

Multi-component DM from Hidden Gauge Sym

Pyungwon Ko (KIAS QUC)

CQUeST 2026 Workshop on
Cosmology and Quantum Spacetime
July 20 – 24 (2026)

Usual Scenarios

- SM + DM only: DM EFT
- SM + DM + Mediators: Simplified models
- Massive dark photon with Proca or Stueckelberg mechanism for dark photon mass: Sometimes, unitarity is violated, resulting in catastrophes
- Recently “Dark Sector” has been considered without any organizing principles

Massive Dark Photon

- Usually, massive spin-1 (such as Dark Photon) V_μ is treated as a Proca field, with Stueckelberg mechanism
- $V_\mu V^\mu H^\dagger H$ operator: (i) either ignored w/o good reason, or (ii) it is kept in the Higgs portal VDM model
- W/O Higgs portals, Such models are fine, renormalizable etc. [massive (scalar) QED, etc..]
- Problematic w/ Higgs portal term : Cannot be simply discarded
- Neither a systematic EFT, or unitary when $m_V \rightarrow 0$
- Better to consider dark Higgs Mechanism for $m_V \neq 0$

**As simple as possible,
but no simpler**

Albert Einstein

Occam's Razor

**Rational for EFT or
Simplified Models**

Criterion for “SIMPLEST”

- The simplest guess would be that the number of new dof is minimal → Simplified Models: often unitarity problem
- One new particle and two new parameters: mass and coupling(s) to the SM
- Easy to analyze and make exclusion plots in 2-dim
- However, SM gauge invariance is usually ignored/violated
- Unitarity is usually violated → The model has to be fixed by introducing New Degrees of Freedom (BSM)

Criterion for “SIMPLEST”

- Proposal: 3 more criteria beyond the minimal # of d.o.f.:
 - Mathematical/Theoretical Consistency: Poincare symmetry, Local Gauge Symmetry and Anomaly Free
 - Realistic Yukawa's for SM fermions (flavor physics)
 - No global symmetries from the outset: All global symmetries are assumed to be accidental like the SM
- Simplest Models with these 3 additional criteria

**Mathematical/theoretical
consistency should be
added to the Simplicity**

How to Construct $\mathcal{L}$?

- Identify local symmetries, as well as particle contents
- Write down all possible (super) renormalizable operators with the presumed symmetries $\rightarrow$ Renormalizable Lagrangian
- Impose Anomaly Cancellation and Realistic Yukawa's
- Identify the accidental global symmetries [NB: Global Sym's in the SM are all accidental]
- Check if Higher Dim Op's conserve/break the accidental global sym's
- Minimal Setup without Theo/Math Inconsistency!!! EFT or Simplified Models are Not Enough & Could Be Misleading!

Contents

- Basic properties of DM: Mass and Lifetime?
- Review of the SM construction
- DM model buildings along the SM construction
- **Some examples:** $U(1)_D \rightarrow Z_2$; VDM w/ HP and GC γ ray;
 $SU(3)_D \rightarrow SU(2)_D$; Dark Monopole, VDM and DR; DQCD (WIMP & SIMP); Two-
componet WIMP model free from DD constraints
- Summary

Based on

- Reviews: JKPS, 72 (2018) 449-465;
- My talk will be mostly about “MODEL BUILDING”, and not on the detailed DM phenomenology
- Based on a series of works with Seungwon Baek, Wanil Park, Myeonghun Park, Hyun Min Lee, Taeil Hur, Soomin Choi, Alexander Natale, Eibun Senaha, Dongwon Jung, Jinmian Li, Jongkuk Kim, Shu-Yu Ho, Hiroshi Yokoya, Takaaki Nomura, Yong Tang, Shu-Yu Ho, Chih-Ting Lu, Yi-Lei Tang, S. Kanemura, Toshinori Matsui, Gang Li, Mitsuru Kakizaki, et al.
- Main message: Phenomenology of massive dark photon can change drastically, whether dark Higgs is included or not!

- Charge/color neutral : no renormalizable int's w/ γ, g
- Eq of State : $\rho \simeq 0$ (*i.e.* $p \simeq 0$)
- $\tau_{\text{DM}} \gg \tau$ (Age of the Universe) or ∞

What is the DM mass ?

- If very light, DM is long lived for the kinematical reason
- Axion and light sterile ν 's are good examples

- If not, reasonable to assume some conserved quantum #, either exactly or approximately conserved
- Local or global Dark Sym

General Comments on SM Construction

Philosophy under the SM construction

- Poincare symmetry
- Local gauge symmetry: exact charged conservation (Universality played an important role)
- All the particle masses from Higgs VEV
- Global symmetries (B , L_α , L_{tot} , etc): Accidental symmetries of underlying gauge theory with specific matter contents. Not assumed from the beginning! And could be violated by gravity
- Better to start with renormalizable models with **unitarity** (Limitation of EFT or Simplified models often used, which is not good at high energy colliders)

Further Observations

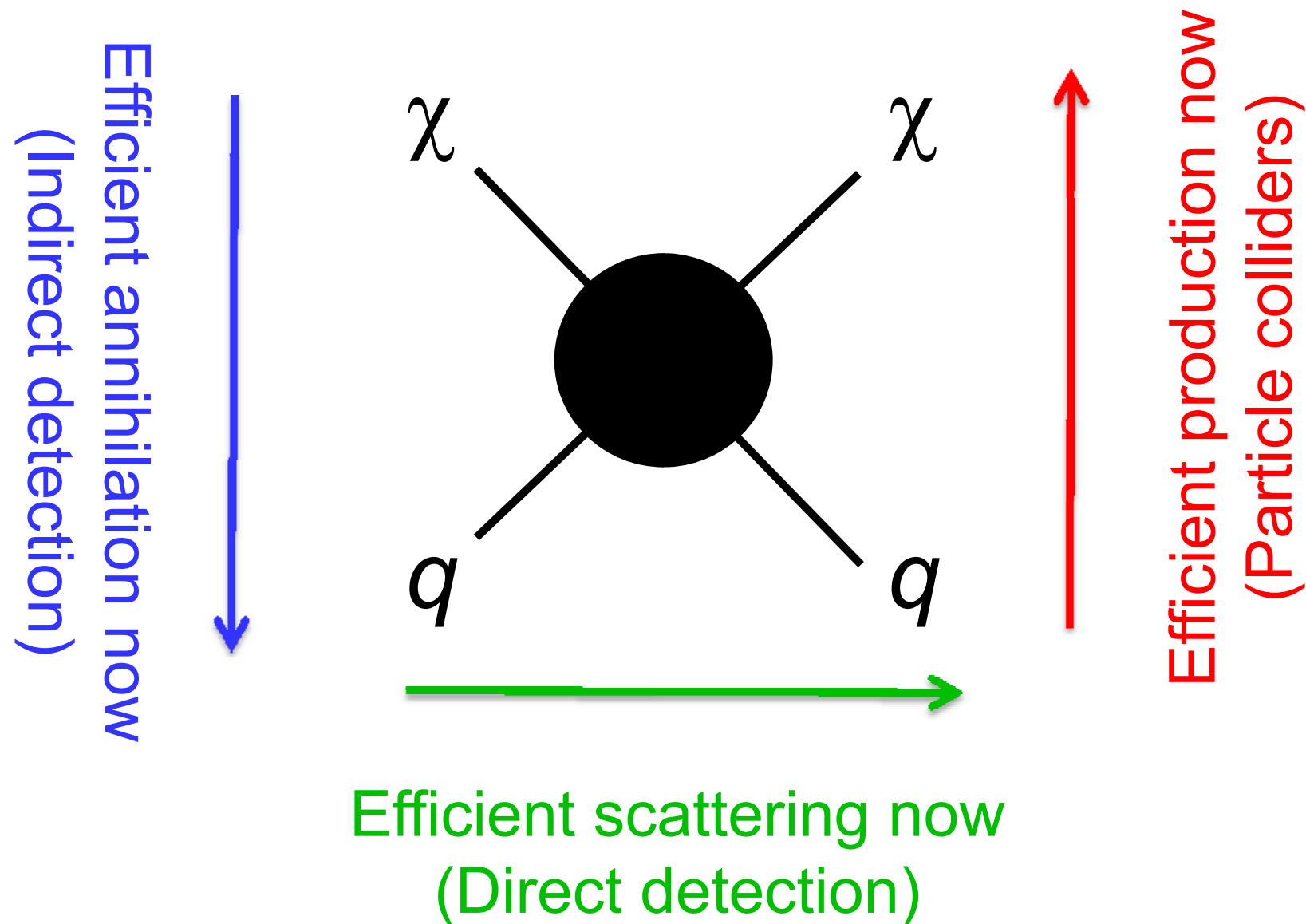
- SM fermions are chiral under the SM gauge group $\longrightarrow$ P violation is Natural, contrary to the original surprise
- No gauge singlets in the SM
- No discrete symmetry exact: P, C, T
- All the matter contents are in fundamental representations of $SU(2)_L \times SU(3)_C$. [$U(1)_Y$ charges look strange]

DM Models in literature

- Top-Down: LSP in SUSY models, LKP in KK models, etc.
- Bottom-Up: ad hoc dark Z_2, Z_3 parities
- Massive dark photon with Stueckelberg mechanism (w/o dark Higgs boson): sometimes could be problematic [see arXiv:2204.04889, for example]
- DM complementarity can be misleading when applied to DM effective theory or simplified DM models w/o full SM gauge symmetry (and dark gauge symmetry)

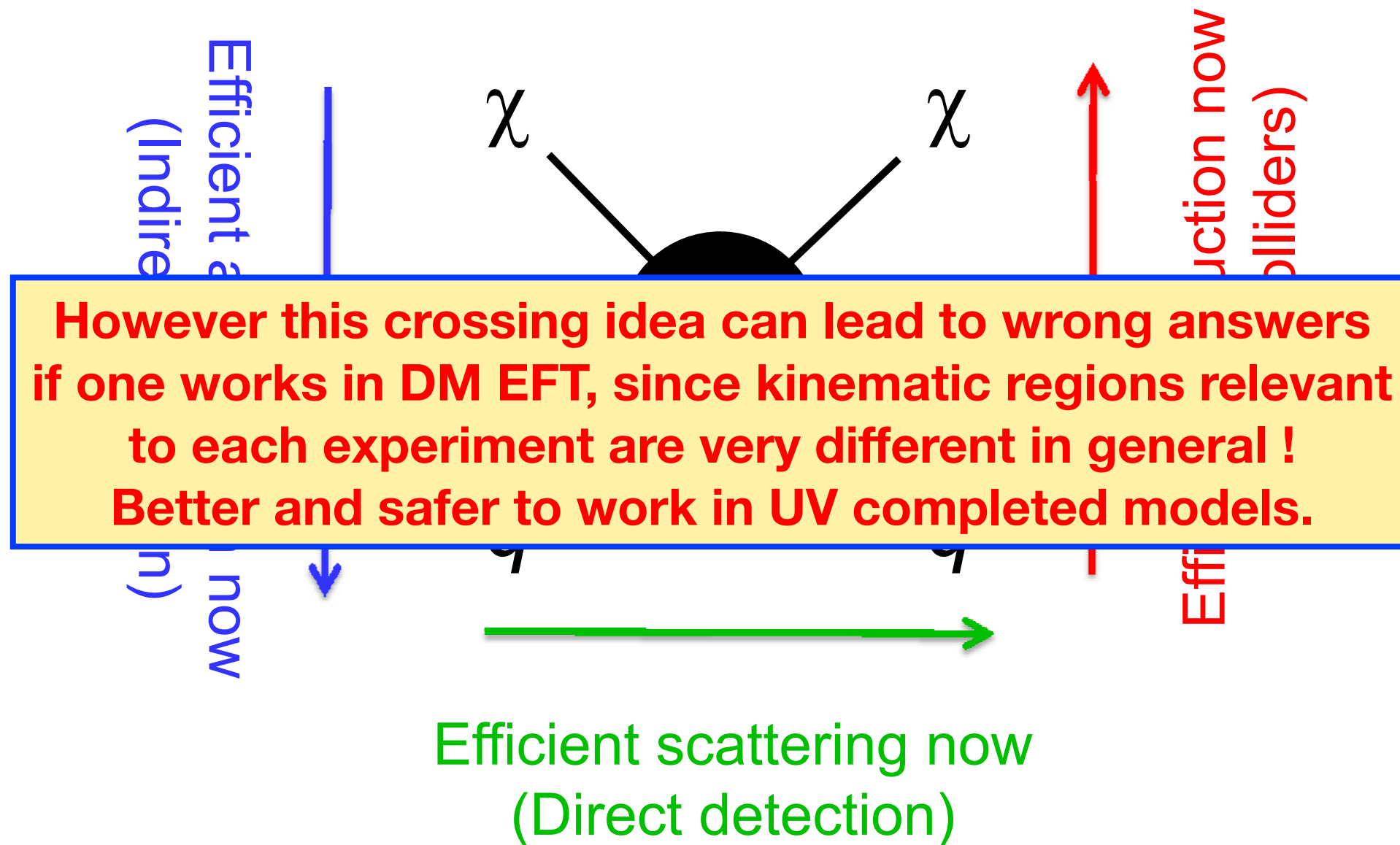
Crossing & WIMP detection

Correct relic density $\rightarrow$ Efficient annihilation then

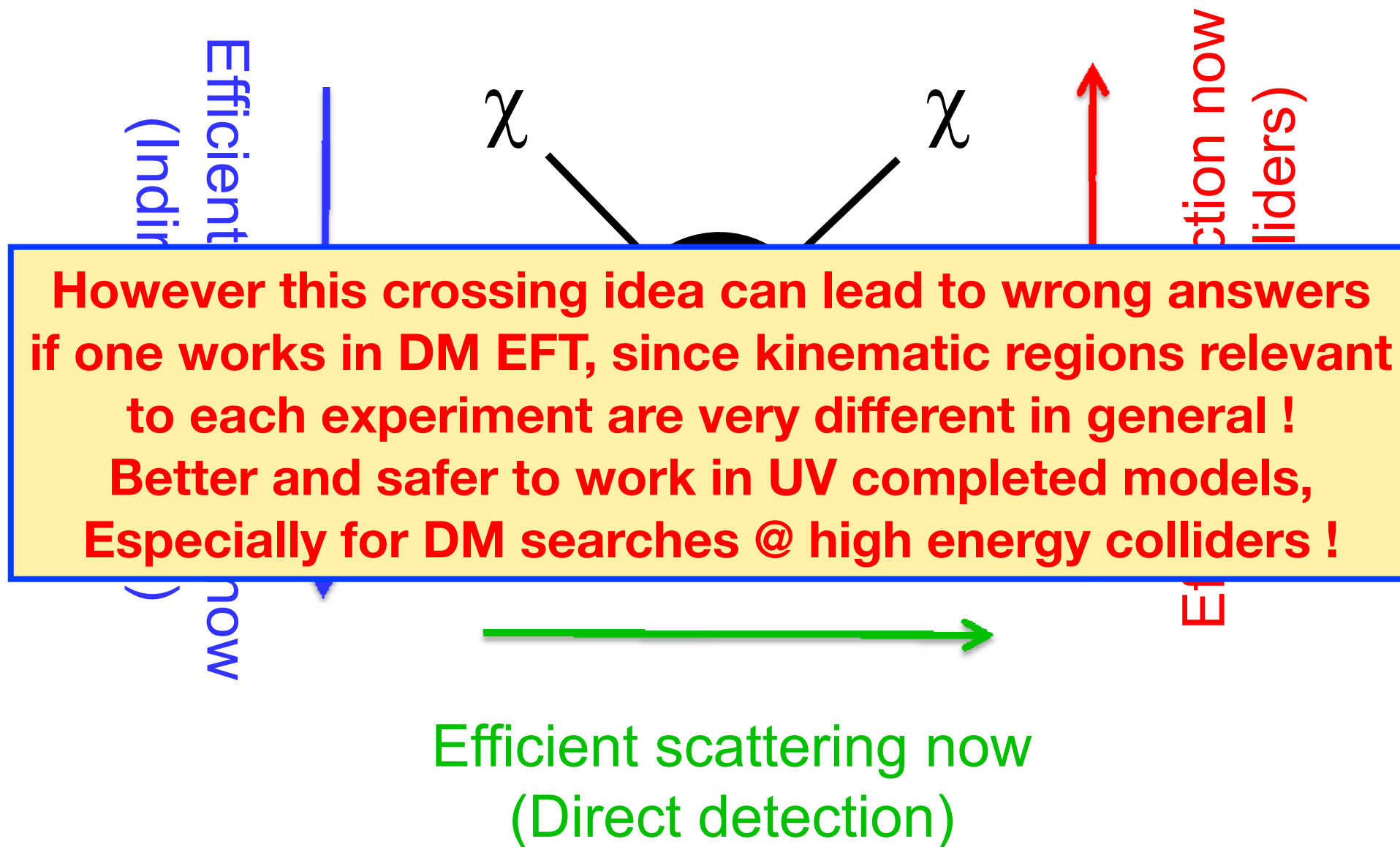


Crossing & WIMP detection

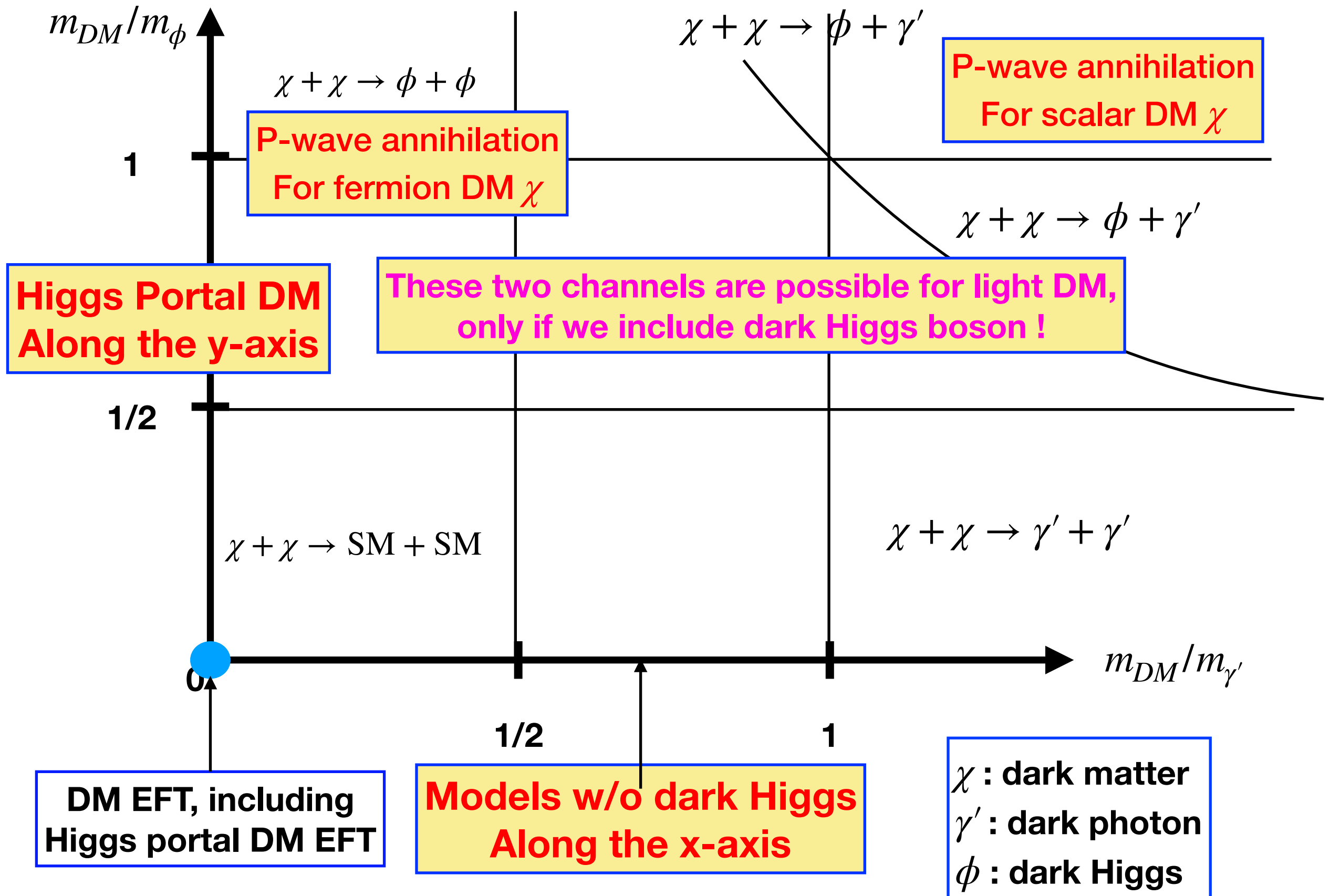
Correct relic density $\rightarrow$ Efficient annihilation then



**Furthermore one can consider on-shell mediators,
dark radiation and inelastic DM, etc..**



Dark sector parameter space for a fixed m_{DM}



Basic properties of DM

- DM: stable or long-lived ($\tau_{\text{DM}} \gg \tau_{\text{universe}}$): **some exact or accidental symmetry**
- DM particle will be described by QFT
- Then there are 3 possibilities:
 - Absolutely stable due to exact gauge symmetries or topological reasons
 - Long-lived due to some accidental sym. **(broken @ dim-6)**
 - Long-lived since it is very light (axion, ν_s , etc.)

DM model buildings along the SM construction

- No global symmetry from the beginning [like the SM. And it is believed to be generically violated by gravity.]
- We will discuss 3 cases separately:
 - Stable DM due to exact gauge symmetries
 - Stable DM due to topological reasons
 - Long-lived DM because of some accidental symmetries
- I will not talk about (very) light DM in this talk

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability
(Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- Electron stability : $U(1)_{\text{em}}$ gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- “(Chiral) dark gauge theories without any global sym”
- Origin of DM stability/longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

In QFT

- DM could be absolutely stable due to **unbroken local gauge symmetry** (DM with local $U(1)_D \rightarrow Z_2, Z_3$, $SU(3)_D \rightarrow SU(2)_D$, etc.) or **topology** (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some **accidental symmetries** (Strongly interacting hidden sector (DQCD), dark pions and dark baryons : Ko et al (2007))
- Kinematically long-lived if DM is very light (axion, sterile ν_s , etc..)

Dark Gauge Symmetry:

DM Stability/Longevity

Z2 real scalar DM

- Simplest DM model with Z2 symmetry : $S \rightarrow -S$

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

- Global Z2 could be broken by gravity effects (higher dim operators)

- e.g. consider Z2 breaking dim-5 op : $\frac{1}{M_{\text{Planck}}} SO_{\text{SM}}^{(4)}$

- Lifetime of EW scale mass “S” is too short to be a DM
- Similarly for singlet fermion DM

Fate of CDM with Z_2 sym

(Baek,Ko,Park,arXiv:1303.4280)

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\text{Planck}}} SO_{\text{SM}}$$

keeping dim-4 SM
operators only

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

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

- Global Z_2 cannot save EW scale DM from decay with long enough lifetime

The lifetime is too short for ~ 100 GeV DM

Fate of CDM with Z_2 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:

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

Problematic !

Perfectly fine !

**Higgs is not good for DM
stability/longvity**

- These arguments will apply to DM models based on ad hoc symmetries (Z_2, Z_3 etc.)
- One way out is to implement Z_2 symmetry as local $U(1)$ symmetry (arXiv:1407.6588 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 $U(1)_H$
- DM phenomenology richer and DM stability/longevity on much more solid ground

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

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

$$- \frac{\lambda_X}{4}(X^\dagger X)^2 - (\mu X^2\phi^\dagger + H.c.) - \frac{\lambda_{XH}}{4}X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4}\phi_X^\dagger\phi_X H^\dagger H - \frac{\lambda_{XH}}{4}X^\dagger X\phi_X^\dagger\phi_X$$

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

Unbroken Local Z2 symmetry
Gauge models for excited DM

$X_R \rightarrow X_I \gamma_h^*$ followed by $\gamma_h^* \rightarrow \gamma \rightarrow e^+ e^-$ 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)

Scalar XDM (X_R & X_I)

Field	ϕ	X	χ
U(1) charge	2	1	1

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\text{SM}} - \frac{1}{4} \hat{X}_{\mu\nu} \hat{X}^{\mu\nu} - \frac{1}{2} \sin \epsilon \hat{X}_{\mu\nu} \hat{B}^{\mu\nu} + D^\mu \phi^\dagger D_\mu \phi + D^\mu X^\dagger D_\mu X - m_X^2 X^\dagger X + m_\phi^2 \phi^\dagger \phi \\ & - \lambda_\phi (\phi^\dagger \phi)^2 - \lambda_X (X^\dagger X)^2 - \lambda_{\phi X} X^\dagger X \phi^\dagger \phi - \lambda_{\phi H} \phi^\dagger \phi H^\dagger H - \lambda_{HX} X^\dagger X H^\dagger H \\ & - \mu (X^2 \phi^\dagger + H.c.), \end{aligned} \quad (1)$$

$$X = \frac{1}{\sqrt{2}}(X_R + iX_I),$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h_H) \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(v_\phi + h_\phi),$$

$$\mathcal{L} \supset \epsilon g_X s_W Z^\mu (X_R \partial_\mu X_I - X_I \partial_\mu X_R) - \frac{g_Z}{2} Z_\mu \bar{\nu}_L \gamma^\mu \nu_L.$$

$$\mathcal{L} \supset g_X Z'^\mu (X_R \partial_\mu X_I - X_I \partial_\mu X_R) - \epsilon e c_W Z'_\mu \bar{e} \gamma^\mu e,$$

$$U(1) \rightarrow Z_2 \text{ by } v_\phi \neq 0 : X \rightarrow -X$$

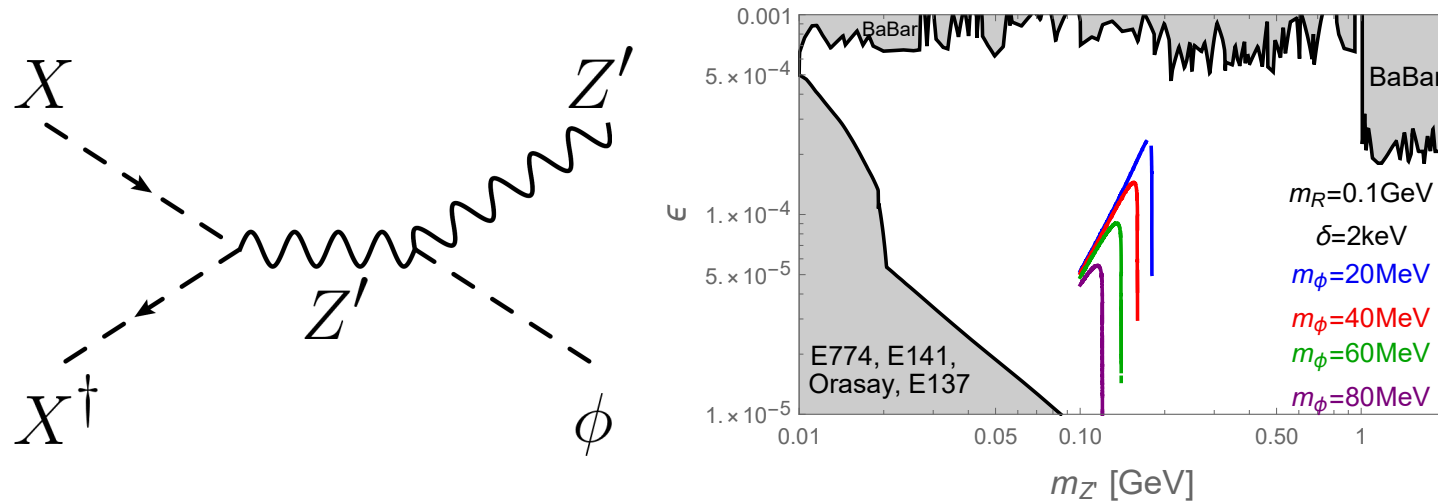


FIG. 1: (*left*) Feynman diagrams relevant for thermal relic density of DM: $XX^\dagger \rightarrow Z'\phi$ and (*right*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for scalar DM case for $\delta = 2$ keV : (a) $m_{\text{DM}} = 0.1$ GeV. Different colors represents $m_\phi = 20, 40, 60, 80$ MeV. The gray areas are excluded by various experiments, from BaBar [61], E774 [62], E141 [63], Orasay [64], and E137 [65], assuming $Z' \rightarrow X_R X_I$ is kinematically forbidden.

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \rightarrow Z'^* \rightarrow Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi m_X^4 (4m_X^2 - m_{Z'}^2)^2} (16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2) \\ \times \left[\{4m_X^2 - (m_{Z'} + m_\phi)^2\} \{4m_X^2 - (m_{Z'} - m_\phi)^2\} \right]^{1/2} + \mathcal{O}(v^4), \quad (10)$$

Fermion XDM (χ_R & χ_I)

$$\mathcal{L} = -\frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}B^{\mu\nu} + \bar{\chi}(i\not{D} - m_\chi)\chi + D_\mu\phi^\dagger D^\mu\phi \\ - \mu^2\phi^\dagger\phi - \lambda_\phi|\phi|^4 - \frac{1}{\sqrt{2}}\left(y\phi^\dagger\bar{\chi}^C\chi + \text{h.c.}\right) - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H$$

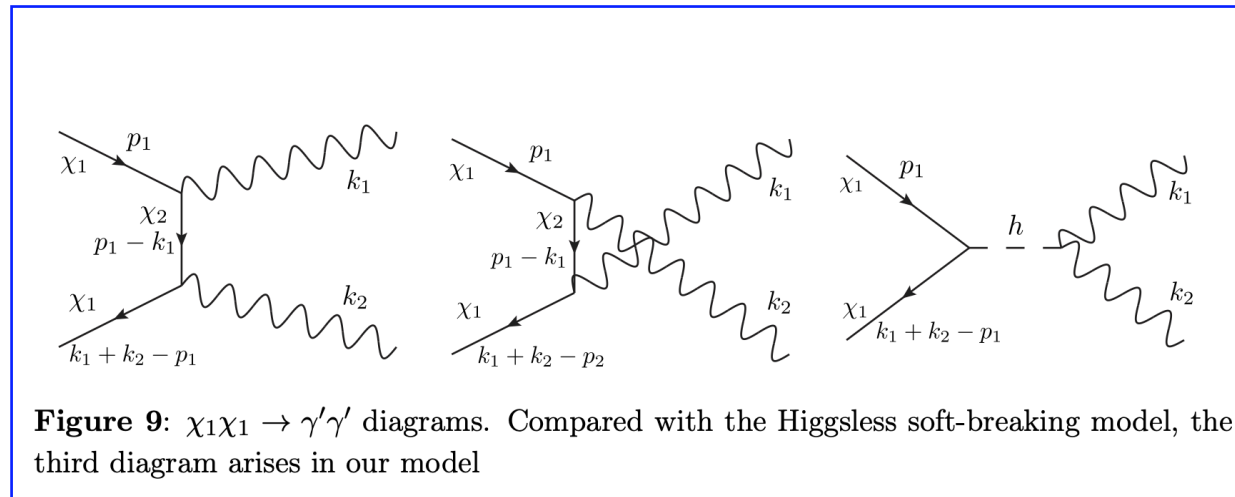
$$\chi = \frac{1}{\sqrt{2}}(\chi_R + i\chi_I), \\ \chi^c = \frac{1}{\sqrt{2}}(\chi_R - i\chi_I), \\ \chi_R^c = \chi_R, \quad \chi_I^c = \chi_I,$$

$$\mathcal{L} = \frac{1}{2}\sum_{i=R,I}\bar{\chi}_i(i\not{D} - m_i)\chi_i - i\frac{g_X}{2}(Z'_\mu + \epsilon s_W Z_\mu)(\bar{\chi}_R\gamma^\mu\chi_I - \bar{\chi}_I\gamma^\mu\chi_R) \\ - \frac{1}{2}yh_\phi(\bar{\chi}_R\chi_R - \bar{\chi}_I\chi_I),$$

$$U(1) \rightarrow Z_2 \text{ by } v_\phi \neq 0 : \chi \rightarrow -\chi$$

Without dark Higgs

P.Ko, T.Matsui, Yi-Lei Tang, arXiv:1910.04311, Appendix A



- Only the first two diagrams if the mass gap is given by hand
- The third diagram if the mass gap is generated by dark Higgs mechanism
- Without the last diagram, the amplitude violates unitarity at large $E_{\gamma'}$

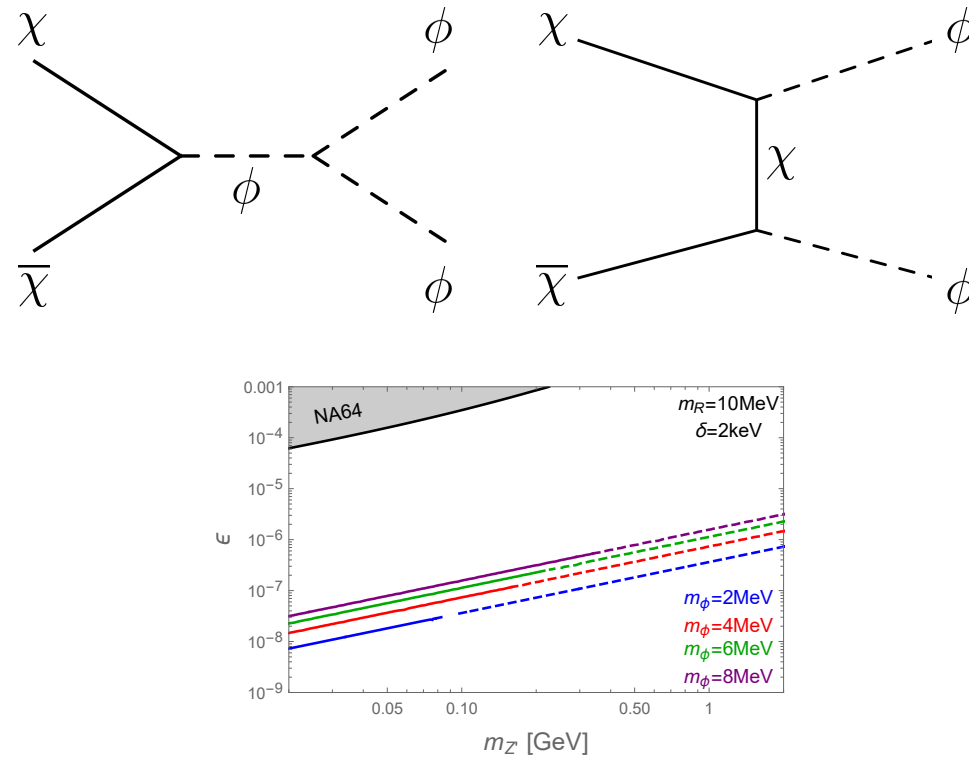


FIG. 2: (*top*) Feynman diagrams for $\chi\bar{\chi} \rightarrow \phi\phi$. (*bottom*) the region in the (m_Z, ϵ) plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for fermion DM case for $\delta = 2$ keV and the fermion DM mass to be $m_R = 10$ MeV. Different colors represents $m_\phi = 2, 4, 6, 8$ MeV. The gray areas are excluded by various experiments, assuming $Z' \rightarrow \chi_R\chi_L$ is kinematically allowed, and the experimental constraint is weaker in the ϵ we are interested in, compared with the scalar DM case in Fig. 1 (right). We also show the current experimental bounds by NA64 [66].

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \rightarrow Z'^* \rightarrow Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi m_X^4 (4m_X^2 - m_{Z'}^2)^2} (16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2) \\ \times \left[\{4m_X^2 - (m_{Z'} + m_\phi)^2\} \{4m_X^2 - (m_{Z'} - m_\phi)^2\} \right]^{1/2} + \mathcal{O}(v^4), \quad (10)$$

Fermion DM : $\chi\bar{\chi} \rightarrow \phi\phi$

$$\sigma v = \frac{y^2 v^2 \sqrt{m_\chi^2 - m_\phi^2}}{96\pi m_\chi} \left[\frac{27\lambda_\phi^2 v_\phi^2}{(4m_\chi^2 - m_\phi^2)^2} + \frac{4y^2 m_\chi^2 (9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4)}{(2m_\chi^2 - m_\phi^2)^4} \right] + \mathcal{O}(v^4), \quad (28)$$

**Crucial to include “dark Higgs” to have
DM pair annihilation in P-wave**

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 h-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 G_h is unbroken
 - If G_h is unbroken and CDM is DM, then no extra scalar boson is necessary (*)
 - If G_h is broken, hDM can be still stable or decay, depending on G_h 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 the Planck scale

Higgs signal strength/DR/DM

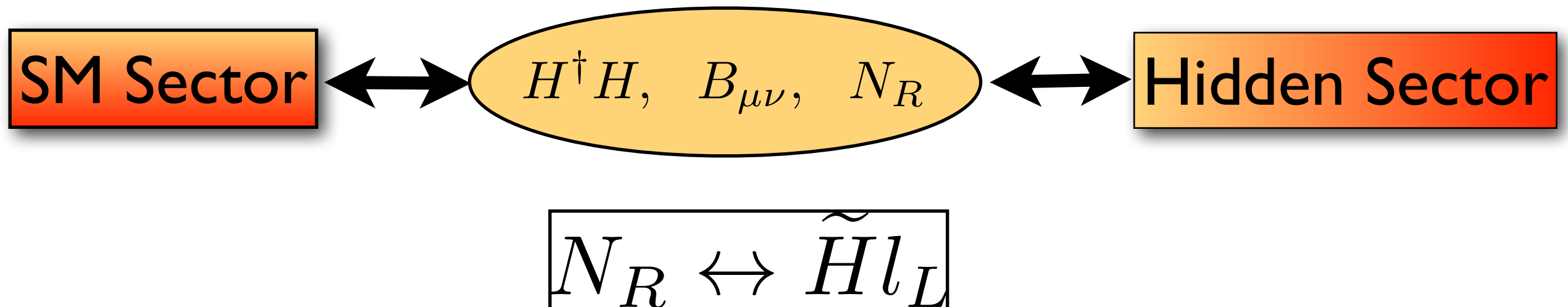
in preparation with Baek and W.I. Park

Models	Unbroken $U(1) \times$	Local Z_2	Unbroken $SU(N)$	Unbroken $SU(N)$ (confining)
Scalar DM	I 0.08 complex scalar	$< I$ ~ 0 real scalar	I $\sim 0.08 \times \#$ complex scalar	I ~ 0 composite hadrons
Fermion DM	$< I$ 0.08 Dirac fermion	$< I$ ~ 0 Majorana	$< I$ $\sim 0.08 \times \#$ Dirac fermion	$< I$ ~ 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



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, Z_2 scalar CDM

Why renormalizable?

&

Limitation of EFT for DM

Higgs portal DM as examples

All invariant
under ad hoc
Z2 symmetry

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

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

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

arXiv:1112.3299, ... 1402.6287, etc.

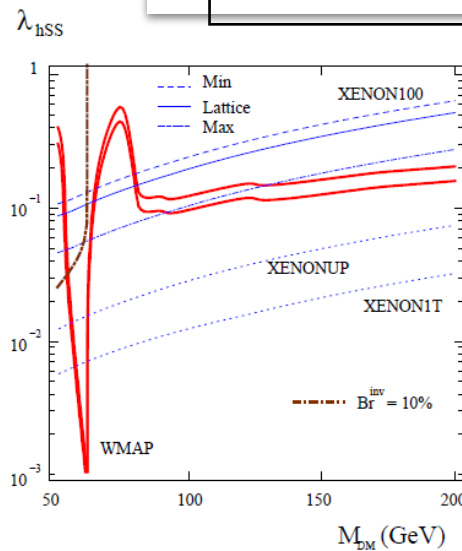


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $\text{Br}^{\text{inv}} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

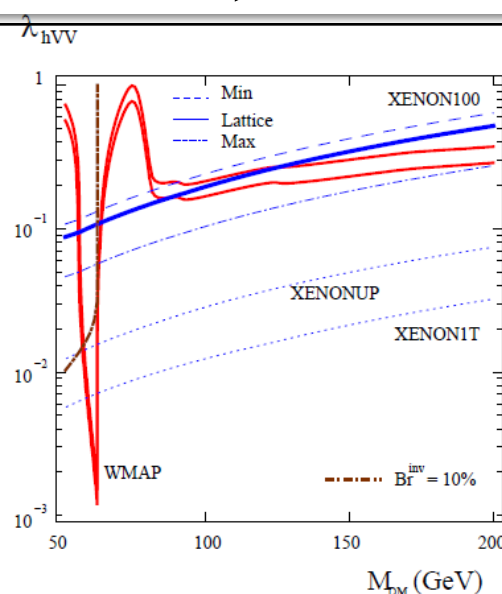


FIG. 2. Same as Fig. 1 for vector DM particles.

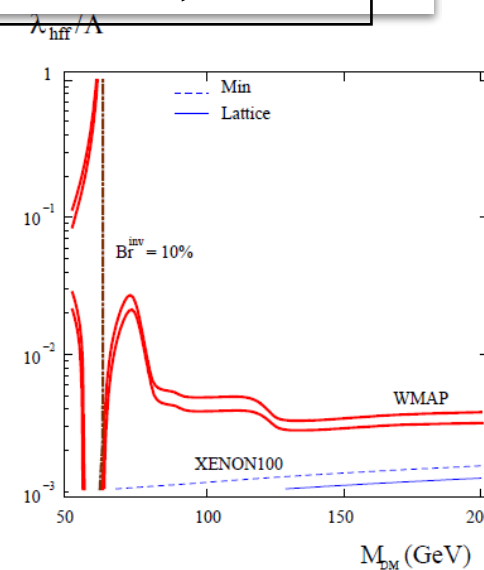


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1} .

Higgs portal DM as examples

All invariant
under ad hoc
Z2 symmetry

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

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

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

- 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

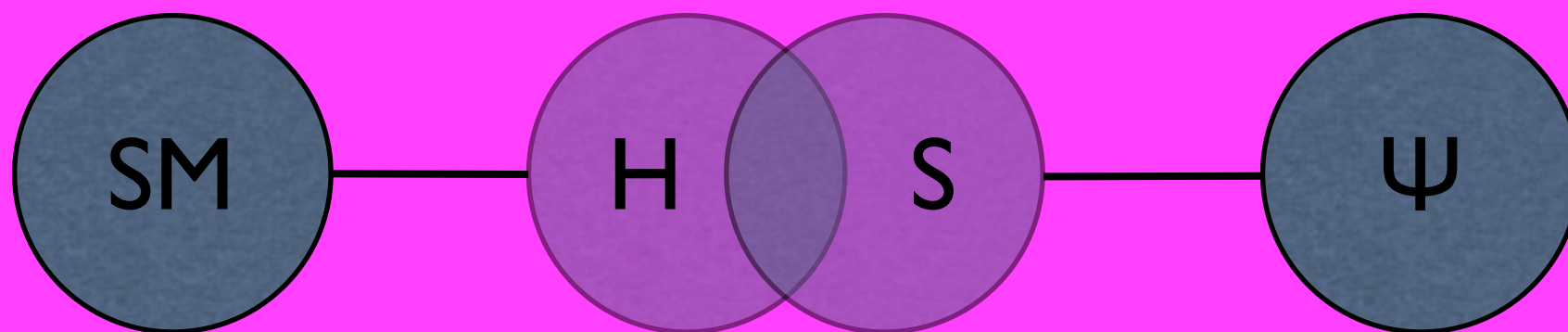
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

→ mixing

→ invisible decay



Production and decay rates are suppressed relative to SM.

☪ This simple model has not been studied properly !!

- Mixing and Eigenstates of Higgs-like bosons

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2} \lambda_{HS} v_S^2,$$

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

at vacuum

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

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

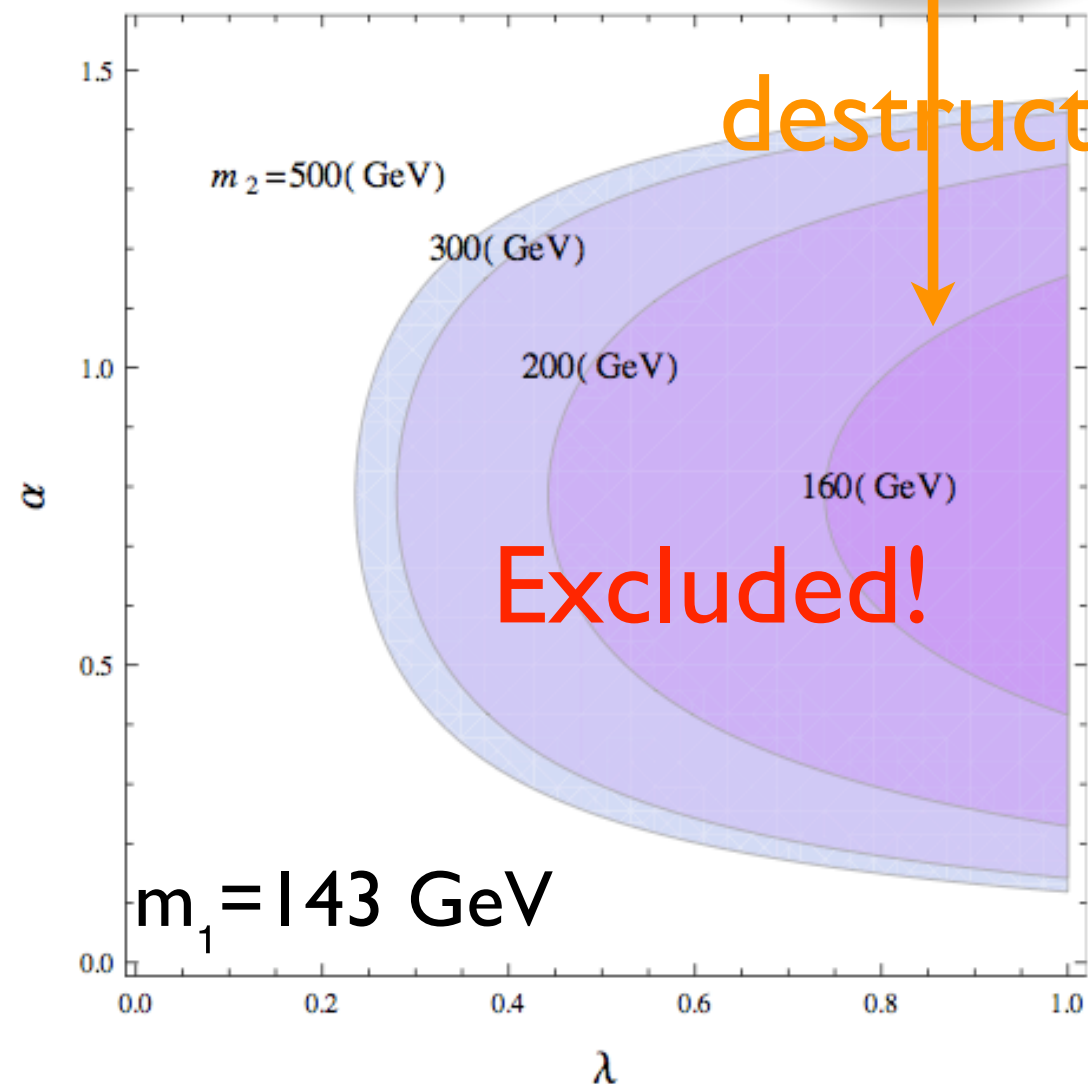
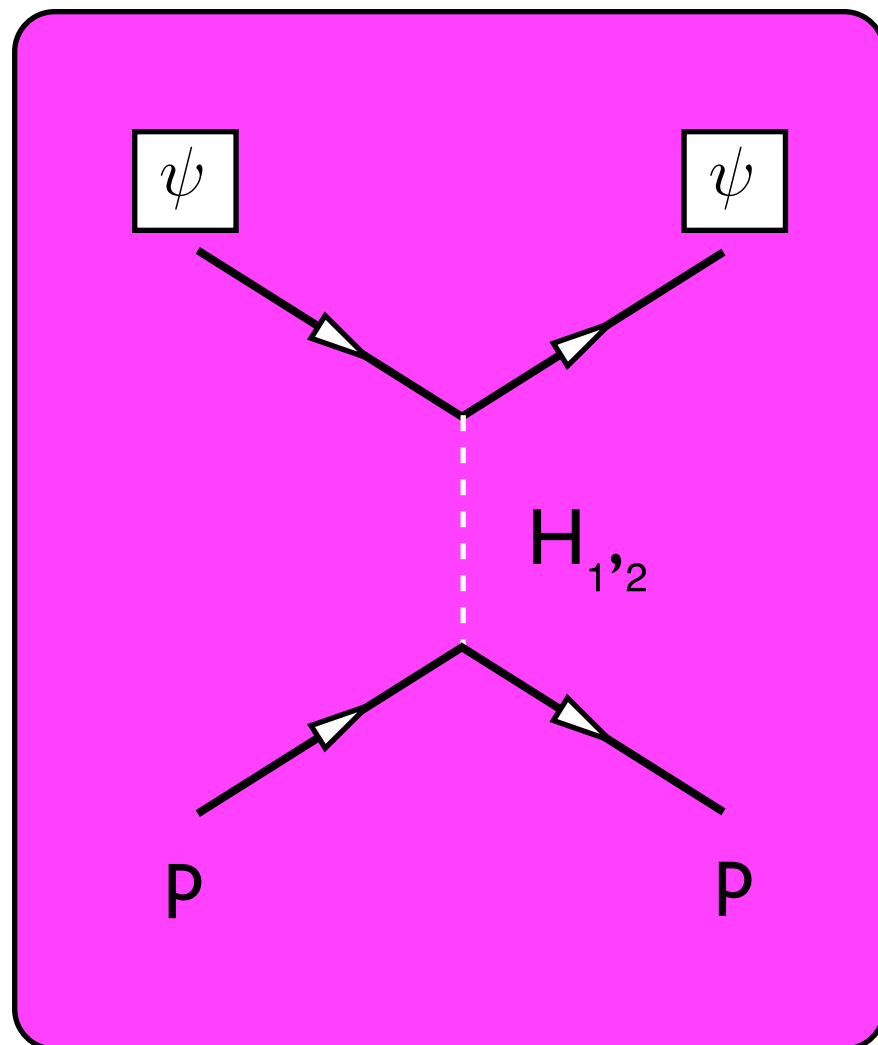
$$H_2 = h \sin \alpha + s \cos \alpha.$$



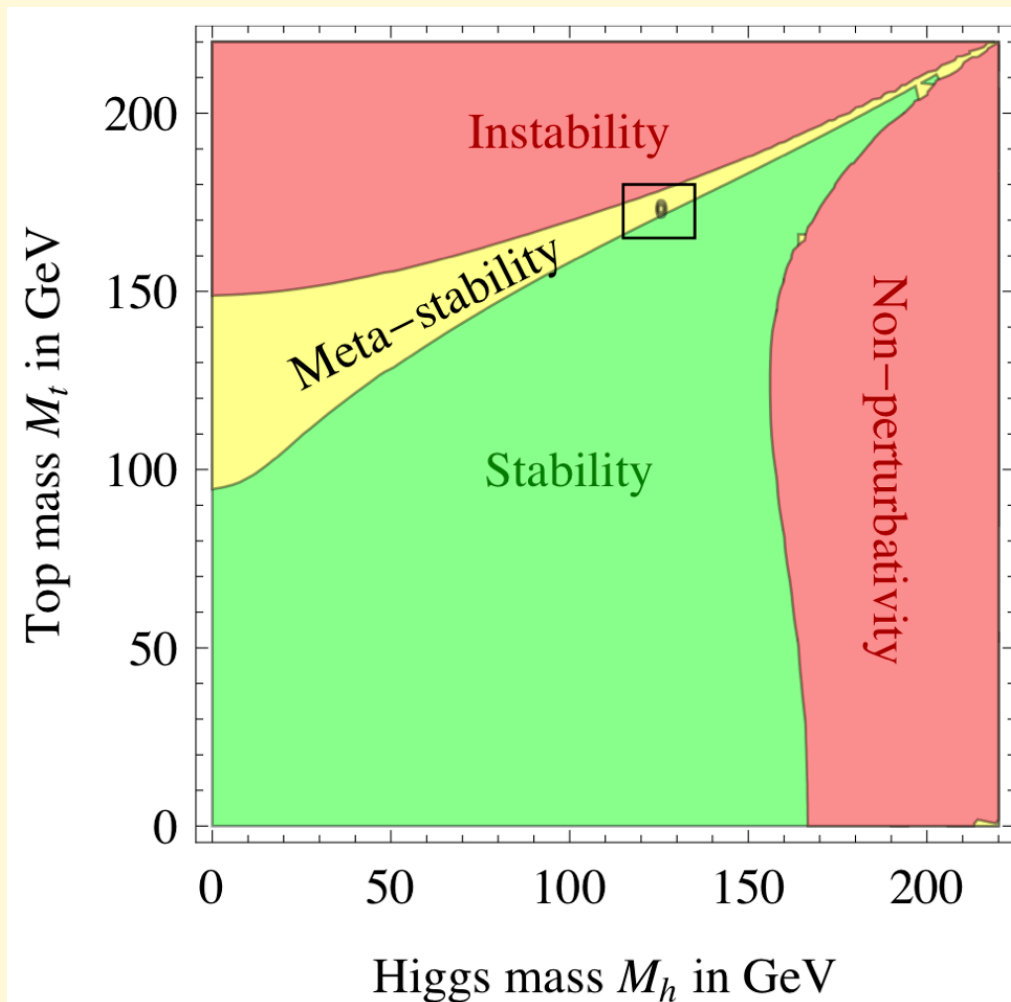
Mixing of Higgs and singlet

- Dark matter to nucleon cross section (constraint)

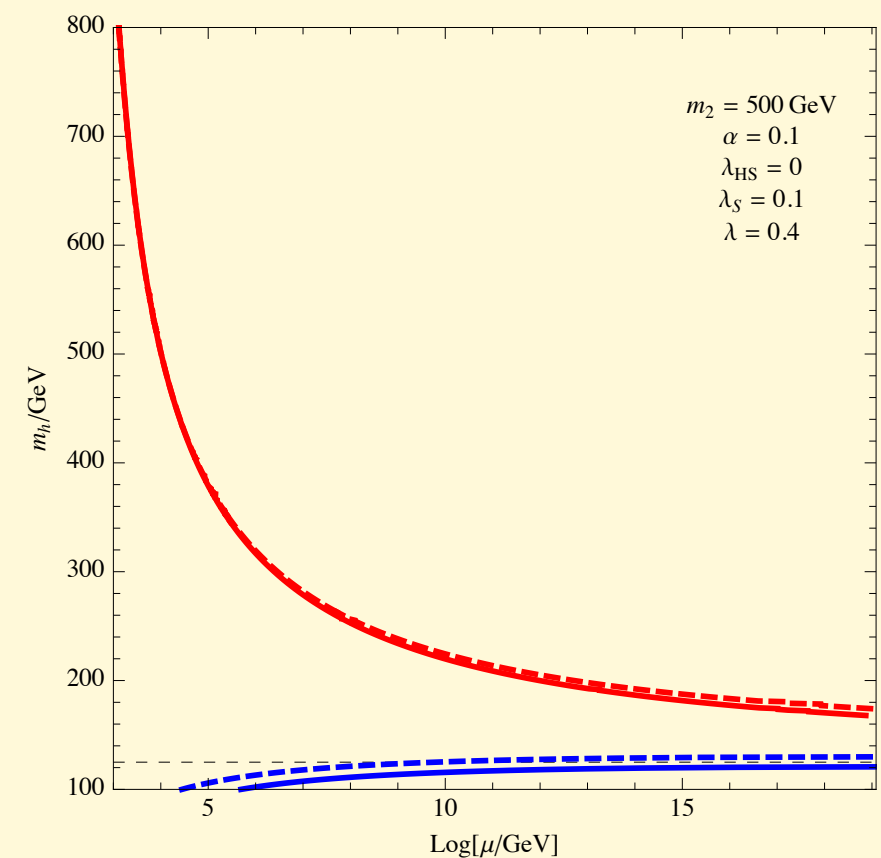
$$\sigma_p \approx \frac{1}{\pi} \mu^2 \lambda_p^2 \simeq 2.7 \times 10^{-2} \frac{m_p^2}{\pi} \left| \left(\frac{m_p}{v} \right) \lambda \sin \alpha \cos \alpha \left(\frac{1}{m_1^2} - \frac{1}{m_2^2} \right) \right|^2$$



Vacuum Stability Improved by the singlet scalar S



A. Strumia, Moriond EW 2013



Baek, Ko, Park, Senaha (2012)

Low energy pheno.

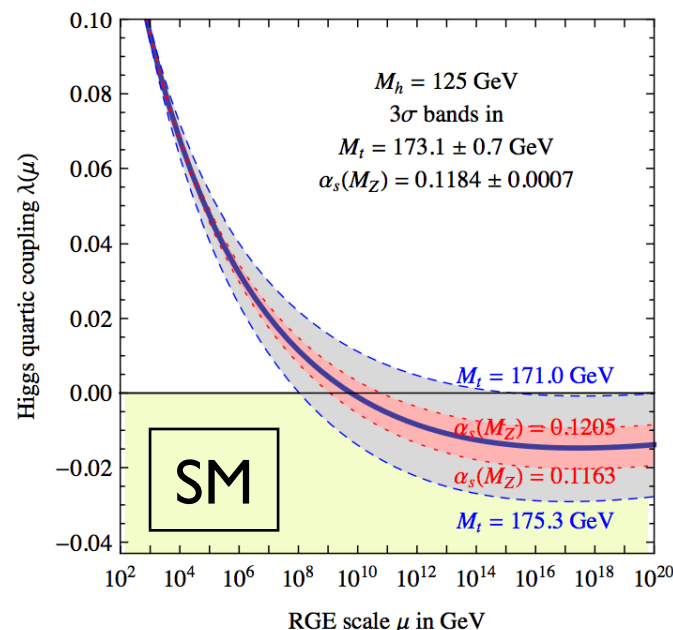
- Universal suppression of collider SM signals

[See 1112.1847, Seungwon Baek, P. Ko & WIP]

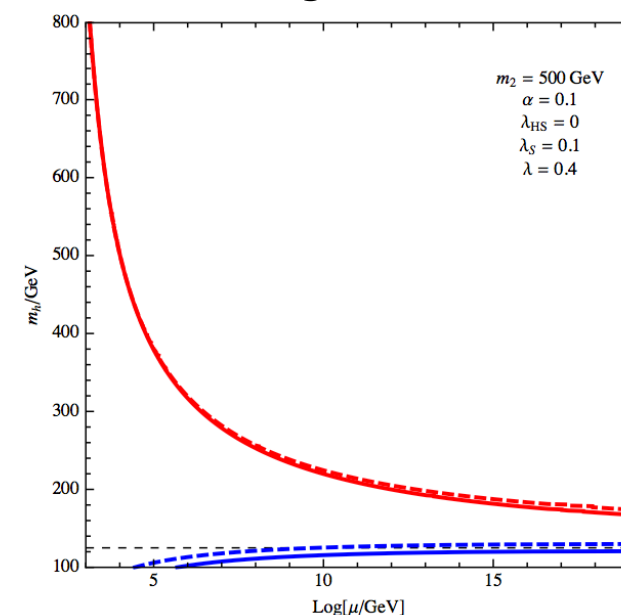
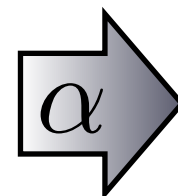
- If “ $m_h > 2 m_\phi$ ”, non-SM Higgs decay!
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

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

➡ If “ $m_\phi > m_h$ ”, vacuum instability can be cured



[G. Degrandi et al., 1205.6497]



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

Similar for Higgs portal Vector DM

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

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- Stueckelberg mechanism ?
- 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 ϕ_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

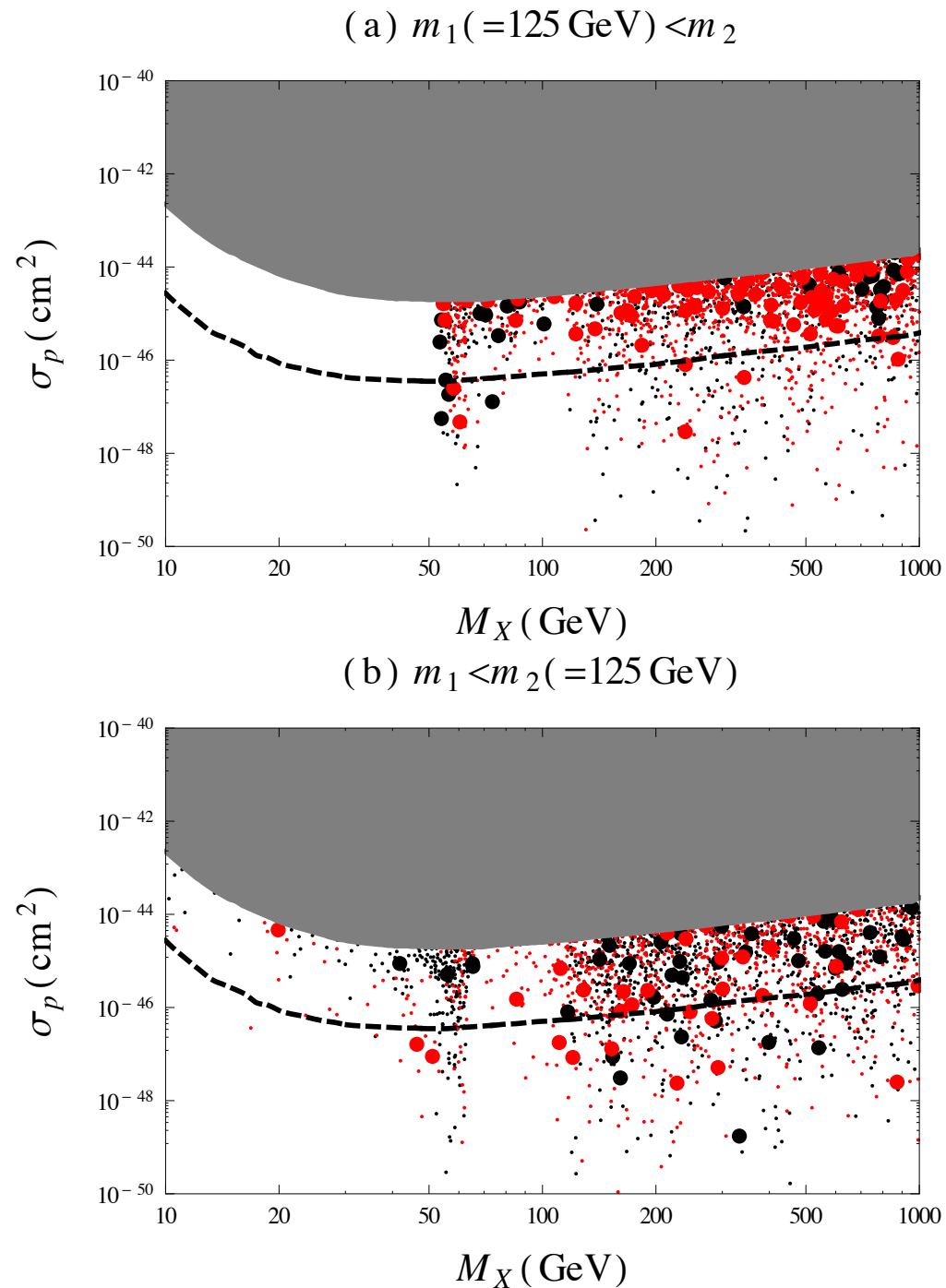


Figure 6. The scattered plot of σ_p as a function of M_X . The big (small) points (do not) satisfy the WMAP relic density constraint within 3σ , while the red-(black-)colored points gives $r_1 > 0.7$ ($r_1 < 0.7$). The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

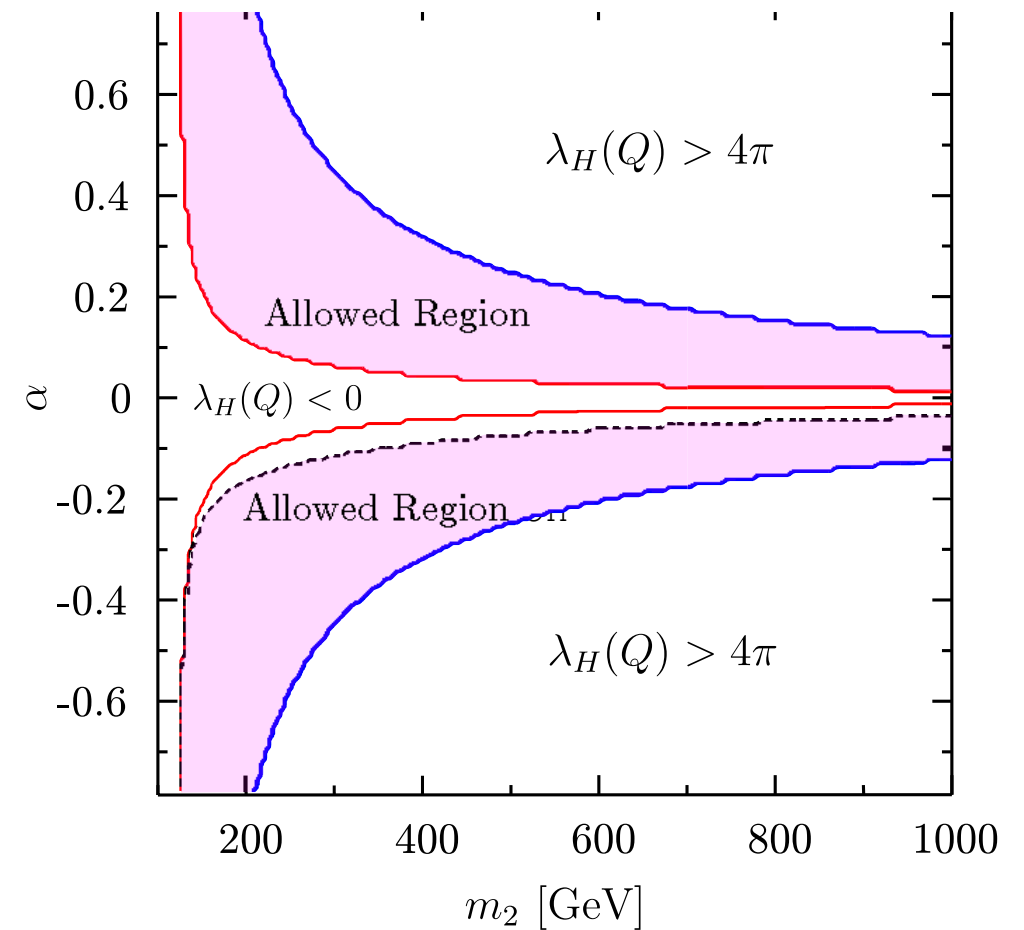


Figure 8. The vacuum stability and perturbativity constraints in the α - m_2 plane. We take $m_1 = 125 \text{ GeV}$, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Higgs portal DM as examples

All invariant
under ad hoc
Z2 symmetry

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

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

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

arXiv:1112.3299, ... 1402.6287, etc.

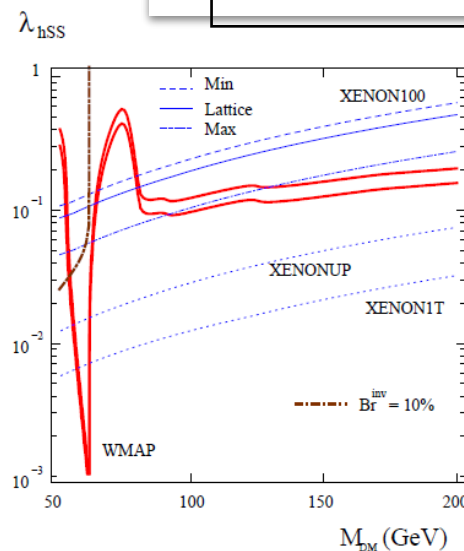


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $\text{Br}^{\text{inv}} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

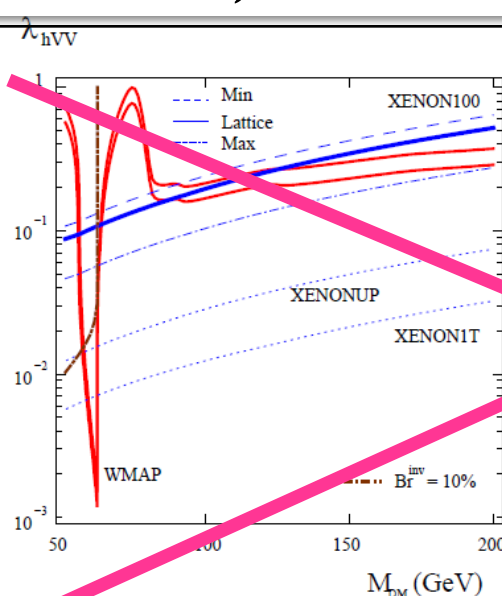


FIG. 2. Same as Fig. 1 for vector DM particles.

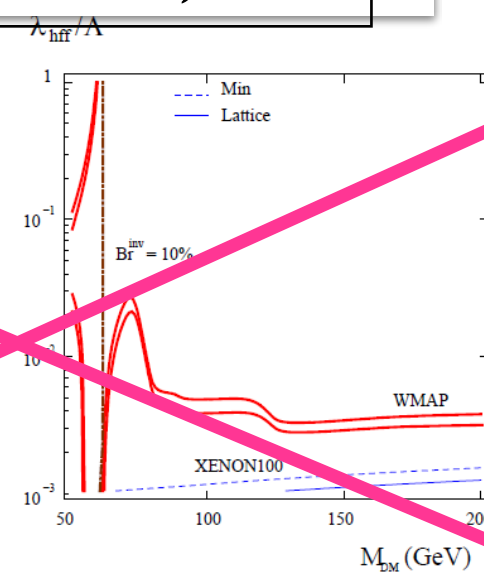
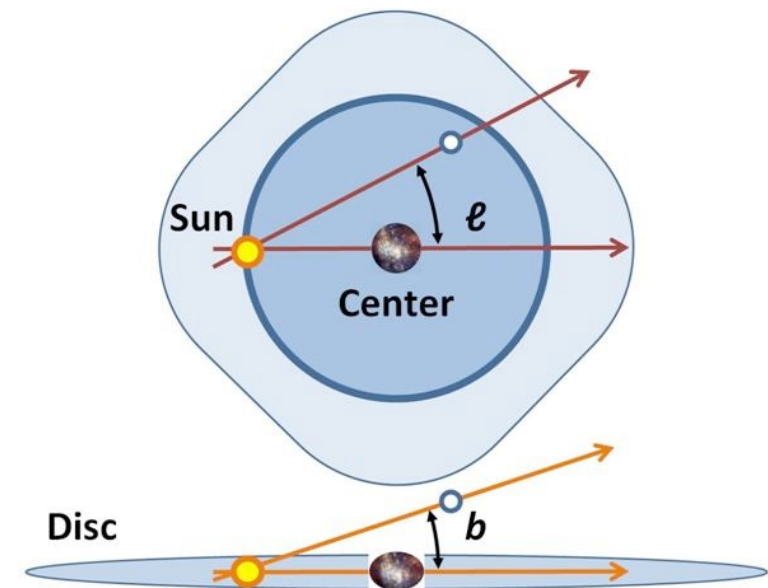
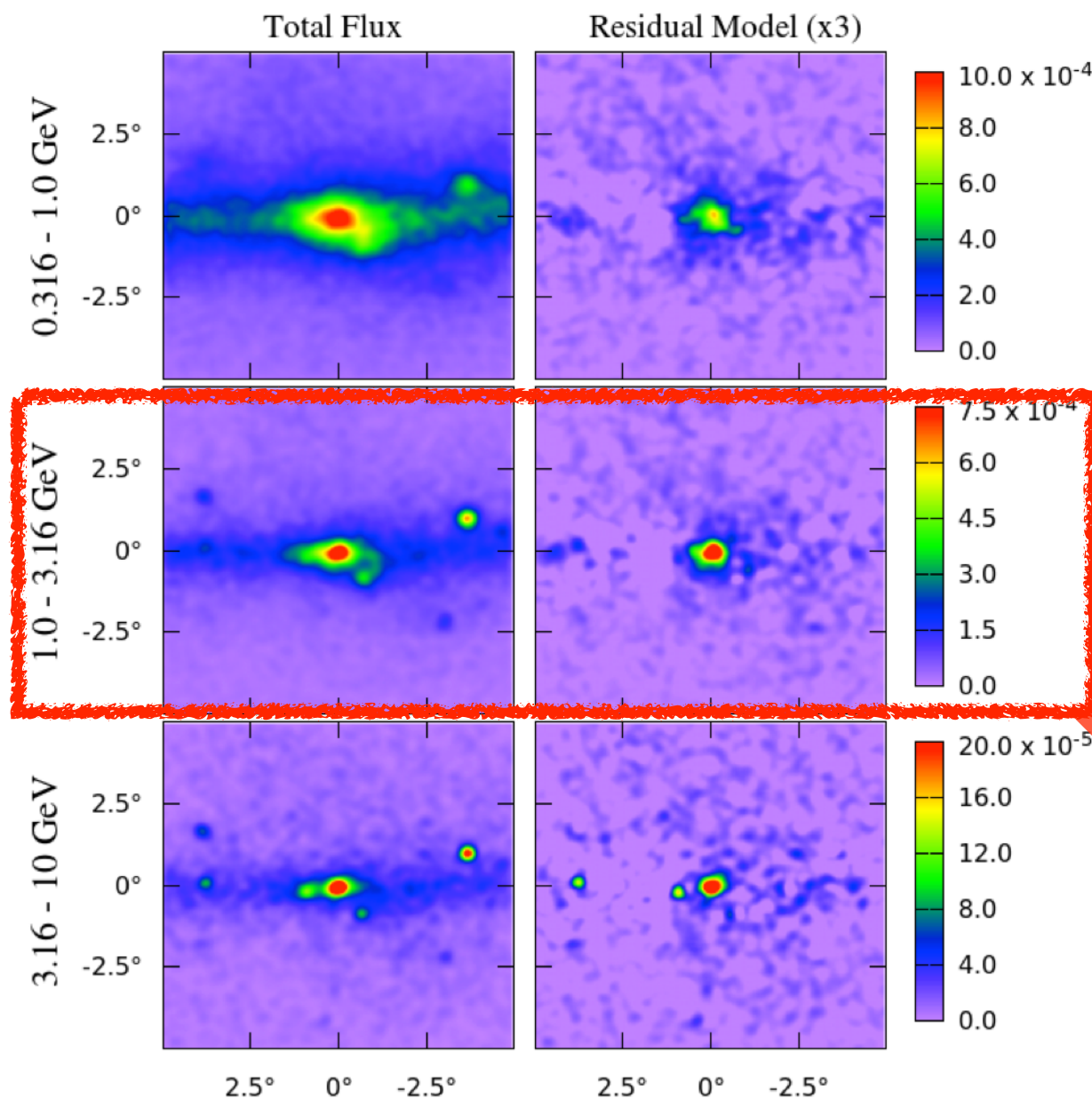


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1} .

Is this any useful in
phenomenology ?

Fermi-LAT GC γ -ray

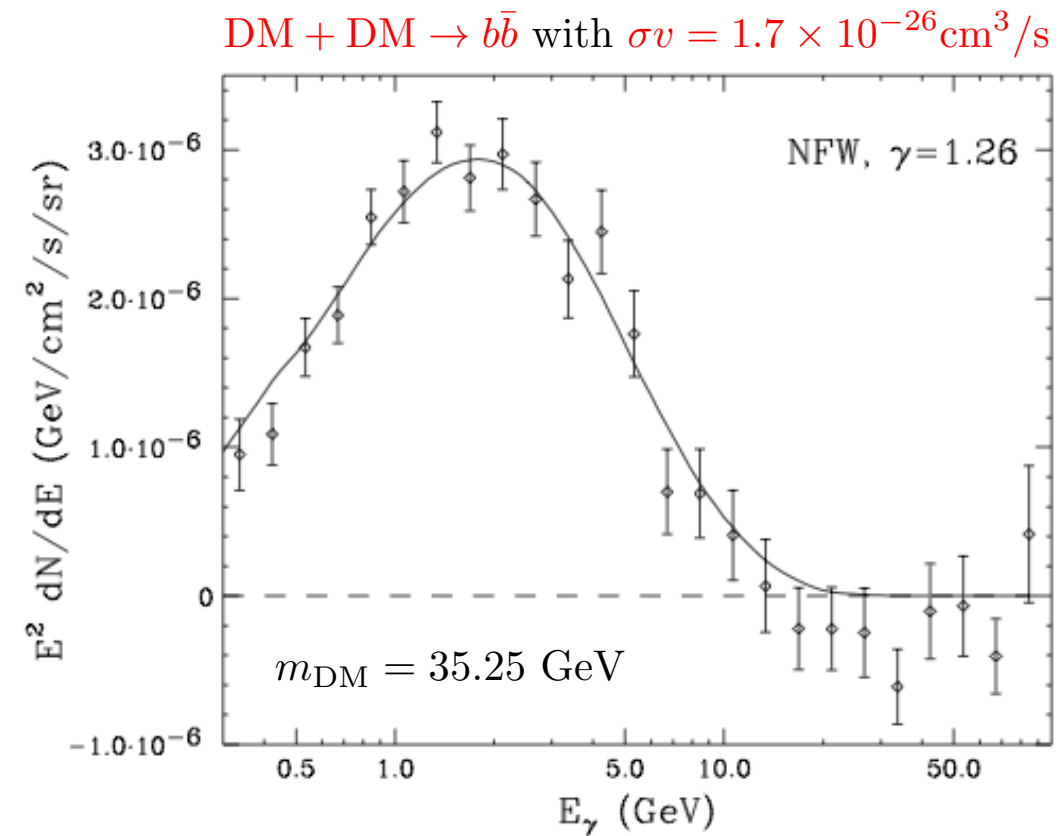
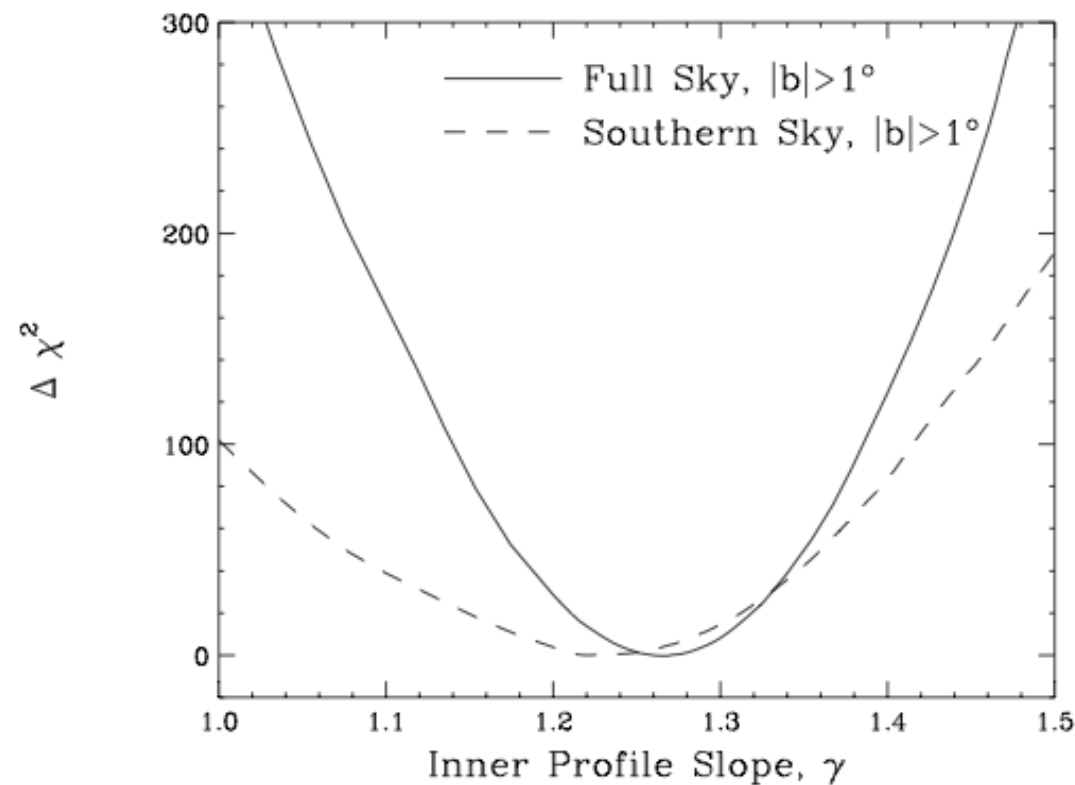
see arXiv:1612.05687 for a recent overview by
C.Karwin, S. Murgia, T. Tait, T.A.Porter, P.Tanedo



$$\text{GC} : b \sim l \lesssim 0.1^\circ$$

extended
GeV scale excess!

● A DM interpretation



* See “1402.6703, T. Daylan et.al.” for other possible channels

● Millisecond Pulsars (astrophysical alternative)

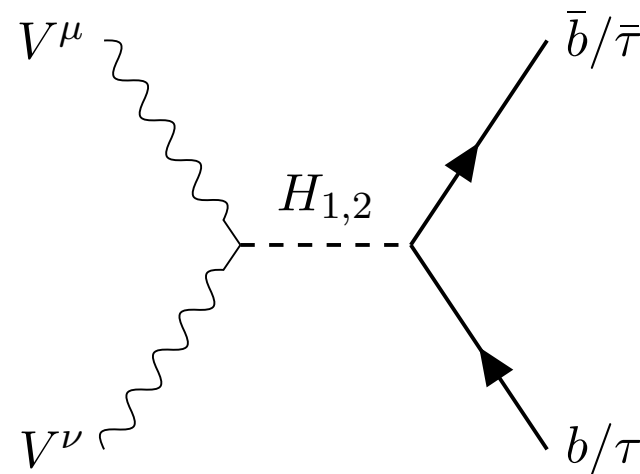
It may or may not be the main source, depending on

- luminosity func.
- bulge population
- distribution of bulge population

* See “1404.2318, Q. Yuan & B. Zhang” and “1407.5625, I. Cholis, D. Hooper & T. Linden”

GC gamma ray in HP VDM

P. Ko, WI Park, Y. Tang. arXiv:1404.5257, JCAP



H2 : 125 GeV Higgs
H1 : absent in EFT

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

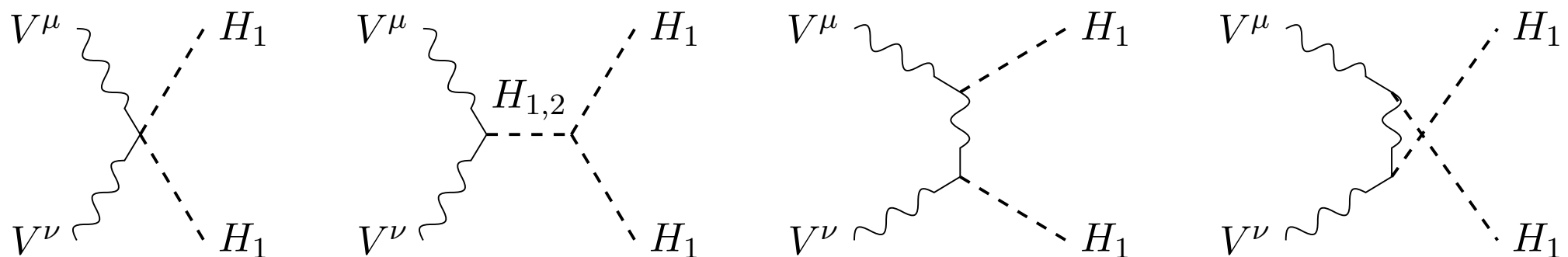


Figure 3. Dominant s/t -channel production of H_1 s that decay dominantly to $b + \bar{b}$

Importance of HP VDM with Dark Higgs Boson

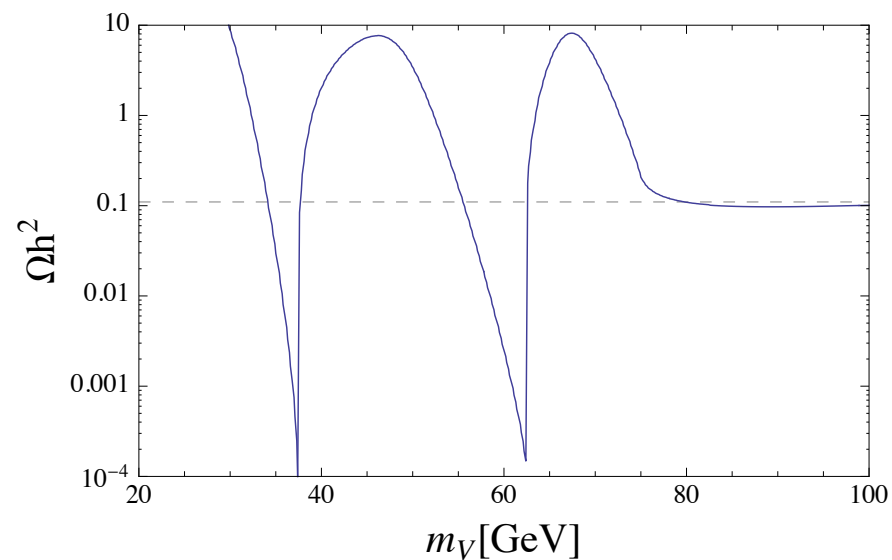


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75$ GeV, $g_X = 0.2$, and $\alpha = 0.1$.

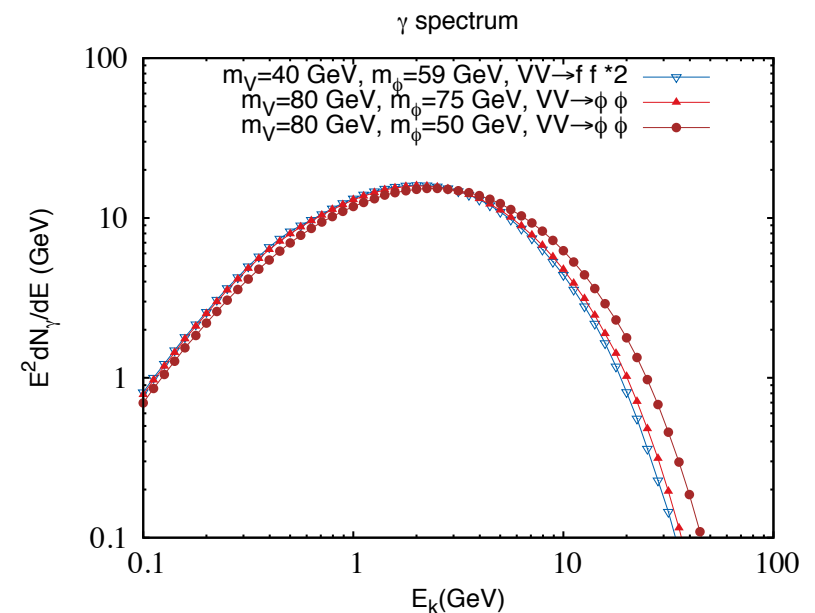


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

And No 2nd neutral scalar (Dark Higgs) in EFT

HP DM @ LHC

2 more relevant parameters

[arXiv: 1405.3530, S. Baek, P. Ko & VIPark, PRD]

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

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

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

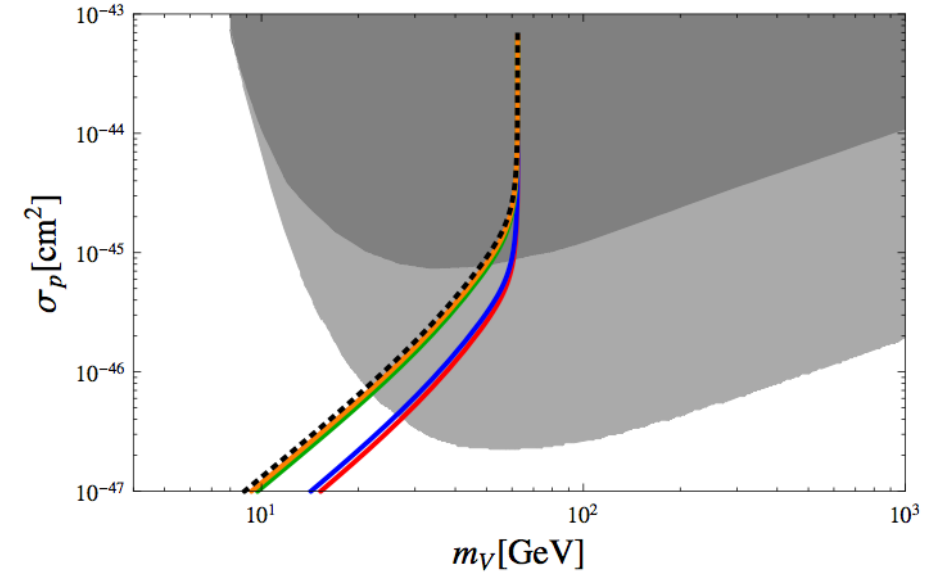
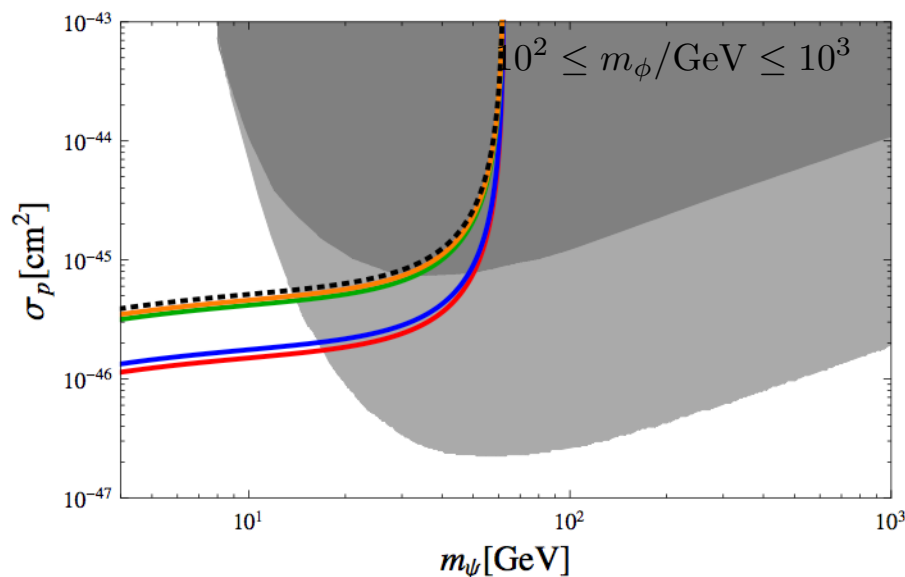
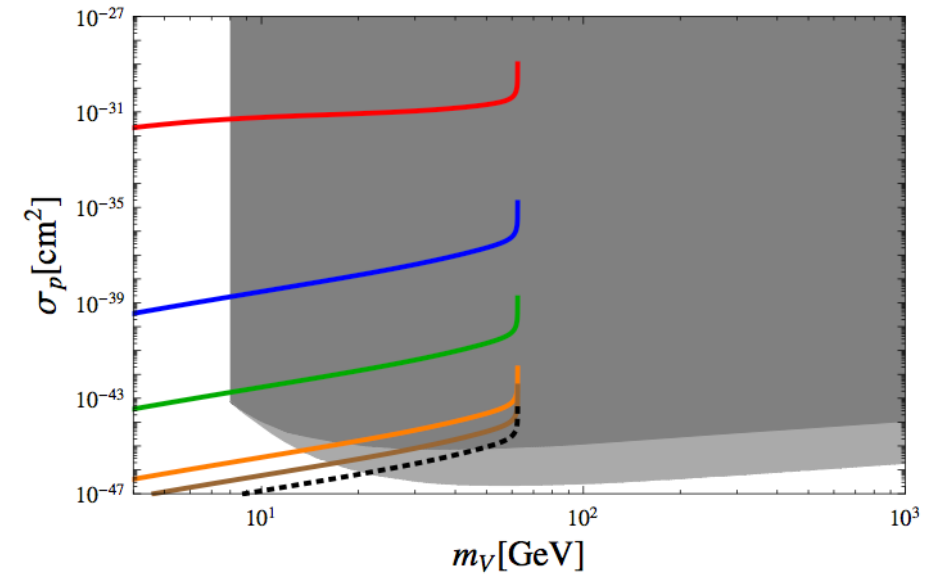
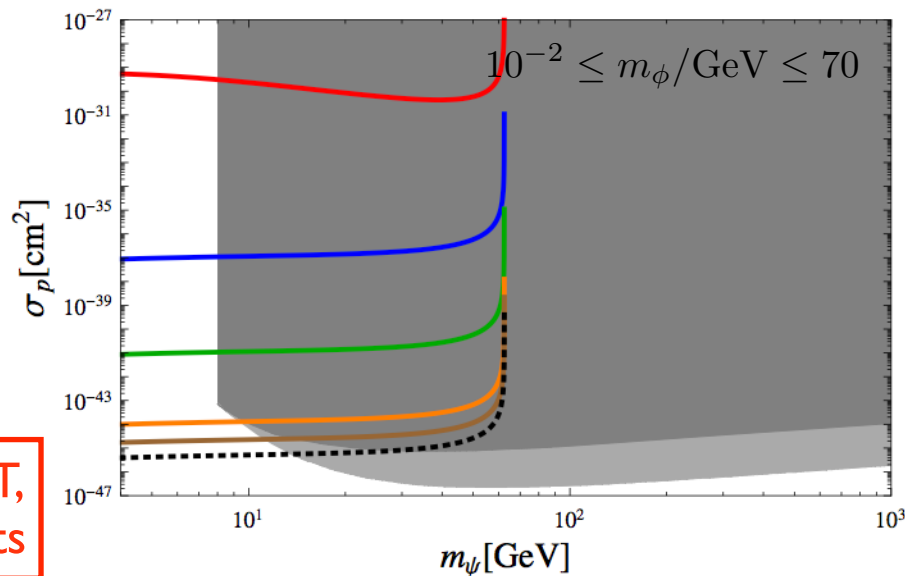
$$\begin{aligned} \mathcal{L}_{\text{SFDM}} = & \bar{\psi} (i \partial - m_\psi - \lambda_\psi S) \psi - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ & + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4. \end{aligned}$$

$$\sigma_p^{\text{SI}} = (\sigma_p^{\text{SI}})_{\text{EFT}} c_\alpha^4 m_h^4 \mathcal{F}(m_{\text{DM}}, \{m_i\}, v)$$

$$\simeq (\sigma_p^{\text{SI}})_{\text{EFT}} c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

EFT

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



Dashed curves: EFT, ATLAS, CMS results

Invisible H decay into a pair of VDM

[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$(\Gamma_h^{\text{inv}})_{\text{EFT}} = \frac{\lambda_{VH}^2}{128\pi} \frac{v_H^2 m_h^3}{m_V^4} \times \left(1 - \frac{4m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right) \left(1 - \frac{4m_V^2}{m_h^2}\right)^{1/2} \quad (23)$$

VS.

$$\Gamma_i^{\text{inv}} = \frac{g_X^2}{32\pi} \frac{m_i^3}{m_V^2} \left(1 - \frac{4m_V^2}{m_i^2} + 12\frac{m_V^4}{m_i^4}\right) \left(1 - \frac{4m_V^2}{m_i^2}\right)^{1/2} \sin^2 \alpha \quad (22)$$

Invisible H decay width : finite for $m_V \rightarrow 0$
in unitary/renormalizable model

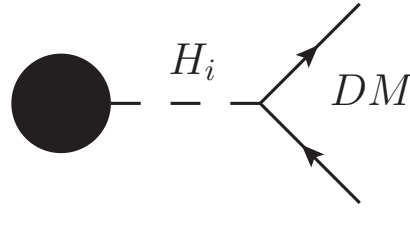
NB: it is infinite in the effective VDM model

$$m_V \propto g_x Q_\Phi v_\Phi$$

$$\frac{g_X^2}{m_V^2} = \frac{g_X^2}{g_X^2 Q_\Phi^2 v_\Phi^2} \rightarrow \frac{1}{v_\Phi^2} = \text{finite}$$

DM Production @ ILC

P Ko, H Yokoya, arXiv:1603.08802, JHEP



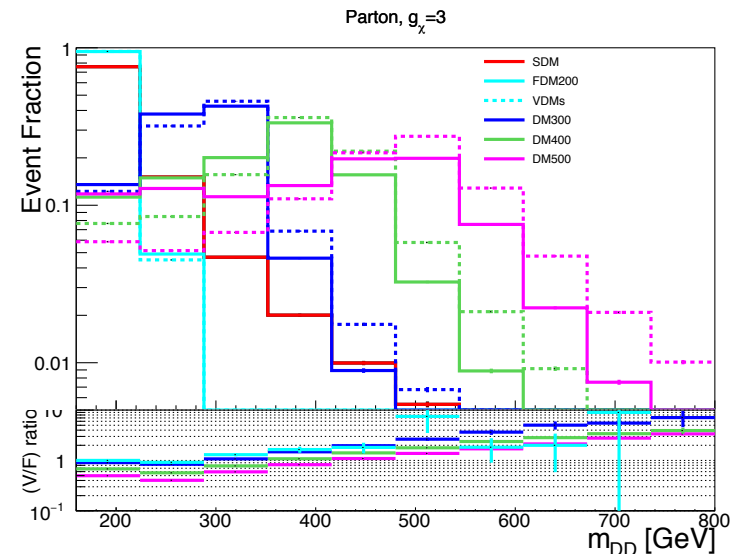
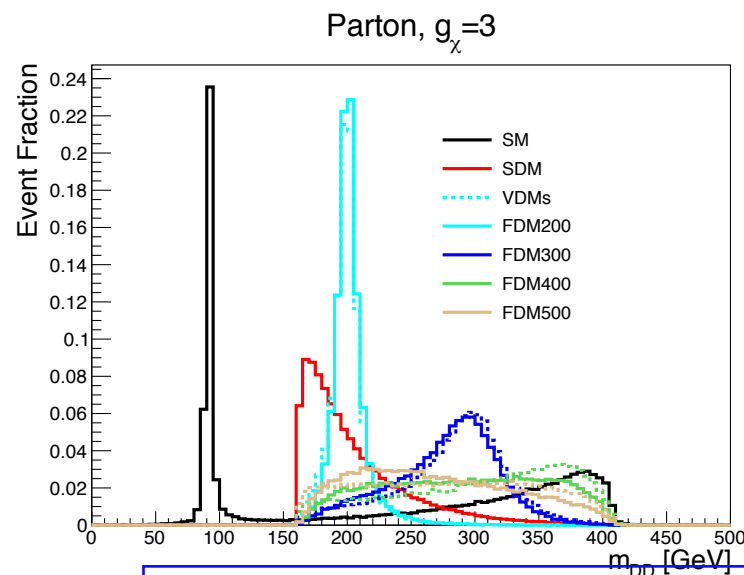
$$t \equiv m_{DD}^2$$

We consider $e^+e^- \rightarrow Z^* \rightarrow ZH_{i=1,2}$
followed by $H_i \rightarrow \bar{\chi}\chi$

$$\frac{d\sigma_{\text{SDM}}}{dt} \propto \sigma_{\text{SDM}}^{h^*} \times \left| \frac{1}{t - m_h^2 + im_h\Gamma_h} \right|^2,$$

$$\frac{d\sigma_{\text{FDM}}}{dt} \propto \sigma_{\text{FDM}}^{h^*} \times \left| \frac{1}{t - m_{H_1}^2 + im_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + im_{H_2}\Gamma_{H_2}} \right|^2 \cdot (2t - 8m_\chi^2),$$

$$\frac{d\sigma_{\text{VDM}}}{dt} \propto \sigma_{\text{VDM}}^{h^*} \times \left| \frac{1}{t - m_{H_1}^2 + im_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + im_{H_2}\Gamma_{H_2}} \right|^2 \cdot \left(2 + \frac{(t - 2m_D^2)^2}{4m_V^4} \right).$$



Fix DM mass = 80 GeV, $\sin(\alpha) = 0.3$,
and vary H_2 mass (200,300,400,500) GeV

Asymptotic behavior in the full theory ($t \equiv m_{\chi\chi}^2$)

$$\text{ScalarDM : } G(t) \sim \frac{1}{(t - m_H^2)^2 + m_H^2 \Gamma_H^2} \quad (5.7)$$

$$\text{SFDM : } G(t) \sim \left| \frac{1}{t - m_1^2 + im_1 \Gamma_1} - \frac{1}{t - m_2^2 + im_2 \Gamma_2} \right|^2 (t - 4m_\chi^2) \quad (5.8)$$

$$\rightarrow \left| \frac{1}{t^2} \right|^2 \times t \sim \frac{1}{t^3} \quad (\text{as } t \rightarrow \infty) \quad (5.9)$$

$$\text{VDM : } G(t) \sim \left| \frac{1}{t - m_1^2 + im_1 \Gamma_1} - \frac{1}{t - m_2^2 + im_2 \Gamma_2} \right|^2 \left[2 + \frac{(t - 2m_V^2)^2}{4m_V^4} \right] \quad (5.10)$$

$$\rightarrow \left| \frac{1}{t^2} \right|^2 \times t^2 \sim \frac{1}{t^2} \quad (\text{as } t \rightarrow \infty) \quad (5.11)$$

Asymptotic behavior w/o the 2nd Higgs (EFT)

$$\text{SFDM : } G(t) \sim \frac{1}{(t - m_H^2)^2 + m_H^2 \Gamma_H^2} (t - 4m_\chi^2) \\ \rightarrow \frac{1}{t} \quad (\text{as } t \rightarrow \infty)$$

$$\text{VDM : } G(t) \sim \frac{1}{(t - m_H^2)^2 + m_H^2 \Gamma_H^2} \left[2 + \frac{(t - 2m_V^2)^2}{4m_V^4} \right] \\ \rightarrow \text{constant} \quad (\text{as } t \rightarrow \infty)$$

**Unitarity is
violated in EFT!**

Baek, Ko, MHPark, WIPark, CHYu
arXiv:1506.06556 [hep-ph]

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3} \bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator S of

$$\mathcal{L}_{int} = \left(\frac{m_q}{v_H} \sin \alpha \right) S \bar{q}q - \lambda_s \cos \alpha S \bar{\chi}\chi$$
- H.M.: A case where a Higgs is a mediator

$$\mathcal{L}_{int} = - \left(\frac{m_q}{v_H} \cos \alpha \right) H \bar{q}q - \lambda_s \sin \alpha H \bar{\chi}\chi$$
- H.P.: Higgs portal model as in eq. (2).

$$\mathcal{L}_{int} = -(H_1 \cos \alpha + H_2 \sin \alpha) \left[\sum_f \frac{m_f}{v_H} \bar{f}f - \frac{2m_W^2}{v_H} W_\mu^+ W^{-\mu} - \frac{m_Z^2}{v_H} Z_\mu Z^\mu \right] + \lambda(H_1 \sin \alpha - H_2 \cos \alpha) \bar{\chi}\chi$$

$$\text{H.P.} \xrightarrow{m_{H_2}^2 \gg \hat{s}} \text{H.M.},$$

$$\text{S.M.} \xrightarrow{m_S^2 \gg \hat{s}} \text{EFT},$$

$$\text{H.M.} \neq \text{EFT}.$$

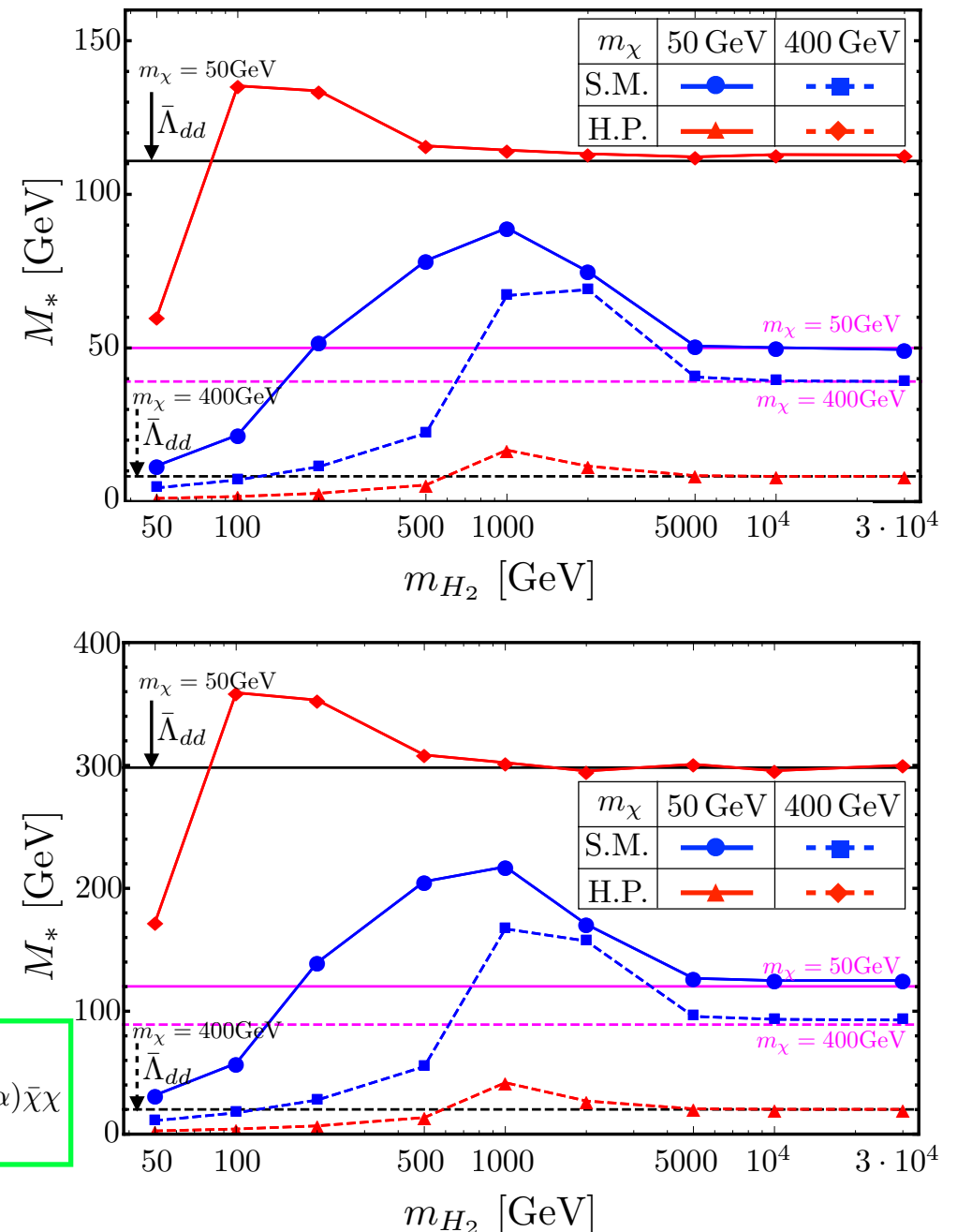


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+ $\cancel{E}_T$ search (upper) and $t\bar{t} + \cancel{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of S.M., H.M., and H.P., are expressed in terms of the effective mass M_* through the Eq.(16)-(20). The solid and dashed lines correspond to $m_\chi = 50$ GeV and 400 GeV in each model, respectively.

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]

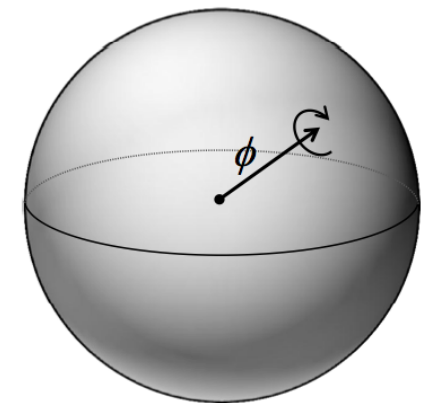
The Model

- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \underbrace{\frac{1}{4} V_{\mu\nu}^a V^{a\mu\nu} + \frac{1}{2} D_\mu \vec{\phi} \cdot D^\mu \vec{\phi} - \frac{\lambda_\phi}{4} (\vec{\phi} \cdot \vec{\phi} - v_\phi^2)^2}_{\text{'t Hooft-Polyakov monopole}} - \underbrace{\frac{\lambda_{\phi H}}{2} \vec{\phi} \cdot \vec{\phi} H^\dagger H}_{\text{Higgs portal}}$$

- Symmetry breaking

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



- 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: $m_M = m_V / \alpha_X$

Stable due to topology and U(1)

- Higgses: $m_{1,2} = \frac{1}{2} \left[m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{(m_{hh}^2 - m_{\phi\phi}^2)^2 + 4m_{\phi h}^4} \right]$

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

DM-DR interactions and H_0 , σ_8 puzzles

Residual Non-Abelian DM&DR

P.Ko&YT, 1609.02307

- Consider $SU(N)$ Yang-Mills gauge fields and a Dark Higgs field Φ

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \lambda_\phi (|\Phi|^2 - v_\phi^2/2)^2,$$

- Take $SU(3)$ as an example,

$$A_\mu^a t^a = \frac{1}{2} \begin{pmatrix} A_\mu^3 + \frac{1}{\sqrt{3}} A_\mu^8 & A_\mu^1 - i A_\mu^2 & A_\mu^4 - i A_\mu^5 \\ A_\mu^1 + i A_\mu^2 & -A_\mu^3 + \frac{1}{\sqrt{3}} A_\mu^8 & A_\mu^6 - i A_\mu^7 \\ A_\mu^4 + i A_\mu^5 & A_\mu^6 + i A_\mu^7 & -\frac{2}{\sqrt{3}} A_\mu^8 \end{pmatrix}.$$

- $SU(3) \rightarrow SU(2)$

$$\langle \Phi \rangle = \begin{pmatrix} 0 & 0 & \frac{v_\phi}{\sqrt{2}} \end{pmatrix}^T, \Phi = \begin{pmatrix} 0 & 0 & \frac{v_\phi + \phi(x)}{\sqrt{2}} \end{pmatrix}^T,$$

The massive gauge bosons $A^{4,\dots,8}$ as dark matter obtain masses,

$$m_{A^{4,5,6,7}} = \frac{1}{2} g v_\phi, \quad m_{A^8} = \frac{1}{\sqrt{3}} g v_\phi,$$

and massless gauge bosons $A_\mu^{1,2,3}$. The physical scalar ϕ can couple to $A_\mu^{4,\dots,8}$ at tree level and to $A^{1,2,3}$ at loop level.

$$SU(N) \rightarrow SU(N-1)$$

- $2N-1$ massive gauge bosons: Dark Matter
- $(N-1)^2-1$ massless gauge bosons: Dark Radiation
- mass spectrum

$$m_{A^{(N-1)^2-1}, \dots, N^2-2} = \frac{1}{2} g v_\phi, \quad m_{A^{N^2-1}} = \frac{\sqrt{N-1}}{\sqrt{2N}} g v_\phi,$$

This can be proved by looking at the structure of f^{abc} . Divide the generators t^a into two subset,

$$a \in [1, 2, \dots, (N-1)^2-1], a \in [(N-1)^2, \dots, N^2-1].$$

Since $[t^a, t^b] = i f^{abc} t^c$ for the first subset forms closed $SU(N-1)$ algebra, we have $f^{abc} = 0$ when only one of a, b and c is from the second subset. If one index is N^2-1 , then other two must be among the second subset to give no vanishing f^{abc} , because t^{N^2-1} commutes with t^a from $SU(N-1)$.

Matter Power Spectrum

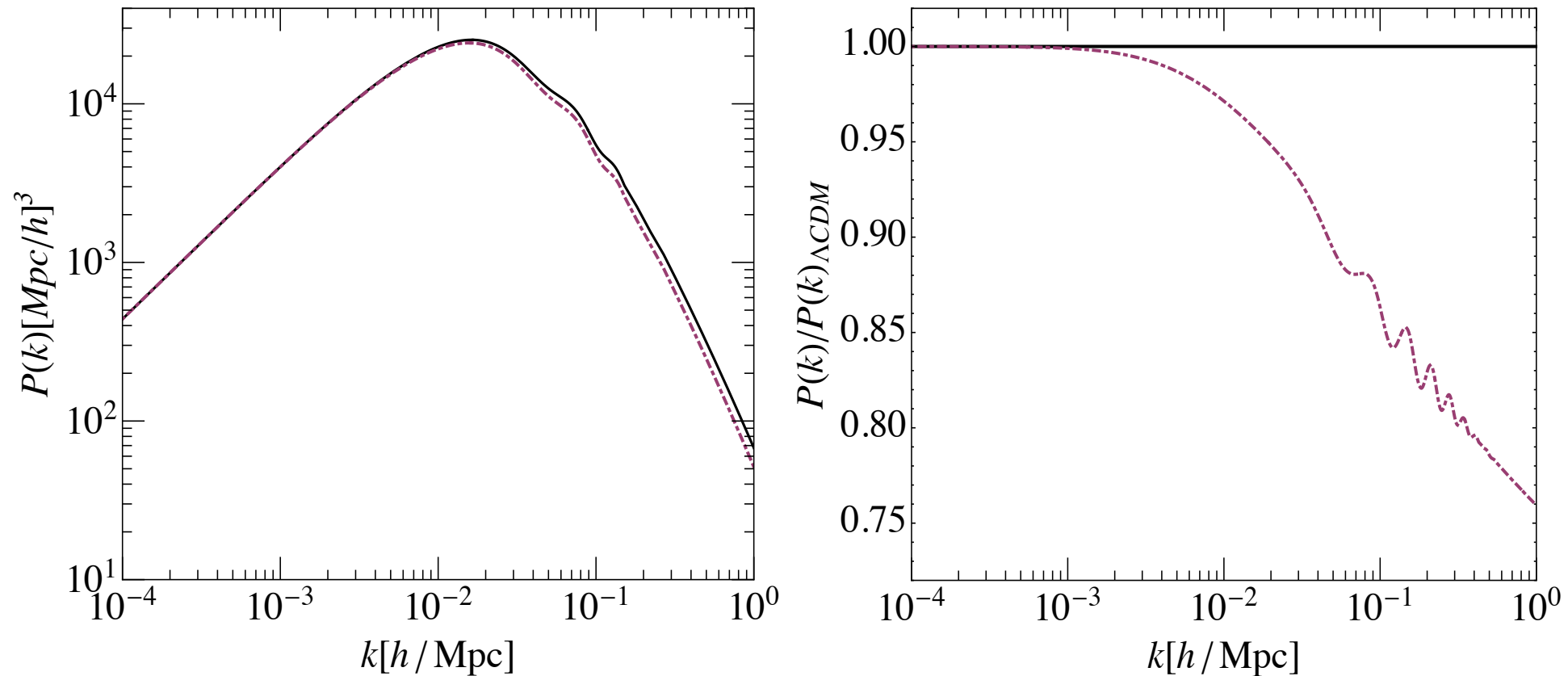


FIG. 3. Matter power spectrum $P(k)$ (left) and ratio (right) with $m_\chi \simeq 10\text{TeV}$ and $g_X^2 \simeq 10^{-7}$, in comparison with ΛCDM . The black solid lines are for ΛCDM and the purple dot-dashed lines for interacting DM-DR case, with input parameters in Eq. 21. We can easily see that $P(k)$ is suppressed for modes that enter horizon at radiation-dominant era. Those little wiggles are due to the well-known baryon acoustic oscillation.

Results

$$\begin{aligned}\Omega_b h^2 &= 0.02227, \Omega_c h^2 = 0.1184, 100\theta_{\text{MC}} = 1.04106, \\ \tau &= 0.067, \ln(10^{10} A_s) = 3.064, n_s = 0.9681,\end{aligned}\tag{21}$$

and treat neutrino mass the same way as Planck did with $\sum m_\nu = 0.06\text{eV}$, which gives $\sigma_8 = 0.815$ in vanilla ΛCDM cosmology. Together with the same inputs as above, we take $\delta N_{\text{eff}} \simeq 0.5$, $m_\chi \simeq 10\text{TeV}$ and $g_X^2 \simeq 10^{-7}$ in the interacting DM-DR case, we have $\sigma_8 \simeq 0.746$ which is much closer to the value $\sigma_8 \simeq 0.730$ given by weak lensing survey CFHTLenS [12].

- Within DM models with local dark SU(3) broken into SU(2), DM, DR and their interactions have common origin!
- And we could increase N_{eff} , H_0 whereas making σ_8 decrease, thereby relaxing the tension between H_0 and σ_8

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

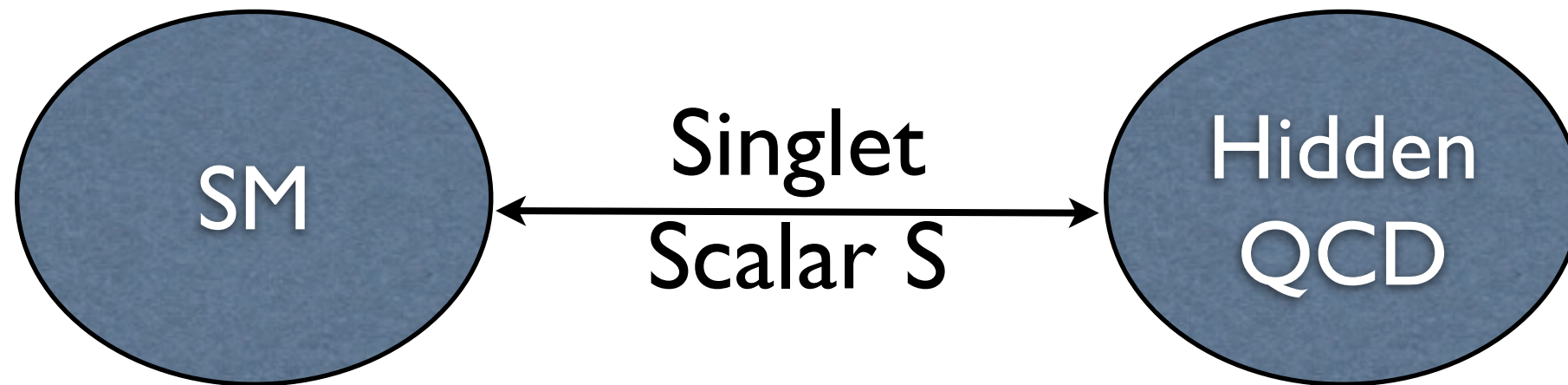
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations :
accidental symmetries of QCD (pion is
stable if we switch off EW interaction;
proton is stable or very long lived)

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

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



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

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

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

Hidden sector lagrangian with new strong interaction

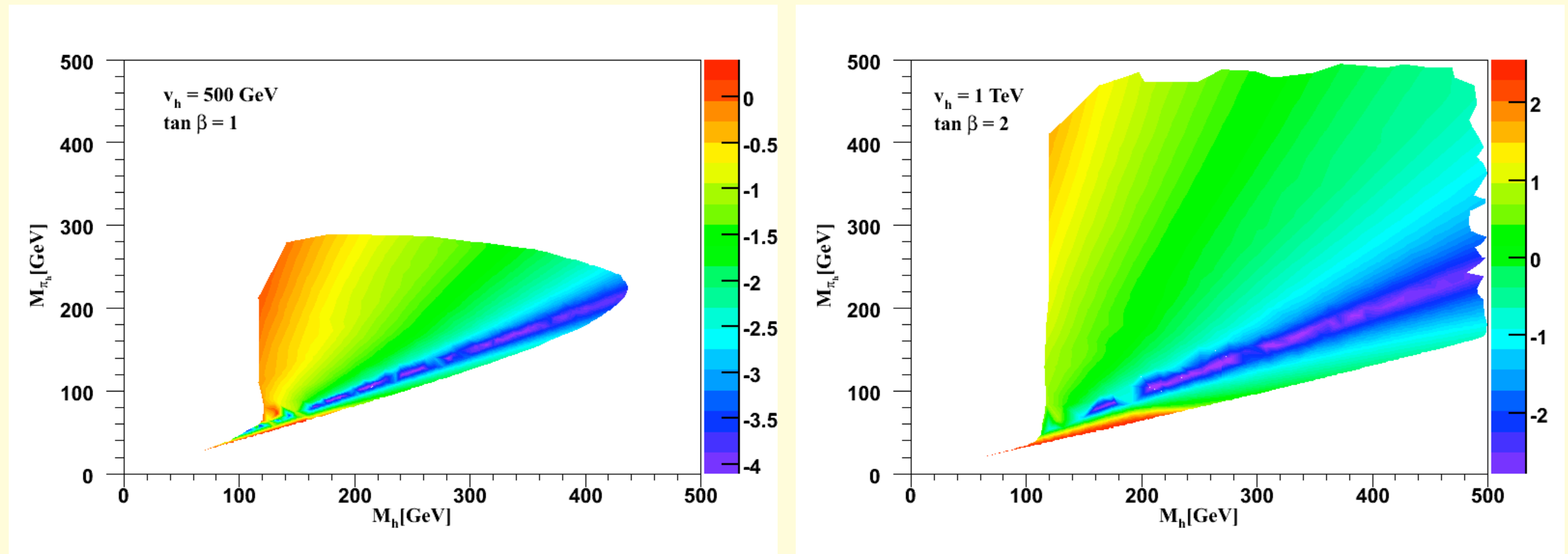
$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4} \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \bar{\mathcal{Q}}_k (i \mathcal{D} \cdot \gamma - \lambda_k S) \mathcal{Q}_k$$

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

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

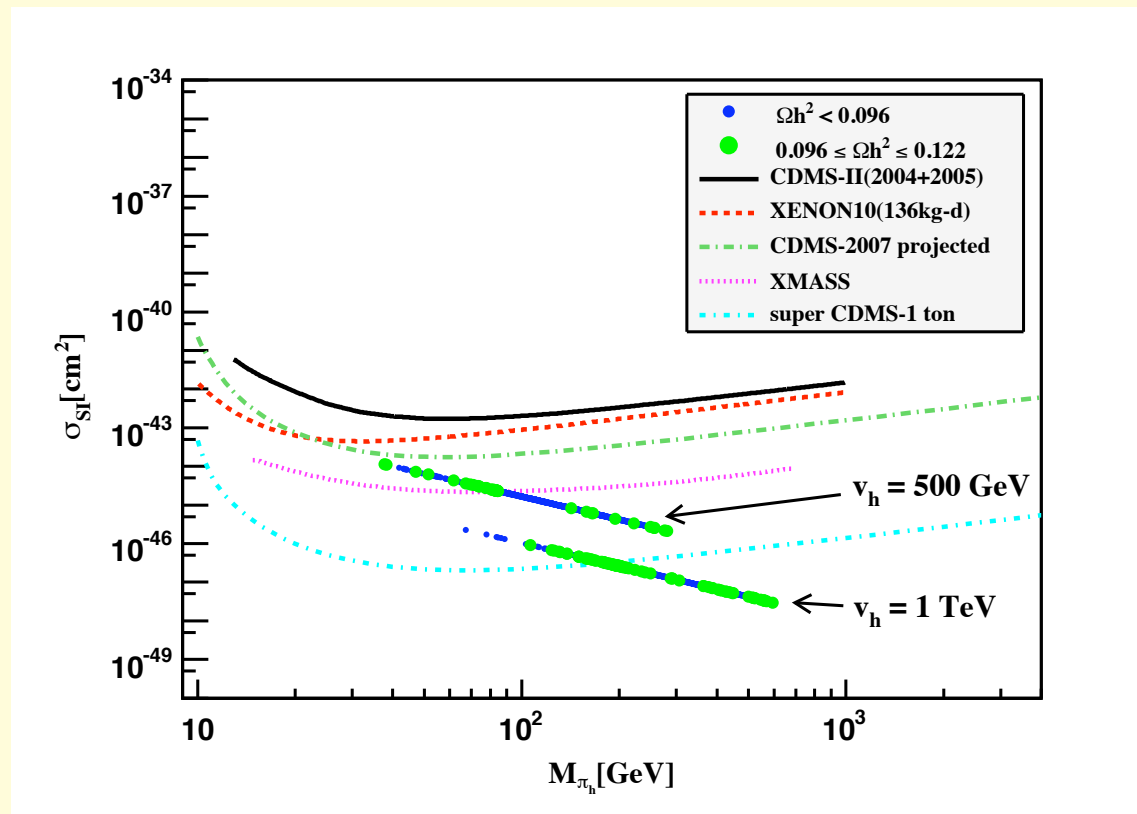
$$\begin{aligned}
 \mathcal{L}_{\text{full}} &= \mathcal{L}_{\text{hidden}}^{\text{eff}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mixing}} \\
 \mathcal{L}_{\text{hidden}}^{\text{eff}} &= \frac{v_h^2}{4} \text{Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2} \text{Tr}[\lambda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

Relic density



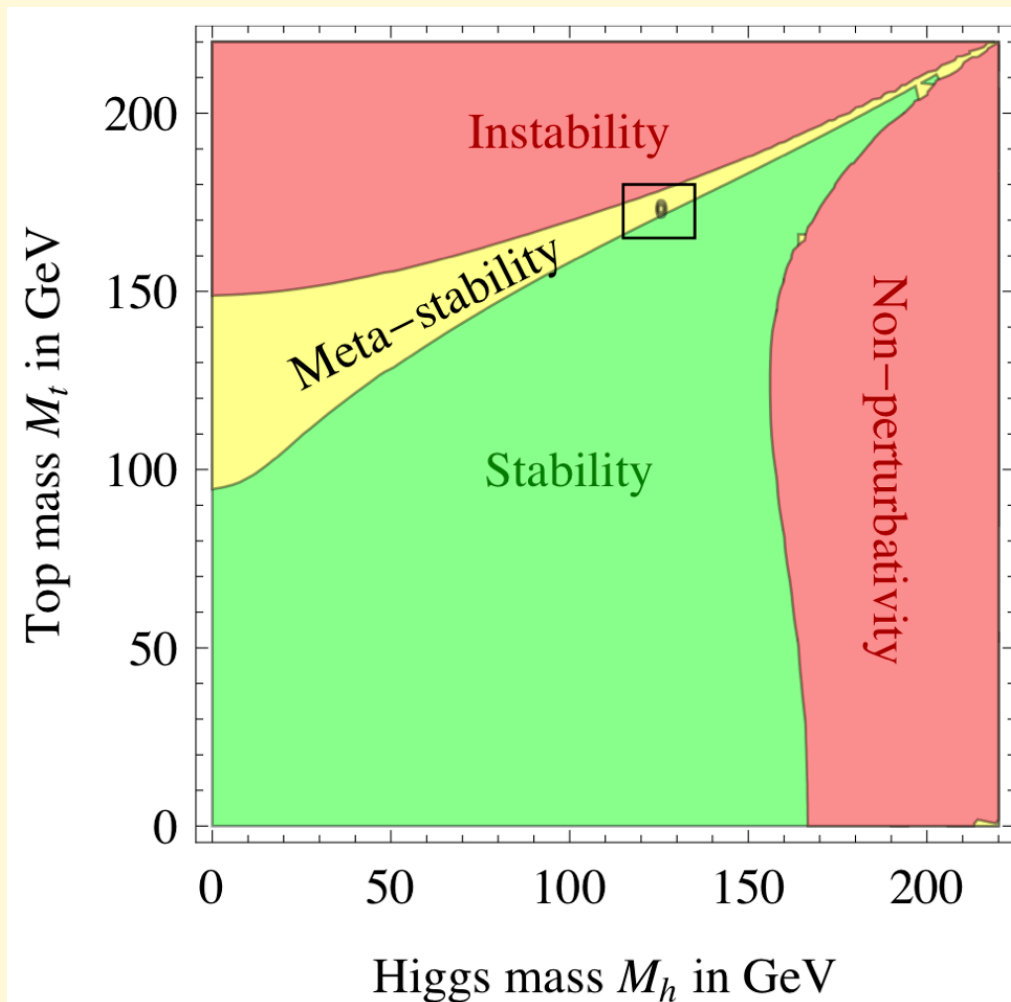
$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for
(a) $v_h = 500$ GeV and $\tan \beta = 1$,
(b) $v_h = 1$ TeV and $\tan \beta = 2$.

Direct Detection Rate

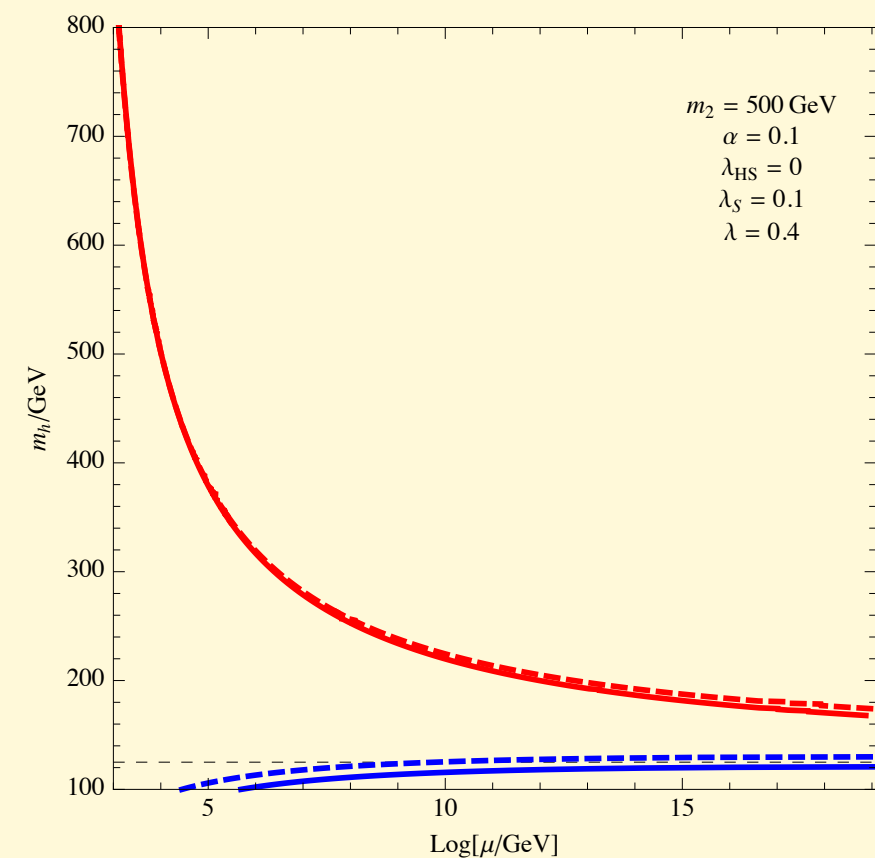


$\sigma_{SI}(\pi_h p \rightarrow \pi_h p)$ as functions of m_{π_h} .
 the upper one: $v_h = 500$ GeV and $\tan \beta = 1$,
 the lower one: $v_h = 1$ TeV and $\tan \beta = 2$.

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

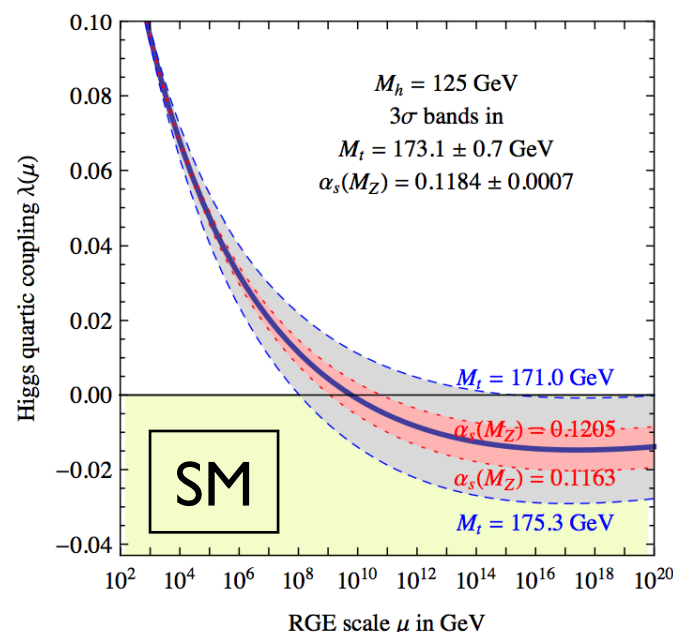
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

- If “ $m_h > 2 m_\phi$ ”, non-SM Higgs decay!

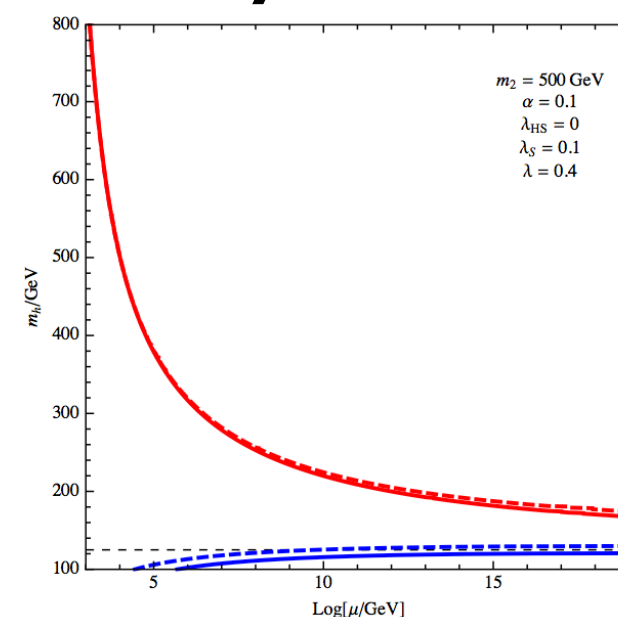
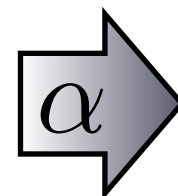
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

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

➔ If “ $m_\phi > m_h$ ”, vacuum instability can be cured.



[G. Degrandi et al., 1205.6497]



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

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is long-lived because of accidental flavor symmetry), 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 $\gg$ self-interacting DM $\gg$ can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations
- Wess-Zumino term: 3 $>$ 2 possible (e.g. Hochberg, Kuflik, Murayam, Volansky, Wacker for $Sp(N)$ case)
- Another approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach; and AdS/QCD approach with H. Hatanaka, D.W. Jung@KIAS)

SIMP Scenario in Dark QCD

SIMP paradigm

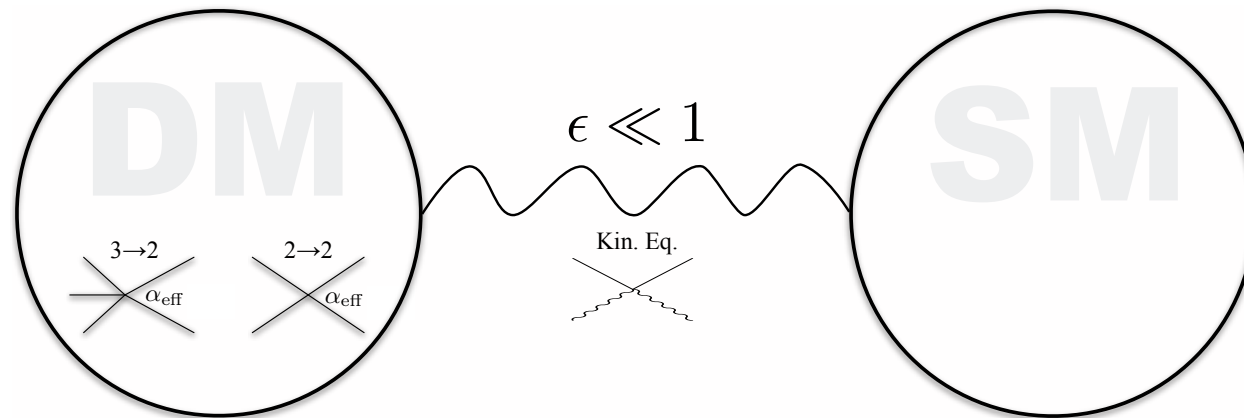


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \rightarrow 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions are naturally predicted to explain small scale structure anomalies while the couplings to the visible sector predict measurable consequences.

**Hochberg, Kuflik, Tolansky, Wacker, arXiv:1402.5143
Phys. Rev. Lett. 113, 171301 (2014)**

SIMP Conditions

Freeze-out :

$$\Gamma_{3 \rightarrow 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3 \rightarrow 2} \sim H(T_F)$$
$$\langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{\alpha_{\text{eff}}^3}{m_{DM}^5}$$

$$\alpha_{\text{eff}} = 1 - 30 \rightarrow m_{DM} \sim 10\text{MeV} - 1\text{GeV}$$

2->2 Self scattering :

$$\frac{\sigma_{\text{scatter}}}{m_{DM}} = \frac{a^2 \alpha_{\text{eff}}^2}{m_{DM}^3}$$

with $a \sim O(1)$

$$\frac{\sigma_{\text{scatter}}}{m_{DM}} \lesssim 1 \text{ cm}^2/\text{g}$$

Dark QCD + WZW

- Dark flavor symmetry $G = \text{SU}(N_f)_L \times \text{SU}(N_f)_R$ is SSB into diagonal $H = \text{SU}(N_f)_V$ by dark QCD condensation
- Effective Lagrangian for NG bosons (dark pions) contain 5-point self interaction : WZW term for π^5 ($G/H = Z$ ($N_f > 2$))

$$\Gamma_{\text{WZ}} = C \int_{M^5} d^5x \text{Tr}(\alpha^5) \quad \text{with} \quad \alpha = dUU^\dagger.$$

$$U = e^{2i\pi/F}$$

$$C = -i \frac{N_c}{240\pi^2}$$

in the absence of external gauge fields

SIMP Dark Mesons

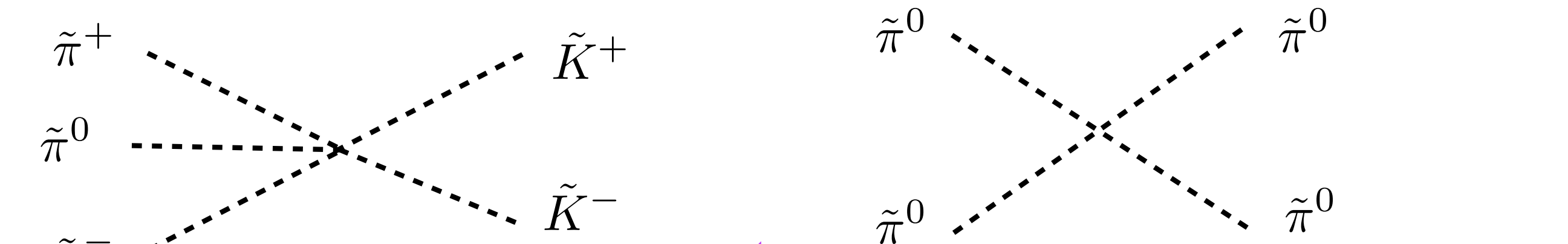


Diagram 1 (Left): 3-to-2 interaction. Incoming particles: $\tilde{\pi}^+$, $\tilde{\pi}^0$, $\tilde{\pi}^-$. Outgoing particles: $\tilde{K}^+$, $\tilde{K}^-$. The diagram shows a vertex where the three incoming lines meet and two outgoing lines emerge.

Diagram 2 (Right): Self-interaction. Incoming particles: $\tilde{\pi}^0$, $\tilde{\pi}^0$. Outgoing particles: $\tilde{\pi}^0$, $\tilde{\pi}^0$. The diagram shows a vertex where two incoming lines meet and two outgoing lines emerge.

Equation 1 (Left):

$$\langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{5\sqrt{5}N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi} \right)^2, \quad \sim \text{const}$$

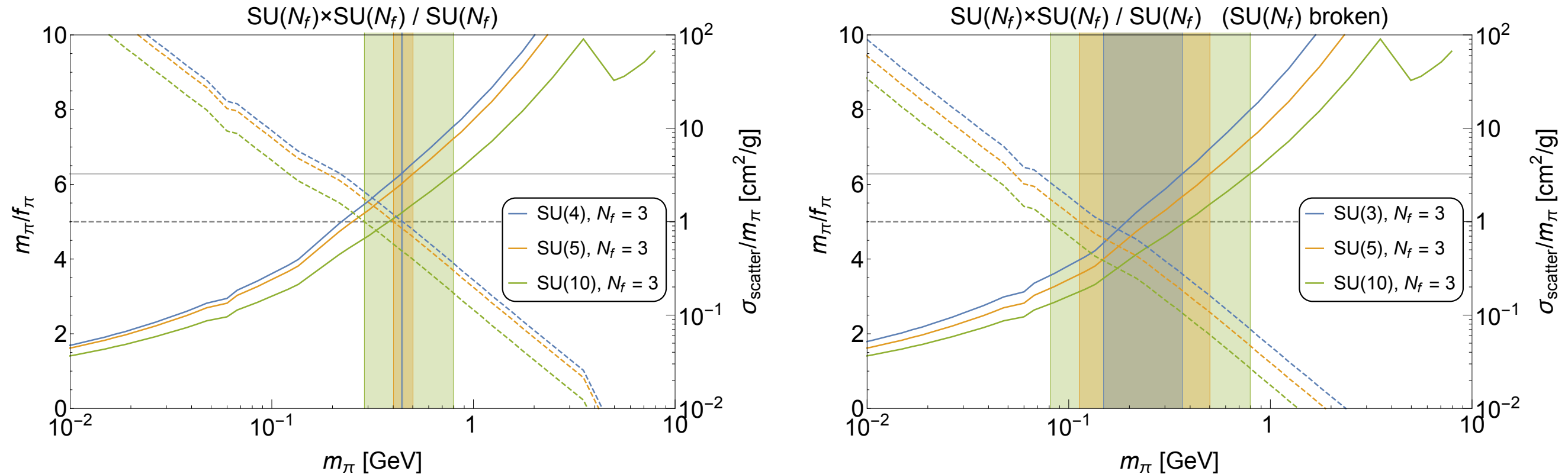
Equation 2 (Right):

$$\sigma_{\text{self}} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2}, \quad \sim \text{const}$$

G_c	G_f/H	N_π	t^2	$N_f^2 a^2$
$\text{SU}(N_c)$	$\frac{\text{SU}(N_f) \times \text{SU}(N_f)}{\text{SU}(N_f)}$ ($N_f \geq 3$)	$N_f^2 - 1$	$\frac{4}{3}N_f(N_f^2 - 1)(N_f^2 - 4)$	$8(N_f - 1)(N_f + 1)(3N_f^4 - 2N_f^2 + 6)$
$\text{SO}(N_c)$	$\text{SU}(N_f)/\text{SO}(N_f)$ ($N_f \geq 3$)	$\frac{1}{2}(N_f + 2)(N_f - 1)$	$\frac{1}{12}N_f(N_f^2 - 1)(N_f^2 - 4)$	$(N_f - 1)(N_f + 2)(3N_f^4 + 7N_f^3 - 2N_f^2 - 12N_f + 24)$
$\text{Sp}(N_c)$	$\text{SU}(2N_f)/\text{Sp}(2N_f)$ ($N_f \geq 2$)	$(2N_f + 1)(N_f - 1)$	$\frac{2}{3}N_f(N_f^2 - 1)(4N_f^2 - 1)$	$4(N_f - 1)(2N_f + 1)(6N_f^4 - 7N_f^3 - N_f^2 + 3N_f + 3)$

[Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL (2015)]

SIMP Parameter Space



Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL

- DM self scattering : $\sigma_{\text{self}}/m_{\text{DM}} < 1 \text{ cm}^2/\text{g}$ **Large $N_c > 3$**
- Validity of ChPT : $m_\pi/f_\pi < 2\pi$ **More serious in NNLO ChPT
Sannino et al, 1507.01590**

Issues in the SIMP w/ hQCD

- Dark flavor sym is not good enough to stabilize dark pion (We have to assume dim-5 operator is highly suppressed)
- Dark baryons can make additional contribution to DM of the universe (It could produce additional diagrams for SIMP)
- Validity region of ChPT : need to include resonances (dark rho meson, dark sigma meson, etc.)
- How to achieve Kinetic equilibrium with the SM ? (Dark sigma meson or adding singlet scalar S may help. Or lifting the mass degeneracy of dark pions can help.)

SIMP + VDM

With Soo Min Choi, Hyun Min Lee, Alexander Natale,
arXiv:1801.07726, PRD (2018)

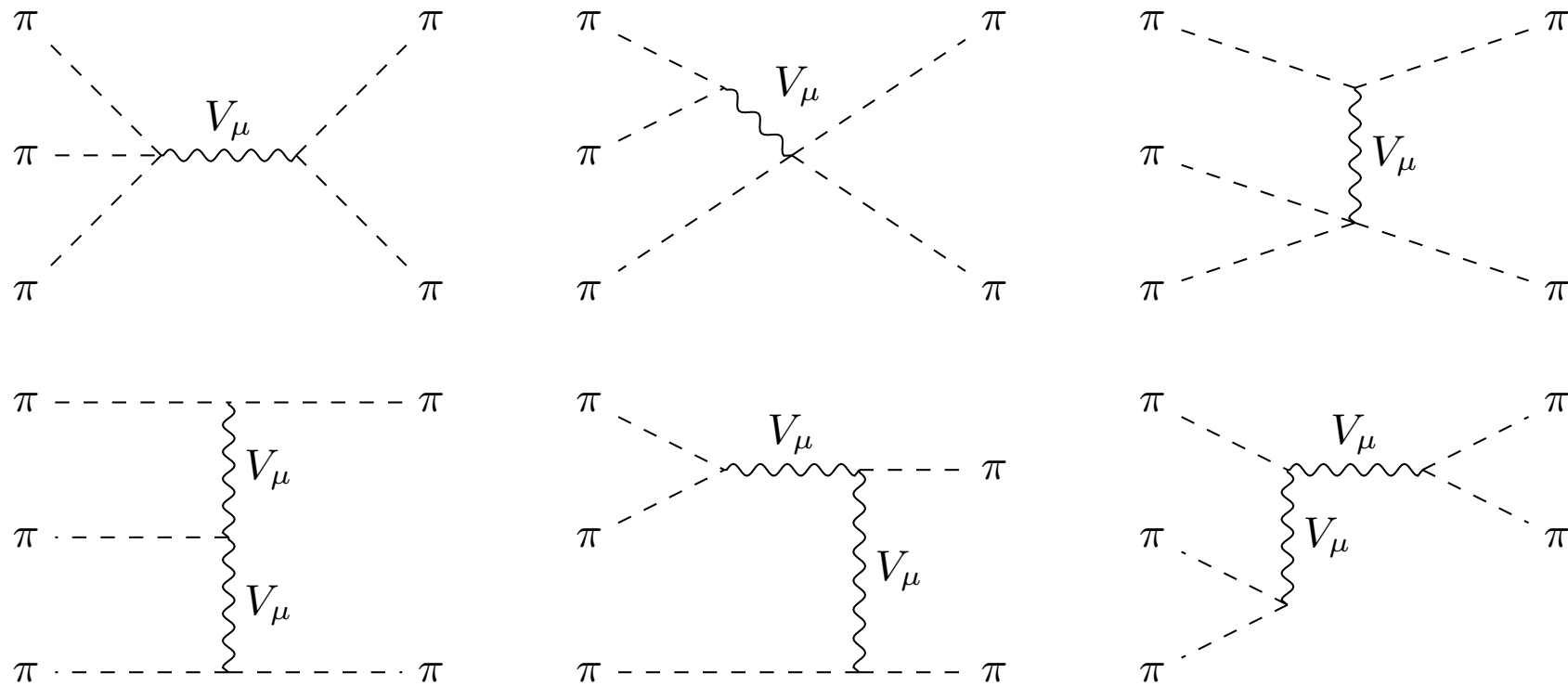


FIG. 1: Feynman diagrams contributing to $3 \rightarrow 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involving dark vector mesons

$$\pi^+ \pi^- \pi^0 \rightarrow \omega \rightarrow K^+ K^- (K^0 \bar{K}^0)$$

$$\gamma = \frac{m_V \Gamma}{9m_\pi^2}, \text{ and } \epsilon = \frac{m_V^2 - 9m_\pi^2}{9m_\pi^2} \text{ (for 3 pi resonance case)}$$

**We choose a small epsilon [say, 0.1 (near resonance)]
and a small gamma (NWA)**

Results

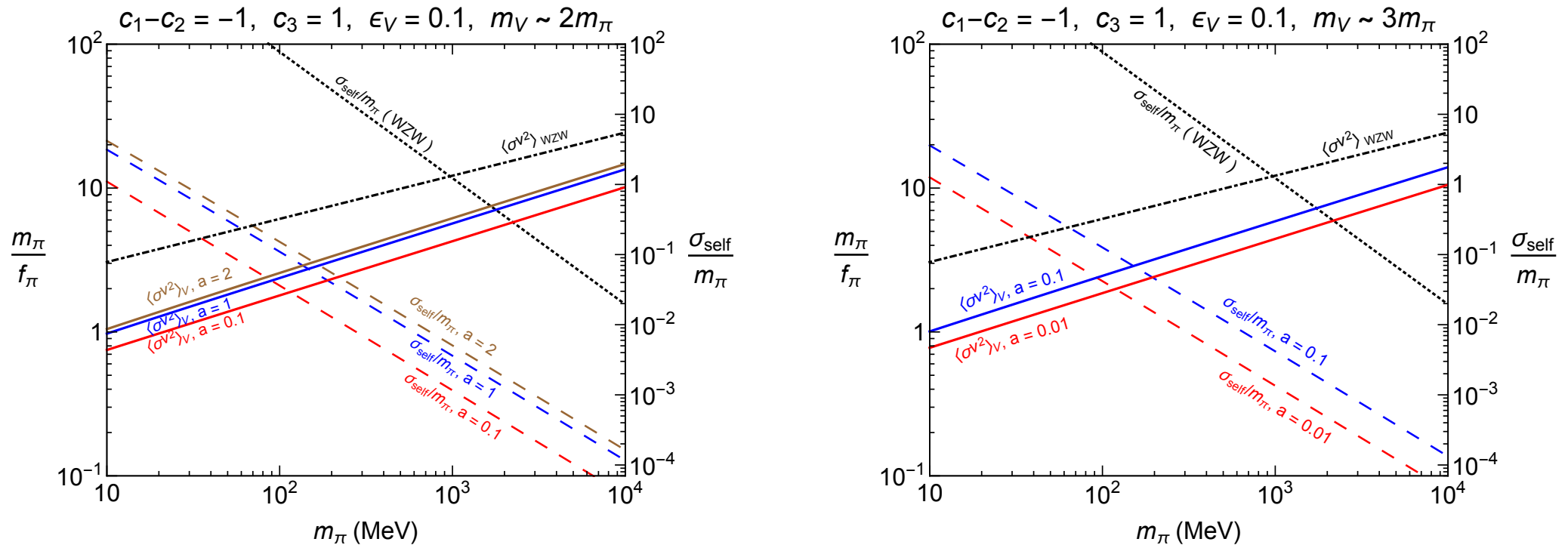


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π . The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition for obtaining the contours of self-scattering cross section. Vector meson masses are taken near the resonances with $m_V = 2(3)m_\pi\sqrt{1 + \epsilon_V}$ on left(right) plots. In both plots, $c_1 - c_2 = -1$ and $\epsilon_V = 0.1$ are taken.

- The allowed parameter space is in a better shape now, especially for 2 pi resonance case

Conclusion

- Hidden (dark) QCD models make an interesting possibility to study the origin of EWSB, (C)DM
- WIMP scenario is still viable, and will be tested to some extent by precise measurements of the Higgs signal strength and by discovery of the singlet scalar, which is however a formidable task unless we are very lucky
- SIMP scenario using $3 \rightarrow 2$ scattering via WZW term is interesting, but there are a few issues which ask for further study (dark resonance could play an important role for thermal relic and kinetic contact with the SM sector)

Simple two-comp DM models free from DD constraints: (Interplay between Higgs Inflation and DM)

- Jinsu Kim, Sarif Khan, PK, arXiv:2309.07839

Basics

- Higgs-portal Assisted Higgs Inflation: 2 scalars, H , ϕ
- Dark Higgs contributes to λ_H (positive contribution)
- Nonminimal couplings: $\xi_h H^\dagger H + \xi_\phi \Phi^\dagger \Phi$
- Generalized Higgs Inflation with two scalar fields and R^2 (Starobinsky)
- No more tight correlation with top quark mass

Model

- SM + Dark sector with $U(1)_D$ charges : $\psi(n_\psi)$, $\phi_D(1)$, and dark photon W_D ($1 \leq n_\psi \leq 100$, $M_{W_D} < M_\psi$)
- Adding dark fermion to the Higgs portal VDM model
- DM candidates: W_D , ψ (assume kinetic mixing = 0)
- Dark photon mass given by dark Higgs mechanism, and new channels for dark photon pair annihilations into a pair of (dark) Higgs boson. [In Stueckelberg, no dark Higgs and the model is not viable, since DM is overproduced.]

Model Lagrangian

$$\mathcal{L} = \mathcal{L}_{\overline{\text{SM}}} + \bar{\psi} (i\gamma^\mu D_\mu - M_\psi) \psi - |D\phi_D|^2 - |DH|^2 - V(\phi_D, H)$$

Gauge Group	Baryon Fields			Lepton Fields		Scalar Field
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	H
SU(2) _L	2	1	1	2	1	2
U(1) _Y	1/6	2/3	-1/3	-1/2	-1	1/2

Table 1. SM particle contents and their corresponding charges under the SM gauge groups.

Gauge Group	Fermionic Fields	Scalar Field
	ψ	ϕ_D
$U(1)_D$	n_ψ	1

Table 2. Dark particle contents and their corresponding charges under the additional Abelian $U(1)_D$ gauge group. They are all SM singlets.

Feynman Diagrams

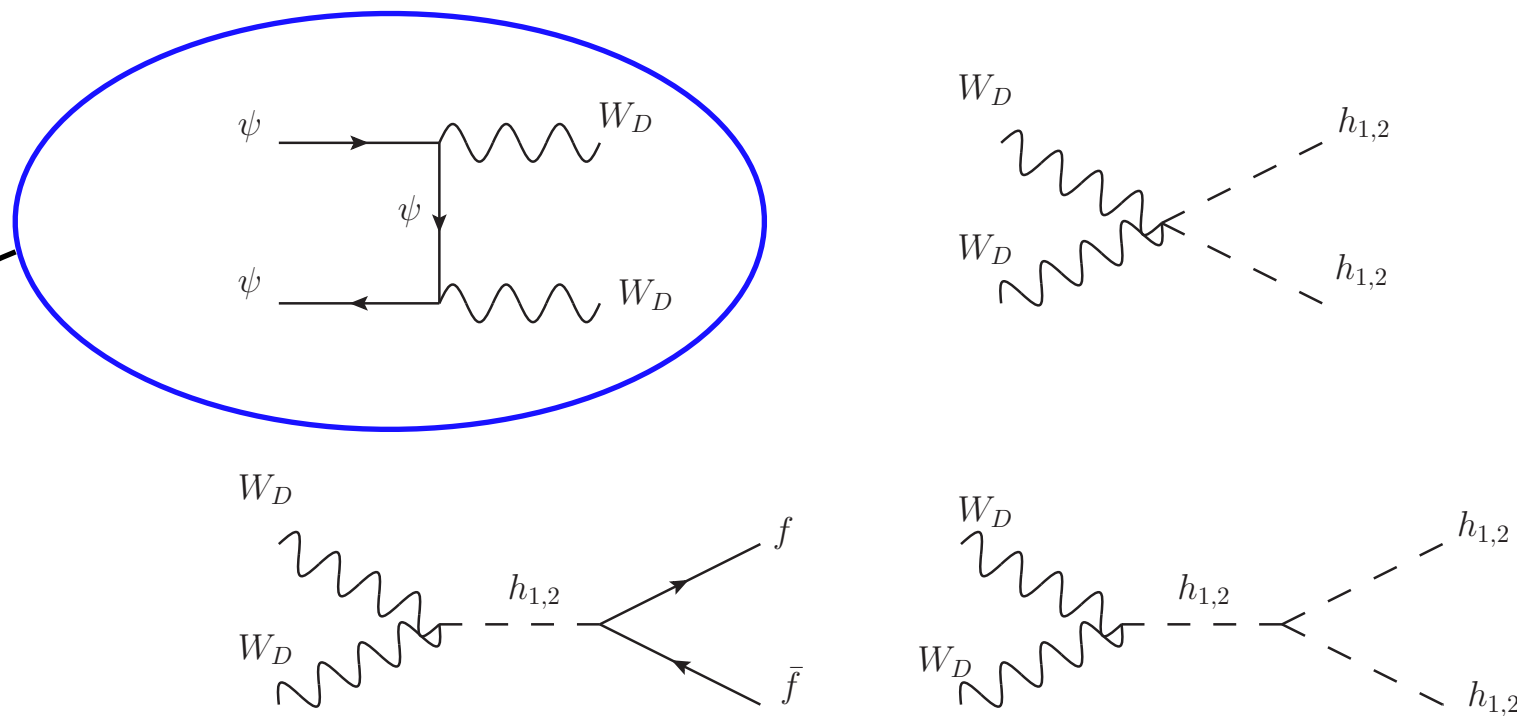


Figure 1. Feynman diagrams relevant for our dark matter analysis.

- We consider $M_{W_D} < M_\psi$. Otherwise ψ DM overproduced because there is no annihilation channels
- Only diagram for ψ DM pair annihilation
- W_D thermalized through **dark Higgs bosons**

(In)Direct Detections

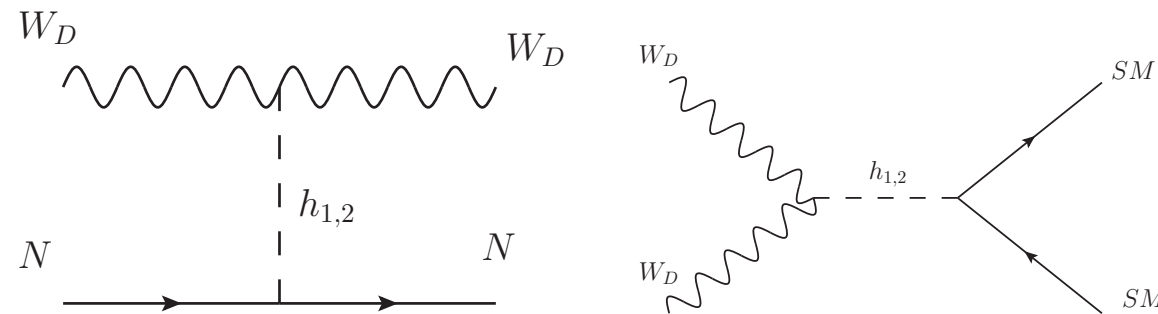
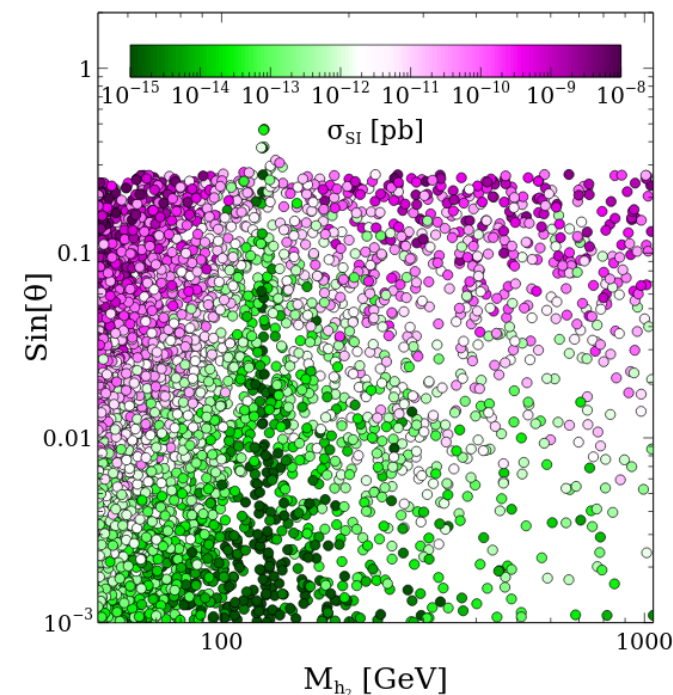
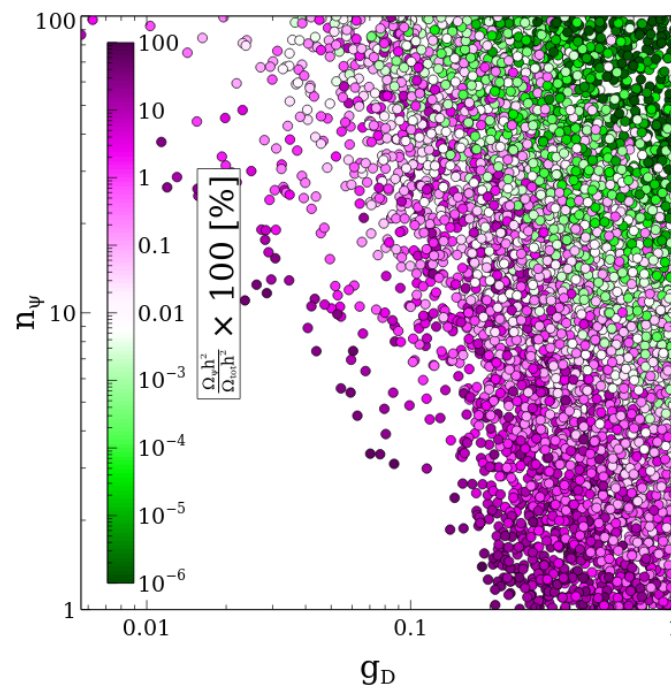


Figure 2. Relevant Feynman diagrams for the direct detection (left) and indirect detection (right) prospects.

- ψ DM : Not sensitive to direct detection experiments
- (In)direct detection signals : controlled by (dark) Higgs
- Cancellation mechanism for direct detection of W_D DM (Ko et al, 2012, etc): $\sigma_{\text{SI}} \propto (1/m_{H_1}^2 - 1/m_{H_2}^2)^2$

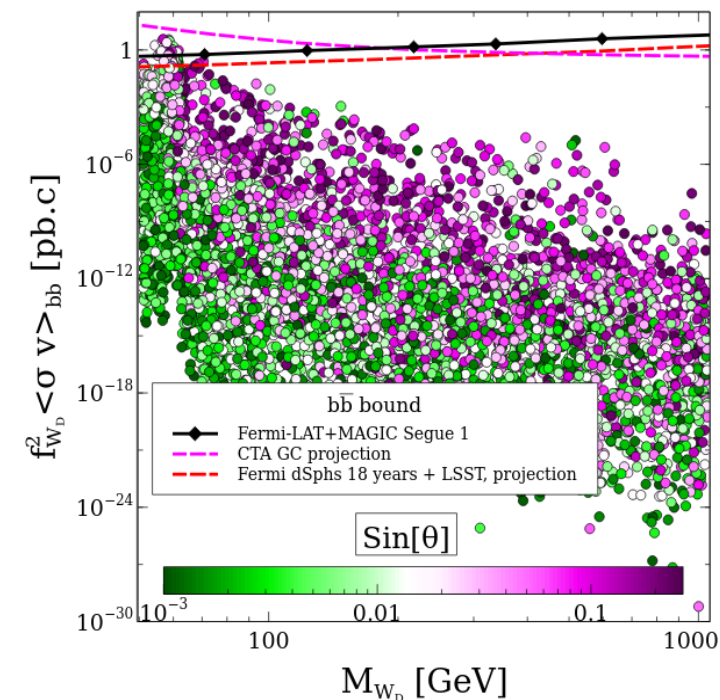
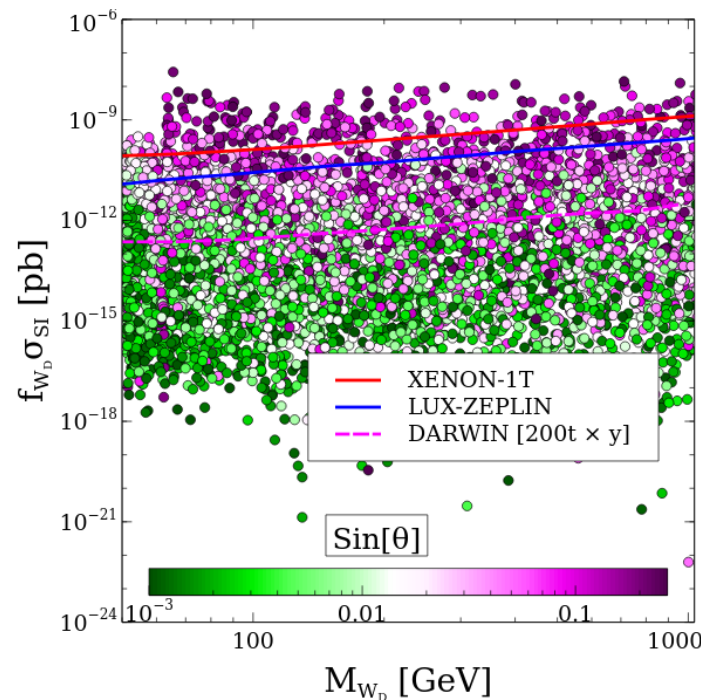
Allowed Ranges

$$50 \leq M_{h_2} [\text{GeV}] \leq 1050, \quad 50 \leq M_{W_D} [\text{GeV}] \leq 1050, \quad 1 \leq (M_\psi - M_{W_D}) [\text{GeV}] \leq 100, \\ 10^{-3} \leq g_D \leq 1, \quad 10^{-3} \leq \sin \theta \leq 0.5, \quad 1 \leq n_\psi \leq 100. \quad (3.7)$$



- Anti—correlation between n_ψ & g_D
- Cancellation between two Higgs boson in σ_{SI}

Detection Prospects



$$f_{W_D} \equiv \Omega_{W_D} / \Omega_{\text{DM}}$$

- Detection strength is suppressed by f_{W_D} (fraction of W_D)
- Although DM is WIMP type, a large portion of parameter space will be accessed in the future

Summary

- Minimal model for weak scale DM : DM + Dark gauge symmetry $\rightarrow$ dark photon, dark Higgs, DR
- The only relevant pheno questions: particle contents, mass scales of these particles and coupling strengths
- Then one can interpret (in)direct DM detection, DM@colliders, and cosmological effects in a consistent way. Otherwise one can have wrong/misleading results
- Sometimes it is crucial to consider both particle physics and cosmological data simultaneously

Impact of dark Higgs -Cosmology

(Higgs-portal assisted Higgs inflation)

[arXiv: 1405.1635, Jinsu Kim, P. Ko, Wan-Il Park]

[arXiv:2309.07839, 2511.04933, Jinsu Kim, Sarif Khan, P. Ko]

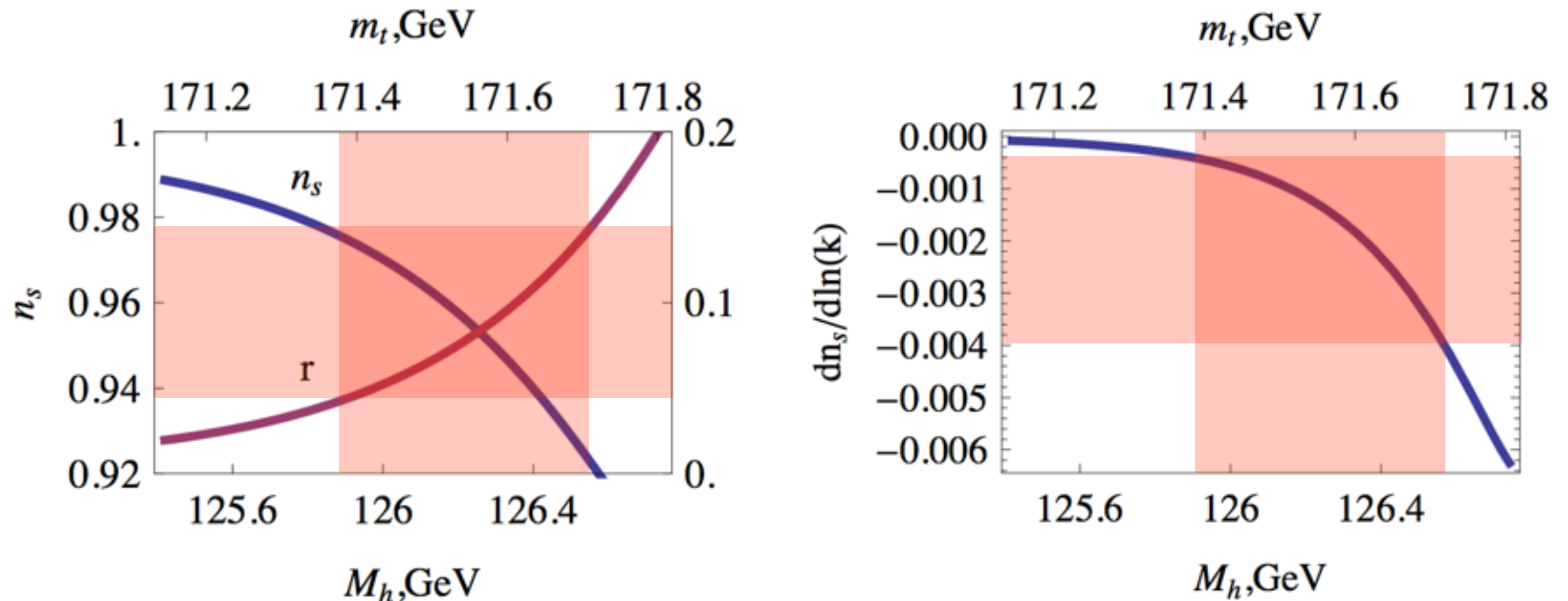
See arXiv:1609.00297, 1802.02947,
for strong 1st order PT and GW productions

- * Higgs inflation in SM may not be possible at the first place.

- * However SM seems to be extended somehow.

- * Higgs portal with dark Higgs saves Higgs inflation

- Prediction of SM Higgs inflation



$$\frac{dn_s}{d\ln k} \sim 10^{-3}$$

Consistence with the MC top mass ?

Higgs portal interaction

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

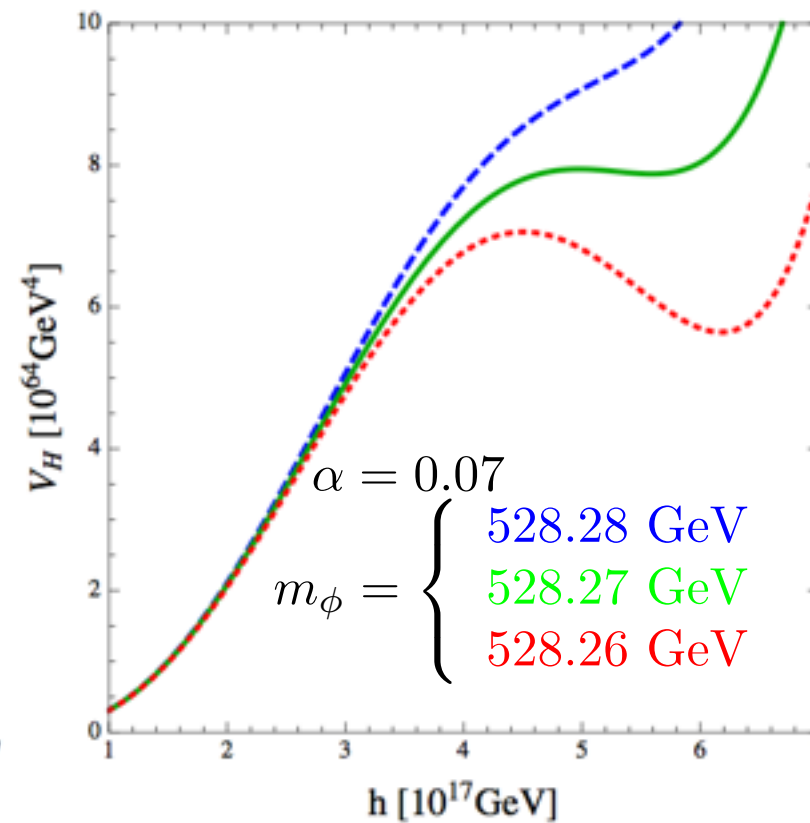
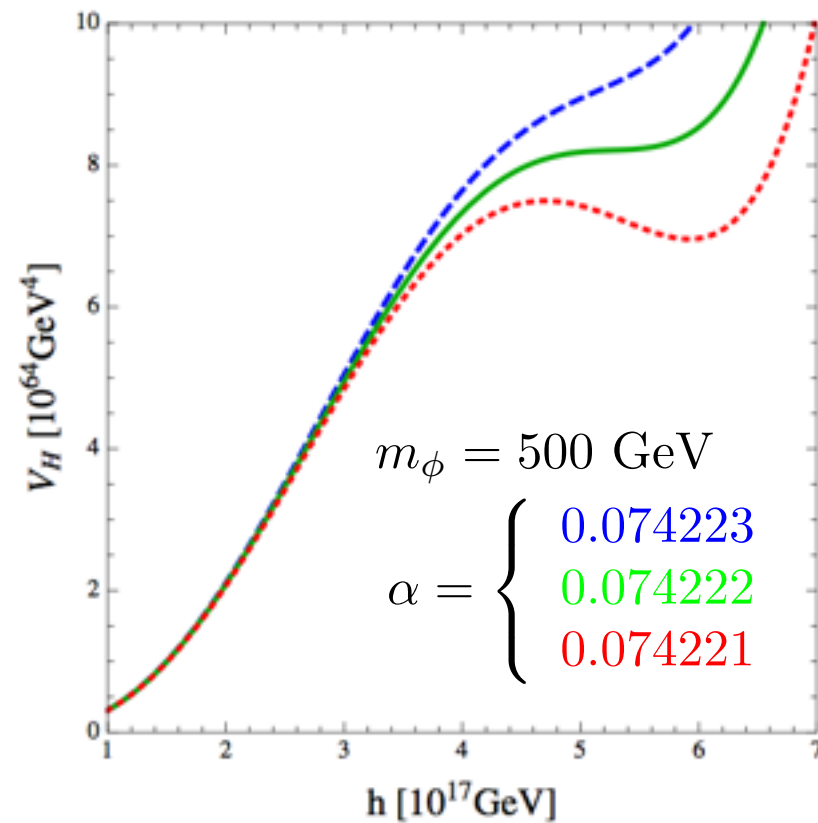
⇒ $\lambda_H > \lambda_H^{\text{SM}}$ for $m_\phi > m_h$ & $\alpha \neq 0$

⇒ Vacuum instability is easily removed.

⇒ Higgs inflation becomes possible for a wide range of m_t and M_h

Higgs portal interaction disconnect m_t and M_h from inflationary observables.

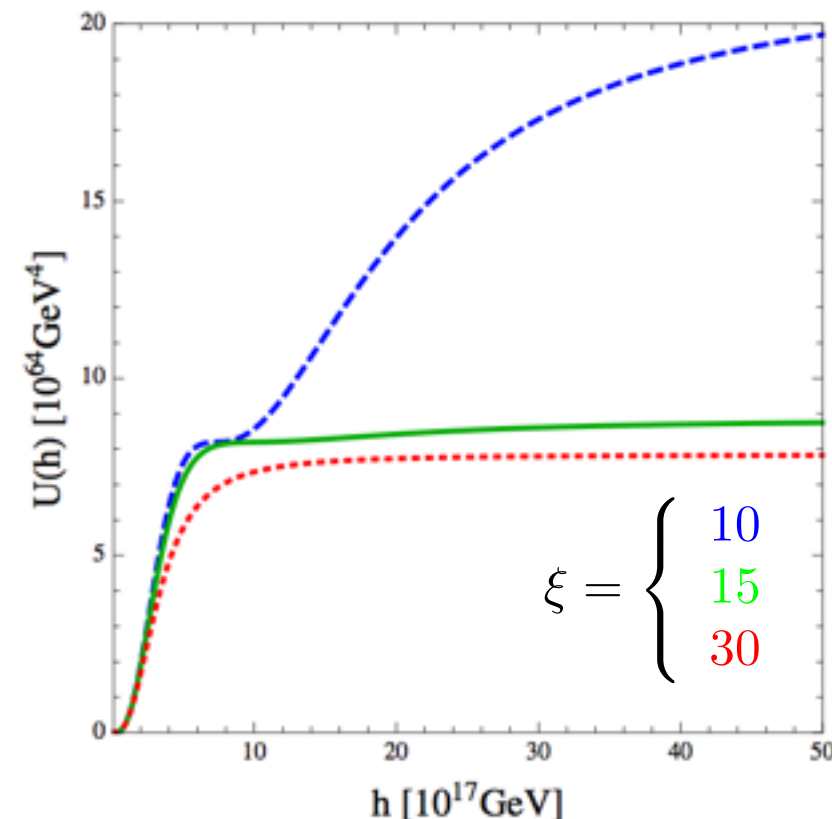
Higgs-portal Higgs inflation



$$m_t = 173.2 \text{ GeV}$$

$$M_h = 125.5 \text{ GeV}$$

* Inflection point control
 (α, m_ϕ) & $\lambda_{\Phi H}$



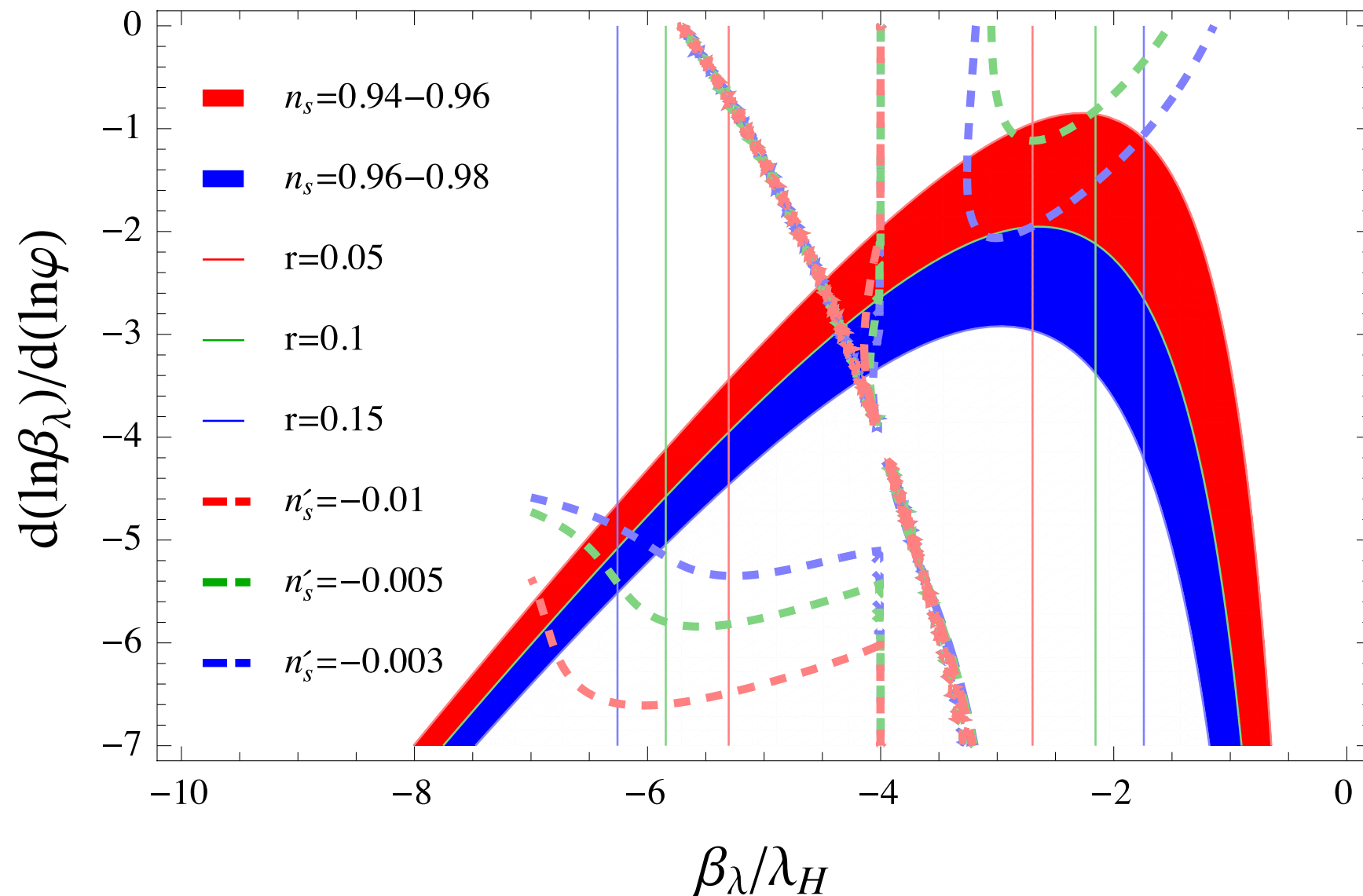
Result of numerical analysis

$k_* \times \text{Mpc}$	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 $\lambda_{\Phi H}$ -

Scale dependence!

Higgs portal assisted HI



possible to have $r \sim \mathcal{O}(0.1)$ with small spectral running independent of top mass

Conclusions

- SM is based on local gauge principles, and all the global symmetries are accidental!
- We can assume the same in dark matter physics: DM stability or longevity due to local dark gauge symmetry or accidental global dark symmetry derived from the underlying local dark gauge symmetry
- Massive dark photon from dark Higgs mechanism
- Dark Higgs boson Naturally appears!

- It improves the **SM stability** up to Planck scale
- It improves **unitarity** of the DM models
- It opens new channels for DM pair annihilations into P-wave, thereby relaxing the CMB constraints on light WIMP ($< \sim 10$ GeV) scenarios
- It can solve many puzzles in simple ways: GC γ -ray excess, 511 keV γ -ray, (in)finite $H \rightarrow VV$ decay width in the Higgs portal VDM model, etc.
- Two-component WIMP scenario is viable due to $Z'Z' \rightarrow \phi(\phi) \rightarrow \text{SM}$
- It modifies the Higgs inflation and phase transitions in early universe
- Should be actively sought for at terrestrial particle physics expt's

- Minimal model for weak scale DM : DM + Dark gauge symmetry $\rightarrow$ dark photon, dark Higgs, DR, H_0 , σ_8 etc.
- The only relevant pheno questions: particle contents, mass scales of these particles and coupling strengths
- Then one can interpret (in)direct DM detection, DM@colliders, and cosmological effects in a consistent way. Otherwise one can have wrong/misleading results
- Sometimes it is crucial to consider both particle physics and cosmological data simultaneously