TAUP XICHANG

The XIX International Conference on Topics in Astroparticle and Underground Physics (TAUP20205)

Beyond the simplest strongly interacting dark matter (SIDM)

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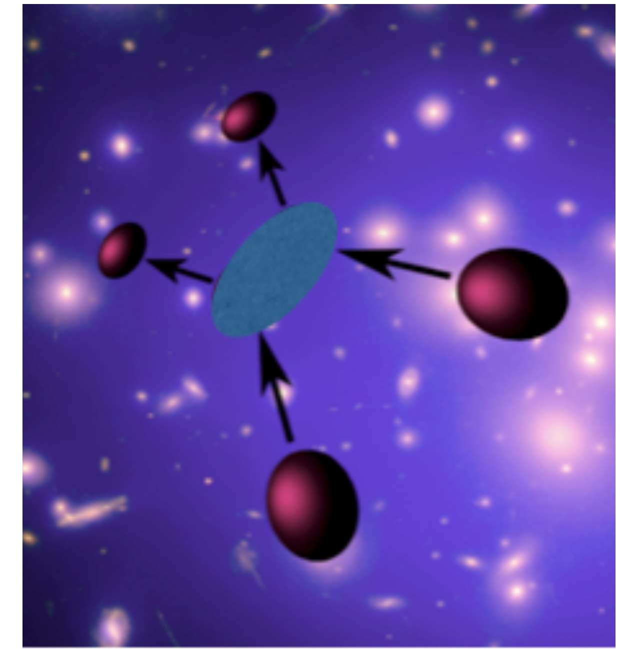
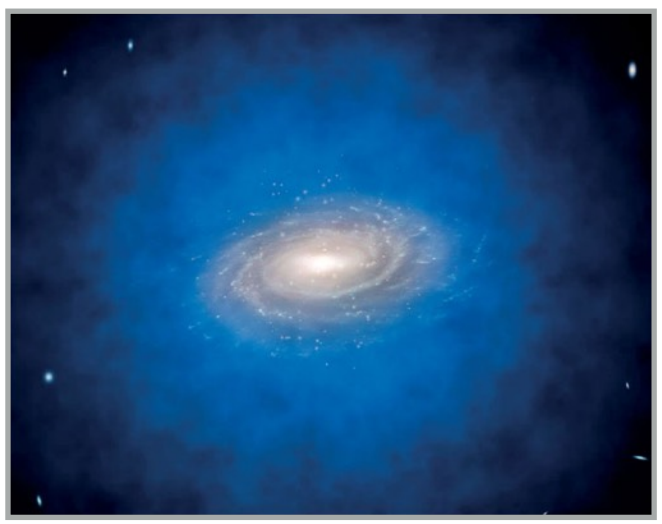
1. A paradigm shift

Non-gravitational interactions of dark matter

Conventional WIMP not found,
suggesting **alternative ideas**:

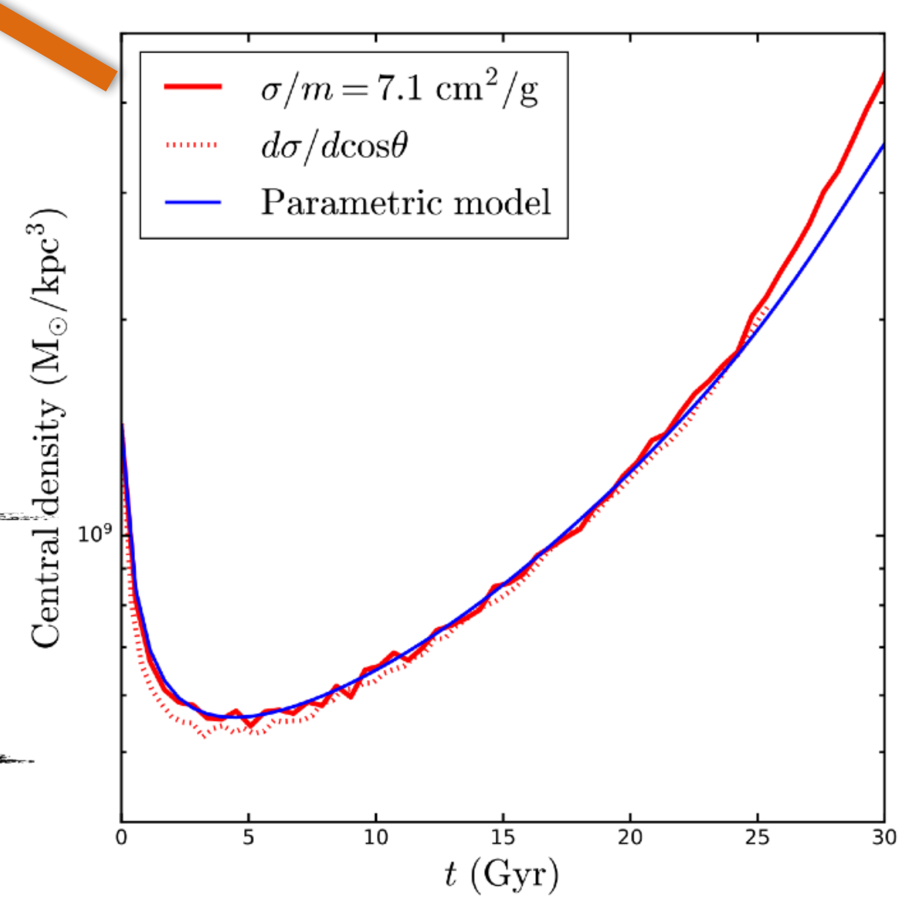


Self-interaction not too far from cm^2/gram



It adds a new d.o.f. to make halos **cored**, or **core-collapsed** via propagating heat faster.

$$t_{\rm SIDM} = \frac{1}{n_{\rm DM}\sigma_{\rm eff} v} = \frac{1}{\rho_{\rm DM}\,\sigma_{\rm eff}/m_{\rm DM}} \sim {\rm Gyr}\left(\frac{m_\odot/{\rm pc}^3}{\rho_{\rm DM}}\right)\left(\frac{{\rm cm}^2/{\rm gram}}{\sigma_{\rm eff}/m_{\rm DM}}\right)\left(\frac{10^{-4}}{v}\right)$$



Taken from D.N. Yang, H.B. Yu et al. 2024

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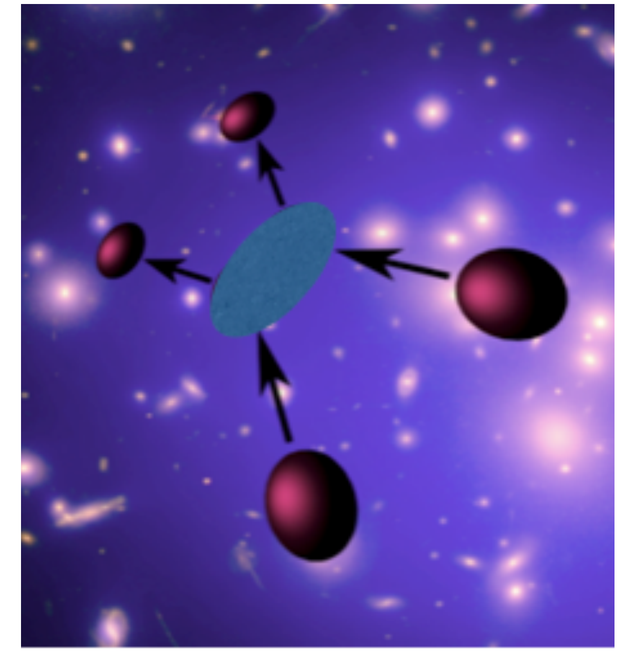
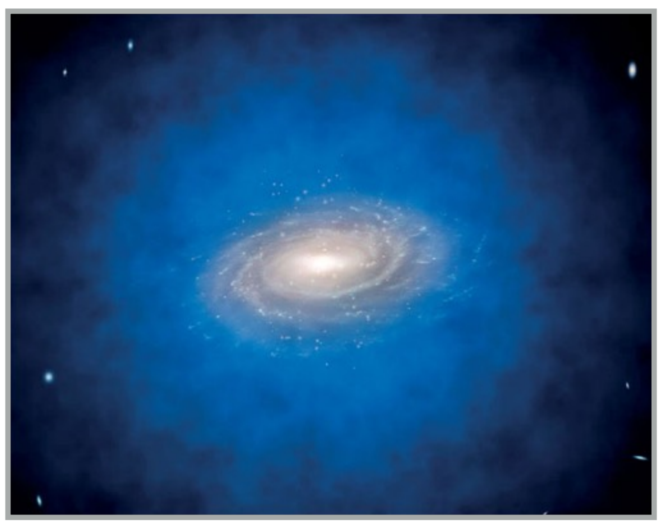
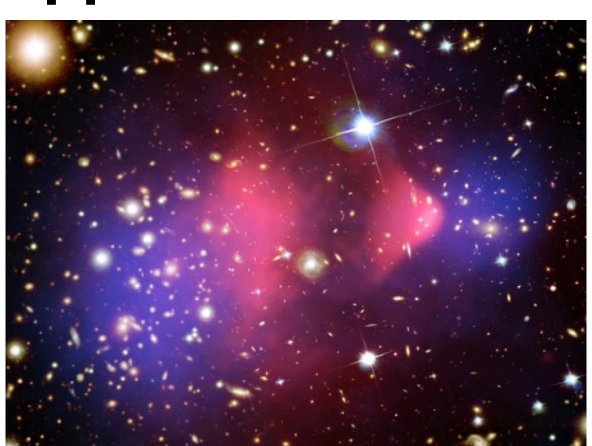


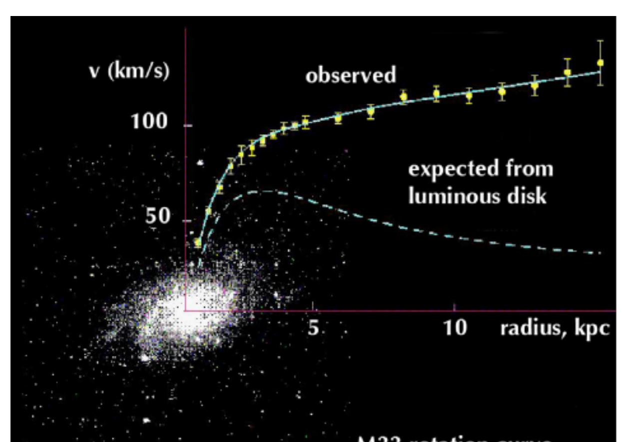
<u>Self-interaction not too far from cm^2/gram</u>



It adds a new d.o.f. to make halos **cored**, or **core-collapsed** via propagating heat faster.

<u>Upper bounds also exist</u> (stronger from larger structures):





An increasing list:

- Core/cusp,
- Too-big-to-fail,
- Galaxy diversities,
- Early galaxy formation,
- SMBH last-pc problem,
- Assembly bias of dwarf galaxies, …

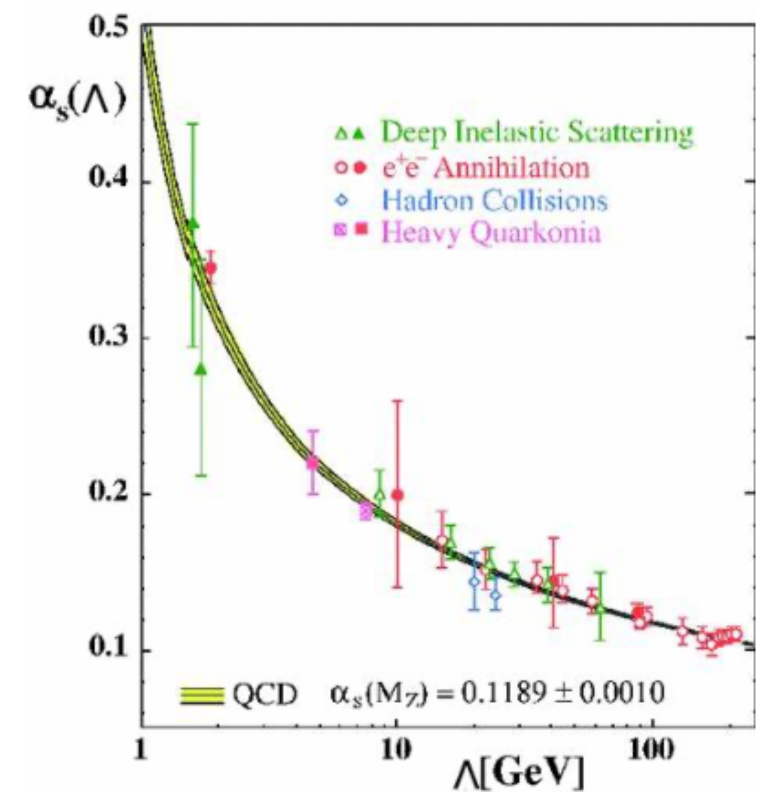
2. SIDM from Strong dynamics

Lightest stable state from strong dynamics

The SIDM candidate can be

- dark baryon (if it is like the SM);
- dark pion (light-quark limit);
- dark glueball (heavy-quark limit);
- large-N nuclei, dark atom,….

Reviews: *J. M. Cline, Z. Liu, et al., 2013, G. D. Kribs &E.T. Neil 2016*



Simplest Framework: self-scattering

$$\frac{\sigma_{\rm SI}}{m_{\rm DM}} \sim \frac{\alpha_S^2}{m_{\rm DM}^3} \sim \frac{1}{m_{\rm DM}^3}$$

cm^2/gram → **sub-GeV DM**

SIDM needs sub-GeV masses for strong-interactions.

(Interesting energy-scale for phase-transition-induced GW/PBH)

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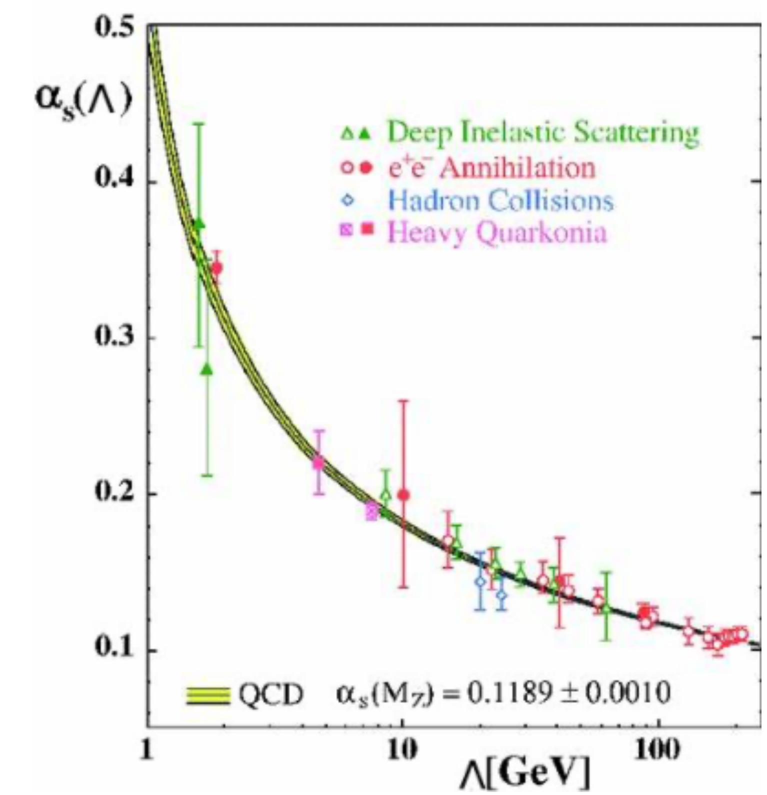
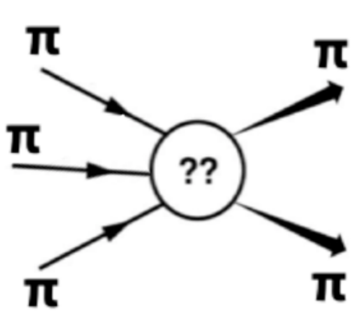
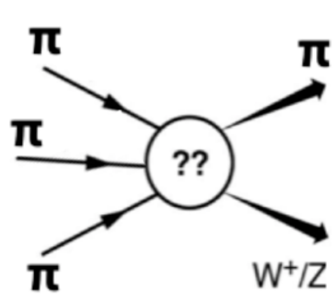


Simplest Framework: N→2 freeze-out

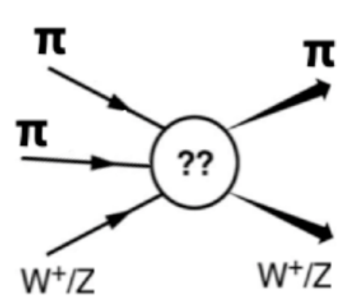
or fine-**tuned freeze-in**



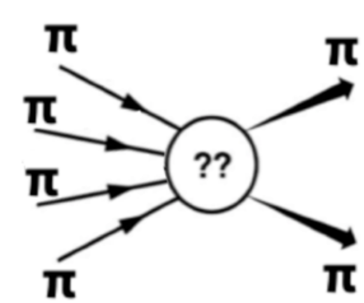
SIMP
[Y.Hochberg, E. Kuflik, T. Volansky, J. G. Wacker 1402.5143, …]



Enable forbidden FO *[J. M. Cline, H. Liu, T. R. Slatyer, W. Xue, 1702.07716, …]*



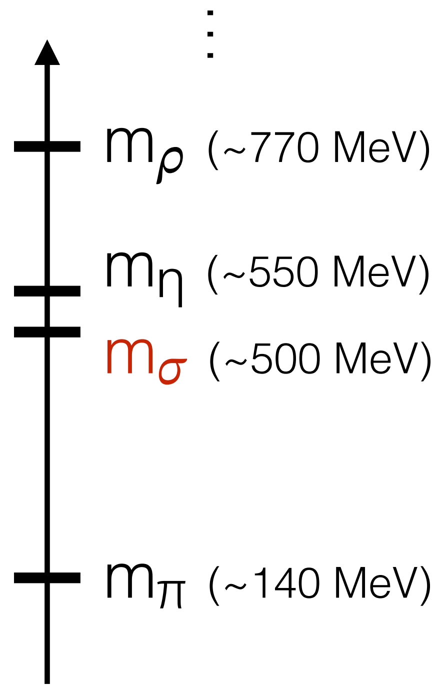
Co-SIMP
[J. Smirnov, J. F. Beacom, 2002.04038, …]



Four-body FO
[N.Bernal, XC 2015, …]

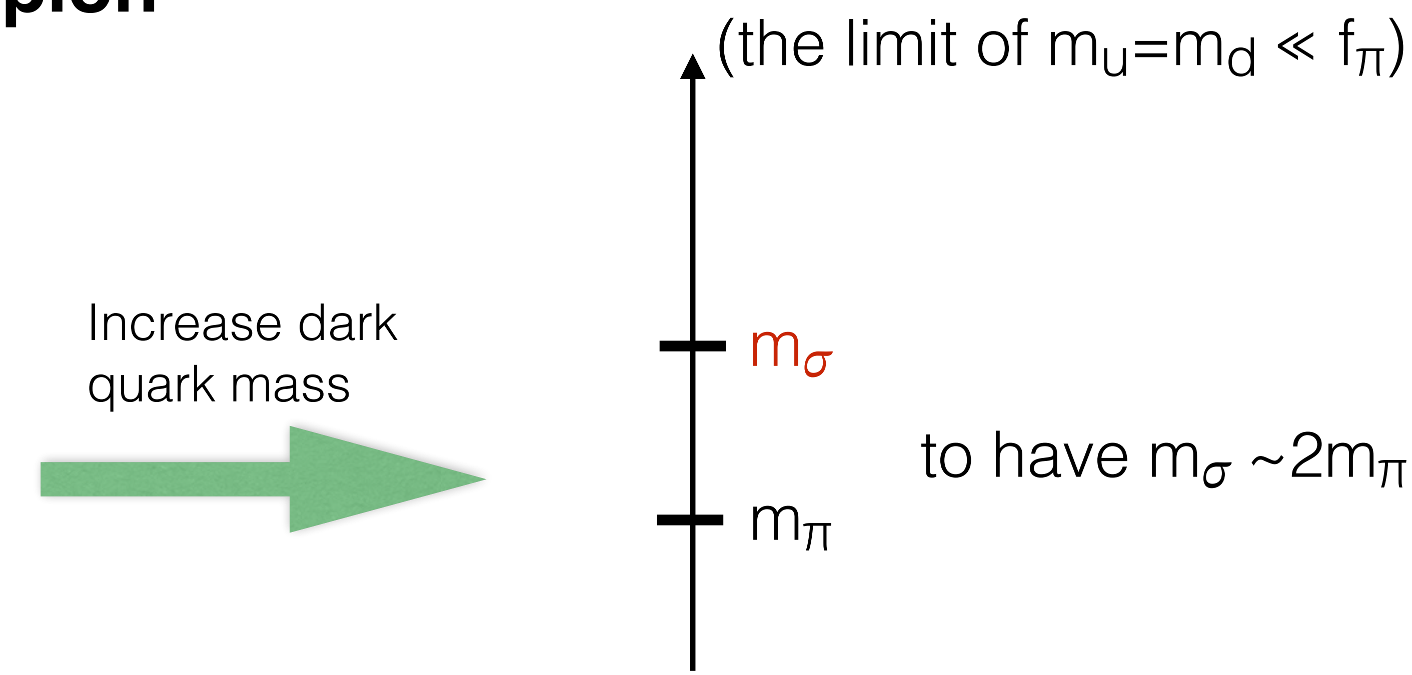
But, **strong dynamics** is hardly simple

Take SIDM candidate as **dark pion**



SM case ($f_\pi \sim 93$ MeV)

Heavier states hardly play any role



Sigma scalar may appear as two-pion molecule / bound state at $m_\pi/f_\pi > 3$ [M. Albaladejo & J. A. Oller 2013].

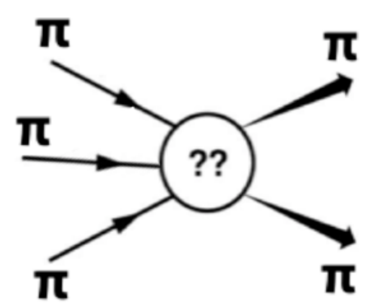
But, **strong dynamics** is hardly simple

One interesting case is $m_\sigma \lesssim 2m_\pi$, appearing as a **(meta-)stable bound state**:

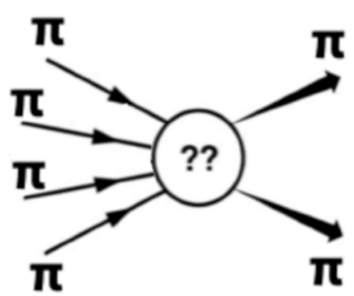
1. Freeze-out can be enhanced by bound state formation.

[XC, M. Nikolic, J.Pradler 2024]

Much **harder** for **more** initial DM particles to meet:



sub-GeV DM



sub-MeV DM

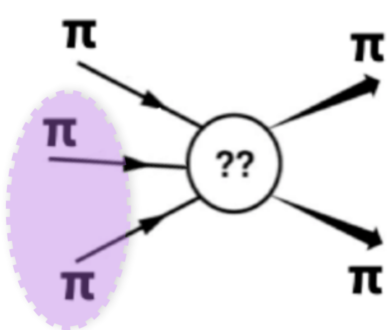
$$\frac{n^{\rm eq}_{(2\pi)}\left|\Psi_{(2\pi)}\right|^2}{s^2} \simeq \frac{\left|\Psi_{(2\pi)}\right|^2}{m_\pi^3} x^{\frac{9}{2}} e^{-2x+\kappa}$$

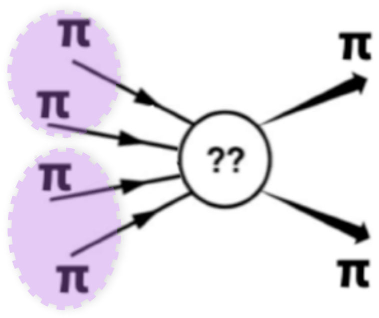
can be larger by $10\text{-}10^4$!

$$\kappa = |E_{\rm B}|/m_\pi$$

[bound state wave-function: **dim-3/2**]

If allow bound state formation:





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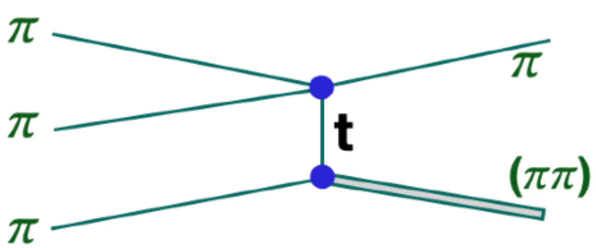
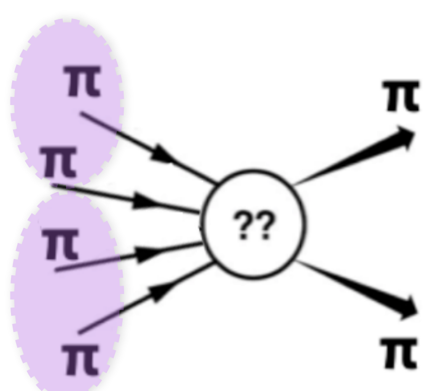
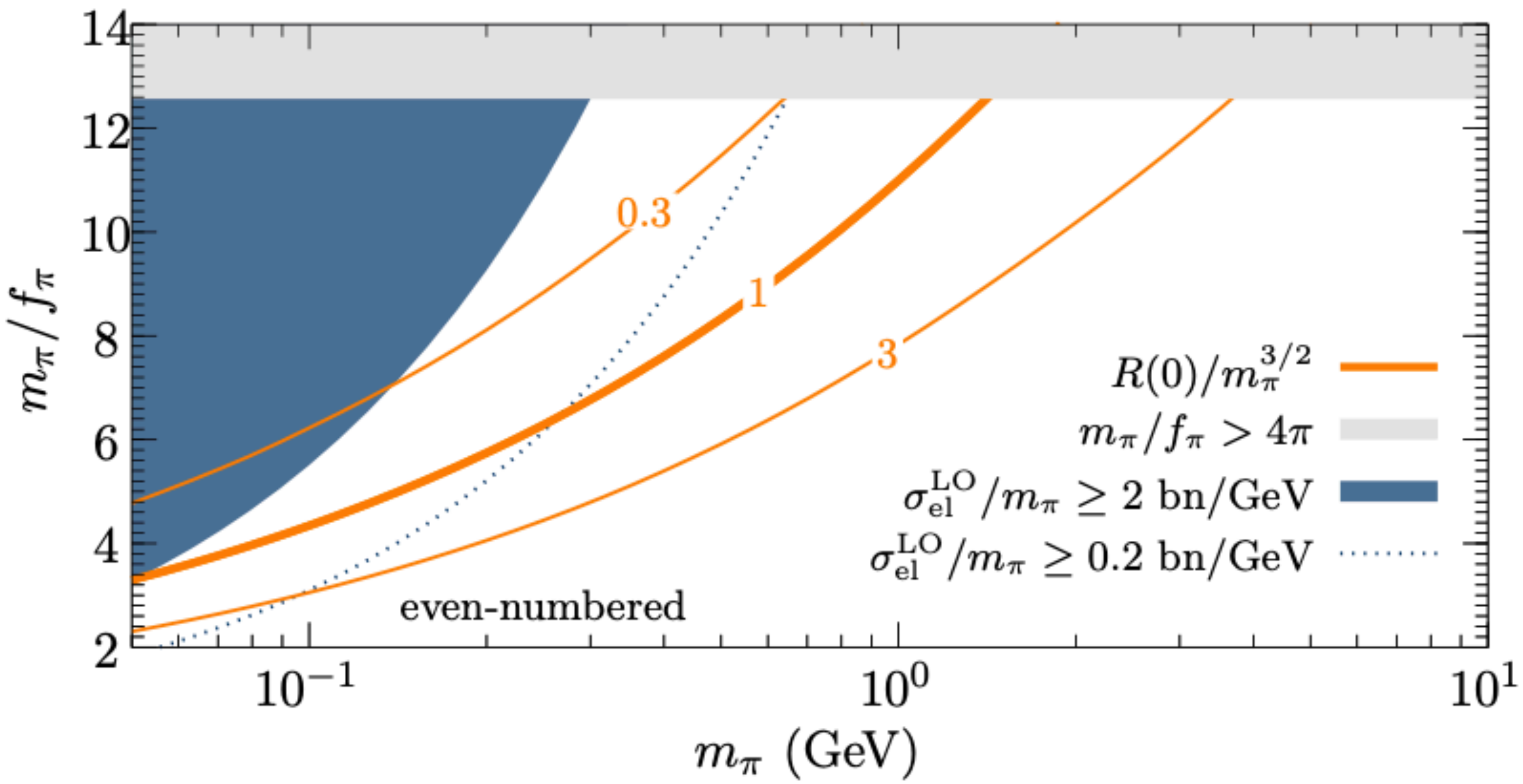






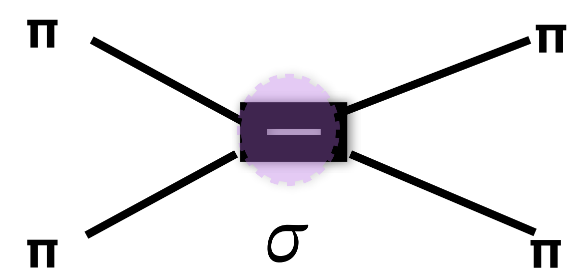
Freeze-out is more efficient, allowing for DM masses above GeV.

But, **strong dynamics** is hardly simple

One interesting case is $m_\sigma \lesssim 2m_\pi$, appearing as a **(meta-)stable bound state**:

2. Resonant-like self-scattering of DM particles.

[XC, M. Nikolic, J.Pradler 2024]



With a bound state (or a resonance) X

scattering amplitude: $$\frac{1}{s - m_X^2 + i\Sigma_X(s)}$$

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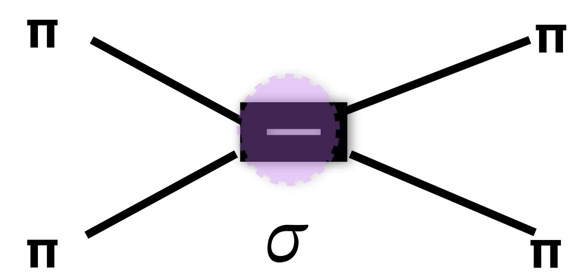
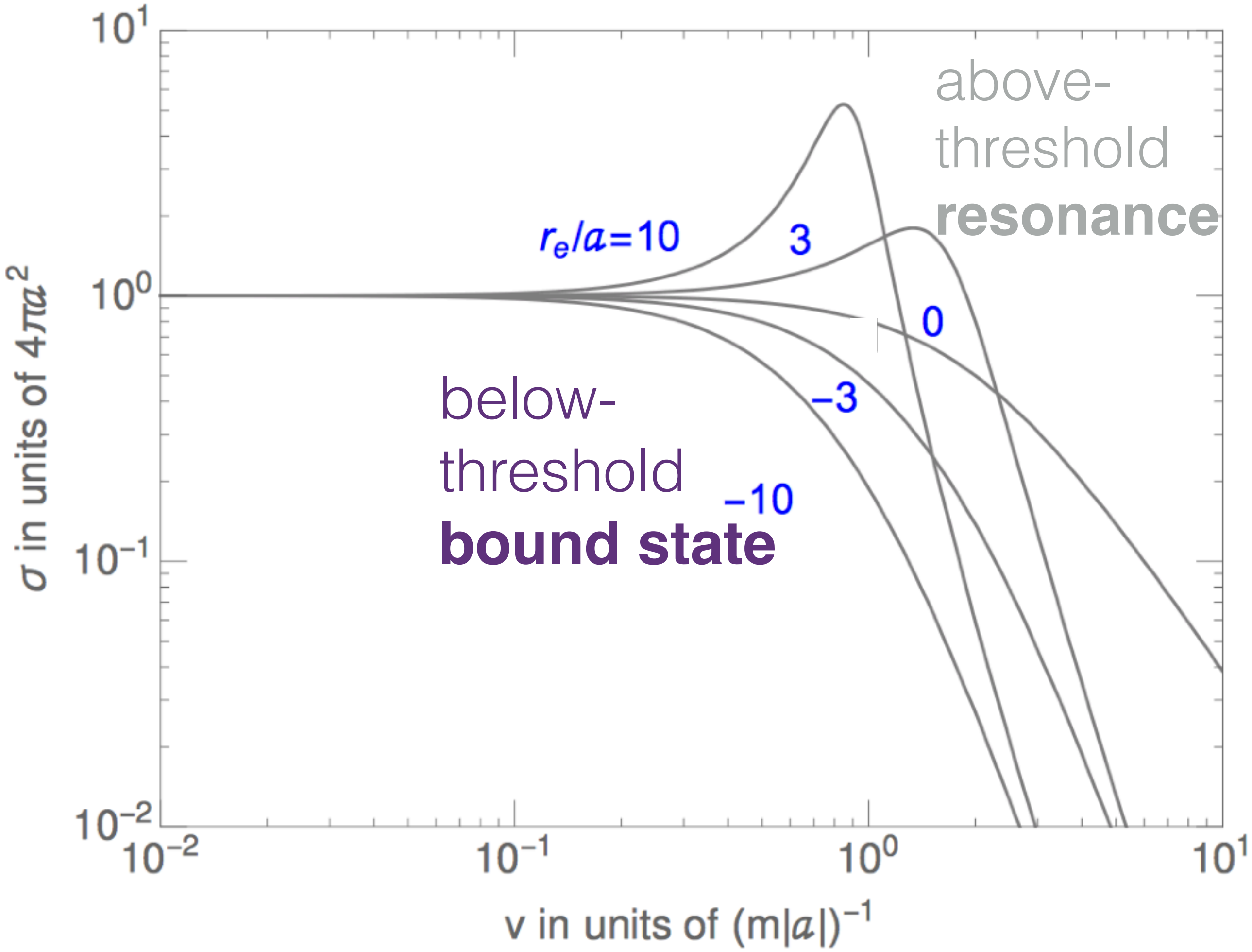




With a bound state (or a resonance) X

scattering amplitude: $\dfrac{1}{s - m_X^2 + i\Sigma_X(s)}$

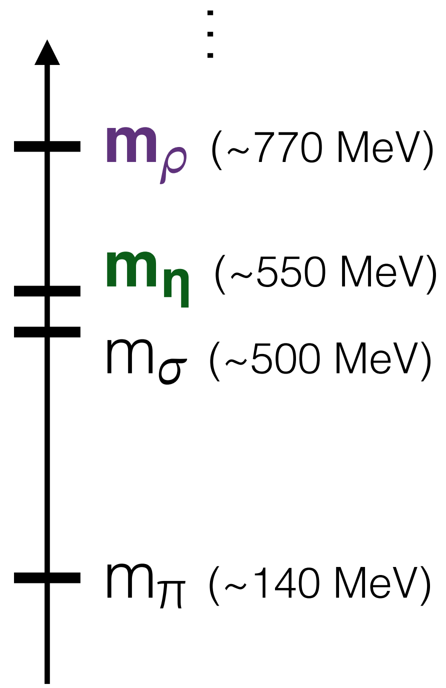
Lead to **smaller self-scattering** at larger velocities, **avoiding bounds from galaxy clusters**.

[XC, C. Garcia-Cely, H. Murayama 2018, 2019]

But, strong dynamics is hardly simplest

Take SIDM candidate as **dark pion**

(the limit of $m_u = m_d \ll f_\pi$)



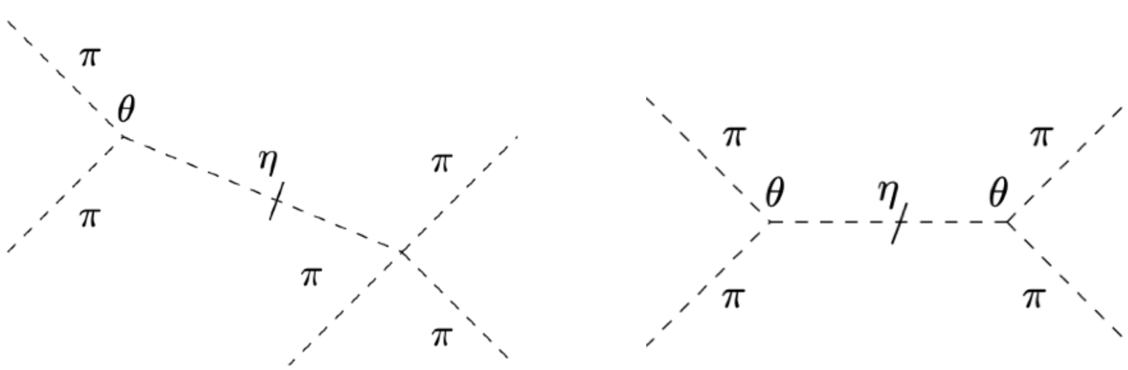
Increase dark quark mass

to have $m_\chi \sim 2m_\pi$

Instead of dark sigma meson, what if dark **eta meson** or dark **rho meson** plays the major role as an intermediate states?

Eta meson, as a pseudo-scalar, couples to two pions via a **CP-violating phase.**

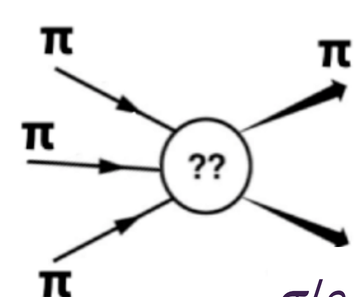
[*C. Garcia-Cely, G. Landini & O. Zapata 2024*].



Rho meson may play a similar role if $m_\rho \sim 2m_\pi$

[*E. Bernreuther, N. Hemme, F. Kahlhoefer & S. Kulkarni 2023*]

Mixing with Z/H may induce additional decay → enable forbidden FO.



σ/ρ → radiation

Non-simplest SIDM may contain dark radiation.

- If dark quarks are charged under **a local U(1)** [e.g. *P. Braata & M. Postma 2023*]

$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}{\rm Tr}\left[\boldsymbol{\pi}\partial_\mu\boldsymbol{\pi}\partial_\nu\boldsymbol{\pi}\partial_\rho\boldsymbol{\pi}\partial_\sigma\boldsymbol{\pi}\right] - i\frac{N_c g_d}{3\pi^2 f_\pi^3}\epsilon^{\mu\nu\rho\sigma}V_\mu {\rm Tr}\left(Q\partial_\mu\boldsymbol{\pi}\partial_\rho\boldsymbol{\pi}\partial_\sigma\boldsymbol{\pi}\right) + \frac{N_c g_d^2}{4\pi^2 f_\pi}\epsilon^{\mu\nu\rho\sigma}(\partial_\mu V_\nu)V_\rho {\rm Tr}\left(Q^2\partial_\sigma\boldsymbol{\pi}\right).$$

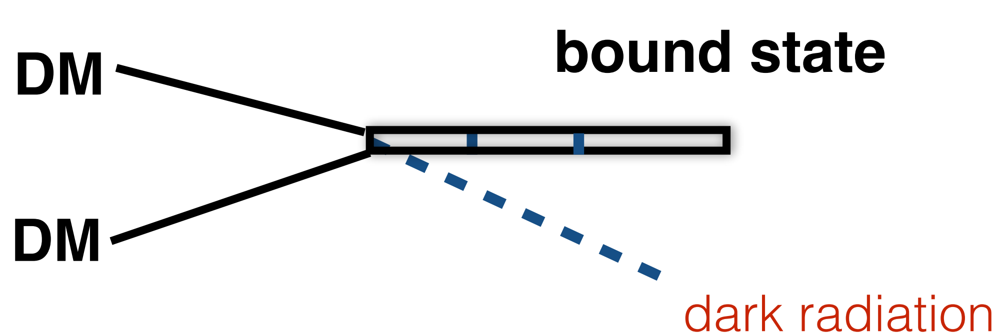
(Not the same as a dark rho meson)

- If a **global U(1)** breaking leads to dark axion [most recently, *Yang Bai, Ting-Kuo Chen et al. 2023*].

$$\mathcal{L} \ni -\frac{3c_{gg}}{16\pi^2 f_a} aF_{\mu\nu}(\rho)F^{\mu\nu}(\rho)$$

(anomalous terms and/or WZW terms)

New processes enter the game:



1. Make bound state formation much easier w.r.t. our earlier work.

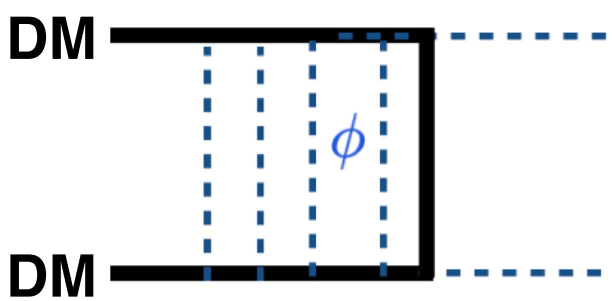
2. Naturally obtains kinetic equilibrium without fine-tuning.

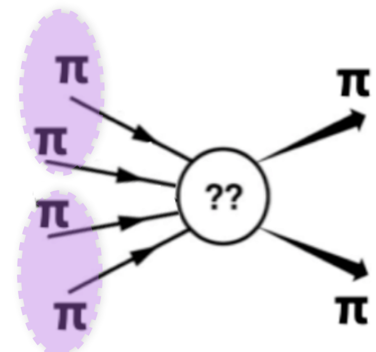
[work in progress]

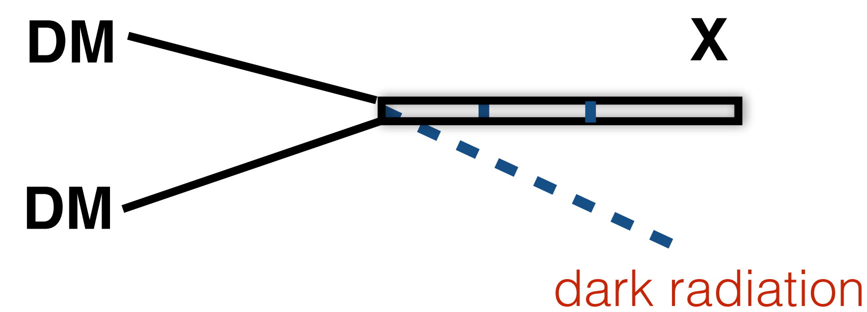
3. Conclusions

What if SIDM is not simplest?

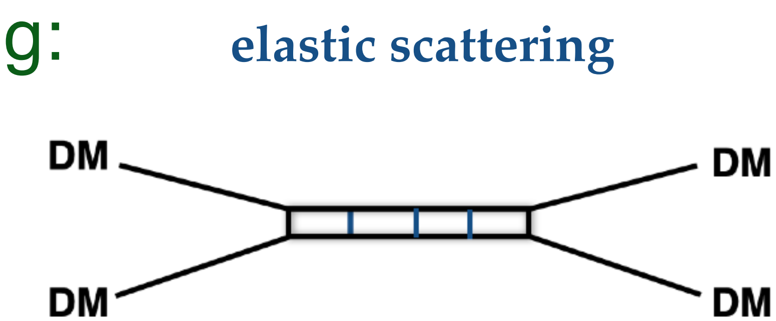
- It may modify **mechanisms/predictions** of DM production:







- It needs to induce **velocity-dependent** self-scattering:

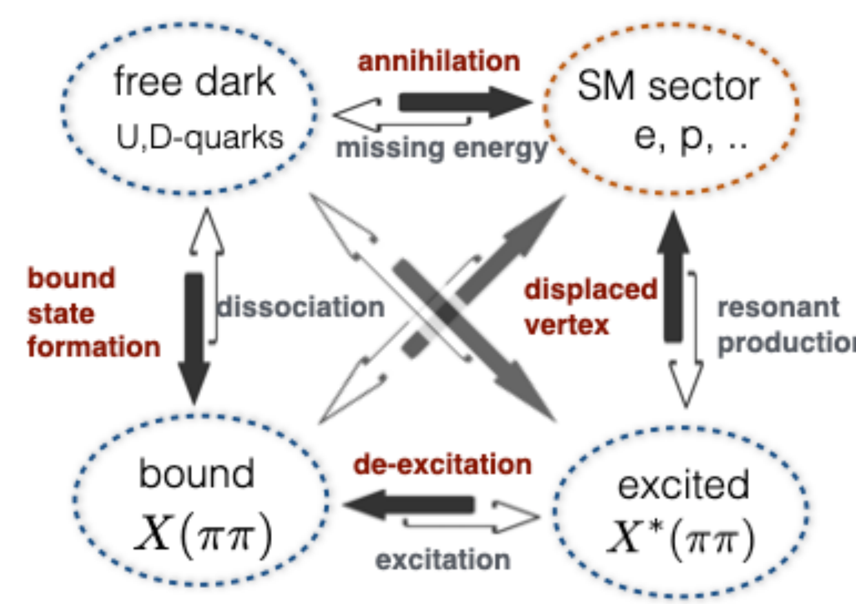


Strong and alleviating galaxy/cluster bounds.

- It also leads to novel signatures in astrophysics & territorial experiments:

Inelastic scatterings of astrophysical DM?

- It may be relevant for baryonic asymmetry too.



Thanks!