Big Bang Nucleosynthesis constraints on resonant DM annihilations

Pieter Braat
Work together with Marco Hufnagel
60th International School on Subnuclear Physics
Erice

Nikhef
University of Amsterdam

Photodisintegration

Short recap: Big Bang Nucleosynthesis is the process in which abundances of the lightest elements are produced

and: observations match theory predictions

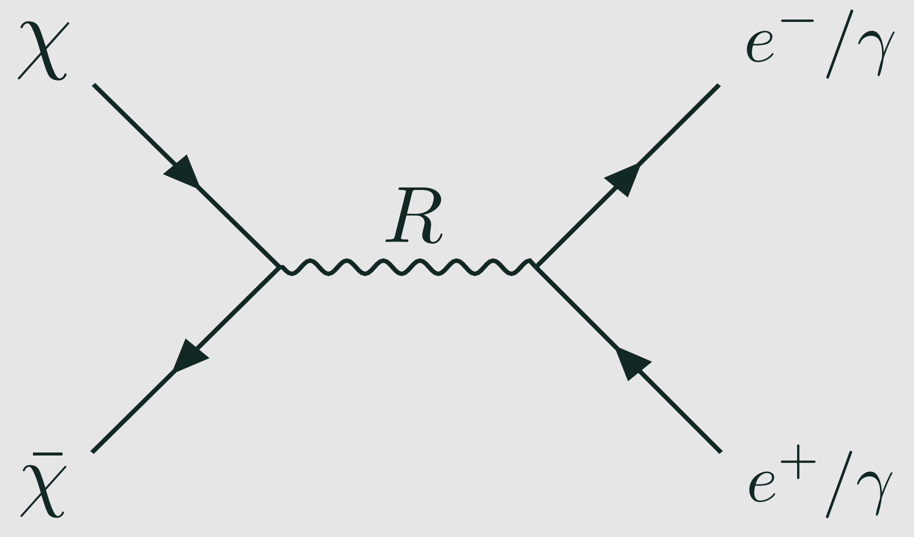
Photodisintegration

Short recap: Big Bang Nucleosynthesis is the process in which abundances of the lightest elements are produced

and: observations match theory predictions

EM energy injection (from BSM Physics) can destroy the newly formed elements

e.g. DM annihilations $\chi\bar{\chi} \to e^-e^+/\gamma\gamma$



Cascade equations

Solve the cascade equations for $X \in \{\gamma, e^-, e^+\}$

$$f_X(E) = \frac{1}{\Gamma_X(E)}\left(\underbrace{S_X(E)}_{\text{source term}} + \int_E^\infty dE' \sum_{X'} \underbrace{K_{X' \to X}(E, E') f_{X'}(E')}_{\text{conversion/scattering}} \right)$$

Cascade equations

Solve the cascade equations for $X \in \{\gamma, e^-, e^+\}$

$$f_X(E) = \frac{1}{\Gamma_X(E)}\Bigg(\underbrace{S_X(E)}_{\text{source term}} + \int_E^\infty dE' \sum_{X'} \underbrace{K_{X' \to X}(E, E') f_{X'}(E')}_{\text{conversion/scattering}} \Bigg)$$

Source term contains monochromatic and final state radiation (FSR) contribution

$$S_X(E) = S_X^{(0)} \delta(E - m_\chi) + S_X^{\mathrm{FSR}}(E)$$

Monochromatic injection depends on the coupling to photons/electrons

$$S_X^{(0)} \propto n_\chi^2 \langle \sigma v \rangle_{\chi\chi \to XX}$$

Final state radiation source accounts for $\chi\chi \to e^+ e^- \gamma$ interactions

$$S_\gamma^{\mathrm{FSR}} \propto n_\chi^2 \langle \sigma v \rangle_{\chi\chi \to e^+ e^-}$$

Cascade equations

Solve the cascade equations for $X \in \{\gamma, e^-, e^+\}$

$$f_X(E) = \frac{1}{\Gamma_X(E)}\Big(\underbrace{S_X(E)}_{\text{source term}} + \int_E^\infty dE' \sum_{X'} \underbrace{K_{X' \to X}(E, E') f_{X'}(E')}_{\text{conversion/scattering}} \Big)$$

Source term contains monochromatic and final state radiation (FSR) contribution

$$S_X(E) = S_X^{(0)} \delta(E - m_\chi) + S_X^{\mathrm{FSR}}(E)$$

Monochromatic injection depends on the coupling to photons/electrons

$$S_X^{(0)} \propto n_\chi^2 \langle \sigma v \rangle_{\chi\chi \to XX}$$

Final state radiation source accounts for $\chi\chi \to e^+ e^- \gamma$ interactions

$$S_\gamma^{\mathrm{FSR}} \propto n_\chi^2 \langle \sigma v \rangle_{\chi\chi \to e^+ e^-}$$

The injected particles scatter via interactions:

- $\gamma\gamma_{\mathrm{th}} \to e^+ e^-$
- $\gamma\gamma_{\mathrm{th}} \to \gamma\gamma$
- $\gamma N \to N e^+ e^-$
- $\gamma e^-_{\mathrm{th}} \to \gamma e^-$
- $e^\pm \gamma_{\mathrm{th}} \to e^\pm \gamma$

Tracking the abundances

Light element abundances $N \in \{n, p, \mathrm{D}, {}^3\mathrm{H}, {}^3\mathrm{He}, {}^4\mathrm{He}, {}^7\mathrm{Li}, {}^7\mathrm{Be}\}$ are tracked via

$$\frac{dT}{dt}\frac{dY_N}{dT} = \sum_{N_i} \underbrace{Y_{N_i} \int_0^\infty dE\, f_\gamma(E)\sigma_{\gamma+N_i\to N}(E)}_{\text{creation}} \underbrace{- Y_N \sum_{N_f} \int_0^\infty dE\, f_\gamma(E)\sigma_{\gamma+N\to N_f}(E)}_{\text{destruction}}$$

No.									E^{th} [MeV]
1	D	+	γ	$\to$	p	+	n			2.22
2	^{3}H	+	γ	$\to$	D	+	n			6.26
3	^{3}H	+	γ	$\to$	p	+	n	+	n	8.48
4	^{3}He	+	γ	$\to$	D	+	p			5.49
5	^{3}He	+	γ	$\to$	n	+	p	+	p	7.12
6	^{4}He	+	γ	$\to$	^{3}H	+	p			19.81
7	^{4}He	+	γ	$\to$	^{3}He	+	n			20.58
8	^{4}He	+	γ	$\to$	D	+	D			23.84
9	^{4}He	+	γ	$\to$	D	+	n	+	p	26.07

Tracking the abundances

- $\gamma\gamma_{\text{th}} \to e^+e^-$
- $\gamma\gamma_{\text{th}} \to \gamma\gamma$
- $\gamma N \to N e^+e^-$
- $\gamma e^-_{\text{th}} \to \gamma e^-$
- $e^\pm\gamma_{\text{th}} \to e^\pm\gamma$

Light element abundances $N \in \{n, p, \mathrm{D}, {}^3\mathrm{H}, {}^3\mathrm{He}, {}^4\mathrm{He}, {}^7\mathrm{Li}, {}^7\mathrm{Be}\}$ are tracked via

$$\frac{dT}{dt}\frac{dY_N}{dT} = \sum_{N_i} \underbrace{Y_{N_i}\int_0^\infty dE\, f_\gamma(E)\sigma_{\gamma+N_i\to N}(E)}_{\text{creation}}$$
$$\underbrace{- Y_N \sum_{N_f}\int_0^\infty dE\, f_\gamma(E)\sigma_{\gamma+N\to N_f}(E)}_{\text{destruction}}$$

No.										E^{th} [MeV]
1	D	+	γ	$\to$	p	+	n			2.22
2	^{3}H	+	γ	$\to$	D	+	n			6.26
3	^{3}H	+	γ	$\to$	p	+	n	+	n	8.48
4	^{3}He	+	γ	$\to$	D	+	p			5.49
5	^{3}He	+	γ	$\to$	n	+	p	+	p	7.12
6	^{4}He	+	γ	$\to$	^{3}H	+	p			19.81
7	^{4}He	+	γ	$\to$	^{3}He	+	n			20.58
8	^{4}He	+	γ	$\to$	D	+	D			23.84
9	^{4}He	+	γ	$\to$	D	+	n	+	p	26.07

Photodisintegration is sensitive to specific temperature range $T \in [10^{-7}, 10^{-2}]$ MeV : well after standard BBN has ended

Tracking the abundances

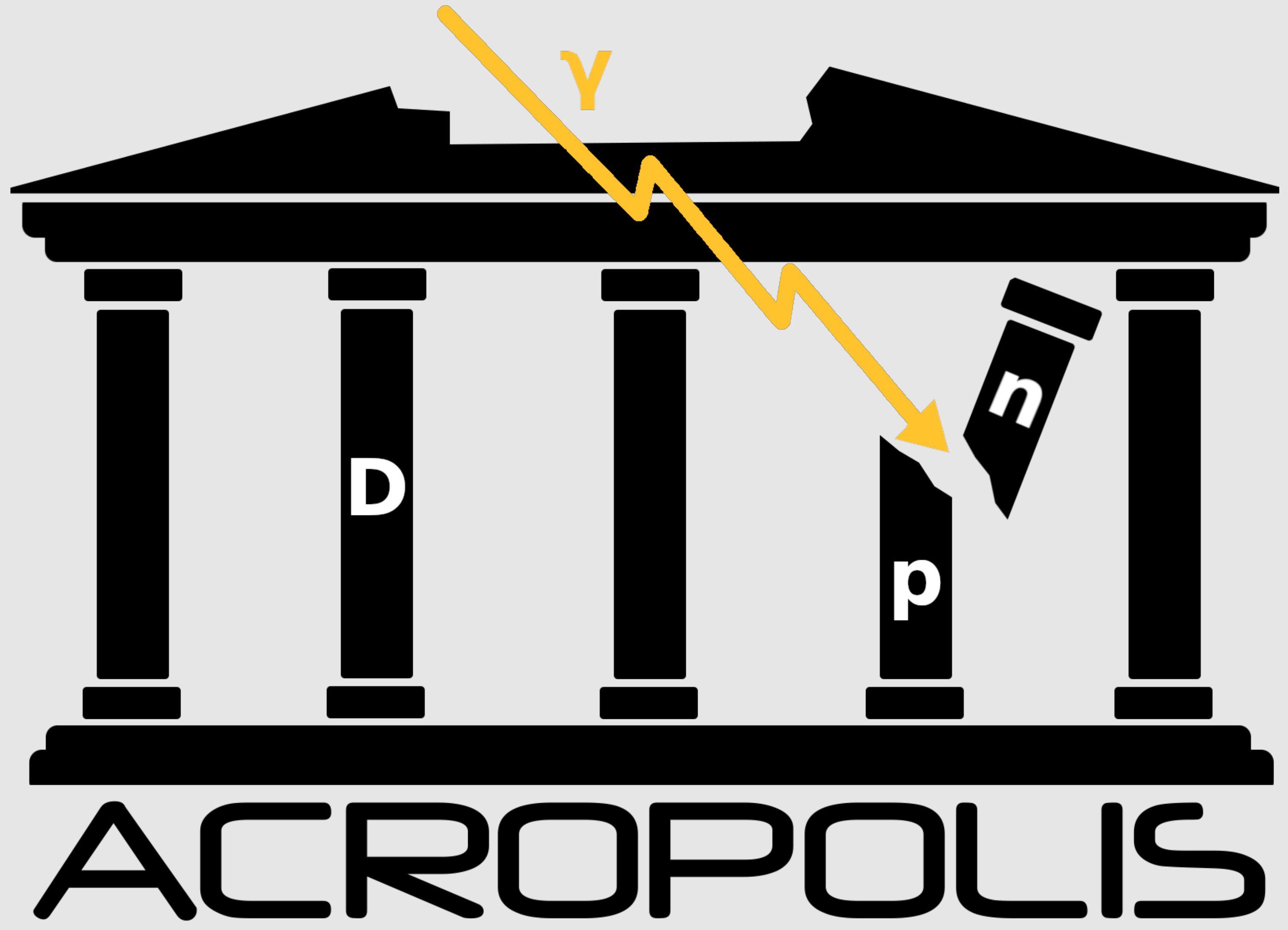
- $\gamma\gamma_{\rm th} \to e^+e^-$
- $\gamma\gamma_{\rm th} \to \gamma\gamma$
- $\gamma N \to N e^+e^-$
- $\gamma e^-_{\rm th} \to \gamma e^-$
- $e^\pm \gamma_{\rm th} \to e^\pm \gamma$

Light element abundances $N \in \{n, p, \mathrm{D}, {}^3\mathrm{H}, {}^3\mathrm{He}, {}^4\mathrm{He}, {}^7\mathrm{Li}, {}^7\mathrm{Be}\}$ are tracked via

$$\frac{dT}{dt}\frac{dY_N}{dT} = \sum_{N_i} \underbrace{Y_{N_i} \int_0^\infty dE\, f_\gamma(E) \sigma_{\gamma+N_i \to N}(E)}_{\text{creation}} \underbrace{- Y_N \sum_{N_f} \int_0^\infty dE\, f_\gamma(E) \sigma_{\gamma+N \to N_f}(E)}_{\text{destruction}}$$

No.										$E^{\rm th}$ [MeV]
1	D	+	γ	$\to$	p	+	n			2.22
2	^{3}H	+	γ	$\to$	D	+	n			6.26
3	^{3}H	+	γ	$\to$	p	+	n	+	n	8.48
4	^{3}He	+	γ	$\to$	D	+	p			5.49
5	^{3}He	+	γ	$\to$	n	+	p	+	p	7.12
6	^{4}He	+	γ	$\to$	^{3}H	+	p			19.81
7	^{4}He	+	γ	$\to$	^{3}He	+	n			20.58
8	^{4}He	+	γ	$\to$	D	+	D			23.84
9	^{4}He	+	γ	$\to$	D	+	n	+	p	26.07

Photodisintegration is sensitive to specific temperature range $T \in [10^{-7}, 10^{-2}]$ MeV : well after standard BBN has ended



In principle complicated system to solve—> ACROPOLIS

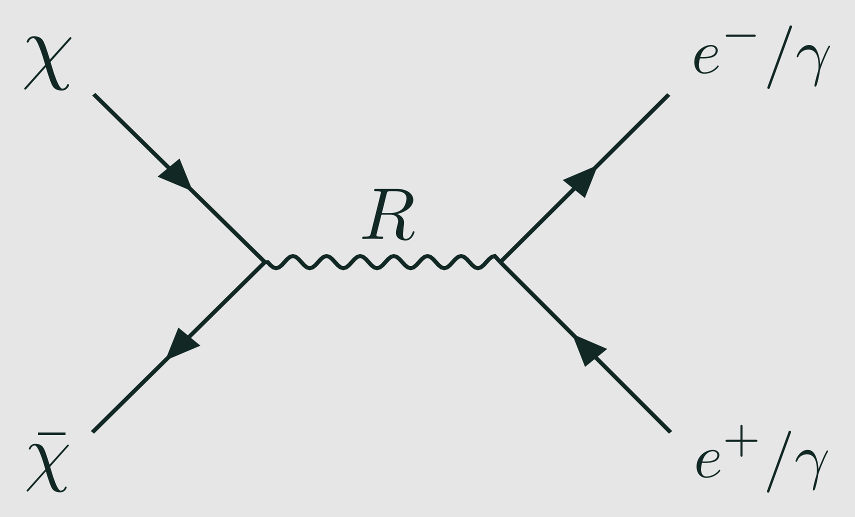
Depta, Hufnagel, Schmidt-Hoberg (2021)

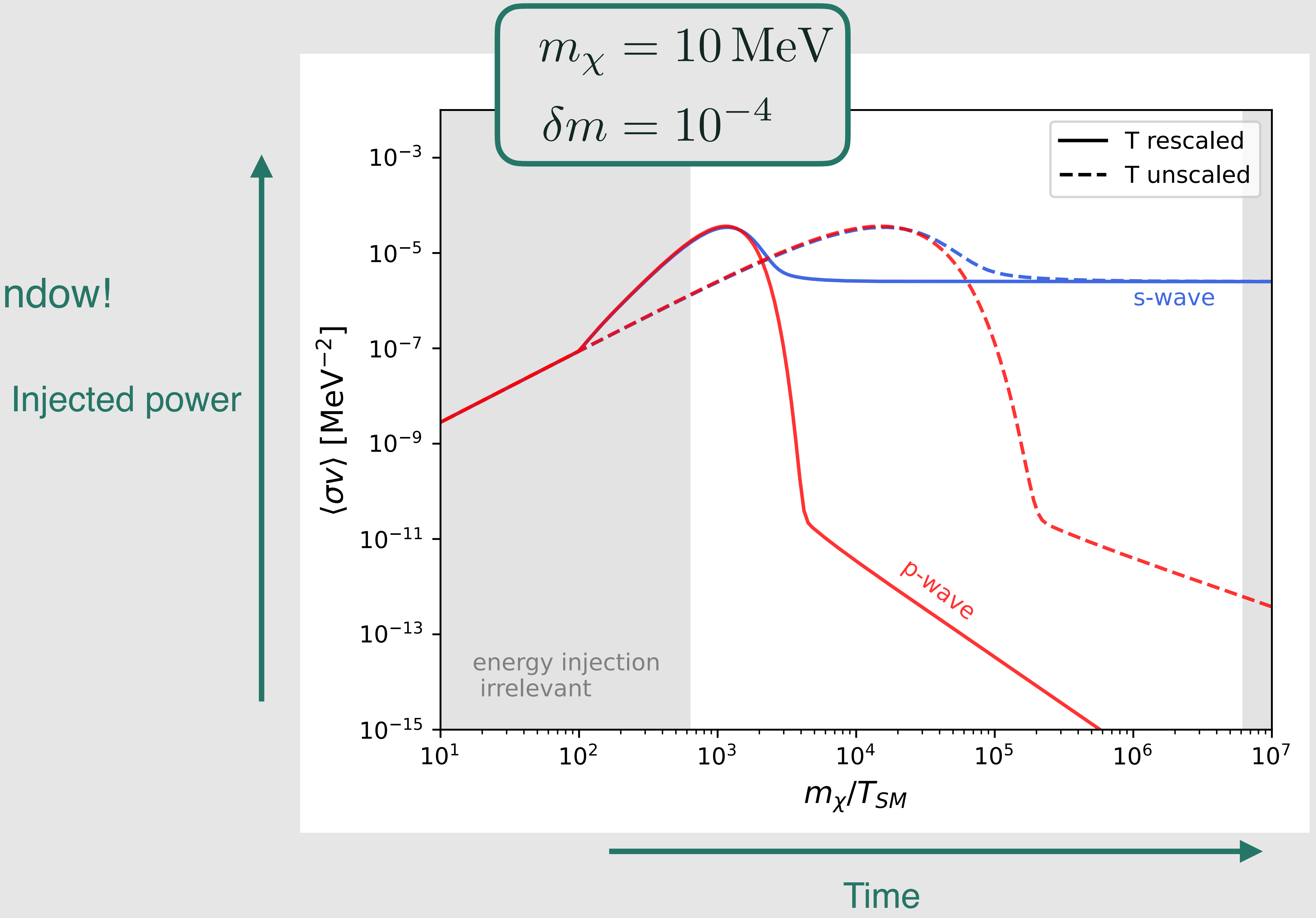
Why resonant annihilations?

Consider dark sector with resonance

$$m_R \equiv m_\chi(2+\delta m)\,, \quad \delta m \ll 1$$

For MeV scale DM, annihilations peak in photodisintegration window!





Why resonant annihilations?

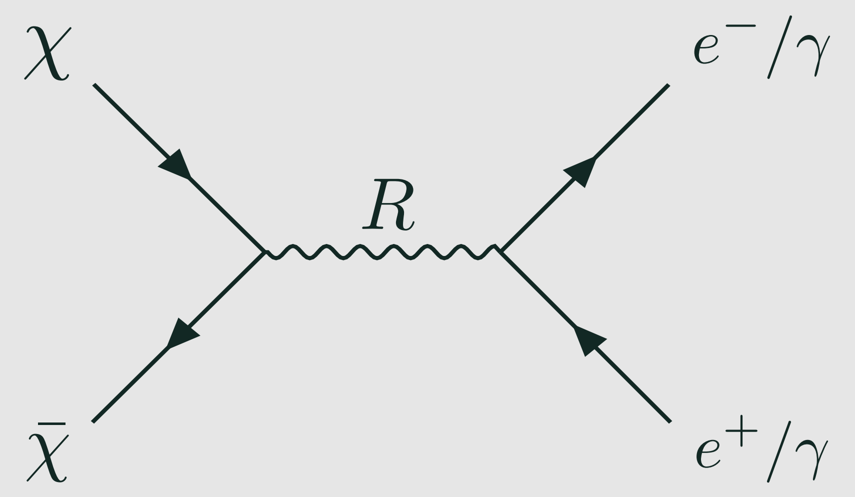
Consider dark sector with resonance

$$m_R \equiv m_\chi(2+\delta m)\,, \quad \delta m \ll 1$$

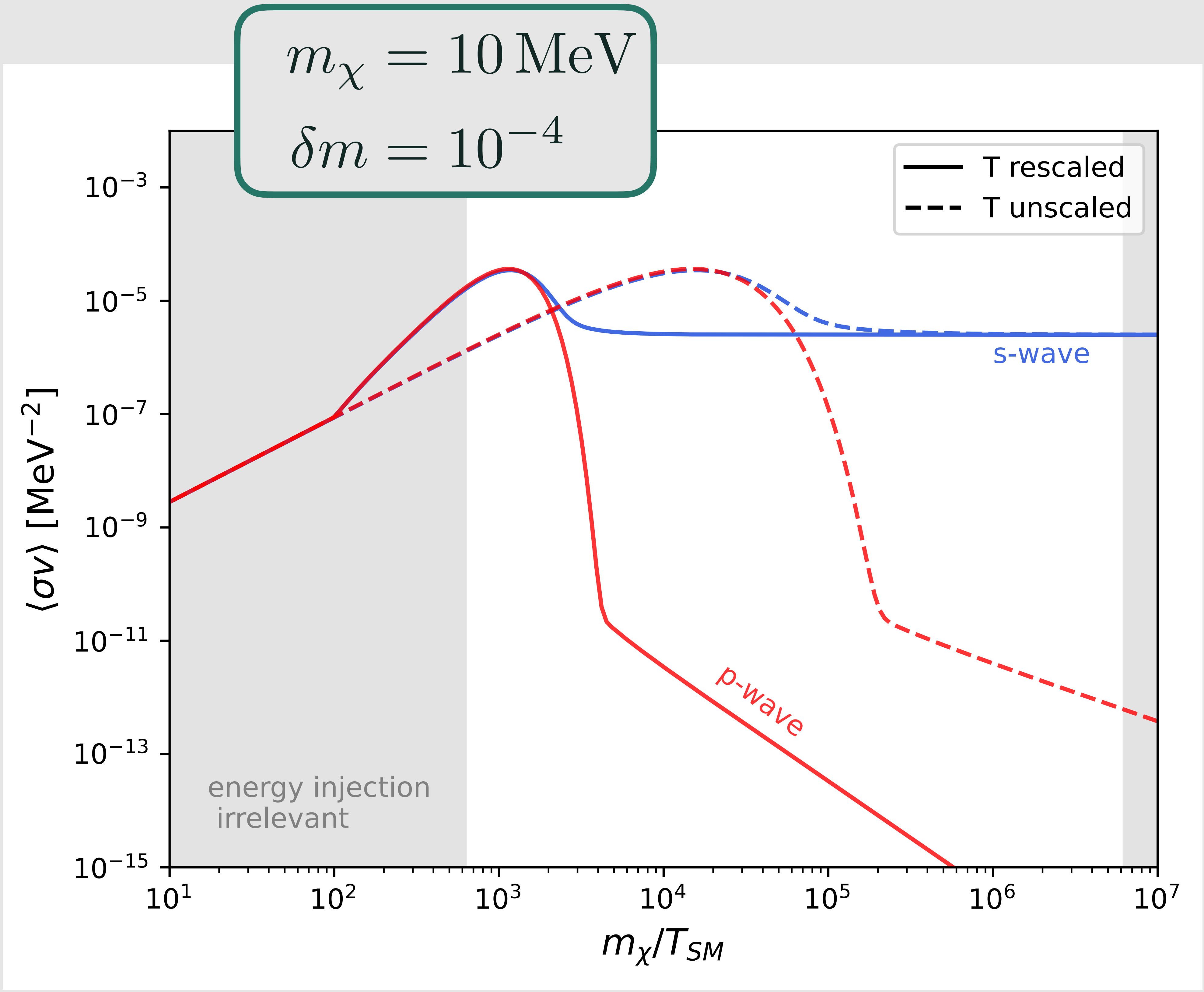
For MeV scale DM, annihilations peak in photodisintegration window!

We can write the annihilation cross section as

$$\sigma_{\rm ann}^{\rm res} = \frac{4\pi S}{m_\chi E(v)} \frac{\Gamma_d(v)\Gamma_v(v_f)/4}{(E(v)-E(v_R))^2+\Gamma(v)^2/4}\,, \quad v_R \equiv 2\sqrt{\delta m}$$



Injected power



Time

Why resonant annihilations?

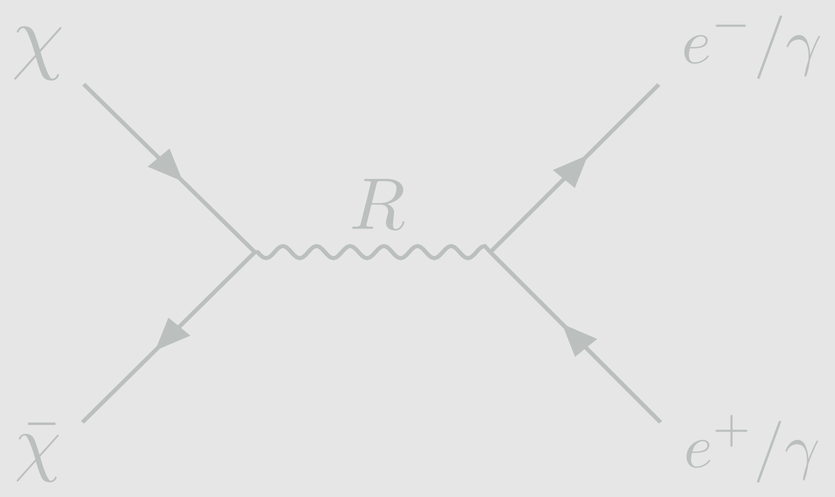
Consider dark sector with resonance

$$m_R \equiv m_\chi(2+\delta m)\,, \quad \delta m \ll 1$$

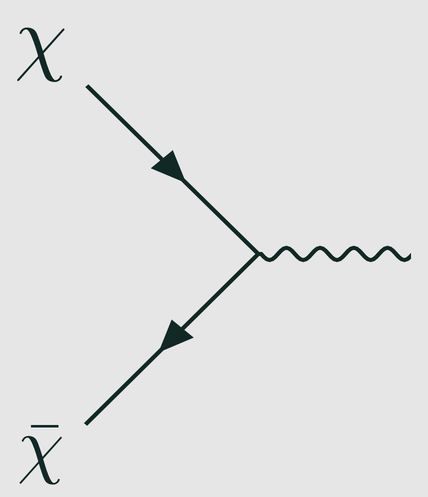
For MeV scale DM, annihilations peak in photodisintegration window!

We can write the annihilation cross section as

$$\sigma_{\rm ann}^{\rm res} = \frac{4\pi S}{m_\chi E(v)}\frac{\Gamma_d(v)\Gamma_v(v_f)/4}{(E(v)-E(v_R))^2+\Gamma(v)^2/4}\,, \quad v_R \equiv 2\sqrt{\delta m}$$

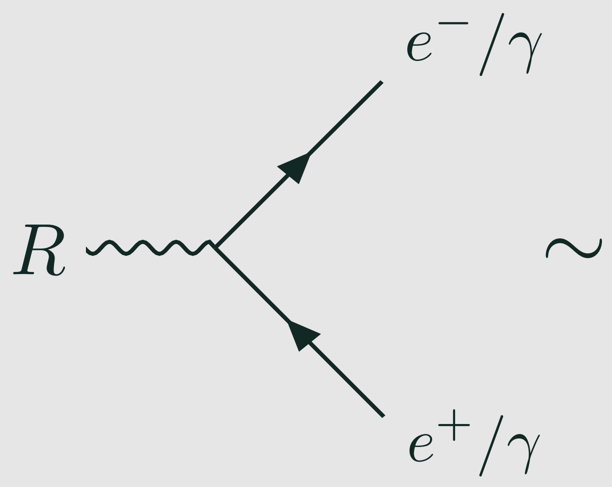


$\sim$



$$R \sim \gamma_d m_R \frac{p^{2n_d+1}}{m_\chi^{2n_d+1}}$$

$\times$



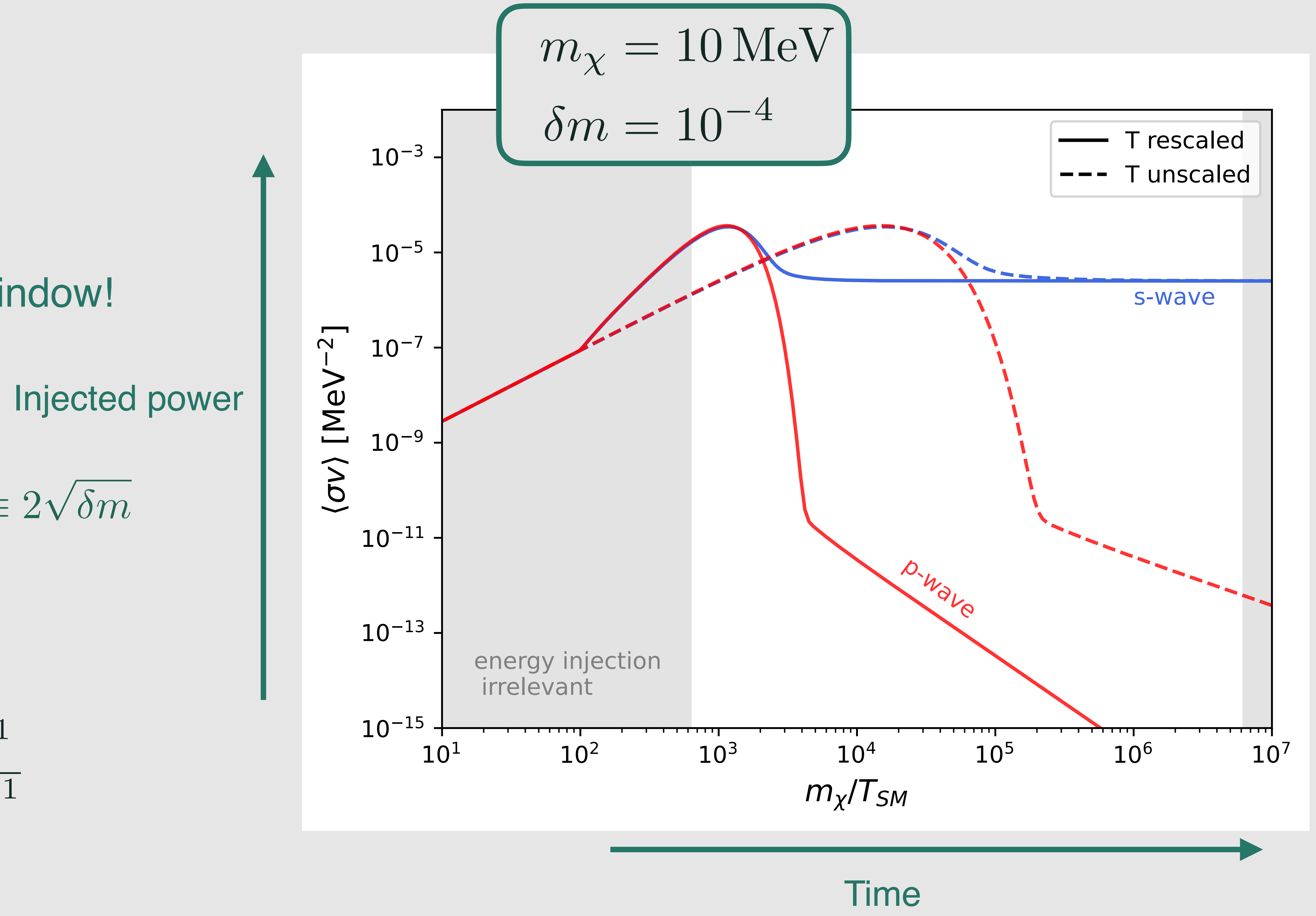
$$\sim \gamma_v m_R \frac{p^3}{m_\chi^3}$$

$\gamma_d :$ dark coupling

$\gamma_v :$ visible coupling

$n_d = 0 \quad s-$wave

$n_d = 1 \quad p-$wave



Model independent setup!

Temperature dependence

Injected energy depends on the thermally averaged cross section

$$\langle \sigma v \rangle_{\rm ann} \overset{T_\chi \ll m_\chi}{=} \frac{4T_\chi^{3/2}}{\sqrt{\pi} m_\chi^{11/2}} \int_0^\infty \mathrm{d}p^2 e^{-p^2 T_\chi / m_\chi^3} p^2 \sigma$$

with DM temperature

$$T_\chi(T) = \begin{cases} T & \text{if T} > \text{T}_{\rm kd} \\ T_{\rm kd} R(T_{\rm kd})^2 / R(T)^2 & \text{if T} < \text{T}_{\rm kd} \end{cases}$$

Temperature dependence

Injected energy depends on the thermally averaged cross section

$$\langle\sigma v\rangle_{\text{ann}} \overset{T_\chi \ll m_\chi}{=} \frac{4T_\chi^{3/2}}{\sqrt{\pi}m_\chi^{11/2}} \int_0^\infty \mathrm{d}p^2 e^{-p^2 T_\chi/m_\chi^3} p^2 \sigma$$

with DM temperature

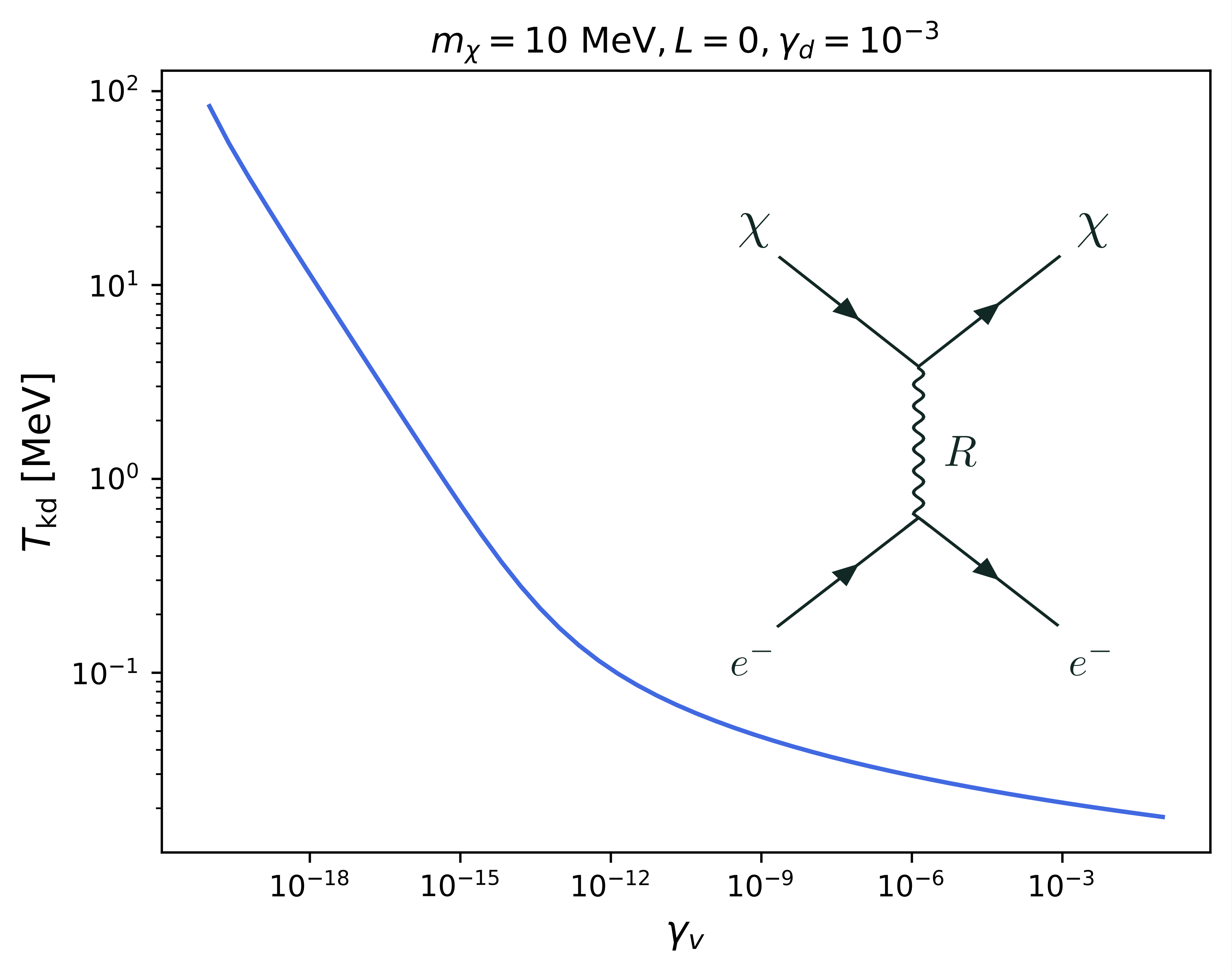
$$T_\chi(T) = \begin{cases} T & \text{if T} > \text{T}_{\text{kd}} \\ T_{\text{kd}} R(T_{\text{kd}})^2/R(T)^2 & \text{if T} < \text{T}_{\text{kd}} \end{cases}$$

Kinetic decoupling when scattering becomes inefficient, i.e. when

$$\Gamma = n_e \langle\sigma v\rangle_{\chi e \to \chi e}\Big|_{T=T_{\text{kd}}} \lesssim H(T_{\text{kd}})$$

Scattering is related to annihilation via crossing symmetry

$$\sigma_{\chi e^- \to \chi e^-} = C\gamma_v\gamma_d \frac{p^2}{m_\chi^4}, \quad C = \mathcal{O}(1) \qquad T \gtrsim m_e$$



Results: single parameter space point

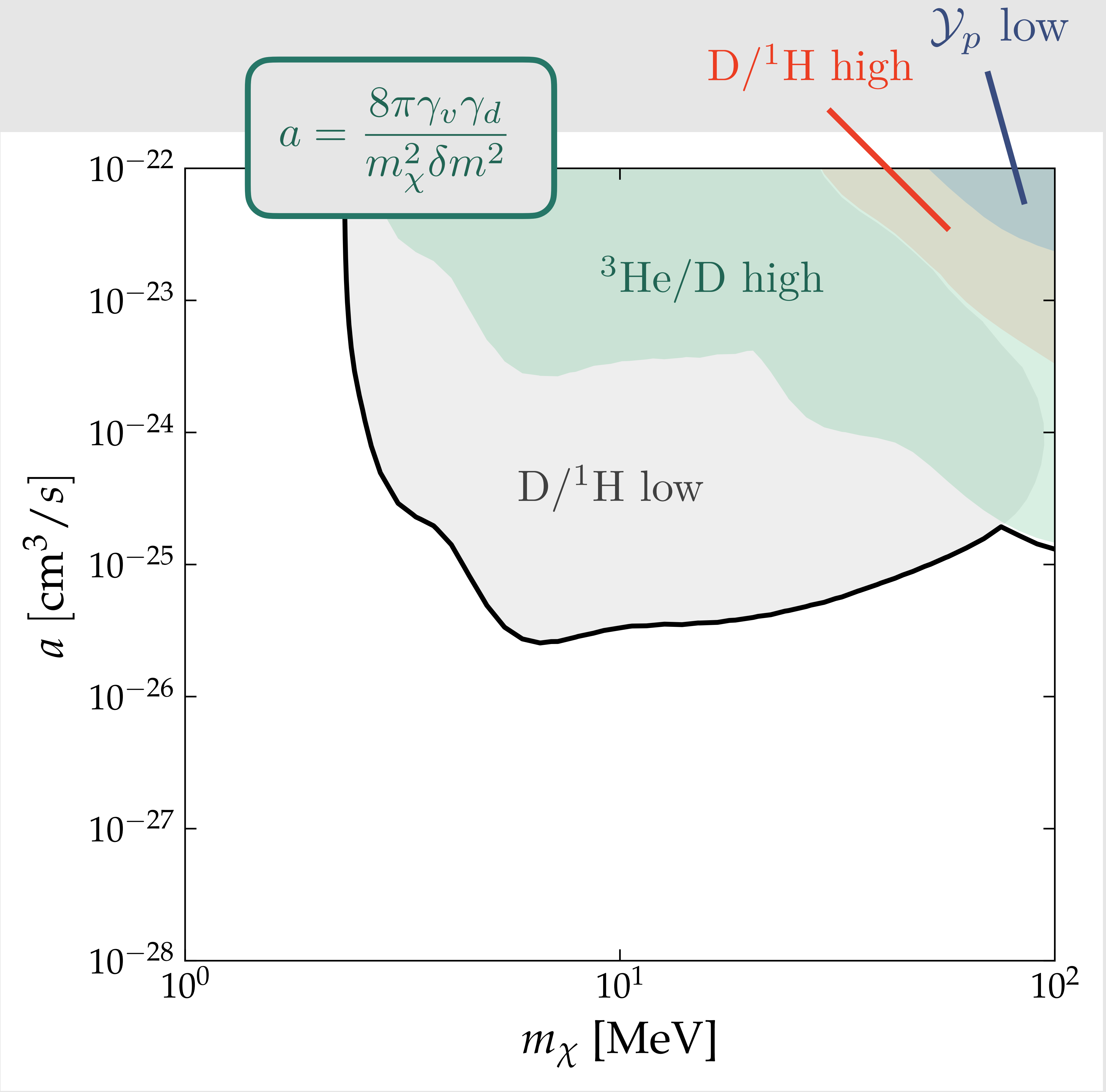
Use BBN observations

$$\mathcal{Y}_p = 0.245 \pm 0.003,$$

$$\mathrm{D}/{}^1\mathrm{H} = (25.47 \pm 0.25) \times 10^{-6}$$ PDG (2022)

$$^3\mathrm{He}/\mathrm{D} = (8.3 \pm 1.5) \times 10^{-1}$$ Geiss and Gloecker (2003)

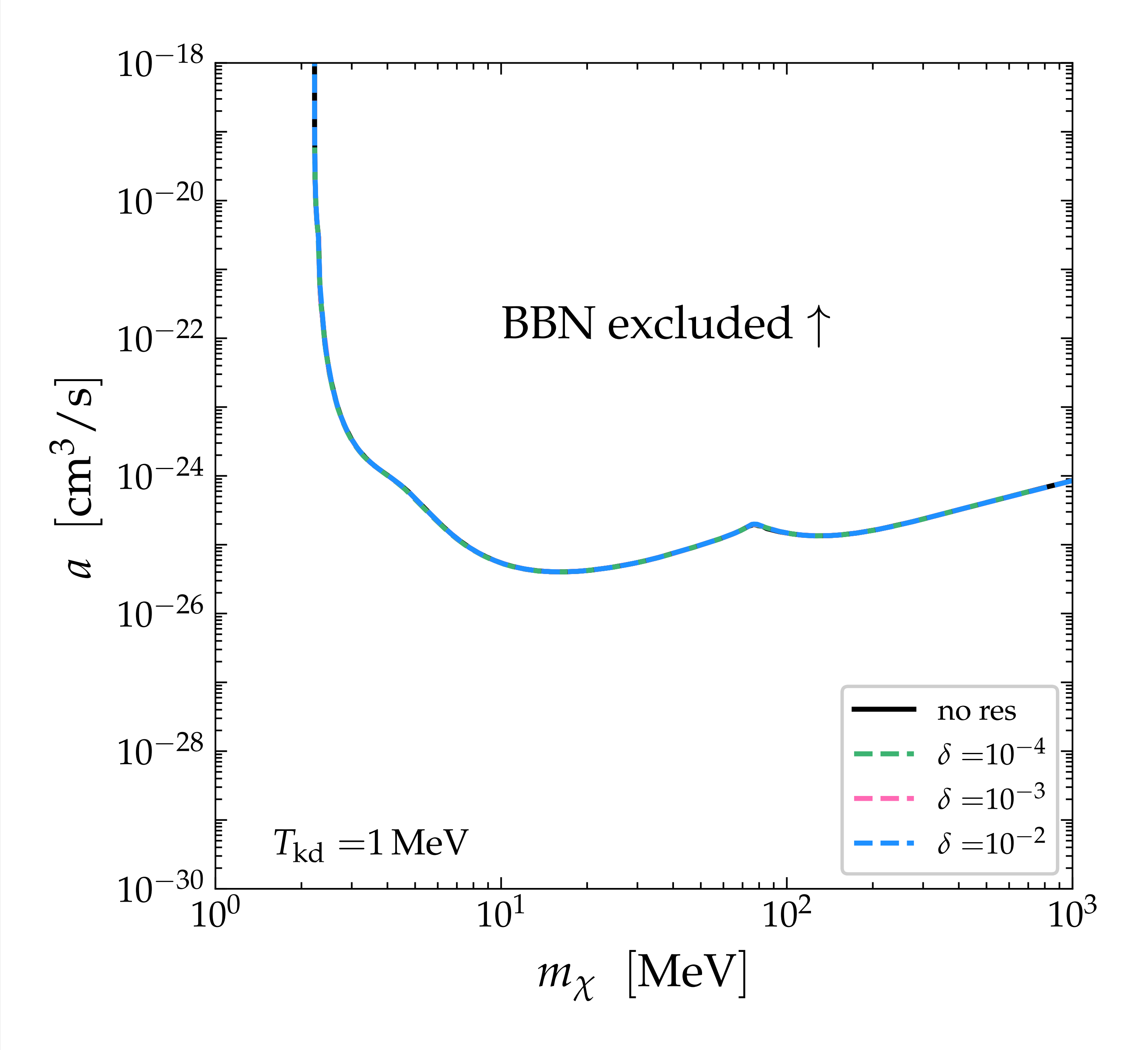
Deuterium abundance is most sensitive to the photodisintegration

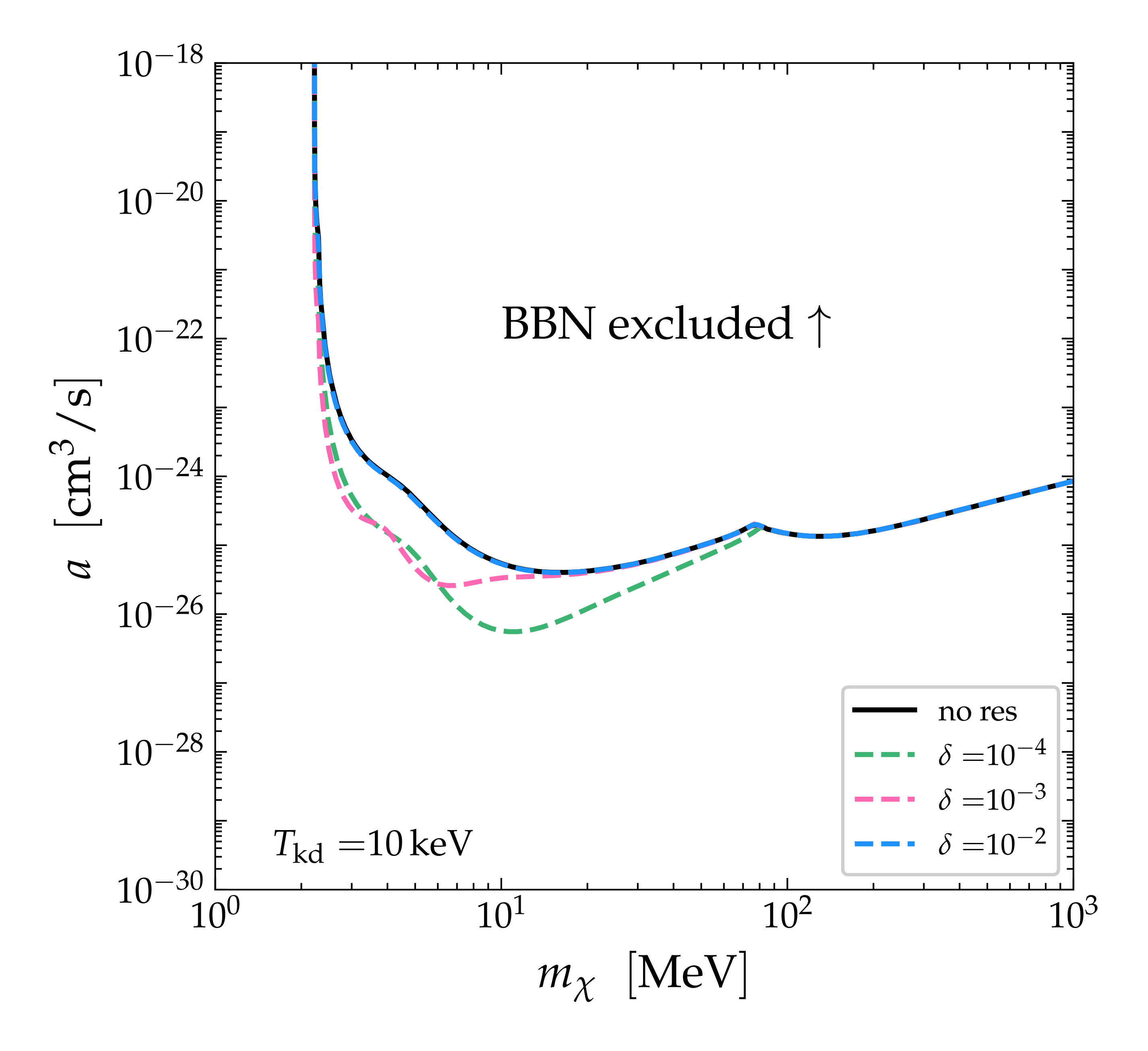


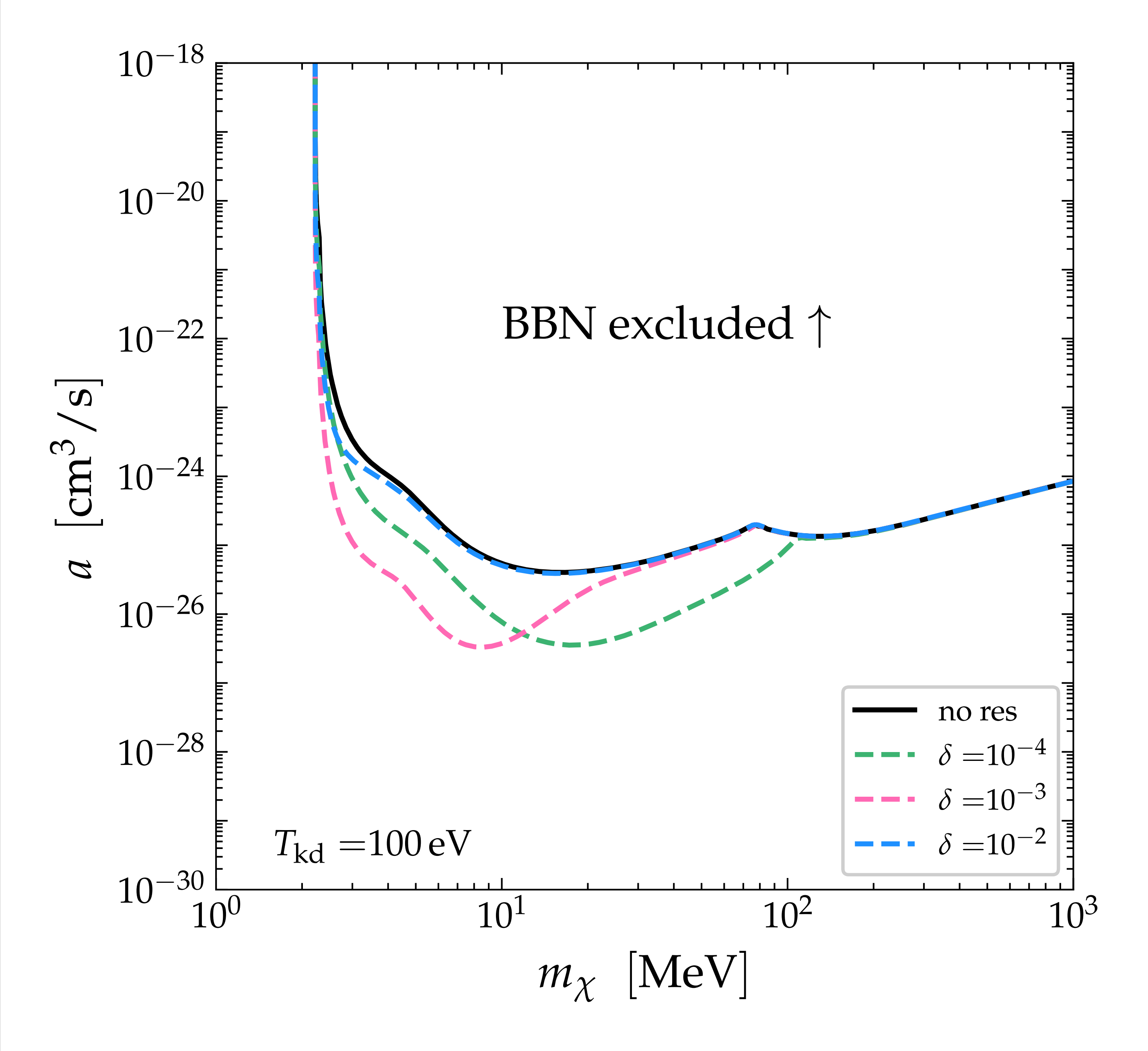
Results (s-wave)

$$\boxed{a = \frac{8\pi\gamma_v\gamma_d}{m_\chi^2\,\delta m^2}}$$

Fixed $T_{\rm kd}$: resonance effect is observable if the decoupling temperature is low enough







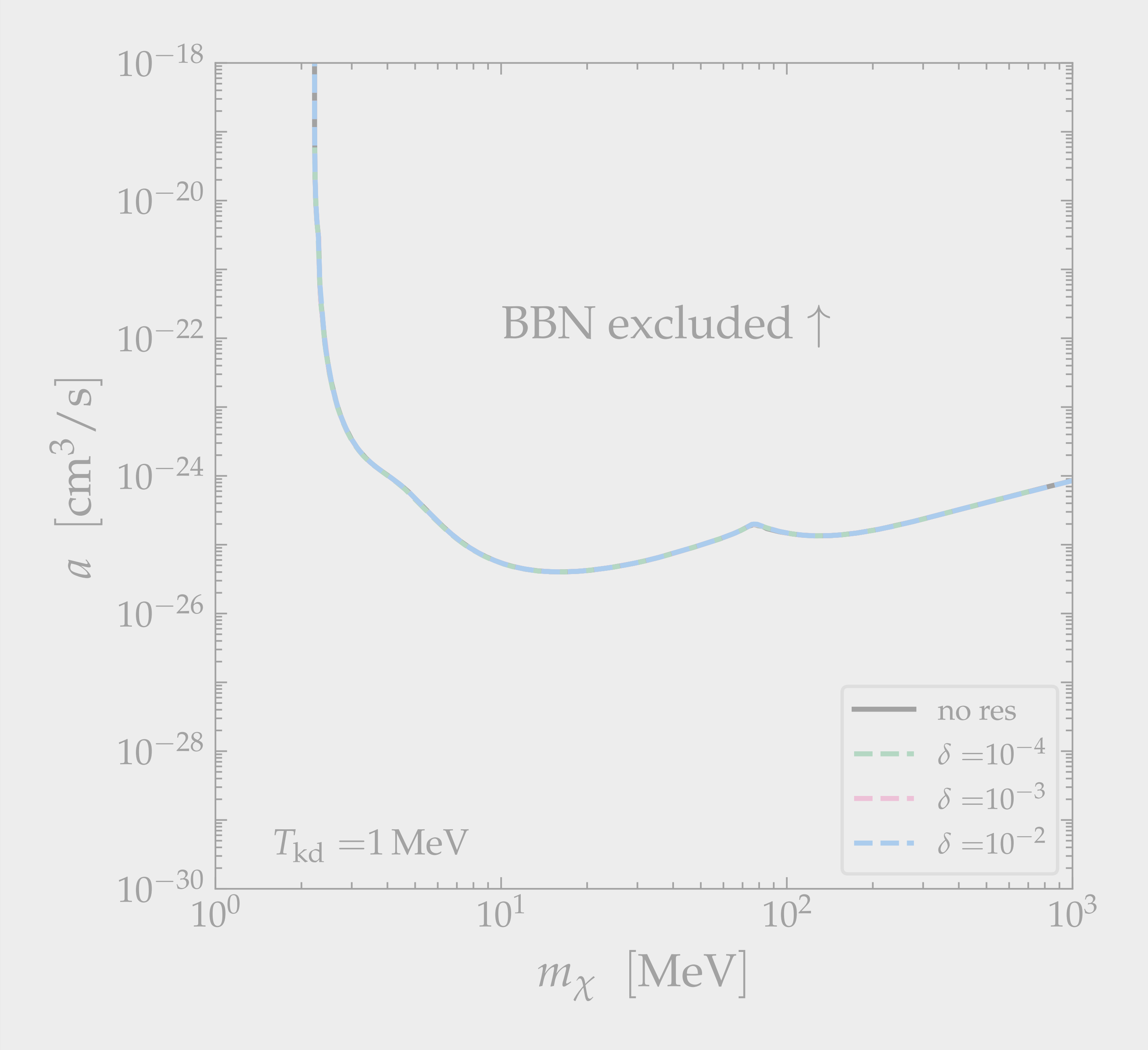
Results (s-wave)

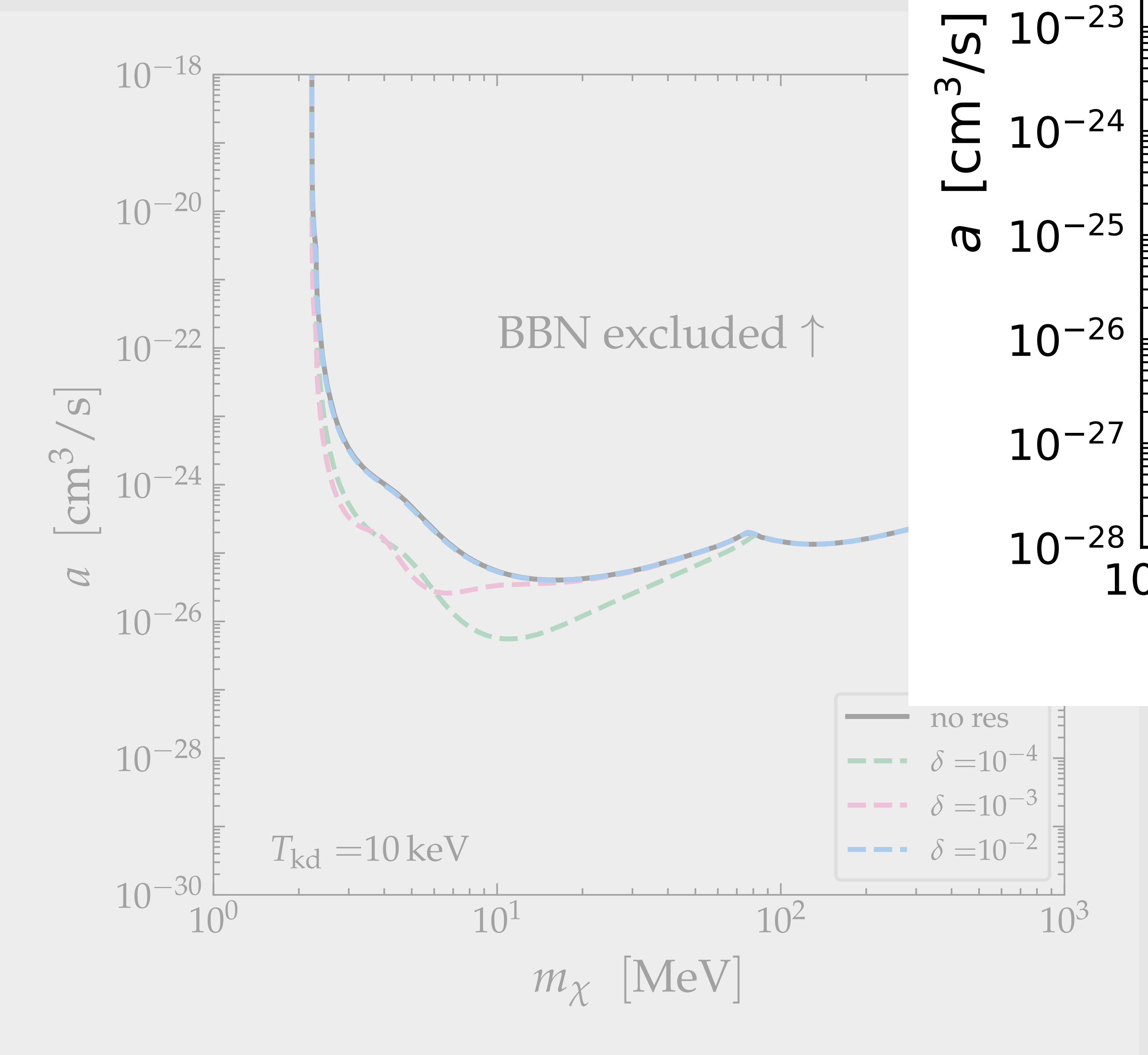
$$a = \frac{8\pi\gamma_v\gamma_d}{m_\chi^2\,\delta m^2}$$

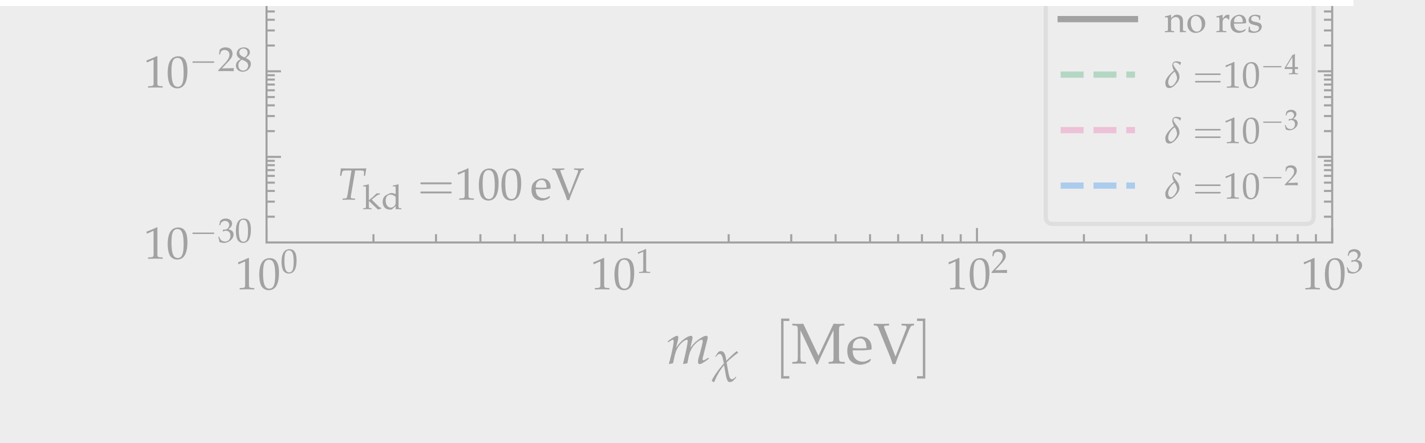
Fixed $T_{\rm kd}$: resonance effect is observable if the decoupling temperature is low enough

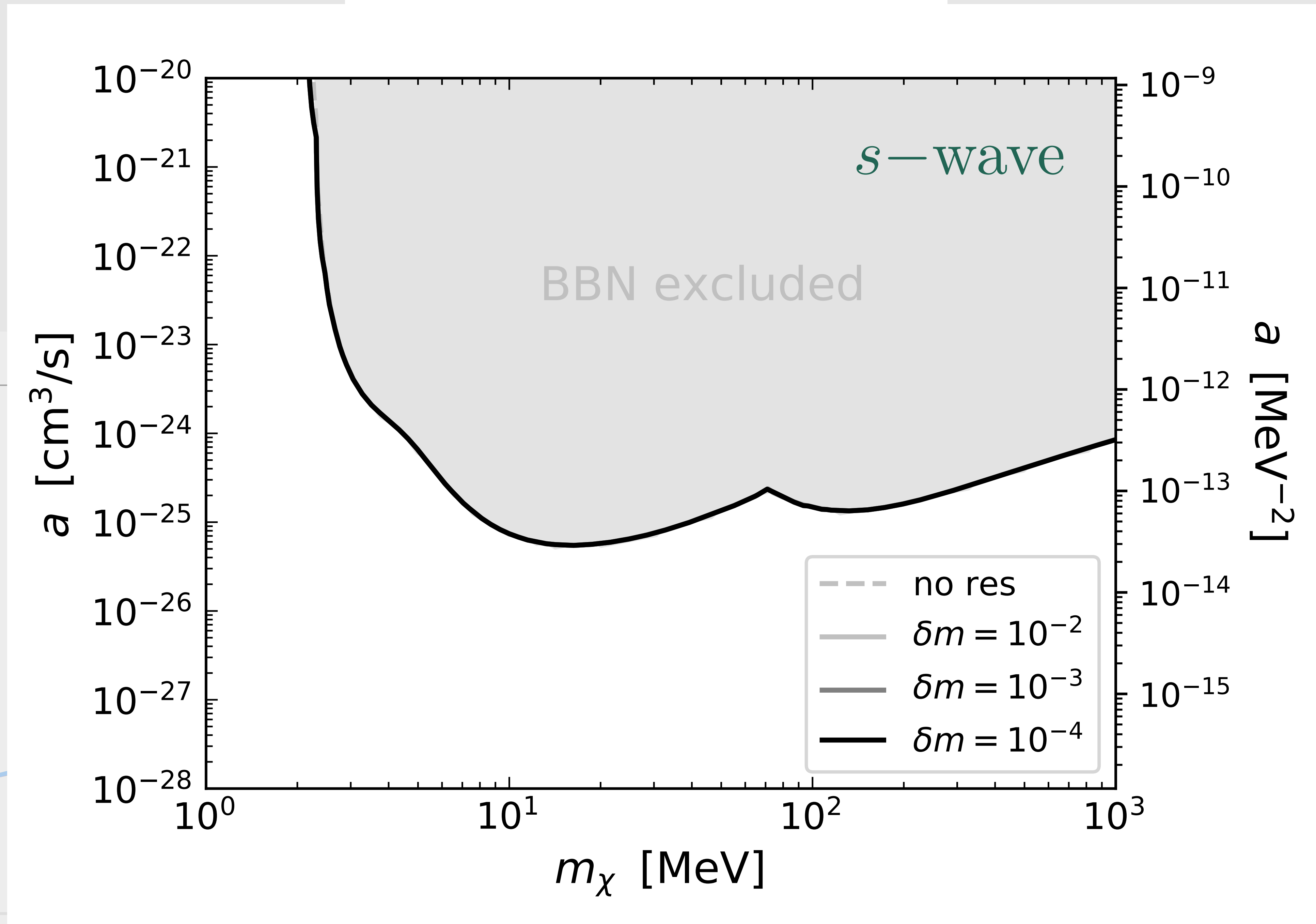
Dynamically determined $T_{\rm kd}$: the resonance is not effective as $T_{\rm kd} \gtrsim 1\,\mathrm{MeV}$

High decoupling temperature pushes the resonance outside the photodisintegration window





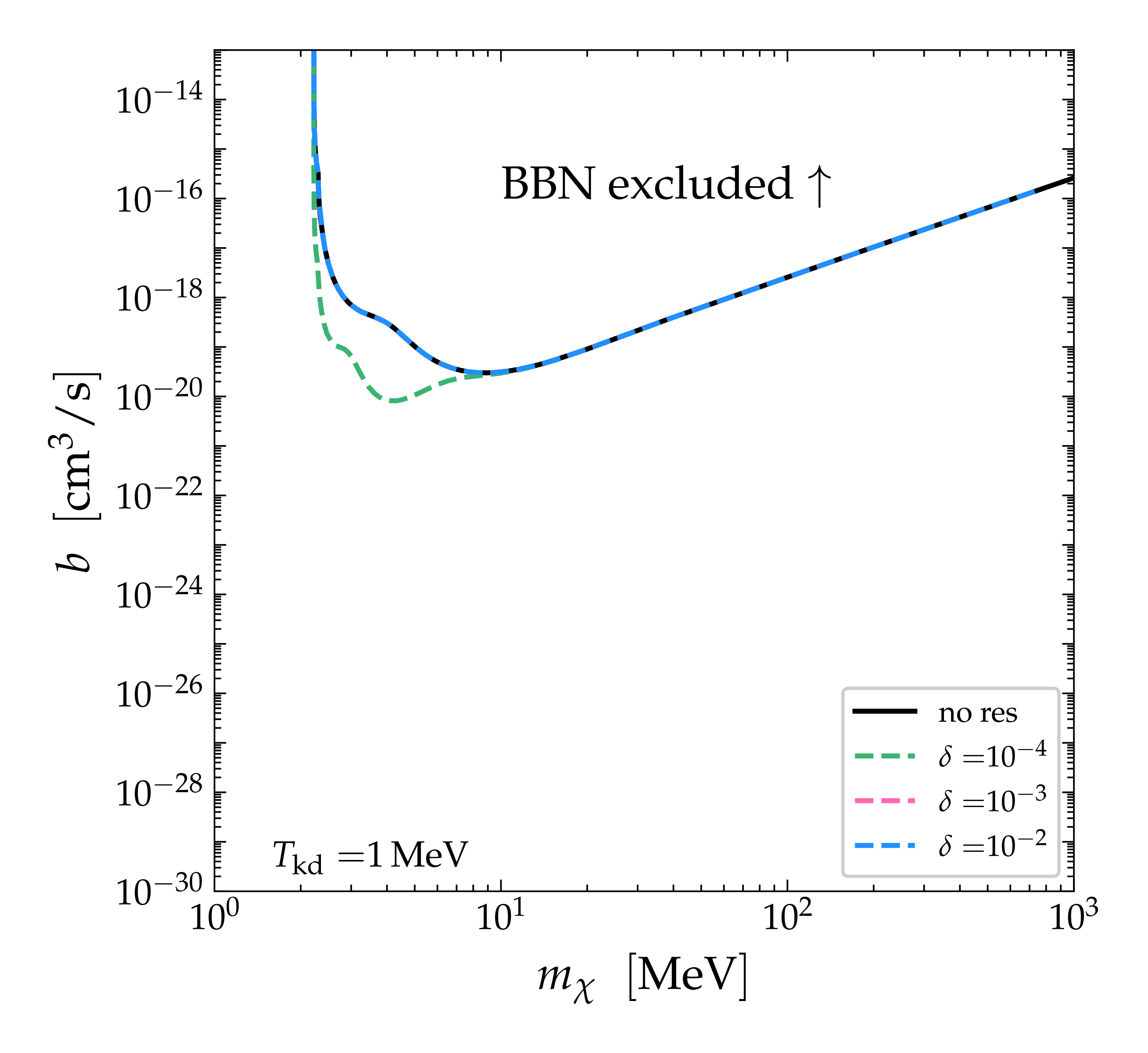


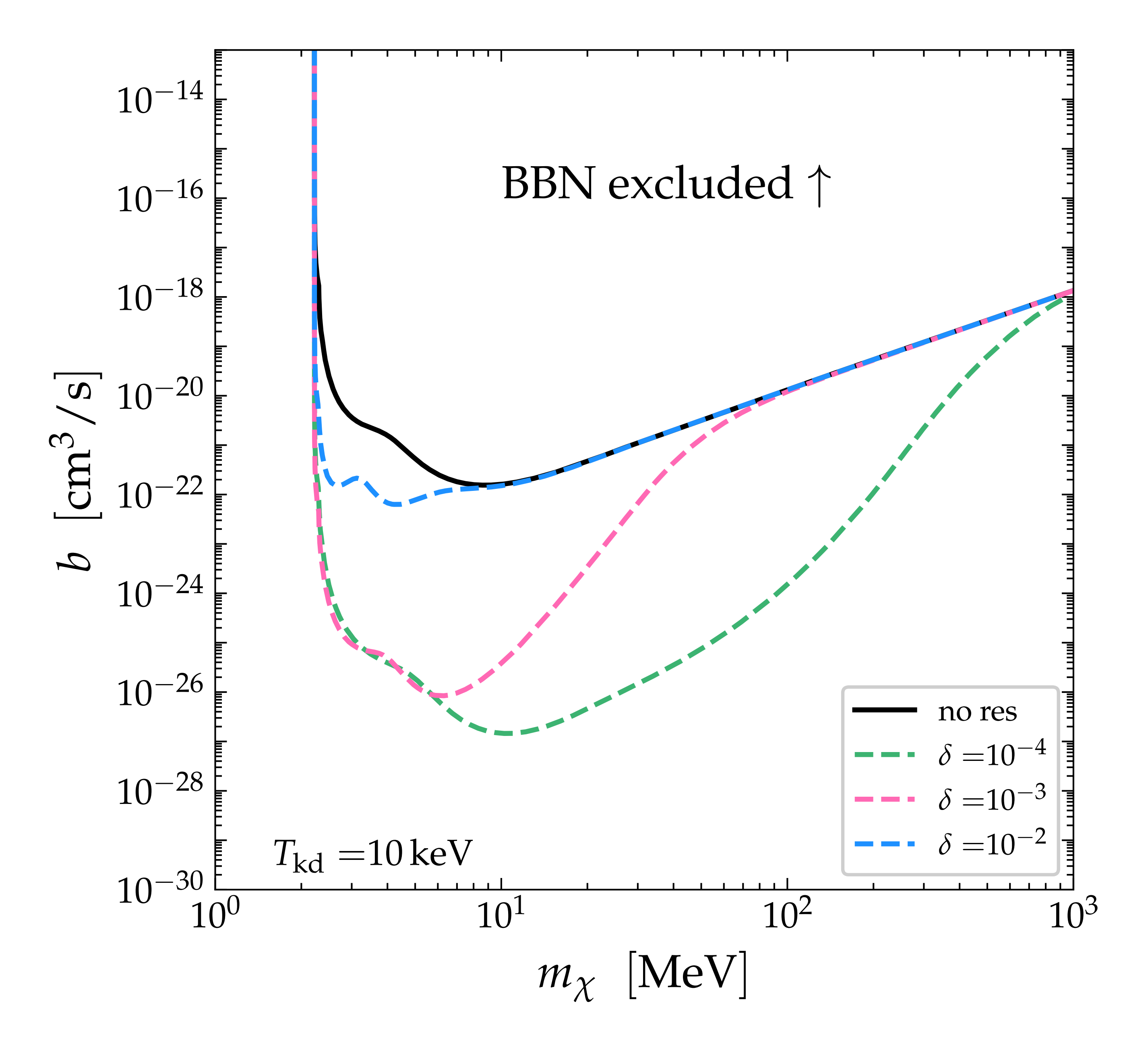


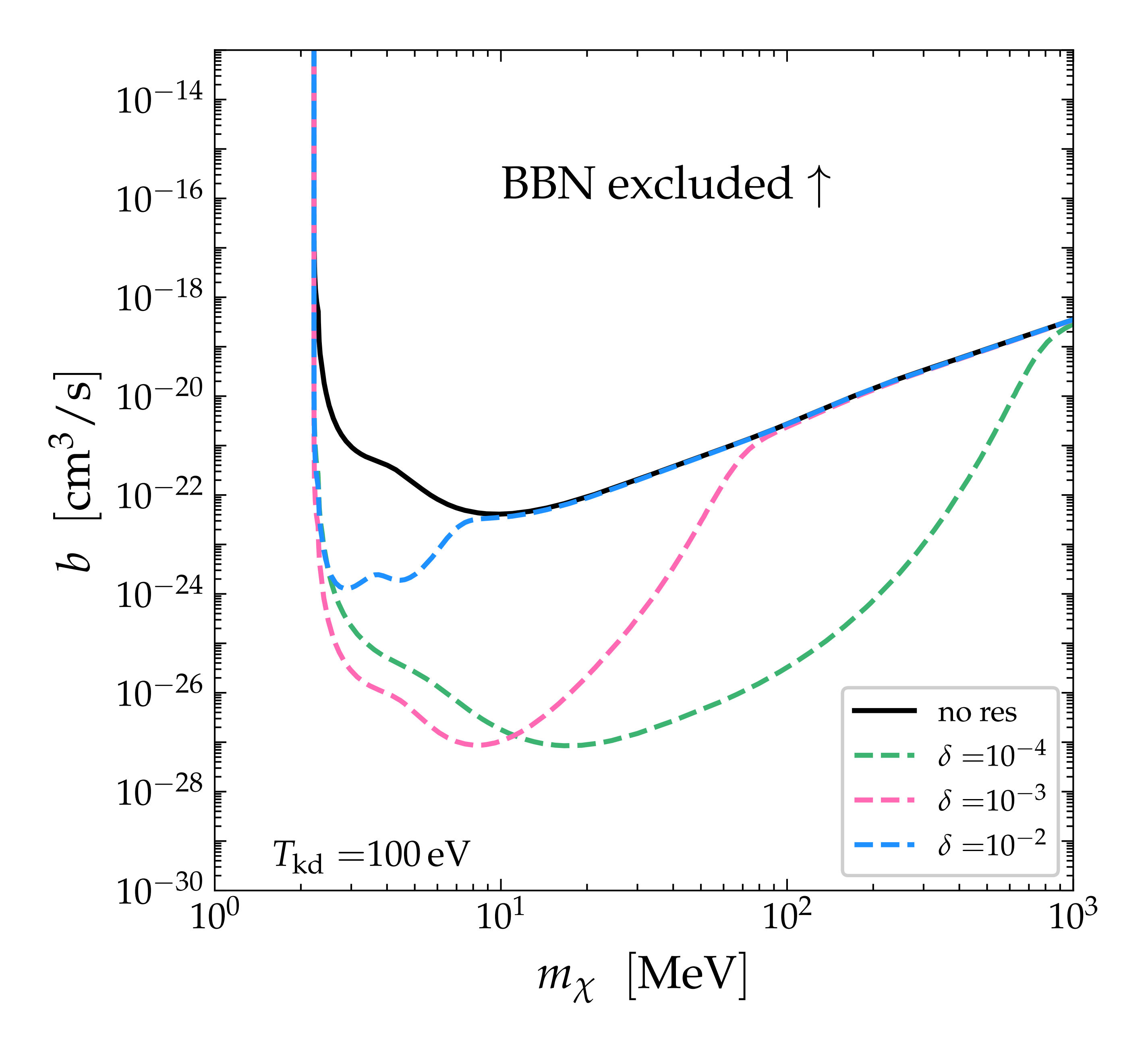
Results (p-wave)

$$b = \frac{2\pi\gamma_v\gamma_d}{m_\chi^2\,\delta m^2}$$

For p-wave, the resonance effect is typically stronger



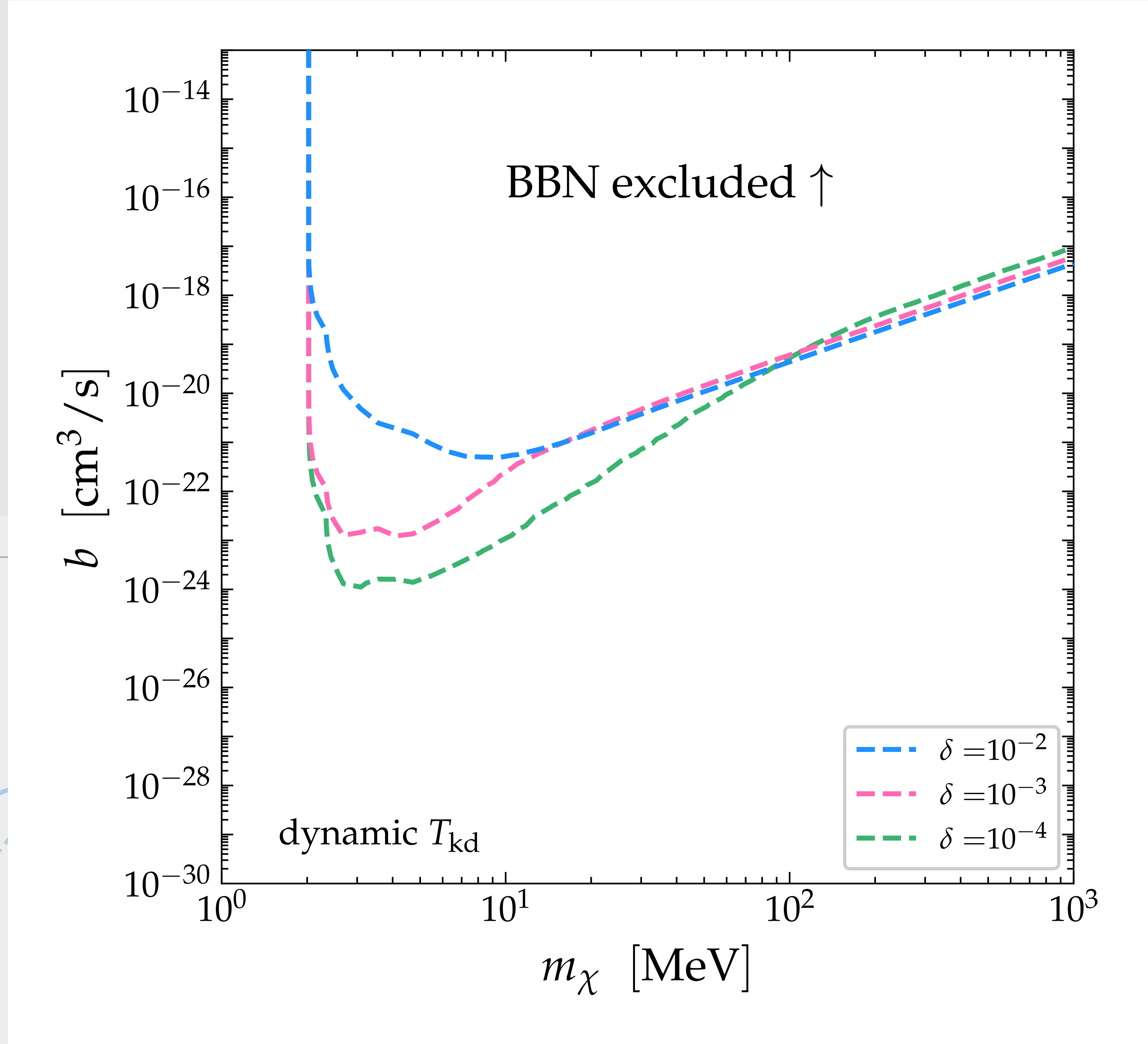




Results (p-wave)

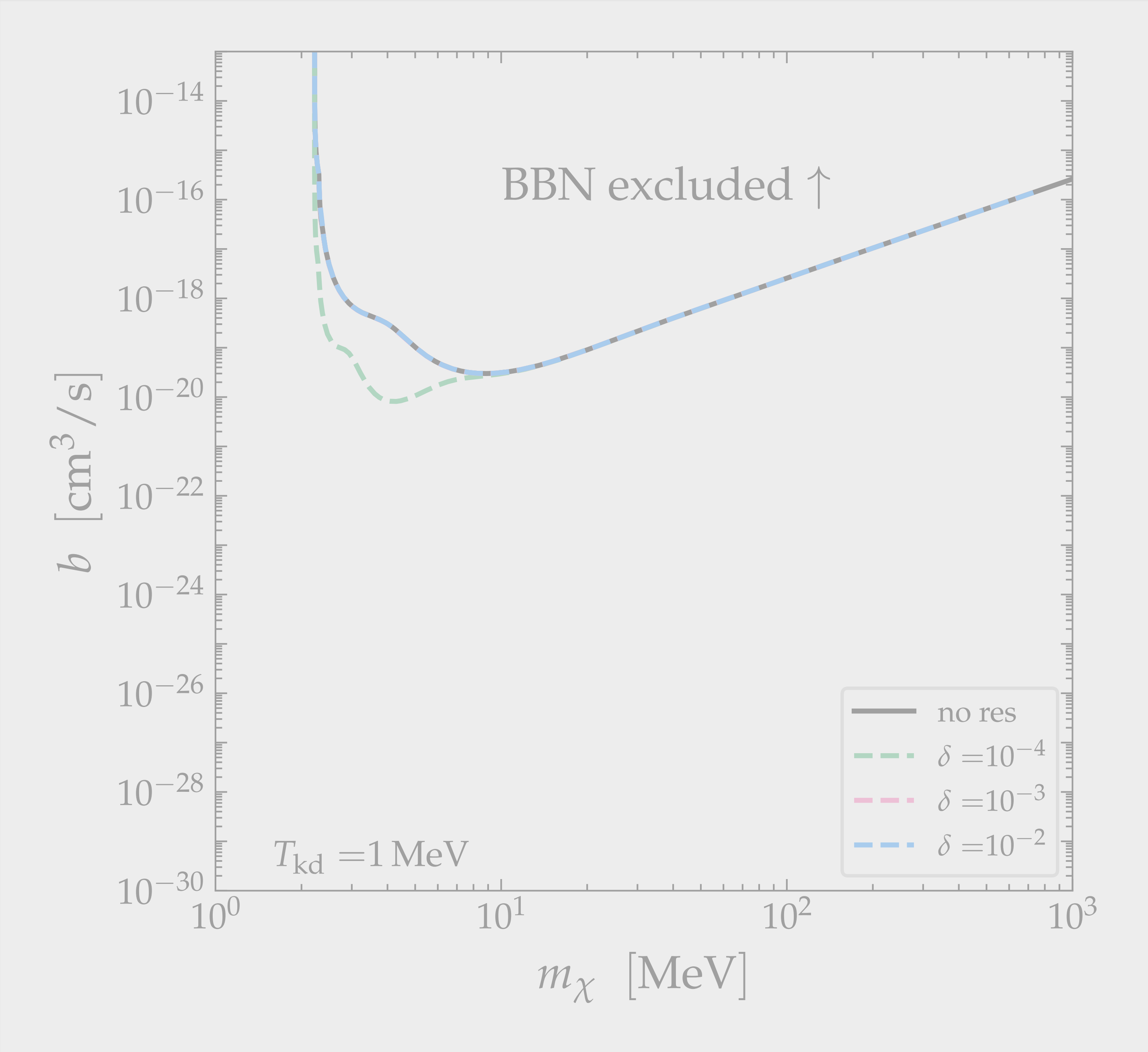
$$b = \frac{2\pi\gamma_v\gamma_d}{m_\chi^2\,\delta m^2}$$

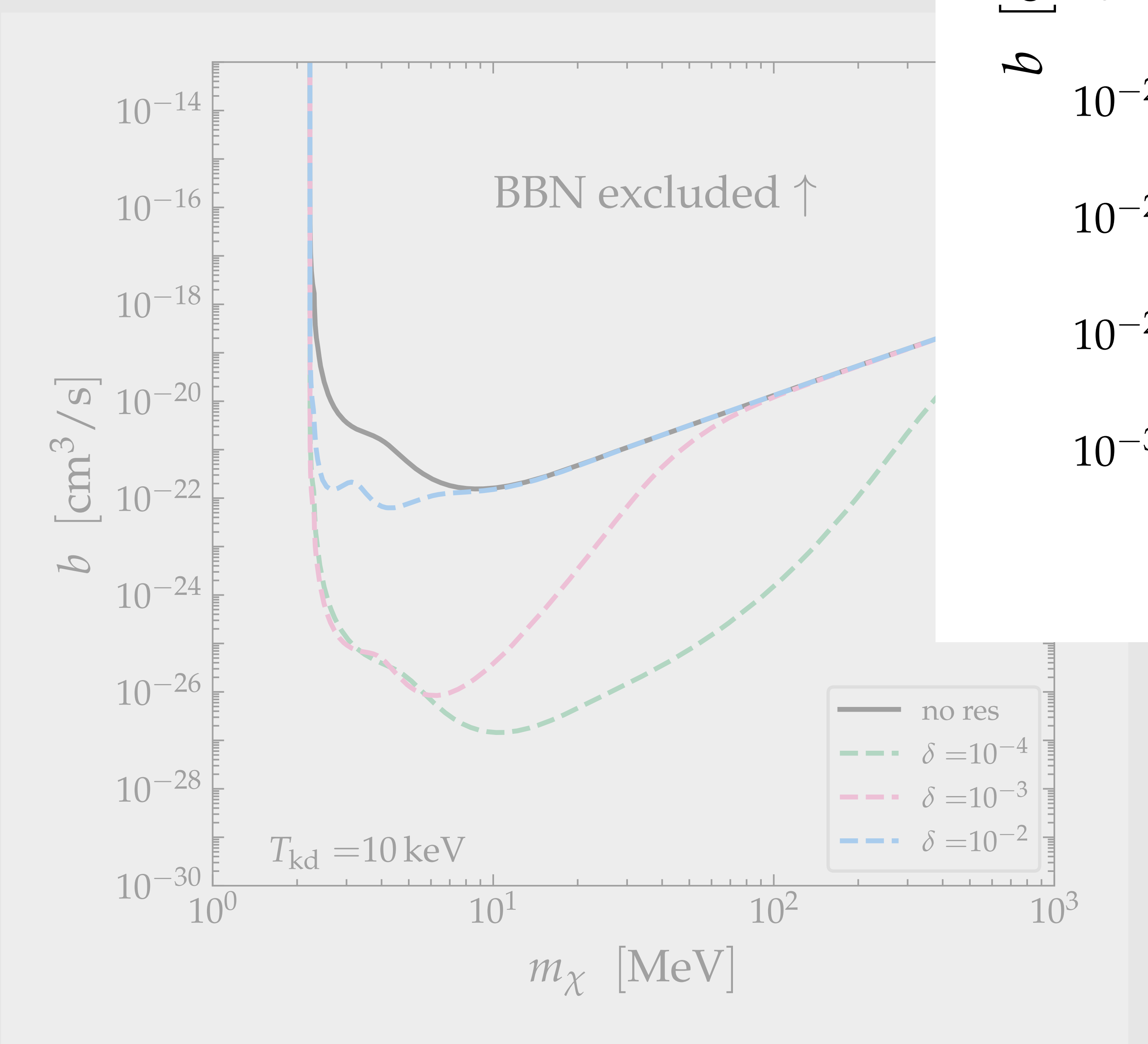
Bounds are weaker than s-wave, so later decoupling

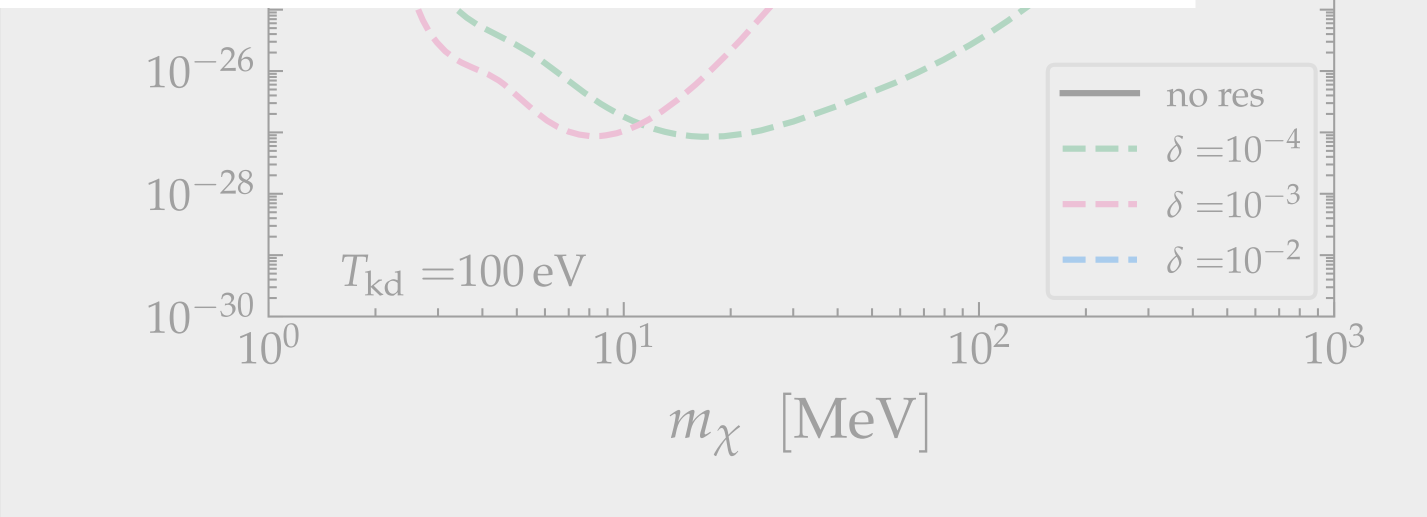


For p-wave, the resonance effect is typically stronger

Dynamical $T_{\rm kd}$: resonance models are more strongly constrained compared to vanilla annihilations







Conclusions

- BBN observations can place stringent bounds on exotic energy injection in the early universe, such as (resonant) s- or p-wave DM annihilations

- Decoupling temperature greatly impacts the constraints; if in thermal equilibrium long enough, resonance model suffers from stronger bounds

- Determining the decoupling dynamically, s-wave resonance does not suffer from increased bounds, whereas p-wave does

- Want to use the code yourself? Will be included in an upcoming version of ACROPOLIS: check the GitHub!

Thank you!

Back up

Intermezzo: core vs cusp

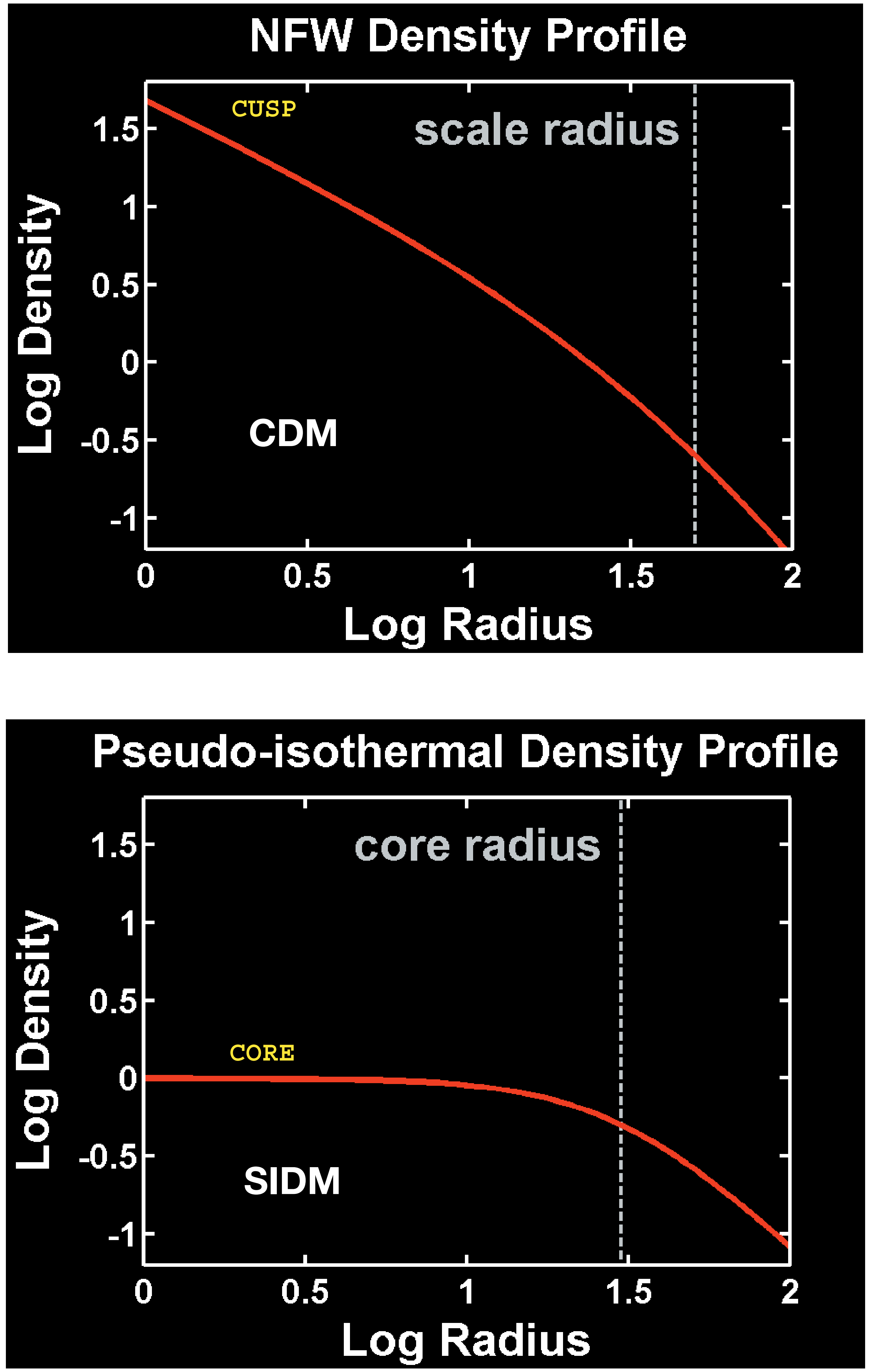
DM self-interactions change the shape of DM density profiles

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]

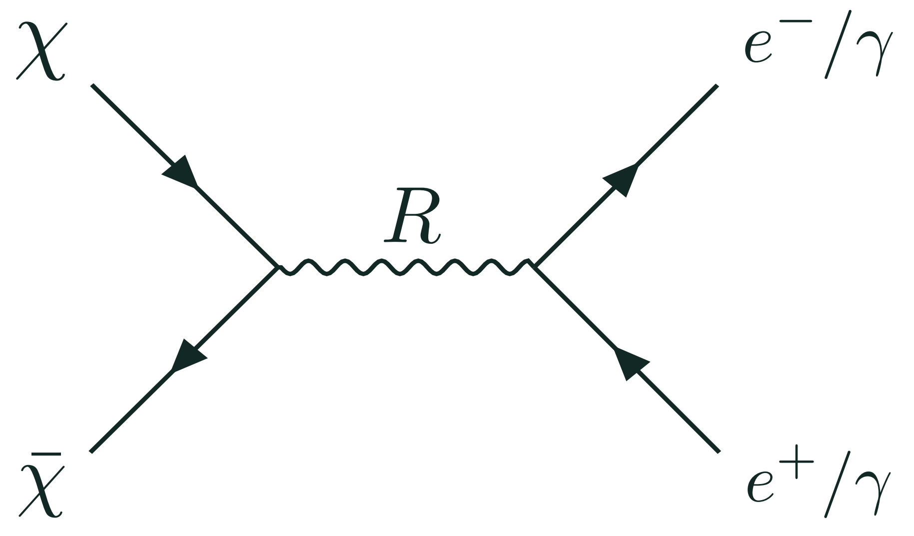
Intermezzo: resonant self-scattering

DM density profiles prefer SIDM models with strength

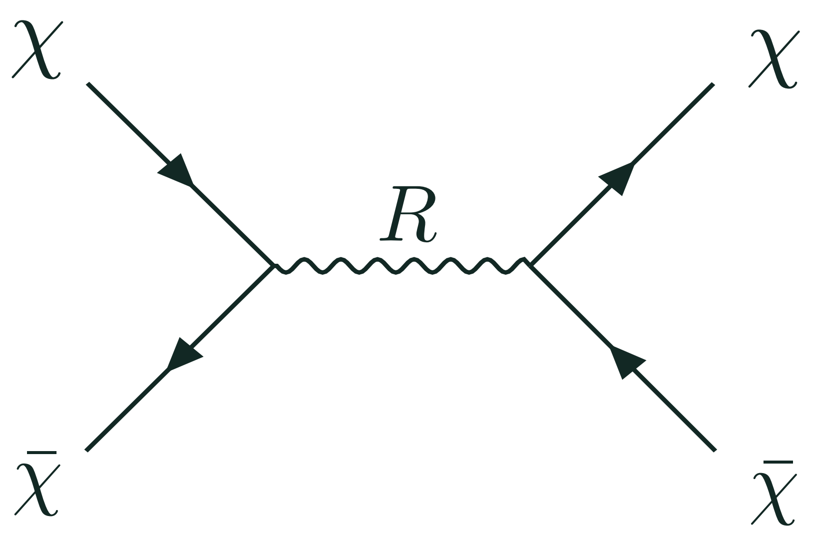
$$\frac{\sigma}{m} \sim 0.1 - 1\ \mathrm{cm}^2/\mathrm{g}$$

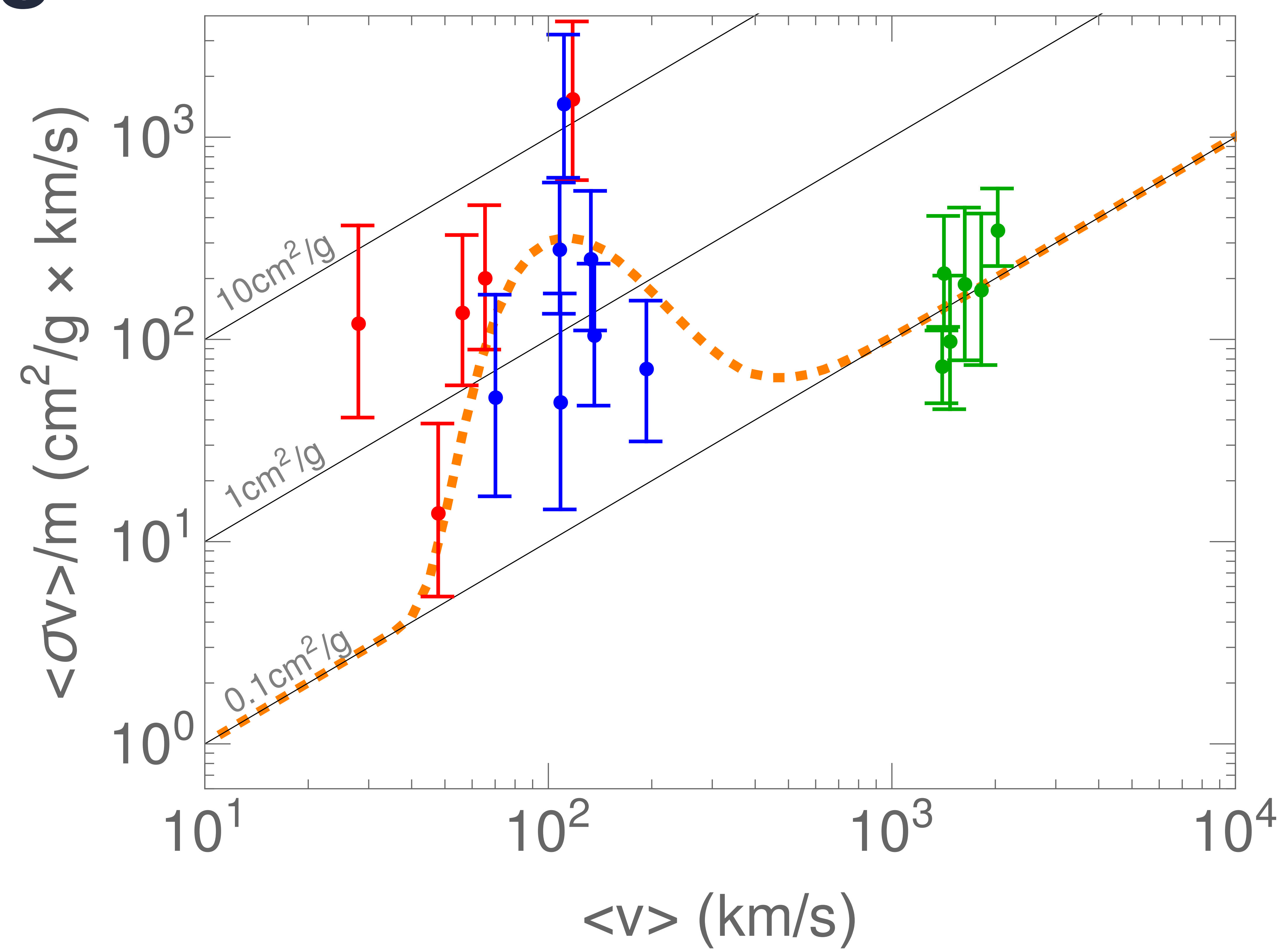
and velocity dependence to accommodate observations at different scales

For any electrophilic model, we also expect (sizeable) self-interactions



$\Rightarrow$





Adapted from Chu et al. [1810.04709]

Typical velocity peaks at galaxy halo sizes, which dictates mass of resonance

$$v_R \equiv 2\sqrt{\delta m} \sim 10^2\,\mathrm{km/s} \quad \Rightarrow \quad \delta m \sim 10^{-8}$$

Photodisintegration window

Light element abundances $N \in \{n, p, \mathrm{D}, {}^3\mathrm{H}, {}^3\mathrm{He}, {}^4\mathrm{He}, {}^7\mathrm{Li}, {}^7\mathrm{Be}\}$

Photodisintegration is sensitive to specific temperature range

At early times highly energetic photons are rapidly depleted from pair creation

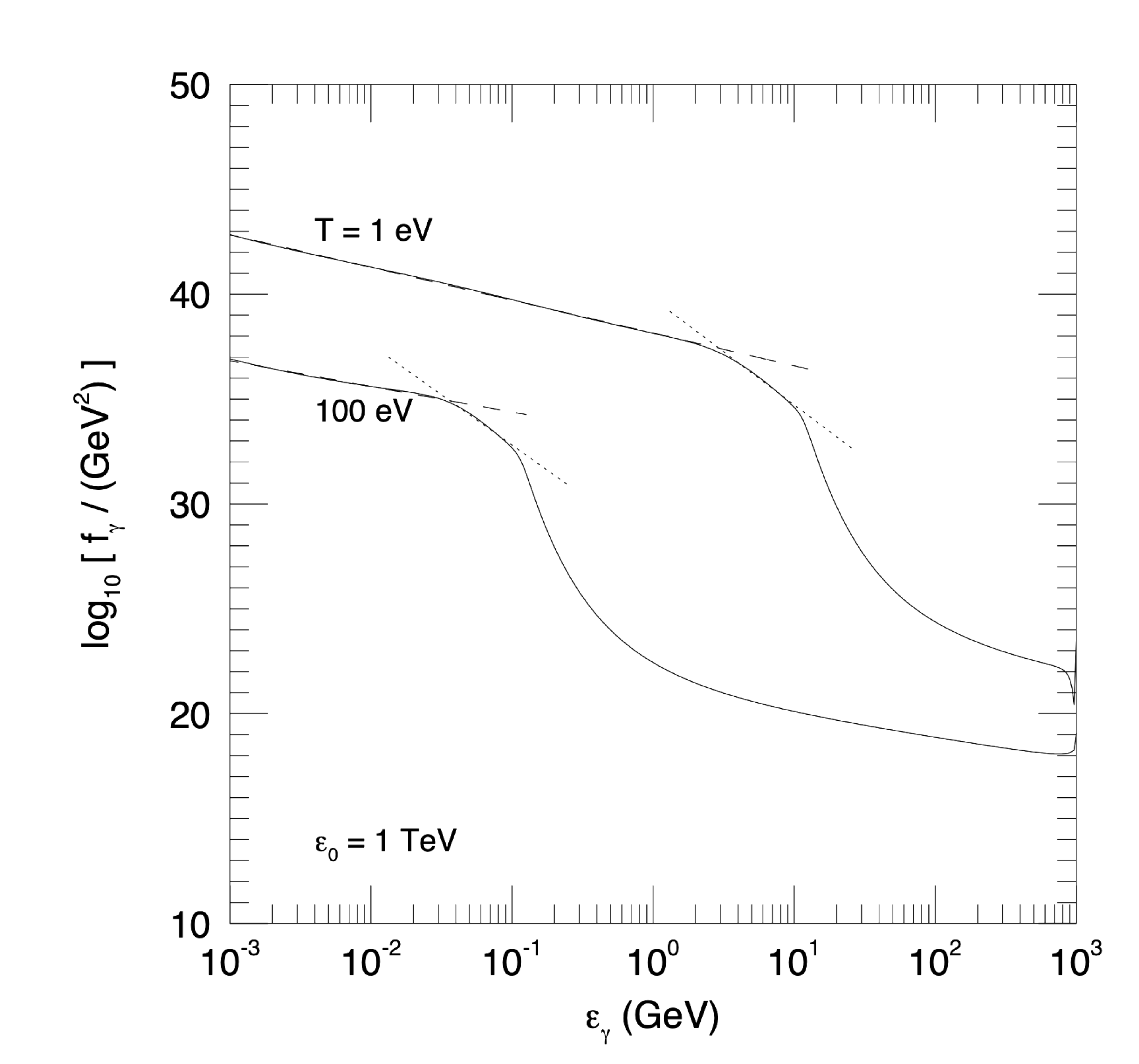
$$\gamma\gamma_{\mathrm{th}} \to e^+ e^-$$

Temperature threshold is

$$E^{\mathrm{th}}_{e^+e^-} \simeq \frac{m_e^2}{22T}$$

At late times, the DM fluid is too diluted for effective annihilations

$T \in [10^{-7}, 10^{-2}]$ MeV : well after standard BBN has ended



from Kawasaki and Moroi (1995) [astro-ph/9412055]

T_{kd} dependence

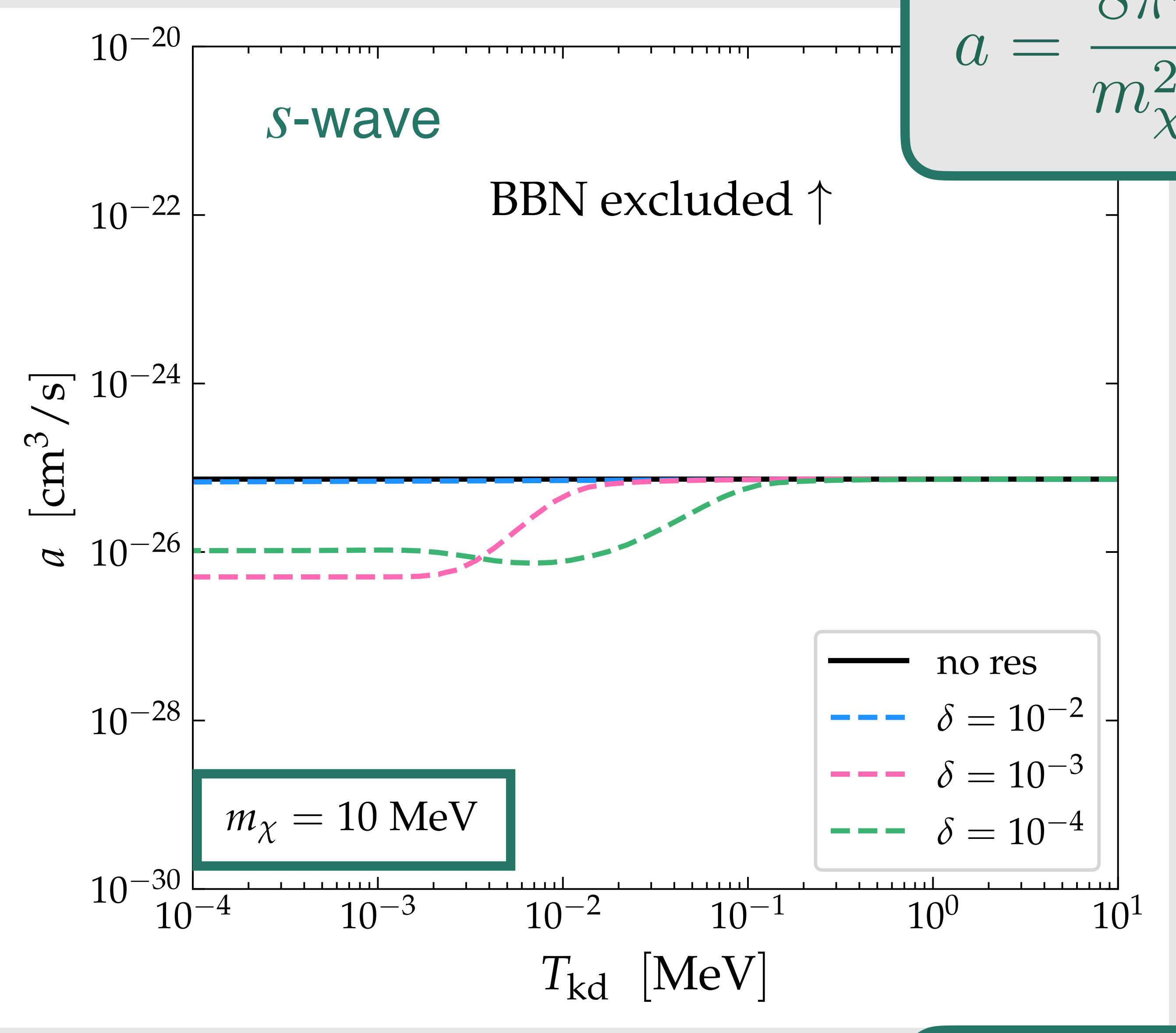
$$T_\chi(T) = \begin{cases} T & \text{if } T > T_{\mathrm{kd}} \\ T_{\mathrm{kd}} R(T_{\mathrm{kd}})^2 / R(T)^2 & \text{if } T < T_{\mathrm{kd}} \end{cases}$$

Setting the stage: understand the decoupling temperature dependence first

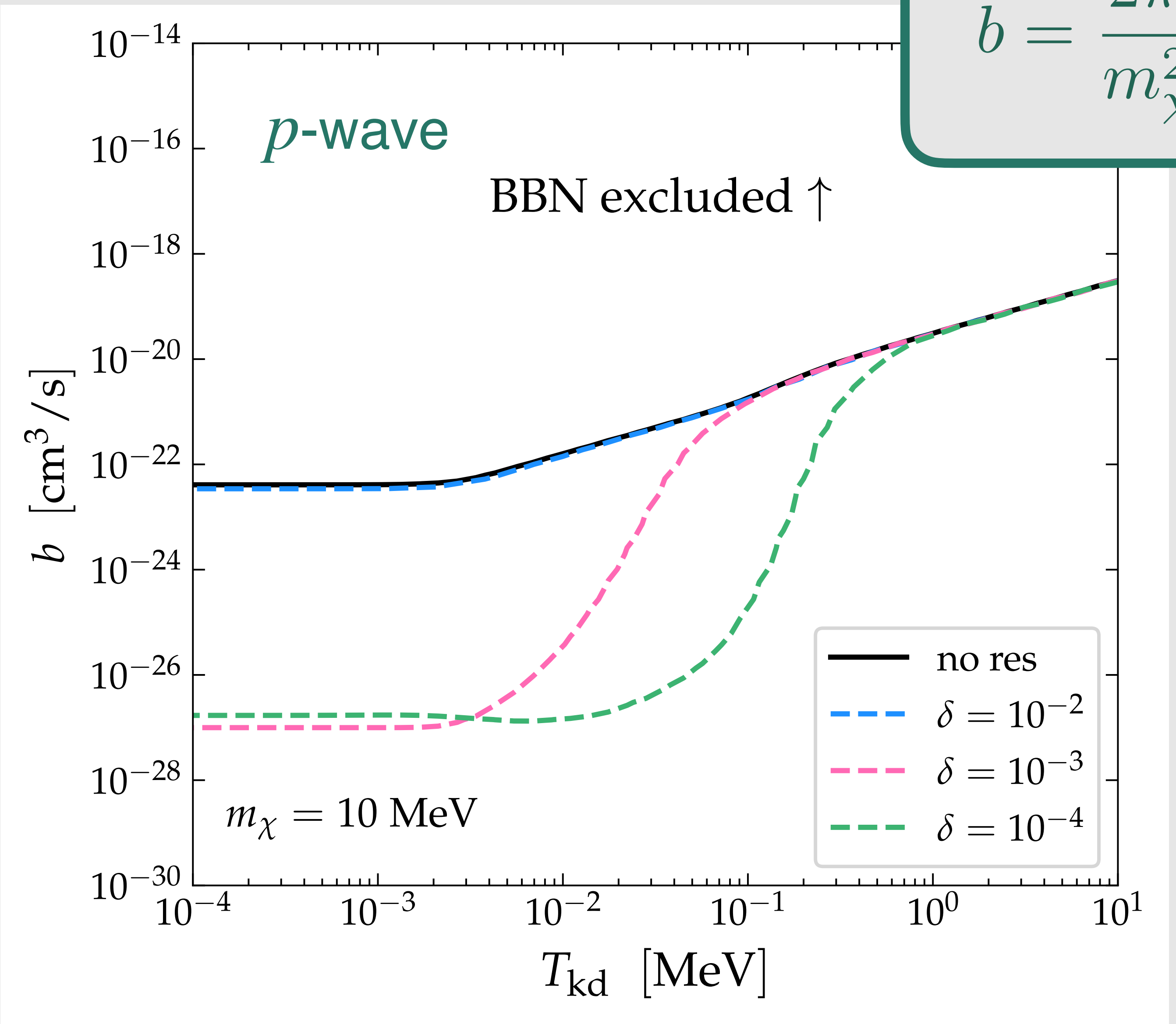
Low masses: early decoupling suppresses resonance effect

If decoupling happens significantly late, resonance model suffers from stronger bounds

$$a = \frac{8\pi \gamma_v \gamma_d}{m_\chi^2 \delta m^2}$$



$$b = \frac{2\pi \gamma_v \gamma_d}{m_\chi^2 \delta m^2}$$



$T_{\rm kd}$ dependence

$$T_\chi(T) = \begin{cases} T & \text{if T} > \text{T}_{\rm kd} \\ T_{\rm kd} R(T_{\rm kd})^2/R(T)^2 & \text{if T} < \text{T}_{\rm kd} \end{cases}$$

Setting the stage: understand the decoupling temperature dependence first

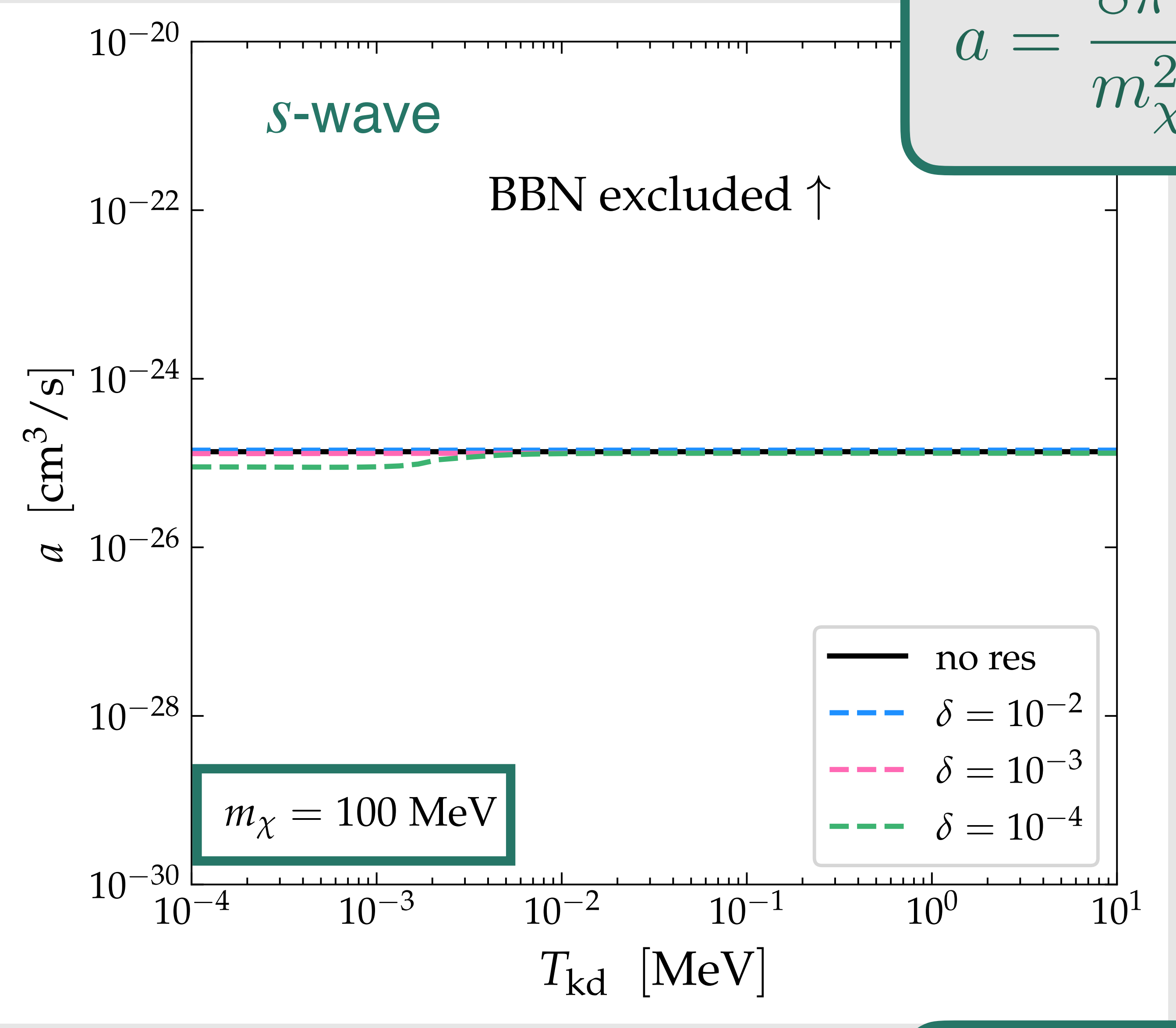
Low masses: early decoupling suppresses resonance effect

If decoupling happens significantly late, resonance model suffers from stronger bounds

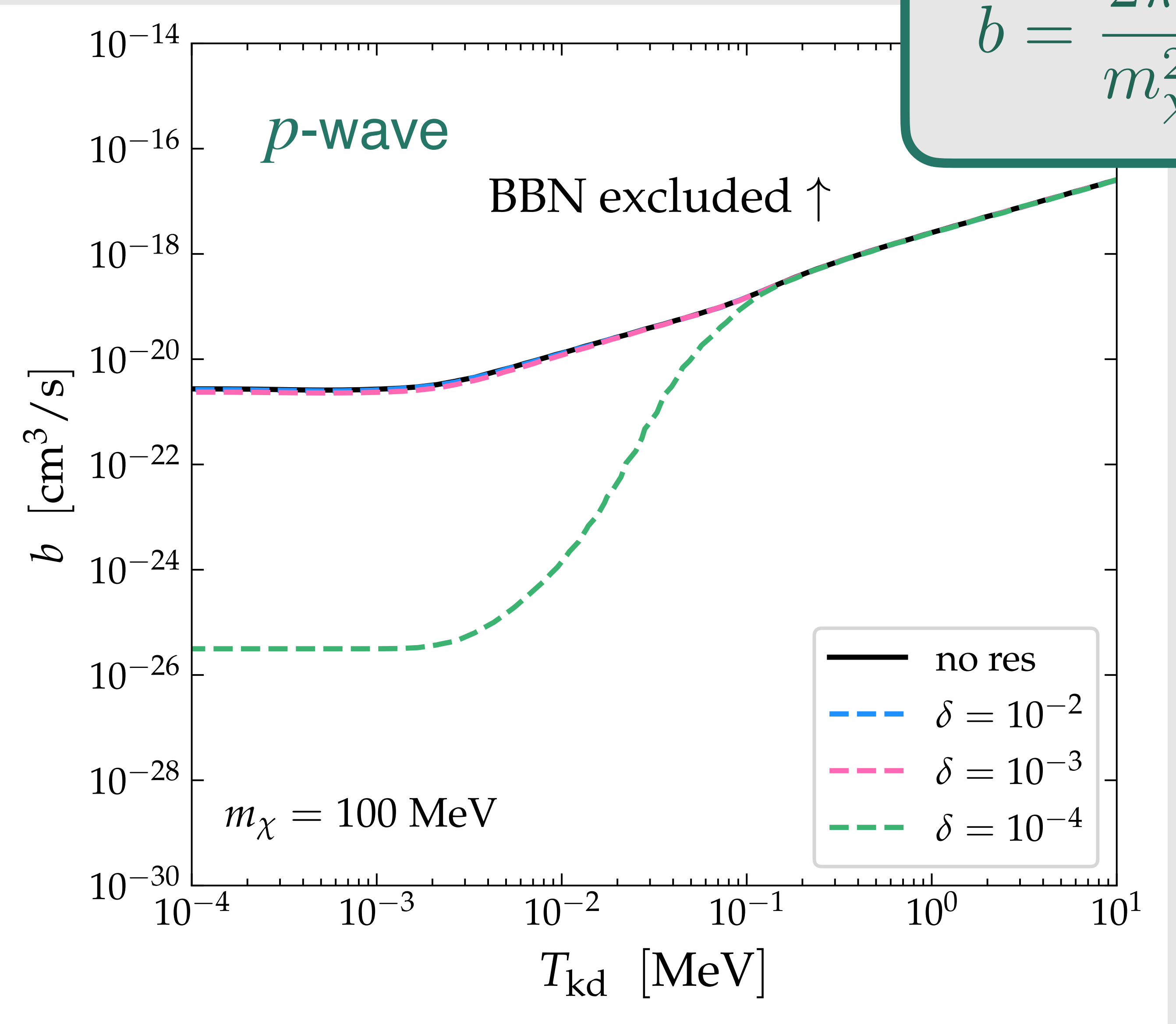
Larger masses: s-wave resonance barely noticeable

For p-wave, the narrow resonances are strongly constrained

Across the board: larger masses are typically less constrained



$$a = \frac{8\pi\gamma_v\gamma_d}{m_\chi^2\delta m^2}$$



$$b = \frac{2\pi\gamma_v\gamma_d}{m_\chi^2\delta m^2}$$

Comparison to other bounds

p-wave results can be quite strict

Comparing the dark photon + scalar model

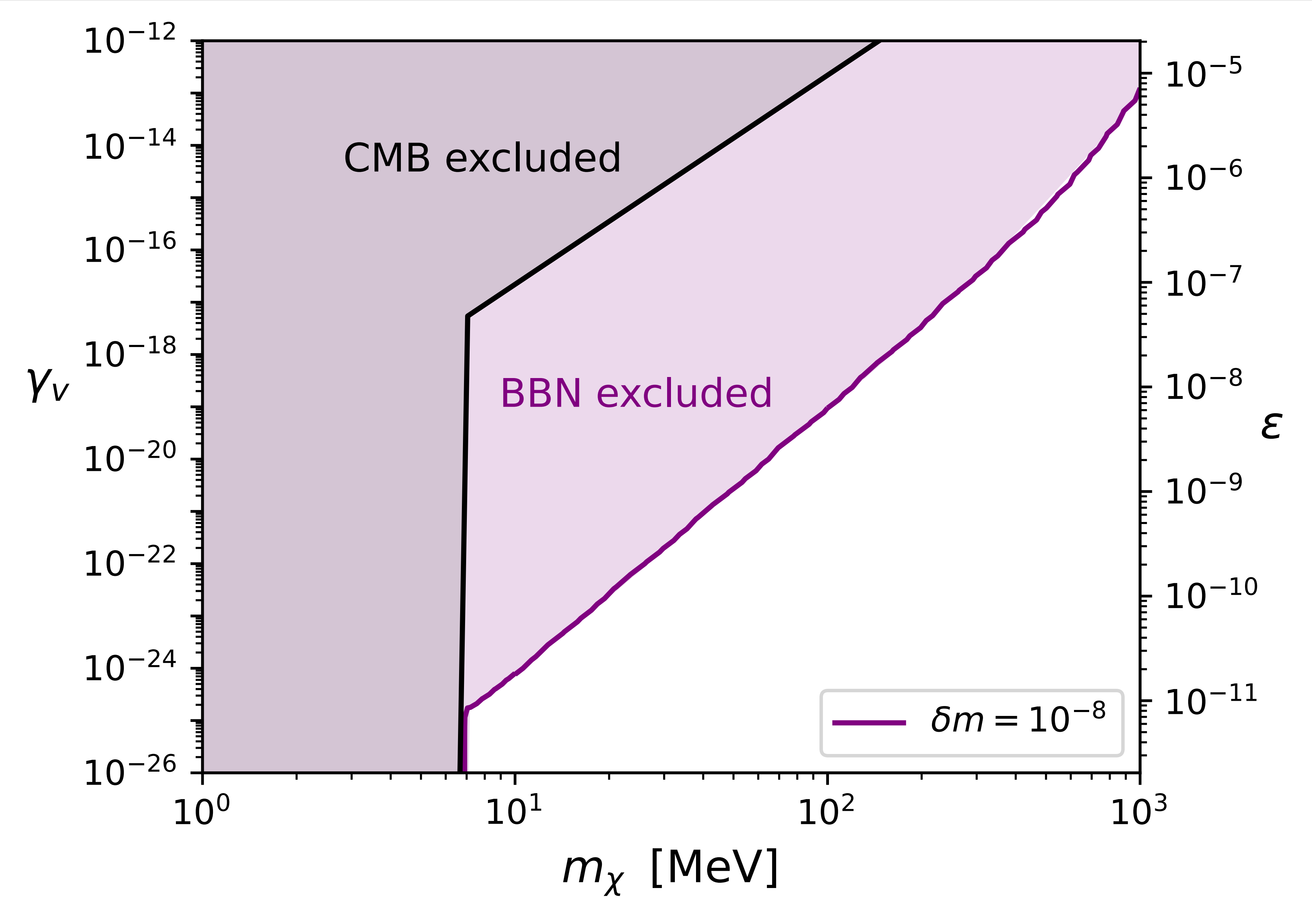
model	Lagrangian	n_d	γ_d	γ_v
2 scalar	$g_1 SS\Phi + g_2 \bar{e}e\Phi$	0	$\frac{g_1^2}{64\pi m^2}$	$\frac{g_2^2}{8\pi}$
$\boxed{\text{scalar + vector}}$	$g_1 \varphi^\dagger \overleftrightarrow{\partial}_\mu \varphi A'^\mu + g_2 \bar{e}\gamma^\mu e A'_\mu$	1	$\frac{g_1^2}{48\pi}$	$\frac{g_2^2}{12\pi}$
fermion + vector	$g_1 \bar{\chi}\gamma^\mu \chi A'_\mu + g_2 \bar{e}\gamma^\mu e A'_\mu$	0	$\frac{g_1}{8\pi}$	$\frac{g_2}{12\pi}$

and parametrizing the visible coupling $g_2 = \epsilon e$

Comparing this model to CMB constraints

$$p_{\text{ann}} = \frac{12\pi \gamma_v \gamma_d}{m_\chi^3 \delta m^2} \frac{T_{\text{SM}}^2}{m_\chi T_{\text{kd}}} < 3.3 \times 10^{-31} \ \text{cm}^3 \text{s}^{-1} \text{MeV}^{-1}$$

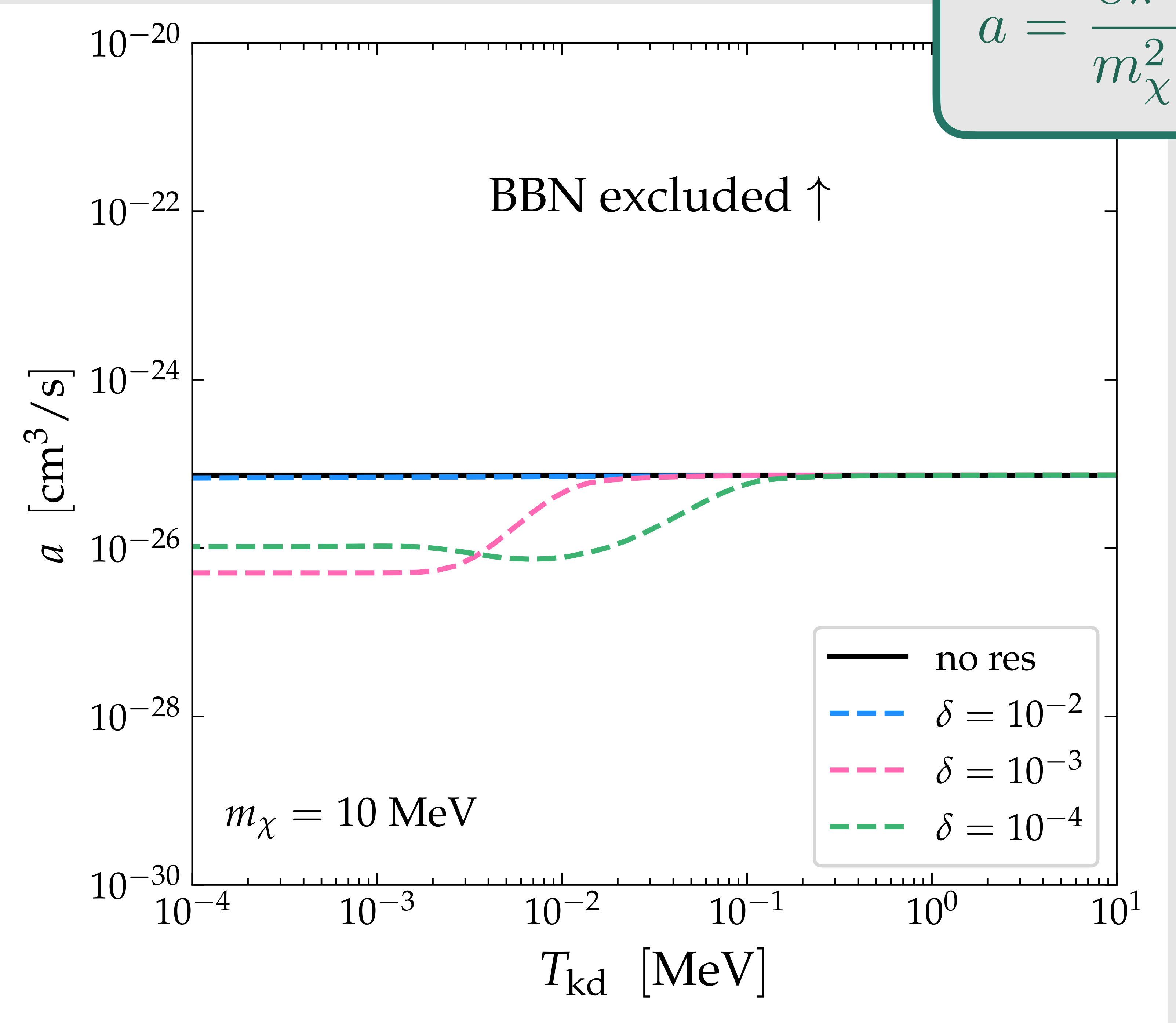
Planck collaboration (2020)



BBN constraints are more strict than CMB, and can probe kinetic mixings down to 10^-11!

Why are the $\delta m = 10^{-3}$ more stringent?

Appears to be a “coincidence”. Resonance and off-resonance contributions compete



$$a = \frac{8\pi\gamma_v\gamma_d}{m_\chi^2\,\delta m^2}$$