Quantum theory of dark matter scattering

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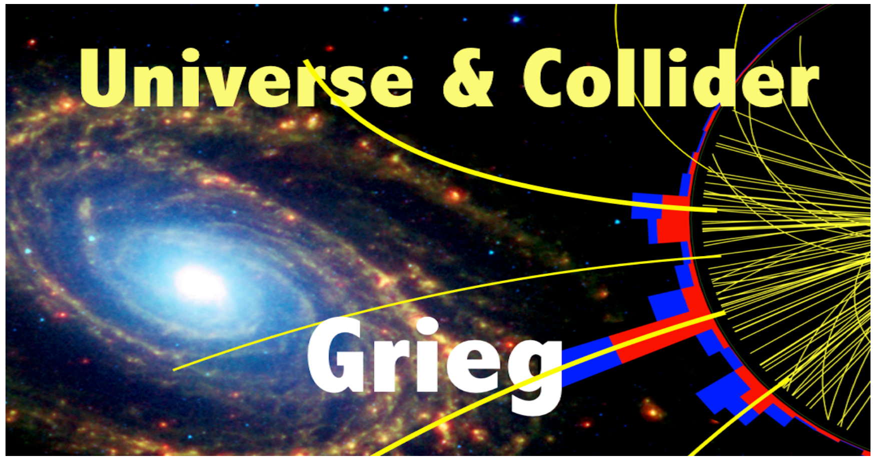

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Based on
<u>AK</u>, Hee Jung Kim and Takumi Kuwahara, JHEP, 2020
<u>AK</u>, Takumi Kuwahara and Ami Patel, JHEP, 2023
<u>AK</u>, Shigeki Matsumoto and Yuki Watanabe, in progress

Apr. 15, 2025 @ HECA seminar

Contents

Dark matter phenomenology

- long-range force
- Sommerfeld enhancement and self-scattering

Scattering theory in quantum mechanics

- Jost function
- effective range theory

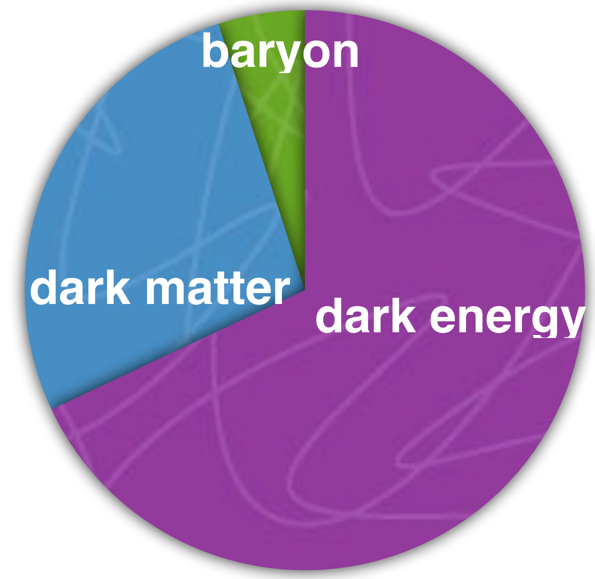
Unitarity

- Omnès solution for Jost function
- violation of Unitarity on zero-energy resonances
- Unitarization

Dark matter

Dark matter

- evident from cosmological observations
  - cosmic microwave background (CMB)…
- one of the biggest mysteries
  - astronomy, cosmology, particle physics…



cosmic energy budget

Long-range force

- mediator lighter than the dark matter
- electroweak-scale or lighter dark matter
  - new dark force (e.g., dark photon)
- TeV-scale dark matter (e.g., weak multiplet)
  - weak force

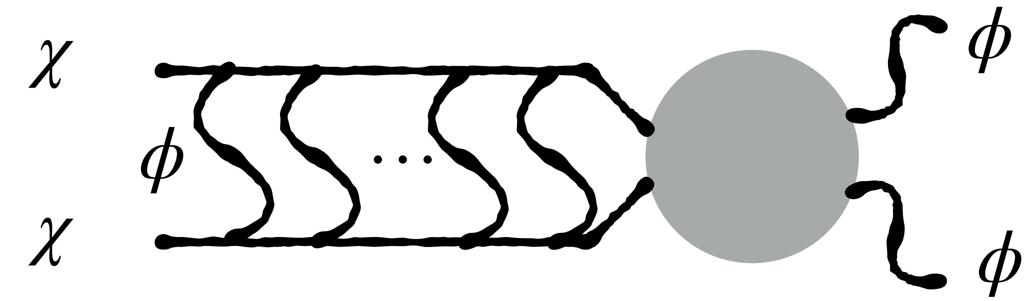
$$V = -\frac{\alpha_\chi}{r} e^{-m_\phi r}$$

- Yukawa potential

Sommerfeld enhancement

Distortion of wave function

- multiple exchanges of a mediator
- non-perturbative but described by the Schrödinger equation (later)



Enhanced annihilation

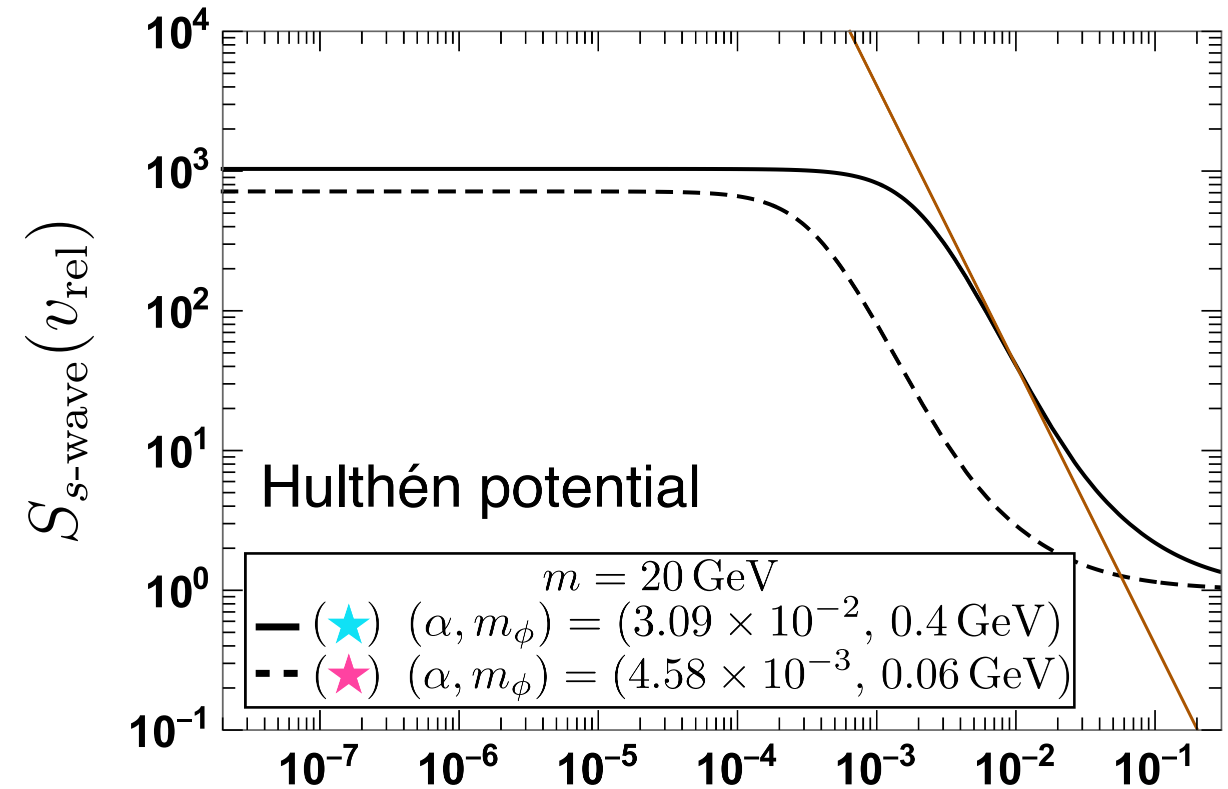
- annihilation cross section is enhanced at low velocity

$$(\sigma_{\rm ann} v_{\rm rel}) = S(\sigma^{(0)}_{\rm ann} v_{\rm rel})$$

- without potential

- Sommerfeld enhancement factor

- larger cross section in the late Universe than the thermal one



AK, Kim and Kuwahara, JHEP, 2020

Indirect detection

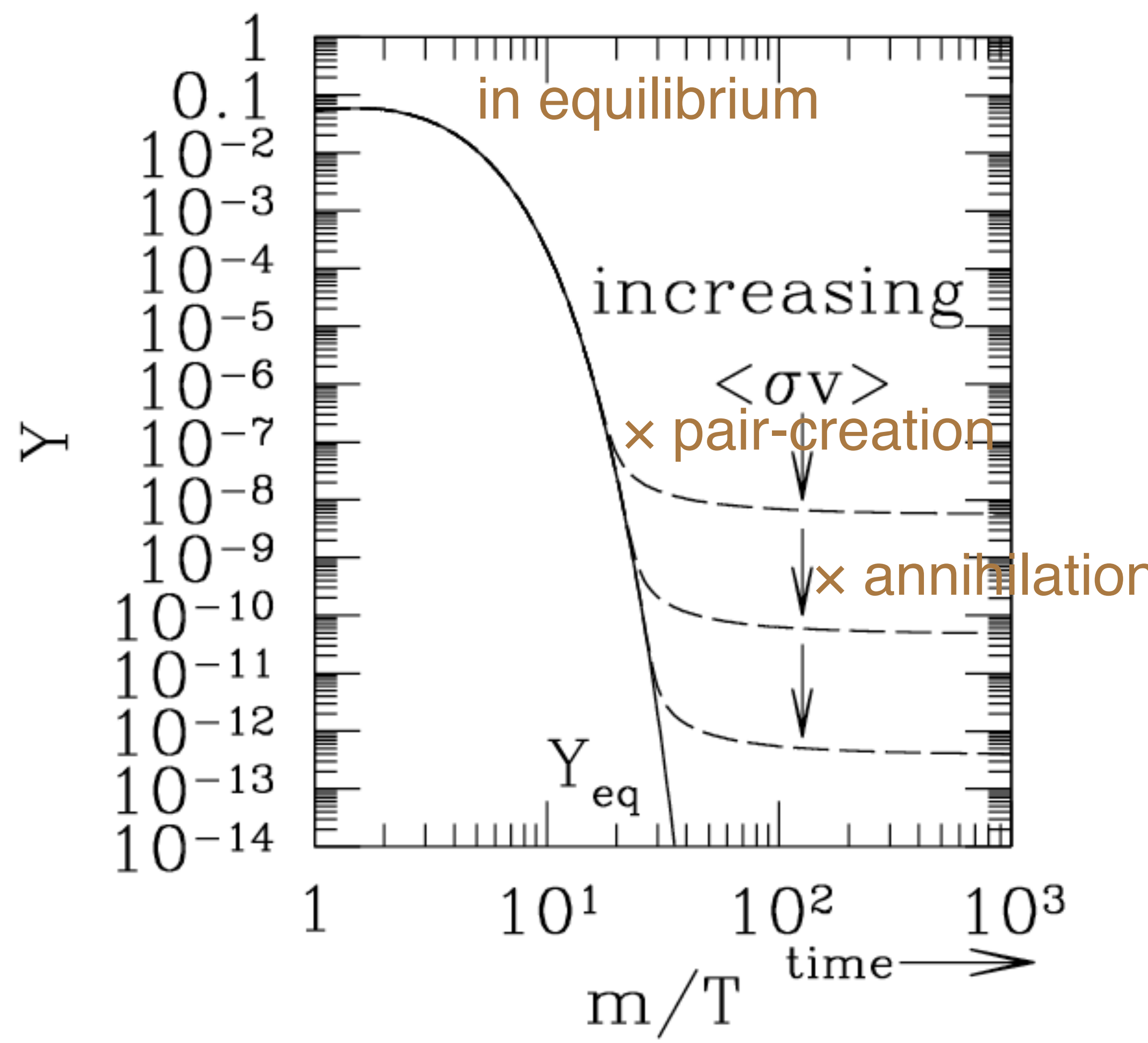
Canonical cross section

- thermal freeze-out (annihilation in the early Universe) $v_{\rm rel} \simeq 1/2$

$$\Omega h^2 = 0.1 \times \frac{3\times 10^{-26}\,{\rm cm^3/s}}{\langle \sigma_{\rm ann} v\rangle}$$

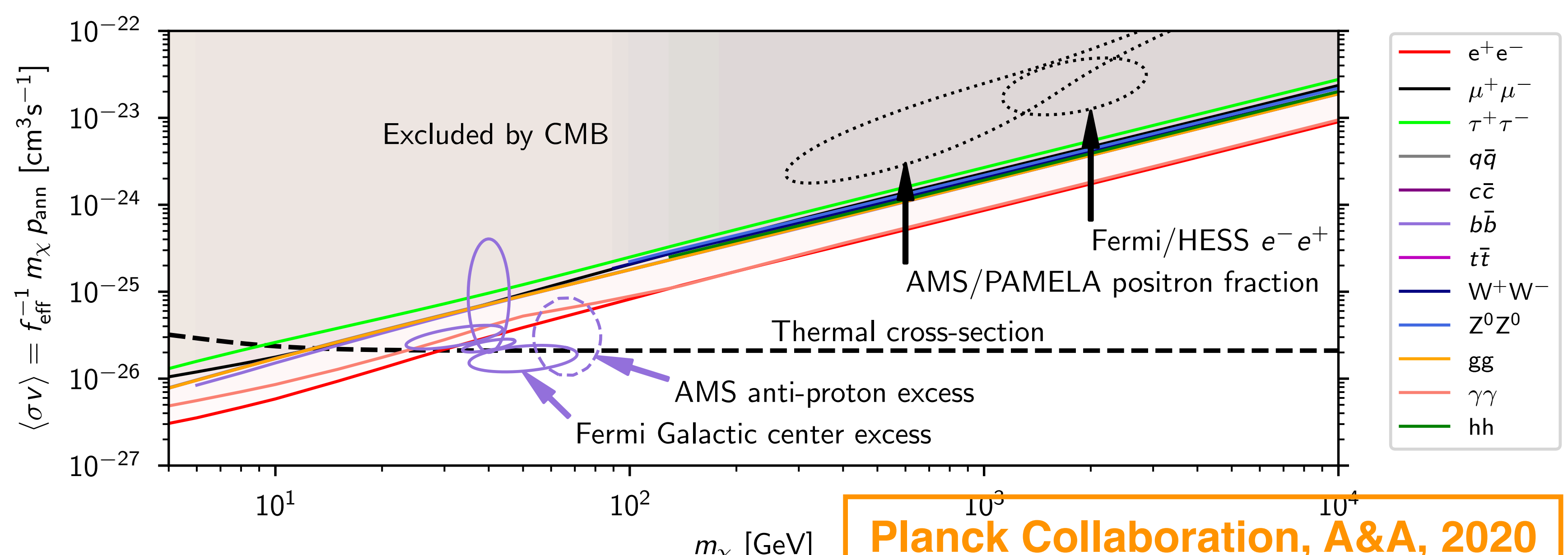
- requires a weak-scale annihilation cross section

$$\langle \sigma_{\rm ann} v\rangle \simeq 1\,{\rm pb}\times c$$



CMB constraints

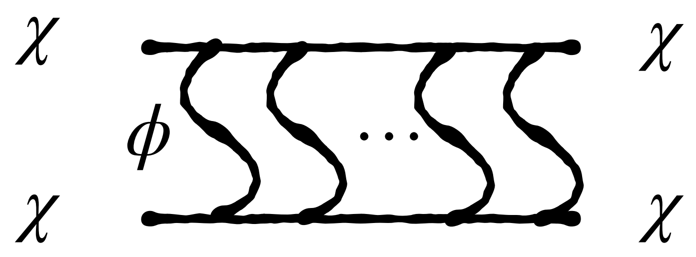
- energy deposit around the last scattering



Self-scattering

The same light mediator

- non-perturbative (infinite exchanges) when the distortion of wave function is significant



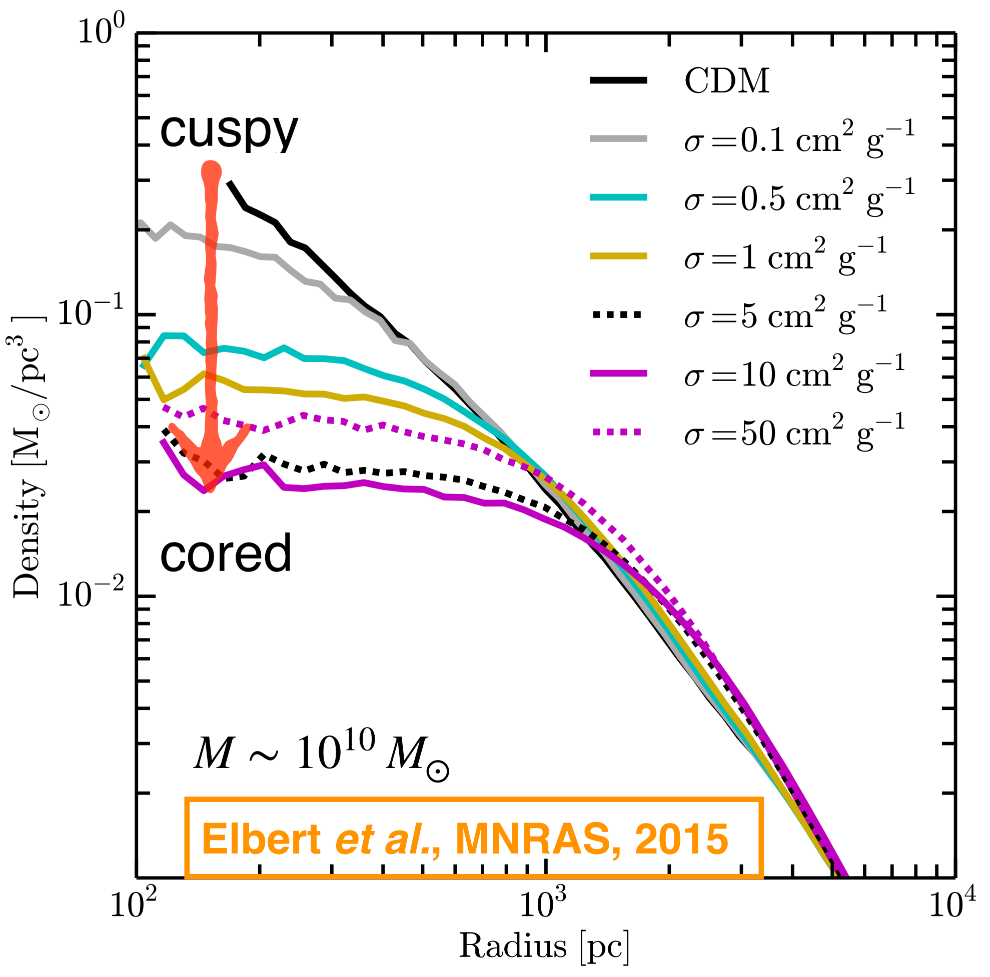
- again described by the Schrödinger equation (later)

Self-interacting dark matter

- interactions among dark matter particles

$$\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g} \sim 1\,\mathrm{barn/GeV}$$

- dark matter density profile inside a halo turns from cuspy to cored



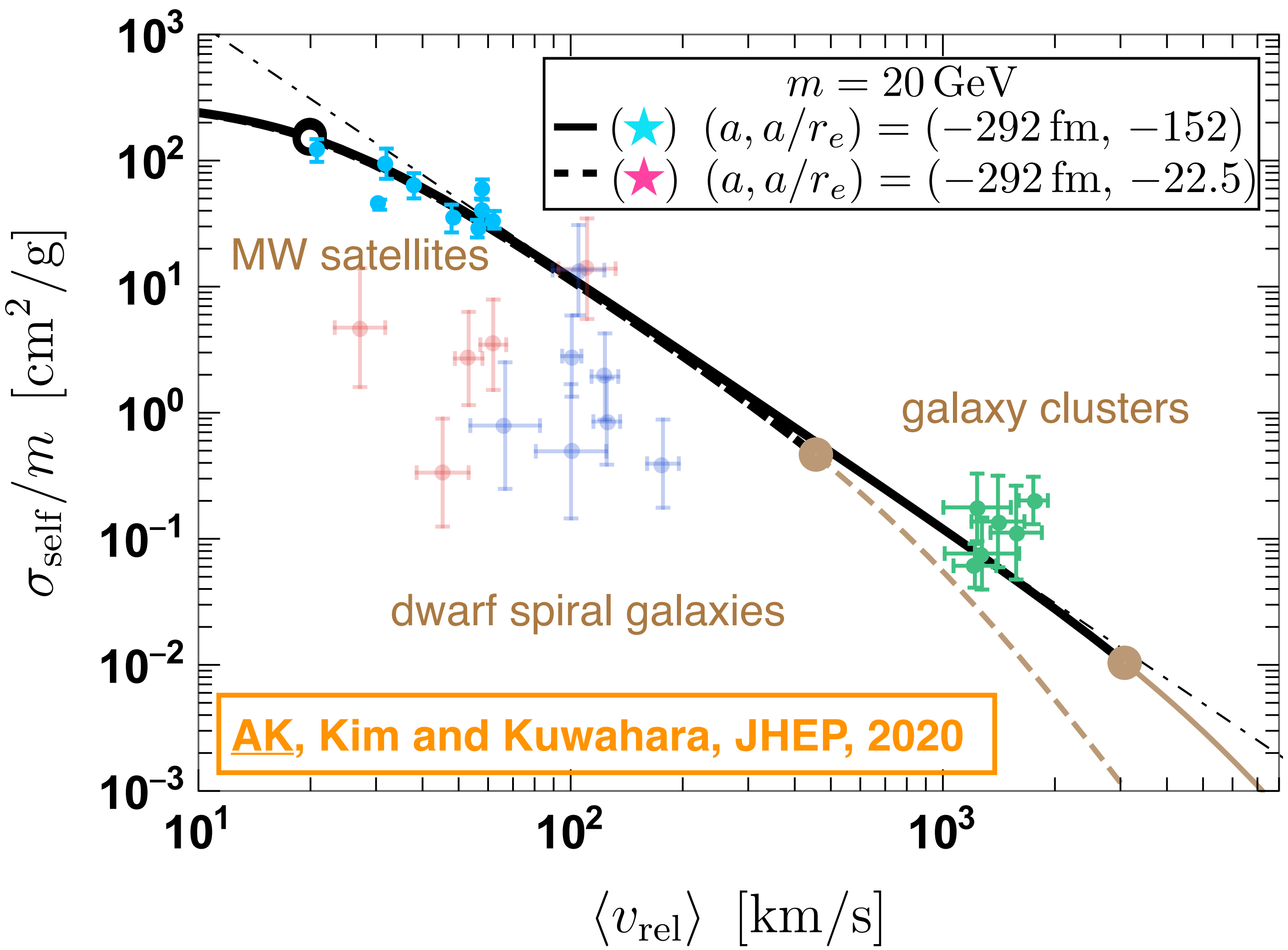
Velocity dependence

Self-interacting dark matter

- cored profile "appear to" provide better fit to astronomical data
- "data" points from astrophysical observations of various size halos

Light mediator

- introduce a velocity dependence, which is compatible with "data"

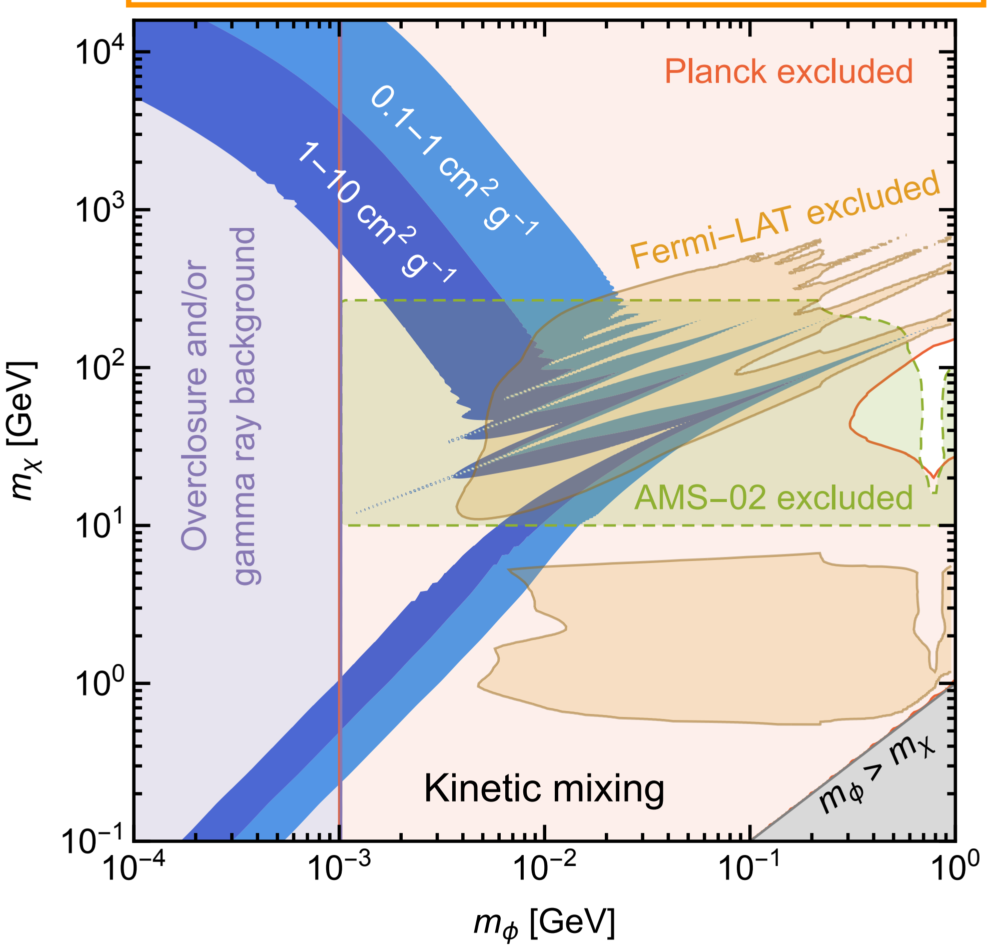


Correlation

Bringmann, Kahlhoefer, Schmidt-Hoberg and Walia, JHEP, 2020

Sommerfeld enhancement and self-scattering

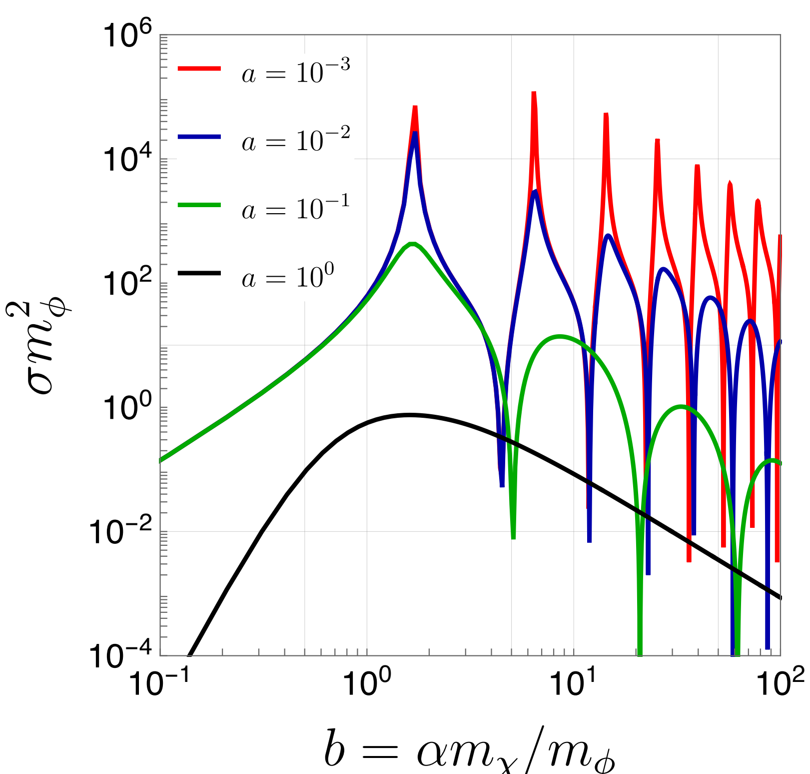
- correlated
  - resonant enhancement occurs at the same parameter point
    - zero-energy resonances (later)
- main obstacle in SIDM model building

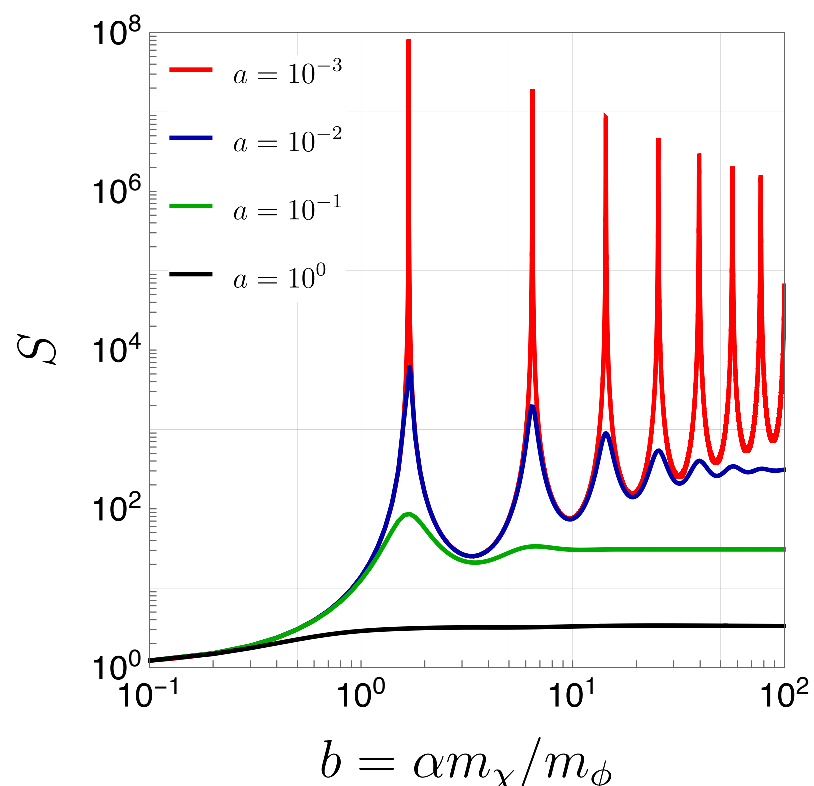


- dark photon

$$a = \frac{v_{\rm rel}}{2\alpha_\chi}$$

$$b = \frac{\alpha_\chi m_\chi}{m_\phi}$$





AK, Kuwahara and Patel, JHEP, 2023

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Scattering theory in quantum mechanics

- Jost function
- effective range theory

Unitarity

- Omnès solution for Jost function
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Scattering in quantum mechanics

Schrödinger equation

Weinberg, “Lectures on Quantum Mechanics”

$$\left[-\frac{1}{2\mu}\nabla^2 + V(r)\right]\psi_k(\vec{x}) = E\psi_k(\vec{x}) \qquad E = \frac{k^2}{2\mu} \qquad k = \mu v_{\rm rel}$$

- potential from long-range force
- reduced mass ($\mu = m/2$ for identical particle)

- scattering state (energy-eigenstate of Schrödinger equation)

$$\psi_k(\vec{x}) \to e^{ikz} + f(k,\theta)\frac{e^{ikr}}{r} \qquad r \to \infty$$

- (initial) plane wave
- scattering amplitude
- out-going spherical wave

Partial-wave decomposition

- motivated by $e^{ikz} = \sum_{\ell=0}^{\infty}(2\ell+1)e^{i\frac{1}{2}\ell\pi}j_\ell(kr)P_\ell(\cos\theta)$

$$\psi_k(\vec{x}) = \sum_{\ell=0}^{\infty}(2\ell+1)e^{i\left(\frac{1}{2}\ell\pi+\delta_\ell(k)\right)}\frac{1}{k}R_{k,\ell}(r)P_\ell(\cos\theta)$$

- phase shift

Sommerfeld enhancement and self-scattering

Scattering phase shift

- radial wave function at infinity

$$R_{k,\ell}(r) \to \frac{\sin(kr - \frac{1}{2}\ell\pi + \delta_\ell(k))}{r} \quad r \to \infty$$

$$f(k,\theta) = \sum_{\ell=0}^{\infty} (2\ell+1) f_\ell(k) P_\ell(\cos\theta) \qquad f_\ell(k) = \frac{e^{2i\delta_\ell(k)} - 1}{2ik}$$

$$\sigma = \sum_{\ell=0}^{\infty} \sigma_\ell \qquad \sigma_\ell = \frac{4\pi}{k^2}(2\ell+1)\sin^2\delta_\ell(k)$$

- diagonalized S-matrix

$$S_\ell(k) = e^{2i\delta_\ell(k)}$$

Sommerfeld enhancement

Iengo, JHEP, 2009

Cassel, J.Phys.G, 2010

- radial wave function around the origin
  - annihilation through the contact interaction (delta function potential)

$$\mathrm{S}_\ell(k) = \left| \frac{R_{k,\ell}(r)}{R^{(0)}_{k,\ell}(r)} \right|^2 \quad r \to 0$$

- without potential

Jost function

How to find $R_{k,\ell}(r)$ in practice?

AK, Kuwahara and Patel, JHEP, 2023

AK, Matsumoto and Watanabe, in progress

- "initial" condition given at the origin (regularity)

$$\mathscr{R}_{k,\ell}(r) \to k j_\ell(kr) \approx k\frac{(kr)^\ell}{(2\ell+1)!!} \qquad r \to 0$$

- radial Schrödinger equation

$$\left[\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr} + k^2 - \frac{\ell(\ell+1)}{r^2} - 2\mu V(r)\right]\mathscr{R}_{k,\ell}(r) = 0$$

- asymptotic behavior of solution

$$\mathscr{R}_{k,\ell}(r) \to \frac{i}{2r}\left[\mathscr{J}_\ell(k)e^{-i\left(kr-\frac{1}{2}\ell\pi\right)} - \mathscr{J}_\ell(-k)e^{i\left(kr-\frac{1}{2}\ell\pi\right)}\right] \quad r \to \infty$$

- Jost function

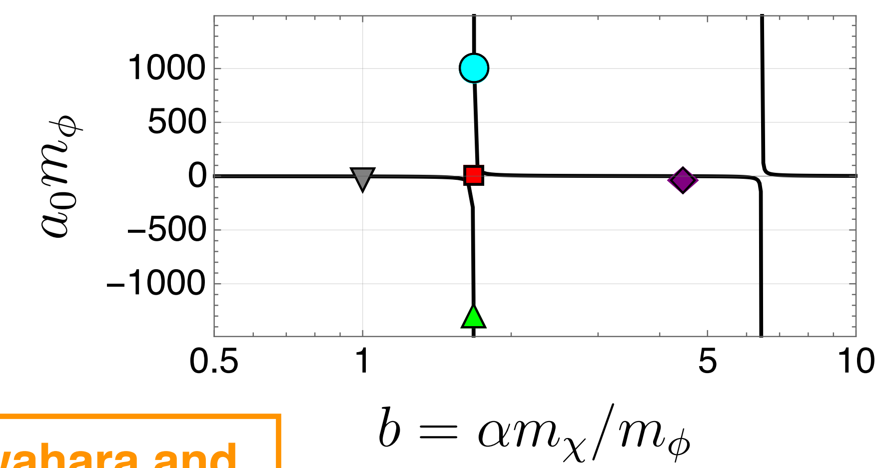
- by comparing asymptotic behavior

$$R_{k,\ell}(r) = \frac{1}{|\mathscr{J}_\ell(k)|}\mathscr{R}_{k,\ell}(r) \quad S_\ell(k) = e^{2i\delta_\ell(k)} = \frac{\mathscr{J}_\ell(-k)}{\mathscr{J}_\ell(k)} \quad \mathrm{S}_\ell(k) = \frac{1}{|\mathscr{J}_\ell(k)|^2}$$

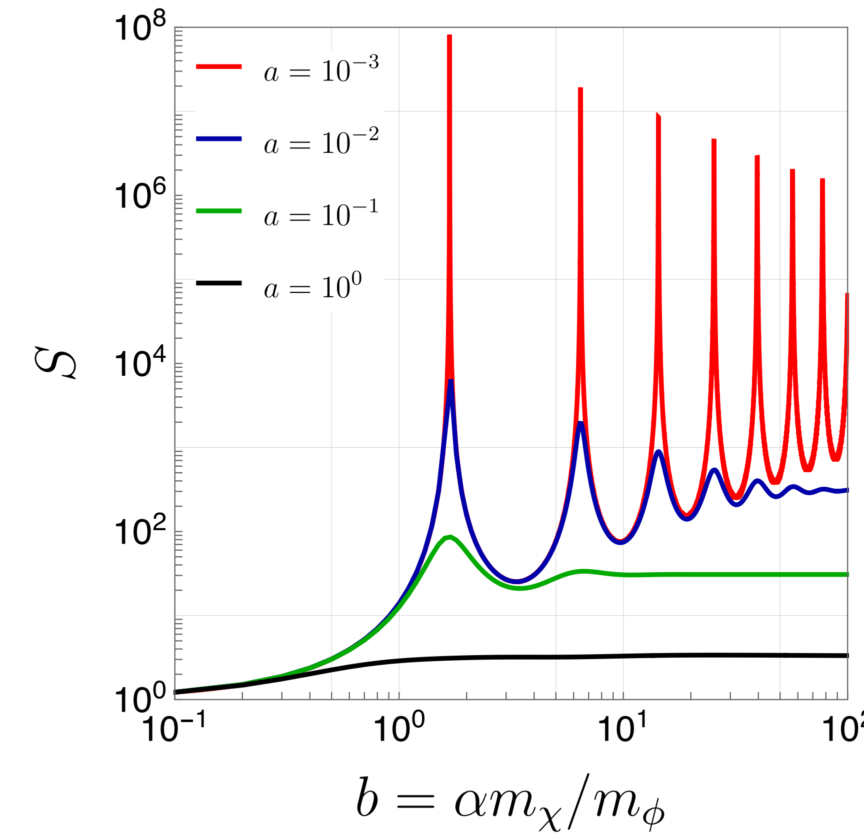
Correlation

Zero-energy resonances

- resonant enhancement occur



AK, Kuwahara and Patel, JHEP, 2023



Effective range theory

$$k^{2\ell+1} \cot \delta_\ell \to -\frac{1}{a_\ell{}^{2\ell+1}} + \frac{1}{2 r_{e,\ell}{}^{2\ell-1}} k^2$$

- scattering length
- effective range

- on resonance $a_0 \to \infty$
- shallow virtual level
  - non-normalizable
- shallow bound state
  - pole of scattering amplitude

Contents

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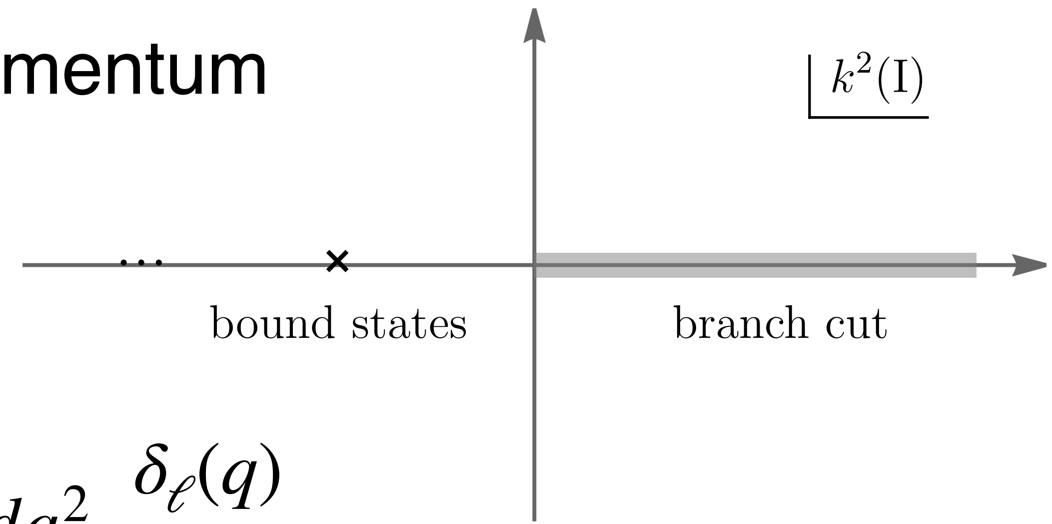
- violation of Unitarity on zero-energy resonances
- Unitarization

Omnès solution

Annihilation matrix element

AK, Kuwahara and Patel, JHEP, 2023

- analytic continuation to complex momentum



$$\Gamma_\ell(k^2) = \frac{1}{\mathcal{J}_\ell(k^2)} = \Omega_\ell(k^2) F_\ell(k^2)$$

$$\Omega_\ell(k^2) = \exp[\omega_\ell(k^2)] \qquad \omega_\ell(k^2) = \frac{1}{\pi}\int_0^\infty dq^2 \frac{\delta_\ell(q)}{q^2 - k^2}$$

- reproducing the brunch cut

$$F_\ell(k^2) = \prod_{b_\ell} \frac{k^2}{k^2 + \kappa_{b,\ell}^2}$$

- rational function reproducing bound-state poles
- numerator is chosen so that no singularity at $k \to 0$
    - discussed next

Omnès solution

Levinson theorem

Weinberg, "Lectures on Quantum Mechanics"

- # of bound states is given by phase shift

$$\delta_\ell(k \to 0) - \delta_\ell(k \to \infty) = \left[\#b_\ell \left(+\frac{1}{2}\right)\right]\pi$$

- excluding virtual levels

- zero in our normalization

- only for s-wave zero-energy resonances

$k \to 0$ behavior

- Omnès function is singular with the power of # of bound states

$$\mathrm{Re}[\omega_\ell(k^2 + i\epsilon)] = \frac{1}{\pi}⨍_0^\infty dq^2 \frac{\delta_\ell(q)}{q^2 - k^2} \quad \to -\left[\#b_\ell \left(+\frac{1}{2}\right)\right] \ln(k^2/\Lambda^2) \quad k \to 0$$

$$\Gamma_\ell(k^2 + i\epsilon) = \exp[\omega_\ell(k^2 + i\epsilon)] F_\ell(k^2) \quad \propto \frac{F_\ell(k^2)}{k^{2\#b_\ell(+1)}} \quad k \to 0$$

$$F_\ell(k^2) = \prod_{b_\ell} \frac{k^2}{k^2 + \kappa_{b,\ell}^2} \propto k^{2\#b_\ell} \quad k \to 0$$

Zero-energy resonances

No cancellation

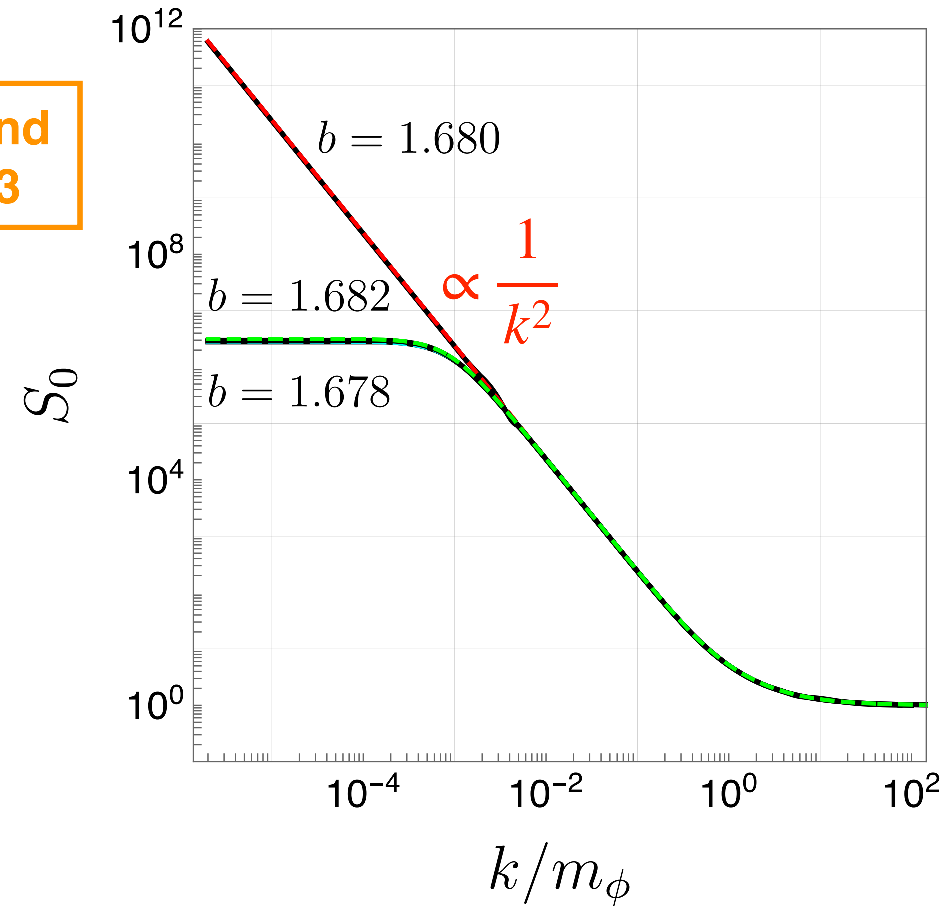
AK, Kuwahara and Patel, JHEP, 2023

- s-wave 1st resonance $\#b_0 = 0$

$$k \to 0 \quad \mathrm{Re}[\omega_0(k^2 + i\epsilon)] \to -\frac{1}{2}\ln(r_{e,0}^2 k^2)$$

- only zero energy "virtual" level $F_0(k^2) = 1$

$$k \to 0 \quad \Gamma_0(k^2) = \exp[\omega_0(k^2)]F_0(k^2) \propto \frac{1}{k}$$

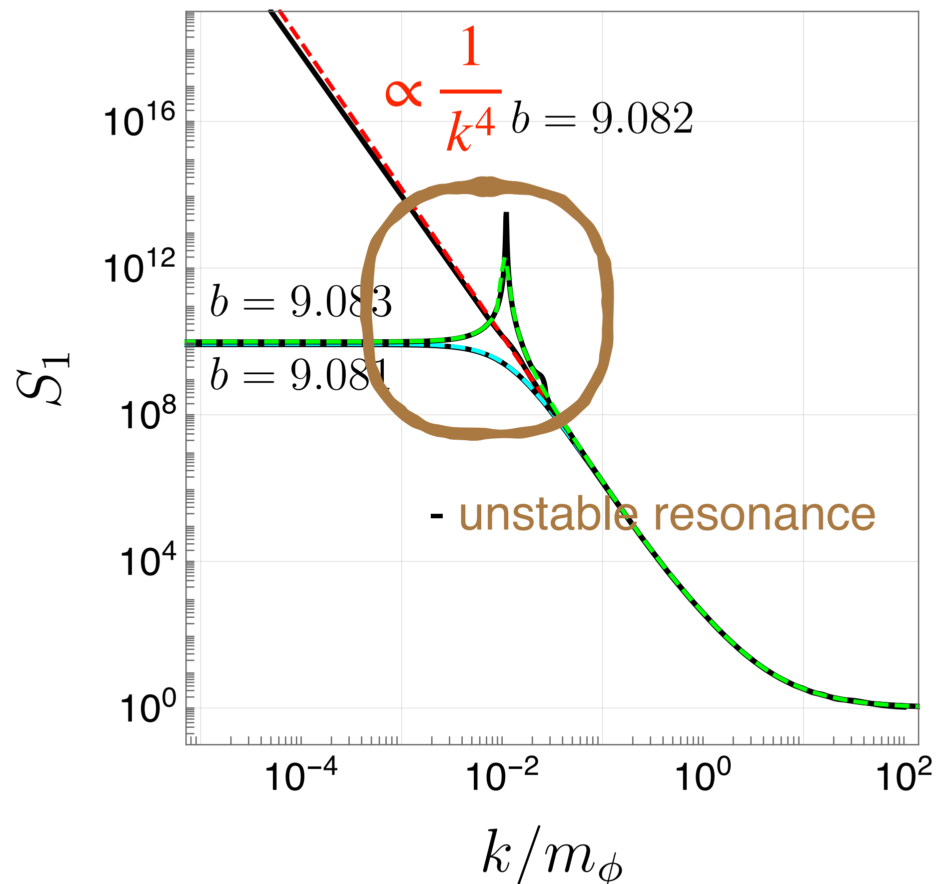


- p-wave 1st resonance $\#b_1 = 1$

$$k \to 0 \quad \mathrm{Re}[\omega_1(k^2)] \to -\ln(r_{e,1}^2 k^2)$$

- zero energy bound state $F_1(k^2) = \frac{k^2}{k^2} = 1$

$$k \to 0 \quad \Gamma_1(k^2) = \exp[\omega_1(k^2)]F_1(k^2) \propto \frac{1}{k^2}$$



Zero-energy resonances

Unitarity violation

- on s- and p-waves zero-energy resonances, partial-wave Unitarity is violated at low velocity

$$(\sigma_{\ell,\mathrm{ann}} v_{\mathrm{rel}}) = \mathrm{S}_\ell (\sigma^{(0)}_{\ell,\mathrm{ann}} v_{\mathrm{rel}}) \qquad (\sigma^{(0)}_{\ell,\mathrm{ann}} v_{\mathrm{rel}}) \propto k^{2\ell} \qquad (\sigma^{\mathrm{Uni}}_{\ell,\mathrm{ann}} v_{\mathrm{rel}}) = \frac{\pi}{\mu k}$$

$$\mathrm{S}_0(k^2) \propto \frac{1}{k^2} \qquad \mathrm{S}_{\ell \geq 1}(k^2) \propto \frac{1}{k^4}$$

- because we ignored a contact interaction including $V \supset u\delta^3(\vec{x})$ annihilation when solving the Schrödinger equation

Self-consistent solution

Blum, Sato and Slatyer, JHEP, 2016

Parikh, Sato and Slatyer, arXiv:2410.18168

AK, Matsumoto and Watanabe, in progress

- incorporating contact interaction is not as easy as one expects

- mathematical fact: there is no bounded wave function if a potential is singular than the centrifugal one

Full scattering state

AK, Matsumoto and Watanabe, in progress

Linear combination of regular and singular solutions

$$\tilde{R}_{k,\ell}(r) = \mathscr{A}_\ell(k)\mathscr{R}_{k,\ell}(r) + \mathscr{B}_\ell(k)\mathscr{S}_{k,\ell}(r)$$ - valid except for the origin

- regular solution we discussed before

- singular solution we introduce now

$$\mathscr{S}_{k,\ell}(r) \to k y_\ell(kr) \approx -k\frac{(2\ell-1)!!}{(kr)^{\ell+1}} \qquad r \to 0$$

$$\mathscr{S}_{k,\ell}(r) \to -\frac{1}{2r}\left[\mathscr{K}_\ell(k)e^{-i\left(kr-\frac{1}{2}\ell\pi\right)} + \mathscr{K}_\ell(-k)e^{i\left(kr-\frac{1}{2}\ell\pi\right)}\right] \qquad r \to \infty$$

- one combination of two unknown coefficients is fixed by requirement of in-coming wave

$$\tilde{R}_{k,\ell}(r) \to \frac{i}{2r}\left[e^{-i\left(kr-\frac{1}{2}\ell\pi\right)} - S_\ell(k)e^{i\left(kr-\frac{1}{2}\ell\pi\right)}\right] \qquad r \to \infty$$

$$\mathscr{A}_\ell(k)\mathscr{J}_\ell(k) + i\mathscr{B}_\ell(k)\mathscr{K}_\ell(k) = 1 \qquad S_\ell(k) = \frac{\mathscr{J}_\ell(-k)}{\mathscr{J}_\ell(k)}\left[1 - i\mathscr{B}_\ell(k)\mathscr{K}_\ell(k)\right] - i\mathscr{B}_\ell(k)\mathscr{K}_\ell(-k)$$

Full scattering state

The other combination is fixed by renormalization condition

$$\mathscr{B}_\ell(k) = \frac{k^{2\ell+1}}{p_\ell(k)\mathscr{J}_\ell(k)} \qquad \tilde{R}_{k,\ell}(r) = \mathscr{B}_\ell(k)\left(\left[p_\ell(k) - k^{2\ell+1}\frac{i\mathscr{K}_\ell(k)}{\mathscr{J}_\ell(k)}\right]\frac{\mathscr{R}_{k,\ell}(r)}{k^{2\ell+1}} + \mathscr{S}_{k,\ell}(r)\right)$$

- potential has delta-function (contact) term

$$V \supset u\delta^3(\vec{x})$$

- kinetic term of singular solution has contact term at the origin

$$\left(-\frac{\nabla^2}{2\mu}\right)\frac{1}{r} = \frac{4\pi}{2\mu}\delta^3(\vec{x})$$

- cancellation between them leads to renormalization condition

$$p_\ell(k) - k^{2\ell+1}\frac{i\mathscr{K}_\ell(k)}{\mathscr{J}_\ell(k)} + \frac{d^{2\ell+1}}{dr^{2\ell+1}}\left[\frac{(kr)^\ell}{(2\ell)!!}r\mathscr{S}_{k,\ell}\right](0)$$

$$= p_\ell(k_0) - k_0^{2\ell+1}\frac{i\mathscr{K}_\ell(k_0)}{\mathscr{J}_\ell(k_0)} + \frac{d^{2\ell+1}}{dr^{2\ell+1}}\left[\frac{(k_0 r)^\ell}{(2\ell)!!}r\mathscr{S}_{k_0,\ell}\right](0)$$

- renormalization scale

Full scattering state

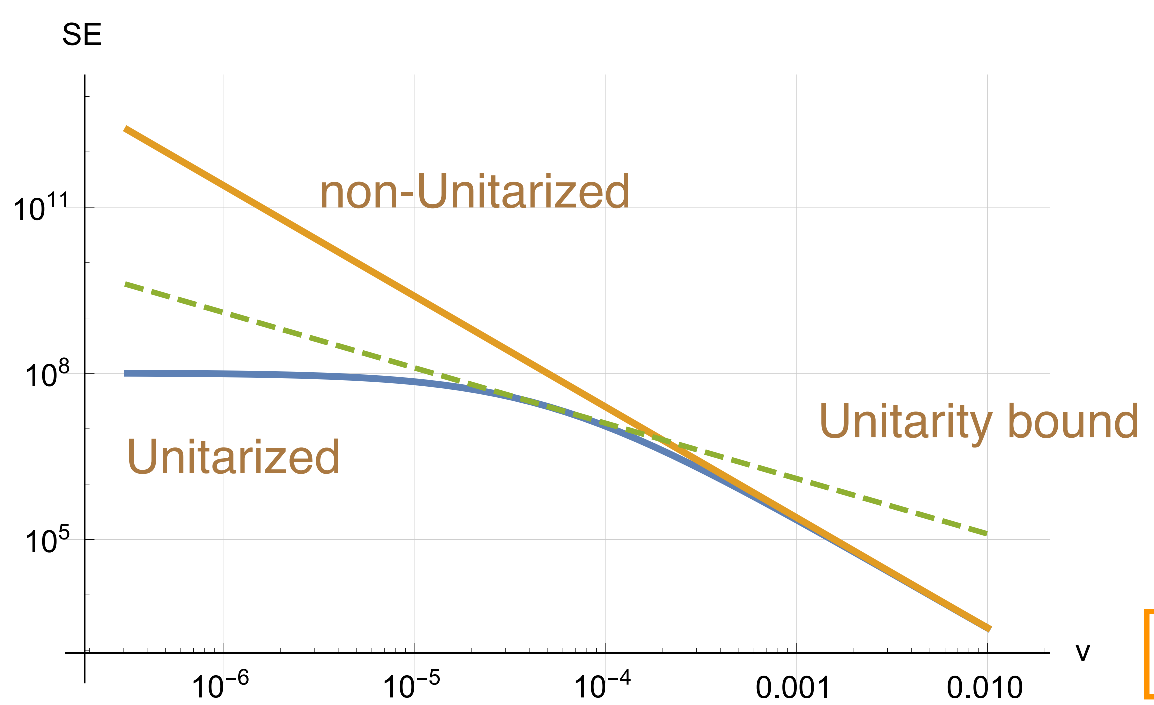
S-matrix

$$S_\ell(k) = \frac{\mathcal{J}_\ell(-k)}{\mathcal{J}_\ell(k)} \frac{p_\ell(k) - k^{2\ell+1}\dfrac{i\mathcal{K}_\ell(k)}{\mathcal{J}_\ell(k)} - k^{2\ell+1}\dfrac{i\mathcal{K}_\ell(-k)}{\mathcal{J}_\ell(-k)}}{p_\ell(k)}$$

- by considering large k, one can determine the renormalized constant by UV cross sections

$$\frac{4\pi}{|p_\ell(k)|^2} = \frac{\sigma^\ell_{\mathrm{sc},0}}{(2\ell+1)k^{4\ell}} \qquad \mathrm{Im}\frac{4\pi}{p_\ell(k)} \approx -\frac{\sigma^\ell_{\mathrm{ann},0}}{(2\ell+1)k^{2\ell-1}}$$

Unitarized Sommerfeld enhancement factor



Blum, Sato and Slatyer, JHEP, 2016

Full scattering state

Bound state with decay width

AK, Matsumoto and Watanabe, in progress

- bound state is a pole of S-matrix
- non-Unitarized S-matrix has a pole at pure imaginary momentum

$$\mathcal{J}_{\ell}(k = i\kappa) = 0$$

- one can find the correction to the pole from Unitarized S-matrix by using properties of Jost function

$$\mathrm{Im}E_B = -\frac{1}{2(4\pi)}\frac{\sigma^{\ell}_{\mathrm{ann},0}v}{(2\ell+1)p^{2\ell}}\left|\frac{(2\ell+1)!!}{\ell!}\frac{d^{\ell}R^{\ell}_B}{dr^{\ell}}(0)\right|^2$$

$$\mathrm{Re}E_B = -\frac{\kappa^2}{2\mu} + \frac{1}{2(4\pi)\mu}\eta\sqrt{\frac{4\pi\sigma^{\ell}_{\mathrm{sc},0}}{(2\ell+1)p^{4\ell}} - \left(\frac{\sigma^{\ell}_{\mathrm{ann},0}}{(2\ell+1)p^{2\ell-1}}\right)^2}\left|\frac{(2\ell+1)!!}{\ell!}\frac{d^{\ell}R^{\ell}_B}{dr^{\ell}}(0)\right|^2$$

Summary

Long-range force of dark matter

- Sommerfeld enhancement and self-scattering cross section
  - indirect detection and structure formation
  - they are correlated

This talk

- zero-energy resonances lead to violation of partial-wave Unitarity for s- and p-waves
  - Omnès solution
- Unitarization requires full scattering state incorporating contact interaction
  - renormalization
- Unitarized S-matrix has a bound state pole with decay width

Thank you

Analytic property

Complex momentum squared

$$\Gamma_\ell(k^2) = \frac{1}{\mathcal{J}_\ell(k^2)}$$

- "real" complex function

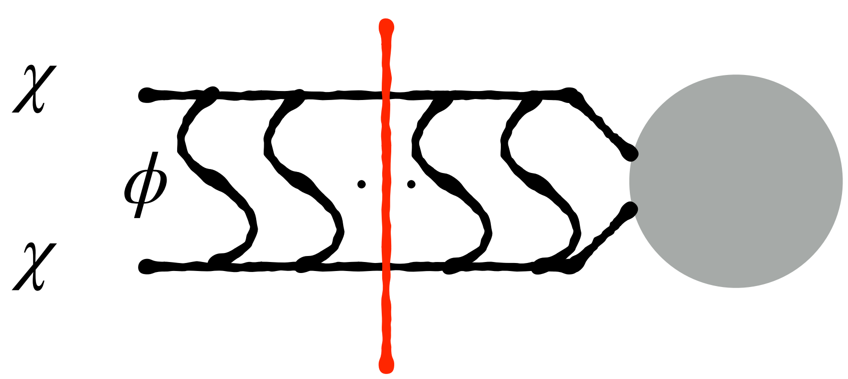
$$\Gamma^*_\ell(k^2) = \Gamma_\ell(k^{2*})$$

- brach cut along real (physical) axis

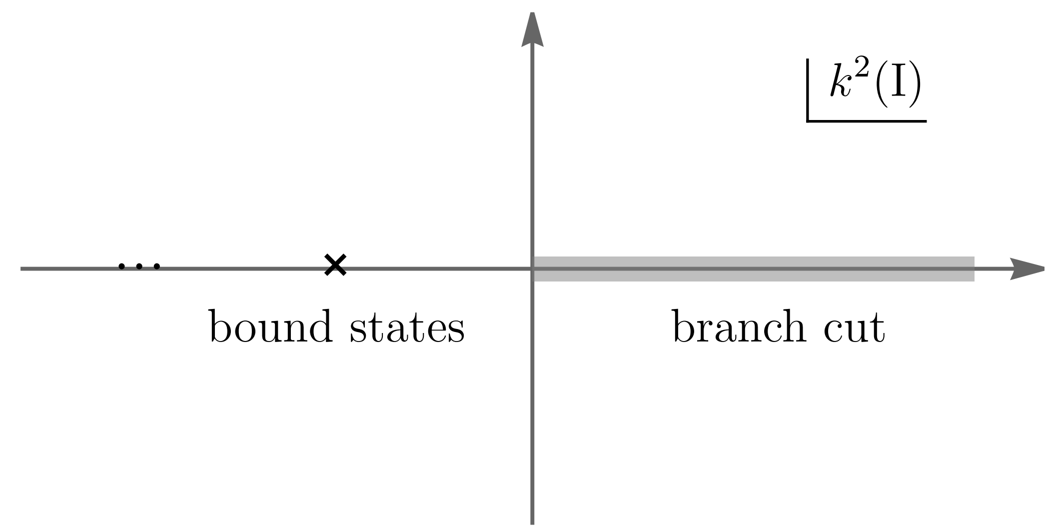
$$\Gamma_\ell(k^2 + i\epsilon) = e^{2i\delta_\ell(k)}\Gamma_\ell(k^2 - i\epsilon)$$

- real k^2

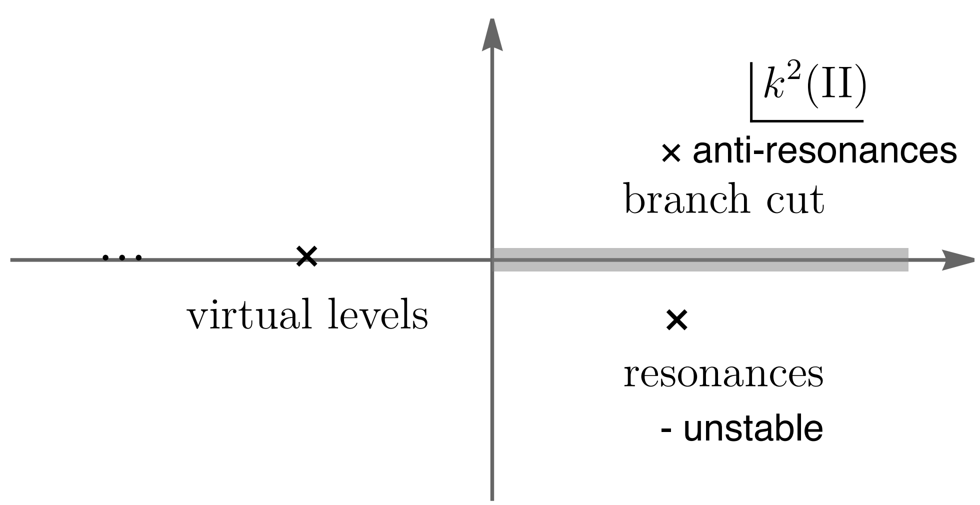
- known as Watson theorem (kind of optical theorem)



- bound states



- 1st Riemann sheet $\mathrm{Im}(k) > 0$



- 2nd Riemann sheet $\mathrm{Im}(k) < 0$

Omnès solution

Levinson theorem

Weinberg, "Lectures on Quantum Mechanics"

- # of bound states is given by phase shift

$$\delta_\ell(k \to 0) - \delta_\ell(k \to \infty) = \left[\#b_\ell \left(+\frac{1}{2}\right)\right]\pi$$

- excluding virtual levels

- zero in our normalization

- only for s-wave zero-energy resonances

- underlying idea
  - consider the system confined in a large sphere

$$R_{k\ell}(r) \to \frac{\sin(kr - \frac{1}{2}\ell\pi + \delta_\ell)}{r}$$

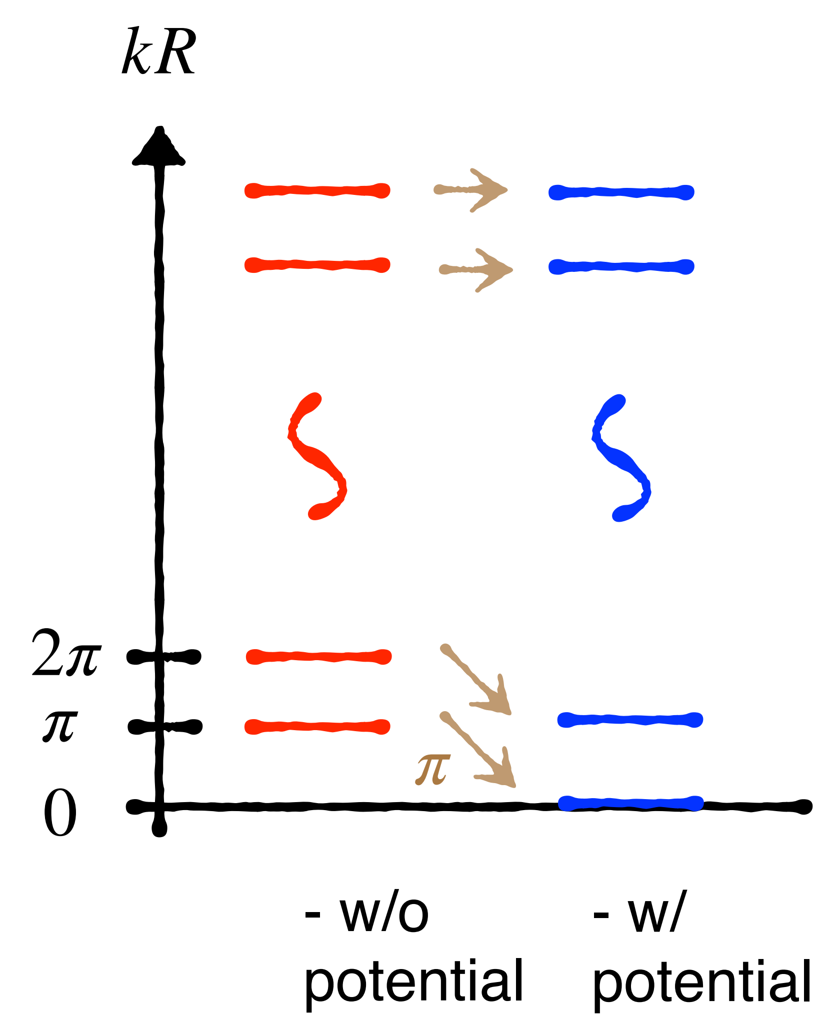
$r \to \infty$

$k > 0$

$$kR - \frac{1}{2}\ell\pi + \delta_\ell = n\pi$$

$n = 0, \pm 1, \pm 2\ldots$

  - scattering states are discretized (countable infinity)
  - decrease in # of scattering states = # of bound states
    - total number does not change

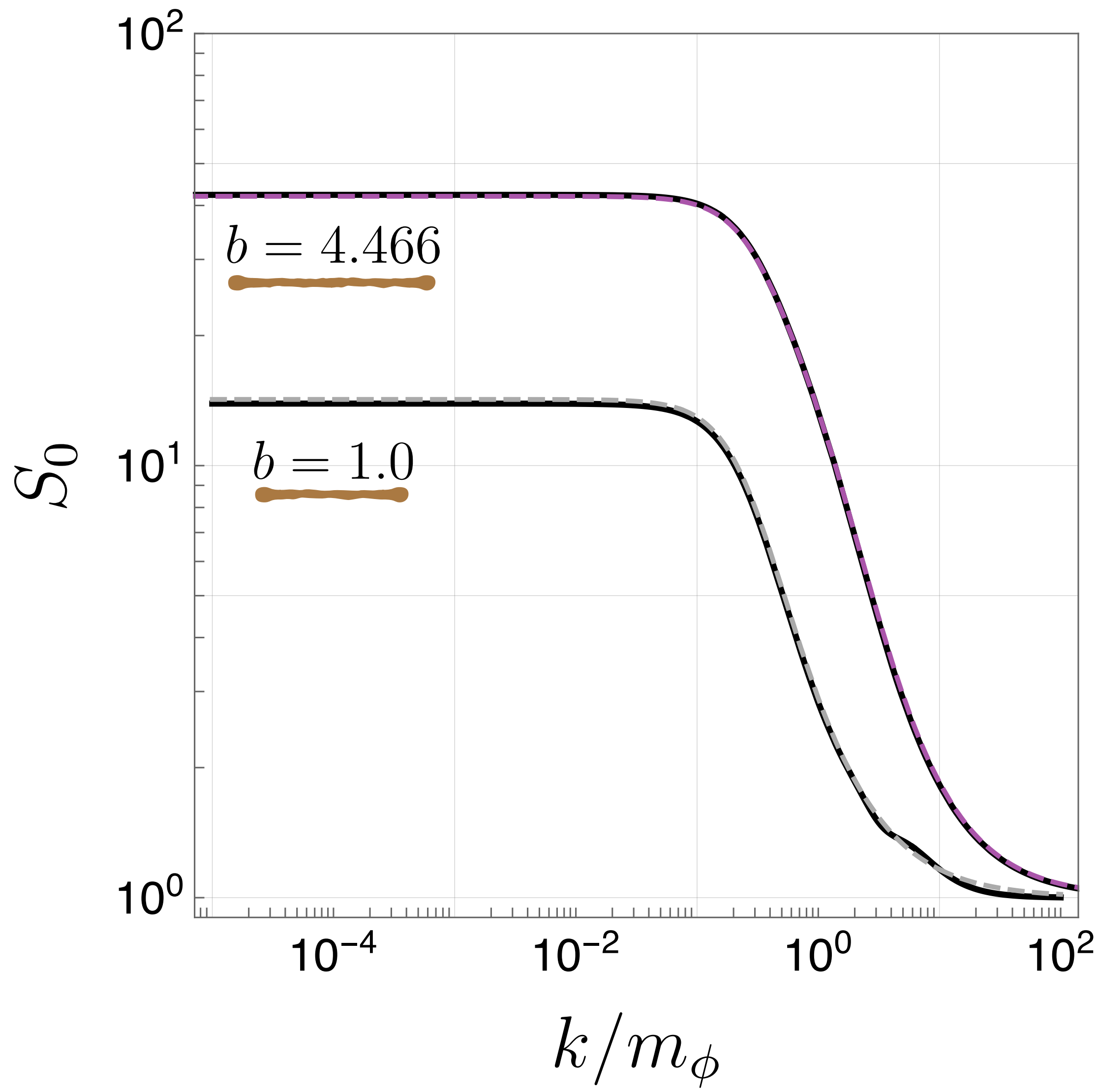


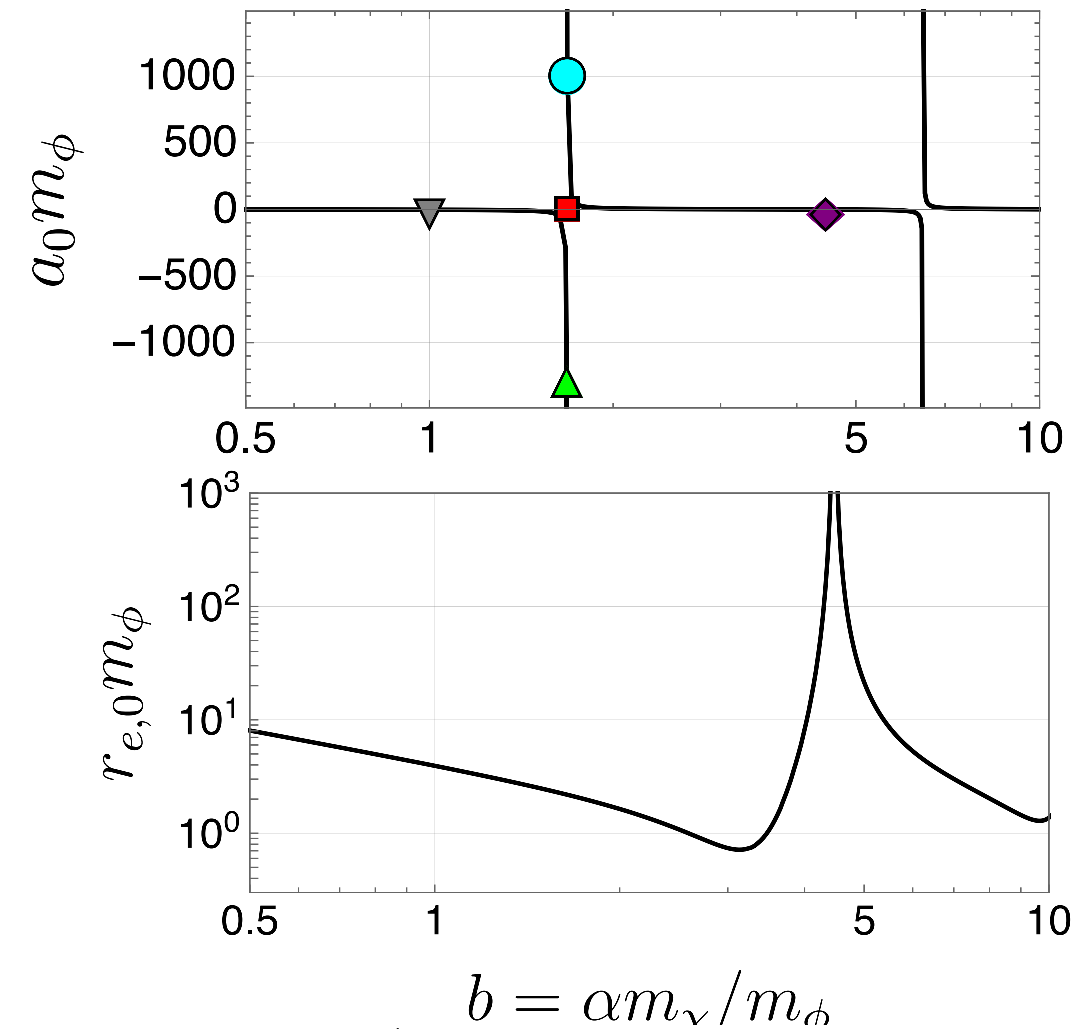
Omnès solution

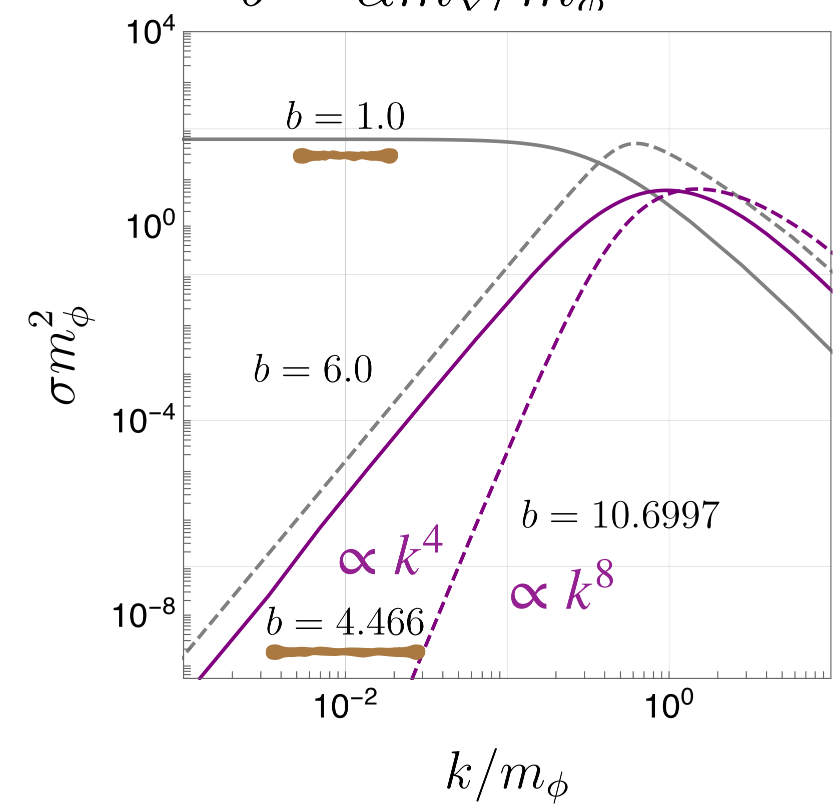
Yukawa potential

AK, Kuwahara and Patel, JHEP, 2023

- s-wave







- Omnès solution agrees with direct computation from scattering state
  - with proper $F_0(k^2)$

Around zero-energy resonances

S-wave

AK, Kuwahara and Patel, JHEP, 2023

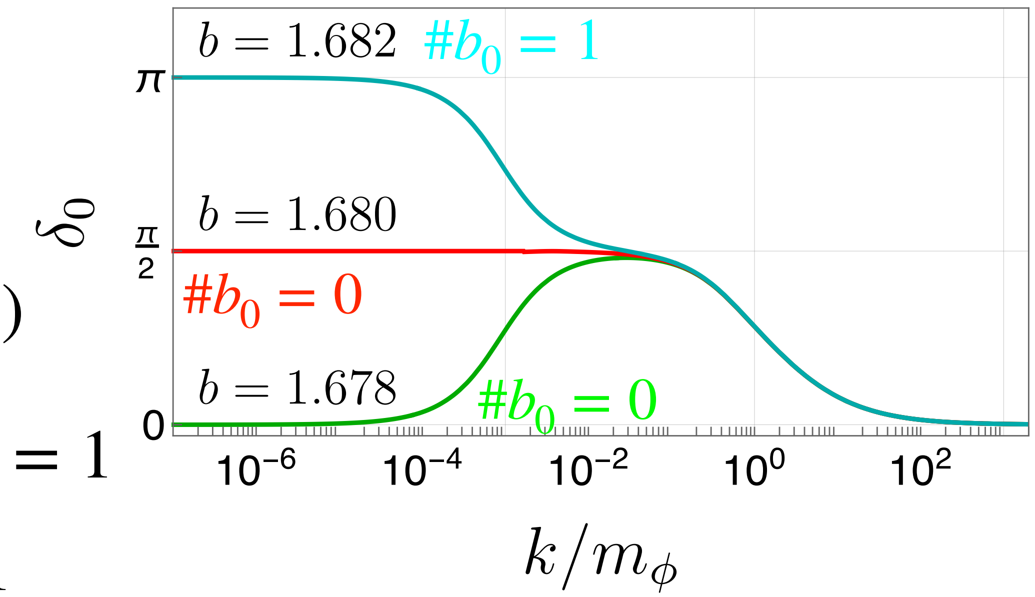
$$\delta_0(k \to 0) = \left[\#b_0 \left(+\frac{1}{2}\right)\right]\pi$$

- on 1st resonance $\#b_0 = 0$

$$k \to 0 \quad \mathrm{Re}[\omega_0(k^2 + i\epsilon)] \to -\frac{1}{2}\ln(r_{e,0}^2 k^2)$$

  - only zero energy "virtual" level $F_0(k^2) = 1$

$$k \to 0 \quad \Gamma_0(k^2) = \exp[\omega_0(k^2)]F_0(k^2) \propto \frac{1}{k}$$



- slightly below the 1st resonance $\#b_0 = 0$
  - no bound state $F_0(k^2) = 1$

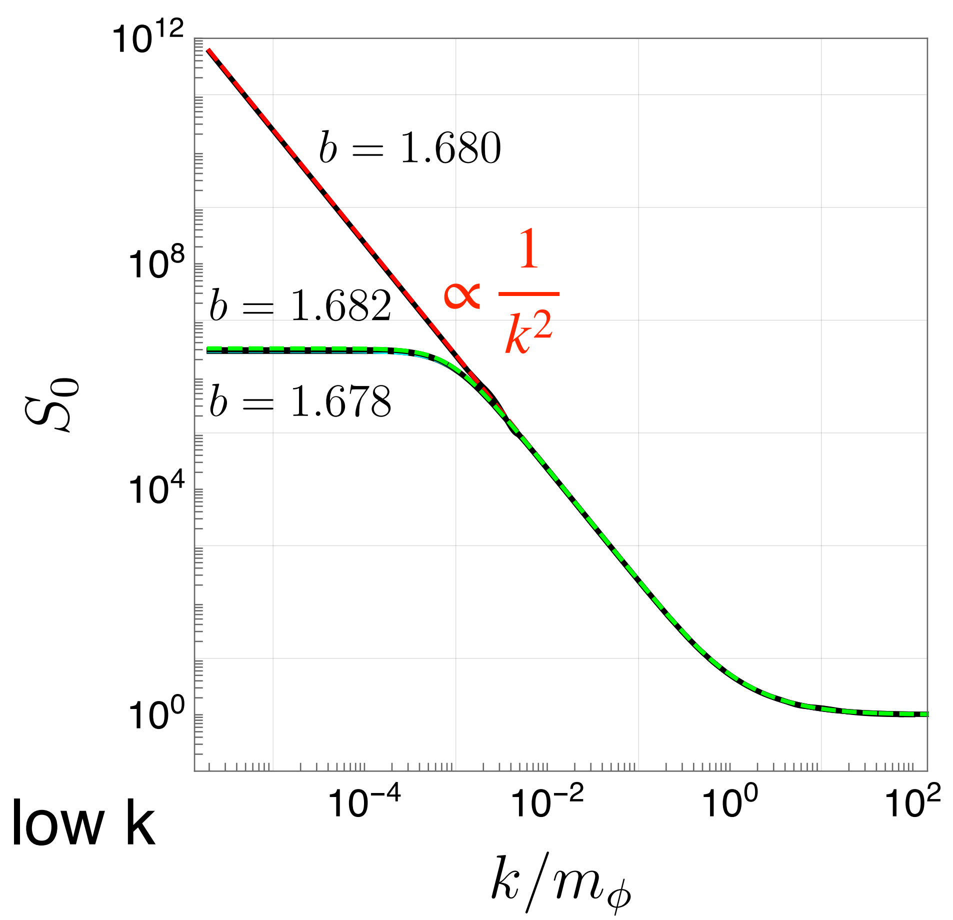
- slightly above the 1st resonance $\#b_0 = 1$

$$k \to 0 \quad \mathrm{Re}[\omega_0(k^2 + i\epsilon)] \to -\ln(r_{e,0}^2 k^2)$$

  - single bound state $F_0(k^2) = \dfrac{k^2}{k^2 + \kappa_{b,0}^2}$

$$k \to 0 \quad \Gamma_0(k^2) \propto \frac{1}{k^2 + \kappa_{b,0}^2}$$

- saturates at low k

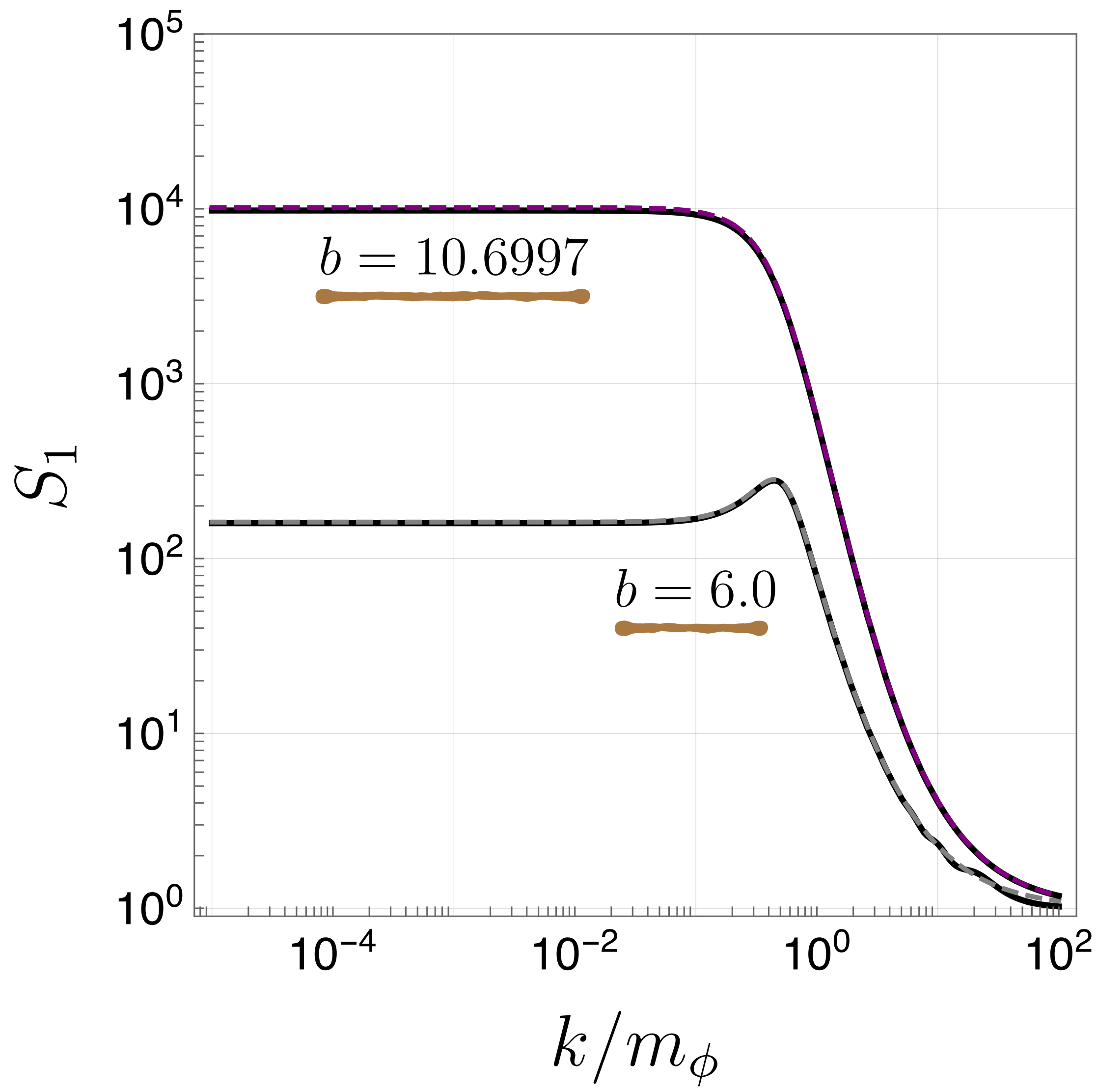


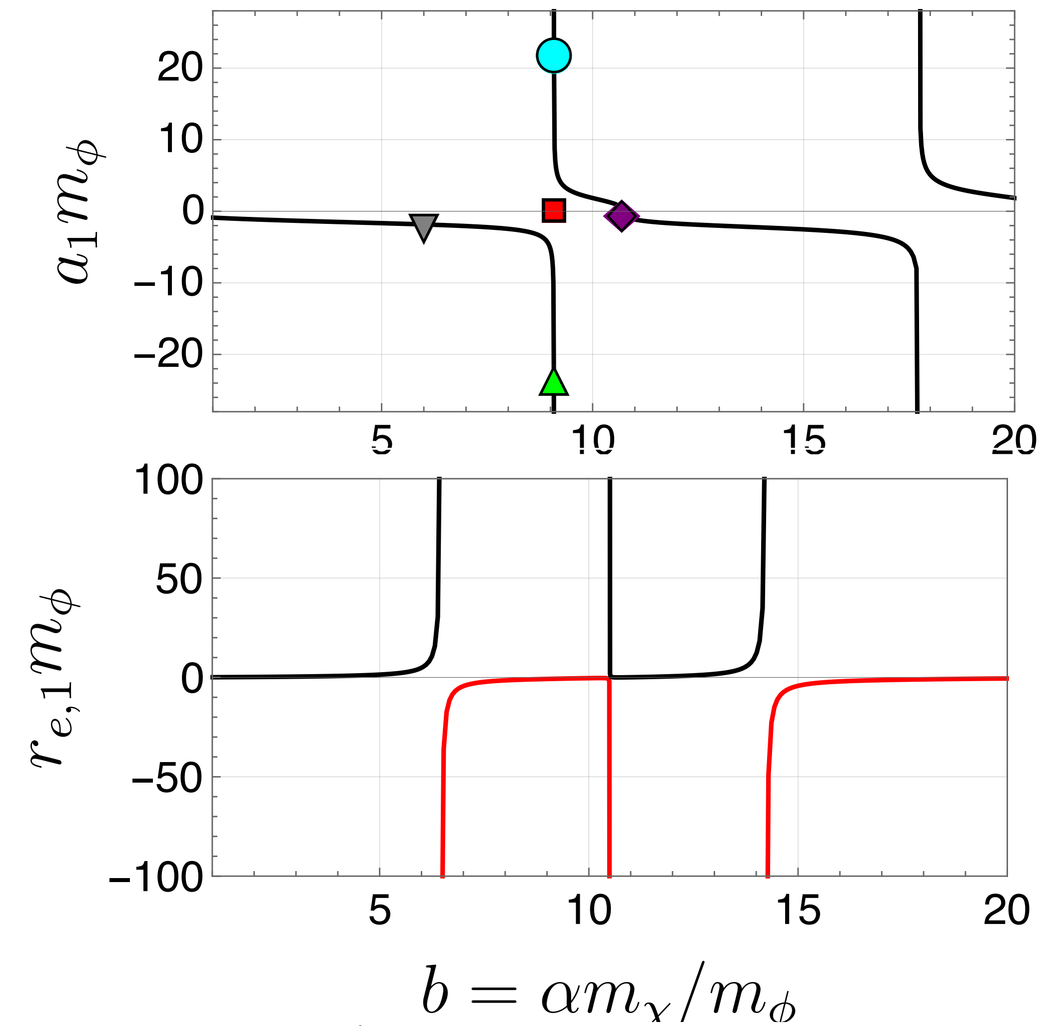
Omnès solution

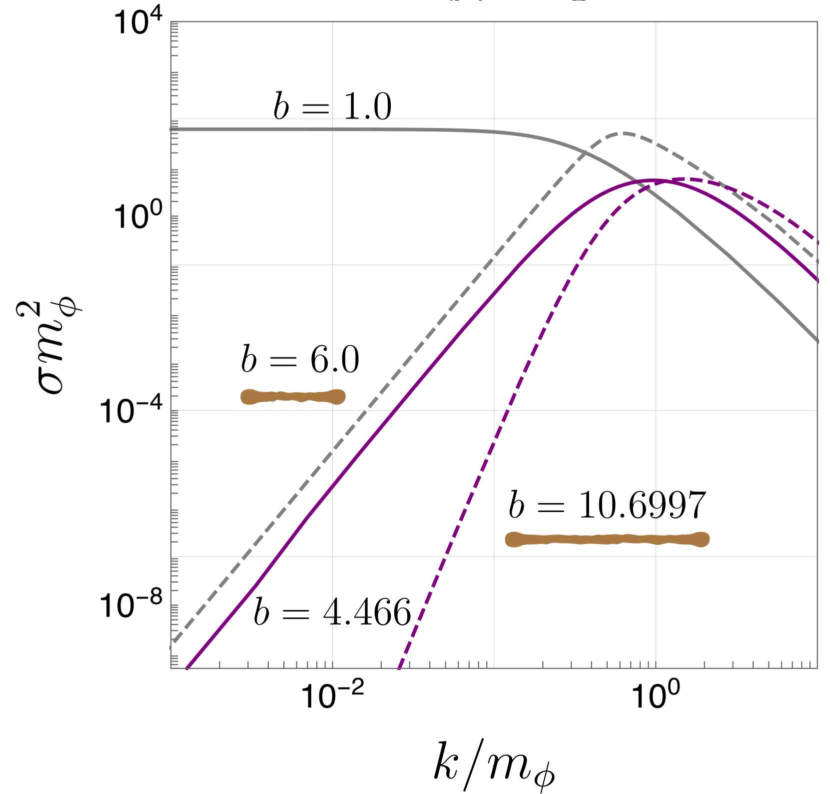
Yukawa potential

AK, Kuwahara and Patel, JHEP, 2023

- p-wave







Around zero-energy resonances

P-wave

$$\delta_1(k \to 0) = \#b_1 \pi$$

- on the 1st resonance $\#b_1 = 1$

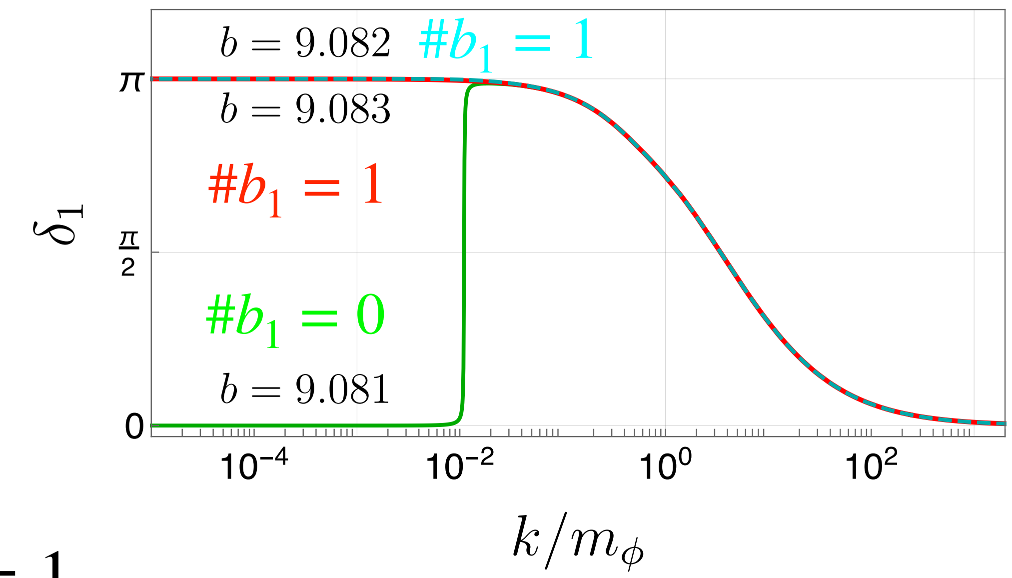
$$k \to 0 \quad \mathrm{Re}[\omega_1(k^2)] \to -\ln(r_{e,1}^2 k^2)$$

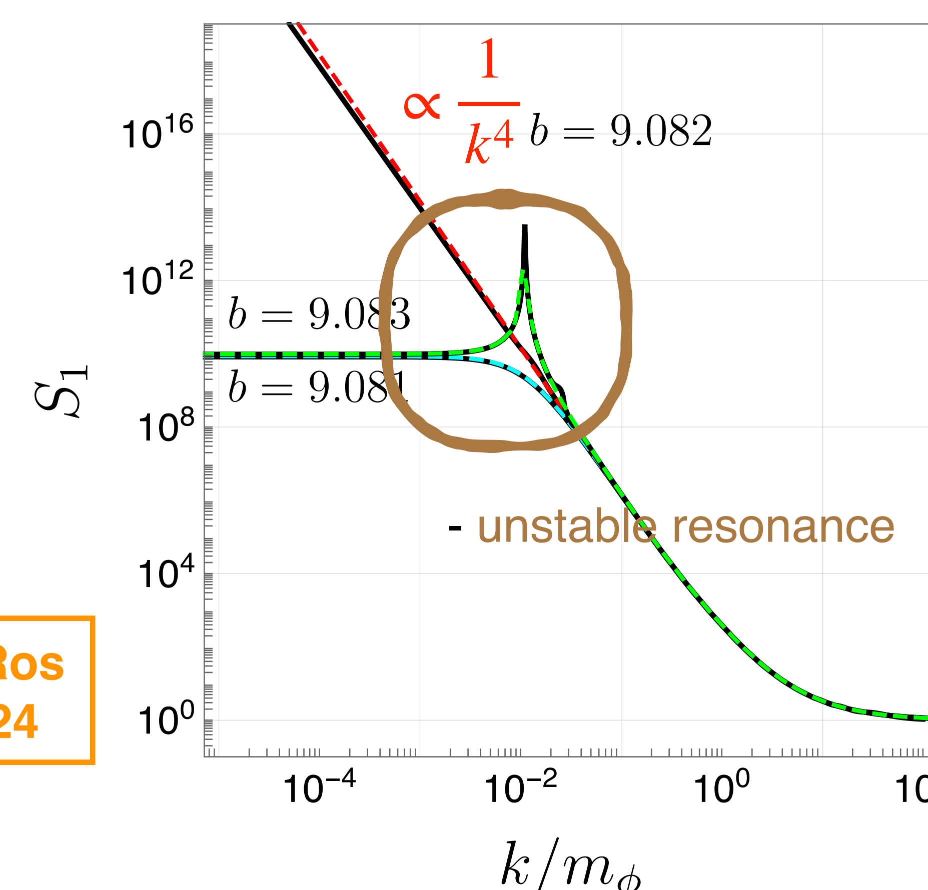
- zero energy bound state $F_1(k^2) = \dfrac{k^2}{k^2} = 1$

$$k \to 0 \quad \Gamma_1(k^2) = \exp[\omega_1(k^2)] F_1(k^2) \propto \frac{1}{k^2}$$

- slightly below/above the 1st resonance
  - similar to s-wave

AK, Kuwahara and Patel, JHEP, 2023





Beneke, Binder, De Ros and Grany, JHEP, 2024

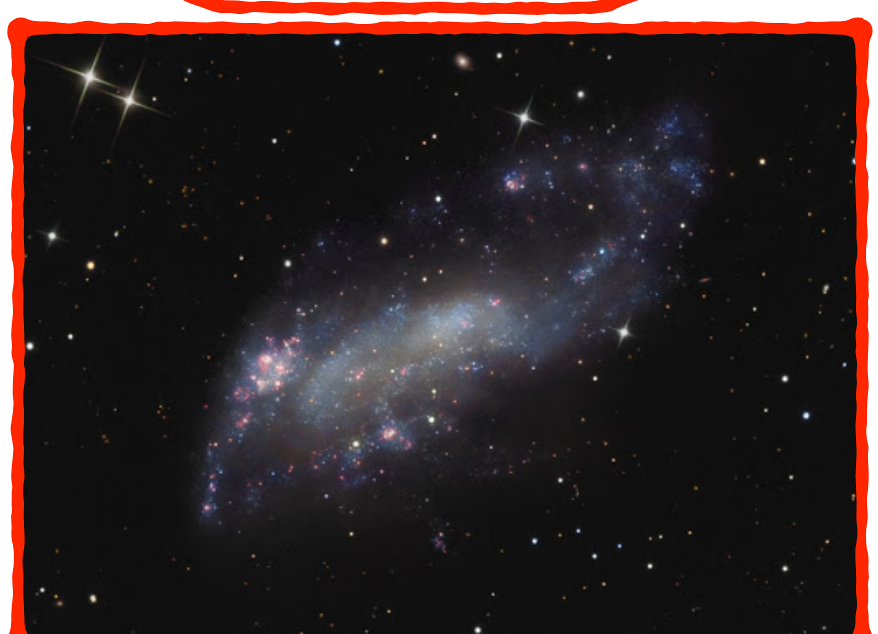
Data points

Overview

- cores in various-size halos

- MW satellite (Draco)

$M_{\text{infall}} \sim 10^9\, M_\odot$



- dwarf spiral galaxy (IC 2574) $M \sim 10^{11}\, M_\odot$

- galaxy cluster (Abell 2744)

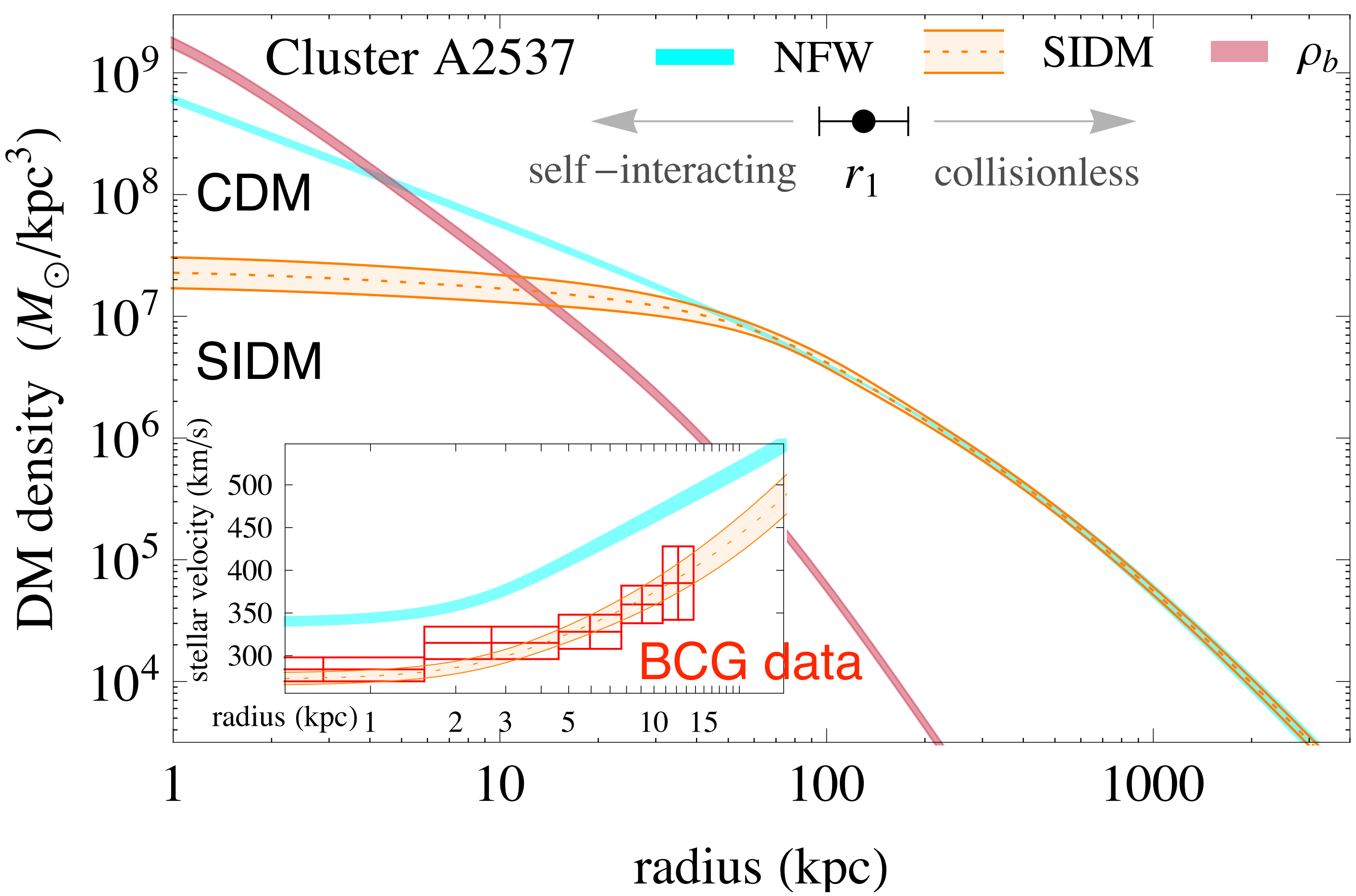
$M \sim 10^{14}\, M_\odot$

Data points

Galaxy clusters

- mass distribution in the outer region is determined by strong/weak gravitational lensing

- stellar kinematics in the central region (brightest cluster galaxies) prefer cored SIDM profile



$\sigma_{\rm self}/m \sim 0.1\,{\rm cm}^2/{\rm g}$

$\langle v_{\rm rel}\rangle \sim 10^3\,{\rm km/s}$

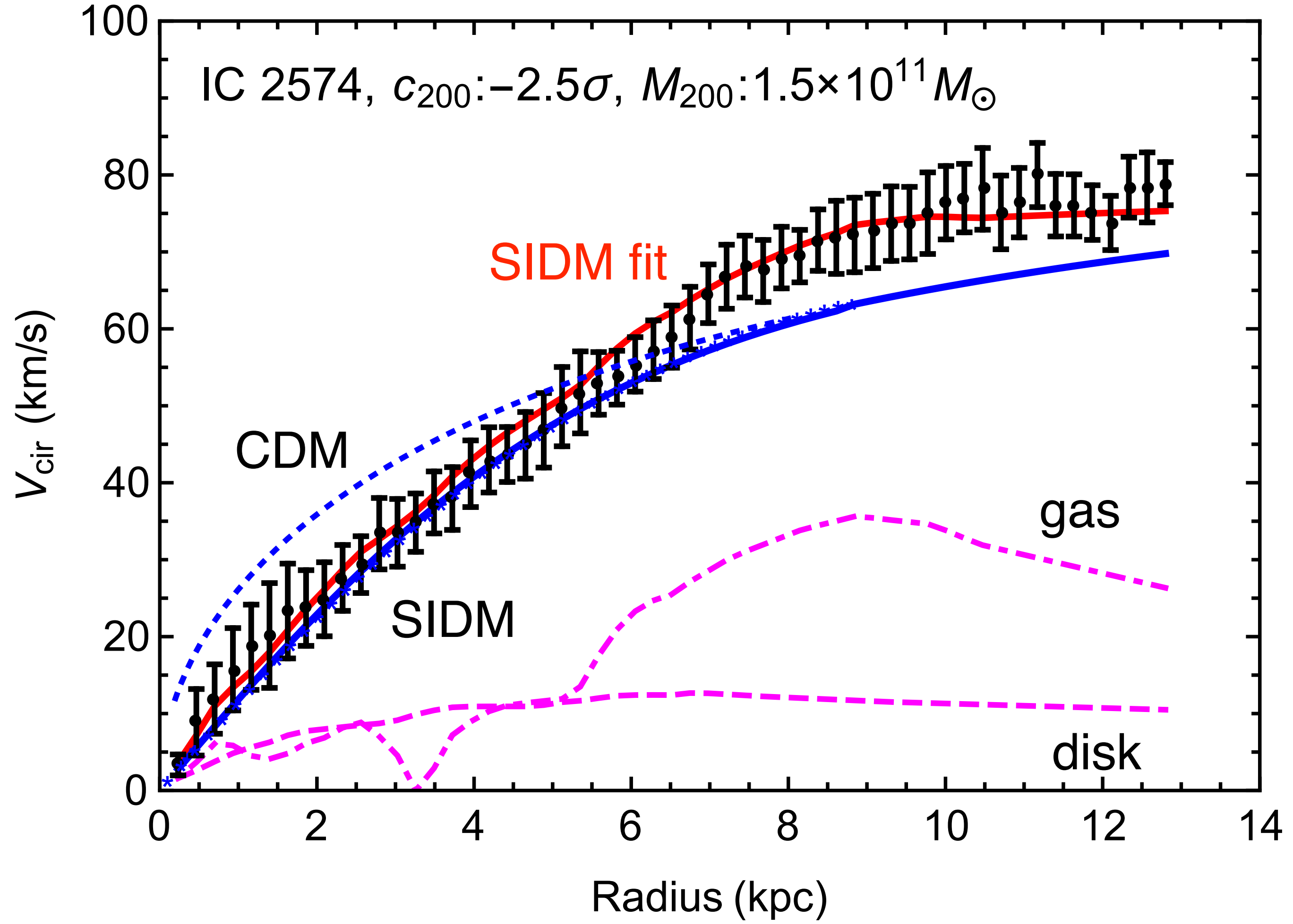
Kaplinghat, Tulin and Yu, PRL, 2016

Data points

Dwarf spiral galaxies

- mass distribution is broadly determined by rotation curves

- rotation velocity in central region (of some galaxies) prefer cored SIDM profile



$\sigma_{\rm self}/m \sim 1\,{\rm cm}^2/{\rm g}$

$\langle v_{\rm rel}\rangle \sim 10^2\,{\rm km/s}$

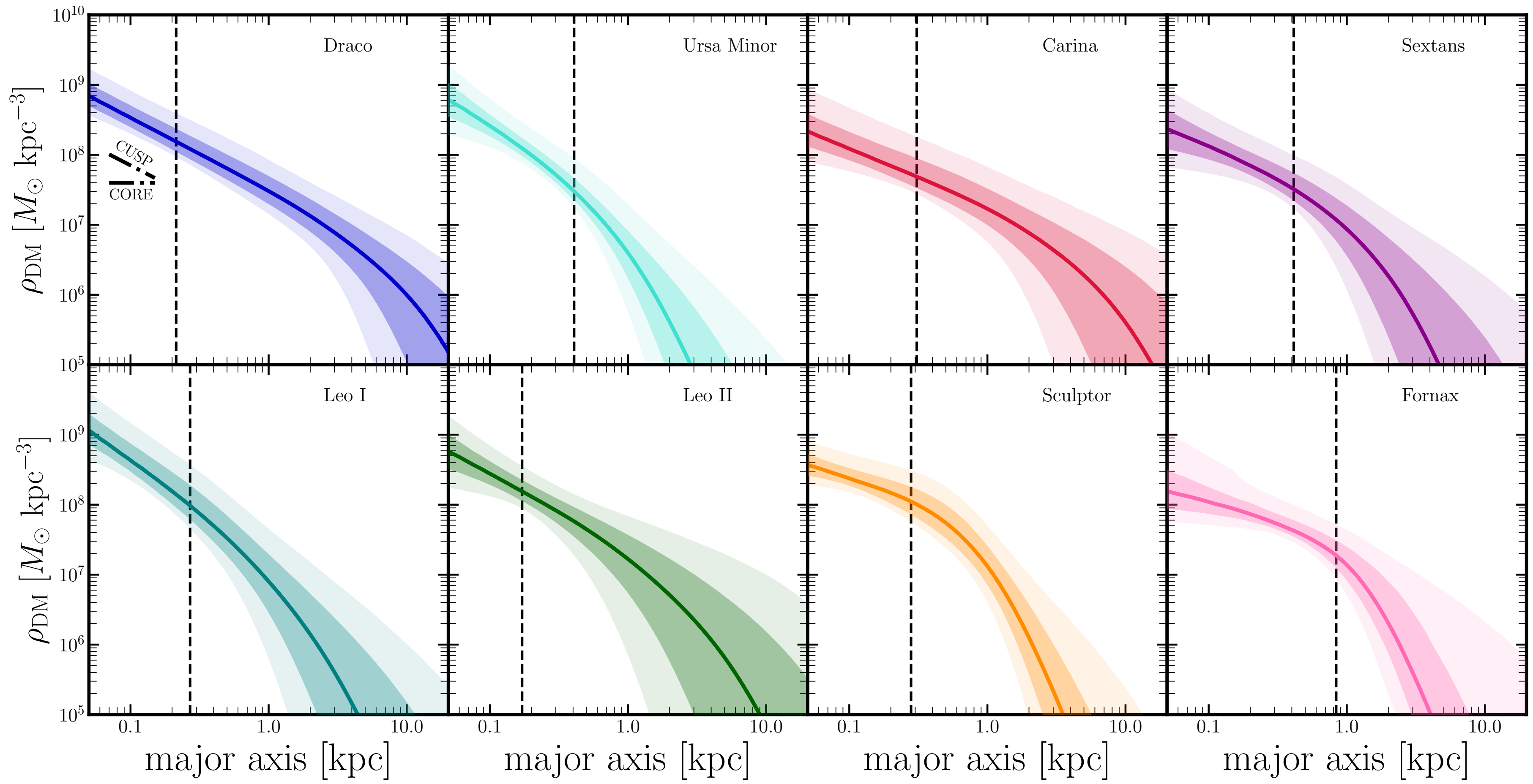
AK, Kaplinghat, Pace and Yu, PRL, 2017

Data points

MW satellites

- mass distribution is determined by stellar kinematics

- stellar kinematics in the central region (of some satellites) prefer cuspy CDM profile



Hayashi, Chiba and Ishiyama, ApJ, 2020

Data points

MW satellites

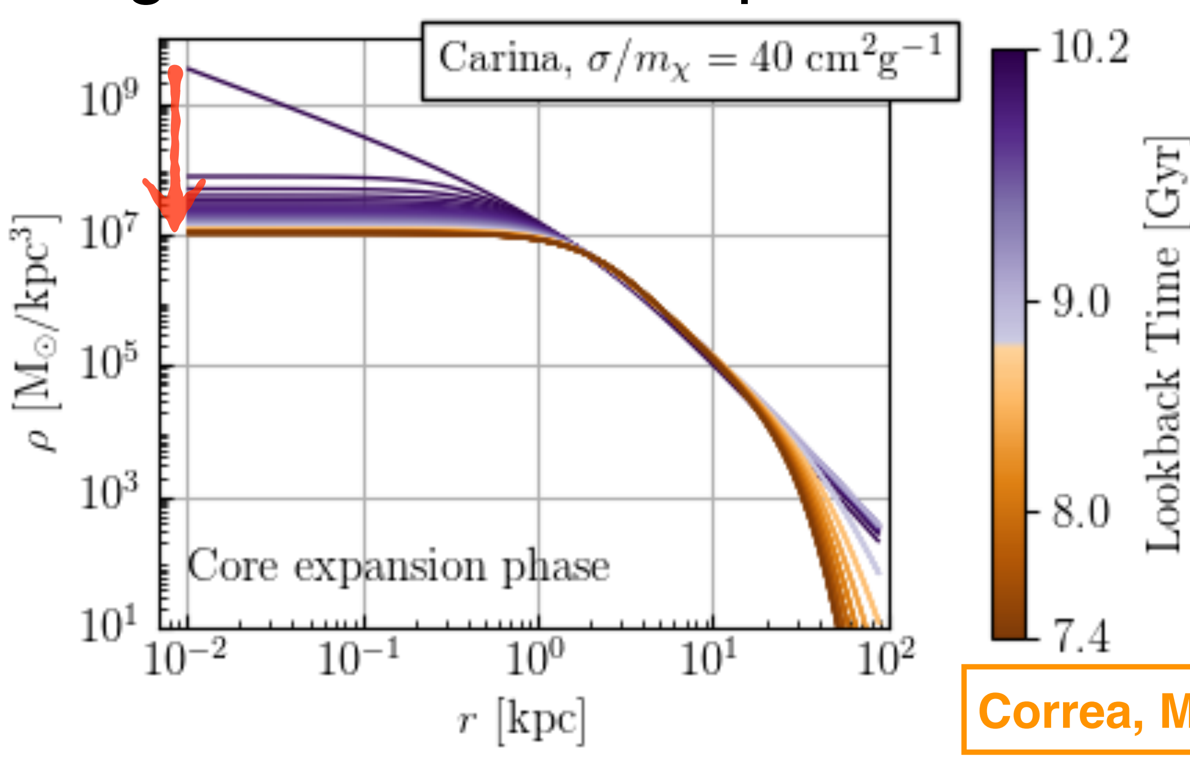
- one possibility is to take as a tiny cross section as $\sigma_{\rm self}/m \simeq 0.01\,{\rm cm^2/g}$

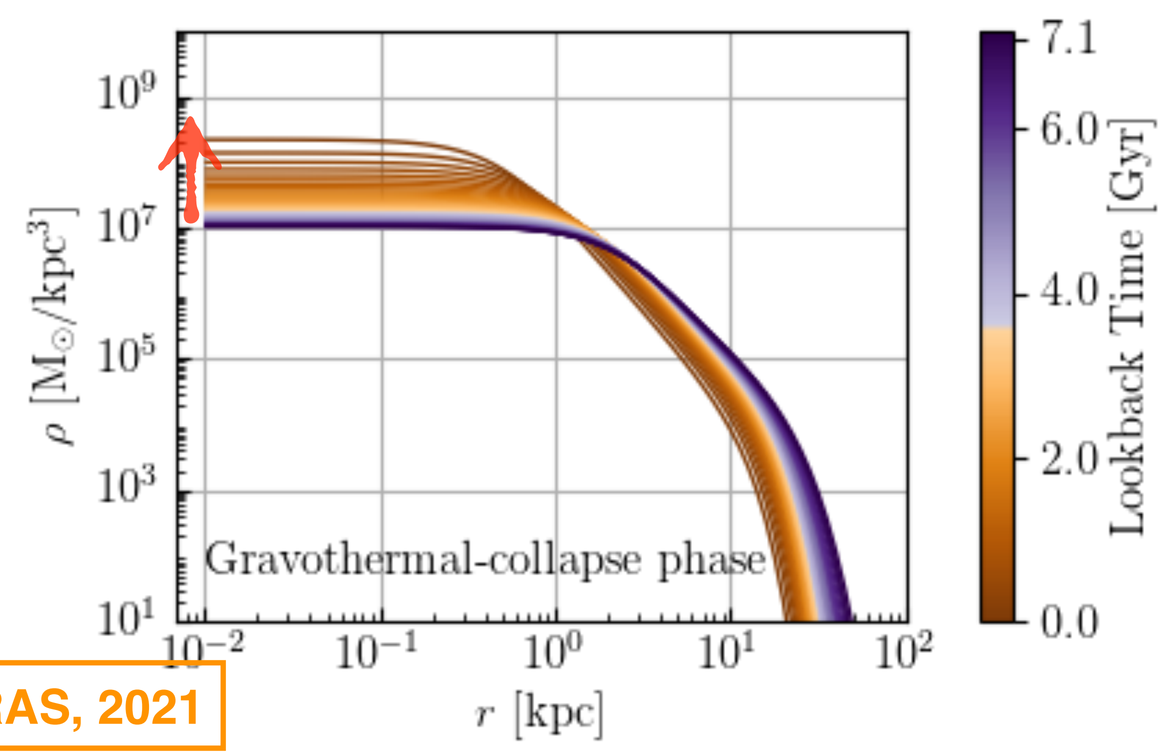
$\langle v_{\rm rel}\rangle \sim 30\,{\rm km/s}$

- resonance? Chu, Garcia-Cely and Murayama, PRL, 2019

- another possibility is to take as a large cross section as $\sigma_{\rm self}/m \sim 40\,{\rm cm^2/g}$ $\langle v_{\rm rel}\rangle \sim 30\,{\rm km/s}$

- gravothermal collapse



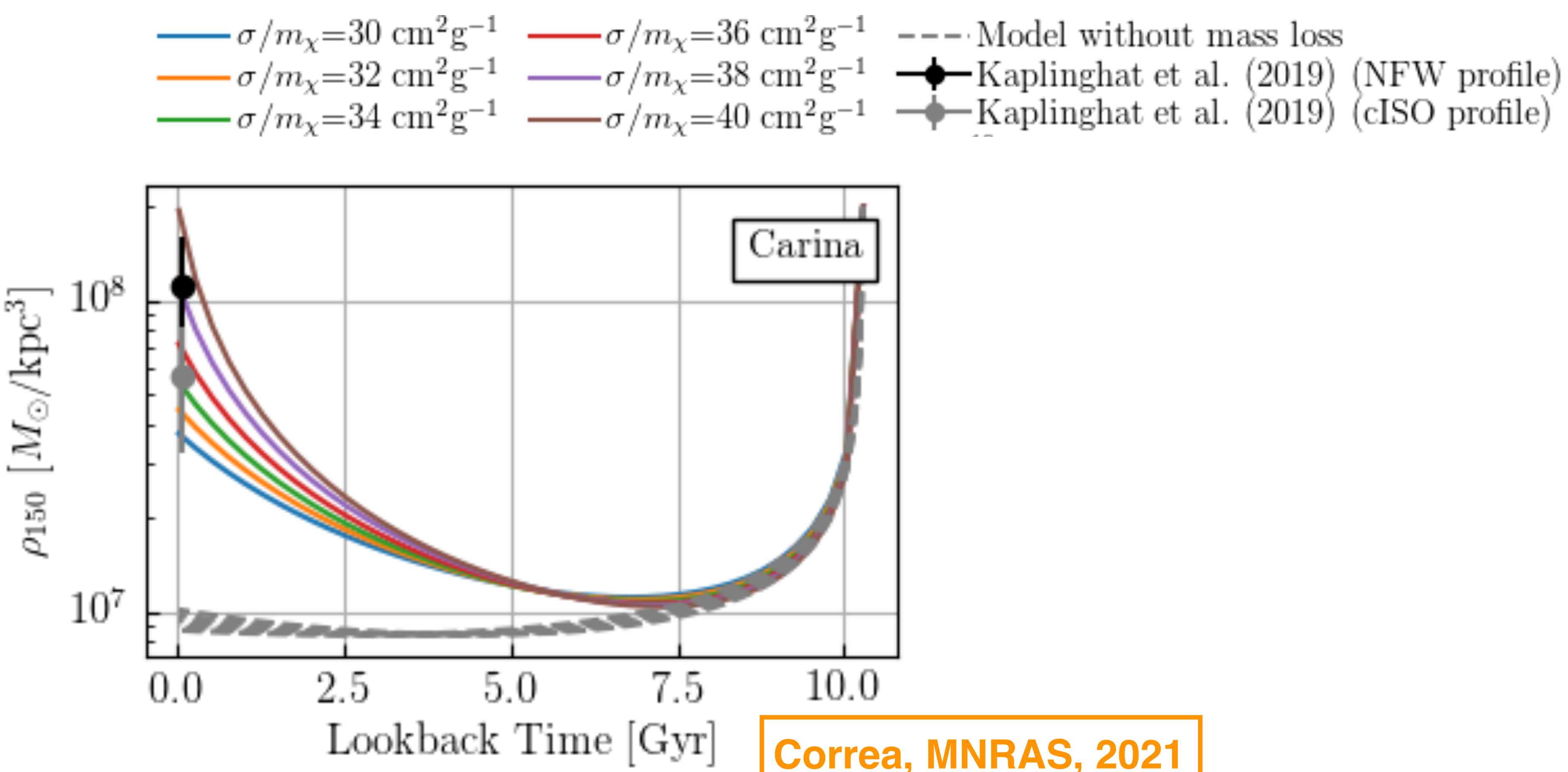


Correa, MNRAS, 2021

Data points

MW satellites

- gravothermal collapse
  - core shrinks and central density gets higher
  - central density at present is very sensitive to the cross section



Correa, MNRAS, 2021