Dark matter coupled to light scalars: the role of bound states

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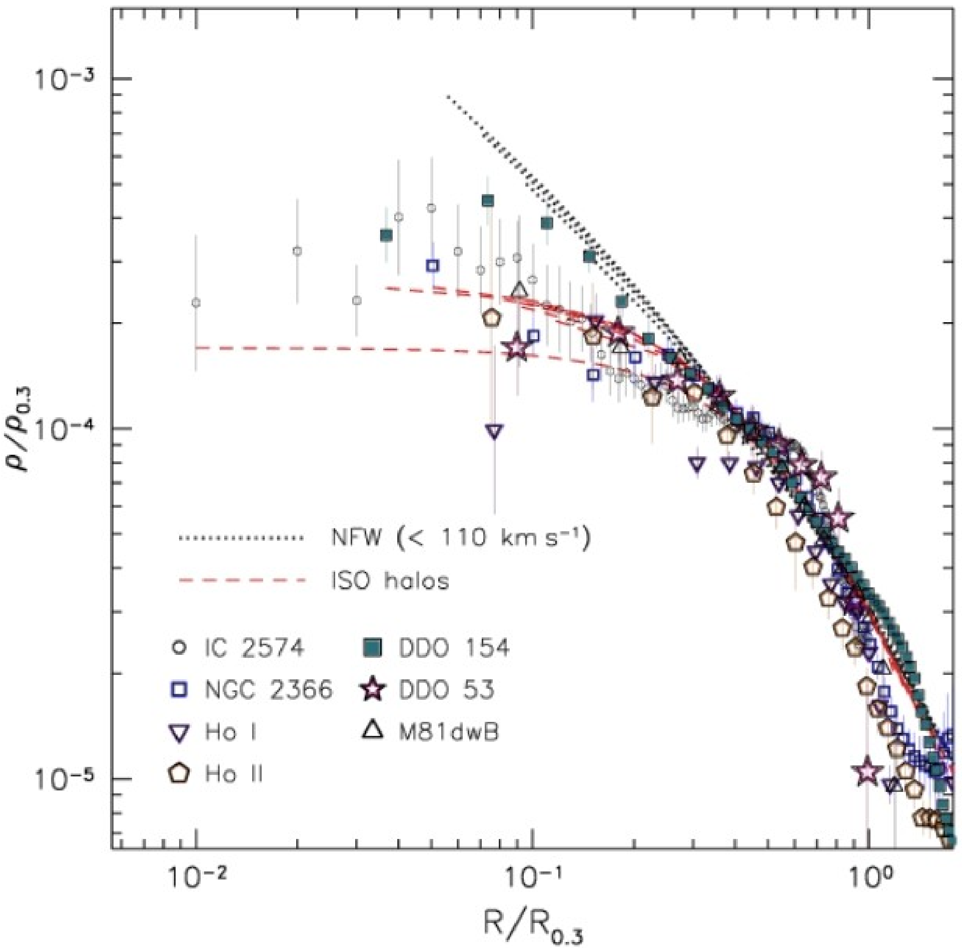
Motivation

- **Self-interacting DM**

→ Small-scale structure problems of collisionless cold DM (*core-vs.-cusp problems, too-big-to-fail*)

→ SUSY, WIMPs

→ Various hidden-sector models



M. Walker 1401.1146

Interaction types

- **Contact-type interactions (heavy mediators)**

  $m_{mediator} \gtrsim m_{DM}$

  Perturbative processes

  e.g. prototypical WIMP scenario $m_{WIMP} \sim m_{Z,W} \sim 100GeV$

- **Long-range interactions (light mediators)**

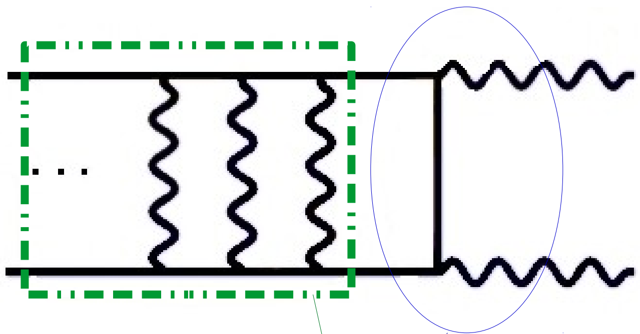
  $m_{mediator} << m_{DM}$

  Non-perturbative effects: Sommerfeld enhancement, Bound states

  Hidden-sector DM, as well as WIMP DM with $m_{DM} \gtrsim$ TeV

The Sommerfeld effect and bound state formation

Annihilation



Sommerfeld Effect

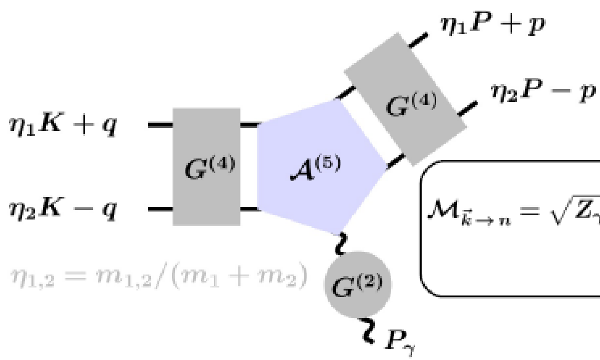
Perturbative

$$\sigma_{ann} v_{rel} = \sigma_0 S_{ann}(\alpha / v_{rel})$$

Fermionic or scalar dark matter

Scalar or vector dark mediator

Bound State Formation

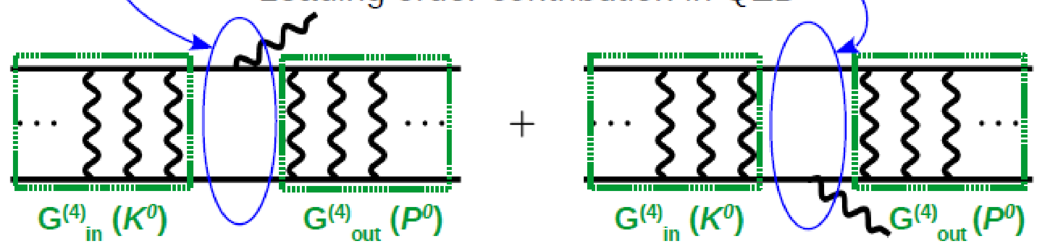


non-perturbative physics

$$\mathcal{M}_{\vec{k} \to n} = \sqrt{Z_\gamma} \int \frac{d^4p}{(2\pi)^4} \frac{d^4q}{(2\pi)^4} \, \underbrace{\tilde{\Psi}^{*}_{\vec{P},n}(p) \, \tilde{\Phi}_{\vec{K},\vec{k}}(q)}_{\text{non-perturbative physics}} \times \underbrace{\mathcal{A}^{(5)}(P_\gamma, \eta_1 P + p, \eta_2 P - p; \, \eta_1 K + q, \eta_2 K - q)}_{\text{perturbative transition diagrams}}$$

perturbative transition diagrams

Leading order contribution in QED

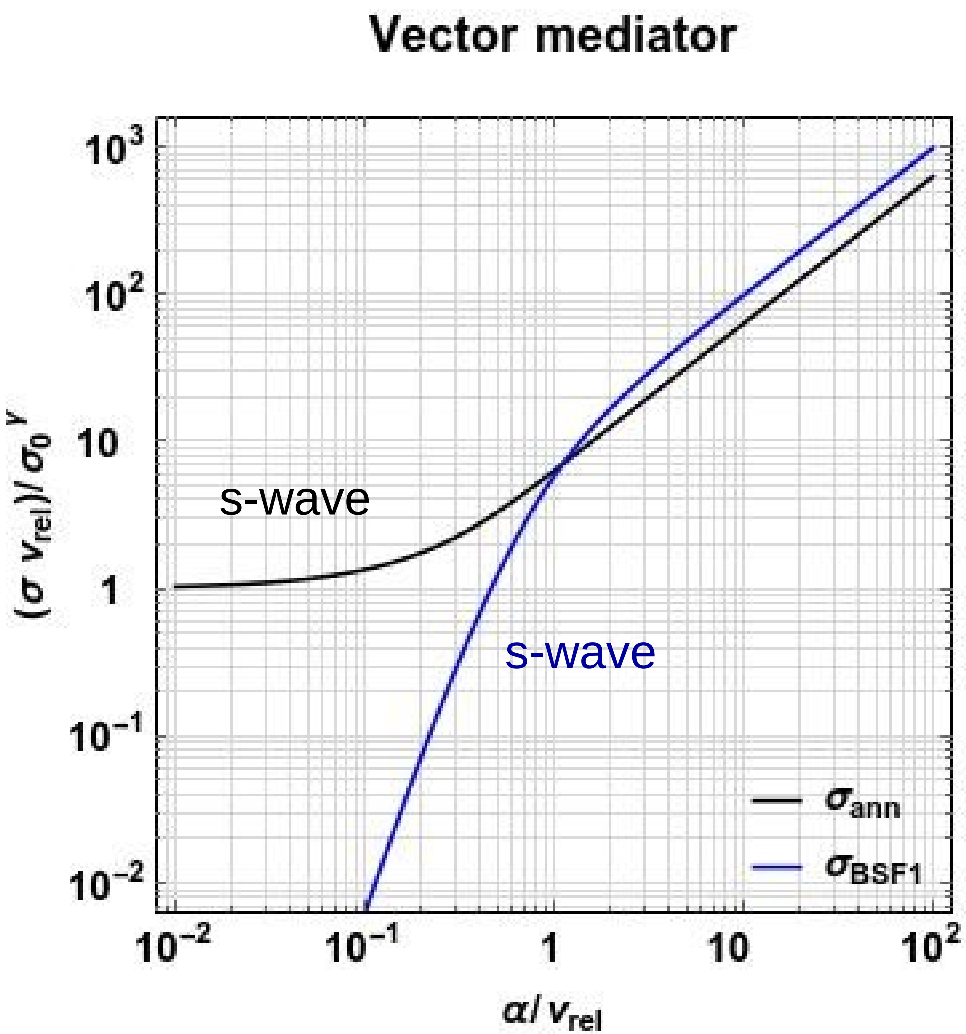


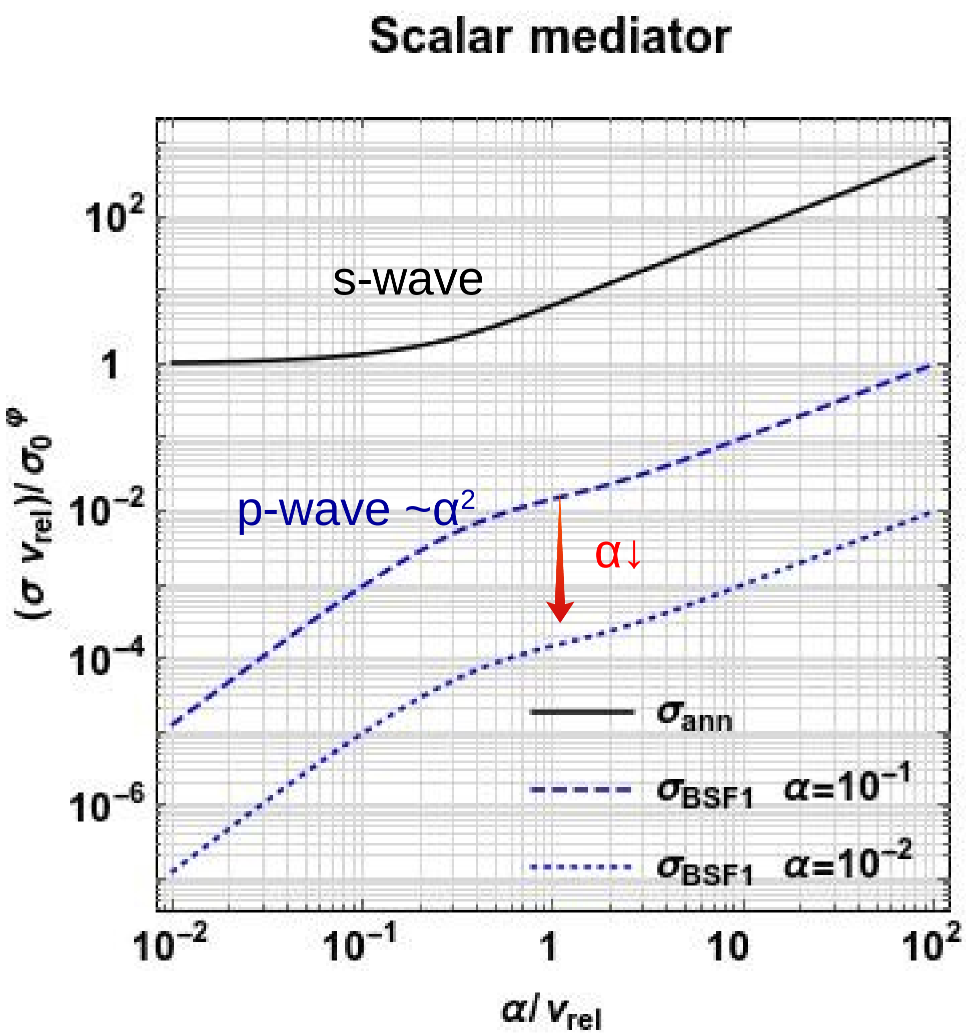
[one-boson-exchange kernel]

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

Scalar vs Vector mediator:
Annihilation and BSF via one-mediator emission

Complex scalar DM





K.Petraki et al. 1611.01394

Scalar vs Vector mediator:

$$\mathcal{M} \sim \int d^3r\phi(r)\{\text{vertex}\}\psi^*(r)e^{-i\mathbf{P}_\varphi \mathbf{r}}$$

The amplitude is evaluated by expanding in the mediator momentum:

$$|\mathbf{P}_\varphi| = \frac{\mu}{2}(\alpha^2 + v_{rel}^2)$$

Vector mediator

Derivative (∇) vertex

$$1 - i\mathbf{P}_\varphi \mathbf{r} + \ldots$$

Leading order term:
non-zero due the derivative vertex

Scalar mediator

Scalar vertex

$$\cancel{1} - i\mathbf{P}_\varphi \mathbf{r} + \ldots$$

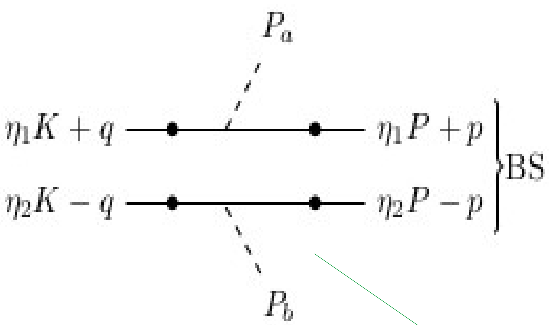
Vanishes due the orthogonality of the wave-functions

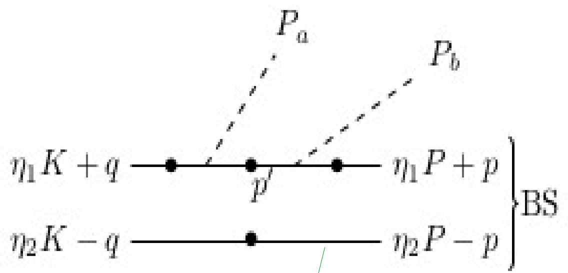
Leading order term: suppressed by α^2

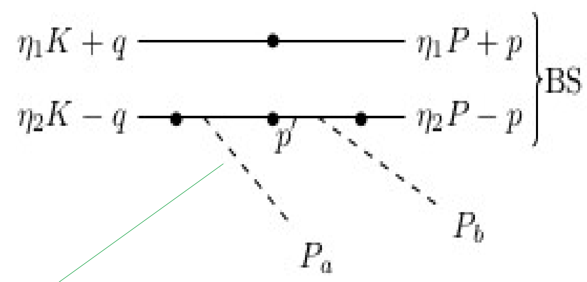
Bound state formation via emission of two scalars

Bound-state formation via one scalar emission is suppressed

Compute bound state formation via two scalar emission





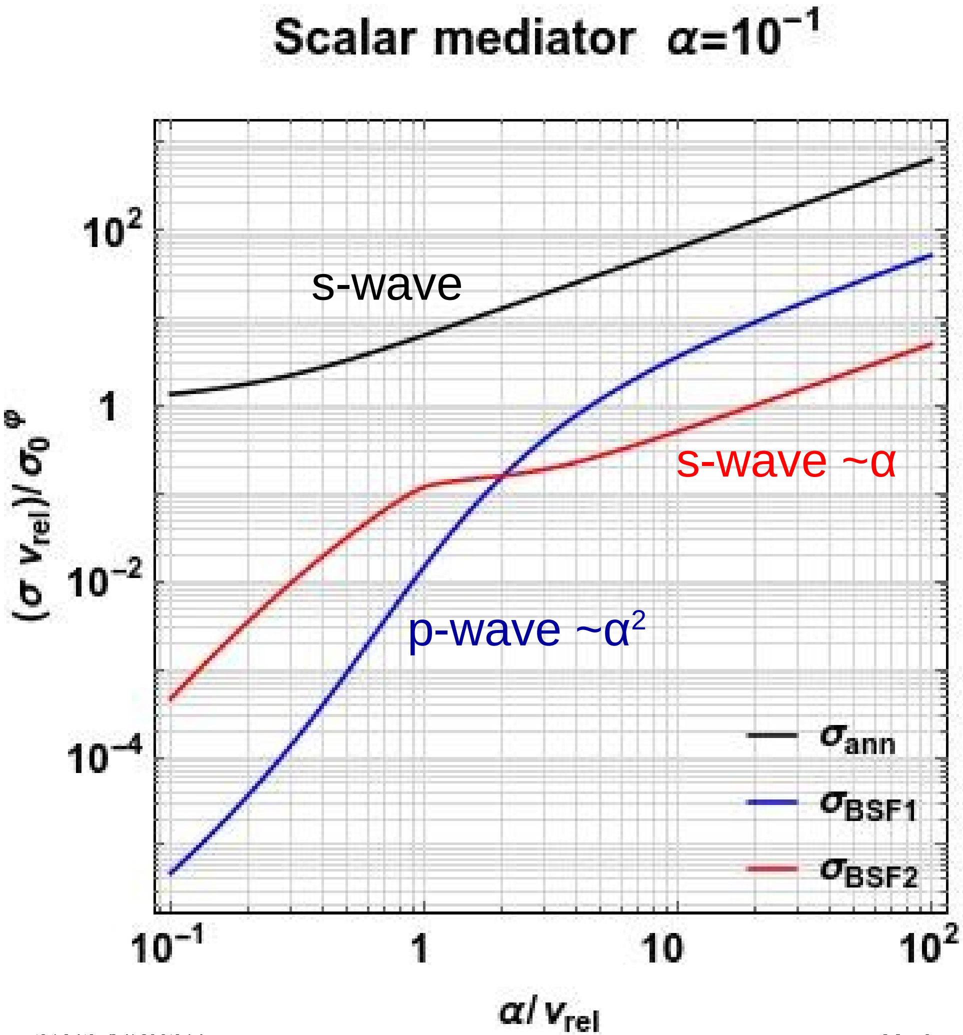


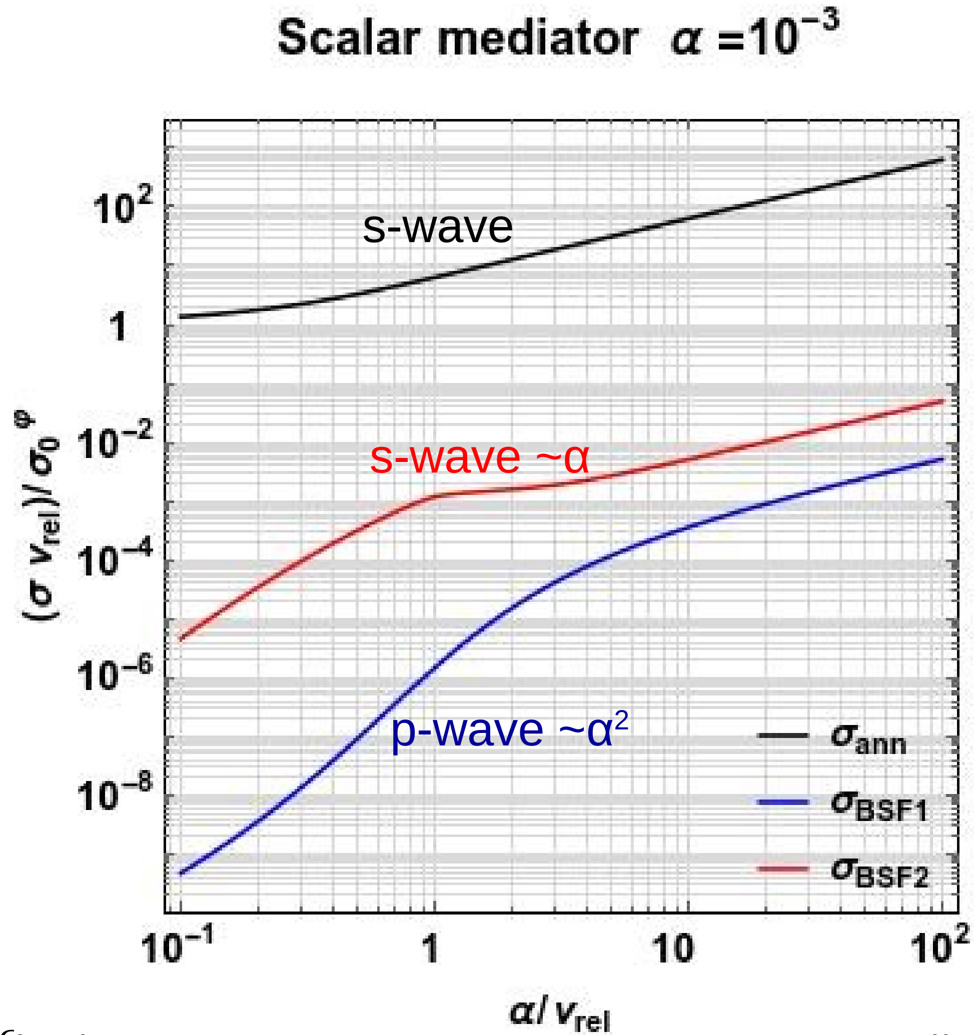
$$\{2\varphi\text{-diagrams}\} \sim \frac{1}{p^2/\mu - P_\varphi}$$

$$\mathcal{M} \sim \int d^3 r \phi(r) \{2\varphi\text{-diagrams}\} \psi^*(r) e^{-i\#\mathbf{P_a r}} e^{-i\#\mathbf{P_b r}}$$

Ann, BSF1 & BSF2 via scalar mediator

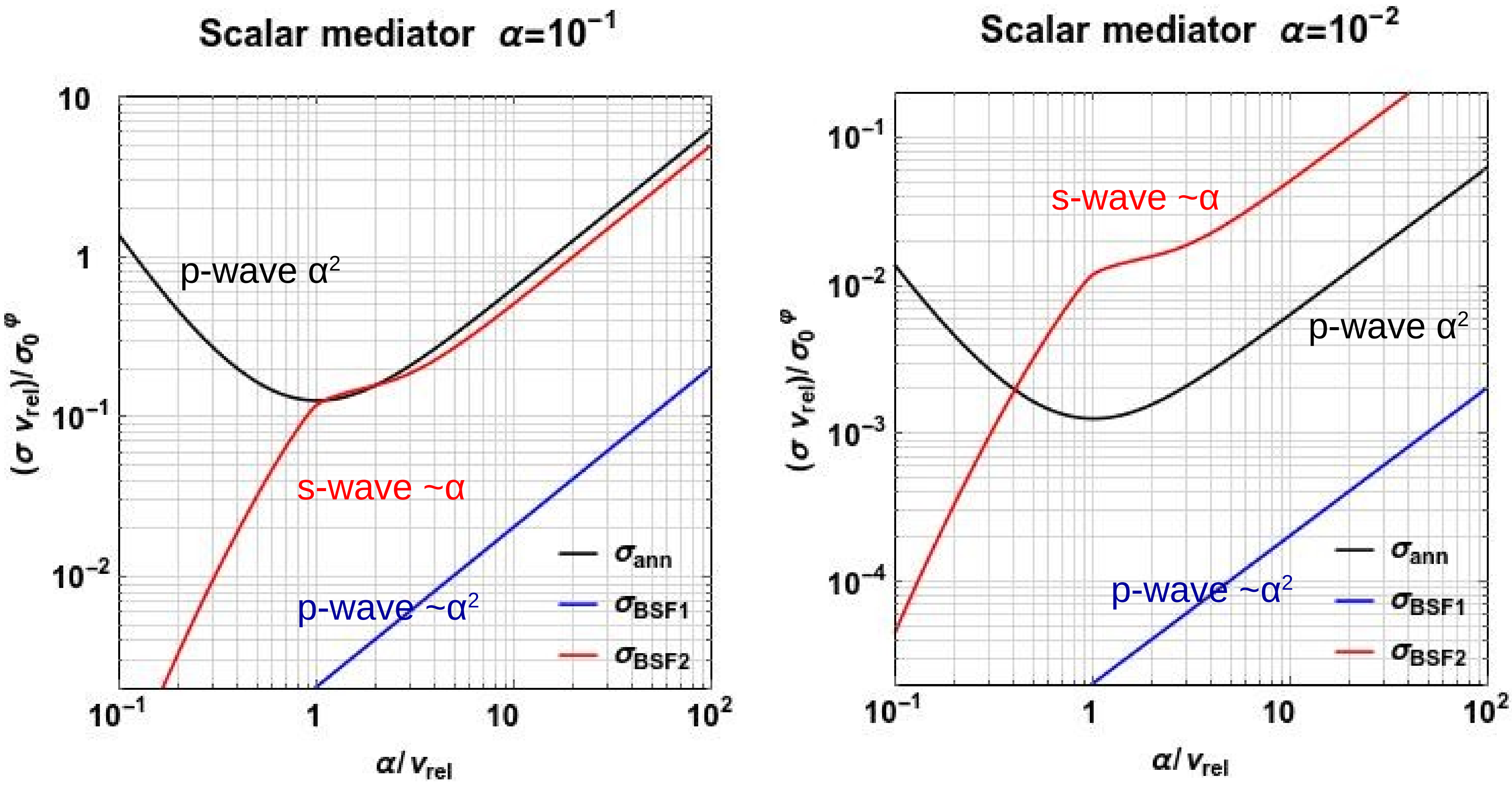
Scalar Dark Matter





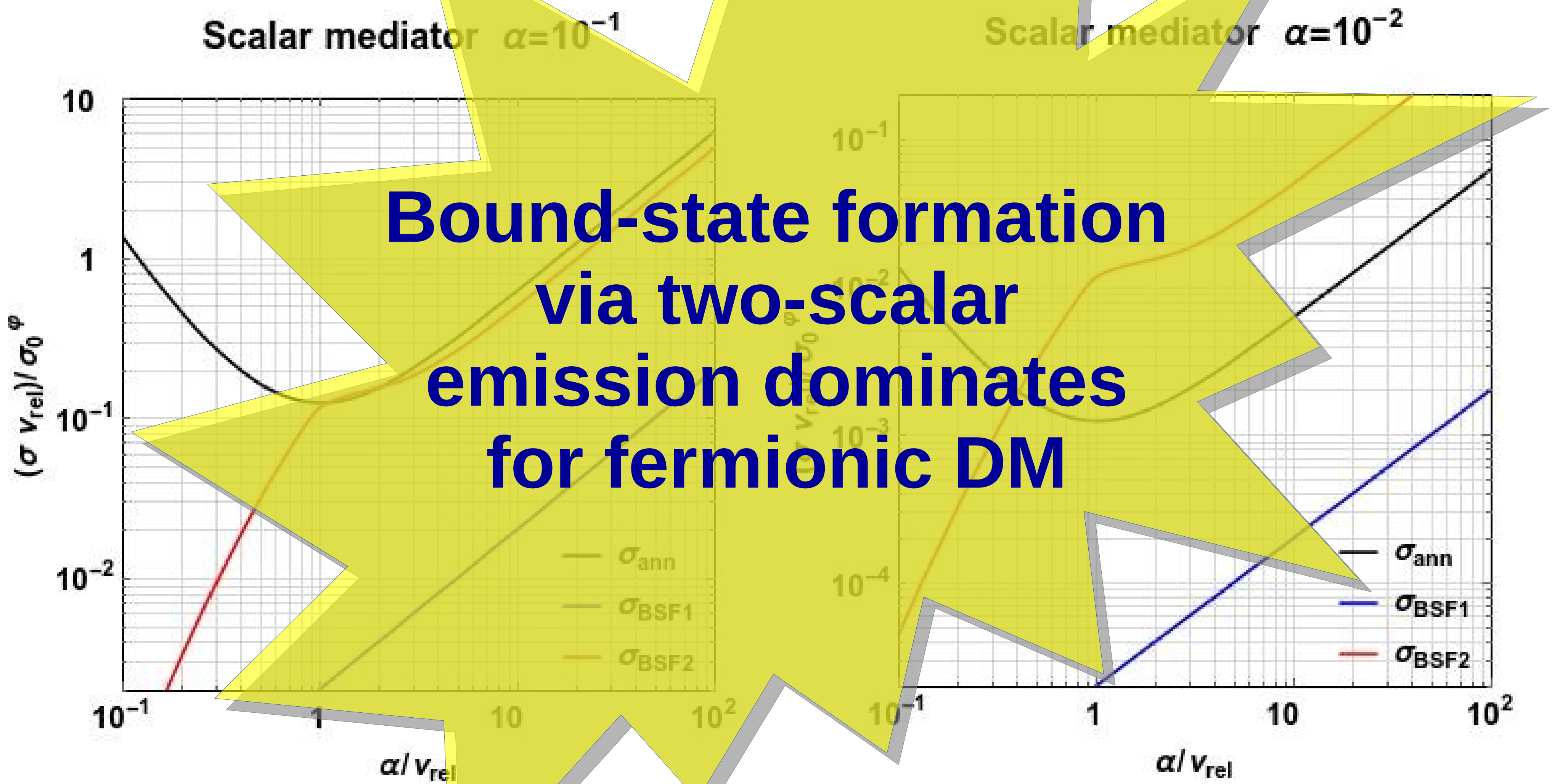
Ann, BSF1 & BSF2 via scalar mediator

Fermionic Dark Matter



Ann, BSF1 & BSF2 via scalar mediator

Fermionic Dark Matter



Bound-state formation via two-scalar emission dominates for fermionic DM

Phenomenological implications of bound states

- **Unstable particle-antiparticle bound states**

  → extra annihilation channel.

- **Stable bound states affect DM interaction rates:**

  → self-scattering inside halos,

  → direct and indirect detection signatures.

Work in progress

- **Particle-particle & antiparticle-antiparticle bound states** → Stable
- **Particle-antiparticle bound states:**

$$\mathcal{L} = i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - m_D\bar{\chi}\chi - g\bar{\chi}\chi\phi + \frac{1}{2}\partial_{\mu}\phi\partial^{\mu}\phi - \frac{1}{2}m_{\phi}^2\phi^2$$

→ Spin 0: Unstable, but decay rate very suppressed (B → 4φ)

→ Spin 1: Stable, due to C-parity symmetry in the Lagrangian!

Bound state formation dominates over annihilation, it is important during DM freeze-out calculations:

→ Freeze-Out depends on the interplay of annihilation, bound-state formation, ionization and decay processes.

Are bound states an important <u>fraction of dark matter</u> today?

Many thanks for your attention

Long-range vs short-range potentials

$$V(r) = -\frac{\alpha}{r} e^{-m_\varphi r}$$

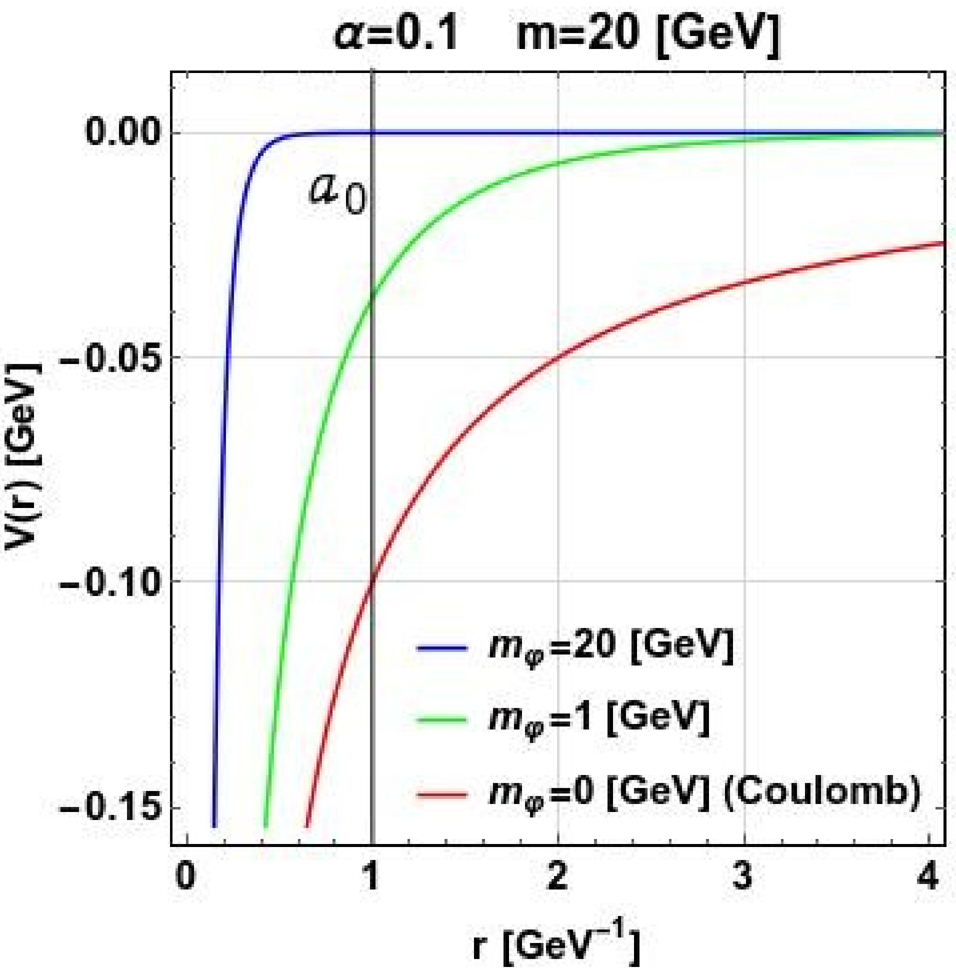
$$\boxed{a_0^{-1} = \mu\alpha} \quad \boxed{r_\varphi^{-1} = m_\varphi}$$

$$\xi = \frac{r_\varphi}{a_0} = \alpha \frac{\mu}{m_\varphi}$$

If ξ ≥ 1, non-perturbative phenomena:

- Sommerfeld effect
- Bound-state formation

Yukawa potential



Models

Real scalar dark matter

$$\mathcal{L}_{\Re,sc} = \frac{1}{2}\partial_\mu X_1 \partial^\mu X_1 + \frac{1}{2}\partial_\mu X_2 \partial^\mu X_2 + \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2}m_1^2 X_1^2 - \frac{1}{2}m_2^2 X_2^2 - \frac{1}{2}m_\varphi^2 \varphi^2 - \frac{1}{2}g_1 m_1 \varphi X_1^2 - \frac{1}{2}g_2 m_2 \varphi X_2^2$$

Imaginary scalar dark matter

$$\mathcal{L}_{\Im,sc} = \partial_\mu X_1^\dagger \partial^\mu X_1 + \partial_\mu X_2^\dagger \partial^\mu X_2 + \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - m_1^2 |X_1|^2 - m_2^2 |X_2|^2 - \frac{1}{2}m_\varphi^2 \varphi^2 - g_1 m_1 \varphi |X_1|^2 - g_2 m_2 \varphi |X_2|^2$$

Fermionic dark matter

$$\mathcal{L}_f = \bar{X}_1 i \not{D} X_1 + \bar{X}_2 i \not{D} X_2 + \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - m_1 \bar{X}_1 X_1 - m_2 \bar{X}_2 X_2 - \frac{1}{2}m_\varphi^2 \varphi^2 - g_1 \varphi \bar{X}_1 X_1 - g_2 \varphi \bar{X}_2 X_2$$

φ is a scalar mediator

Dark matter self-interactions from a general spin-0 mediators

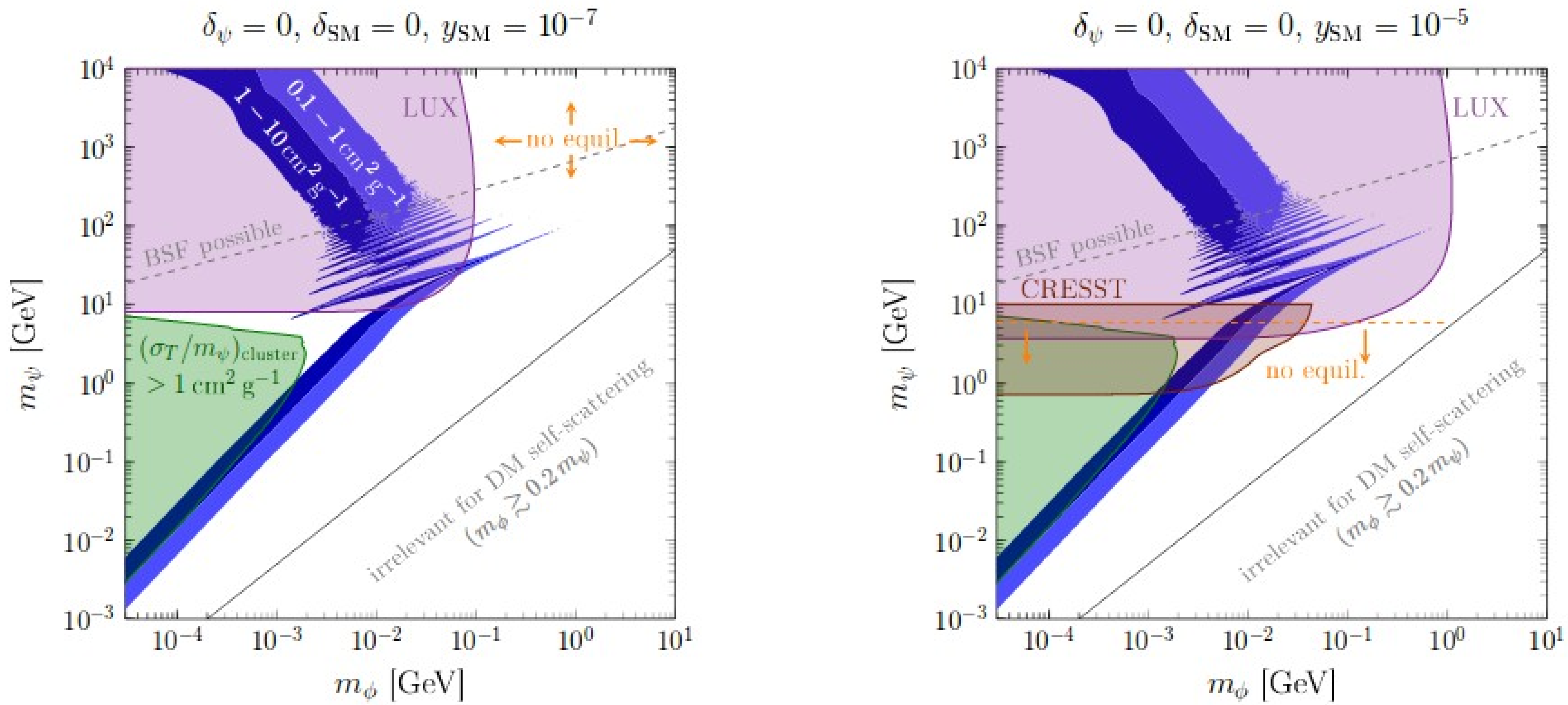
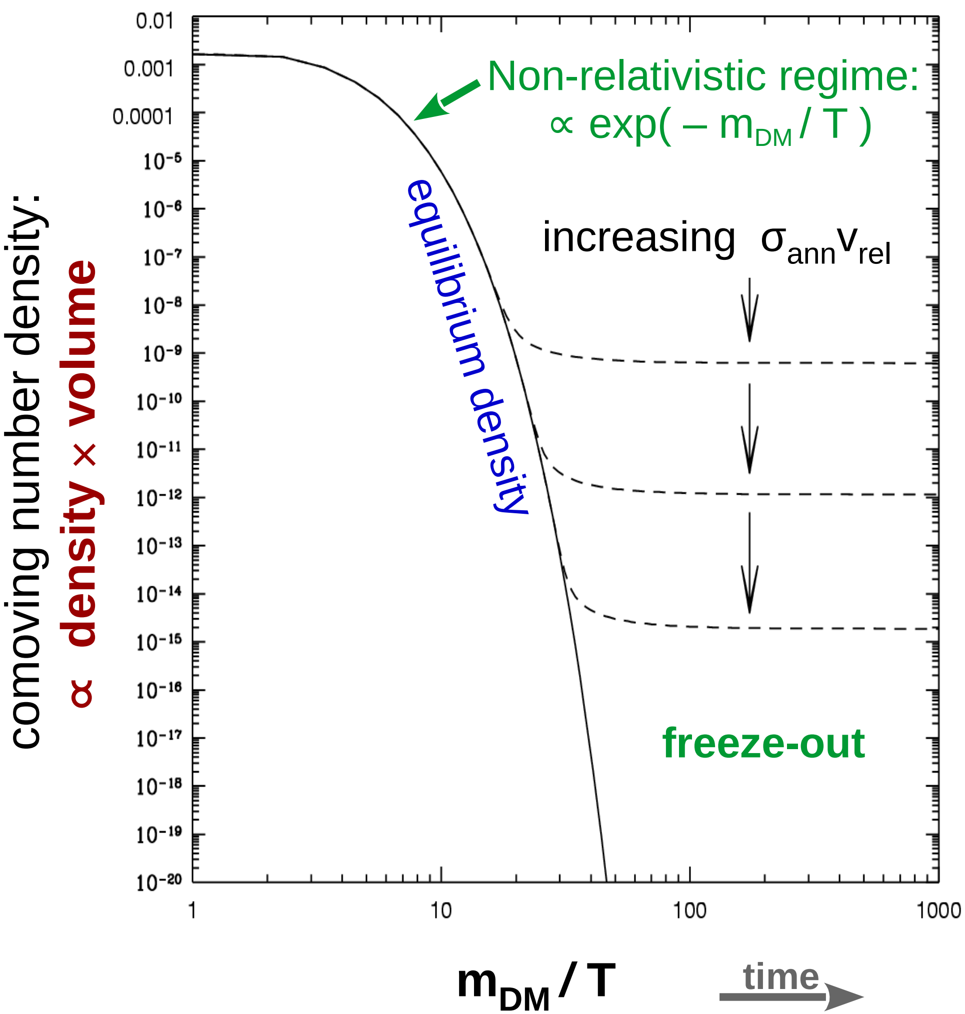


Figure 2. Constraints and interesting parameter regions for the case of purely scalar couplings both to DM and to SM fermions ($\delta_\psi = \delta_{SM} = 0$) for fixed SM coupling y_{SM} (top row) and fixed self-interaction cross section σ_T/m_ψ (bottom row). In all panels y_ψ is fixed by the relic density requirement. Note that for $10^{-7} \lesssim y_{SM} \lesssim 10^{-4}$ and $m_\phi \lesssim 0.1\,\mathrm{GeV}$ constraints from SN1987a (not shown) may also become relevant.

F. Kahlhoefer et all. 1704.02149

Thermal freeze-out



Early universe:

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

DM density $n_X = n_X(T)$

As universe expands and cools

⇒ Density decreases

⇒ Annihilations become inefficient

⇒ Exponential decrease of n_X stalls: **freeze-out**

⇒ Relic density $\Omega_X \simeq 0.26 \times \left[\frac{3 \times 10^{-26}\, cm^3/s}{\langle \sigma_{ann} v_{rel} \rangle} \right]$

1 pb ~ σ_{Weak}

WIMP miracle!