

Strongly interacting dark sector with dark pion DM: WIMP vs. SIMP

Pyungwon Ko (KIAS)

**NCTS Annual Theory Meeting 2019
Hsinchu, Taiwan, Dec 12-14 (2019)**

Contents

- Introduction
- Hidden (Dark) QCD scenario
- WIMP scenario with the S-H portal
- SIMP scenario in dark QCD
- SIMP + dark resonances (vector, scalar, etc.)

Introduction

Current Status of SM

- Only Higgs (\sim SM) and Nothing Else So far at the LHC
- Nature is described by Quantum Local Gauge Theories
- All the observed particles carry some gauge charges (no gauge singlets observed so far)
- Only fundamental rep's of matter have been observed
- Unitarity and gauge invariance played key roles in development of the SM

Motivations for BSM

- Neutrino masses and mixings

Leptogenesis

- Baryogenesis

- Inflation (inflaton)

Starobinsky

?

Higgs Inflation

- Nonbaryonic DM

Many candidates

- Origin of EWSB and Cosmological Const ?

Can we attack these problems ?

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 ?

- 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
- Important to implement this properly in QFT which is supposed to a framework to describe DM properties (including its interactions)

- Also, very often extra particles (the so-called mediators, scalar, vector etc) are introduced to solve three puzzles in CDM paradigm in terms of DM self-interaction
- DR and its interaction with DM may help to relax the tension between H_0 and σ_8
- Phenomenologically nice, but theoretically rather ad hoc
- Good organizing principle : dark gauge sym

SM vs. DM Physics

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries (they are accidental)
- Electron stability : $U(1)_{\text{em}}$ gauge invariance, electric charge conservation and massless photon
- Proton longevity : baryon # is an accidental sym of the SM, broken by dim-6 operator
- 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
- “Dark gauge theories without any ad hoc global sym”
- Origin of DM stability/longevity : unbroken dark gauge sym and/or resulting accidental global sym as in the SM, and not from ad hoc global symmetries
- Just like the SM (conservative)

Local Dark Gauge Sym

- Well tested principle in the SM
- Completely fix the dynamics of DM, SM
- Guarantees stability/longevity of DM (global symmetry broken by gravity) even in the presence of nonrenormalizable operators
- Force mediators already present in a gauge invariant way (Only issue is the mass scales and coupling strengths)
- Predictable amount of dark radiation, and DM-DR interactions affects H_0 and σ_8

NB: The first 3 points are also true in the minimal DM scenarios
(No new gauge sym, just SM gauge symmetries)

Theory Consistency can be very important for phenomenology

- Existence of positron vs. electron self energy in classical E&M and QED : compatibility between relativity and causality
- Quadratic divergence in the ΔM_K and too excessive FCNC problem in K decays were cured by charm (GIM) : anomaly free chiral gauge theory
- New chiral gauge interaction \rightarrow need to introduce extra Higgs doublets for realistic Yukawa interactions
- Important with working in theoretically & mathematically consistent theory (or models) for phenomenology

In QFT

- DM could be absolutely stable due to **unbroken local gauge symmetry** [DM with local Z_2, Z_3 etc. or continuous one (e.g. $SU(3)$ broken to $SU(2)$] or **topology** (hidden sector monopole + vector DM + dark radiation), OR
- DM could be long lived due to some **accidental symmetries** (hidden sector pions and baryons)
→ THIS TALK
- Exceptions : light DM (axion, sterile ν 's which are kinematically long lived), and gravitino

Key Ideas

- Stability/Longevity of Dark Matter (DM)
- Local Dark Gauge Symmetry
- Thermal DM through Singlet Portals (especially Higgs Portal)
- Connections between Higgs, DM and Higgs Inflation, especially the role of “Dark Higgs”
- Improved vacuum stability, Self Interacting DM, GC gamma ray excess, Higgs inflation, CMB and LSS, etc.

Hidden (Dark) QCD Scenario

hQCD (Dark QCD): WIMP & SIMP

- Strassler + Zurek (2006) : hQCD + $U(1)'$, new collider signatures but no discussion on DM from hQCD. hep-ph/0604261. PLB (2007)
- B. Patt and F. Wilczek, hep-ph/0605188. “Higgs portal”
- Hur, Ko, Jung, Lee (2007): EWSB and CDM from h-QCD, arXiv:0709.1218 [hep-ph], PLB (2011)
- Hur, Ko (2007) : scale inv. extension of SM+hQCD. All the mass scales (including DM mass) from hQCD, written in 2007, arXiv:1103.2571 [hep-ph] PRL(2011)
- Proceedings: Int.J.Mod.Phys. A23 (2008) 3348-3351, AIP Conf.Proc. 1178 (2009) 37-43, arXiv:1012.0103 (ICHEP), etc
- Many works on scale sym. models or dark QCD models during the past years (apology for not citing all of them)
- Hochberg et al. : SIMP in Dark QCD (2014, 2015)
- Hatanaka, Jung, Ko : AdS/QCD approach, arXiv:1606.02969, JHEP (2016)

Hidden Sector

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

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, ignoring dim-5 operators; proton is stable or very long lived)

$$\frac{1}{M_{\text{Planck}}} H^\dagger H \bar{q}_h \gamma_5 q_h$$

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 \gg 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

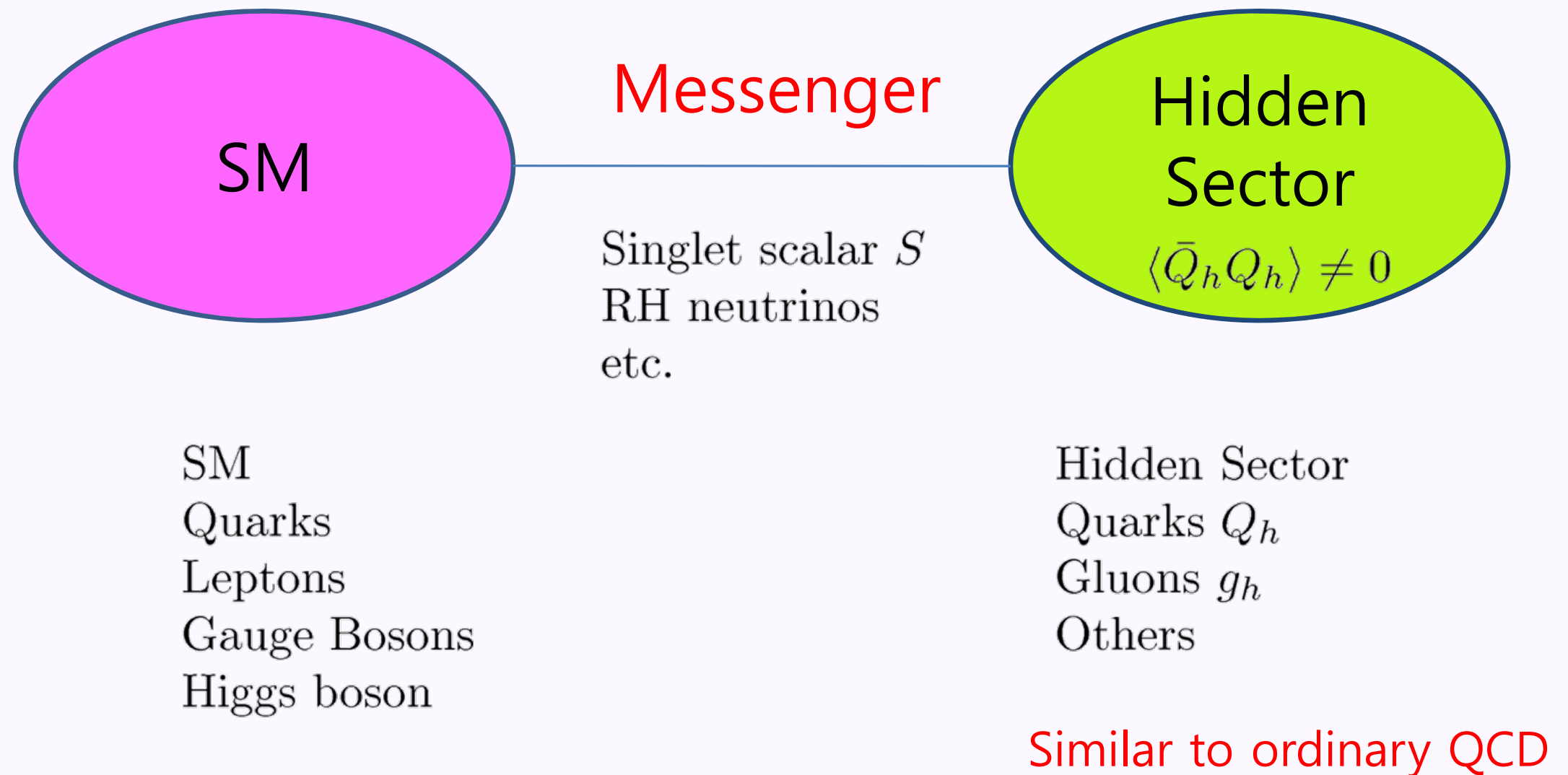
WIMP scenario with the Higgs-Singlet portal

- Hur, Jung, Ko, Lee, arXiv:0709.1218
- Hur, Ko, 1103.2571, PRL (2011)
- Hatanaka, Jung, Ko, 1606.02969, JHEP (2016)

And proceedings:

- Int. J. Mod. Phys. A23 (2008) 3348-3351
- AIP Conf. Proc. 1178 (2009) 37-43
- ICHEP 2010 Proceeding, hep-ph/1012.0103

Basic Picture



Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector \sim 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

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

● Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$

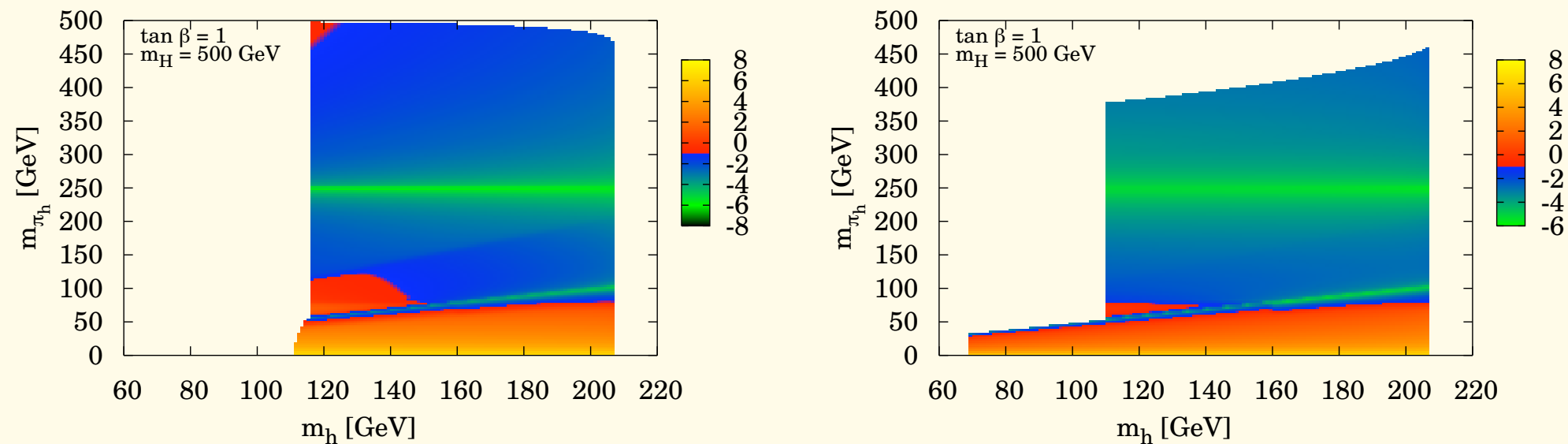
● Consider the following phase:

Not present in the two-Higgs Doublet model

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

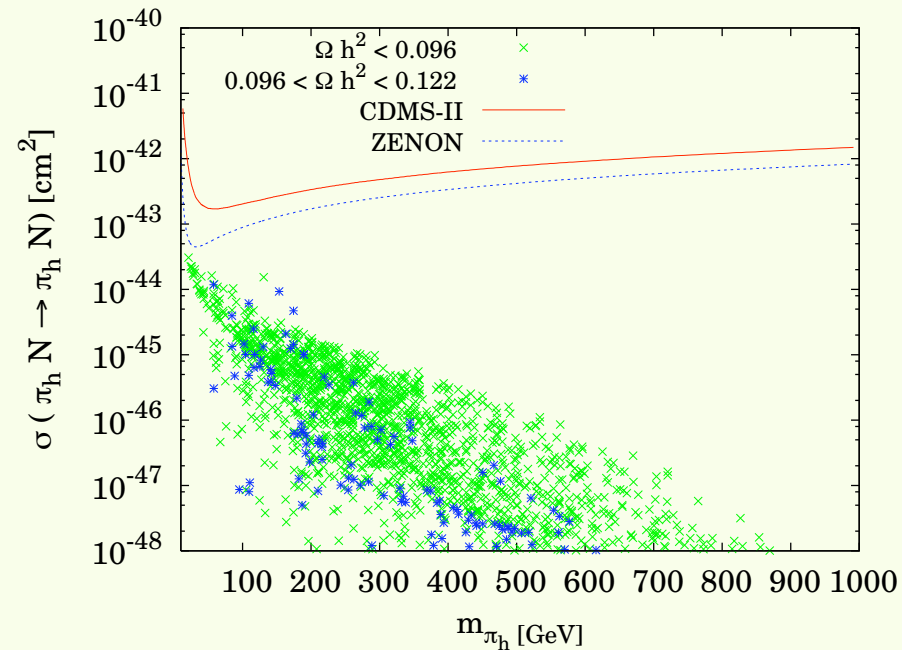
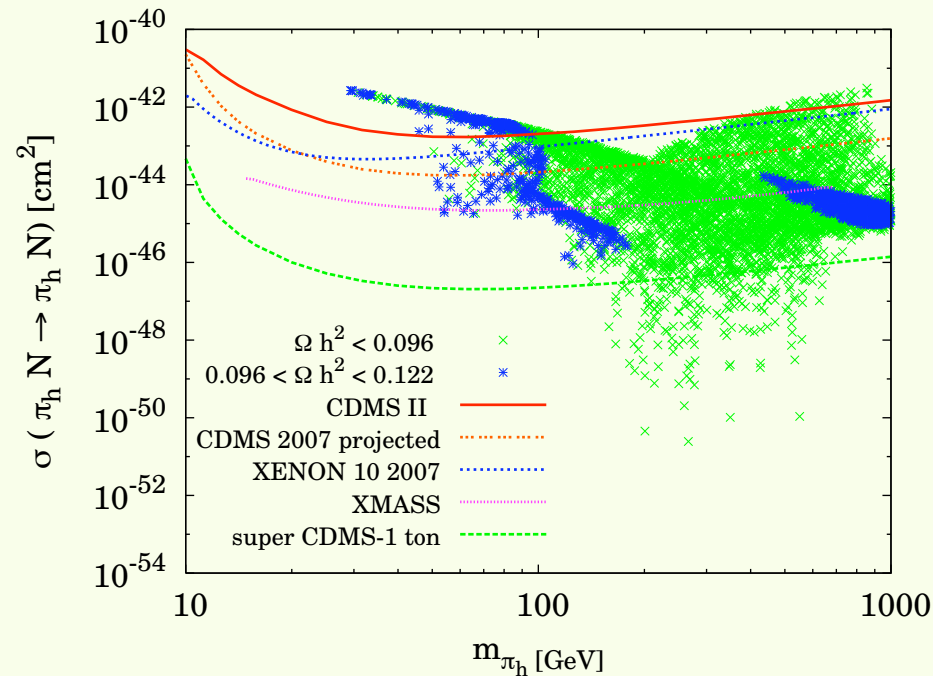
● Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1\lambda'_2 > \lambda_3^2$

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



- $\sigma_{SI}(\pi_h p \rightarrow \pi_h p)$ 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 also 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

Classical Scale Sym Model

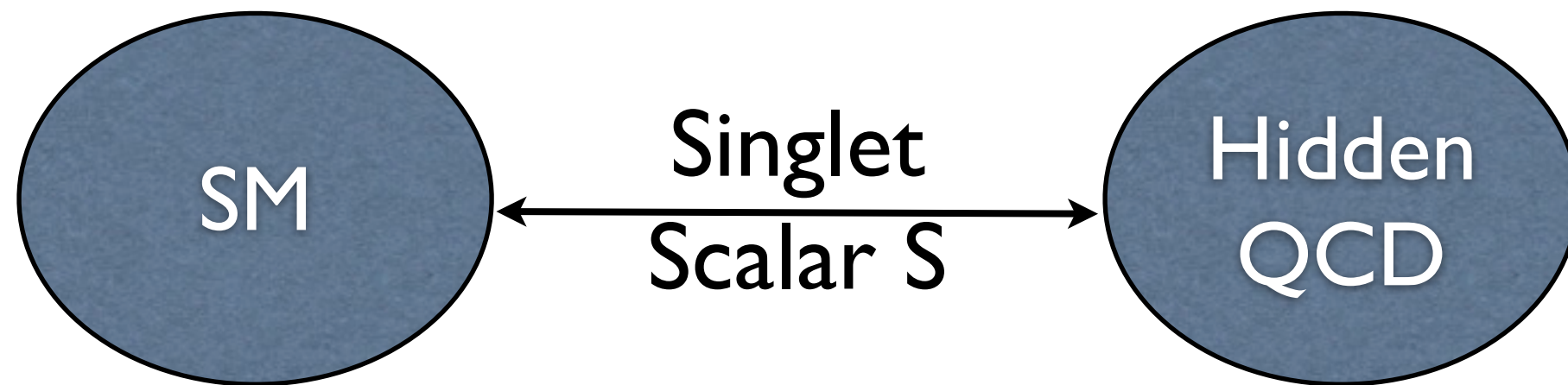
- Scale invariant extension of the SM + hQCD
- Mass scale is generated by nonperturbative strong dynamics in the hidden sector
- EWSB and CDM from hQCD sector

All the masses (including CDM mass)
from hidden sector strong dynamics

Appraisal of Scale Invariance

- May be the only way to understand the origin of mass dynamically (including spontaneous sym breaking)
- Without it, we can always write scalar mass terms for any scalar fields, and Dirac mass terms for Dirac fermions, the origin of which is completely unknown
- Probably only way to control higher dimensional op's suppressed by Planck scale

Model I (Scalar Messenger)



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

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

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

Model considered by Meissner and Nicolai, hep-th/0612165

Hidden sector lagrangian with new strong interaction

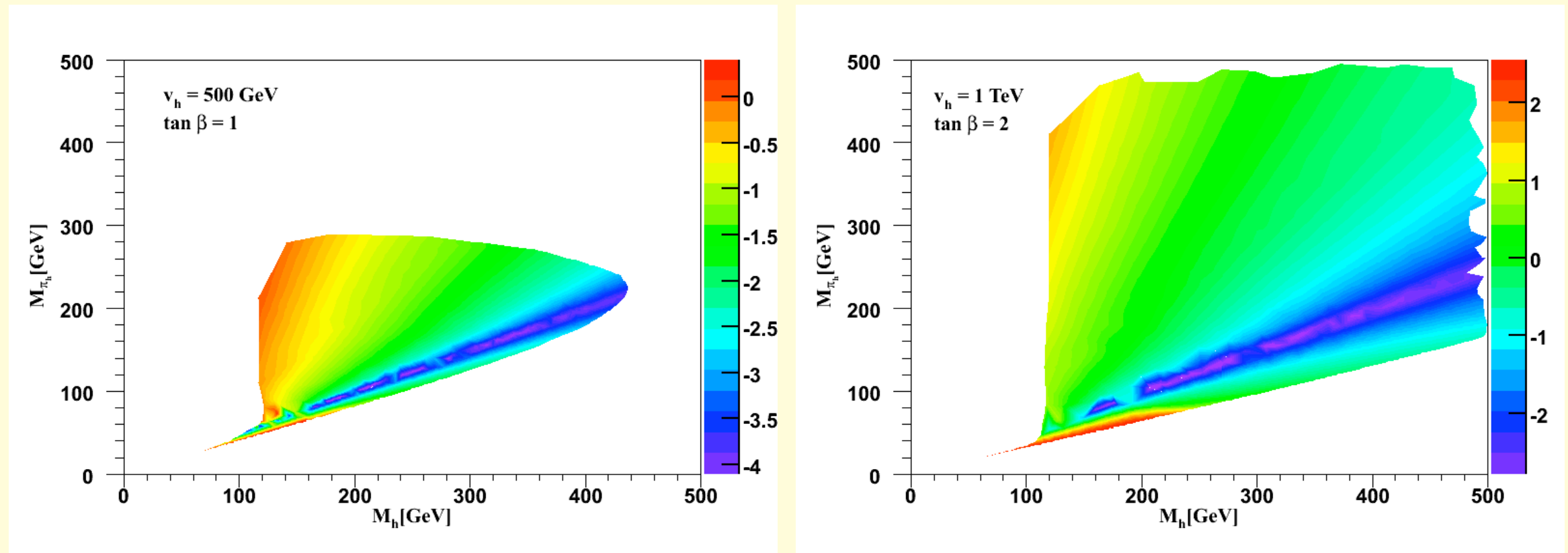
$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4} \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \bar{\mathcal{Q}}_k (i \mathcal{D} \cdot \gamma - \lambda_k S) \mathcal{Q}_k$$

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

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

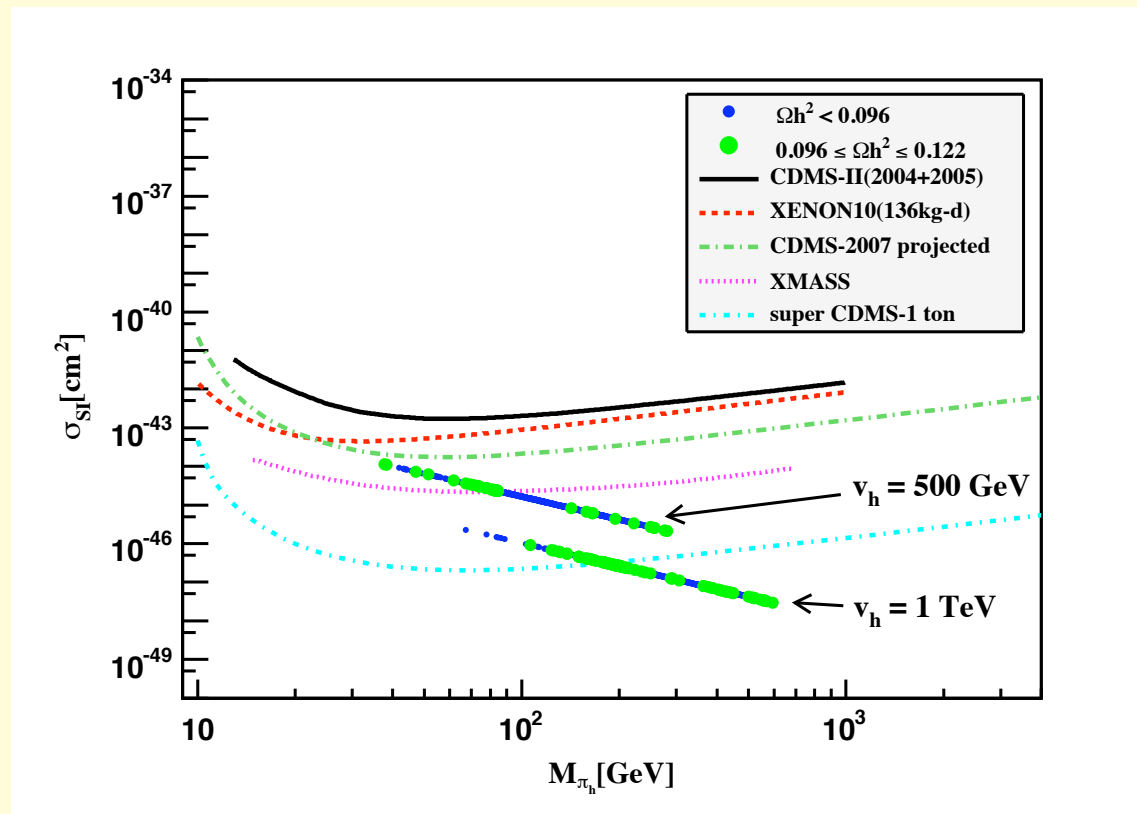
$$\begin{aligned}
 \mathcal{L}_{\text{full}} &= \mathcal{L}_{\text{hidden}}^{\text{eff}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mixing}} \\
 \mathcal{L}_{\text{hidden}}^{\text{eff}} &= \frac{v_h^2}{4} \text{Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2} \text{Tr}[\lambda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

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 $\tan \beta = 2$.

Comparison with the previous models

- Dark gauge symmetry is unbroken (DM could be absolutely stable if they appeared in the asymptotic states), but confining like QCD (No long range dark force, DM becomes composite)
- 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

- Additional singlet scalar improves the vacuum stability up to Planck scale
- Can modify Higgs inflation scenario (Higgs-portal assisted Higgs inflation [arXiv:1405.1635, JCAP (2017) with Jinsu Kim, WIPark]
- The 2nd scalar could be very very elusive
- Can we find the 2nd scalar at LHC ?
- We will see if this class of DM can survive the LHC Higgs data in the coming years

SIMP scenario + dark resonances

**arXiv:1801.07726, PRD (2018)
Soo-Min Choi, Hyunmin Lee (CAU)
and Alexander Natale (KIAS)**

SIMP Scenario in Dark QCD

SIMP paradigm

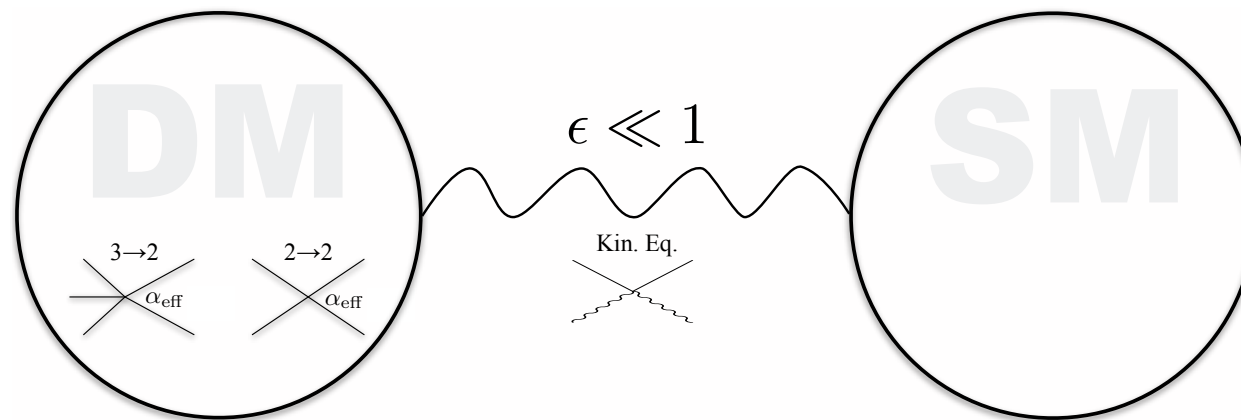


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \rightarrow 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions 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 ($G/H = Z$ ($N_f > 2$))

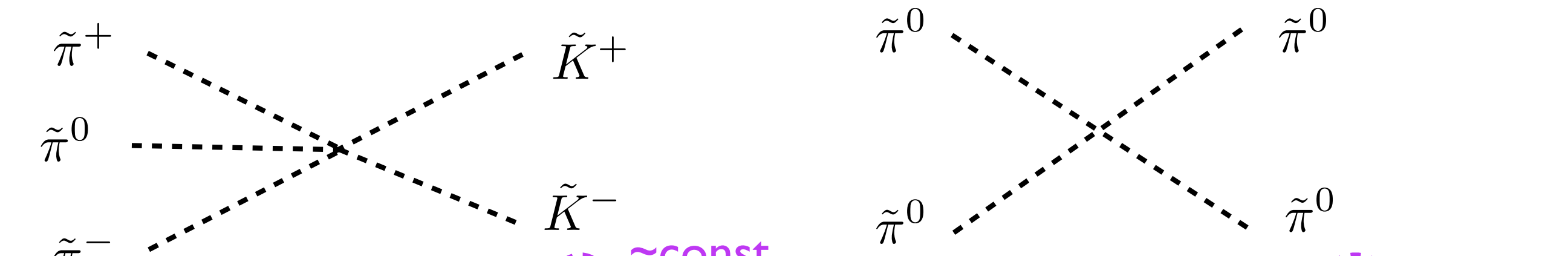
$$\Gamma_{\text{WZ}} = C \int_{M^5} d^5x \text{Tr}(\alpha^5) \quad \text{with} \quad \alpha = dUU^\dagger.$$

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

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

in the absence of external gauge fields

SIMP Dark Mesons



The left diagram shows a 3-to-2 interaction where three incoming dark mesons ($\tilde{\pi}^+$, $\tilde{\pi}^0$, $\tilde{\pi}^-$) exchange a dark meson (\tilde{K}^+ or \tilde{K}^-) to produce two outgoing dark mesons. The right diagram shows a self-interaction where two incoming dark mesons ($\tilde{\pi}^0$) exchange a dark meson to produce two outgoing dark mesons ($\tilde{\pi}^0$).

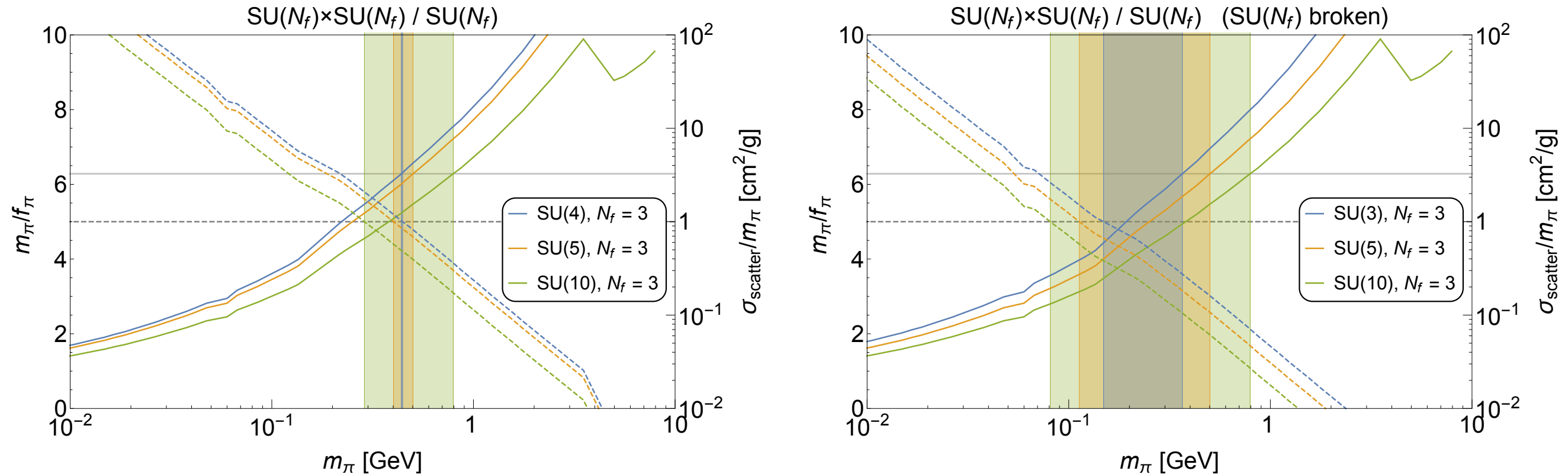
$$\langle \sigma v^2 \rangle_{3 \rightarrow 2} = \frac{5\sqrt{5}N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi} \right)^2, \quad \sigma_{\text{self}} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2}$$

Annotations: $\sim \text{const}$ (purple dashed circles) highlight the N_π^3 and N_π^2 terms in the equations.

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.  this talk)
- 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.)

Digression on ChPT + VM

- We consider G_{global} SSB into H_{global} : non Linear sigma model on $G_{\text{global}}/H_{\text{global}}$ is equivalent to linear sigma model on $G_{\text{global}} \times H_{\text{local}}$
- Vector meson \sim gauge field for H_{local}
 - **CCWZ (1969)**
 - **Bando, Kugo, Yamawaki, Phys. Rept. 164, 217 (1988)**

The Lagrangian \mathcal{L}_A can be cast into the following form in terms of a new exponential field $U(x)$ defined as $\Sigma(x) \equiv \xi_L^\dagger(x)\xi_R(x) = \exp[2i\pi(x)/f_\pi]$ with $\xi_L^\dagger(x) = \xi_R(x) = \exp[i\pi(x)/f_\pi]$:

$$\Sigma(x) \rightarrow L\Sigma(x)R^\dagger$$

Note that the π field is normalized in such a way that

$$\pi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & \pi^+ K^+ & \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 & K^0 \\ K^- & \frac{K^0}{\sqrt{6}} & -\frac{2}{\sqrt{6}}\eta_8 + \frac{1}{\sqrt{3}}\eta_0 \end{pmatrix} \quad (6)$$

Vector meson as hidden local gauge boson

$$\begin{aligned}
 \xi_L(x) &\rightarrow U(x)\xi_L(x)L^\dagger \\
 \xi_R(x) &\rightarrow U(x)\xi_R(x)R^\dagger \\
 gV_\mu(x) &\rightarrow U(x) [\partial_\mu - igV_\mu(x)] U^\dagger(x) \\
 D_\mu \xi_L &= (\partial_\mu - igV_\mu)\xi_L(x) + i\xi_L(x)l_\mu \\
 D_\mu \xi_R &= (\partial_\mu - igV_\mu)\xi_R(x) + i\xi_R(x)l_\mu
 \end{aligned}$$

$$V_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & \rho_\mu^+ K_\mu^{*+} & K_\mu^{*0} \\ \rho_\mu^- & -\frac{1}{\sqrt{2}}\rho_\mu^0 + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & -\frac{2}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} \\ K_\mu^{*-} & \frac{K_\mu^{*0}}{K_\mu^{*0}} & \end{pmatrix} \quad (7)$$

Ch Lagrangian (pi,V)

The chiral Lagrangian for pions and vector mesons is given by

$$\begin{aligned}
 \mathcal{L} &= \mathcal{L}_A + \mathcal{L}_m + \mathcal{L}_B + \mathcal{L}_{\text{kin}}(V) + \Gamma^{\text{anom}}(\xi_L, \xi_R, V, l, r) \\
 \mathcal{L}_A &= -\frac{f_\pi^2}{4} \text{Tr} \left[(D_\mu \xi_L) \xi_L^\dagger - (D_\mu \xi_R) \xi_R^\dagger \right]^2 \\
 \mathcal{L}_m &= -\frac{f_\pi^2}{2} \text{Tr} \left[\mu (\Sigma + \Sigma^\dagger) \right] \\
 \mathcal{L}_B &= -a \frac{f_\pi^2}{4} \text{Tr} \left[(D_\mu \xi_L) \xi_L^\dagger + (D_\mu \xi_R) \xi_R^\dagger \right]^2 \\
 \mathcal{L}_{\text{kin}} &= -\frac{1}{2} \text{Tr} [F_{\mu\nu} F^{\mu\nu}] \\
 F_{\mu\nu} &= \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]
 \end{aligned}$$

$ \begin{aligned} \mathcal{L}_B &= m_V^2 \text{Tr} V_\mu V^\mu - 2ig_{V\pi\pi} \text{Tr} (V_\mu [\partial^\mu \pi, \pi]) + \dots \\ m_V^2 &= ag^2 f_\pi^2 \\ g_{V\pi\pi} &= \frac{1}{2} ag \end{aligned} $
--

**a~2 and g~6
in real QCD.
In Dark QCD,
we consider
they are free**

Another useful quantities

$$\begin{aligned}\xi(x) &\rightarrow L\xi(x)U^\dagger(x) = U(x)\xi(x)R^\dagger \\ \mathcal{A}_\mu(x) &\equiv \frac{i}{2} \left[\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger \right] \\ &\rightarrow U(x) \mathcal{A}_\mu(x) U^\dagger(x) \\ \mathcal{V}_\mu(x) &\equiv \frac{i}{2} \left[\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger \right] \\ &\rightarrow U(x) \mathcal{V}_\mu(x) U^\dagger(x) + U(x) \partial_\mu U^\dagger(x) \\ V_\mu(x) &\rightarrow U(x) V_\mu(x) U^\dagger(x) + U(x) \partial_\mu U^\dagger(x)\end{aligned}$$

**Here 'V' is the vector meson associated with
hidden local gauge symmetry**

WZW (gauged)

$$\begin{aligned}\Gamma_{LR}(U, l_\mu, r_\mu) = & C \int_{M^5} d^5x \operatorname{Tr}(\alpha^5) \\ & + 5C \int_{M^4} d^4x \operatorname{Tr} \{ i(l\alpha^3 + r\beta^3) - [(dl\,l + l\,dl)\alpha + (dr\,r + r\,dr)\beta] + (dl\,dU\,rU^{-1} - dr\,dU^{-1}\,lU) \\ & + (rU^{-1}\,lU\beta^2 - lU\,rU^{-1}\alpha^2) + \tfrac{1}{2}[(l\alpha)^2 - (r\beta)^2] + i[l^3\alpha + r^3\beta] \\ & + i[(dr\,r + r\,dr)U^{-1}\,lU - (dl\,l + l\,dl)U\,rU^{-1}] + i[lU\,rU^{-1}\,l\alpha + rU^{-1}\,lU\,r\beta] . \\ & + [r^3U^{-1}\,lU - l^3U\,rU^{-1} + \tfrac{1}{2}(U\,rU^{-1}\,l)^2] \} ,\end{aligned}$$

WZW with vector mesons

$$\begin{aligned}
 \hat{\alpha}_L &= D\xi_L \cdot \xi_L^\dagger = \alpha_L - igV + i\hat{l} \\
 \hat{\alpha}_R &= D\xi_R \cdot \xi_R^\dagger = \alpha_L - igV + i\hat{r} \\
 \alpha_L &= d\xi_L \cdot \xi_L^\dagger, \\
 \alpha_R &= d\xi_R \cdot \xi_R^\dagger \\
 \hat{l} &= \xi_L \cdot \xi_L^\dagger, \\
 \hat{r} &= \xi_R \cdot \xi_R^\dagger \\
 F_V &= dV - igV^2 \\
 \hat{F}_L &= \xi_L \cdot F_L \cdot \xi_L^\dagger = \xi_L(dl - il^2)\xi_L^\dagger \\
 \hat{F}_R &= \xi_R \cdot F_R \cdot \xi_R^\dagger = \xi_R(dr - ir^2)\xi_R^\dagger
 \end{aligned}$$

$$\Gamma^{\text{anom}} = \Gamma_{\text{WZW}} + \sum_{i=1}^4 c_i \mathcal{L}_i$$

$$\begin{aligned}
 \mathcal{L}_1 &= \text{TR} [\hat{\alpha}_L^3 \hat{\alpha}_R - \hat{\alpha}_R^3 \hat{\alpha}_L] - (\xi_L = \xi_R = 1, V = 0, l, r) \\
 \mathcal{L}_2 &= \text{TR} [\hat{\alpha}_L \hat{\alpha}_R \hat{\alpha}_L \hat{\alpha}_R] - (\xi_L = \xi_R = 1, V = 0, l, r) \\
 \mathcal{L}_3 &= i\text{Tr} [F_V (\hat{\alpha}_L \hat{\alpha}_R - \hat{\alpha}_R \hat{\alpha}_L)] - (\xi_L = \xi_R = 1, V = 0, l, r) \\
 \mathcal{L}_4 &= i\text{Tr} [\hat{F}_L \hat{\alpha}_L \hat{\alpha}_R - \hat{F}_R \hat{\alpha}_R \hat{\alpha}_L] - (\xi_L = \xi_R = 1, V = 0, l, r)
 \end{aligned}$$

- Fujiwara, Kugo, Yamawaki et al., Prog. Theo. Phys. 73, 926 (1985)
- P.Ko, PRD44, 139 (1991) 139 for a useful compact summary

SIMP + VDM

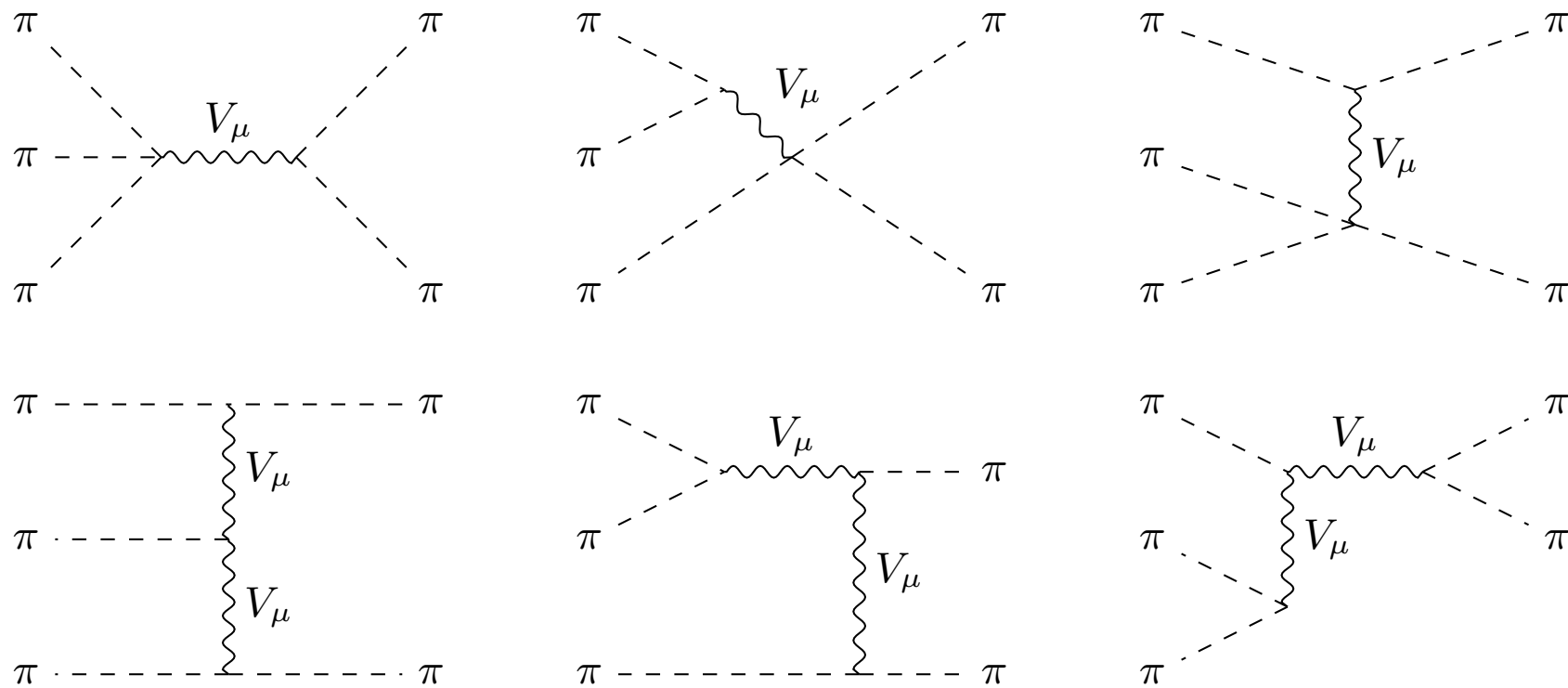


FIG. 1: Feynman diagrams contributing to $3 \rightarrow 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involveng 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

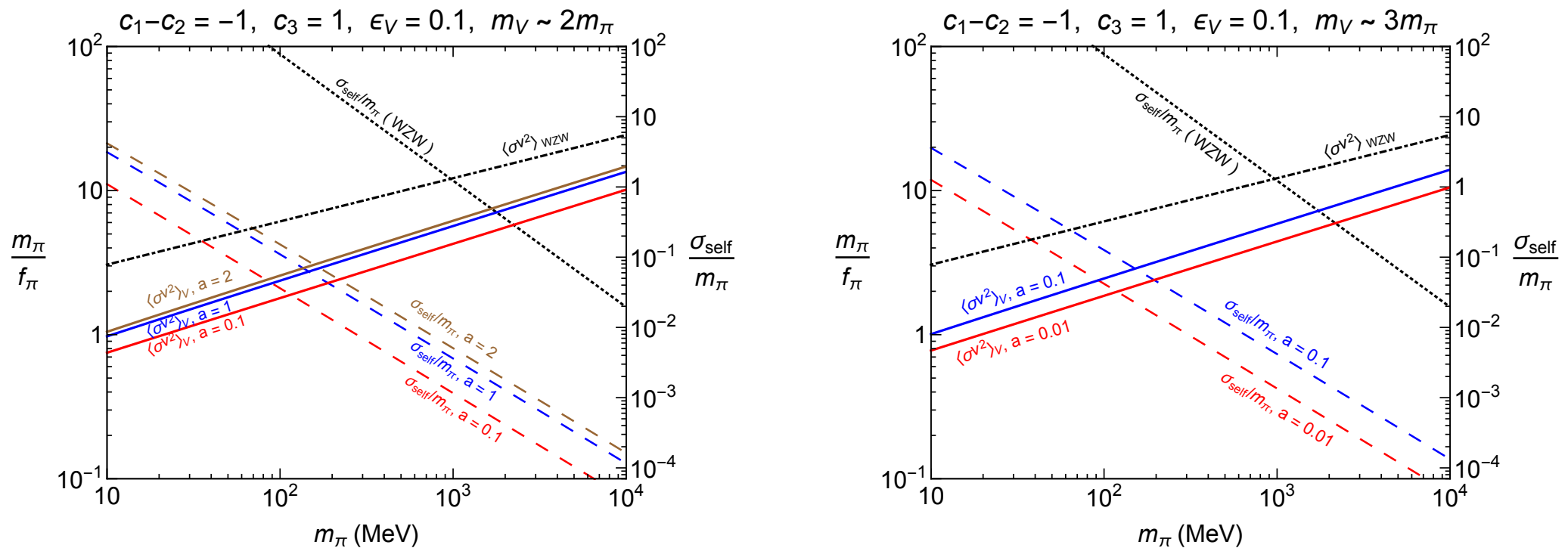


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π . The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition 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

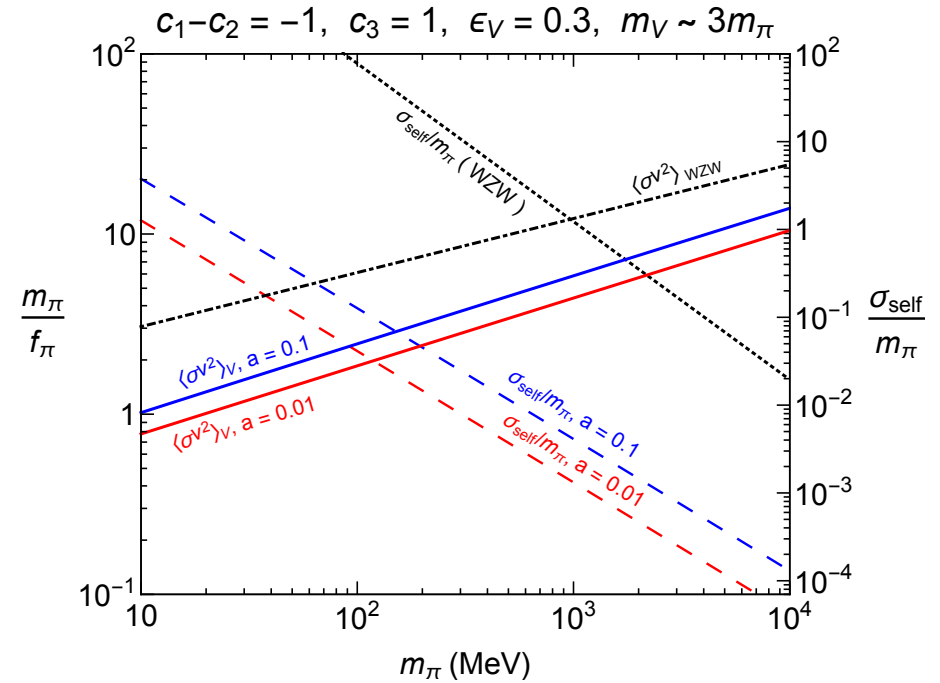
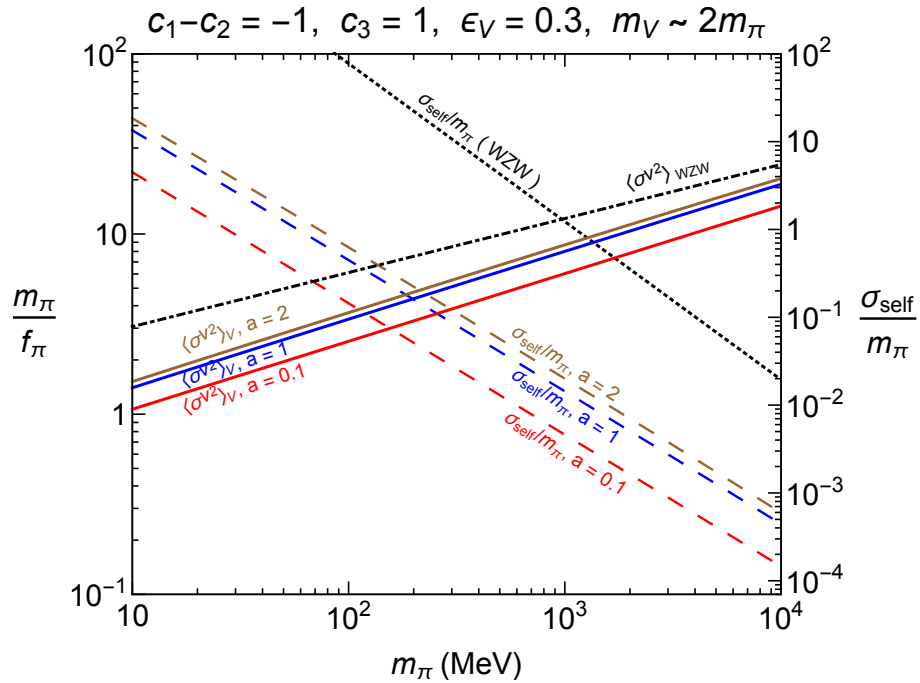


FIG. 3: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.3$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

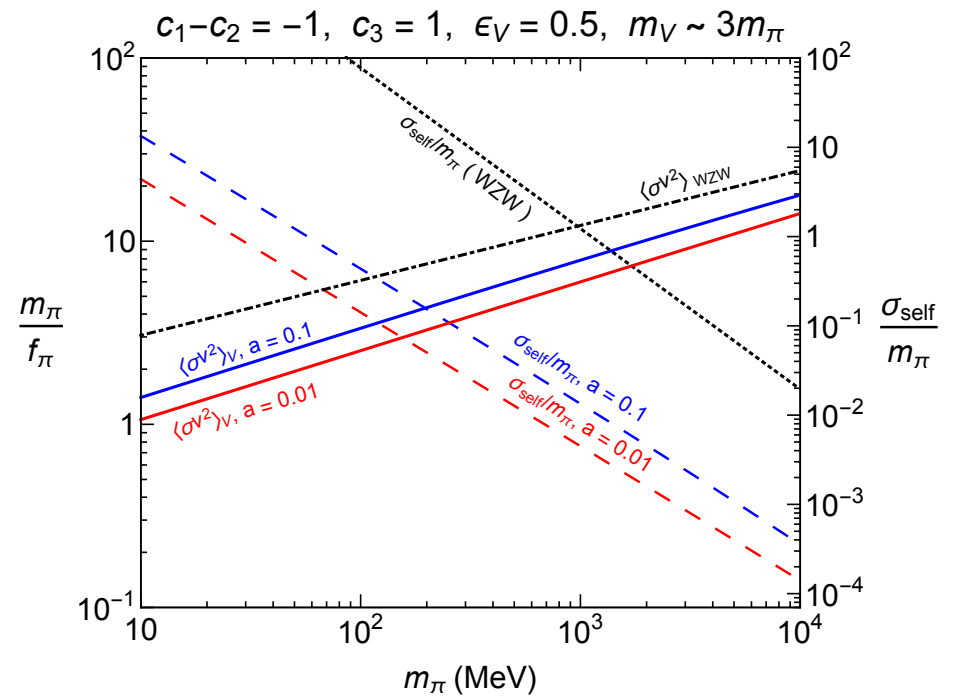
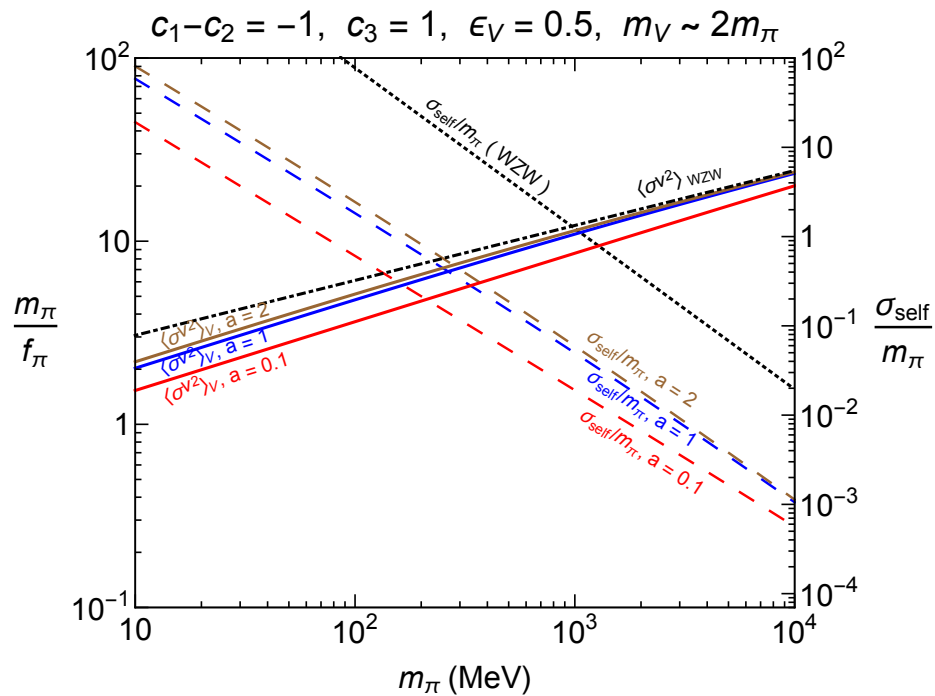


FIG. 4: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.5$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

Conclusion

- Hidden (dark) QCD models make an interesting possibility to study the origin of EWSB and (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)