Nonperturbative Effects in Late Time Dark Matter Phenomenology

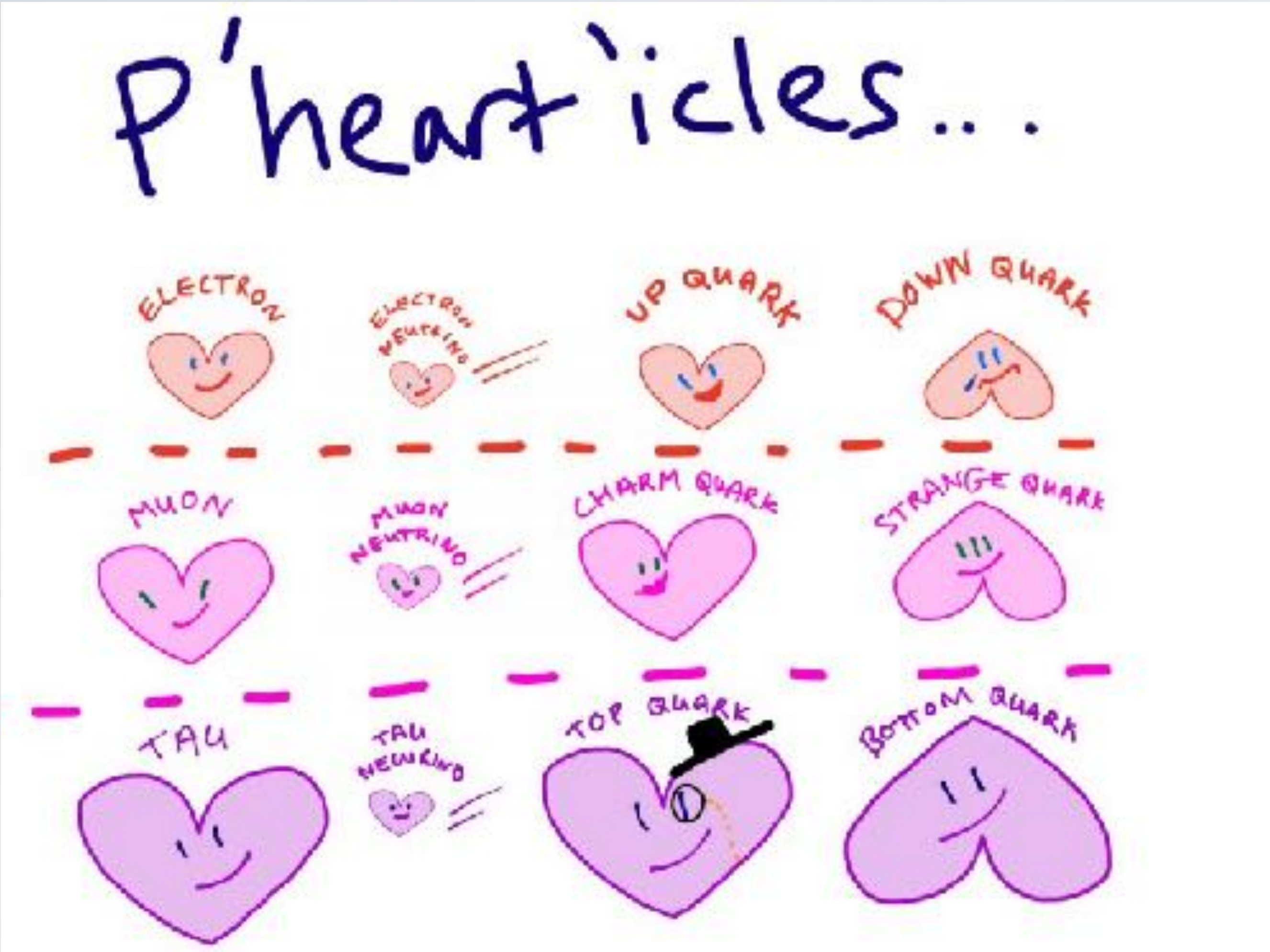
Anirban Das

DSU Workshop 2018, LAPTh, Annecy-le-vieux

Based on-

PRL 118, 251101, AD & Basudeb Dasgupta

PRD 97, 023002, AD & Basudeb Dasgupta



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It is natural to expect the dark sector to contain more particles other than the DM candidate

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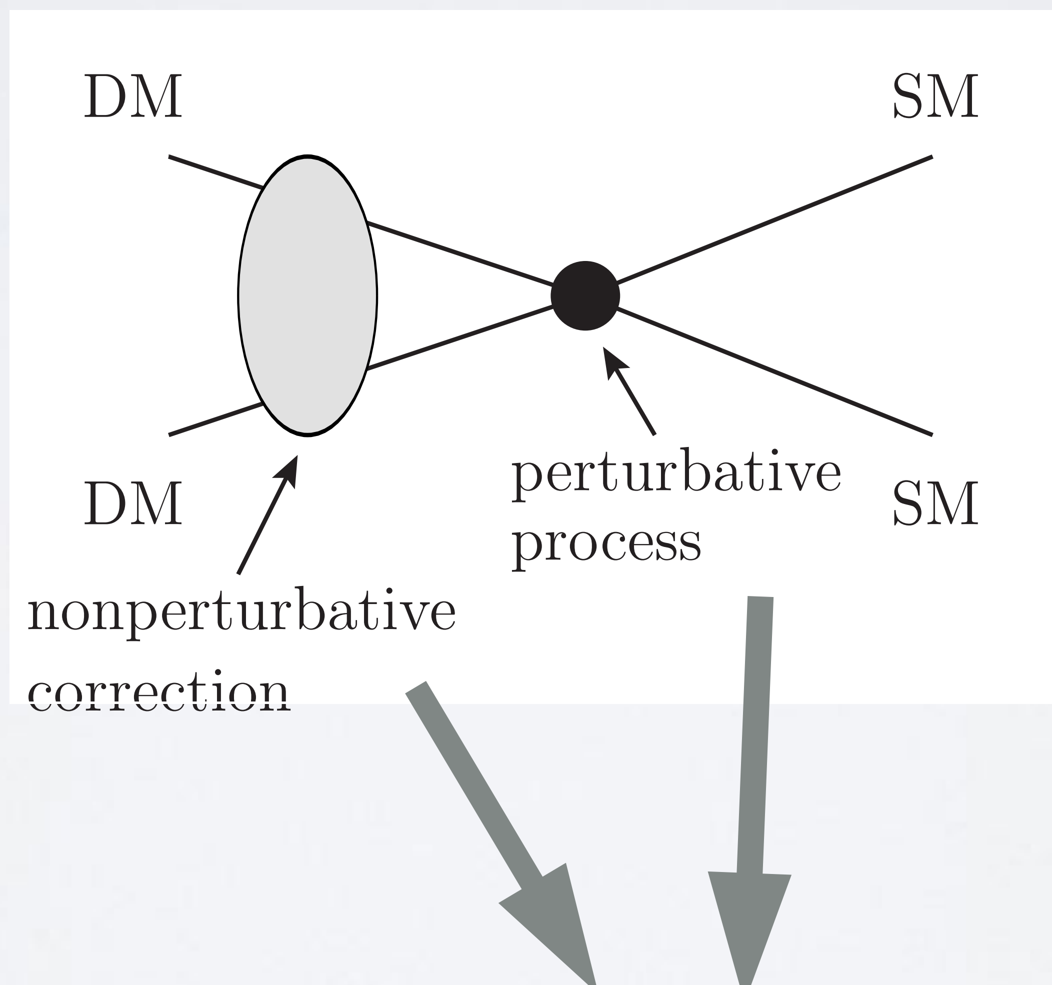
SIDM scenario

Light force carrying particles cause Sommerfeld effect

Sommerfeld Effect

A nonperturbative correction to the tree level annihilation cross-section. This can enhance/suppress the annihilation rate by several orders of magnitudes.



$$\sigma_\ell \equiv S_\ell \sigma_{0\ell} , \quad \ell = 0, 1, \ldots$$

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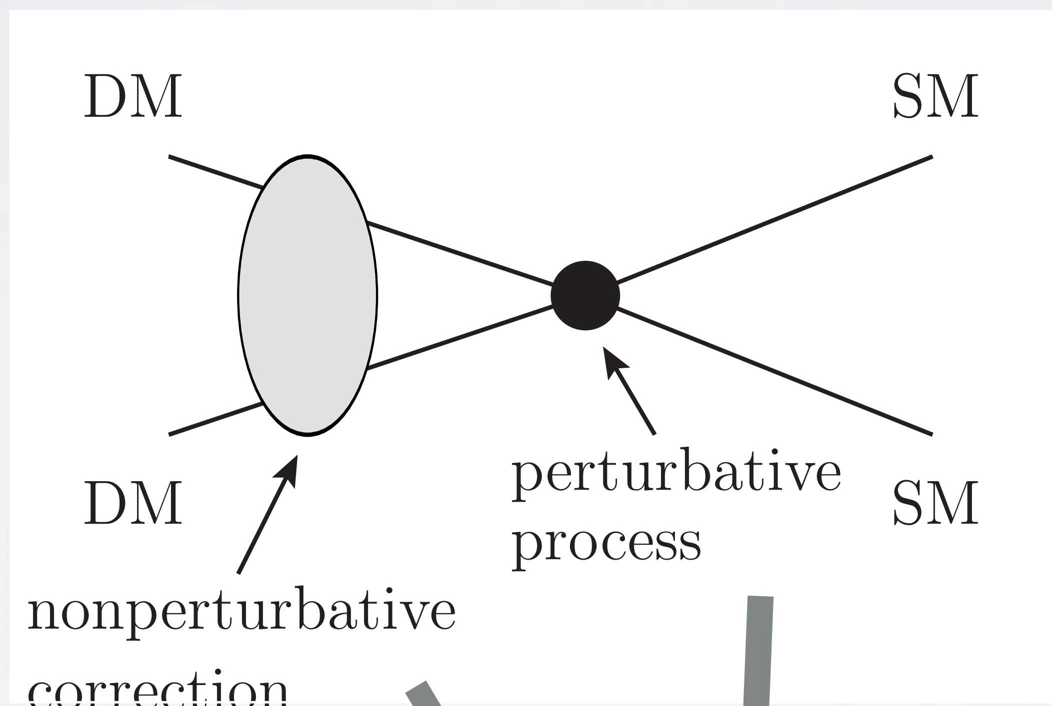

Selection Rule Here

$$\sigma_\ell \equiv S_\ell \sigma_{0\ell} \,, \quad \ell = 0, 1, \ldots$$

The dark sector

$$\mathcal{L} \supset \partial^\mu \phi^\dagger \partial_\mu \phi + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \mathcal{L}_{U(1)-\text{breaking}}$$

$$+ i\overline{\chi}\gamma_\mu \partial^\mu \chi - M\overline{\chi}\chi - \left(\frac{f}{\sqrt{2}} \phi \overline{\chi}\chi^c + h.c. \right) .$$

S. Weinberg 2013, C. Garcia-Cely et al. 2013, X. Chu et al. 2014

$$-\frac{f}{2}\rho(\bar{\chi}_1\chi_1 - \bar{\chi}_2\chi_2) - \frac{f}{2}\eta(\bar{\chi}_1\chi_2 + \bar{\chi}_2\chi_1)$$

V_ρ V_η

Two Majorana particles $m_\chi, m_\chi + \Delta$

Annihilation is *p*-wave suppressed, but coannihilation is not.

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V_ρ $\quad$ V_η

Two Majorana particles $m_\chi, m_\chi + \Delta$

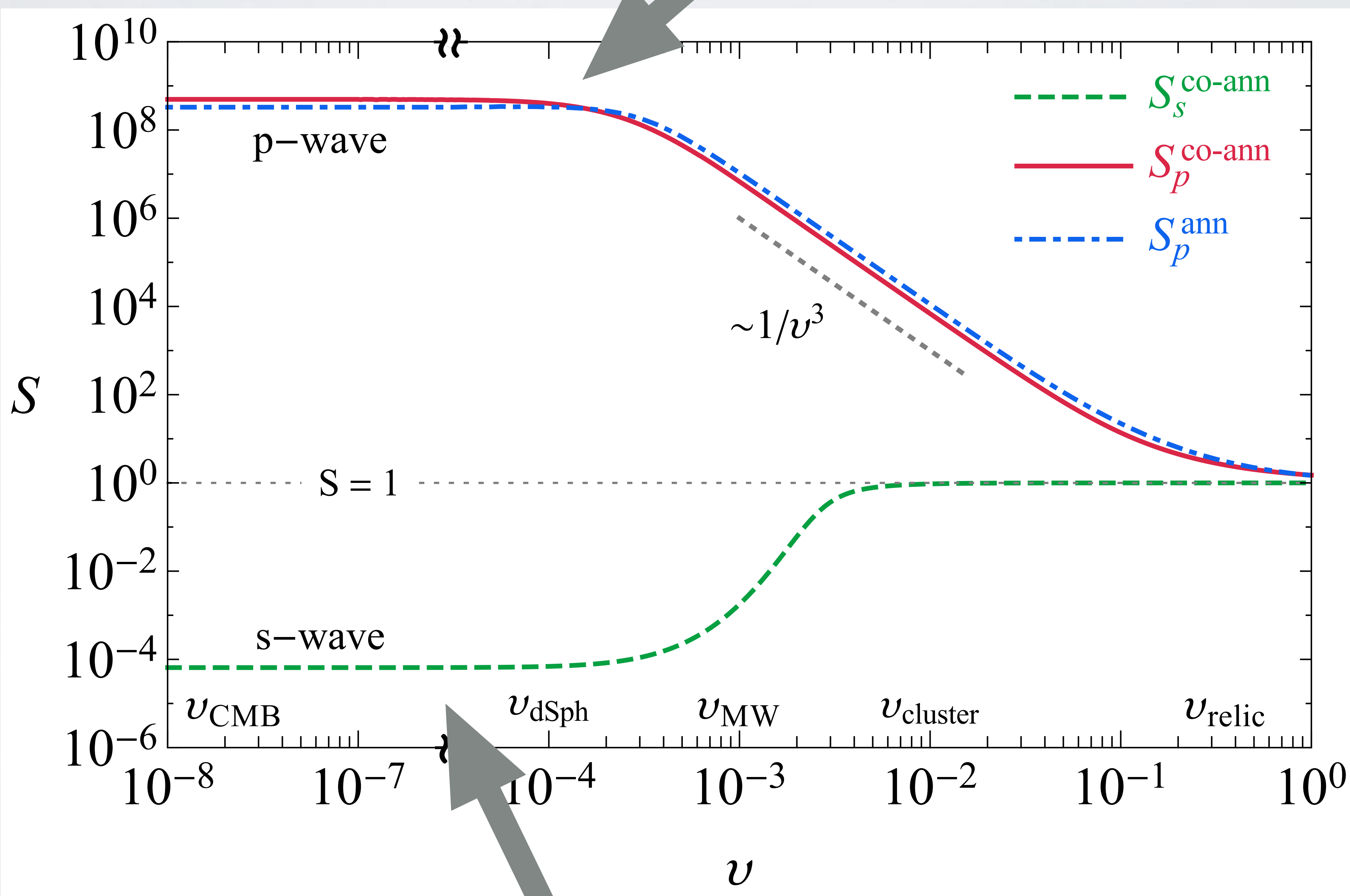
$\chi_1\chi_1, \chi_2\chi_2 \to \rho\rho, \eta\eta$ → S_p^{ann}

$\chi_1\chi_2 \to \rho\eta$ → $S_s^{\mathrm{co-ann}}, S_p^{\mathrm{co-ann}}$

Velocity dependence of the Sommerfeld Factors

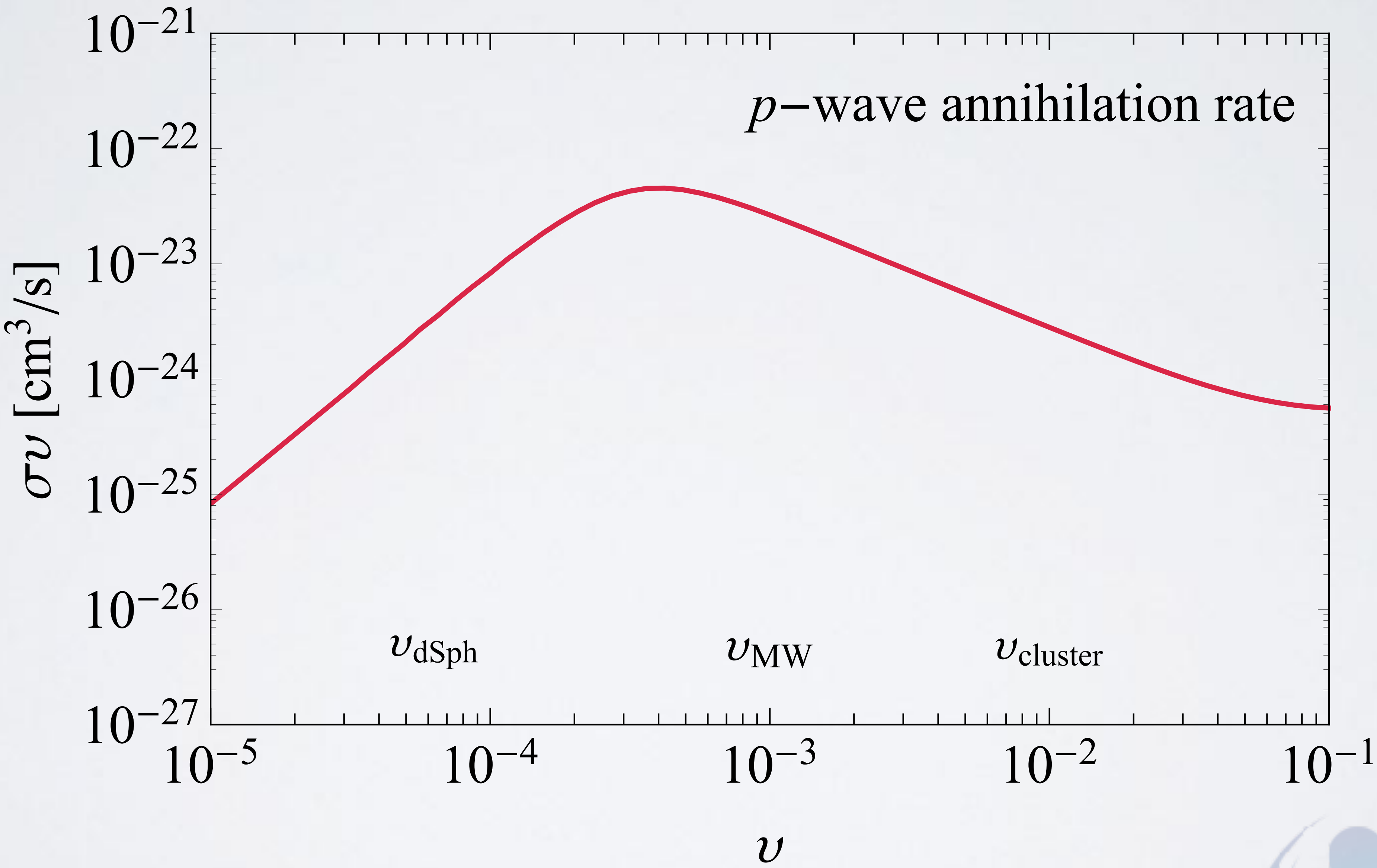
$$\sigma_\ell \equiv S_\ell \sigma_{0\ell}\,, \quad \ell = 0, 1, \ldots$$

$$S_p \gg 1$$



$$S_s \ll 1$$

DM annihilation today is given by p-wave process !



Explanation

- The coannihilation states are symmetric under exchange symmetry $|\chi_1\chi_2\rangle \leftrightarrow |\chi_2\chi_1\rangle$

$$|\chi_1\chi_2\rangle = (-1)^{\ell+s}|\chi_2\chi_1\rangle$$

- The exchange symmetry $|\chi_1\chi_1\rangle \leftrightarrow |\chi_2\chi_2\rangle$ is approximate

$$|\chi_2\chi_2\rangle \simeq (-1)^{\ell+s}|\chi_1\chi_1\rangle + \mathcal{O}(\Delta/m_\chi)$$

- The equations can be combined into a single equation with an effective potential

$$V_{\rm eff} = V_\rho + (-1)^{\ell+s}V_\eta$$

$\ell = 0, s = 1$

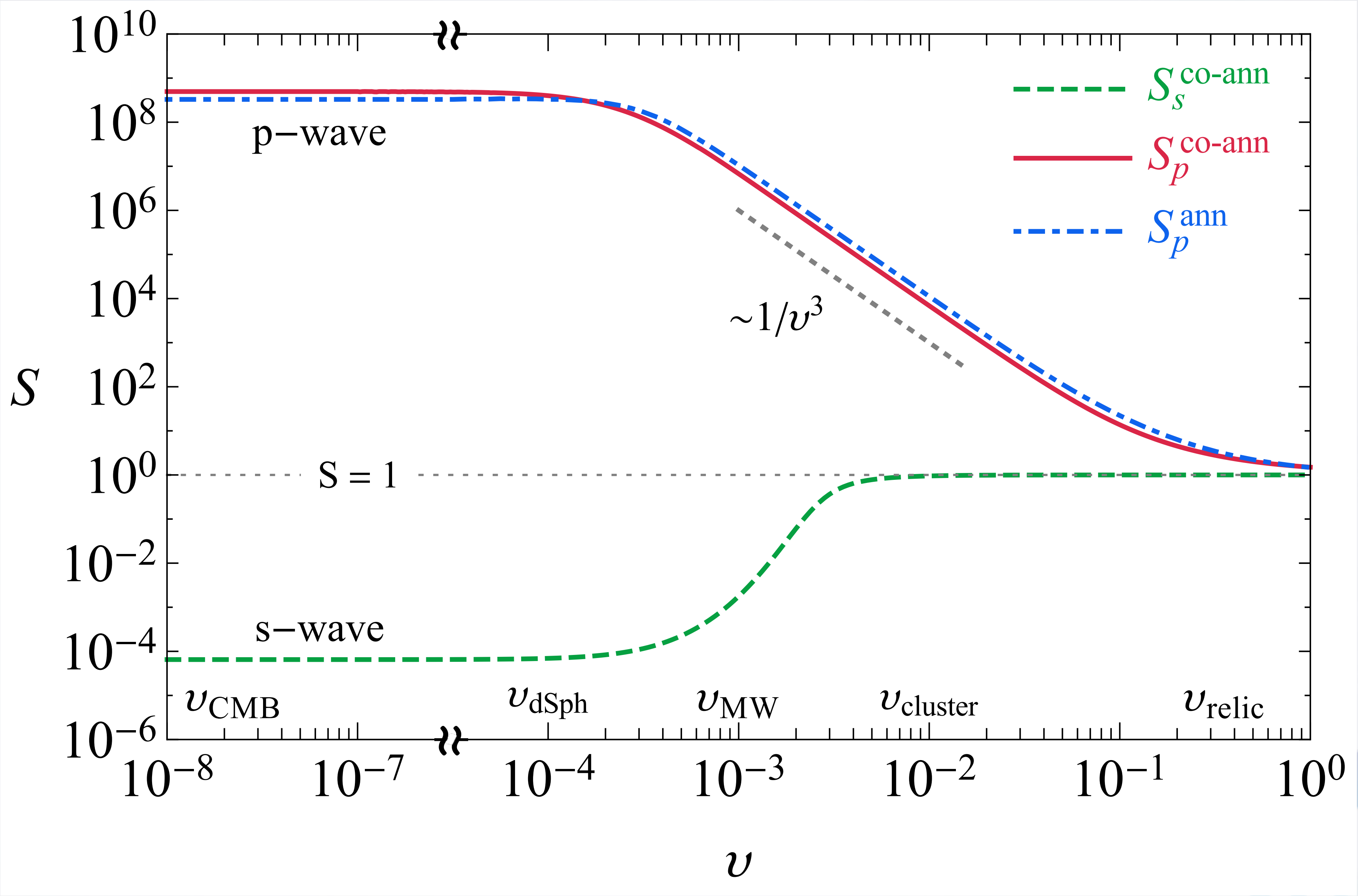
$$V_{\rm eff} = V_\rho - V_\eta$$

$\ell = 1, s = 1$

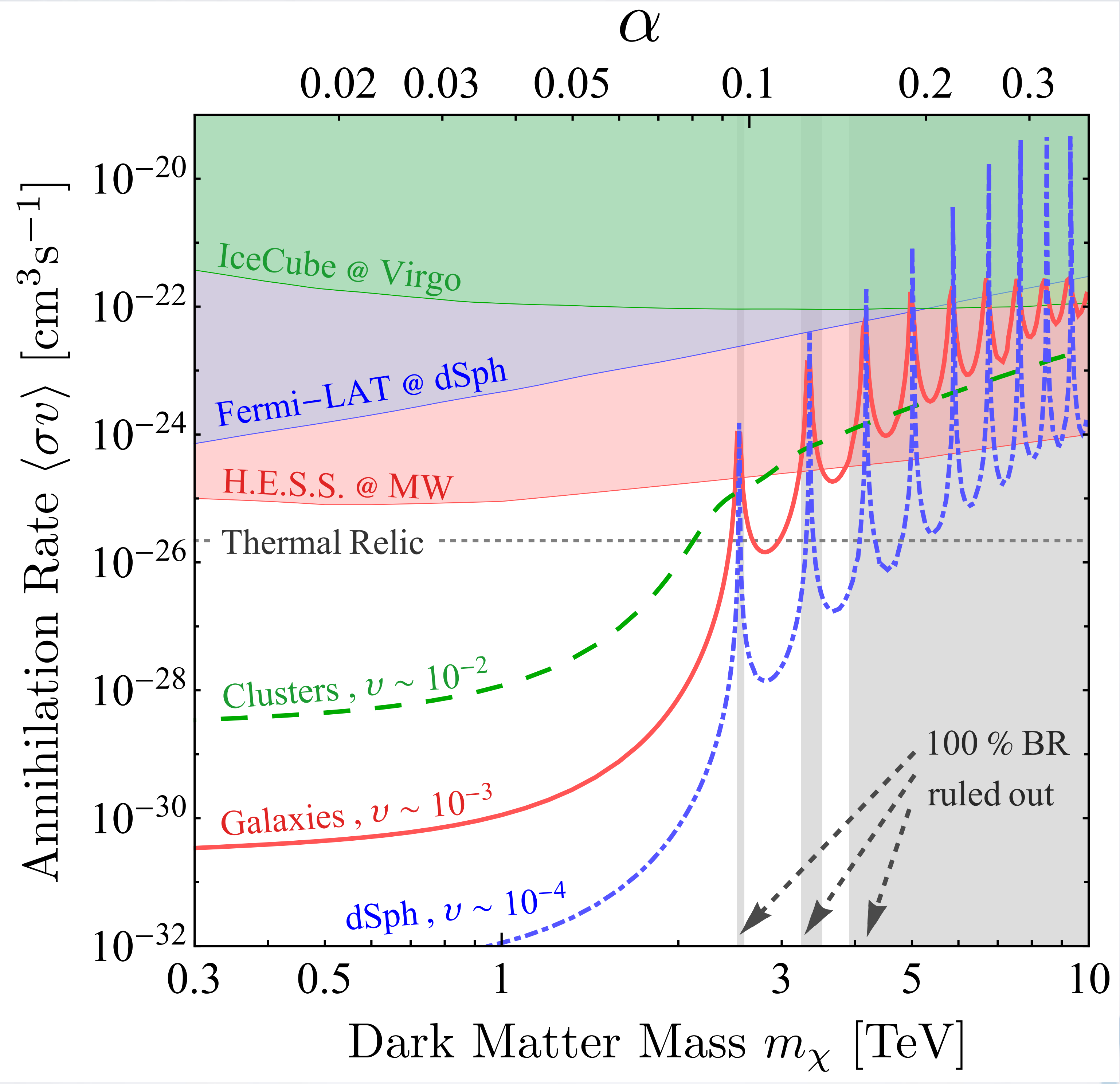
$$V_{\rm eff} = V_\rho + V_\eta$$

Explanation

$$V_{\rm eff}^{\ell=0} = -\frac{\alpha e^{-m_\rho r}}{r} + \frac{\alpha e^{-m_\eta r}}{r}, \quad V_{\rm eff}^{\ell=1} = -\frac{\alpha e^{-m_\rho r}}{r} - \frac{\alpha e^{-m_\eta r}}{r}$$

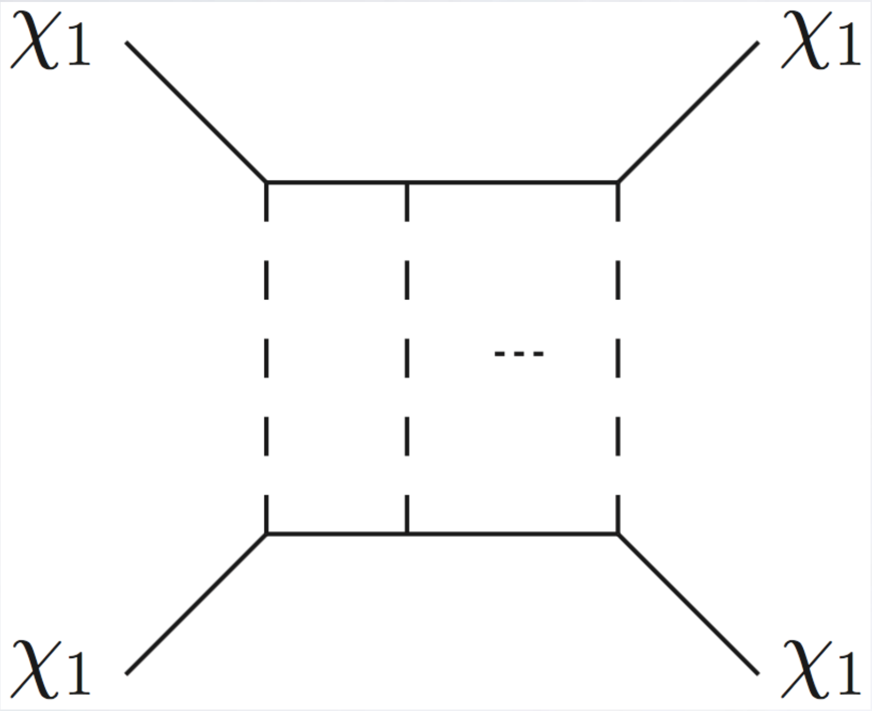


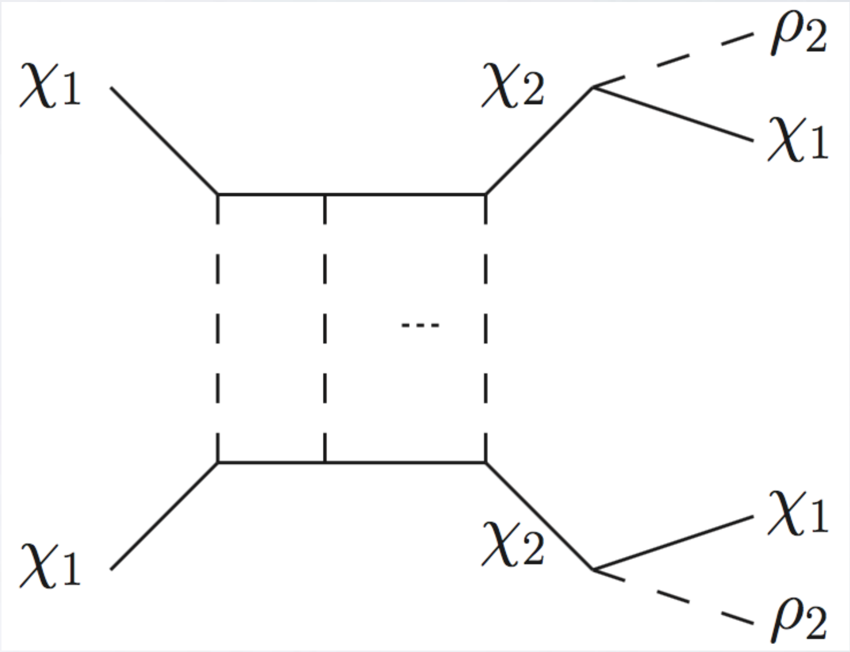
This also explains the large annihilation rate in the MW



Self-scattering of multilevel dark matter

$$\mathcal{L}_{\rm int} = f\rho_1(\overline{\chi}_1\chi_1 - \overline{\chi}_2\chi_2) + f\rho_2(\overline{\chi}_1\chi_2 + \overline{\chi}_2\chi_1)$$



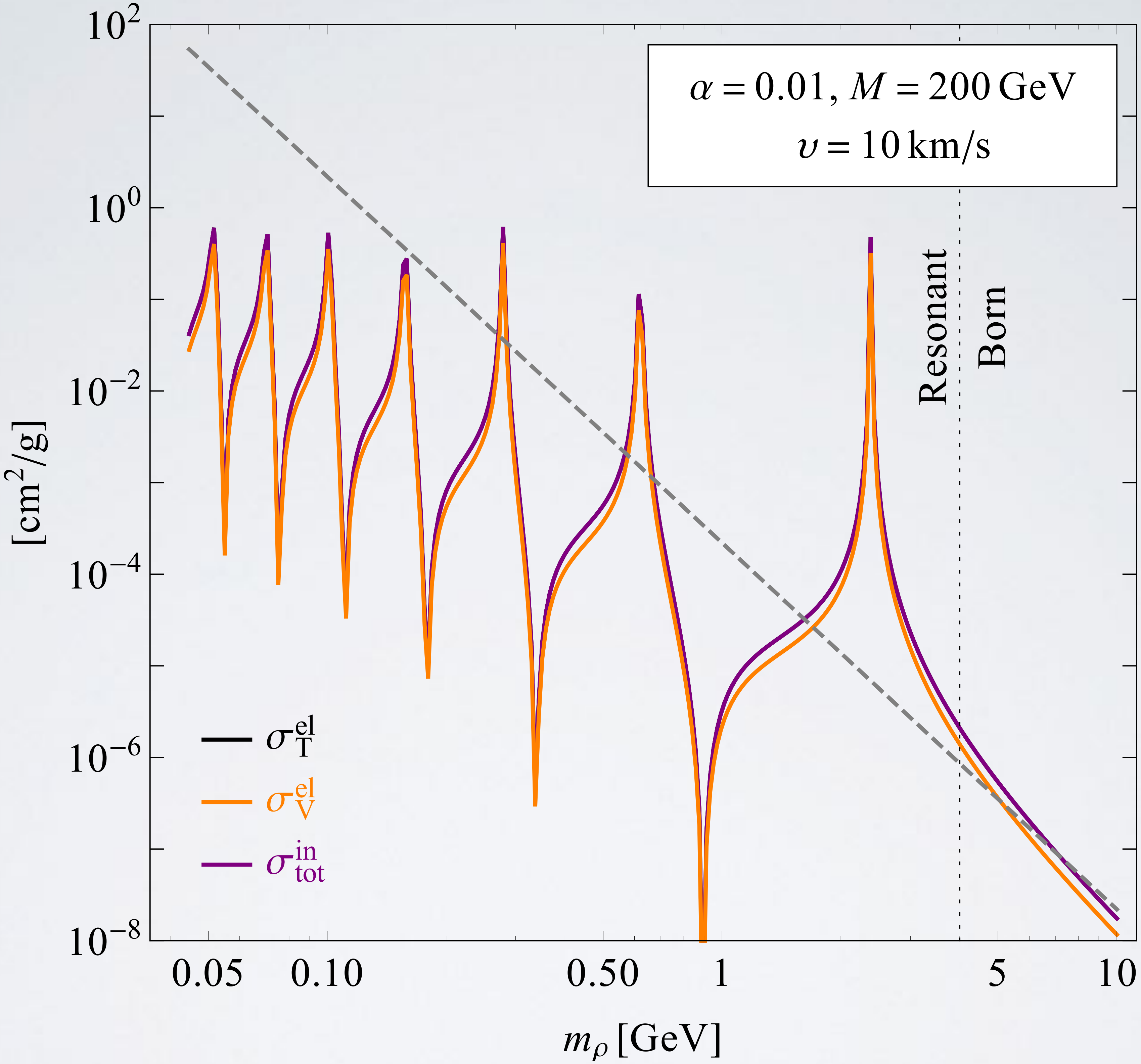


$$|\chi_1\chi_1\rangle \rightarrow |\chi_1\chi_1\rangle$$

Elastic scattering

$$|\chi_1\chi_1\rangle \rightarrow |\chi_2\chi_2\rangle$$

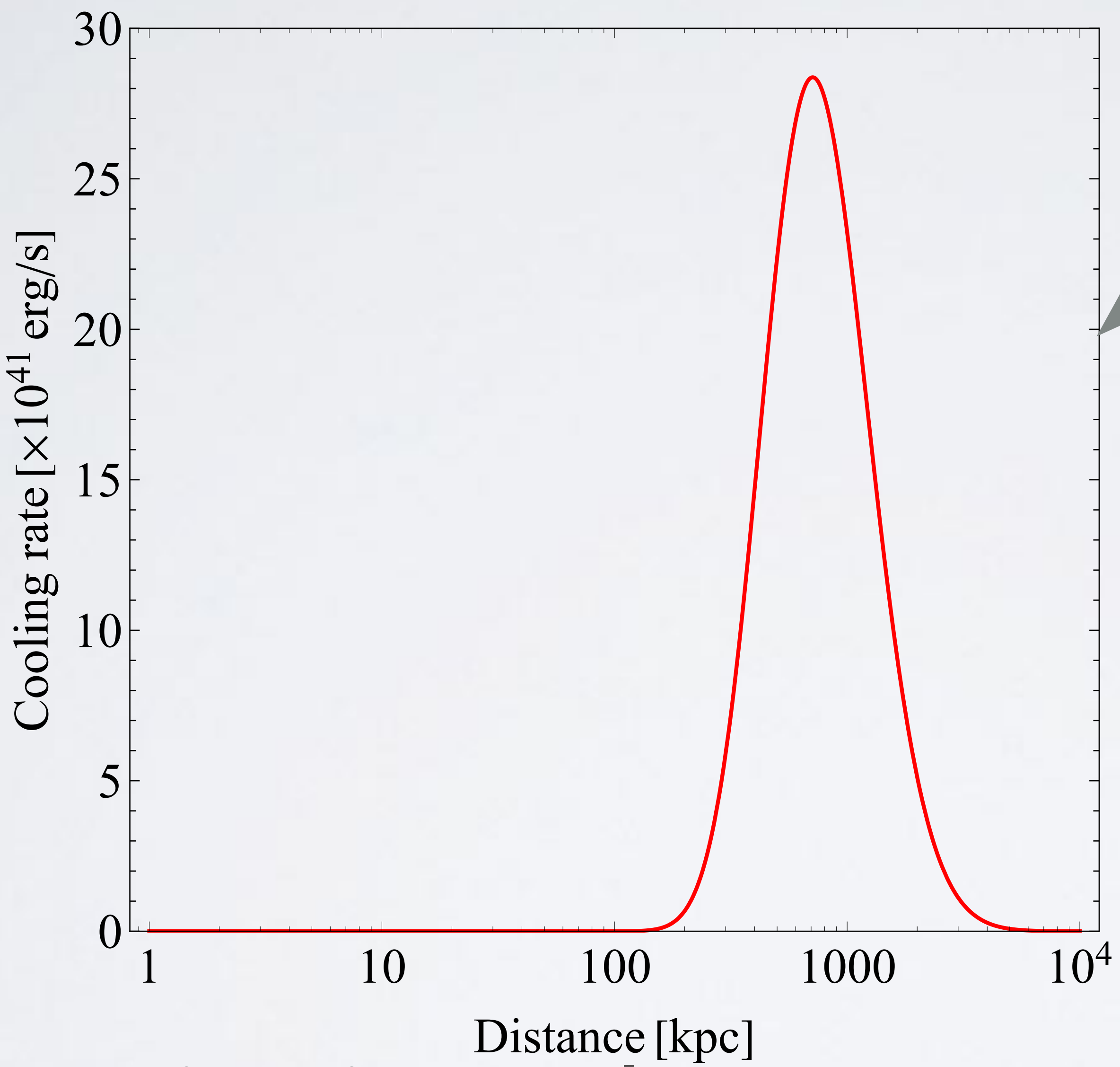
Inelastic scattering



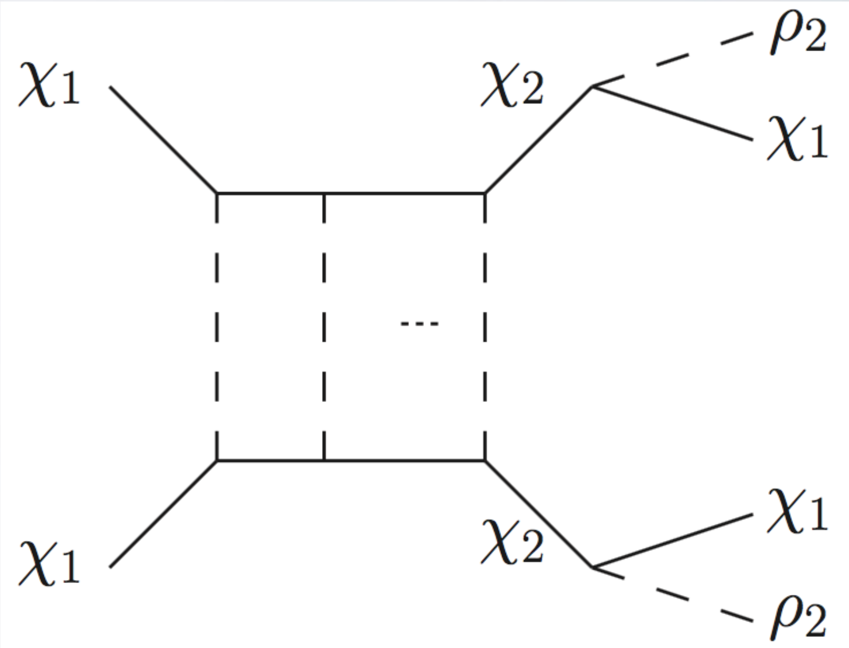
Large inelastic cross section

DM Halo Cools at a faster rate…

$$\frac{dE}{dt} = 4\pi r^2 dr\, \frac{2\Delta}{M} \rho(r)^2 \int_0^\infty \frac{\sigma_{\rm in}}{M} \bar{v}(r) f(v) dv$$



Cooling rate in a cluster

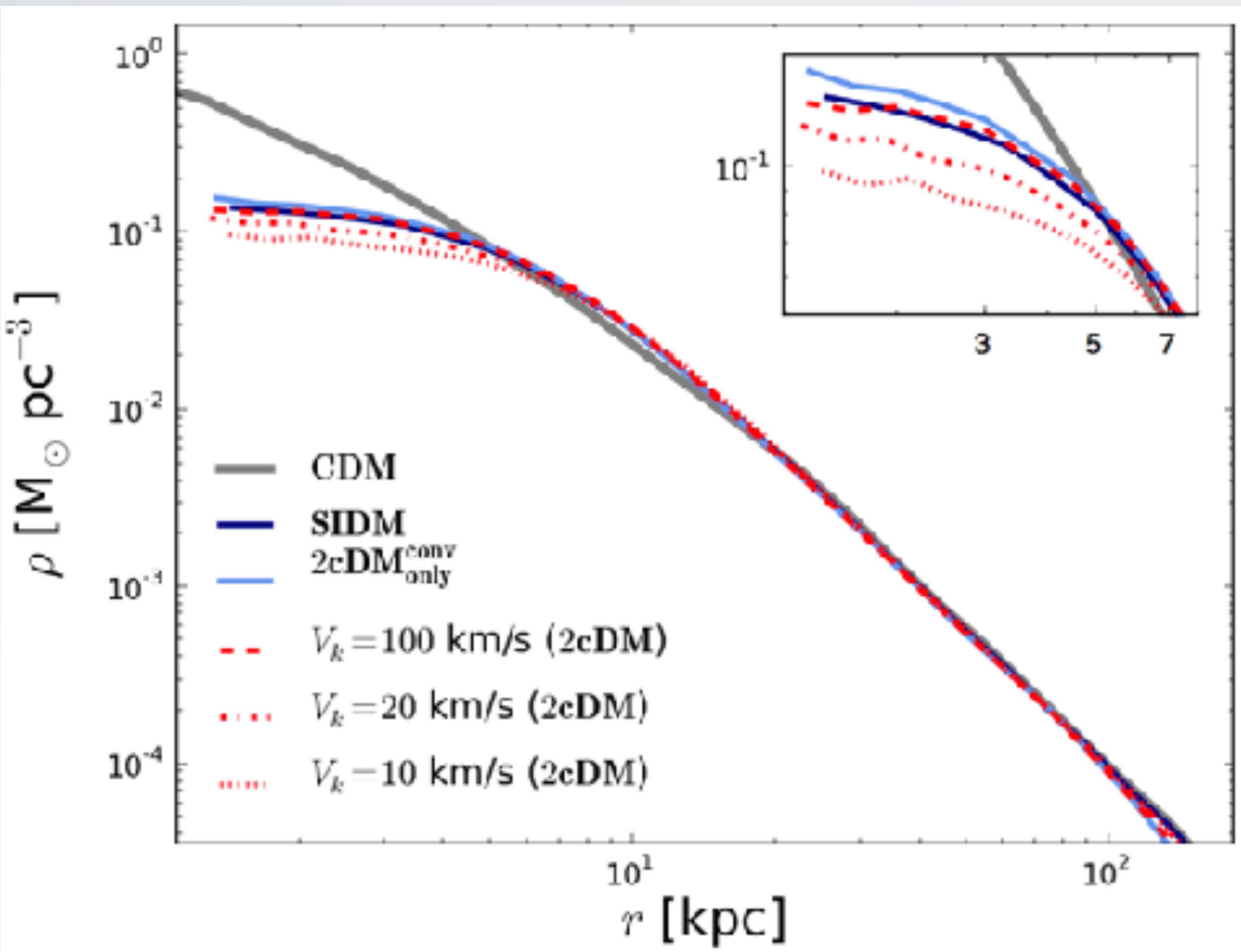


Upscattering time scale

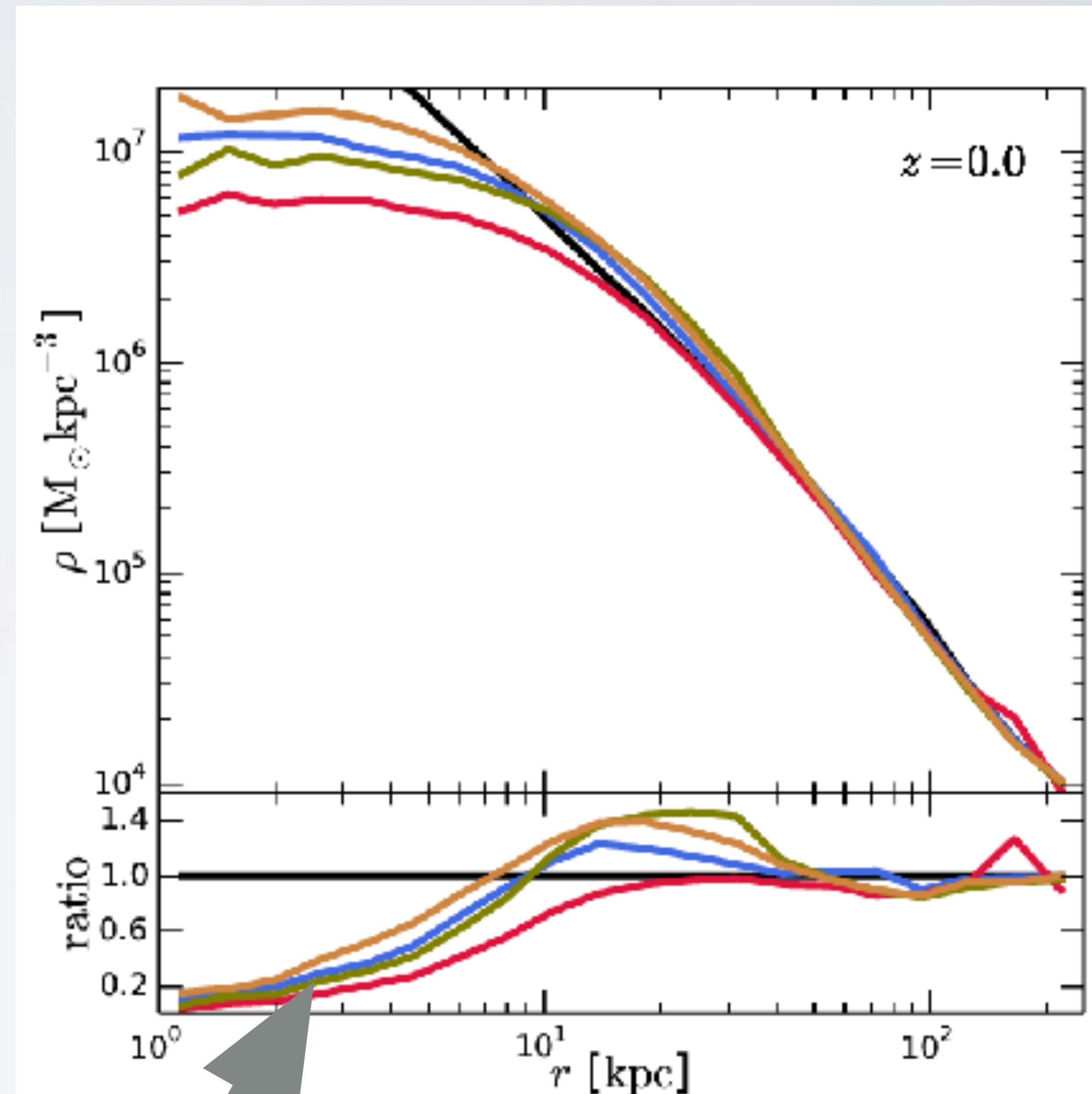
$$t_{\rm up} \simeq 10^{11}\ {\rm yrs}\ \frac{10^5\ {\rm M_\odot kpc^{-3}}}{\rho}\ \frac{1\ {\rm cm^2 g^{-1}}}{\sigma_{\rm in}/M}\ \frac{10^3\ {\rm kms^{-1}}}{v}\ (\gtrsim t_{\rm age})$$

But small inelastic scatt. can have large effects…

Simulations with inelastic processes



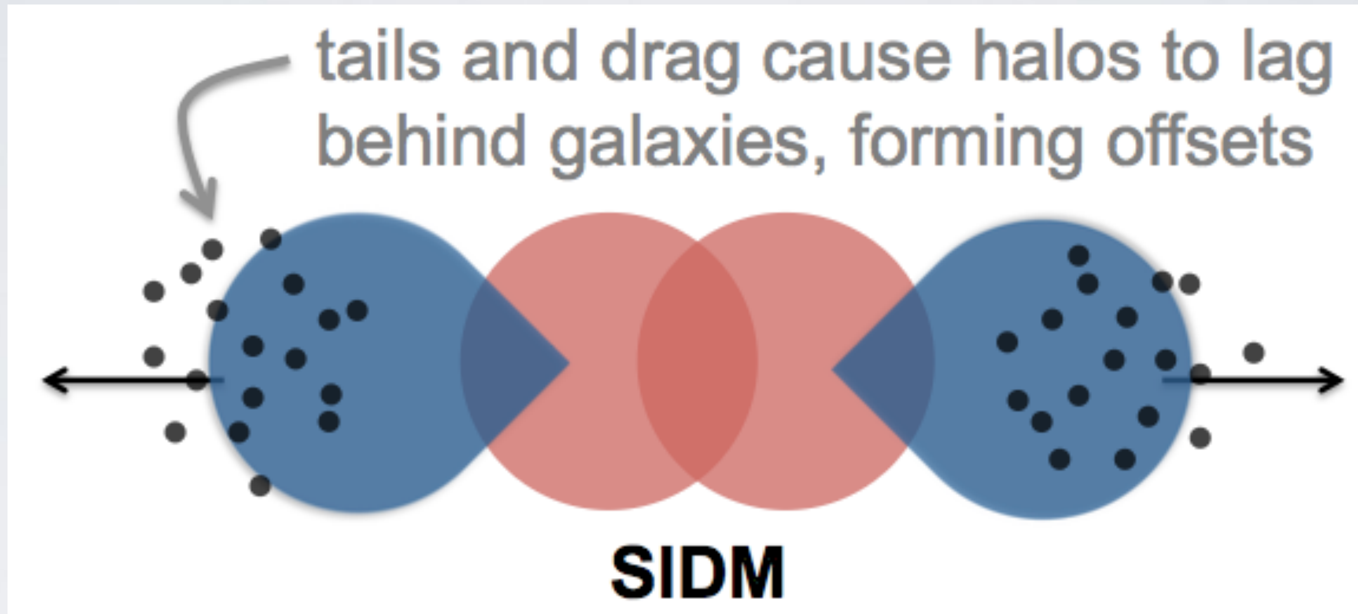
Keita et al, 1711.11078, 1711.11085



Mark et al, 1805.03203

5 times smaller inelastic cross section

Additional drag force



Kim et al., MNRAS 469, 2017

$$\frac{F_{\rm drag}}{M} = \frac{(\sigma_{\rm el} + \sigma_{\rm in})\rho_\chi}{4Mv_0^2} + \frac{2\Delta}{M}\frac{\rho_\chi \sigma_{\rm in}}{M}$$

New term

Additional effects seem small but needs to be verified in simulations

Summary

- Contrary to our expectation, $S_p \gg 1$ but $S_s \ll 1$.
- Particle exchange symmetry $\longrightarrow$ selection mechanism in the enhancement mechanism.
- DM annihilation rate is preferably enhanced in the galaxies.
- DM can dissipate energy through upscattering induced decay of the excited state and predict faster halo cooling rate.
- The upscattering and decay also contributes to an extra drag force between colliding halos.
- DM N-body simulations are needed to quantify the impacts of these mechanisms.

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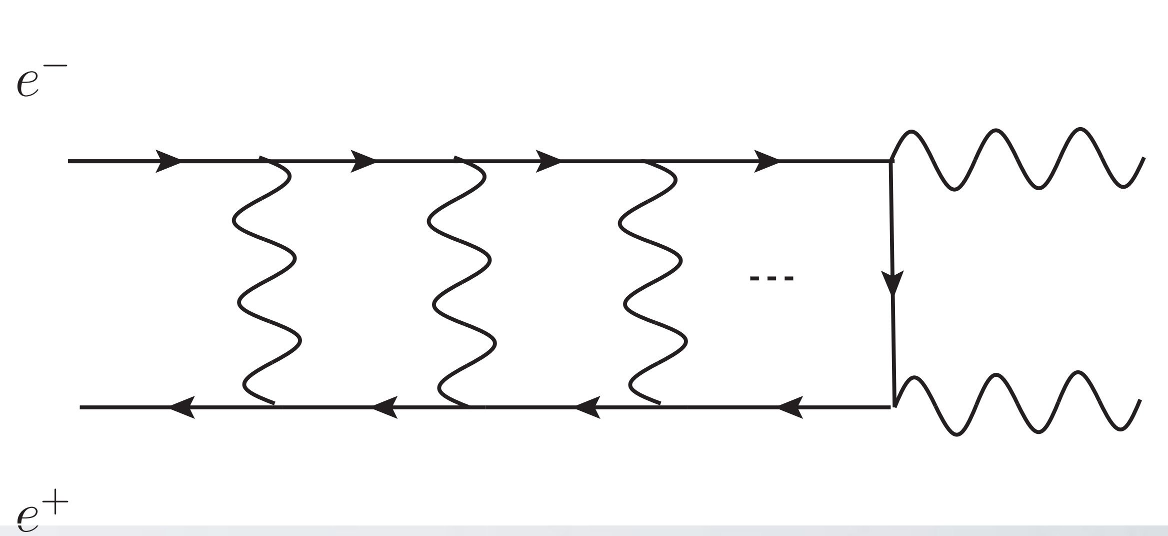
Thank you!

Back ups

α-scaling in a ladder graph



Typical momentum exchange ~ αm_χ

$$|\mathbf{p}| \sim \alpha m_\chi \implies p^0 \sim \frac{|\mathbf{p}|^2}{2m_\chi} \sim \alpha^2 m_\chi$$

One photon exchange graph ~ $\frac{\alpha}{|\mathbf{q}|^2} \sim \frac{1}{\alpha}$

Two photon exchange graph ~ $\alpha^2 \left(\frac{1}{\alpha^2}\right)^2 \left(\frac{1}{\alpha^2}\right)^2 \alpha^5 \sim \frac{1}{\alpha}$

To compute the Sommerfeld factors

$$\left[\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d}{dr}\right)+k^2-\frac{l(l+1)}{r^2}-2\mu V(r)\right]\Psi_l(r)=0$$

$$V_{11}=V_{22}=-\frac{\alpha e^{-m_\rho r}}{r} \qquad V_{12}=V_{21}=-\frac{\alpha e^{-m_\eta r}}{r}$$

↓

We solve the Schroedinger eqns with these potentials

↙ ↘

$$S_p^{\text{ann}} \qquad S_s^{\text{co-ann}}, S_p^{\text{co-ann}}$$

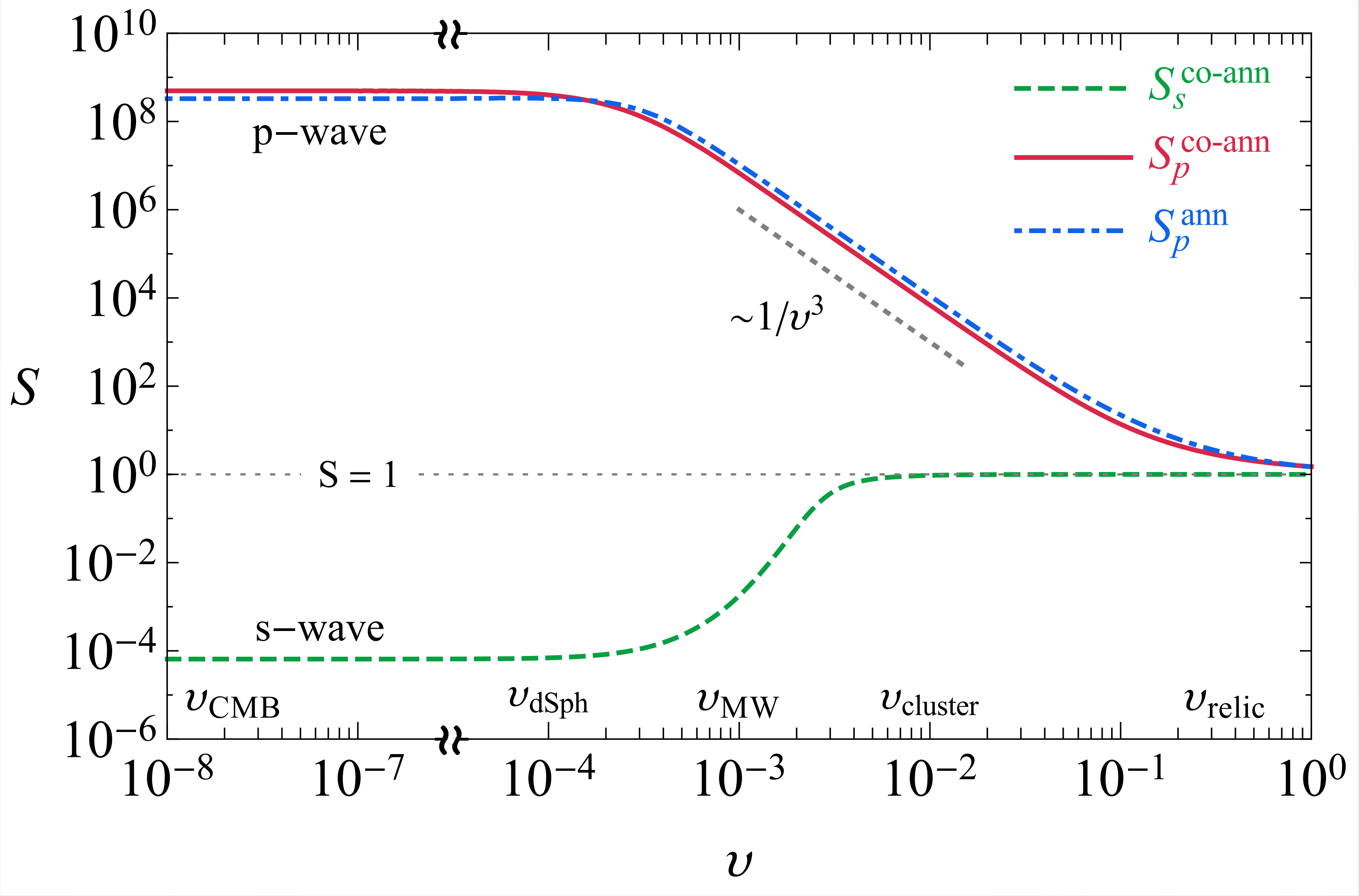
Explanation using Particle Exchange Symmetry

- Suppose *A* & *B* are two fermions-

$$|BA\rangle = (-1)^{\ell+s}|AB\rangle$$

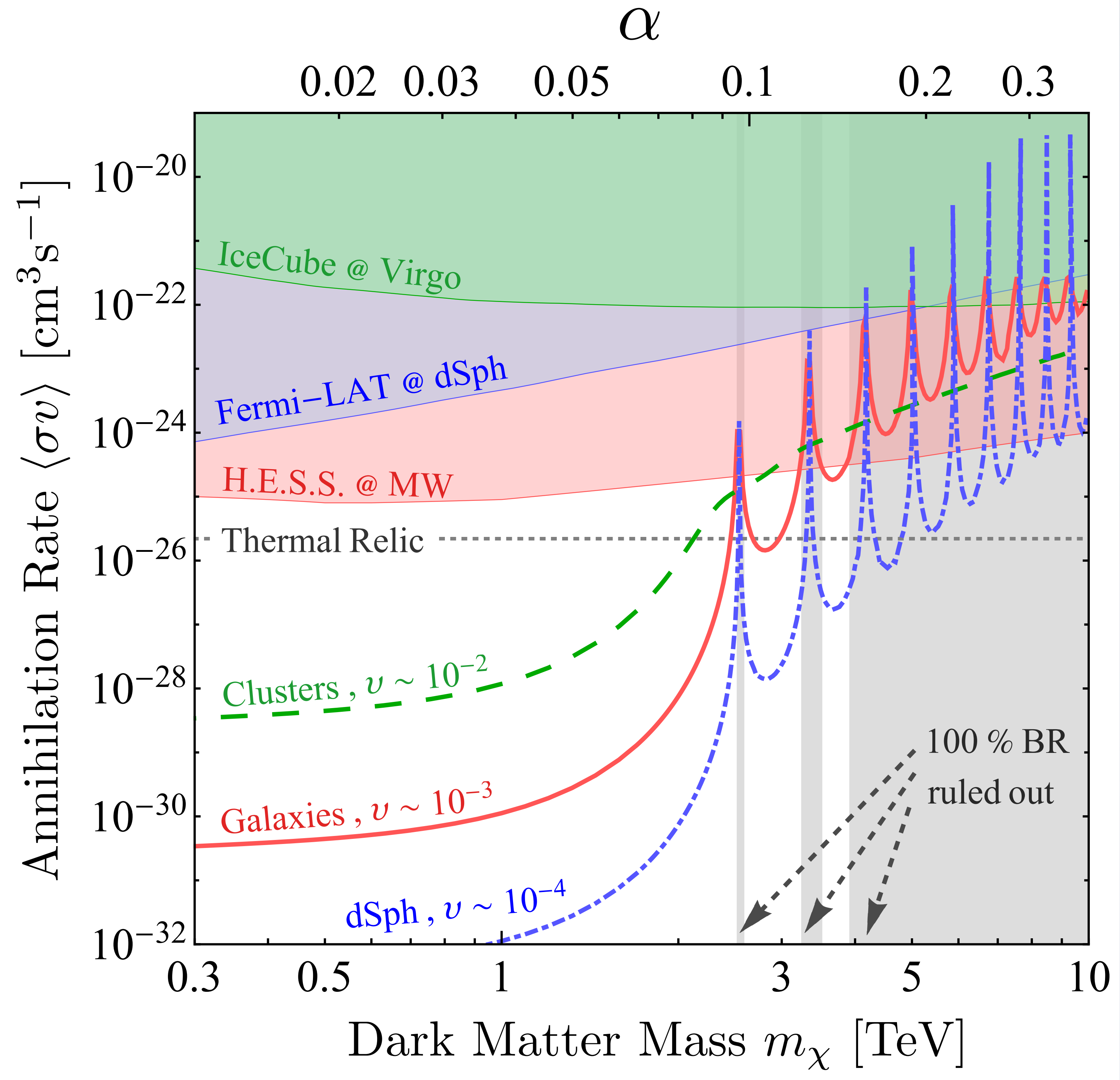
- $(-1)^{\ell}$ from angular momentum
- $(-1)^{s+1}$ from spin
- (-1) from Wick exchange of spinors

Back ups



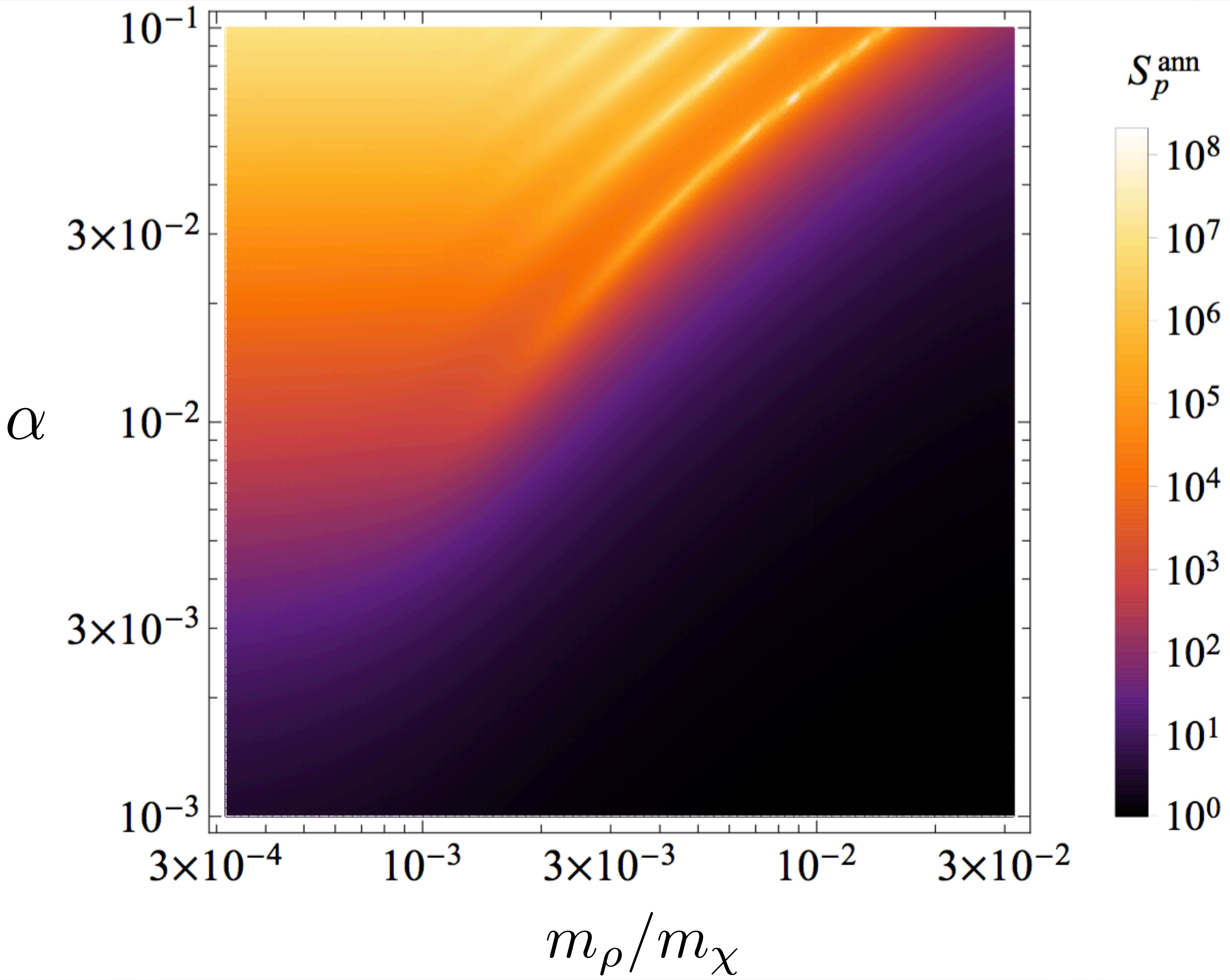
$$\Delta/m_\chi = 10^{-3},\ m_\rho/m_\chi = 10^{-3},\ m_{\text{th}} = 0.9 m_\rho,\ \alpha = 0.1$$

Back ups



$$\Delta = 10\,\mathrm{GeV},\ m_\rho = 30\,\mathrm{GeV}$$

Back ups



Resonances at $\dfrac{6\alpha m_\chi}{\pi^2 m_\rho} = (n+2)^2$

$$\Delta/m_\chi = 0.001,\ v = 10^{-3}$$

Back ups

Pure off-diagonal interaction