



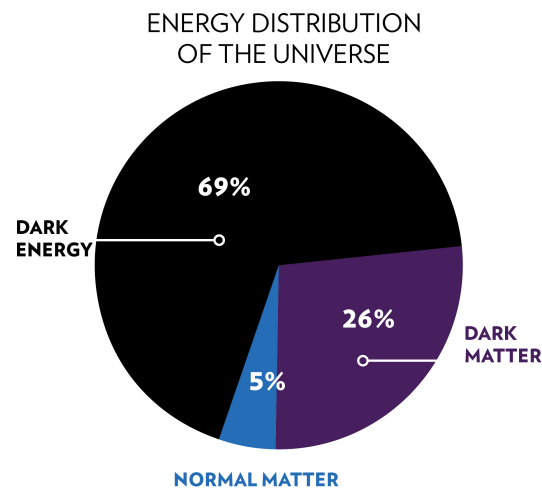
Unitarizing SIMP scenario with dark vector resonances

Soo-Min Choi (Chung-Ang University)

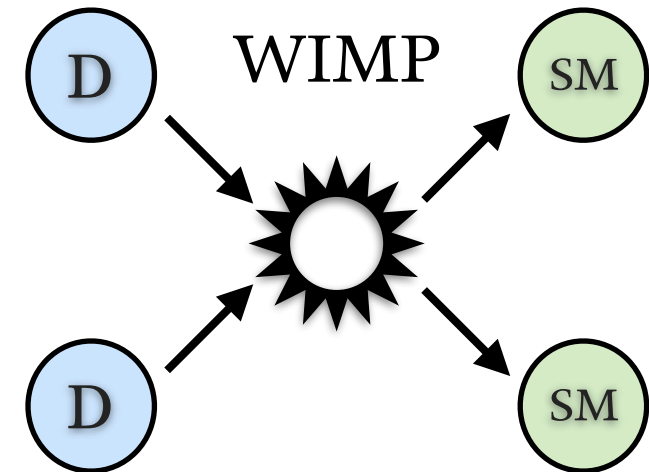
SMC, Hyun Min Lee (CAU),
Pyungwon Ko, Alexander Natale (KIAS)
Phys. Rev. D98 (2018) no.1, 015034

COSMO 2018
August 28, 2018 IBS, Daejeon

Bullet Cluster & WIMP

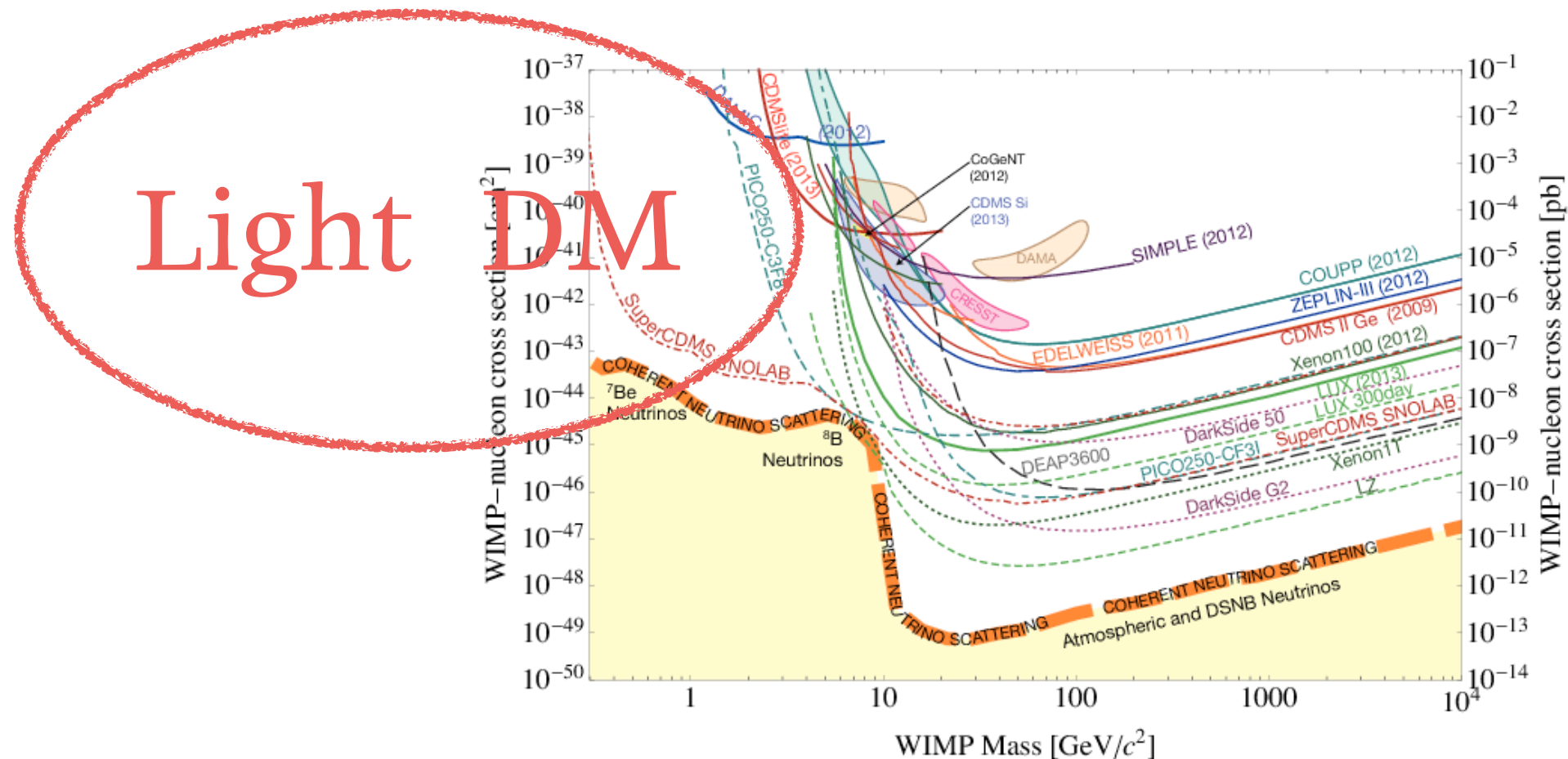


Chandra X-ray observatory



- So many indirect evidences for dark matter
- Bullet : Gravitational Lensing vs X-ray
Self-interaction bound : $\frac{\sigma_{\text{self}}}{m_\chi} \lesssim 1\text{cm}^2/\text{g}$
- WIMP : The most popular mechanism for dark matter
General freeze-out process is $\chi\chi \rightarrow f_{\text{SM}}\bar{f}_{\text{SM}}$
Mass scale is $\mathcal{O}(100\text{ GeV})$ for the relic density
Negligible self-interaction of WIMP

Direct Detection of WIMP

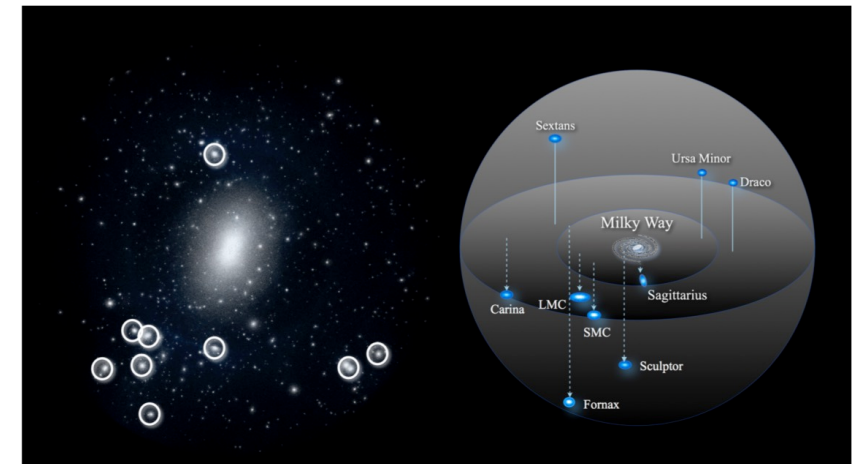
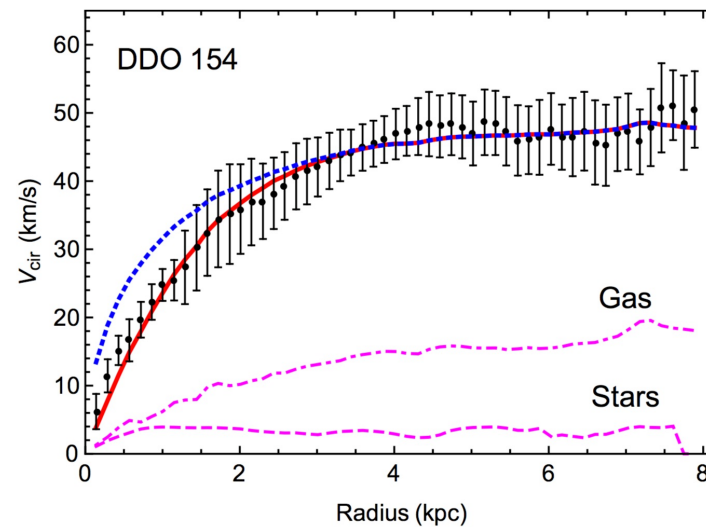
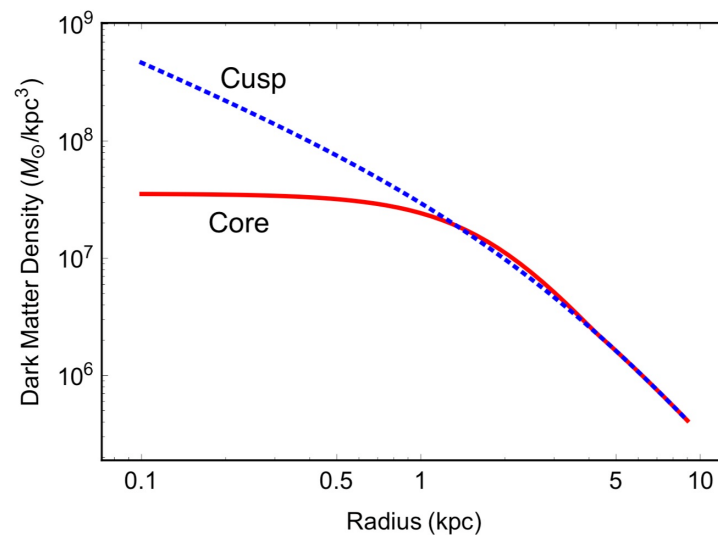


- No direct evidence for WIMP
- Direct detection is the important experiment !

M. W. Goodman, E. Witten (1985) and J. Cooley, (2014)

Small Scale Problems

Mismatch b/w Observation and Λ CDM Simulation



● Core-Cusp Problem

Sim. (Cuspy) vs Obs. (Cored)
DM density profiles

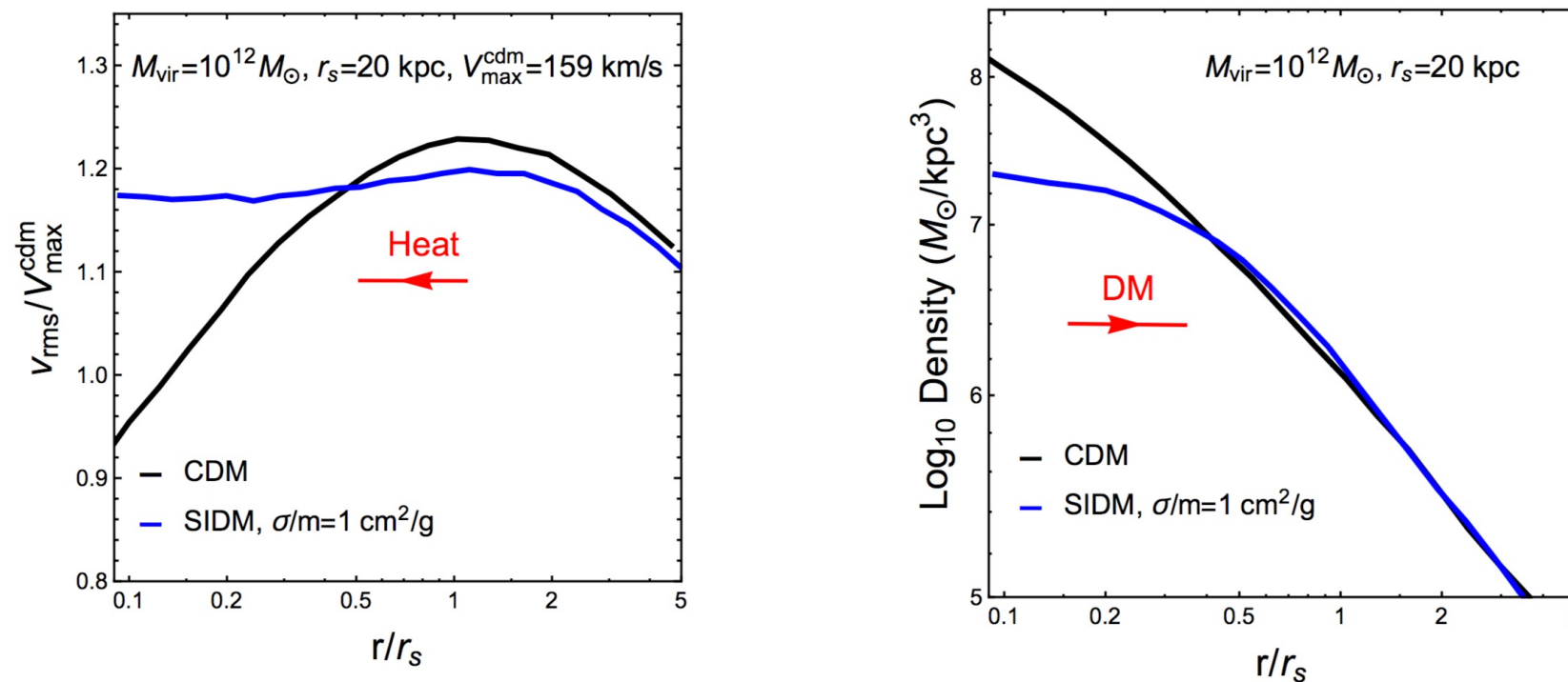
● Too-big-to-fail Problem

Too dense subhalos in Sim. ?

Bullet & Small Scale $\longrightarrow$ $0.1 \text{ cm}^2/\text{g} \lesssim \frac{\sigma_{\text{self}}}{m_\chi} \lesssim 1 \text{ cm}^2/\text{g}$

See, Sean Tulin and Hai-Bo Yu (2017), D. H. Weinberg et al (2013)

Self-Interacting Dark Matter



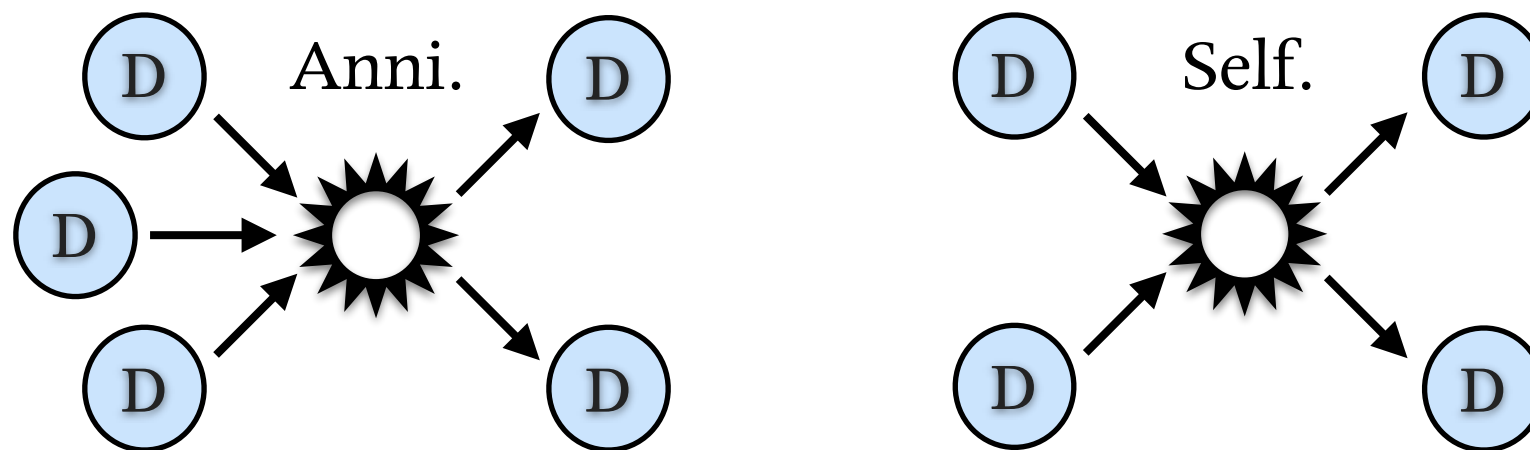
See, Sean Tulin and Hai-Bo Yu (2017)

Models for Self-Interacting Dark Matter ?

- Sommerfeld Enhancement
- Light Dark Matter as alternatives to WIMPs :
Strongly Interacting Massive particles (SIMP)

SIMP Dark Matter

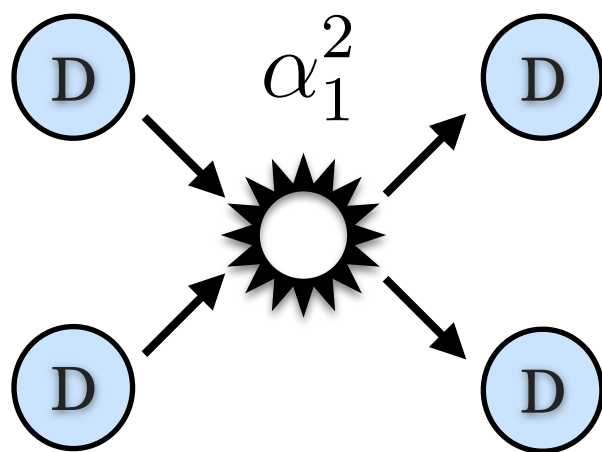
- Strongly Interacting Massive Particles
- Freeze-out process is 3 to 2 **self**-annihilation $\chi\chi\chi \rightarrow \chi\chi$ with $\langle\sigma v^2\rangle \propto \alpha^3/m_\chi^5$
- Mass scale of SIMP is $\mathcal{O}(10 - 100)$ MeV with the large coupling $\alpha \sim 1$ for the relic density
(WIMP : $\langle\sigma v\rangle \propto \alpha^2/m_\chi^2$, $\alpha \sim 1/30$)



Y. Hochberg, E. Kuflik, T. Volansky and J. G. Wacker (2014)

Why SIMP for SIDM?

Standard annihilating dark matters have tuning

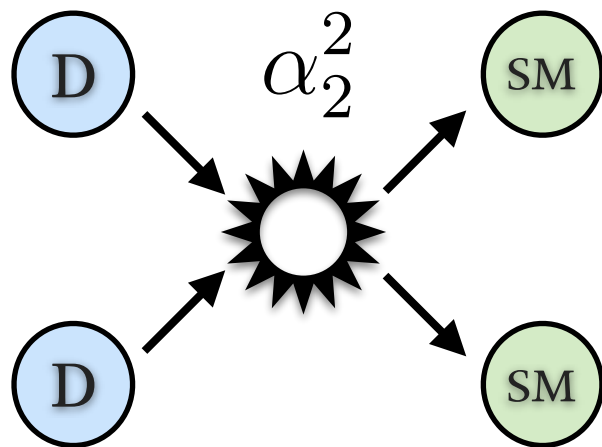


For the natural $\mathcal{O}(1)$ natural coupling

$$\sigma_{\text{self}} = \frac{\alpha_1^2}{m_\chi^2} \sim 0.1 \text{ b}$$

From $\Omega_\chi h^2 \sim 0.1 \left(\frac{1 \text{ pb}}{\langle \sigma_{\text{anni.}} v \rangle} \right)$,

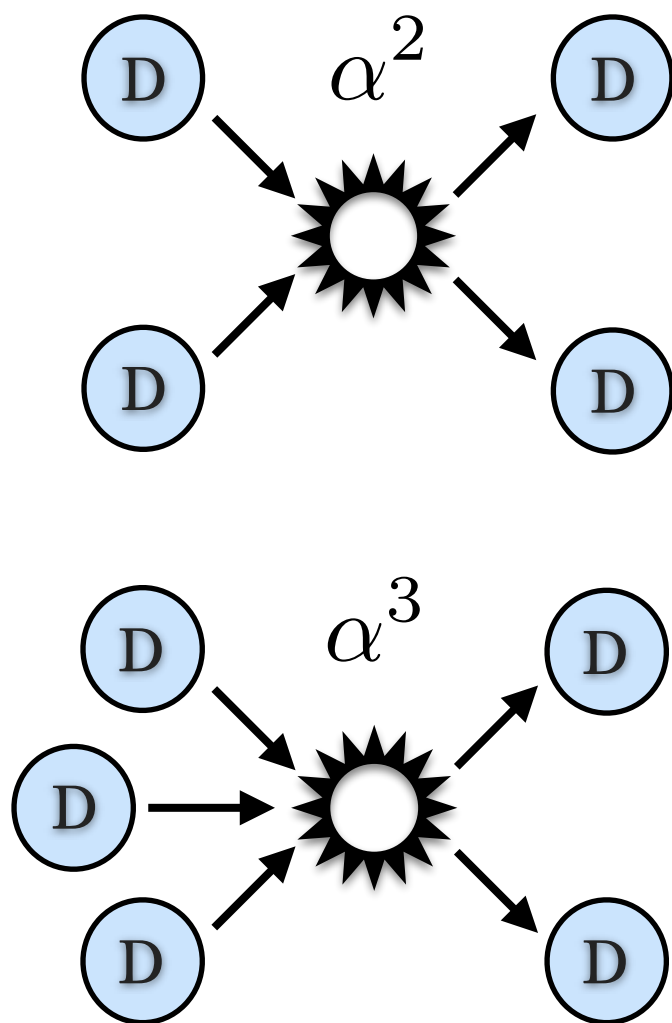
$$\langle \sigma_{\text{anni.}} v \rangle = \frac{\alpha_2^2}{m_\chi^2} \sim 1 \text{ pb}$$



$$\therefore \frac{\alpha_2^2}{\alpha_1^2} \sim 10^{-11} \Rightarrow \text{Must be tuned}$$

Why SIMP for SIDM?

SIMP is a natural mechanism of self-interacting dark matter



For the $\mathcal{O}(1)$ natural coupling

$$\sigma_{\text{self}} = \frac{\alpha^2}{m_\chi^2} \sim 0.1 \text{ b}$$

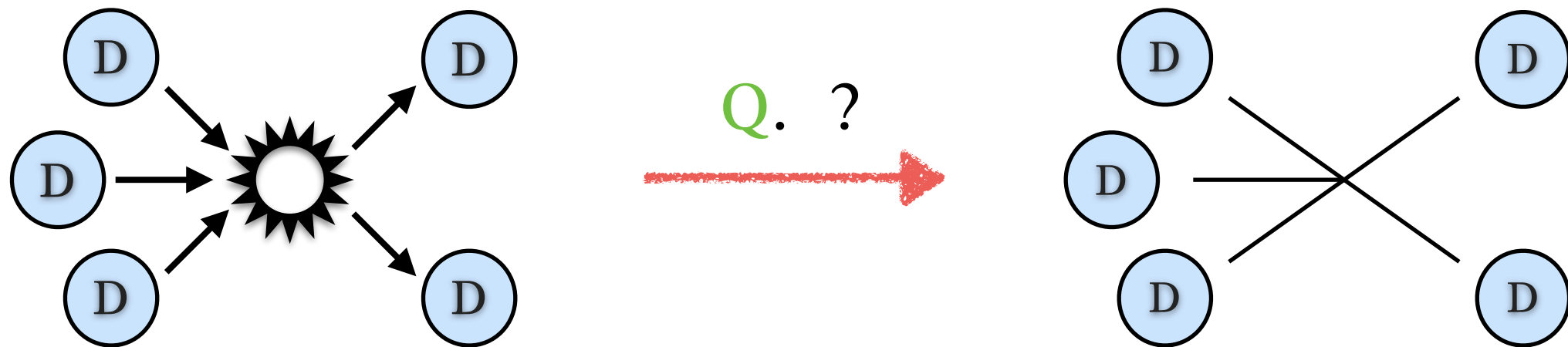
From $\Omega_\chi h^2 \sim 0.1 \left(\frac{1 \text{ pb}}{\langle \sigma_{\text{eff.}} v \rangle} \right)$,

$$\langle \sigma_{\text{eff.}} v \rangle = n_\chi \langle \sigma v^2 \rangle = n_\chi \times \frac{\alpha^3}{m_\chi^5}$$

$$= R \times \sigma_{\text{self}} = 1 \text{ pb}$$

$$\left(\because R = \frac{g_\chi \alpha}{(2\pi)^{3/2}} x_f^{-3/2} e^{-x_f} \sim 10^{-11} \right)$$

The SIMPlest realization



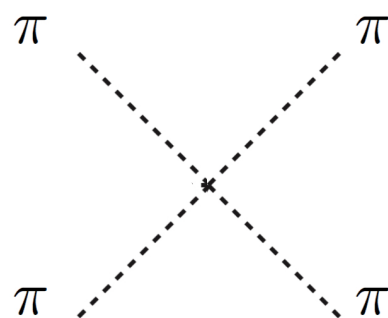
A. WZW term for Dark ChPT

- Like Standard Model QCD, $\mathcal{L} = -\frac{1}{4}G_{\mu\nu}^a G^{\mu\nu a} + \sum_{i=1}^3 \bar{Q}_i i\gamma^\mu D_\mu Q_i$
- Global $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$ by condensation and pions have degenerated masses.
- Dark Pions have WZW term which contains color number as a topological index $\longrightarrow \mathcal{L}_{\text{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \text{Tr}[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi]$

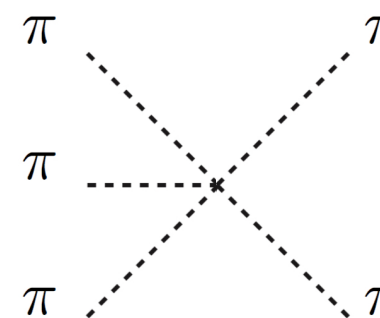
Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J. G. Wacker (2014)

Perturbativity Problem

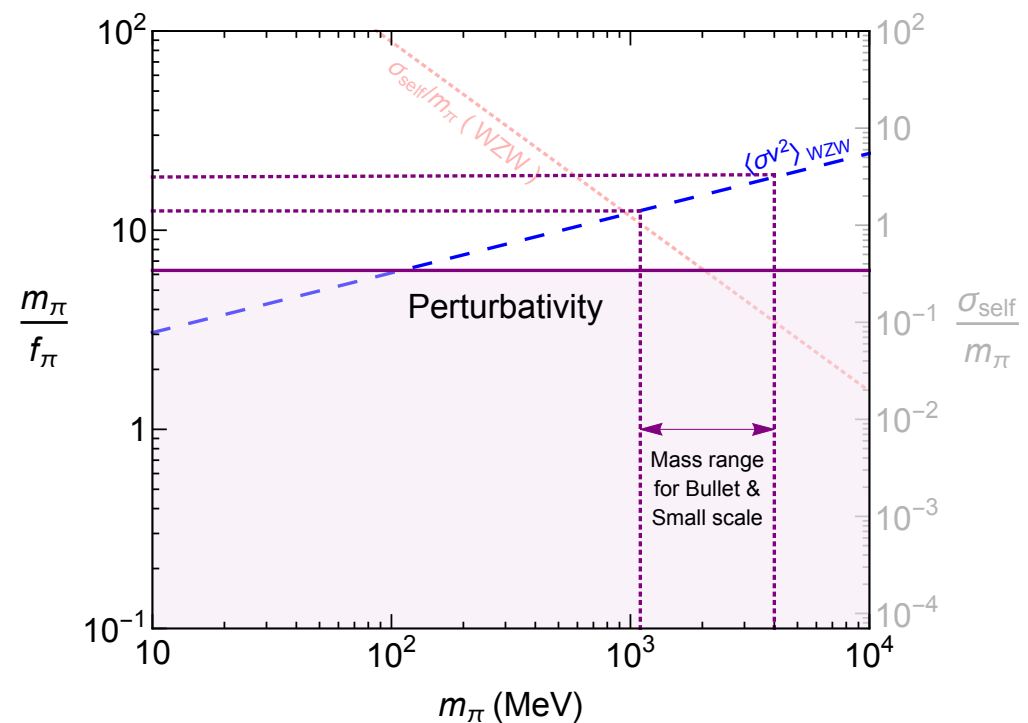
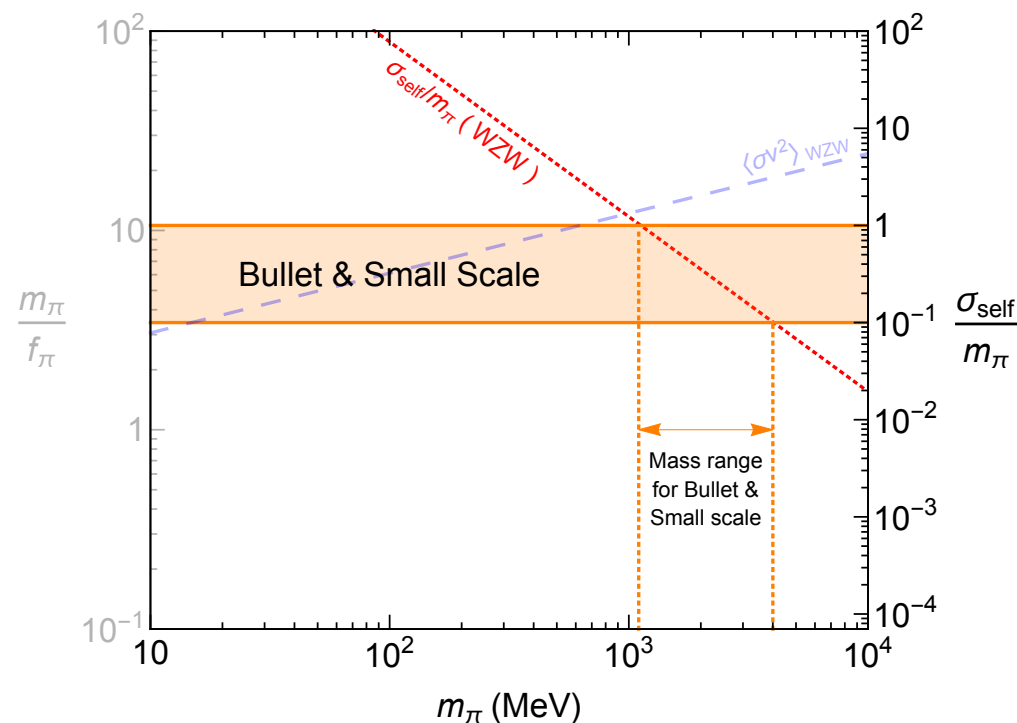
- This minimal SIMP with pions only has **perturbativity problem**. So Leading order ChPT will break down. ($m_\pi/f_\pi \sim 2\pi$)



$$\propto \frac{(m_\pi/f_\pi)^4}{m_\pi^2}$$



$$\propto \frac{(m_\pi/f_\pi)^{10}}{m_\pi^5}$$



M. Hansen, K.Langaebler and F. Sannino (2015)

Dark Pion with Vector Mesons

- Non-linearly transformed $G_{\text{global}}/H_{\text{global}} = SU(3)_L \times SU(3)_R/SU(3)_V$
= Integrating out the vector mesons from linearly realized $G_{\text{global}} \times H_{\text{local}}$
- Vector mesons are the massive gauge fields of a local $SU(3)_V (\equiv H_{\text{local}})$ and they have degenerated masses
- Vector mesons mediate pion interactions.

$$\mathcal{L} = \mathcal{L}_\pi - \frac{1}{2} \text{Tr}(V_{\mu\nu} V^{\mu\nu}) + \Delta\mathcal{L}_V + \mathcal{L}_{\text{anon.}}$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$\Delta\mathcal{L}_V = m_V^2 \text{Tr}(V_\mu V^\mu) - iag \text{Tr}(V_\mu [\partial^\mu \pi, \pi]) - \frac{a}{4f_\pi^2} \text{Tr}([\pi, \partial_\mu \pi]^2)$$

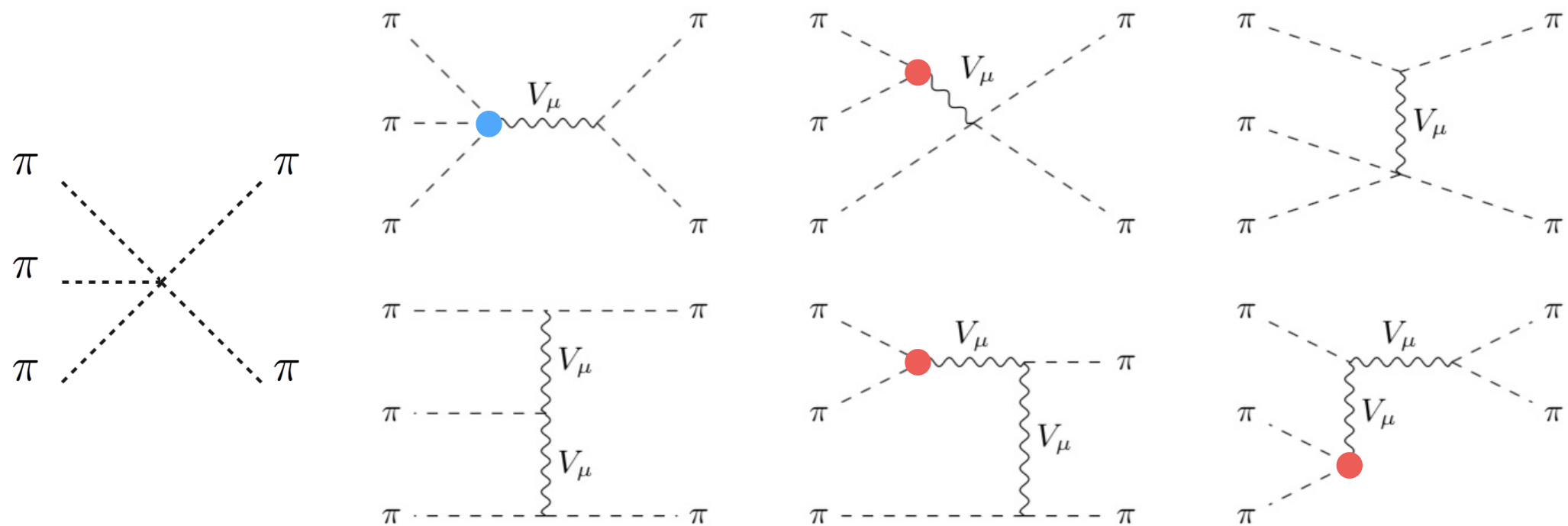
$$m_V^2 = ag^2 f_\pi^2$$

M. Bando et al (1988), P. Ko (1991), [SMC](#), H. M. Lee, P. Ko and A. Natale (2018)

Dark Pion with Vector Mesons

$$\begin{aligned}\Delta\mathcal{L}_V + \mathcal{L}_{\text{anom.}} &= \Delta\mathcal{L}_V + \mathcal{L}_{\text{WZW}} - 15(c_1\mathcal{L}_1 + c_2\mathcal{L}_2 + c_3\mathcal{L}_3) \\ &\supset -iag\text{Tr}(V_\mu[\partial^\mu\pi, \pi]) - \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \text{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi] \\ &\quad - \frac{igN_c(c_1 - c_2)}{4\pi^2 f_\pi^3} \epsilon^{\mu\nu\rho\sigma} \text{Tr}[V_\mu\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi] + \frac{gN_c c_3}{8\pi^2 f_\pi} \epsilon^{\mu\nu\rho\sigma} \text{Tr}[(\partial_\mu V_\nu)(V_\rho\partial_\sigma\pi - \partial_\rho\pi V_\sigma)]\end{aligned}$$

7 types of 5-point interactions with 2 types of resonances



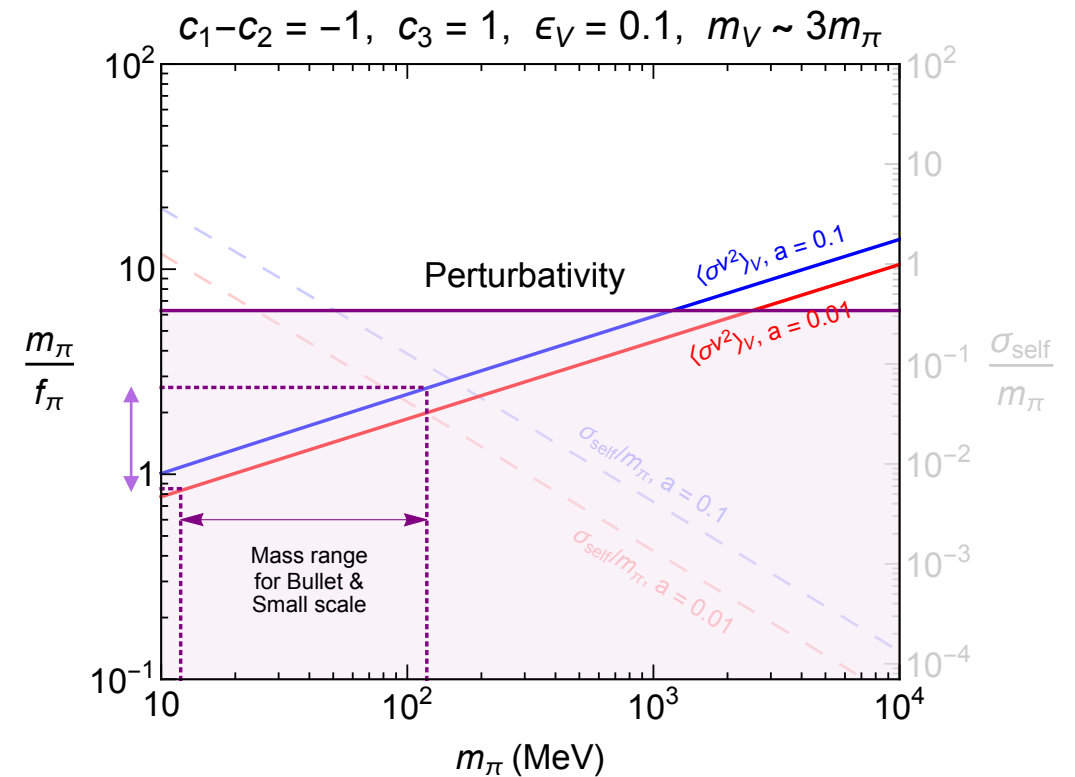
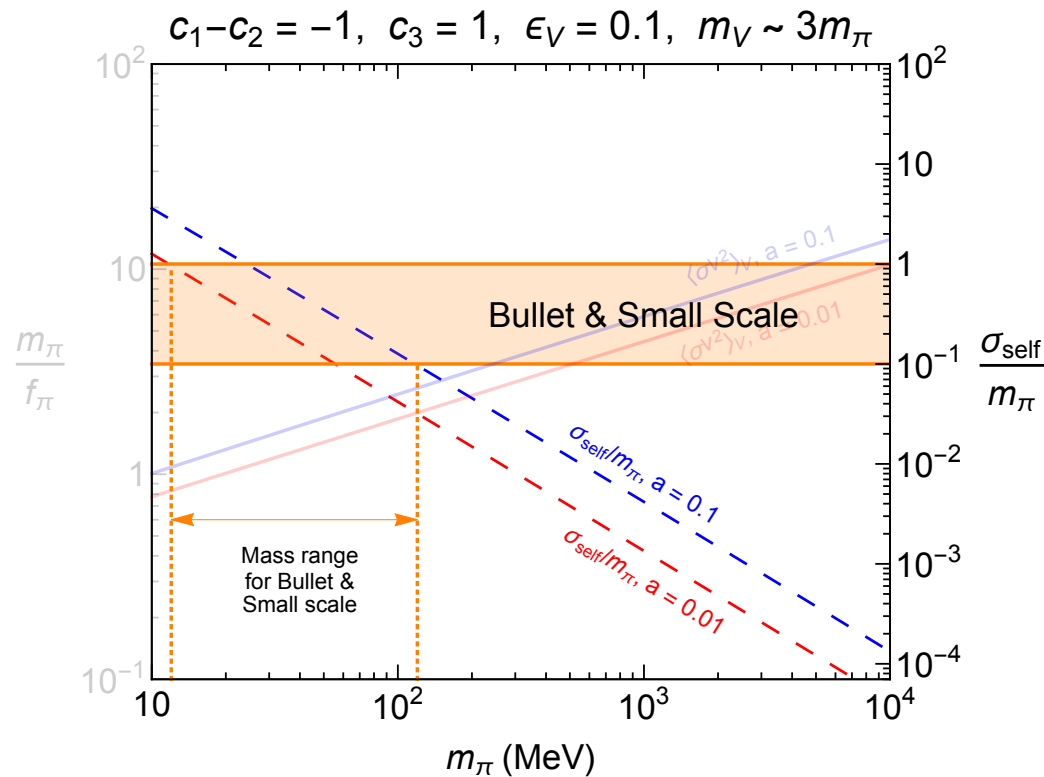
SMC, H. M. Lee, P. Ko and A. Natale (2018)

Dark Pion with Vector Mesons

- Large effects appear on **resonance** (3-pion resonance : $(m_V = 3m_\pi\sqrt{1 + \epsilon_V})$)
- Expansion parameter (m_π/f_π) can be smaller by vector meson mediated diagrams.

$$\begin{array}{c} \pi \\ \pi \\ \pi \end{array} \begin{array}{c} \diagup \\ \diagdown \\ \diagup \end{array} \begin{array}{c} \bullet \\ \text{---} V_\mu \text{---} \bullet \end{array} \begin{array}{c} \diagdown \\ \diagup \\ \diagdown \end{array} \begin{array}{c} \pi \\ \pi \\ \pi \end{array} \propto \left(\frac{m_\pi}{f_\pi} \right)^{10} \frac{(c_1 - c_2)^2}{(s - m_V^2)^2 + m_V^2 \Gamma_V^2}$$

$$\& \quad s \sim \left(3m_\pi + \frac{1}{2}m_\pi(v_1^2 + v_2^2 + v_3^2) \right)^2 \quad @ \text{ COM frame}$$

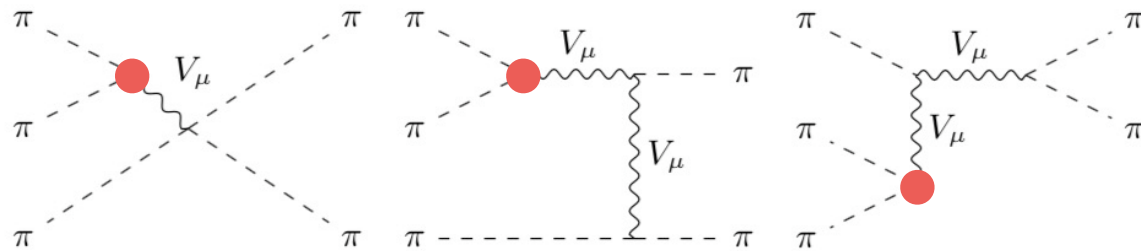


SMC, H. M. Lee, P. Ko and A. Natale (2018)

For thermal average, SMC, H. M. Lee (2016), SMC, H. M. Lee and M. S. Seo (2017)

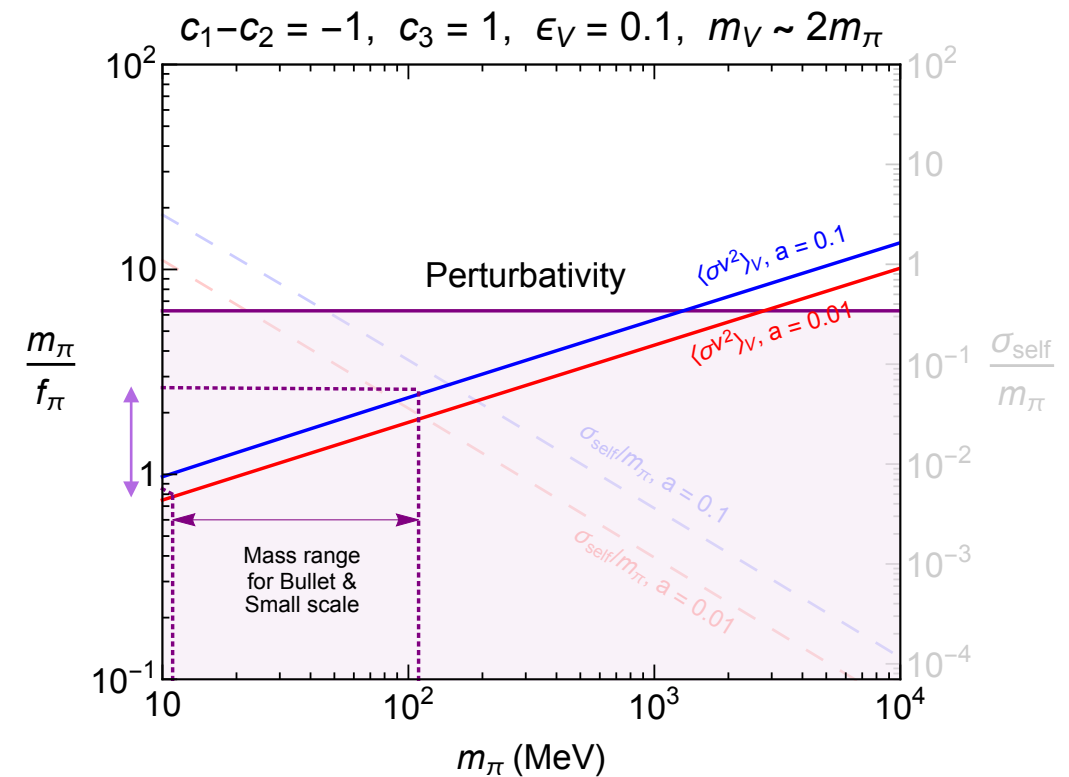
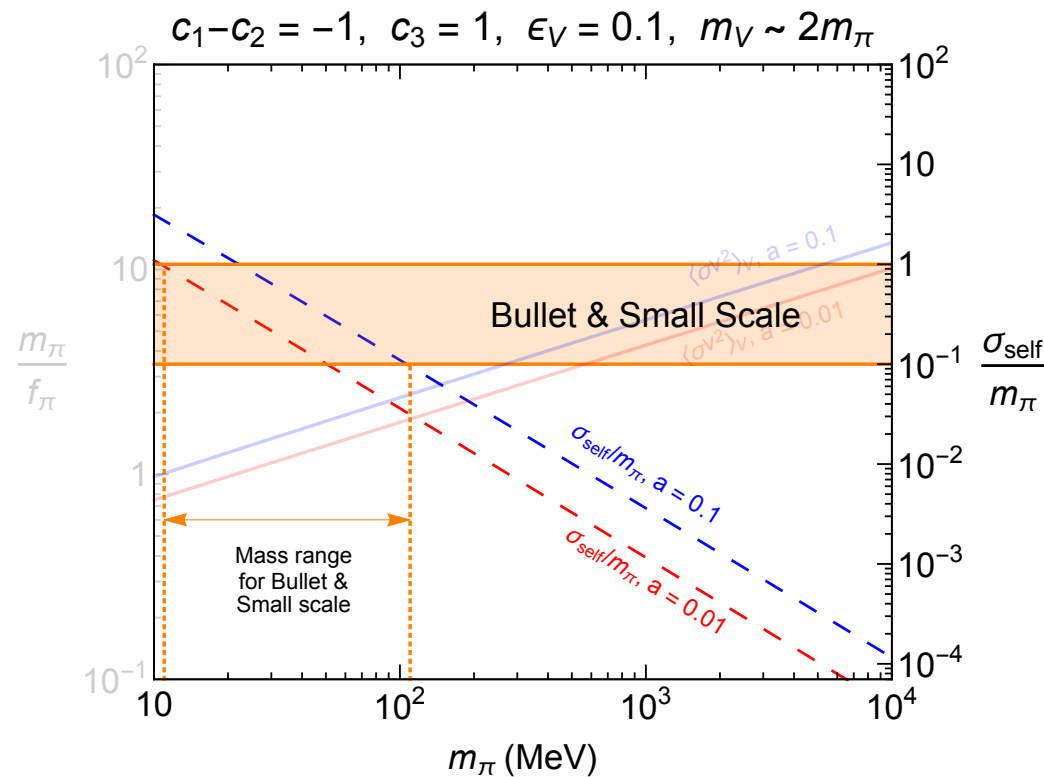
Dark Pion with **Vector Mesons**

- Large effects appear on **resonance** (**2**-pion resonance : $(m_V = 2m_\pi\sqrt{1 + \epsilon_V})$)
- Expansion parameter (m_π/f_π) can be smaller by vector meson mediated diagrams.



$$\propto \left(\frac{m_\pi}{f_\pi}\right)^{10} \frac{(c_1 - c_2)^2}{(s - m_V^2)^2 + m_V^2 \Gamma_V^2}$$

$$\& \quad s \sim \left(2m_\pi + \frac{1}{2}m_\pi(v_1^2 + v_2^2)\right)^2 - m_\pi^2 v_3^2 \quad @ \text{ COM frame}$$

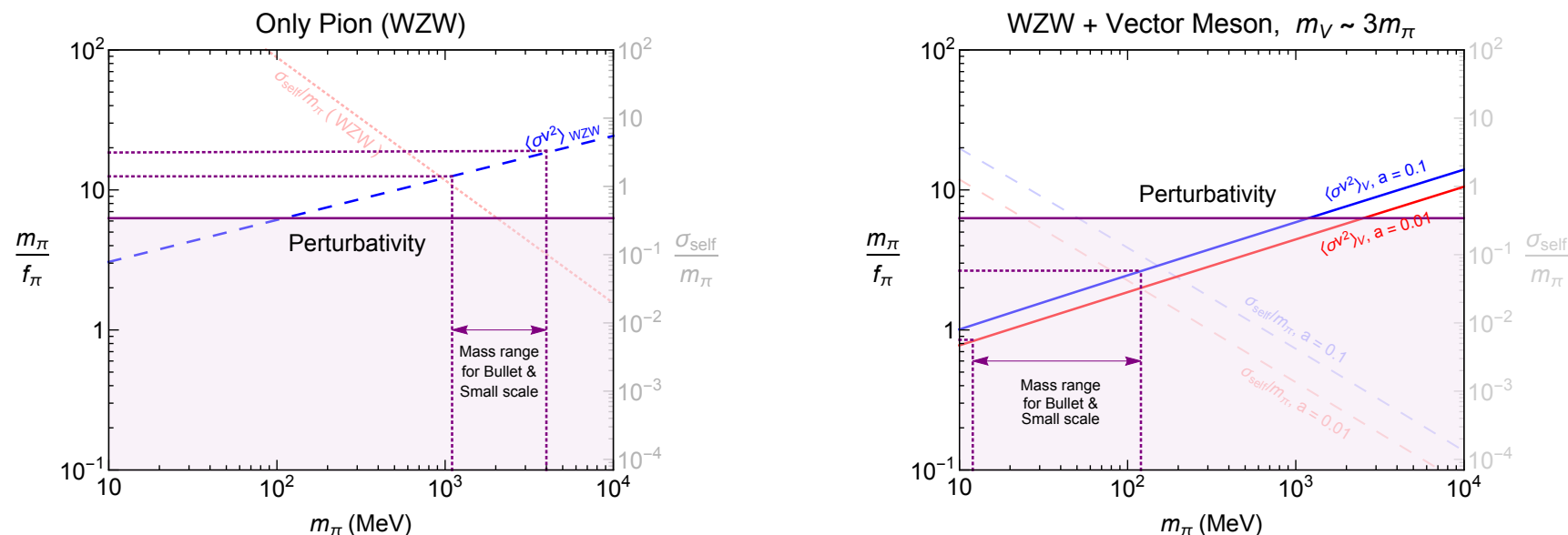


[SMC](#), H. M. Lee, P. Ko and A. Natale (2018)

For thermal average, [SMC](#), H. M. Lee (2016), [SMC](#), H. M. Lee and M. S. Seo (2017)

Conclusions

- We have considered a SIMP scenario of dark pions which are the pseudo-Goldstones from dark flavor symmetry and strongly coupled from dark QCD interactions.
- Including vector mesons in the hidden gauge symmetry, we showed that the perturbativity problem of SIMP scenarios in dark ChPT can be alleviated.



- Resonance masses of dark vector mesons can be searched through the kinetic mixing via dark photon.
- More general cases with non-degenerate pion masses and kinetic equilibrium conditions with dark sigma field or dark photon are in progress.

Back-up $\left(m_V = 2(3)m_\pi \sqrt{1 + \epsilon_V} \right)$

