Resonant pionic dark matter

Based on work with Marieke Postma

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Core vs cusp

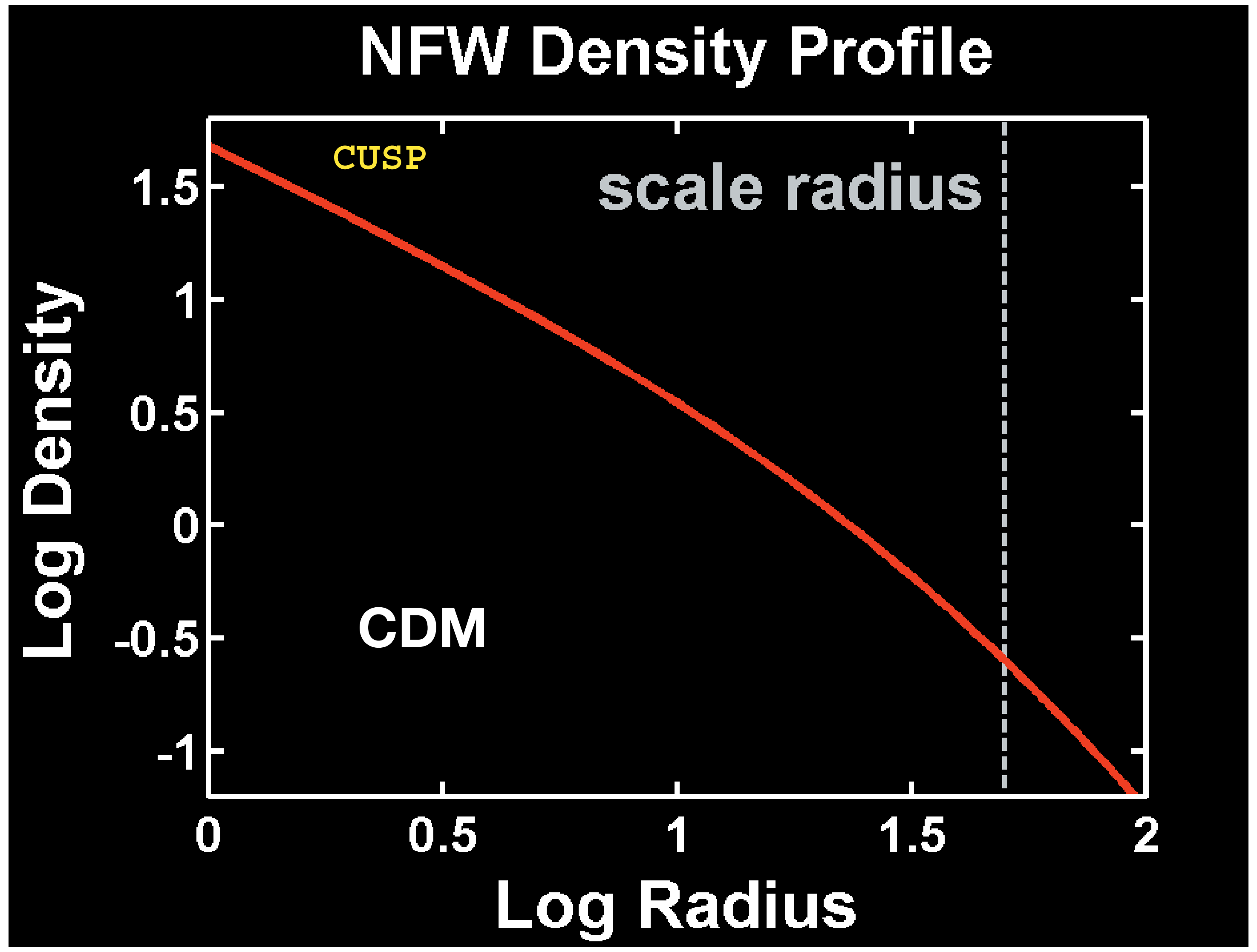
DM self-interactions change the shape of DM density profiles

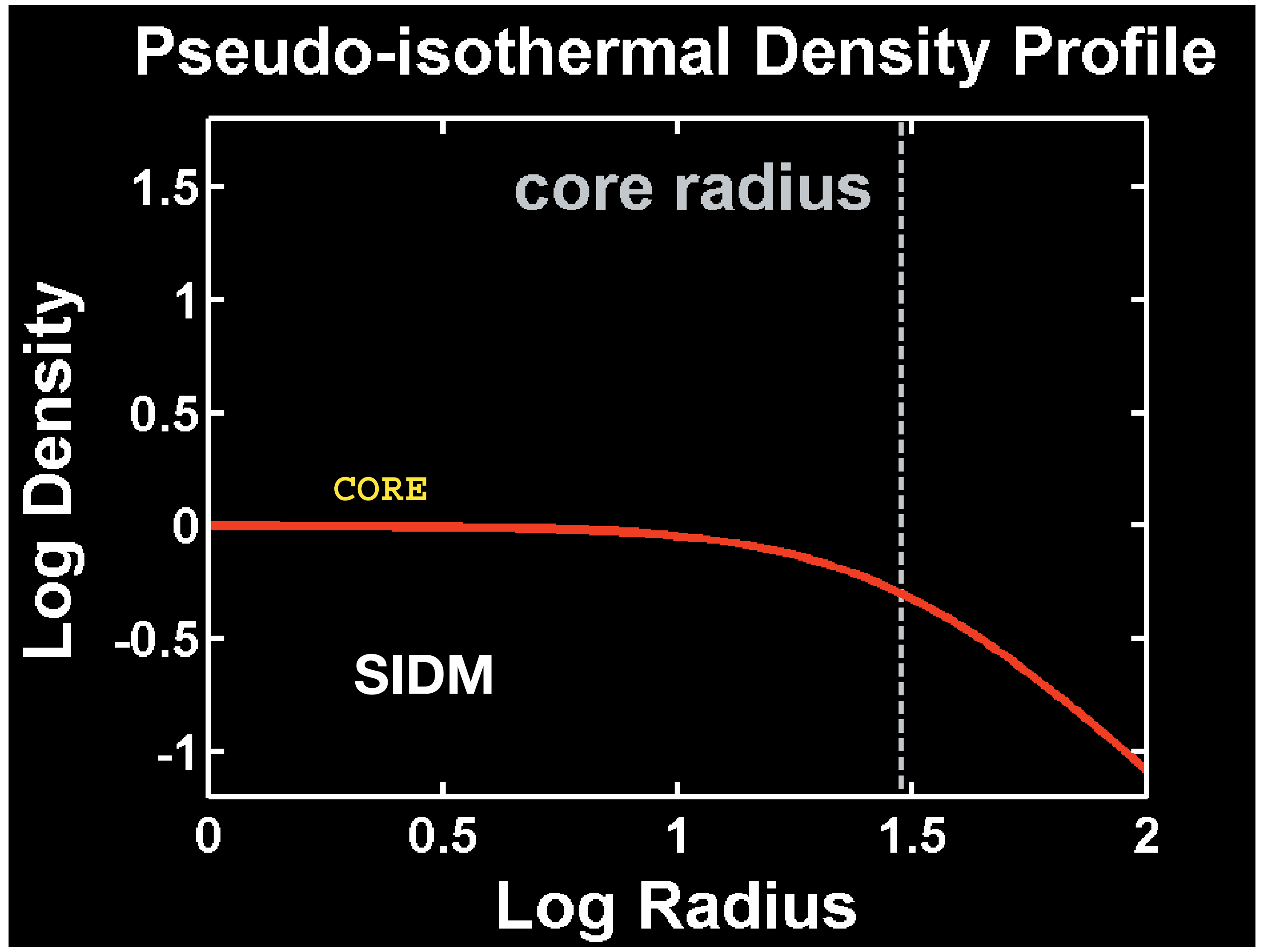
Collisionless dark matter (CDM) predicts Navarro-Frenk-White profile

$$\rho(r)^{\mathrm{NFW}} \propto (r/r_s)^{-1}(1+r/r_s)^{-2}$$

Self-interacting DM (SIDM) predicts core-like profile: NFW away at large r, in center efficient heat transfer (isothermal)

$$\rho(r)^{\mathrm{SIDM}} \propto \begin{cases} \text{const.} & r \ll r_1 \\ \rho(r)^{\mathrm{NFW}} & r \gg r_1 \end{cases}$$





Del Popolo et al. [2209.14151]

Resonant scattering

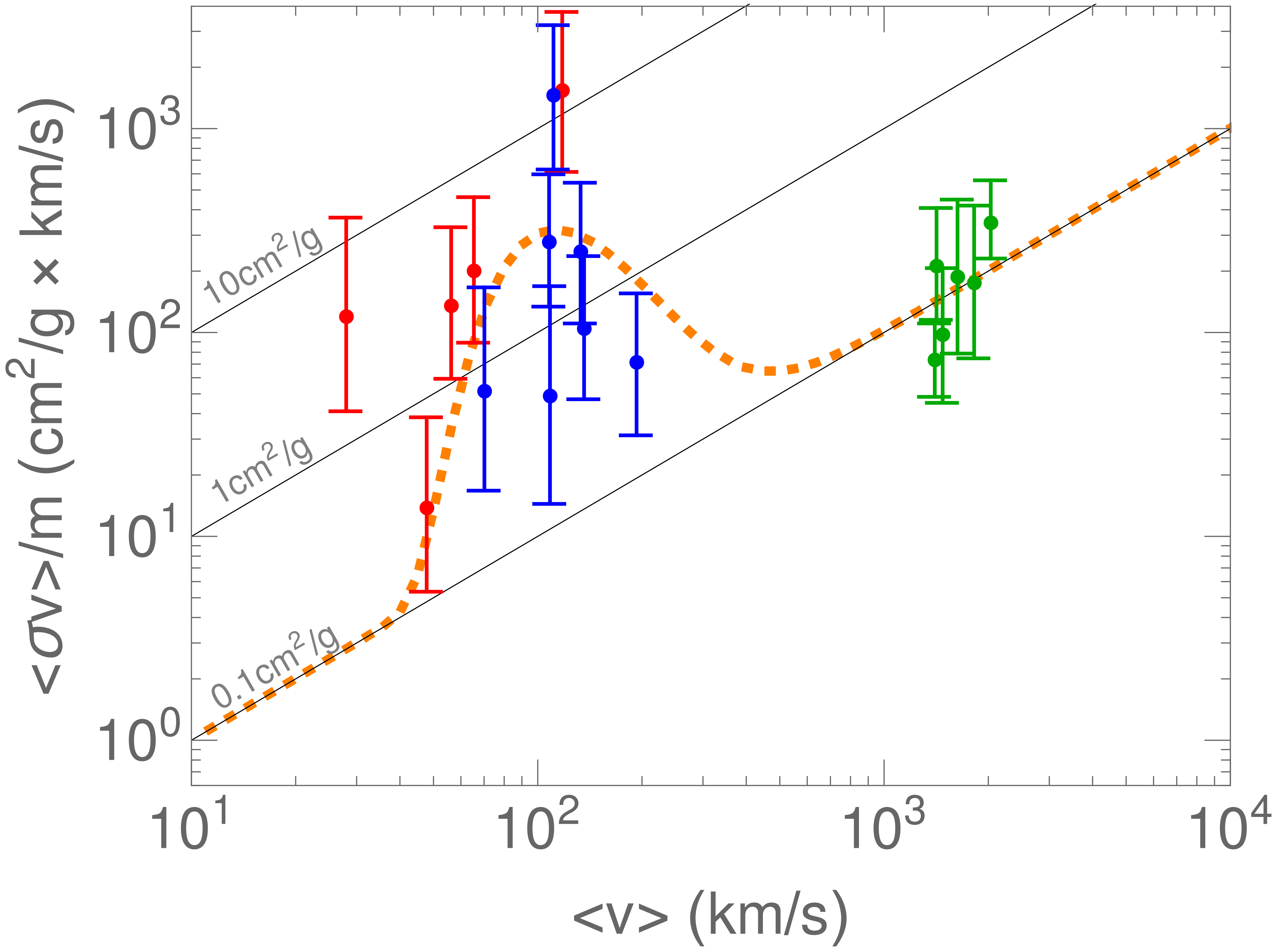
DM density profiles prefer self-interacting DM models with strength

$$\frac{\sigma}{m} \sim 0.1 - 1\ \mathrm{cm}^2/\mathrm{g}$$

and velocity dependence to accommodate observations at different scales

Resonant (p-wave) scattering can provide good fit to the data

$$\sigma = \underbrace{\sigma_0}_{\text{const.}} + \underbrace{\frac{4\pi S}{m_\pi E(v)} \frac{\Gamma(v)^2/4}{(E(v) - E(v_R))^2 + \Gamma(v)^2/4}}_{v-\text{dep}}$$



Adapted from Chu et al. [1810.04709]

$$\langle \sigma v \rangle = \int_0^{v_{\max}} dv\ \sigma v f(v, \langle v \rangle), \quad f(v, \langle v \rangle) \propto v^2 e^{-v^2/\langle v \rangle^2}$$

Dark pions

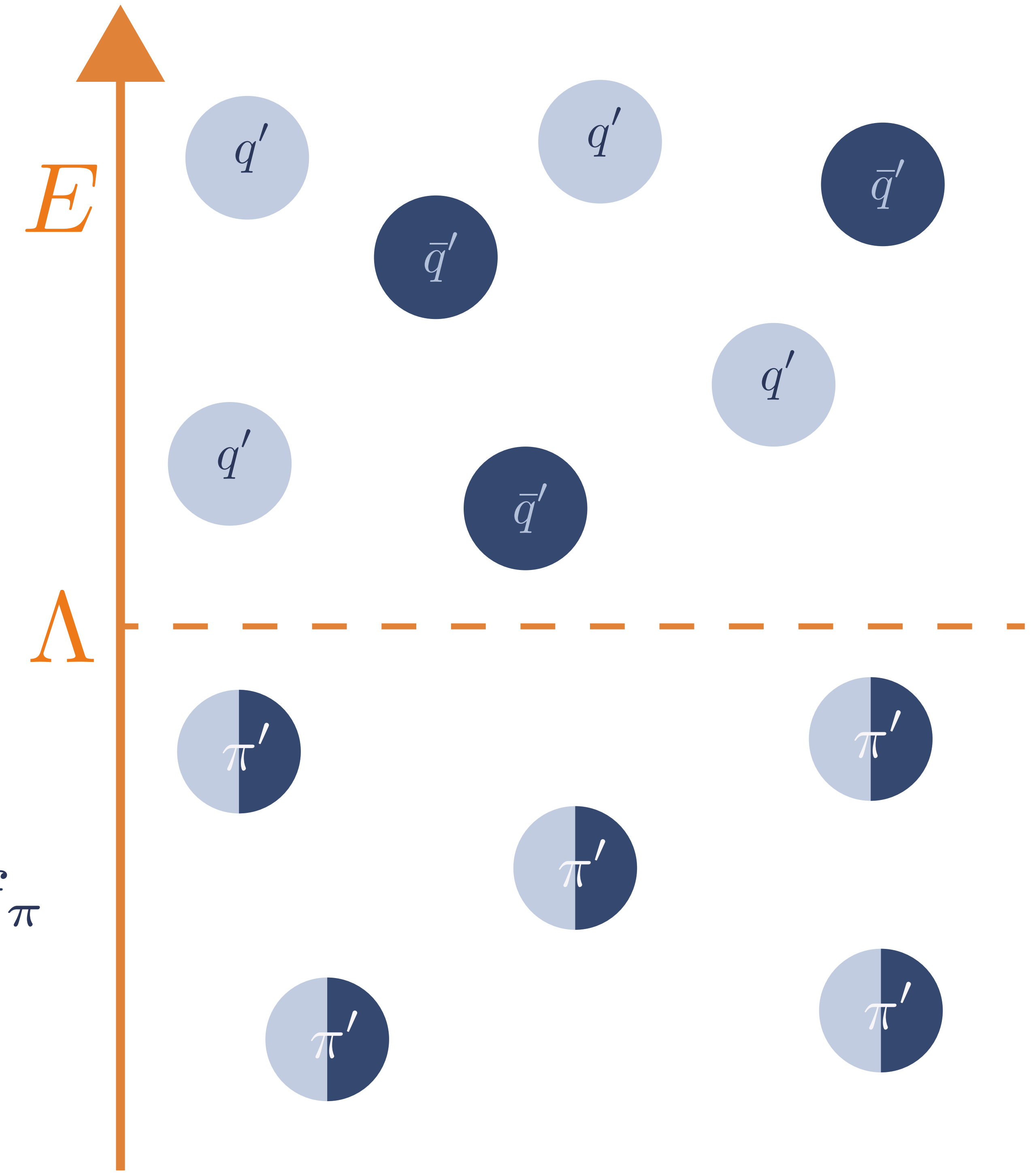
Dark QCD: dark sector with a dark $SU(N_c)$ gauge symmetry and N_f dark quark flavours

At low energies, phenomenology described by dark pions π' that make up the DM ($N_f^2 - 1$ of them)

We work with chiral perturbation theory (χPT):

$$\mathcal{L}_{\chi \mathrm{PT}} = \frac{f_\pi^2}{4} \mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger) + \frac{m_\pi^2 f_\pi^2}{2} \mathrm{Tr}(U + U^\dagger),$$

$$U = e^{2i\boldsymbol{\pi}/f_\pi}$$
$$\boldsymbol{\pi} = \pi^a T^a$$



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$$= \underbrace{\mathrm{Tr}(\partial_\mu \boldsymbol{\pi} \partial^\mu \boldsymbol{\pi}) - m_\pi^2 \mathrm{Tr}(\boldsymbol{\pi}^2)}_{\text{kinetic}} + \underbrace{\frac{\xi^2}{m_\pi^2}\mathcal{O}(\boldsymbol{\pi}^4) + \frac{\xi^4}{m_\pi^4}\mathcal{O}(\boldsymbol{\pi}^6) + \ldots}_{\text{self-interactions}},$$

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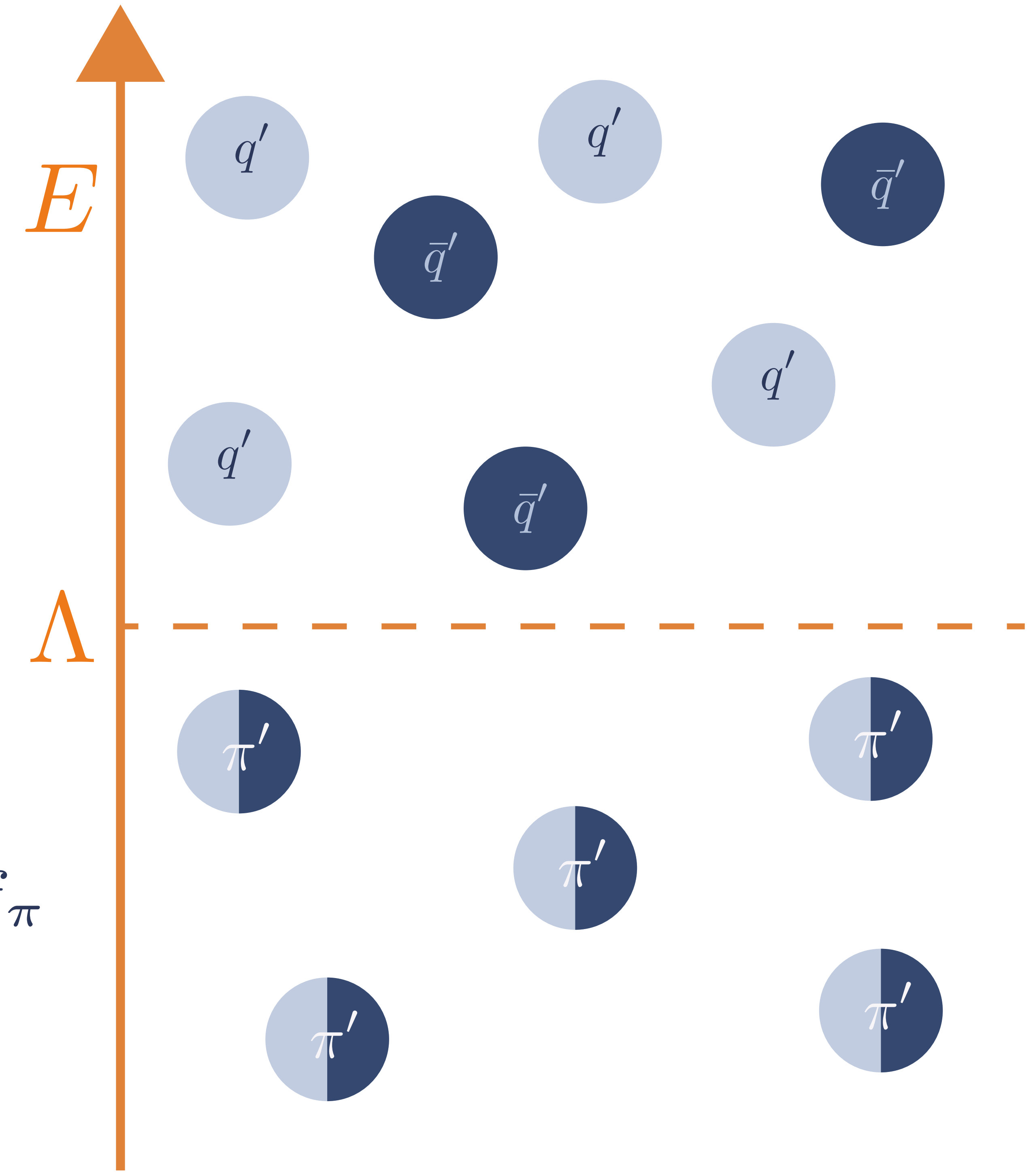
$$\xi \equiv \frac{m_\pi}{f_\pi} \lesssim 4\pi$$



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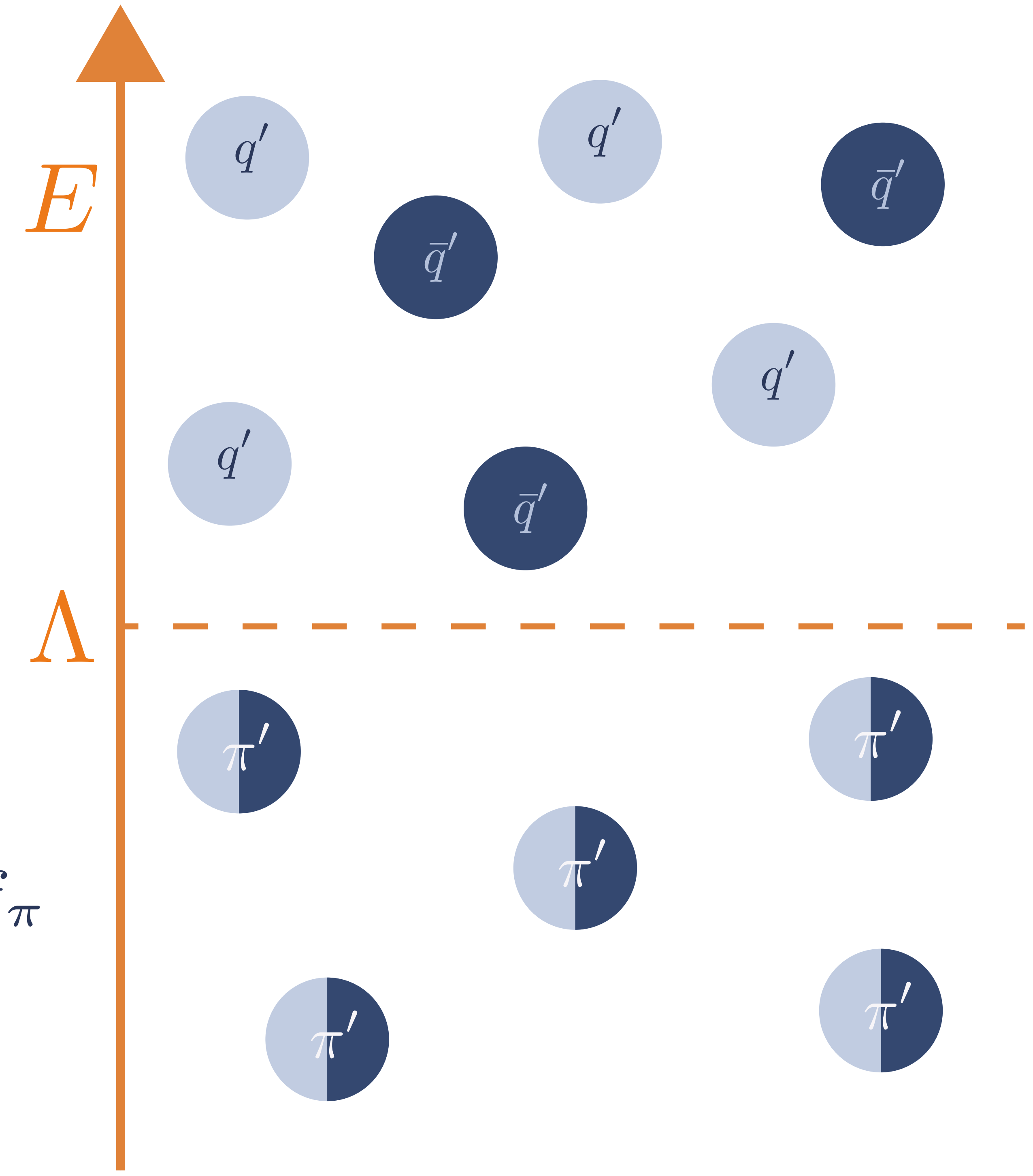

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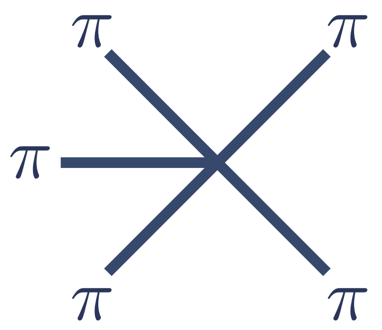
For $N_f \geq 3$ the Wess-Zumino-Witten (WZW) term is non-vanishing:

$$\mathcal{L}_{WZW} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}(\boldsymbol{\pi}\partial_\mu\boldsymbol{\pi}\partial_\nu\boldsymbol{\pi}\partial_\rho\boldsymbol{\pi}\partial_\sigma\boldsymbol{\pi})$$

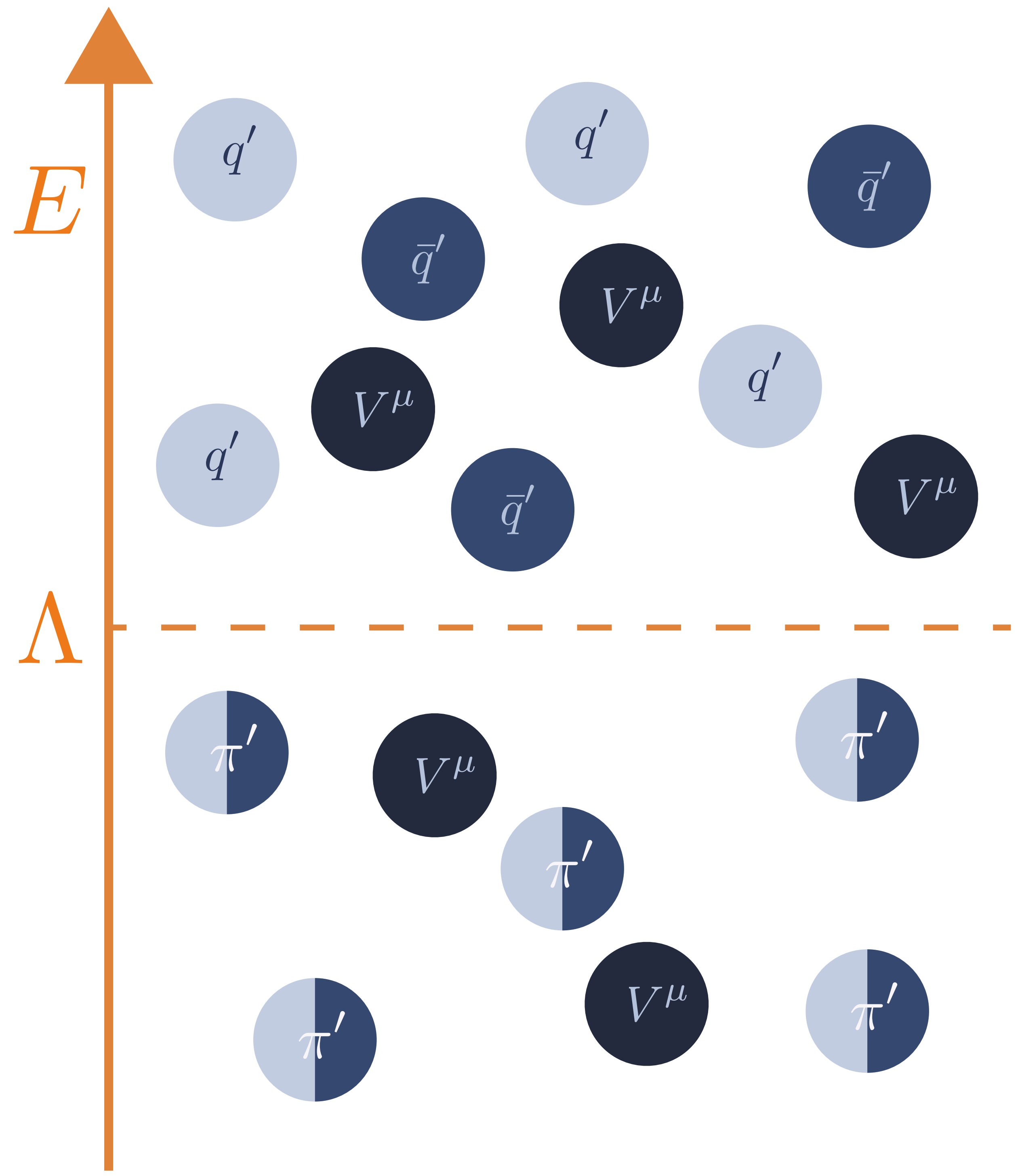


$\Rightarrow$ SIMPs!

Dark pions and dark photons

Dark photon: dark copy of $U(1)_d$, but with a *massive* gauge boson with mass close to twice the dark pion mass

$$\mathcal{L}_V = -\frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V V_\mu^2, \qquad m_V = m_\pi(2 + \delta m)$$



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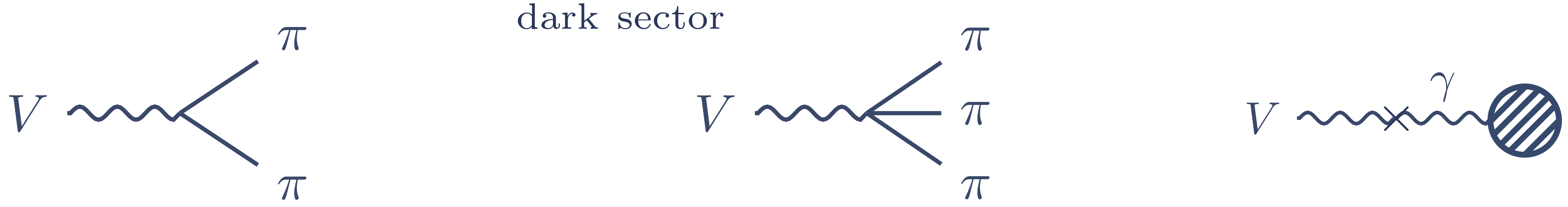
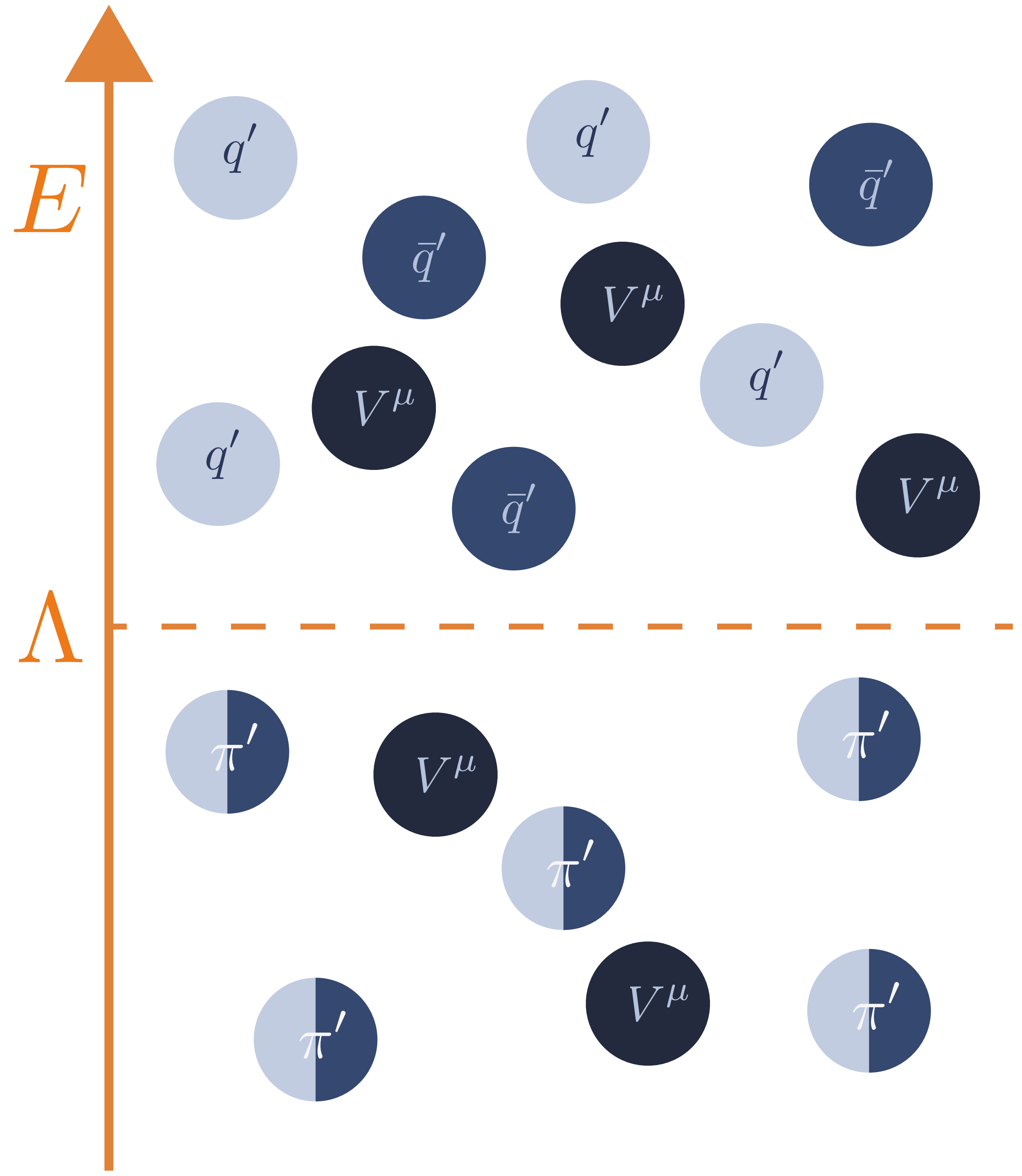
$$\underbrace{+\,2ig_D V^\mu \mathrm{Tr}(Q[\boldsymbol{\pi},\partial_\mu\boldsymbol{\pi}]) - i\frac{N_c g_D}{3\pi^2 f_\pi^3}\epsilon^{\mu\nu\rho\sigma}V_\mu \mathrm{Tr}(Q\partial_\nu\boldsymbol{\pi}\partial_\rho\boldsymbol{\pi}\partial_\sigma\boldsymbol{\pi})}_{\text{dark sector}} - \underbrace{\epsilon V_\mu J^\mu_{\mathrm{SM}}}_{\mathrm{SM}}$$





$$Q = \mathrm{diag}(1,-1,1,-1,\ldots)$$

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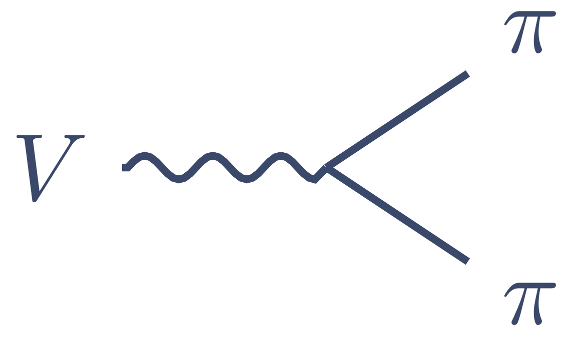

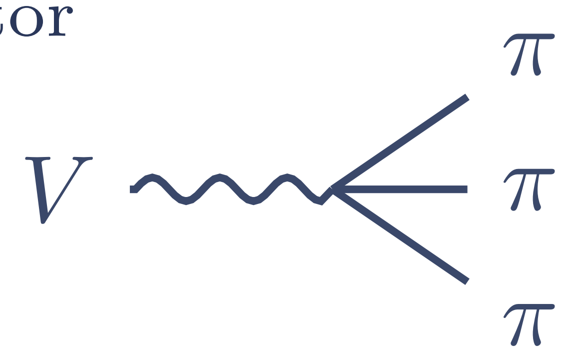

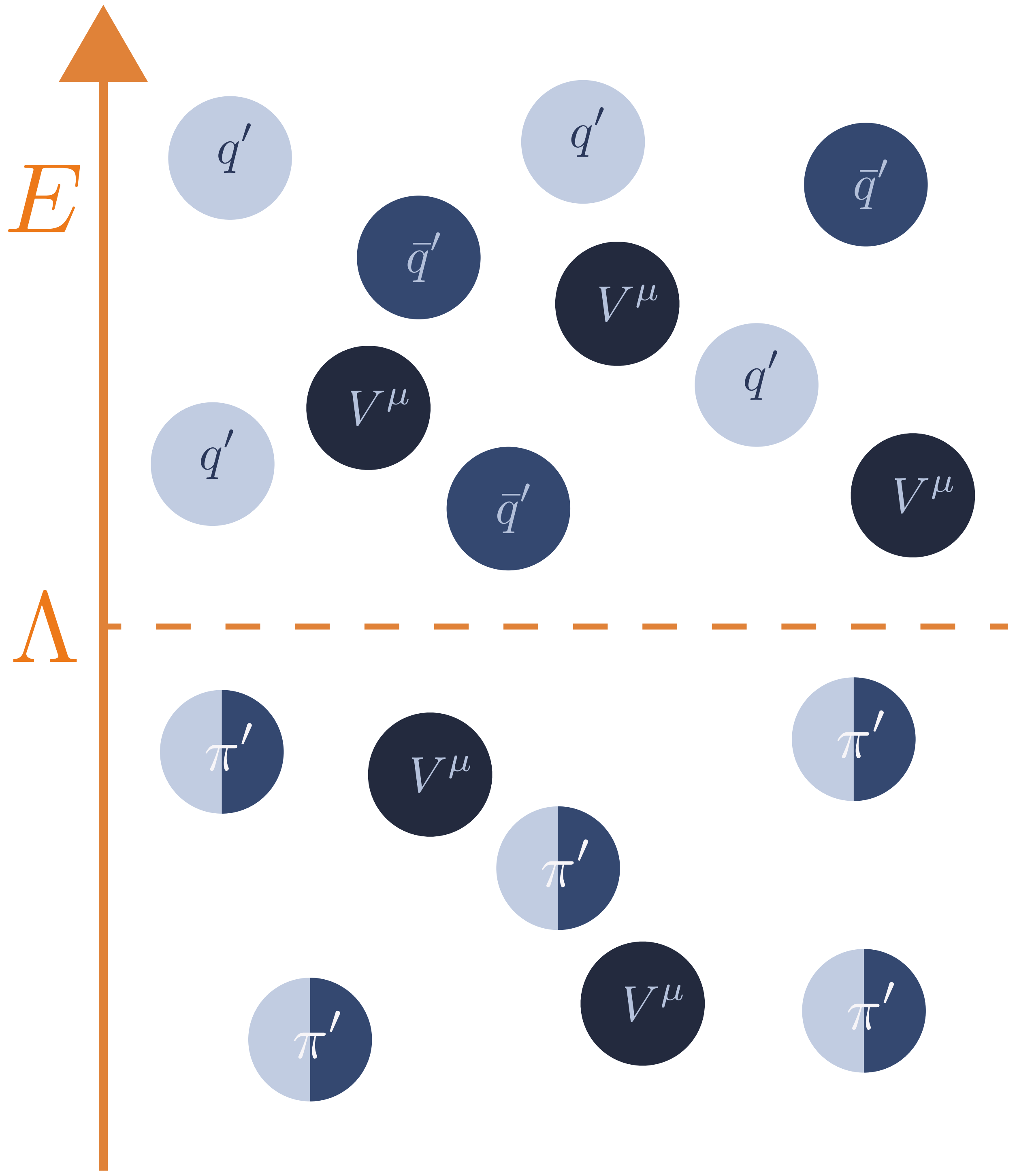

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Minimal setup:

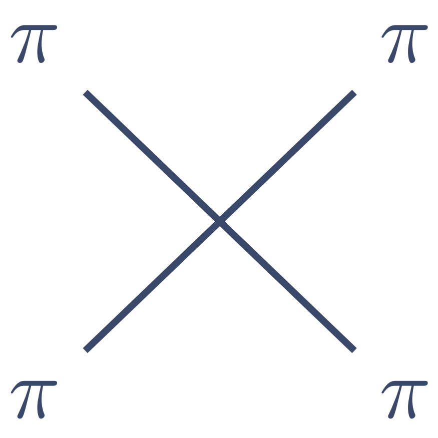
- Pions naturally have self-interactions of the right strength
- Pions are a natural SIMP candidate
- Dark photon acts as resonance, which can be tuned to address small scale structure
- Parameters $\{m_\pi, \xi, g_D, \delta m, \epsilon\}$

Self-interactions

Self-interaction cross section contains a constant part and Breit-Wigner shape for resonance

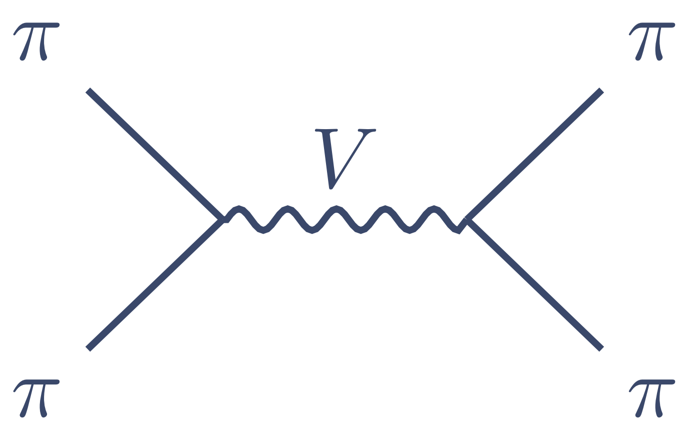
$$\sigma = \underbrace{\sigma_0}_{\text{const.}} + \underbrace{\frac{4\pi S}{m_\pi E(v)} \frac{\Gamma(v)^2/4}{(E(v)-E(v_R))^2 + \Gamma(v)^2/4}}_{v-\text{dep}}$$

The pions have a *constant* contact interaction

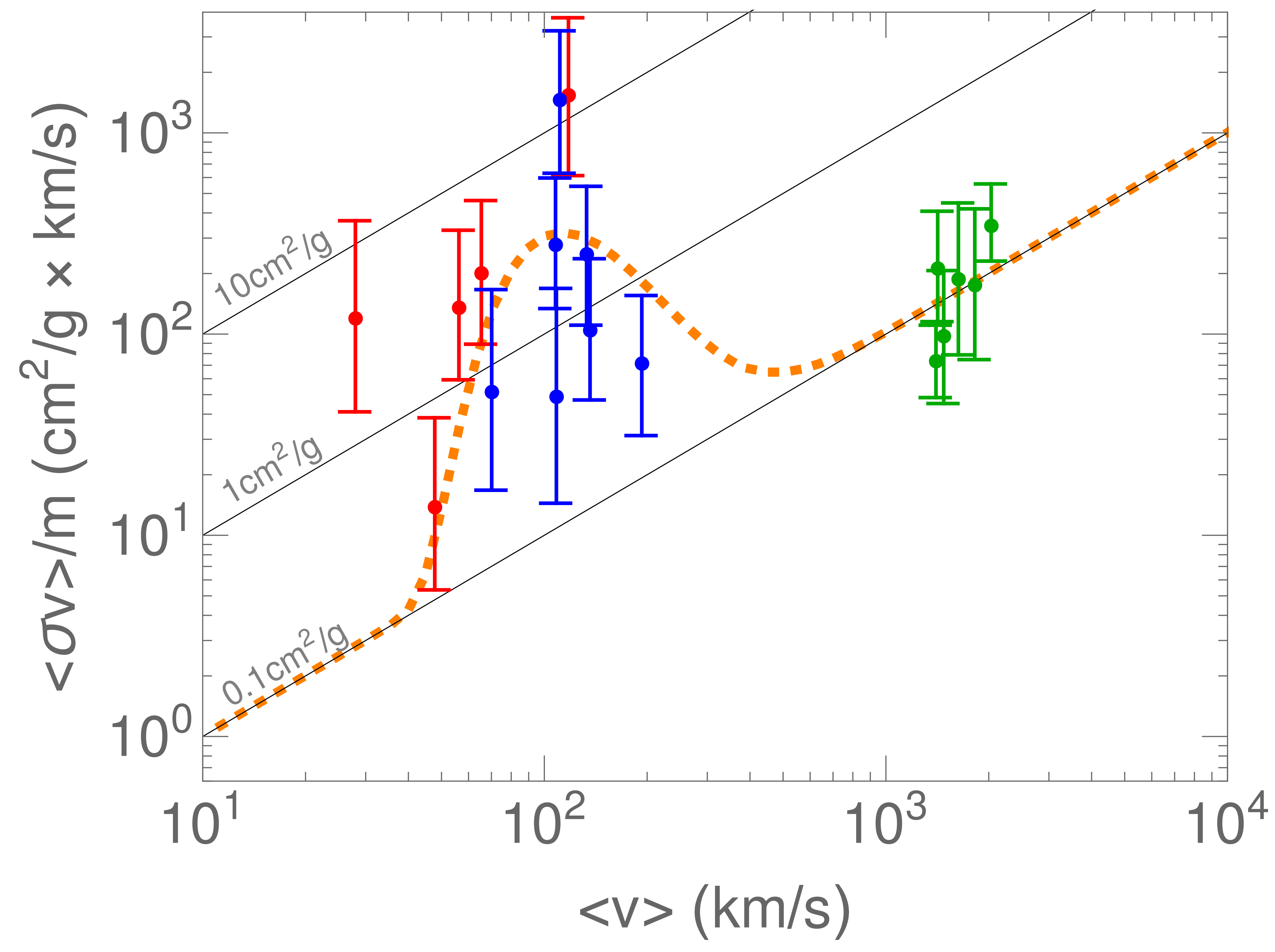


$$\sigma_{\text{contact}} \overset{p \ll m_\pi}{\approx} \frac{N_f^2}{64\pi(N_f^2-1)} \frac{\xi^4}{m_\pi^2} \quad \text{(large } N_f\text{)}$$

Dark photon exchange gives velocity dependence



$$\Gamma(v) = \frac{g_D^2}{48\pi} m_V v^3$$



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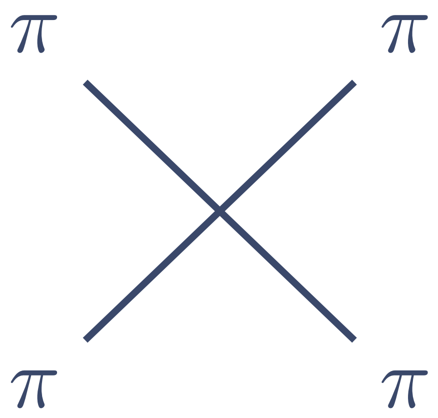

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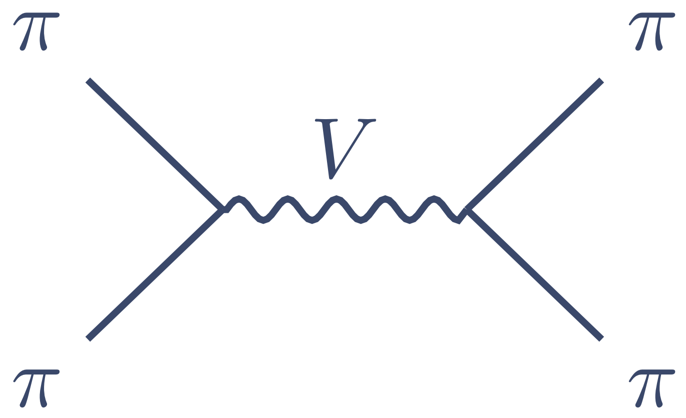

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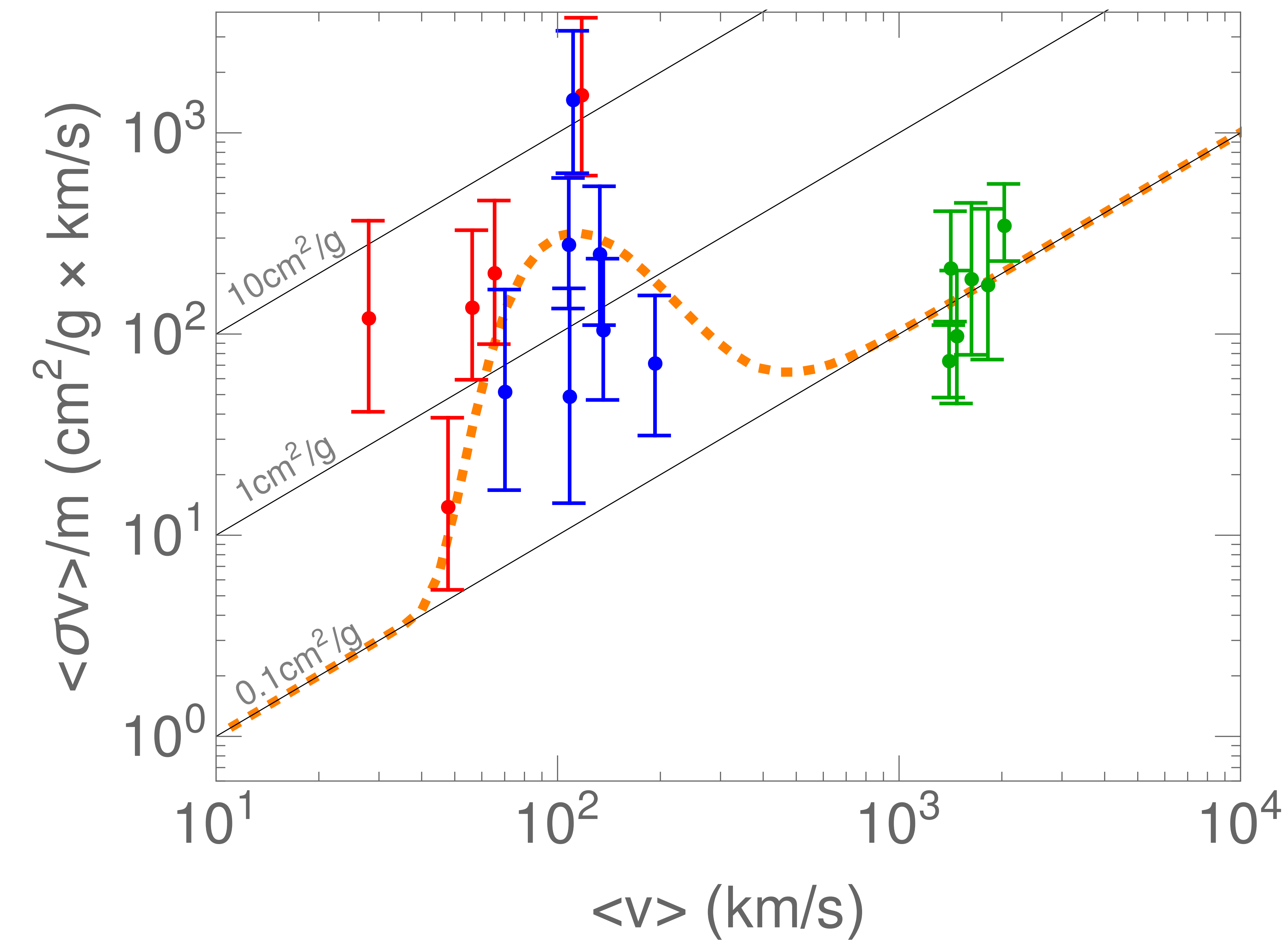

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4 out of 5 parameters of the model $\{m_\pi, \xi, g_D, \delta m\}$ can be expressed in terms of 1 parameter (m_π)

Peak position dictates mass splitting

$$v_R = 108 \text{ km/s} \Rightarrow \frac{\delta m}{m_\pi} \sim 10^{-7.5}$$

extremely small!

Relic abundance

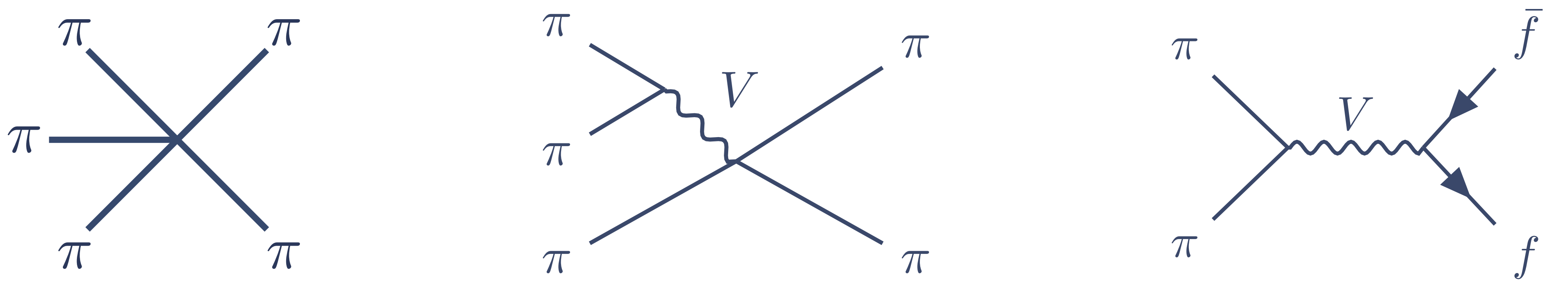
We wish to produce the DM relic density

$$\Omega_{\rm DM} h^2 = 0.12010$$ Planck collaboration (2018)

Solve the Boltzmann equation that contains two contributions:

- SIMP-like $3 \to 2$ interactions within dark sector
- WIMP-like $2 \to 2$ annihilations to SM particles (ϵ^2-*suppressed*, but resonantly *enhanced*)

$$\dot{n} + 3Hn = -\underbrace{\langle \sigma v^2 \rangle_{3\to 2}(n^3 - n^2 n_{\rm eq})}_{\text{dark sector}} - \underbrace{\langle \sigma v \rangle_{2\to 2}(n^2 - n_{\rm eq})}_{\text{DM DM}\to\text{SM}}$$



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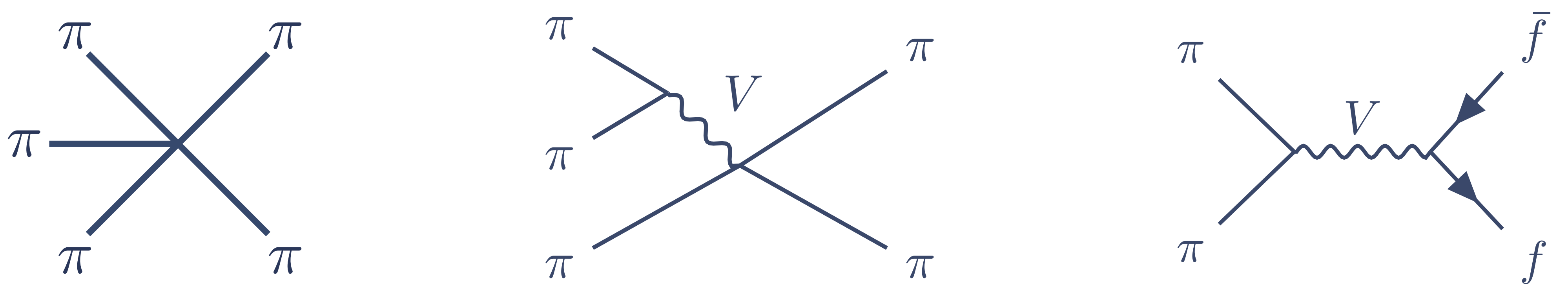
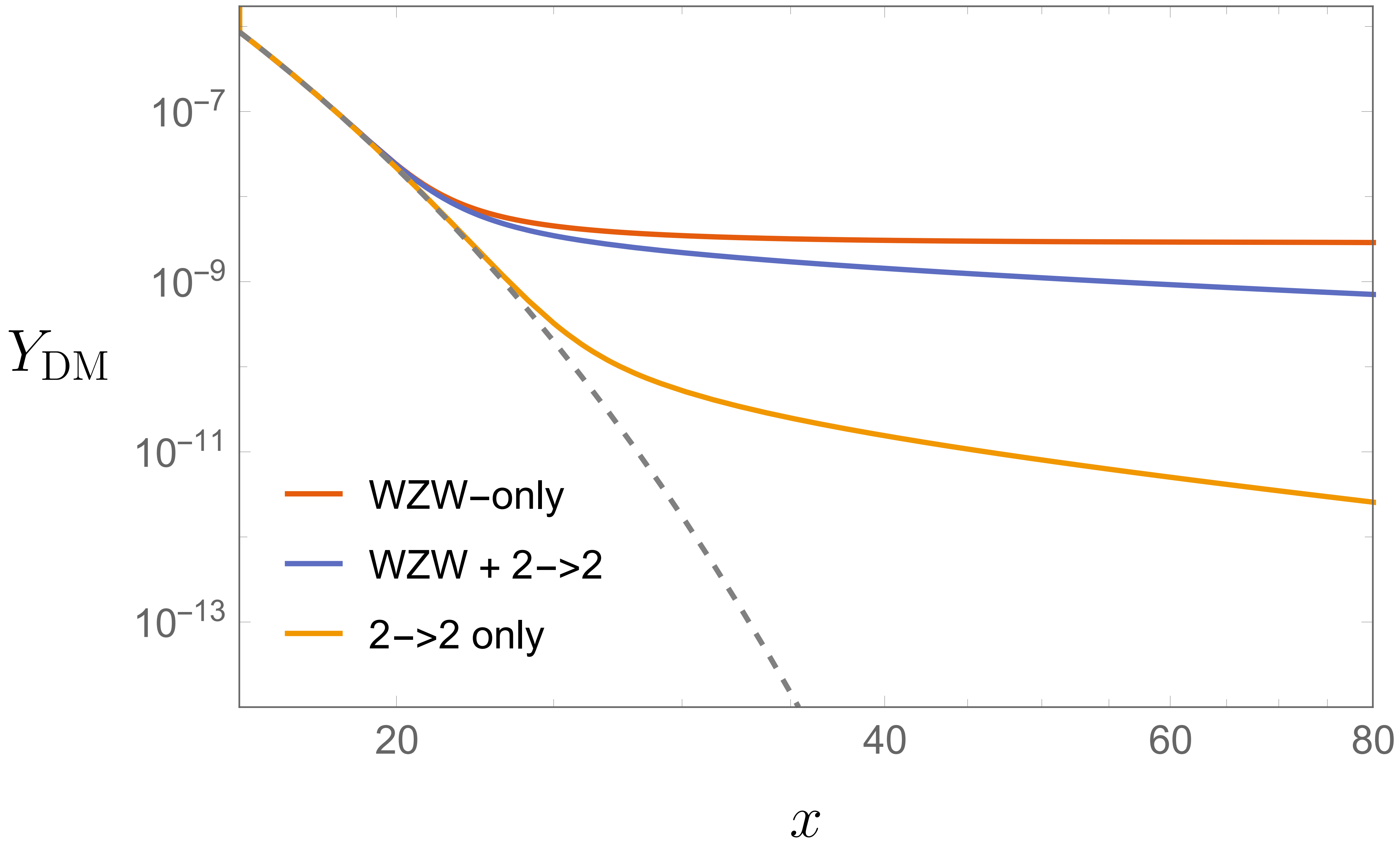


In dimensionless quantities $Y \equiv \frac{n_{\rm DM}}{s}$, $x = \frac{m}{T}$

$$\frac{dY}{dx} = -\frac{\lambda_{3\to 2}}{x^7}(Y^3 - Y_{\rm eq} Y^2) - \frac{\lambda_{2\to 2}}{\sqrt{x}} e^{-\delta m x}(Y^2 - Y_{\rm eq}^2)$$



Extended *period* of (slow) freeze-out!

until $x \sim \delta m^{-1}$

Viable parameter space

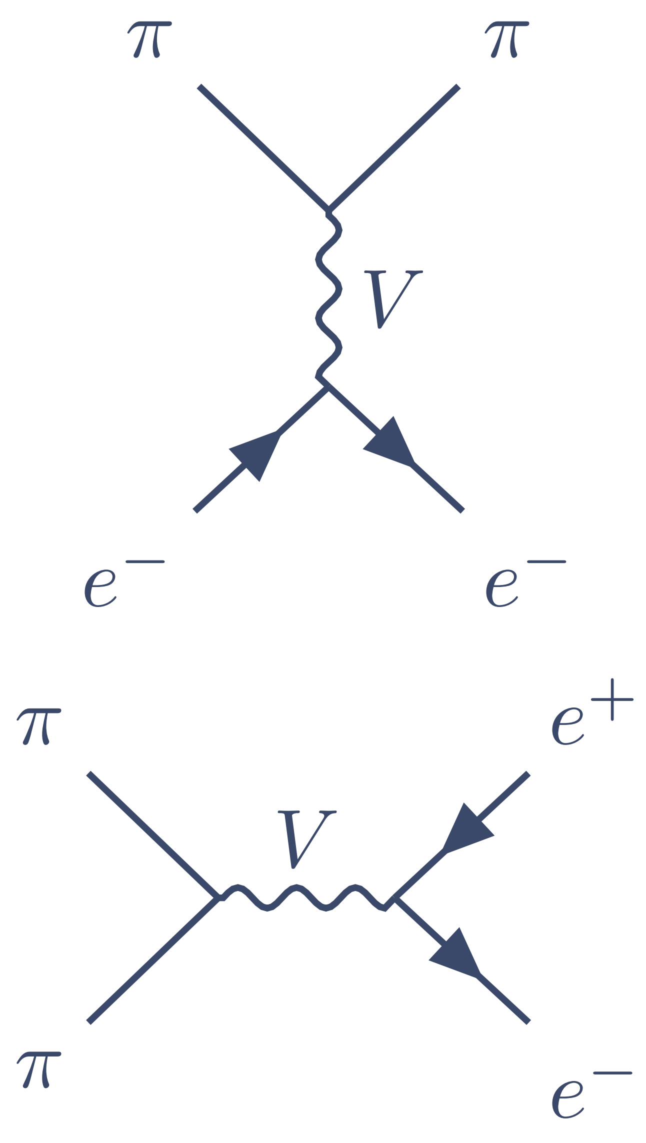
Kinetic mixing ϵ is constrained by different probes:

Fixed $\begin{cases} \delta m = 10^{-7.5} \\ \sigma/m = 0.11\ \mathrm{cm}^2/\mathrm{g} \quad \text{(fixes } \xi\text{)} \\ g_D = 0.21\left(\frac{m_\pi}{100\ \mathrm{MeV}}\right)^{3/2} \end{cases}$

- Require dark and SM sectors be in thermal equilibrium at freeze-out

$$\Gamma(x_f) \gtrsim H(x_f)$$

$$\Gamma = n_{\mathrm{SM}} \langle \sigma v \rangle_{\pi e \to \pi e}$$

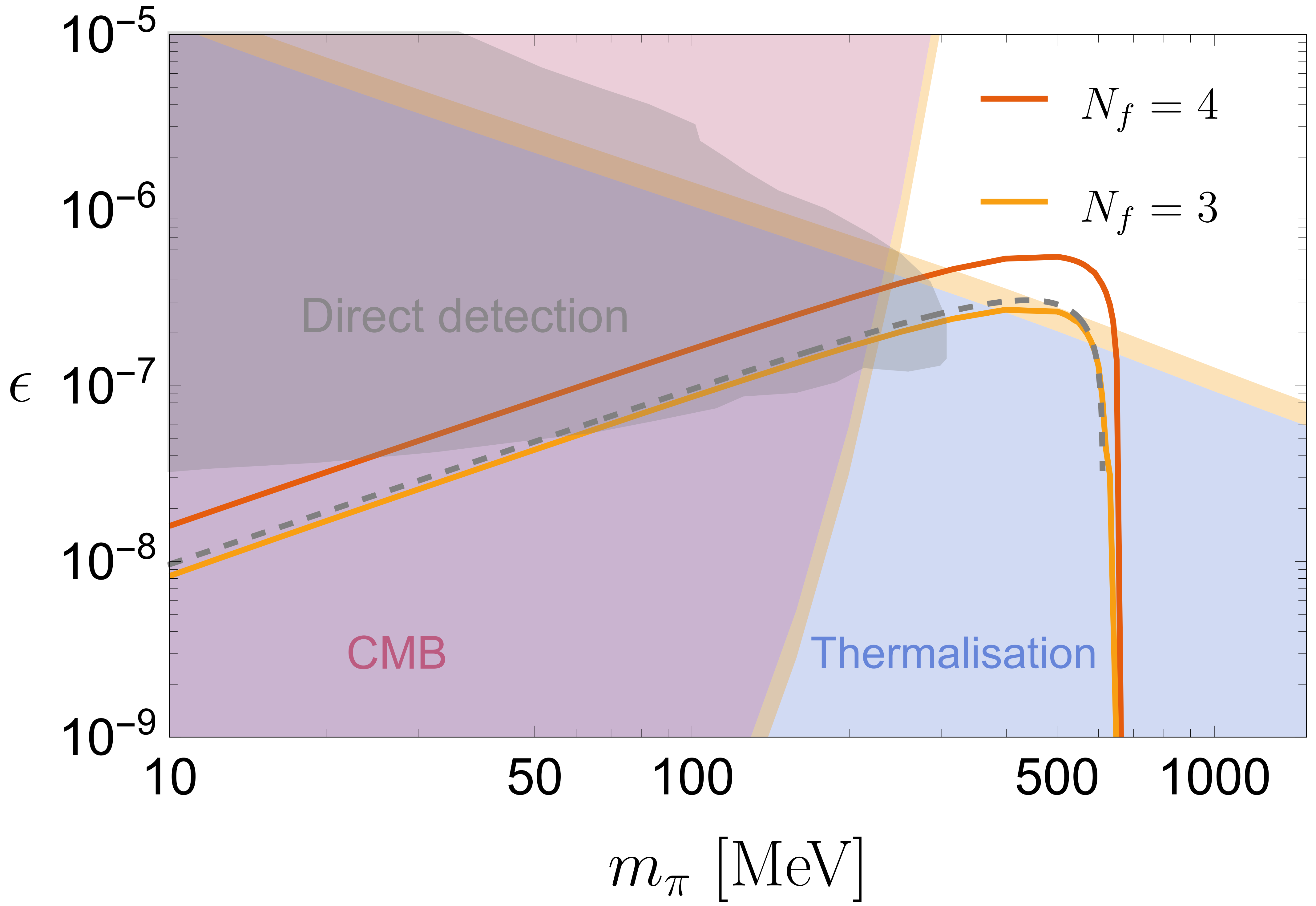


- Energy injection in the CMB

$$p_{\mathrm{ann}} = f(z) \frac{\langle \sigma v \rangle_{\pi\pi \to e^+ e^-}}{m_\pi} < 3.3 \times 10^{-31} \mathrm{cm}^3 \mathrm{s}^{-1} \mathrm{MeV}^{-1}$$

Planck collaboration (2018)

- Direct detection



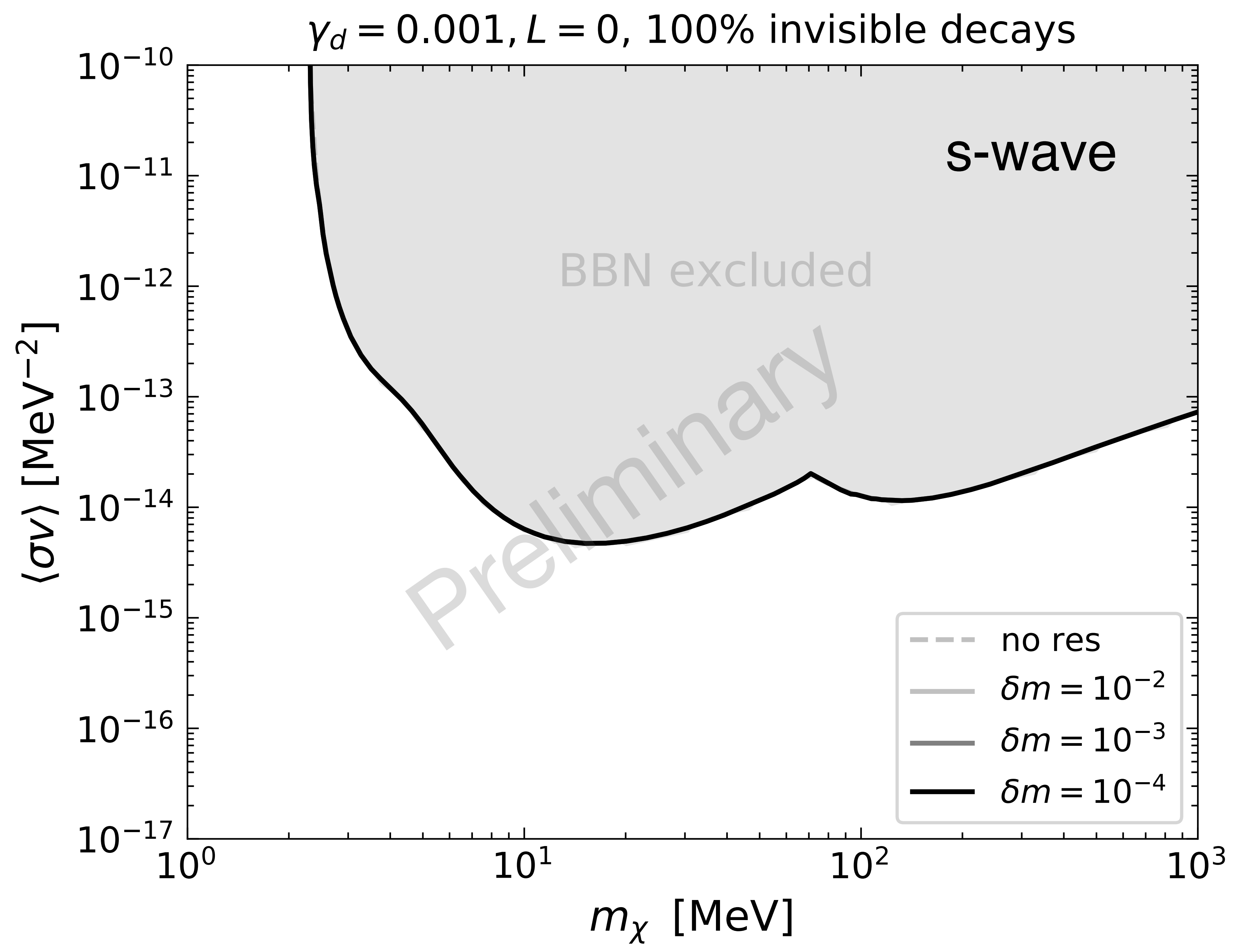
PB, Marieke Postma [2301.04513]

Viable model for $N_f = 4$ quarks!

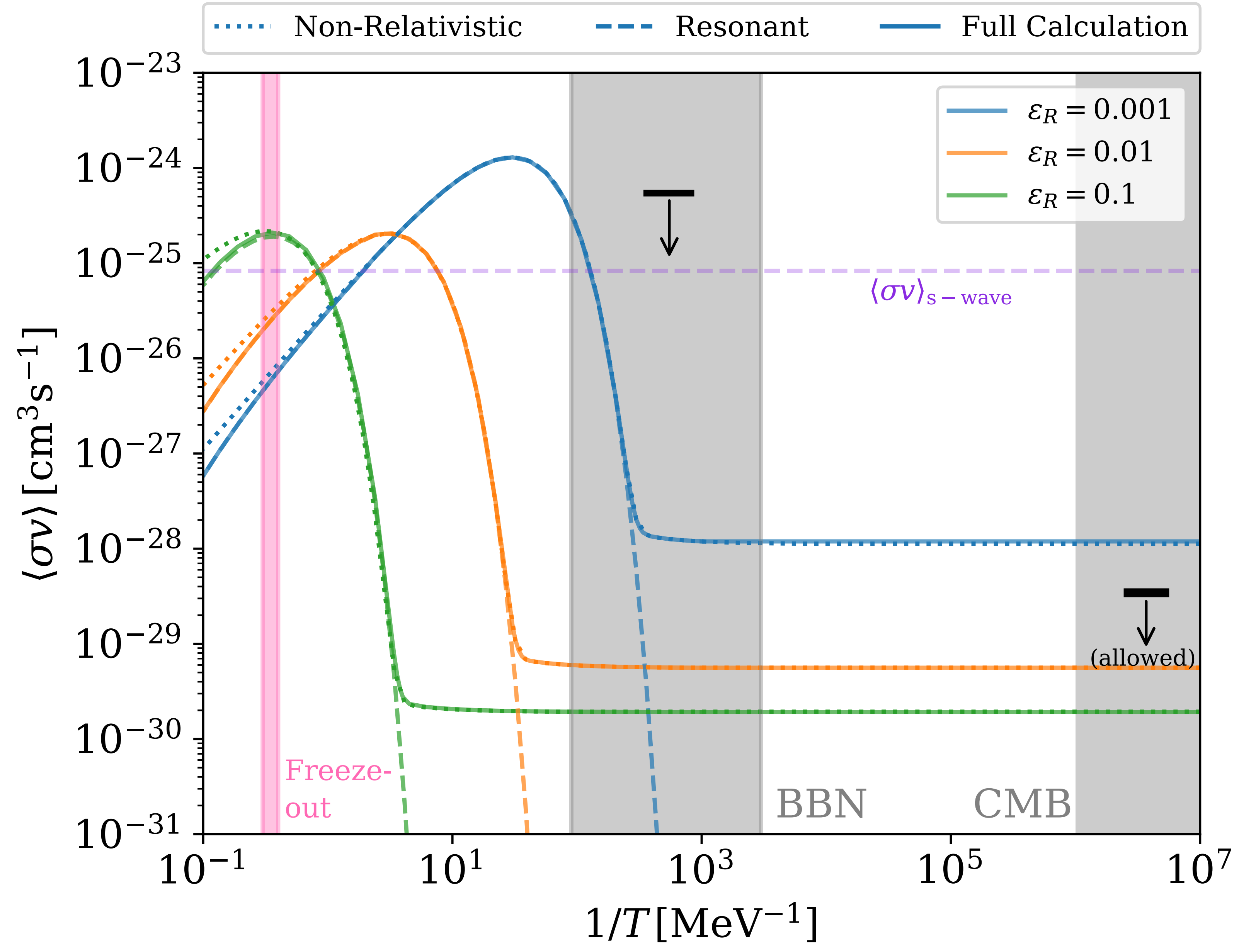
BBN bounds

DM annihilations after the end of BBN can disintegrate formed light element abundances

Effect of resonant annihilations with small mass splittings has not been explored: can have effective energy injection at late times

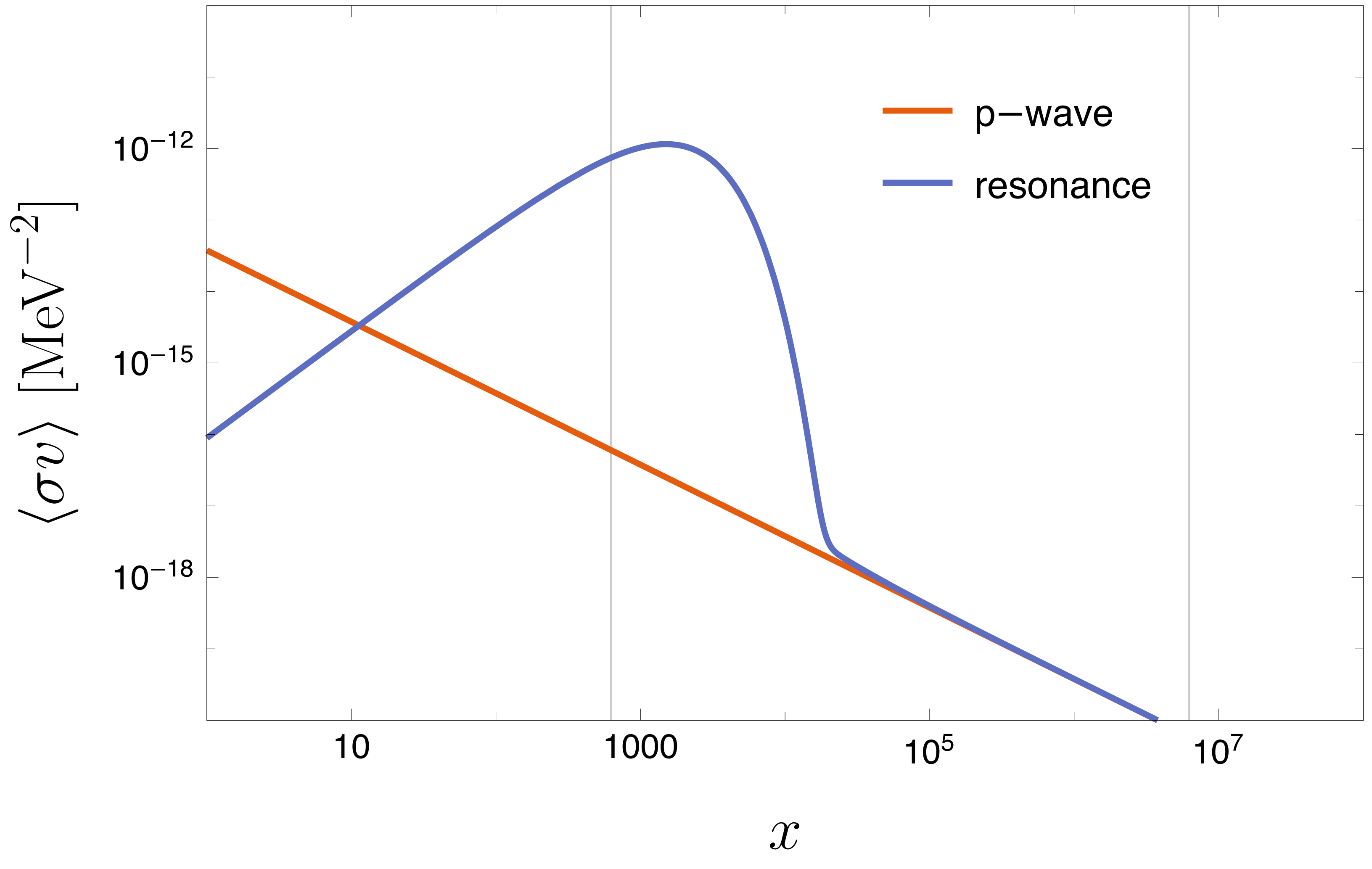


s-wave



Bernreuther et al. [2010.14522]

p-wave



Conclusions

- *Velocity-dependent* DM self-interactions can account for small scale structure problems at different scales (galaxies/clusters)

- A minimal setup containing dark pion and *resonantly produced* dark photons naturally gives the correct self-interactions (strength and velocity dependence), at the expense of a highly tuned photon mass

- As a result of the small mass splitting of the dark photons, DM *freeze-out* occurs over an *extended period of time*

- A viable setup evading CMB, thermalisation and direct detection bounds is obtained for $N_f = 4$ *quarks*

Thank you!

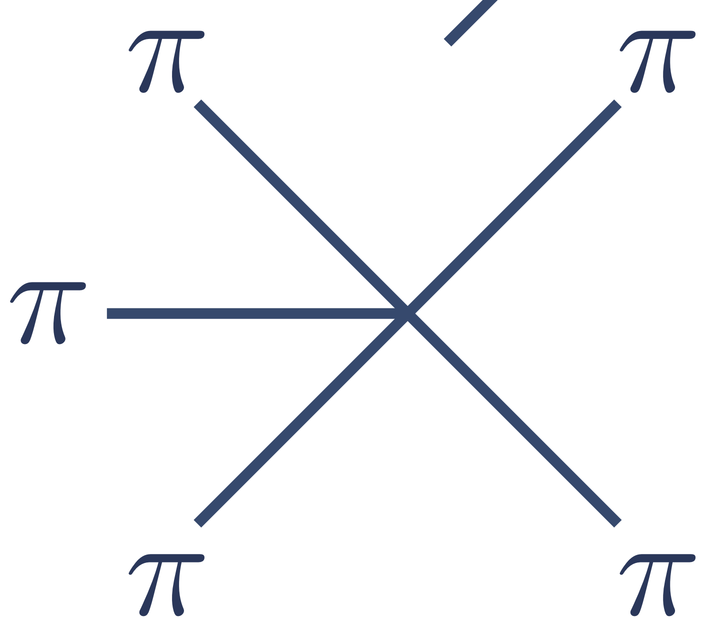
Backup

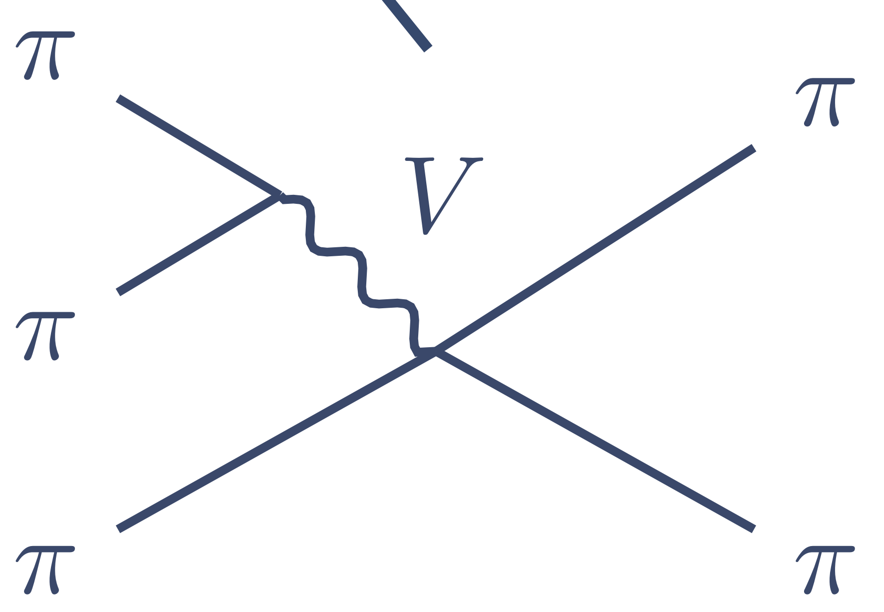
Resonance effect on relic density

$3 \to 2$ cross section is also resonantly enhanced

$$\dot{n} + 3Hn = -\langle \sigma v^2 \rangle_{3\to 2}(n^3 - n^2 n_{\rm eq})$$

$$\langle \sigma v^2 \rangle_{3\to 2} = \langle \sigma v^2 \rangle^{\rm 5pnt}_{3\to 2} + \langle \sigma v^2 \rangle^{\rm res}_{3\to 2}$$

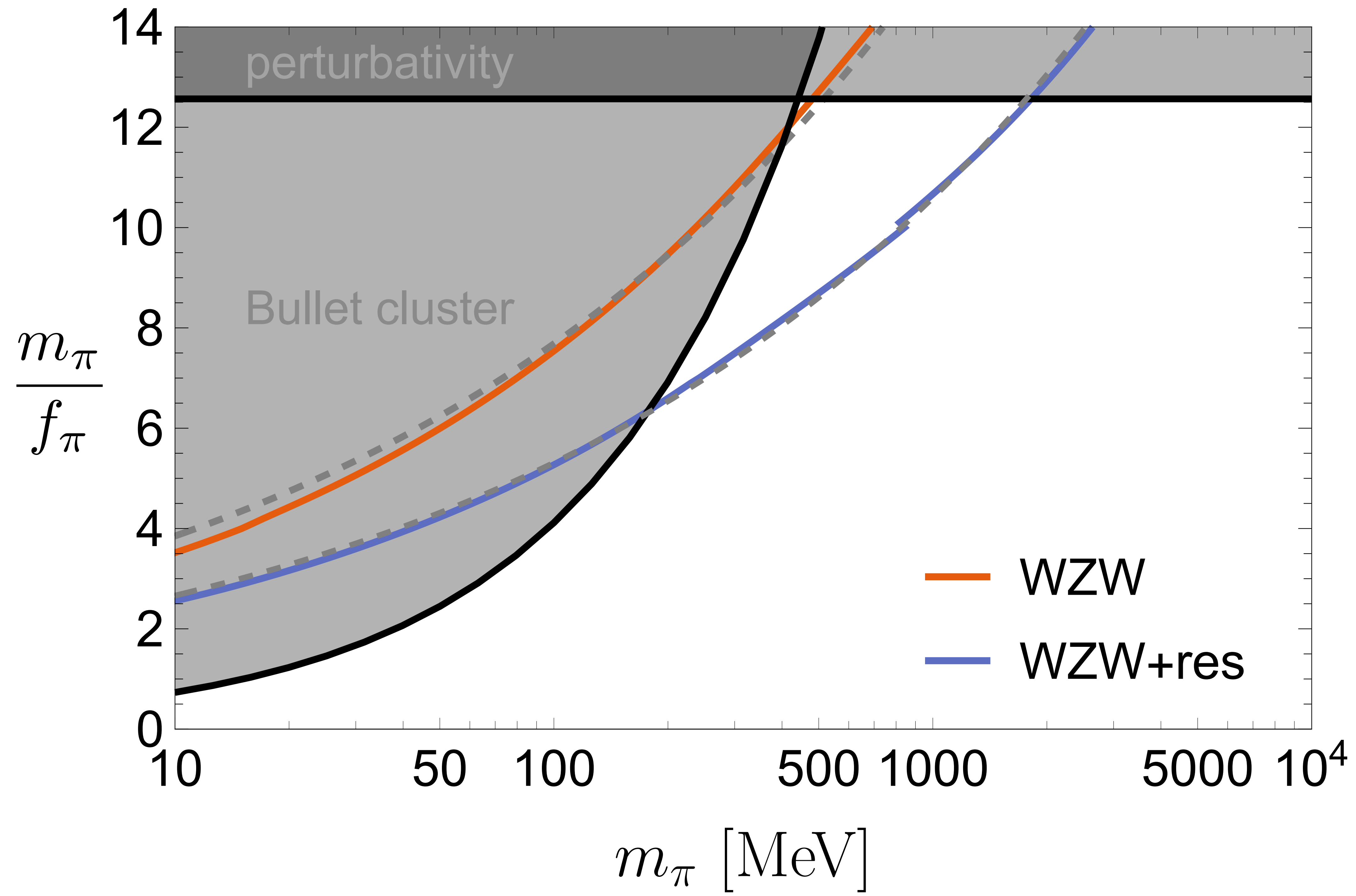




$$\langle \sigma v^2 \rangle^{\rm 5pnt}_{3\to 2} = \frac{5\sqrt{5}N_c^2}{1536\pi^5 N_f}\frac{\xi^{10}}{x^2 m_\pi^5}$$

$$\langle \sigma v^2 \rangle^{\rm 5res}_{3\to 2} = \frac{5\sqrt{5}N_c^2}{45\pi^{5/2} N_f C_4}\frac{\alpha_d \xi^6 \sqrt{x}}{m_\pi^5} e^{-\delta m x}$$

(large N_f)



PB, Marieke Postma [2301.04513]

Without resonance, it is hard to produce the correct relic density while evading bounds

Adding the resonance opens up part of the parameter space!

Dropping small scale structure

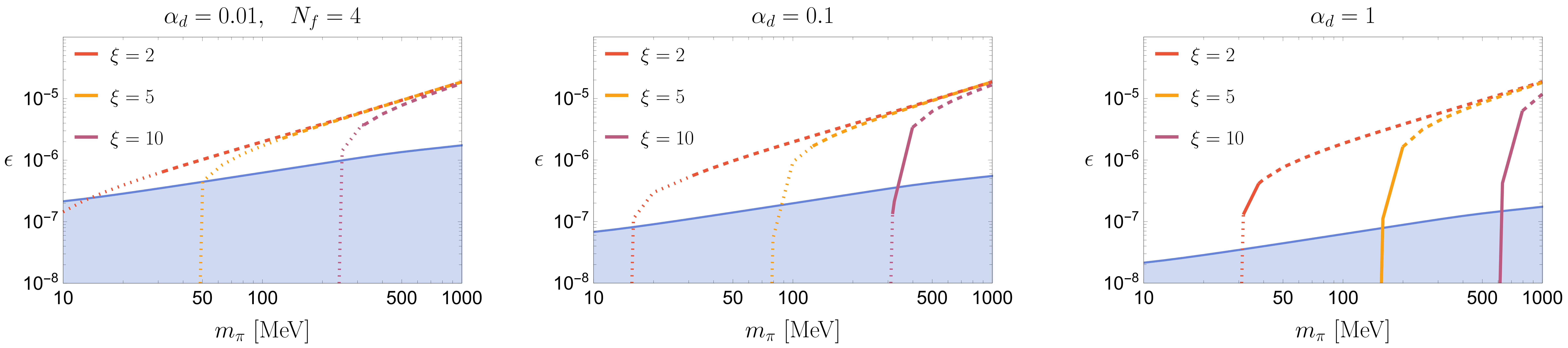
$\delta m = 10^{-3}$

Excluded by Bullet cluster

WIMP-like pions

SIMP-like pions

Model also works for other choice of parameters, but cannot address small scale issues



PB, Marieke Postma [2301.04513]

Resonance is *strong*, need large α_d or ξ to stay in SIMP-regime