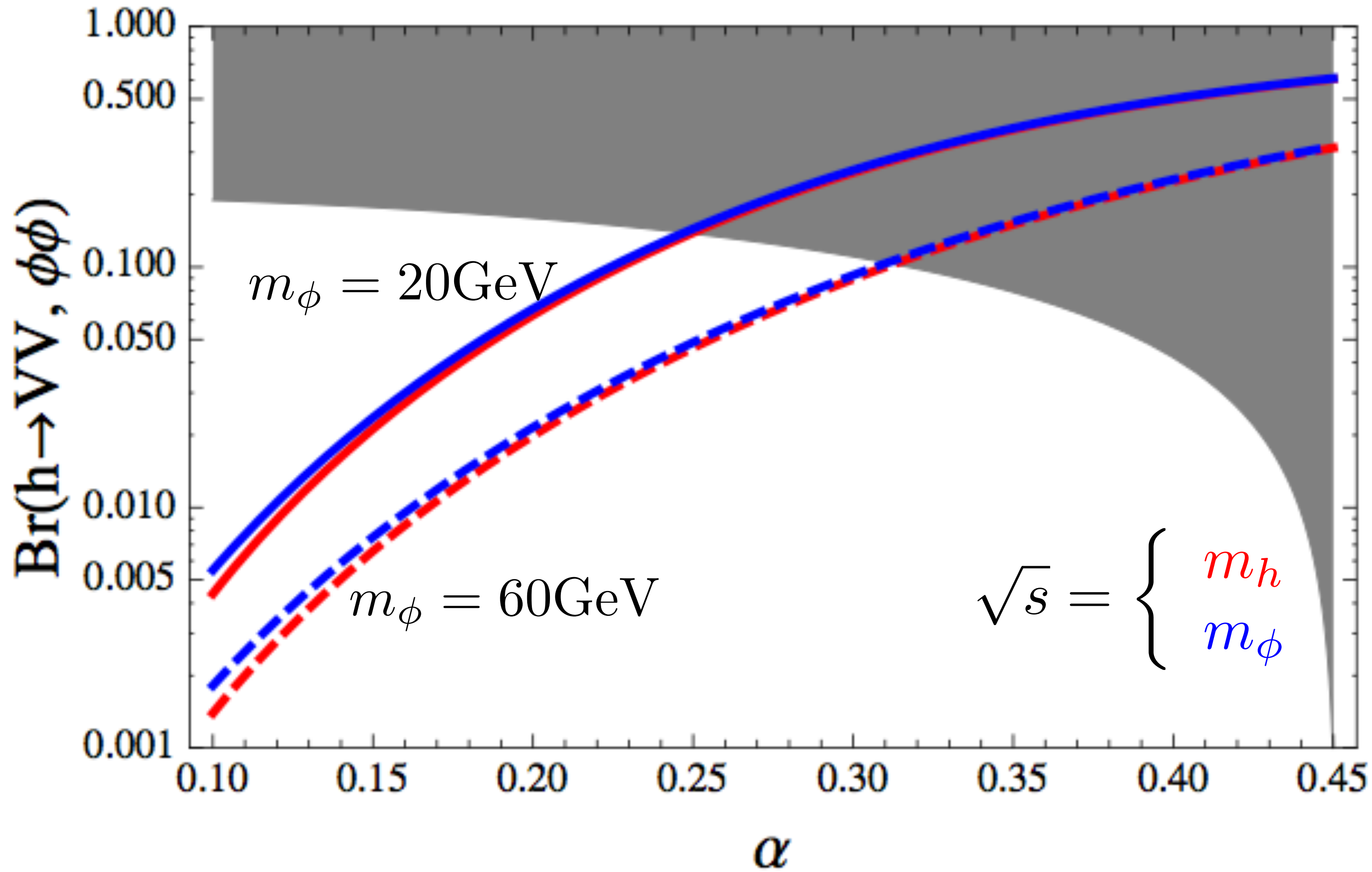
[G. Degrassi et al., 1205.6497]

- Constraint on a light scalar from LEP

Signal strength

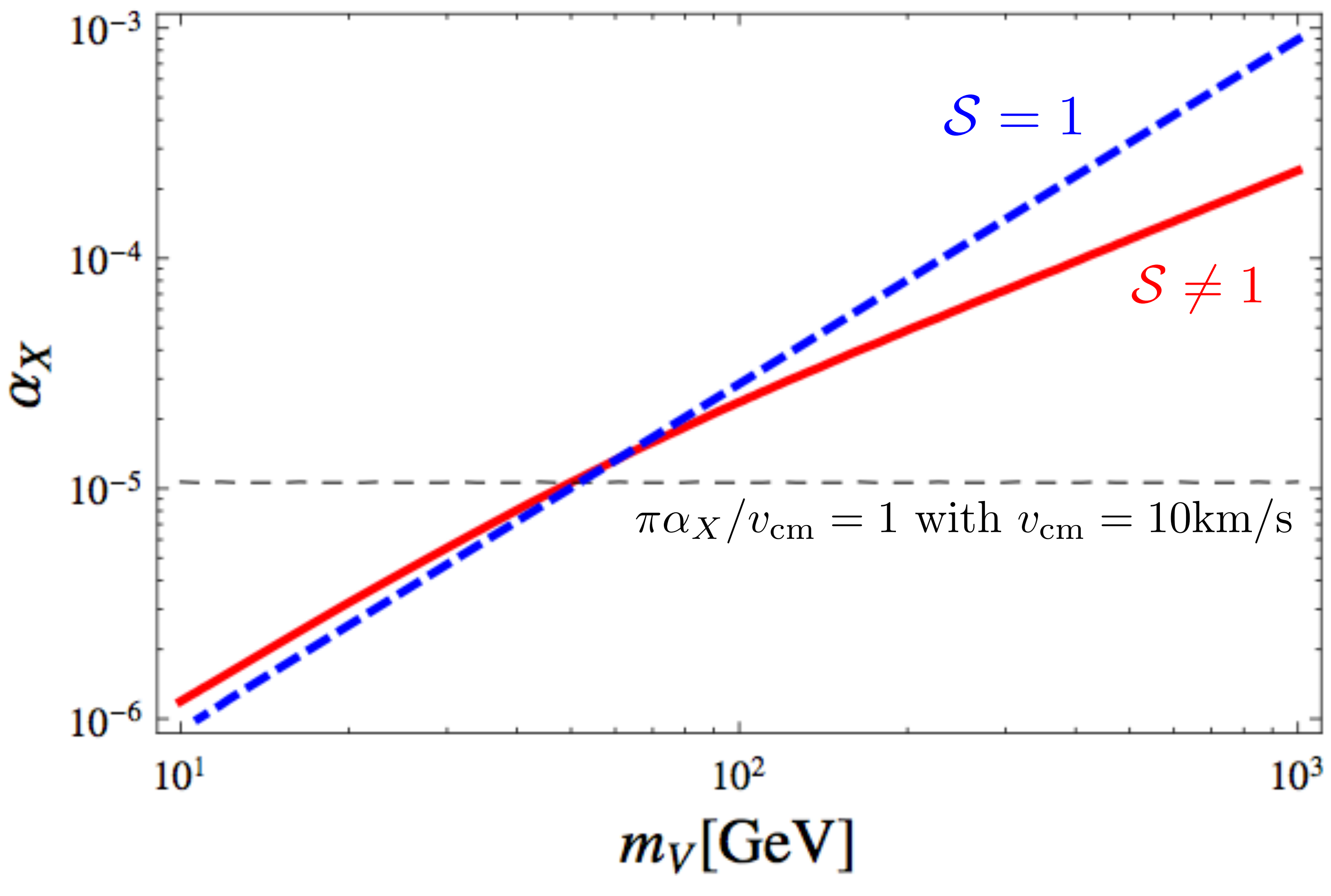


Branching fraction of SM Higgs to dark fields



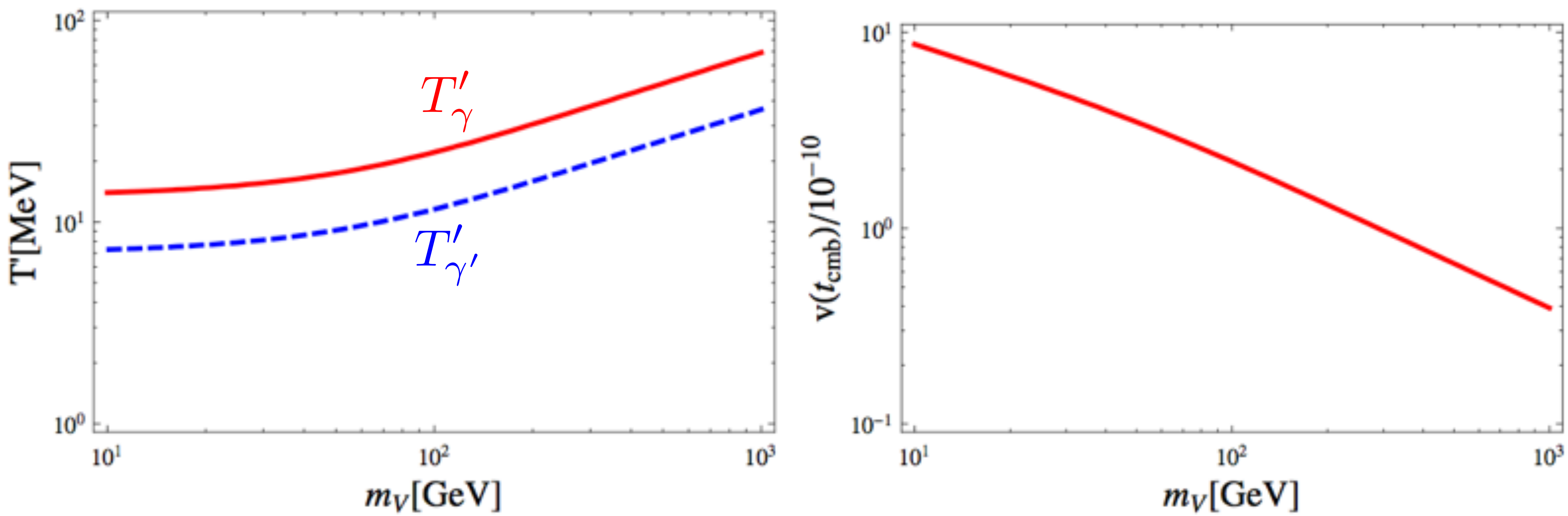
Constraints on α_X

- From small scale structure formation

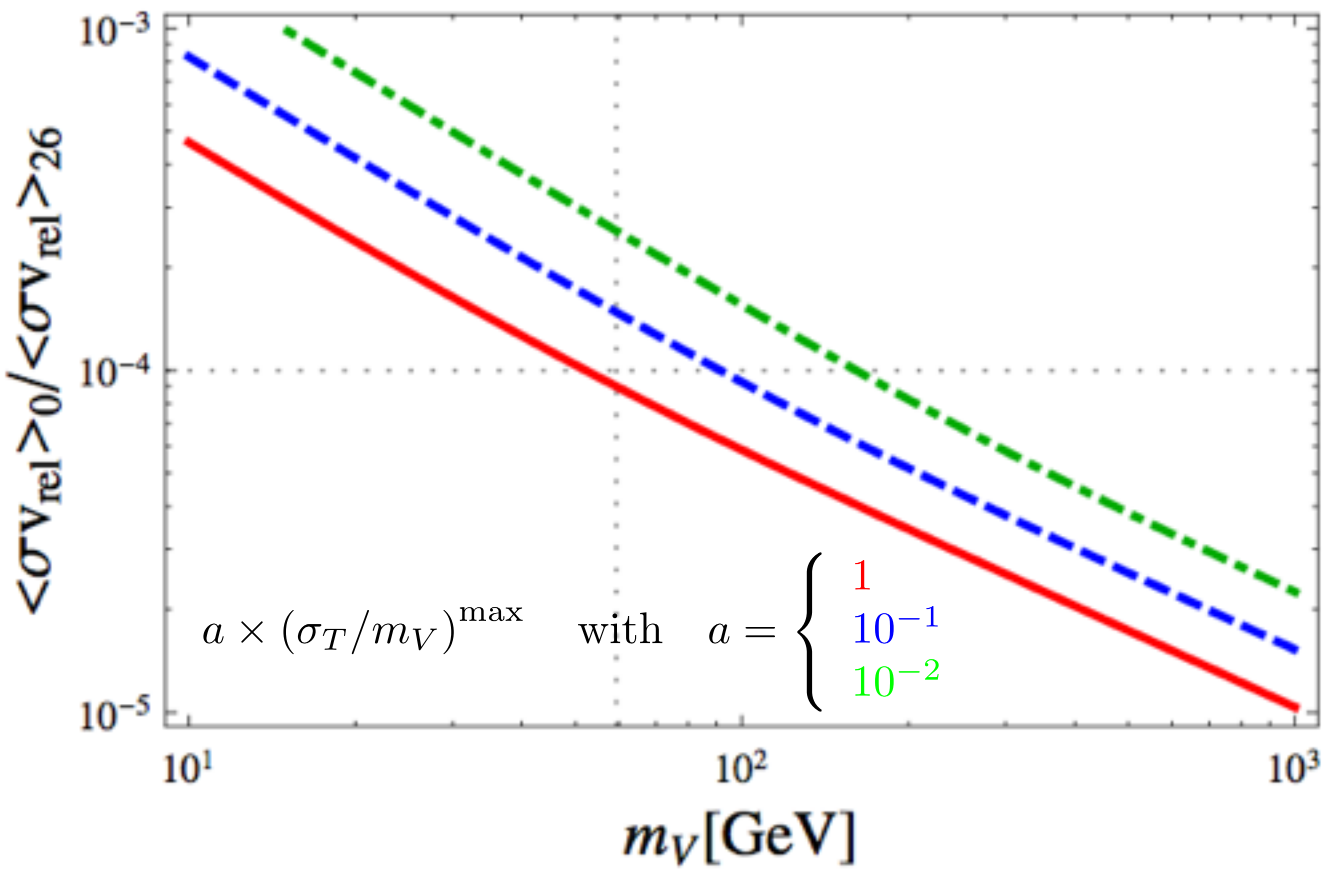


- Last kinetic decoupling and velocity of DM

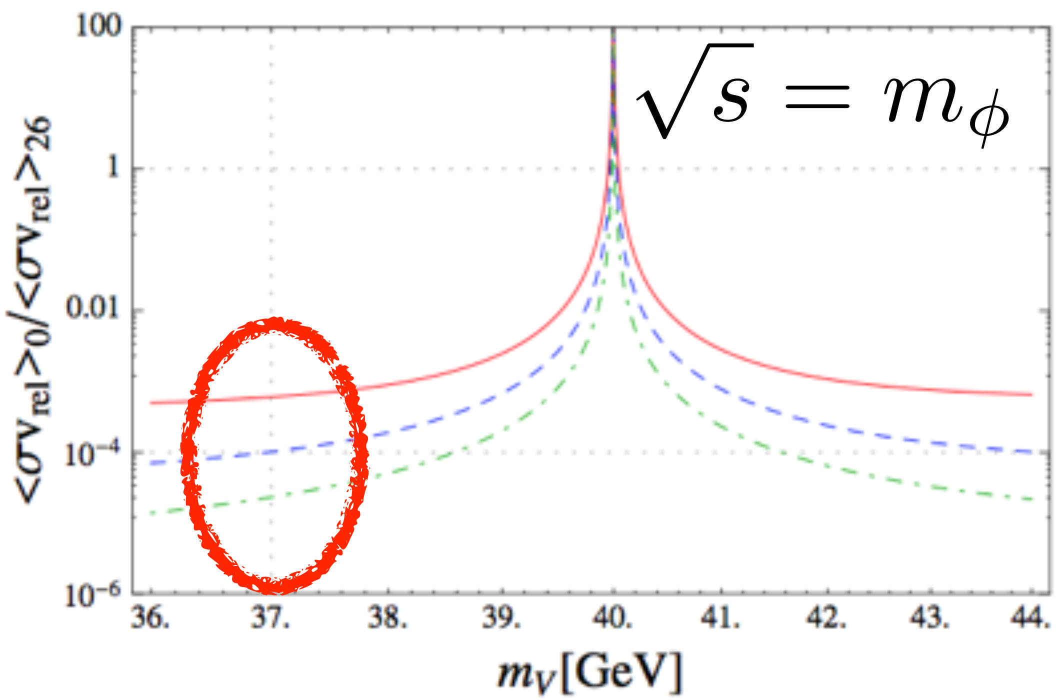
$$v' = \sqrt{3T'_{\gamma'}/m_V} \quad \& \quad v(t_{\rm cmb}) = v'\left(\frac{T_{\rm cmb}}{T'_{\rm kd}}\right)$$

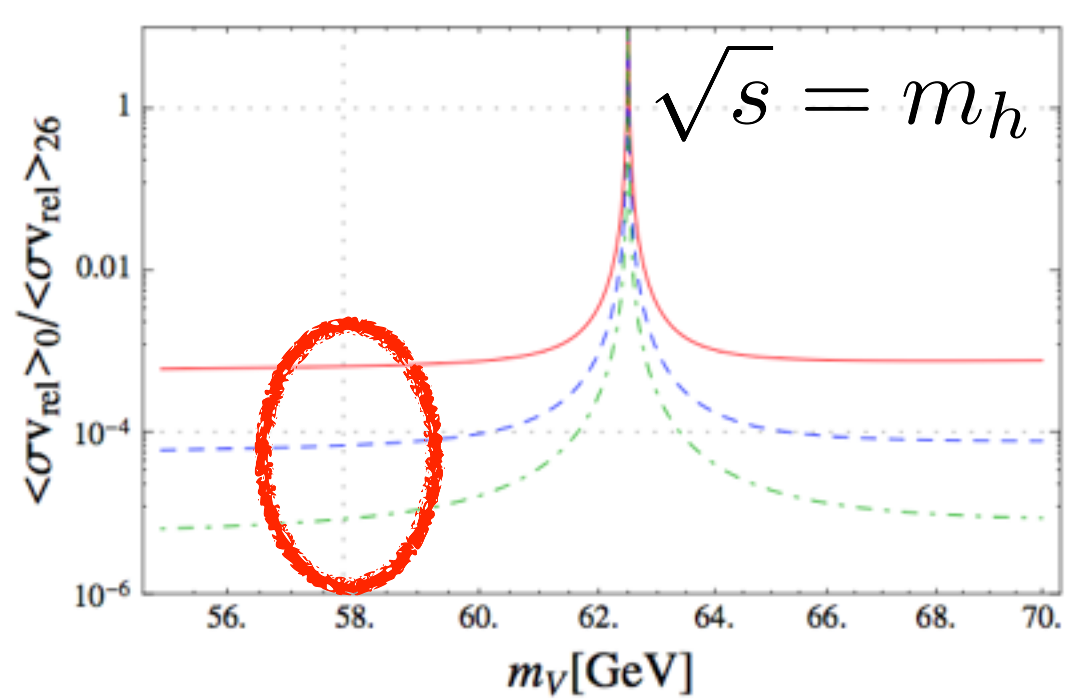


- Upper-bound of DM annihilation cross section



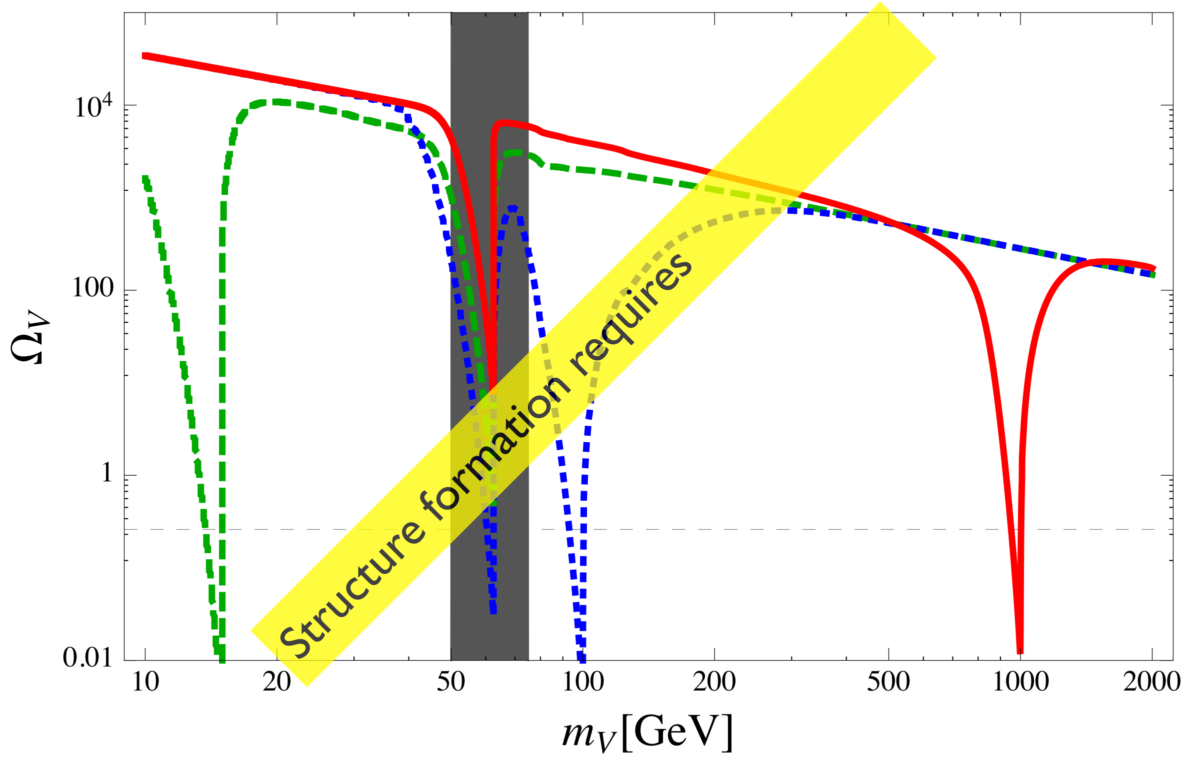
- DM annihilation cross section via s-channel

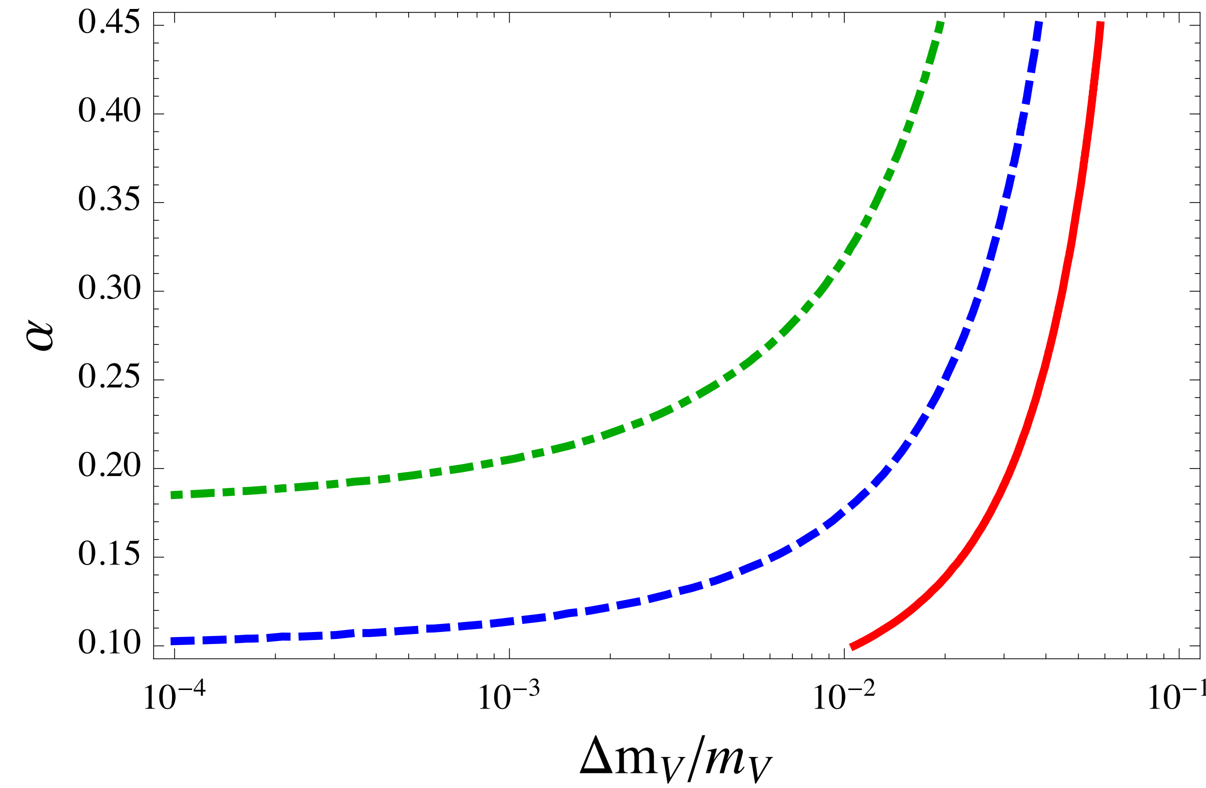


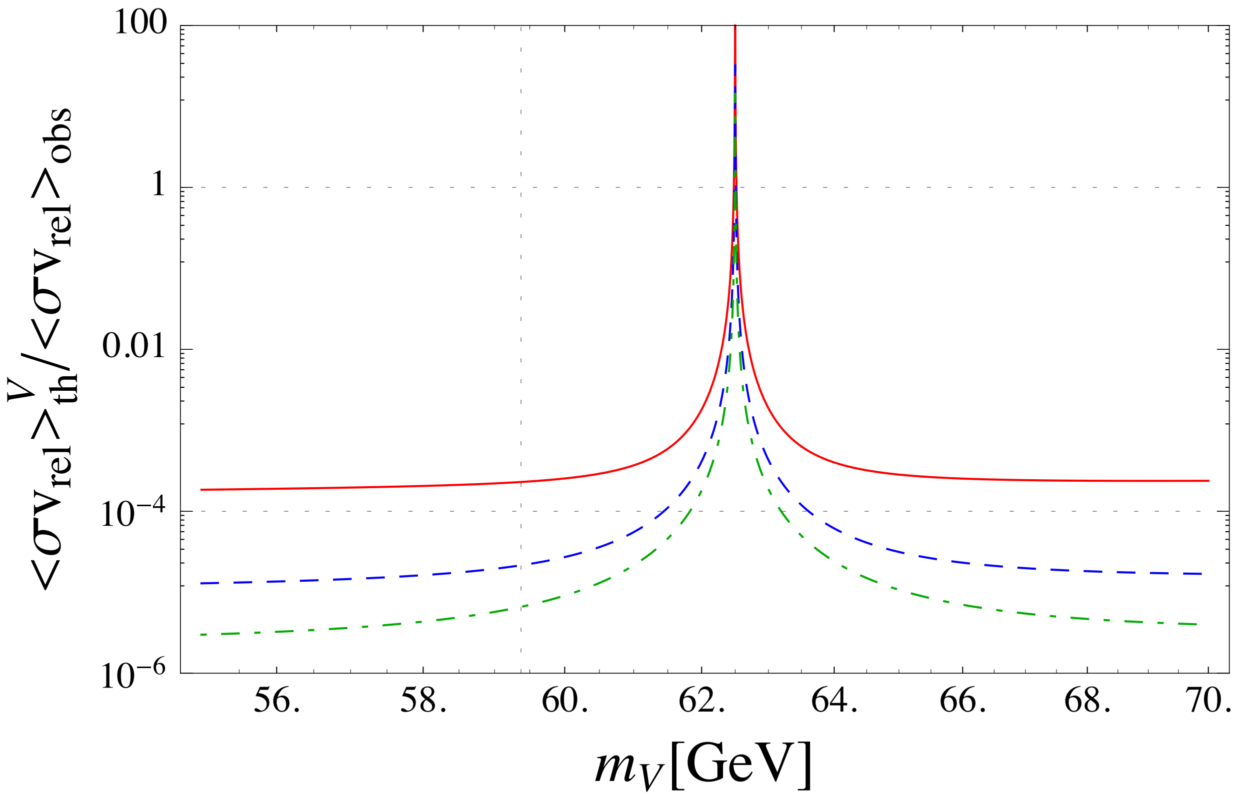


Relic densities

- VDM (thermal freeze-out)







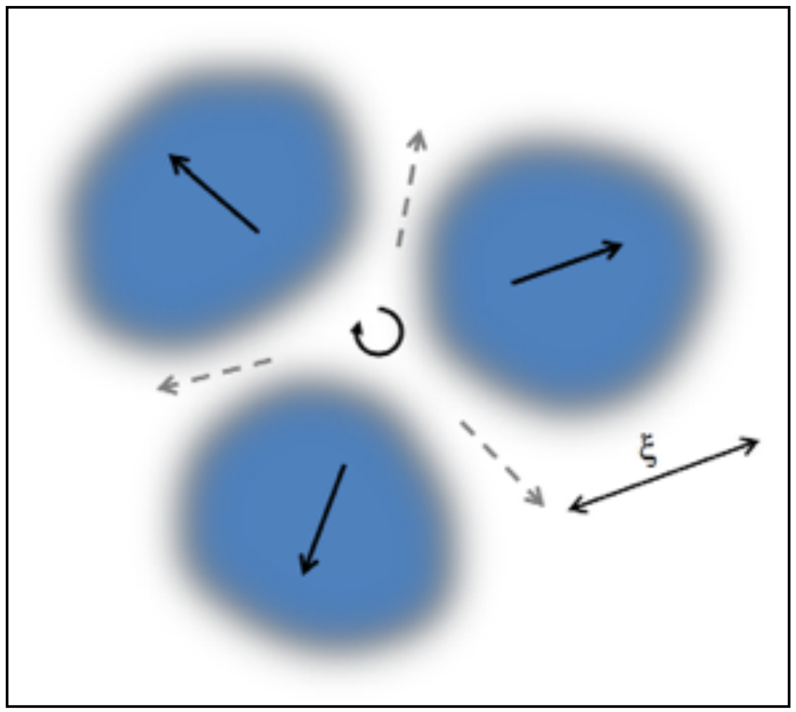
Note!

CMB – constraint

$$\Rightarrow \langle \sigma v \rangle_0 \lesssim 10^2 (v_{DM}/\alpha_X) \langle \sigma v \rangle_{fz}$$

$$\Rightarrow \Delta m_V / m_V = \mathcal{O}(10^{-4} - 10^{-1})$$

- Monopoles (Kibble-Zurek mechanism)-1/2



$$\epsilon \equiv (T_c - T)/T_c$$

$$\xi = \xi_0 |\epsilon|^{-\nu}, \ \xi_0^{-1} \sim \sqrt{|m_\phi(0)^2|}$$

$$\tau = \tau_0 |\epsilon|^{-\mu}, \ \tau_0 \approx \xi_0$$

$$\tau_Q = (t - t_c)/|\epsilon| \to \tau_0 |\epsilon|^{-(1+\mu)}$$

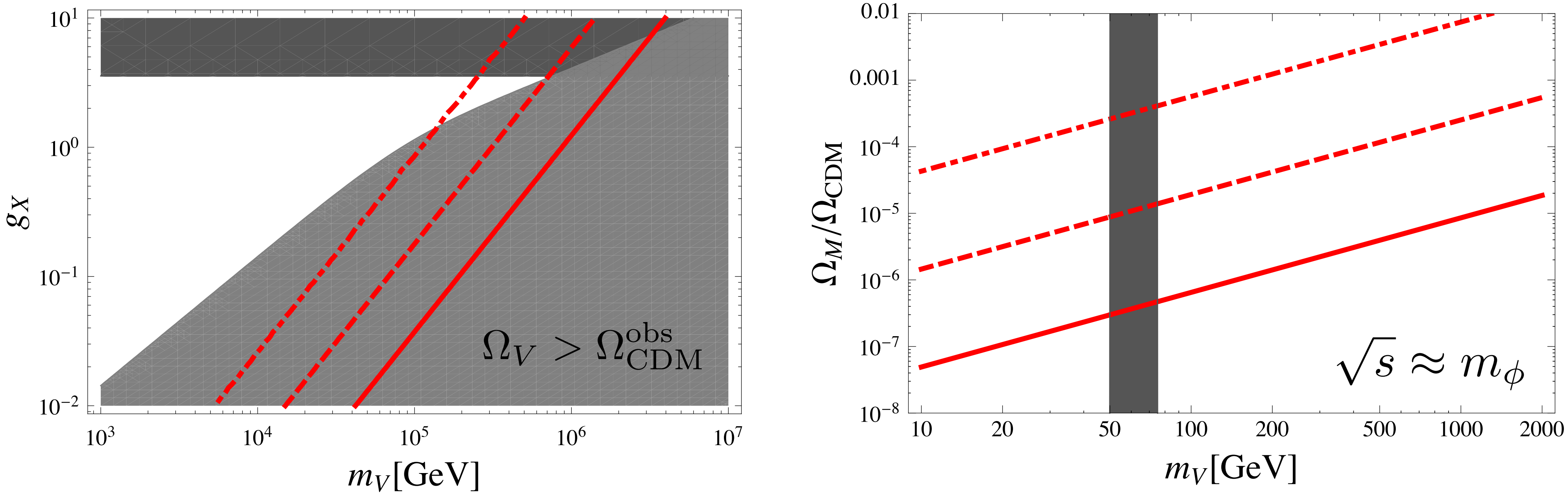
$$\Rightarrow \xi \sim \xi_0 (\tau_Q/\tau_0)^{-\frac{\nu}{1+\mu}}$$

$$n \sim 1/\xi^3 \quad \Rightarrow \quad Y_i \approx \frac{\left(\sqrt{\lambda_\phi/2}\right)^3}{C_S} \left[\frac{1}{\sqrt{\lambda_\phi/2}} C_0^{1/2} \frac{m}{hM_{\rm P}} \right]^{3\nu/(1+\mu)}$$

$$\text{Landau} - \text{Ginzburg form of } V(\phi) : \Rightarrow \nu = \mu = 1/2$$

$$\text{Quantum} - \text{corrected} : \Rightarrow \nu = \mu = 0.7$$

- # Monopoles (relic density)-2/2



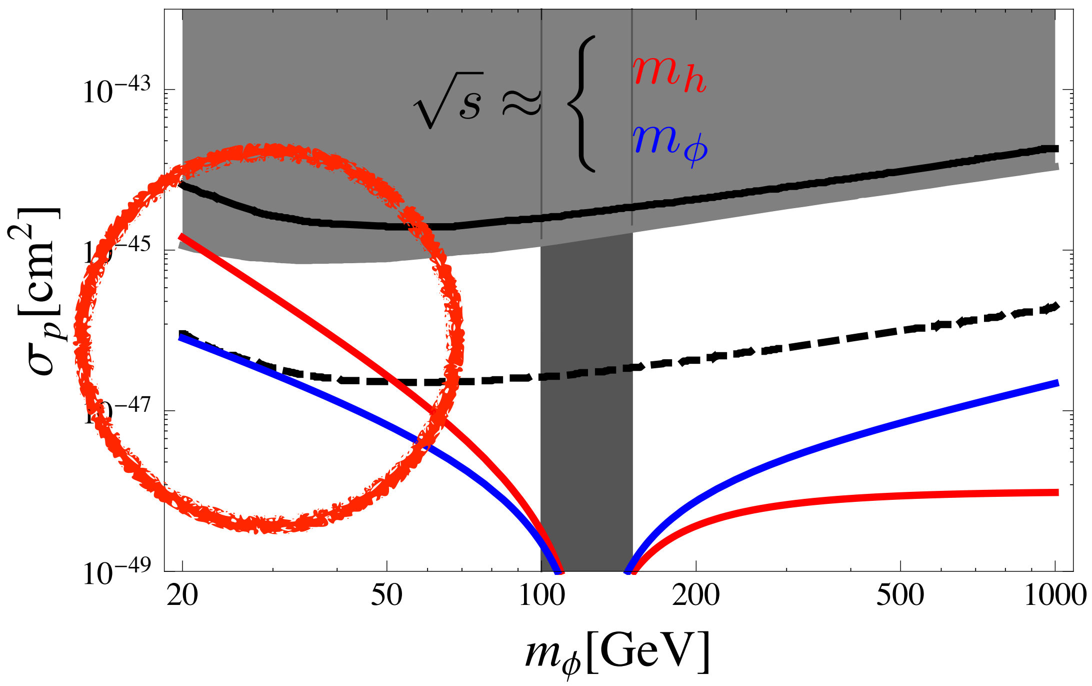
$$\underline{g_X \lesssim 9 \times 10^{-2} \, (m_V/1\text{TeV})^{3/4}} \Rightarrow \underline{v_\Phi \gtrsim \mathcal{O}(10)\text{TeV}}$$

(from structure formation)

The relic abundance of monopoles is negligible.

Direct detection

- VDM-nucleon



$$\sigma_p = \frac{4\mu_V^2}{\pi}\left(\frac{g_X s_\alpha c_\alpha m_p}{2v_H}\right)^2\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)^2 f_p^2$$

$m_\phi \lesssim 60\mathrm{Ge}V$ might be probed.

- Monopole-nucleon

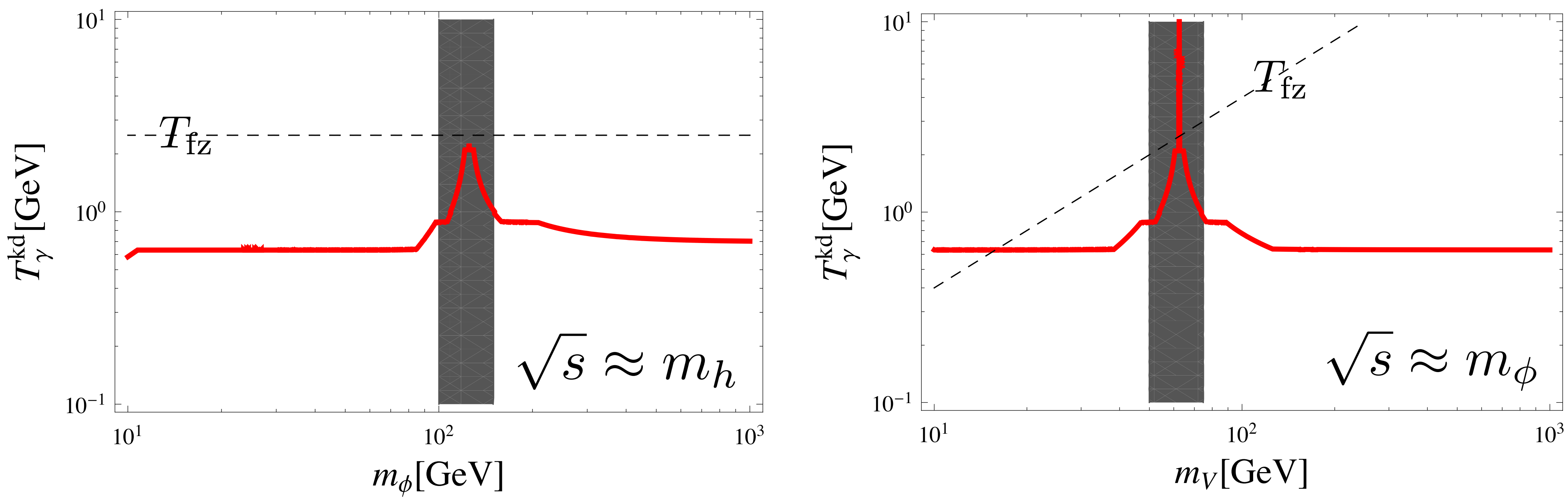
$$\sigma_p \lesssim \frac{\lambda_{\Phi H}^2}{64\pi m_{\mathrm{M}}^2}\left(\frac{m_p}{m_h}\right)^4 f_p^2 \simeq \frac{3.4\times 10^{-28}}{\mathrm{GeV}^2}\left(\frac{\lambda_{\Phi H}}{0.1}\right)^2\left(\frac{10^7\,\mathrm{GeV}}{m_{\mathrm{M}}}\right)^2$$

$\Rightarrow$ It is too small to be detected directly.

DR from dark photon

- T at kinetic decoupling of DR

Higgses mediate DM-SM scattering $\Rightarrow$ $\mathcal{M} = -v_\Phi g_X^2 \sin\alpha\cos\alpha\left(\frac{1}{t-m_1^2} - \frac{1}{t-m_2^2}\right)\frac{\sqrt{2}m_f}{v_H}$



$$T_{\rm QCD} < T_{\rm kd} \leq T_{\rm fz} \sim m_V/25$$

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{g_{\rm DR}}{2}\left(\frac{g_{*S}(T_0)}{g_{*S}(T_{\rm DR,kd})}\right)^{4/3} \approx 0.08 - 0.11$$

Conclusion

- Hidden sector may be guided by gauge principle as standard model.
- When a dark gauge symmetry is unbroken, Higgs portal interaction is crucial to have acceptable phenomenology.
- Non-Abelian dark gauge sym. broken to U(1) provides a nice example of VDM accompanying stable monopoles and dark radiation thanks to the Higgs portal interaction without small scale puzzles of DM.

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,

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

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

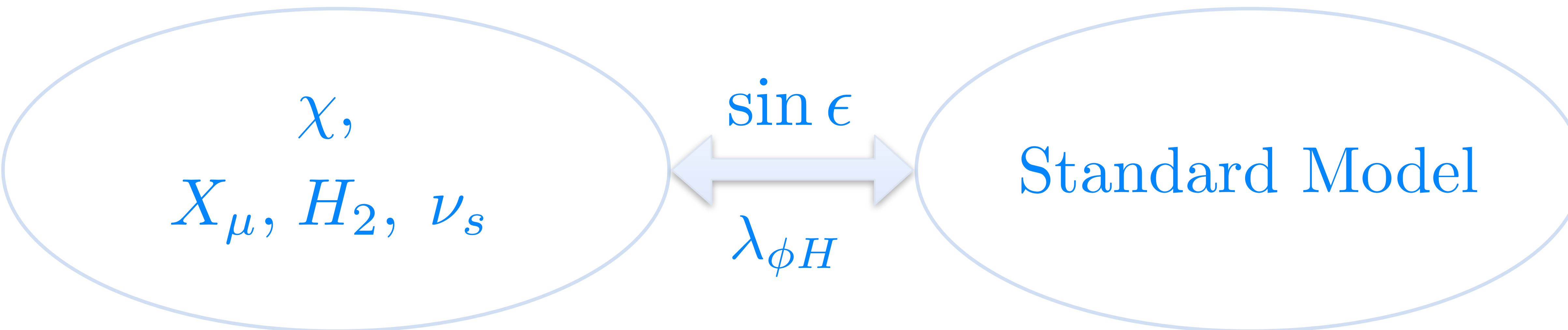
- Dark Matter, dark gauge boson, dark Higgs, and 4 sterile neutrinos,

$\chi,$

$X_\mu, H_2, \ \nu_s$

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.

ΔN_{eff}(BBN)

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

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

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

and

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

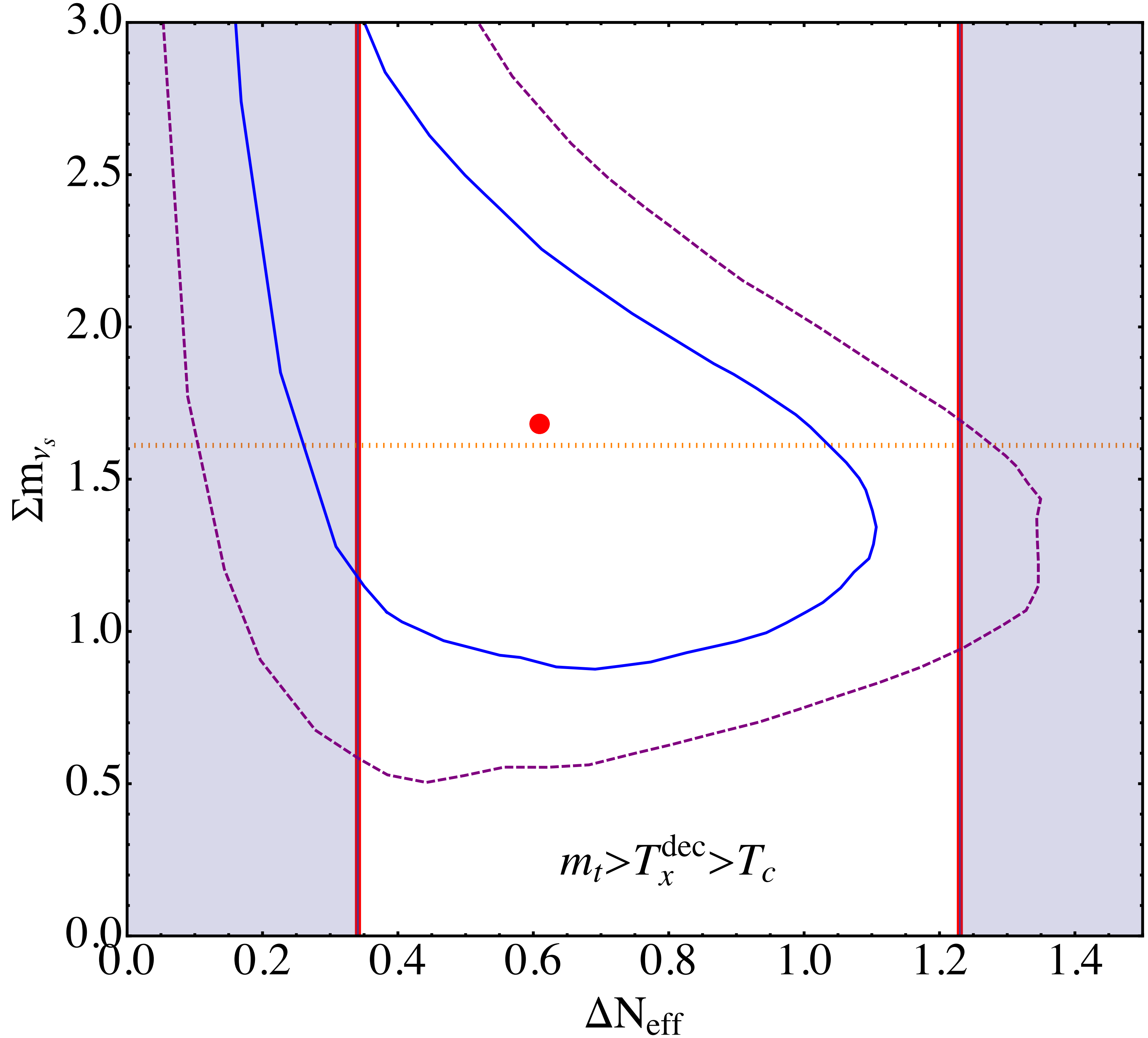
$$g_{*s}^x\left(T_{\text{bbn}}\right) = \frac{7}{8} \times (4 \times 2) = 7.$$

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

It gives

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

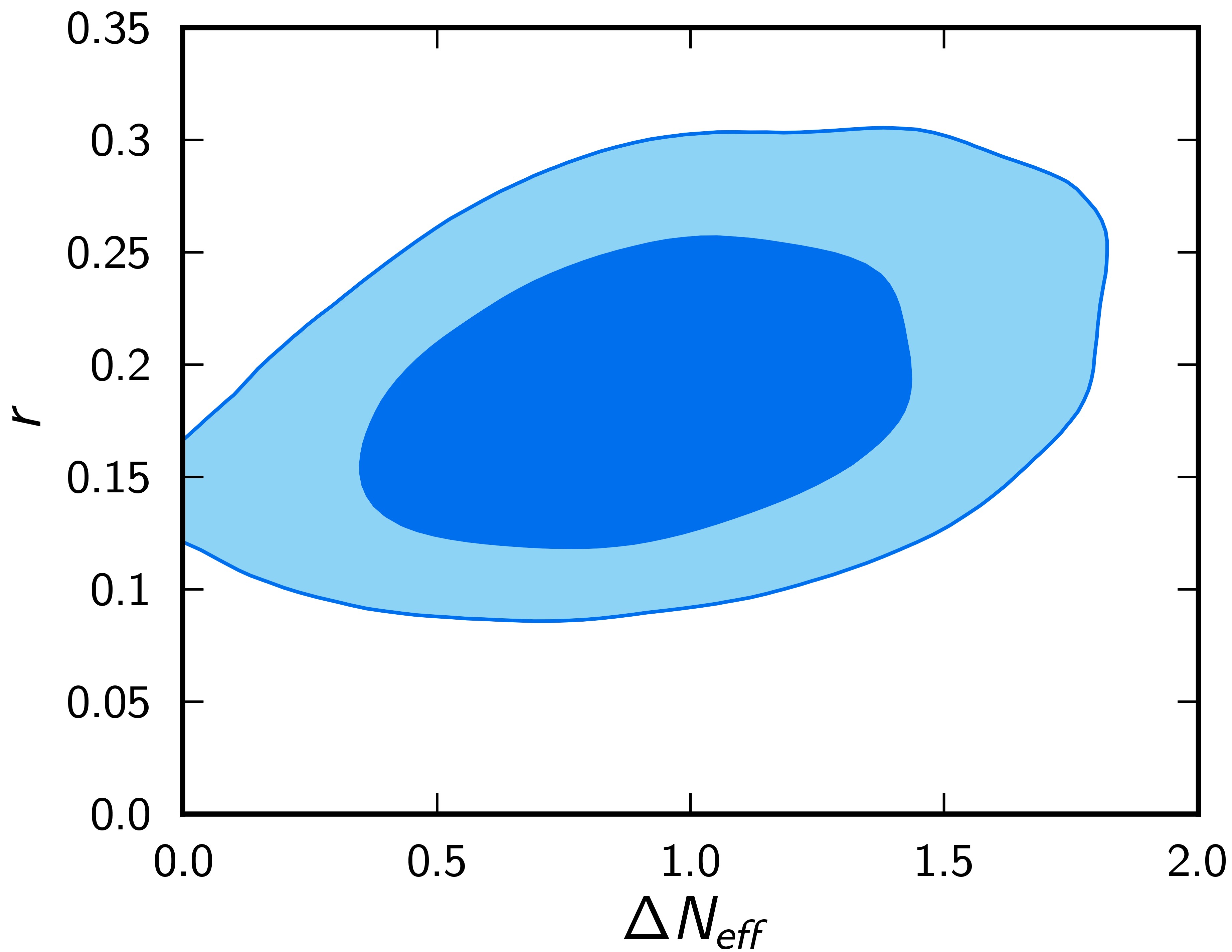
ΔN_{eff}(CMB) and m_{ν_s}



Contours for CMB data, *1308.3255*

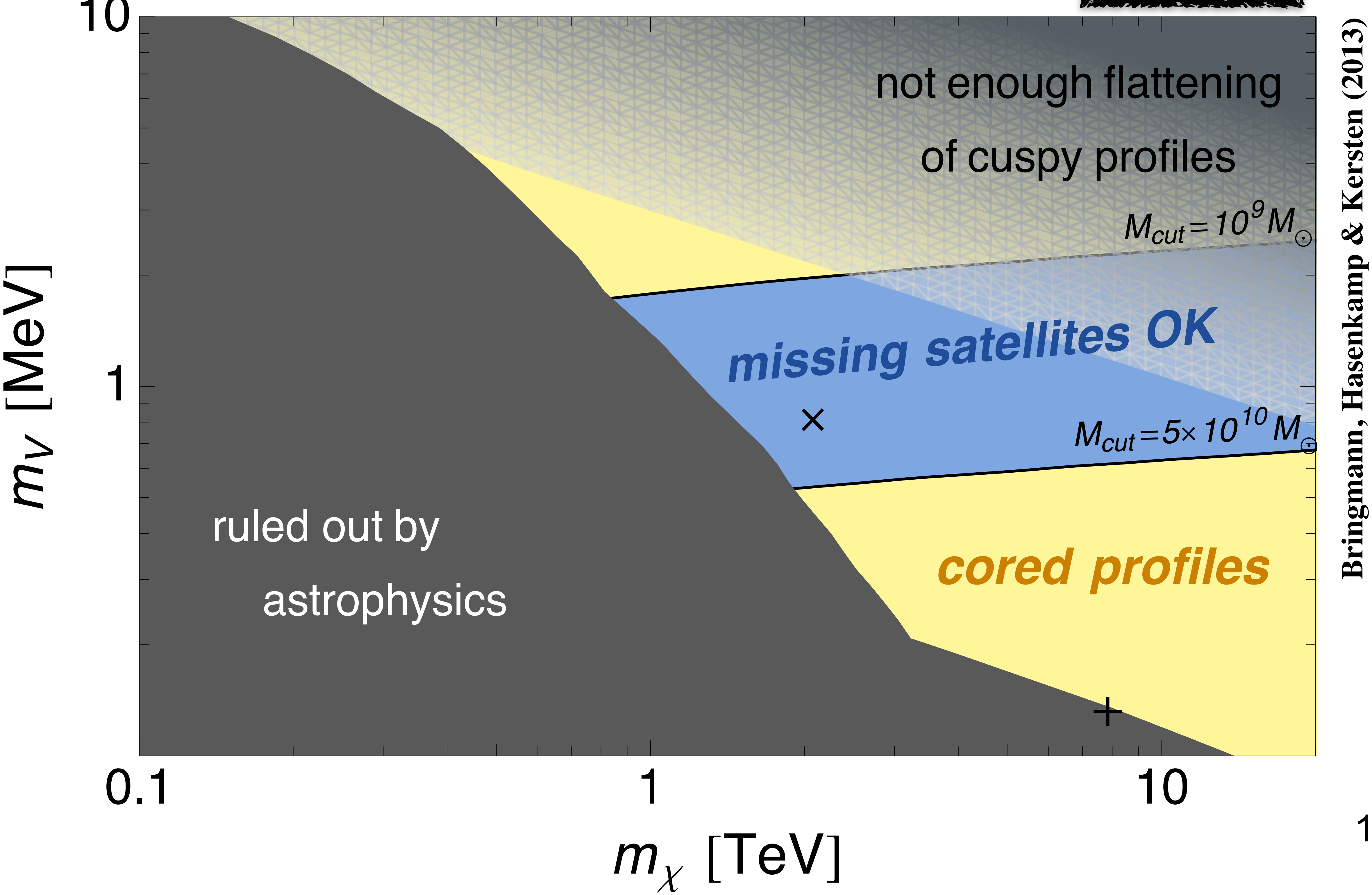
Dot line marks the centre value for 3+2 scenario for neutrino

ΔN_{eff} helps reconcile Planck and BICEP2



How?

1312.4947



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

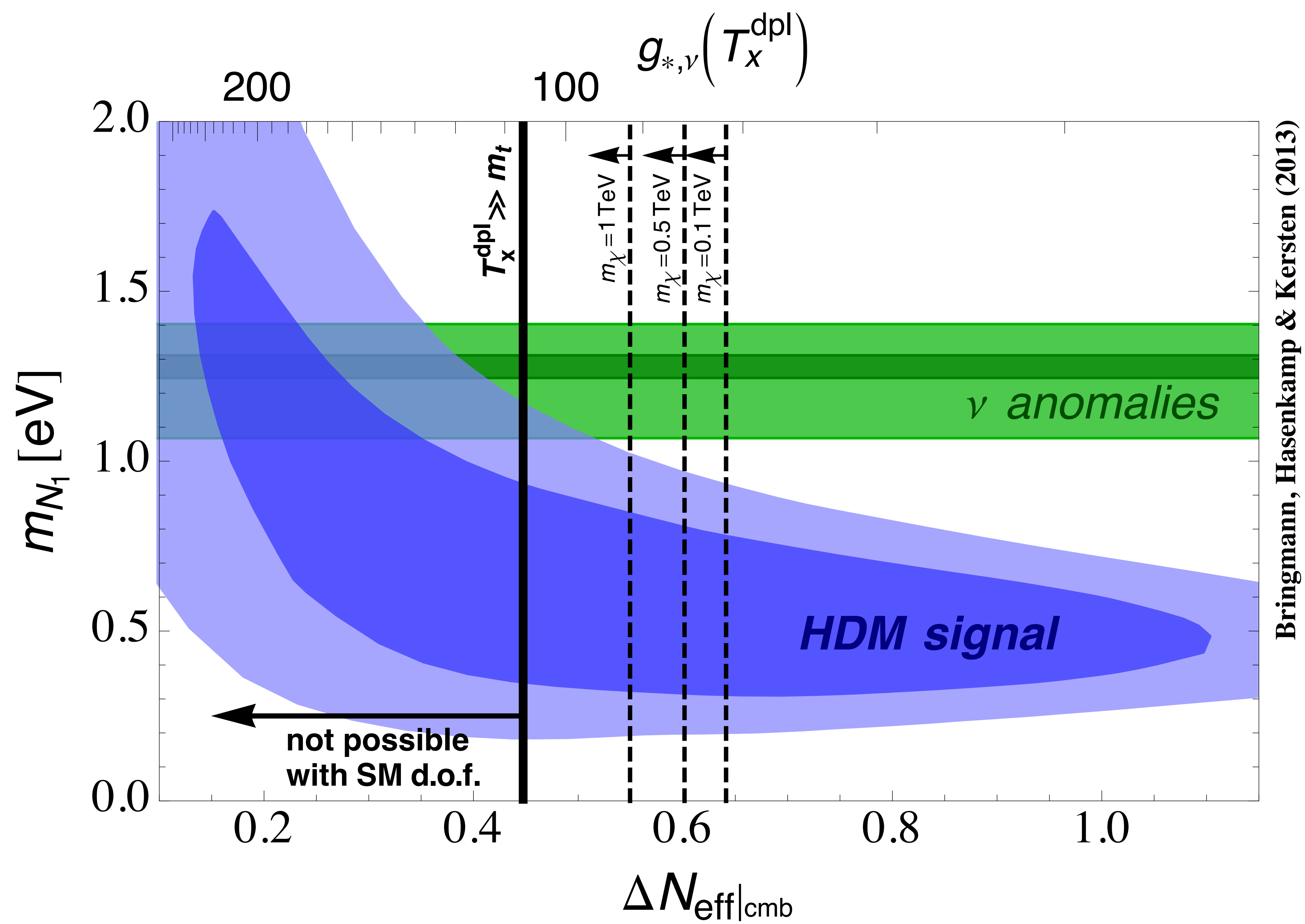
$$\mathcal{L}_R \supset -\frac{1}{2}\overline{\nu^c_{R_1}}M_1\nu_{R_1} - \frac{1}{2}\overline{\nu^c_{R_2}}M_2\nu_{R_2} - \overline{\nu^c_{R_1}}M_{RR}\nu_{R_2} - \overline{\nu_L}M_{LR}\nu_{R_1} + \text{h.c.}\,, \tag{3}$$

from dim-5 operator

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

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 !