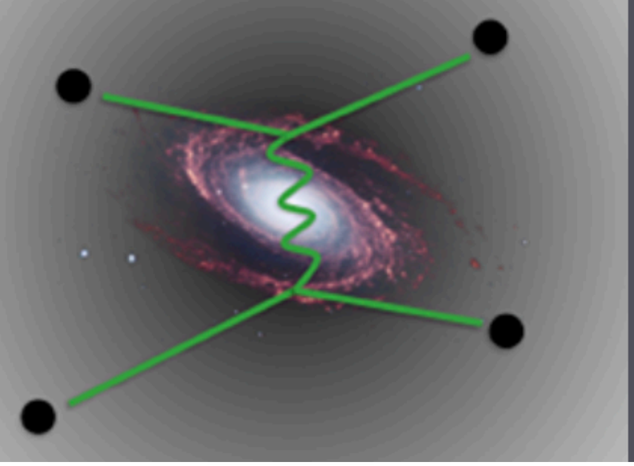

Valencia Workshop on the Small-Scale Structure of the Universe and Self-Interacting Dark Matter

Self-interacting dark matter
from
dark sectors

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unesco
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Under the auspices
of UNESCO

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University of Chinese Academy of Sciences

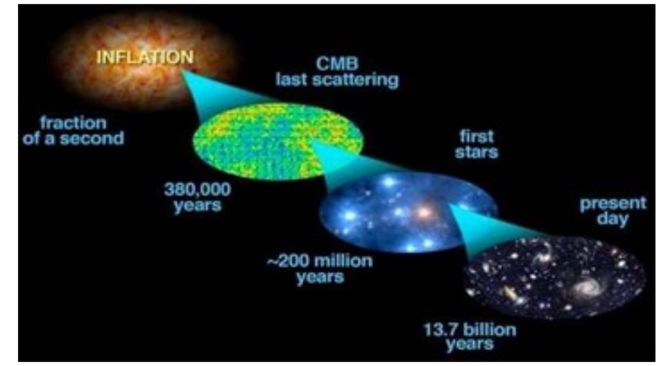
1. A paradigm shift

Understand **Dark Matter astrophysics** (DM): Gpc-Mpc✓, **kpc-pc?**

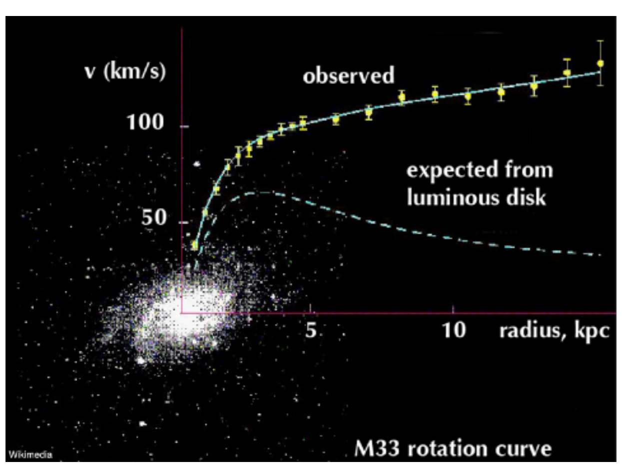
Structures grow:

— from quantum to classic

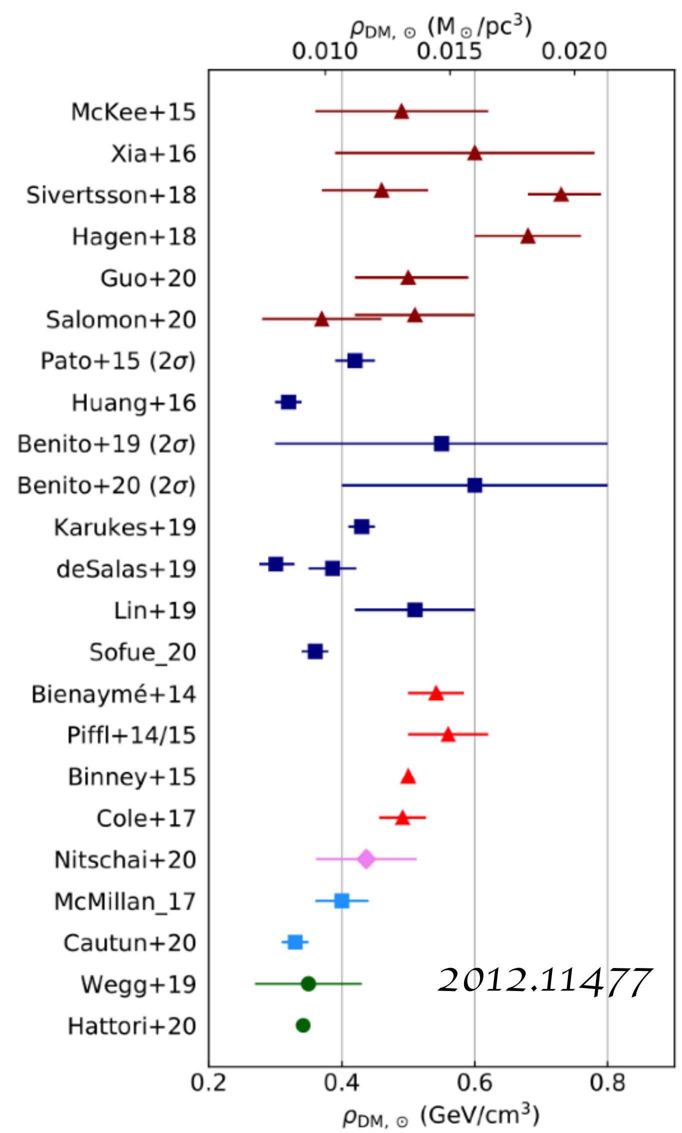
— from dark to visible

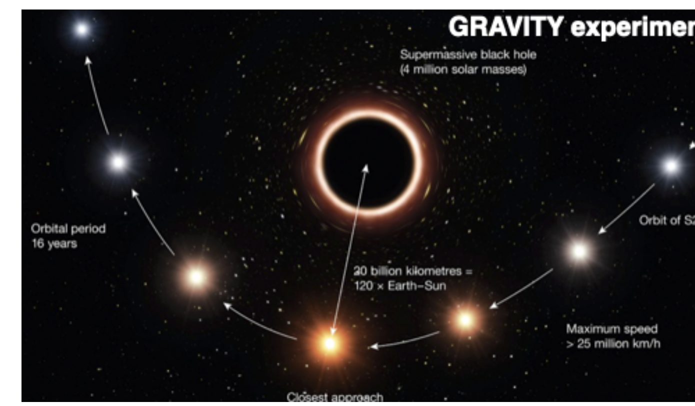


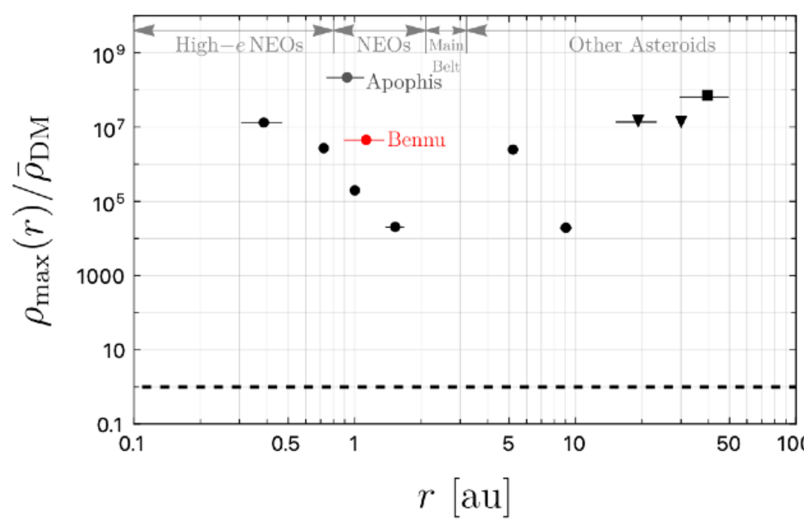
In colliding clusters, **gas** interacts, while **DM** (**+ stars**) pass through each other.



Gravity goes on well beyond the gas-dense region and inner galaxy.



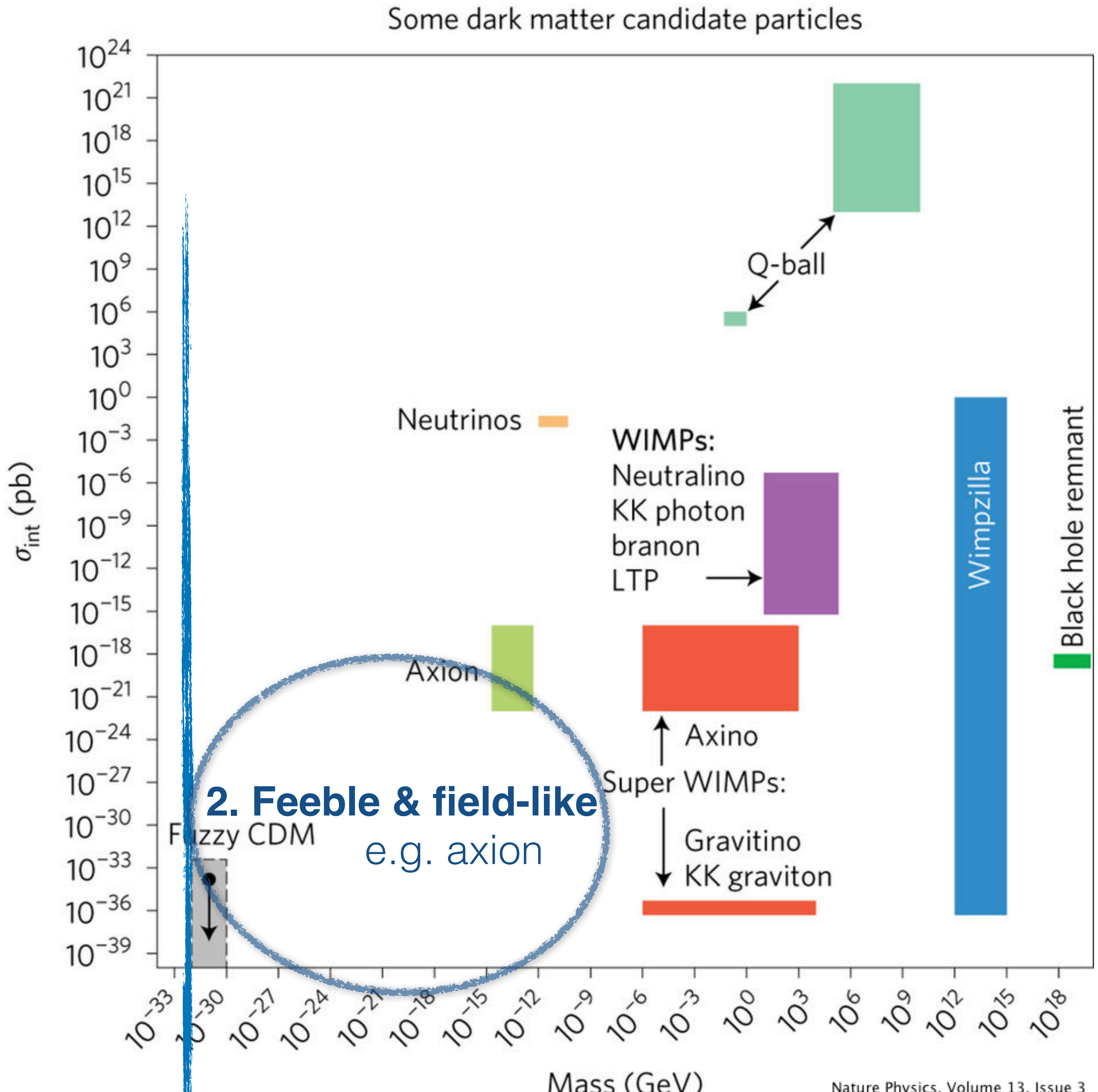




Not confirmed in local group [2210.03749], or in Galactic centre, yet.

Understand **non-gravitational interactions** of DM

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



1. **big&rare**: e.g. defects, black holes

$10^3\, m_\odot$

To make sure Universe smooth for CMB photons.

Size of dwarf halos.

Understand **non-gravitational interactions** of DM

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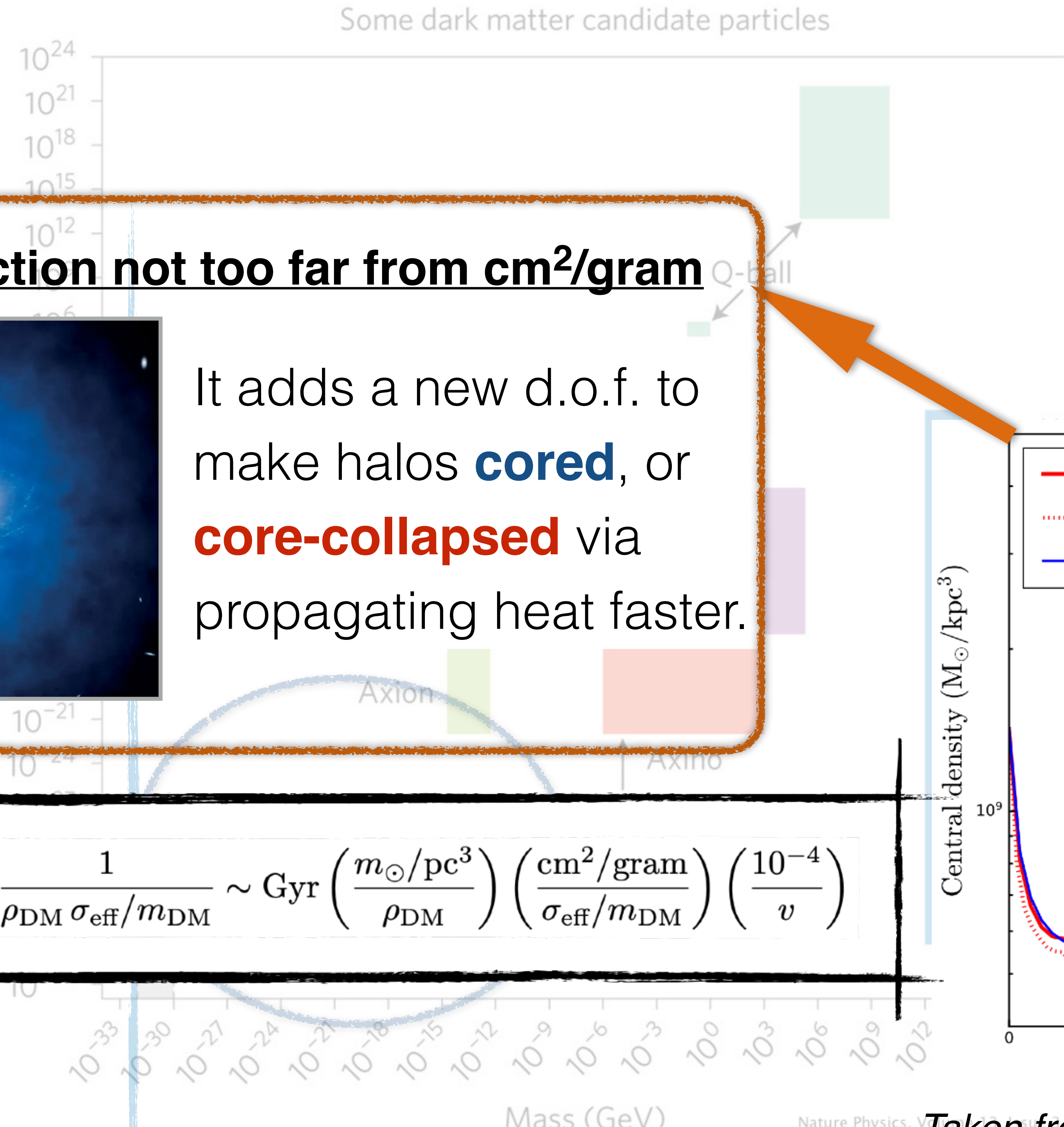
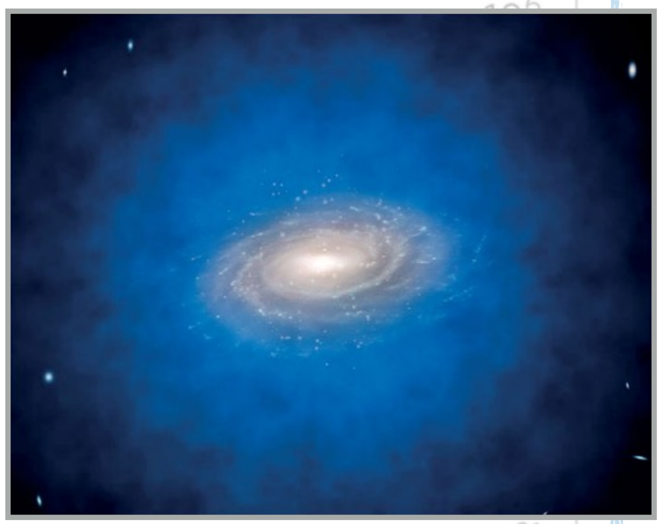
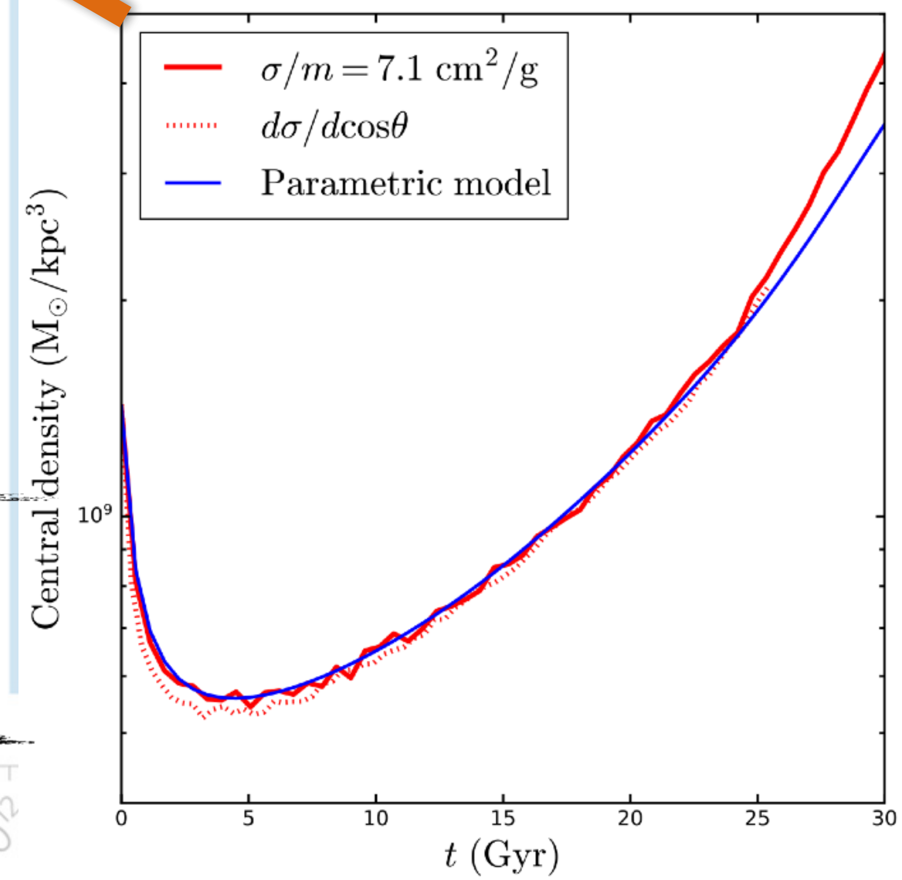


3. Self-interaction not too far from cm^2/gram



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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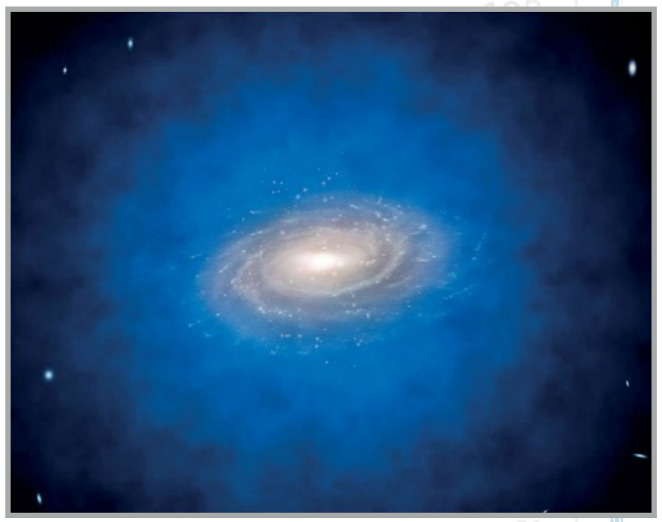
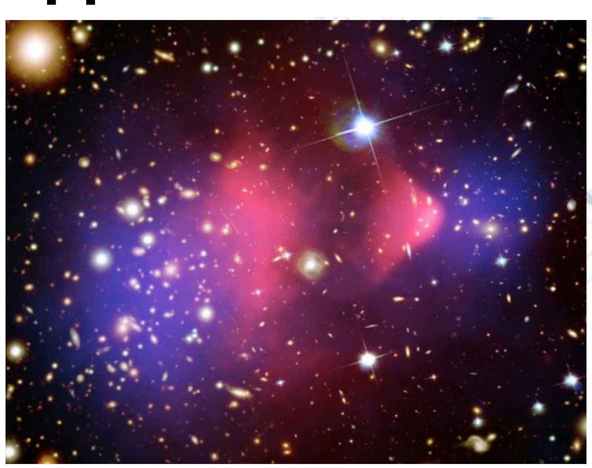


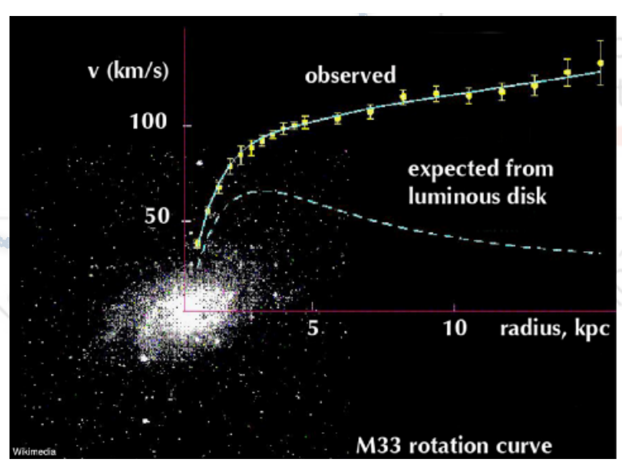
It adds a new d.o.f. to make halos **cored**, or **core-collapsed** via propagating heat faster.

An increasing list:

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

Upper bounds also exist (stronger from larger structures):





Such DM candidates should satisfy:

At most **very weak** interaction
with visible matter.

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

Strong self-interactions among dark matter.

Upper bounds also exist (stronger from larger structures):

Preferably, self-interaction decreases with halo size.

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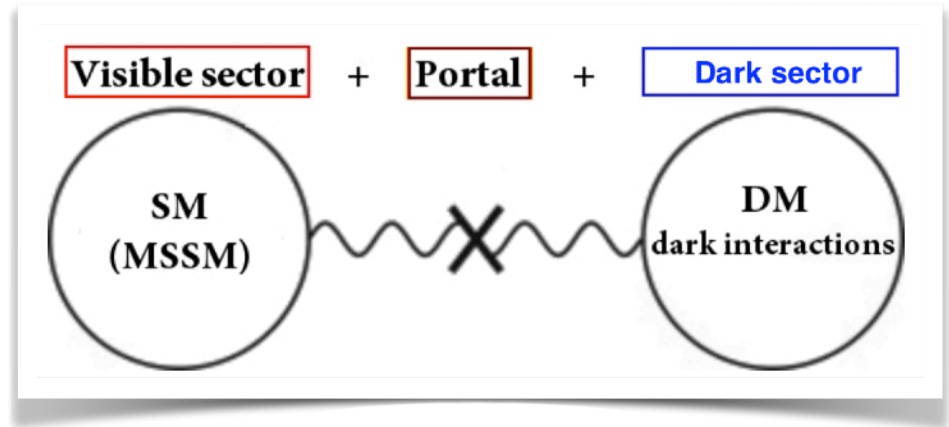

At most **very weak** interaction with visible matter.

A sector with its own structure.

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

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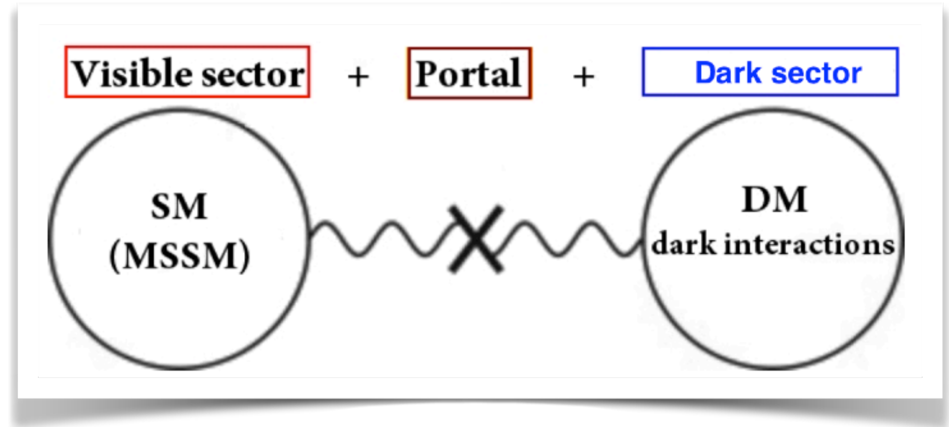

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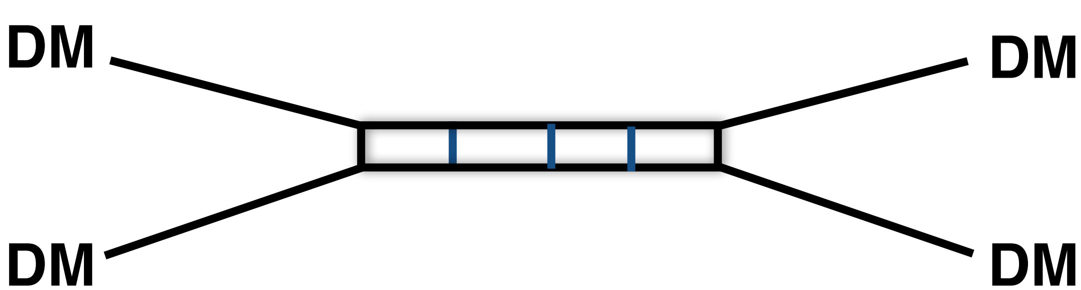
Self-interaction not too far from $cm^2/gram$

Strong self-interactions among dark matter.

A) Parametric enhancements



1. **A long-range force** (or equivalently, a **light mediator**)

   [D.N. Spergel & P. J. Steinhardt 1999, J. Feng, M. Kaplinghat & H.-B. Yu 2009, ...]

2. **A below-threshod bound state** or **above-threshod resonance**

   [J. D. March-Russell &S. M. West 2008, E. Braaten & H. W. Hammer 2013, XC, C. Garcia-Cely, H. Murayama 2018, ...]

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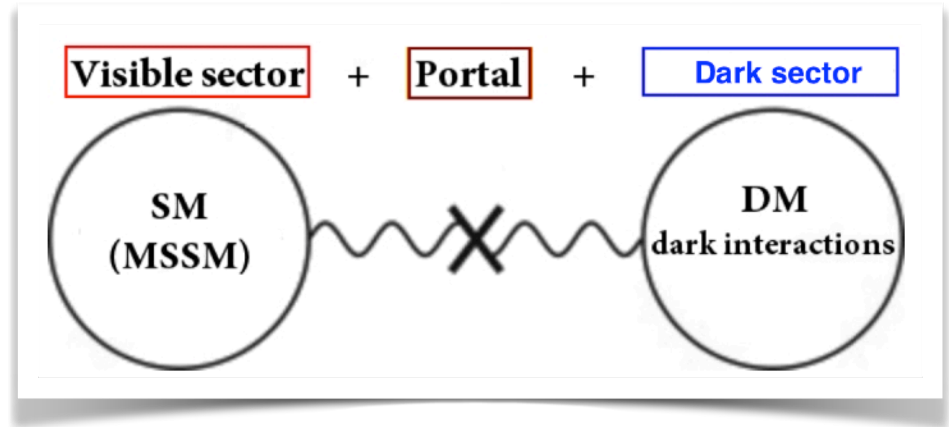

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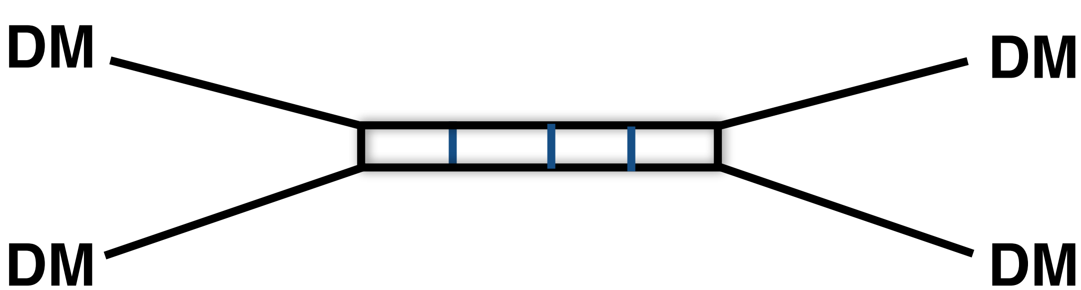

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B) Strong dynamics

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

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

cm^2/gram → **sub-GeV DM**

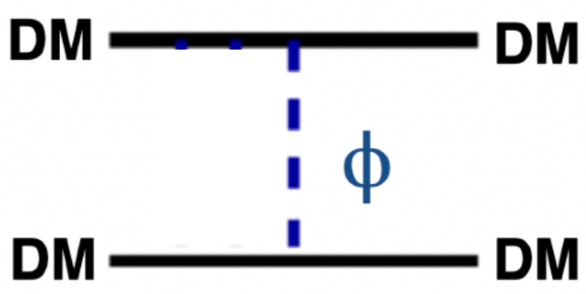
self-coupled keV-MeV DM (fluid) *[F. Atrio-Barandela & S. Davidson 1997, S. Hannestad & R.J. Scherrer 2000]*

More recently, *R.Garani, M. Redi, A. Tesi 2022.*

2. SIDM from parametric enhancements

Most popular **dark sector SIDM** scenario**:**

- introduce **a light mediator**



Even at tree level

t-channel propagator $\sim \frac{1}{t - m_\phi^2}$

leading to velocity-dependent enhancement $\frac{m_{\rm DM}^2}{m_{\rm DM}^2 v_{\rm DM}^2 + m_\phi^2}$

self-interaction decreases with halo size.

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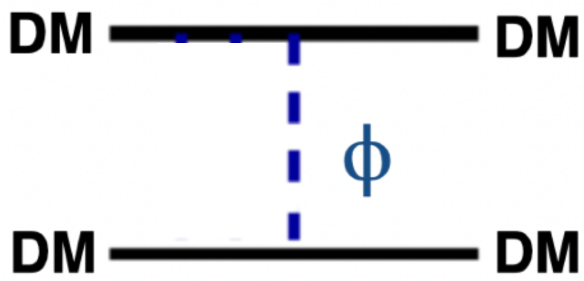

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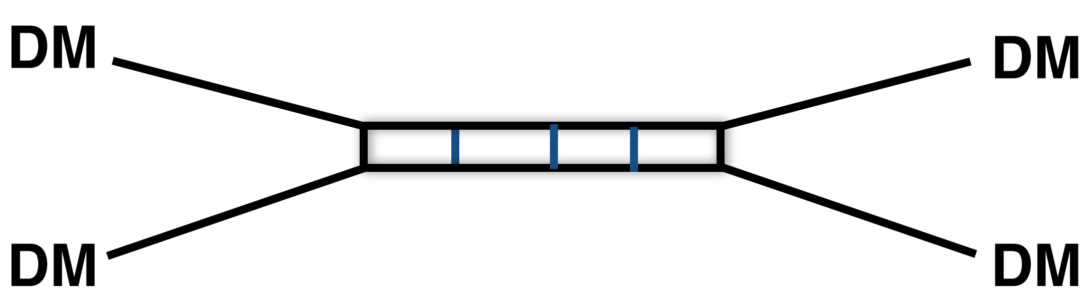
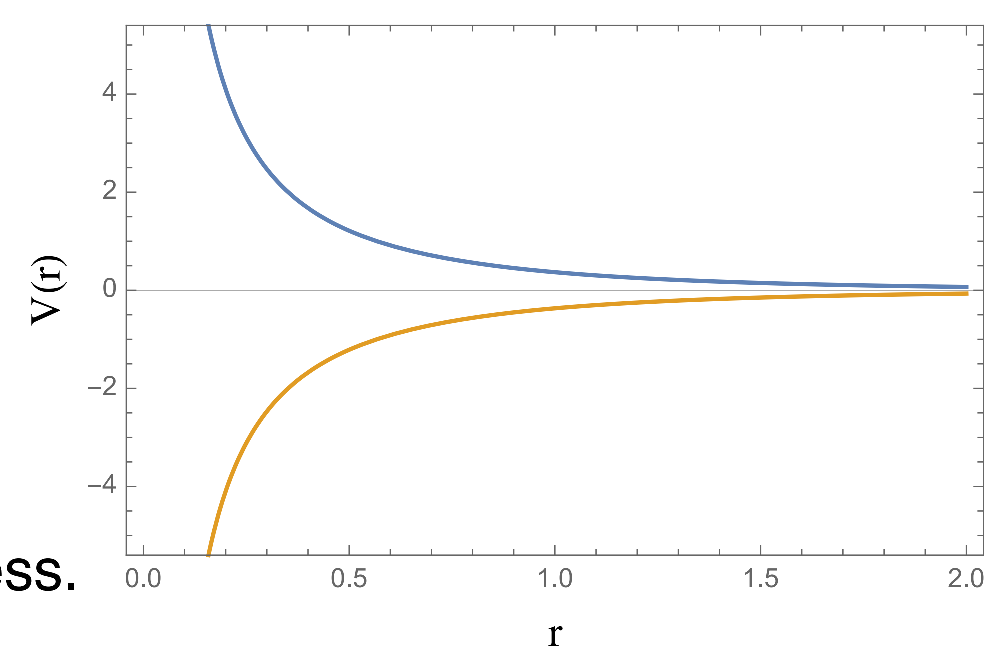
(1st-order Born approximation does not always work)



At non-relativistic limit, better described by a potential:

$$V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$$



Scattered phase-shifts contain full information of the process.

(But difficult to solve for $\ell \gg 100$)

Most popular **dark sector SIDM** scenario:

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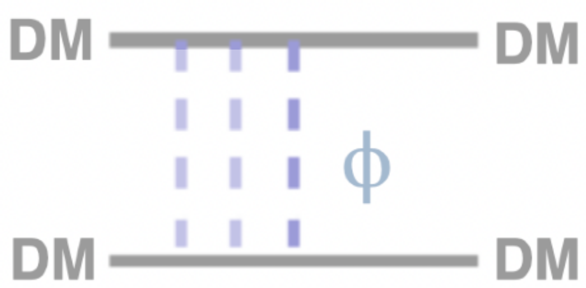

$$\sim \frac{1}{t - m_\phi^2}$$

$$\frac{m_{\rm DM}^2}{m_{\rm DM}^2 v_{\rm DM}^2 + m_\phi^2}$$

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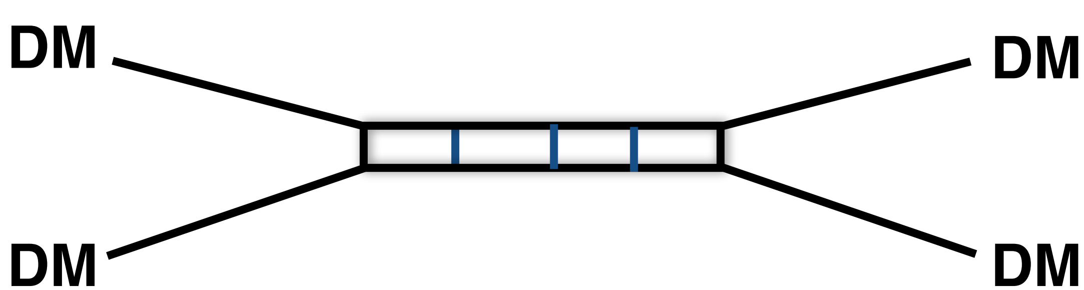
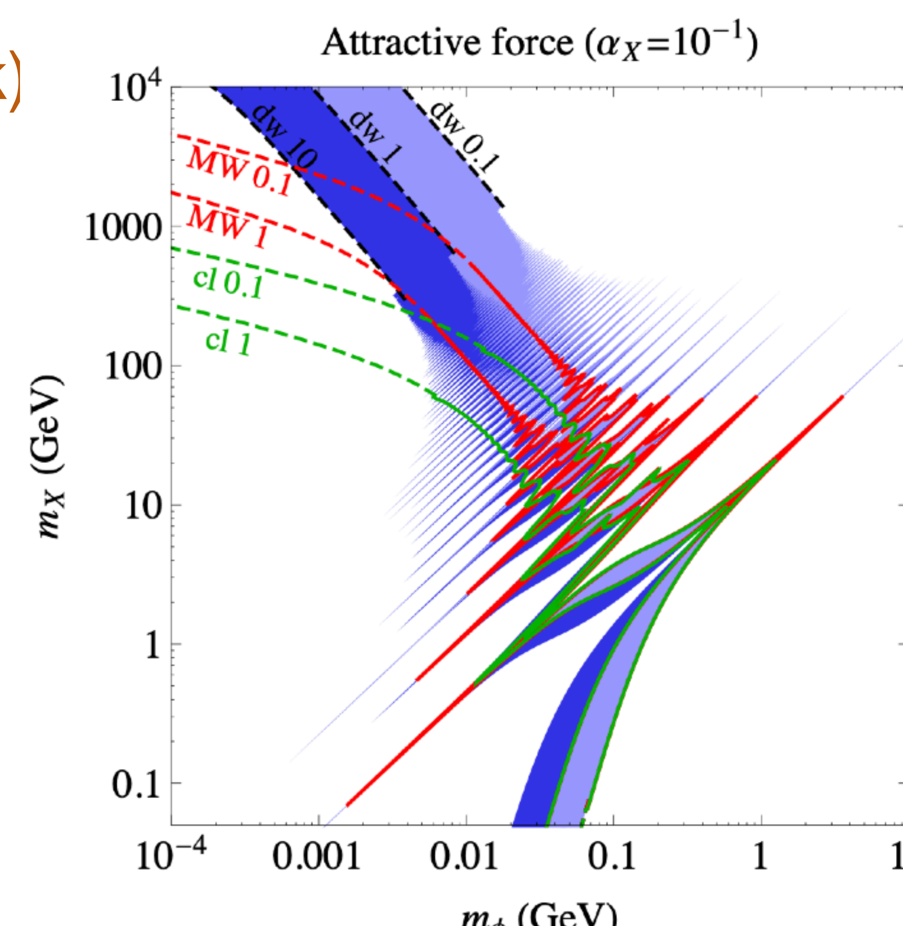


For instance, **bound state solutions** allowed for attractive $\alpha_X m_{\rm DM}/m_\phi \gtrsim 1.7$

(resonant enhancements at zero-energy bounds states)



Taken from S. Tulin, H.-B. Yu, K. M. Zurek 2013

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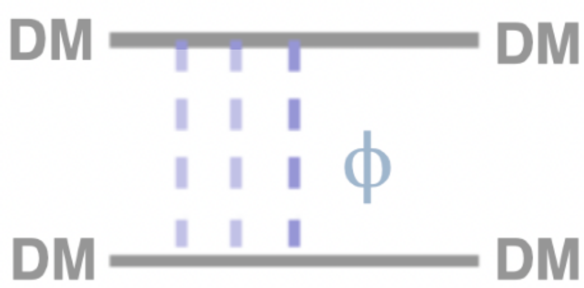


$$\sim \frac{1}{t - m_\phi^2}$$

$$\frac{m_{\rm DM}^2}{m_{\rm DM}^2 v_{\rm DM}^2 + m_\phi^2}$$

Potential signals of such dark sector models depend on the **destiny of light mediator:**

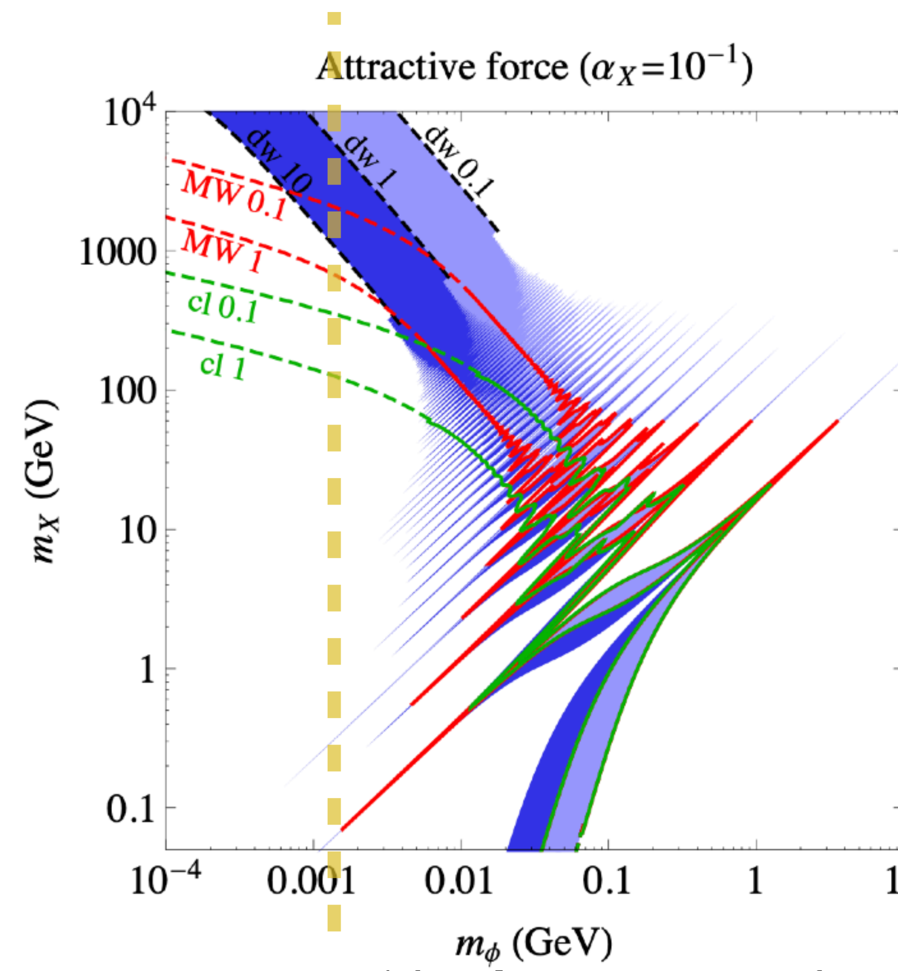
↳ displaced vertices at intensity frontier?

↳ enhanced cosmic ray excesses?

↳ anomalous stellar cooling?

↳ dark radiation?

[J. L. Feng, M. Kaplinghat & H.-B. Yu 2009, S. Tulin, H.-B. Yu & K. M. Zurek 2012, 2013, M.Kaplinghat, S. Tulin, H.-B. Yu 2013, M. Abdullah, A. DiFranzo, A. Rajaraman, Tim M. P. Tait, et al. 2014, N. Bernal, XC, C. Garcia-Cely, T. Hambye, B. Zaldivar 2015, N.Bernal, XC, S. Kulkarni, J. Pradler 2019, R. Coy, T. Hambye,M. H.G. Tytgat & L. Vanderheyden 2021, ...]



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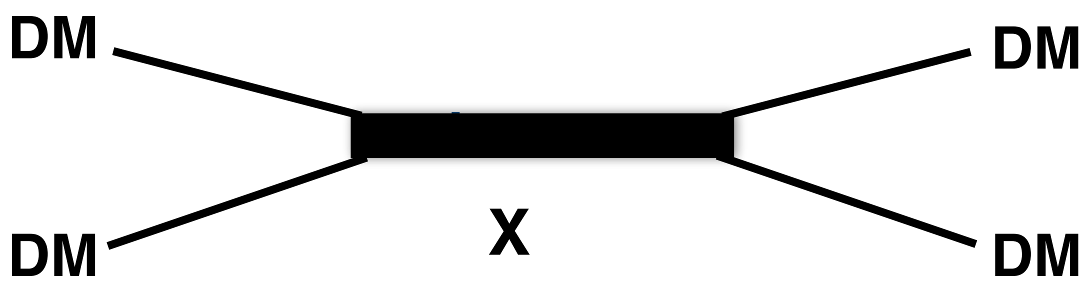
New interesting **dark sector SIDM** scenarios:

- introduce **a heavy mediator X**



s-channel propagator $\sim \dfrac{1}{s - m_X^2 + i\Sigma_X(s)}$

Large enhancement at $m_X \sim 2m_{DM}$

&

velocity-dependence depending on location of m_X

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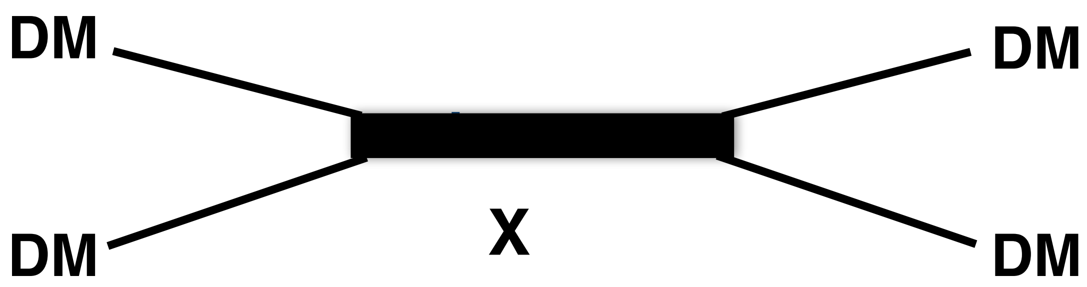

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Large enhancement at $m_X \sim 2m_{DM}$

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velocity-dependence depending on location of m_X

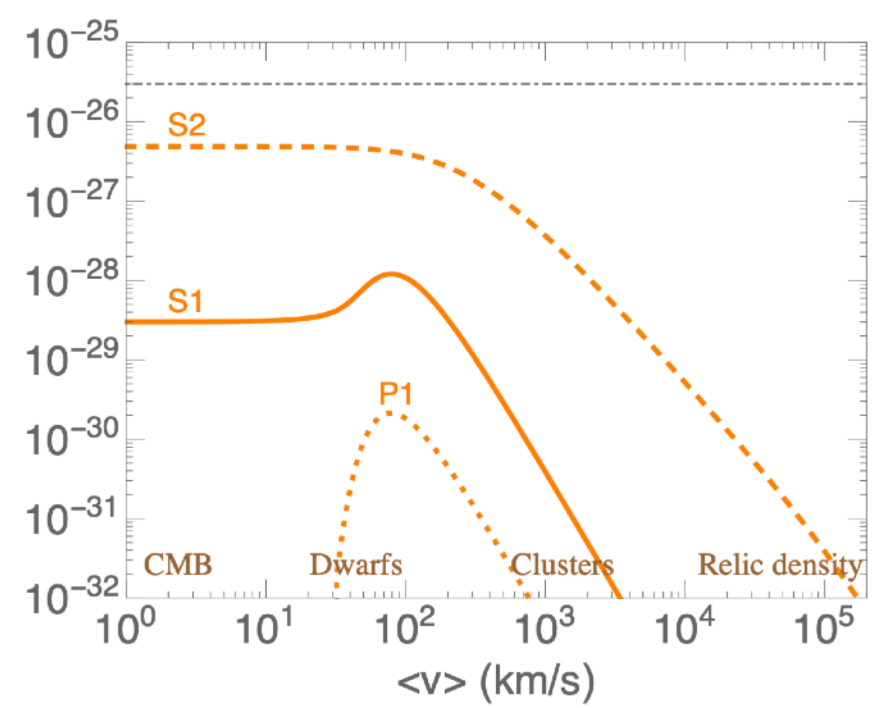
a) If $m_X > 2m_{DM}$, X is treated as a Breit-Wigner resonance *[XC, C. Garcia-Cely, H. Murayama 2018]*

self-scattering cross section peaks at the resonant velocity:

$$v_R^2 \hat{=} \frac{m_X - 2m_{\rm DM}}{2m_{\rm DM}} \ll 1$$

and decreases quickly for $v \gg v_R$.

- novel feature in astrophysics [e.g. *D. Gilman, Y.-M. Zhong& J. Bovy 2022, ...*].
- fine-tuning to get tiny v_R? *[Y.-D. Tsai, R. McGehee, H. Murayama 2020, ...]*



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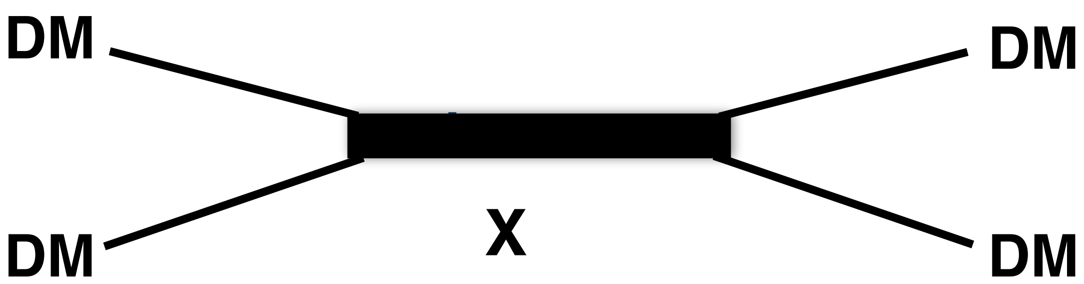

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b) If $m_X < 2m_{DM}$, X may naturally appear as a weak bound state

appears already for an attractive light mediator.

No peak, as $$v_R^2 \hat{=} \frac{m_X - 2m_{\rm DM}}{2m_{\rm DM}} < 0$$

self-interaction decreases with halo size.

↠ Such dark sector scenarios also have interesting applications in BAU/co-genesis [e.g. *M. Becker, K. Fridell, J. Harz & C. Hati 2024, ...*]

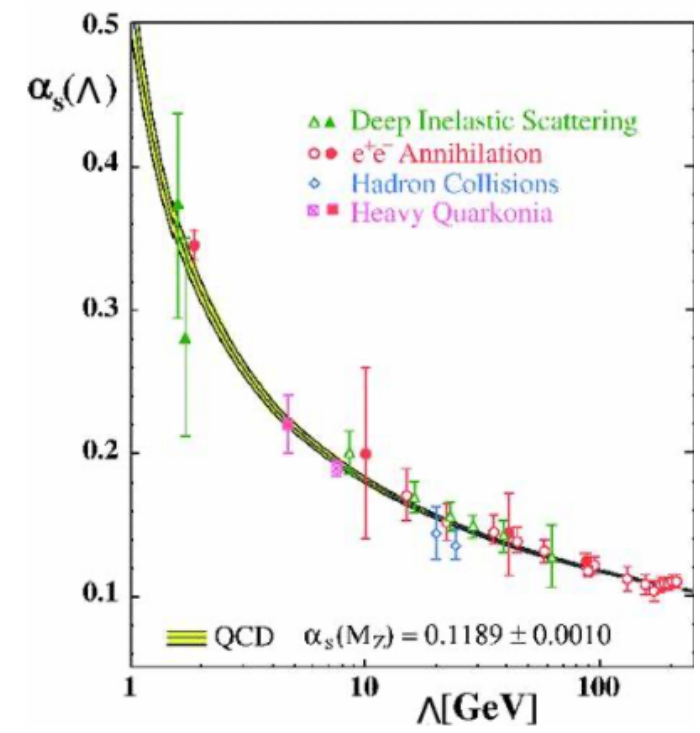
3. SIDM from Strong dynamics

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,….

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



Need to be described by chiral EFT or lattice methods.

SIDM needs strong-interactions for sub-GeV masses.

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

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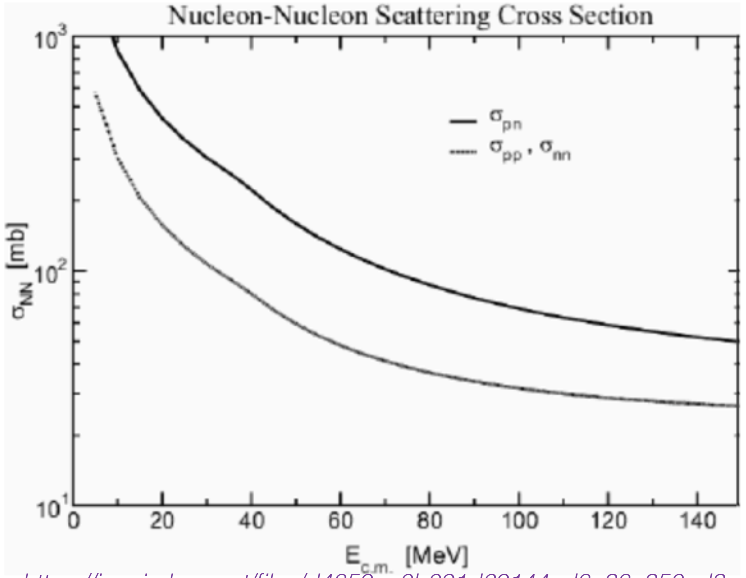
Production mechanism:

DM could be asymmetric, to prevent significant self-annihilation.

5 GeV to explain coincidence, or other co-genesis?

Velocity-dependent scattering:

Similar to SM nucleon scattering, naively dominated by **pion-**exchange.



https://inspirehep.net/files/d4859aa0b091d69144ed8e38e350cd3c

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Production mechanism:

DM has to be symmetric, two-body annihilation seems too strong.

One thus needs **tuned freeze-in**, or N→2 freeze-out (FO):

↳ also applies to weaker coupled sub-MeV SIDM.

(e.g. production mechanisms of sterile neutrinos)

No obvious built-in mechanism to have velocity-dependence.

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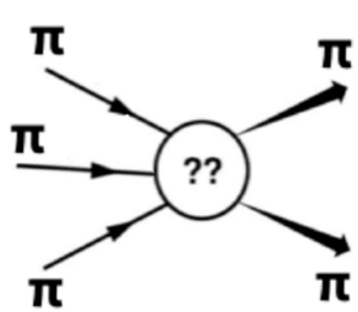
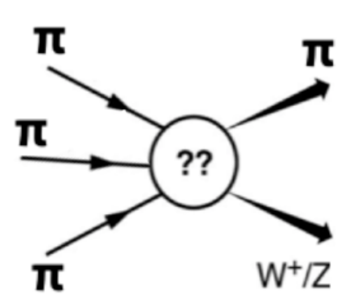
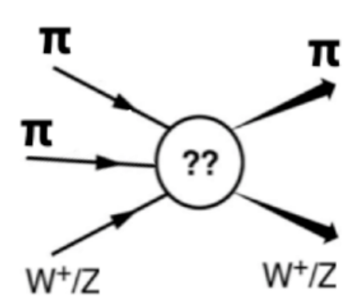


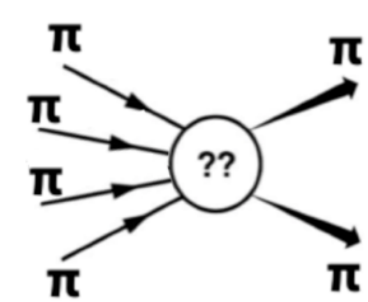
SIMP
[Y.Hochberg, E. Kuflik, T. Volansky, J. G. Wacker 1402.5143, ...]



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, ...]

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Production mechanism:

Has to be symmetric, two-body annihilation seems too strong.

One thus needs tuned freeze-in, or **N→2 freeze-out** (FO):

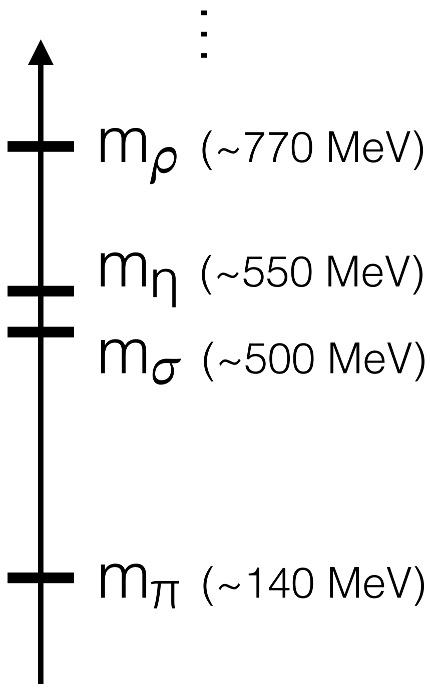
Velocity-dependent scattering?

Not explicitly.

Luckily (or unluckily), sectors of strong-dynamics are complicated.

Lightest stable state from strong dynamics

Take SIDM candidate as **dark pion**

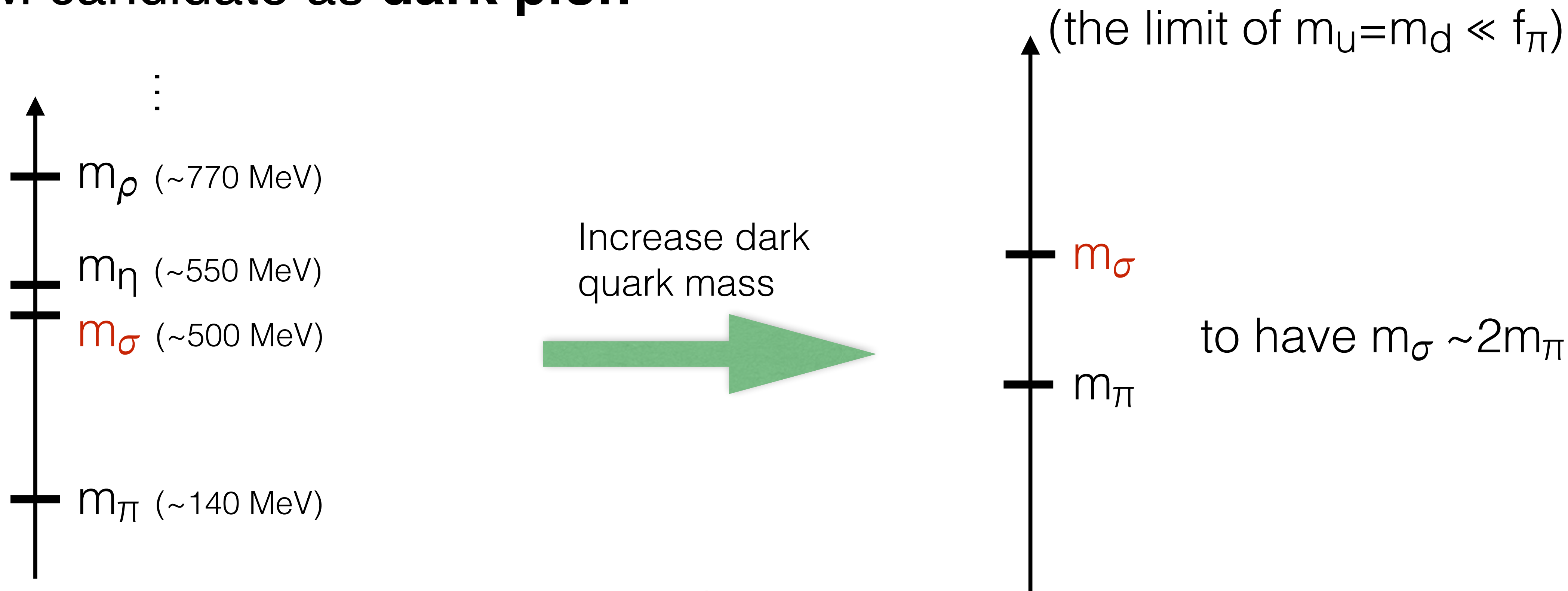


SM case ($f_\pi \sim$ 93 MeV)

Heavier states hardly play any role

Lightest stable state from strong dynamics

Take SIDM candidate as **dark pion**



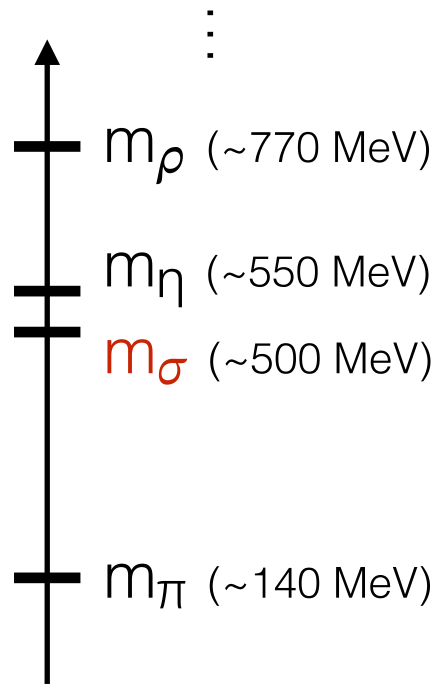
SM case (f_π ~ 93 MeV)

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].

Lightest stable state from strong dynamics

Take SIDM candidate as **dark pion**



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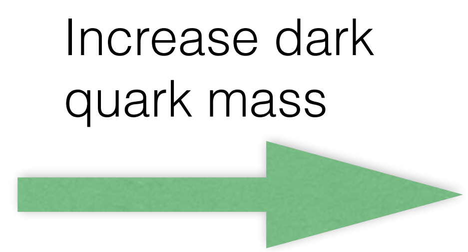
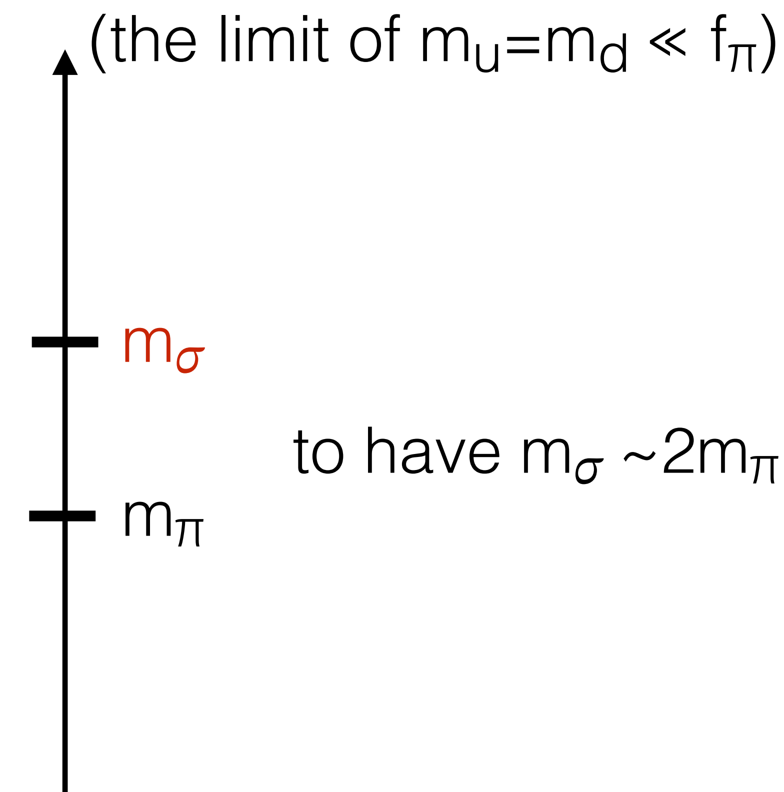


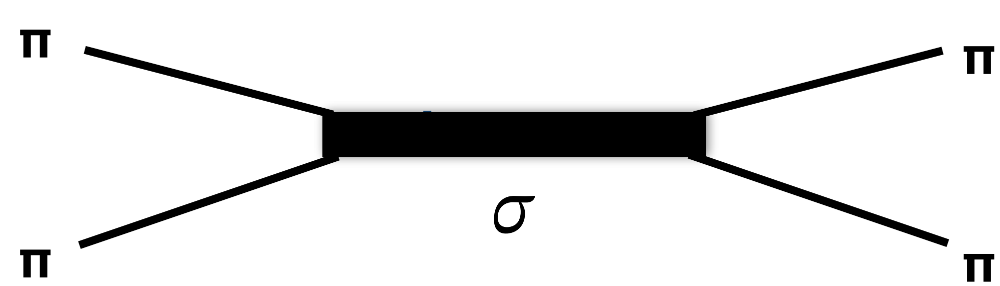


to have $m_\sigma \sim 2m_\pi$

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

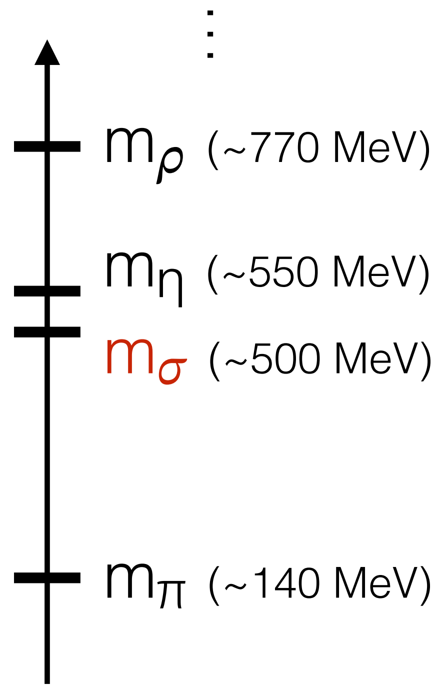
One interesting case is $m_\sigma \lesssim 2m_\pi$, appearing as a **(meta-)stable bound state**:

1. self-interaction decreases with halo size.



Lightest stable state from strong dynamics

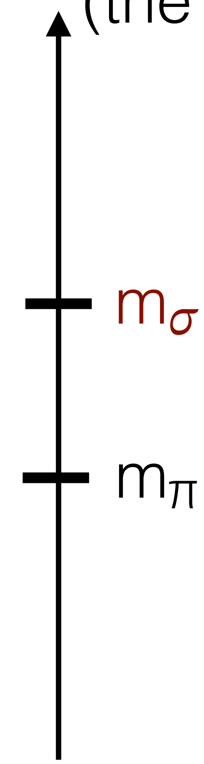
Take SIDM candidate as **dark pion**



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

Increase dark quark mass

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

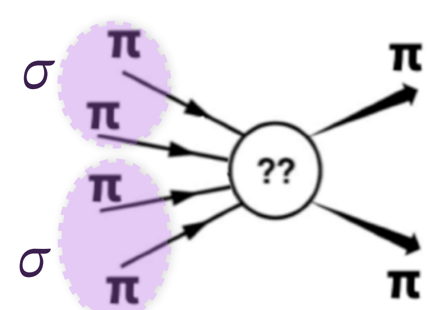


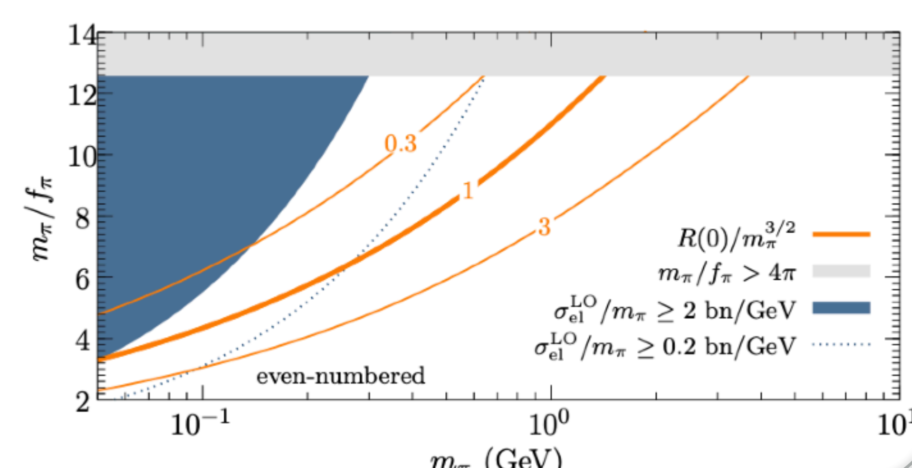
to have $m_\sigma \sim 2m_\pi$

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

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

2. Freeze-out can be enhanced by bound state formation [*XC, M. Nikolic, J.Pradler 2024*].





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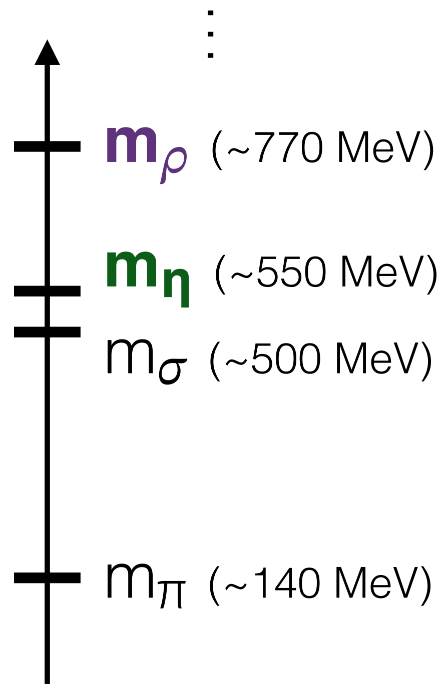
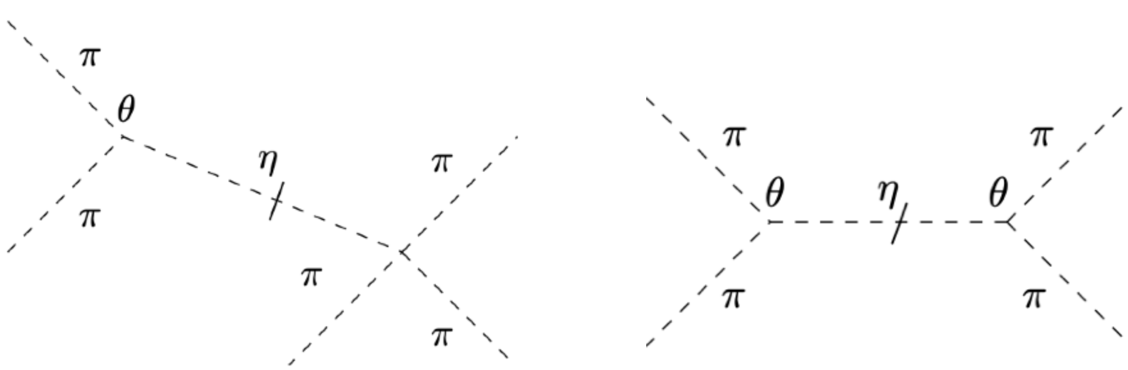


Increase dark quark mass

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

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

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

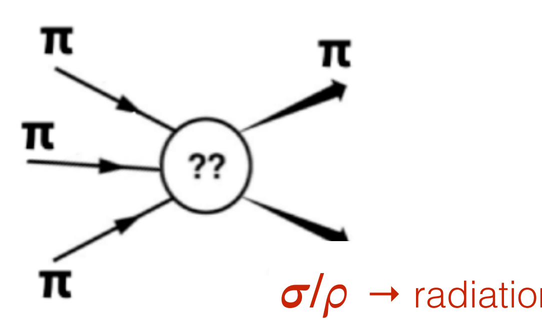


Rho meson may play a similar role if $m_\rho \sim 2m_\pi$

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

(with additional p-wave suppression)

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



Lightest stable state from strong dynamics

Take SIDM candidate as **dark pion** (and the limit of $m_u = m_d \ll f_\pi$)

Beyond mesons, other particles can help too.

such as **gauged Wess-Zumino-Witten terms** and/or **dark axion**.

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

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

(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)

SIDM candidate can also be **dark glueball:**

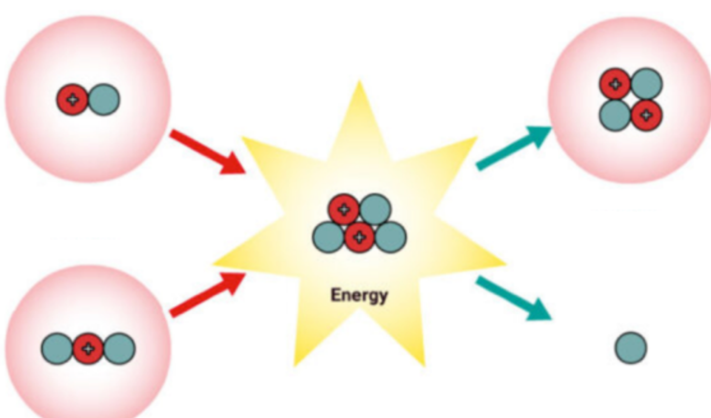
- **Glueball-onium** is also possible *[e.g. F.Giacosa, A. Pilloni, E.Trotti 2021]*

Or, **many stable states** 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, ….**

[e.g. *M. B. Wise and Y. Zhang 2014. E. Hardy, R. Lasenby, J. March-Russell &S. M. West, 2014, 2015, M. I. Gresham, H. K. Lou, and K. M. Zurek, 2017, 2018* …]



↳ Dark fusion?

[e.g. *S. D. McDermott 2017,* …]

↳ Energy equipartition?

[See Daneng Yang's talk]

Binding/kinetic energy heats up halo core?

↳ Finite-sized (puffy) DM?

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

Form-factor induces velocity-dependence?

4. Beyond dark sector models

What we are now?

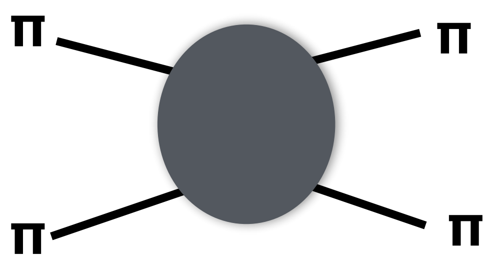
Strong self-interactions without underlying UV theory

→ Similar to **hadron physics before quarks**.

S-matrix (bootstrap) methods developed in 1960s.

Assuming analyticity, crossing, unitarity etc, **elastic scattering** amplitude has certain form:

$$T_{ab,cd} = A(s,t,u)\delta_{ab}\delta_{cd} + A(t,s,u)\delta_{ac}\delta_{bd} + A(u,t,s)\delta_{ad}\delta_{bc}$$



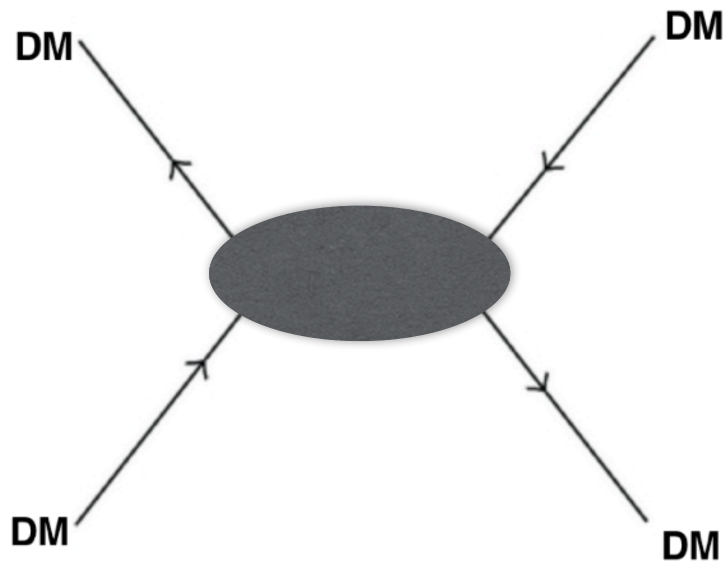
$$\begin{aligned} A(s,t,u) &= T_0 + \frac{1}{\pi}\int_4^\infty dx\, \frac{\sigma_1(x)}{x-s} + \frac{1}{\pi}\int_4^\infty dx\, \sigma_2(x)\left[\frac{1}{x-t} + \frac{1}{x-u}\right] \\ &+ \frac{1}{\pi^2}\int_4^\infty dx \int_4^\infty dy\, \frac{\rho_1(x,y)}{x-s}\left[\frac{1}{y-t} + \frac{1}{y-u}\right] \\ &+ \frac{1}{\pi^2}\int_4^\infty dx \int_4^\infty dy\, \frac{\rho_2(x,y)}{(x-t)(y-u)} \end{aligned}$$

[Relevant recent work: *Y.f. He &M Kruczenski 2023, 2024, A. Guerrieria, K. Haringa & N. Su 2024, J. A. Oller 2024, ...*]

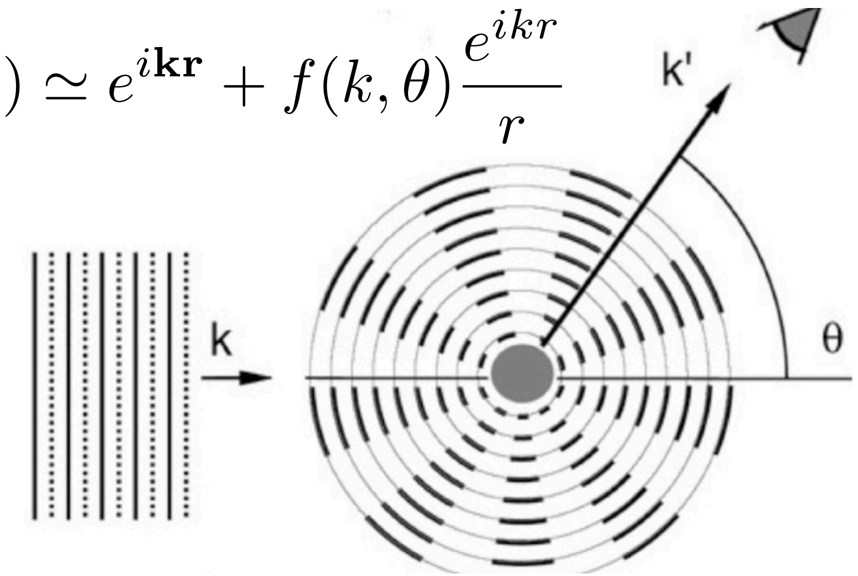
Unlikely to have many data points at different kinetic energies for SIDM

But, still possible to get **some information under simply assumptions**.

Go beyond concrete dark sector models



$$\psi(r) \simeq e^{i\mathbf{kr}} + f(k,\theta)\frac{e^{ikr}}{r}$$



$$f_\ell(k) \equiv \frac{e^{2i\delta_\ell(k)}-1}{2ik} = \frac{1}{k\left(\cot\delta_\ell(k) - i\right)}$$

Assume **s-channel-dominated self-scattering**

— quite likely as high-ℓ partial waves receive velocity suppression.

— not for very-long-range force, where many partial waves contribute.

boundary conditions of **finite-range potential** allows an expansion of the phase shift at very low velocities *[Schwinger, Blatt&Jackson, Bethe, 1940s]* :

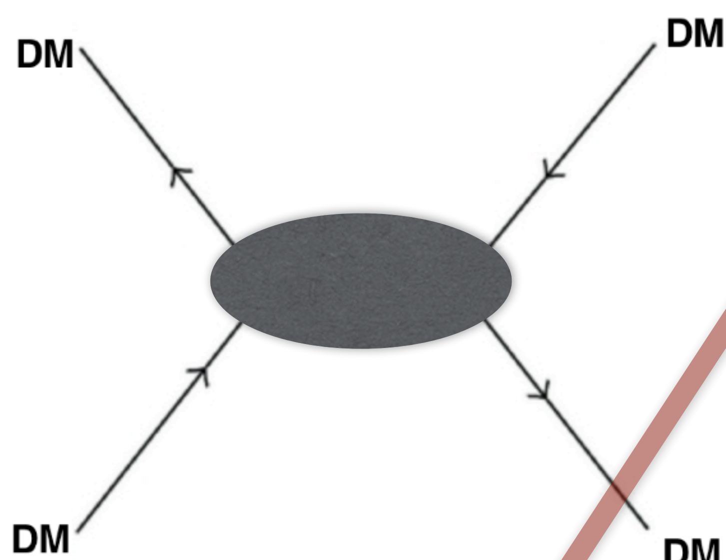
$$k\cot\delta_0 = -\frac{1}{a_0} + \frac{k^2}{2r_{e,0}} + \mathcal{O}(k^4)$$

(strong non-relativistic scattering, suggesting *Im*[δ_0] << *Re*[δ_0], and neglected)

Effective-range parametrization of SIDM [XC, C. Garcia-Cely, H. Murayama 2019]

S-wave self-interaction: $\sigma_0 = \frac{4\pi}{k^2}\sin^2\delta_0 \approx \frac{4\pi a^2}{1 + k^2\left(a^2 - a r_e\right) + \frac{1}{4}a^2 r_e^2 k^4}$

(angle-independent)



- For hard scattering $(1/k \gg |a| \gg |r_e|)$.

$$\sigma_0 \to 4\pi a^2$$ (contact interaction)

- For very large scattering length $(a \to \infty)$:

$$\sigma_0 \to \frac{4\pi}{k^2}$$ **Unitary fermi gas?**

$$k \cot\delta_0 = -\frac{1}{a_0} + \frac{k^2}{2 r_{e,0}} + \mathcal{O}(k^4)$$

Effective-range parametrization of SIDM [XC, C. García-Cely, H. Murayama 2019]

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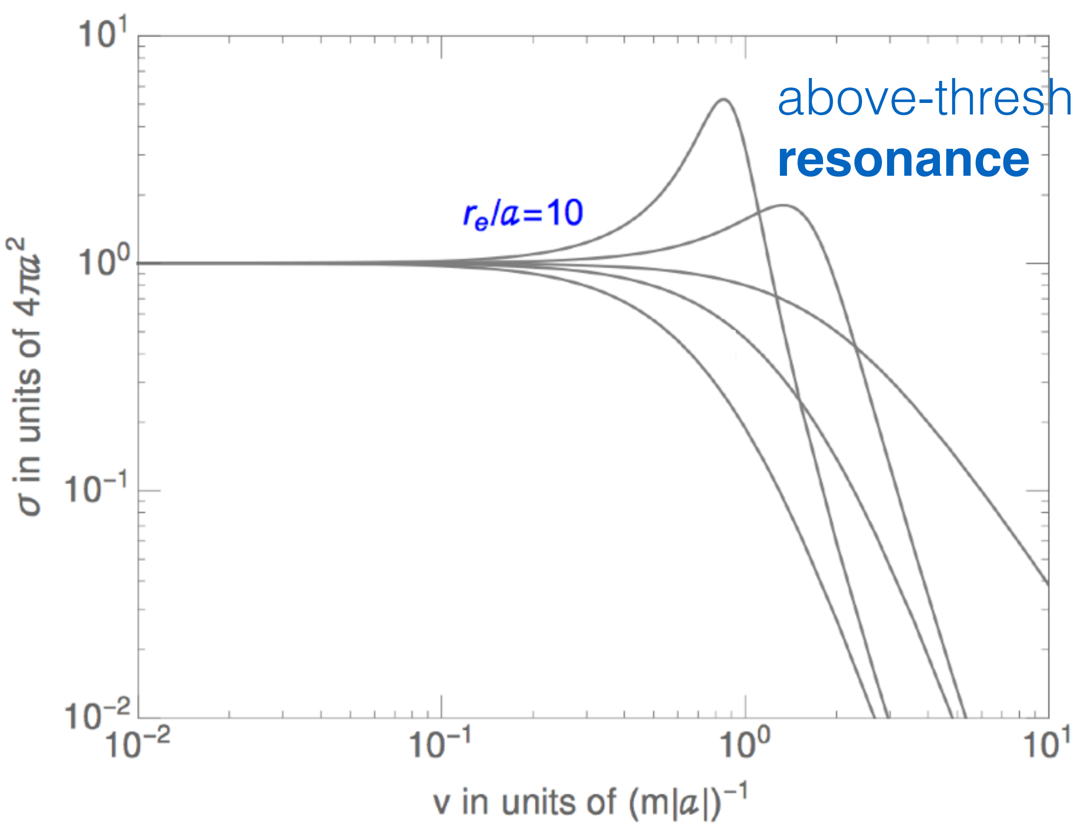

Take **Breit-Wigner resonance** from PDG

$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{4\pi}{k^2}\left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4}\right] B_{in}B_{out}$$

J=0, and classical limit does treat $S_{1,2}$.

Br=1, as $Im[\delta_0]$ neglected.

That is,

a and r_e are both functions of E_0 and $\Gamma(E_0)$.

$$(\, m_{\rm DM},\, a,\, r_e \,)$$

An easy way to parametrize **resonant SIDM.**

Effective-range parametrization of SIDM [XC, C. Garcia-Cely, H. Murayama 2019]

S-wave self-interaction: $\sigma_0 = \frac{4\pi}{k^2}\sin^2\delta_0 \approx \frac{4\pi a^2}{1 + k^2\left(a^2 - a r_e\right) + \frac{1}{4}a^2 r_e^2 k^4}$

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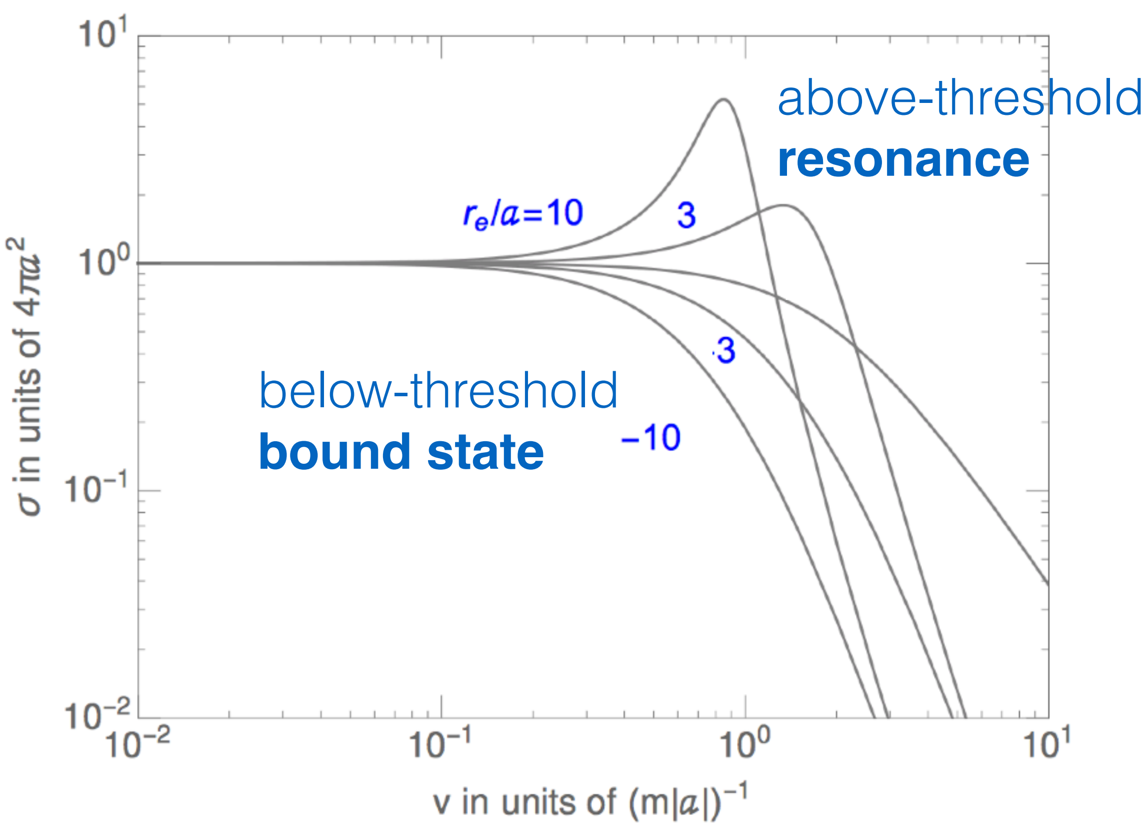
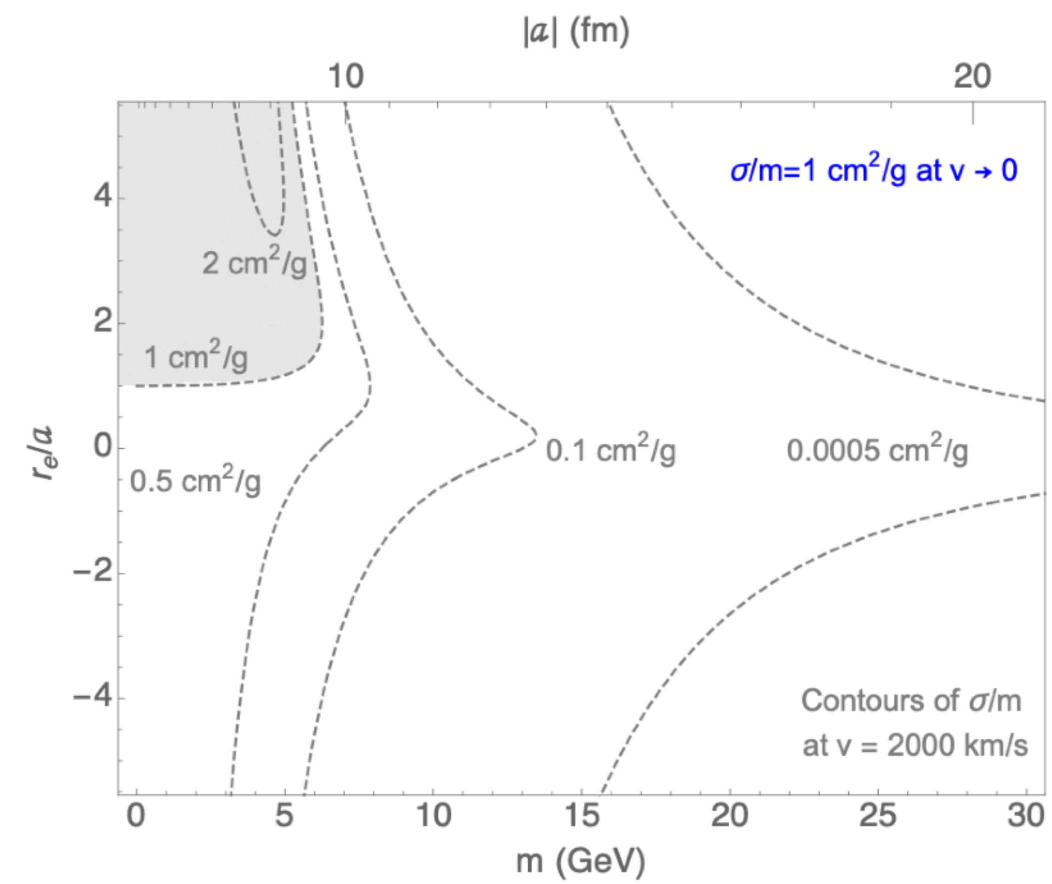




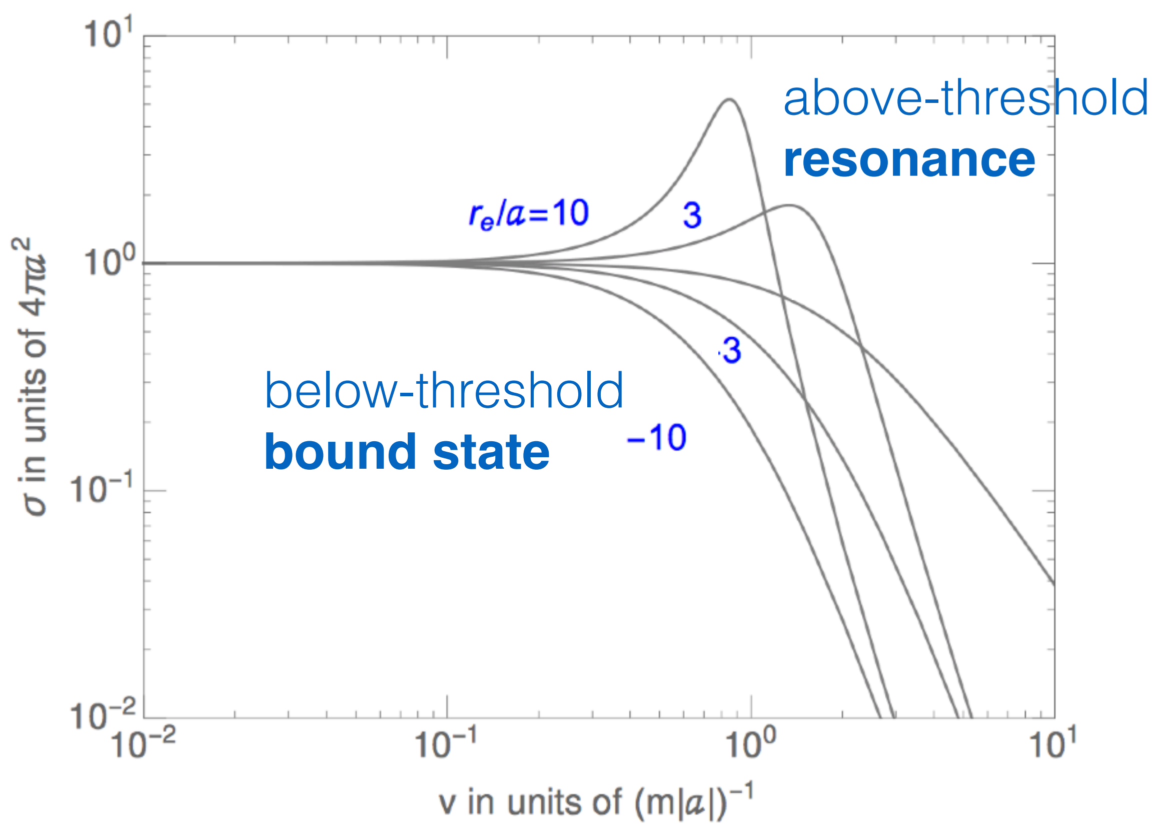
$$(\, m_{\rm DM}, \, a, \, r_e \,)$$

An easy way to parametrize general **S-wave-dominated SIDM.**

e.g. resonant/bound-state SIDM, Yukawa SIDM with mediator mass larger than k, …

Effective-range parametrization of SIDM [XC, C. García-Cely, H. Murayama 2019]

S-wave self-interaction: $\sigma_0 = \frac{4\pi}{k^2}\sin^2\delta_0 \approx \frac{4\pi a^2}{1 + k^2\left(a^2 - a r_e\right) + \frac{1}{4}a^2 r_e^2 k^4}$



Explains why so often to have **DM self-scattering decreasing with higher velocities.**

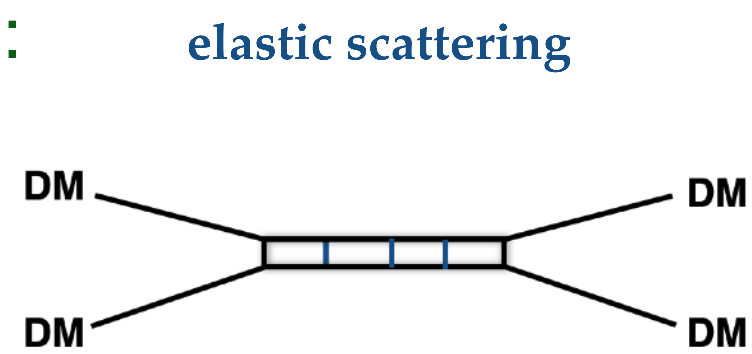
A few data points may suggest the existence of **bound state** or **resonance**, modifying freeze-out.

5. Conclusions

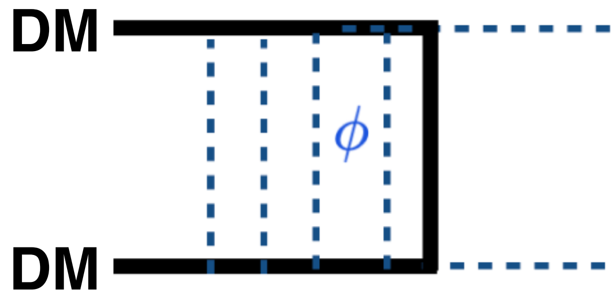
DM self-scattering from dark sector physics

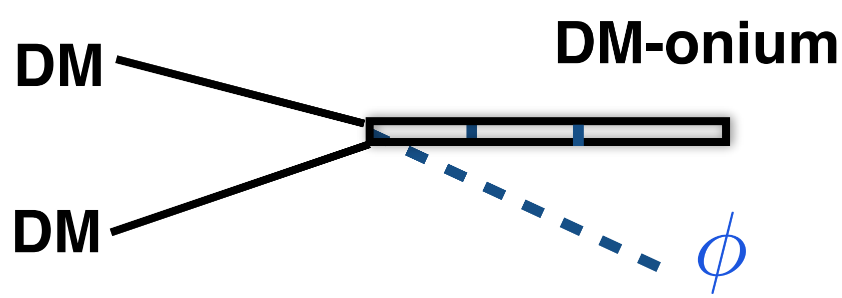
- It needs to induce **velocity-dependent** self-scattering:

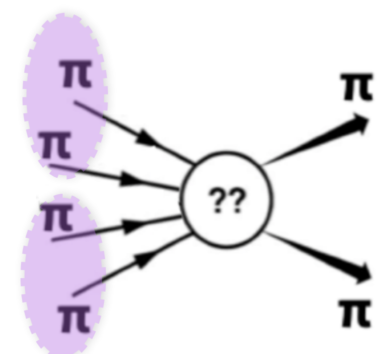
Strong and alleviating galaxy/cluster bounds.



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







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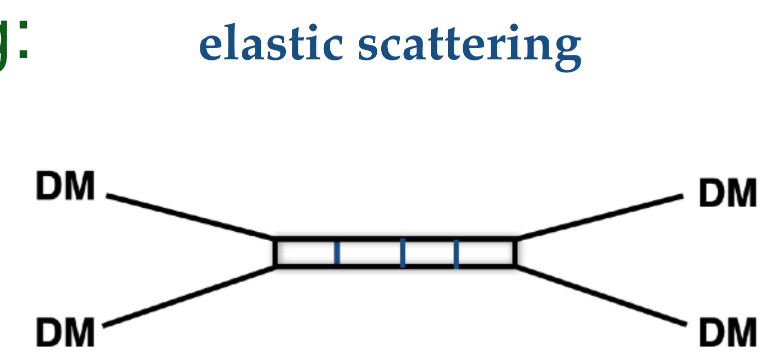
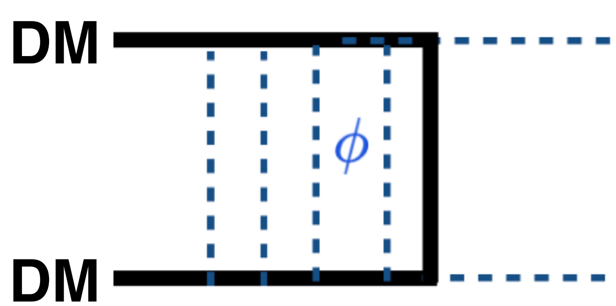
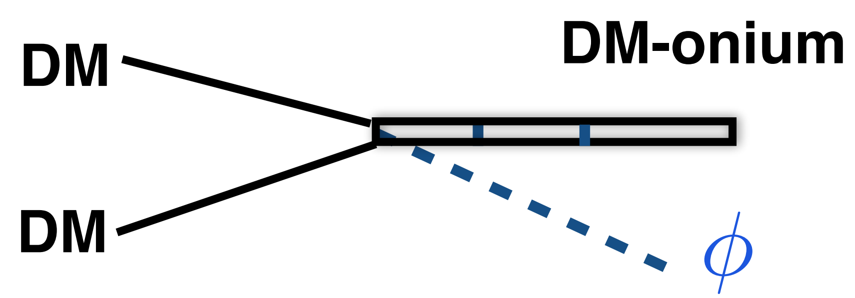
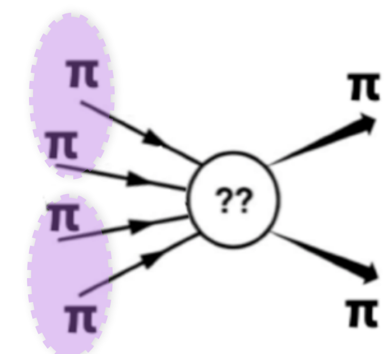


Strong and alleviating galaxy/cluster bounds.

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



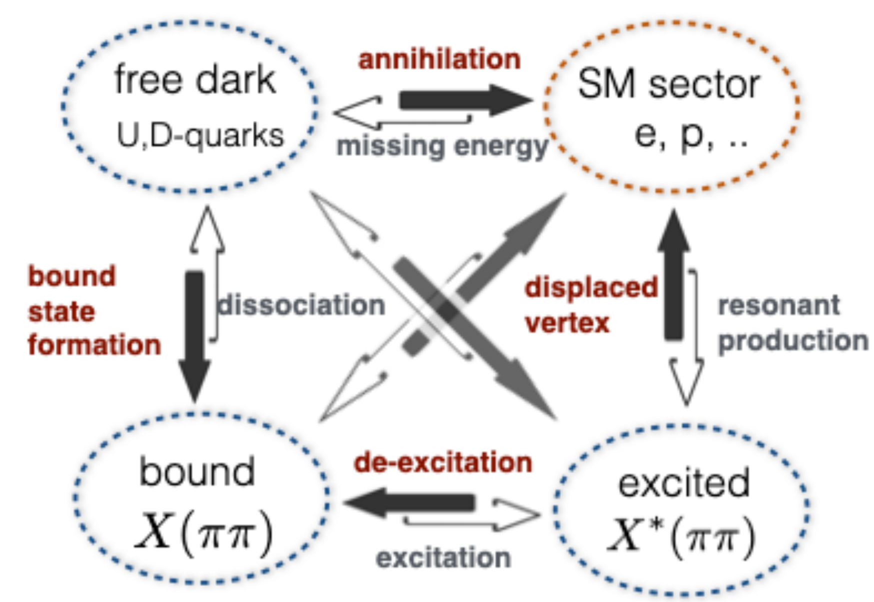




- It also leads to novel signatures in astrophysics & territorial experiments:

Inelastic scatterings of astrophysical DM?

- It may be relevant for baryonic asymmetry too.



Thanks!