

# Vector Resonances and SIMPs

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Work in progress with

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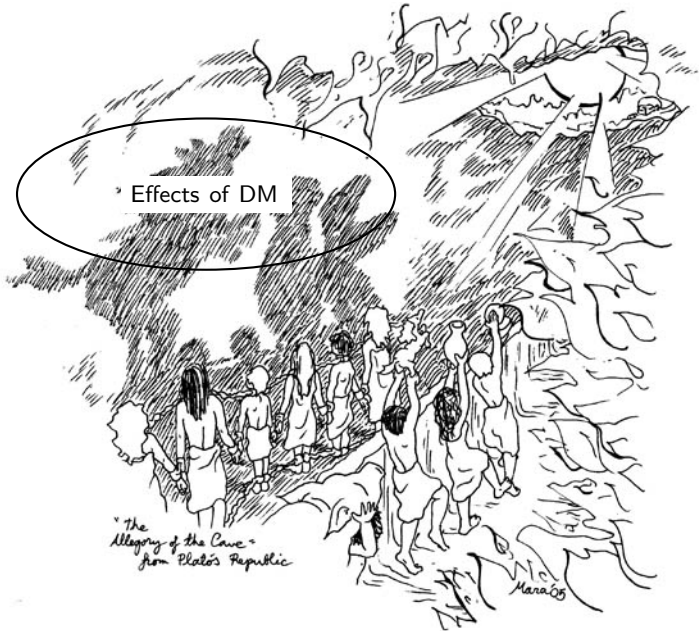
June 22nd, 2017



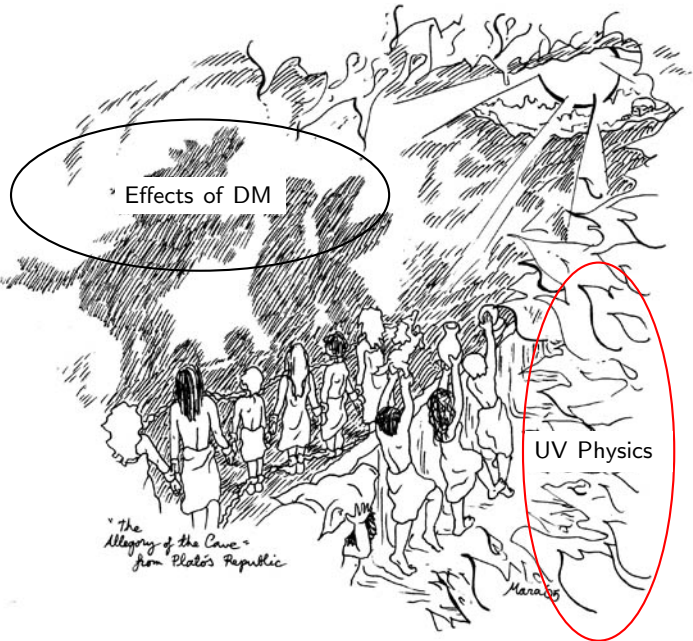


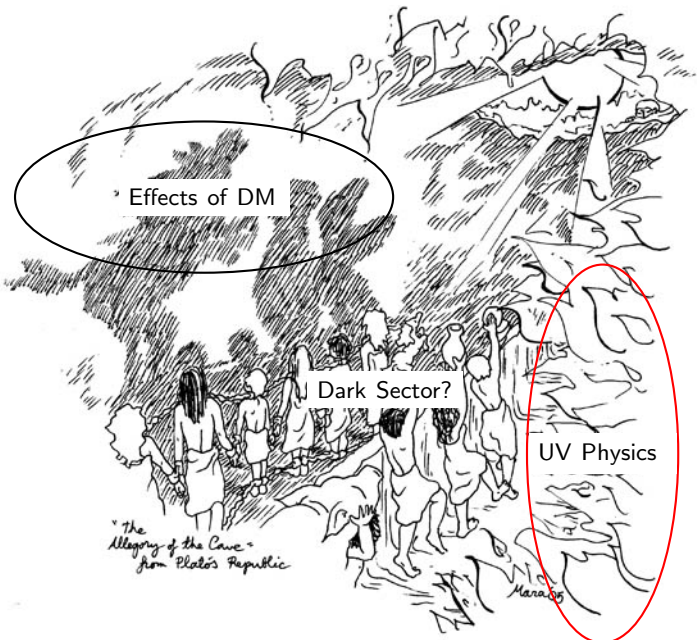
"The Allegory of the Cave"  
from Plato's Republic

Effects of DM



"The Allegory of the Cave" from Plato's Republic





Effects of DM

Dark Sector?

UV Physics

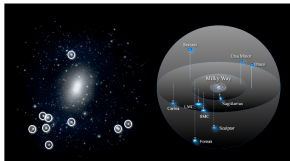
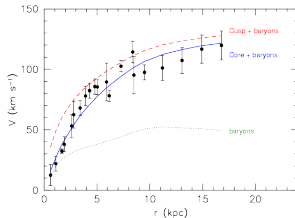
The Allegory of the Cave from Plato's Republic

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# CDM Puzzles

Weak mass scale roughly fits correct relic density with mass  $\sim TeV$ , hence, the 'WIMP' miracle, however (D.H. Weinberg et al, 2013)...

- CDM simulations **too 'cuspy'** compared to observations
- Missing halos/**too-big-too-fail**
- CDM still hasn't been seen but needs DM-SM to 'freeze' out

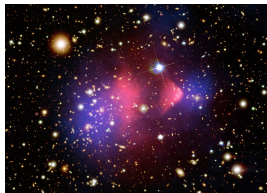


# Self-Interacting DM

Introducing **self interaction** flattens DM density in Core.

→ see [S. Tulin, H.-B. Yu 2017](#) for a recent review ←

Constrained by **Bullet Cluster** observations  $\sigma_{self} \lesssim 1 \text{ cm}^2/\text{g}$ ,  
but  $\sigma_{SIDM} \gtrsim 0.1 \text{ cm}^2/\text{g}$  ( $\sim 10^{-24} \text{ cm}^2/\text{GeV}$ )



[D.H. Weinberg et al, 2013](#)

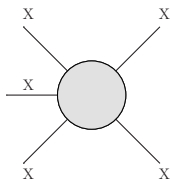
Weak scale implies  $\sigma/m \sim 10^{-38} \text{ cm}^2/\text{GeV}$

# Strongly Interacting DM?

WIMP Relic is a balance between  $\sigma_{ann.}$  and  $\sigma_{scat.}$ .  
If DM-SM interaction is very weak ( $\sigma_{SM} \ll \sigma_{2 \rightarrow 2}$ )?

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Relic Density is fixed by 3-to-2...



...then  $m_{DM} \sim \alpha_{eff} (T_{eq}^2 M_{Pl})^{1/3} \sim 100$  MeV, and this leads to a **strong**  $\alpha_{eff}$  and can explain self-interaction cross section  $\sim 10^{-24} \text{ cm}^2/\text{GeV}$ .

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



To produce relevant  $\sigma_{scat.}$  use a strongly-coupled gauge theory ( $SU(N_c)$ ):

$$\mathcal{L}_{SIMP} = -1/4 F_{\mu\nu}^a F^{\mu\nu a} + i\bar{Q}_i \not{D} Q_i$$

Where a **global symmetry** (G)  $SU(N_f) \times SU(N_f)$  is broken to  $SU(N_f)$ ,  
similarly to the **SM QCD**.

Since this is a strongly coupled theory, the  $Q$ 's show up via composite states (pions) **dark pions**, which are the cosmological DM.

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**Note:** The Gauge and global symmetries can be  $SU(N_c)$ ,  $Sp(N_c)$ , etc.

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

After chiral symmetry breaking there are  $N_f^2 - 1$  pion fields with dynamics that can be approximated to leading order:

$$\mathcal{L}_\pi = \frac{f_\pi^2}{16} \text{Tr} \partial_\mu \Sigma \partial^\mu \Sigma^\dagger - 1/2 m_Q \mu^3 \text{Tr} \Sigma + c.c.,$$

where  $\Sigma = \exp(i2\pi/f_\pi)$  and  $\pi = T_a \pi_a$ .

Expanding  $\Sigma$  leads to even-pion interaction terms (no 3-to-2 yet).

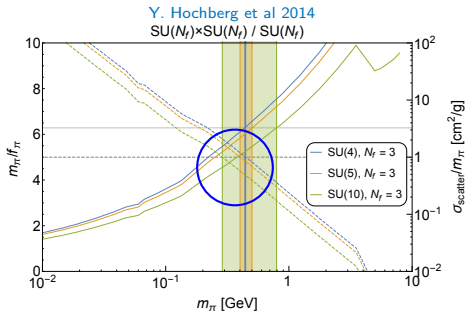
The 3-to-2 terms are generated from **Wess-Zumino-Witten Term** (Wess, Zumino 1971; Witten 1983):

$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \text{Tr} [\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \partial_\sigma \pi]$$

# ChPT: Issues

- Strongly coupled theories are complicated, but UV Lagrangian is **very simple**
- Can produce correct relic (QCD-like  $SU(3) \times SU(3)/SU(3)$  are very constrained)
- Interesting alternative to WIMP paradigm

But...generically requires large  $m_\pi/f_\pi$  to be realistic:



# ChPT: Vector Mesons

Leading order ChPT breaks down as NLO and NNLO effects *become sizable for large*  $m_\pi/f_\pi$  (M. Hansen et al 2015) after leading order **vector mesons** should be included as well.

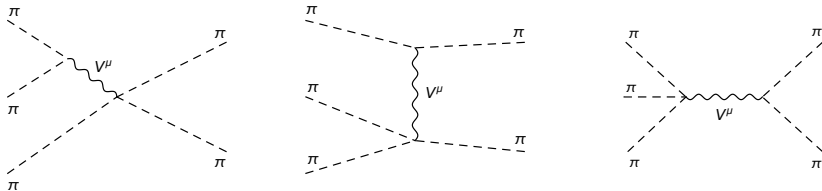
We expand the leading order ChPT with the vector meson ( $N_f, N_c = 3$ ):

$$\mathcal{L} = \mathcal{L} + m_V^2 \text{Tr}[V_\mu V^\mu] - i2g_{V\pi\pi} \text{Tr}[V_\mu [\partial^\mu \pi, \pi]] + \mathcal{L}_{Anom} + \dots$$

where  $V_\mu = T^a V_\mu^a$ ,  $m_V = ag^2 f_\pi^2$ ,  $g_{V\pi\pi} = 1/2ag$ , and  $\mathcal{L}_{Anom}$  is the anomalous term which generates  $V\pi\pi\pi$  terms.

# New Channels

$V^\mu$  terms, analogous to WZW, generate new 3-to-2 interactions:

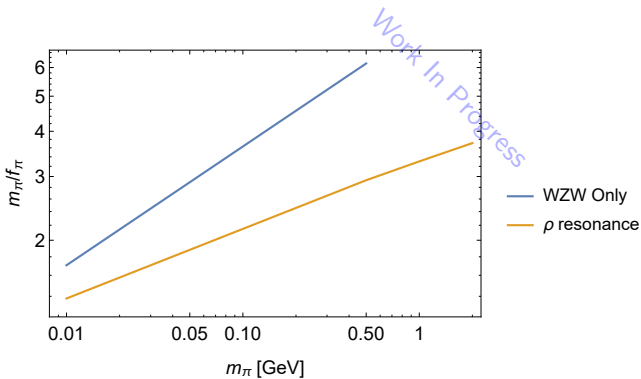


Leads to resonances near  $m_V \approx 2m_\pi$  ( $m_V \approx 3m_\pi$ )

Near these resonance poles, care must be taken with the thermal average.

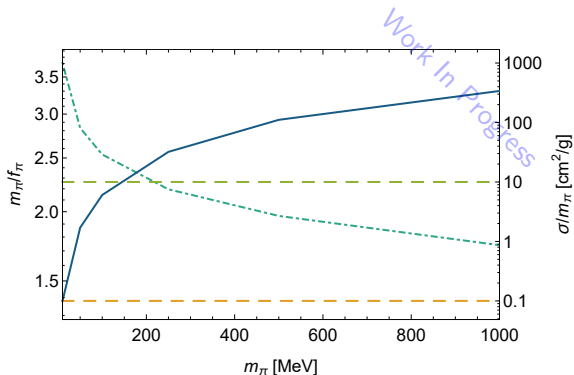
# Thermal Average

Building on work in [S-M. Choi, H.M. Lee et al 2017](#), the thermal average can be properly computed near resonance, and compared to the results of the 'SIMPlEst' model:



# Results

Fixing  $a$ ,  $m_V/m_\pi$ ,  $m_\pi$  while scanning the  $f_\pi$  with  $\Omega h^2 \approx 0.119$  and then determining  $\sigma_{scat.}$  yields:



# Summary & Conclusions

- Interesting alternative to WIMP paradigm with 3-to-2 freezeout
- Can solve puzzles with CDM model
- Addition of **Vector Mesons** in a composite model have important consequences
- Vector resonances in 3-to-2 can make QCD-like SIMP models viable



Thank you!

Thank you for your time and attention!