Big Bang Nucleosynthesis constraints on resonant DM annihilations

or: what can we learn about Dark Matter from the first few minutes after the Big Bang?

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Jamboree 2024

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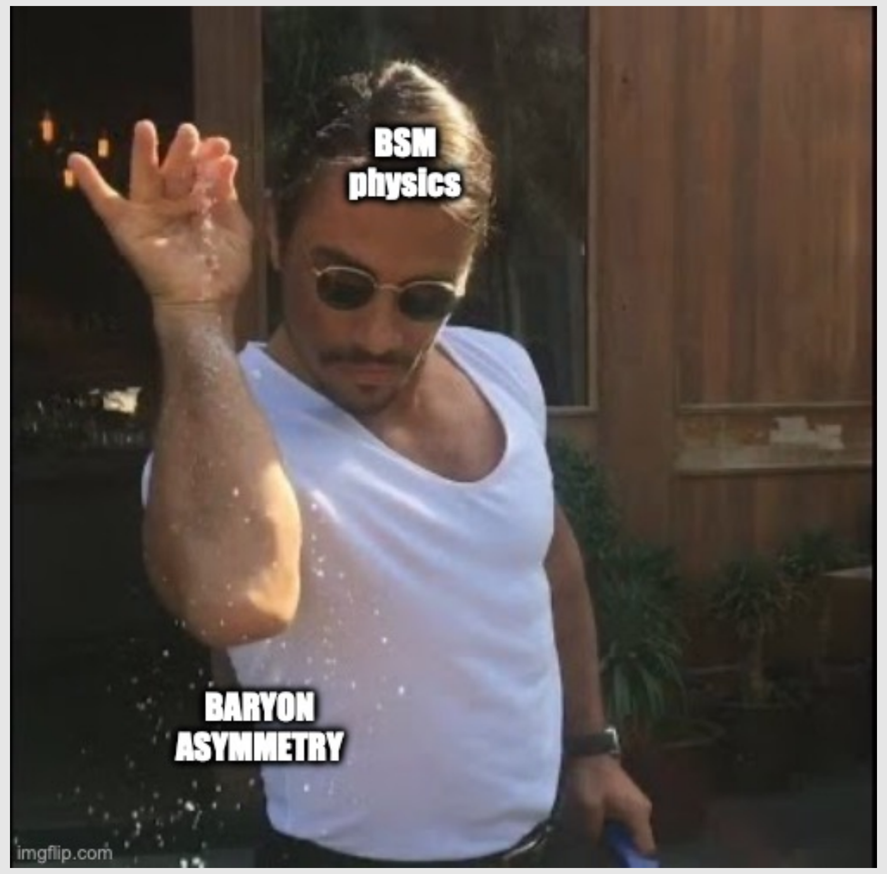
Big Bang Nucleosynthesis 101

or: primordial light element formation in a nutshell

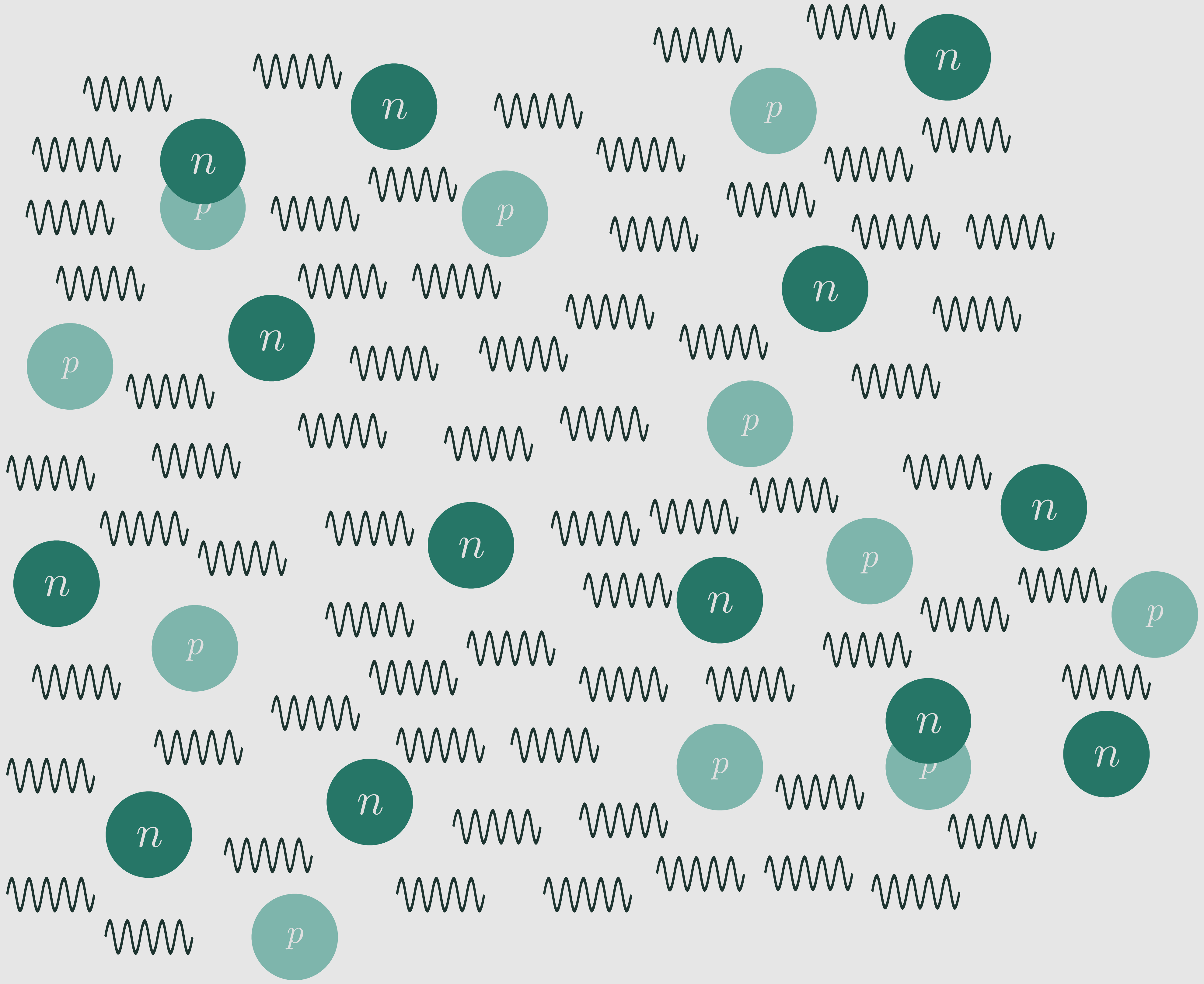
During Big Bang nucleosynthesis (BBN) the lightest elements are formed, e.g. deuterium formation

$$n + p \rightleftarrows D + \gamma$$



There are many more photons than baryons

$$\eta_b \equiv \frac{n_b}{n_\gamma} \sim 10^{-9}$$



$T > 1\,\mathrm{MeV}$

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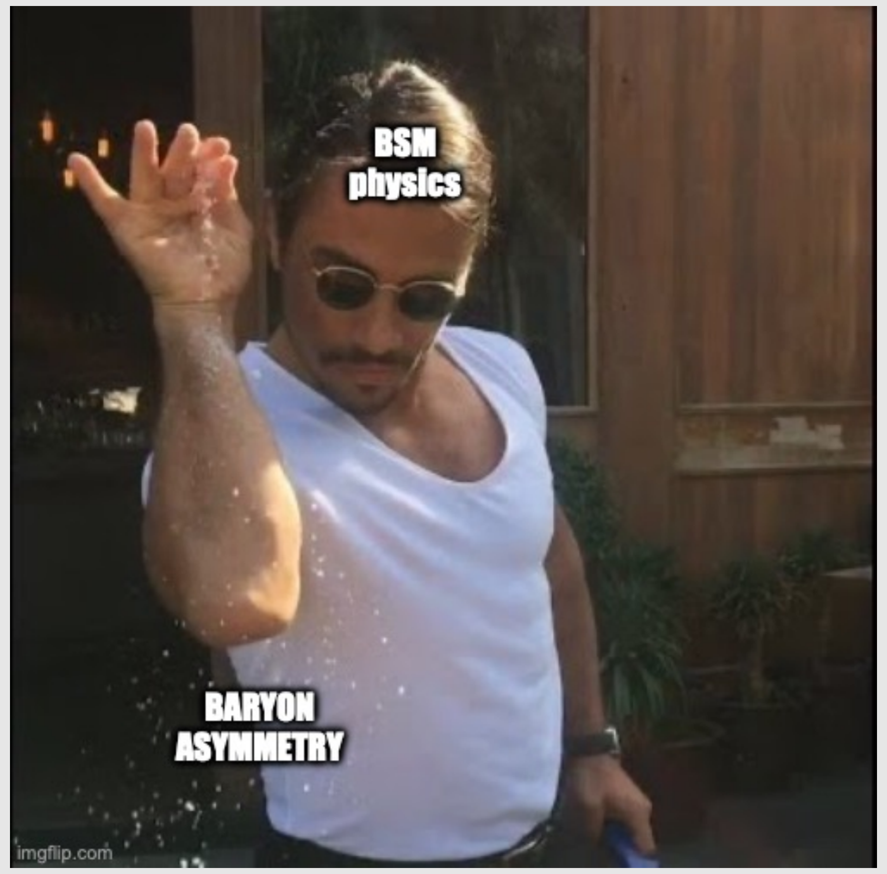

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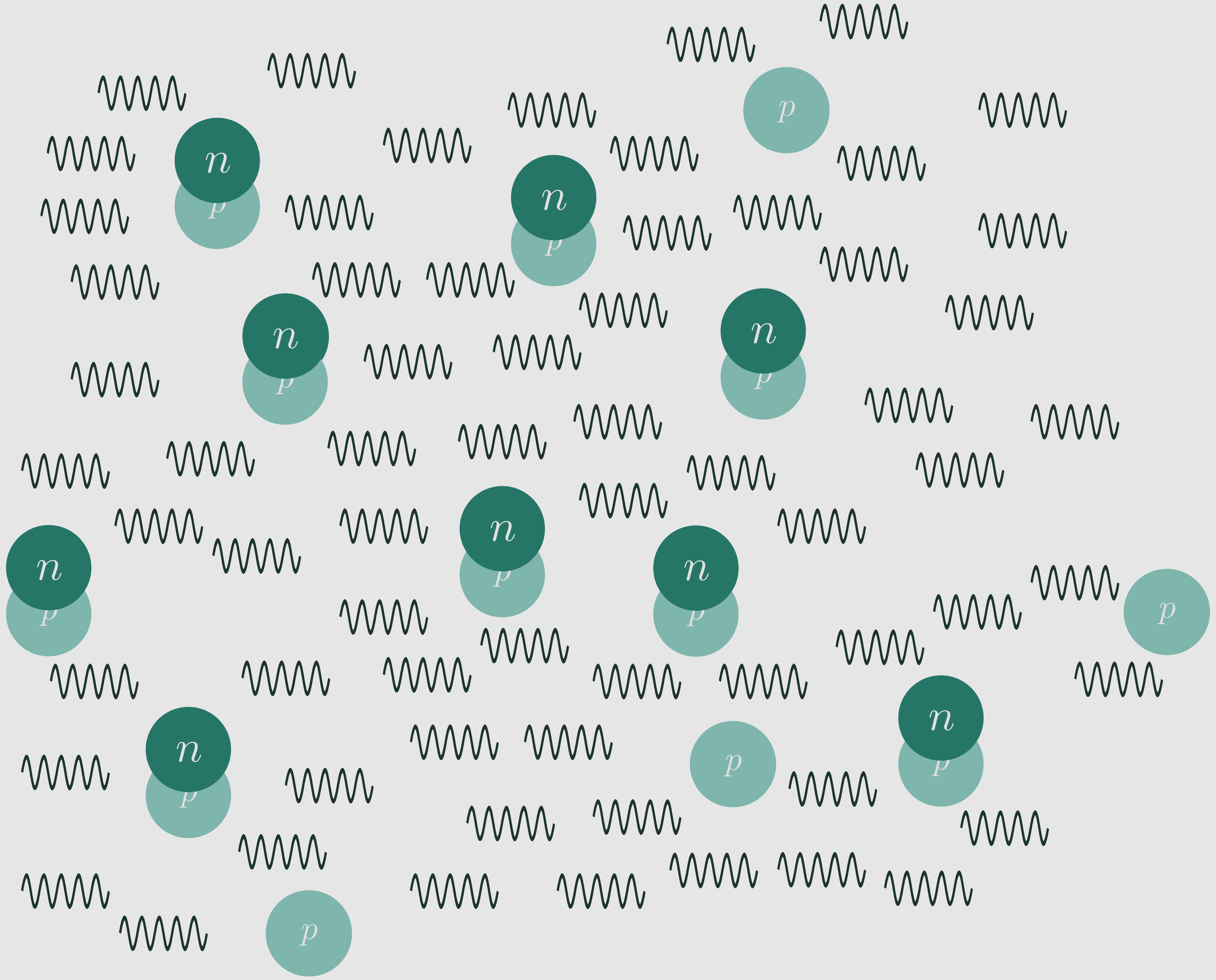
Although the binding energy of deuterium ~ few MeV, this process doesn't start until

$$T_{\rm BBN} \sim (0.1 - 1)\ \text{MeV} \quad \Rightarrow \quad t_{\rm BBN} \sim (1 - 300)\ \text{s}$$

Quickly thereafter, the deuterium is converted to heavier elements



$$T \sim 1\ \text{MeV}$$

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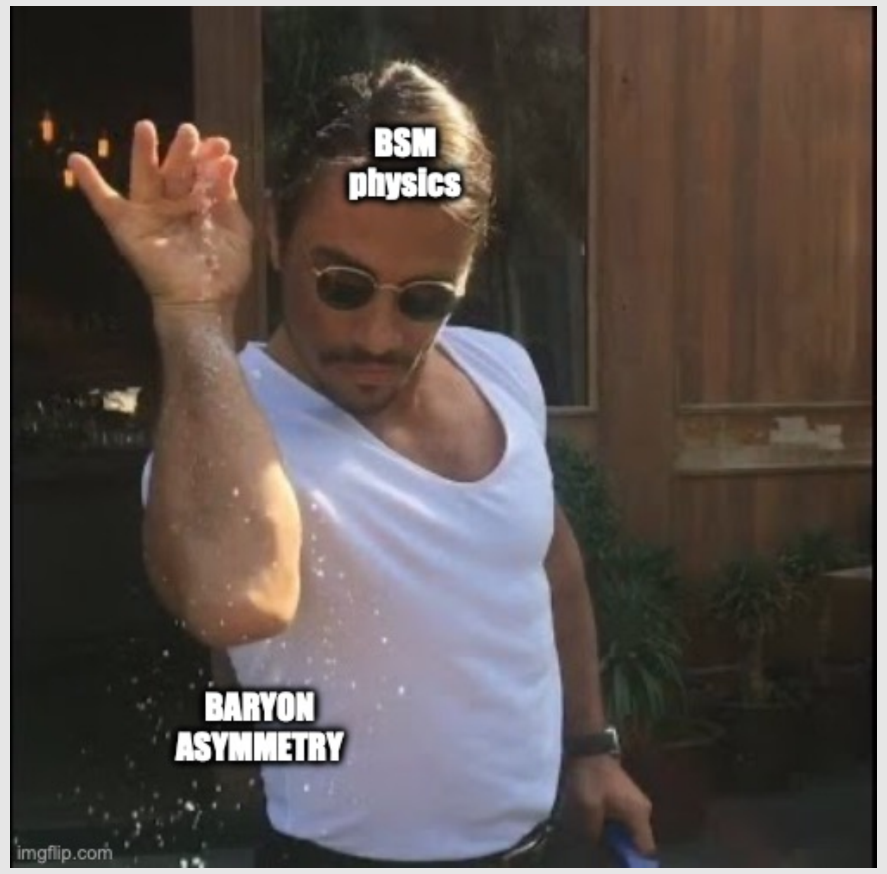

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Big Bang Nucleosynthesis 102

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Combining input from nuclear/particle physics and cosmology, we can predict the abundances quite precisely (theory)

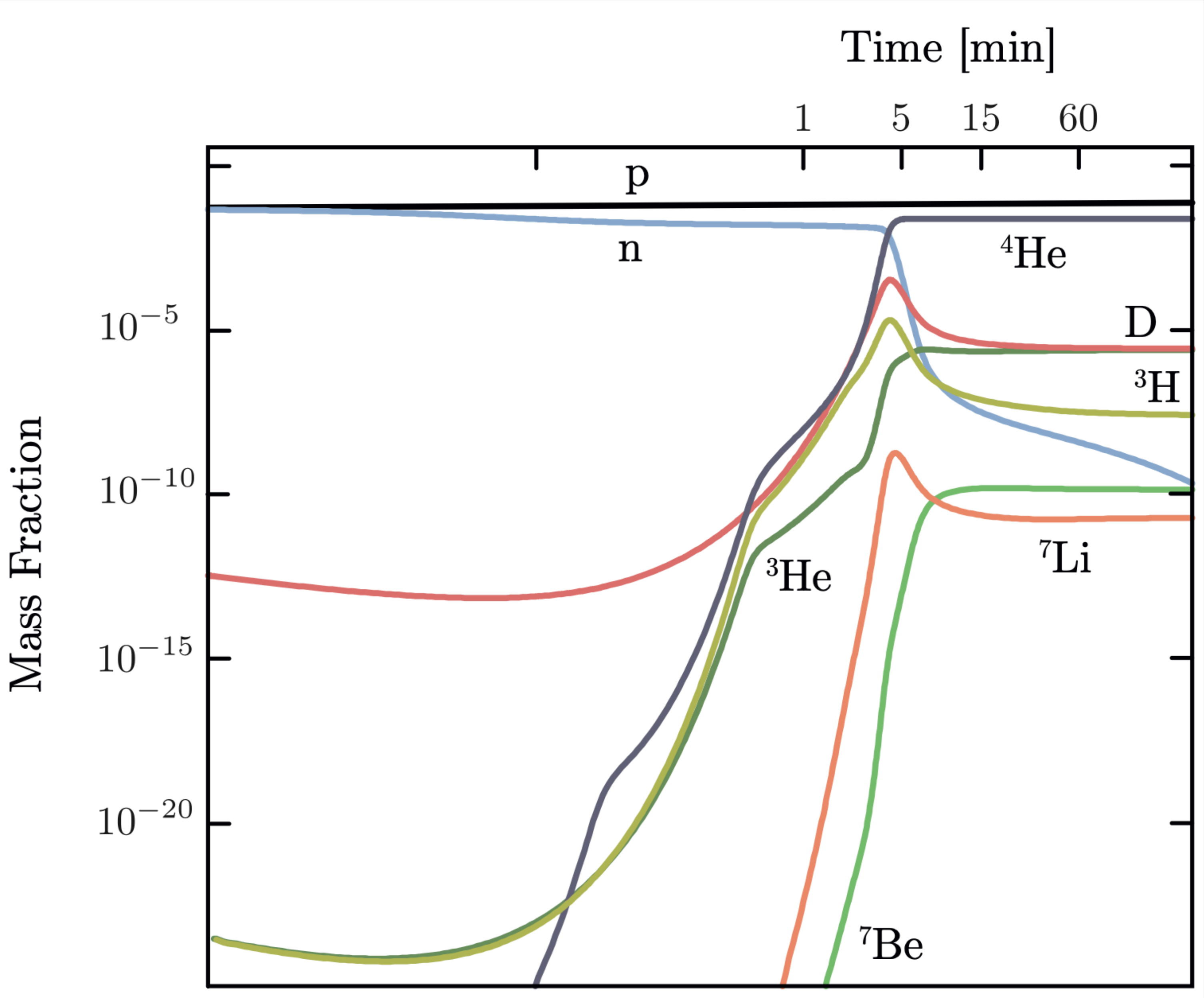

Figure taken from Baumann Cosmology lecture notes

E.g. Helium-4 mass fraction $\mathcal{Y}_p \equiv \frac{\rho(^4\text{He})}{\rho(^1\text{H})} \sim \frac{1}{4}$

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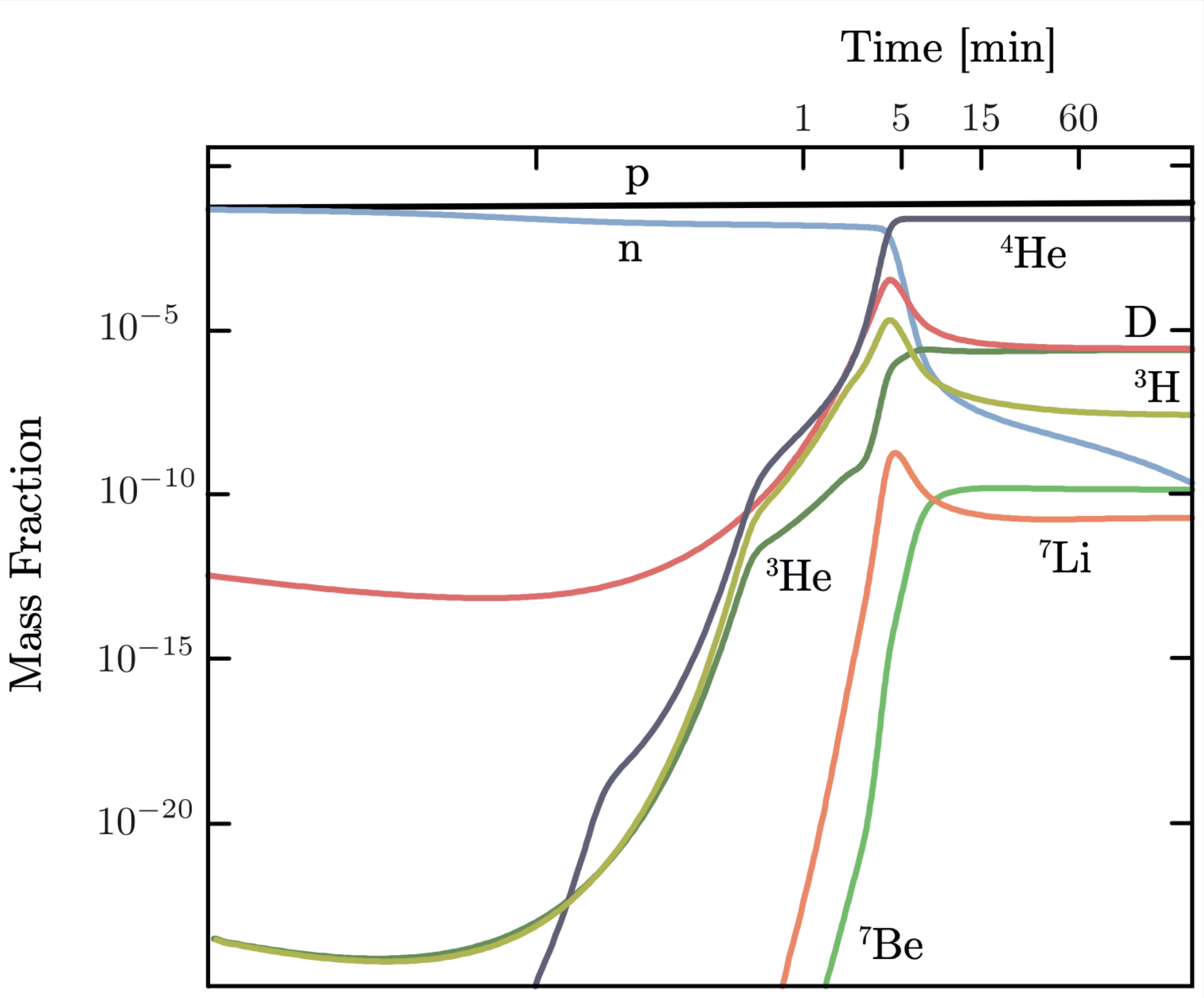

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Observations from primordial gas clouds

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

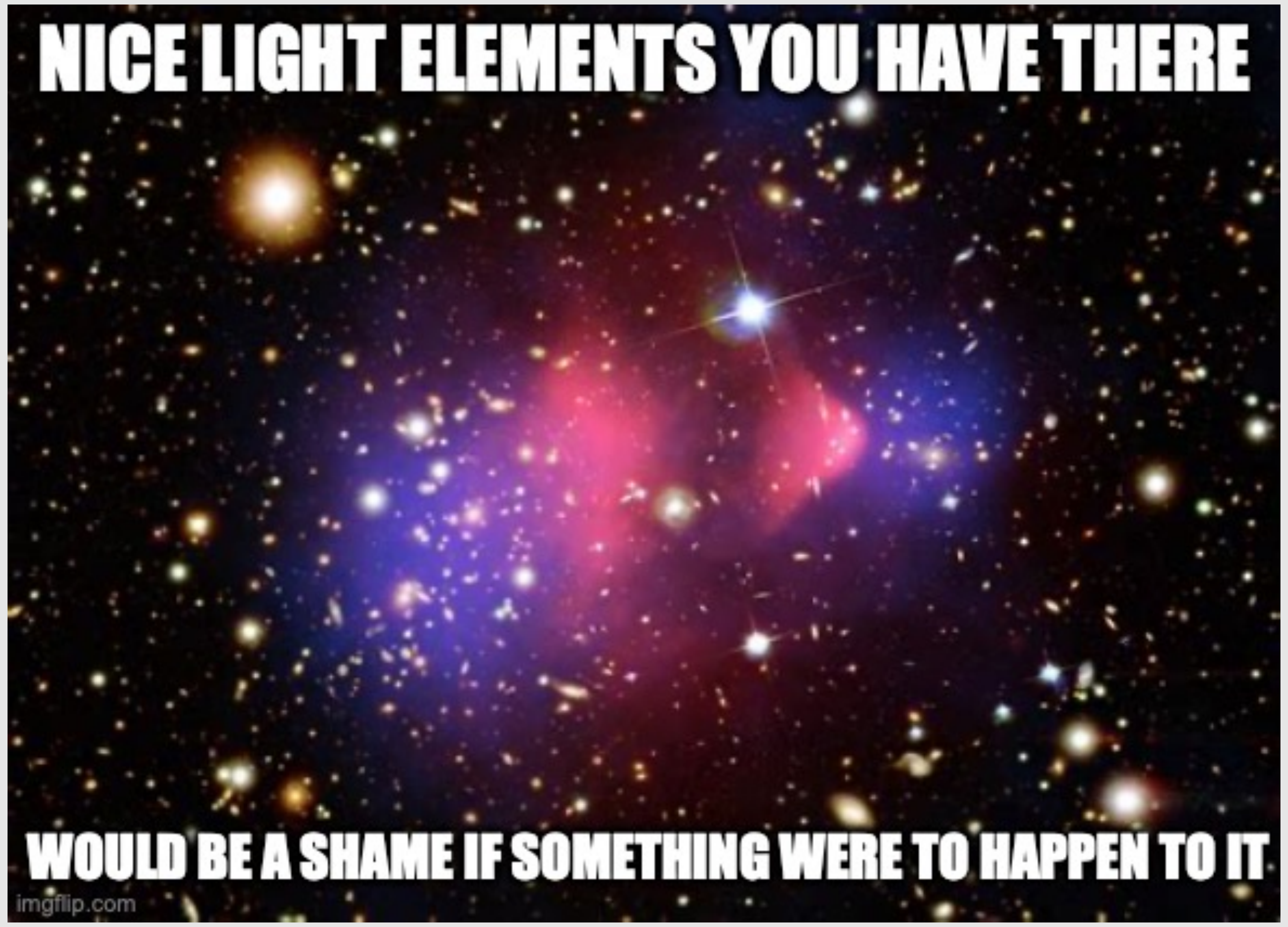
$$\text{D}/^1\text{H} = (25.47 \pm 0.25) \times 10^{-6}$$

PDG (2022)

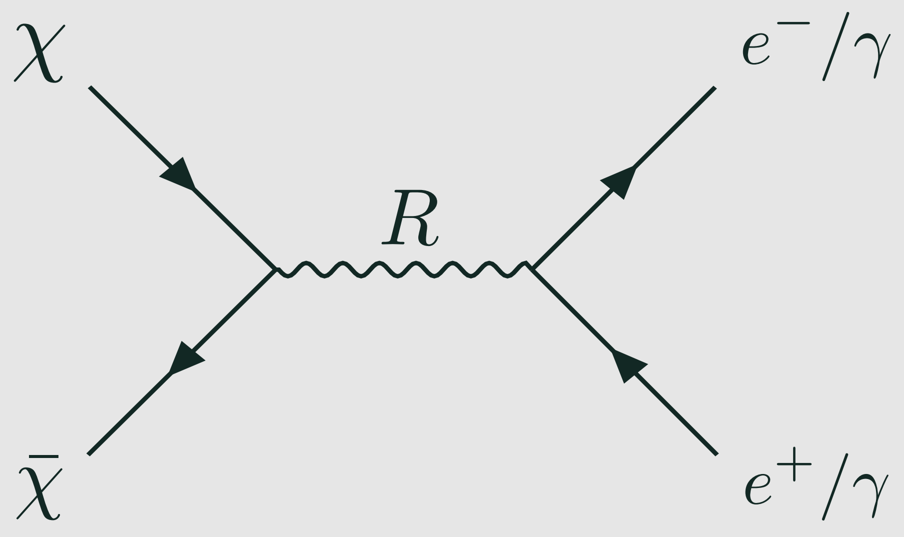
$\Rightarrow$ Can use observations to constrain new physics

Photodisintegration

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



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



The injected particles scatter via interactions:

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

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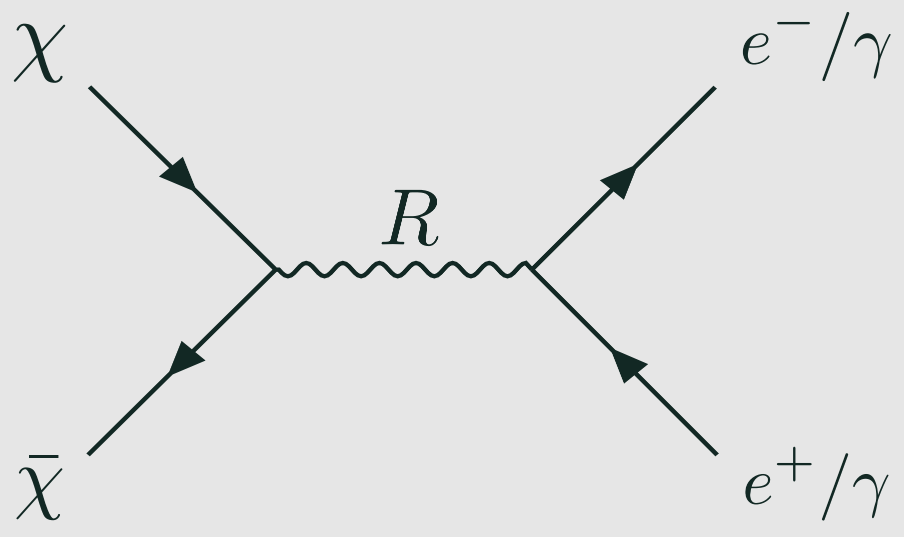

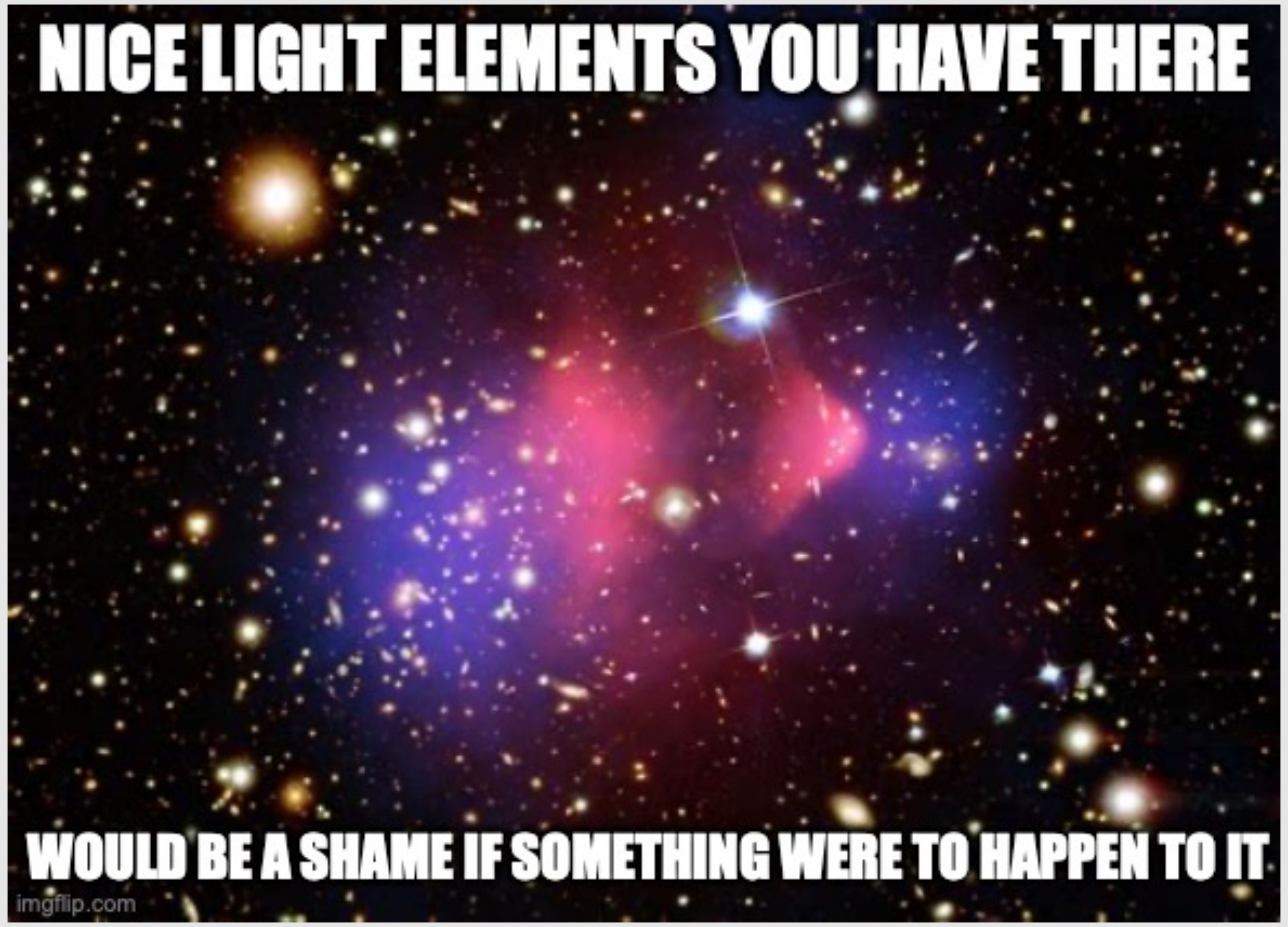

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Photodisintegration is sensitive to specific temperature range

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

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

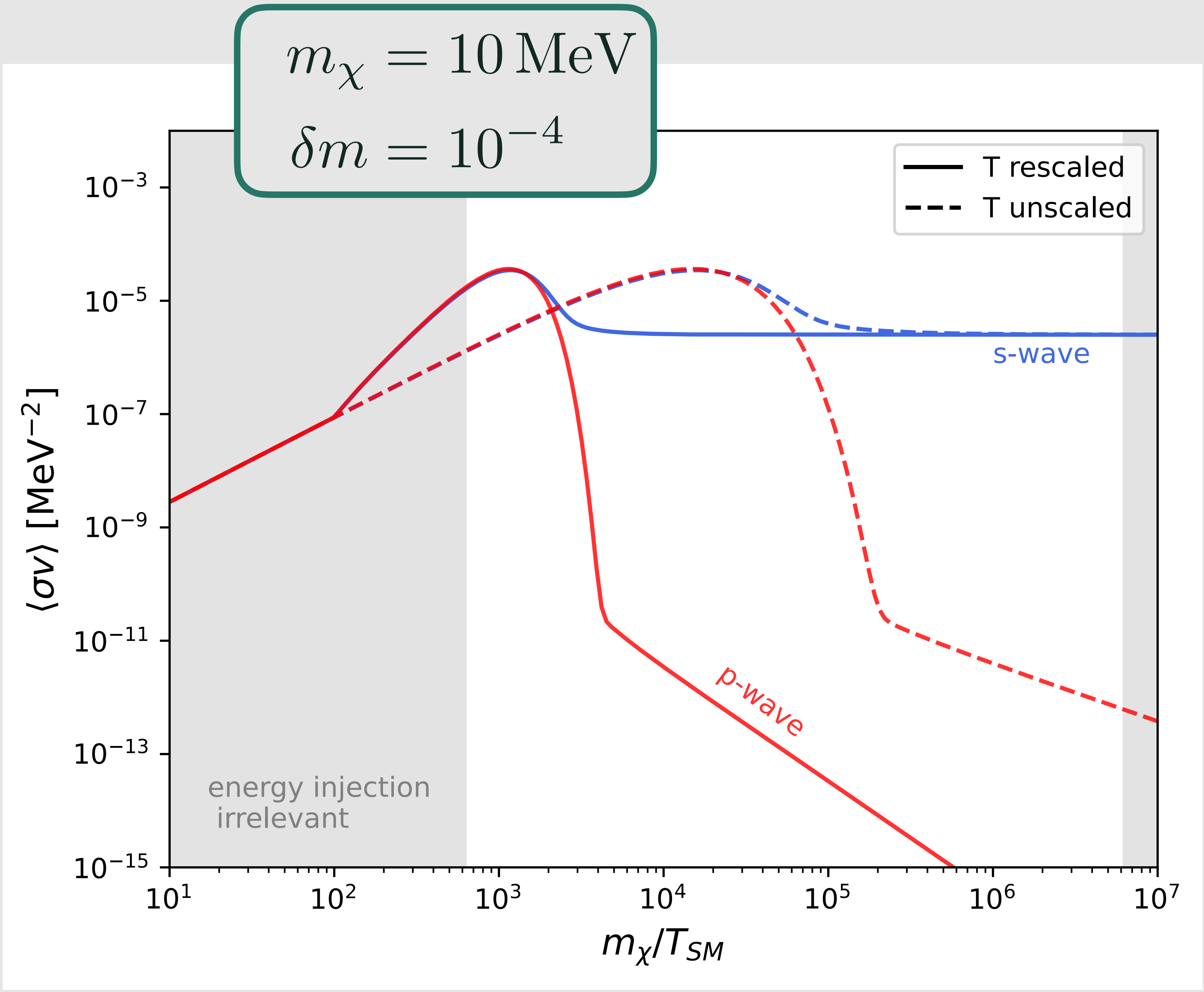
Why resonant annihilations?

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!

Injected power



Time

Why resonant annihilations?

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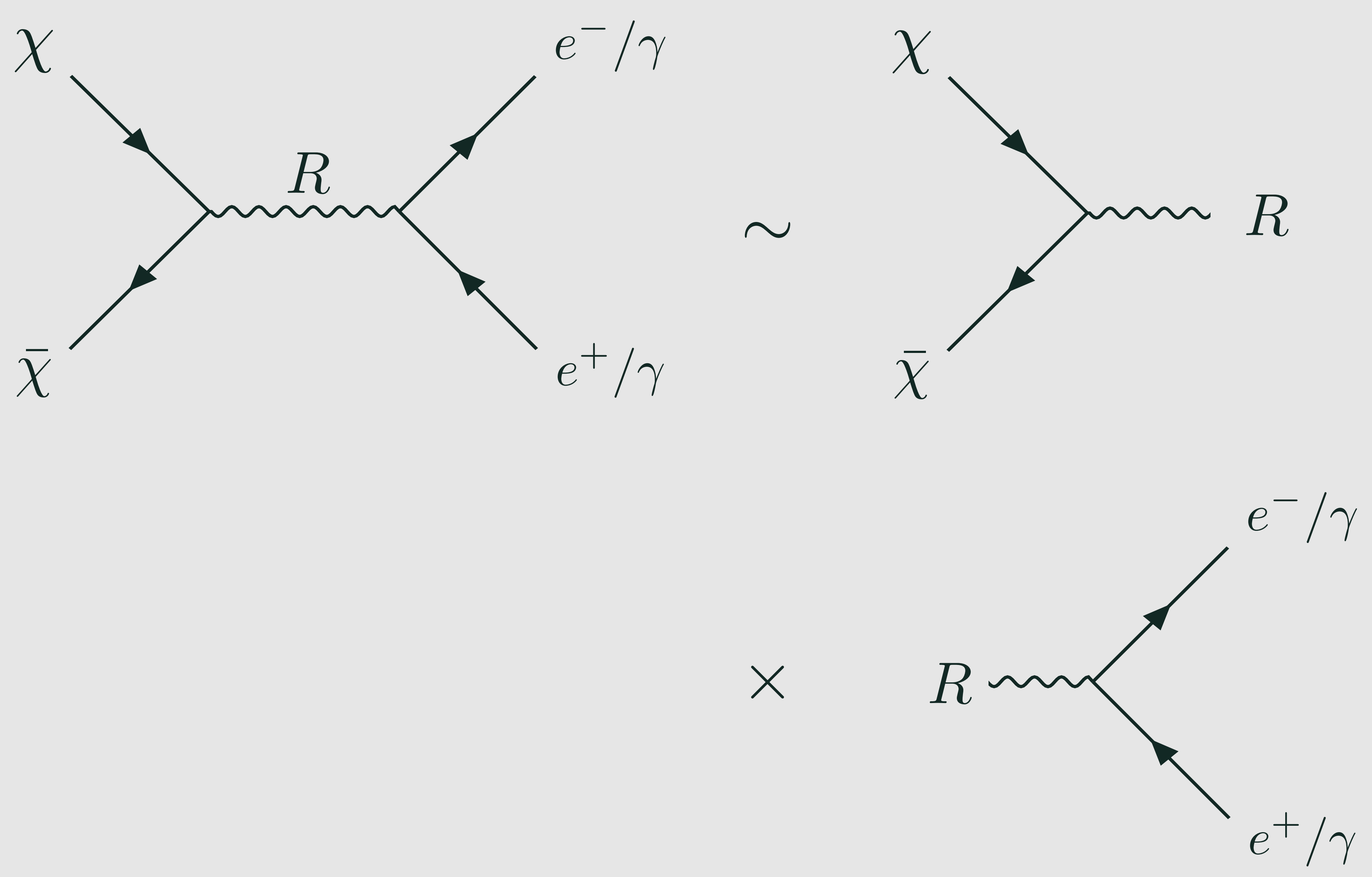
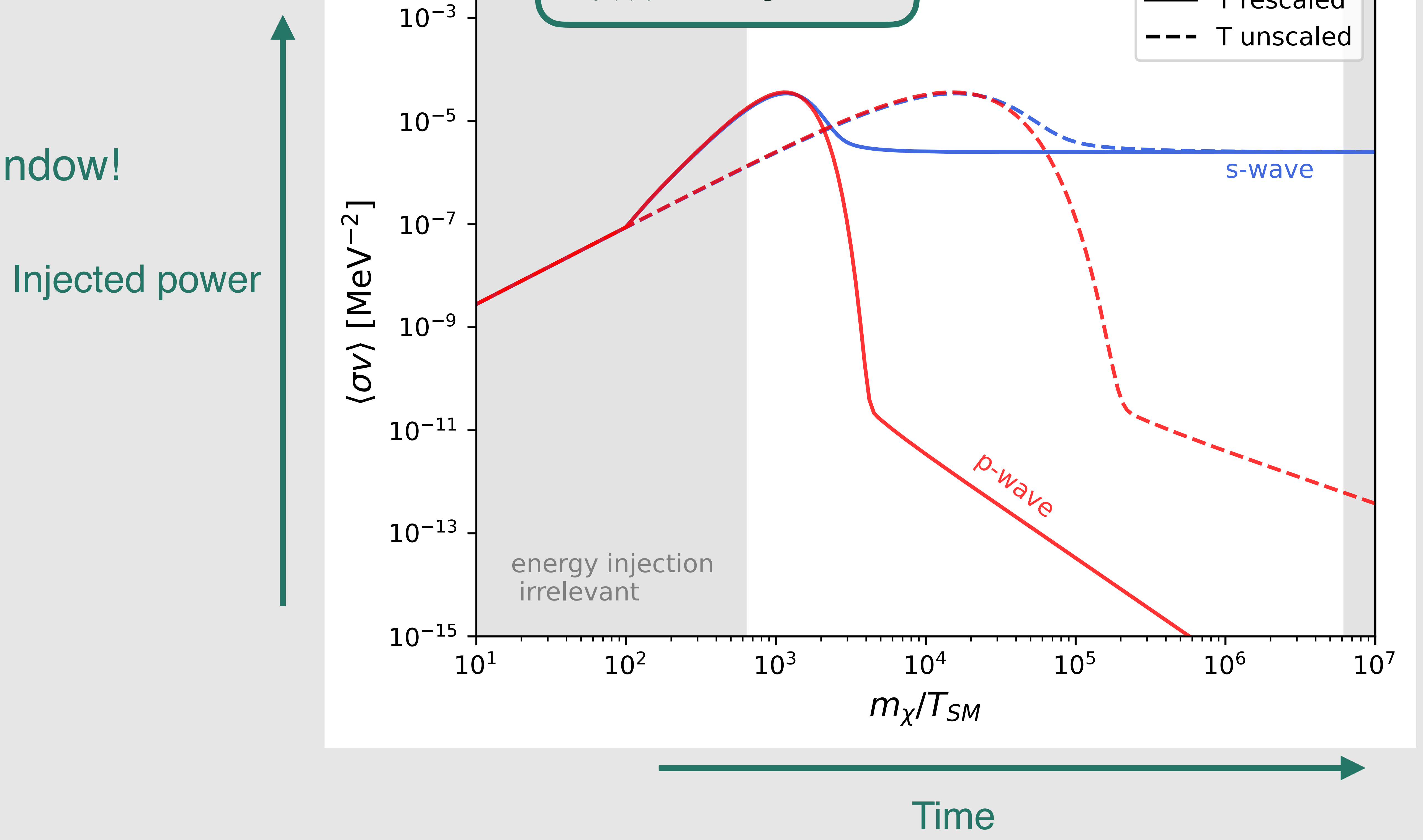


$m_\chi = 10\,\mathrm{MeV}$

$\delta m = 10^{-4}$



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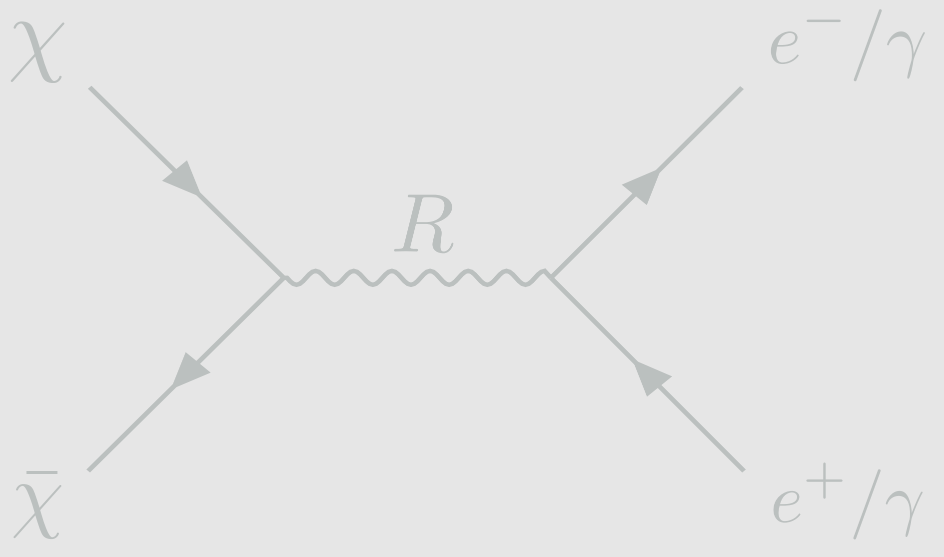
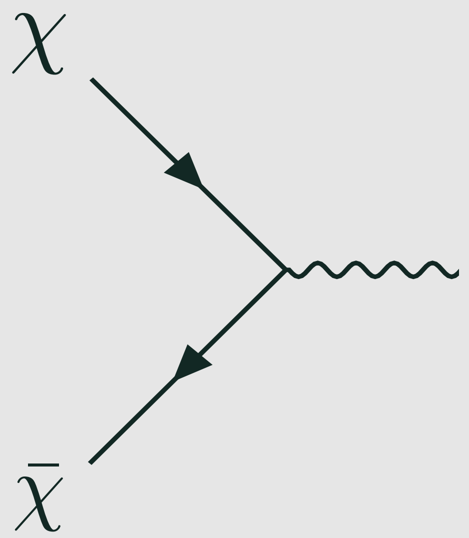
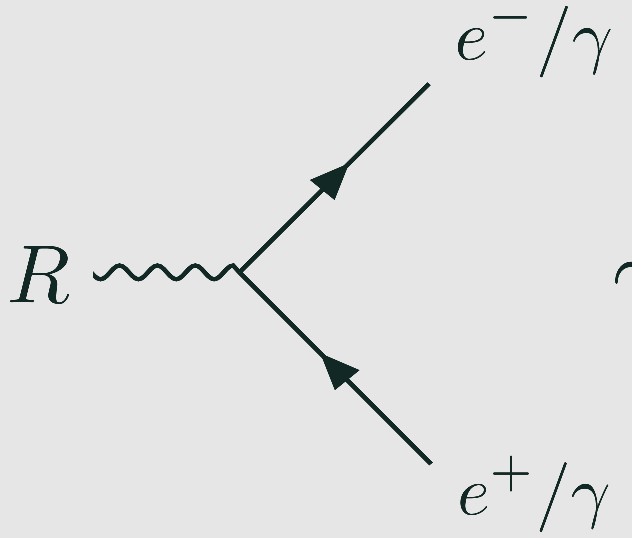


$\sim$

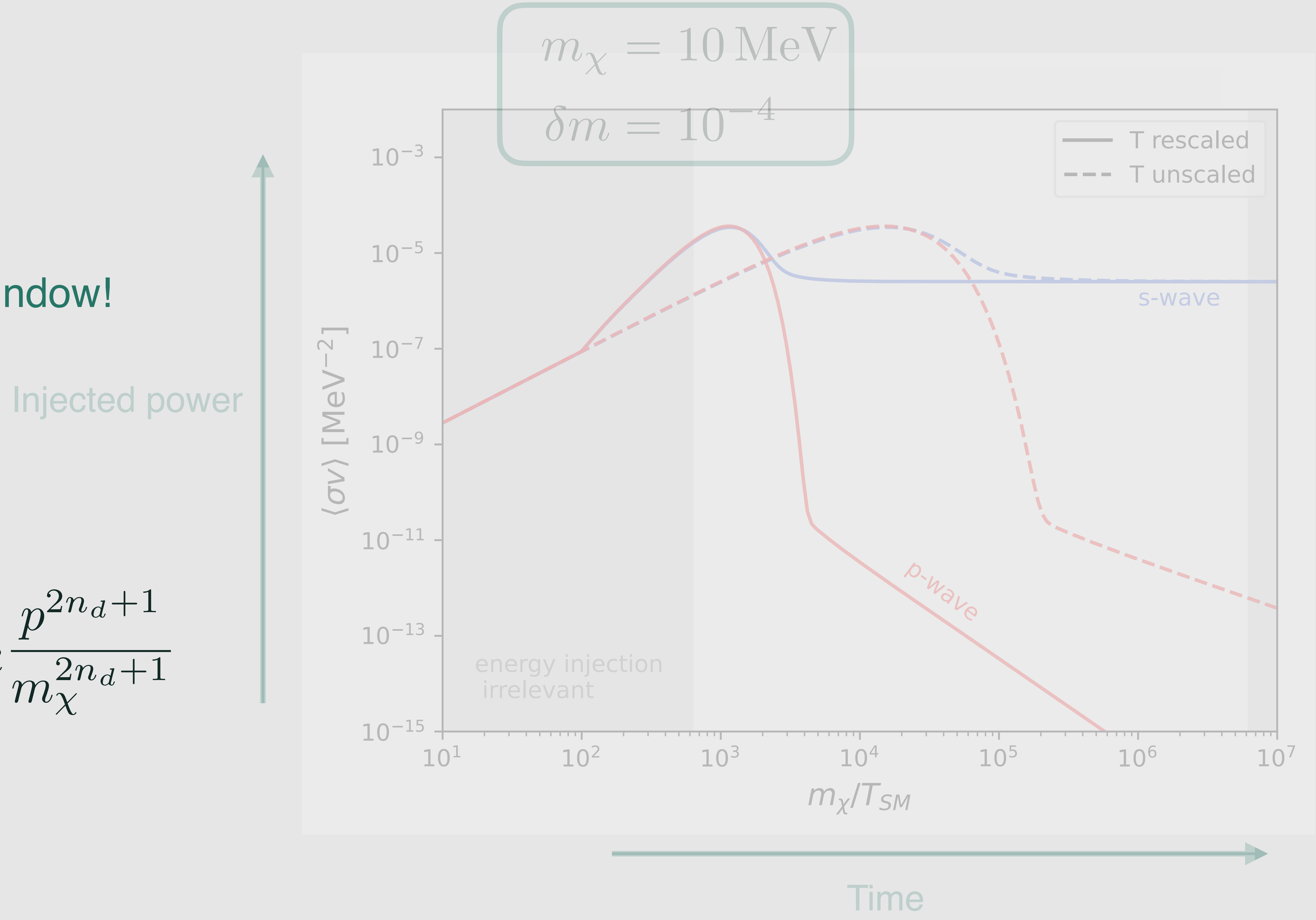


$$\sim \gamma_d m_R \frac{p^{2n_d+1}}{m_\chi^{2n_d+1}}$$

$\times$



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



γ_d : dark coupling
γ_v : visible coupling
$n_d = 0$ $s-$wave
$n_d = 1$ $p-$wave

Model independent setup!

Results (s-wave)

Observations and theory match —> we can constrain the strength of the DM annihilations

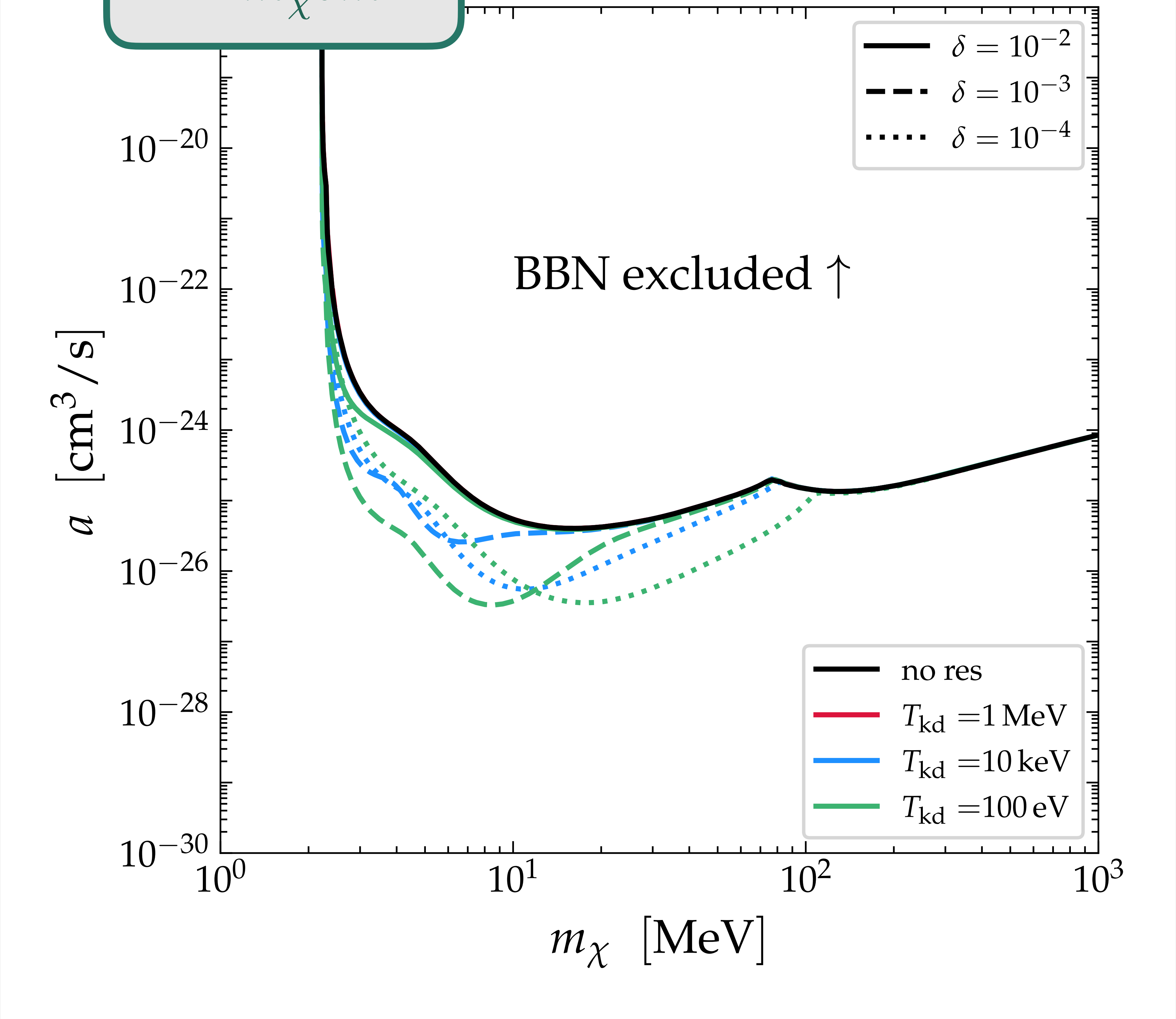
The constraints depend on the kinetic decoupling temperature

$$T_\chi(T_{\rm SM}) = \begin{cases} T_{\rm SM} & T \geq T_{\rm kd} \\ T_{\rm SM}^2/T_{\rm kd} & T < T_{\rm kd} \end{cases}$$

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

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

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



Same story for a p-wave resonance!

Conclusions

- The first few minutes after the Big Bang provide a powerful probe of BSM physics
- One example is DM that annihilates resonantly into SM photons or electrons, which would disintegrate light elements
- Using BBN observations we can constrain the DM annihilation cross section
- The constraints depend on kinetic decoupling temperature; if the dark and SM sector remain in thermal contact long enough, the resonance strengthens the bounds

Thank you!

Back up

Temperature dependence

Injected energy depends on the thermally averaged cross section

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

with DM temperature

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

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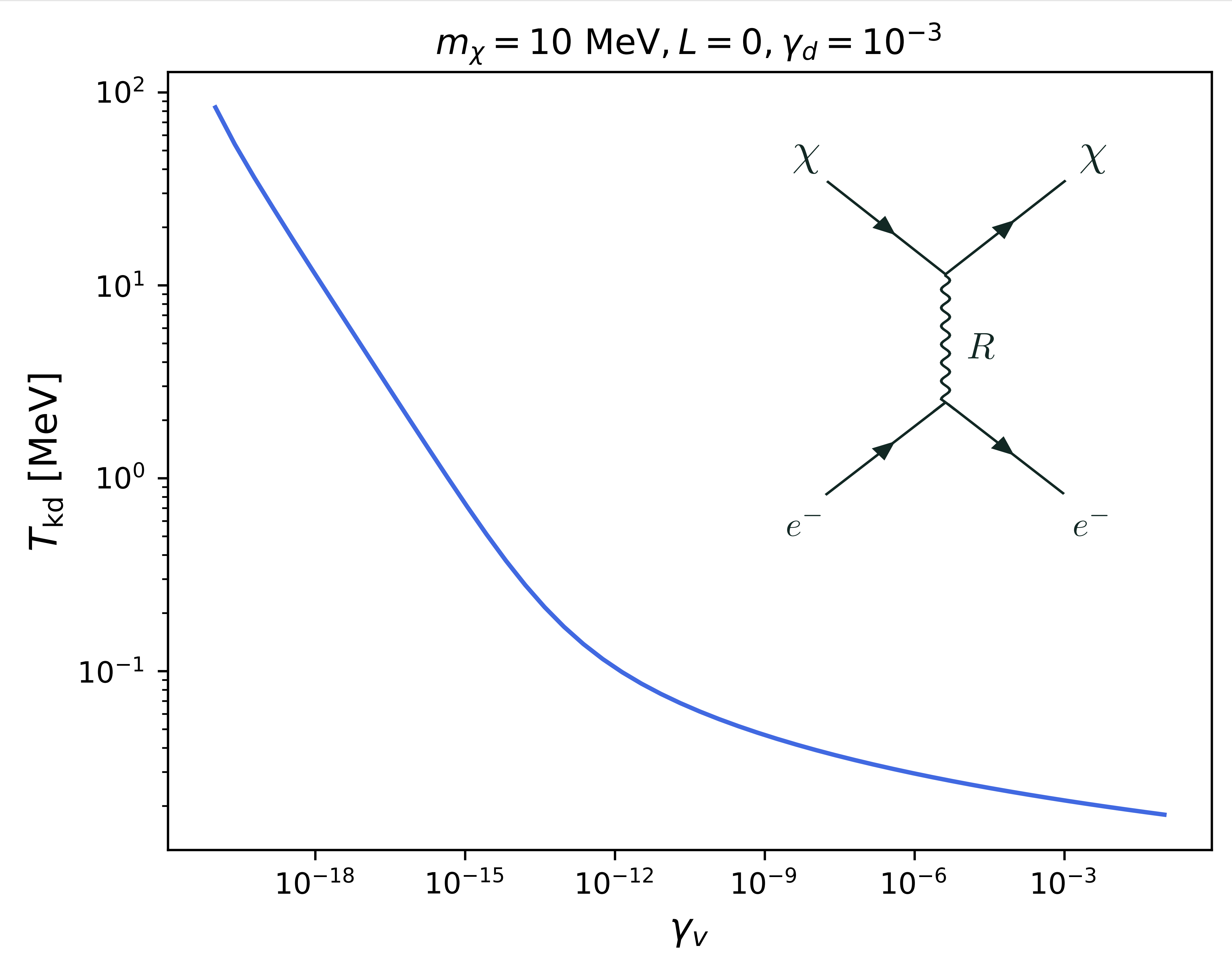
Scattering is related to annihilation via crossing symmetry

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



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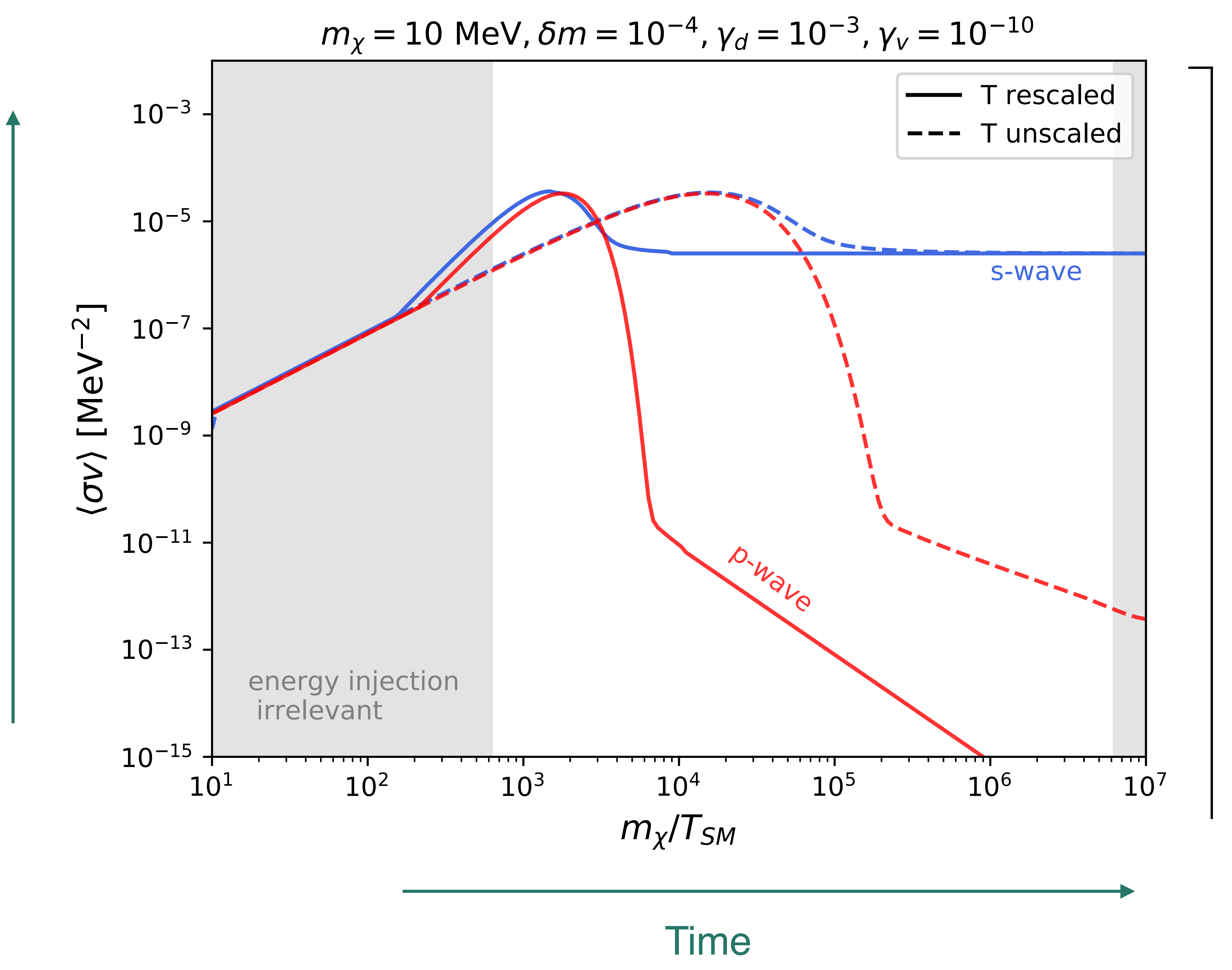

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Comparison to other bounds

p-wave results can be quite strict

Comparing the dark photon + scalar model

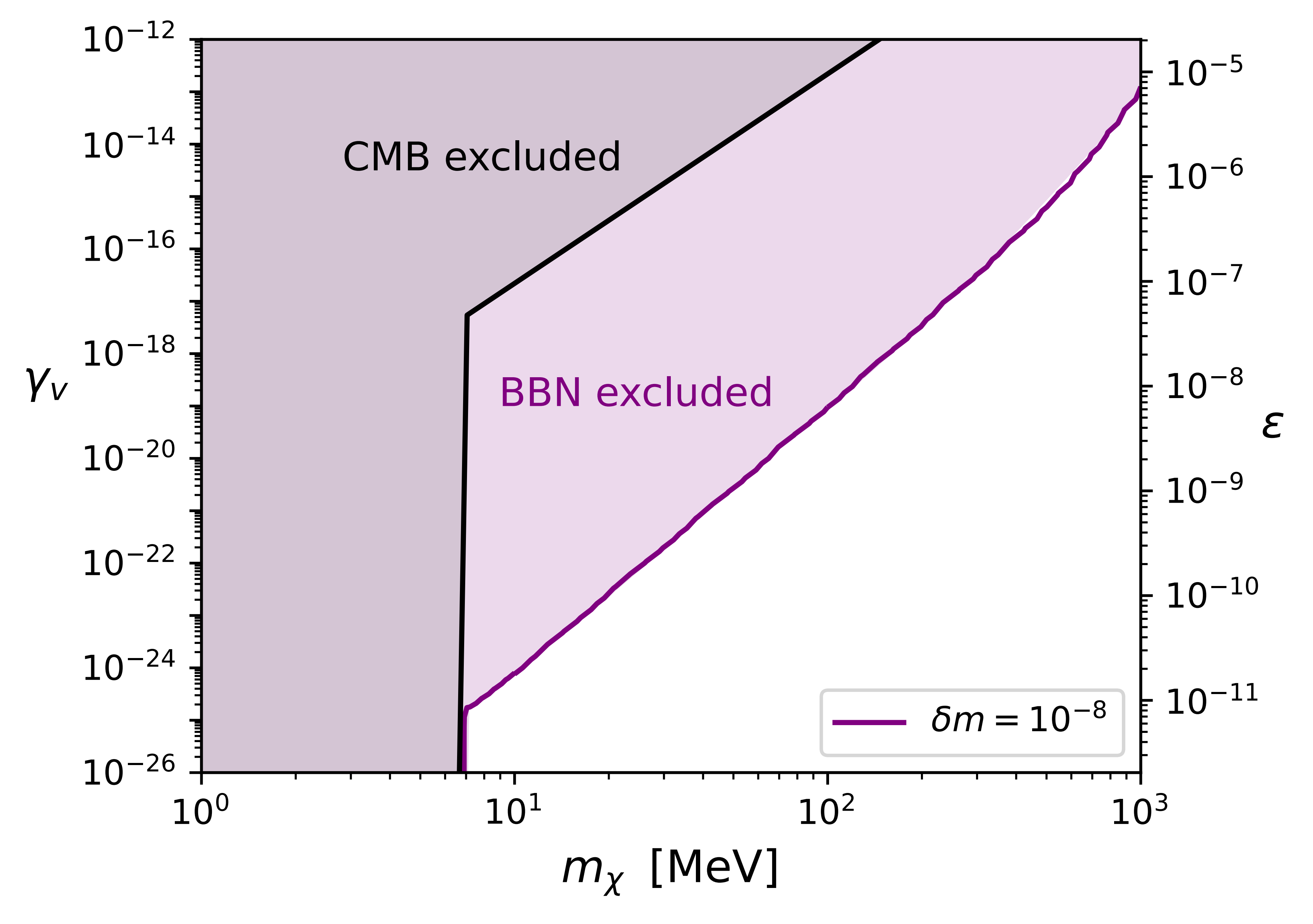
model	Lagrangian	n_d	γ_d	γ_v
2 scalar	$g_1 SS\Phi + g_2 \bar{e} e \Phi$	0	$\frac{g_1^2}{64\pi m^2}$	$\frac{g_2^2}{8\pi}$
scalar + vector	$g_1 \varphi^\dagger \overleftrightarrow{\partial}_\mu \varphi A'^\mu + g_2 \bar{e}\gamma^\mu e A'_\mu$	1	$\frac{g_1^2}{48\pi}$	$\frac{g_2^2}{12\pi}$
fermion + vector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

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

Comparing this model to CMB constraints

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

Planck collaboration (2020)



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