# Dark matter going nuclear: light force mediators and bound states

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# What do we think about when we think about dark matter?

## Interaction with the SM

| **Portal operators** | **SM interactions** | **Heavy mediators** |
|---|---|---|
| $\epsilon F^{\mu\nu}_{Y} F_{D\,\mu\nu}$<br>$(\mu\phi + \lambda\phi^2)\lvert H\rvert^2$<br>$yLHN$ | WIMPs | EFTs |

## Production mechanism

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

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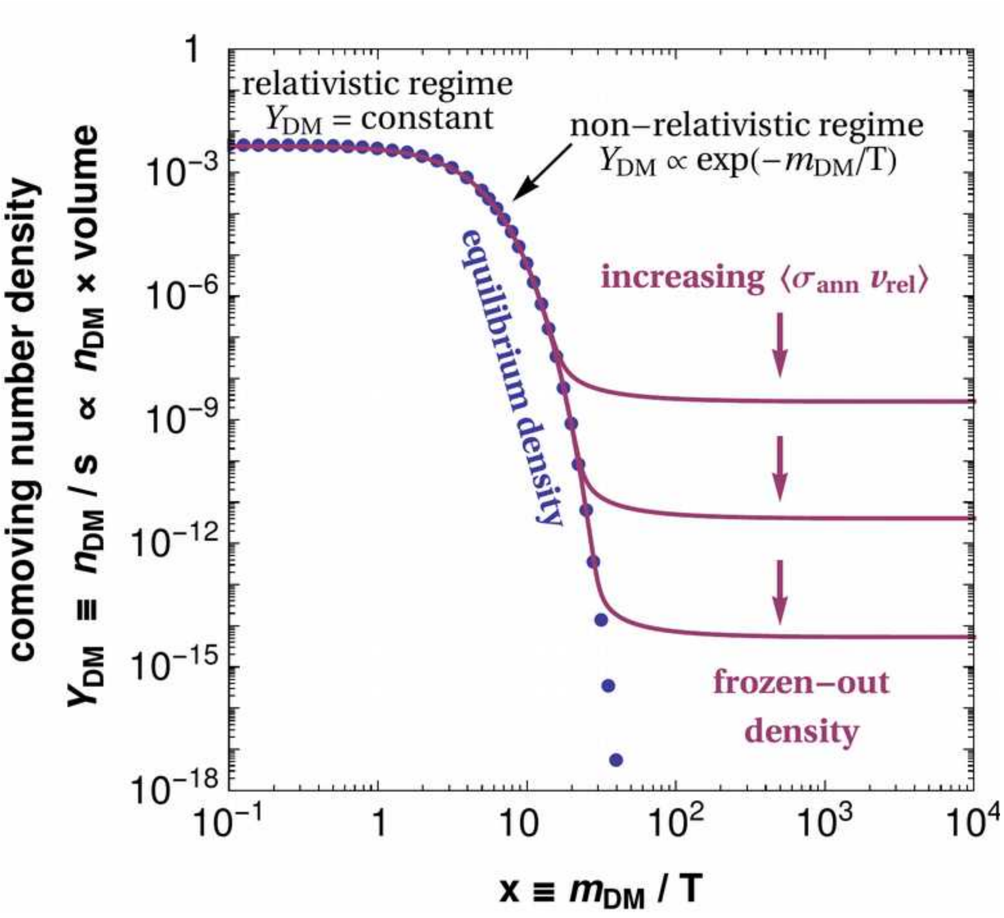
**depends on the couplings of DM to other particles, which are the very probes of the DM properties**

# 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

**$T < m_{DM} / 25$**

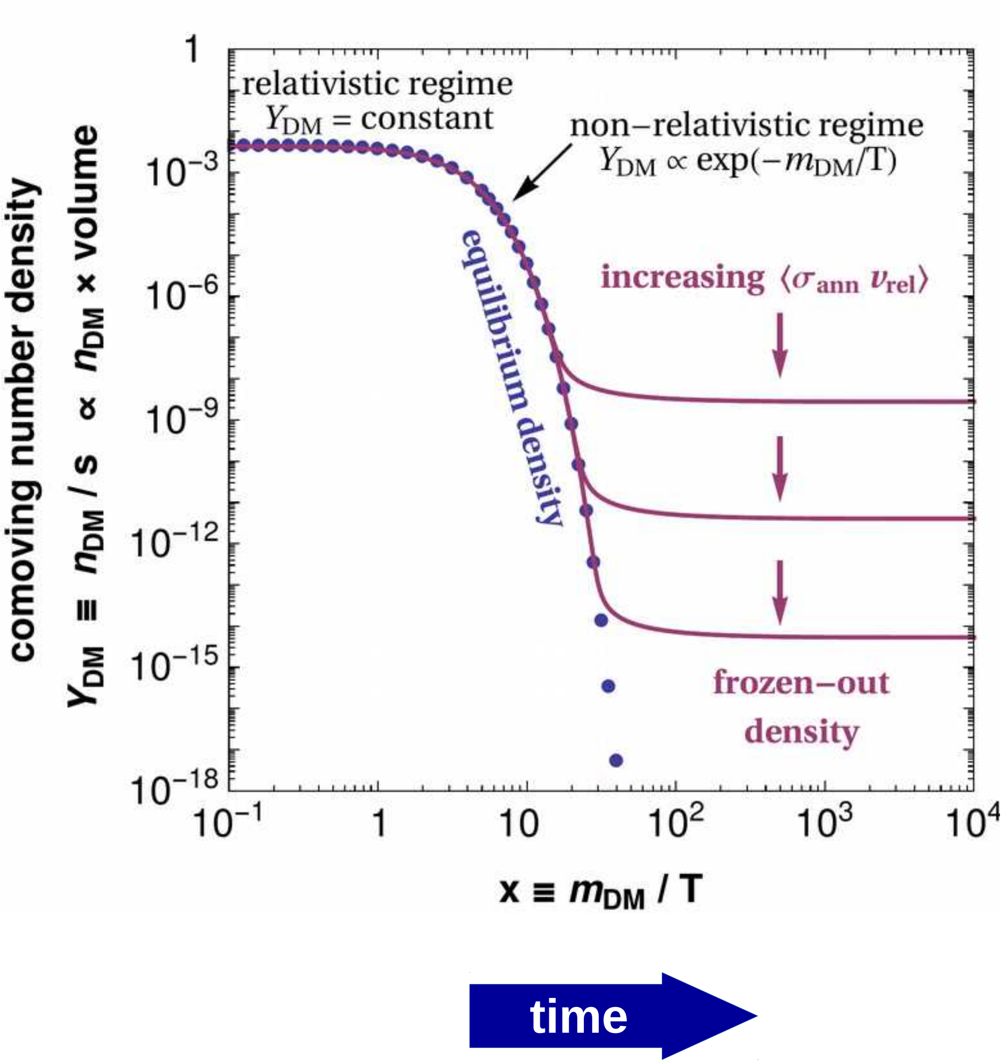
Density too small, annihilations stall

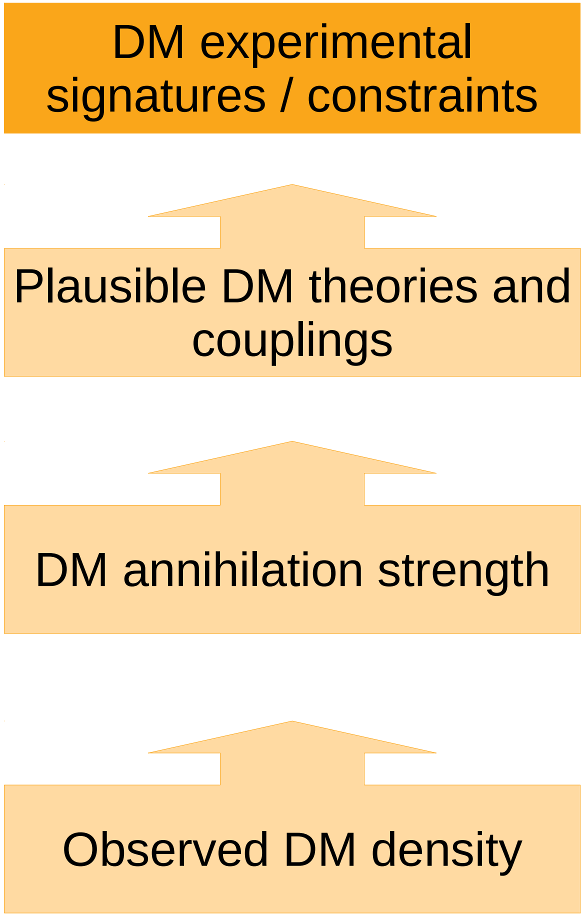
**⇒ Freeze-out!**

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

**1 pb ~ $\sigma_{Weak}$**
**WIMP miracle!**

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




DM experimental signatures / constraints

Plausible DM theories and couplings

DM annihilation strength

Observed DM density

# WIMPs and variations

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

or

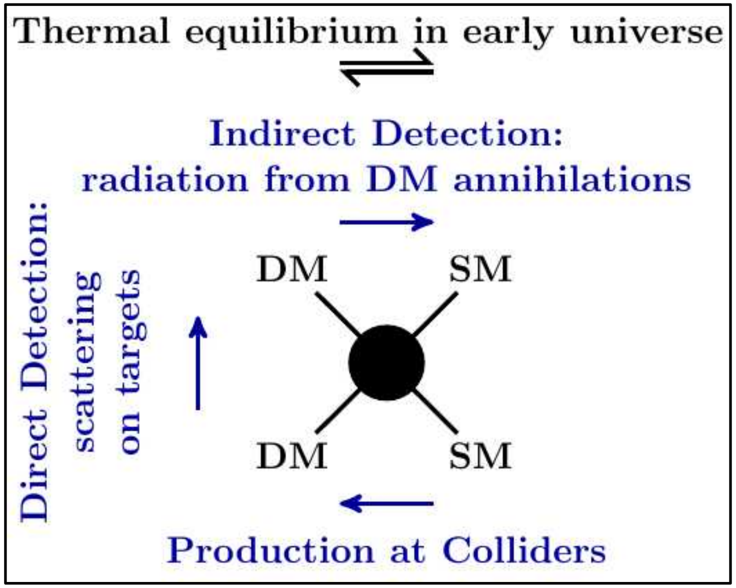
weakly coupled to SM
via non-SM interactions,

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

or

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

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



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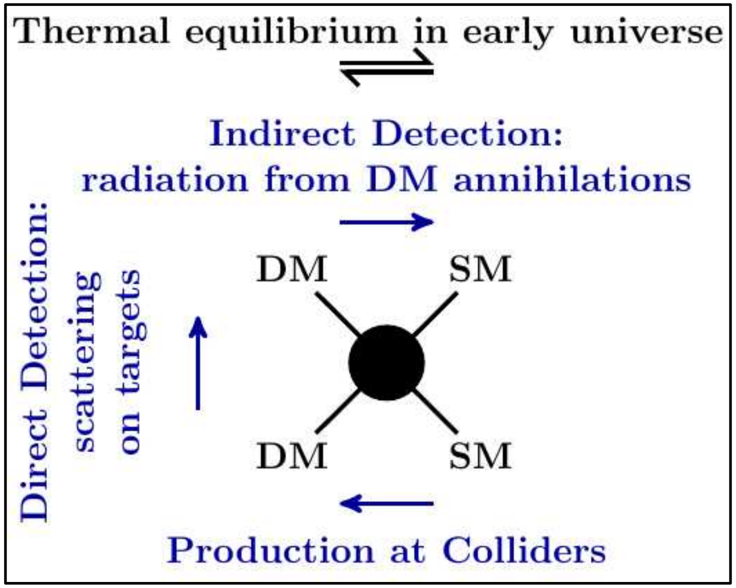

Significant
constraints.

No discovery
so far.

# What now?

## Diversify dark matter searches

### 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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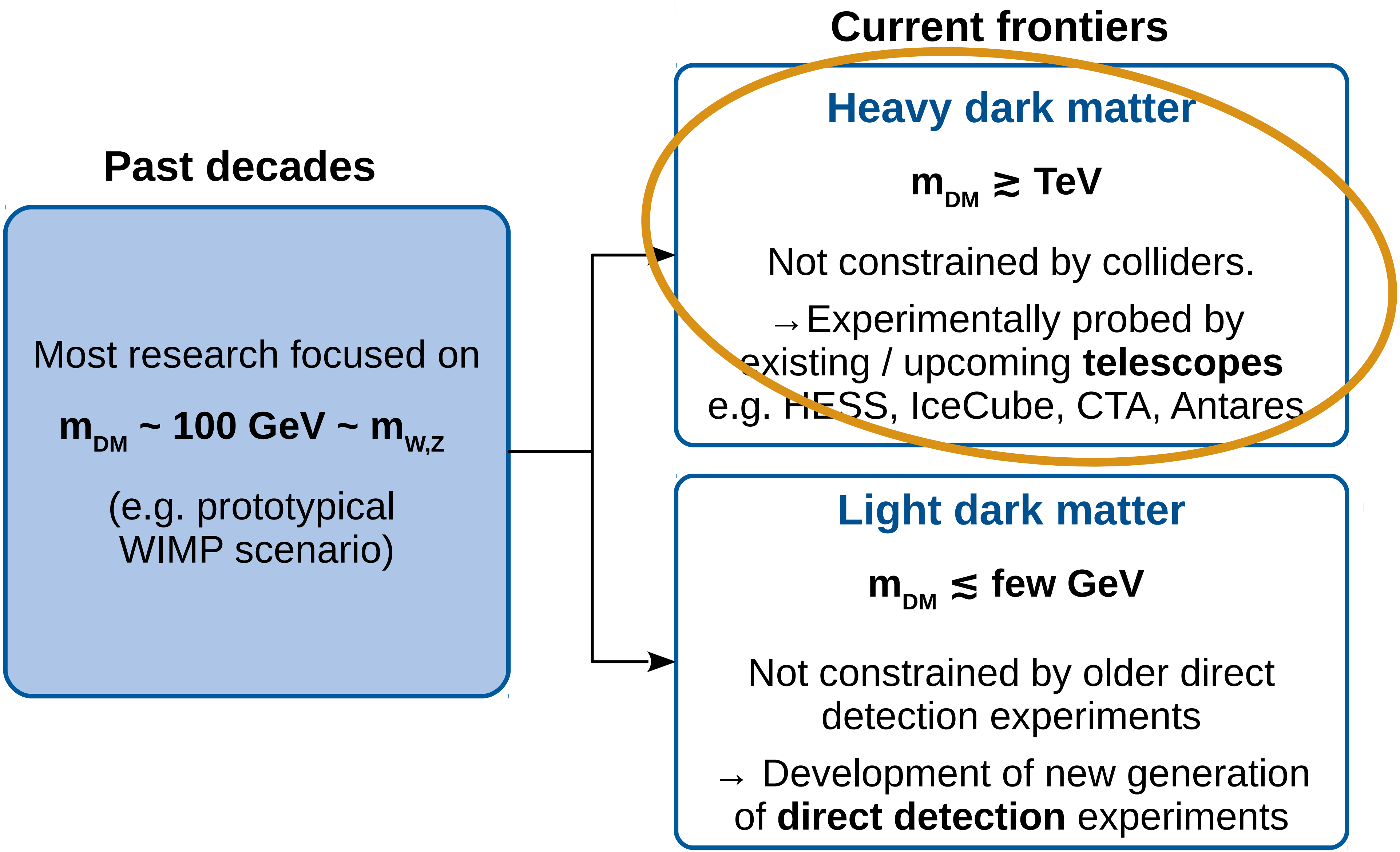

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# Heavy ($m_{DM} \gtrsim$ TeV) dark matter

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

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

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

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For the theorists:

**How do we calculate DM related processes?**
**E.g. DM annihilation, elastic scattering etc?**

# What’s different about long-range interactions?

# Interactions among humans

**Outcome of an evening at the pub**

**=** $\mathcal{M}$ (exchanges at the pub, characters of individuals)

if individuals are sufficiently independent

**=** $\mathcal{A}$ (exchanges at the pub) x $\mathcal{Z}_i$ (character of each individual)

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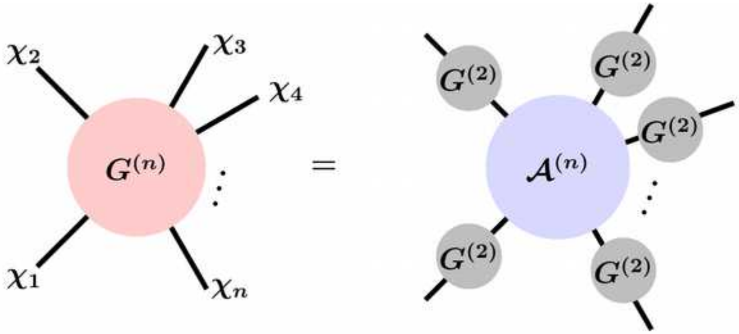
= $\mathcal{A}$ (exchanges at the pub) x $Z_i$(character of each individual)

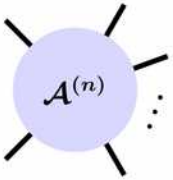
$Z_i$(character of each individual) =

character born with + influences from all past interactions with other humans /cultures

# **Contact-type** vs long-range interactions

## Scattering processes



where  includes all connected diagrams with the 1PI factors amputated.

# **Contact-type** vs long-range interactions

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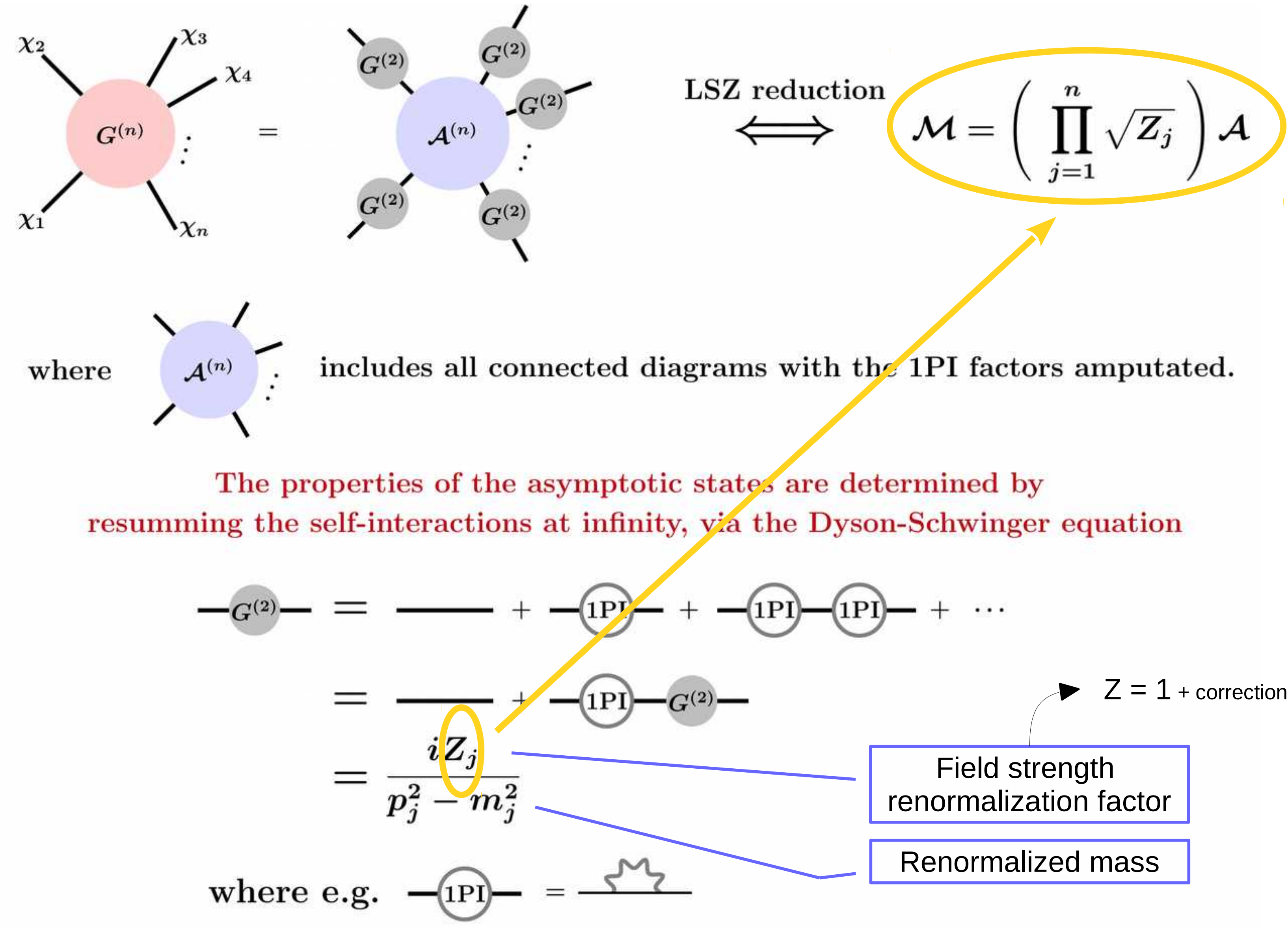


$$\mathcal{M} = \left( \prod_{j=1}^{n} \sqrt{Z_j} \right) \mathcal{A}$$

where $\mathcal{A}^{(n)}$ includes all connected diagrams with the 1PI factors amputated.

The properties of the asymptotic states are determined by resumming the self-interactions at infinity, via the Dyson-Schwinger equation

$$= \frac{iZ_j}{p_j^2 - m_j^2}$$

where e.g.

Z = 1 + corrections due to couplings

Field strength renormalization factor

Renormalized mass

# Contact-type vs **long-range** interactions

## Scattering processes

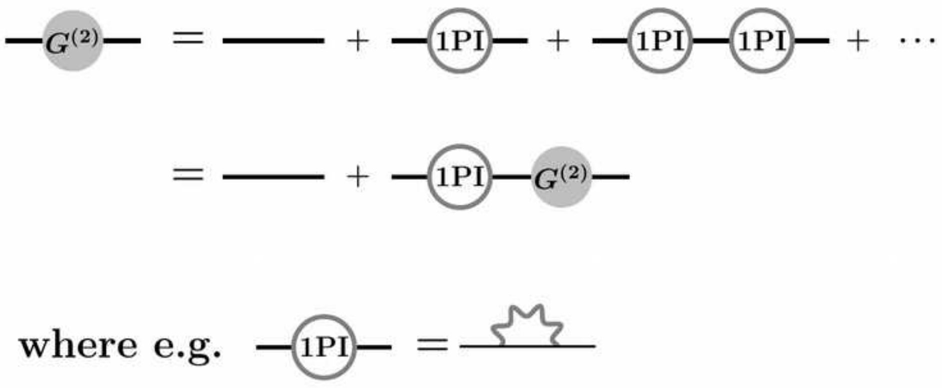
The particles interact at very large distance. We cannot define the asymptotic states by isolating the particles at infinity.

What do we do?

**Resum 2-particle interactions at infinity!**

# Contact-type vs long-range interactions

## Scattering processes



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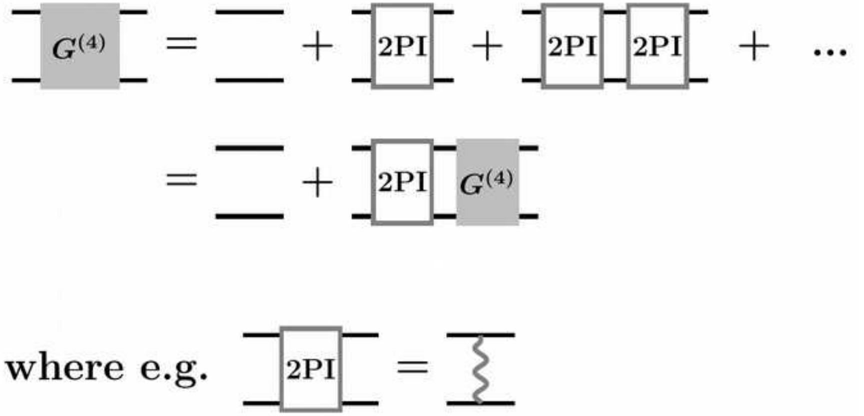


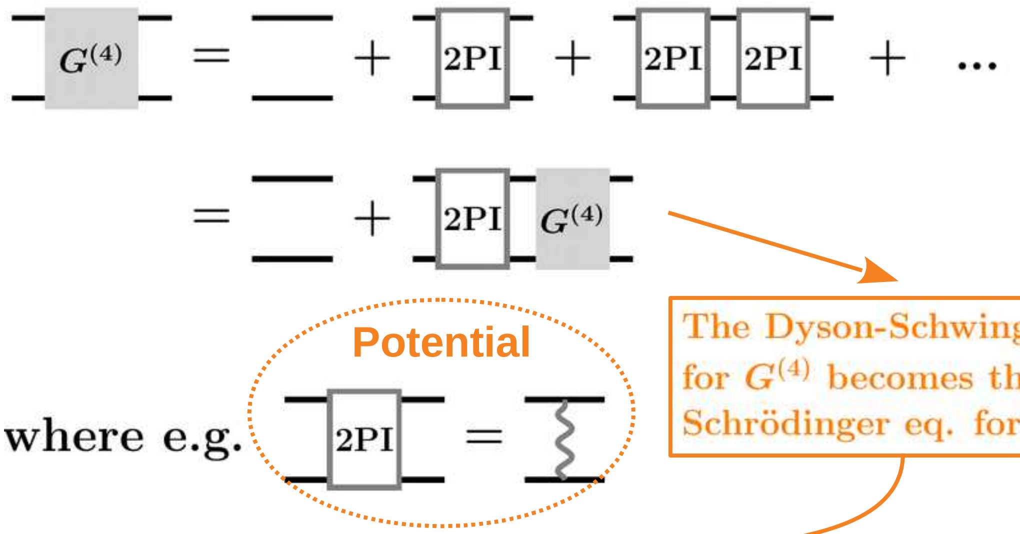
$$\mathcal{M} = \int \frac{d^3q}{(2\pi)^3} \phi_{\vec{k}}(\vec{q}) \mathcal{A}(\vec{q})$$

**field strength renormalization factors / form factors / wavefunctions**

$$G^{(2)} \sim Z/\text{singularity} \quad \leftrightarrow \quad G^{(4)} \sim [\phi_{\vec{k}}]^2/\text{singularity}$$

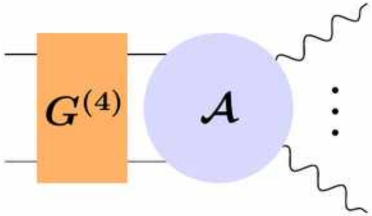
# Long-range interactions

## Scattering states and bound states



The Dyson-Schwinger eq. for $G^{(4)}$ becomes the Schrödinger eq. for $\psi_{\vec{k}}$

$$\mathcal{M} = \int \frac{d^3q}{(2\pi)^3} \psi_{\vec{k}}(\vec{q}) \mathcal{A}(\vec{q})$$



**Continuous spectrum**

$$\psi_{\vec{k}}(\vec{r}) \neq e^{i\vec{k}\cdot\vec{r}}$$

**Scattering states**
**"Sommerfeld effect"**

**Discrete spectrum**

$$\psi_{n\ell m}(\vec{r})$$

**Bound states**

Momentum exchange in propagators ***p* ~ *μ α***
⇒ ladder diagrams ∝ *1 / α*
⇒ ***non-perturbative effects at perturbative coupling !***

# 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**

- Production in early universe, e.g. freeze-out
- Indirect detection
- 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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# Freeze-out with bound states

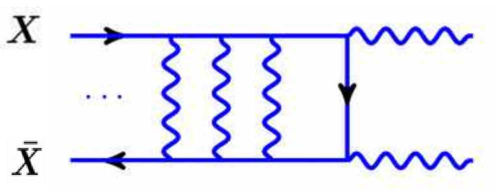
- Dark U(1) sector
- Neutralino-squark coannihilation
- The Higgs as a *light* force mediator

# Dark U(1) sector

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

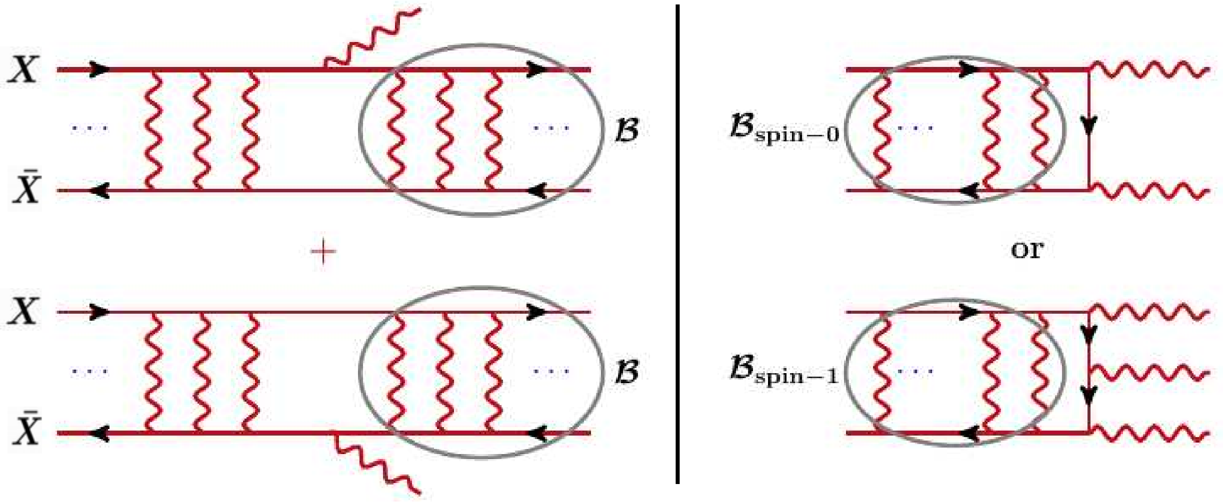
Direct annihilation

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

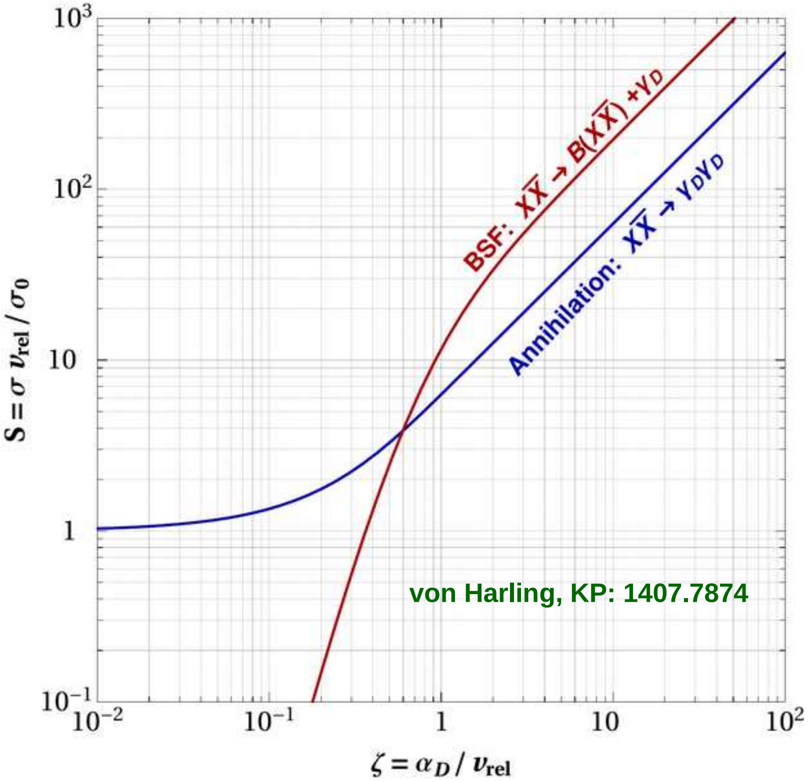


$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm ann}(\alpha_D / v_{\rm rel})$$

Bound-state formation and decay



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

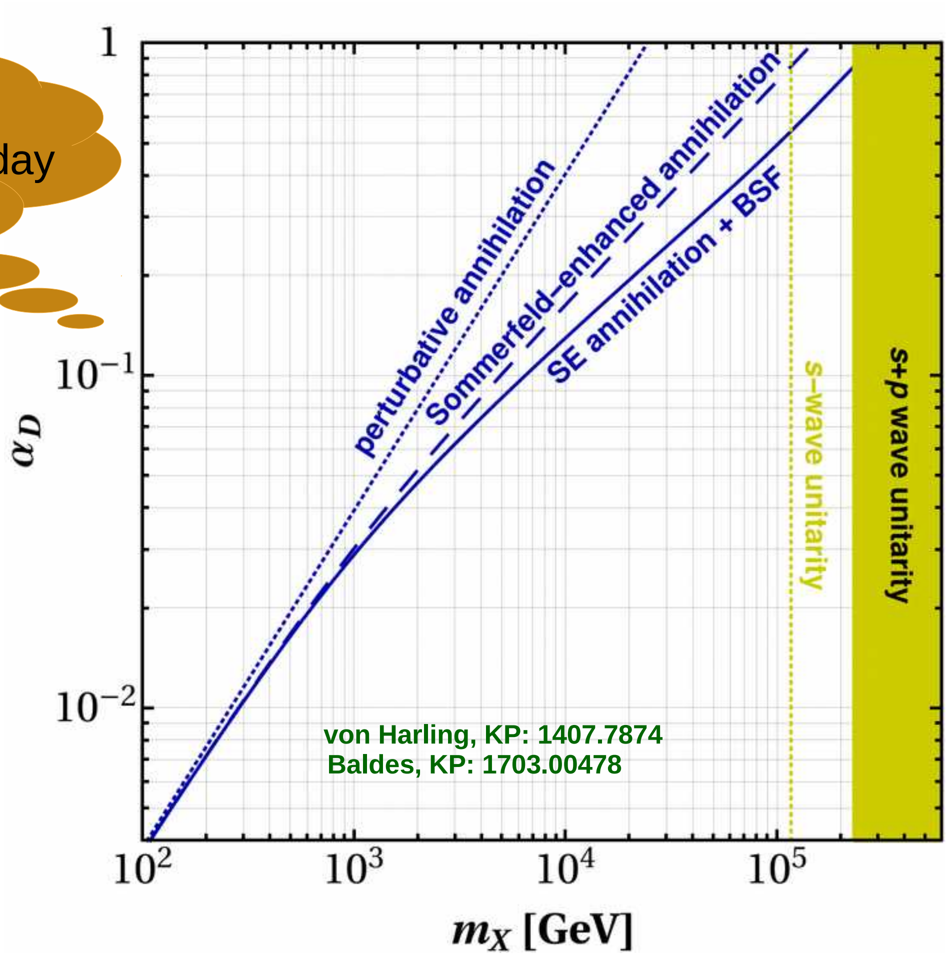


von Harling, KP: 1407.7874

# Thermal freeze-out with long-range interactions

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

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



von Harling, KP: 1407.7874
Baldes, KP: 1703.00478

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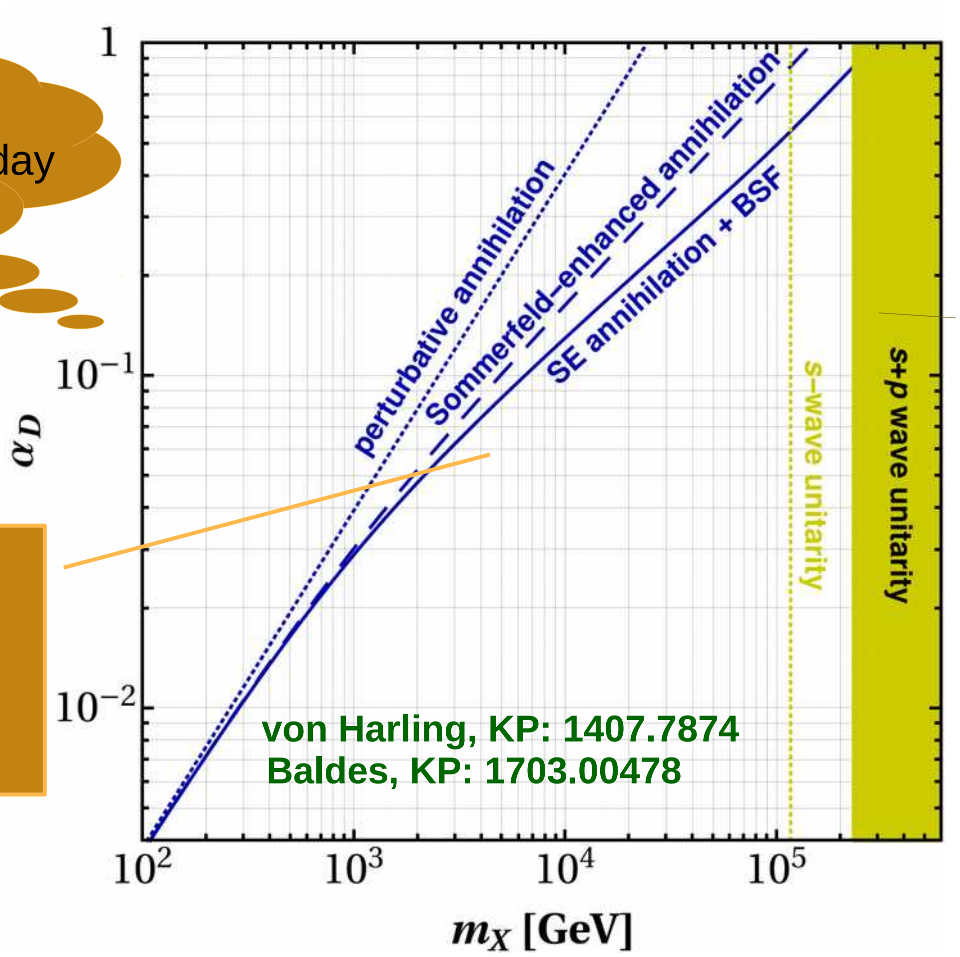

**von Harling, KP: 1407.7874**
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Long-range effects indeed become at $m_{DM} \gtrsim$ few TeV.

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-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

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

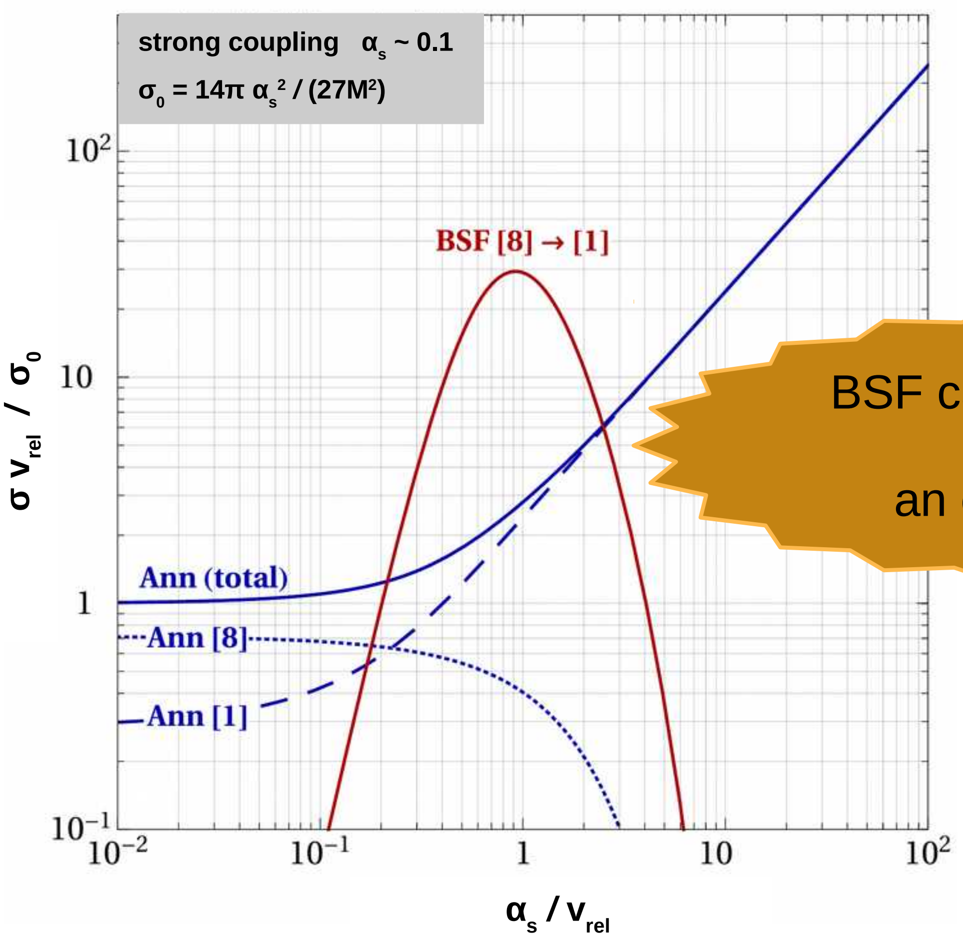
$$\sigma^{\mathrm{eff}}_{\mathrm{ann}} = [\,n^2_{\mathrm{LSP}}\,\sigma^{\mathrm{LSP}}_{\mathrm{ann}} + n^2_{\mathrm{NLSP}}\,\boxed{\sigma^{\mathrm{NLSP}}_{\mathrm{ann}}} + n_{\mathrm{LSP}}\,n_{\mathrm{NLSP}}\,\sigma^{\mathrm{LSP-NLSP}}_{\mathrm{ann}}\,]/n^2_{\mathrm{tot}}$$

**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



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

**Harz, KP: 1805.01200**

# DM coannihilation with scalar colour triplet

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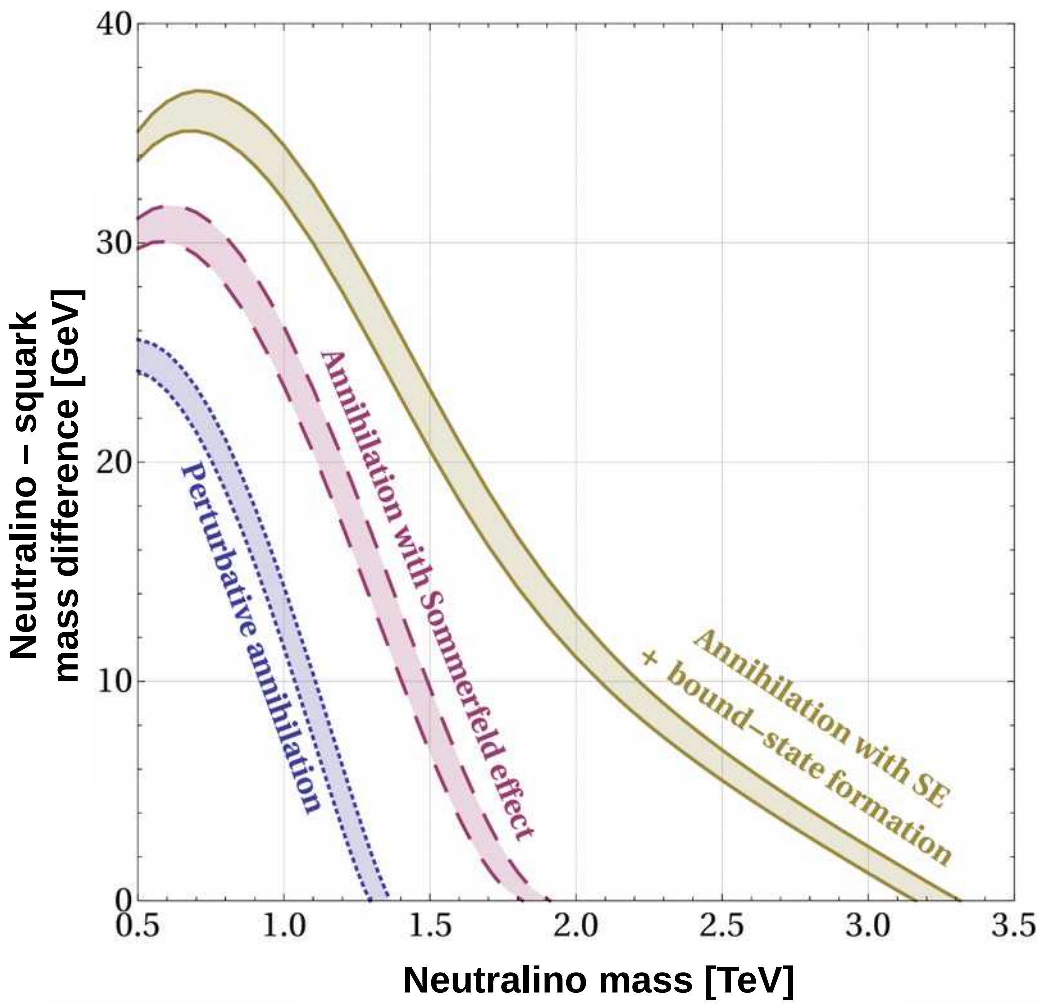

Effect on relic density: much much larger than obs uncertainty in $\Omega_{DM}$

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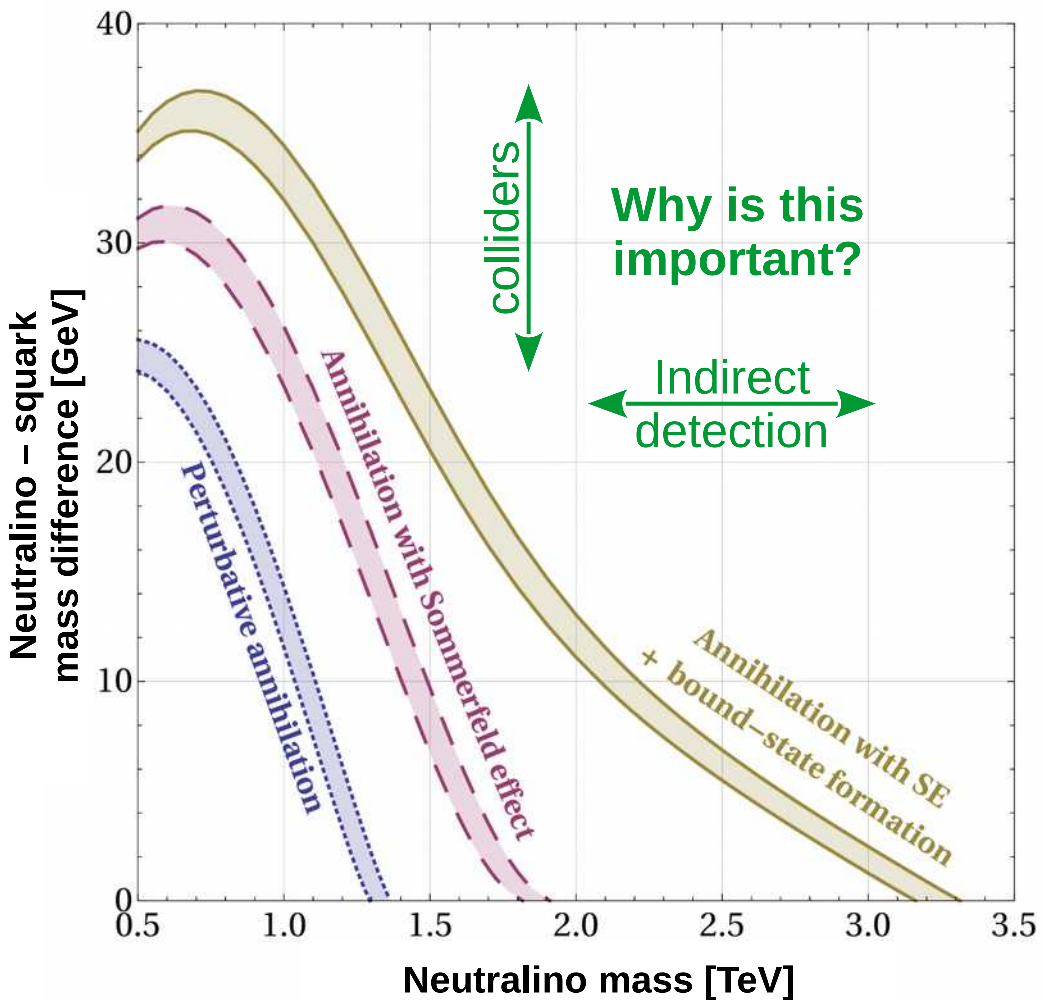

**Why is this important?**

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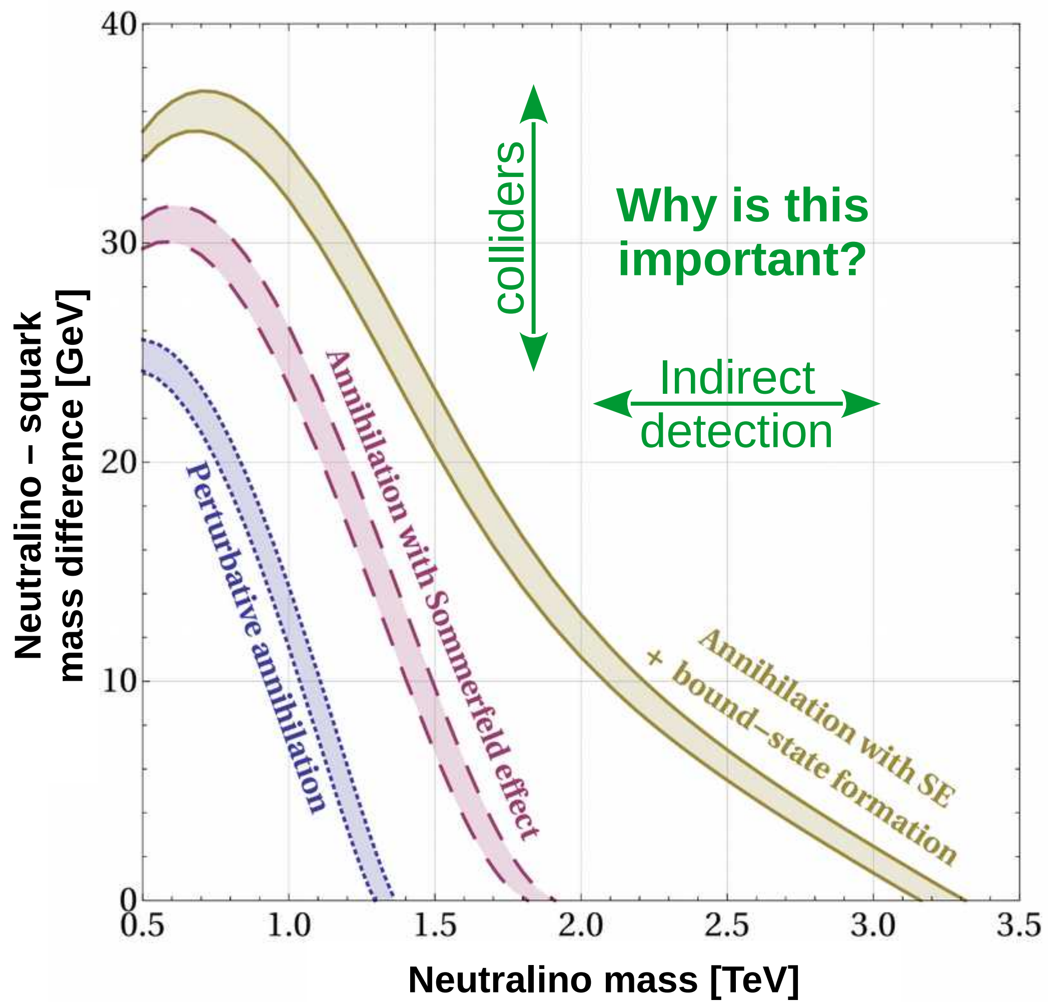

colliders

**Why is this important?**

Indirect detection

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

**Not the final picture!**

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# Really ???

- The Higgs is too heavy (heavier than all SM gauge bosons)

- Direct DM coupling to the Higgs constrained to be very small by direct detection experiments

# The Higgs as a *light* force mediator

# Really ???

- The Higgs is too heavy (heavier than all SM gauge bosons)

  *Yes, but what if $m_{DM}$ > TeV?*

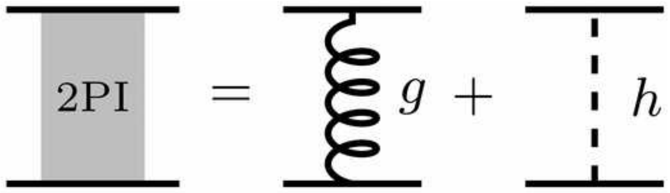
- Direct DM coupling to the Higgs constrained to be very small by direct detection experiments

  *Yes, but not the coupling of the DM coannihilating partners to the Higgs*

And in any case,
new and unexpected things happen sometimes,
so let's calculate, then think

# Higgs enhancement and relic density

## MSSM-inspired toy model

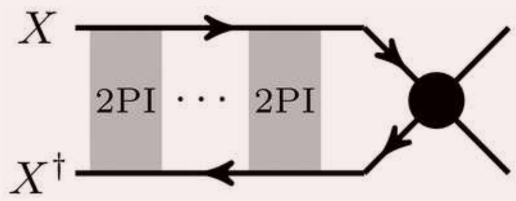


$$V(r) = -\frac{\alpha_g}{r} \boxed{- \frac{\alpha_h}{r}\, e^{-m_h r}}$$

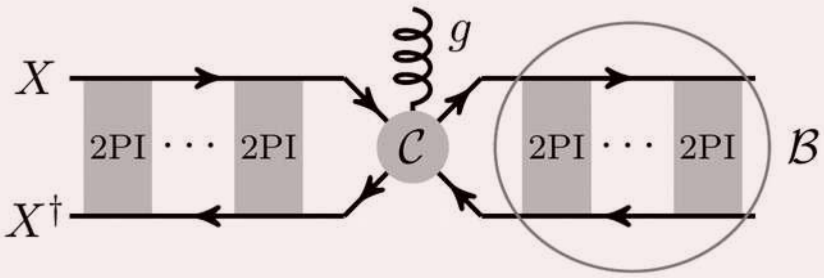
**gluon exchange**

**Higgs exchange,** typically thought to be too contact-type

Enhancement of direct annihilation



Higgs-mediated bound states



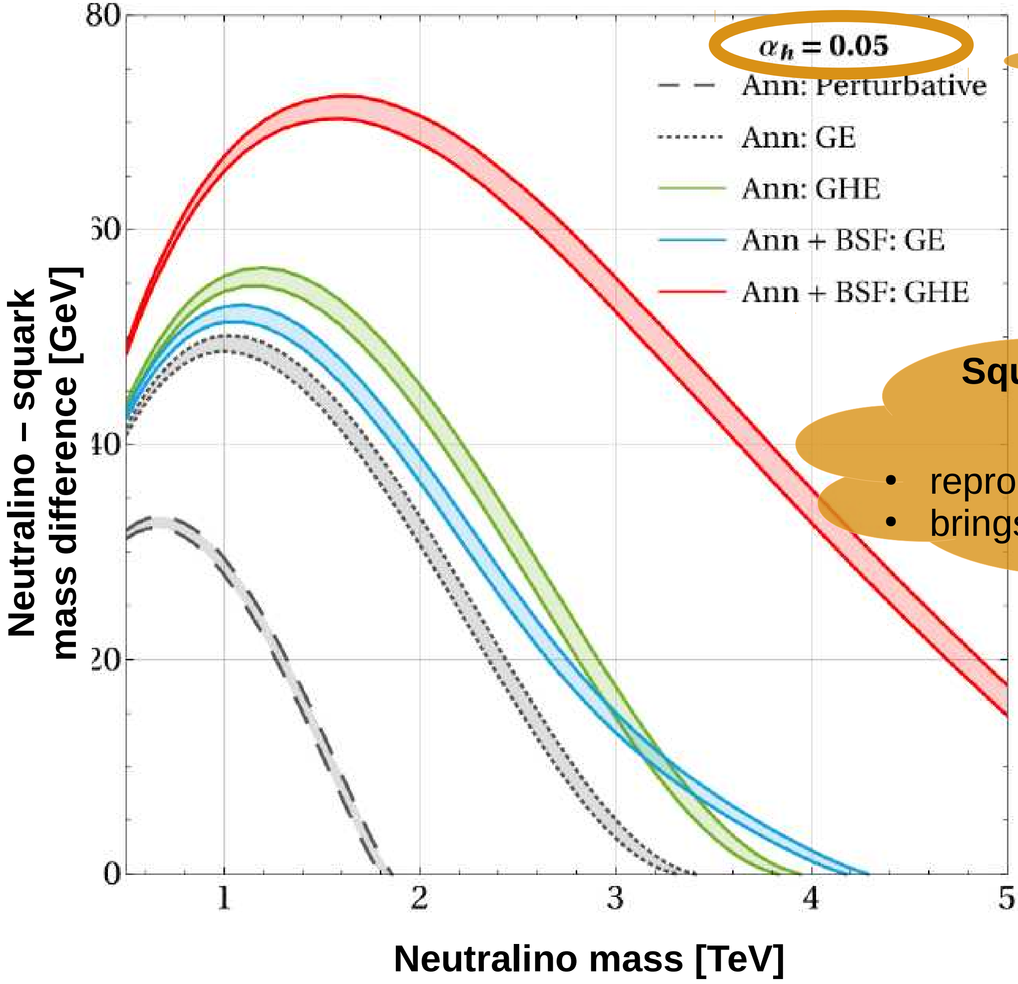
**Gluon potential influences the long-range effect of the Higgs!**

**Harz and KP: 1711.03552, 1901.10030**

# DM coannihilation with scalar colour triplet

## MSSM-inspired toy model

## The effect of the Higgs-mediated potential



**Squark-antisquark-Higgs coupling**

Large $\alpha_h$

- 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**
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- **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 $\beta$ decay of nucleus.

# Renormalisable WIMP models with coupling to the Higgs

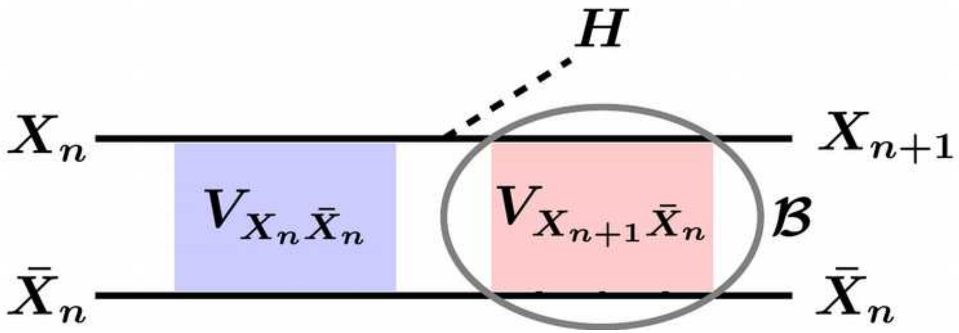
In some prototypical WIMP models,
DM is the lightest linear combination of the neutral components of
SU(2) multiplets that couple to the Higgs

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

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!**



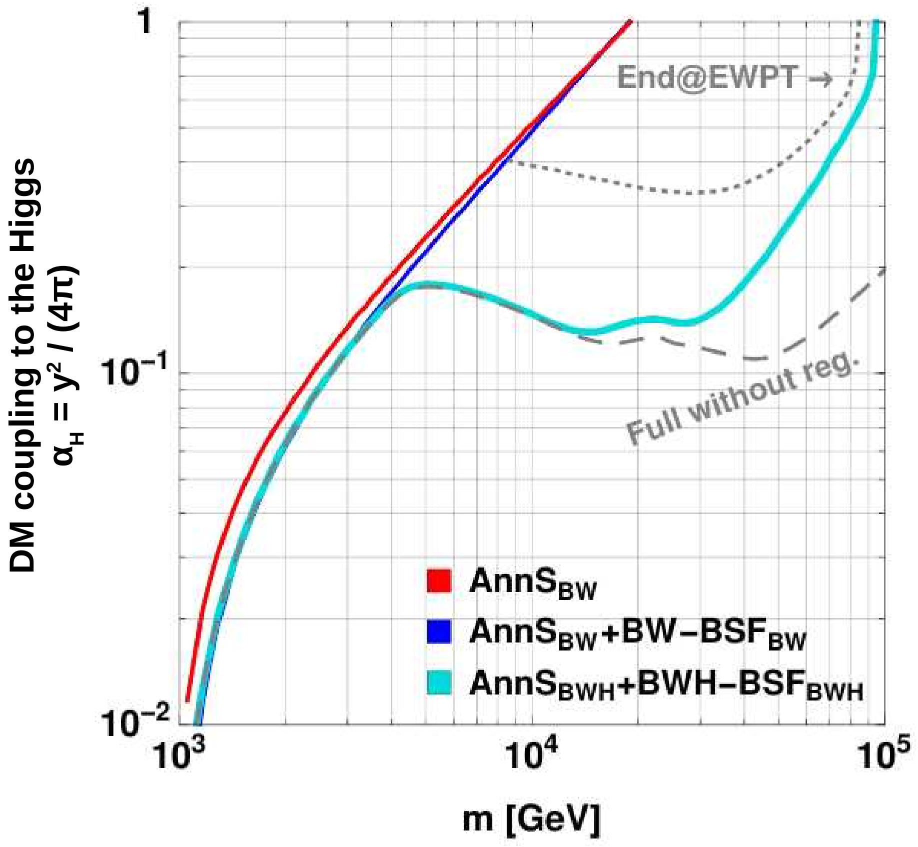
**Change in potential
⇒ monopole transition!**

# Renormalisable WIMP models with coupling to the Higgs

***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 $m_{DM} > 5\text{TeV}$



**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?

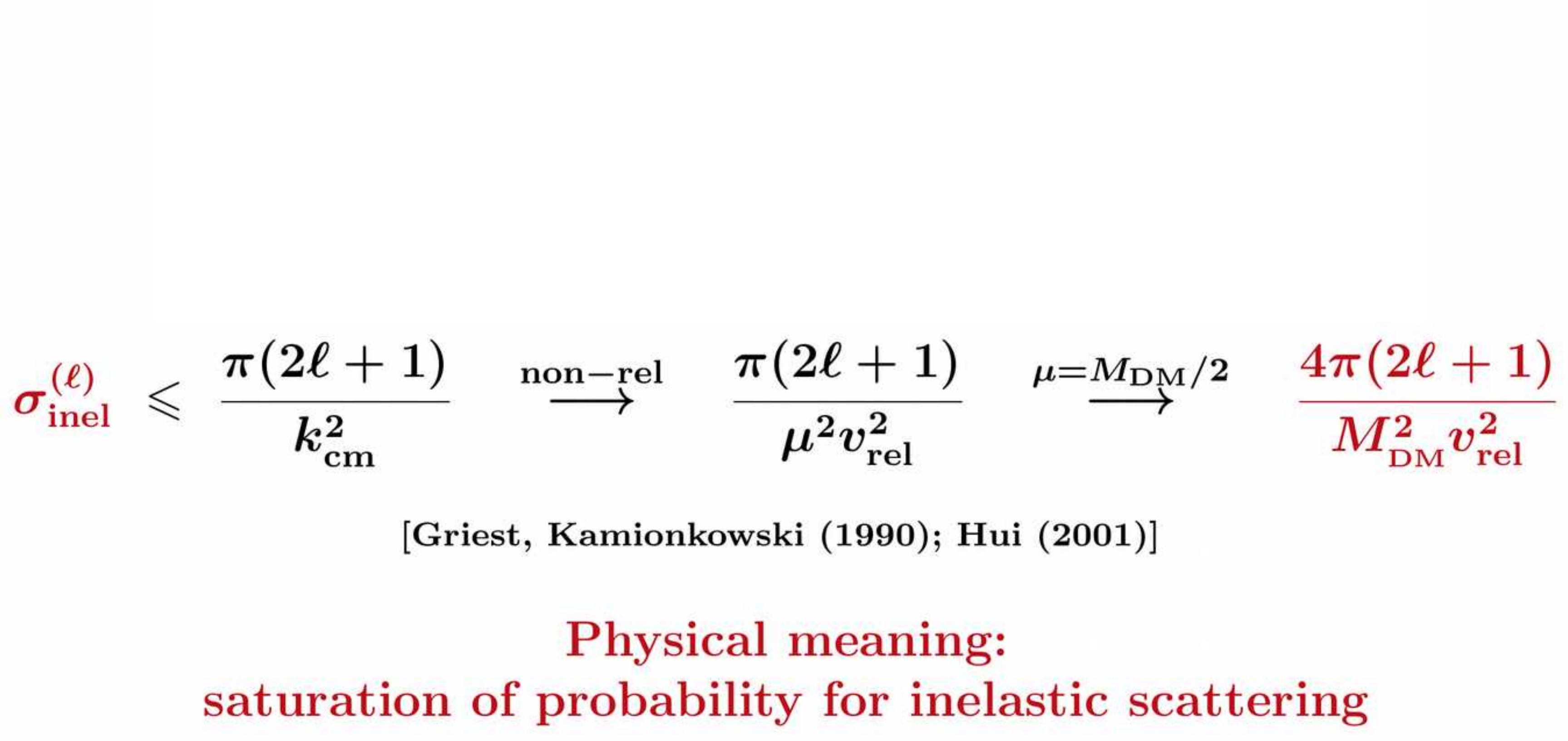
Is it a coincidence that
non-perturbative effects arise in all these models
at the multi-TeV regime?

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

If so, what else can we learn from it?

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

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

**Implies upper bound on the mass of thermal-relic DM**

**Griest, Kamionkowski (1990)**

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

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

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

- 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?

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

Parametric dependence on mass and velocity implies that **$\sigma_{\mathrm{uni}}$ 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 $m_{\mathrm{DM}} \gtrsim$ 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

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  - 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

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