Perspectives on dark matter

Kallia Petraki

Sorbonne University, LPTHE, Paris and Nikhef, Amsterdam

CosmoChart
Horizon 2020, grant agreement No 101002846

Planck conference
Paris, 31 May 2022

Classification schemes
of dark matter candidates

Interaction with the SM

Portal operators	SM interactions	Heavy mediators
$\epsilon\, F_Y^{\mu\nu} F_{D\,\mu\nu}$ $(\mu\phi + \lambda\phi^2)\lvert H\rvert^2$ $y LHN$	WIMPs	EFTs

(Self-) interaction type

Long-range	Contact type
Light mediators $m_{med} << m_{DM}$	Heavy mediators $m_{med} \gtrsim m_{DM}$

Production mechanism

Scalar condensates	Collapse of density perturbations	Freeze-in	Asymmetric freeze-out	Symmetric freeze-out
Q-balls Axions	Primordial black holes	Sterile neutrinos Gravitinos	Hidden sector models, e.g. dark U(1), dark QCD	WIMPs, Hidden sectors

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Talk by Alex Kusenko

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Talks by Tony Gherghetta, Geraldine Servant

Talk by Keith Olive

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This talk

Interaction with the SM

Portal operators

$\epsilon F_Y^{\mu\nu} F_{D\,\mu\nu}$

$(\mu\phi + \lambda\phi^2)|H|^2$

$yLHN$

SM interactions

WIMPs

Heavy mediators

EFTs

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Scalar condensates

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Collapse of density perturbations

Primordial black holes

Freeze-in

Sterile neutrinos

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Asymmetric freeze-out

Hidden sector models, e.g. dark U(1) dark QCD

Symmetric freeze-out

WIMPs, Hidden sectors

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Frontiers in dark matter searches

- **Heavy DM**

  Particles with m $\gtrsim$ TeV coupled to SM via the Weak or other interactions not constrained by collider experiments

  → existing and upcoming telescopes observing multi-TeV sky with increasing sensitivity, e.g. HESS, IceCube, CTA, Antares

- **Light DM**

  Particles with m $\lesssim$ few GeV, possibly coupled to SM via a portal interaction, not constrained by older direct detection experiments

  → development of new generation of direct detection experiments

Frontiers in dark matter searches

- **Heavy DM**

  Particles with m ≳ TeV coupled to SM via the Weak or other interactions not constrained by collider experiments

  → existing and upcoming telescopes observing multi-TeV sky with increasing sensitivity, e.g. HESS, IceCube, CTA, Antares

- **Light DM**

  Partic

  → … ents

> - Simple thermal-relic WIMP models live in the (multi-)TeV scale.
> - Thermal-relic DM can be as heavy as few × 100 TeV.
>
> **How heavy can thermal-relic DM be, and what are the underlying dynamics of heavy (≳ TeV) thermal-relic DM?**

heavy

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Long-range interactions

If dark matter is very heavy, then:

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

μ: reduced mass $(m_{\rm DM}/2)$

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$$\mu: \text{ reduced mass } (m_{\text{DM}}/2)$$

Relevant for various models

- Self-interacting DM
- WIMP DM with m_{DM} > few TeV.
- WIMP DM with m_{DM} < TeV,
  in scenarios of DM co-annihilation with coloured partners.

+ other models with dark forces

What’s different about long-range interactions?

Distorts wavefunctions of free particles pairs

⇒ affects all cross-sections

⇒ freeze-out, indirect detection, DM self-scattering

Unstable bound states
⇒ extra annihilation channel

- Freeze-out — **von Harling, Petraki 1407.7874**
- Indirect detection — **Pospelov, Ritz 0810.5167; March-Russel, West 0812.0559**
- Novel low-energy indirect detection signals — **Kusenko, Pearce 1303.7294**
- Colliders — **Shepherd, Tait, Zaharijas 0901.2125**

Stable bound states
(particularly of asymmetric DM)

- Elastic scattering
- Novel low-energy indirect detection signals — **Kusenko, Pearce 1303.7294**
- Black holes via dissipation — **Flores, Kusenko 2008.12456**

Alex Kusenko's talk

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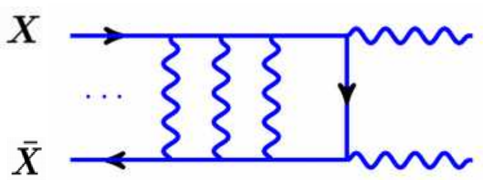
Freeze-out with bound states

- Dark U(1) sector
- Neutralino-squark coannihilation
- The role of the Higgs

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

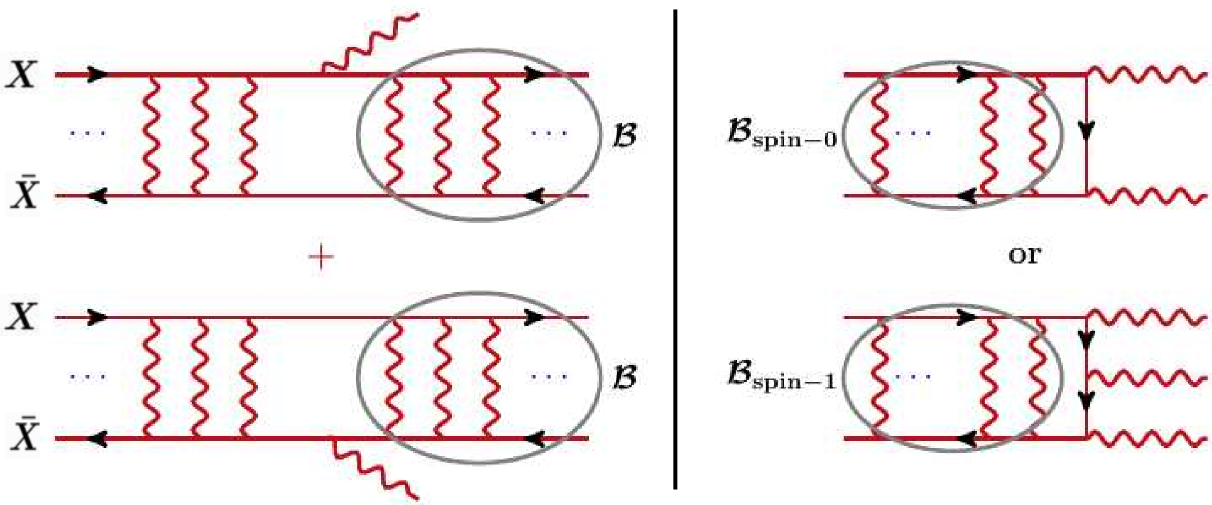
Direct annihilation

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

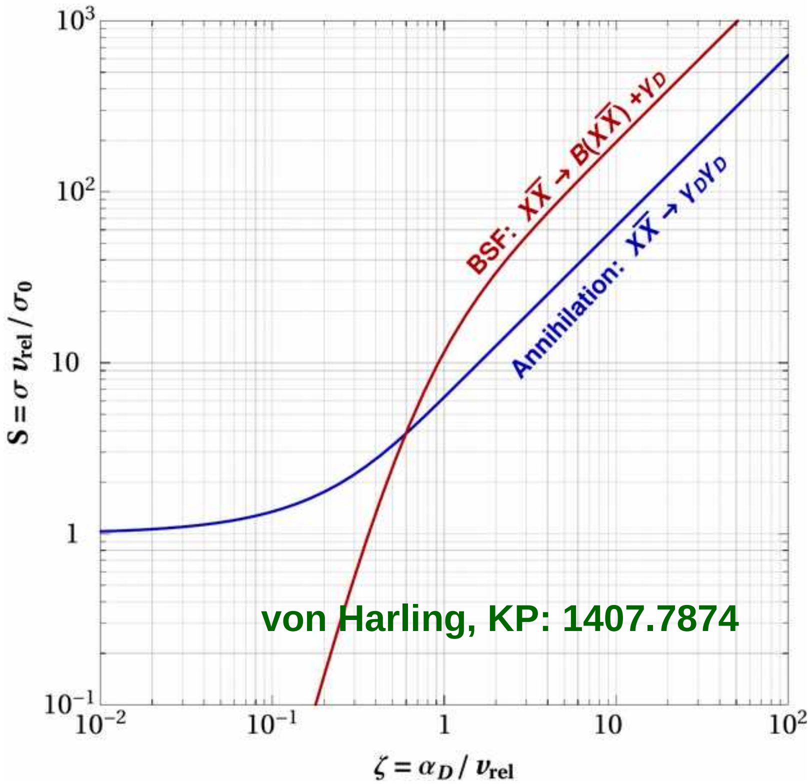


$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm ann}(\alpha_D / v_{\rm rel})$$

Bound-state formation and decay



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



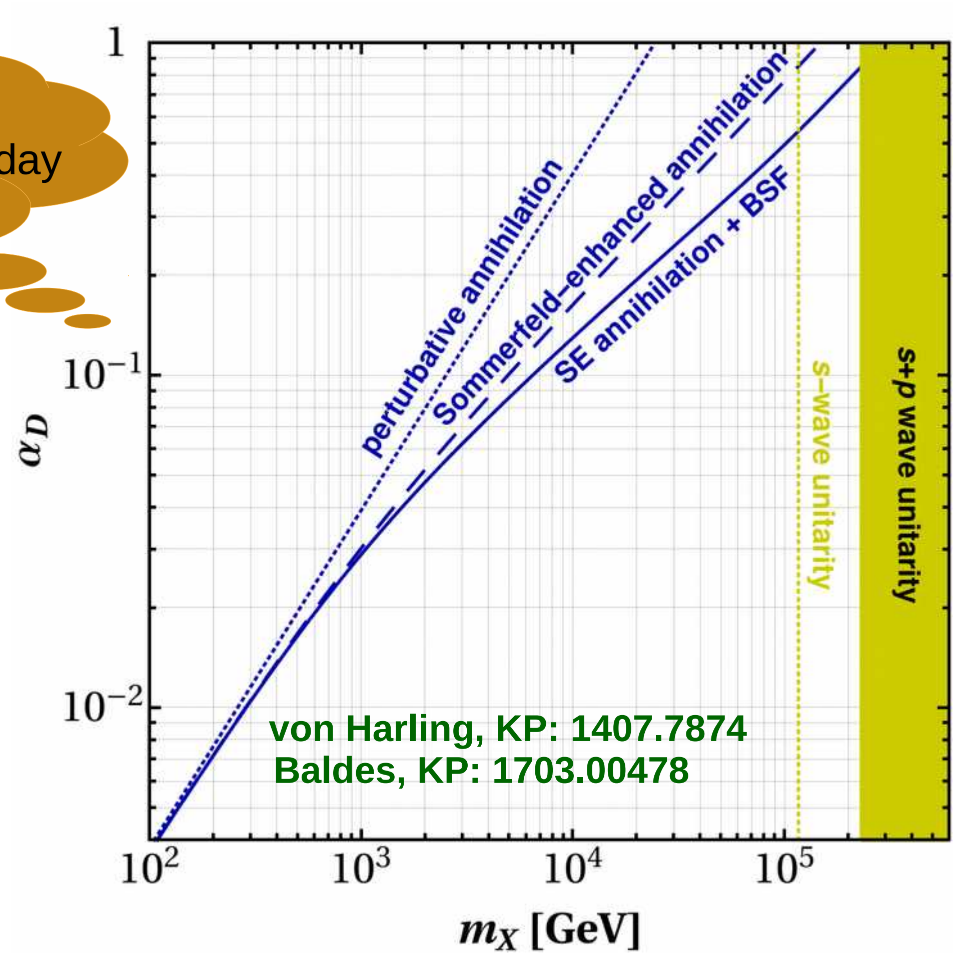
$$S_{\rm ann} \simeq \left(\frac{2\pi\zeta}{1-e^{-2\pi\zeta}}\right) \xrightarrow{\zeta \gtrsim 1} 2\pi\zeta$$

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

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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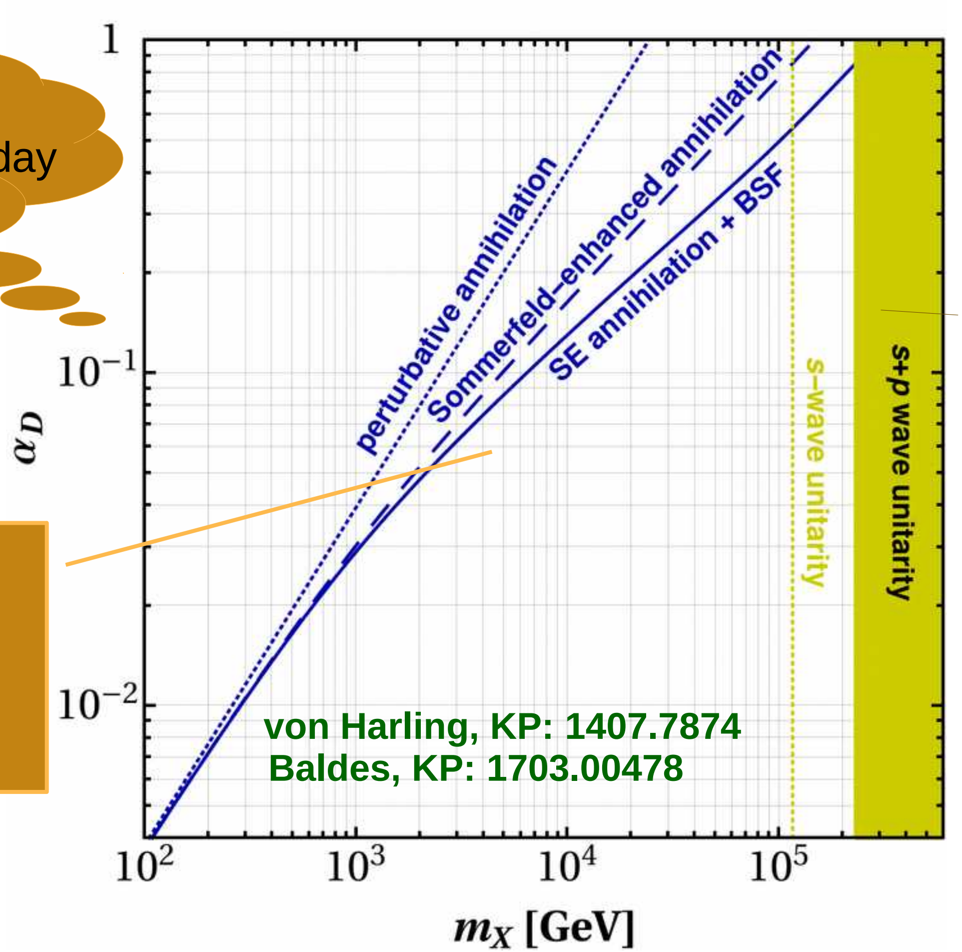


Long-range effects indeed become at $m_{DM} \gtrsim$ few TeV.

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!

Neutralino in SUSY models

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

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

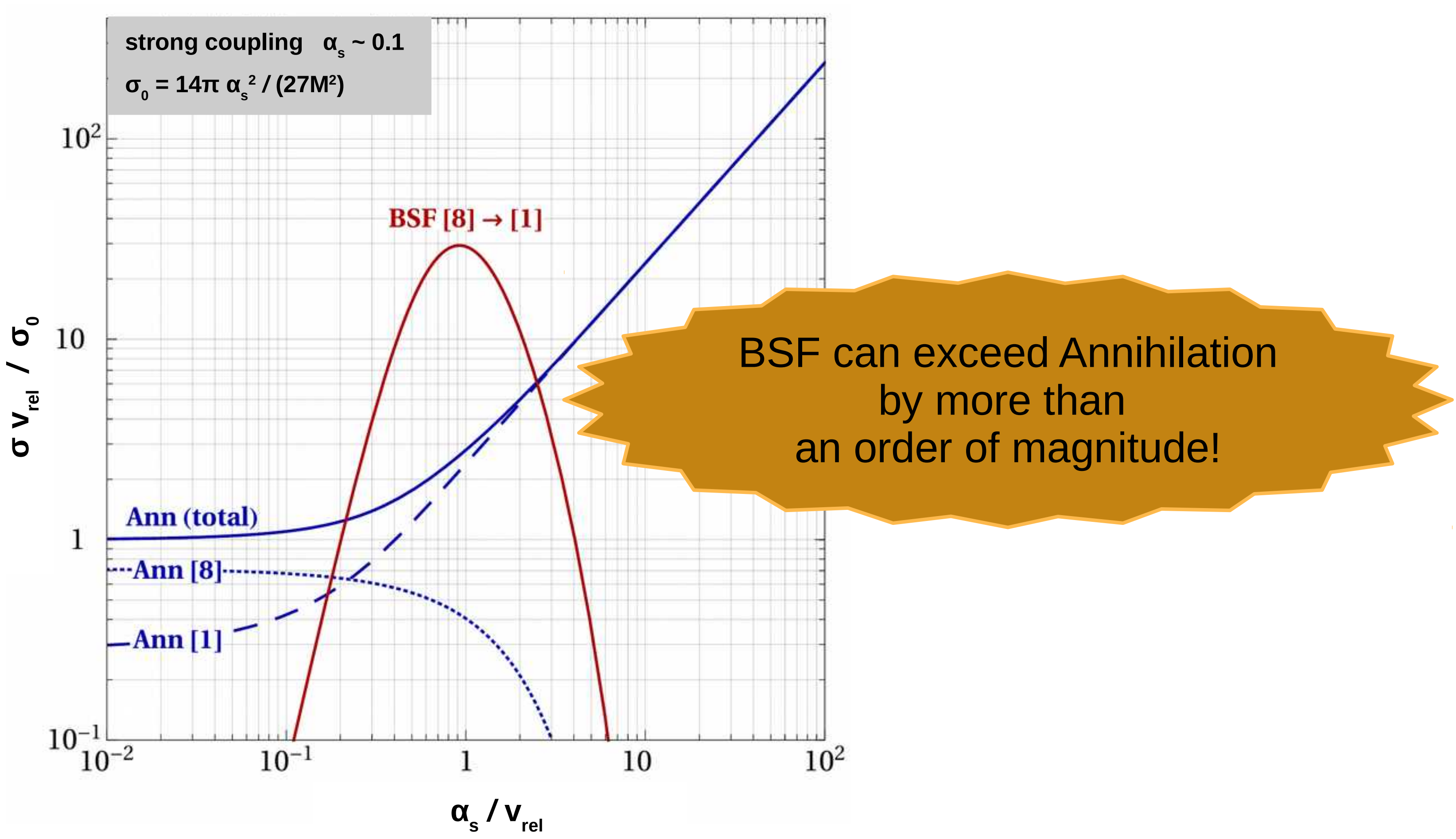
$$\sigma^{\rm eff}_{\rm ann} = [\, n^2_{\rm LSP}\, \sigma^{\rm LSP}_{\rm ann} + n^2_{\rm NLSP}\, \sigma^{\rm NLSP}_{\rm ann} + n_{\rm LSP}\, n_{\rm NLSP}\, \sigma^{\rm LSP-NLSP}_{\rm ann}\,]/n^2_{\rm tot}$$

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

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

Bound-state formation *vs* Annihilation



Harz, KP: 1805.01200

DM coannihilation with scalar colour triplet

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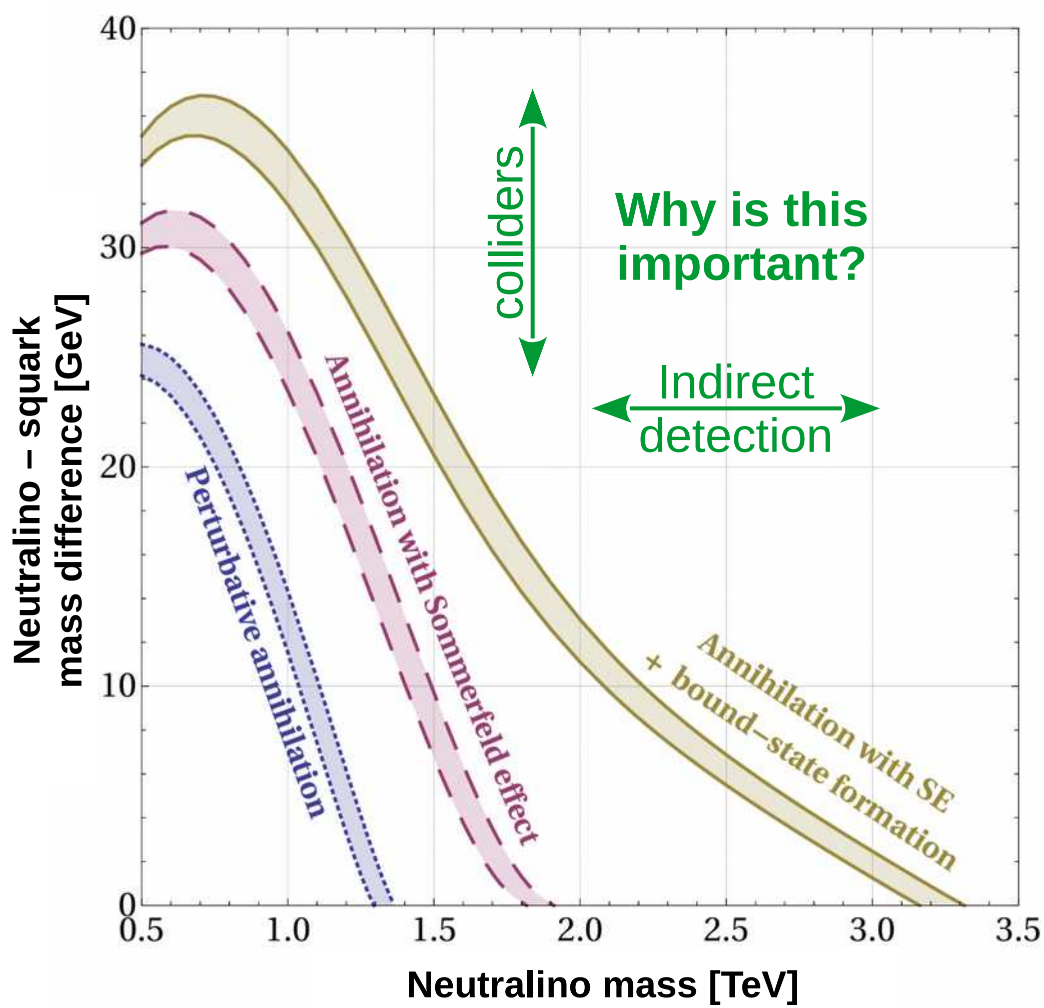


Effect on relic density: much much larger than obs uncertainty in Ω_{DM}

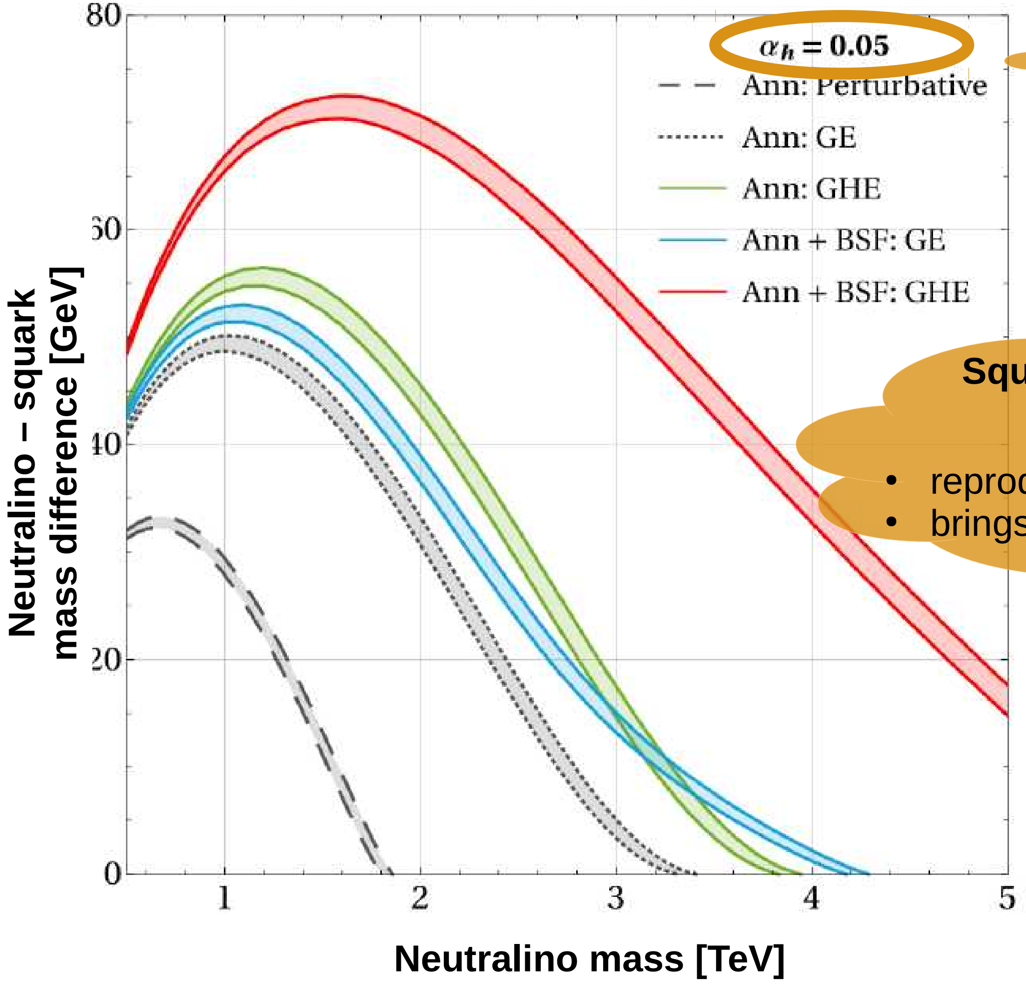
Not the final picture!

Harz, KP: 1805.01200

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

Not the final picture!

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**

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 WIMP models with coupling to the Higgs

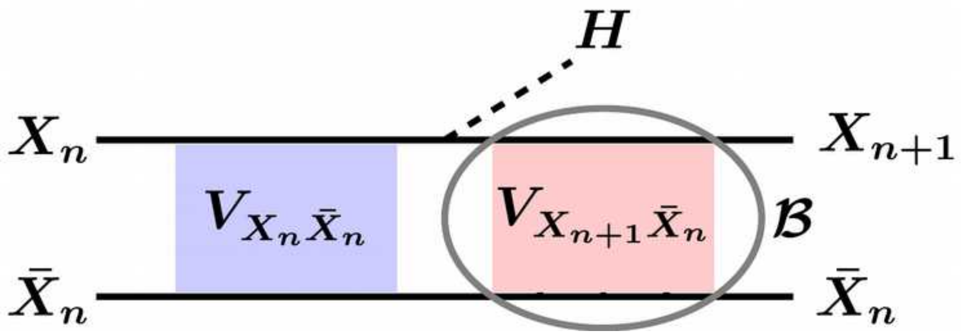
In some prototypical WIMP models,
DM is the lightest linear combination of the neutral components of
SU(2) multiplets that couple to the Higgs

$$\delta\mathcal{L} \supset -y\bar{X}_n H X_{n+1} + \text{h.c.}$$

Includes many SUSY scenarios,
e.g. Wino-Higgsino, coloured coannihition

If m > 5 TeV, DM freeze-out begins before electroweak phase transition.

⇒ Bound-state formation via Higgs-doublet emission!



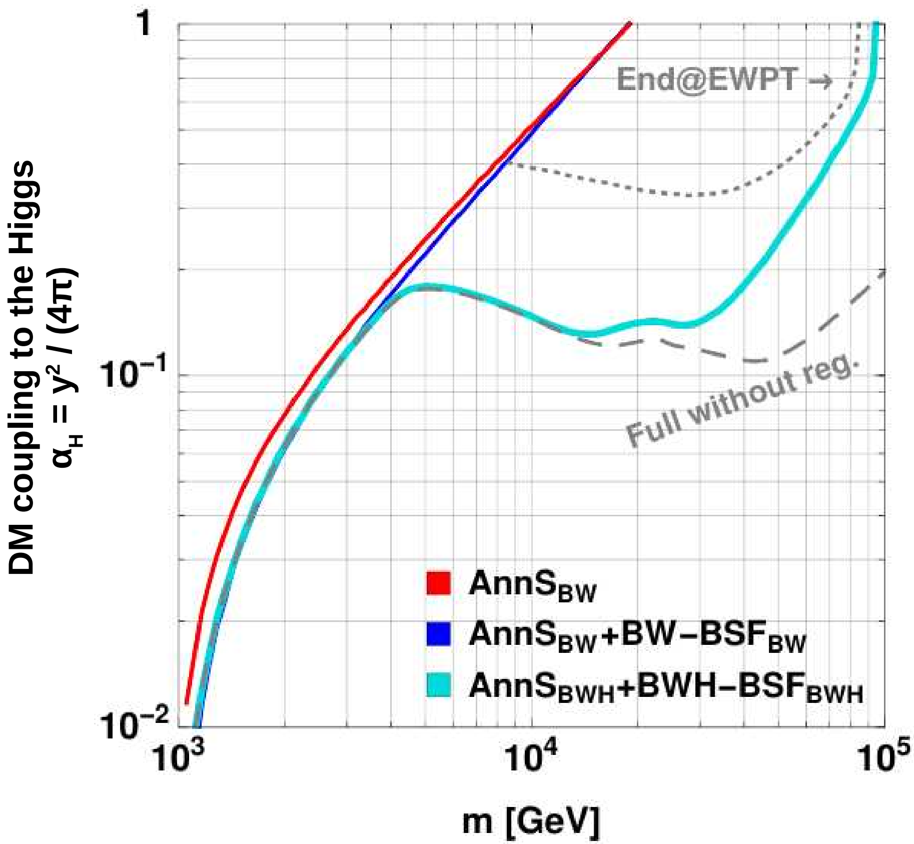
Change in potential
⇒ monopole transition!

Renormalisable WIMP models with coupling to the Higgs

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} > 5TeV



Huge effect!

~ 10^2 in relic density!

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

Oncala, KP: 2101.08666/7

Many studies of bound-state effects on DM freeze-out

In this conference

- **“Closing the window on WIMP dark matter models”**, Salvatore BOTTARO (Monday 30/05)
- **“Sommerfeld Effect and Bound State Formation in Simplified Dark Matter Models”**, Emanuele COPELLO (Wednesday 01/06)

Is it random that non-perturbative effects arise
in all these models at multi-TeV?

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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to understand and *predict* it?

If so, what else can we learn from it?

Think
good old
unitarity

Partial-wave unitarity limit

$$S^\dagger S = 1 \quad \xrightarrow{S=1+iT} \quad -i(T - T^\dagger) = T^\dagger T$$

Project on a partial wave and
insert complete set of states on RHS

$$\Downarrow$$

$$\sigma^{(\ell)}_{\rm inel} \leqslant \frac{\pi(2\ell+1)}{k^2_{\rm cm}} \quad \xrightarrow{\rm non-rel} \quad \frac{\pi(2\ell+1)}{\mu^2 v^2_{\rm rel}} \quad \xrightarrow{\mu=M_{\rm DM}/2} \quad \frac{4\pi(2\ell+1)}{M^2_{\rm DM} v^2_{\rm rel}}$$

[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, $\sigma v_{\rm rel}$ = constant
- Considers only s-wave annihilation

Partial-wave unitarity limit

in non-relativistic regime

What interactions can realise the unitarity limit?

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

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} ≳ 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 / realised 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.
  - 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 to the thermal-relic scenario...**