Dark Pion DM: WIMP vs. SIMP

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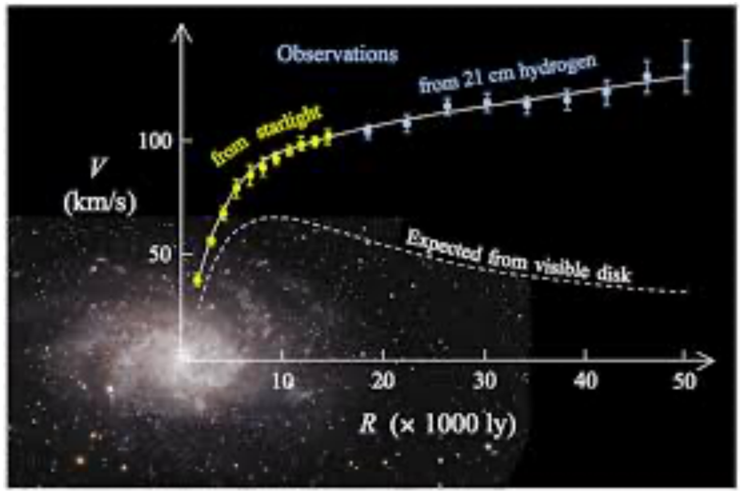
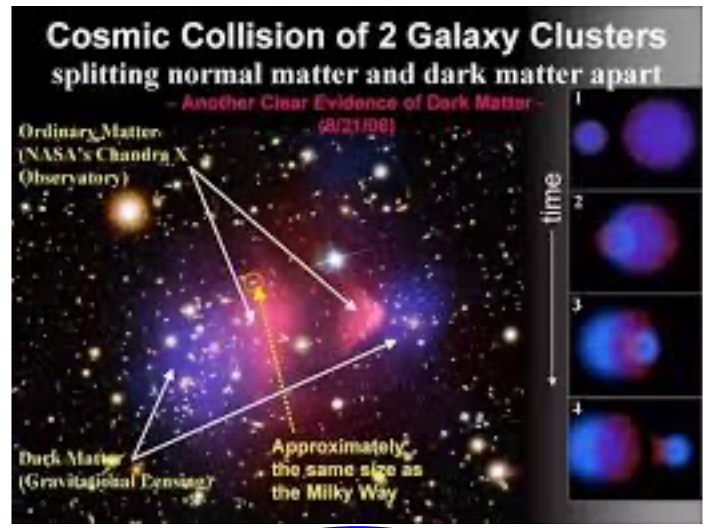
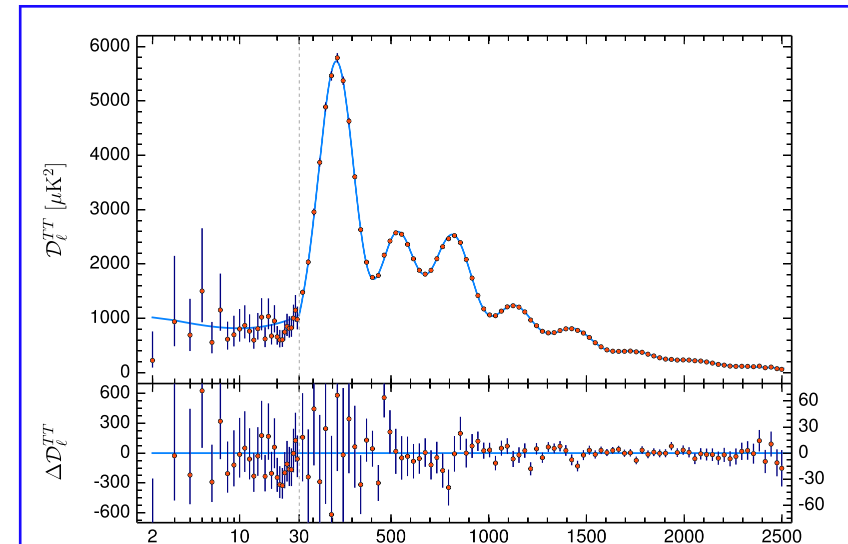
DM : Brief Introduction

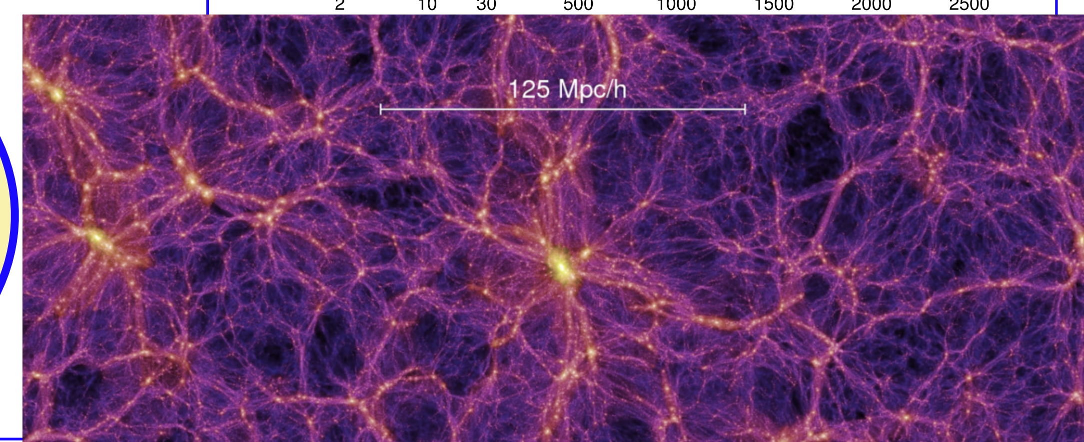
Evidences for DM

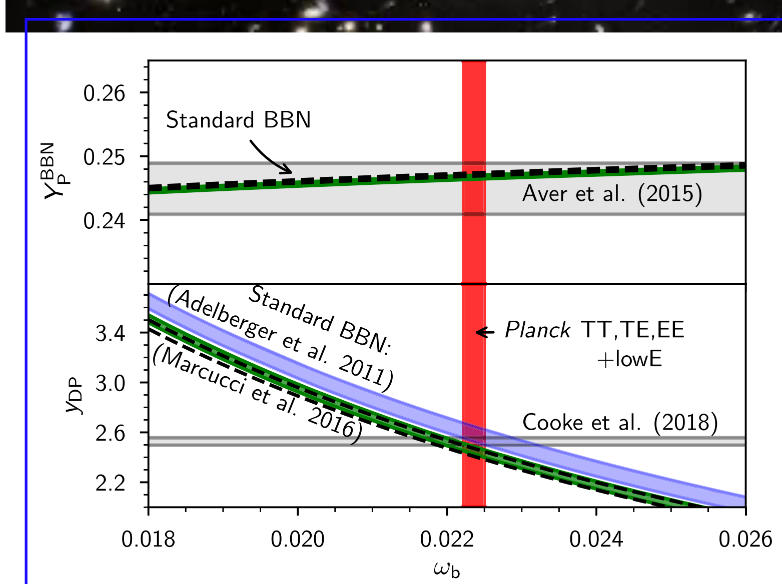


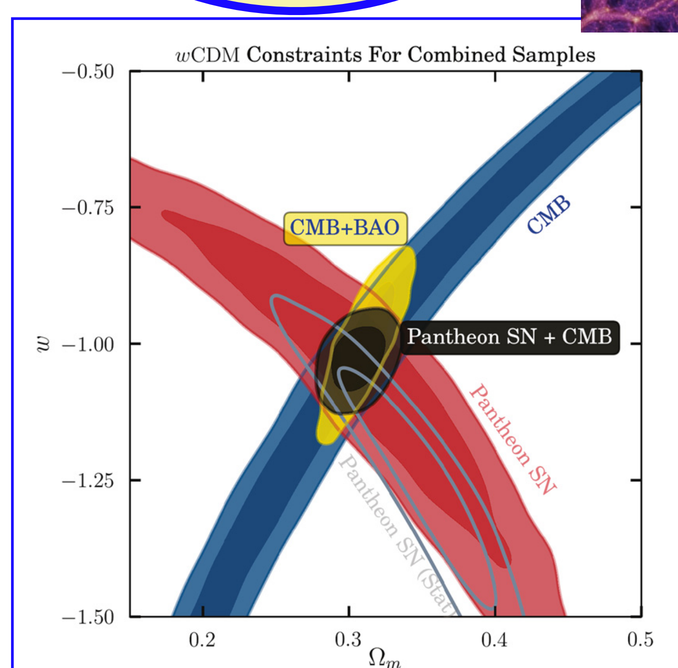


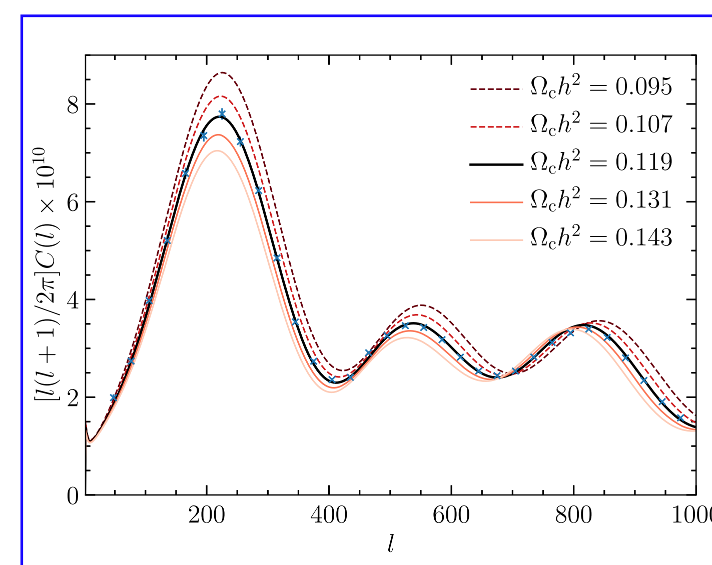


GRAVITY

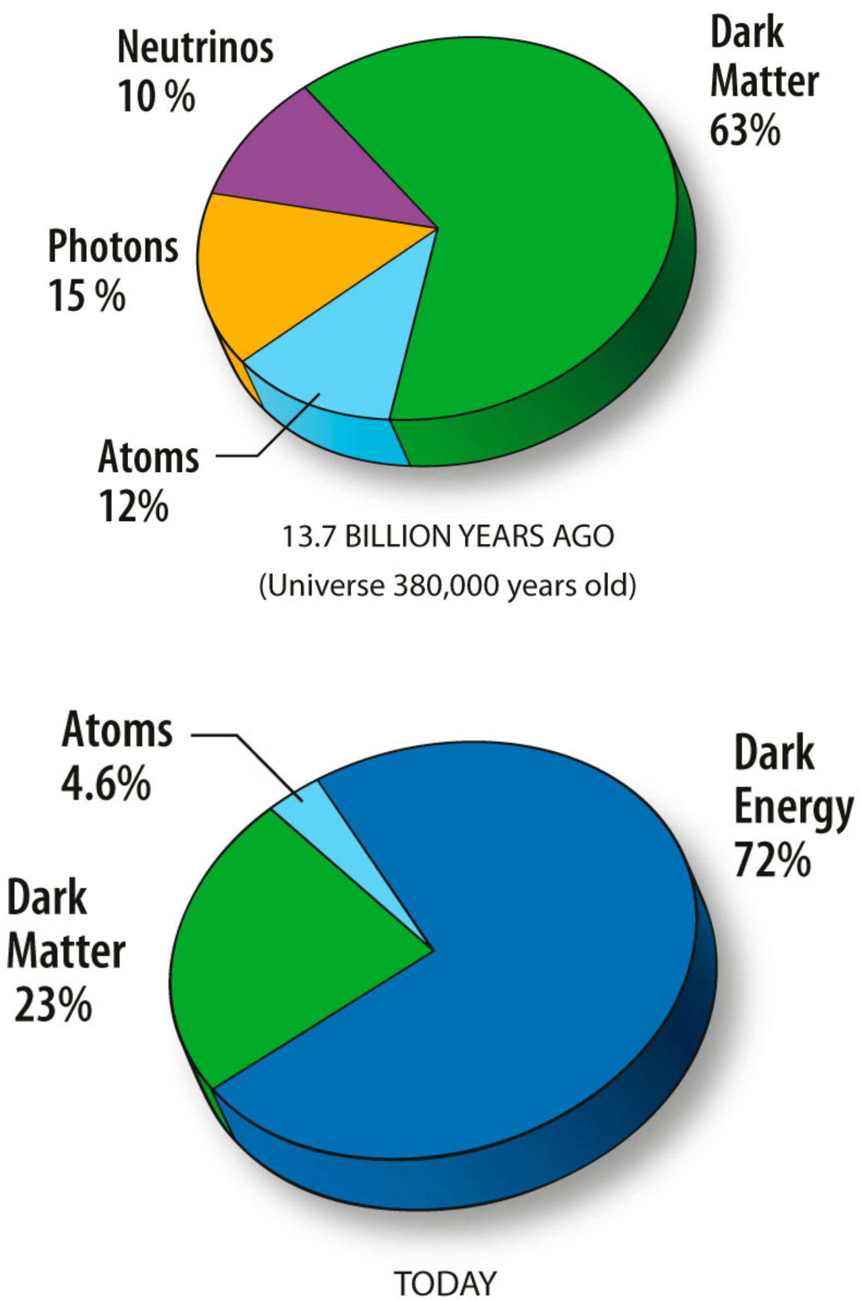


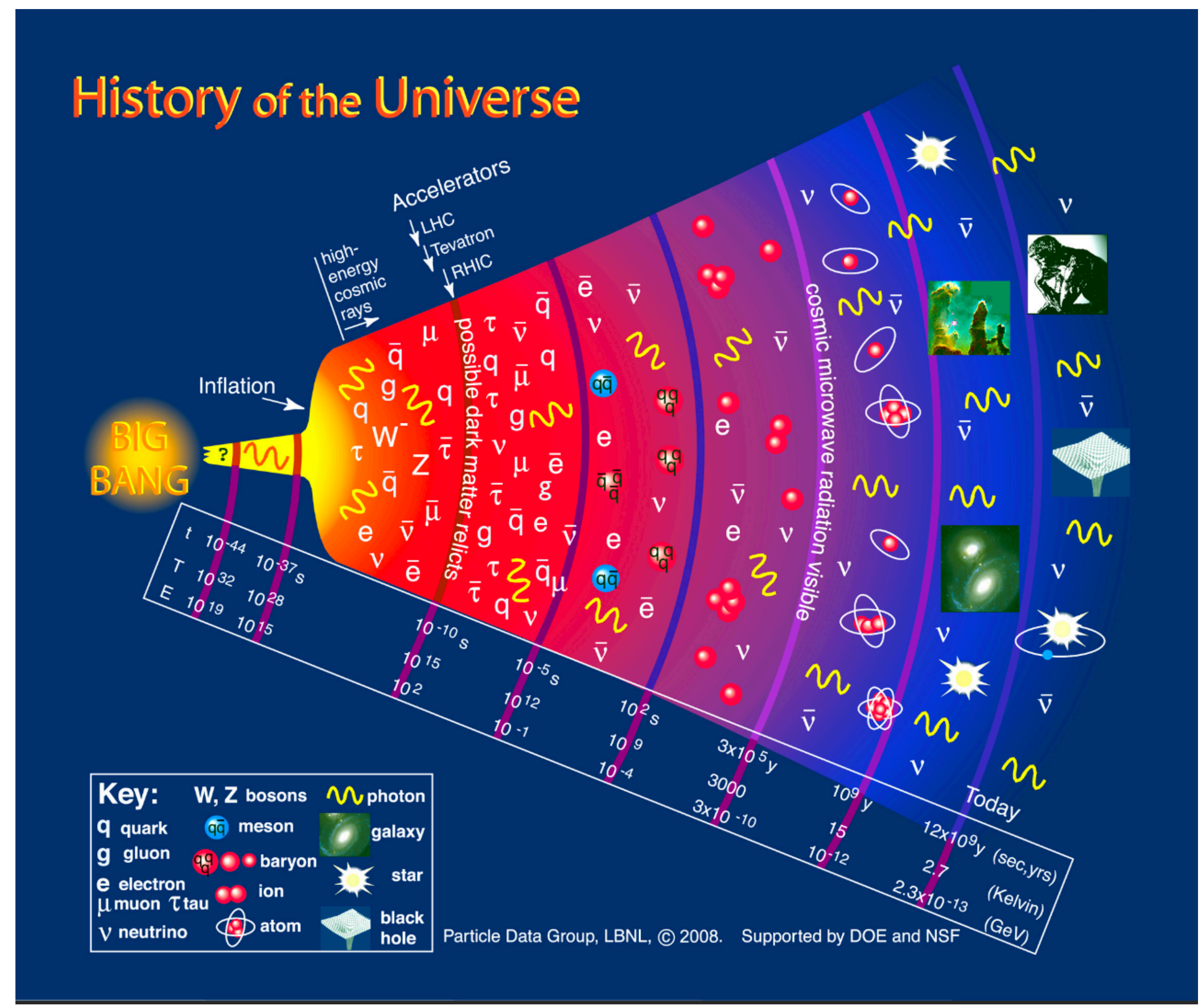






Cos. Concordance Model





KNOWNS

- Feels Gravity > Currently evidences come only thru this
- Its lifetime >> Age of Universe
- $\rho(\simeq m) \gg \ p(\simeq 0)$ (Nonrel.)
- $\Omega_{\rm DM} \sim 5\ \Omega_{\rm Baryon}$
- $\rho_{\rm local} \sim 0.3{\rm GeV/cm}^3$
- It forms a halo, not a disk

UNKNOWNS

- Mass, Spin ?
- How many species ?
- Any internal quantum #'s ?
- Any internal structures ?
- Interactions w/ SM particles ?
- DM self int. ? ($\sigma_{\chi\chi}/m_\chi \lesssim 1g/cm^2$)
- Almost nothing known about particle physics nature of DM

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)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 (I)

- Kinematically long-lived if DM is very light (axion, sterile ν_s ,...)
- DM could be absolutely stable due to unbroken local gauge symmetry
    - DM with local Z2 (inelastic), Z3 (semi-annihilation)
    - $SU(3)_D \to SU(2)_D$ (and 2 more works) for H_0, σ_8 (2016)

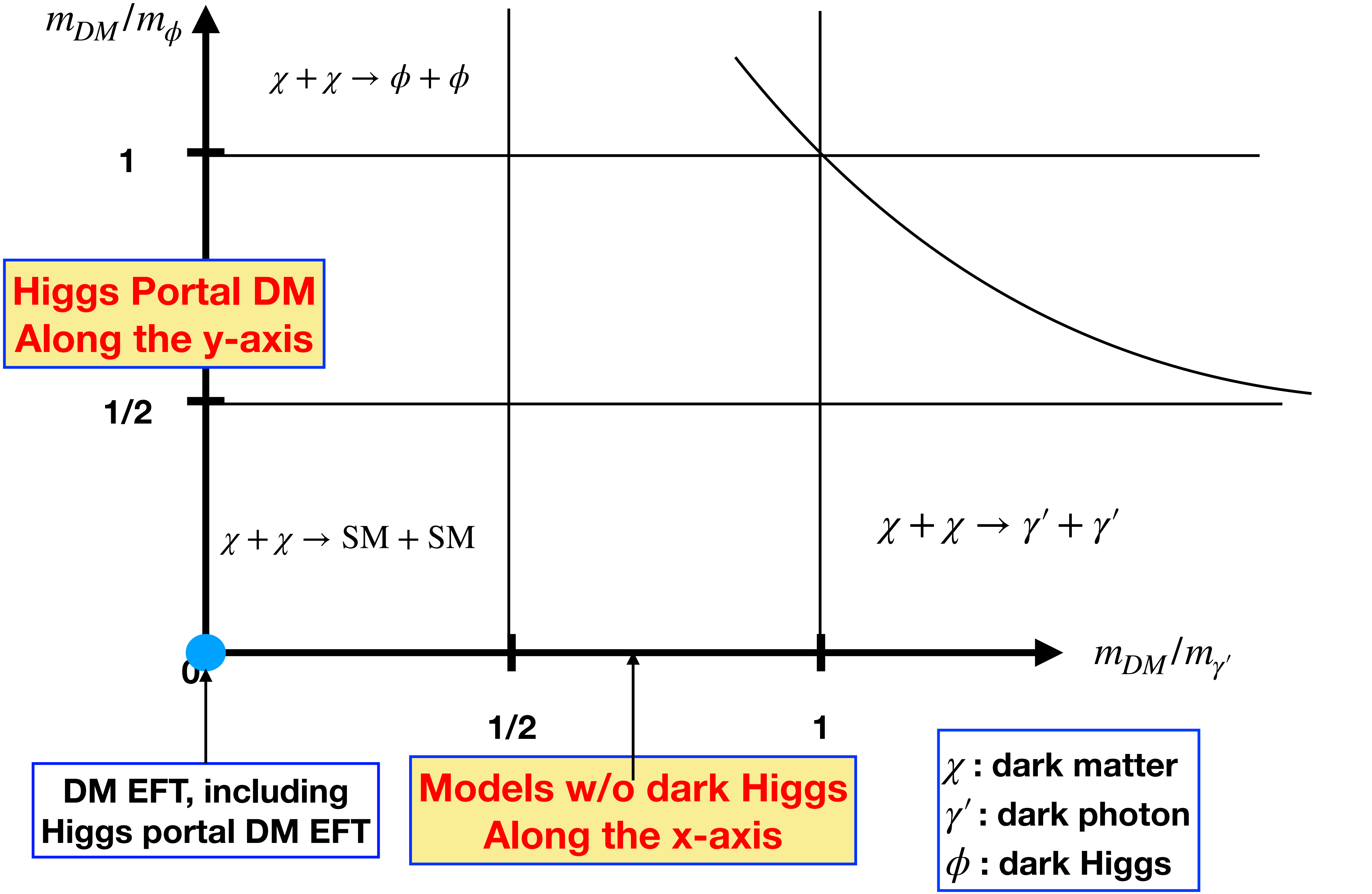
In QFT (II)

- DM could be stable due to nontrivial topology: hidden monopole DM+VDM+DR
- Longevity of DM could be due to some accidental symmetries of unbroken/broken dark gauge symmetries
  - EWSB and CDM from hQCD, and scale invariant extensions : dark pions and dark baryons : Hur, Ko et al (2007)
  - Dark gauge sym completely broken

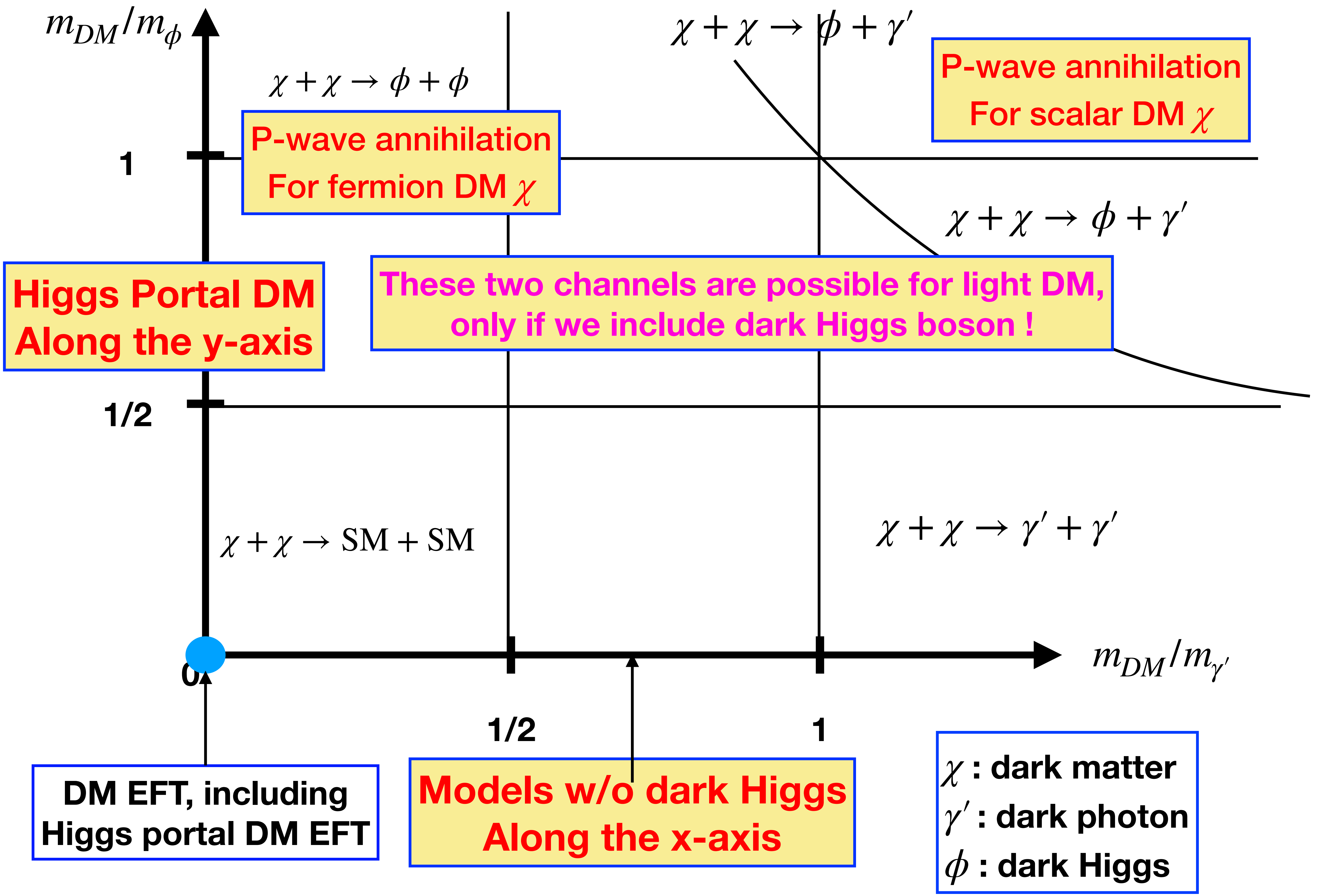
Landscape of dark sector

- DM EFT : DM + SM (unitarity violation in most cases)
- (Improved) Simplified Model for DM : DM + SM + Mediators (without full SM gauge symmetry) Full SM gauge symmetry was imposed by P Ko, A Natale, MH Park, H Yokoya (2016)
- DM stabilized by global symmetry can not protect DM to decay fast from dim-5 operators from gravity : Need to introduce dark gauge symmetry [S Baek, P Ko, WI Park (2013)] : Now called as a "dark sector"
- (Excited) DM, DR, (Light) Mediators with dark gauge symmetry
- Only questions: mass scales and couplings (various mechanisms)

Dark sector parameter space for a fixed m_{DM}



Dark sector parameter space for a fixed m_{DM}



Hidden (Dark) QCD Scenario (with CSI)

hQCD (Dark QCD)

- 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 dark QCD models during the past years (mostly without scale invariace, 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) $\frac{1}{M_{\rm Planck}} H^\dagger H \overline{q_h} \gamma_5 q_h$ **can be forbidden by CSI**

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

Appraisal of Scale Invariance

- May be the only way to understand the origin of mass dynamically (including spontaneous sym breaking)

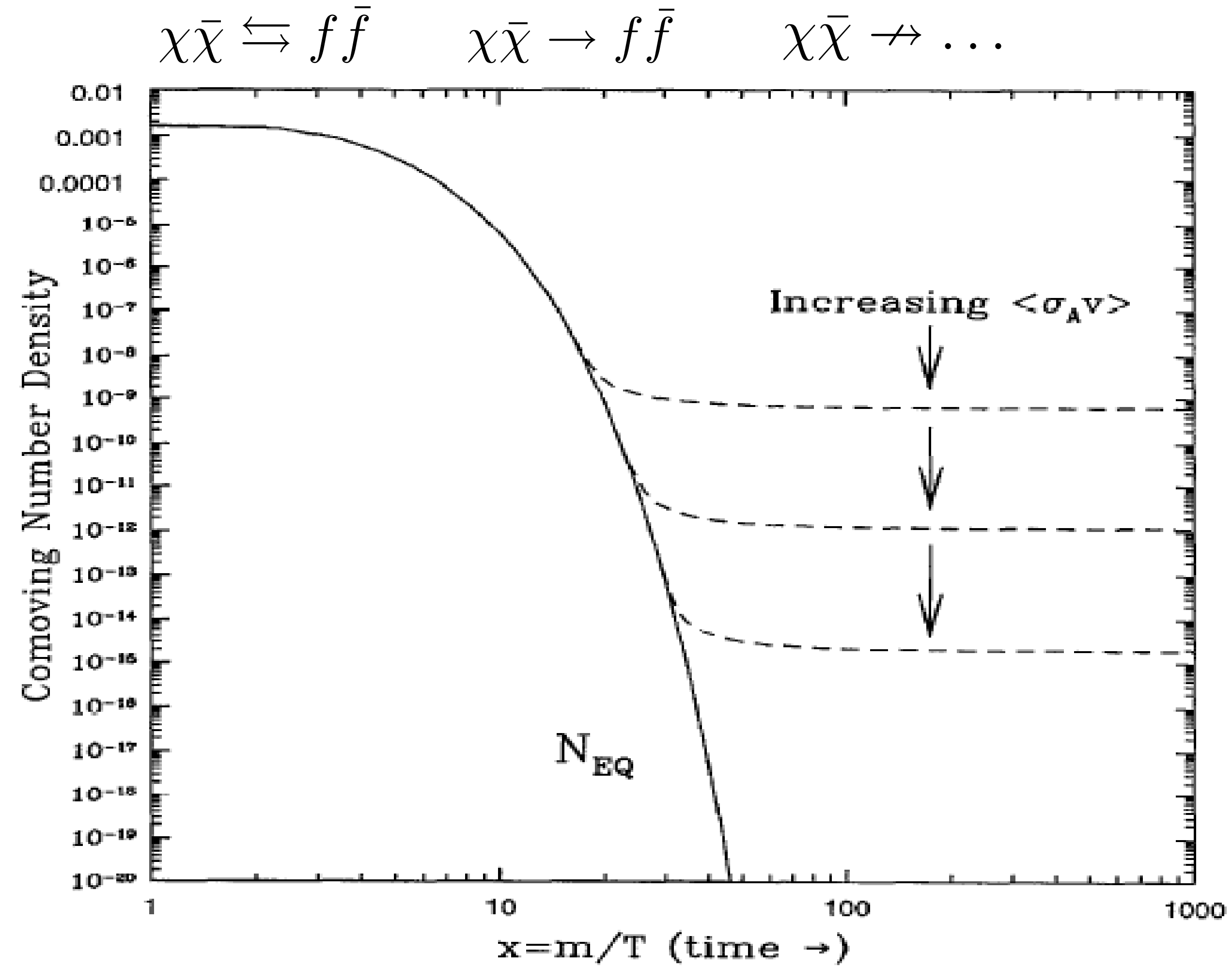
- Without it, we can always write scalar mass terms for any scalar fields, and Dirac mass terms for Dirac fermions, the origin of which is completely unknown

- Probably only way to control higher dimensional op's suppressed by Planck scale

WIMP's
(Weakly Interacting Massive Particles)

Freez-out & Thermal Relic

- X (CDM) is initially in thermal equilibrium
- As universe cools down, X only decreases by pair annihilation
- As universe expands, X eventually decouples from the SM



- Boltzmann Equation :

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\mathrm{eq}}^2 \right]$$

Dilution from expansion

$X + X \to SM + SM$

$SM + SM \to X + X$

- Freez-out when interaction rate drops expansion rate

$$n_{\mathrm{eq}} \langle \sigma v \rangle \sim H$$

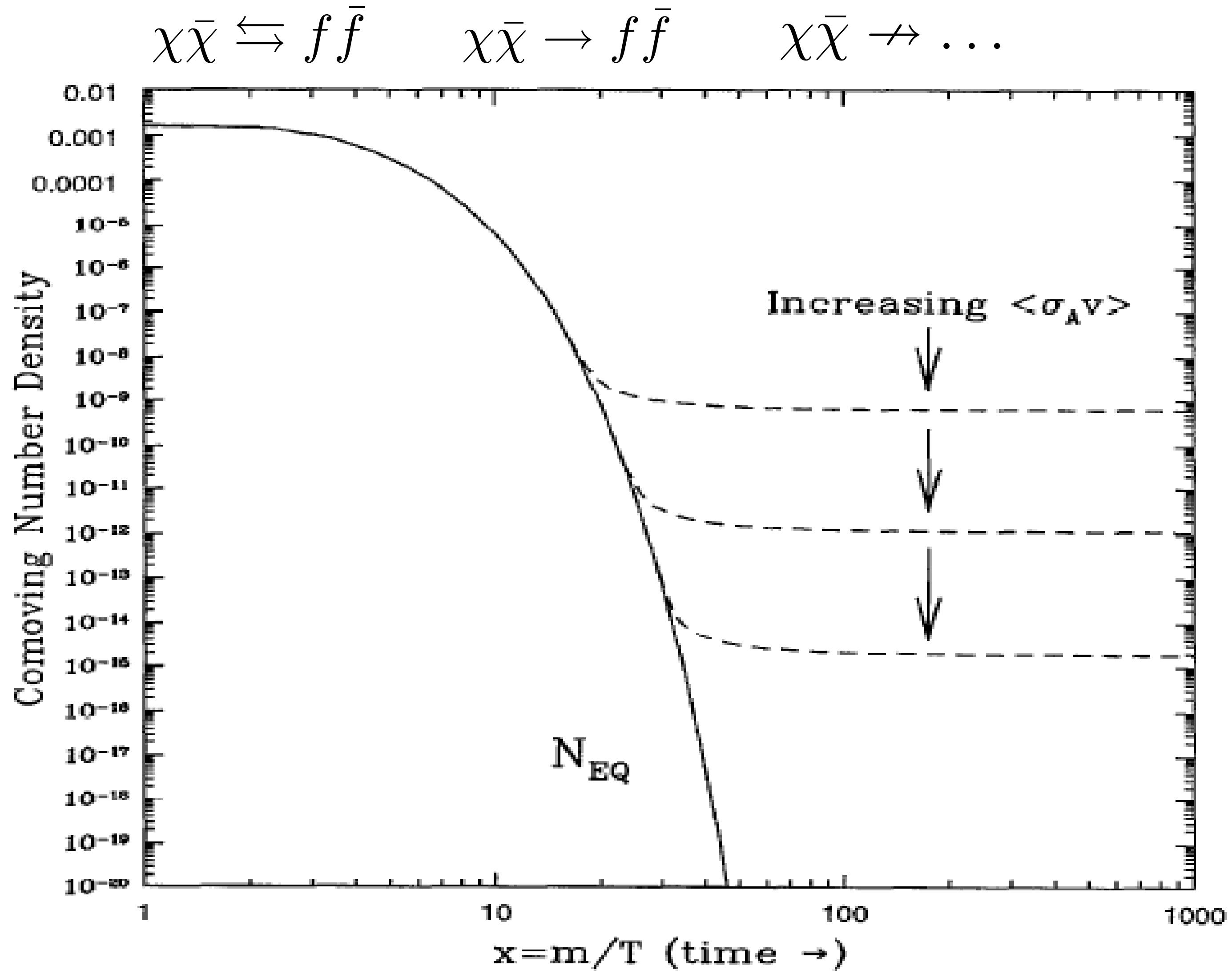
$(mT)^{3/2} e^{-m/T}$ $\quad m^{-2} \quad$ T^2/M_{Pl}

- Freeze-out Temp ~ m/25

In the end, we get

$$\Omega_X \approx \frac{6\times 10^{27} cm^3 s^{-1}}{\langle \sigma_{\rm ann} v\rangle}$$

$$\Omega_{\rm DM} \approx 0.23 \text{ for}$$
$$\langle \sigma v\rangle = 3\times 10^{-26} cm^3/s$$



$$\langle \sigma v\rangle \approx \frac{\alpha_w}{M^2} \approx \frac{\alpha_w}{1TeV^2} \rightarrow \Omega_X \sim O(\text{few}\times 0.1)$$

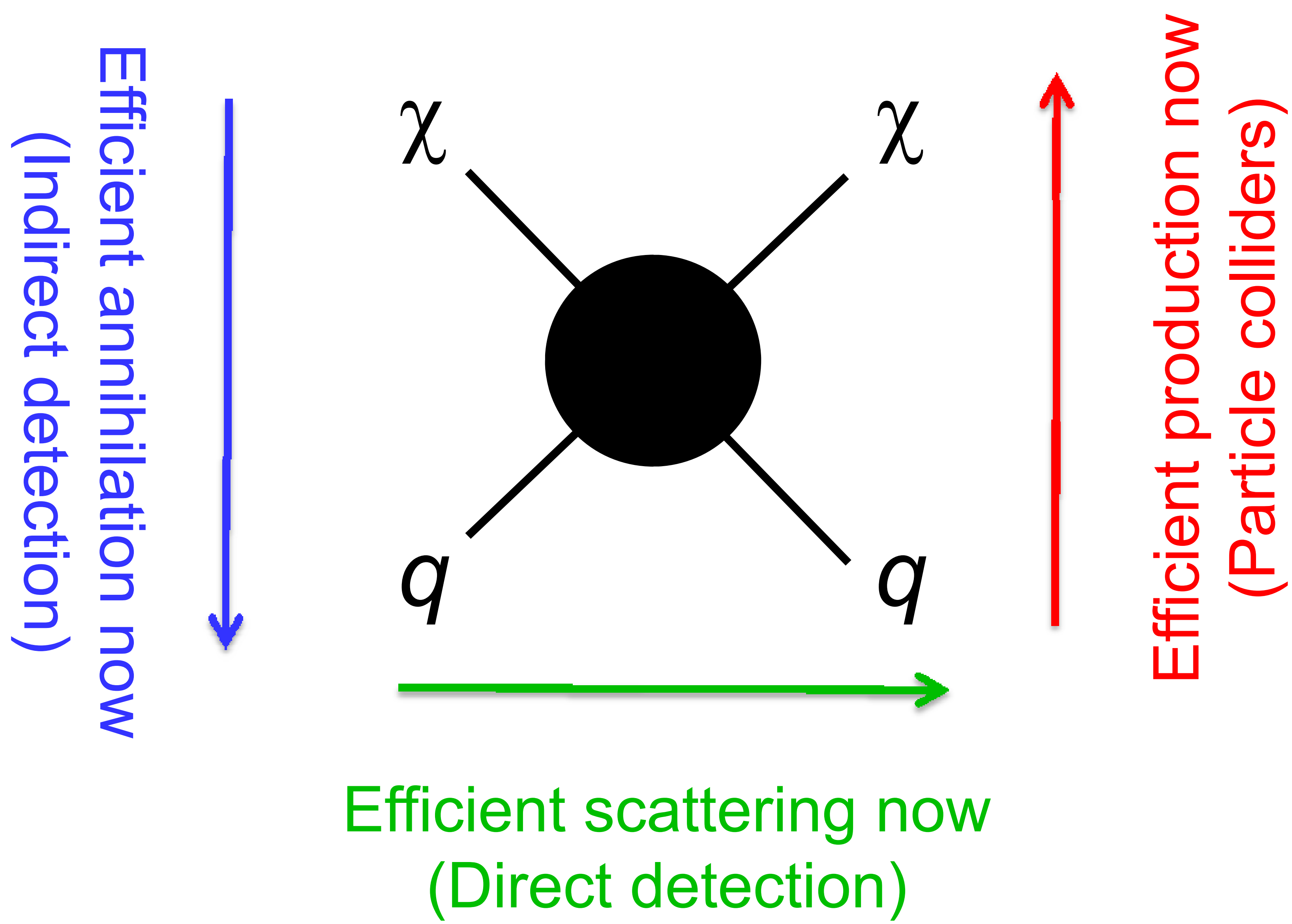
Weak x-section: WIMP

WIMP is nice, since

- WIMP in chemical equilibrium in the early universe has the right density to be the CDM
- The annihilation cross section that determines the WIMP relic density is related with the WIMP annihilation rate in indirect DM searches (upto kinematical factor)
- Crossing diagram may give sizable direct scattering cross section
- In most SUSY models, this is not the case because of coannihilations and resonant annihilation

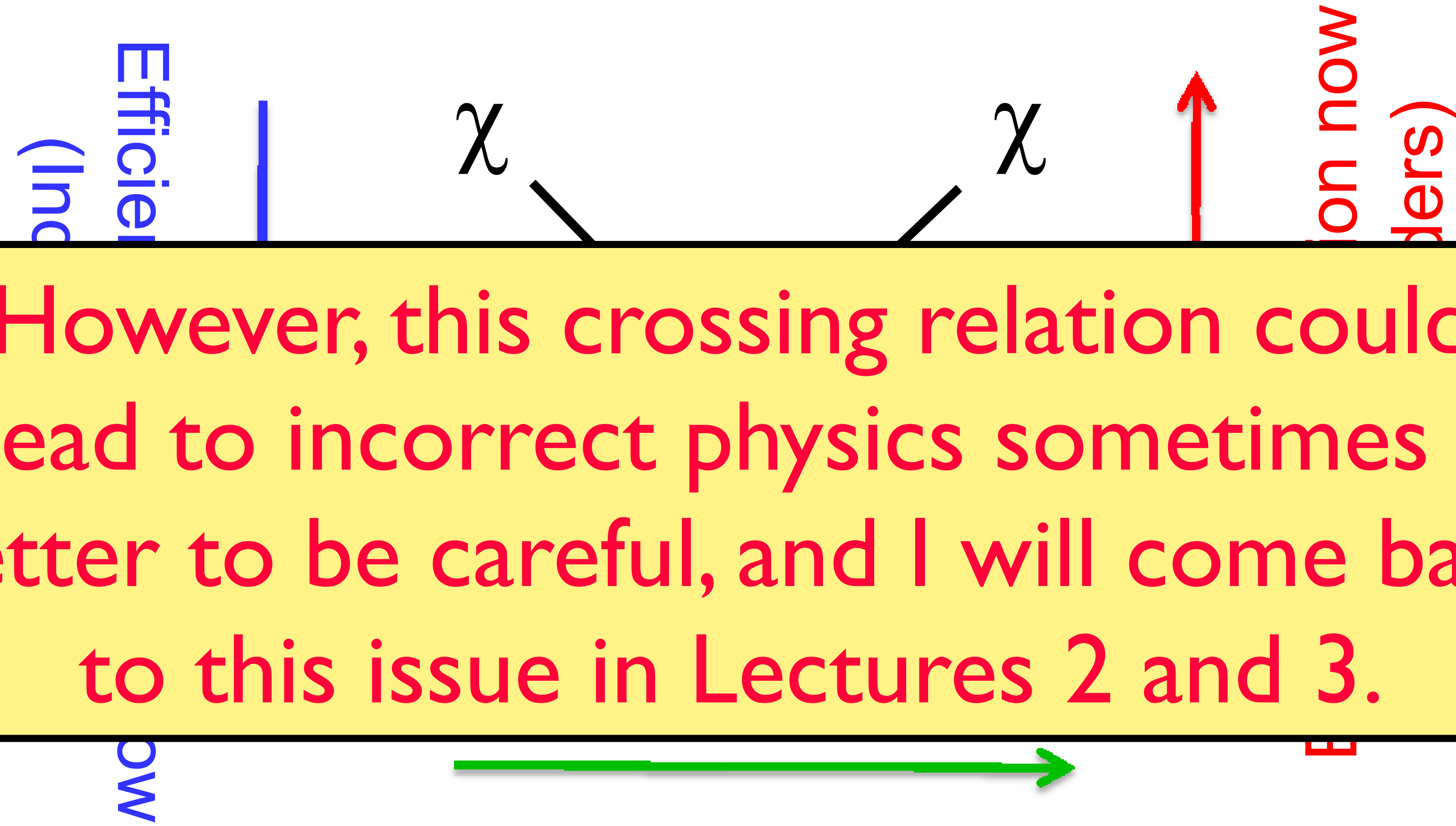
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then



However, this crossing relation could lead to incorrect physics sometimes ! Better to be careful, and I will come back to this issue in Lectures 2 and 3.

Efficient scattering now
(Direct detection)

WIMP scenario with the Higgs-Singlet scalar portal

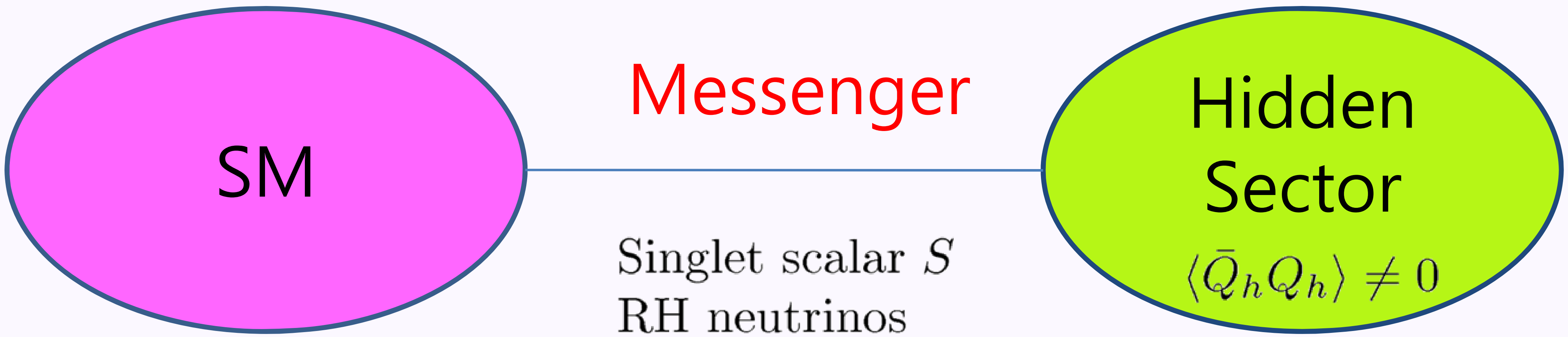
- **Hur, Jung, Ko, Lee, arXiv:0709.1218, PLB (2011)**
- **Hur, Ko, 1103.2571, PRL (2011)**
- **Hatanaka, Jung, Ko, 1606.02969, JHEP (2016)**

And proceedings:

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

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture



Singlet scalar S
RH neutrinos
etc.

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Key Observations

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

- Potential for H_1 and H_2

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

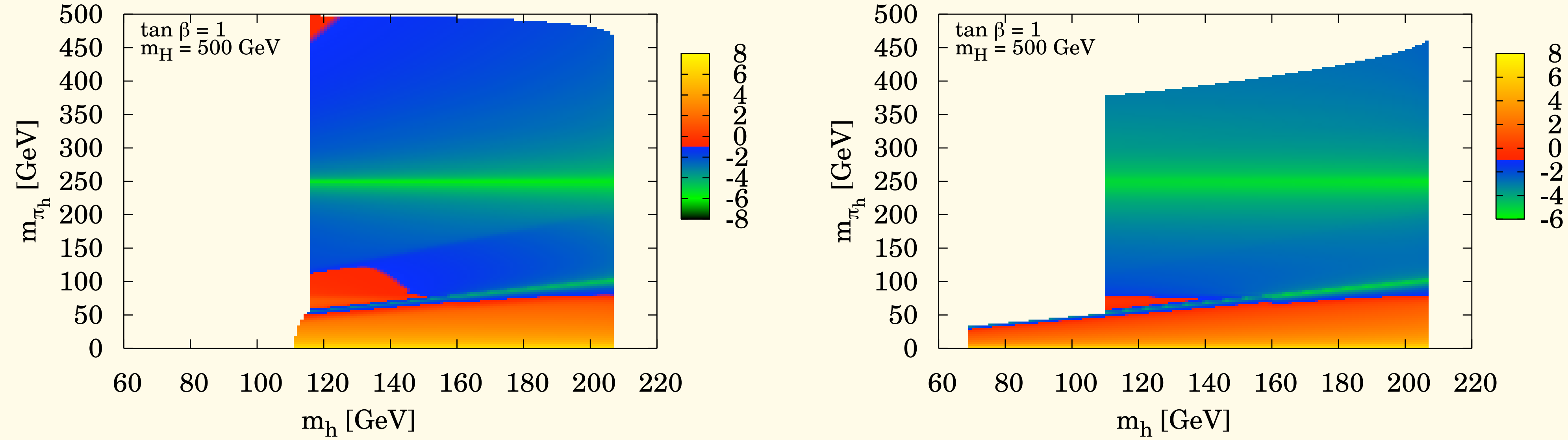
Not present in the two-Higgs Doublet model

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

$$H_1 = \left(\begin{array}{c} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{array} \right), \qquad H_2 = \left(\begin{array}{c} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{array} \right)$$

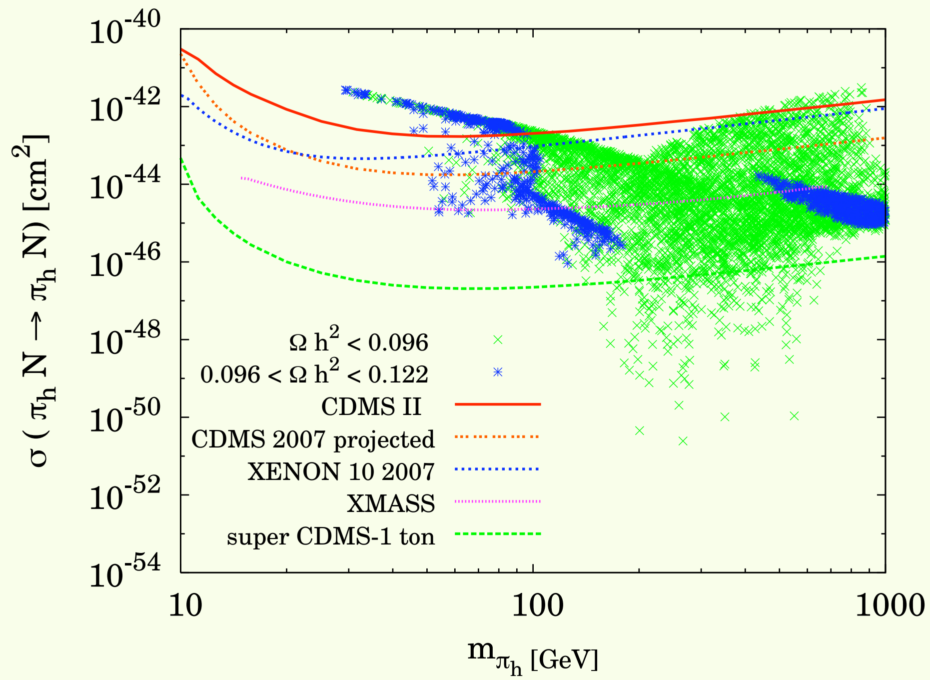
- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

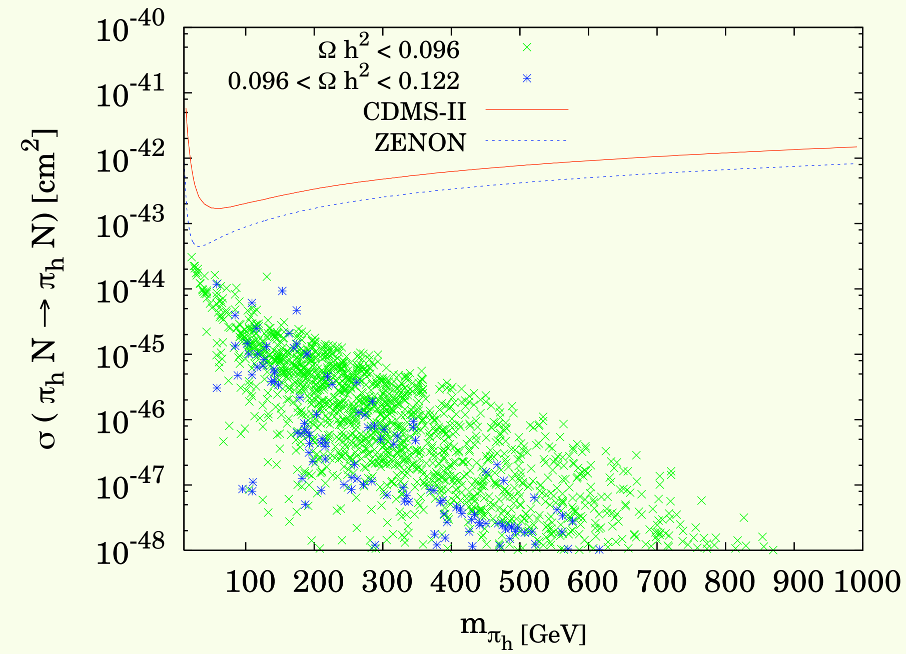
Relic Density



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

Direct detection rate





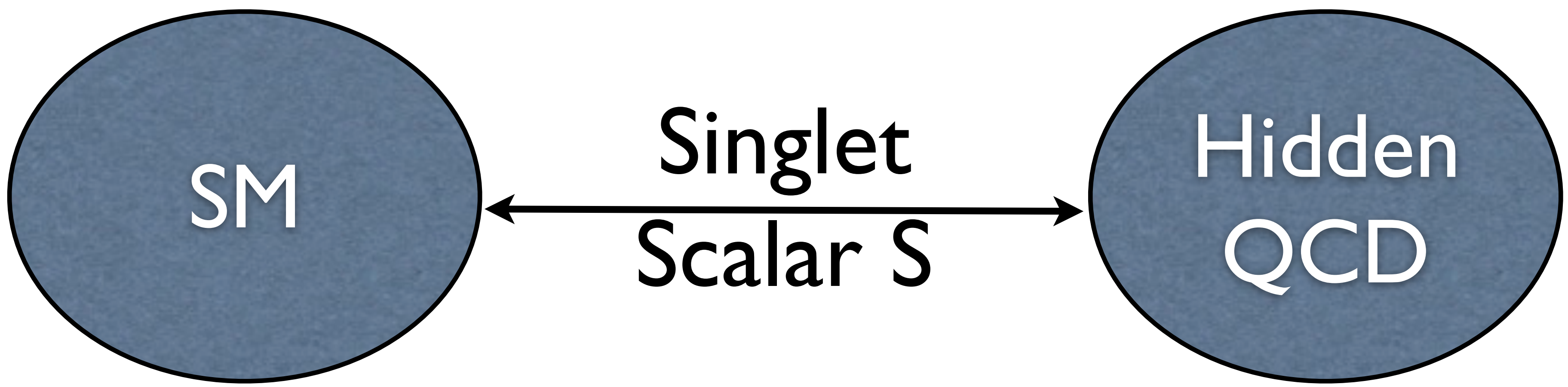
- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be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

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 : Stabilized by dark flavor sym with the help of Scale Invariance

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

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

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

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

Hidden sector lagrangian with new strong interaction

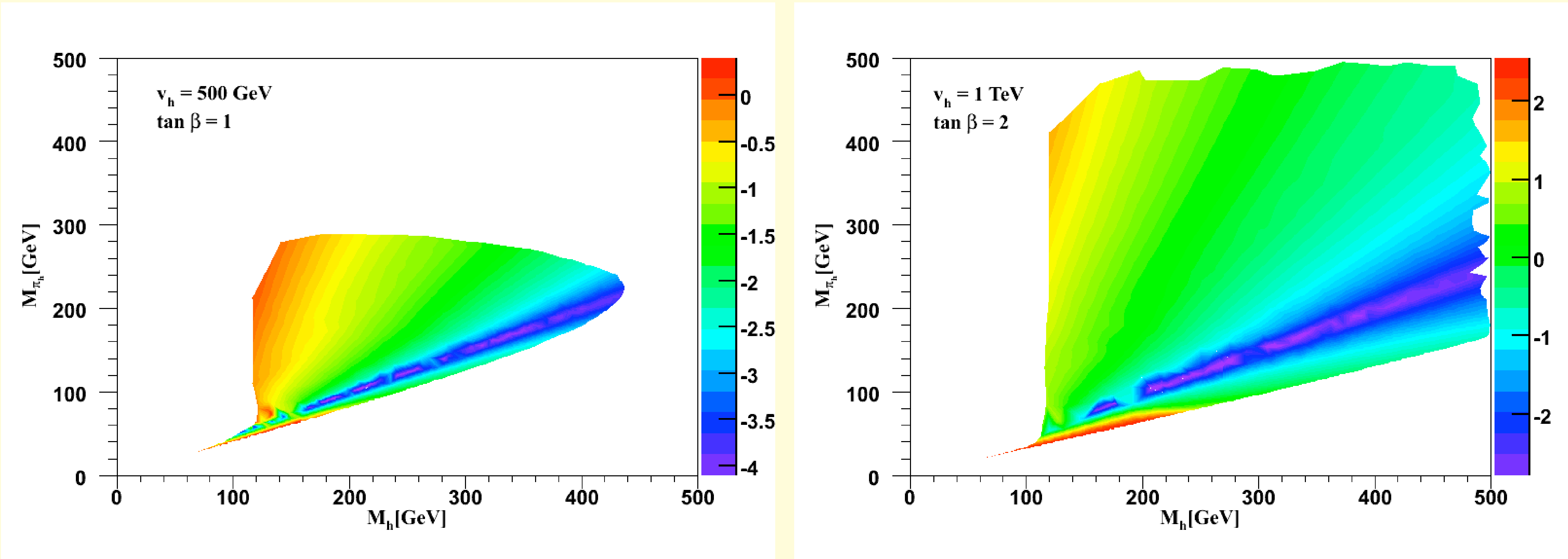
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

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

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

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

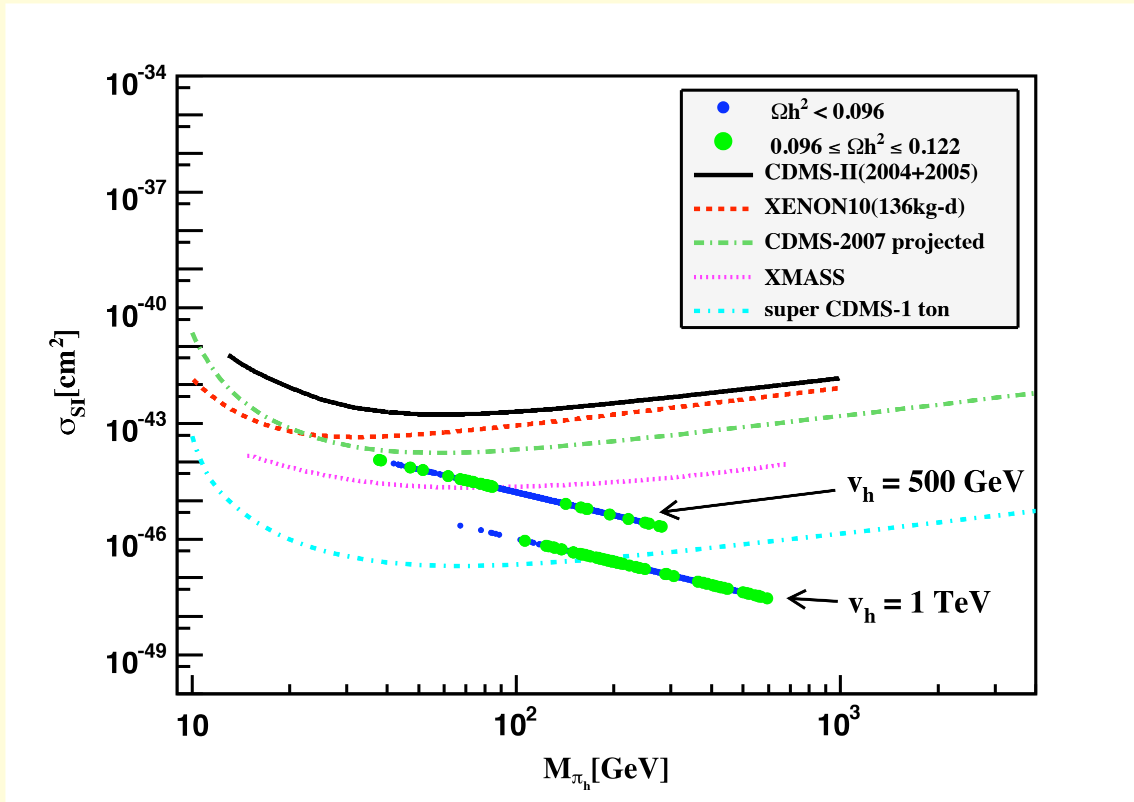
Relic density



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

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

Direct Detection Rate



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

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

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

Comparison with the other works

- 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 (dim transmutation)
- 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 or other experiments ?
- We will see if this class of DM can survive the LHC Higgs data in the coming years

SIMP scenario in DQCD + Dark resonances (ρ_D, ω_D ..)

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

SIMP paradigm

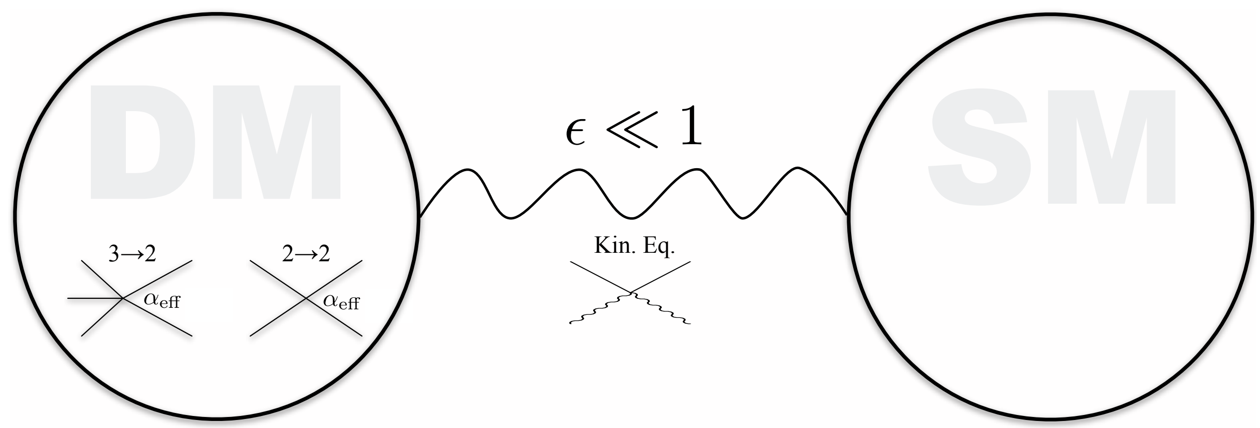


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \to 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions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

$$\Gamma_{3\to 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3\to 2} \sim H(T_F)$$

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{\alpha_{\rm eff}^3}{m_{\rm DM}^5}$$

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

2->2 Self scattering :

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

with a~O(1)

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

Dark QCD + WZW

- Dark flavor symmetry G=SU(Nf)L x SU(Nf)R is SSB into diagonal H=SU(Nf)V by dark $\langle \bar{q}q \rangle$ condensation

- Effective Lagrangian for NG bosons (dark pions) contain 5-point self interaction : WZW term for $\Pi_5(G/H) = Z(N_f > 2)$

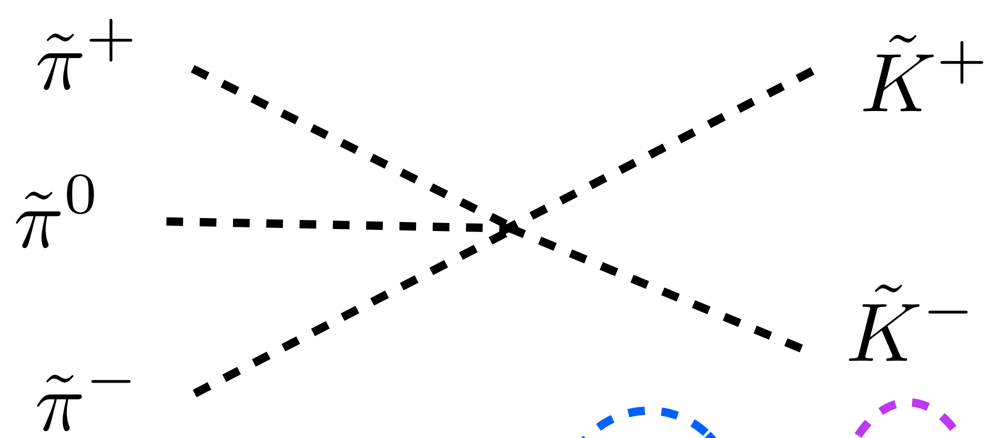
$$\Gamma_{\mathrm{WZ}} = C \int_{M^5} d^5x \ \mathrm{Tr}(\alpha^5) \qquad \text{with} \quad \alpha = dUU^\dagger.$$

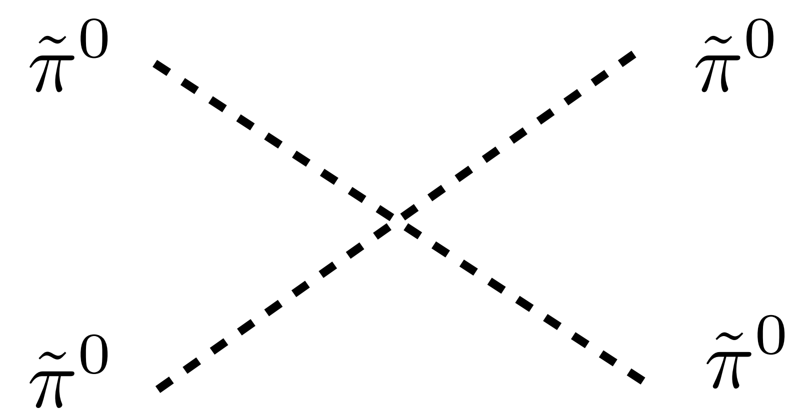
$$U = e^{2i\pi/F}$$

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

in the absence of external gauge fields

SIMP Dark Mesons





~const

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

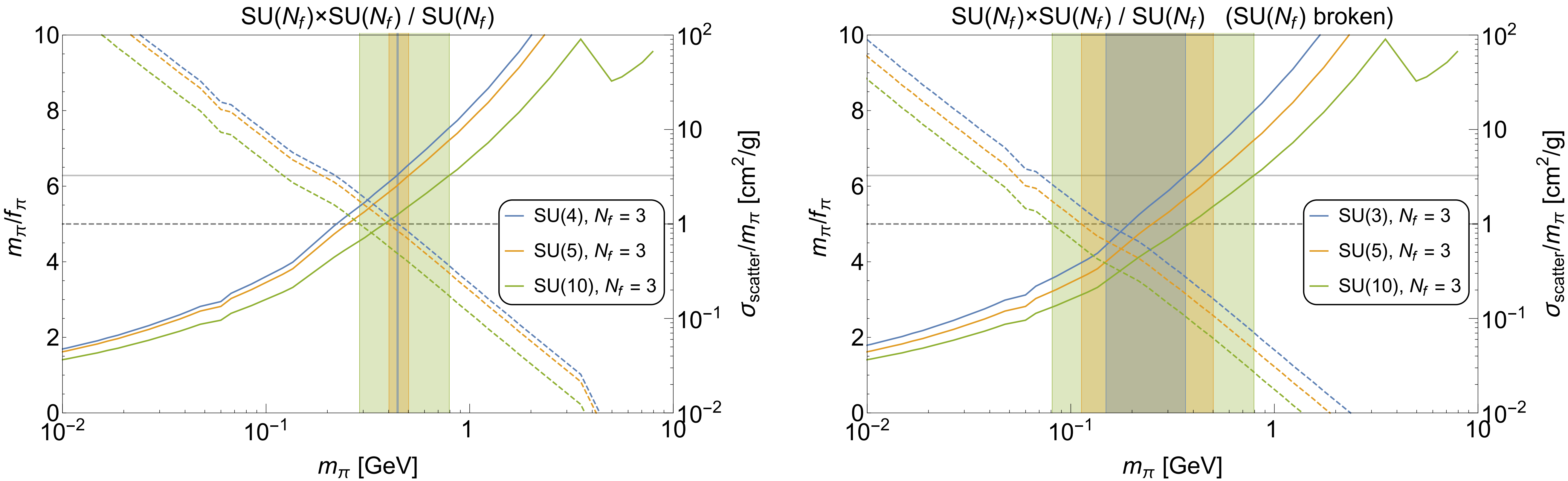
~const

$$\sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2}$$

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

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

SIMP Parameter Space



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

- DM self scattering : $\sigma_{\rm self}/m_{\rm DM} < 1\,{\rm cm}^2/{\rm g}$

Large Nc > 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. Work in progress.)

Digression on ChPT + VM

- We consider G_{global} SSB into H_{global} : non Linear sigma model on G_{global}/H_{global} is equivalent to linear sigma model on G_{global} X H_{local}

- Vector meson ~ 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 $\xi_L^\dagger(x) = \xi_R(x) = \exp[i\pi(x)/f_\pi]$:

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

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

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

Vector meson as hidden local gauge boson

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

$$
V_\mu = \frac{1}{\sqrt{2}} \left(\begin{array}{ccc} \frac{1}{\sqrt{2}}\rho^0_\mu + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & \rho^+_\mu K^{*+}_\mu & \\ \rho^-_\mu & -\frac{1}{\sqrt{2}}\rho^0_\mu + \frac{1}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}_\mu} & -\frac{2}{\sqrt{6}}\omega_{8\mu} + \frac{1}{\sqrt{3}}\omega_{0\mu} \end{array} \right) \tag{7}
$$

Ch Lagrangian (pi,V)

The chiral Lagrangian for pions and vector mesons is given by

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

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

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

Another useful quantities

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

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

WZW (gauged)

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

WZW with vector mesons

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

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

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

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

SIMP + VDM

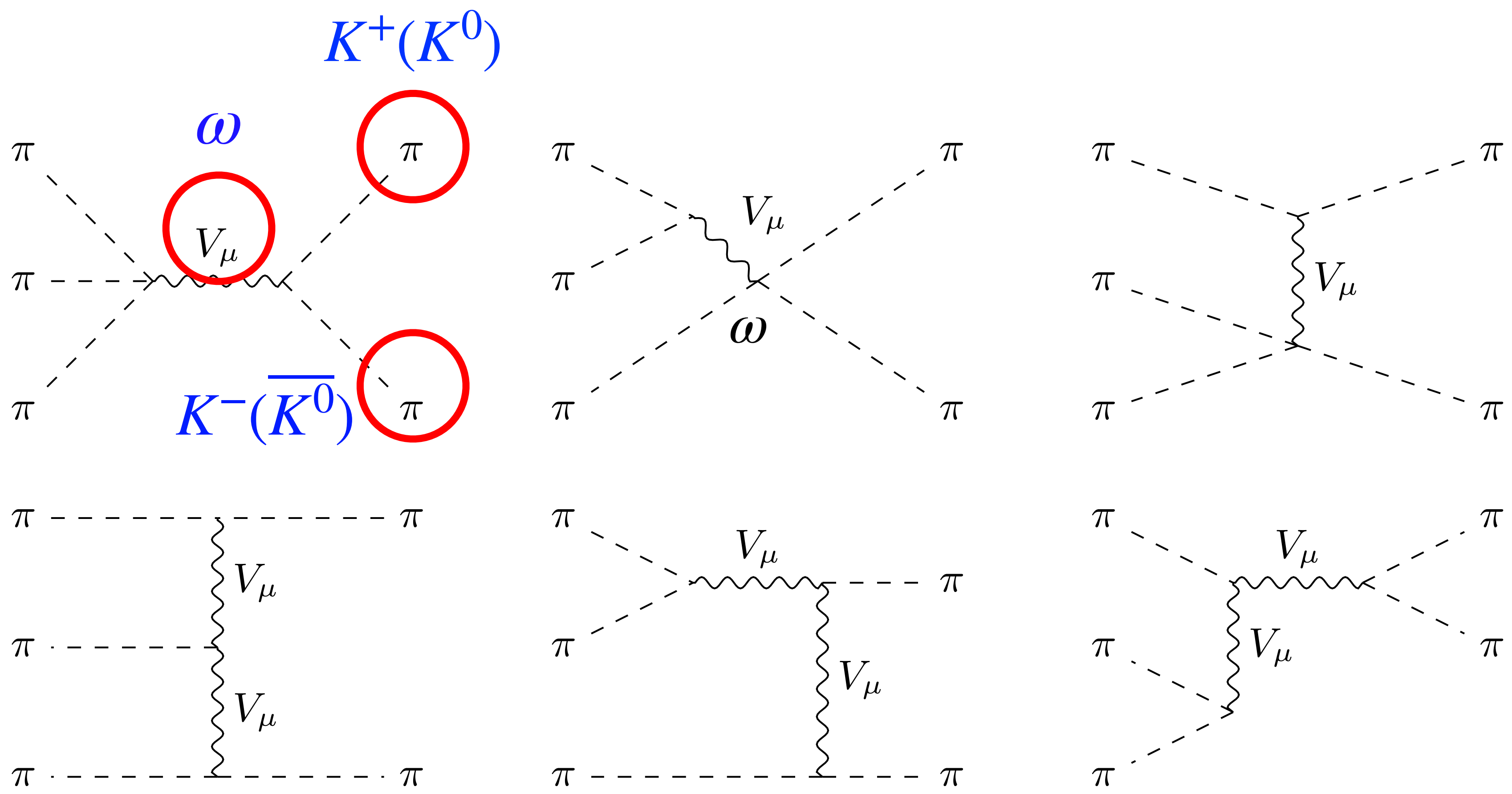


FIG. 1: Feynman diagrams contributing to $3 \to 2$ processes for the dark pions with the vector meson interactions.

SIMP + VM

New diagrams involving dark vector mesons

$$\pi^+\pi^-\pi^0 \to \omega \to K^+K^-(K^0\overline{K^0})$$

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

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

We can dial m_π and m_V independently !

- $m_\pi \propto \Lambda_{QCD} m_q$
- $m_V^2 \propto \Lambda_{QCD}^2$

Results

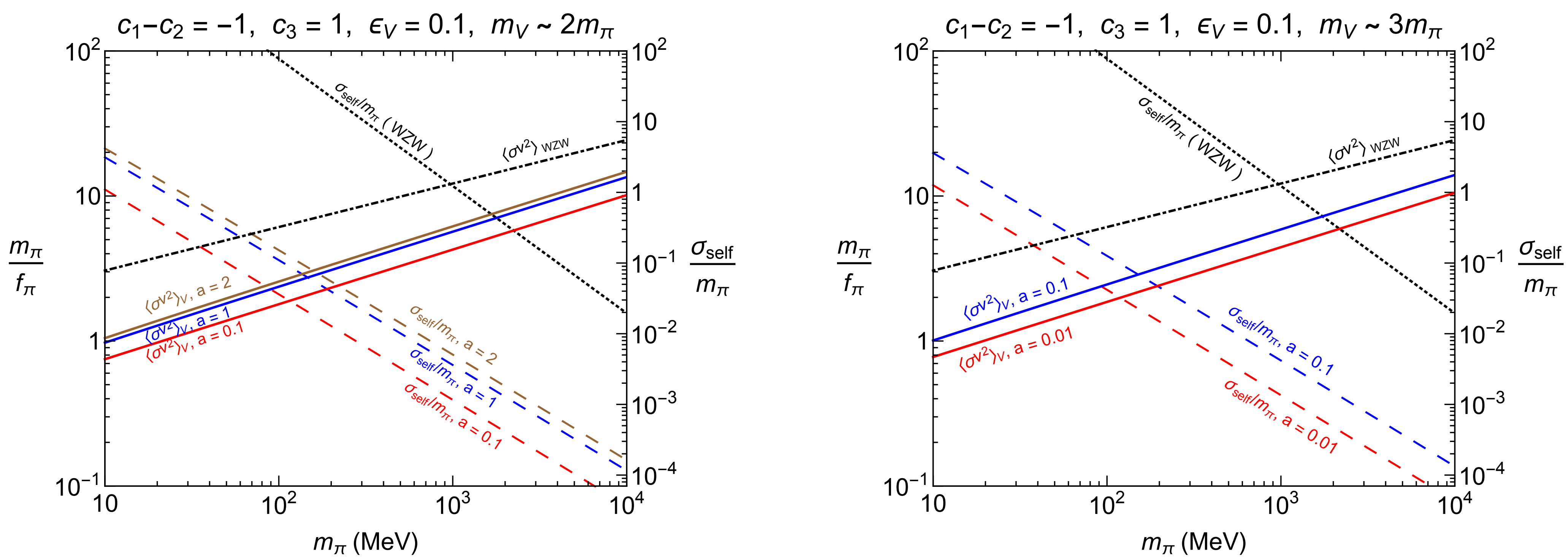


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π. The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition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

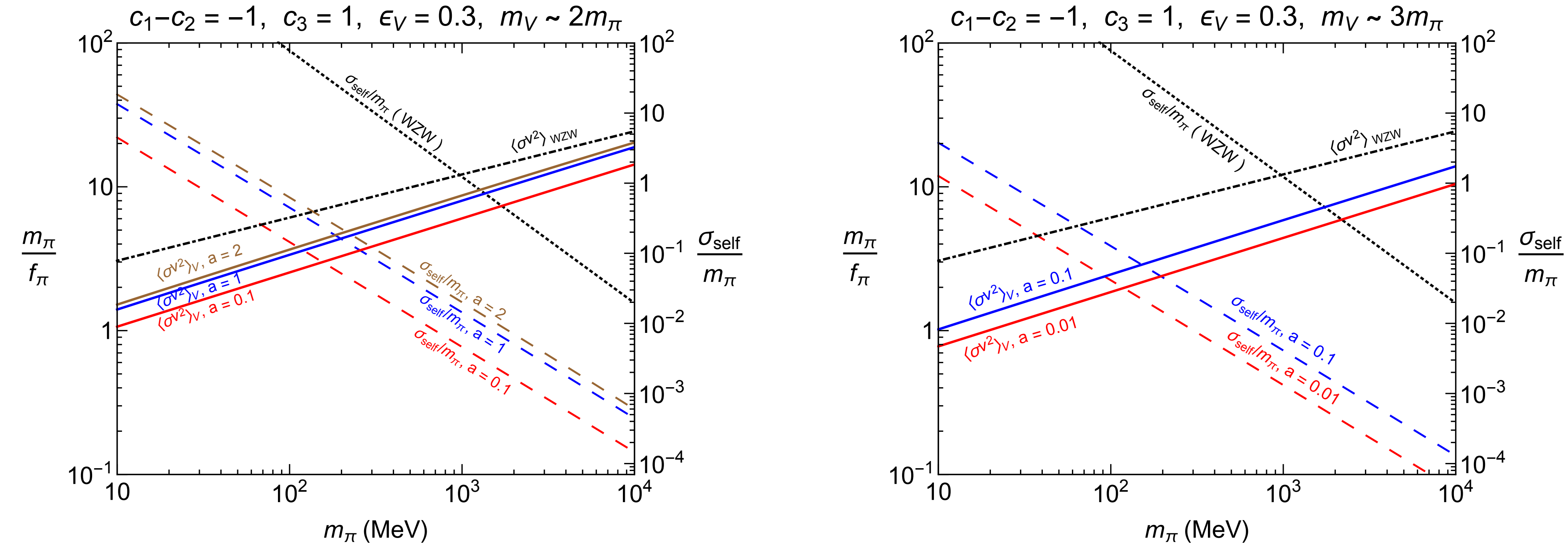


FIG. 3: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.3$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

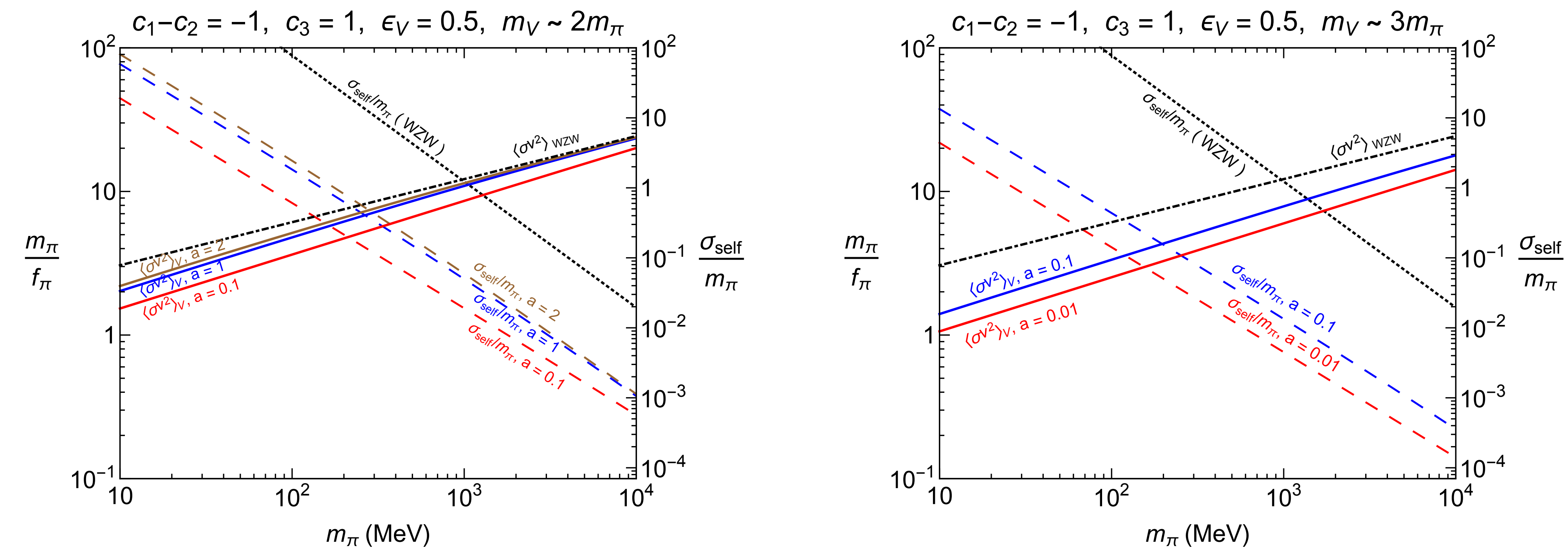


FIG. 4: Similar contours of relic density for m_π and m_π/f_π and self-scattering cross section per DM mass as in Fig. 2. Vector meson masses are taken off the resonance with $\epsilon_V = 0.5$, and $c_1 - c_2 = -1$ and $c_3 = 1$ are chosen.

Conclusion

- Hidden (dark) QCD models with CSI 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->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)