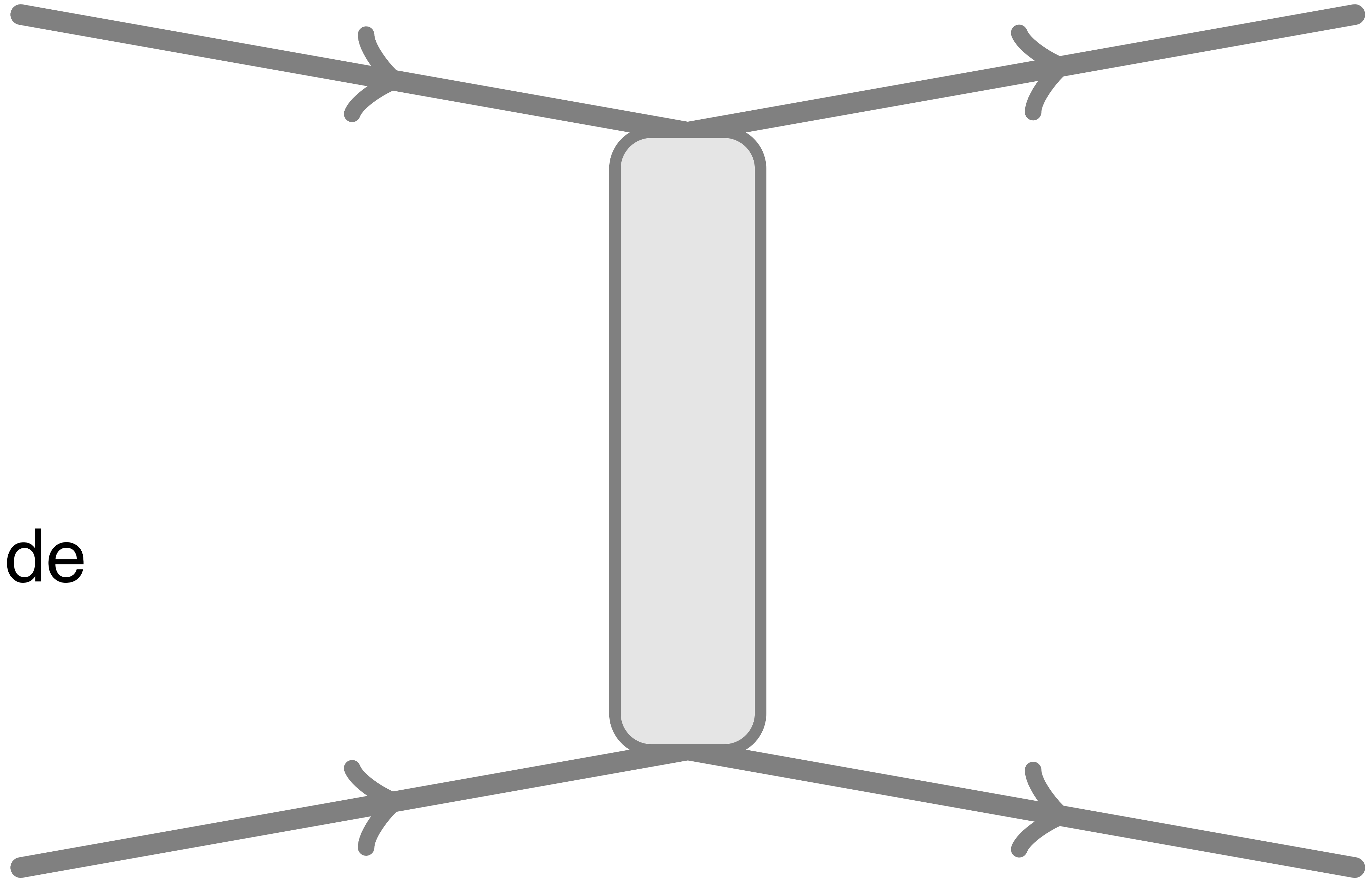
Continuum Mediated Self-Interacting Dark Matter

Self-Interactions from a Near-Conformal Mediator



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2102.05674 (accepted by JHEP)

May 25, 2021

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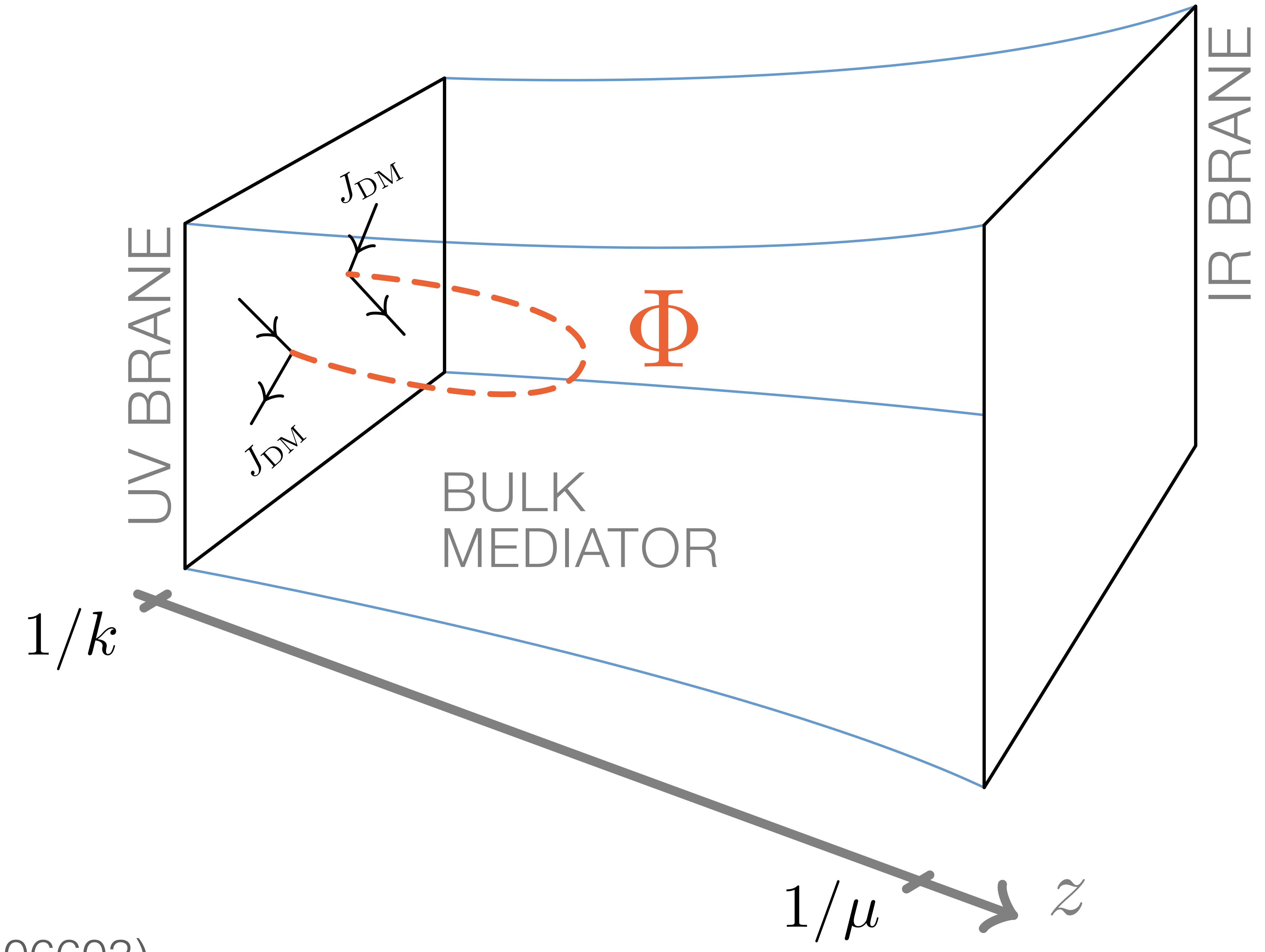
Phenomenology 2021

Continuum Mediated Dark Matter Interactions

New phenomenology from a bulk scalar mediator

- Near-conformal model dual to 5D model with a mass gap
- Based on the warped dark sector framework
  Brax, Fichet, Tanedo: 1906.02199
- Non-integer power law potential
- Observables sensitive to non-integer power
- Other new phenomenology i.e. opacity: censors the IR brane

Costantino, Fichet, Tanedo (2002.12335) & Costantino, Fichet (2011.06603)



Previous Works

Warped dark sectors and continuum mediated interactions

Randall Sundrum II
Randall, Sundrum (hep-th/9906064)

Unparticles
Strassler (0801.0629)
Chen, Kim (0909.1878)
Friedland, Giannotti, Graesser (0902.3676, 0905.2607)

Conformal hidden sectors
Ghergetta, von Harling (1002.2967)
von Harling, McDonald (1203.6646)

Continuum-mediated dark matter-baryon scattering
Katz, Reece, Sajjad (1509.03628)

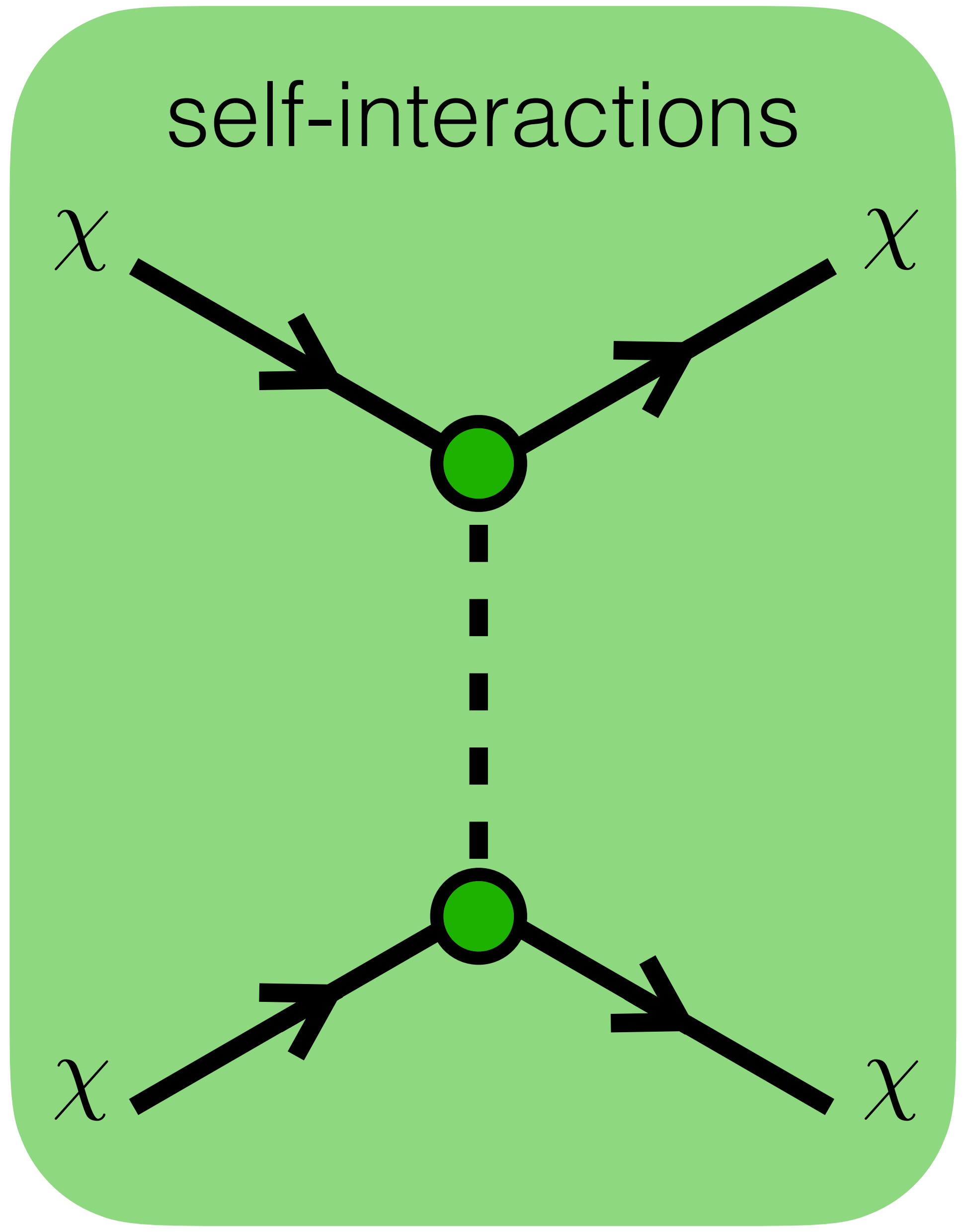
Warped dark sector
Brax, Fichet, Tanedo (1906.02199)

Continuum Dark Matter
Csáki et al. (2105.07035)

Dark Sectors

Dark matter + light mediator(s)

- No definitive evidence for WIMP dark matter
- No direct coupling to the Standard Model
- Dark matter interacts through one or more light mediators
- The mediator has different couplings to the dark matter and Standard Model



Self-Interacting Dark Matter

Why care?

Dwarf

$$v \sim 10 \text{ km/s}$$

$$\sigma/m \sim 1 \text{ cm}^2/\text{g}$$

Cluster

$$v \sim 1500 \text{ km/s}$$

$$\sigma/m \lesssim 0.1 \text{ cm}^2/\text{g}$$

- Self-interactions thermalize galactic inner halo and reduce the central density
- Scattering rate: $\sigma v\,(\rho/m)$
- Velocity dependent scattering cross section may resolve small scale structure anomalies in dwarf spheroidal galaxies i.e. core-cusp problem
- Quantum mechanical resonances and non-perturbative effects imply a numerical approach is required for much of parameter space

Tulin, Yu and Zurek (1302.3898)

What is the Necessary Spectrum?

Phenomenological model

$$\mathcal{L} \supset g_\chi \phi_\mu \bar{\chi} \gamma^\mu \chi$$

Asymmetry in the dark matter abundance results in a purely repulsive force

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

Benchmark model

$$\alpha_\chi = \frac{g_\chi^2}{4\pi} = \frac{1}{137}$$

$$m_\chi = 15 \text{ GeV} \quad m_\phi = 17 \text{ MeV}$$

Kaplinghat, Tulin, Yu (1508.03339)

DM mass for symmetric freeze out constrained to sub-GeV scale by cluster observations
Huo et al. (1709.09717)

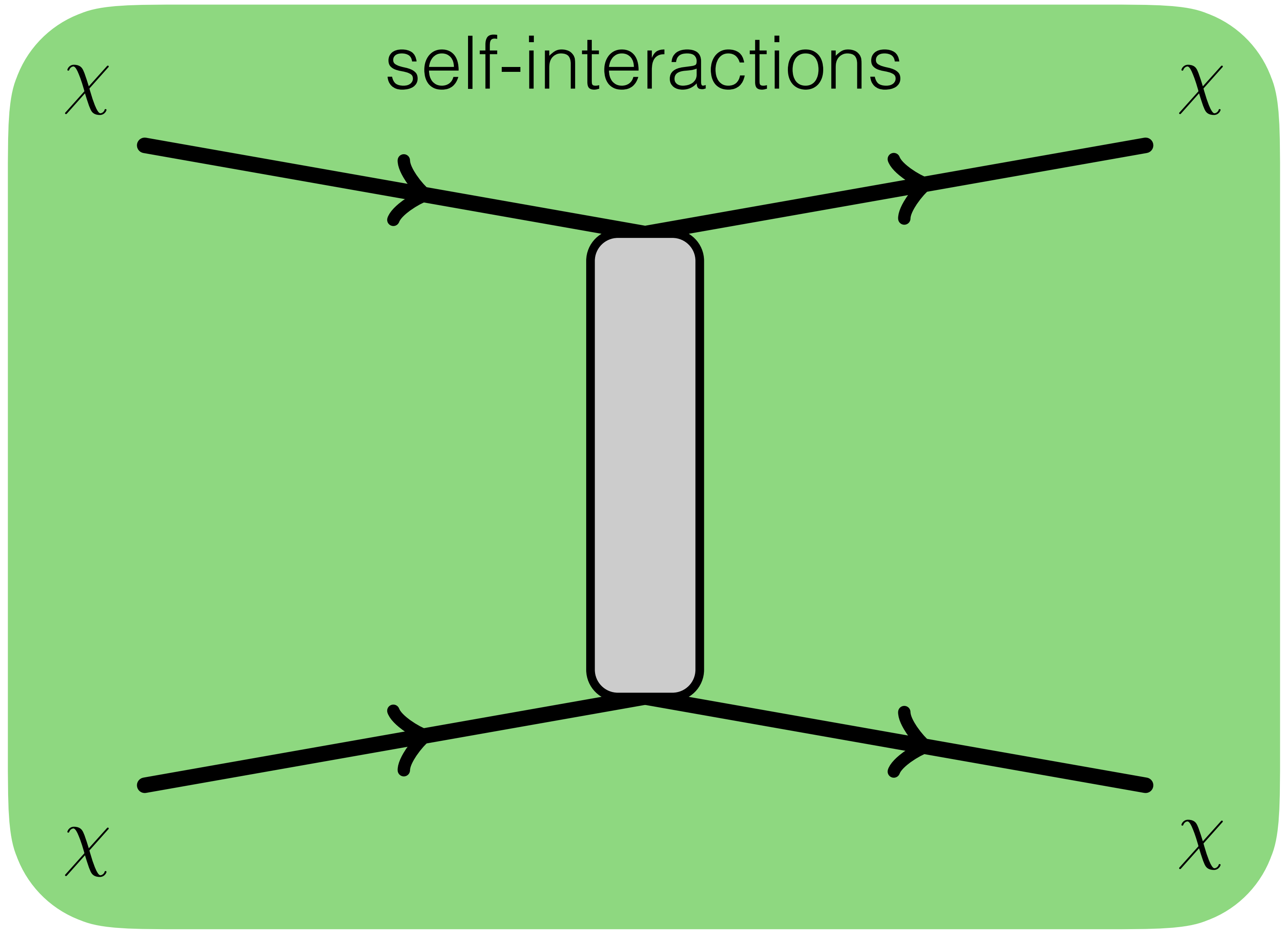
A Continuum Dark Sector

Dark matter + continuum mediator

- Near-conformal model dual to a slice of AdS_5
  Brax, Fichet, Tanedo: 1906.02199

- Brane localized dark matter only interacts through a 5D bulk mediator

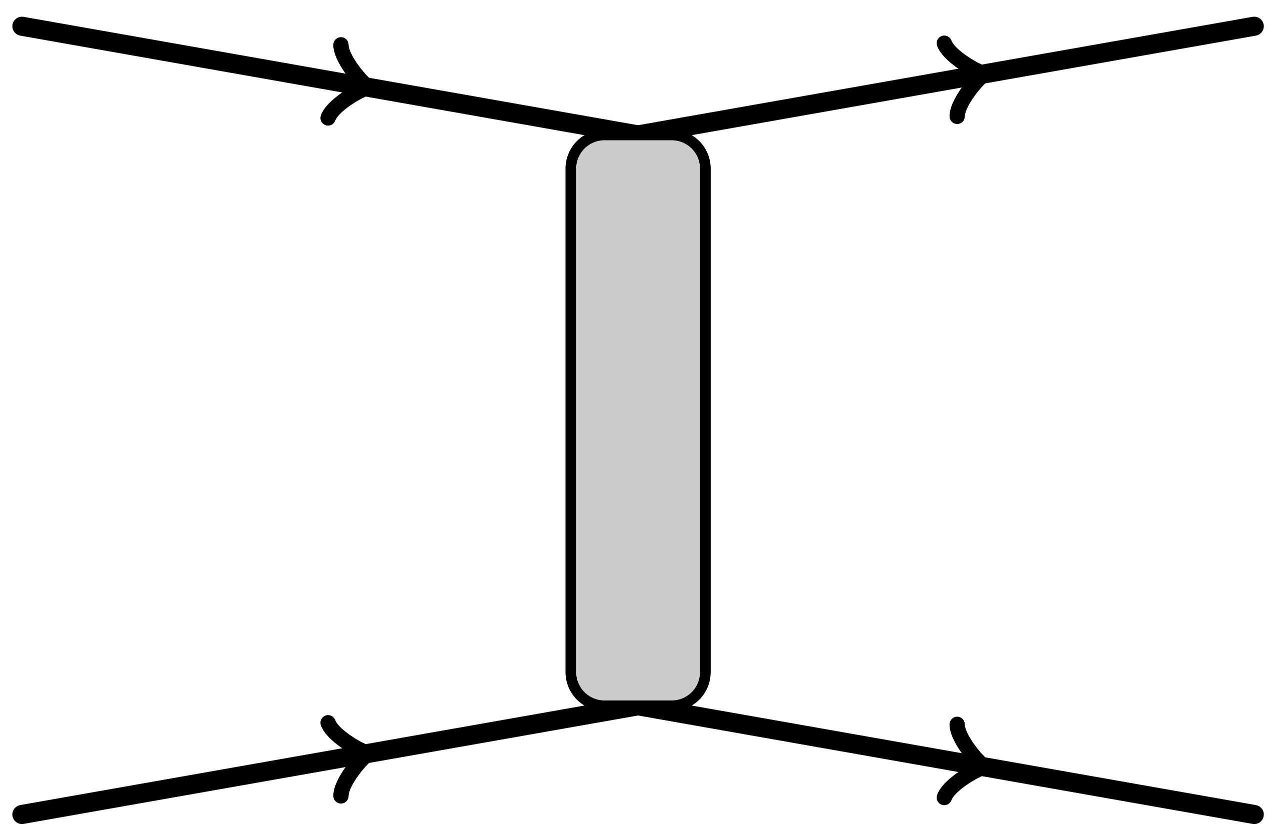
- Interactions are mediated by a ***continuum*** of states



Continuum Mediated SIDM

Conformal description

Currents of elementary dark matter exchange a scalar operator of dimension $\Delta \geq 1$

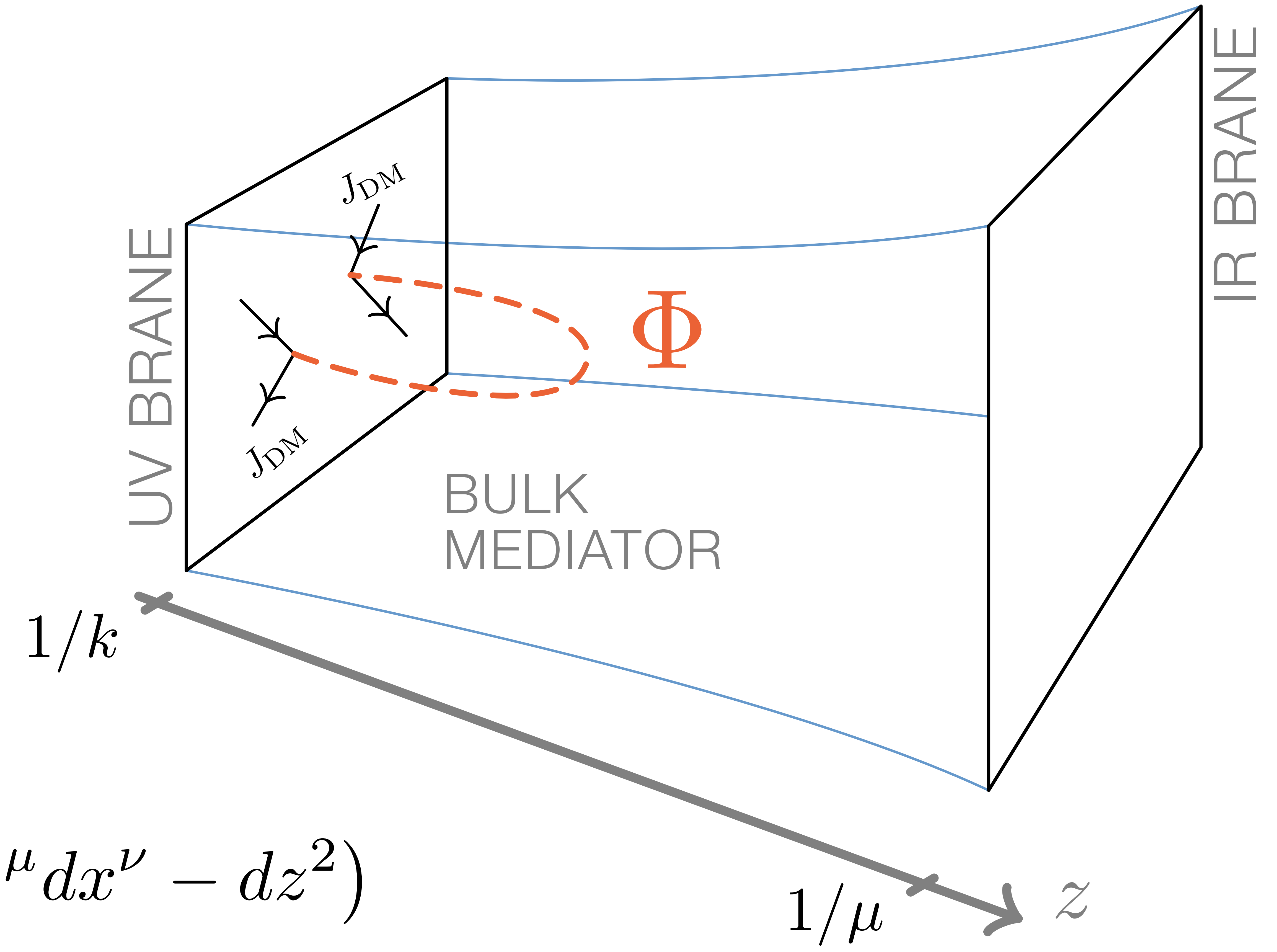


$$= J_{\rm DM}(q) \frac{1}{\left(\sqrt{-q^2}\right)^{4-2\Delta}} J_{\rm DM}(-q)$$

5D Description

A slice of AdS_5

CFT Limit: $z_{\rm IR} = \frac{1}{\mu} \to \infty$



$\mu \ll k$

$k \sim 10 - 10^3$ TeV

$\mu \sim 0.1 - 100$ MeV

Interactions are mediated by a tower of KK modes

$m_{\rm KK} \sim \pi\mu$

AdS curvature

$$ds^2 = (kz)^{-2}\left(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\right)$$

Action

Brane-localized dark matter with a bulk mediator

UV BRANE

IR BRANE

BRANE LOCALIZED MASS/KINETIC TERMS

BULK SCALAR

SPIN-1/2 DARK MATTER

$$S = \int_{z_{\mathrm{UV}}}^{z_{\mathrm{IR}}} dz \int d^4x \left[\sqrt{g}\mathcal{L}_\Phi + \sqrt{\bar{g}}\left(\mathcal{L}_\chi + \mathcal{L}_{\mathrm{int}} + \mathcal{L}_\Phi^{\mathrm{UV}}\right)\delta(z - z_{\mathrm{UV}}) + \sqrt{\bar{g}}\mathcal{L}_\Phi^{\mathrm{IR}}\delta(z - z_{\mathrm{IR}})\right]$$

INDUCED METRIC ON THE BRANES

DARK MATTER-SCALAR INTERACTIONS

$$\sqrt{\bar{g}} = (kz)^{-4}$$

$$\mathcal{L}_\Phi = \frac{1}{2}\left[(\partial_M \Phi)(\partial^M \Phi) - M_\Phi^2 \Phi^2\right]$$

$$\mathcal{L}_\Phi^i = \frac{1}{2k}\Phi B_i\left[\partial^2\right]\Phi$$

$$B_i\left[\partial^2\right] = m_i^2 + c_i\partial^2 + \ldots$$

$$\mathcal{L}_\chi = \bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi$$

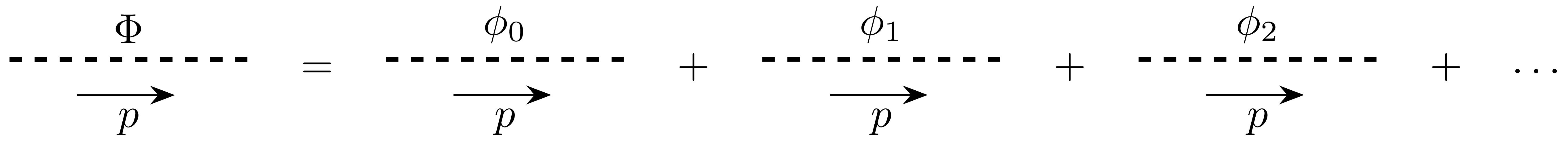
$$\mathcal{L}_{\mathrm{int}} = \frac{\lambda}{\sqrt{k}}\Phi\bar{\chi}\chi$$

Bulk Scalar Propagator

Three representations

The UV-UV bulk scalar propagator is crucial for determining the scattering potential

Kaluza-Klein:



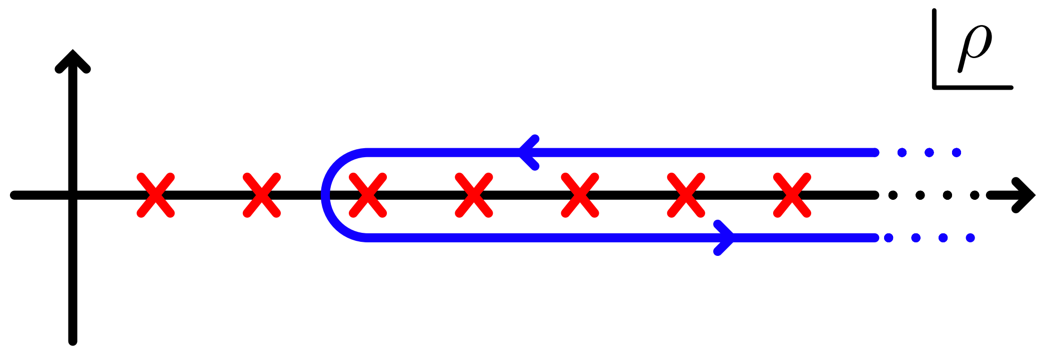
$$G_p(z,z') = i \sum_n \frac{f_n(z) f_n(z')}{p^2 - m_n^2 + i\epsilon}$$

Canonical:

$$\langle \Phi(p,z)\Phi(-p,z')\rangle$$

$$G_p(z,z') = i\frac{\pi k^3 (zz')^2}{2} \frac{\left[\tilde{Y}_\alpha^{\mathrm{UV}} J_\alpha(pz_<) - \tilde{J}_\alpha^{\mathrm{UV}} Y_\alpha(pz_<)\right]\left[\tilde{Y}_\alpha^{\mathrm{IR}} J_\alpha(pz_>) - \tilde{J}_\alpha^{\mathrm{IR}} Y_\alpha(pz_>)\right]}{\tilde{J}_\alpha^{\mathrm{UV}}\tilde{Y}_\alpha^{\mathrm{IR}} - \tilde{Y}_\alpha^{\mathrm{UV}}\tilde{J}_\alpha^{\mathrm{IR}}}$$

Spectral:



$$G_p(z,z') = \frac{1}{2\pi i}\int_0^\infty d\rho\, \frac{\mathrm{Disc}_\rho\left[G_{\sqrt{\rho}}(z,z')\right]}{\rho - p^2}$$

Canonical Representation

Asymptotics and spectrum $|p| \gg \mu$

$$\alpha = \sqrt{4 + M_\Phi^2/k^2} = 2 - \Delta$$

$$\Delta \geq 1 \implies \alpha \leq 1$$

$0 < \alpha < 1$

$$G_p(z_{\rm UV}, z_{\rm UV}) = \frac{i}{2k} \frac{\Gamma(\alpha)}{\Gamma(-\alpha+1)} \left(\frac{4k^2}{p^2}\right)^\alpha S_\alpha^{-1}(p)$$

$$S_\alpha(p) = \frac{\sin\left(\frac{p}{\mu} - \frac{\pi}{4}(1-2\alpha)\right)}{\sin\left(\frac{p}{\mu} - \frac{\pi}{4}(1+2\alpha)\right)} \approx (-1)^\alpha$$

$$m_n \approx \left(n - \frac{\alpha}{2} + \frac{1}{4}\right)\pi\mu$$

$\mathrm{Im}(p/\mu) \gtrsim 1$

$\alpha = 1$

$$G_p(z_{\rm UV}, z_{\rm UV}) = \frac{(2+b_{\rm IR})2ik}{p^2\left[(2+b_{\rm IR})(2c_{\rm UV}k + \log(k^2/\mu^2)) - b_{\rm IR}\right] - 4b_{\rm IR}\mu^2}$$

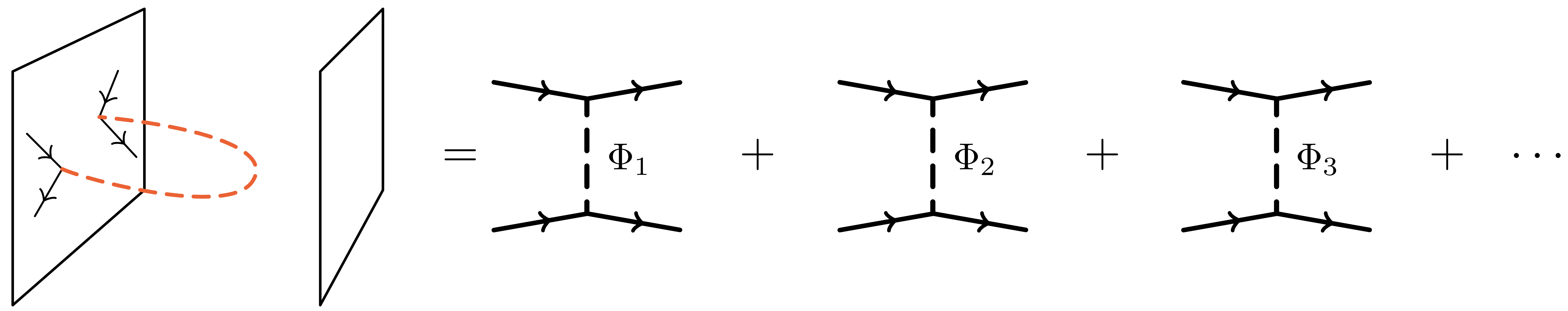
Light mode in the spectrum!

$$m_0^2 = \frac{4b_{\rm IR}\mu^2}{(2+b_{\rm IR})\left[2c_{\rm UV}k + \log(k^2/\mu^2)\right] - b_{\rm IR}}$$

Brane-localized mass and kinetic terms: $b_i = \frac{m_i^2}{k^2} + (2-\alpha)$ $\quad b_{\rm UV} = 0$

Continuum-Mediated Potential

Kaluza-Klein representation



Sum of Yukawa potentials!

$$G_p(z, z') = i \sum_n \frac{f_n(z) f_n(z')}{p^2 - m_n^2 + i\epsilon} \quad \Longrightarrow \quad V(r) = -\frac{1}{4\pi} \frac{\lambda^2}{k} \sum_n f_n(z_{\rm UV})^2 \frac{e^{-m_n r}}{r}$$

Continuum-Mediated Potential

Spectral representation

$$G_p(z,z') = \frac{1}{2\pi i}\int_0^\infty d\rho \, \frac{\mathrm{Disc}_\rho\left[G_{\sqrt{\rho}}(z,z')\right]}{\rho - p^2}$$

$$i\mathcal{M} \equiv -4im_\chi^2 \tilde{V}\left(|\mathbf{q}|\right) = -4\frac{\lambda^2}{k} G_{|\mathbf{q}|}\left(z_{\mathrm{UV}}, z_{\mathrm{UV}}\right)$$

Zwicky: 1610.06090

We consider only the t-channel diagrams, *i.e.* the dark matter is ***distinguishable***

$$V(r) = -\frac{1}{8\pi^2}\frac{\lambda^2}{k}\int_0^\infty d\rho \, \mathrm{Disc}_\rho\left[G_{\sqrt{\rho}}(z_{\mathrm{UV}}, z_{\mathrm{UV}})\right] \, \frac{e^{-\sqrt{\rho}r}}{r}$$

Poles of the propagator merge into a branch cut discontinuity

The discontinuity is calculated with the canonical representation of the propagator

Continuum-Mediated Potential

$$0 < \alpha < 1$$

$$V(r) = -\frac{\lambda^2}{2\pi^{3/2}} \frac{\Gamma(3/2-\alpha)}{\Gamma(1-\alpha)} \frac{1}{r} \left(\frac{1}{kr}\right)^{2-2\alpha} Q(2-2\alpha, m_1 r)$$

Non-Integer Power
$1/2 < \alpha < 1$

Regularized Incomplete Gamma function from mass gap

$$\alpha = 1$$

$$V(r) \sim -\frac{\lambda^2}{4\pi r} e^{-m_0 r}$$

Mass of the light mode in the spectrum

Behaves similar to ordinary SIDM!

Phenomenological Regimes

Ordinary SIDM

$$V(r) \sim \alpha_\chi \frac{e^{-m_\phi r}}{r}$$

Deformation of the wave function by the Hamiltonian	Born: $\frac{\alpha_\chi m_\chi}{m_\phi} \ll 1$	non-perturbative: $\frac{\alpha_\chi m_\chi}{m_\phi} \gg 1$	Ladder diagrams
Zeroth order WKB approximation	resonant: $\frac{m_\chi v}{m_\phi} \ll 1$	classical: $\frac{m_\chi v}{m_\phi} \gg 1$	

Phenomenological Regimes

Continuum mediator

Effective coupling

$$\alpha_\chi^{\text{eff}} = \frac{\lambda^2 m_1}{4\pi k} \sum_n \frac{f_n^2(z_{\text{UV}})}{m_n} \approx \frac{\lambda^2}{4\pi} \left[\frac{4}{2\alpha - 1} \frac{1}{\Gamma(1-\alpha)^2} \right] \left(\frac{m_1}{2k} \right)^{2-2\alpha}$$

Deformation of the wave function by the Hamiltonian

Born: $\frac{\alpha_\chi^{\text{eff}} m_\chi}{m_1} \ll 1$

non-perturbative: $\frac{\alpha_\chi^{\text{eff}} m_\chi}{m_1} \gg 1$

Ladder diagrams

Zeroth order WKB approximation

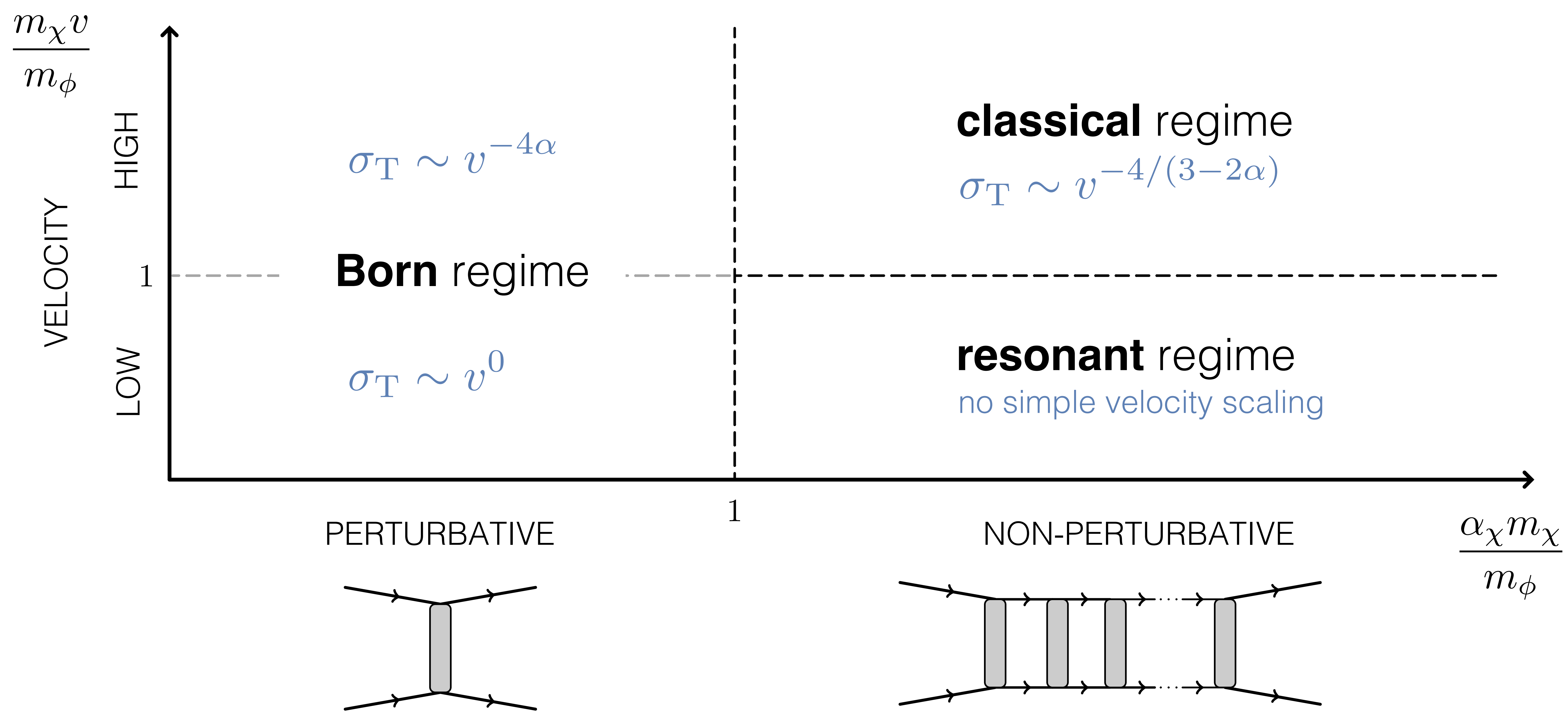
Classical: $\frac{m_\chi v}{m_1} \gg 1$

Resonant: $\frac{m_\chi v}{m_1} \ll 1$

Transfer Cross Section Regimes

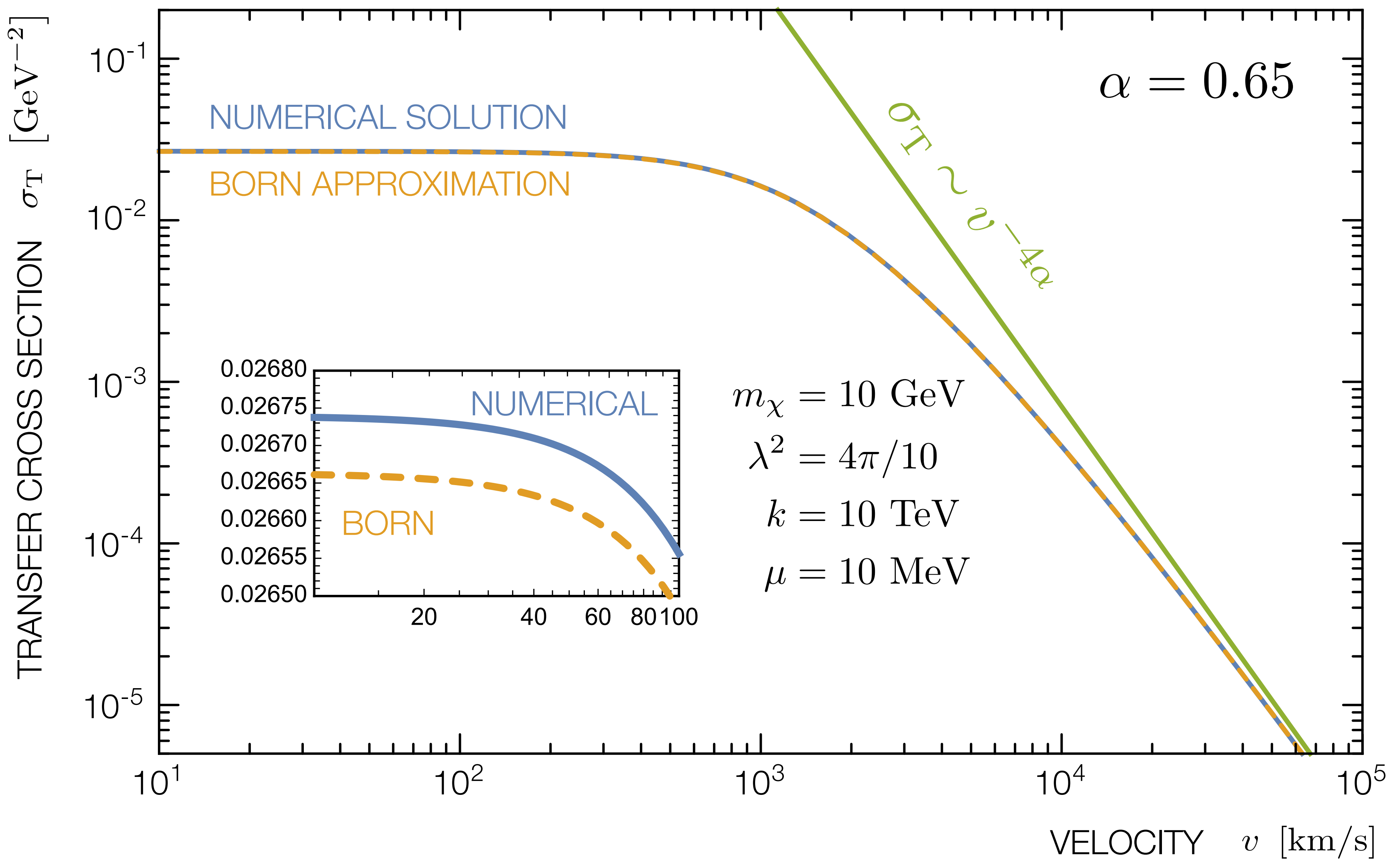
Summary of velocity scaling

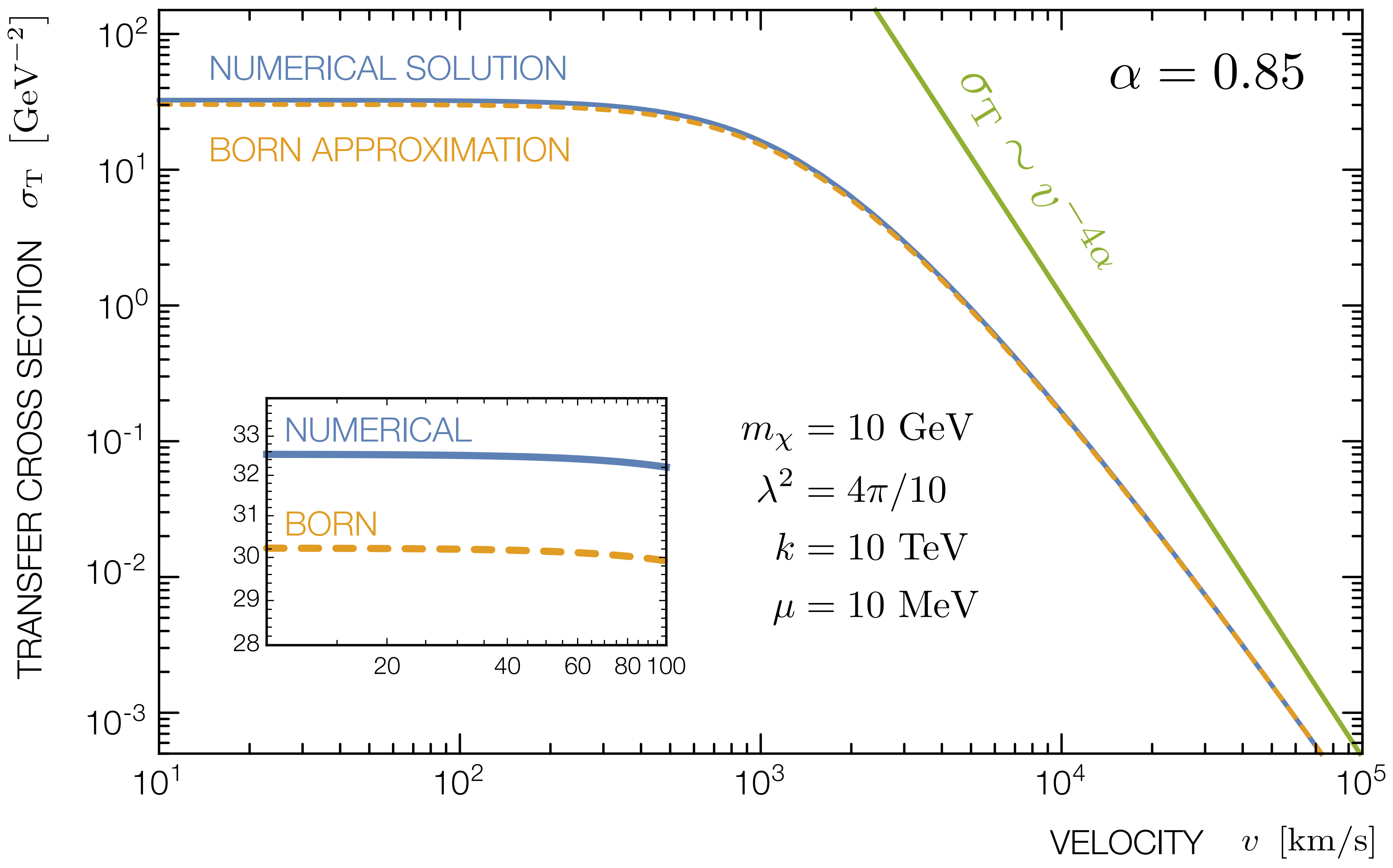
$$\sigma_{\mathrm{T}} = \int d\Omega \frac{d\sigma}{d\Omega} (1 - \cos\theta)$$



Transfer Cross Section

Continuum-mediated Born regime

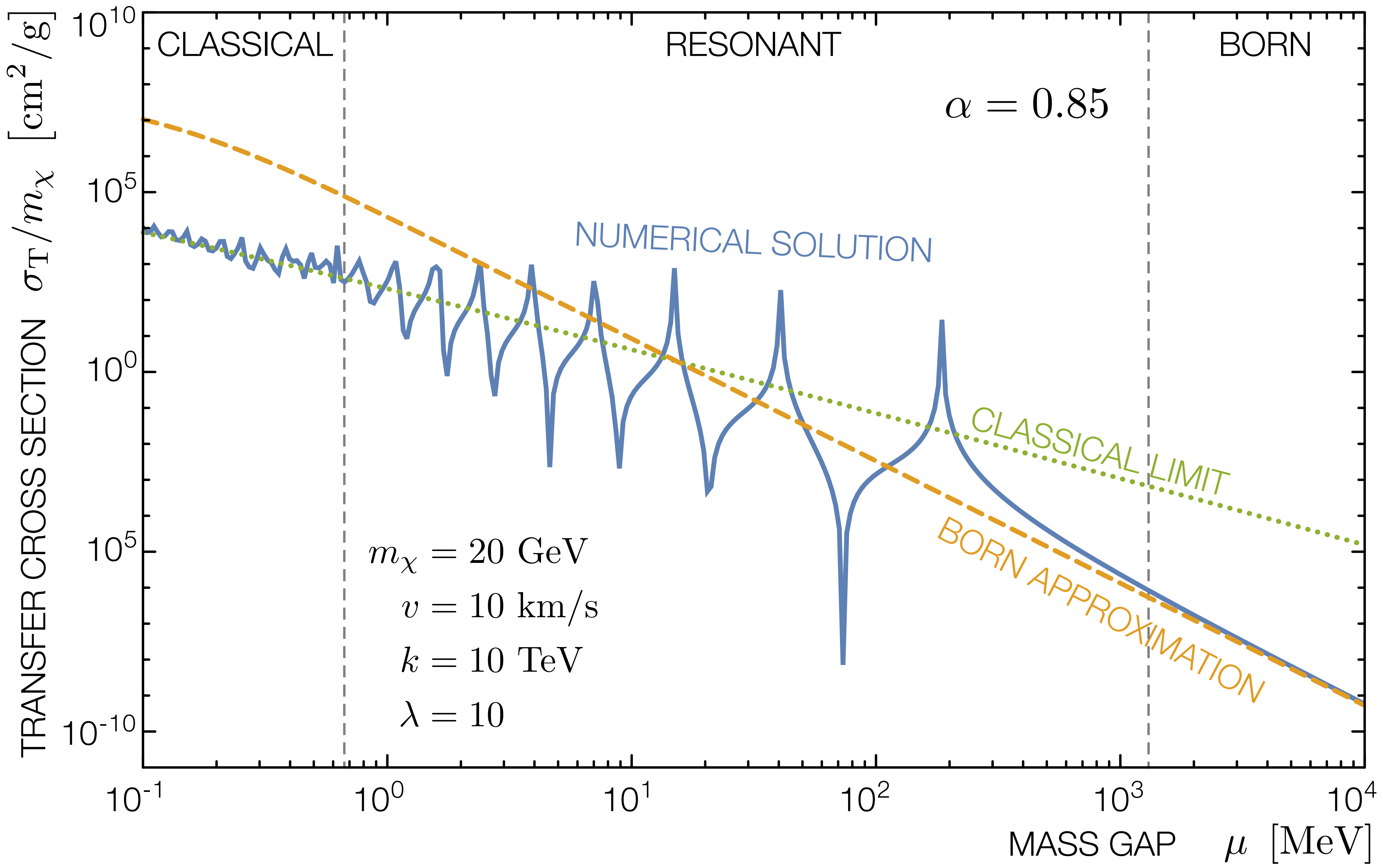


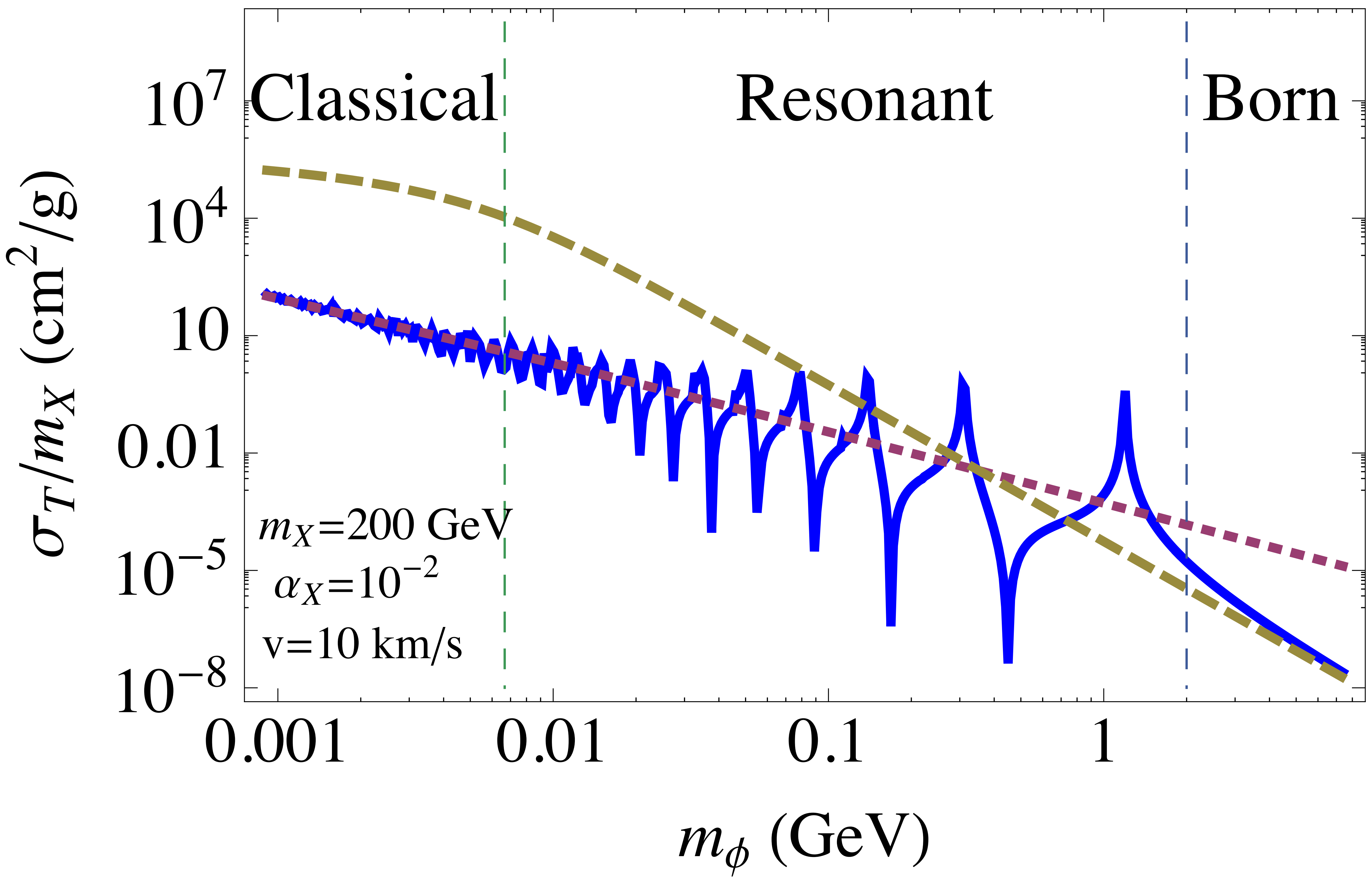


Numerical solution approaches the analytic result for high velocity

Realization of Transfer Cross Section Regimes

Comparison to SIDM

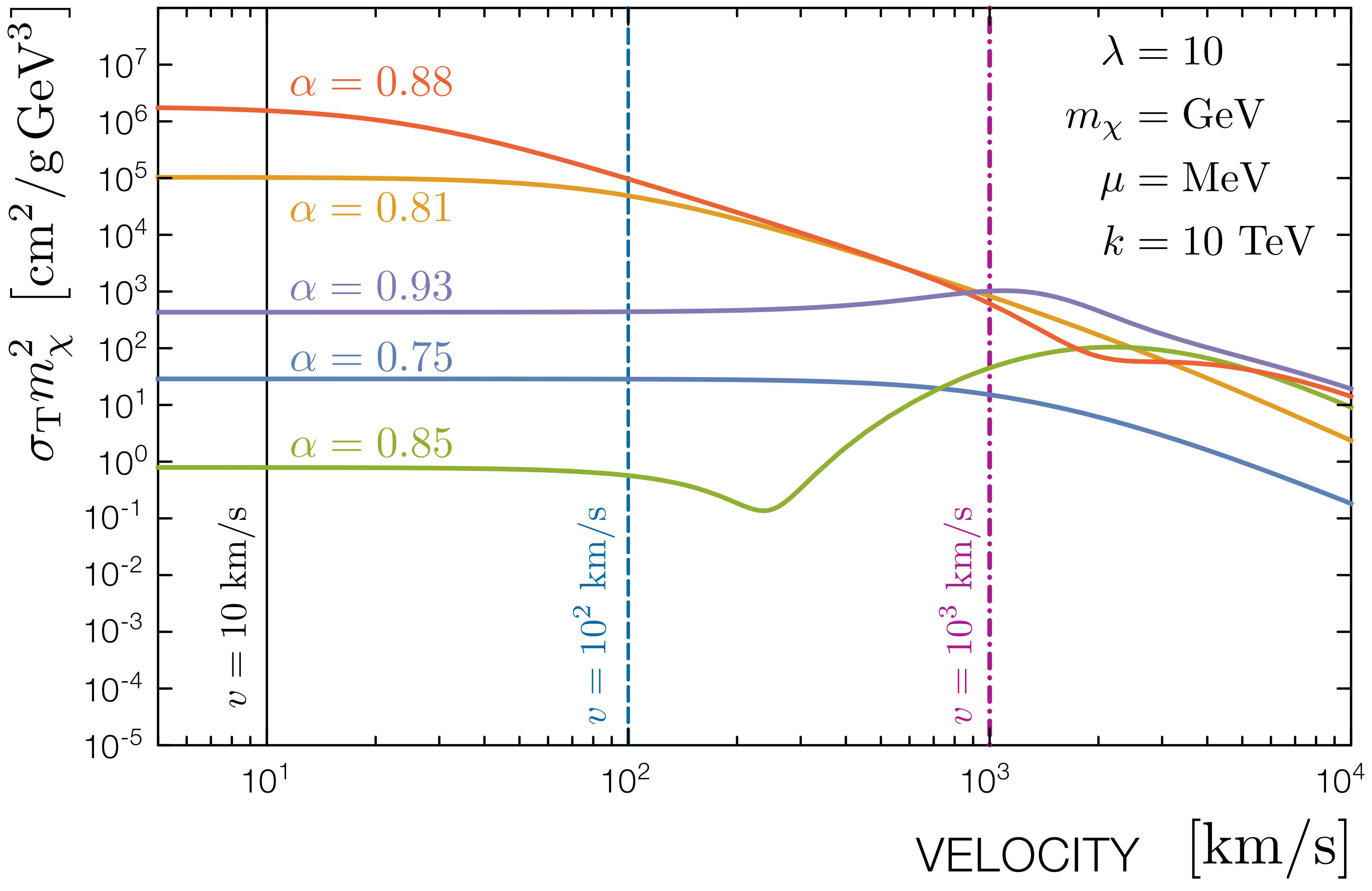


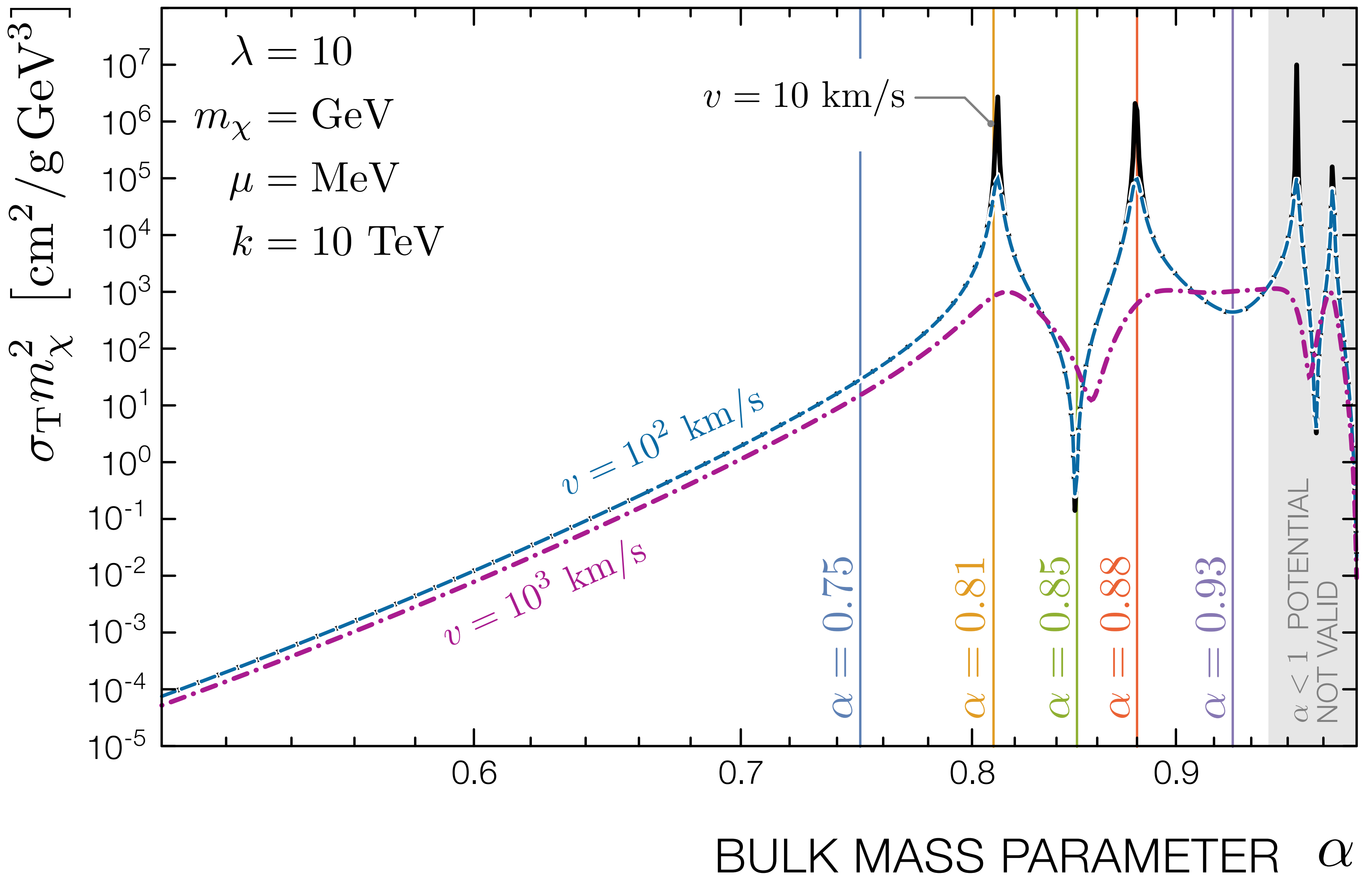


Tulin, Yu and Zurek (1302.3898)

Numerical Results

Resonances and the bulk mass parameter

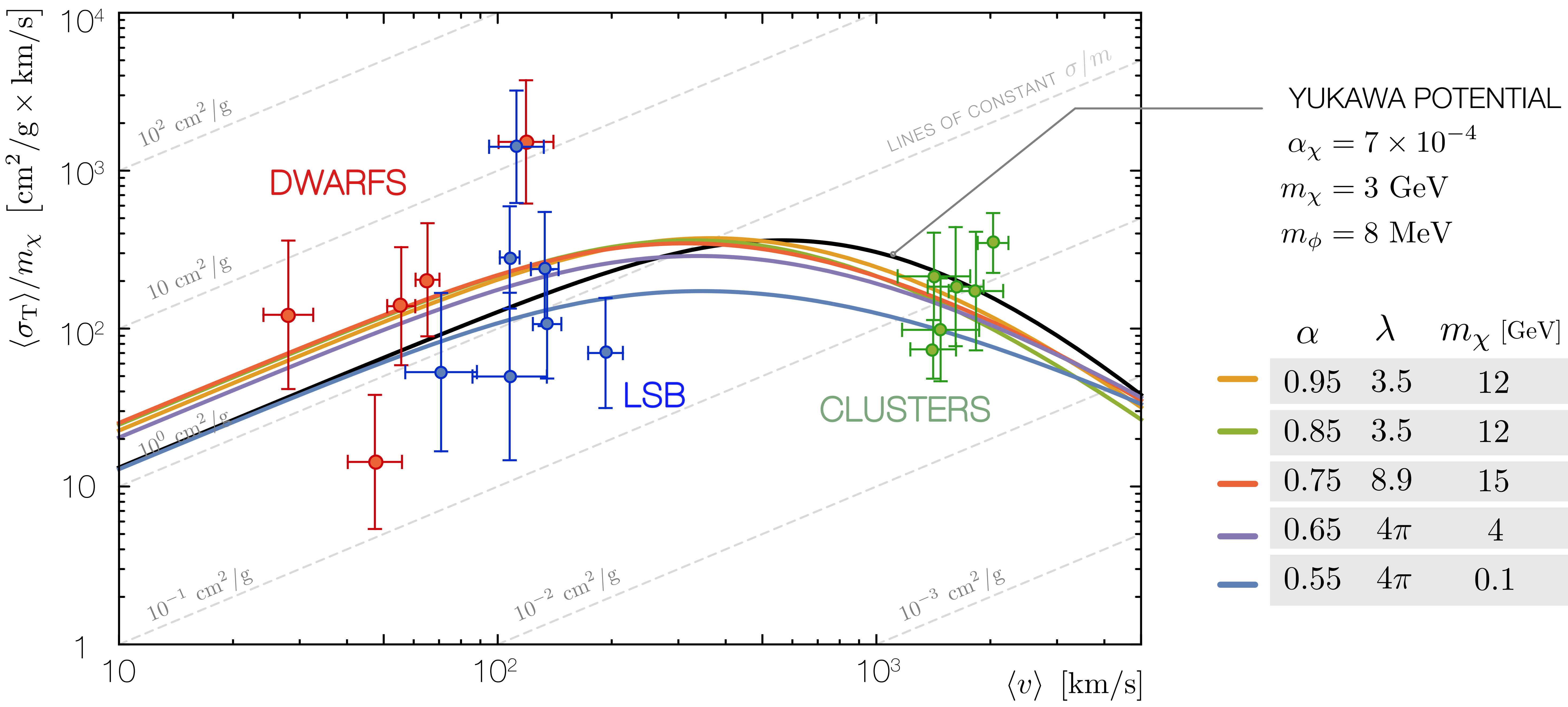




The transfer cross section is highly sensitive to the bulk mass parameter displaying resonances and anti-resonances

Numerical Results

Comparison to astrophysical data

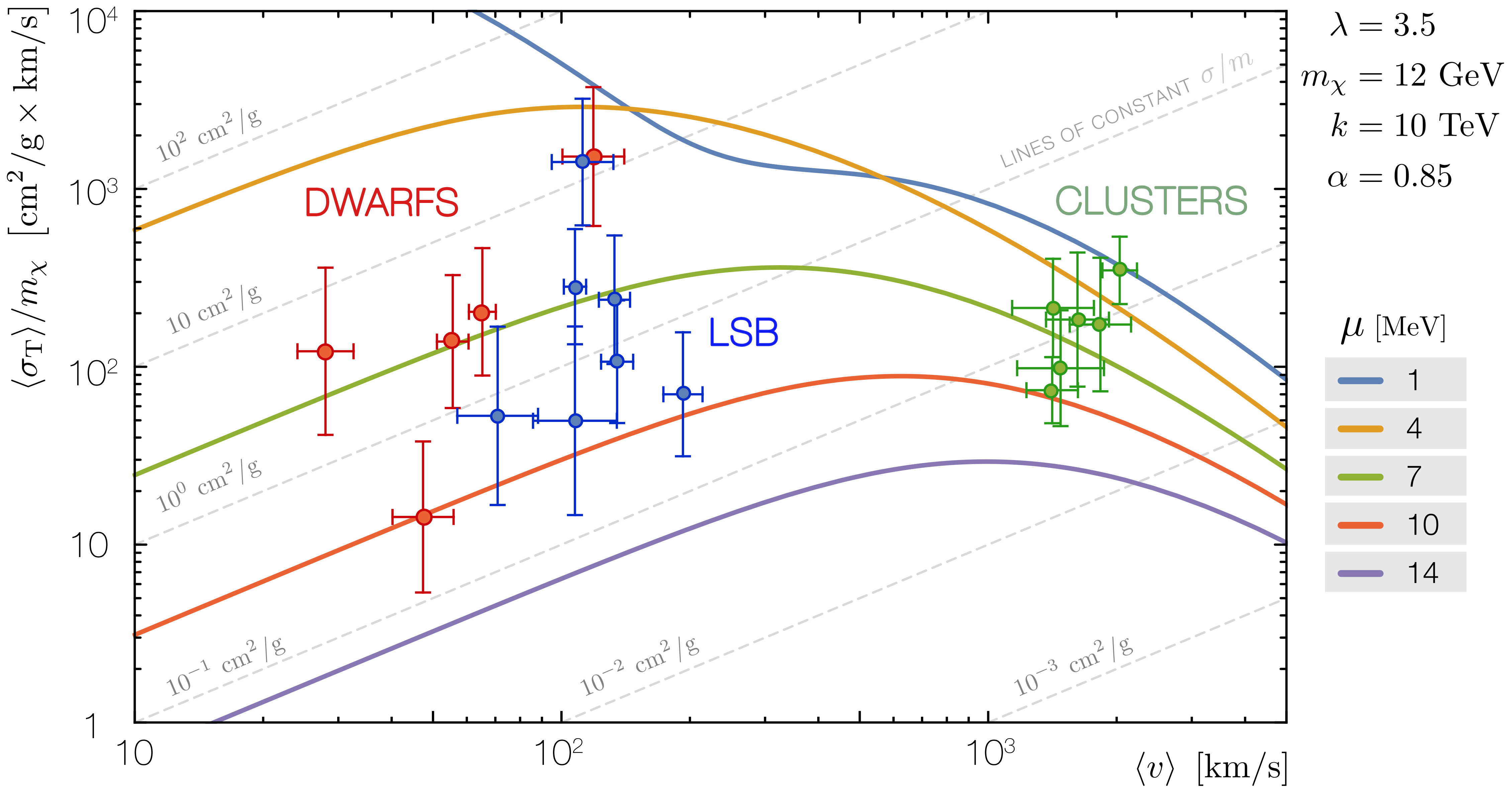


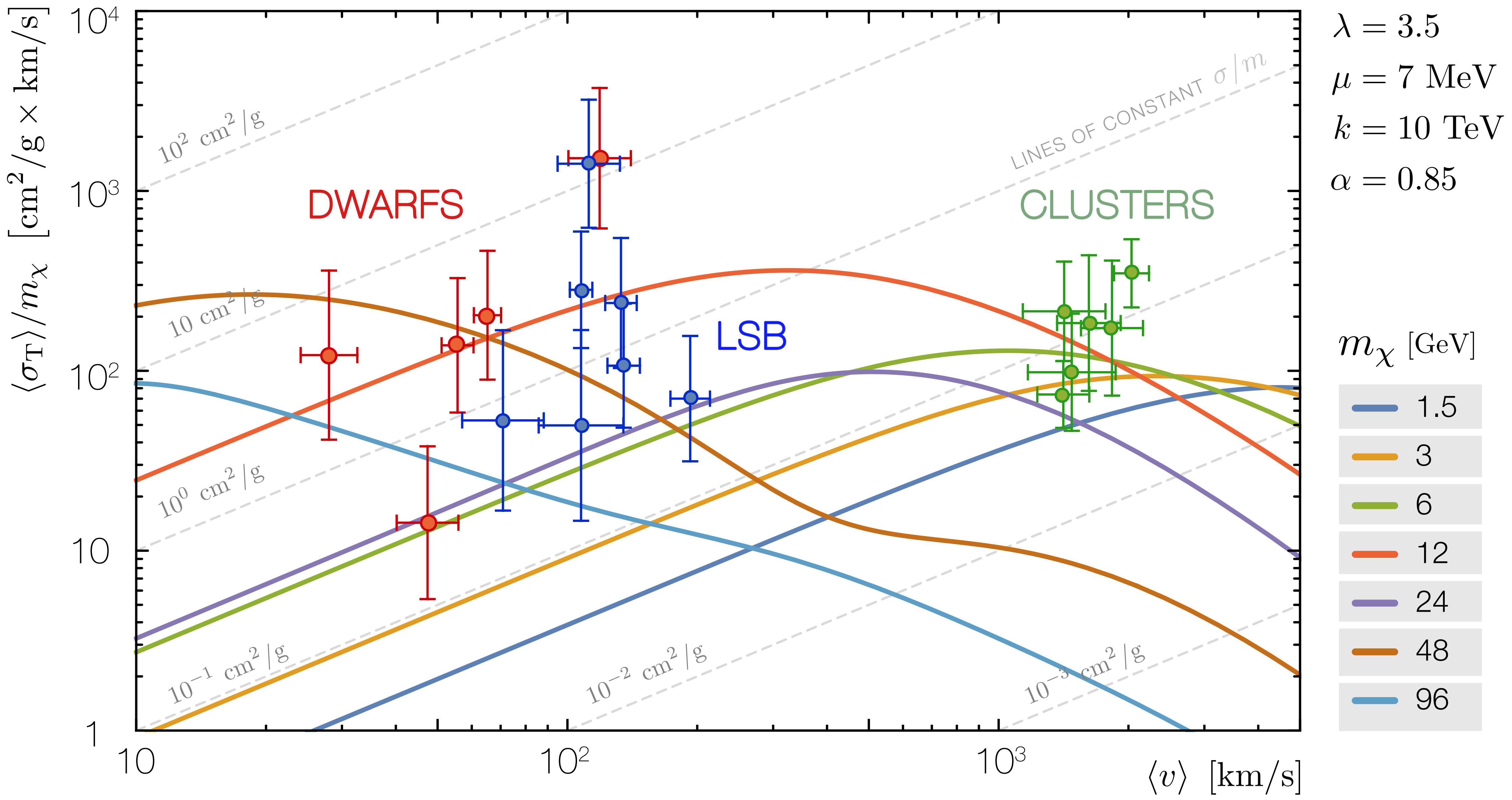
	α	λ	m_χ [GeV]	μ [MeV]
(orange)	0.95	3.5	12	10
(green)	0.85	3.5	12	7
(red)	0.75	8.9	15	15
(purple)	0.65	4π	4	1
(blue)	0.55	4π	0.1	0.02

The cross section can fit the data for a variety of benchmarks

Numerical Results

Rough parameter scan





The cross section varies drastically with the model parameters

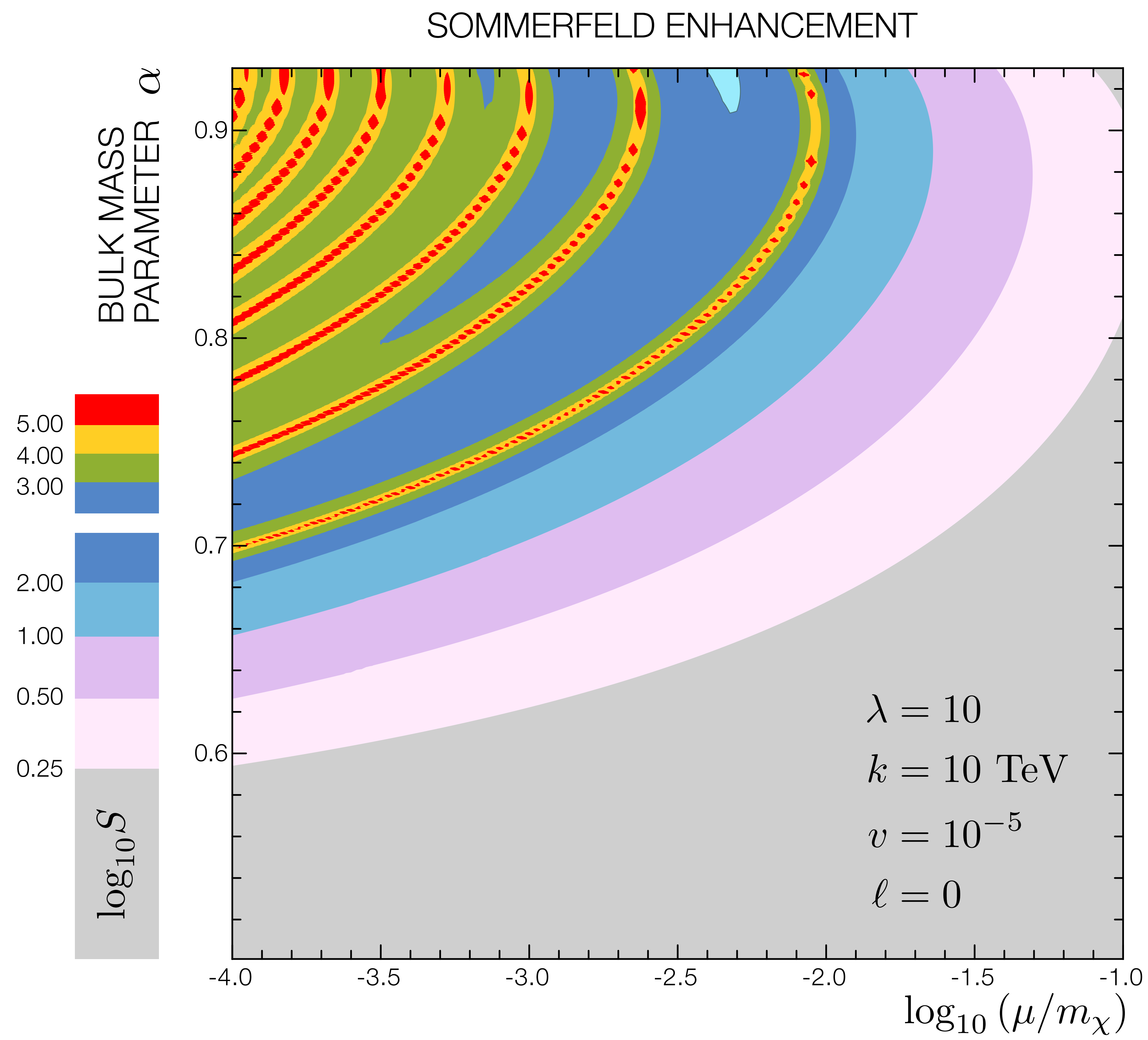
Continuum-Mediated Sommerfeld Enhancements

Numerical results

Nontrivial pattern of resonances for large coupling

The Sommerfeld enhancement quickly decreases as $\alpha \to 1/2$

The enhancement can be found exactly for the case $\alpha = 1/2$ but requires a short distance cutoff



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Conclusion

Summary

$0 < \alpha < 1$ — Non-integer potential

$\alpha = 1$ — Yukawa-like

Non-trivial velocity scaling for the different phenomenological regimes

$$\sigma_{\mathrm{T}} \sim \begin{cases} v^{0} & \text{Born (low velocity)} \\ v^{-4\alpha} & \text{Born (high velocity)} \\ v^{-4/(3-2\alpha)} & \text{Classical} \\ \text{no simple scaling} & \text{Resonant} \end{cases}$$

Astrophysical data can be fit by a variety of benchmarks

Both the transfer cross section and Sommerfeld enhancement display a nontrivial pattern of resonances dependent on the bulk mass parameter

Future directions

Warped dark photon: Phenomenology of a massive spin-1 bulk mediator