Unitarizing SIMP scenario with dark vector resonances

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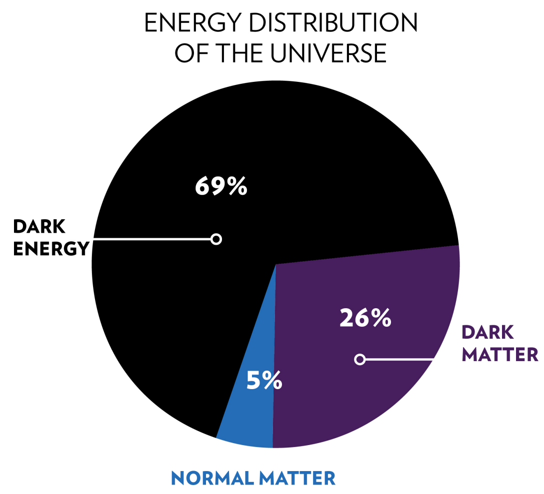
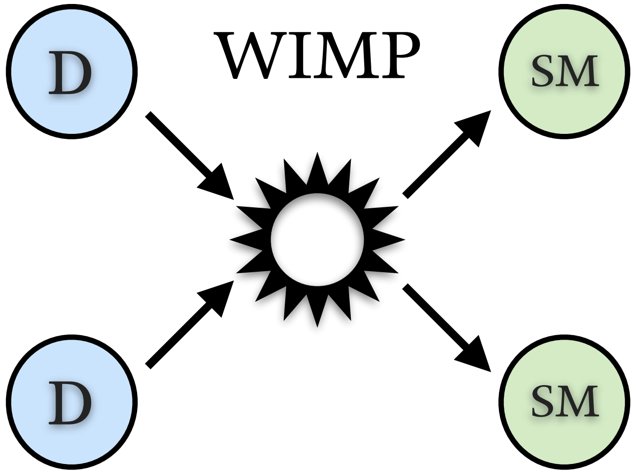
Bullet Cluster & WIMP

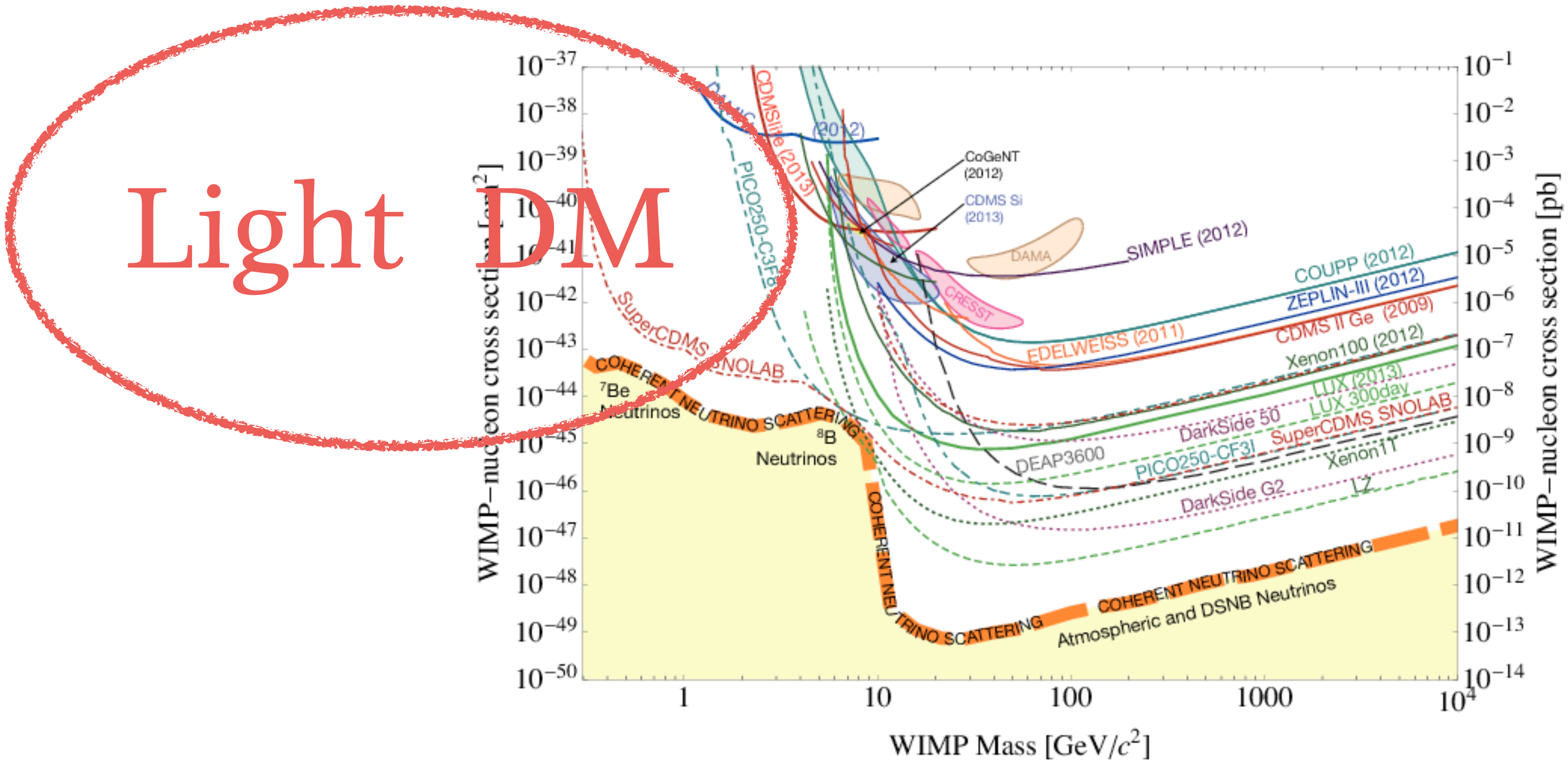


Chandra X-ray observatory



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

Direct Detection of WIMP

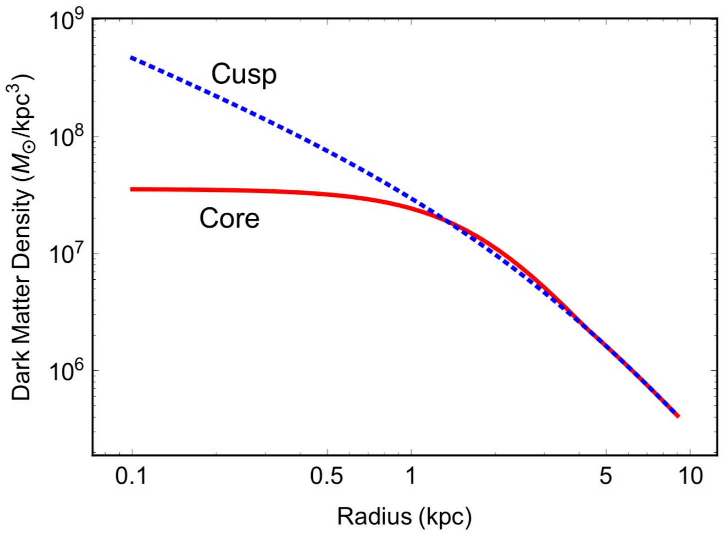


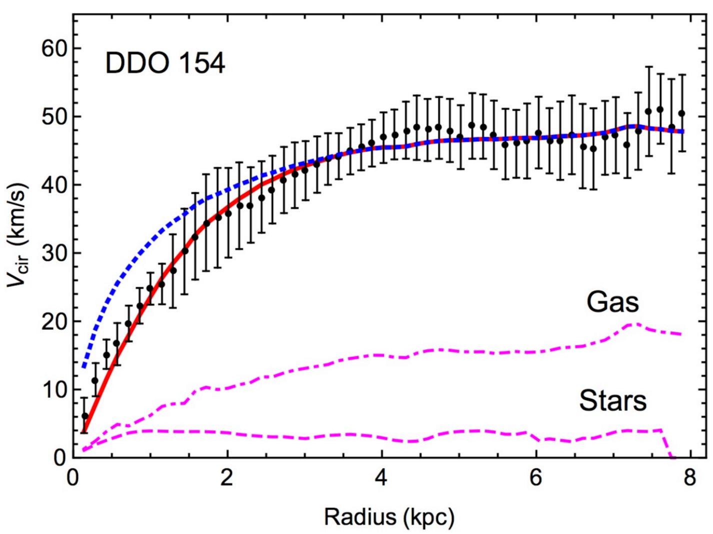
- No direct evidence for WIMP
- Direct detection is the important experiment !

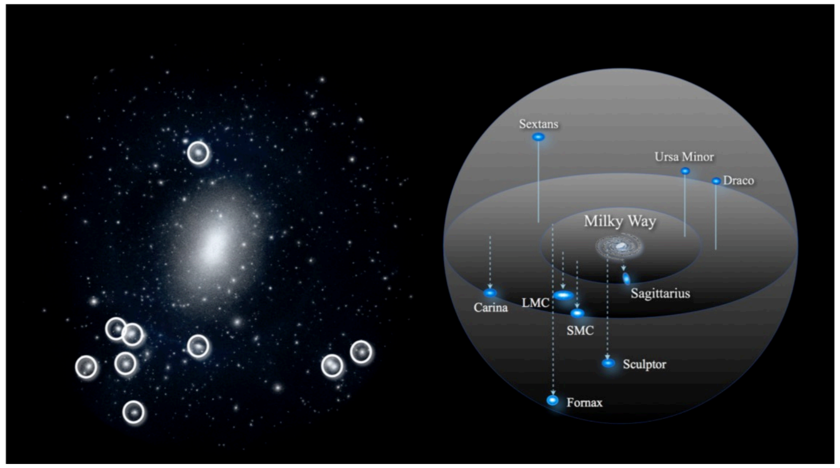
M. W. Goodman, E. Witten (1985) and J. Cooley, (2014)

Small Scale Problems

Mismatch b/w Observation and ΛCDM Simulation







- Core-Cusp Problem

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

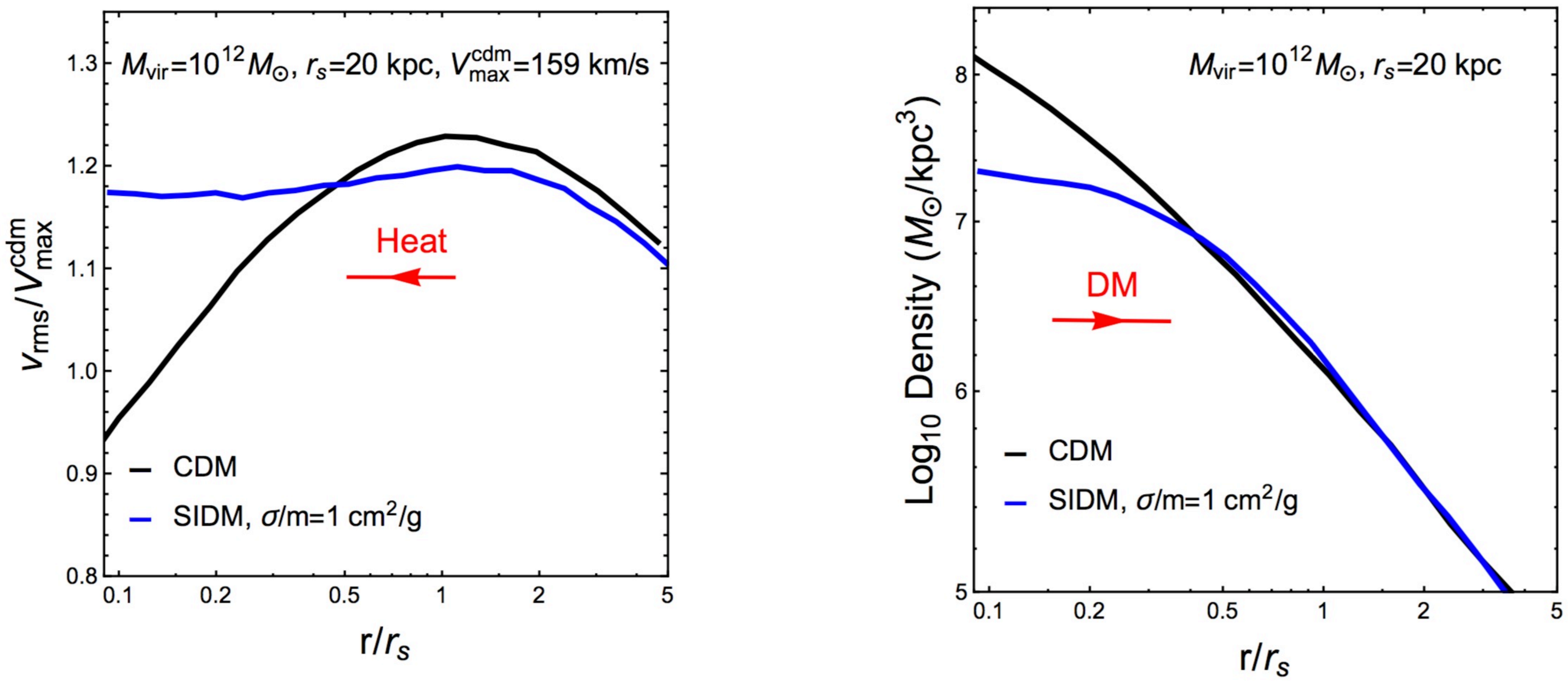
- Too-big-to-fail Problem

Too dense subhalos in Sim. ?

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

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

Self-Interacting Dark Matter



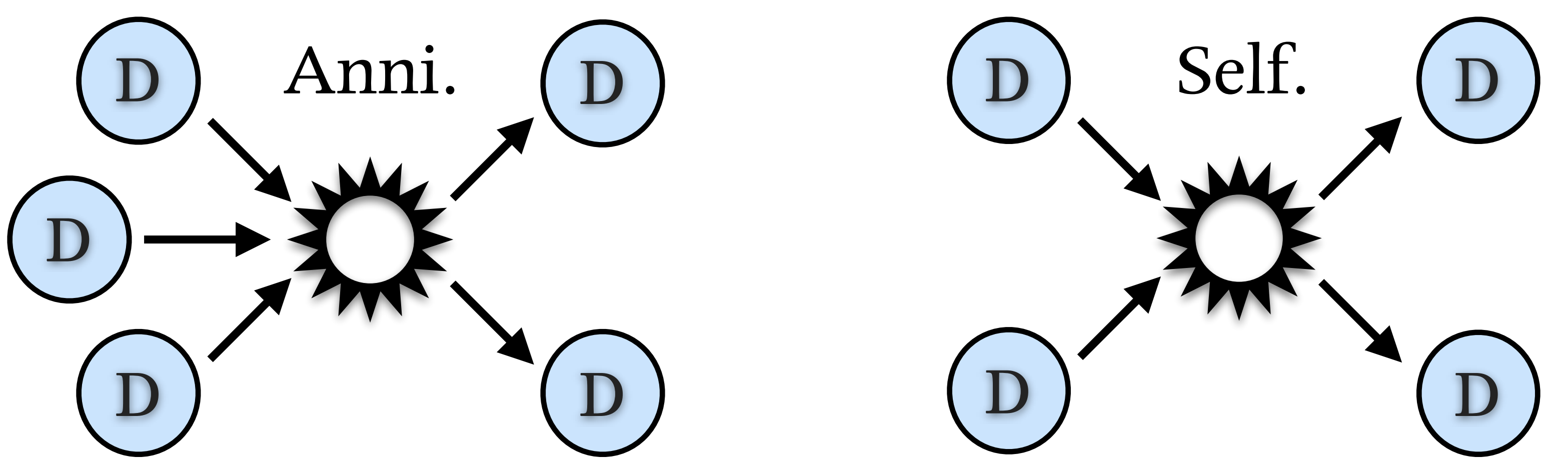
See, Sean Tulin and Hai-Bo Yu (2017)

Models for Self-Interacting Dark Matter ?

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

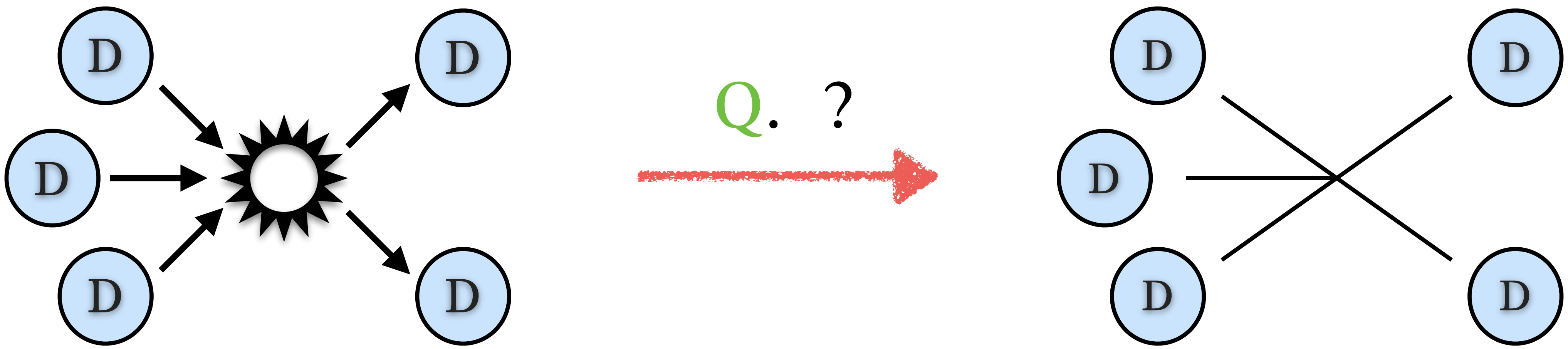
SIMP Dark Matter

- Strongly Interacting Massive Particles
- Freeze-out process is 3 to 2 self-annihilation $\chi\chi\chi \to \chi\chi$ with $\langle \sigma v^2 \rangle \propto \alpha^3/m_\chi^5$ and the mass scale is $\mathcal{O}(100\ \mathrm{MeV})$ for the relic density $(\Rightarrow \alpha \gtrsim 1)$
- The self-interaction can be much larger than WIMP $\sigma_{\rm self} \propto \alpha^2/m_\chi^2$



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

The SIMPlest realization



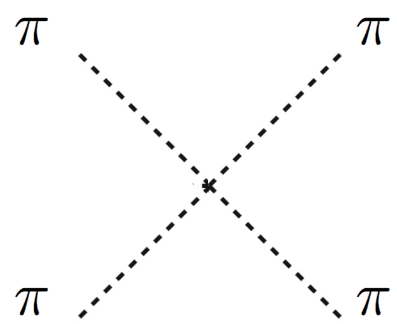
A. WZW term for Dark ChPT

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

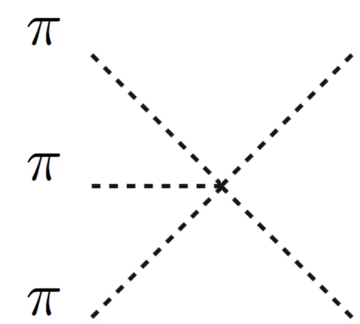
Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J. G. Wacker (2014)

Perturbativity Problem

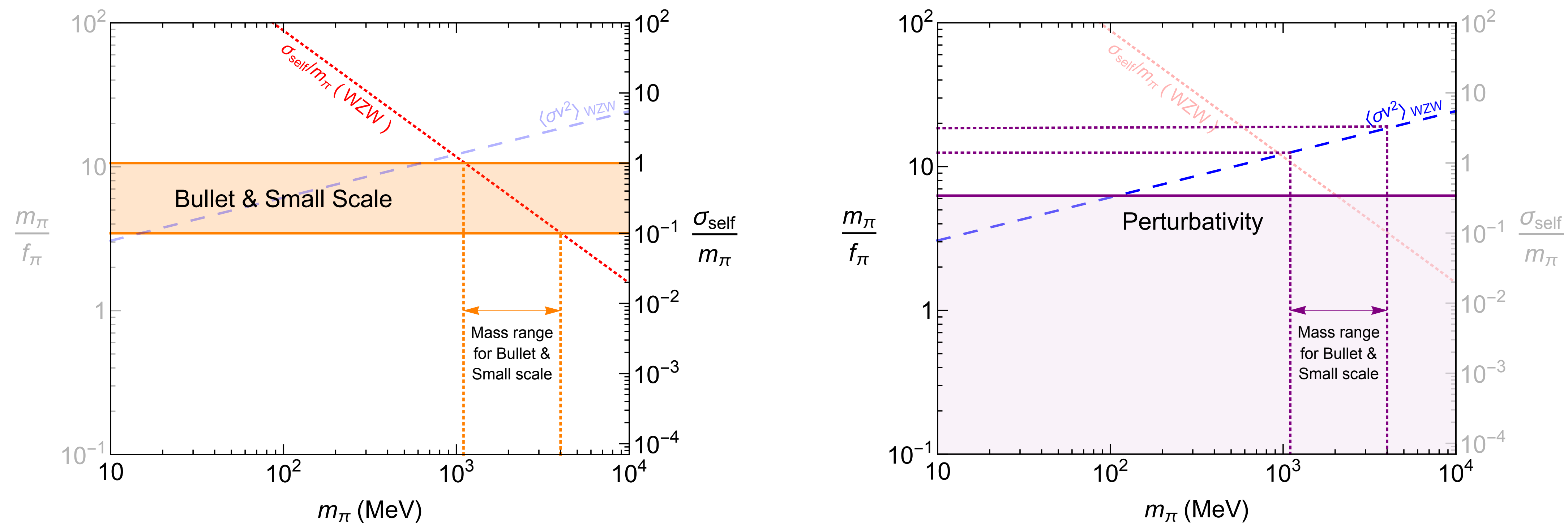
- This minimal SIMP with pions only has perturbativity problem. So Leading order ChPT will breaks down. $(m_\pi/f_\pi \sim 2\pi)$



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



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



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

Dark Pion with Vector Mesons

- Non-linearly transformed $G_{\rm global}/H_{\rm global} = SU(3)_L \times SU(3)_R/SU(3)_V$

  $=$ Integrating out the vector mesons from linearly realized $G_{\rm global} \times H_{\rm local}$

- Vector mesons are the massive gauge fields of a local $SU(3)_V (\equiv H_{\rm local})$ and they have degenerated masses

- Vector mesons mediate pion interactions.

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

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

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

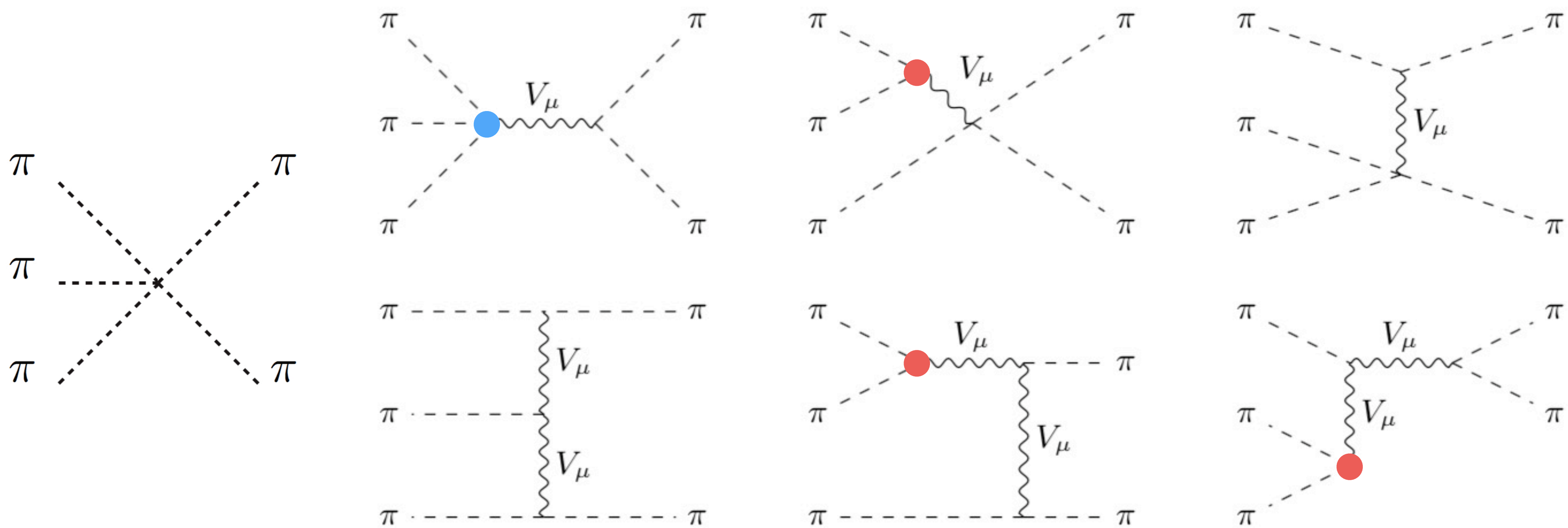
$$m_V^2 = ag^2 f_\pi^2$$

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

Dark Pion with Vector Mesons

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

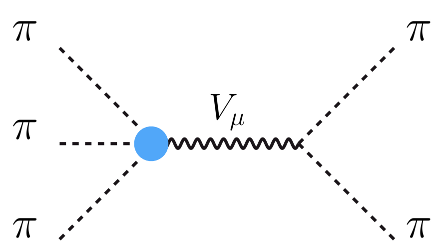
7 types of 5-point interactions with 2 types of resonances



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

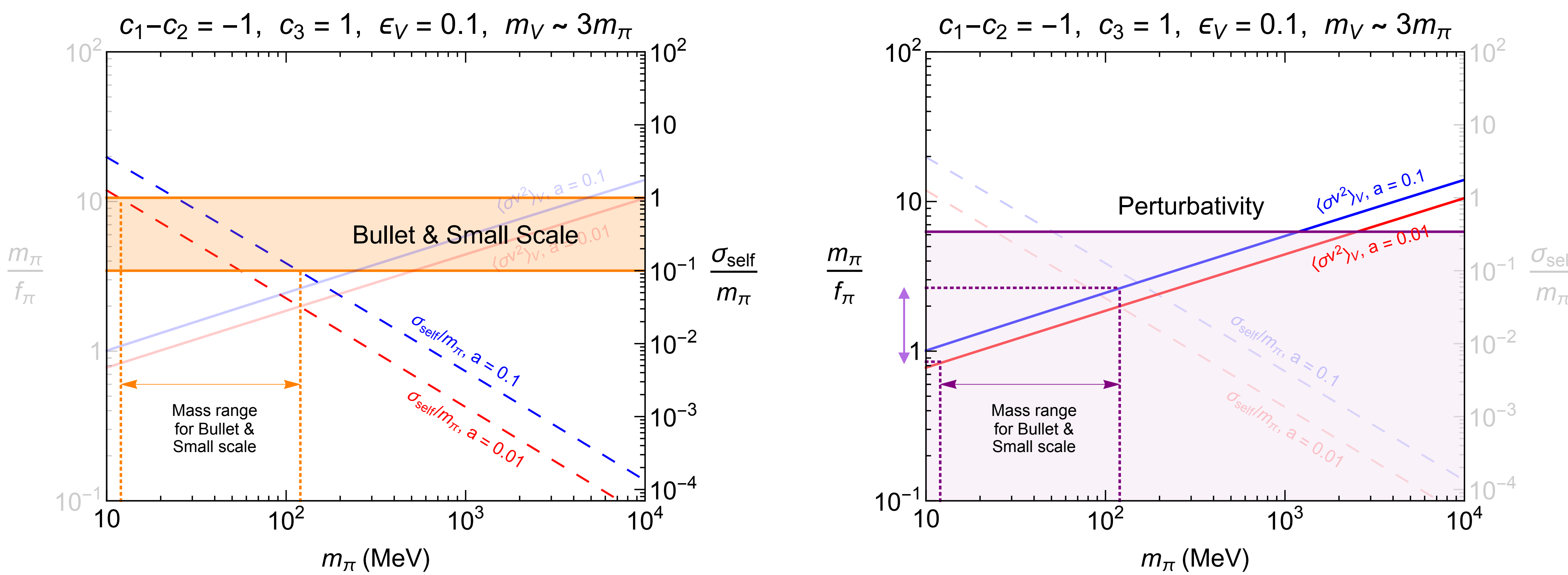
Dark Pion with Vector Mesons

- 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.



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

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

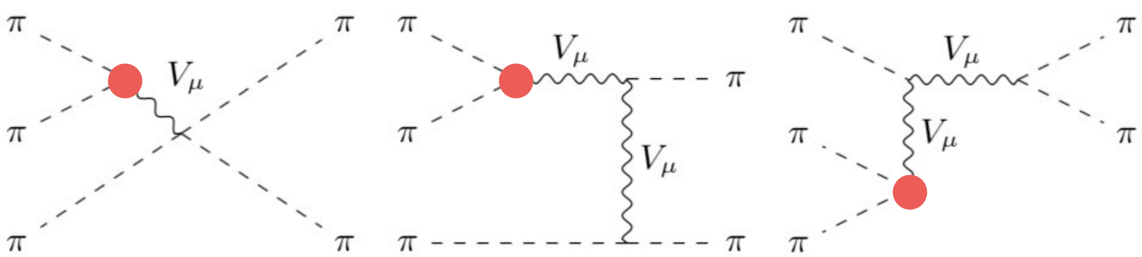


SMC, H. M. Lee, P. Ko and A. Natale (2018)

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

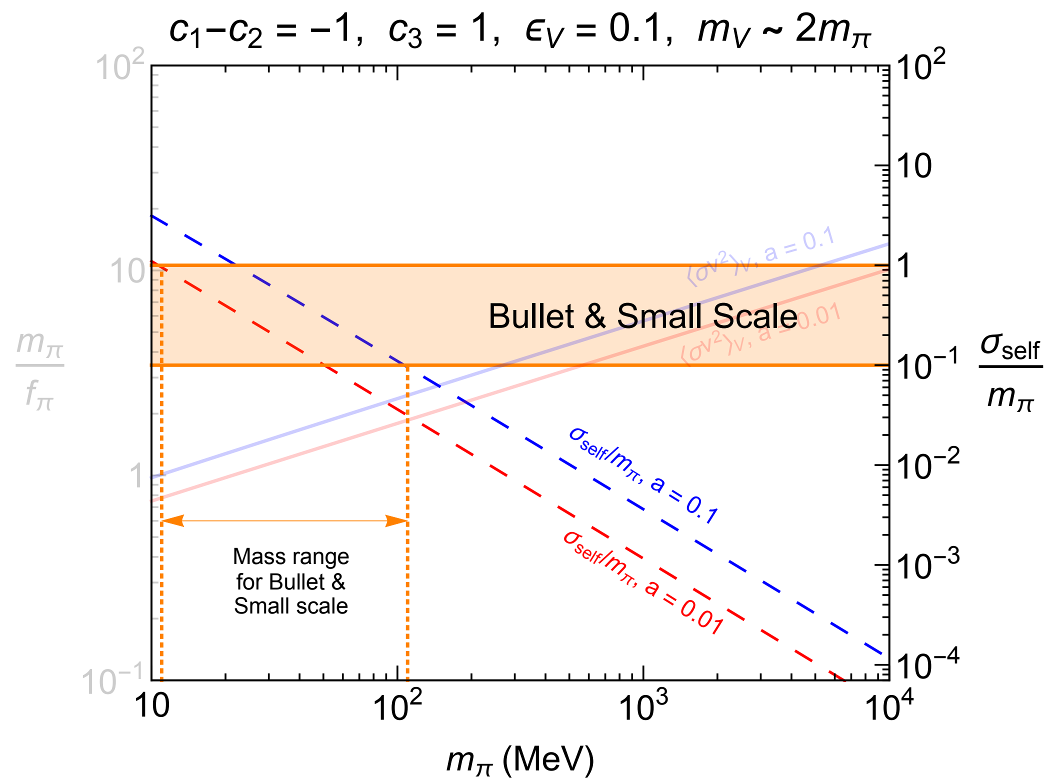
Dark Pion with Vector Mesons

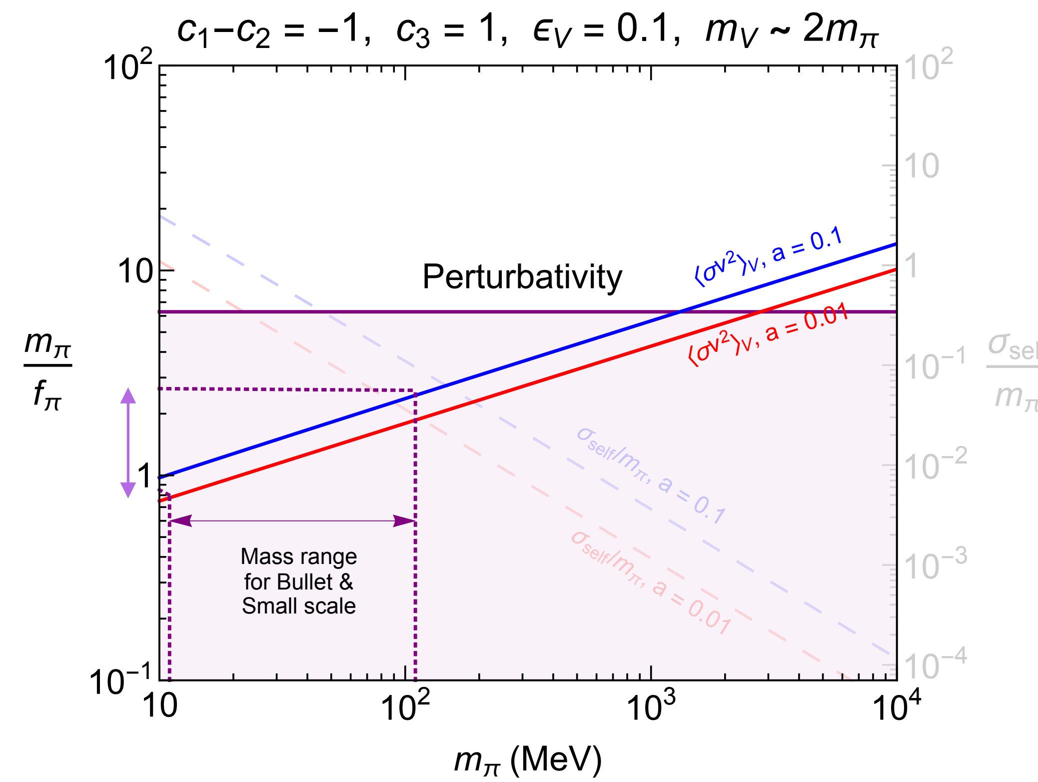
- Large effects appear on resonance (2-pion resonance : $(m_V = 2m_\pi\sqrt{1+\epsilon_V})$)
- Expansion parameter (m_π/f_π) can be smaller by vector meson mediated diagrams.



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

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





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

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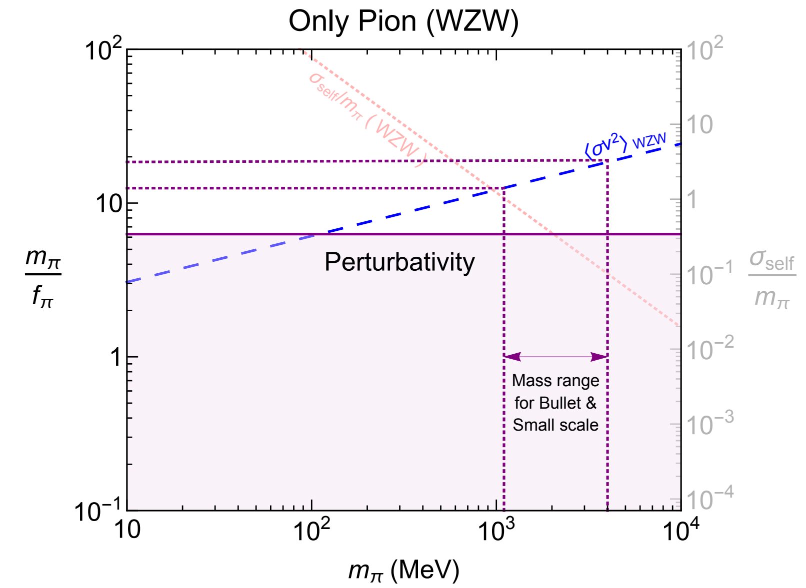
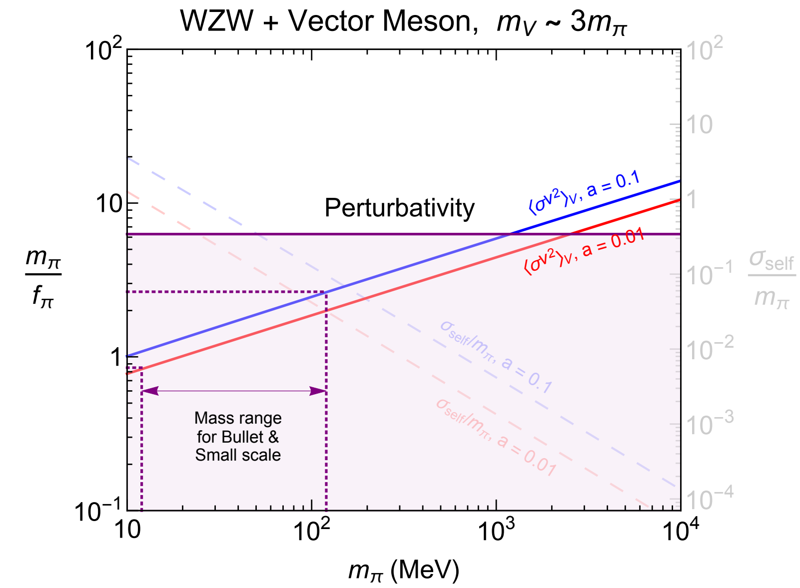
Conclusions

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