The 2025 Beijing Particle Physics and Cosmology Symposium (BPCS 2025): early Universe, gravitational-wave templates, collider phenomenology

The roles of bound state in dark sectors

Xiaoyong Chu (ICTP-AP, UCAS)

In collaboration with Camilo Garcia-Cely, Hitoshi Murayama, Josef Pradler etc.

中国科学院大学
University of Chinese Academy of Sciences

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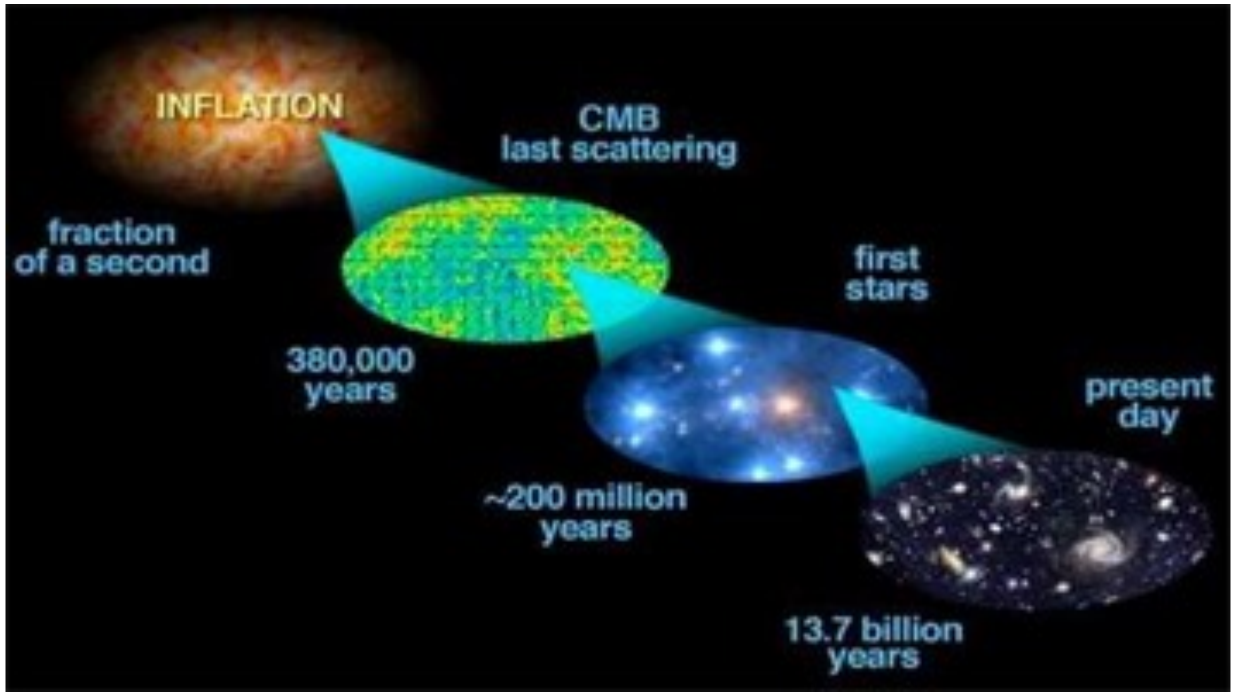
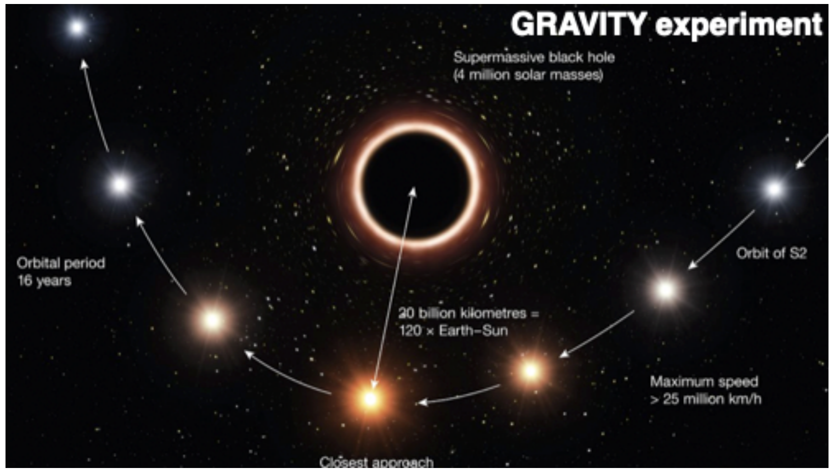
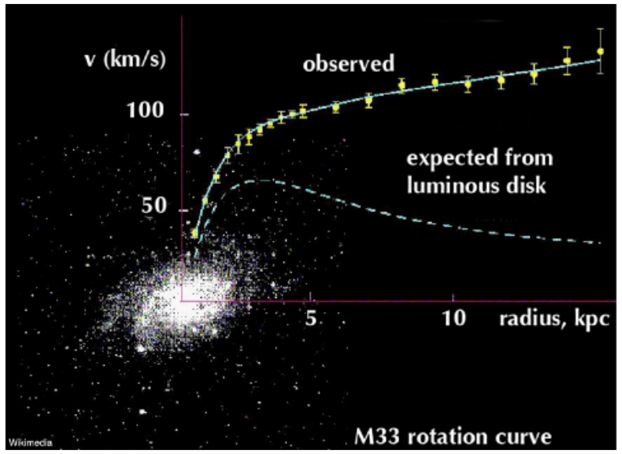
What we know about **dark matter** from **cosmology**?

Structures grow:
- from quantum to classic
- from dark to visible







Existence below pc-scale?
Not confirmed.

What we know about **dark matter** from **cosmology**?

Structures grow:

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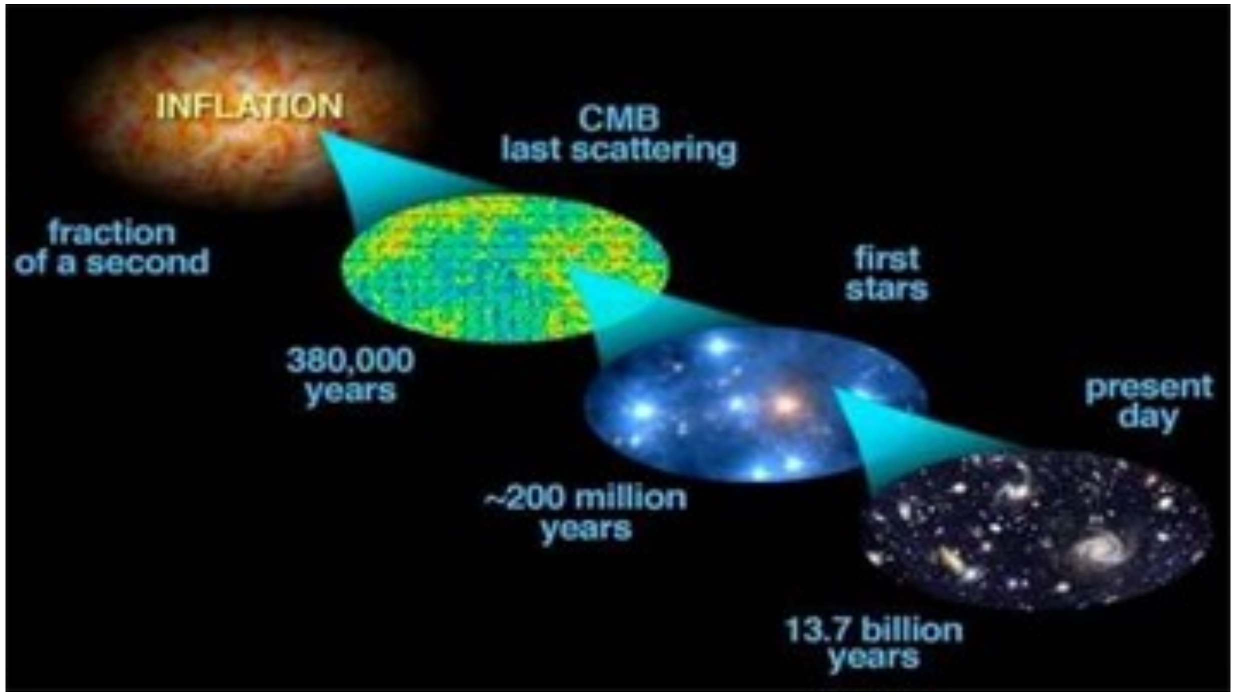
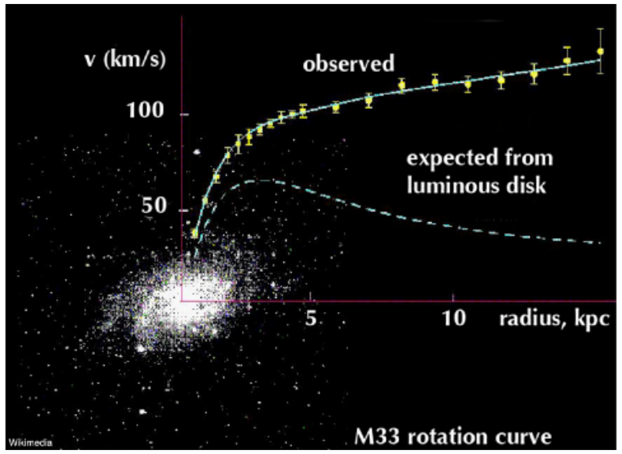
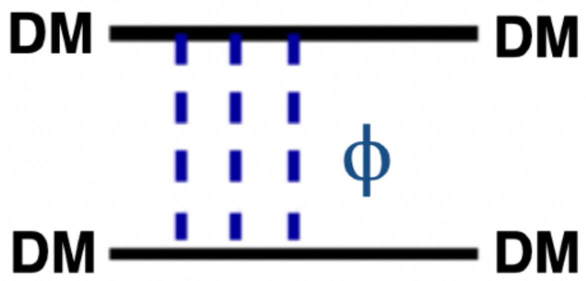




This allows for a lot of model building, **from the aspect of particle physics**.

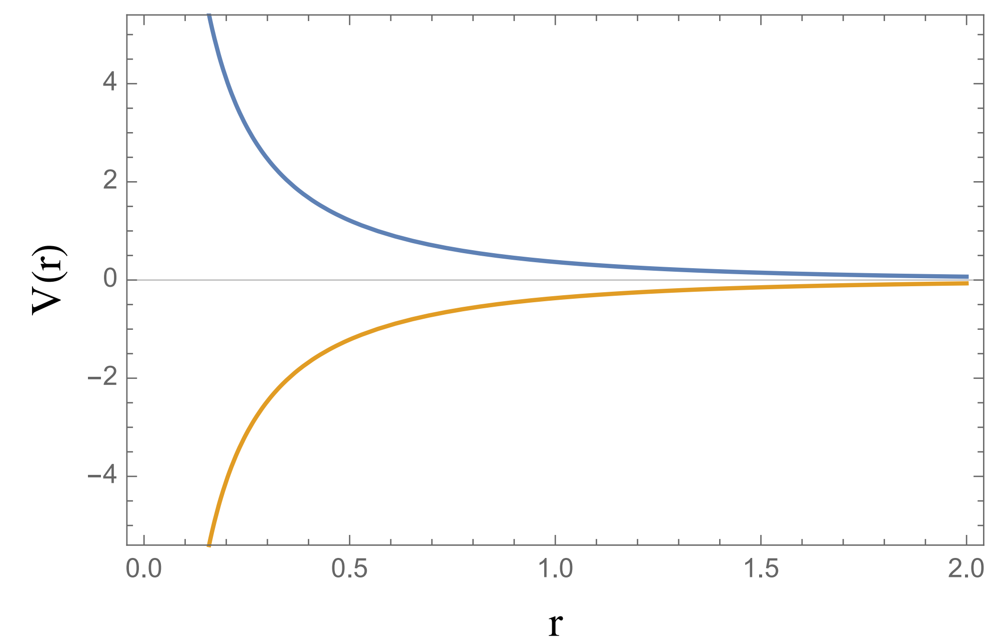
Particle models of bound state (or resonance)

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



Described by a **Yukawa** potential at non-relativistic limit:

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



Bound state solutions allowed for

$$\alpha_X m_{\rm DM}/m_\phi \gtrsim 1.7$$

non-perturbative

Conditions	α $m_X < m_\phi$	α $m_X > m_\phi$
$\varkappa = k/m_\phi >> 1$	Born	classical
$\varkappa = k/m_\phi << 1$	Born	resonant

DM velocity is relatively low

Particle models of bound state (or resonance)

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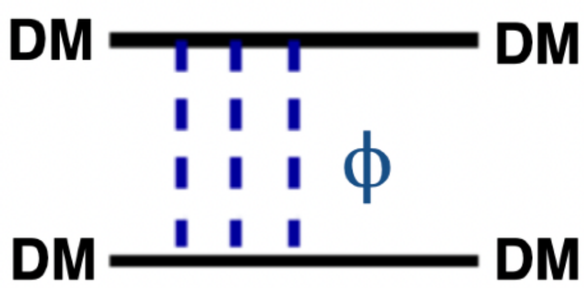

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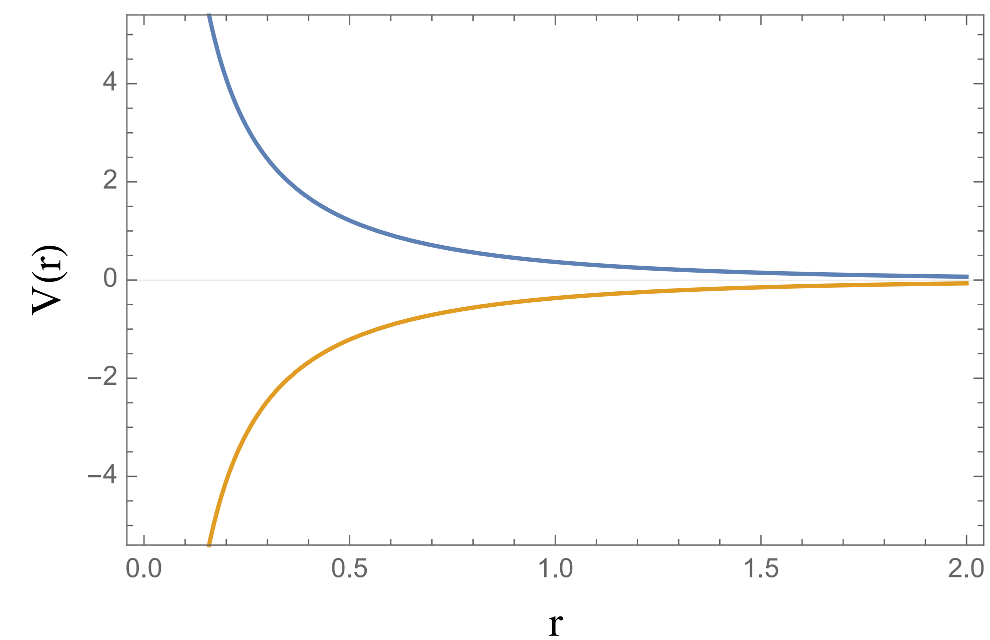

Bound state solutions allowed for

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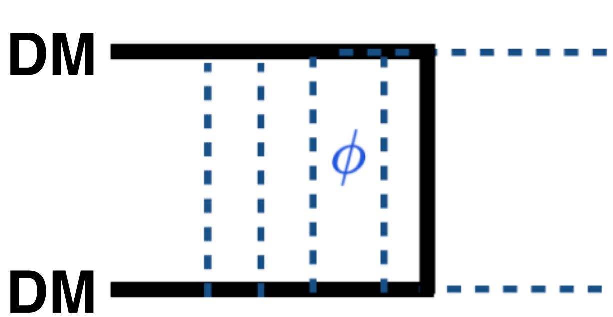
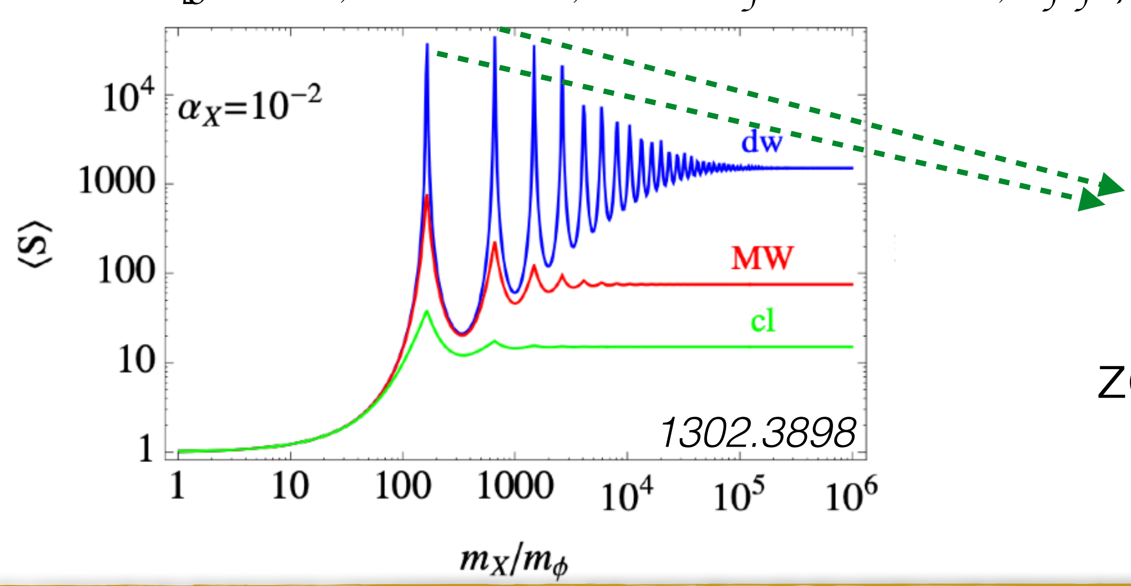
Most well-known example: **Sommerfeld** enhancement

[J. Hisano, S. Matsumoto, M. M. Nojiri and O. Saito, hep-ph/0412403]





$$\frac{\alpha_X m_X}{\kappa m_\phi} = n^2\,, \quad n = 1,\, 2,\, 3,\, \ldots$$

zero-energy bound states

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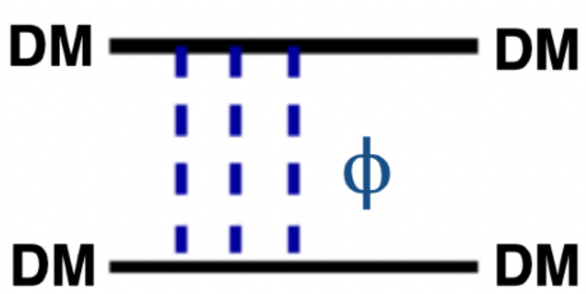

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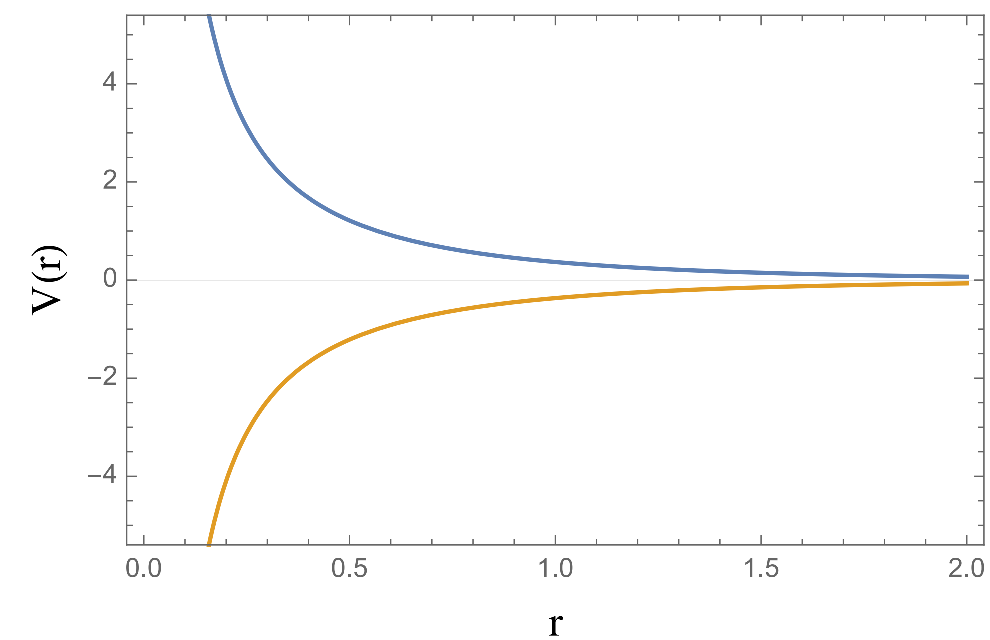
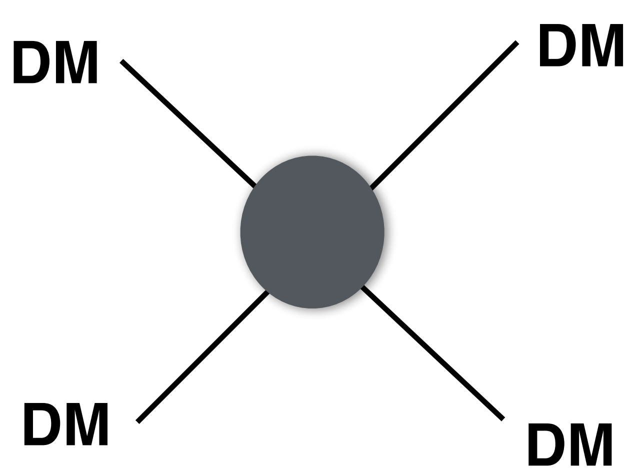


Bound state solutions allowed for

$$\alpha_X m_{\rm DM} / m_\phi \gtrsim 1.7$$

Or:

- **Strong enough couplings** *[such as dark QCD models]*



Pole in S-matrix amplitude *[e.g. pion-onium 2309.12402. 2409.16790]*

Variational method *[e.g. contact terms, L. I. Schiff (1963)]*

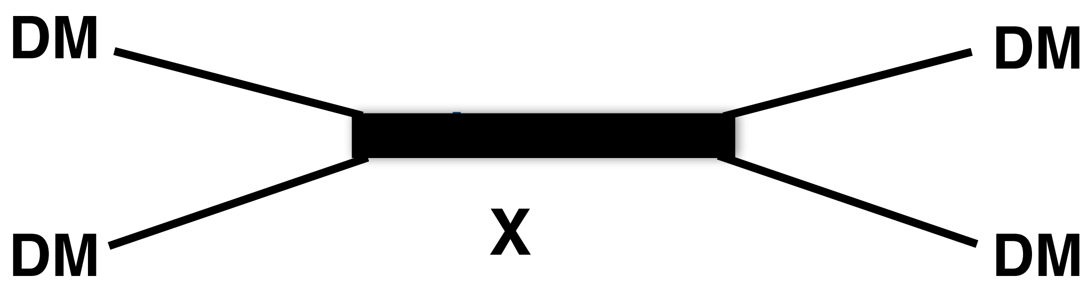
Lattice method *[e.g. glueball-onium 2110.05582]*

2. Bound state (resonance) in dark matter elastic scattering

Dark matter elastic scattering

Resonant DM self-scattering *[XC, C. García-Cely, H. Murayama 2018]*

A s-channel Feynman diagram



has the 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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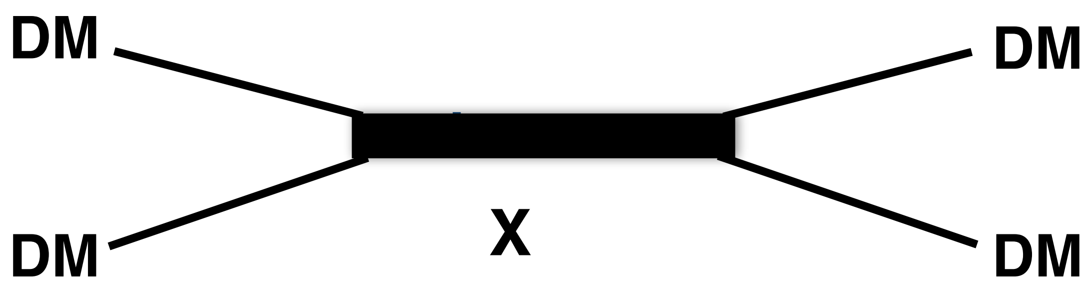

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Large enhancement at $m_X \sim 2m_{DM}$

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velocity-dependence depending on location of m_X

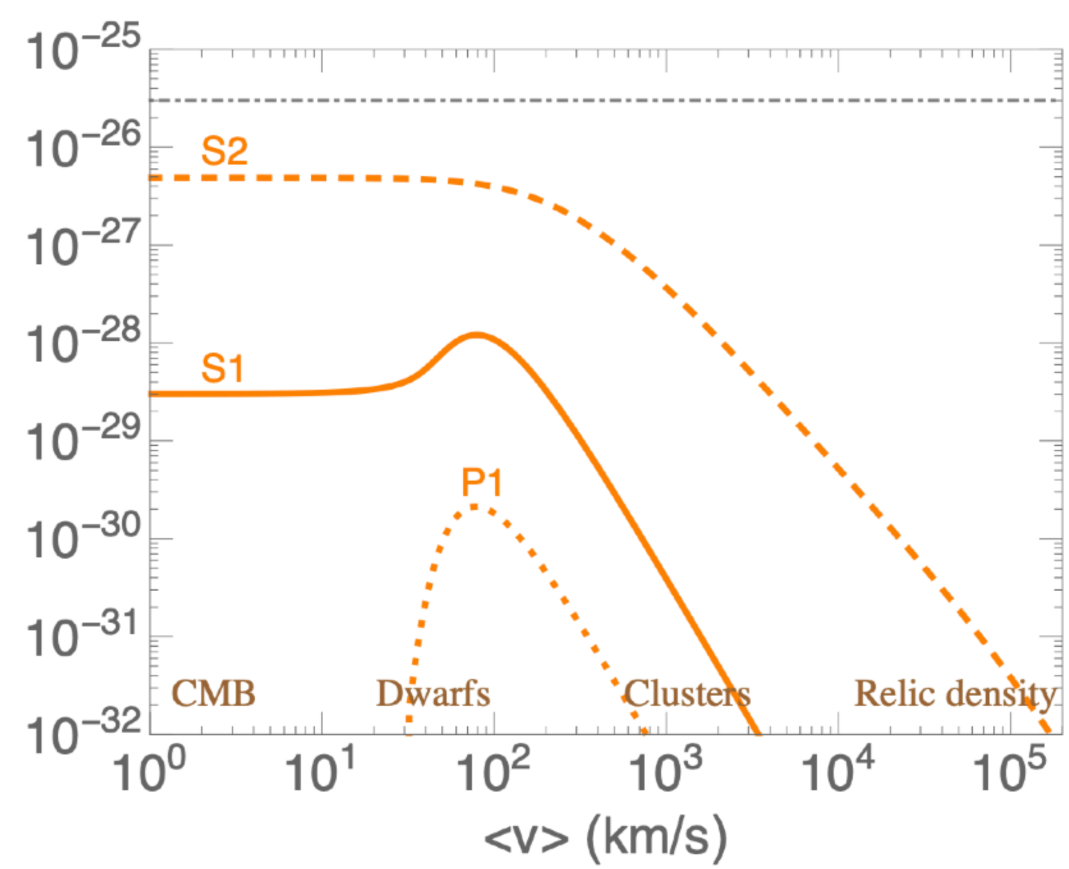
a) If $m_X > 2m_{DM}$, X is treated as a Breit-Wigner resonance

self-scattering cross section peaks at the resonant velocity:

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

and decreases quickly for $v \gg v_R$.

- Modifying the decay width gives narrow/broad resonance.



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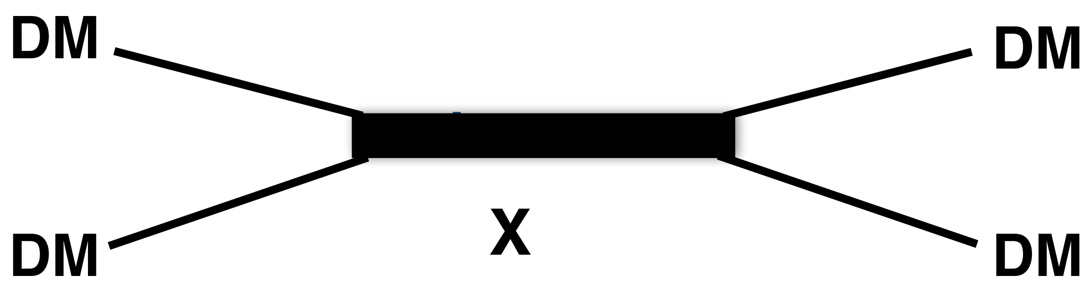

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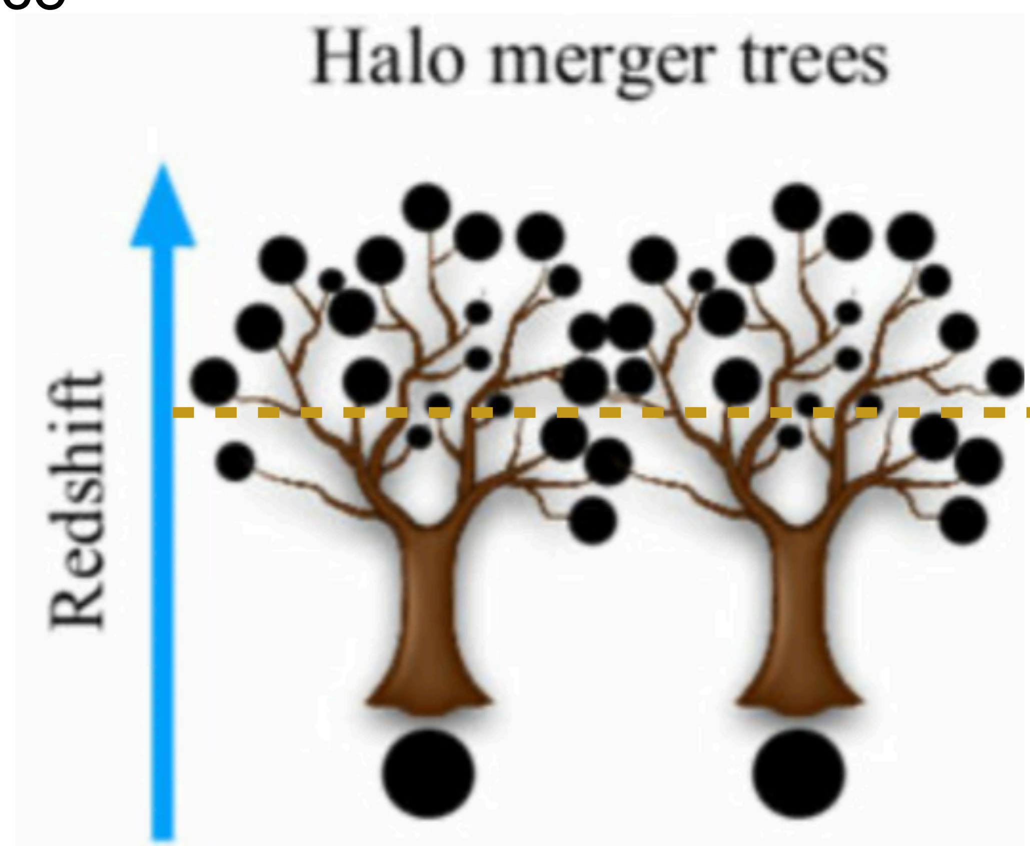
- Modifying the decay width gives **narrow**/broad **resonance**.

- Novel feature in astrophysics: extreme Xsection for certain size of DM halos .



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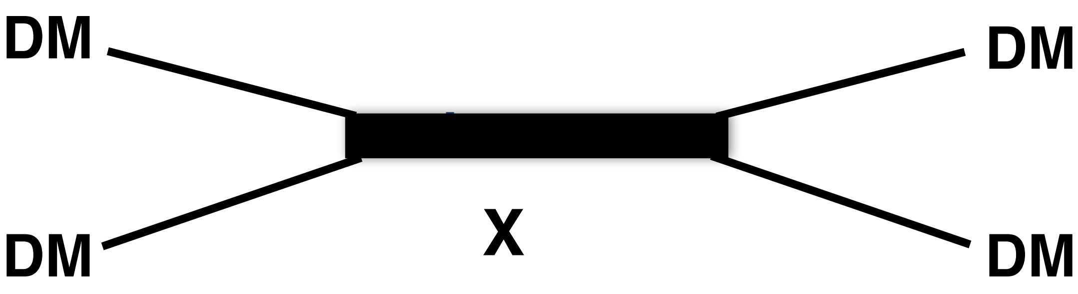

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Large enhancement at $m_X \sim 2m_{DM}$

&

velocity-dependence depending on location of m_X

a) If $m_X > 2m_{DM}$, X is treated as a Breit-Wigner resonance

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

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

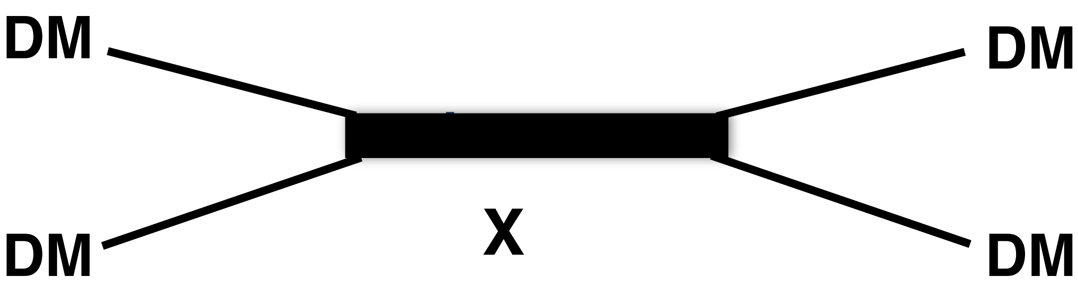
self-interaction decreases with halo size.

appears already for an attractive light mediator above.

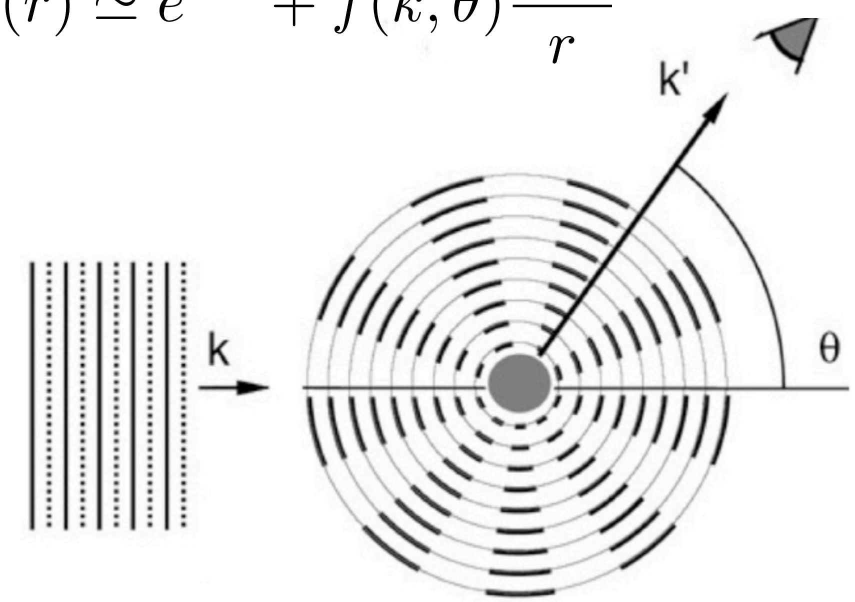
Dark matter elastic scattering

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

Basic quantum scattering theory:



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



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

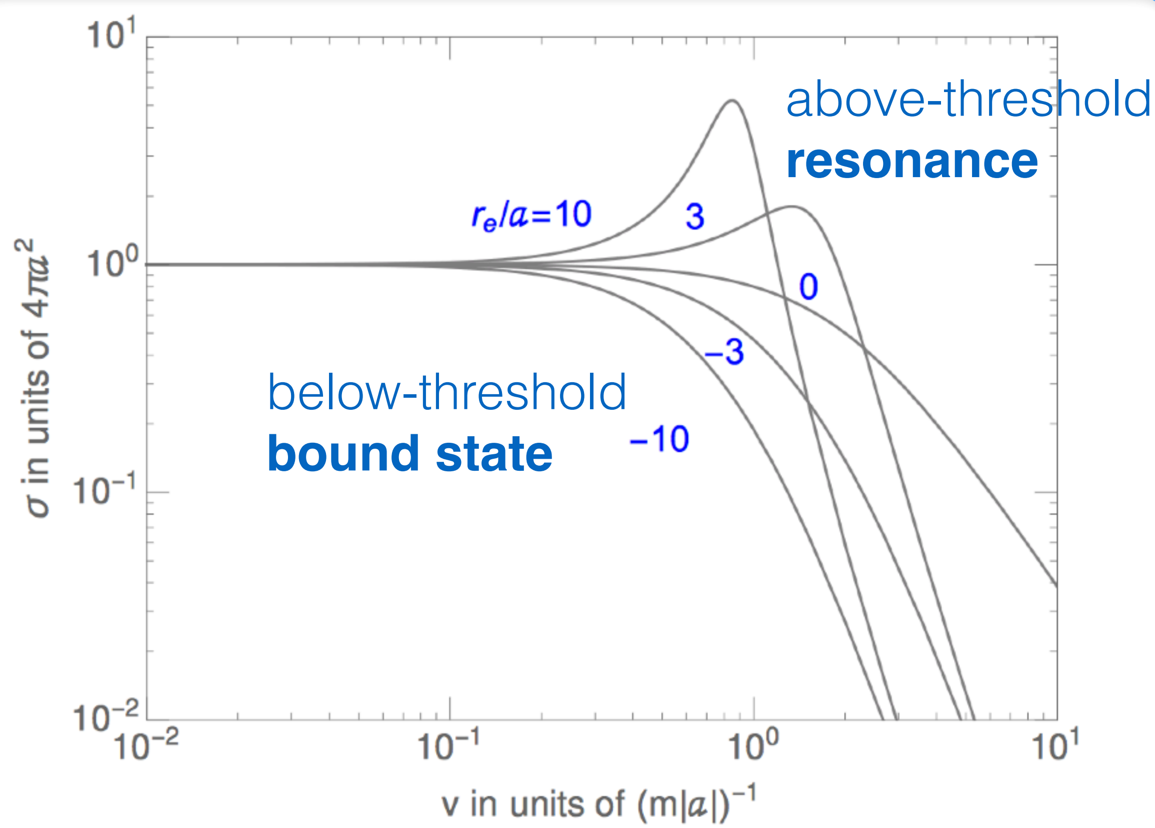
Boundary conditions of short-range potential allows an expansion of the phase shift at very low velocities *[Schwinger, Blatt&Jackson, Bethe, 1940s]* :

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

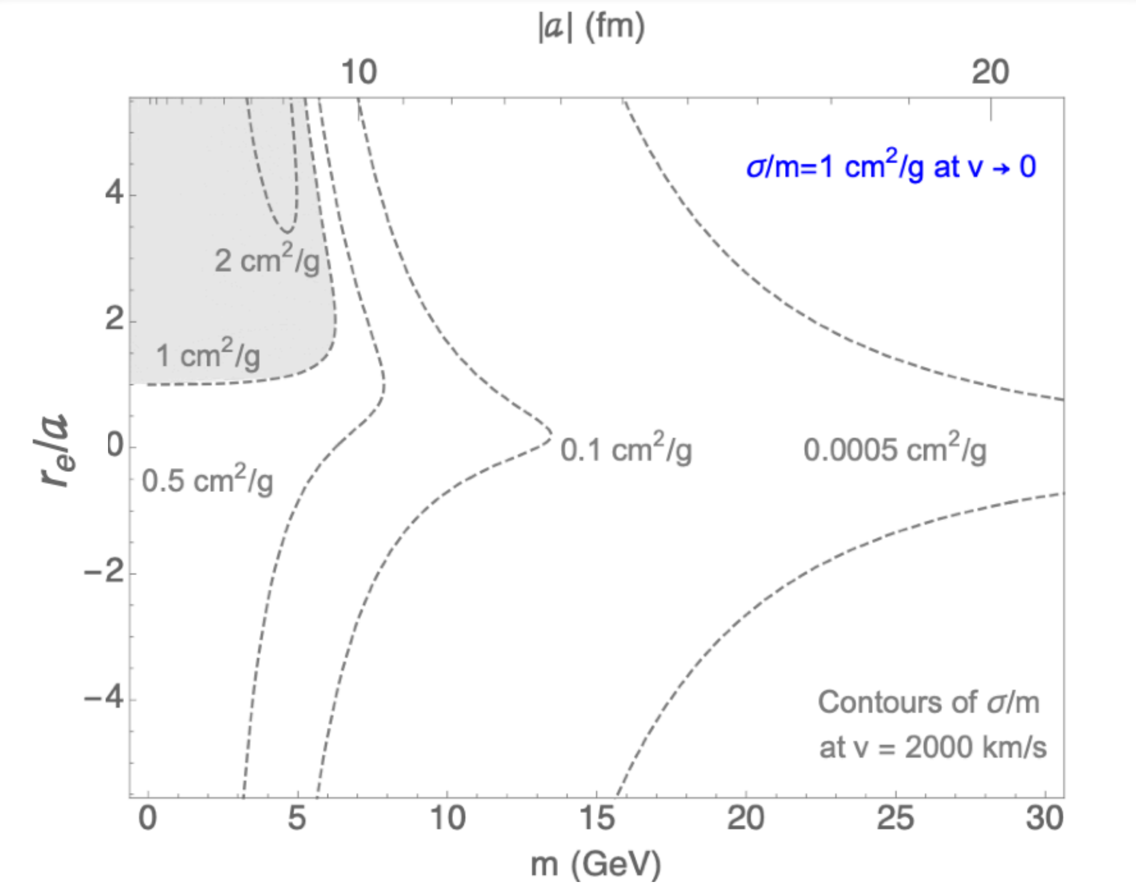
Dark matter elastic scattering

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

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



- Generally, larger σ at low velocities



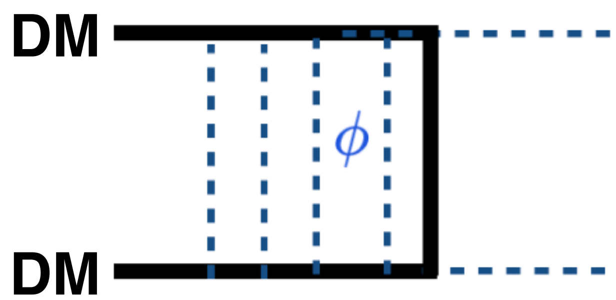
- (Nearly) model-independent exclusion

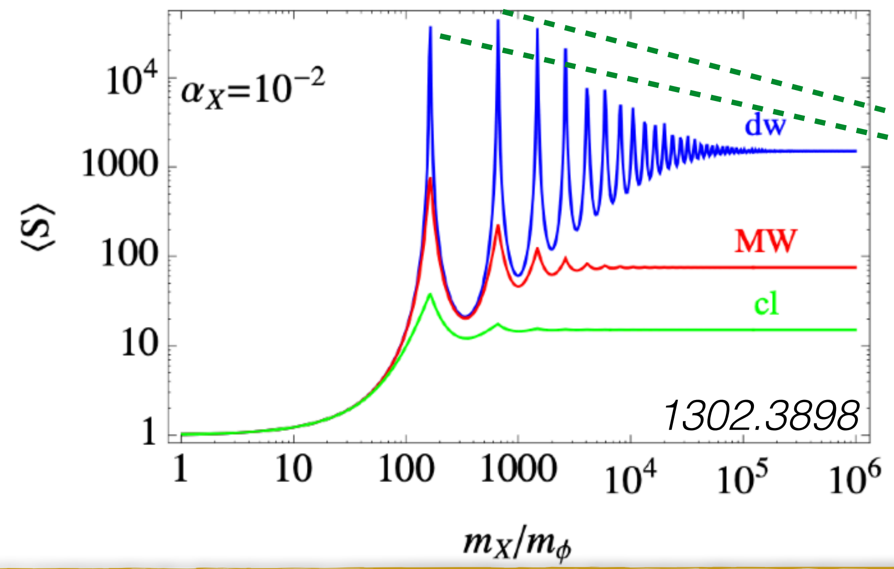
3. Bound state (resonance) in dark matter annihilation

From **two-body annihilation**

Most well-known example: **Sommerfeld** enhancement

[J. Hisano, S. Matsumoto, M. M. Nojiri and O. Saito, hep-ph/0412403]



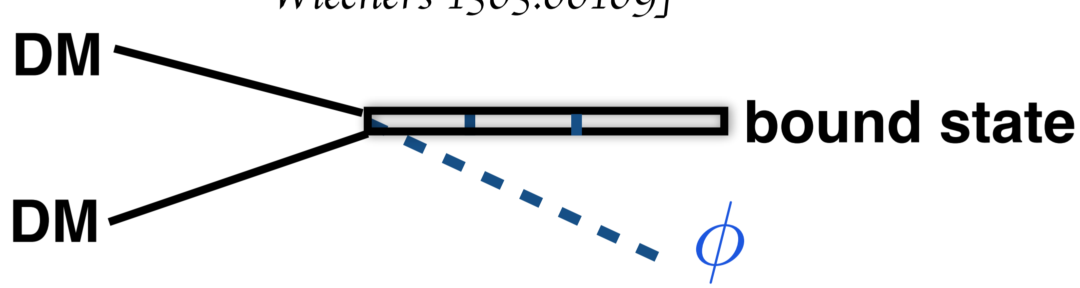


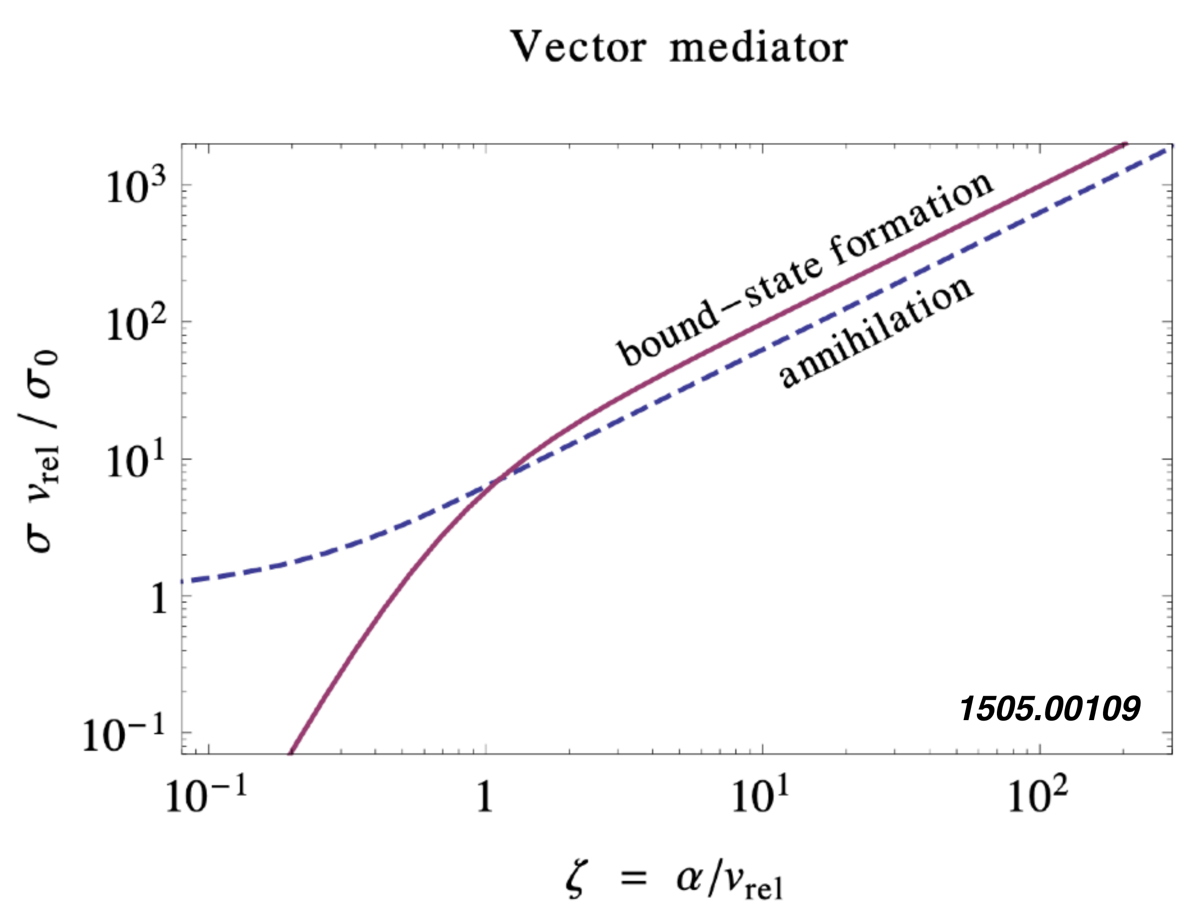
$$\frac{\alpha_X m_X}{\kappa m_\phi} = n^2 , \quad n = 1, 2, 3, \ldots$$

zero-energy bound states

Radiative bound state formation

[e.g. J. March-Russell&S. M. West 0812.0559, K. Petraki, M. Postma, M. Wiechers 1505.00109]





To **N-body DM self-annihilation**

Self-interaction so strong

&

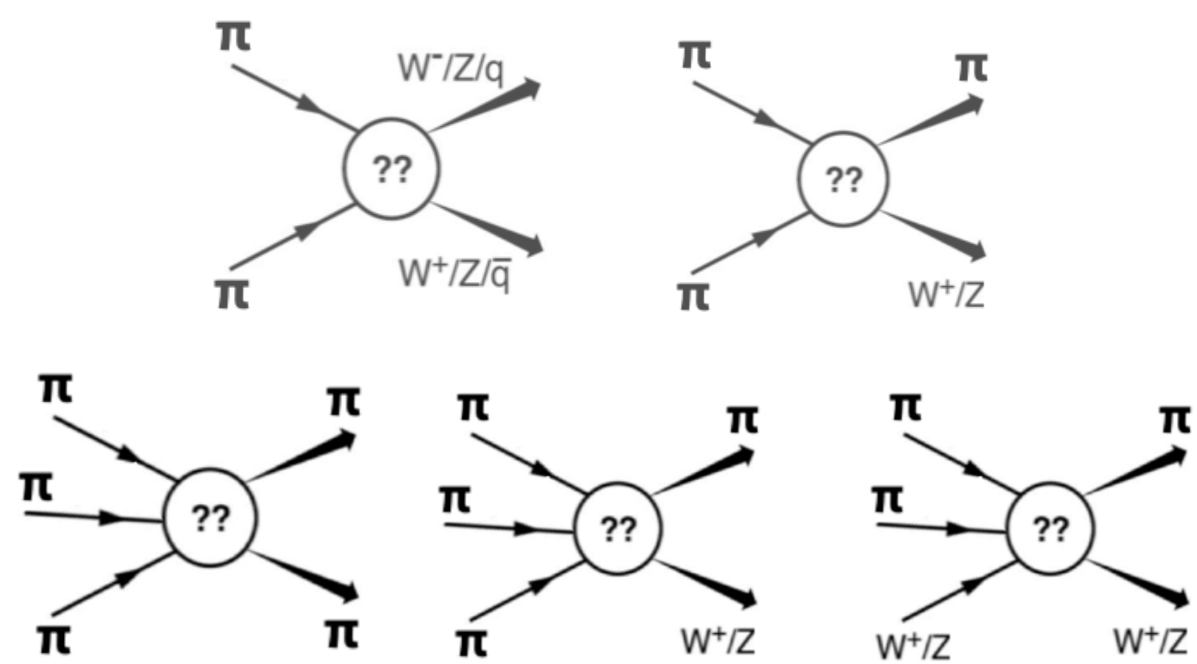
DM does not couple to lighter species much.

DM particles need to eat themselves, to reduce total DM number density.

Initially thermalized DM (as **π**)

essentially, it is **mass-reduction**

three-body



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, ...]

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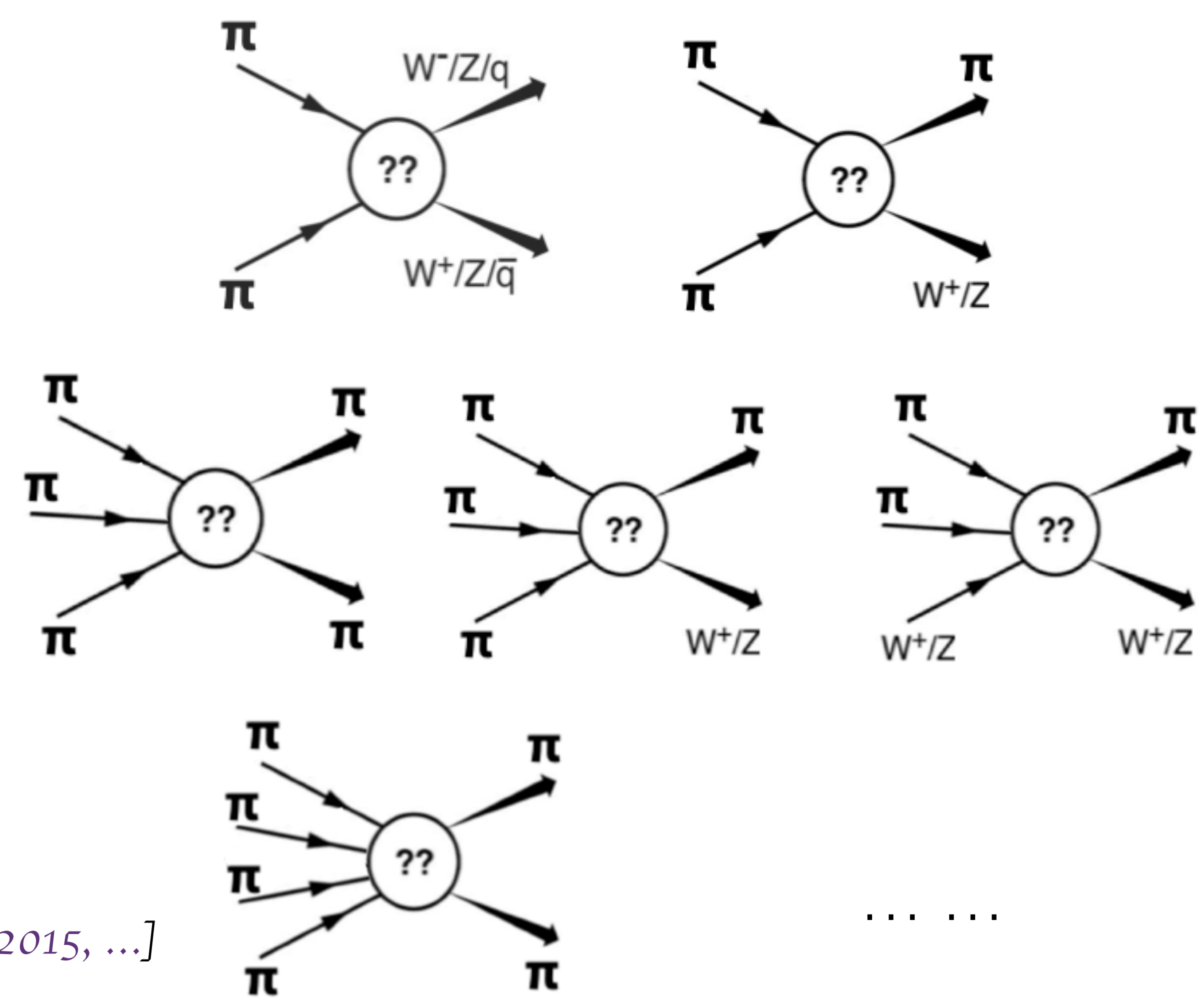
Unitarity limit

two-body

three-body

four-body

[N.Bernal, XC, 2015, ...]



… …

sub-PeV mass

GeV mass

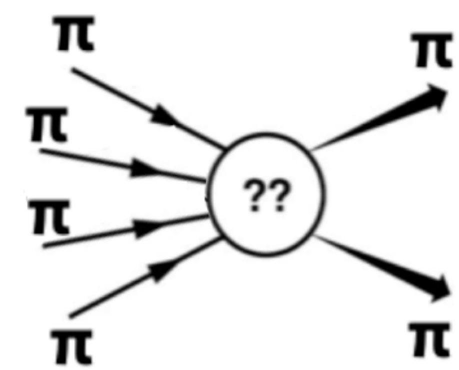
sub-MeV mass

Catalyzed freeze-out *[XC, M. Nikolic, J.Pradler 2024]*

Take a dark pion model (two equal-mass dark quarks confine):

$$V \ni \frac{m_\pi^2}{2}\pi^2 + \mathcal{O}(1)\frac{m_\pi^2}{f_\pi^2}\pi^4 + \mathcal{O}(1)\frac{m_\pi^2}{f_\pi^4}\pi^6 + \ldots$$

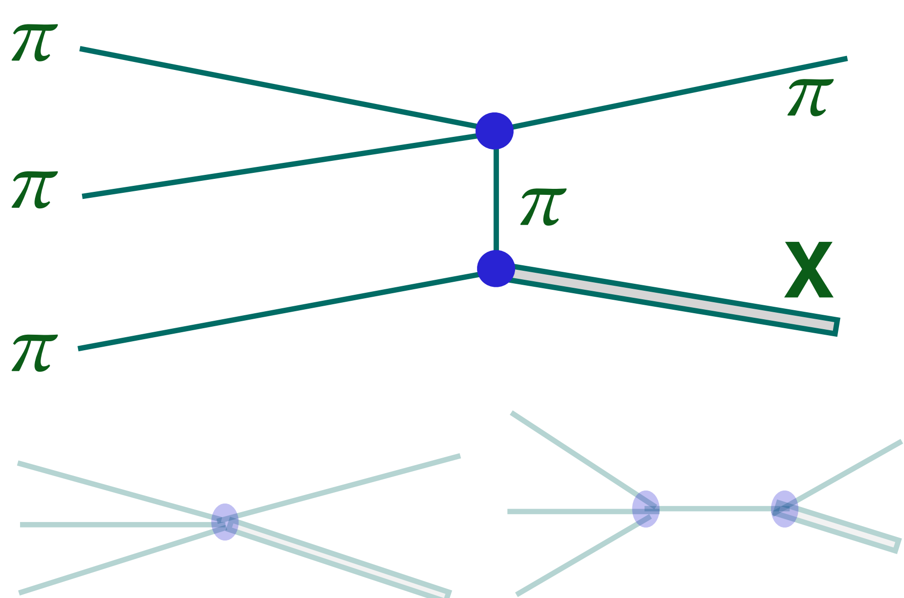
[e.g. D.B.Kaplan nucl-th/9610052, E.Braaten&H.-W.Hammer cond-mat/0410417, B.Grinstein & M.Trott 0704.1505, ..].



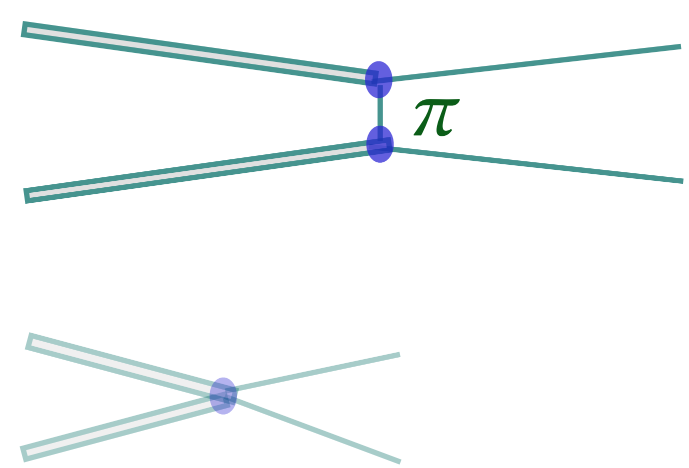
free **DM freeze-out**

Add **bound state formation**, leading to **processes**:

1. bound state formation



2. catalysed mass reduction



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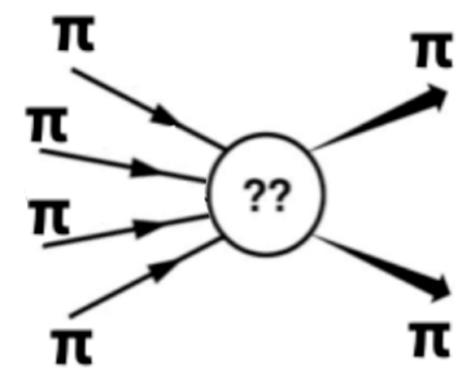


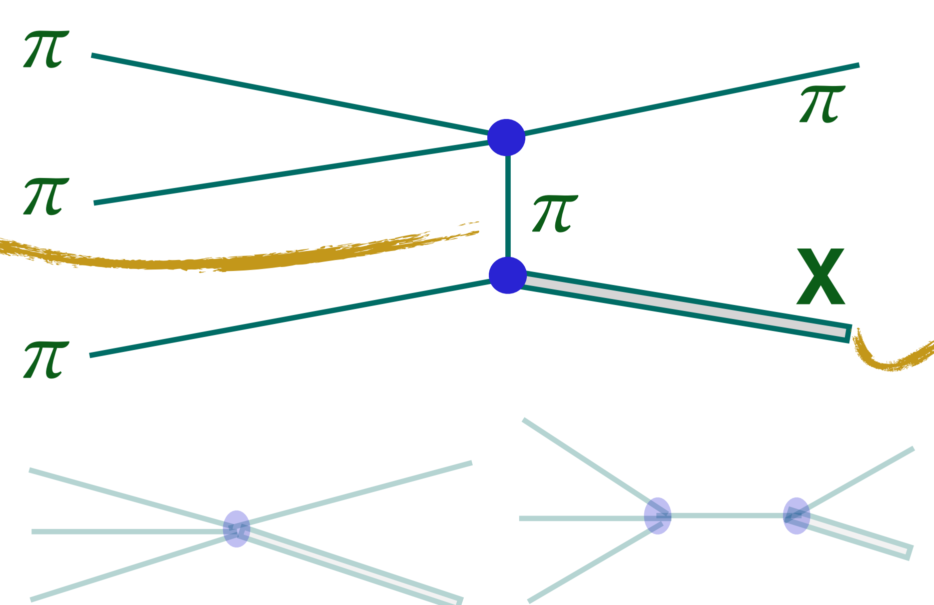
free **DM freeze-out**

At non-relativistic limit:

a t-channel resonant enhancement!

$$\sim \frac{1}{t - m_\pi^2} \propto \frac{1}{m_X^2 - 4m_\pi^2} \propto \frac{1}{E_B}$$

1. bound state formation

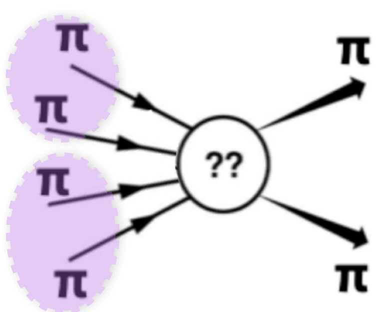


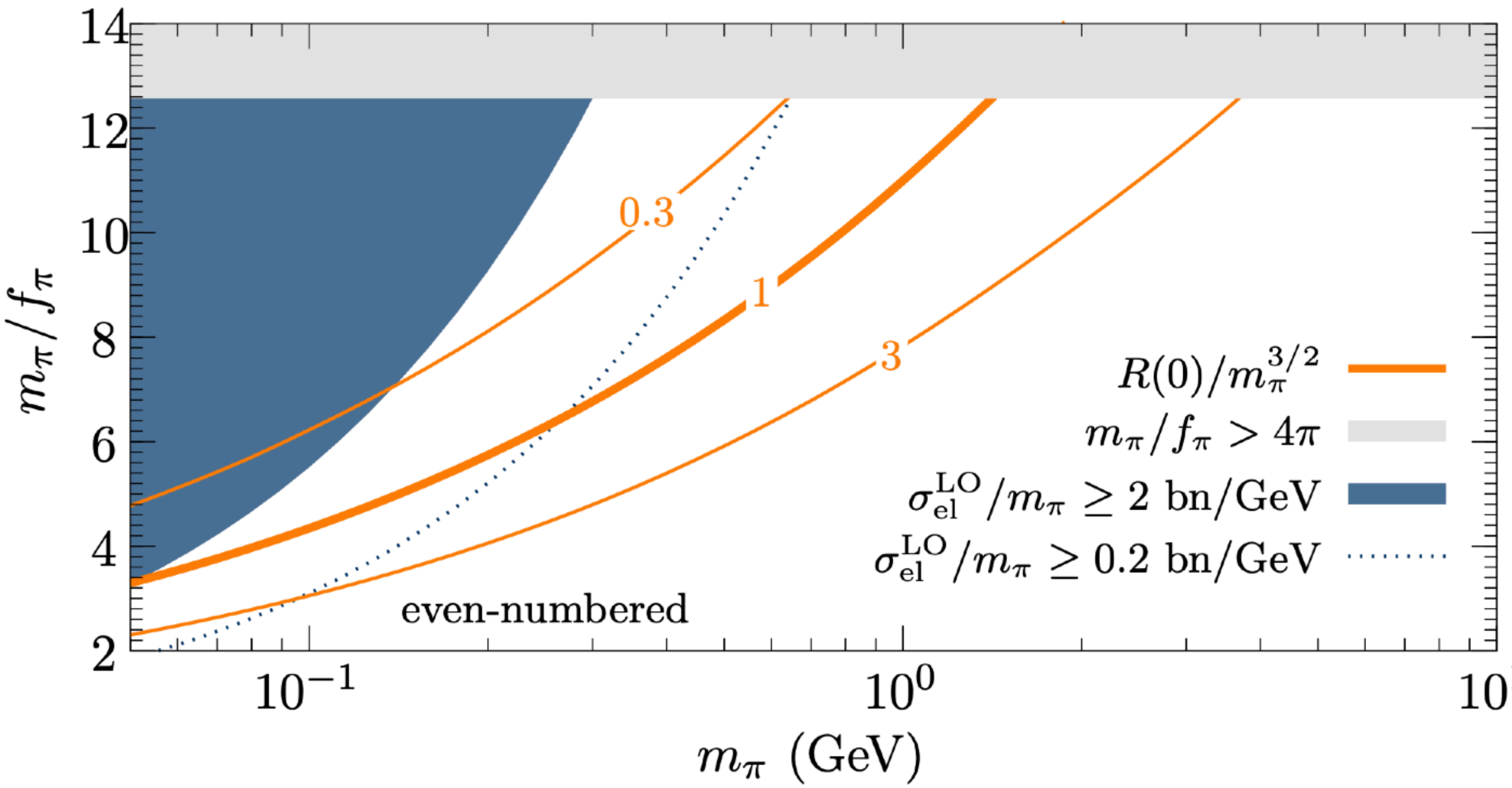
Three-body bound state formation:

Radiative (two-body) bound state formation would make it even easier!

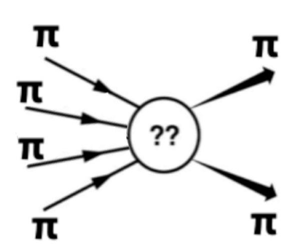
Catalyzed freeze-out *[XC, M. Nikolic, J.Pradler 2024]*

Scan of the parameters：





Now **DM mass above GeV** is achievable with **perturbative** couplings.

In contrast,  freeze-out requires sub-MeV DM.

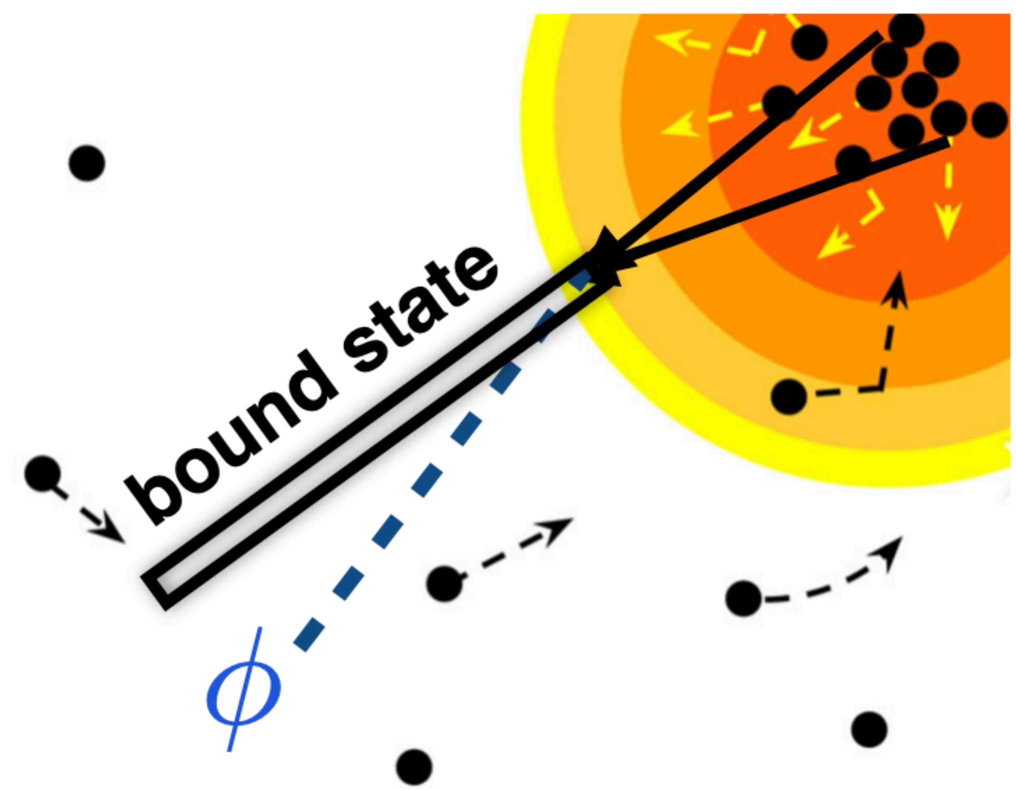
4. Beyond & Summary

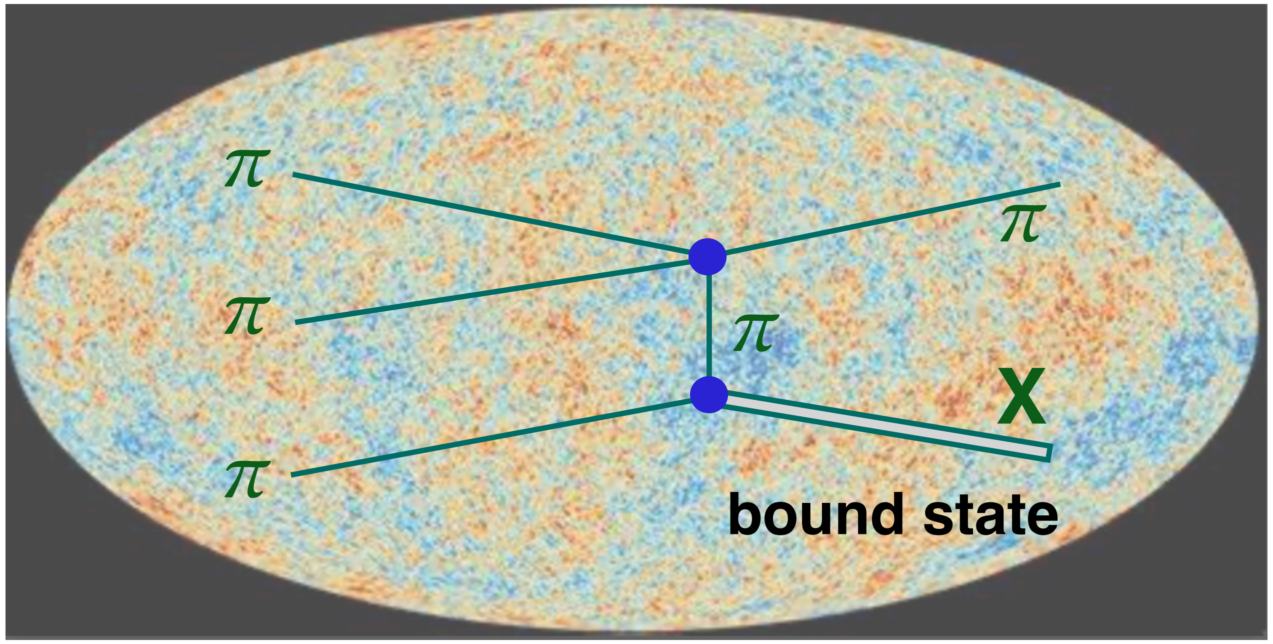
Bound state (resonance) modify a lot of things

1. Bound state formation leads to new astrophysical observables:

Indirect/direct/cosmological signals of asymmetric dark matter

[*L. Pearce&A. Kusenko, 2013, XC, R. Garani, C. García-Cely, T. Hambye 2024, etc.*]





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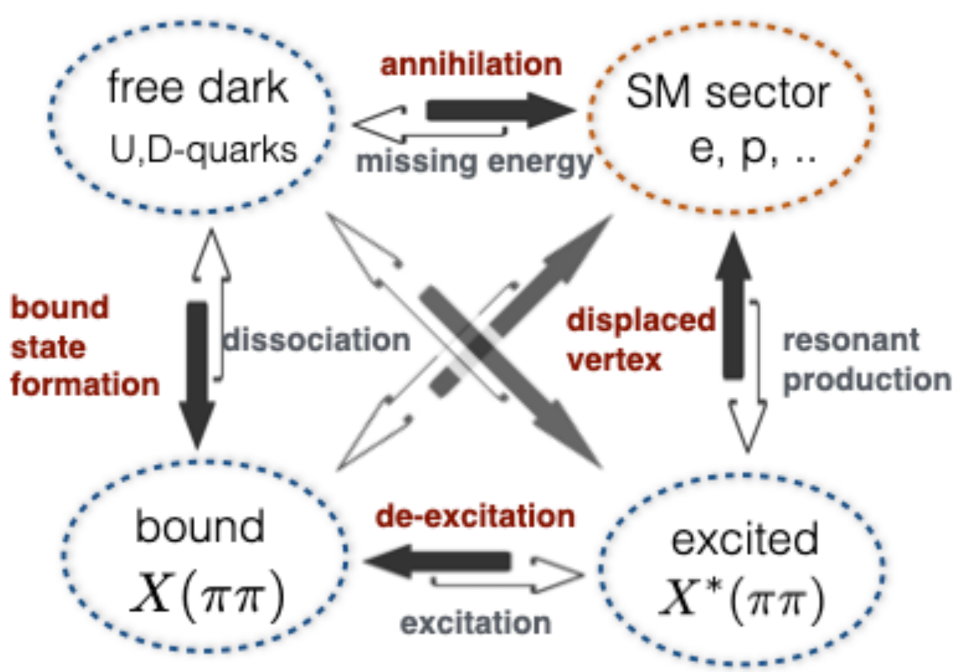
2. Presence of bound state leads to novel signatures in colliders too:

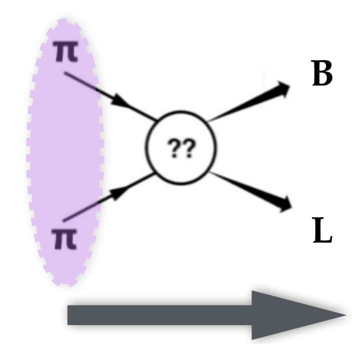


Also dark shower, soft cluster, …

3. It adds new ingredients to DM freeze-in/out *[work in progress]*. For co-genesis, if one makes X-decay violate B and C/CP:

Very different from standard WIMPy baryogenesis.

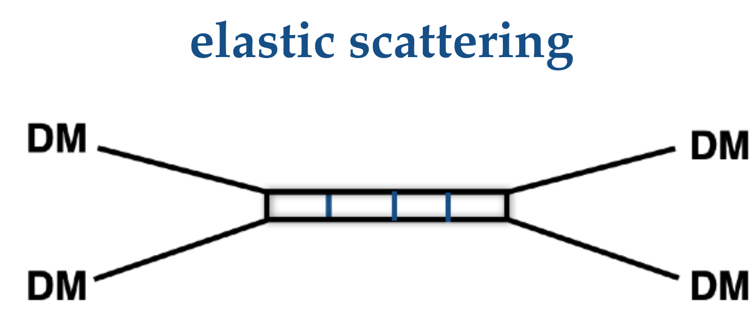
[Framework studied by M. Becker, K. Fridell, J. Harz, C. Hati, 2408.08361]



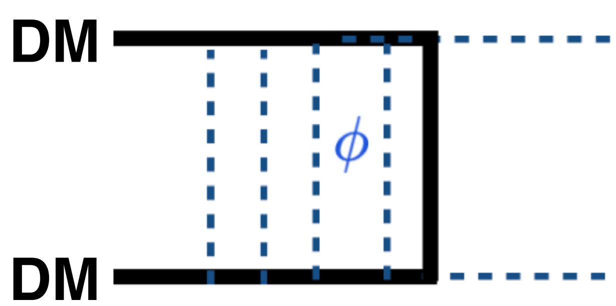
Conclusions

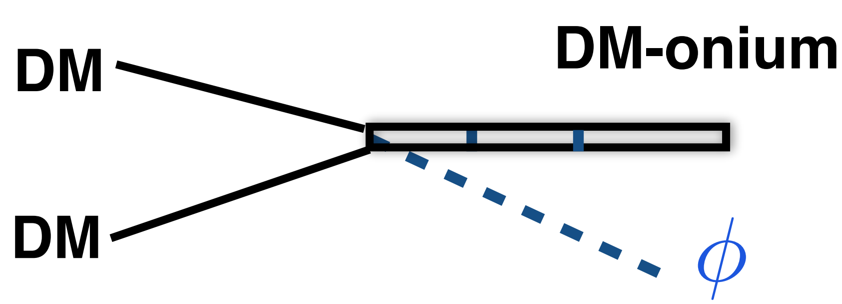
- Bound state induces **velocity-dependent** self-scattering:

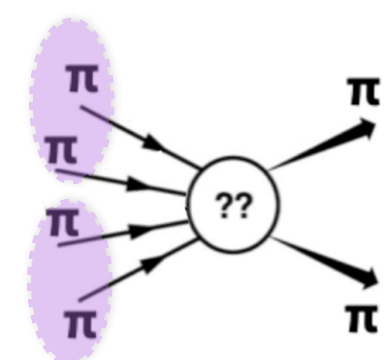
Generate strong SIDM and alleviate cluster bounds.



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







- It suggests new experimental signatures, and opens up more DM/BAU model building.

Thanks!