# Dark matter bound states

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# Dark matter production in the early universe

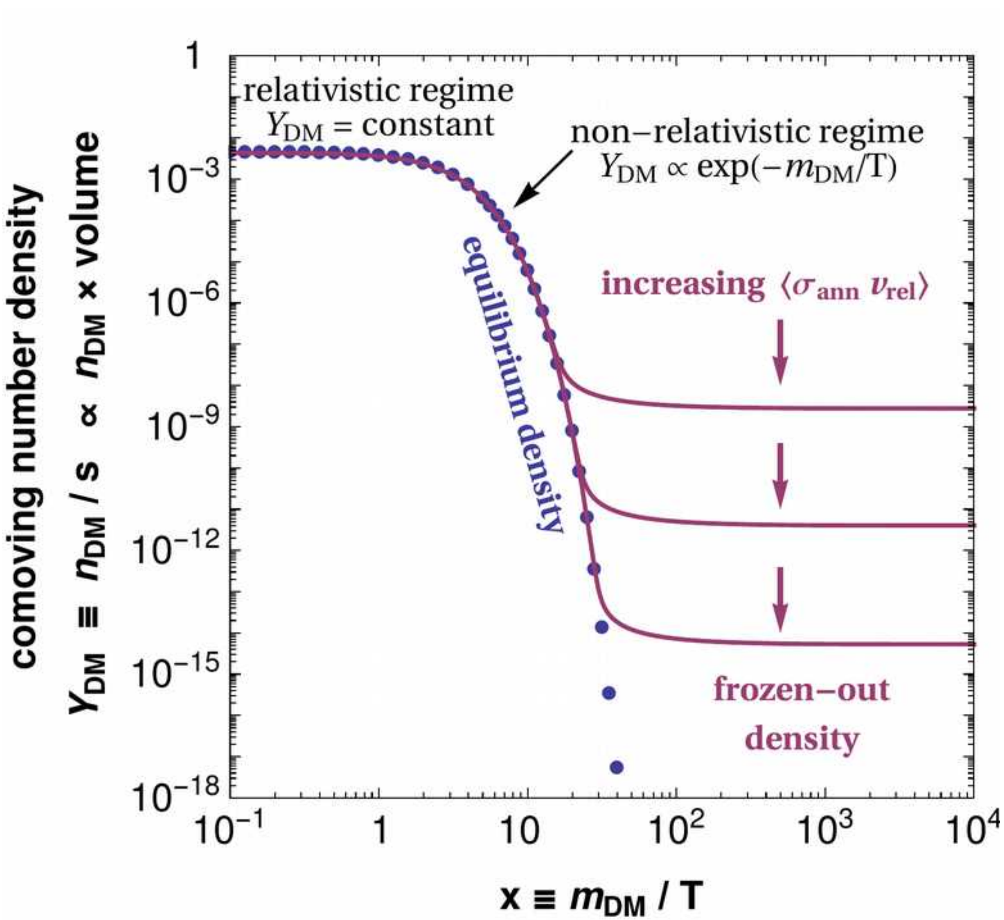
Why do we care?

Production depends on

the couplings of DM to other particles,

which are the very probes of the DM properties

# 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 ~ $\sigma_{Weak}$**
**WIMP miracle!**

# WIMPs and variations

**W**eakly coupled to SM
via $W^{\pm}$, Z, H
e.g. LSP in SUSY

or

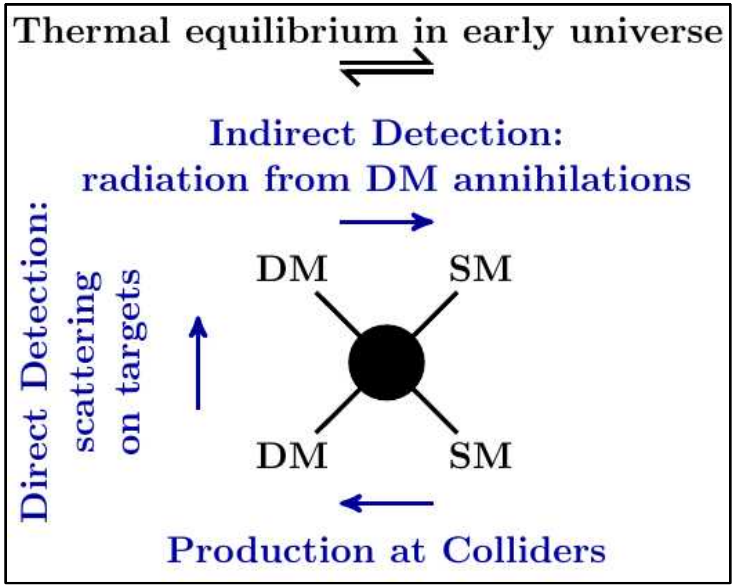
weakly coupled to SM
via non-SM interactions,

$$e.g.\ \delta L = \frac{\bar{X}\gamma^{\mu}X\ \bar{q}\gamma_{\mu}q}{\Lambda^2}$$

or

weakly coupled to light dark-sector
particles that couple (feebly) to SM,

e.g. DM coupled to dark photon
kinetically mixed with Hypercharge




Significant constraints.

No discovery so far.

# What now?

**Diversify dark matter searches**

- **Heavier 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

- **Lighter 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

# Wh

- 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 ($\gtrsim$ TeV) thermal-relic DM?**

- **Heavier D**

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# Long-range interactions

**If dark matter is very heavy, then:**

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

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

# Long-range interactions

**If dark matter is very heavy, then:**

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

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

**Relevant for various models**

- Self-interacting DM
- DM explanations of astrophysical anomalies, e.g. galactic positrons, IceCube PeV neutrinos

- 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

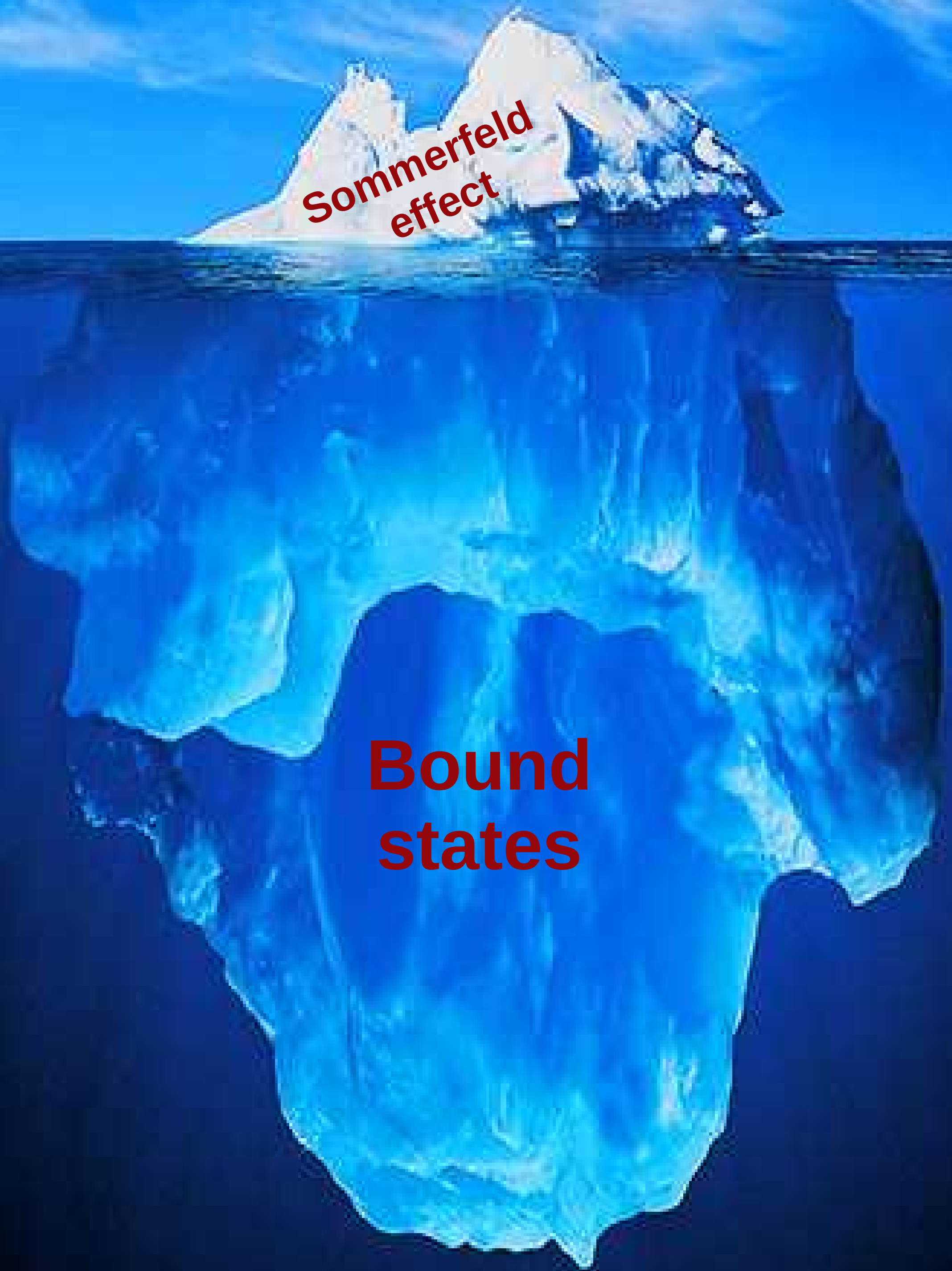
**Sommerfeld effect**

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

- Freeze-out ⇒ changes correlation of parameters (mass – couplings)
- 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

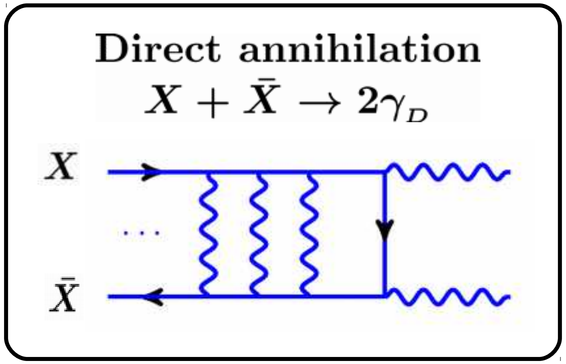
## Bound states and density of thermal relic DM

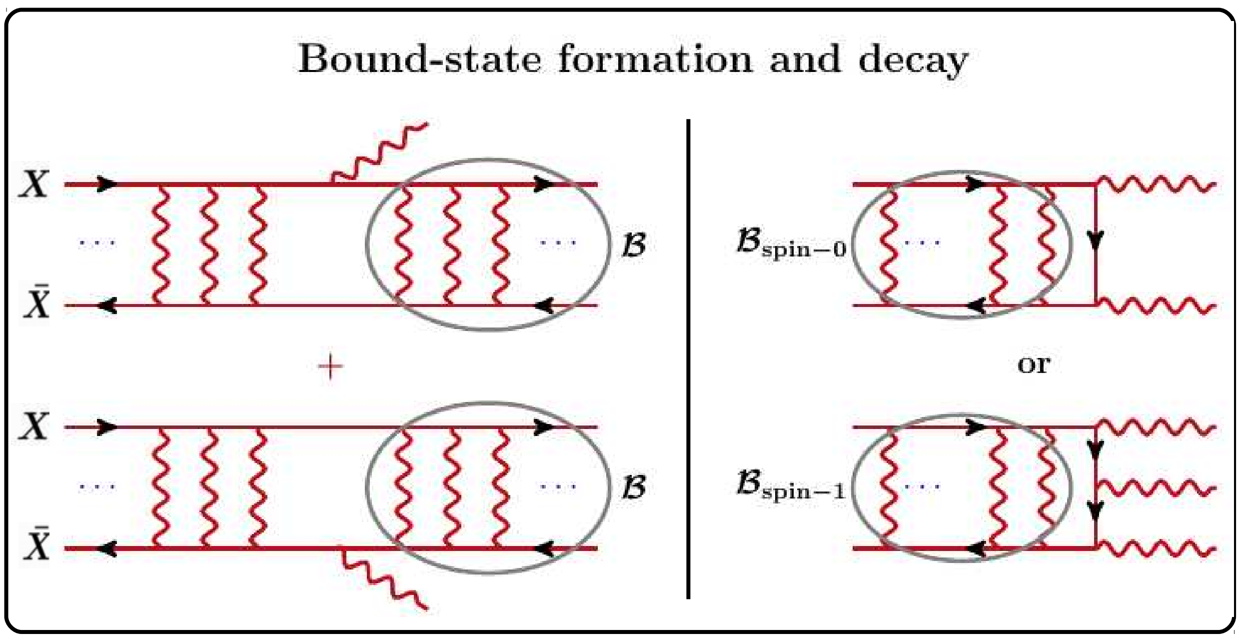
- Dark U(1) sector
- Unitarity limit and long-range interactions
- Neutralino-squark coannihilation scenarios
- The Higgs-doublet as a light mediator

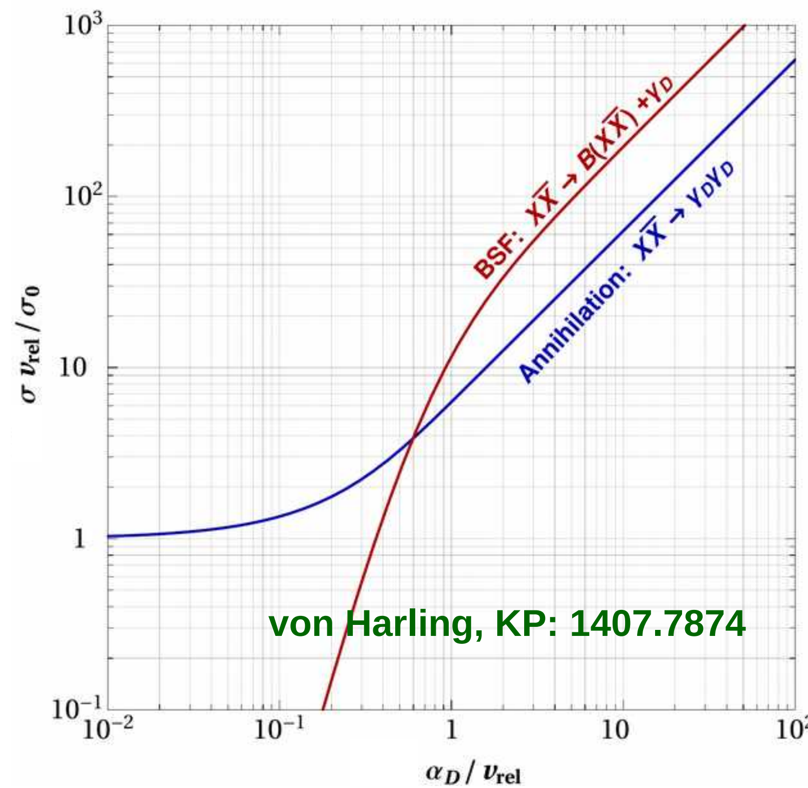
# Dark U(1) sector

# Thermal freeze-out with long-range interactions

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



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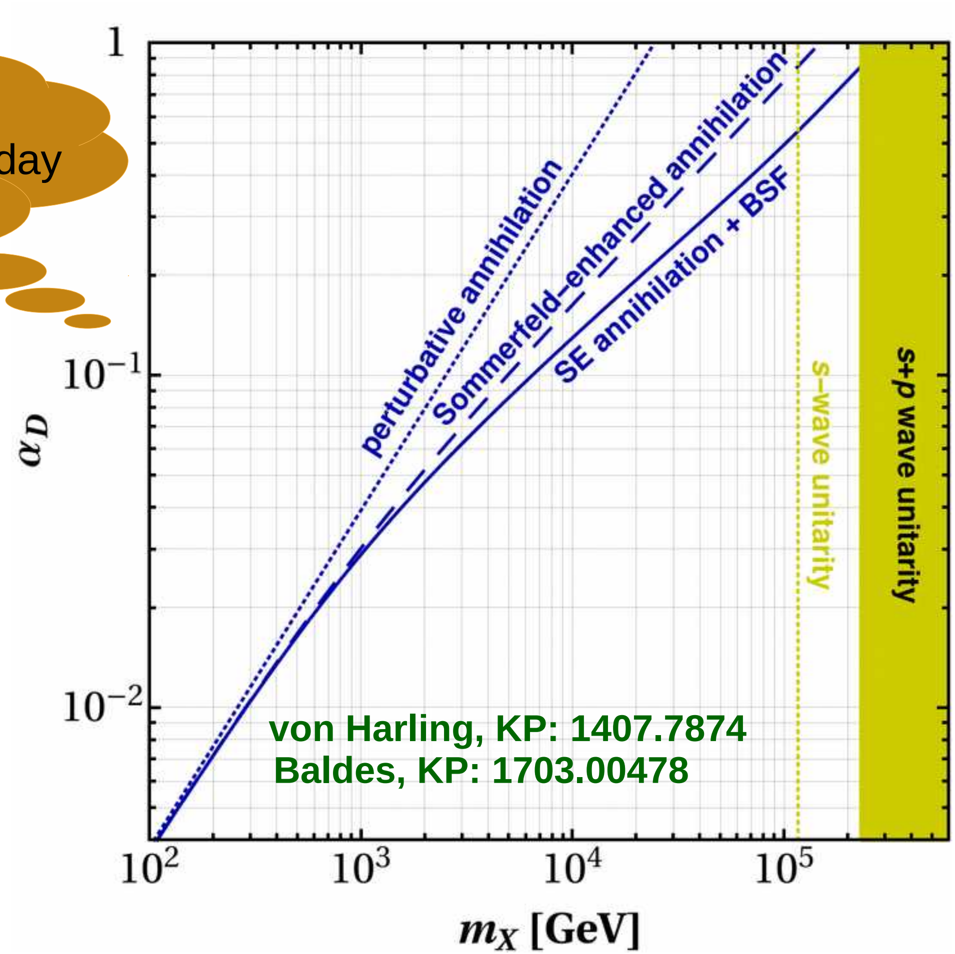
Important because it determines DM interactions today (direct, indirect detection)



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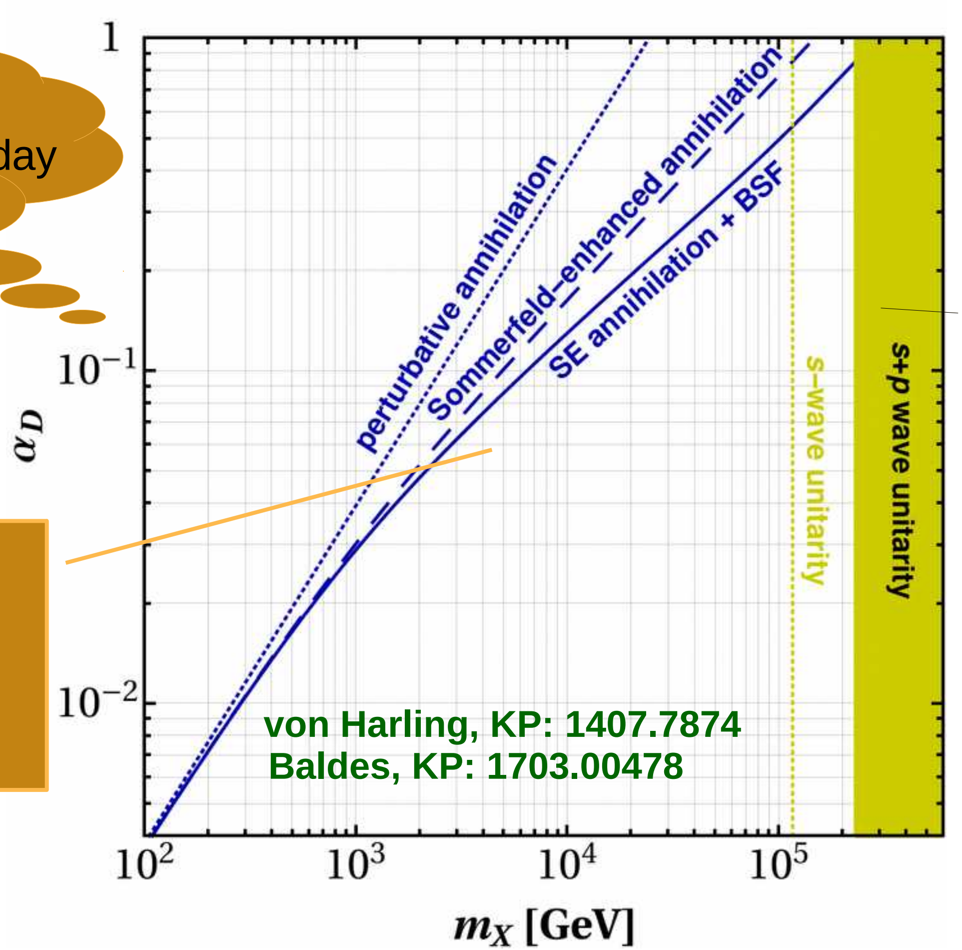



Long-range effects indeed become at $m_{DM} \gtrsim$ few TeV.

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!**

## Unitarity limit and long-range interactions

# Partial-wave unitarity limit

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

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

# Partial-wave 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 implies that $\sigma_{uni}$ can be approached / attained only by long-range interactions.

Long-range interactions imply bound states, which may form by higher partial waves

- Upper limit on mass of thermal relic DM higher
  - **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

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

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

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

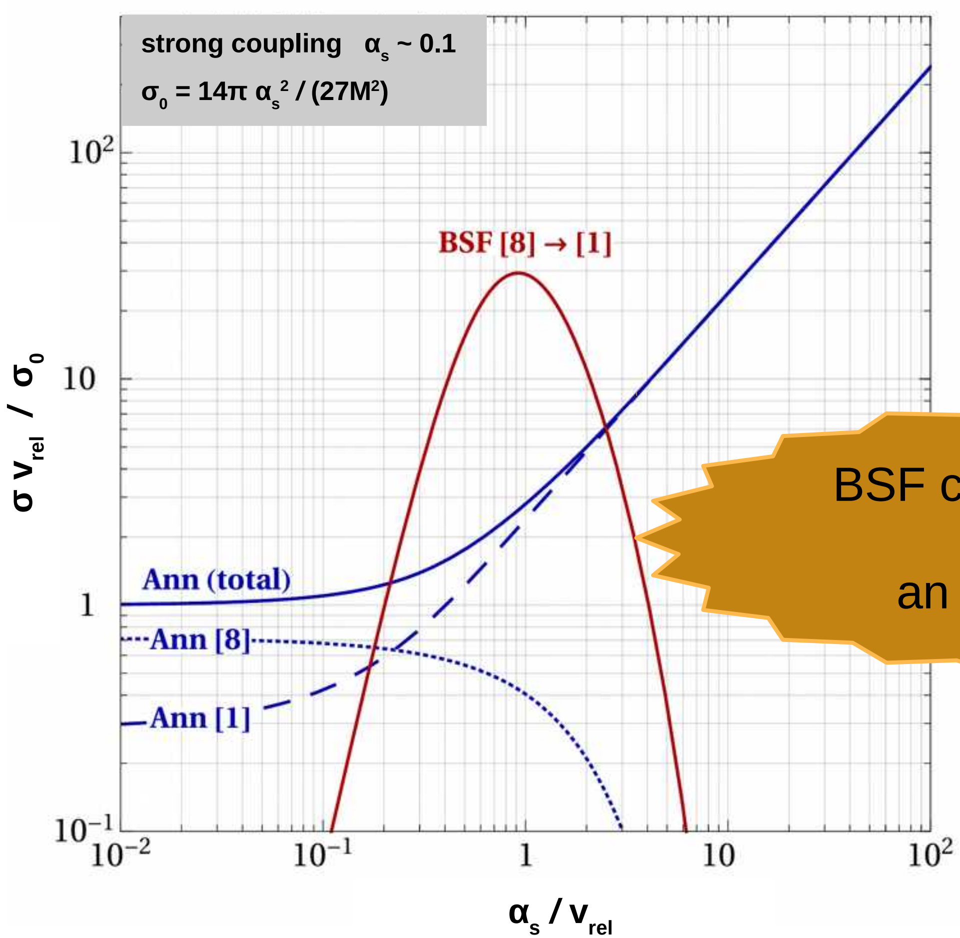
# DM coannihilation with scalar colour triplet

## MSSM-inspired toy model

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

# DM coannihilation with scalar colour triplet
## MSSM-inspired toy model

Bound-state formation *vs* Annihilation




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

Harz, KP: 1805.01200

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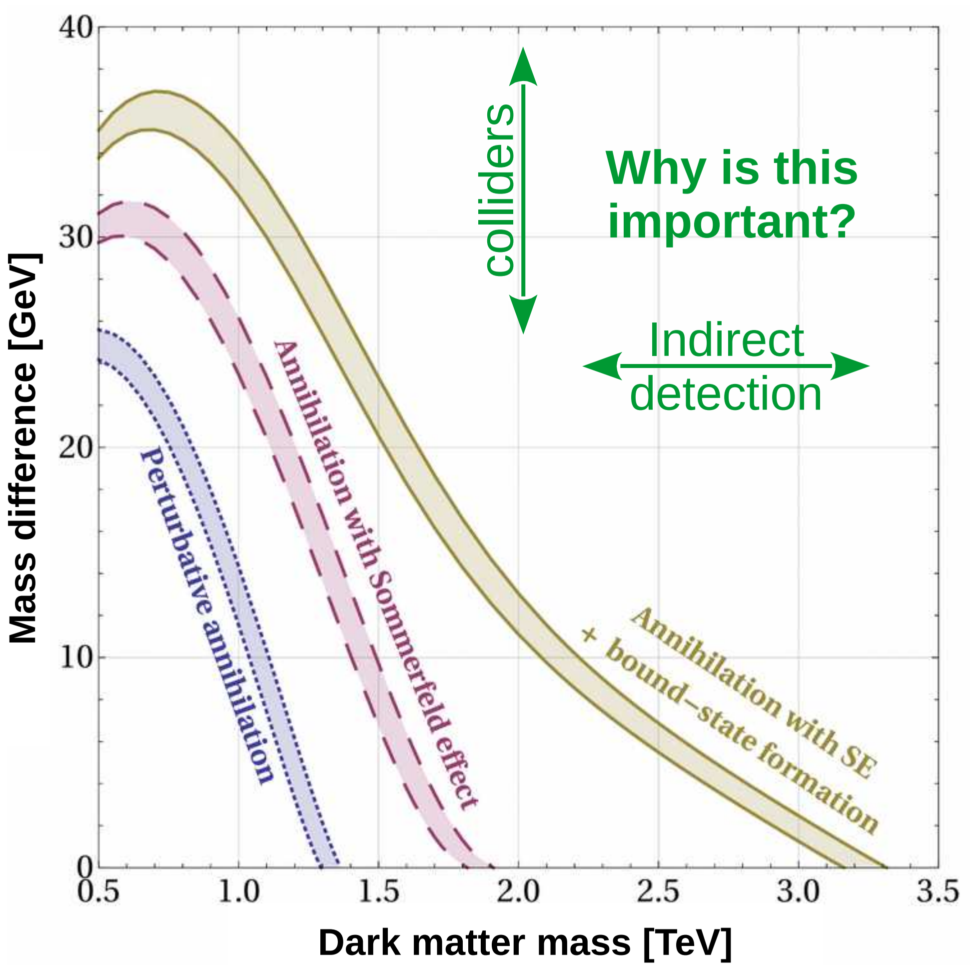



Effect on relic density: much much larger than obs uncertainty in $\Omega_{DM}$

**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

- 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 !

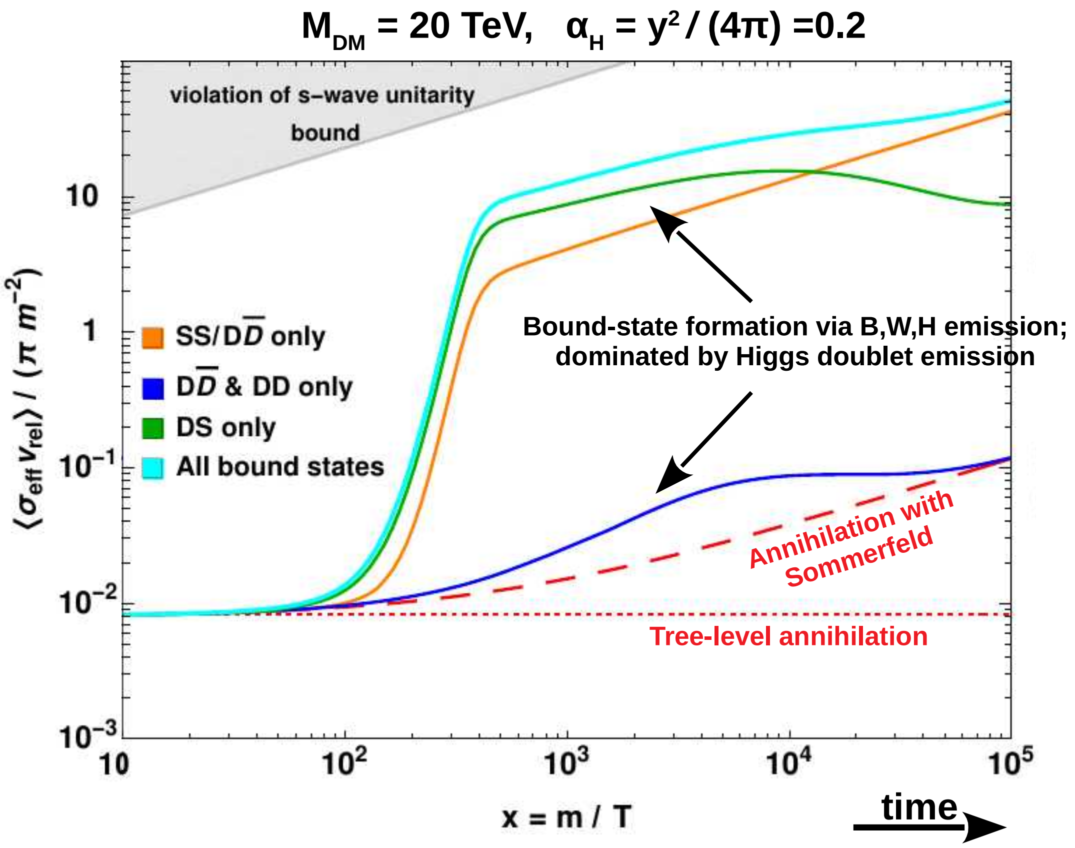
Ko,Matsui,Tang:1910:04311
Oncala, KP: 1911.02605
Oncala, KP: 2101.08666/7

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

# Renormalisable Higgs-portal WIMP models

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

*D* & *S* co-annihilate; freeze-out begins before the EWPT if $M_{DM}$ > 5TeV

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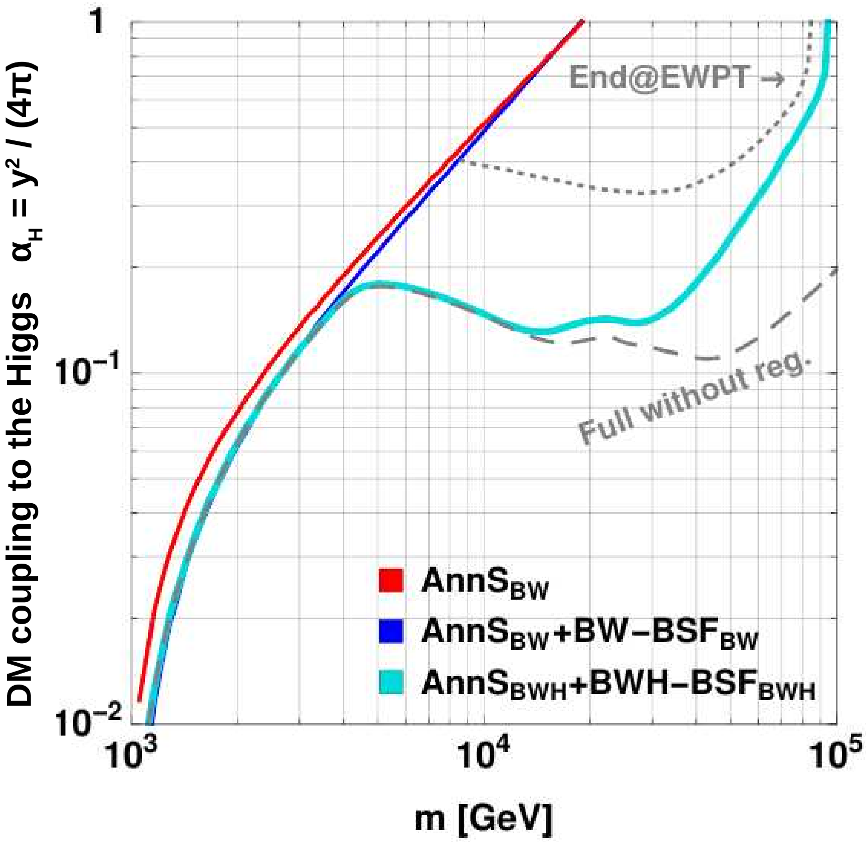


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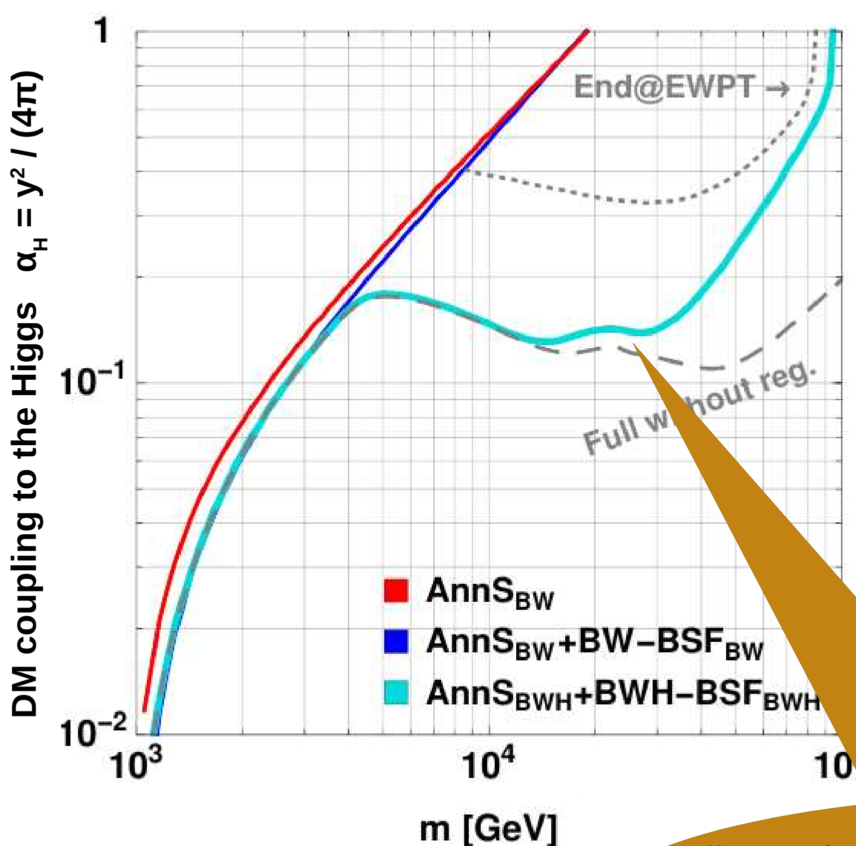


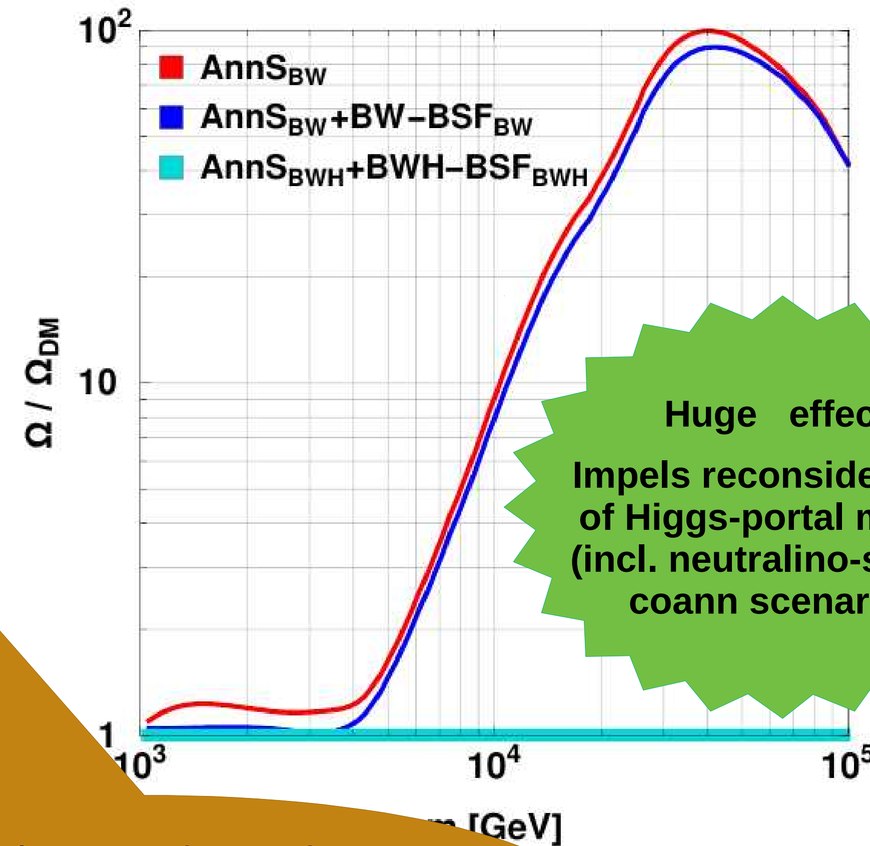


**Huge effect!**

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

Effect only at large $\alpha_H$, due to phase-space suppression in Higgs emission.

For higher multiplets, important effect expected also at lower $\alpha_H$.

**Oncala, KP: 2101.08666/7**

# Conclusion

- **Bound states impel complete reconsideration of thermal decoupling at / above the TeV scale.**

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

- **Important 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