SIMPly add a dark photon

Based on work with Marieke Postma
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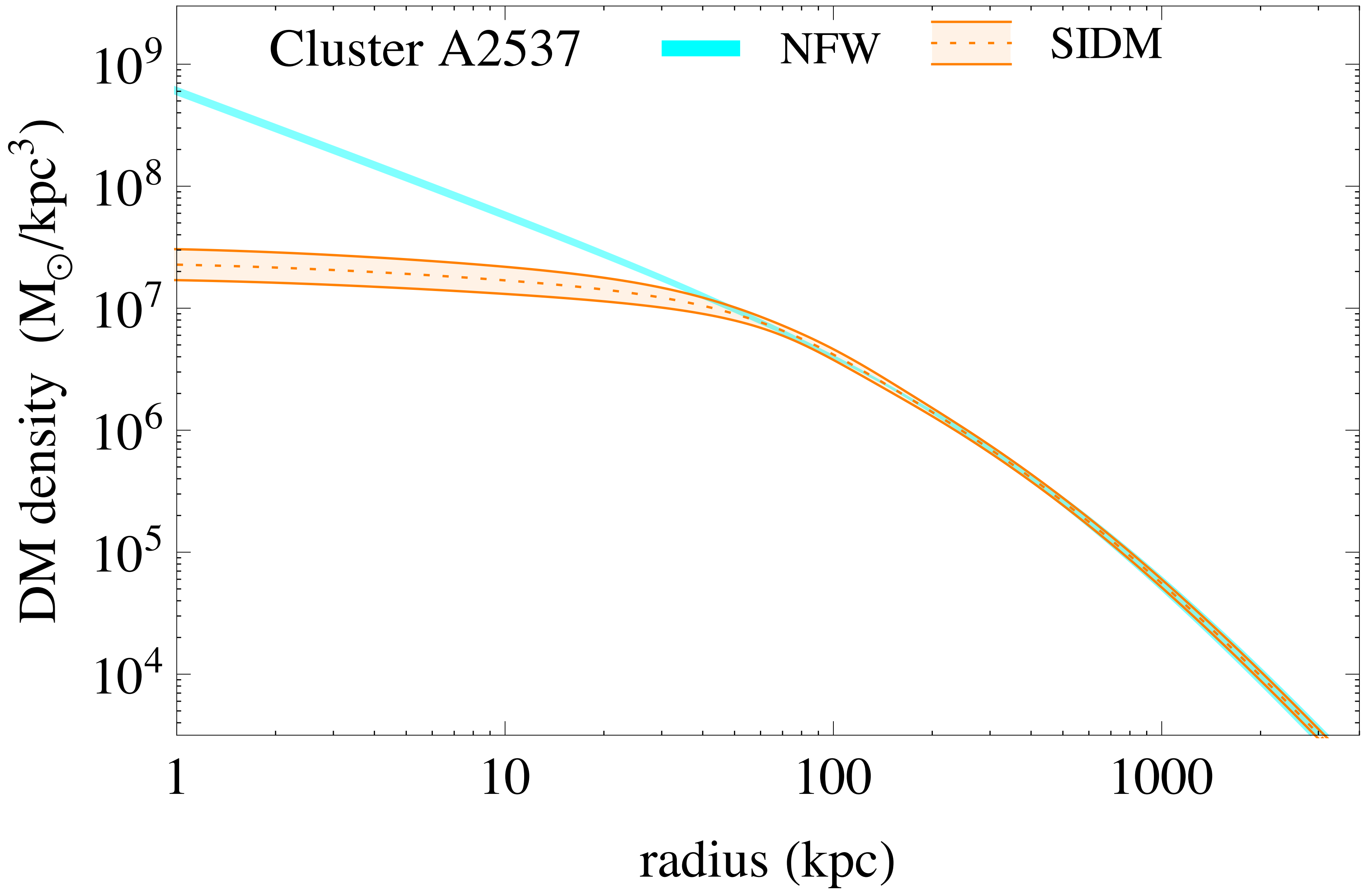
Pieter Braat
pbraat@nikhef.nl
Light Dark World 23
19-09-23

Nikhef
University of Amsterdam

Motivation: small scale structure problems

Observations of DM halos prefer self-interacting DM over collisionless DM: *cusp-core* problem



Adapted from Kaplinghat et al. [1508.03339]

The required self-interactions are strong

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

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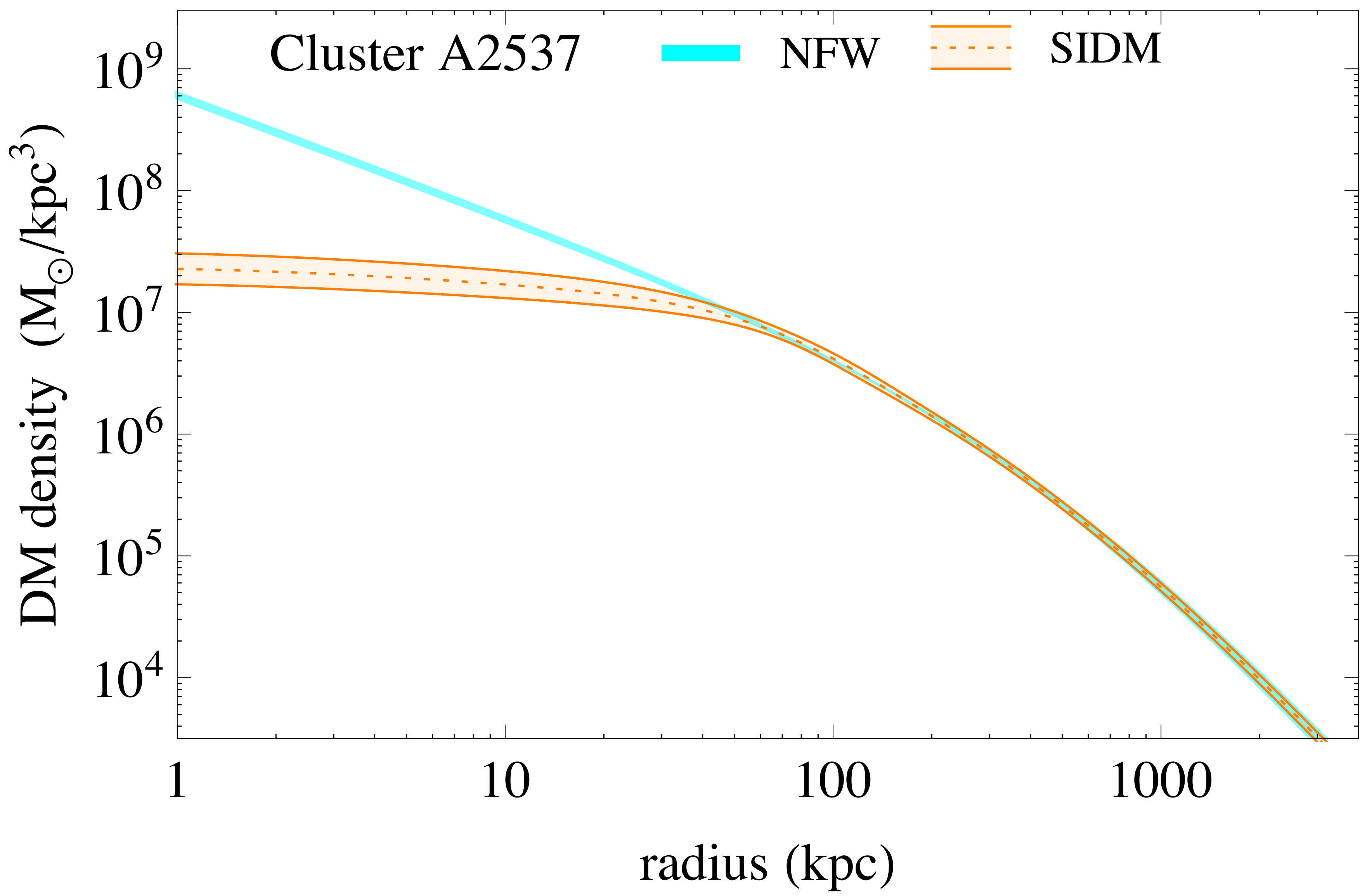

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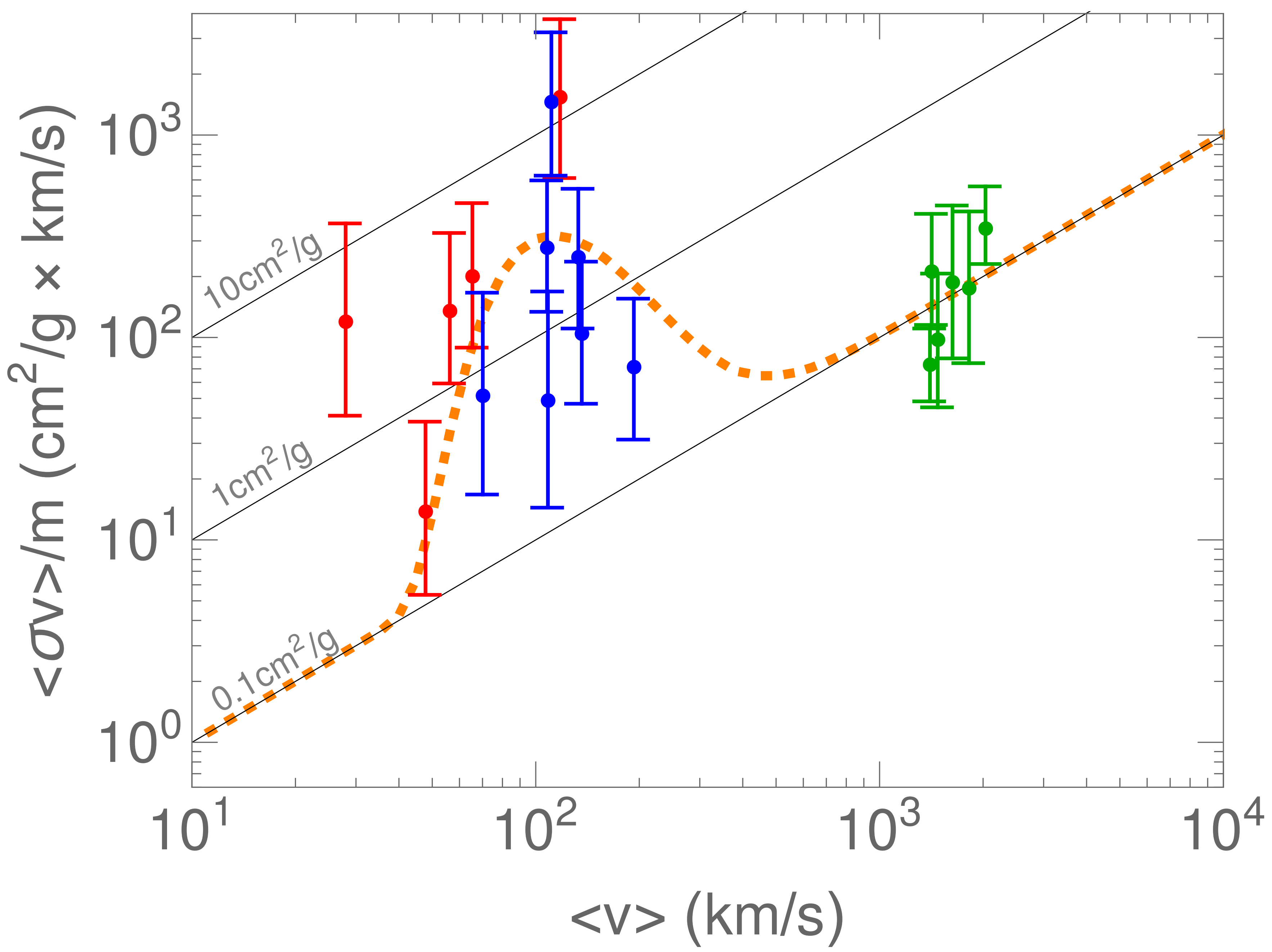
$$\frac{\sigma}{m} \sim 0.1 - 1\ \mathrm{cm}^2/\mathrm{g}$$

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

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



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Dark pions and photons

Dark matter: pions

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

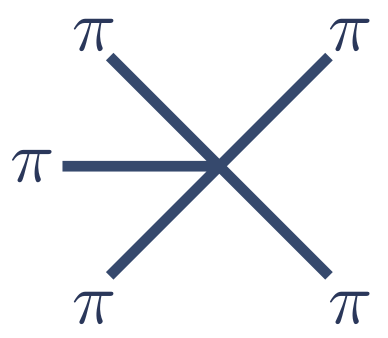
At low energies, phenomenology described by dark pions π' that make up the DM ($N_f^2 - 1$ of them)

$$\boldsymbol{\pi} = \pi^a T^a$$

$$\mathcal{L}_{\chi\mathrm{PT}} = \mathrm{Tr}(\partial_\mu \boldsymbol{\pi} \partial^\mu \boldsymbol{\pi}) - m_\pi^2 \mathrm{Tr}(\boldsymbol{\pi}^2) + \frac{m_\pi^2}{f_\pi^2} \mathcal{O}(\boldsymbol{\pi}^4) + \dots$$

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!

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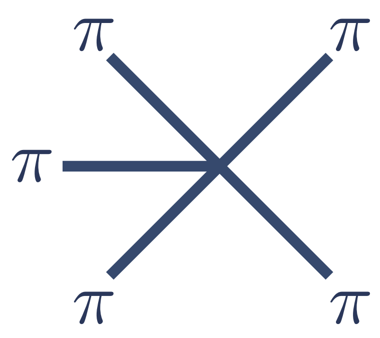

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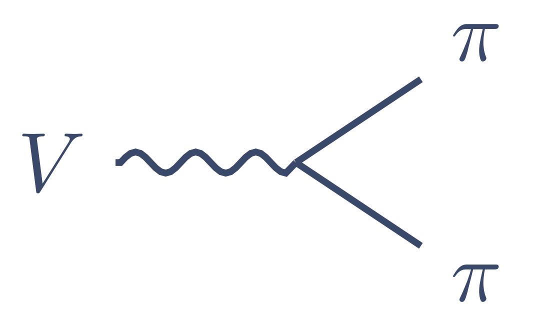
Resonance: dark photon

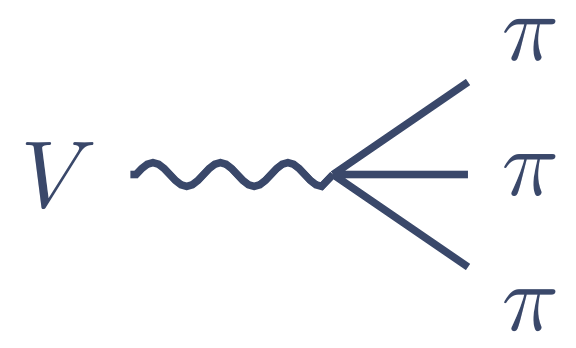
Dark copy of $U(1)_d$, but with a *massive* gauge boson with mass close to twice the dark pion mass $m_V = m_\pi(2 + \delta m)$

$$\mathcal{L}_V = -\frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V V_\mu^2 \qquad Q = \mathrm{diag}(1, -1, 1, -1, \ldots)$$

$$+ 2ig_D V^\mu \mathrm{Tr}(Q[\boldsymbol{\pi}, \partial_\mu \boldsymbol{\pi}])$$



$$- i\frac{N_c g_D}{3\pi^2 f_\pi^3}\epsilon^{\mu\nu\rho\sigma}V_\mu \mathrm{Tr}(Q\partial_\nu\boldsymbol{\pi}\partial_\rho\boldsymbol{\pi}\partial_\sigma\boldsymbol{\pi})$$



$$- \epsilon V_\mu J_{\mathrm{SM}}^\mu$$

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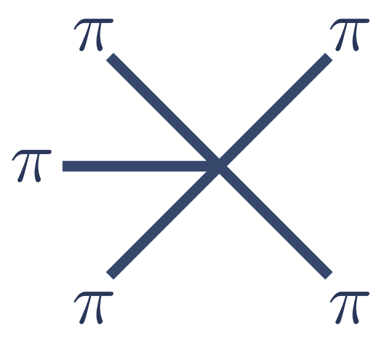

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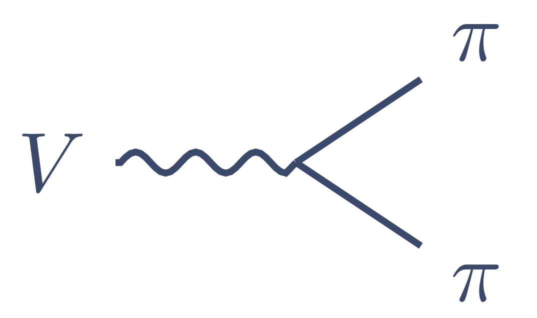

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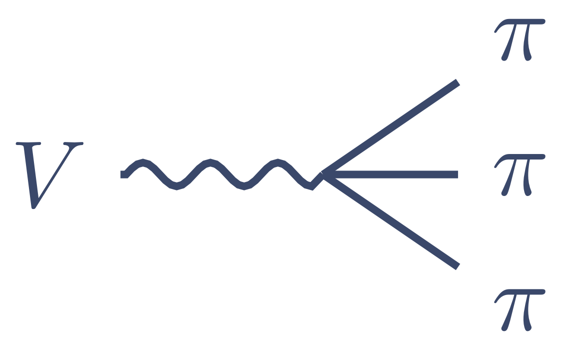

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Minimal setup: parameters $\{m_\pi, f_\pi, g_D, \delta m, \epsilon\}$

Relic abundance

We wish to produce the DM relic density

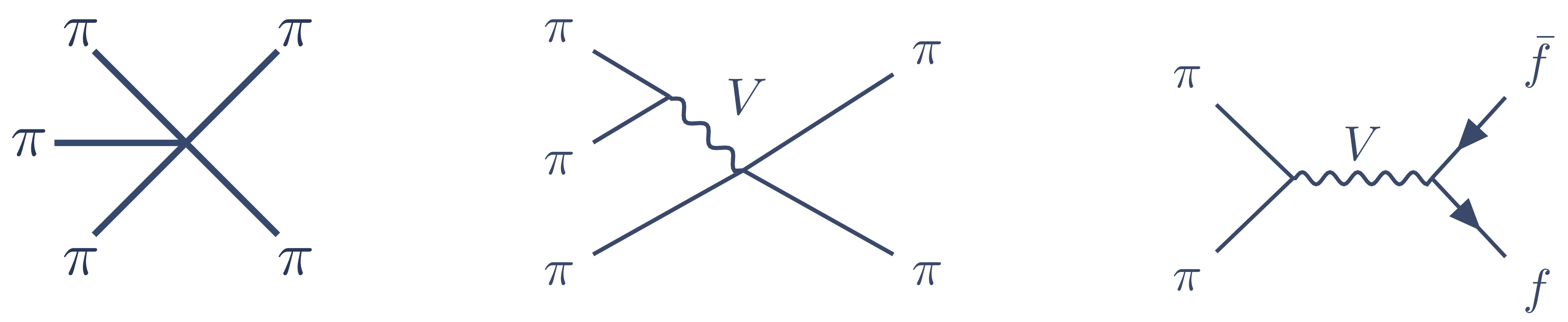
$$\Omega_{\rm DM} h^2 = 0.12010$$

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 states (ϵ^2-*suppressed*, but resonantly *enhanced*)

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



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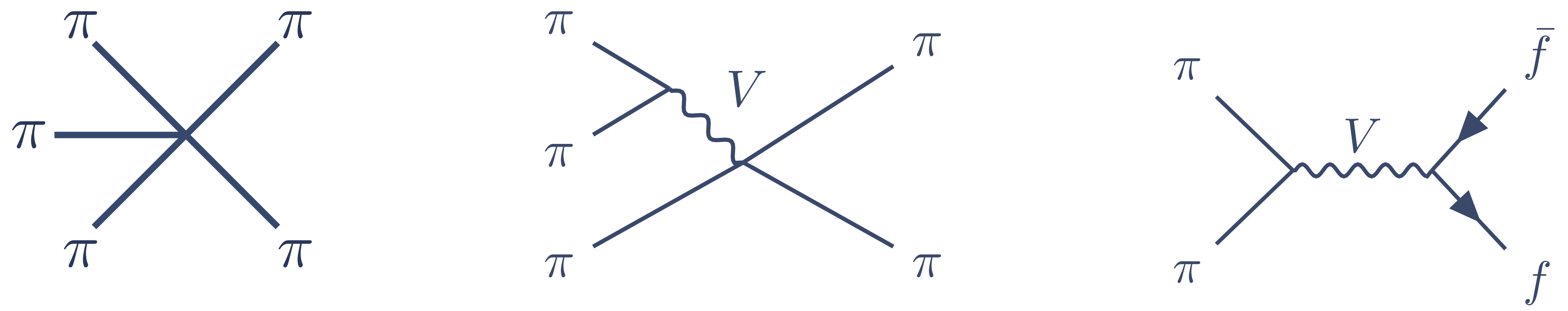
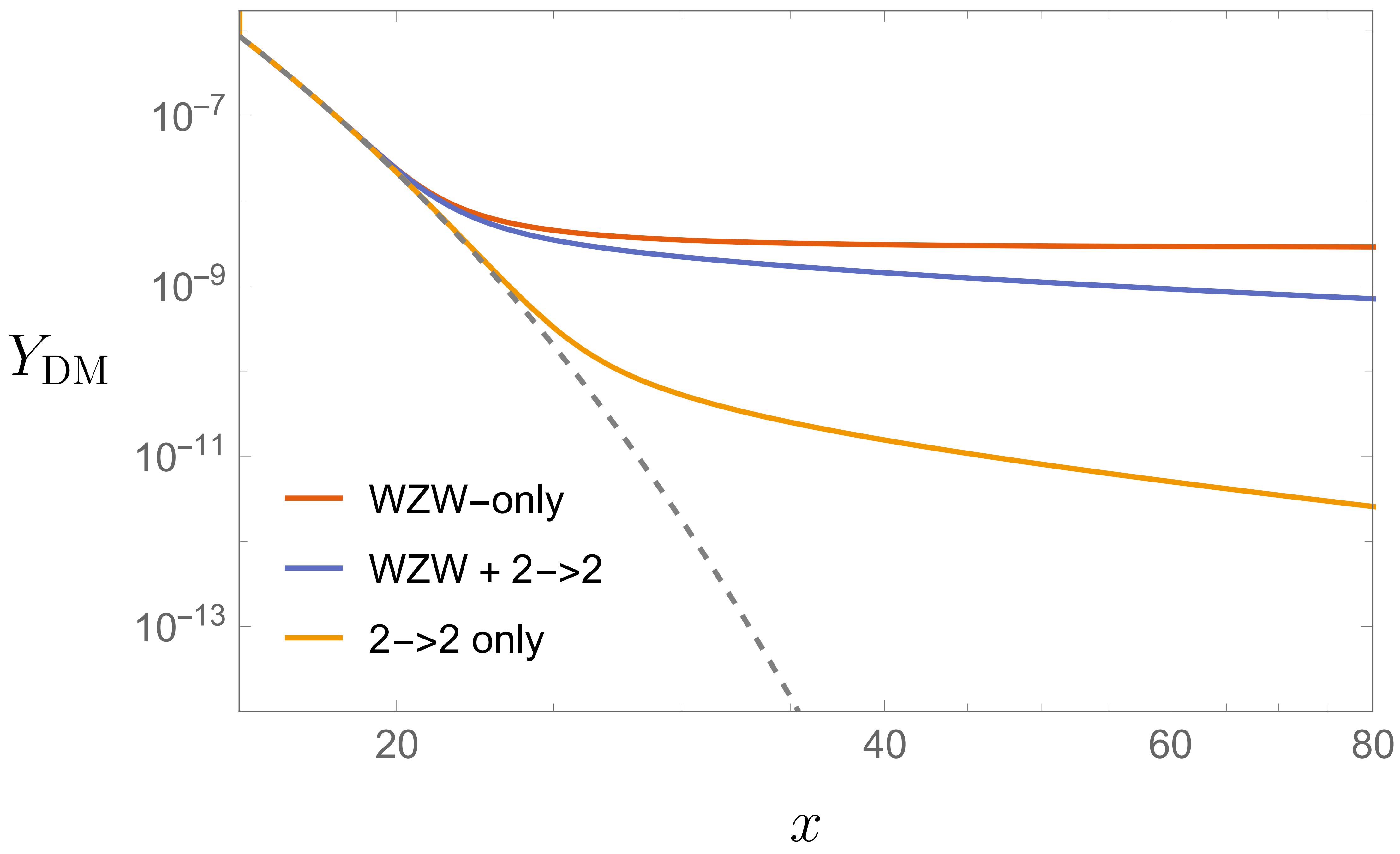


In dimensionless quantities: $Y \equiv \dfrac{n_{\mathrm{DM}}}{s}, \quad x = \dfrac{m}{T}$

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



Extended *period* of (slow) freeze-out until $x \sim \delta m^{-1}$

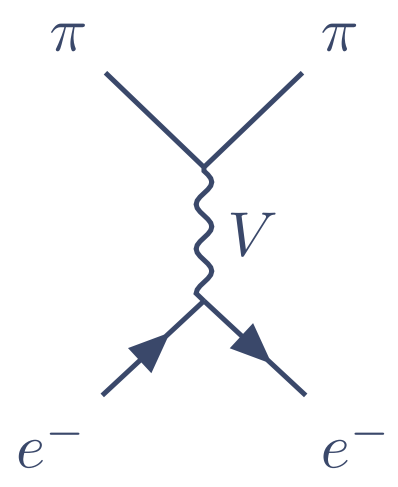
Viable parameter space

Kinetic mixing ϵ is constrained by different probes:

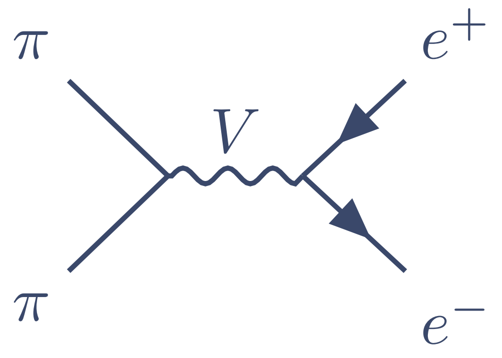
- Require dark and SM sectors be in thermal equilibrium at freeze-out

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

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



- Cosmological bounds:
  - Photodisintegration of light elements (BBN) **PB** [2309.xxxxx]
  - Energy injection in 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: beam dump experiments

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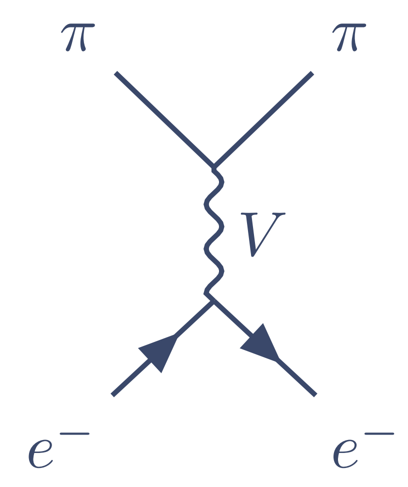

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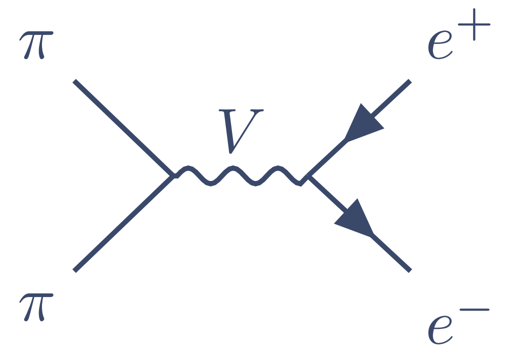

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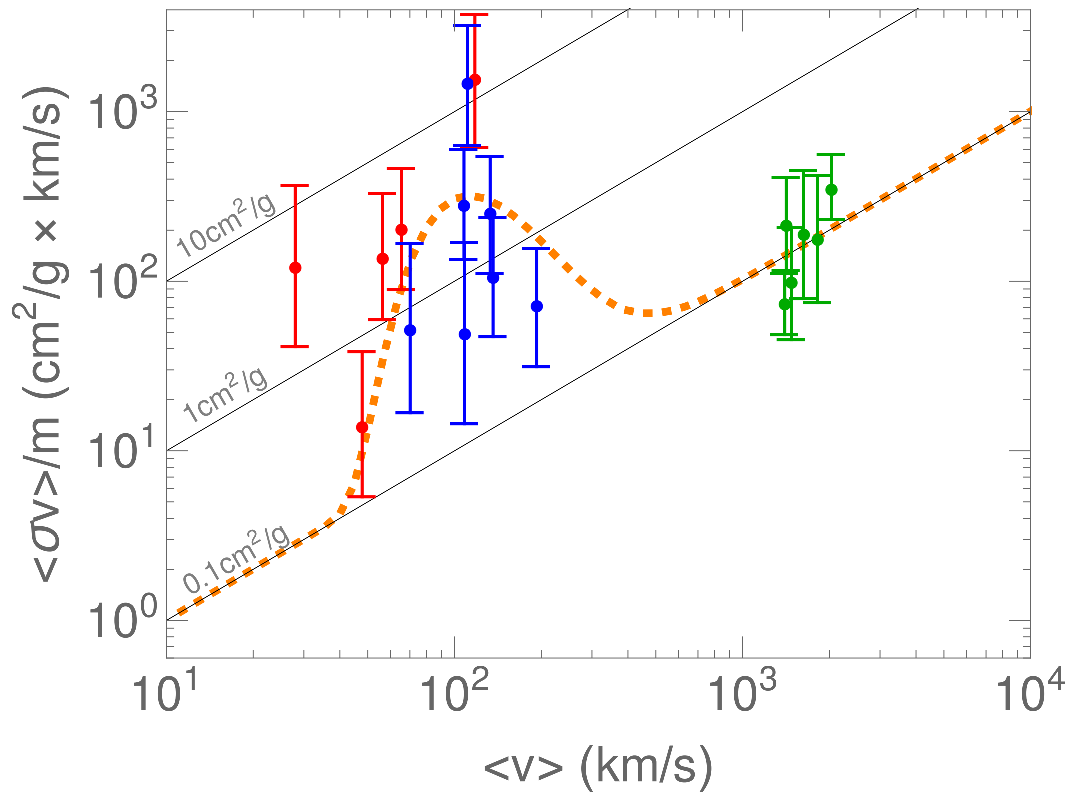

Fixed $\begin{cases} \delta m = 10^{-7.5} \\ \sigma/m = 0.11\ {\rm cm}^2/{\rm g} \quad \text{(fixes } \frac{m_\pi}{f_\pi}\text{)} \\ g_D = 0.21\left(\frac{m_\pi}{100\ {\rm MeV}}\right)^{3/2} \end{cases}$

$$\{m_\pi, \xi, g_D, \delta m, \epsilon\}$$

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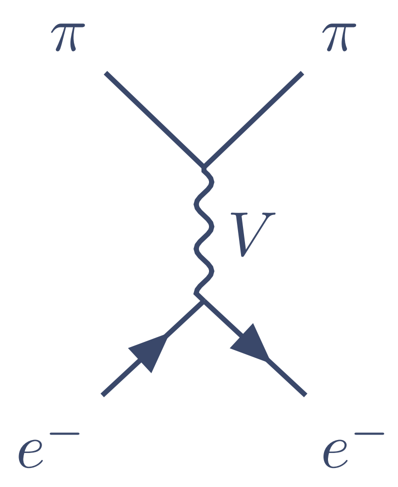

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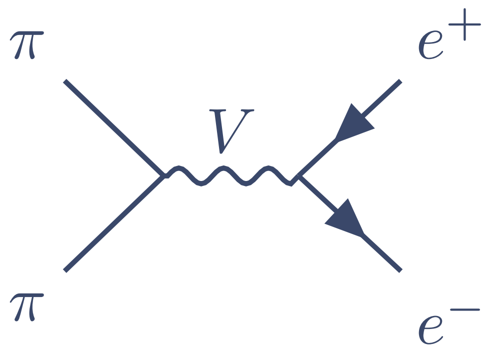

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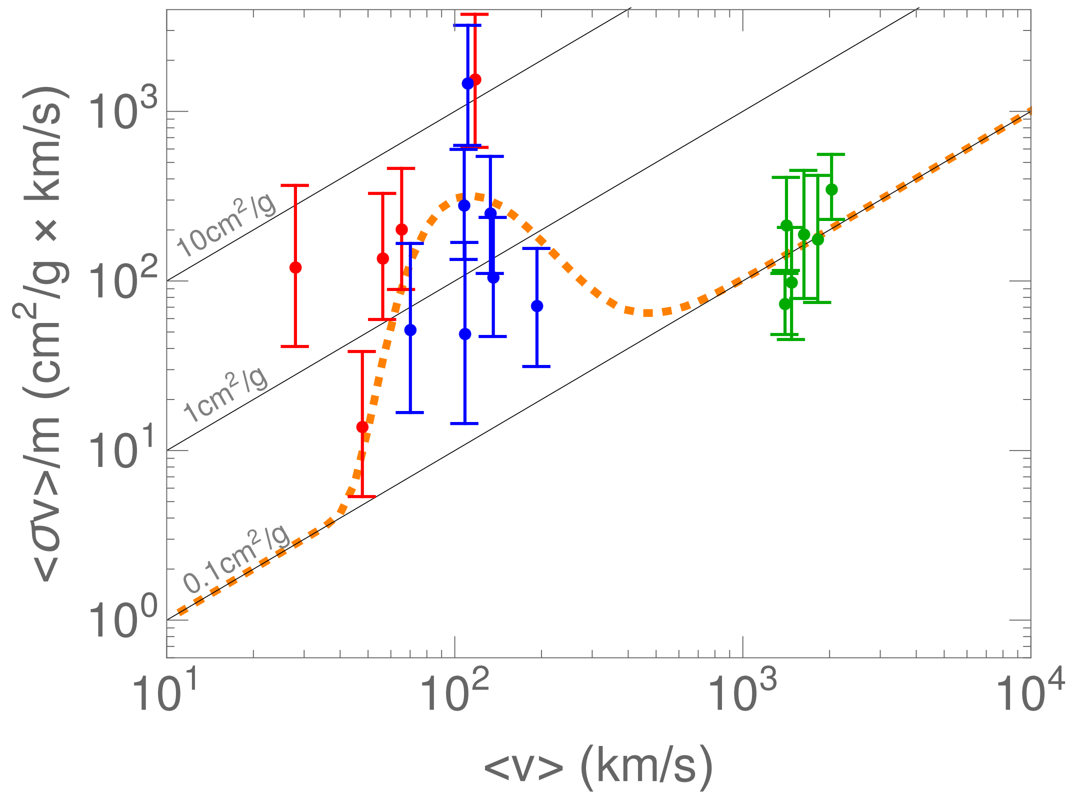

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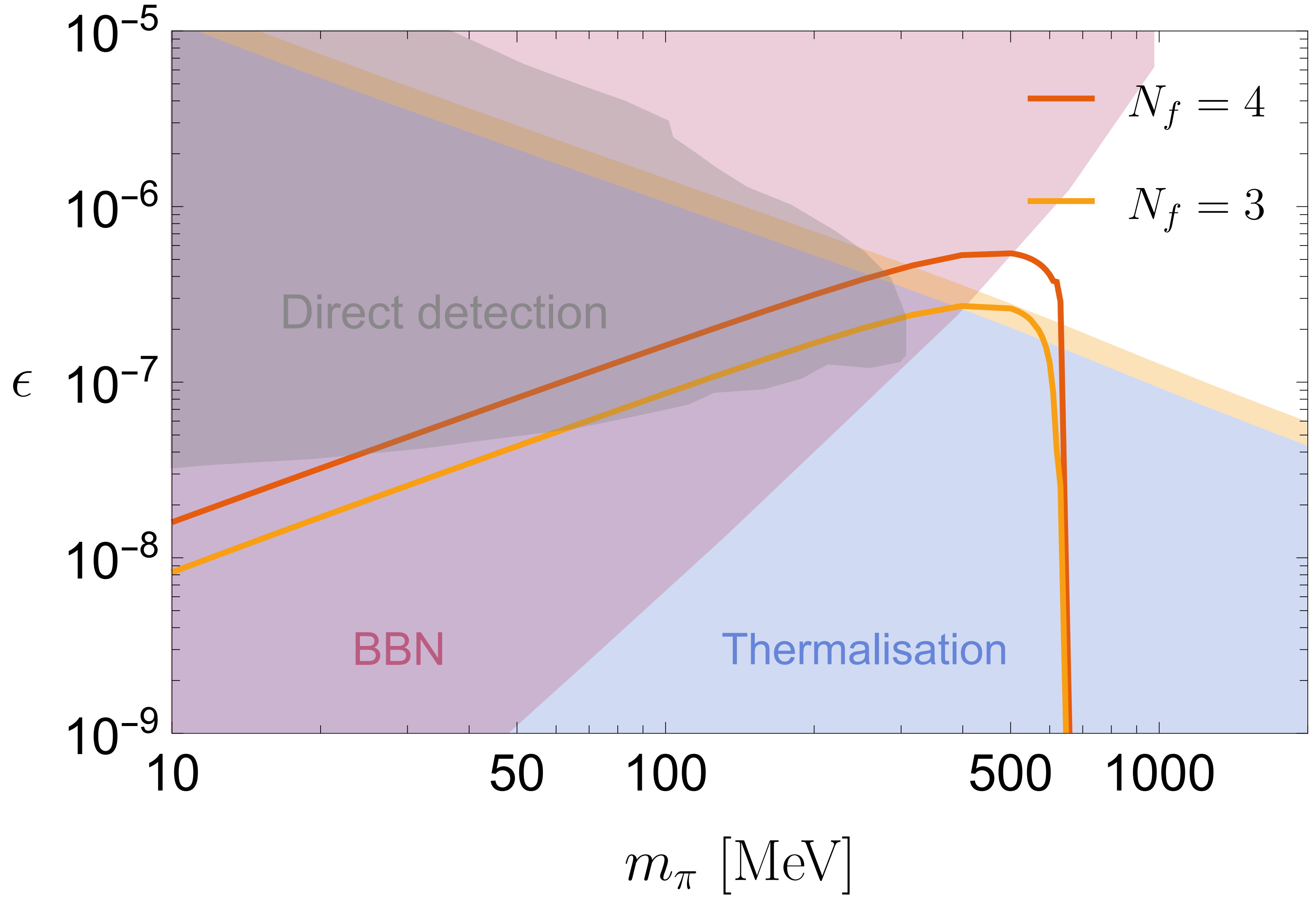


PB, Marieke Postma [2301.04513]

Viable model for $N_f = 4$ quarks!

Conclusions

- Observations of DM halos hint at DM with strong self-interactions: small scale structure problems

- *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 BBN, thermalisation and direct detection bounds is obtained for $N_f = 4$ *quarks*

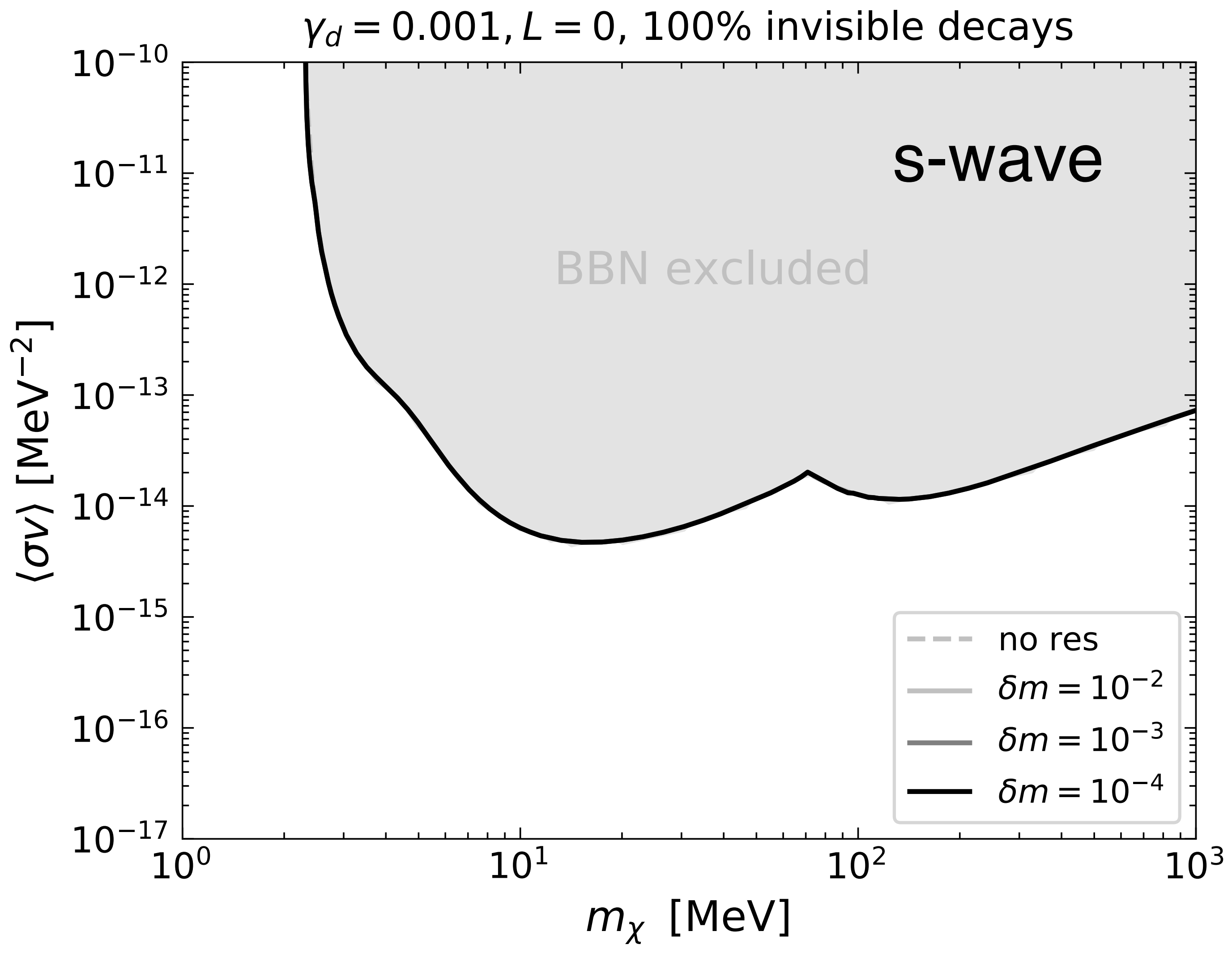
Thank you!

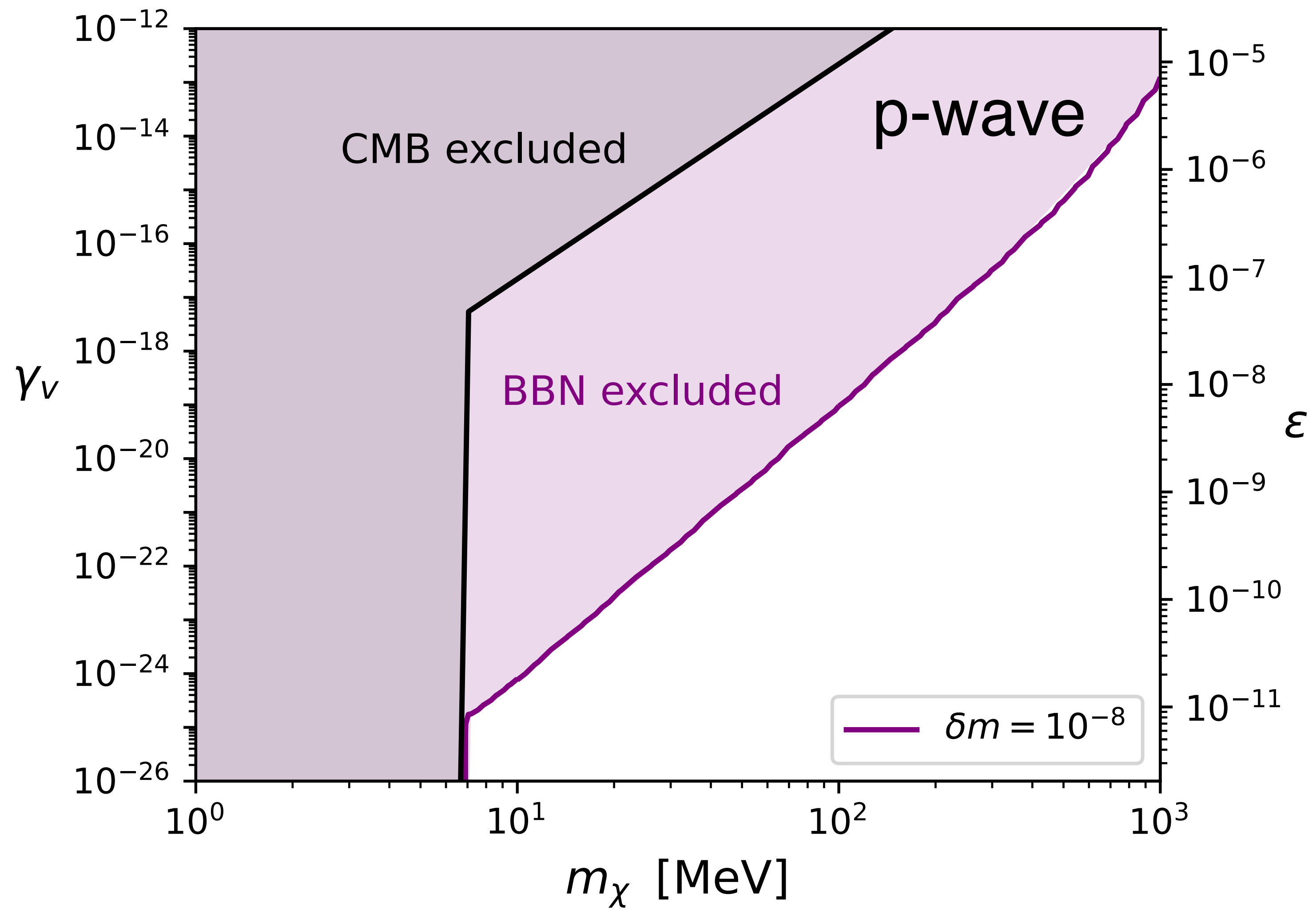
Backup

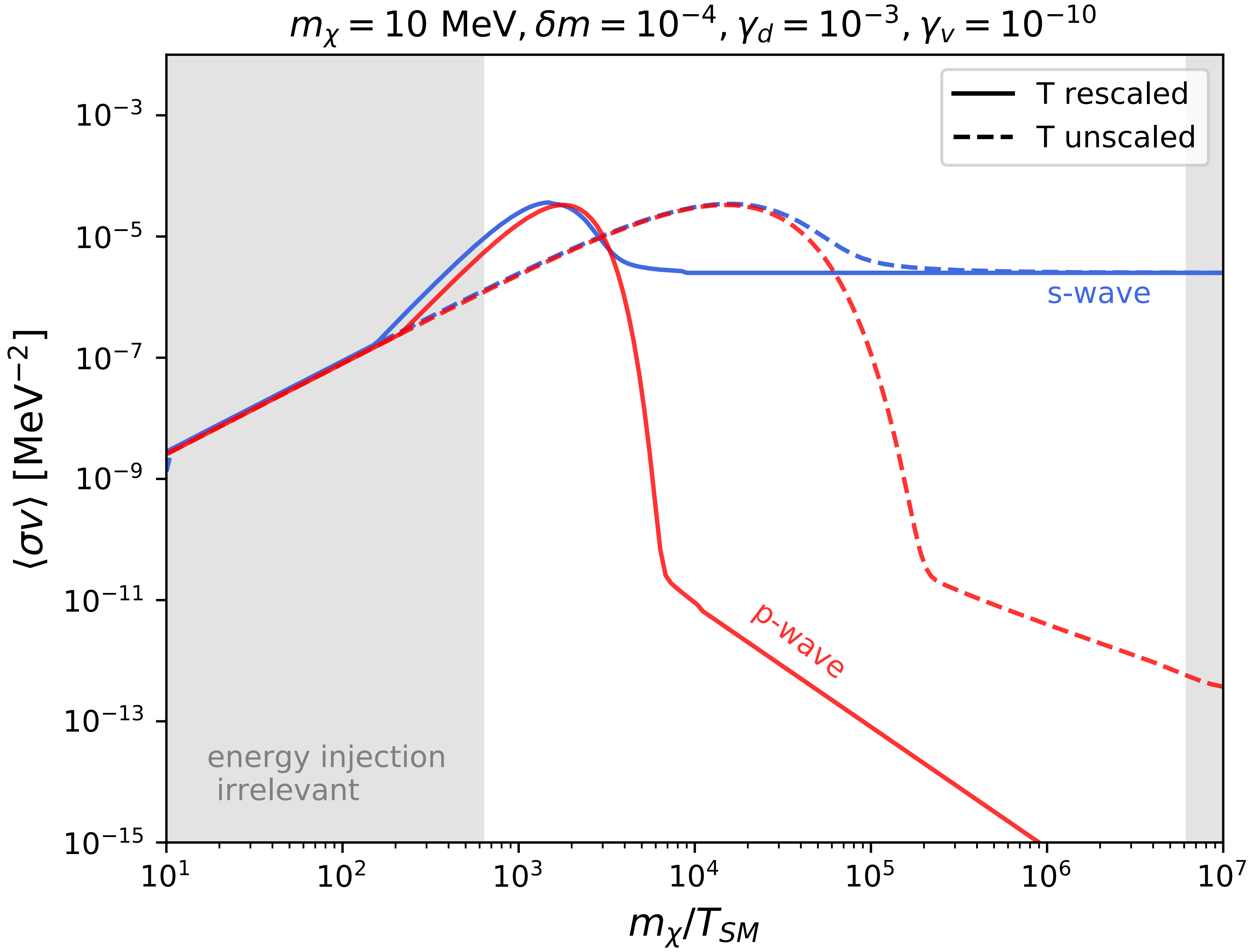
BBN bounds

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





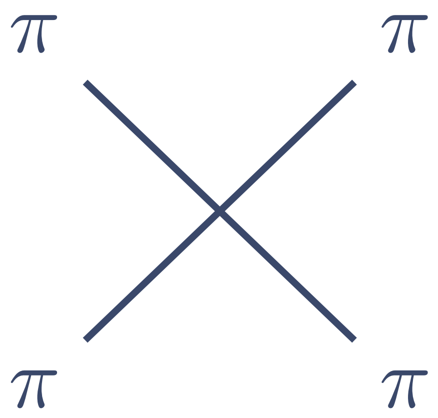


Self-interactions

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

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

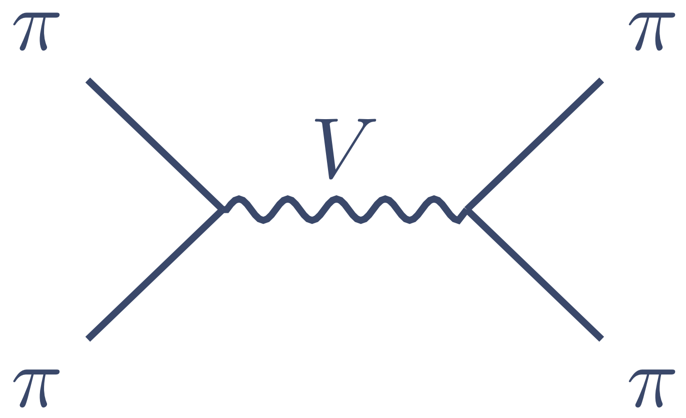
The pions have a *constant* contact interaction



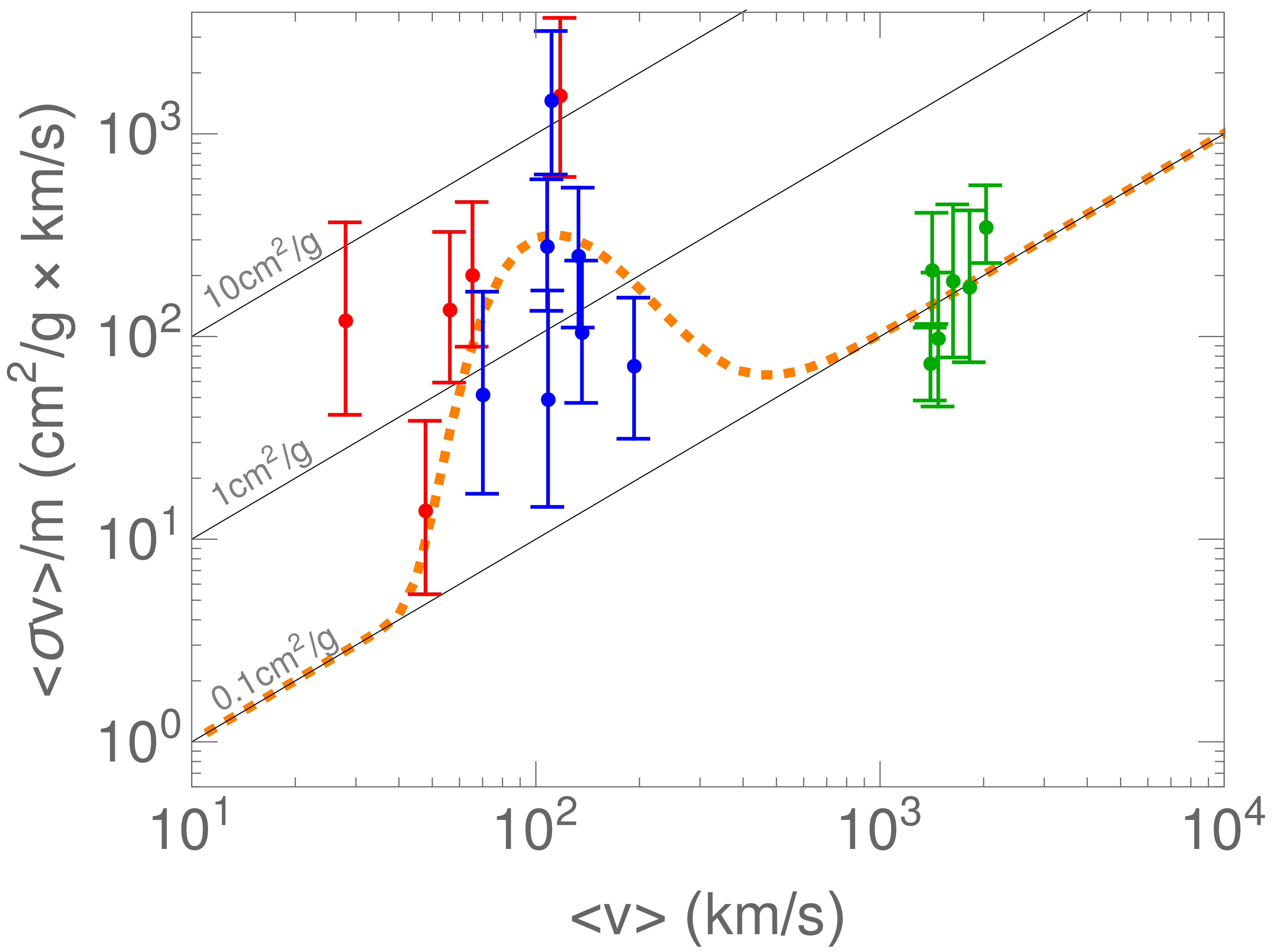
$$\sigma_{\text{contact}} \overset{p\ll m_\pi}{\approx} \frac{N_f^2}{64\pi(N_f^2-1)} \frac{\xi^4}{m_\pi^2}$$

(large N_f)

Dark photon exchange gives velocity dependence



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



Adapted from Chu et al. [1810.04709]

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

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

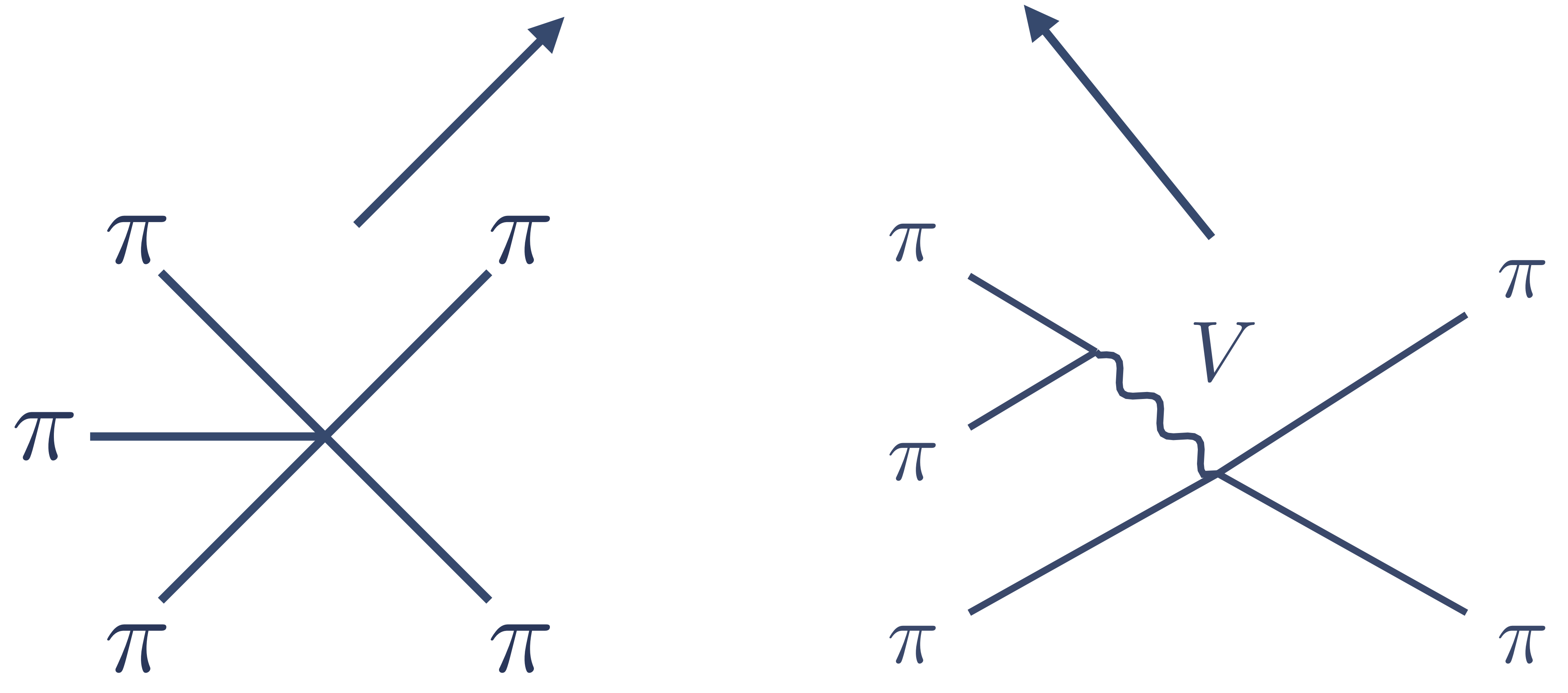
extremely small!

Resonance effect on relic density

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

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

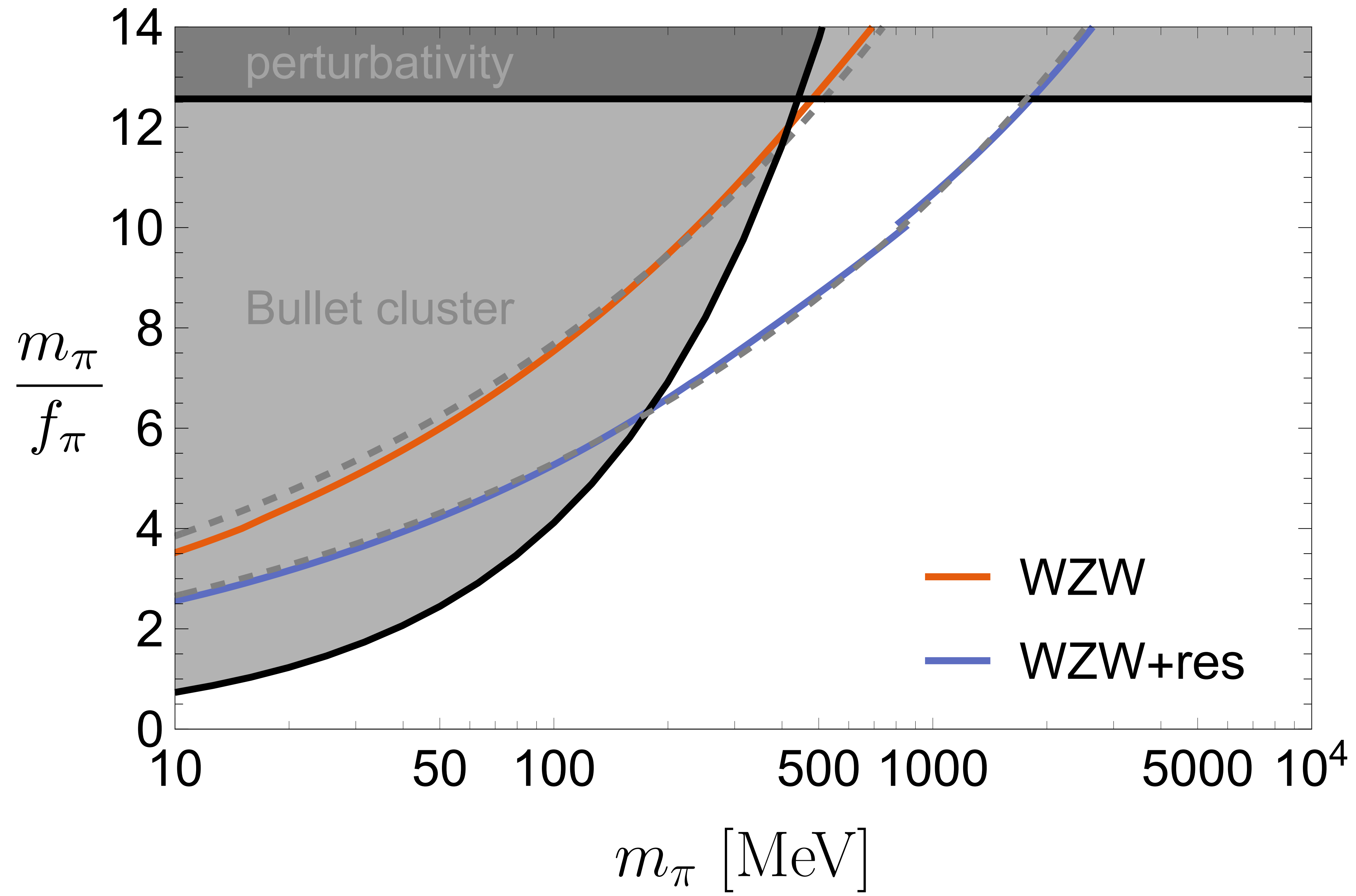
$$\langle \sigma v^2 \rangle_{3\to 2} = \langle \sigma v^2 \rangle^{\rm 5pnt}_{3\to 2} + \langle \sigma v^2 \rangle^{\rm res}_{3\to 2}$$



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

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

(large N_f)



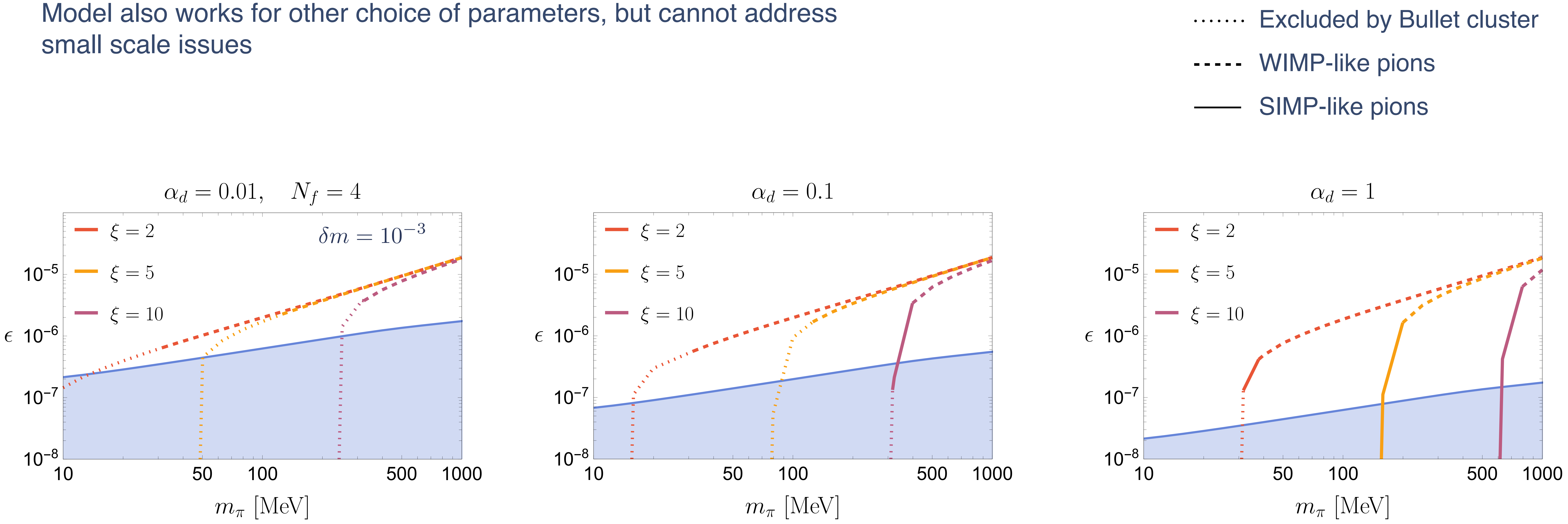
PB, Marieke Postma [2301.04513]

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

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



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