Metastable bound states and dark matter freeze-out

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Frontiers in particle dark matter searches

(very simplistic summary)

Past decades

Most research focused on

m_{DM} ~ 100 GeV ~ $m_{W,Z}$

(e.g. prototypical WIMP scenario)

Current frontiers

Heavy dark matter

$m_{DM} \gtrsim$ TeV

Not constrained by colliders.

→ Experimentally probed by existing / upcoming **telescopes** e.g. HESS, IceCube, CTA, Antares

Light dark matter

$m_{DM} \lesssim$ few GeV

Not constrained by older direct detection experiments

→ Development of new generation of **direct detection** experiments

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Heavy ($m_{DM} \gtrsim$ TeV) dark matter

How does the phenomenology of dark matter look like?
(in popular scenarios, e.g. thermal-relic DM)

New type of dynamics emerges:
Long-range interactions

$$\lambda_B \sim \frac{1}{\mu v_{\rm rel}}, \frac{1}{\mu \alpha} \lesssim \frac{1}{m_{\rm mediator}} \sim \text{interaction range}$$

μ: reduced mass ($m_{\rm DM}/2$)

Heavy (m

Does this occur in models we care about?

- WIMPs with m > few TeV
- WIMPs with m < TeV co-annihilating with coloured/charged particles
- Self-interacting DM

erges:

L interactions

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…type… …nerges:

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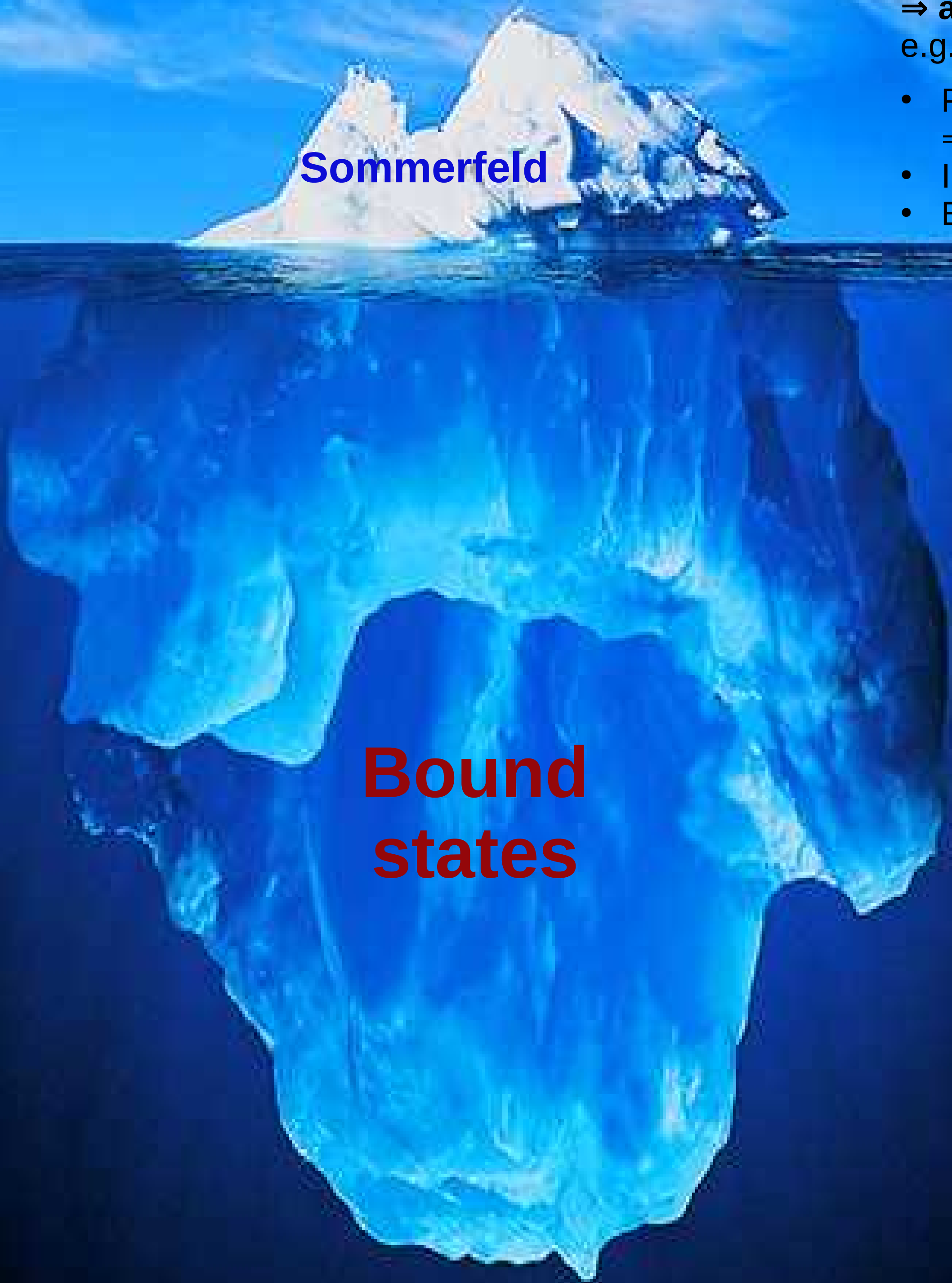
What changes when the interactions are long-ranged?

Implications of non-perturbative effects



Distortion of scattering-state wavefunctions
⇒ affects all cross-sections
e.g. annihilation, elastic scattering

- Production in early universe, e.g. freeze-out
  ⇒ changes correlation of parameters (mass – couplings)
- Indirect detection signals
- Elastic scattering

Unstable bound states (positronium-like)
⇒ extra annihilation channel

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- Novel low-energy indirect detection signals
- Colliders

Stable bound states

- Elastic scattering (usually screening)
- Novel low-energy indirect detection signals
- Inelastic scattering in direct detection experiments (?)

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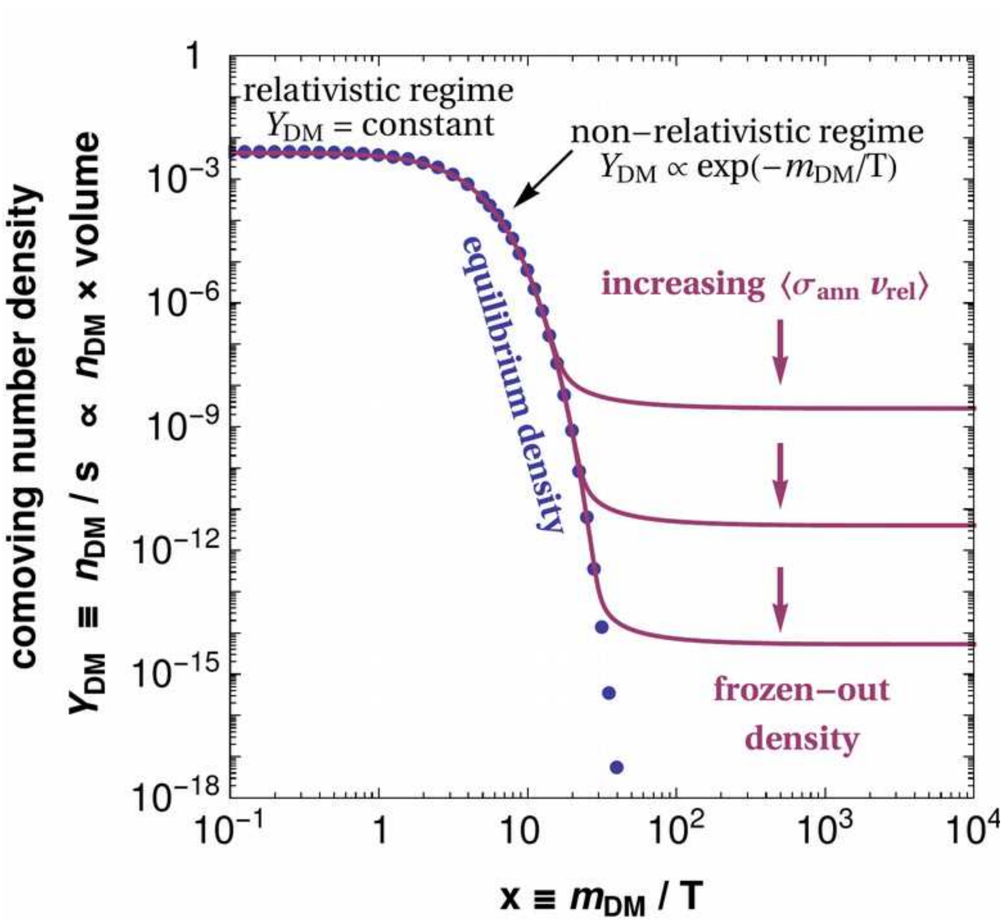
Dark matter production via **thermal freeze-out**



time

$T > m_{DM}$

DM kept in chemical & kinetic equilibrium with the plasma, via

$X + \bar{X} \leftrightarrow f + \bar{f}$

$n_{DM} \sim T^3$ or Y_{DM} = constant

$T < m_{DM}$

$Y_{DM} \propto \exp(-m_{DM} / T)$, while still in equilibrium

$T < m_{DM} / 25$

Density too small, annihilations stall

⇒ Freeze-out!

$$\Omega \simeq 0.26 \times \left(\frac{1pb \cdot c}{\sigma_{ann} v_{rel}} \right)$$

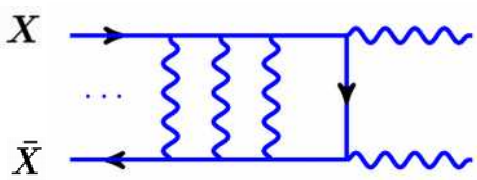
1 pb ~ σ_{Weak}

WIMP miracle!

Dark U(1) model: Dirac DM $X,\bar{X}$ coupled to γ_D

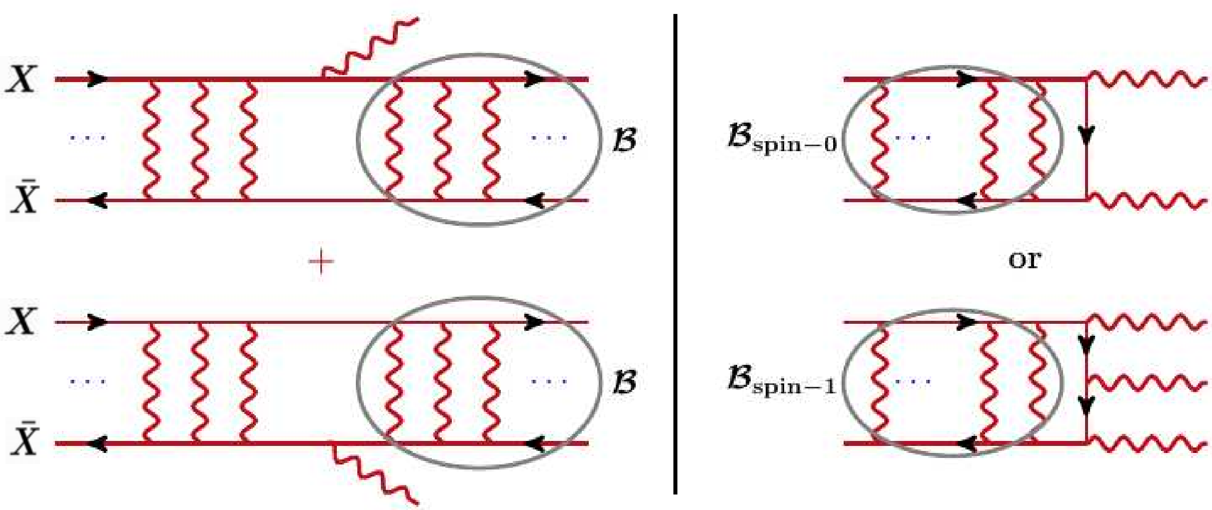
Direct annihilation

$$X + \bar{X} \to 2\gamma_D$$

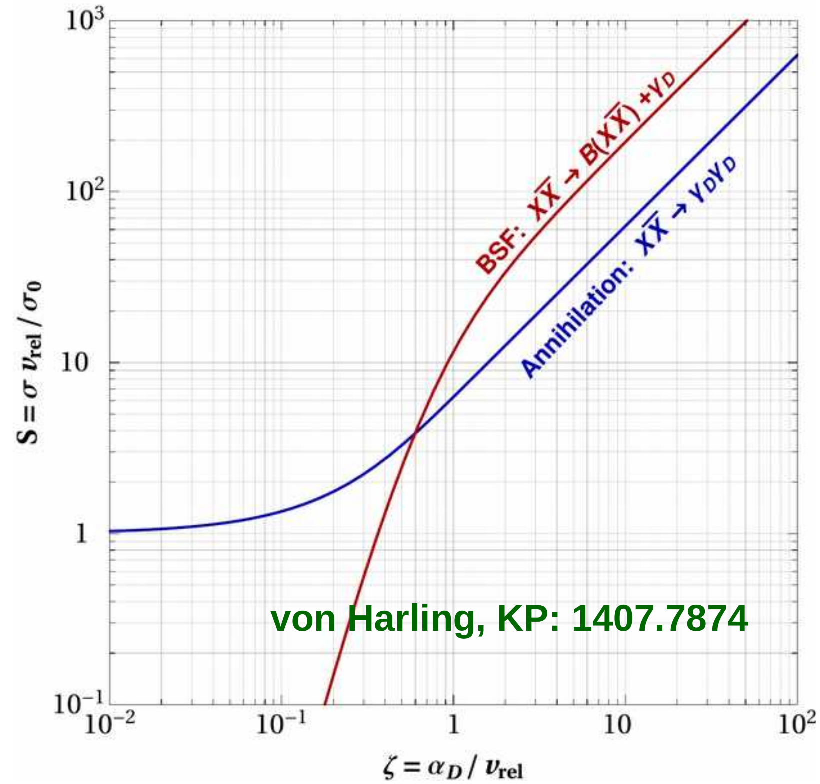


$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm ann}(\alpha_D / v_{\rm rel})$$

Bound-state formation and decay



$$\sigma_{\rm BSF} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm BSF}(\alpha_D / v_{\rm rel})$$



$$S_{\rm ann} \simeq \left(\frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}\right) \xrightarrow{\zeta \gtrsim 1} 2\pi\zeta$$

$$S_{\rm BSF} \simeq \left(\frac{2\pi\zeta}{1 - e^{-2\pi\zeta}}\right) \frac{2^9 \zeta^4 e^{-4\zeta \,{\rm arccot}\zeta}}{3(1+\zeta^2)^2} \xrightarrow{\zeta \gtrsim 1} 3.13 \times 2\pi\zeta$$

Thermal freeze-out with bound states

Boltzmann equations

free particles: $$\frac{dn}{dt} + 3Hn = -\langle \sigma^{\rm ann} v_{\rm rel} \rangle \left(n^2 - n^{\rm eq\ 2} \right) - \sum_{\mathcal{B}} \left(\langle \sigma^{\rm BSF}_{\mathcal{B}}\, v_{\rm rel} \rangle\, n^2 - \Gamma^{\rm ion}_{\mathcal{B}}\, n_{\mathcal{B}} \right)$$

bound states: $$\frac{dn_{\mathcal{B}}}{dt} + 3Hn_{\mathcal{B}} = + \left(\langle \sigma^{\rm BSF}_{\mathcal{B}}\, v_{\rm rel} \rangle\, n^2 - \Gamma^{\rm ion}_{\mathcal{B}}\, n_{\mathcal{B}} \right) - \Gamma^{\rm dec}_{\mathcal{B}} \left(n_{\mathcal{B}} - n^{\rm eq}_{\mathcal{B}} \right) - \sum_{\mathcal{B}' \neq \mathcal{B}} \left(\Gamma^{\rm trans}_{\mathcal{B} \to \mathcal{B}'} n_{\mathcal{B}} - \Gamma^{\rm trans}_{\mathcal{B}' \to \mathcal{B}} n_{\mathcal{B}'} \right)$$

Processes		Detailed balance
Bound state formation (BSF) Ionisation (ion)	$X + \bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$ $\mathcal{B}(X\bar{X}) + \gamma_D \to X + \bar{X}$	$\langle \sigma^{\rm BSF}_{\mathcal{B}} v_{\rm rel} \rangle (n^{\rm eq})^2 = \Gamma^{\rm ion}_{\mathcal{B}}\, n^{\rm eq}_{\mathcal{B}}$
Decay (dec)	$\mathcal{B}(X\bar{X}) \to 2\gamma_D$ or $3\gamma_D$	
Transitions (trans)	$\mathcal{B}(X\bar{X}) \to \mathcal{B}'(X\bar{X}) + \gamma_D$ $\mathcal{B}(X\bar{X}) + \gamma_D \to \mathcal{B}'(X\bar{X})$	$\Gamma^{\rm trans}_{\mathcal{B} \to \mathcal{B}'}\, n^{\rm eq}_{\mathcal{B}} = \Gamma^{\rm trans}_{\mathcal{B}' \to \mathcal{B}}\, n^{\rm eq}_{\mathcal{B}'}$

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Typically at least one rate is large enough

$$\Gamma^{\rm ion}_{\mathcal{B}} + \Gamma^{\rm dec}_{\mathcal{B}} + \Gamma^{\rm trans}_{\mathcal{B}} \gg H$$

to keep bound states close to equilibrium

$\Rightarrow$ set $dn_{\mathcal{B}}/dt + 3Hn_{\mathcal{B}} \simeq 0$

$\Rightarrow$ get algebraic equations for $n_{\mathcal{B}}$ in terms of n, $n^{\rm eq}_{\mathcal{B}}$

$\Rightarrow$ re-employ it in Boltzmann equation for n

Ellis, Luo, Olive: 1503.07142

Complete treatement:
Binder, Filimonova, Petraki, White 2112.00042

Thermal freeze-out with bound states

Boltzmann equations and effective cross-section

free particles: $$\frac{dn}{dt} + 3Hn = -\langle\sigma^{\rm ann} v_{\rm rel}\rangle \left(n^2 - n^{{\rm eq}\ 2}\right) - \sum_{\mathcal{B}} \left(\langle\sigma^{\rm BSF}_{\mathcal{B}} v_{\rm rel}\rangle\, n^2 - \Gamma^{\rm ion}_{\mathcal{B}}\, n_{\mathcal{B}}\right)$$

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$$\frac{dn}{dt} + 3Hn = -\langle\sigma^{\rm eff} v_{\rm rel}\rangle \left(n^2 - n^{{\rm eq}\ 2}\right)$$

where, neglecting bound-to-bound transitions,

$$\langle\sigma^{\rm eff} v_{\rm rel}\rangle \equiv \langle\sigma^{\rm ann} v_{\rm rel}\rangle + \sum_{\mathcal{B}} \langle\sigma^{\rm BSF}_{\mathcal{B}} v_{\rm rel}\rangle \times \frac{\Gamma^{\rm dec}_{\mathcal{B}}}{\Gamma^{\rm dec}_{\mathcal{B}} + \Gamma^{\rm ion}_{\mathcal{B}}}$$

Attractor solution is the equilibrium density

efficiency factors

$$r_{\mathcal{B}} = \sum_{\mathcal{B}'} \Gamma^{\rm dec}_{\mathcal{B}'} \left(\mathbb{\Gamma}^{\rm ion} + \mathbb{\Gamma}^{\rm dec} + \mathbb{\Gamma}^{\rm trans} - \mathbb{T}\right)^{-1}_{\mathcal{B}'\mathcal{B}}$$

Binder, Filimonova, Petraki, White 2112.00042

Thermal freeze-out with bound states

Effective cross-section

$$\frac{dn}{dt} + 3Hn = -\langle \sigma^{\rm eff} v_{\rm rel}\rangle \left(n^2 - n^{\rm eq\ 2}\right)$$

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At $T \gg$ Binding Energy $\Rightarrow$ $\Gamma_{\mathcal{B}}^{\rm ion} \gg \Gamma_{\mathcal{B}}^{\rm dec}$,

$$\langle \sigma_{\mathcal{B}}^{\rm BSF} v_{\rm rel}\rangle \frac{\Gamma_{\mathcal{B}}^{\rm dec}}{\Gamma_{\mathcal{B}}^{\rm dec} + \Gamma_{\mathcal{B}}^{\rm ion}} \simeq \langle \sigma_{\mathcal{B}}^{\rm BSF} v_{\rm rel}\rangle \frac{\Gamma_{\mathcal{B}}^{\rm dec}}{\Gamma_{\mathcal{B}}^{\rm ion}} = \frac{n_{\mathcal{B}}^{\rm eq}}{(n^{\rm eq})^2}\,\Gamma_{\mathcal{B}}^{\rm dec}$$

$$\simeq \frac{g_{\mathcal{B}}}{g_X^2}\left(\frac{4\pi}{m_X T}\right)^{3/2} \times e^{|E_{\mathcal{B}}|/T}\,\Gamma_{\mathcal{B}}^{\rm dec}$$

$$\Downarrow$$

Independent of actual BSF cross-section!

$\Gamma_{\mathcal{B}}^{\rm dec} \propto (\sigma^{\rm ann} v_{\rm rel}) \rightarrow$ modest increase over the direct annihilation, but increases exponentially as T drops.

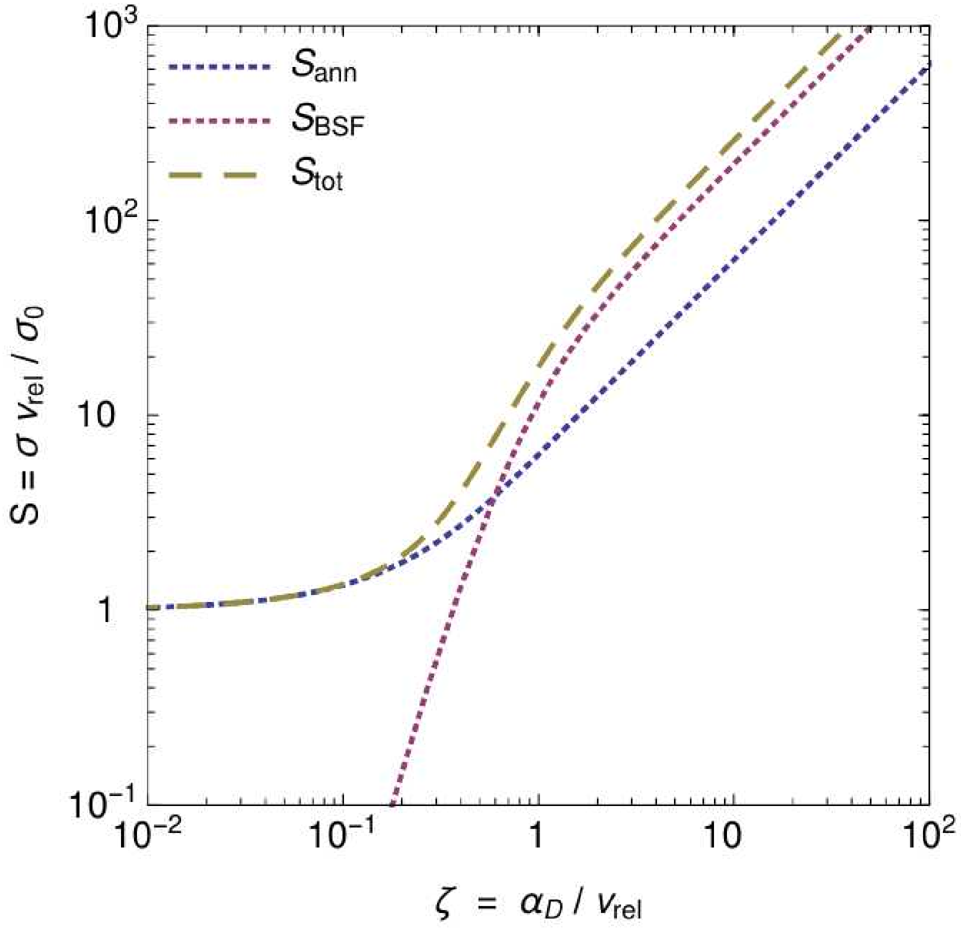
At $T \lesssim$ Binding Energy $\Rightarrow$ $\Gamma_{\mathcal{B}}^{\rm ion} \ll \Gamma_{\mathcal{B}}^{\rm dec}$,

$$\langle \sigma_{\mathcal{B}}^{\rm BSF} v_{\rm rel}\rangle \frac{\Gamma_{\mathcal{B}}^{\rm dec}}{\Gamma_{\mathcal{B}}^{\rm dec} + \Gamma_{\mathcal{B}}^{\rm ion}} \simeq \langle \sigma_{\mathcal{B}}^{\rm BSF} v_{\rm rel}\rangle.$$

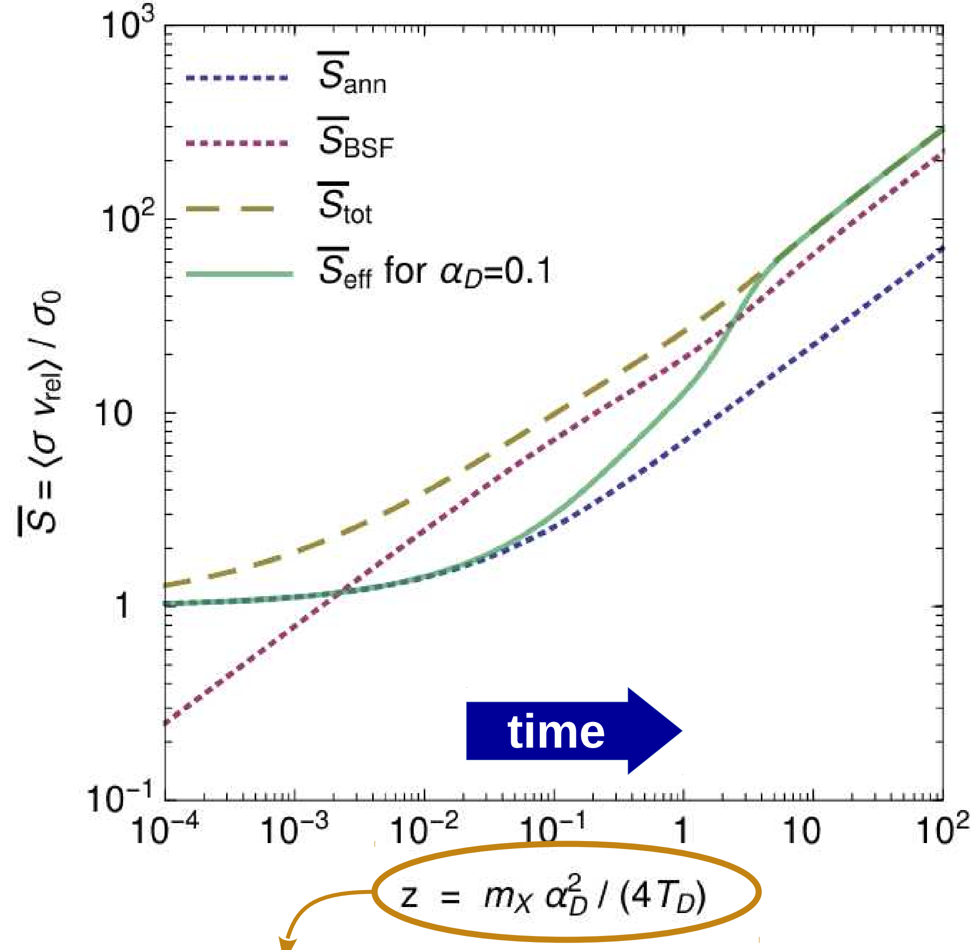
Typically, most of DM destruction due to BSF occurs in this regime.

Effective cross-section in dark U(1) model

Cross-sections



Thermally averaged cross-sections

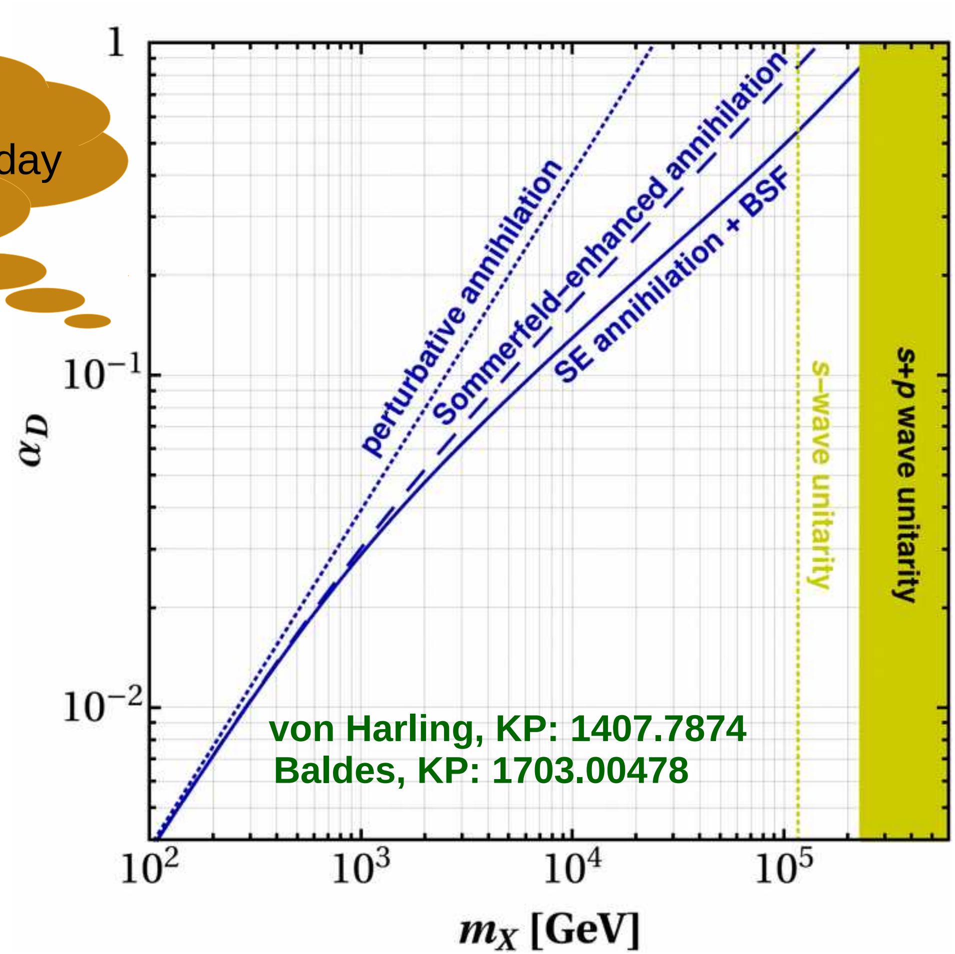


binding energy / temperature

Thermal freeze-out with long-range interactions

Dark U(1) model: Dirac DM $X,\bar{X}$ coupled to γ_D

Important because it determines DM interactions today (direct, indirect detection)



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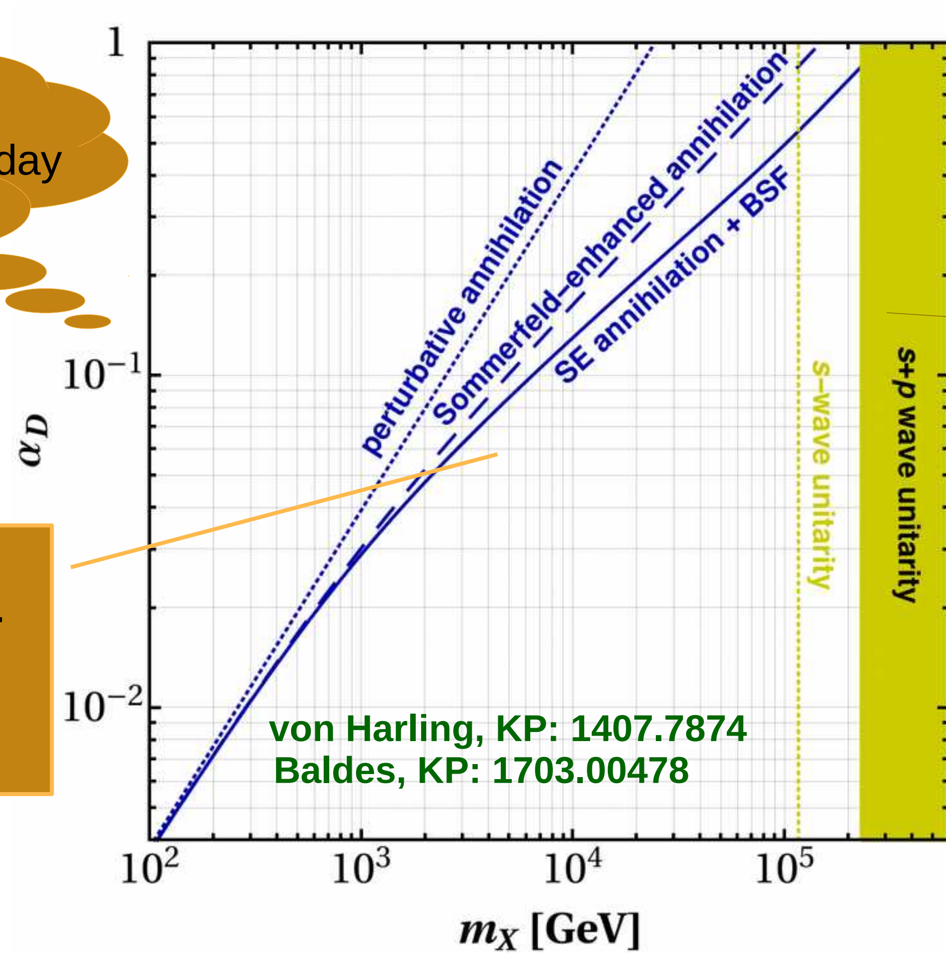

Long-range effects indeed become at $m_{DM} \gtrsim$ few TeV.

Verifies expectation from unitarity arguments!

Dominant annihilation mode: ***s*-wave**.

Dominant BSF mode: ***p*-wave**

Same order!

Higher partial waves Important / dominant in multi-TeV regime.

DM may be even heavier!

Thermal freeze-out with bound states

Boltzmann equations and effective cross-section

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Binder, Filimonova, Petraki, White 2112.00042

Bound-to-bound transitions only enhance the total effective cross-section!

A corollary
Saha equilibrium for metastable bound states

$$\frac{n_{\mathcal{B}}}{n_{\mathcal{B}}^{\rm eq}} = \left(\frac{n_{\rm free}}{n_{\rm free}^{\rm eq}}\right)^2 - \left[\left(\frac{n_{\rm free}}{n_{\rm free}^{\rm eq}}\right)^2 - 1\right] r_{\mathcal{B}}$$

Binder, Filimonova, Petraki, White 2112.00042

$$r_{\mathcal{B}} = \sum_{\mathcal{B}'} \Gamma^{\rm dec}_{\mathcal{B}'} \left(\mathbb{\Gamma}^{\rm ion} + \mathbb{\Gamma}^{\rm dec} + \mathbb{\Gamma}^{\rm trans} - \mathbb{T}\right)^{-1}_{\mathcal{B}'\mathcal{B}}$$

$r_{\mathcal{B}} = 0$

$r_{\mathcal{B}} = 1$

$$\frac{n_{\mathcal{B}}}{n_{\mathcal{B}}^{\rm eq}} = \left(\frac{n_{\rm free}}{n_{\rm free}^{\rm eq}}\right)^2$$

Standard Saha equilibrium

$$\frac{n_{\mathcal{B}}}{n_{\mathcal{B}}^{\rm eq}} = 1$$

Particles with decay rate > Hubble

Neutralino-squark co-annihilation scenarios

Squark-neutralino co-annihilation scenarios

- Degenerate spectrum → soft jets → evade LHC constraints
- Large stop-Higgs coupling reproduces measured Higgs mass and brings the lightest stop close in mass with the LSP

⇒ DM density determined by "effective" Boltzmann equation

$$n_{\rm tot} = n_{\rm LSP} + n_{\rm NLSP}$$

$$\sigma^{\rm eff}_{\rm ann} = [\, n^2_{\rm LSP}\, \sigma^{\rm LSP}_{\rm ann} + n^2_{\rm NLSP}\, \sigma^{\rm NLSP}_{\rm ann} + n_{\rm LSP}\, n_{\rm NLSP}\, \sigma^{\rm LSP-NLSP}_{\rm ann} \,]/n^2_{\rm tot}$$

Scenario probed in colliders.
Important to compute DM density accurately!
→ **QCD corrections**

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

$$\begin{aligned}\mathcal{L} \;\supset\; & \frac{1}{2}\overline{\chi^c}\, i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\,\overline{\chi^c}\chi \\ + \; & \left[(\partial_\mu + ig_s G^a_\mu T^a)X\right]^\dagger \left[(\partial^\mu + ig_s G^{a,\mu}T^a)X\right] - m_X^2|X|^2 \\ + \; & (\chi \leftrightarrow X, X^\dagger) \text{ interactions in chemical equilibrium during freeze-out}\end{aligned}$$

DM coannihilation with scalar colour triplet

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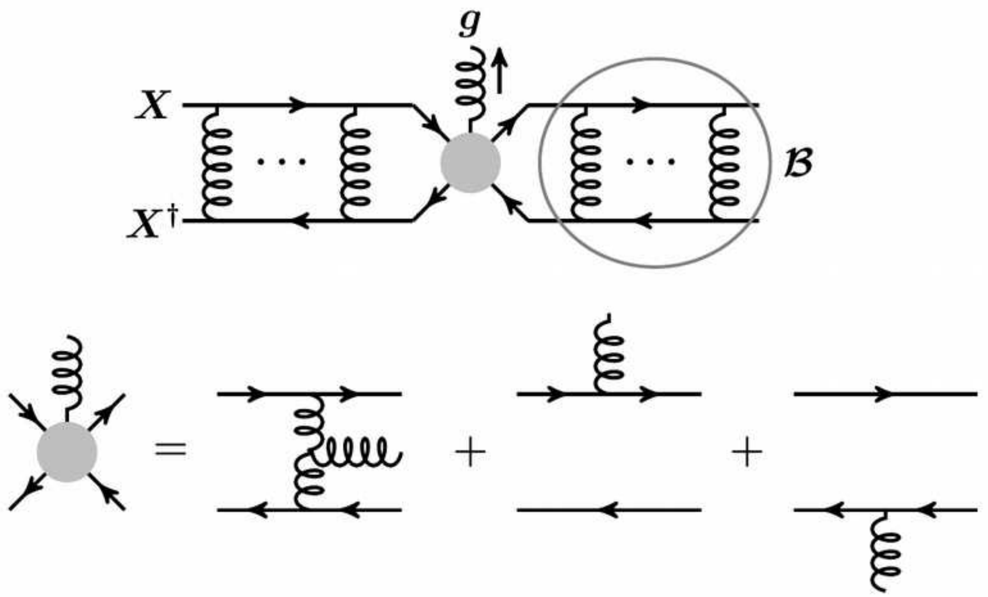
Bound-state formation and decay



Allowed transitions

$$(X + X^\dagger)_{[8]} \rightarrow (X + X^\dagger)_{[1]} + g_{[8]}$$
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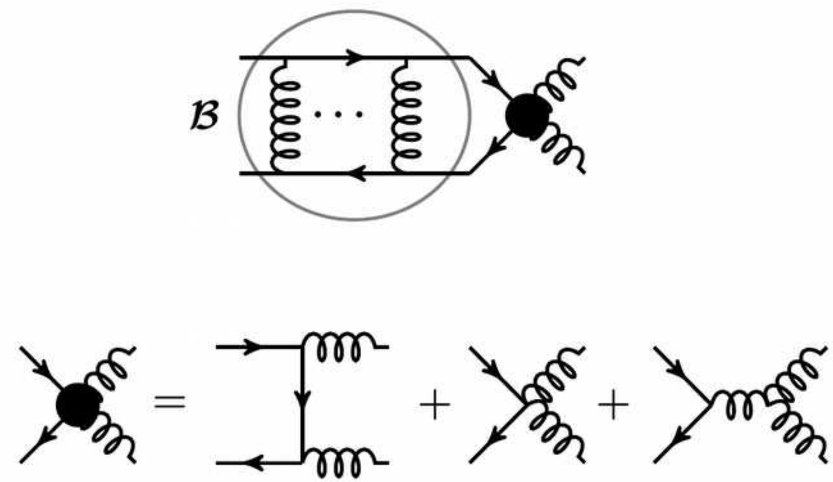
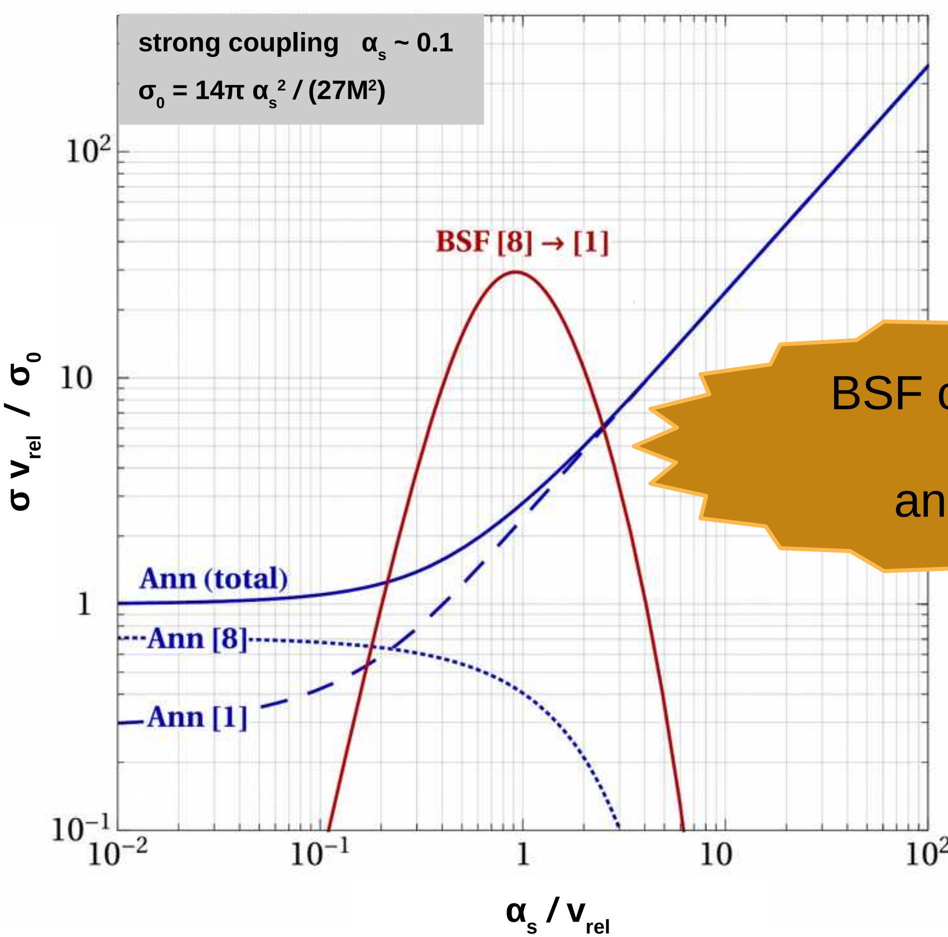


DM coannihilation with scalar colour triplet

MSSM-inspired toy model

Bound-state formation *vs* Annihilation

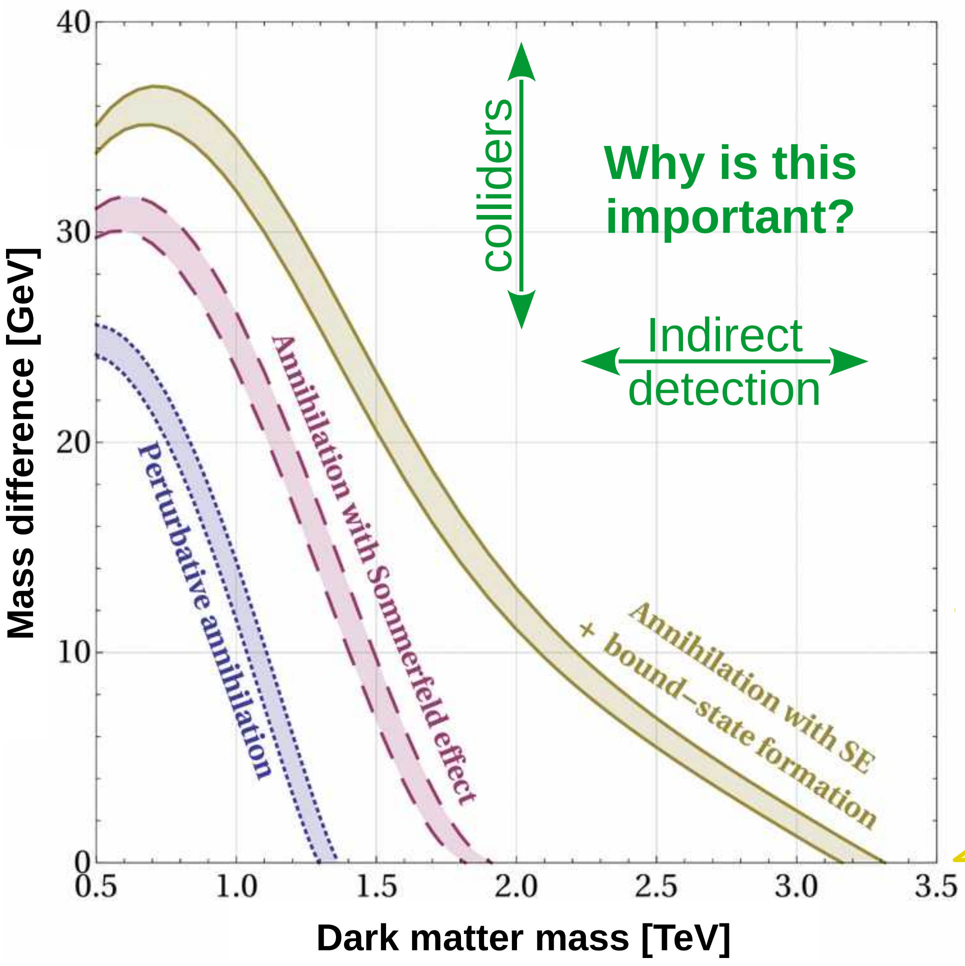


BSF can exceed Annihilation
by more than
an order of magnitude!

Harz, KP: 1805.01200

DM coannihilation with scalar colour triplet

MSSM-inspired toy model



Effect on relic density: much much larger than obs uncertainty in Ω_{DM}

Not the final picture!

Harz, KP: 1805.01200

Squark-neutralino co-annihilation scenarios

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Scenario probed in colliders.
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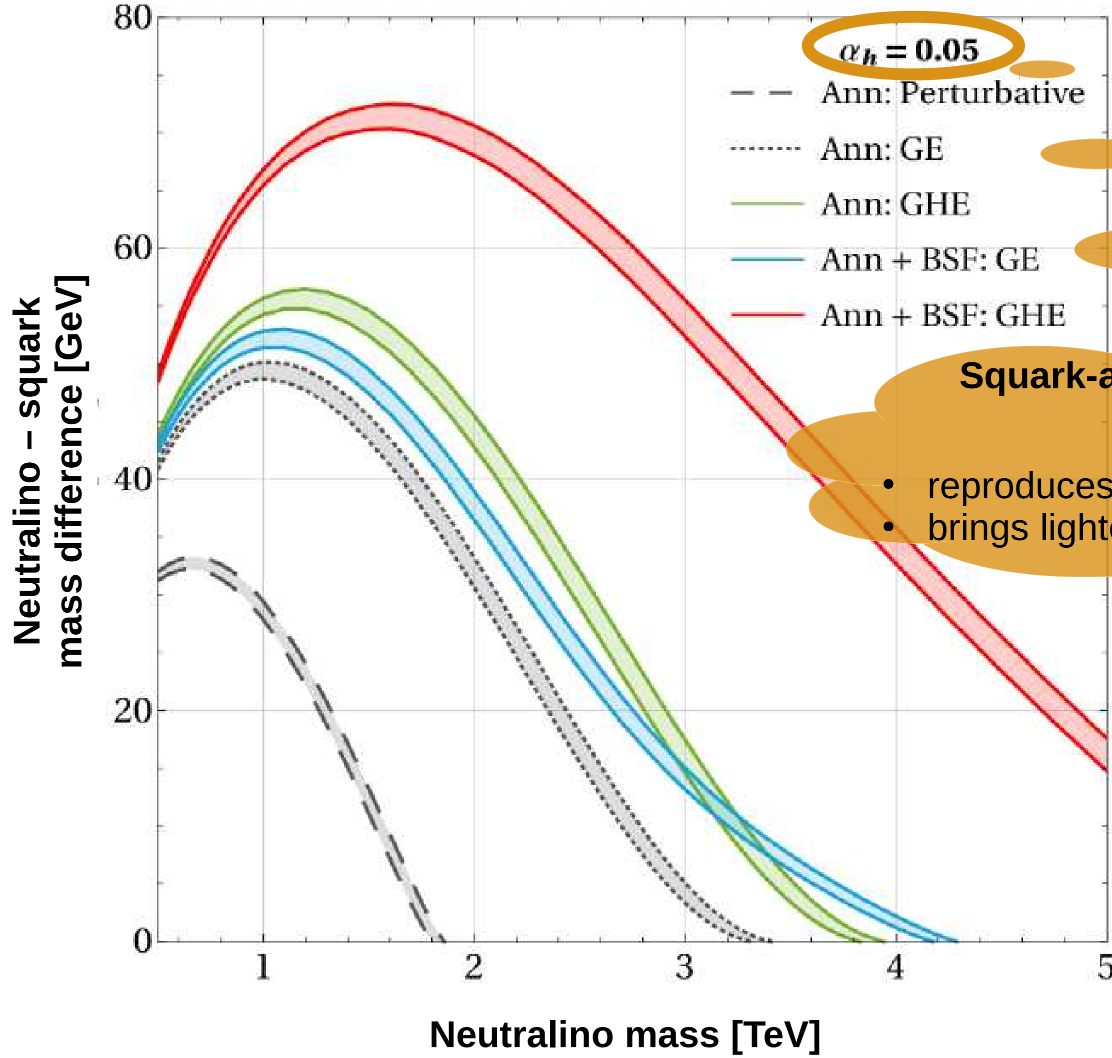
The Higgs as a light mediator

- Sommerfeld enhancement of direct annihilation Harz, KP: 1711.03552
- Binding of bound states Harz, KP: 1901.10030

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

The effect of the Higgs-mediated potential



Squark-antisquark-Higgs coupling

Large α_h

- reproduces measured Higgs mass
- brings lightest stop close in mass with LSP

Harz and KP: 1711.03552, 1901.10030

The Higgs as a light mediator

- Sommerfeld enhancement of direct annihilation — Harz, KP: 1711.03552
- Binding of bound states — Harz, KP: 1901.10030

- **Formation of bound states via Higgs (*doublet*) emission ?**

Capture via emission of neutral scalar suppressed,
due to selection rules: quadruple transitions

March-Russel, West 0812.0559
KP, Postma, Wiechers: 1505.00109
An, Wise, Zhang: 1606.02305
KP, Postma, de Vries: 1611.01394

Capture via emission of charged scalar [or its Goldstone mode]
very very rapid: monopole transitions !

Ko,Matsui,Tang: 1910:04311
Oncala, KP: 1911.02605
Oncala, KP: 2101.08666
Oncala, KP: 2101.08667

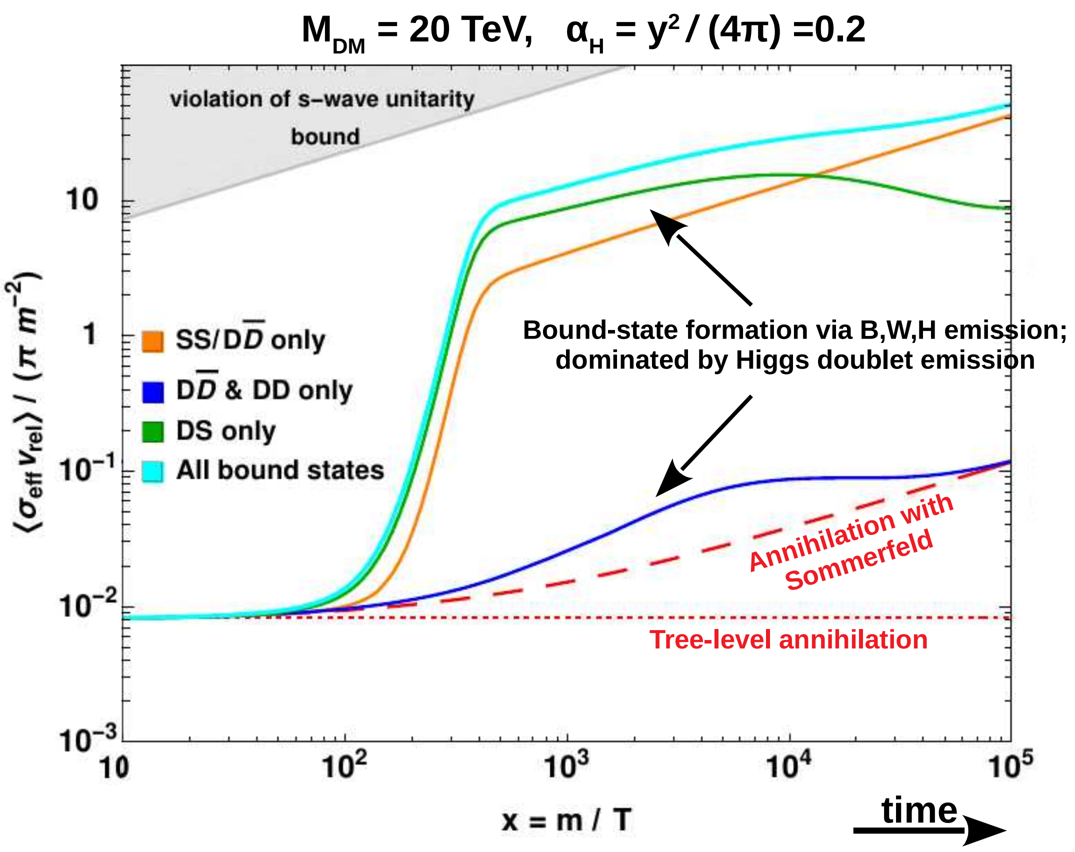
Sudden change in effective Hamiltonian precipitates transitions.
Akin to atomic transitions precipitated by β decay of nucleus.

Renormalisable Higgs-portal WIMP models

***S*inglet-*D*oublet coupled to the Higgs:** $L \supset -y \bar{D} H S$

$m_D \simeq m_S \rightarrow D$ and S co-annihilate.

Freeze-out begins before the EWPT if $m_{DM} > 5\text{TeV}$



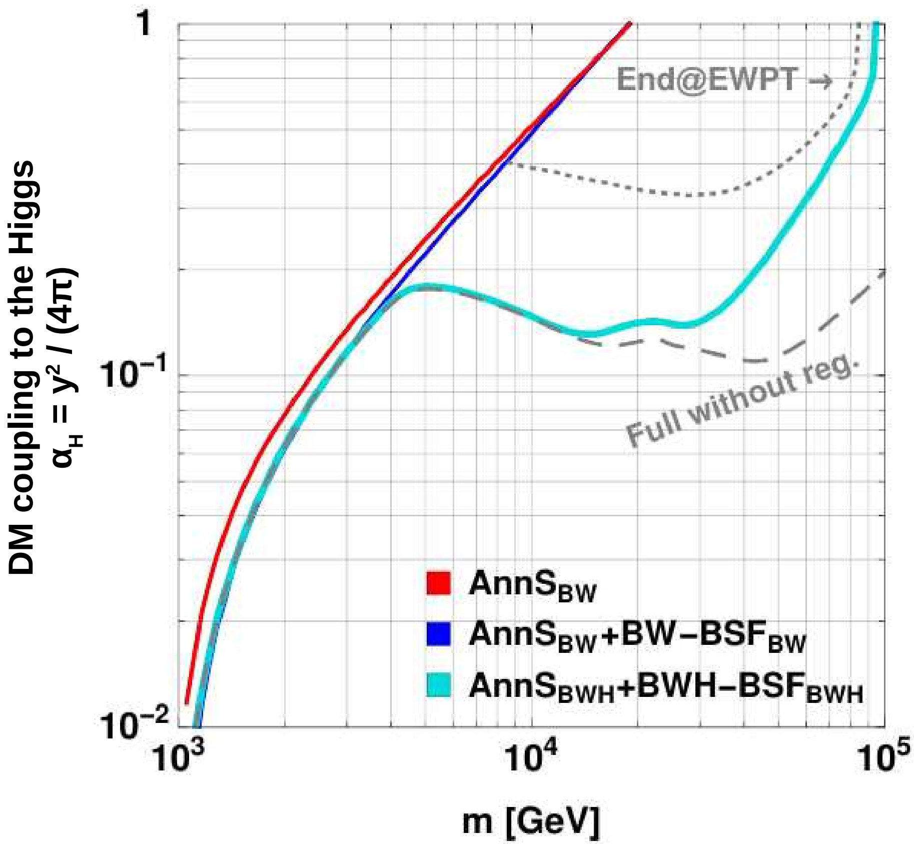
Oncala, KP: 2101.08666/7

Renormalisable Higgs-portal WIMP models

Singlet-**D**oublet coupled to the Higgs: $L \supset - y\, \bar{D}\, H\, S$

$m_D \simeq m_S \rightarrow D$ and S co-annihilate.

Freeze-out begins before the EWPT if $m_{DM} > 5$TeV



Huge effect!

~ 10^2 in relic density!

Impels reconsideration of Higgs-portal models (incl. neutralino-squark coann scenarios)

Oncala, KP: 2101.08666/7

Is it a coincidence that
non-perturbative effects arise in all these models
at the multi-TeV regime?

Or is there a model-independent way
to understand and *predict* it?

If so, what else can we learn from it?

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If so, what else can we learn from it?

Think
good old
unitarity

Partial-wave unitarity limit

$$\sigma_{\rm inel}^{(\ell)} \leqslant \frac{\pi(2\ell+1)}{k_{\rm cm}^2} \xrightarrow{\rm non-rel} \frac{\pi(2\ell+1)}{\mu^2 v_{\rm rel}^2} \xrightarrow{\mu=M_{\rm DM}/2} \frac{4\pi(2\ell+1)}{M_{\rm DM}^2 v_{\rm rel}^2}$$

[Griest, Kamionkowski (1990); Hui (2001)]

Physical meaning:
saturation of probability for inelastic scattering

Partial-wave unitarity limit

in non-relativistic regime

$$\sigma_{\rm inel}^{(\ell)} v_{\rm rel} \leqslant \sigma_{\rm uni}^{(\ell)} v_{\rm rel} = \frac{4\pi(2\ell+1)}{M_{\rm DM}^2 v_{\rm rel}}$$

Implies upper bound on the mass of thermal-relic DM

Griest, Kamionkowski (1990)

$$\sigma_{\rm ann} v_{\rm rel} \simeq 2.2\times 10^{-26}\ {\rm cm}^3/{\rm s} \leqslant \frac{4\pi}{M_{\rm DM}^2 v_{\rm rel}}$$

$$\langle v_{\rm rel}^2\rangle^{1/2} = (6T/M_{\rm DM})^{1/2} \xrightarrow[M_{\rm DM}/T\,\approx\,25]{\rm freeze-out} 0.49$$

$$\Rightarrow M_{\rm uni} \simeq \begin{cases} 117\ {\rm TeV}, & \text{self-conjugate DM} \\ 83\ {\rm TeV}, & \text{non-self-conjugate DM} \end{cases}$$

- Assumes contact-type interactions, σv_{rel} = constant
- Considers only s-wave annihilation

Partial-wave unitarity limit

in non-relativistic regime

What interactions can realise the unitarity limit?

$$\sigma_{\text{inel}}^{(\ell)} v_{\text{rel}} \leqslant \sigma_{\text{uni}}^{(\ell)} v_{\text{rel}} = \frac{4\pi(2\ell+1)}{M_{\text{DM}}^2 v_{\text{rel}}}$$

Parametric dependence on mass and velocity implies that
σ_{uni} can be approached or attained only by long-range interactions

Long-range interactions imply **bound states**, which may form by **higher partial waves** of the scattering state that contribute at the same order.

- **Thermal relic DM can be much heavier than anticipated.**
  - **In viable thermal scenarios, expect long-range behavior at $m_{DM} \gtrsim$ few TeV** (important for exps)
  - **No model-independent unitarity limit on mass of thermal relic DM!**

Baldes, KP: 1703.00478

Conclusions

- **Bound states impel complete reconsideration of thermal decoupling at / above the TeV scale: *emergence of a new type of inelasticity***

  Unitarity limit can be approached / attained only by long-range interactions
  ⇒ bound states play very important role! **Baldes, KP: 1703.00478**

  There is no unitarity limit on the mass of thermal relic DM!

- **Experimental implications:**
  - DM heavier than anticipated: multi-TeV probes very important

    ⇒ build the 100 TeV collider :)
  - Indirect detection:

    Enhanced rates due to BSF
    Novel signals: low-energy radiation emitted in BSF
    Indirect detection of asymmetric DM
  - Colliders: improved detection prospects due increased mass gap in coannihilation scenarios

- **Effects *not* limited freeze-out scenario:**
  freeze-in, asymmetric DM, self-interacting DM, stable bound states