Bound states of annihilating dark matter

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Long-range interactions
mediated by
massless or light particles

Bound states

Long-range interactions

- Self-interacting DM
- DM explanations of astrophysical anomalies, e.g. galactic positrons
- Little hierarchy problem, e.g. twin Higgs models
- Sectors with stable particles in String Theory

Hidden sector DM

- WIMP DM with m_{DM} > few TeV ! [Hisano et al. 2002]
- Particular scenarios of sub-TeV WIMPs

- Minimal DM [Cirelli et al.]
- LHC implications for SUSY
- Direct/Indirect detection constraints

Co-annihilating with,
or produced by the decays of
charged/coloured particles
[(c)MSSM]

Bound states — Phenomenological implications

- **Asymmetric DM → Stable bound states**
  - Kinetic decoupling of DM from radiation, in the early universe
  - DM self-scattering in halos: Screening
    [KP, Pearce, Kusenko (2014)]
  - Indirect detection signals: Radiative level transitions
    [Pearce, Kusenko (2013); Cline et al. (2014);
    Detmold, McCullough, Pochinsky (2014); Pearce, KP, Kusenko (2015)]
  - Direct detection signals: Screening, inelastic scattering

- **Symmetric / Self-conjugate DM → Unstable bound states**
  Formation + Decay = Extra annihilation channel
  - Relic abundance [von Harling, KP (2014); Ellis et al. (2015)]
  - Indirect detection [Cirelli, Panci, KP, Sala, Taoso, (in preparation)]

Bound states — Varieties

A. Confining theories
Hadronic-like bound states ("non-perturbative non-perturbative bound states").

Cosmologically, they definitely form.
May leave a remnant weakly coupled long(-ish)-range interaction.

B. Weakly coupled theories
"Perturbative non-perturbative bound states", e.g. atoms.

Formation efficiency depends on the details:

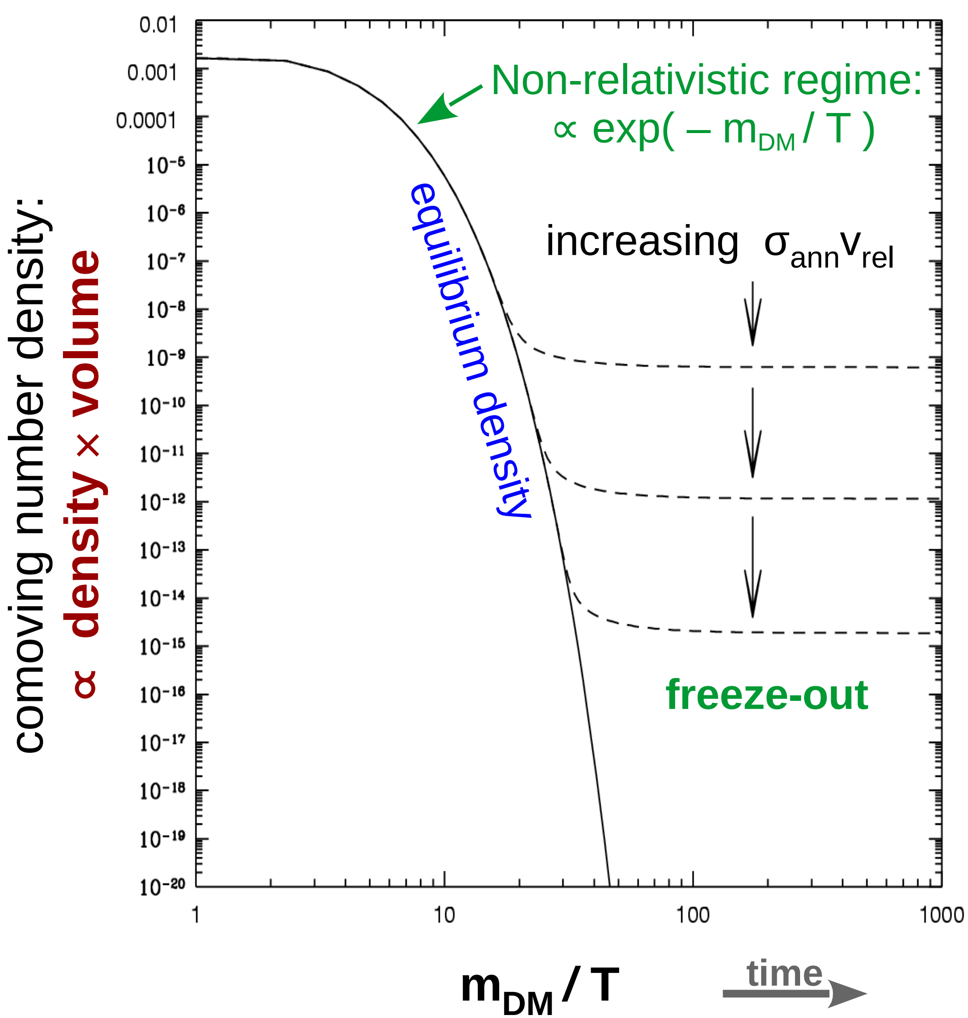
(i) bound-state formation cross-section, and

(ii) thermodynamic environment
(early universe, DM halos, interior of stars)

Outline

- Effect of bound-state formation and decay on the relic density.
- Indirect detection signals.

Relic density of symmetric DM with contact interactions



- Early universe:

  DM kept in chemical equilibrium via annihilations, $\chi + \bar{\chi} \leftrightarrow f + \bar{f}$.

  DM density $n_\chi = n_\chi(T)$

- As universe expands and cools

  ⇒ Density decreases
  ⇒ Annihilations become inefficient
  ⇒ Exponential decrease of $n_\chi(T)$ stalls: **freeze-out**
  ⇒ Relic density

$$\Omega_\chi \simeq 0.26 \times \left[\frac{3 \times 10^{-26}\ cm^3/s}{\langle \sigma_{ann} v_{rel} \rangle} \right]$$

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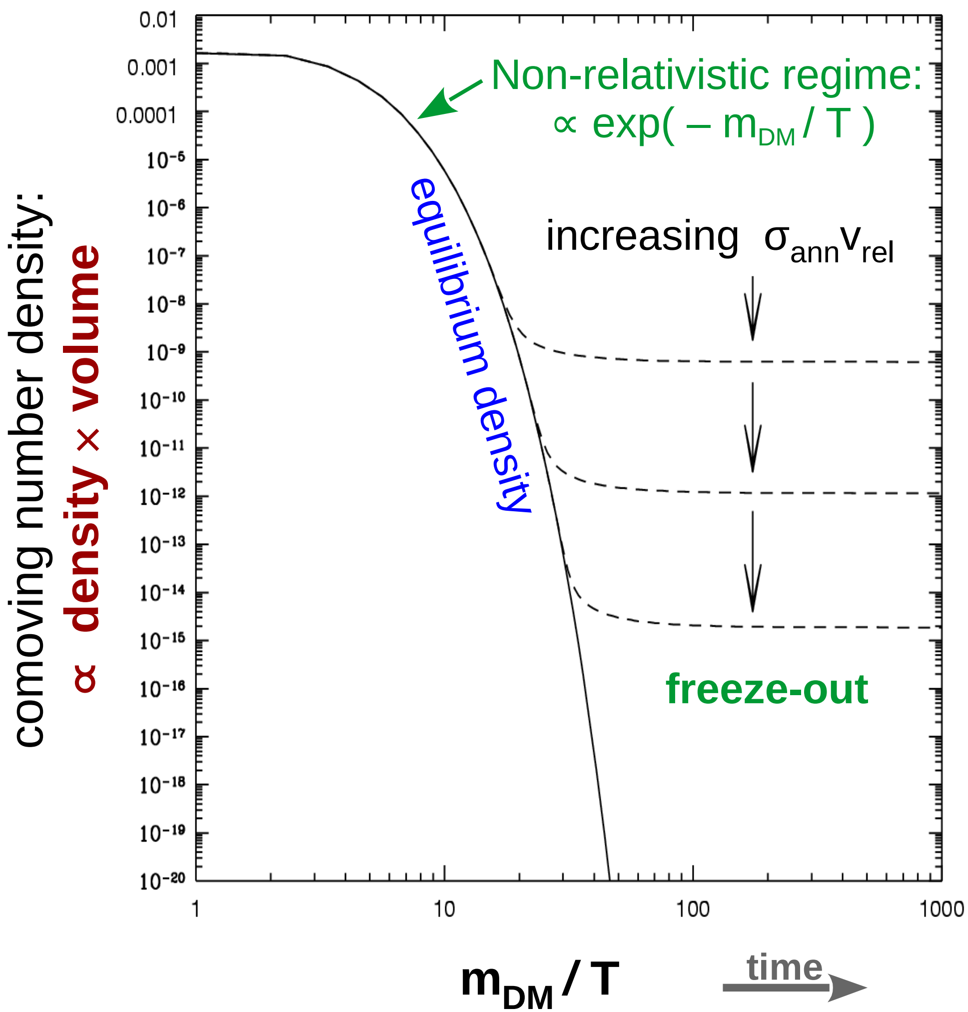

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$$\Omega_\chi \simeq 0.26 \times \left[\frac{3 \times 10^{-26}\ cm^3/s}{\langle \sigma_{ann} v_{rel} \rangle} \right]$$

Assumption:
$\sigma_{ann} v_{rel} \simeq \sigma_0 + \sigma_1 v_{rel}^2 + \ldots$
Valid for contact interactions.

Toy model:
Dark QED

Dirac fermions (χ, $\bar{\chi}$) of mass *m*, coupled to a massless dark photon γ, with dark fine-structure constant α.

Very important parameter:
$\zeta = \alpha / v_{rel}$

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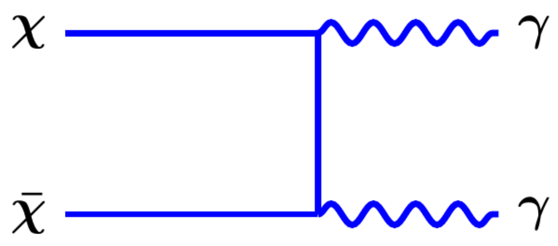
Standard pertubative calculation

Annihilation

$\chi + \bar{\chi} \rightarrow \gamma + \gamma$



$$\sigma_{ann} v_{rel} = \pi \alpha^2 / m^2 \equiv \sigma_0$$

Toy model: Dark QED

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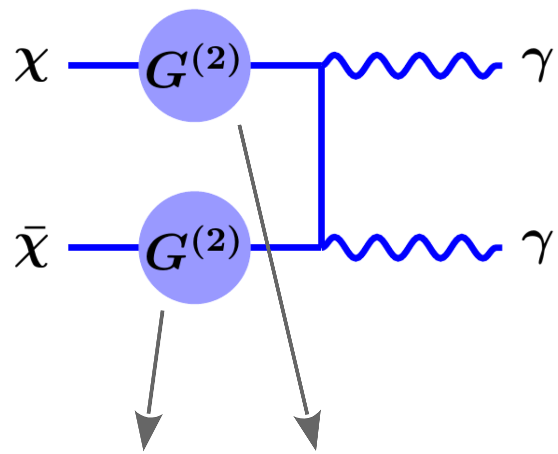
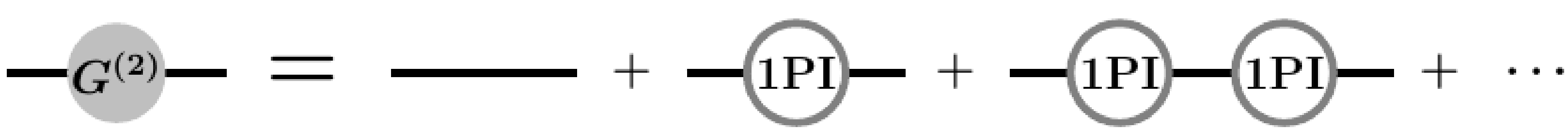
Fancy pertubative calculation

Annihilation
$\chi + \bar{\chi} \rightarrow \gamma + \gamma$

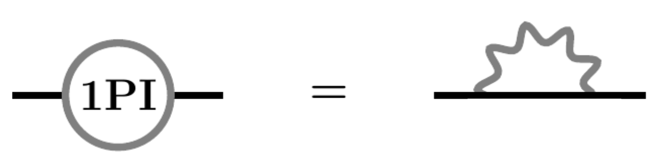


$$\sigma_{\text{ann}} v_{\text{rel}} = \pi\alpha^2/m^2\,[1 + \mathcal{O}(\alpha^2)]$$

Re-summation of 1PI graphs



where



Relic density of symmetric DM with long-range interactions

Processes

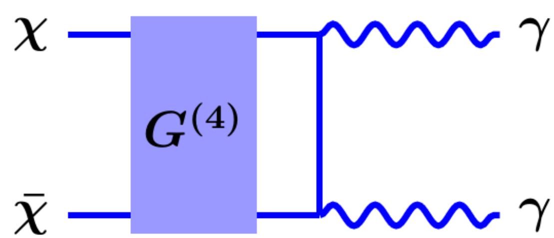
Toy model:
Dark QED

**Dirac fermions (χ, $\bar{\chi}$) of mass *m*,
coupled to a massless dark photon γ,
with dark fine-structure constant α.**

Very important parameter:
$\zeta = \alpha / \mathbf{v}_{\mathrm{rel}}$

In the presence of
a long-range interaction

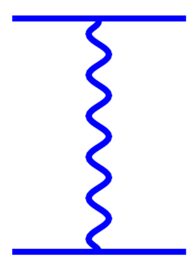
Annihilation
$\chi + \bar{\chi} \rightarrow \gamma + \gamma$



$$\sigma_{\mathrm{ann}} v_{\mathrm{rel}} = \pi \alpha^2 / m^2 \times S(\alpha / v_{\mathrm{rel}})$$

Re-summation of 2PI graphs.

Lowest order kernel:



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Very important parameter:
$\zeta = \alpha / v_{rel}$

Annihilation

$$\chi + \bar{\chi} \rightarrow \gamma + \gamma$$

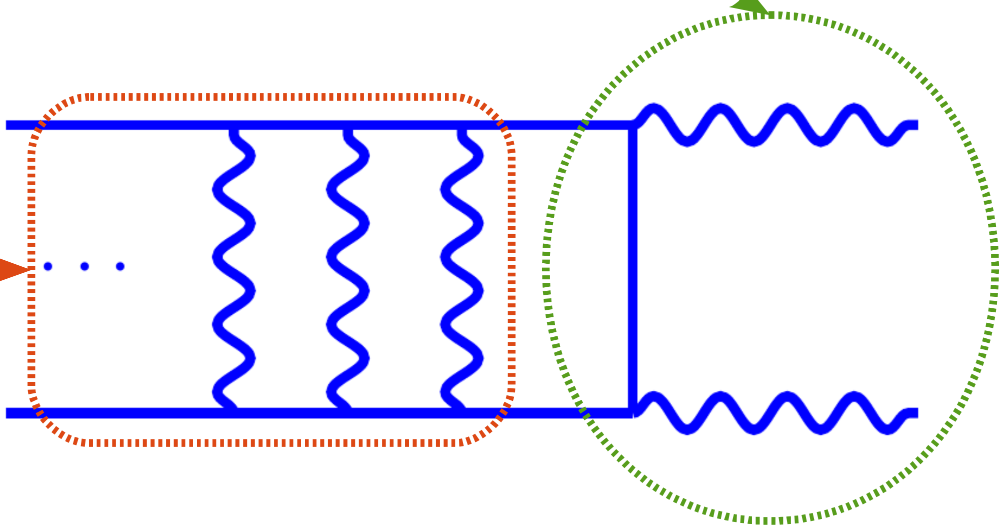
$$\sigma_{ann} v_{rel} = \sigma_0 \, S_{ann}(\zeta)$$

$$\sigma_0 = \pi \alpha^2 / m^2$$

$$S_{ann}(\zeta) = \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}$$

$$S_{ann}(\zeta \ll 1) \simeq 1$$

$$S_{ann}(\zeta \gtrsim 1) \simeq 2\pi\zeta$$



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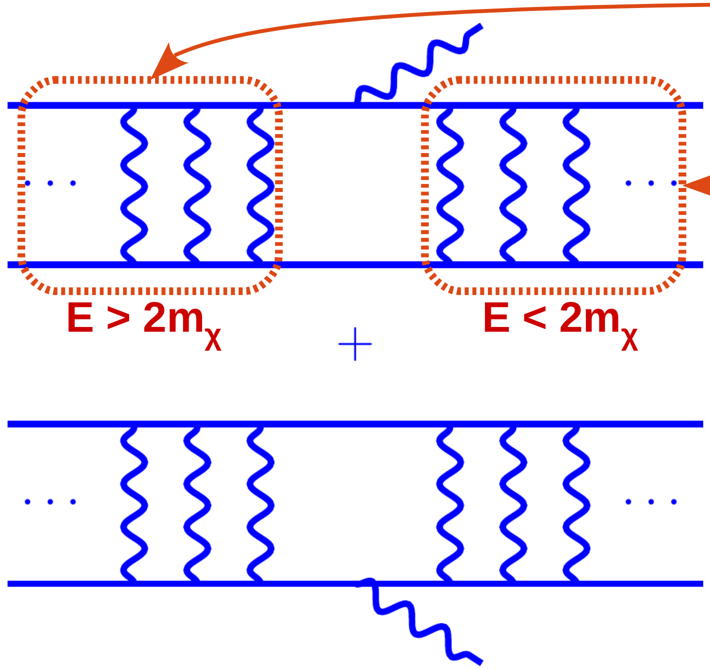

Bound state formation and decay

$$\boxed{\chi + \bar{\chi}} \rightarrow \boxed{(\chi\bar{\chi})_{bound}} + \gamma$$

$$(\chi\bar{\chi})_{bound} \rightarrow 2\gamma \quad \textit{or} \quad 3\gamma$$

$$\sigma_{BSF} v_{rel} = \sigma_0 S_{BSF}(\zeta)$$

$$\sigma_0 = \pi \alpha^2 / m^2$$

$$S_{BSF}(\zeta) = \left[\frac{2^9}{3 e^{4\zeta \operatorname{arccot}(\zeta)}} \frac{\zeta^4}{(1+\zeta^2)^2} \right] \frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}$$

$$S_{BSF}(\zeta \ll 1) \simeq \frac{2^9 \zeta^4}{3} \ll 1$$

$$S_{BSF}(\zeta \gtrsim 1) \simeq \frac{2^9}{3e^4} \times 2\pi\zeta \simeq 3.13 \times S_{ann}$$

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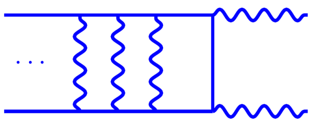
Annihilation

$$\chi + \bar{\chi} \to \gamma + \gamma$$



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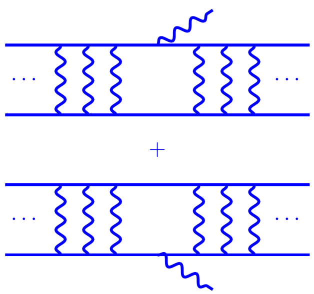

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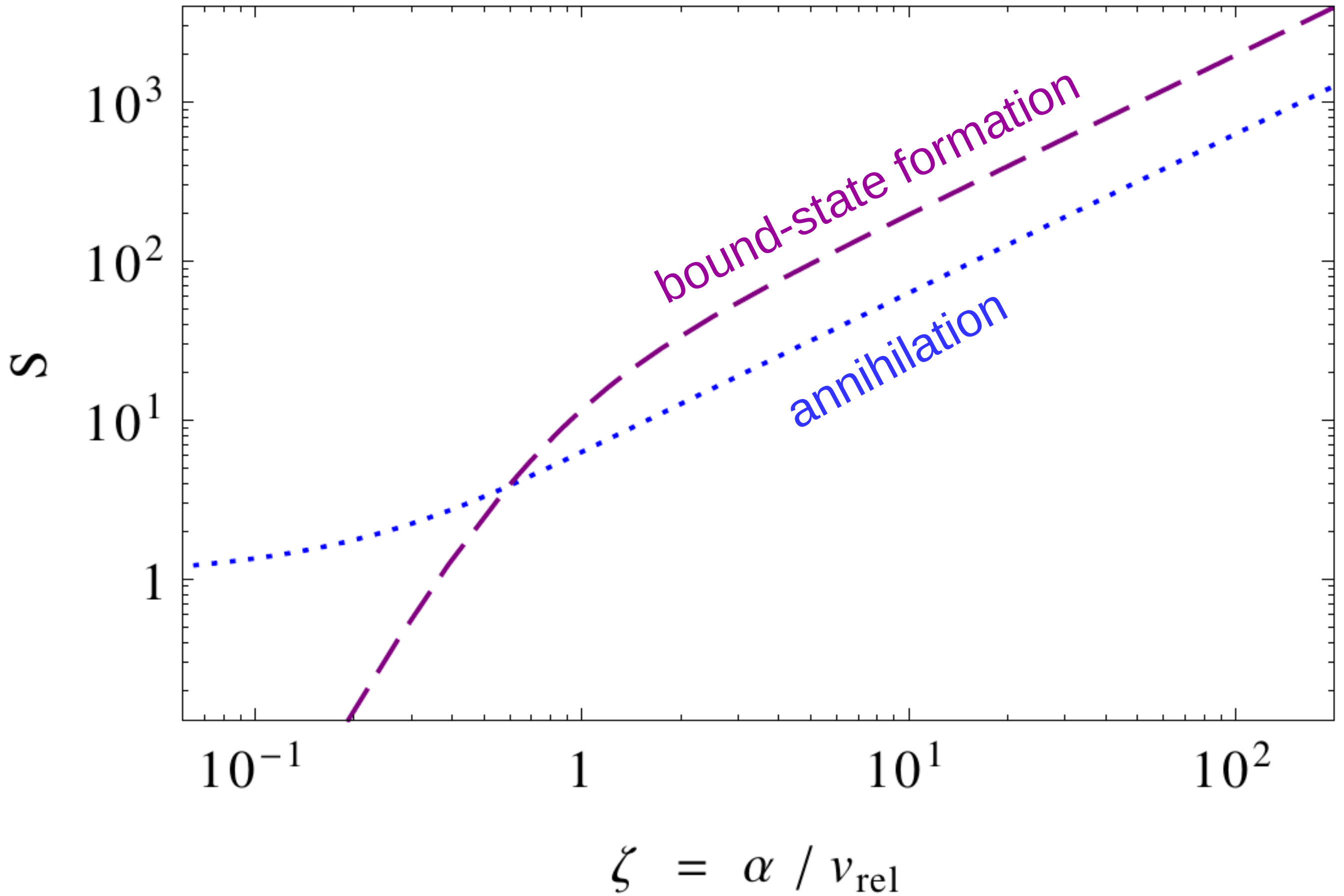


BSF dominates over annihilation everywhere the Sommerfeld effect is important (ζ > 1) !

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\left(n_\chi^2 - n_\chi^{eq\;2}\right)\langle\sigma_{ann} v_{rel}\rangle - n_\chi^2\langle\sigma_{BSF} v_{rel}\rangle + \left(n_{\uparrow\downarrow} + n_{\uparrow\uparrow}\right)\Gamma_{ion}$$

$$\frac{dn_{\uparrow\downarrow}}{dt} + 3Hn_{\uparrow\downarrow} = +\frac{1}{4} n_\chi^2\langle\sigma_{BSF} v_{rel}\rangle - n_{\uparrow\downarrow}\left(\Gamma_{ion} + \Gamma_{decay,\uparrow\downarrow}\right)$$

$$\frac{dn_{\uparrow\uparrow}}{dt} + 3Hn_{\uparrow\uparrow} = +\frac{3}{4} n_\chi^2\langle\sigma_{BSF} v_{rel}\rangle - n_{\uparrow\uparrow}\left(\Gamma_{ion} + \Gamma_{decay,\uparrow\uparrow}\right)$$

BSF important when $\Gamma_{\text{decay}} > \Gamma_{\text{ion}}$ (T)

$(\chi\bar{\chi})_{\uparrow\downarrow} \to 2\gamma$: $\quad \Gamma_{decay,\uparrow\downarrow} = \alpha^5 (m/2)$

$(\chi\bar{\chi})_{\uparrow\uparrow} \to 3\gamma$: $\quad \Gamma_{decay,\uparrow\uparrow} = \dfrac{4(\pi^2-9)}{9\pi}\,\alpha^6 (m/2)$

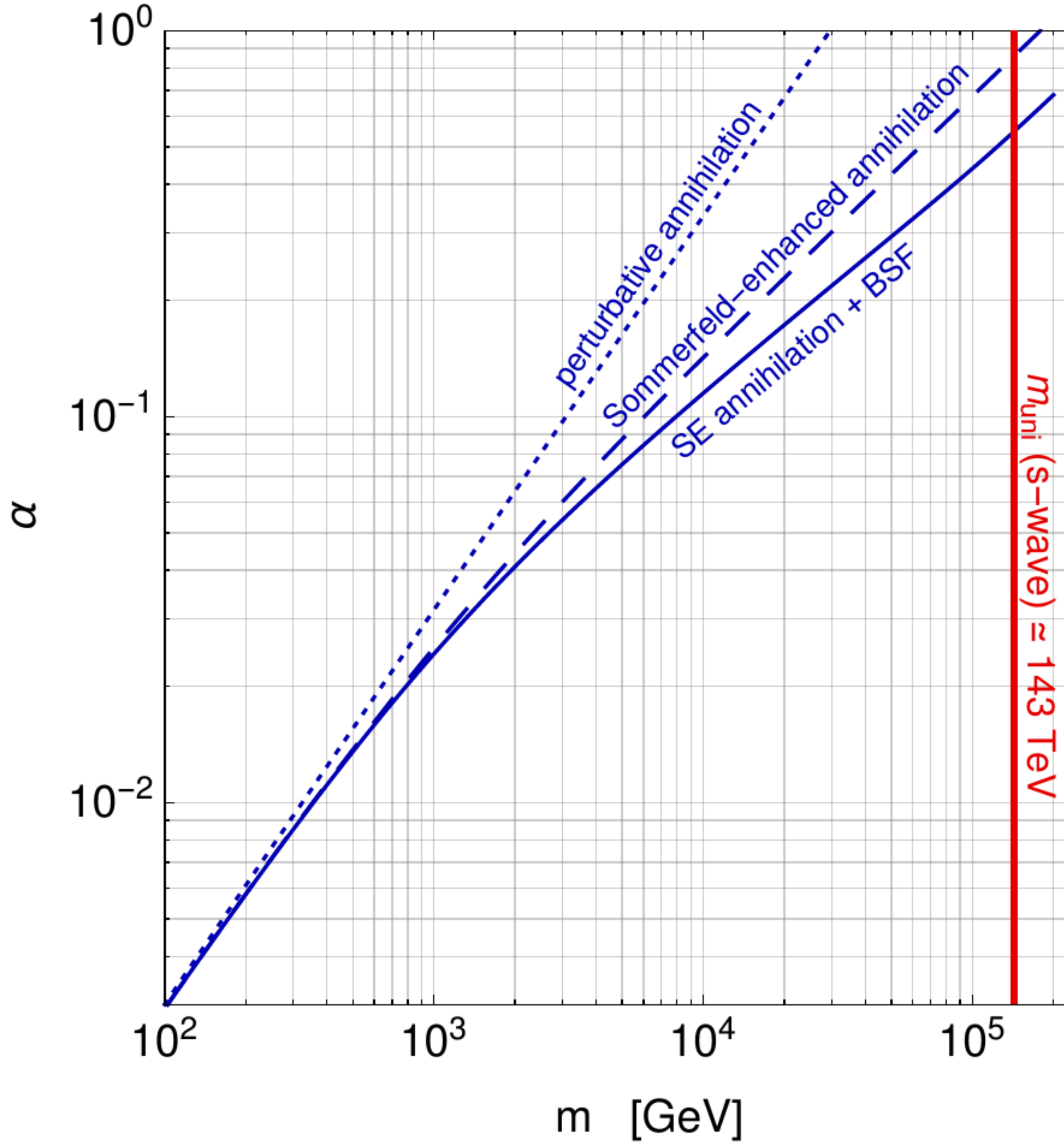
$(\chi\bar{\chi})_{\uparrow\downarrow \text{ or } \uparrow\uparrow} + \gamma \to \chi + \bar{\chi}$: $\quad \Gamma_{ion}(T) = \dfrac{2}{(2\pi)^3}\, 4\pi \displaystyle\int_0^\infty d\omega\, \frac{\omega^2}{e^{\omega/T}-1}\,\sigma_{ion}(\omega)$

[von Harling, KP (2014)]

Relic density of symmetric DM with long-range interactions

[von Harling, KP (2014)]

Determination of $\alpha(m)$ or $m(\alpha)$



Recent claim [An, Wise, Zhang (2016)]:
BSF does not affect relic density because of ionisation.

Ionisation suppresses the effect of BSF on the relic density.

It has been properly taken into account
by solving the full Boltzmann equations.

There is still a significant effect.

Relic density of symmetric DM with long-range interactions

[von Harling, KP (2014)]

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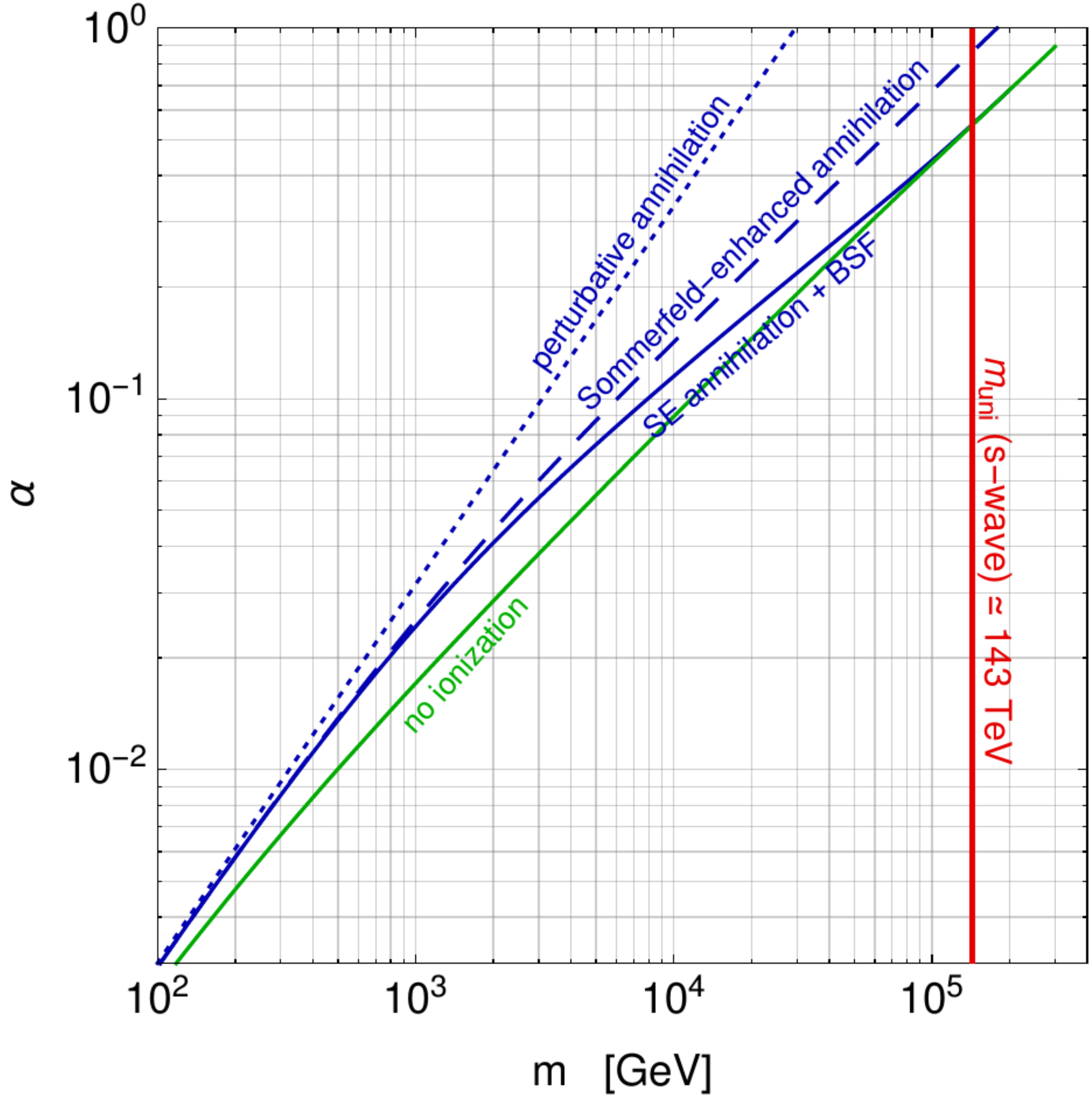
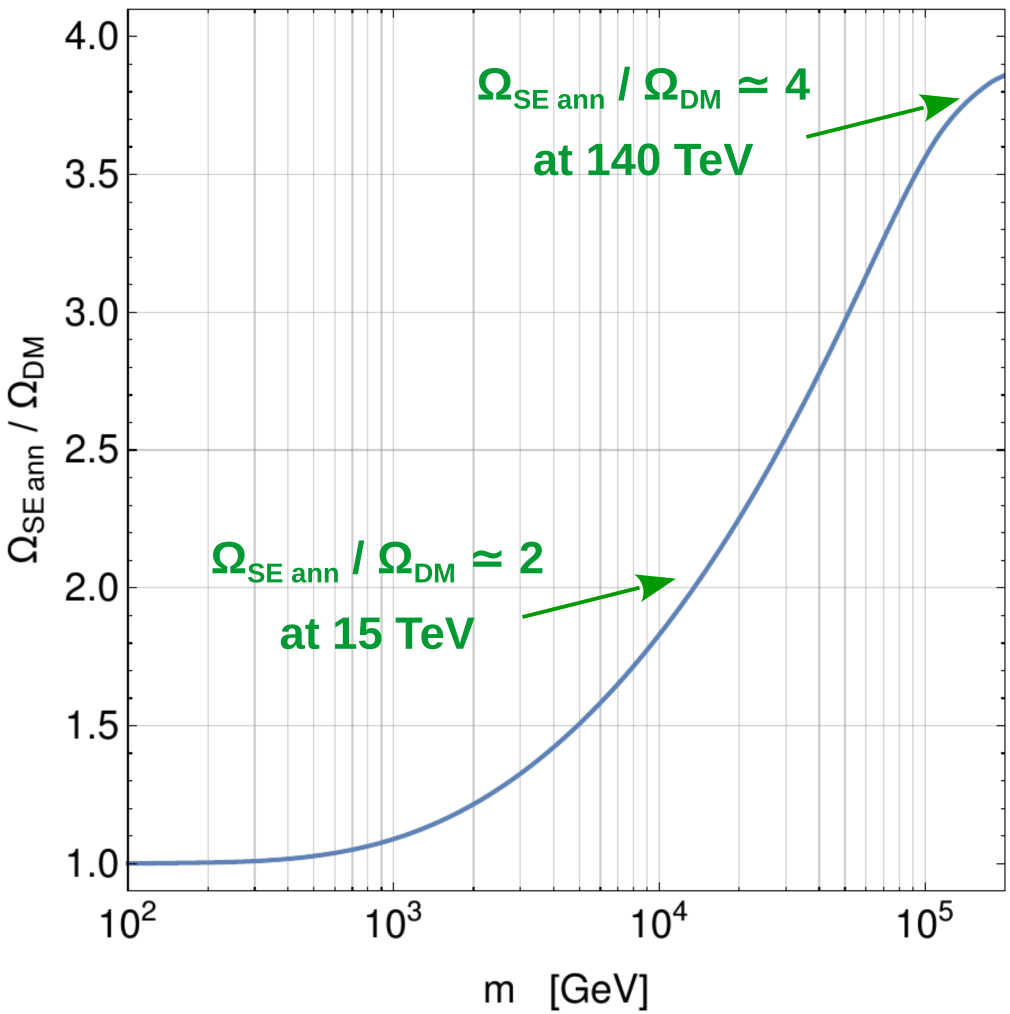


Relic density of symmetric DM with long-range interactions

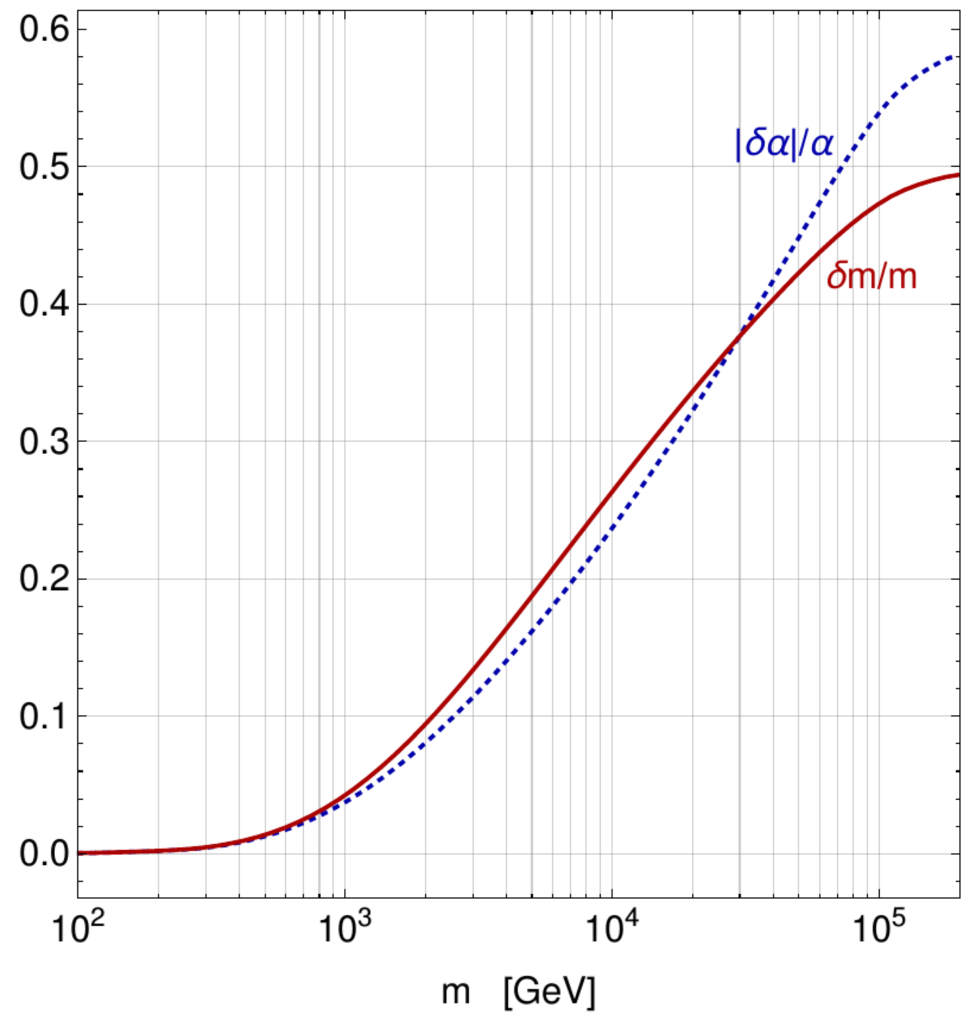
[von Harling, KP (2014)]

Effect on DM density, coupling, mass

Much larger than the experimental uncertainty of 1% .



Larger than the experimental sensitivity.



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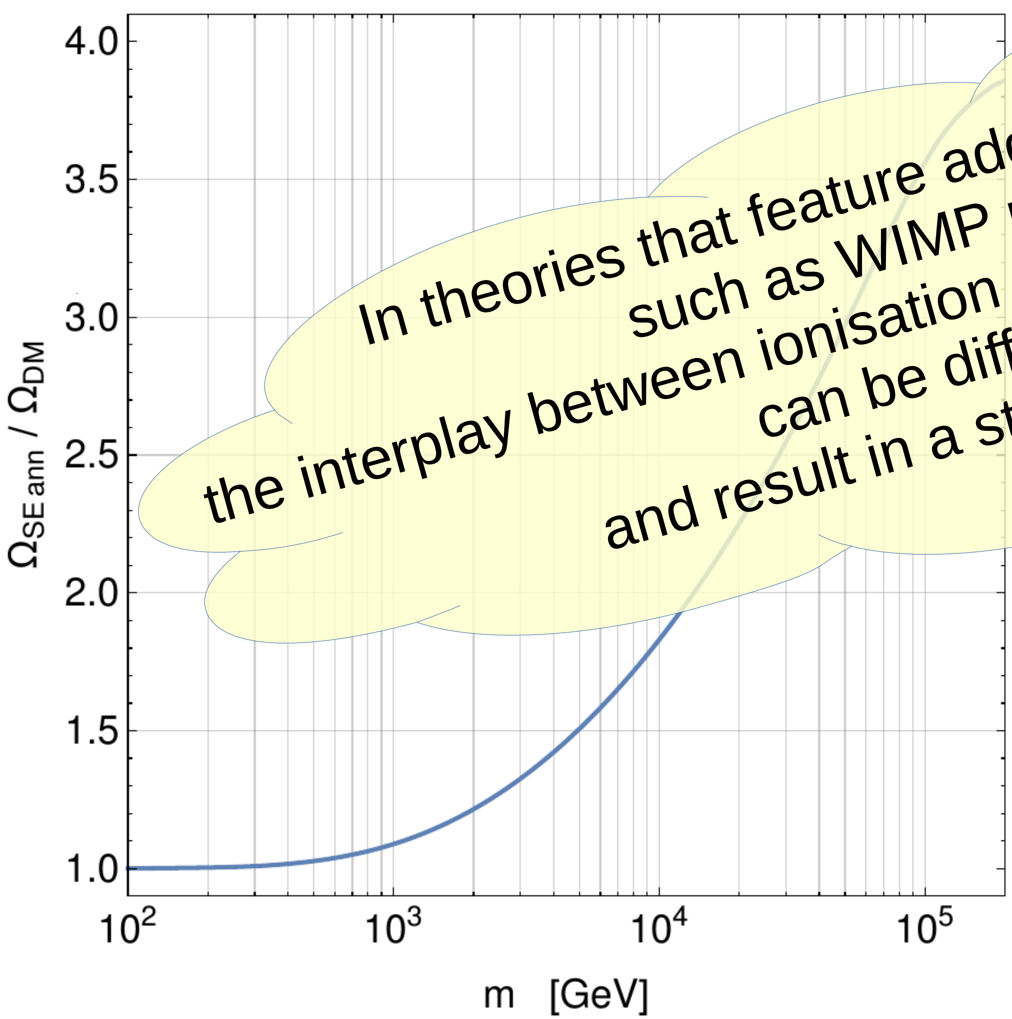

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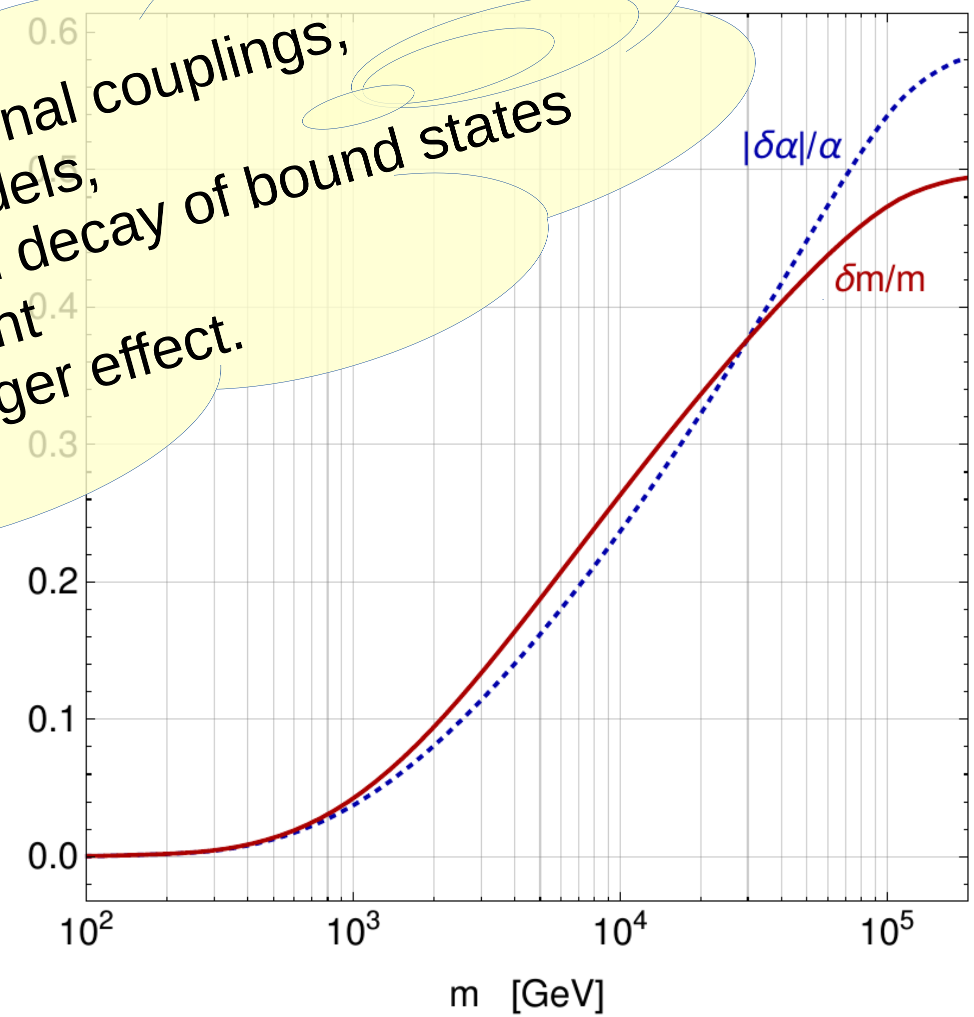


In theories that feature additional couplings,
such as WIMP models,
the interplay between ionisation and decay of bound states
can be different
and result in a stronger effect.

Bound states of annihilating DM
Generalisations needed

Massive mediators

Different interactions,
e.g. scalar mediator.

Non-Abelian
non-confining theories,
e.g. EW interactions.

Relic density

Indirect detection

Massive vector mediator: Cross-sections

[An, Wise, Zhang (2016); KP, Postma, de Vries (in preparation)]

- **Two parameters needed:**

  $\boldsymbol{\zeta = \alpha / v_{rel}}$ and $\boldsymbol{\xi = m_{DM}\, \alpha / (2m_{\varphi})}$

  [velocity dependence] [model dependence]

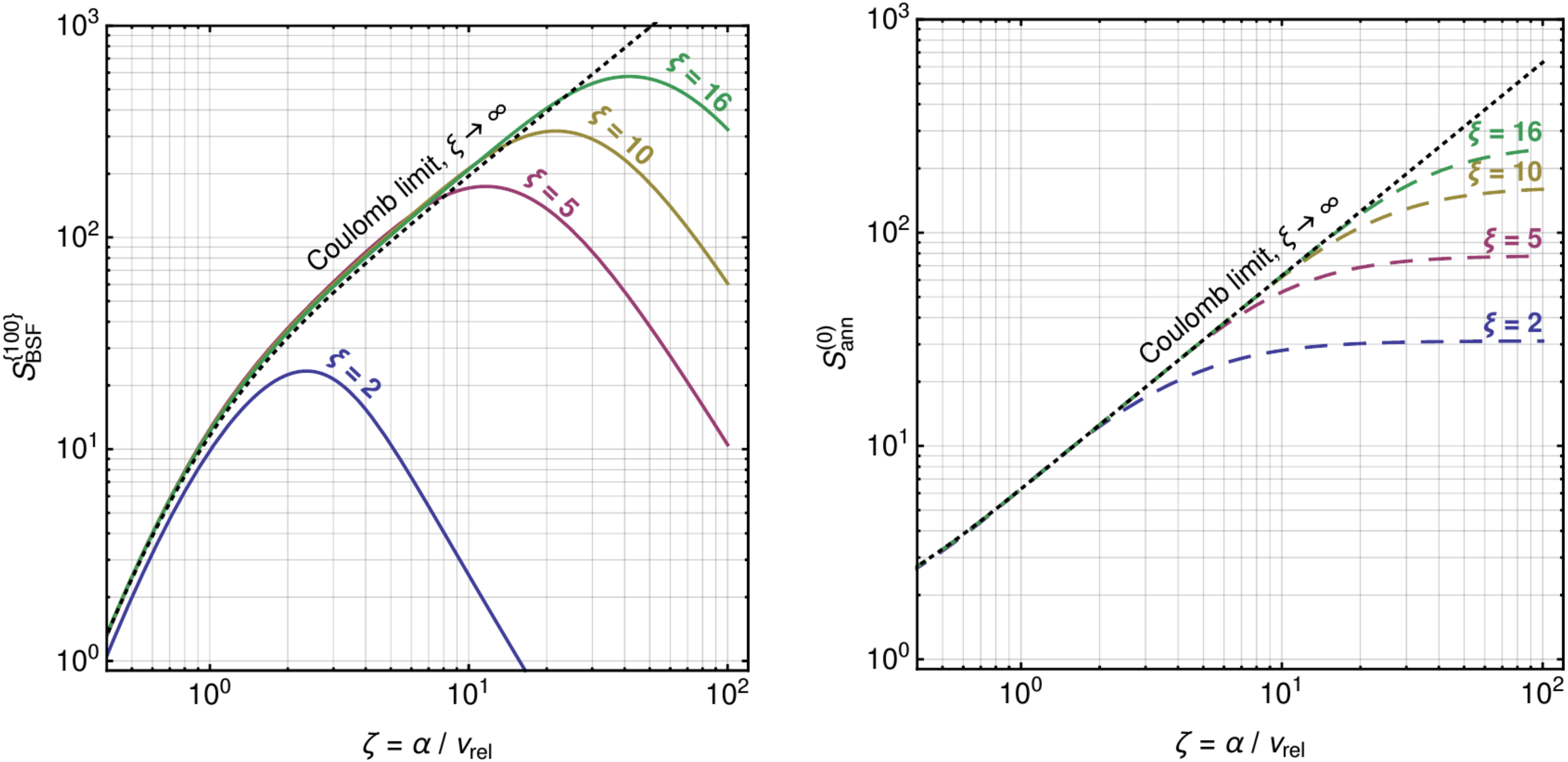
- **At low enough velocities (large ζ)**
  - $\sigma_{ann}\, v_{rel} \sim$ constant (saturation of $1/v_{rel}$ enhancement)
  - $\sigma_{ann}\, v_{rel} \sim v_{rel}^2$ (suppression)

- **Resonances at discrete ξ values,** which are different for annihilation and BSF. Precise location:
  - Annihilation: ζ independent
  - BSF: Mild ζ dependence

[KP, Postma, de Vries (in preparation)]

Parameters:
$\zeta = \alpha / v_{rel}$
$\xi = m_{DM}\, \alpha / (2 m_\varphi)$

Vector mediator: ξ values away from $\ell = 0$ and $\ell = 1$ resonances



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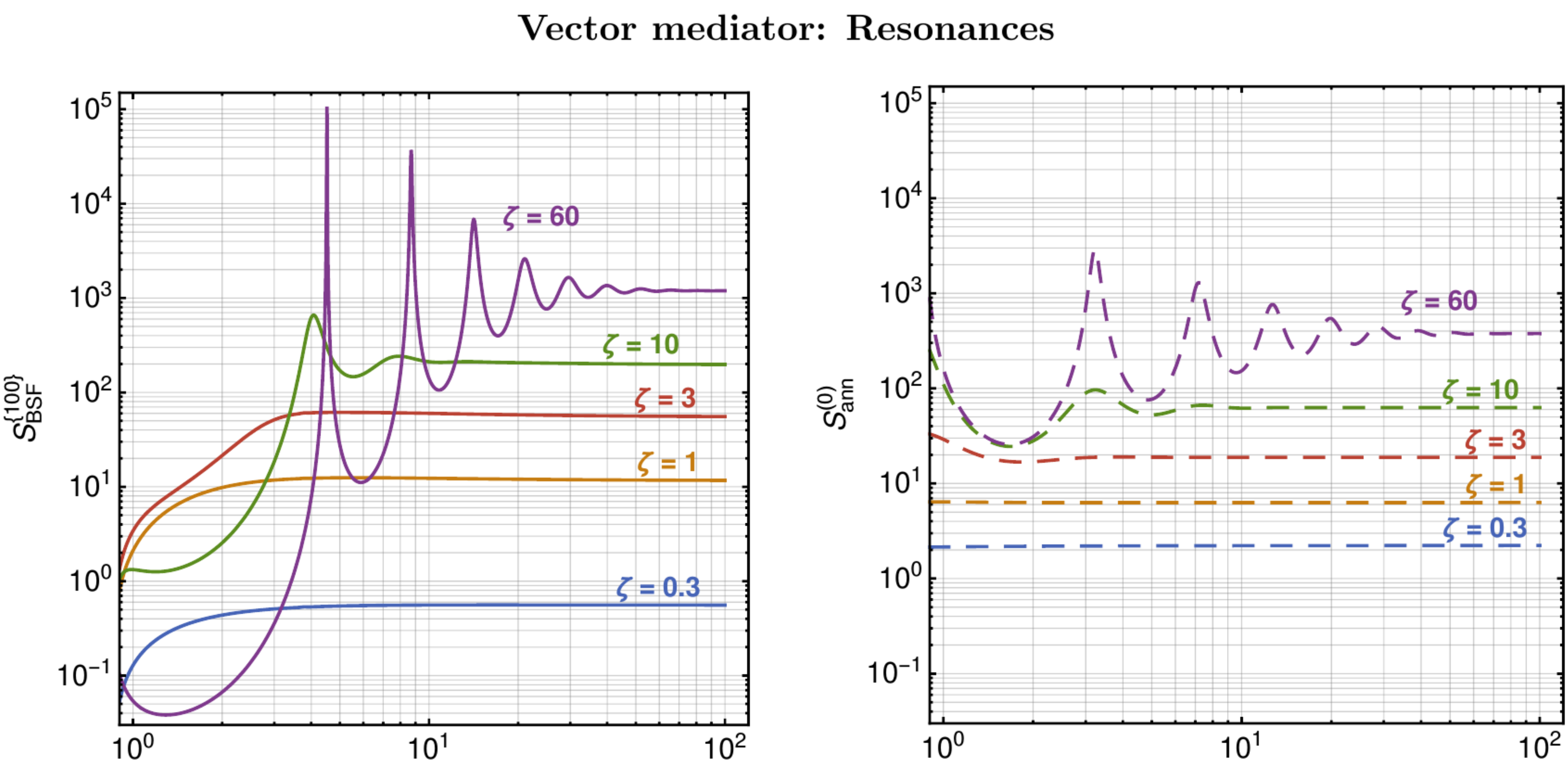

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Parameters:
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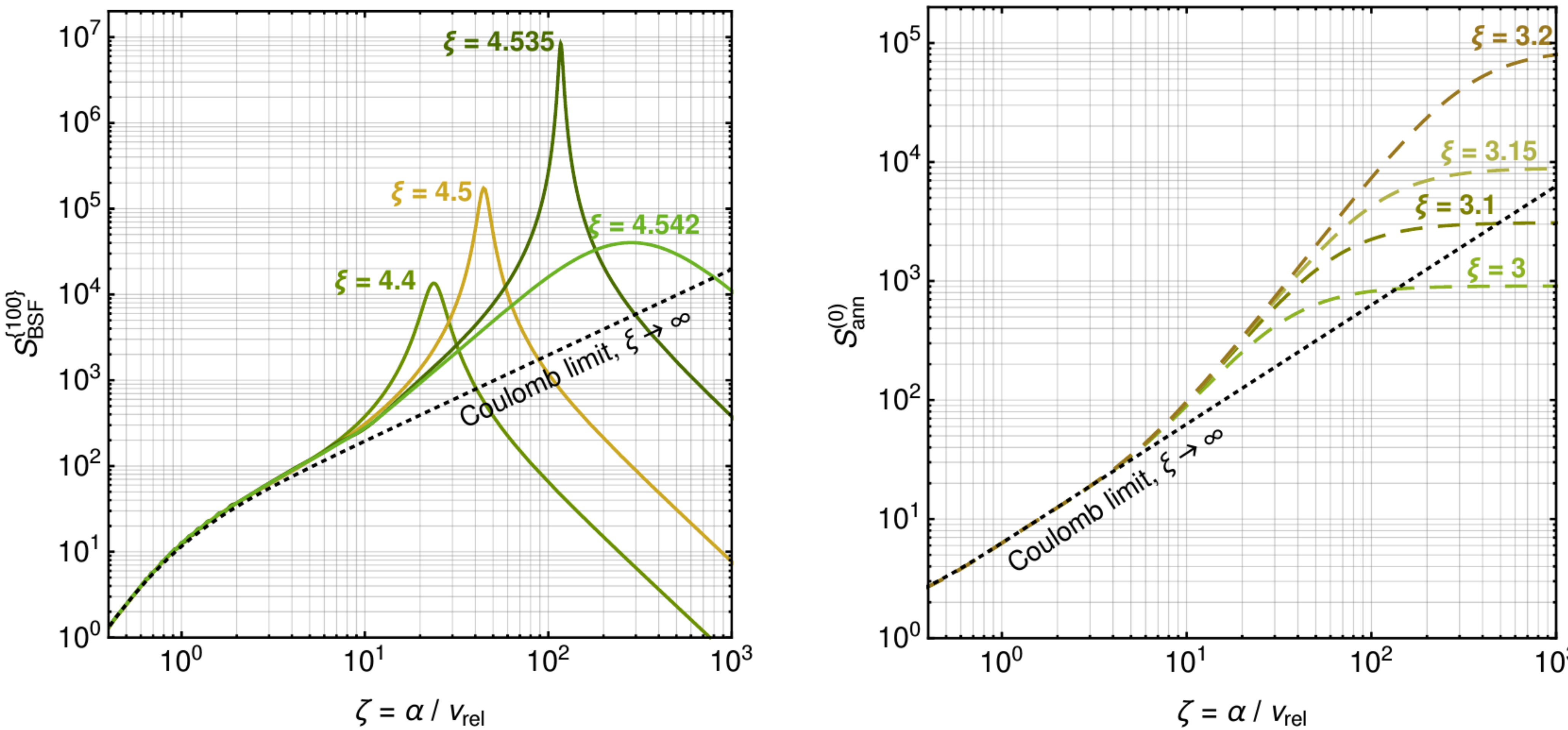
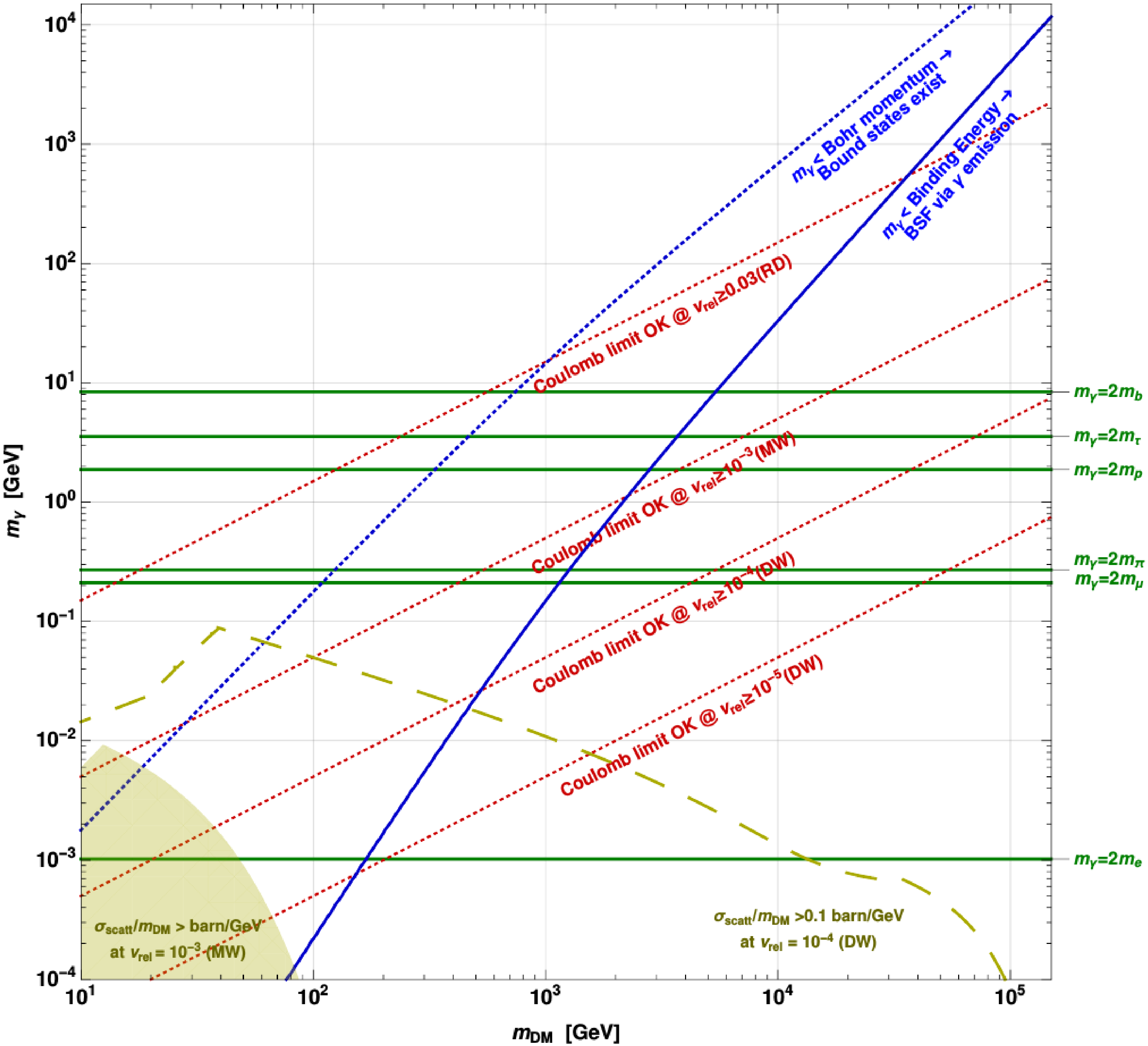
Vector mediator

ξ values near the $n = 2$, $\ell = 1$ resonance | **ξ values near the $n = 2$, $\ell = 0$ resonance**





m_γ < Bohr momentum → Bound states exist
m_γ < Binding Energy → BSF via γ emission
Coulomb limit OK @ v_{rel}≥0.03(RD)
Coulomb limit OK @ v_{rel}≥10^{-3}(MW)
Coulomb limit OK @ v_{rel}≥10^{-4}(DW)
Coulomb limit OK @ v_{rel}≥10^{-5}(DW)
$m_\gamma=2m_b$
$m_\gamma=2m_\tau$
$m_\gamma=2m_p$
$m_\gamma=2m_\pi$
$m_\gamma=2m_\mu$
$m_\gamma=2m_e$
σ_{scatt}/m_{DM} > barn/GeV at $v_{rel} = 10^{-3}$ (MW)
σ_{scatt}/m_{DM} >0.1 barn/GeV at $v_{rel} = 10^{-4}$ (DW)
m_γ [GeV]
m_{DM} [GeV]

Massive (vector or scalar) mediators

Take-home message:

Combination of annihilation & BSF processes,
different velocity dependence,
and resonant features

⇓

rich phenomenology

First step: Constraints on hidden broken U(1) model kinetically mixed with Hypercharge, using Fermi data
[Cirelli, Panci, KP, Sala, Taoso (in progress)]