Dark matter bound states

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CosmoChart

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Frontiers in dark matter

(simplistic description)

- **Heavy DM**

  Particles with **m $\gtrsim$ TeV** coupled to the Standard Model 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

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- **Light DM**

  Partic…
  interact…

  → developme… …ments

- 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?

Long-range interactions

If dark matter is very heavy, then in many scenarios:

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

μ: reduced mass $(m_{\rm DM}/2)$

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Relevant for various models

- Self-interacting DM
- WIMP DM with m_{DM} > few TeV. [Hisano et al. 2002]
- WIMP DM with m_{DM} < TeV,
  in scenarios of DM co-annihilation with coloured partners.

Implications of long-range interactions

Sommerfeld effect

distortion of wavefunctions ⇒
affects all cross-sections, incl. annihilation

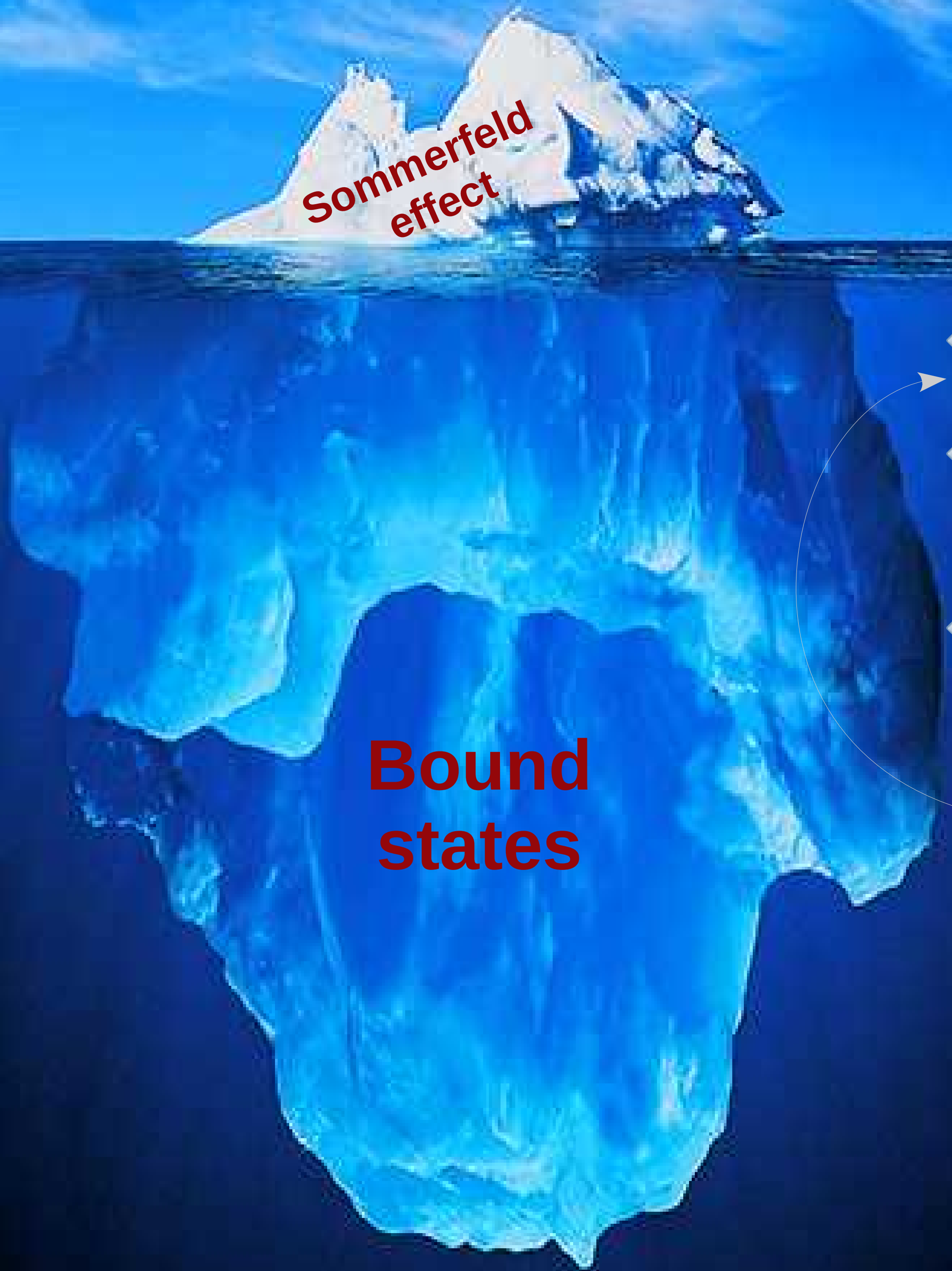
- Freeze-out ⇒ alters mass – coupling correlation
- Indirect detection signals

Bound states

- **Unstable bound states ⇒ extra annihilation channel**
  - **Freeze-out**
  - Indirect detection
  - Novel low-energy indirect detection signals
- **Stable bound states (particularly important for asymmetric DM)**
  - Novel low-energy indirect detection signals
  - Affect DM self-interactions (screening)
  - Inelastic scattering in direct detection experiments (?)

Outline

Bound states and thermal-relic dark matter

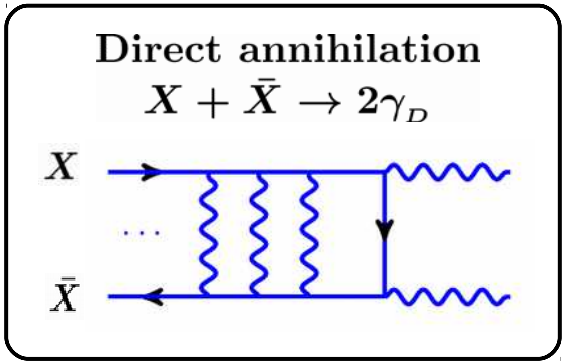


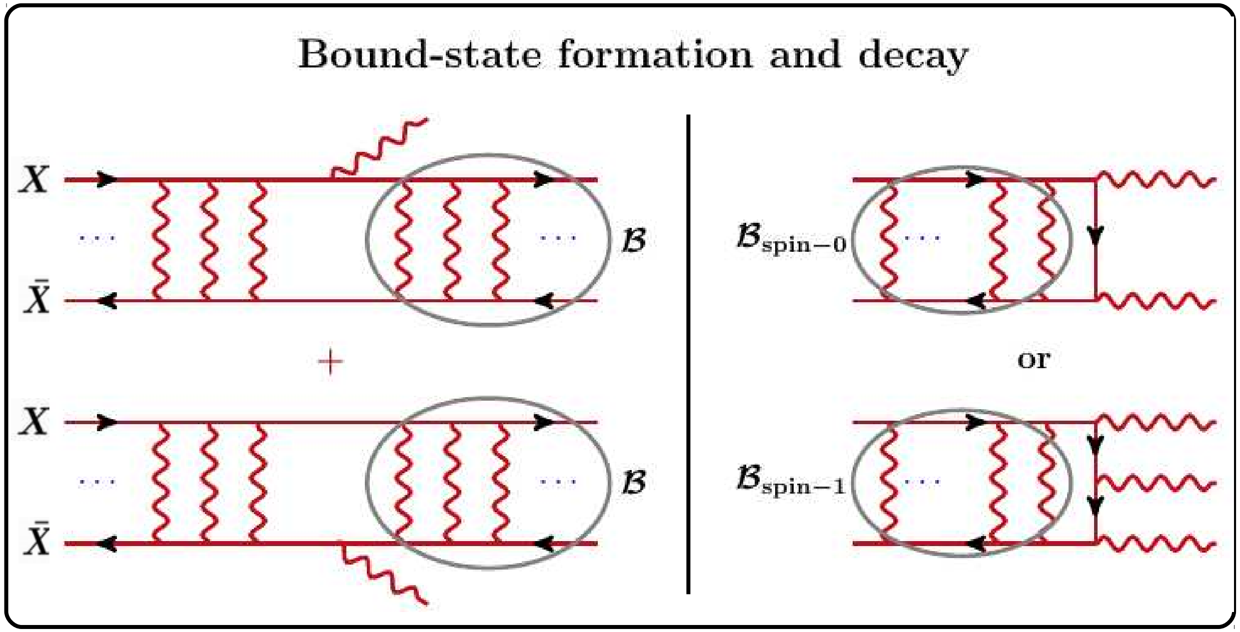
- Abelian: dark U(1) sector
- Non-Abelian: neutralino-squark coannihilation
- The Higgs*!*
- Unitarity limit and long-range interactions

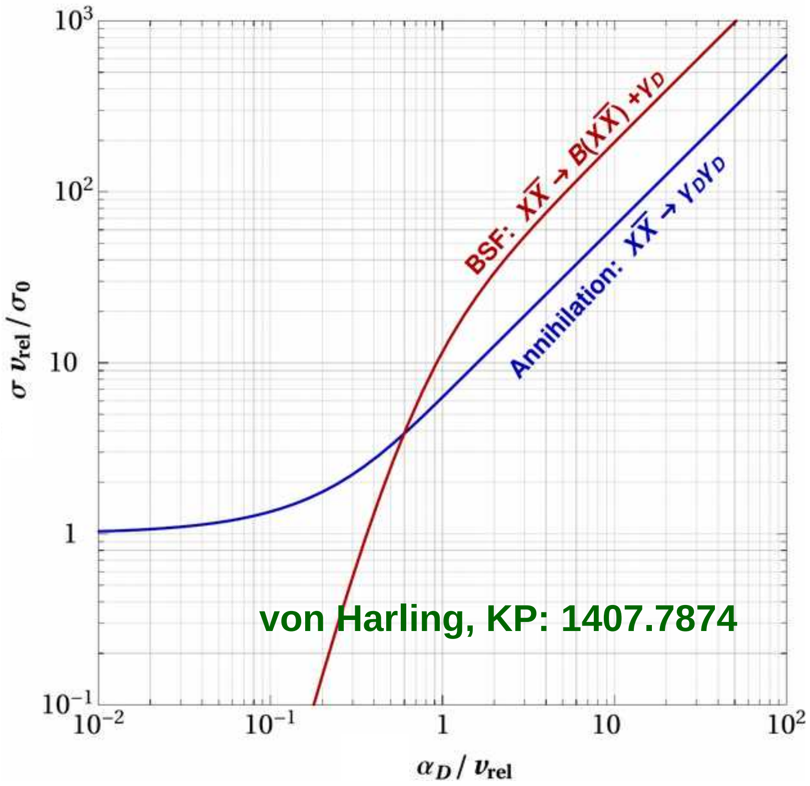
Dark U(1) sector

Thermal freeze-out with long-range interactions

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



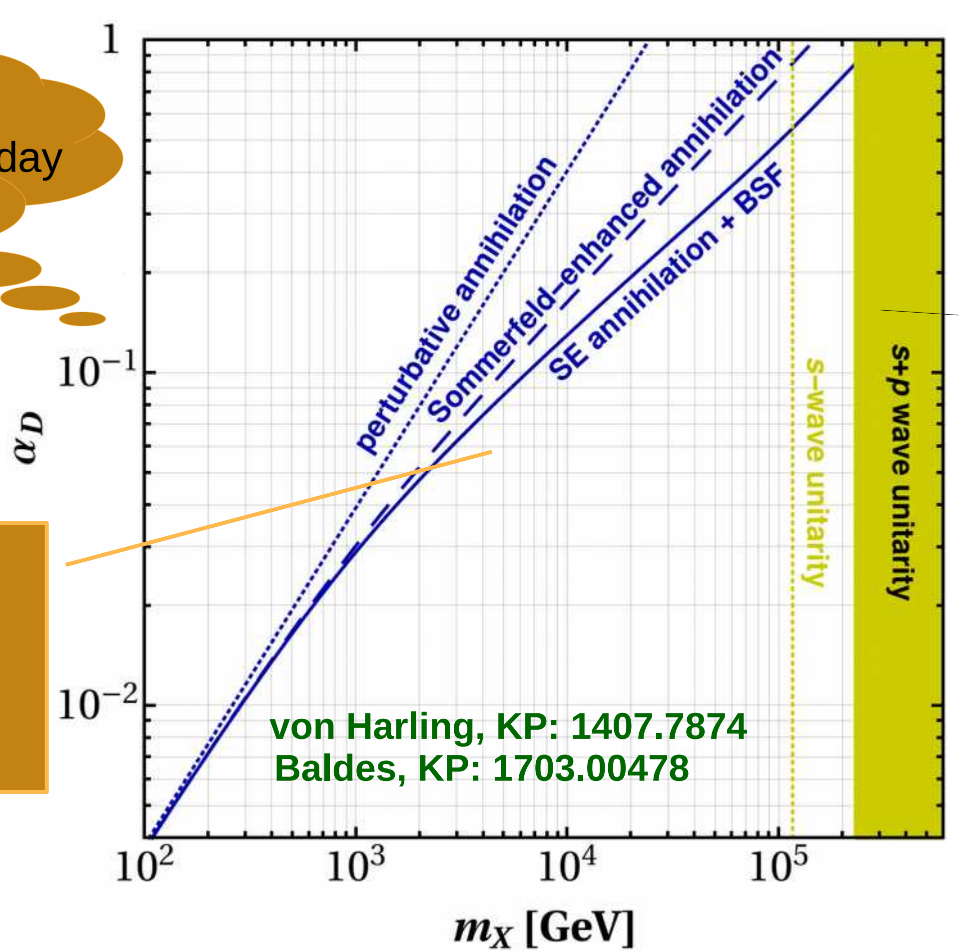




Thermal freeze-out with long-range interactions

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

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



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!

Unitarity limit and long-range interactions

Partial-wave unitarity limit

in non-relativistic regime

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

Implies upper bound on the mass of thermal-relic DM

Griest, Kamionkowski (1990)

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

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

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

- 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?

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

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.**

- **Thermal relic DM can be much heavier than anticipated**
  - **In viable thermal scenarios, expect long-range behavior at $m_{DM} \gtrsim$ few TeV!**

Baldes, KP: 1703.00478

Neutralino-squark co-annihilation scenarios

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

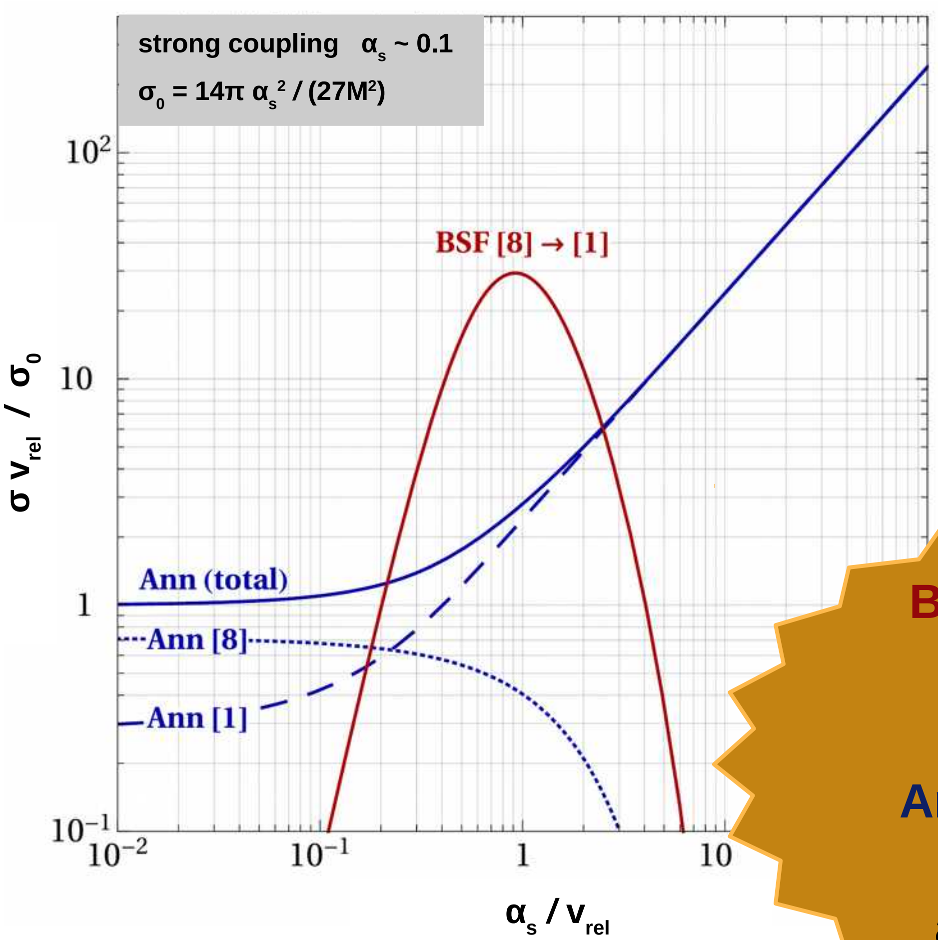
$$n_{\rm tot} = n_{\rm LSP} + n_{\rm NLSP}$$

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

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 via gluon emission

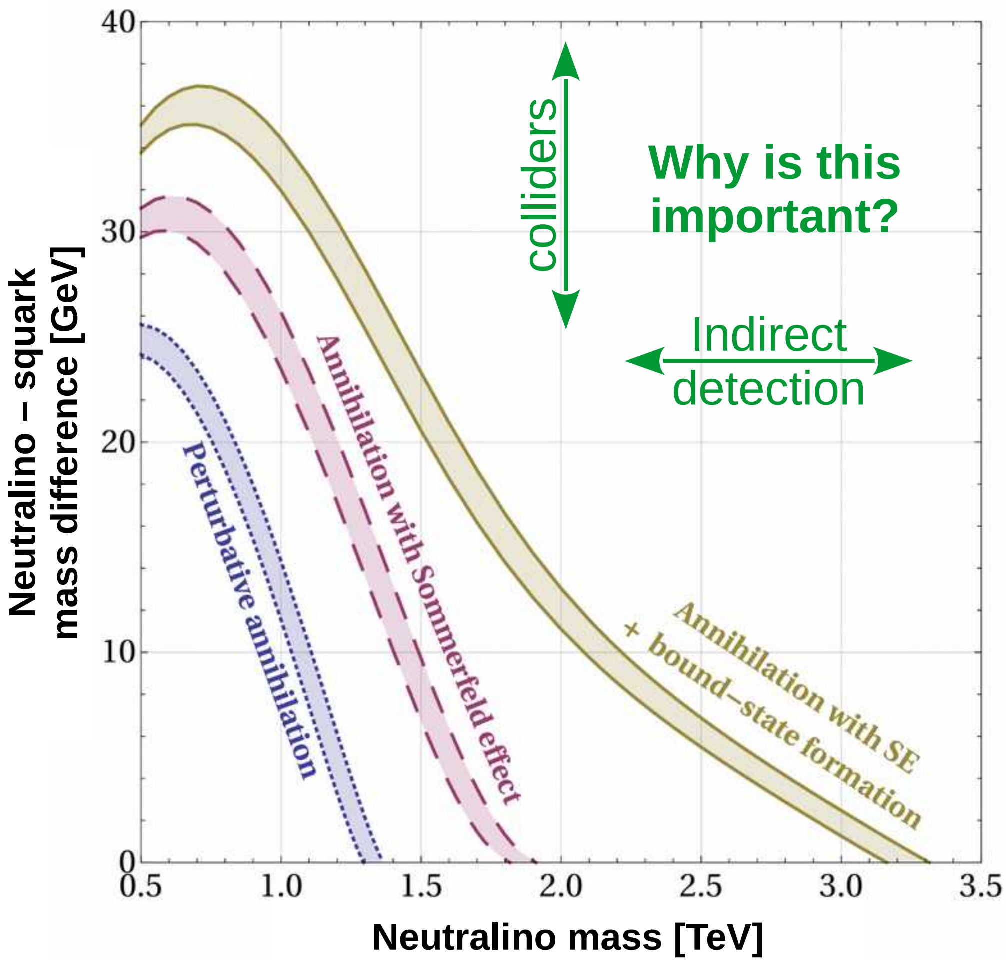
can exceed

Annihilation into gluons

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}

Harz, KP: 1805.01200

The Higgs doublet as a light mediator

The Higgs as a light mediator

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

Higgs enhancement and relic density

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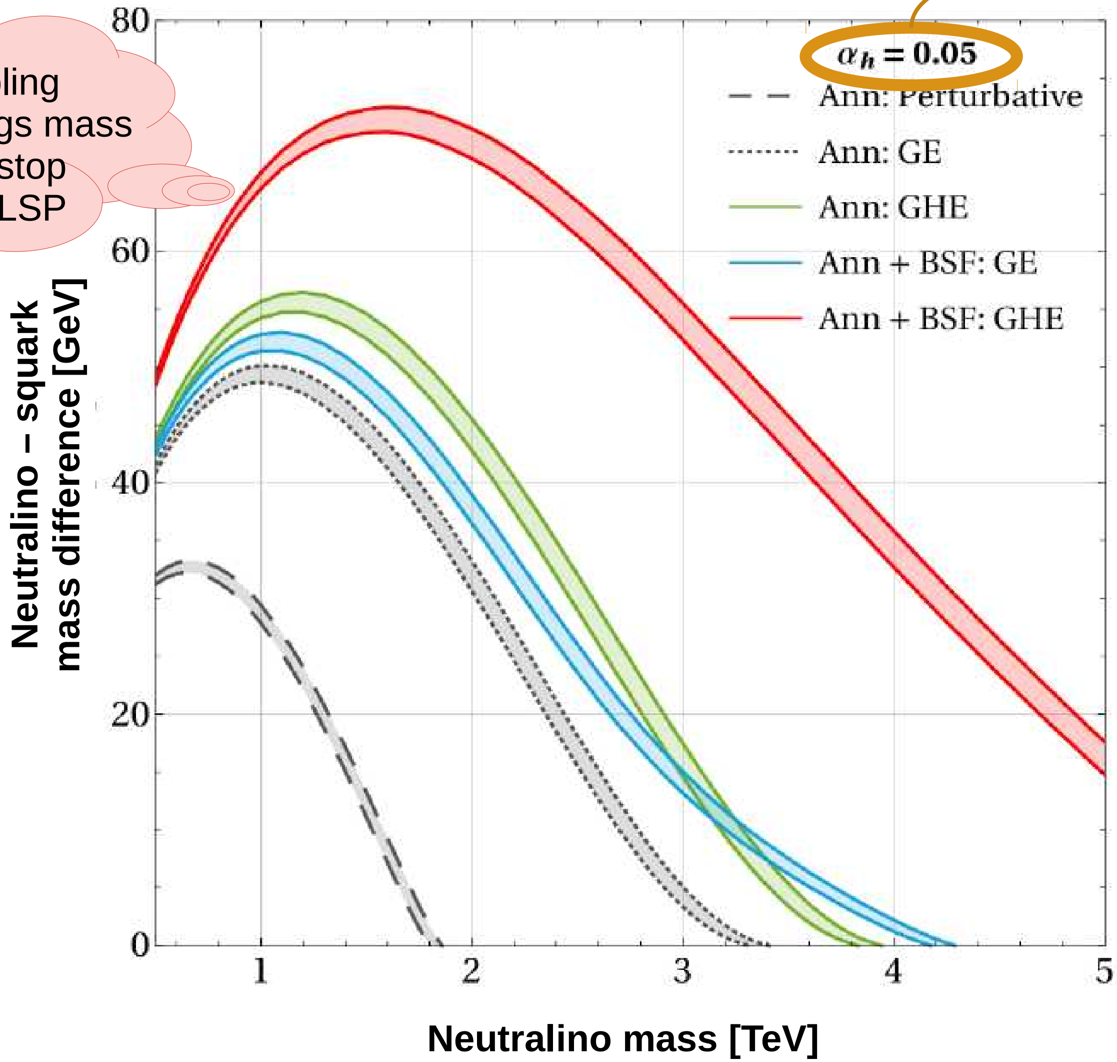
Large stop-Higgs coupling reproduces measured Higgs mass and brings the lightest stop close in mass with the LSP



Squark-antisquark-Higgs coupling

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

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: 2101.08666/7

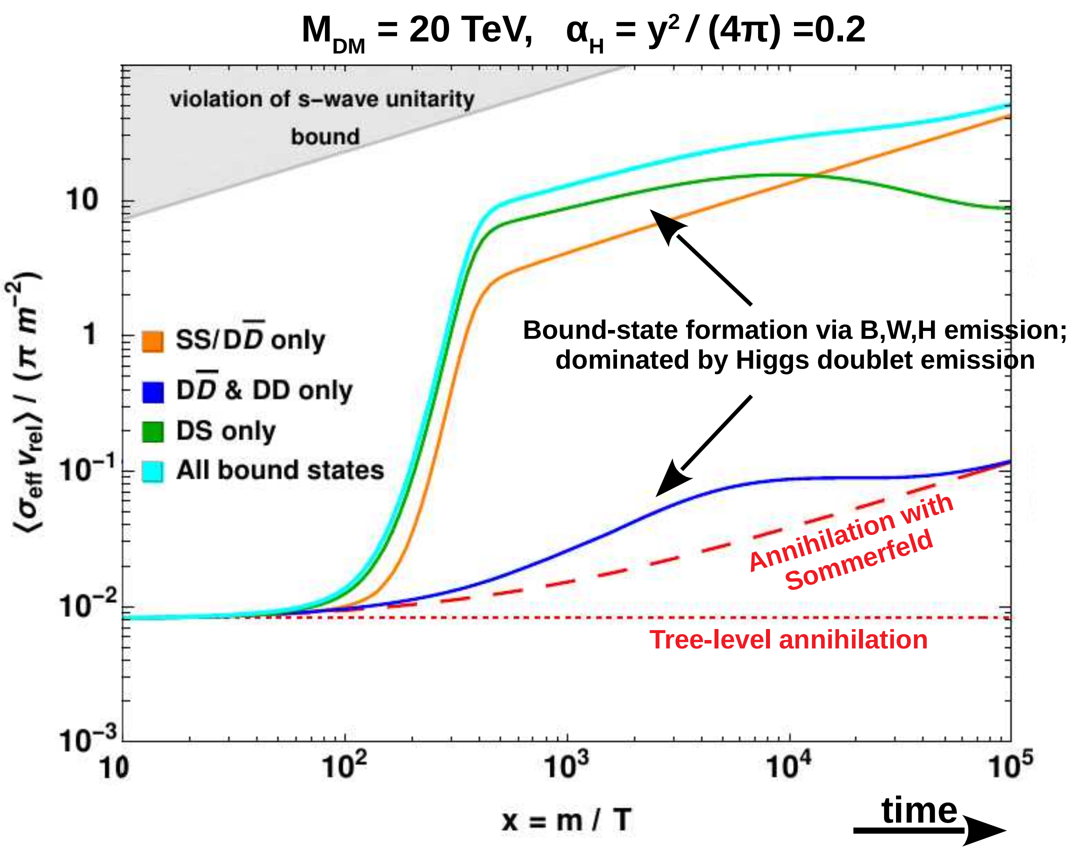
Sudden change in effective Hamiltonian precipitates transitions.
Akin to atomic transitions precipitated by β decay of nucleus.

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} > 5TeV



Oncala, KP: 2101.08666/7

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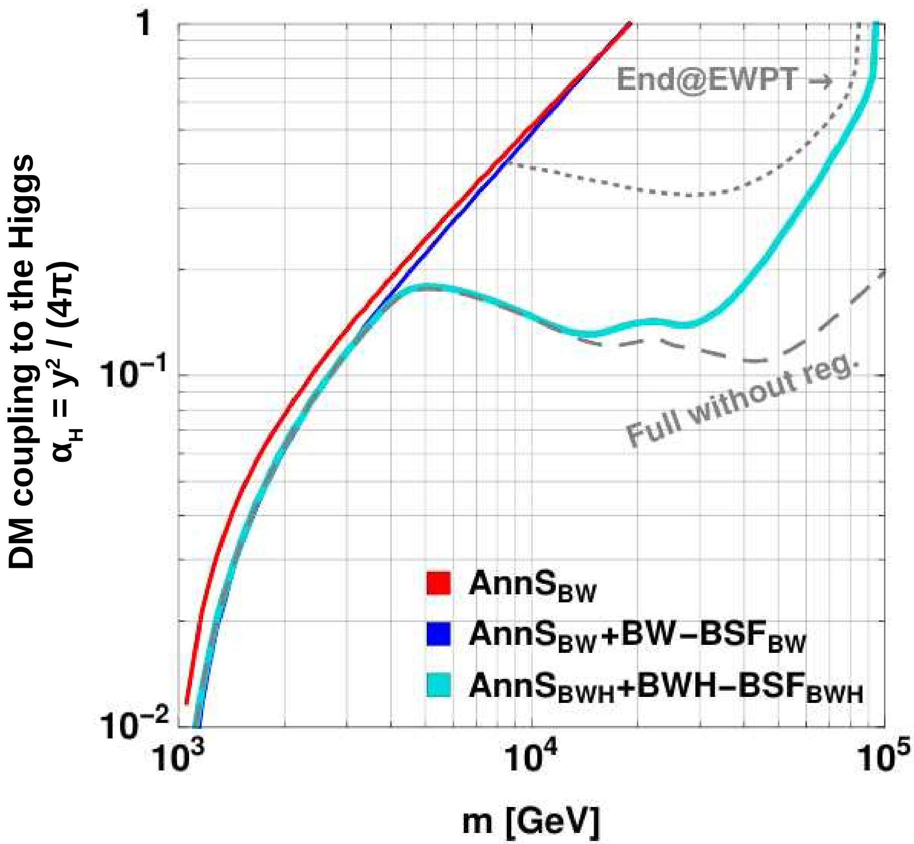

Huge effect!

~ 10^2 in relic density!

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

Oncala, KP: 2101.08666/7

Conclusion

Bound states indicate the onset of a new type of inelasticity

- **Non-relativistic unitarity limit ↔ long-range interactions**
  ⇒ bound states play very important role! **Baldes, KP: 1703.00478**

- **Complete reconsideration of DM thermal decoupling at $m_{DM} \gtrsim$ TeV.**
  Essentially no unitarity limit on mass of thermal relic DM!

- **Important experimental implications for dark matter:**
  - 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