Dark matter going nuclear: the role of bound states in thermal decoupling

Kallia Petraki

Sorbonne University, LPTHE, Paris and Nikhef, Amsterdam

BNL, 15 April 2021

Dark matter production in the early universe

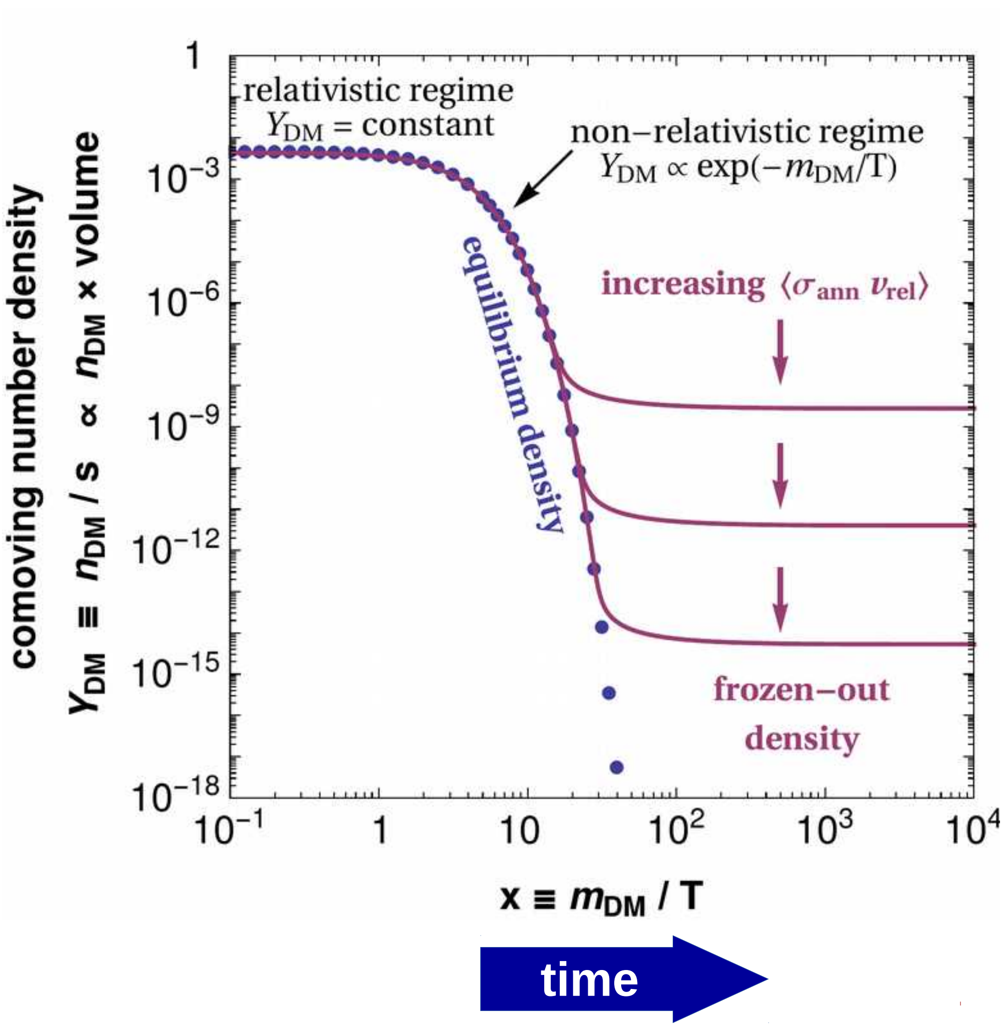
Why do we care?

Production depends on

the couplings of DM to other particles,

which are the very probes of the DM properties

Thermal freeze-out



$T > m_{DM}$

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!

WIMPs and variations

Weakly 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

WIMPs and variations

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

or

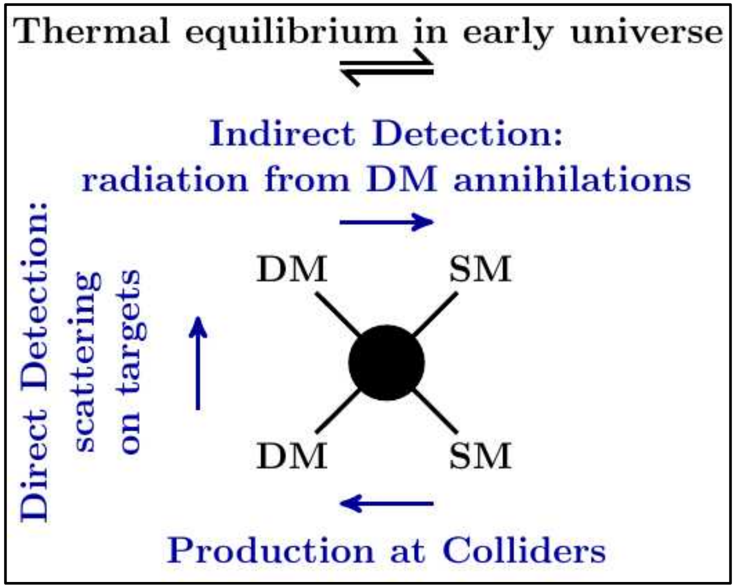
weakly coupled to SM
via non-SM interactions,

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

or

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

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



WIMPs and variations

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

or

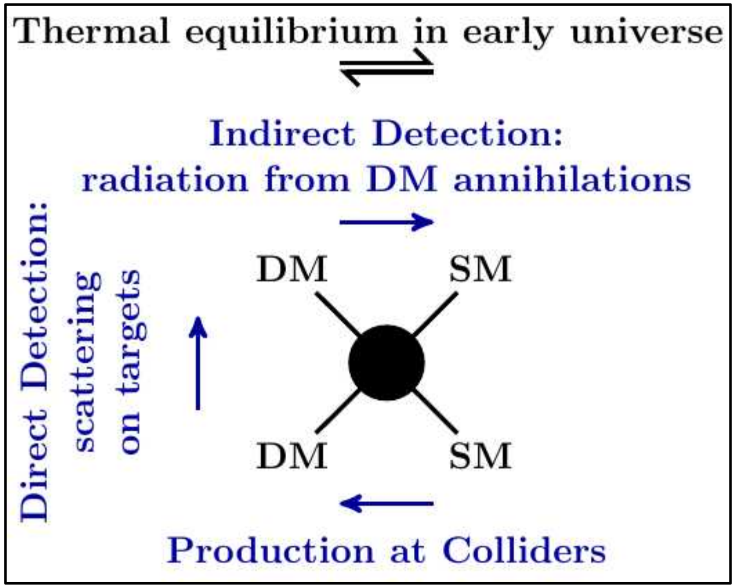
weakly coupled to SM
via non-SM interactions,

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

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

  see e.g. 2008.00692: WIMP prospects with CTA
  Rinchiuso, Macias, Moulin, Rodd, Slatyer

- **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 (≳ TeV) thermal-relic DM?

- **Heavier DM**

Particles with m ≳ TeV ... to SM via the Weak or other interactions not con... d by collider experiments

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

see e.g. 2008.00692: WIMP prospects with CTA Rinchiuso, Macias, Moulin, Rodd, Slatyer

- **Lighter DM**

Particles with m ≲ 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

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 ($m_{\rm DM}/2$)

Long-range interactions
Motivation

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

μ: reduced mass ($m_{\text{DM}}/2$)

- Self-interacting DM
- DM explanations of astrophysical anomalies, e.g. galactic positrons, IceCube PeV neutrinos
- Sectors with stable particles in String Theory

- 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 freeze-out ⇒ changes correlation of parameters (mass – couplings)
- Affects indirect detection signals
  - rates
  - velocity dependence
  - parametric resonances

Implications of long-range interactions

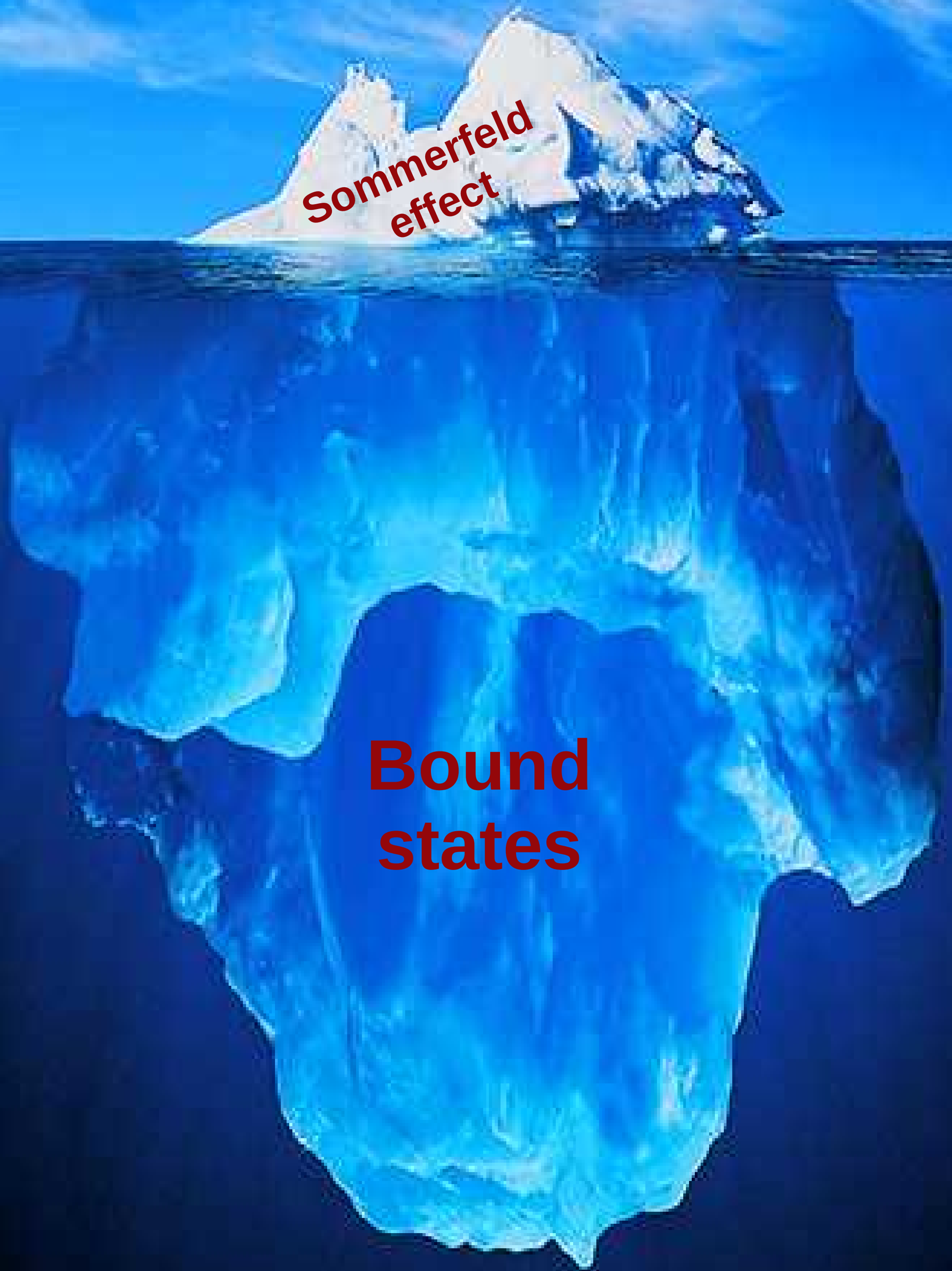
Sommerfeld effect

distortion of scattering-state wavefunctions

- Affects freeze-out ⇒ changes correlation of parameters (mass – couplings)
- Affects indirect detection signals
  - rates
  - velocity dependence
  - parametric resonances

Bound states

- **Unstable bound states ⇒ extra annihilation channel**
  - **Freeze-out**
  - Indirect detection (different velocity dependence, resonances than annihilation)
  - 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 125 GeV Higgs as a light mediator
- Bound-state formation via emission of a charged scalar
- Bound-state formation via Higgs-doublet emission

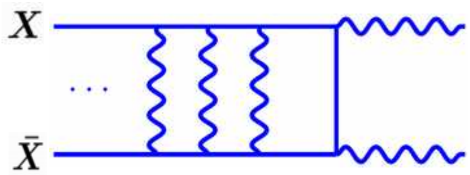
1. Dark U(1) sector

Thermal freeze-out with long-range interactions

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

Direct annihilation

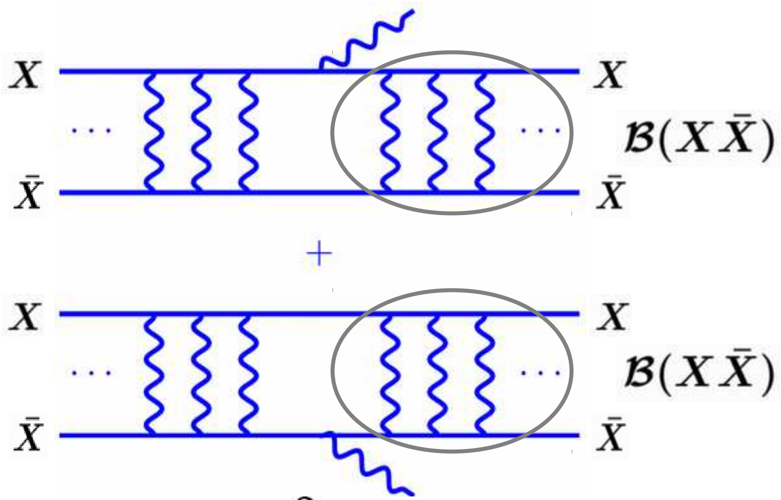
$$X + \bar{X} \to 2\gamma_D$$



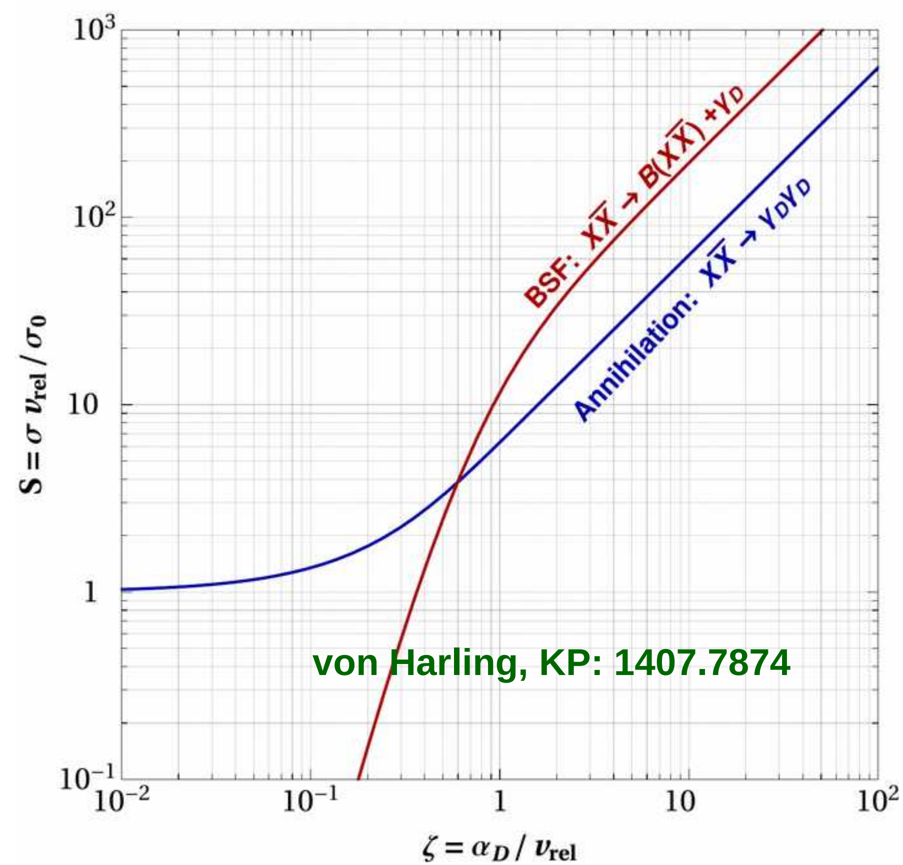
$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm ann}(\alpha_D / v_{\rm rel})$$

Radiative bound-state formation

$$X + \bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$$



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



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

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

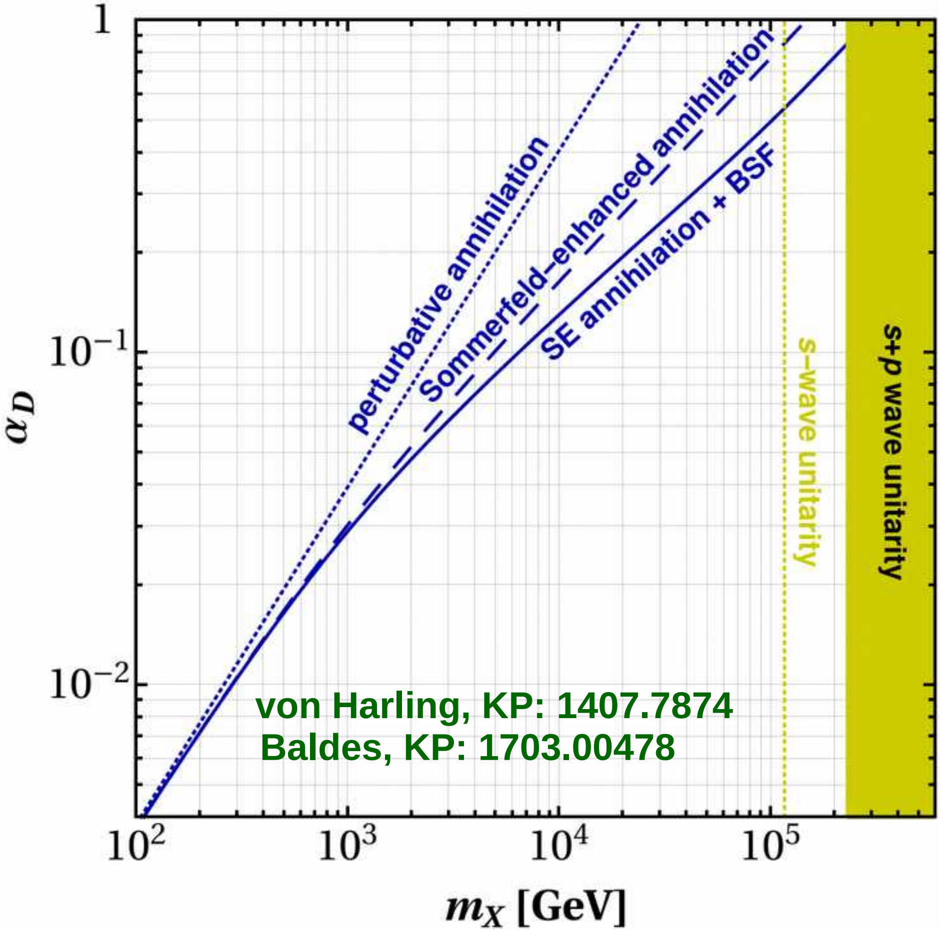
Thermal freeze-out with long-range interactions

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

Direct Annihilation $X\bar{X} \to \gamma_D \gamma_D$

Bound-state formation $X\bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$

and decay $\mathcal{B}(X\bar{X}) \to 2\gamma_D$ or $3\gamma_D$



Thermal freeze-out with long-range interactions

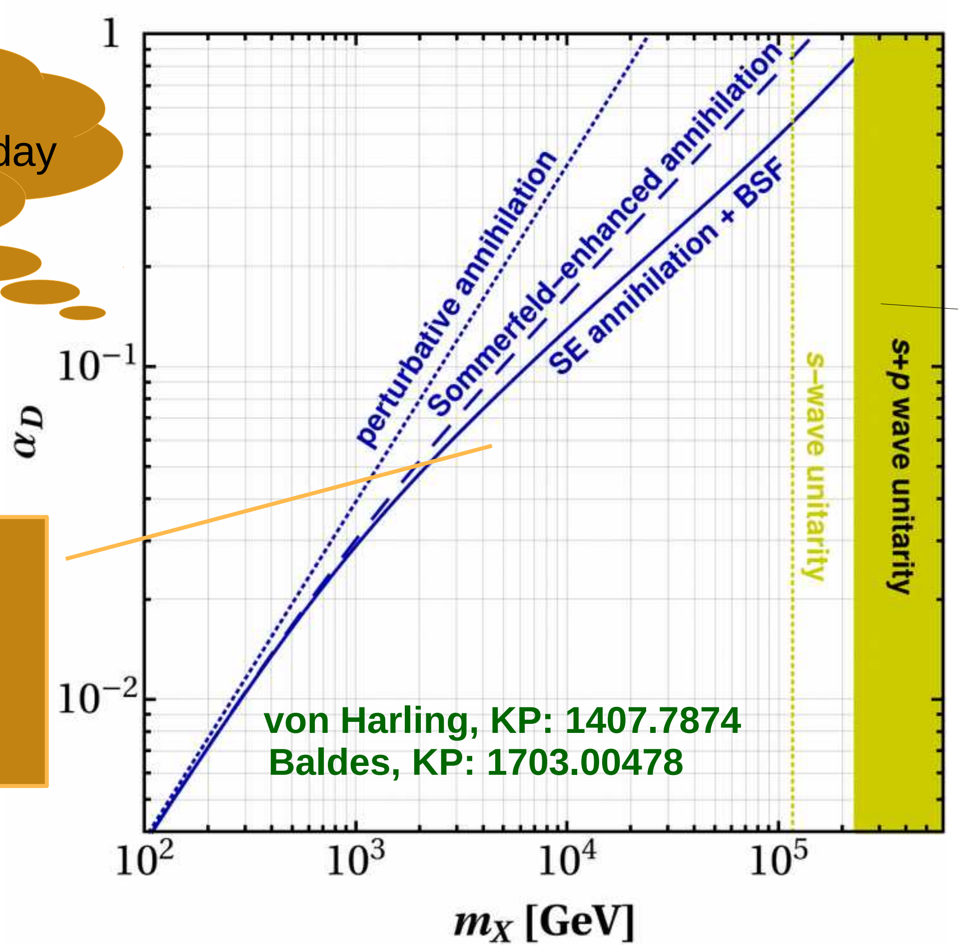
Dark U(1) model: Dirac DM $X,\bar{X}$ coupled to γ_D

$$\text{Direct Annihilation} \quad X\bar{X} \to \gamma_D \gamma_D$$

$$\text{Bound-state formation} \quad X\bar{X} \to \mathcal{B}(X\bar{X}) + \gamma_D$$

$$\text{and decay} \quad \mathcal{B}(X\bar{X}) \to 2\gamma_D \ \text{ or } \ 3\gamma_D$$

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.

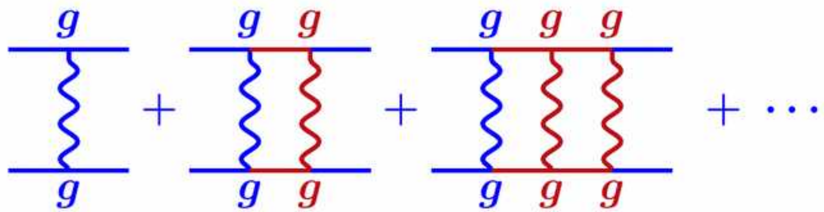
DM may be even heavier!

What just happened?

Making sense of the ladder diagrams

Every mediator exchange introduces an
$\alpha = g^2/(4\pi)$ suppression in the amplitude.
How did we get an enhancement and bound states?

Bound-state ladder

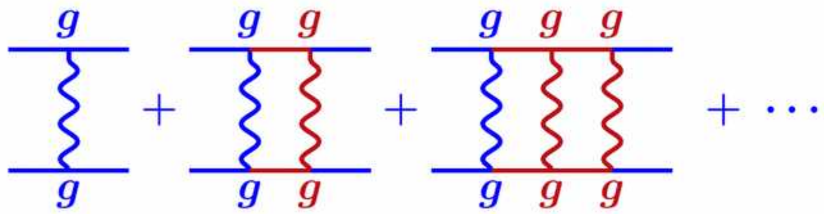


What just happened?

Making sense of the ladder diagrams

Every mediator exchange introduces an $\alpha = g^2/(4\pi)$ suppression in the amplitude. How did we get an enhancement and bound states?

Bound-state ladder



Energy and momentum exchange scale with α!

- Momentum transfer: $|\vec{q}| \sim \mu\alpha$.
- Energy transfer: $q^0 \sim |\vec{q}|^2/\mu \sim \mu\alpha^2$.
- Off-shellness of interacting particles: $q^0 \sim |\vec{q}|^2/\mu \sim \mu\alpha^2$.

one boson exchange $\sim \alpha \times \frac{1}{(\mu\alpha)^2} \propto \frac{1}{\alpha}$

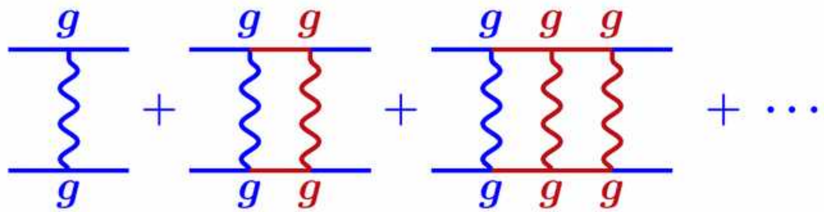
each added loop $\sim \alpha \times \int dq^0 d^3q \, \frac{1}{q_1 - m_1} \frac{1}{q_2 - m_2} \frac{1}{q_\gamma^2}$

$\sim \alpha \times (\mu\alpha^2)(\mu\alpha)^3 \frac{1}{\mu\alpha^2} \frac{1}{\mu\alpha^2} \frac{1}{(\mu\alpha)^2}$

~ 1

What just happened?
Making sense of the ladder diagrams

Every mediator exchange introduces an
$\alpha = g^2/(4\pi)$ suppression in the amplitude.
How did we get an enhancement and bound states?

Bound-state ladder 

Energy and momentum exchange scale with α!

- Momentum transfer: $|\vec{q}| \sim \mu\alpha$.
- Energy transfer: $q^0 \sim |\vec{q}|^2/\mu \sim \mu\alpha^2$.
- Off-shellness of interacting particles: $q^0 \sim |\vec{q}|^2/\mu \sim \mu\alpha^2$.

1/α scaling responsible for non-perturbative effects (not largeness of coupling)

one boson exchange $\sim \alpha \times \frac{1}{(\mu\alpha)^2} \propto \frac{1}{\alpha}$

each added loop $\sim \alpha \times \int dq^0 d^3q \, \frac{1}{q_1 - m_1} \frac{1}{q_2 - m_2} \frac{1}{q_\gamma^2}$

$\sim \alpha \times (\mu\alpha^2)(\mu\alpha)^3 \frac{1}{\mu\alpha^2} \frac{1}{\mu\alpha^2} \frac{1}{(\mu\alpha)^2}$

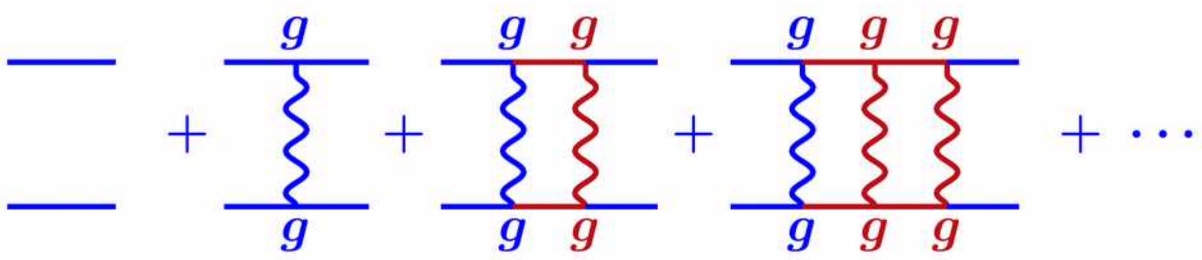
~ 1

What just happened?

Making sense of the ladder diagrams

Every mediator exchange introduces an
$\alpha = g^2/(4\pi)$ suppression in the amplitude.
How did we get an enhancement and bound states?

Scattering state ladder



Energy and momentum exchange scale with both α and $v_{\rm rel}$!

$\mu v_{\rm rel}$ is the *expectation value* of the momentum in CM frame,
the quantum uncertainty scales with α.

The Sommerfeld effect appears when
quantum uncertainty $\sim$ *expectation value*.

2. Unitarity limit and long-range interactions

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

$$\Downarrow$$

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

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

Physical meaning:
saturation of probability for inelastic scattering

Partial-wave unitarity limit

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

Implies upper bound on the mass of thermal-relic DM

Griest, Kamionkowski (1990)

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

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

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

Partial-wave unitarity limit

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

Implies upper bound on the mass of thermal-relic DM

Griest, Kamionkowski (1990)

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

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

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

Two assumptions to be questioned

1. "one does not expect $\sigma v_{\rm rel} \propto 1/v_{\rm rel}$ for annihilation channels in a non-relativistic expansion."

2. The s-wave yields the dominant contribution to the annihilation cross-section.

Partial-wave unitarity limit

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

1) Velocity dependence of σ_{uni}

- Assuming $\sigma_{ann}v_{rel}$ = const., setting it to maximal (inevitably for a fixed v_{rel}) and thermal averaging formally incorrect!

  ⇒ Unitarity violation at larger v_{rel}, non-maximal cross-section at smaller v_{rel}.

- Sommerfeld-enhanced inelastic processes exhibit exactly this velocity dependence at large couplings / small velocities, e.g. in QED

$$\sigma^{\ell=0}_{\rm ann} v_{\rm rel} \simeq \frac{\pi\alpha_D^2}{M_{\rm DM}^2} \times \frac{2\pi\alpha_D/v_{\rm rel}}{1-\exp(-2\pi\alpha_D/v_{\rm rel})} \xrightarrow{\alpha_D \gg v_{\rm rel}} \frac{2\pi^2\alpha_D^3}{M_{\rm DM}^2 v_{\rm rel}}$$

⇒ Velocity dependence of σ_{uni} definitely *not* unphysical!

Baldes, KP: 1703.00478

Partial-wave unitarity limit

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

Parametric

1) ~~Velocity~~ dependence of $\sigma_{\rm uni}$

What can we learn?

For a contact-type interaction, mediated by heavy particle with $m_{\rm med} \gtrsim M_{\rm DM}$,

$$\sigma_{\rm ann} v_{\rm rel} \sim \frac{\alpha_D^2 M_{\rm DM}^2}{m_{\rm med}^4} \lesssim \frac{4\pi}{M_{\rm DM}^2 v_{\rm rel}}.$$

Approaching unitarity limit requires large coupling (no surprise)

$$\alpha_D \sim m_{\rm med}^4 / M_{\rm DM}^4 \gtrsim 1.$$

Calculation violates unitarity if

$$m_{\rm med} < \alpha_D^{1/2} M_{\rm DM} \lesssim \alpha_D M_{\rm DM}.$$

Comparison between physical scales
⇒ violation signals new effect at play!

Baldes, KP: 1703.00478

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

1) ~~Velocity~~ dependence of σ_{uni}

What can we learn?

For a contact-type interaction, mediated by heavy particle with $m_{\rm med} \gtrsim M_{\rm DM}$,

$$\sigma_{\rm ann} v_{\rm rel} \sim \frac{\alpha_D^2 M_{\rm DM}^2}{m_{\rm med}^4} \lesssim \frac{4\pi}{M_{\rm DM}^2 v_{\rm rel}}.$$

Approaching unitarity limit requires large coupling (no surprise)

$$\alpha_D \sim m_{\rm med}^4 / M_{\rm DM}^4 \gtrsim 1.$$

Calculation violates unitarity if

$$m_{\rm med} < \alpha_D^{1/2} M_{\rm DM} \lesssim \alpha_D M_{\rm DM}.$$

Comparison between physical scales
$\Rightarrow$ violation signals new effect at play!

Including the Sommerfeld enhancement, for a light mediator, e.g. dark QED

$$\sigma_{\rm ann} v_{\rm rel} \simeq \frac{2\pi^2 \alpha_D^3}{M_{\rm DM}^2 v_{\rm rel}} \lesssim \frac{4\pi}{M_{\rm DM}^2 v_{\rm rel}}.$$

Unitarity indicates range of validity

$$\alpha_D \lesssim 0.86$$

Only numerical bound on a dimensionless coupling
$\Rightarrow$ include (resummed) higher order corrections

Baldes, KP: 1703.00478

Partial-wave unitarity limit

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

1) Velocity dependence of σ_{uni}

Proper thermal average and taking into account delayed chemical decoupling

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

$$M_{\rm uni} \simeq \begin{cases} 198\ \text{TeV}, & \text{self-conjugate DM} \\ 138\ \text{TeV}, & \text{non-self-conjugate DM} \end{cases}$$

s-wave annihilation

Baldes, KP: 1703.00478

Partial-wave unitarity limit

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

2) Higher partial waves

In direct annihilation processes, *s*-wave dominates.

- For contact-type interactions, higher ℓ are $v_{\rm rel}^{2\ell}$ suppressed:

$$\sigma_{\rm ann} v_{\rm rel} = \sum_{\ell} \sum_{r=0}^{\infty} c_{\ell r} \, v_{\rm rel}{}^{2\ell+2r}$$

- For long-range interactions:

$$\sigma_{X\bar{X}\to VV}^{(\ell=0)} v_{\rm rel} \simeq \frac{\pi\alpha_D^2}{M_{\rm DM}^2} \times \left(\frac{2\pi\alpha_D/v_{\rm rel}}{1-e^{-2\pi\alpha_D/v_{\rm rel}}}\right) \xrightarrow{\alpha_D \gg v_{\rm rel}} \frac{2\pi^2\alpha_D^3}{M_{\rm DM}^2 v_{\rm rel}}$$

$$\sigma_{X\bar{X}\to SS}^{(\ell=1)} v_{\rm rel} \simeq \frac{3\pi\alpha_D^2}{8M_{\rm DM}^2} v_{\rm rel}^2 \times \left(\frac{2\pi\alpha_D/v_{\rm rel}}{1-e^{-2\pi\alpha_D/v_{\rm rel}}}\right)\left(1+\frac{\alpha_D^2}{v_{\rm rel}^2}\right) \xrightarrow{\alpha_D \gg v_{\rm rel}} \frac{6\pi^2\alpha_D^5}{8M_{\rm DM}^2 v_{\rm rel}}$$

Same $v_{\rm rel}$ scaling (as expected from unitarity!), albeit $v_{\rm rel}^2 \to \alpha_D^2$ suppression.

Baldes, KP: 1703.00478

Partial-wave unitarity limit

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

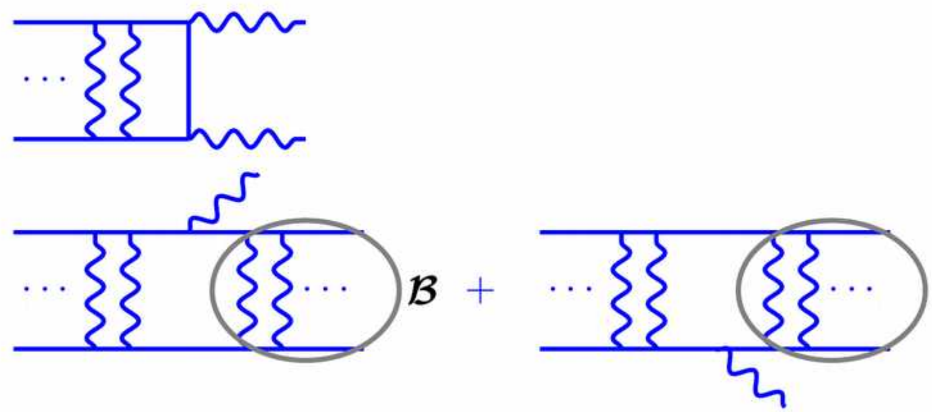
2) Higher partial waves

In direct annihilation processes, *s*-wave dominates.

However, DM may annihilate via formation and decay of bound states.
The bound-state ladder reduces the order of the diagram!

$$\sigma^{(\ell=0)}_{\rm ann} v_{\rm rel} \xrightarrow{\alpha_D \gg v_{\rm rel}} \frac{2\pi^2\alpha_D^3}{M^2_{\rm DM} v_{\rm rel}}$$

$$\sigma^{(\ell=1)}_{\rm BSF} v_{\rm rel} \xrightarrow{\alpha_D \gg v_{\rm rel}} 3.13 \times \frac{2\pi^2\alpha_D^3}{M^2_{\rm DM} v_{\rm rel}}$$



Both *s*- and *p*- wave saturate their unitarity limit at $\alpha_D \simeq 0.86$.
⇒ Consider combined bound on DM mass, $M_{\rm uni} \simeq 276$ TeV

Baldes, KP: 1703.00478

Partial-wave unitarity limit

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

Higher partial waves important for DM depletion in the early universe
⇒ higher $M_{\rm uni}$

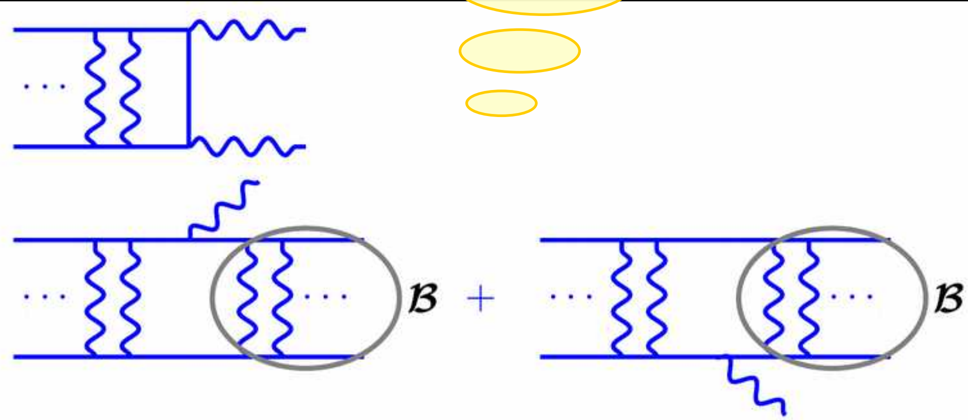
2) Higher partial waves

In direct annihilation processes, *s*-wave dominates.

However, DM may annihilate via formation and decay of bound states.
The bound-state ladder reduces the order of the diagram!

$$\sigma_{\rm ann}^{(\ell=0)} v_{\rm rel} \xrightarrow{\alpha_D \gg v_{\rm rel}} \frac{2\pi^2\alpha_D^3}{M_{\rm DM}^2 v_{\rm rel}}$$

$$\sigma_{\rm BSF}^{(\ell=1)} v_{\rm rel} \xrightarrow{\alpha_D \gg v_{\rm rel}} 3.13 \times \frac{2\pi^2\alpha_D^3}{M_{\rm DM}^2 v_{\rm rel}}$$



Both *s*- and *p*- wave saturate their unitarity limit at $\alpha_D \simeq 0.86$.
⇒ Consider combined bound on DM mass, $M_{\rm uni} \simeq 276$ TeV

Baldes, KP: 1703.00478

Partial-wave unitarity limit

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

Can be approached or realised only in models with attractive long-range interactions

Baldes, KP: 1703.00478

Generic conclusion:

In viable thermal-relic DM scenarios, expect long-range behaviour at $m_{DM} \gtrsim$ few TeV!

- Implications for all experimental probes: DM mass and/or couplings different than otherwise estimated.
- Indirect detection in the multi-TeV regime: non-perturbative effects (Sommerfeld, BSF) must be considered

Cirelli, Panci, KP, Sala, Taoso 1612.07295
Baldes, KP 1703.00478
Baldes, Cirelli, Panci, KP, Sala, Taoso 1712.07489
Cirelli, Gouttenoire, KP, Sala 1811.03608

What about WIMPs ?

- Long-range condition: $\alpha_2 M_{DM} \gtrsim m_W \Rightarrow M_{DM} \gtrsim 3$ TeV
- Long-range effects more important for DM in higher $SU_L(2)$ multiplets
  - Pure 3-plet (Wino-like): $M_{DM} \sim 3$ TeV, only Sommerfeld important.
  - Pure 5-plet: $M_{DM} \sim 14$ TeV, Sommerfeld & bound states important.
- Mixed multiplet and coannihilation scenarios: more complexity
  - Neutralino-squark co-annihilation
  - Higgs-portal models

3. 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

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

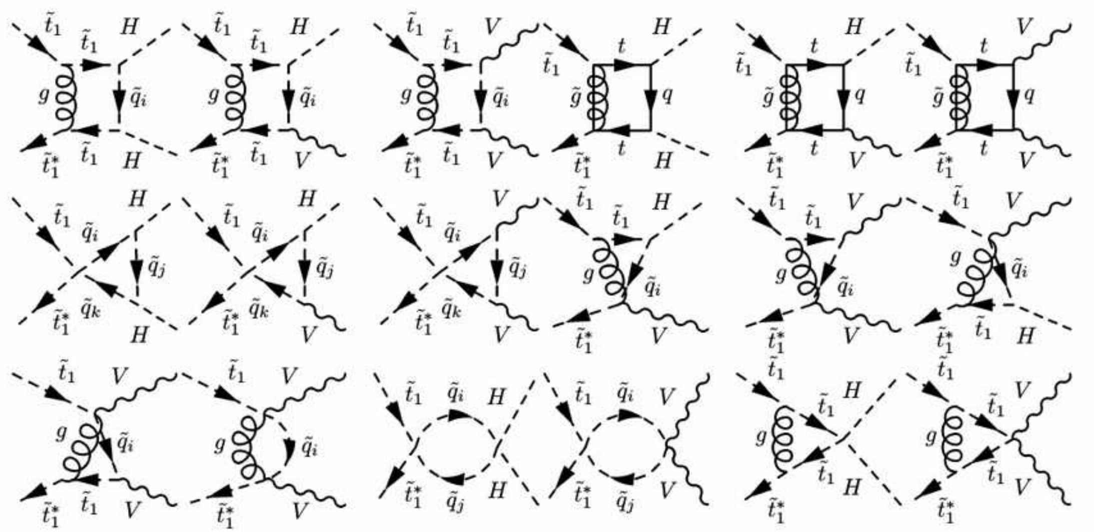
$$\sigma^{\rm eff}_{\rm ann} = [\, n^2_{\rm LSP}\, \sigma^{\rm LSP}_{\rm ann} + n^2_{\rm NLSP}\, \sigma^{\rm NLSP}_{\rm ann} + n_{\rm LSP}\, n_{\rm NLSP}\, \sigma^{\rm LSP-NLSP}_{\rm ann} \,]/n^2_{\rm tot}$$

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

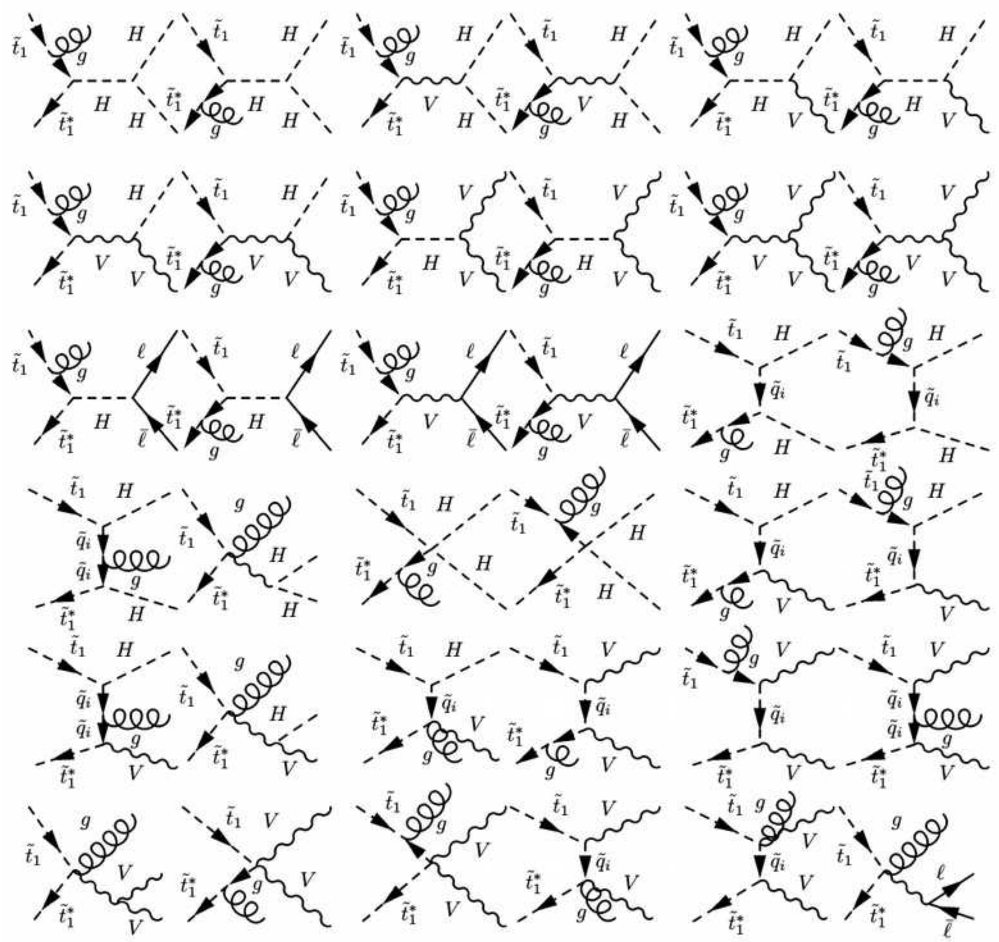
QCD corrections to stop annihilation

[Klasen+ (since 2014), DM@NLO]

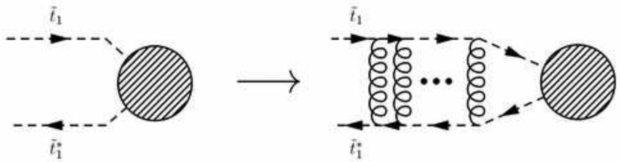
QCD loop corrections



Gluon emission



Sommerfeld effect

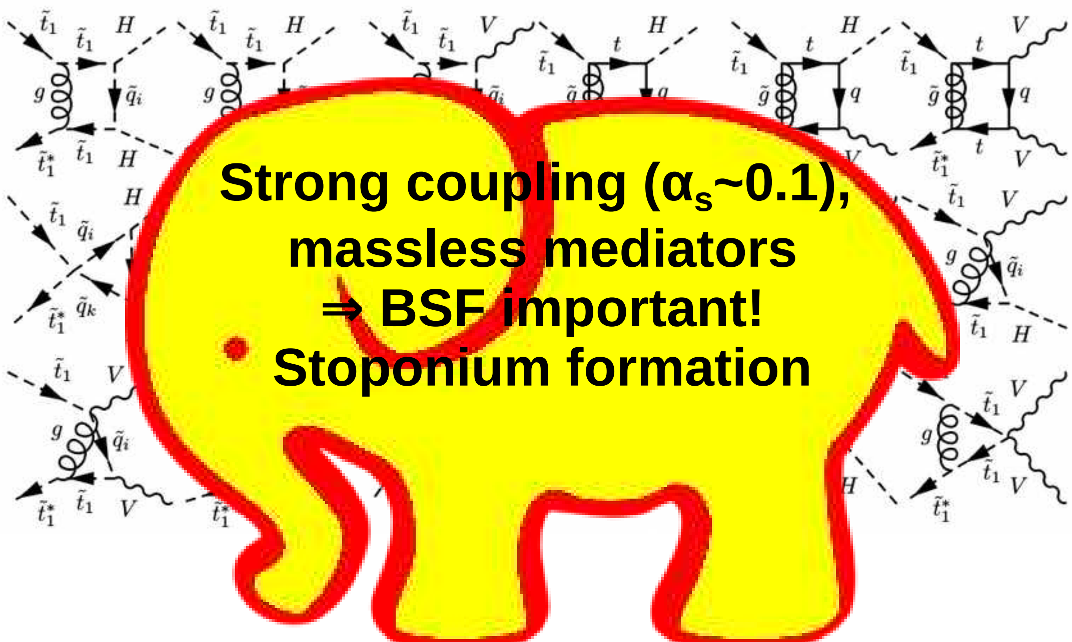


broadly, the most important

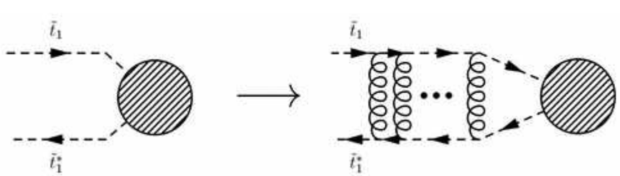
QCD corrections to stop annihilation

[Klasen+ (since 2014), DM@NLO]

QCD loop corrections

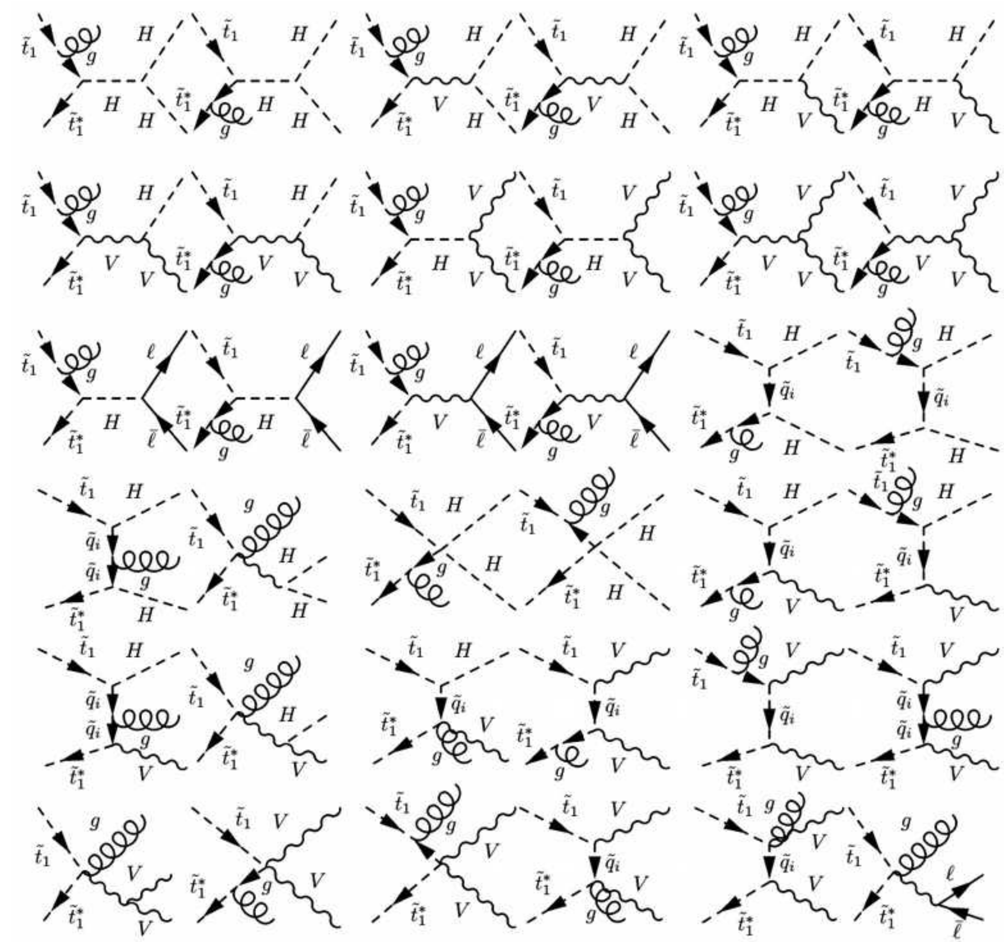


Sommerfeld effect



broadly, the most important

Gluon emission



DM coannihilation with scalar colour triplet

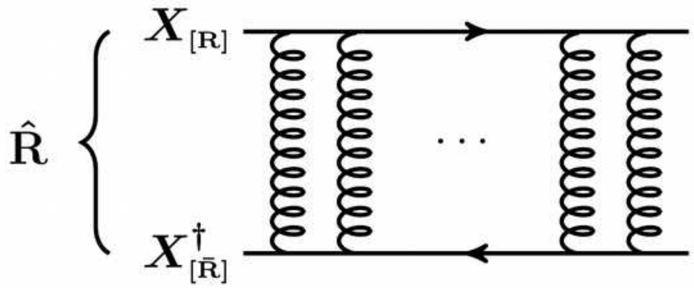
MSSM-inspired toy model

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

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

Long-range interaction



$$R \otimes \bar{R} = \sum_{\hat{R}} \hat{R} = 1 \oplus \text{adj} + \cdots$$

$$V(r) = -\,\alpha_{g,[\hat{R}]} \,/\, r$$

$$\alpha_{g,[\hat{R}]} = \alpha_s \times \left[C_2(R) - C_2(\hat{R})/2\right]$$

where $\alpha_s = g_s^2/(4\pi)$

for SU(3)

$$3 \otimes \bar{3} = 1 \oplus 8$$

$$\alpha_{g,[1]} = +\,(4/3)\alpha_s \quad \text{attractive}$$

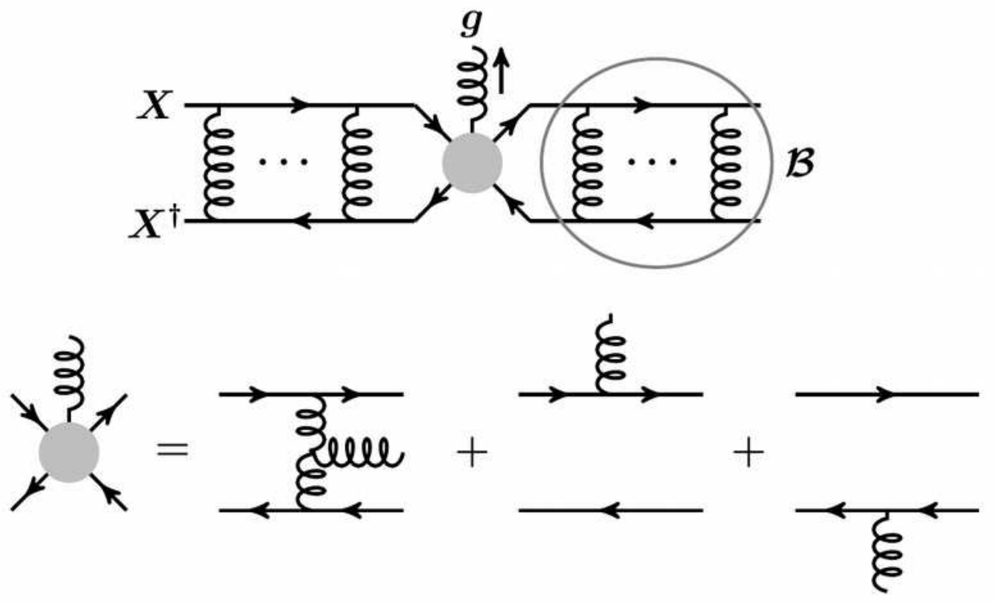
$$\alpha_{g,[8]} = -\,(1/6)\alpha_s \quad \text{repulsive}$$

with $\alpha_s \sim 0.1$ at $m_X \sim \text{TeV}$

DM coannihilation with scalar colour triplet

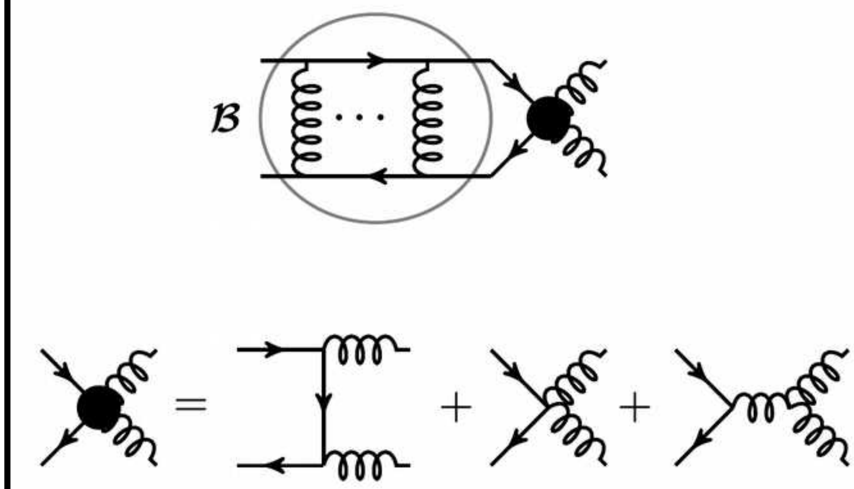
MSSM-inspired toy model

Bound-state formation and decay



Allowed transitions

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



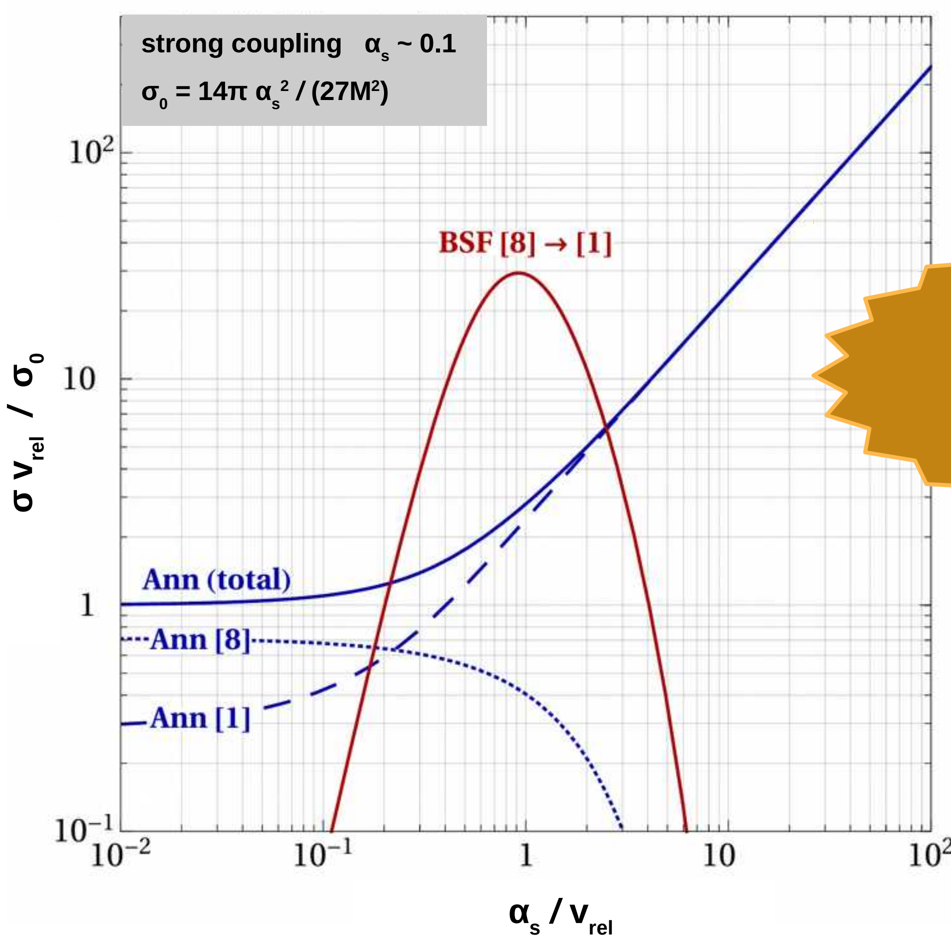
Harz, KP 1805.01200: Cross-sections for radiative BSF in non-Abelian theories

In agreement with Brambilla, Escobedo, Ghiglieri, Vairo 1109.5826:
Gluo-dissociation of quarkonium in pNRQCD

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

Bound-state formation *vs* Annihilation

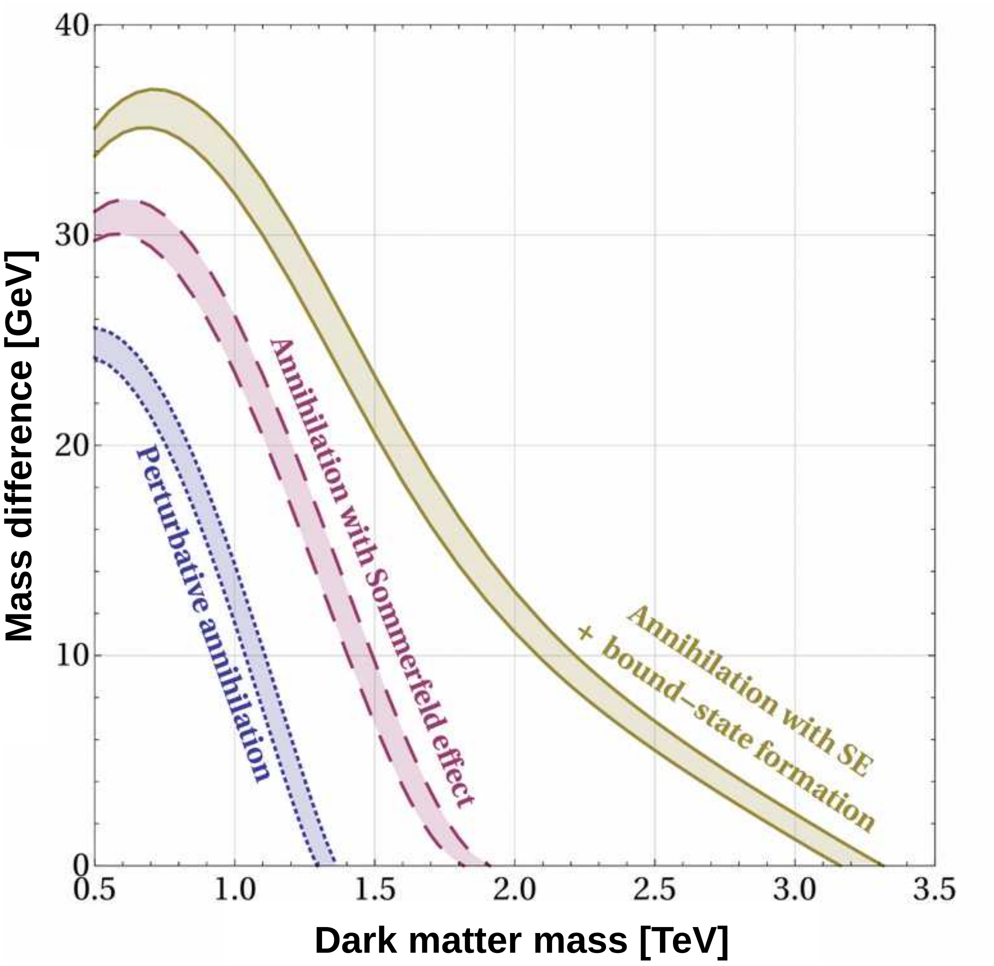


BSF can exceed Ann by more than an order of magnitude!

Harz, KP 1805.01200: Cross-sections for radiative BSF in non-Abelian theories

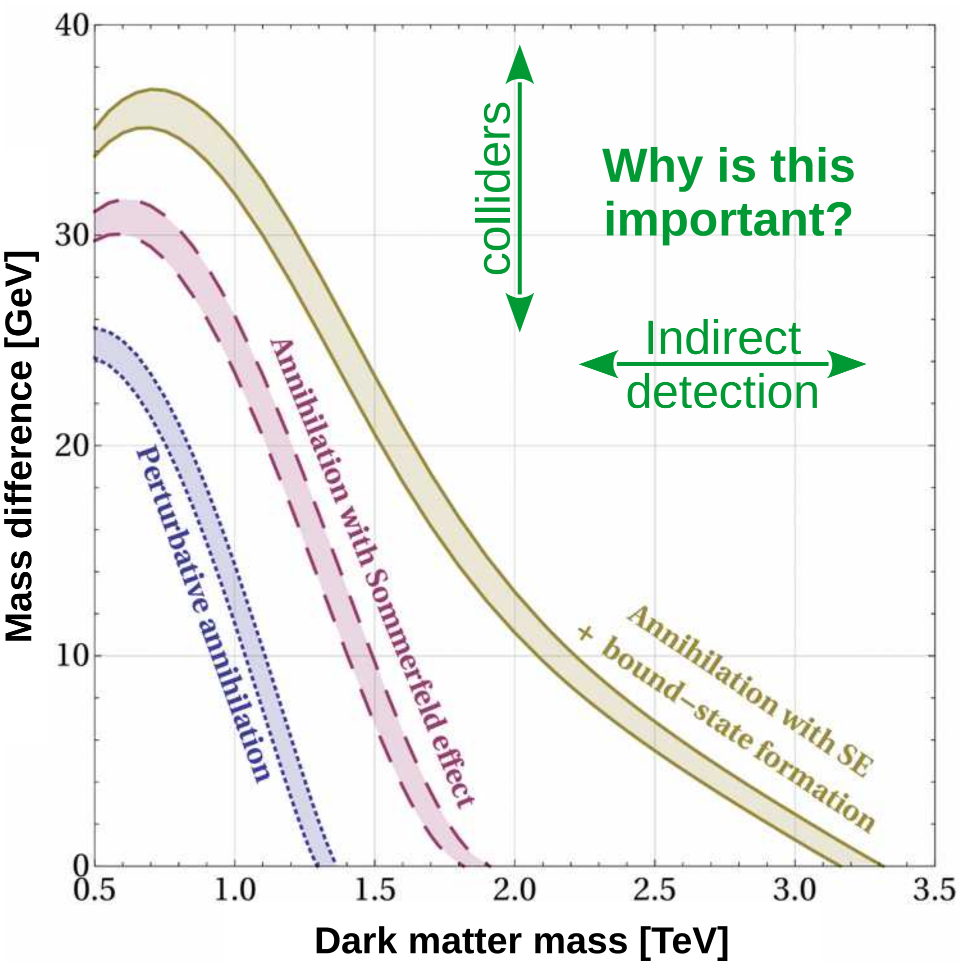
In agreement with Brambilla, Escobedo, Ghiglieri, Vairo 1109.5826:
Gluo-dissociation of quarkonium in pNRQCD

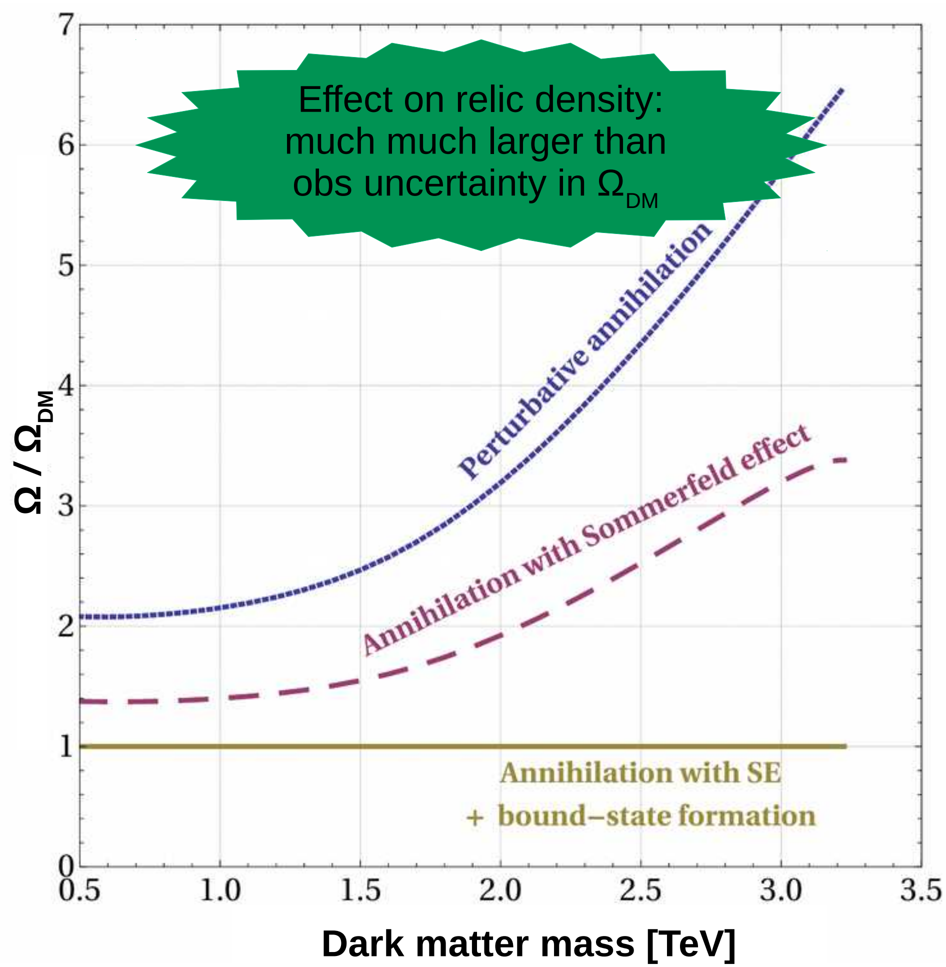
DM coannihilation with scalar colour triplet
MSSM-inspired toy model



Harz, KP: 1805.01200

DM coannihilation with scalar colour triplet
MSSM-inspired toy model





Harz, KP: 1805.01200

4. The SM Higgs as a light mediator

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**

Higgs enhancement and relic density

MSSM-inspired toy model

DM co-annihilating with scalar colour-triplet
that has a sizeable coupling to the Higgs

e.g. stop-neutralino co-annihilation scenarios with large *A* terms

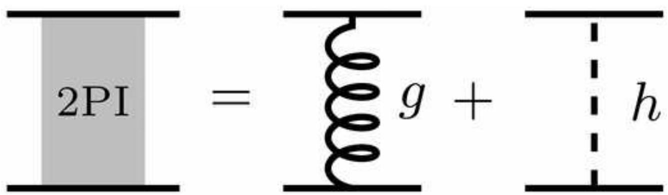
$$\begin{aligned}
\mathcal{L} \supset\ & \frac{1}{2}\overline{\chi^c}\, i\partial\!\!\!/ \chi - \frac{1}{2} m_\chi \overline{\chi^c}\chi \\
+\ & \left[(\partial_\mu + i g_s G^a_\mu T^a) X\right]^\dagger \left[(\partial^\mu + i g_s G^{a,\mu} T^a) X\right] - m_X^2 |X|^2 \\
+\ & \frac{1}{2}\partial_\mu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

$$\alpha_s = \frac{g_s^2}{4\pi} \qquad \alpha_h = \frac{g_h^2}{16\pi}$$

Harz, KP: 1711.03552, 1901.10030

Higgs enhancement and relic density

MSSM-inspired toy model

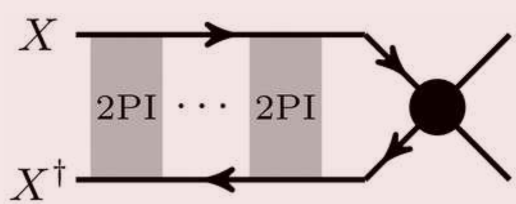


$$V(r) = -\frac{\alpha_g}{r} - \frac{\alpha_h}{r}\, e^{-m_h r}$$

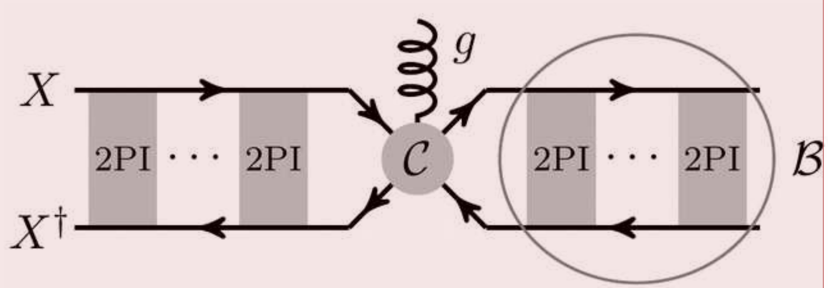
gluon exchange

Higgs exchange, typically thought to be too short-range

Enhancement of direct annihilation



Higgs-mediated bound states



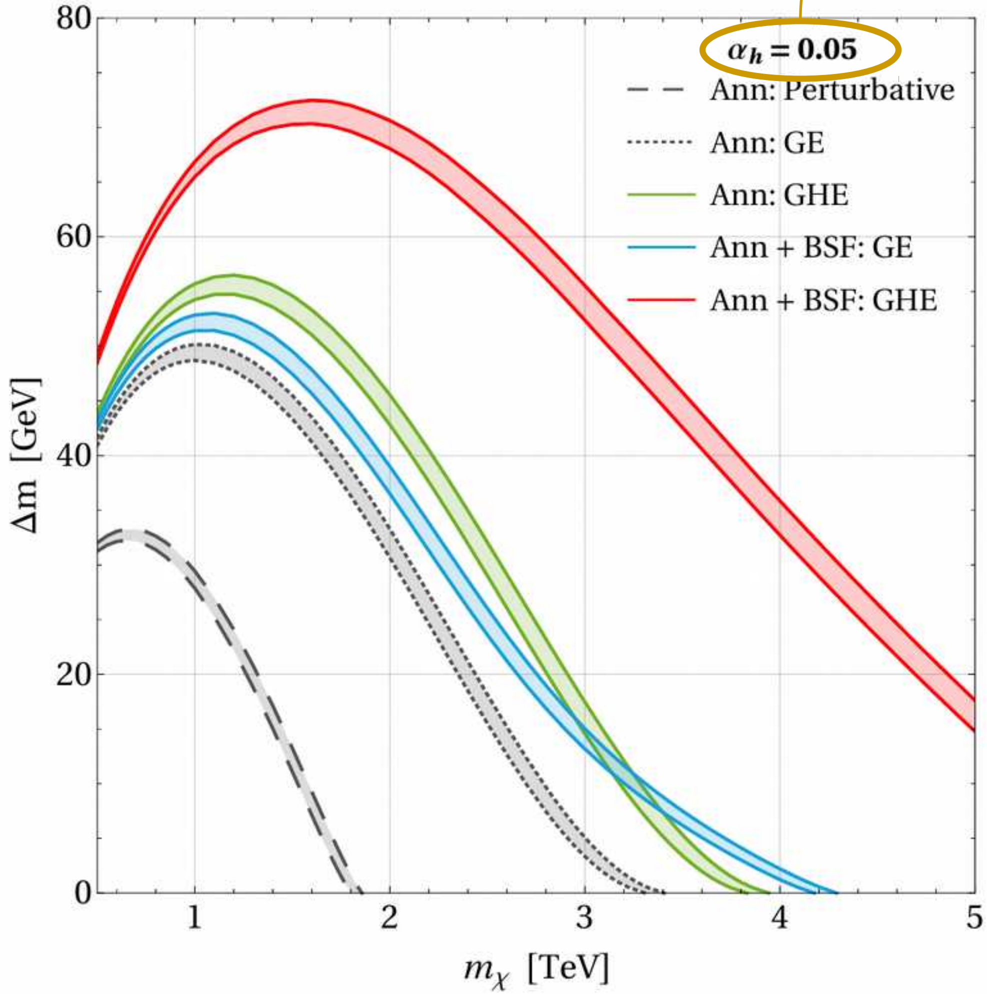
Gluon potential influences the long-range effect of the Higgs!

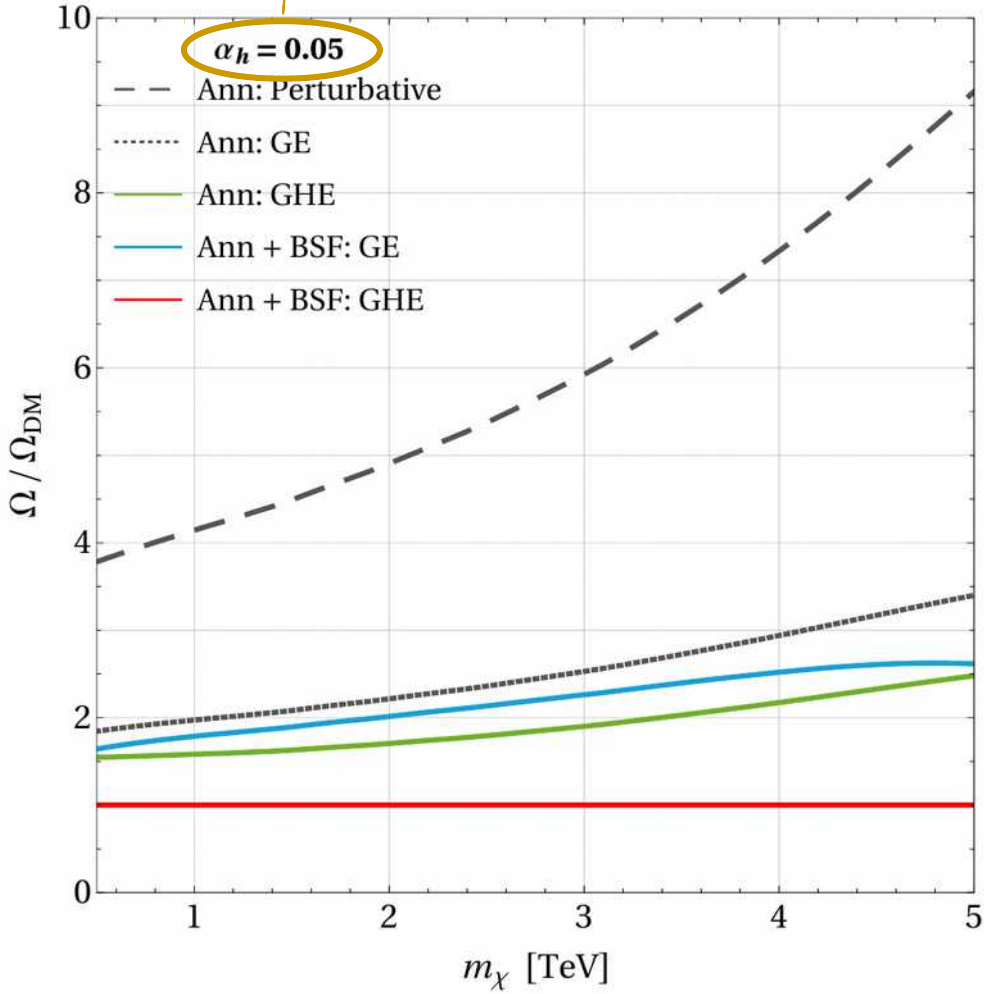
Harz, KP: 1711.03552, 1901.10030

Higgs enhancement and relic density

MSSM-inspired toy model

Moderate coupling, appears in MSSM





Harz, KP: 1711.03552, 1901.10030

Higgs as a light mediator

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

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.

5. Bound-state formation via emission of a charged scalar

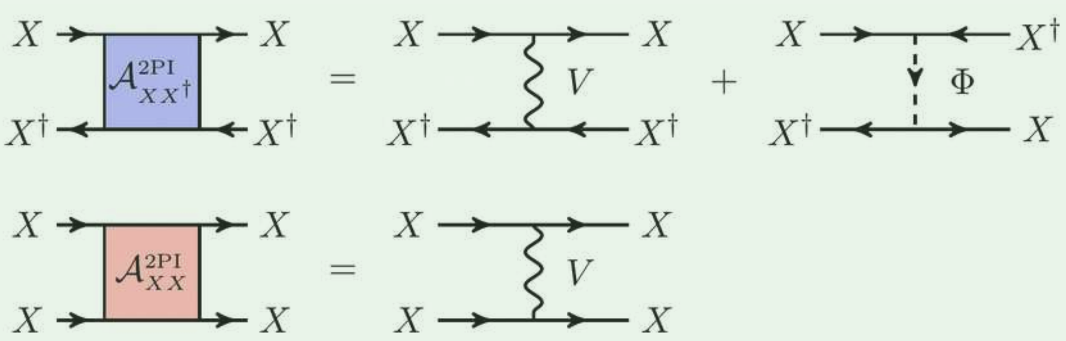
BSF via emission of a *charged* scalar

U(1) model:

scalar DM *X,X†* coupled to doubly charged light scalar *Φ*

$$\mathcal{L} \supset \; -igX^\dagger V^\mu(\partial_\mu X) \; -i2g\Phi^\dagger V^\mu(\partial_\mu \Phi) \; -\frac{y m_X}{2} XX\Phi^\dagger + h.c.$$

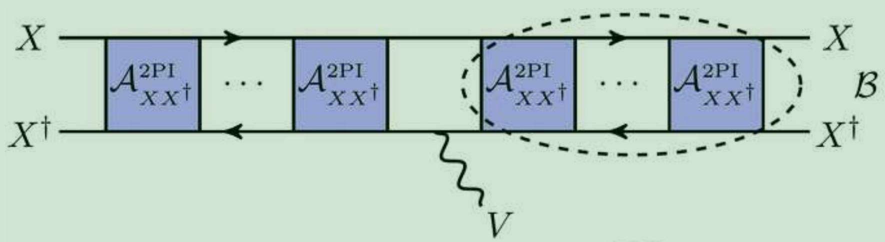
$$m_X \gg m_\Phi$$



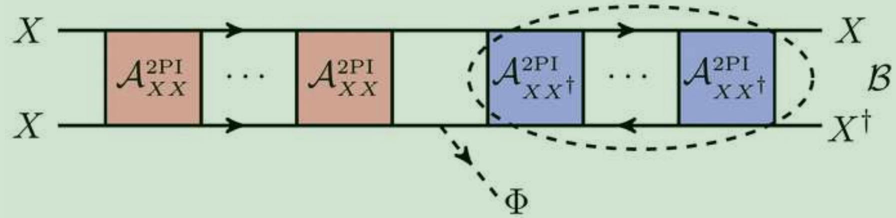
$$U_{XX^\dagger}(r) \;=\; -\frac{\alpha_V}{r} \;-(-1)^\ell \,\frac{\alpha_\Phi}{r}\, e^{-m_\Phi r}$$

$$U_{XX}(r) \;=\; +\frac{\alpha_V}{r}$$

BSF$_V$



BSF$_\Phi$

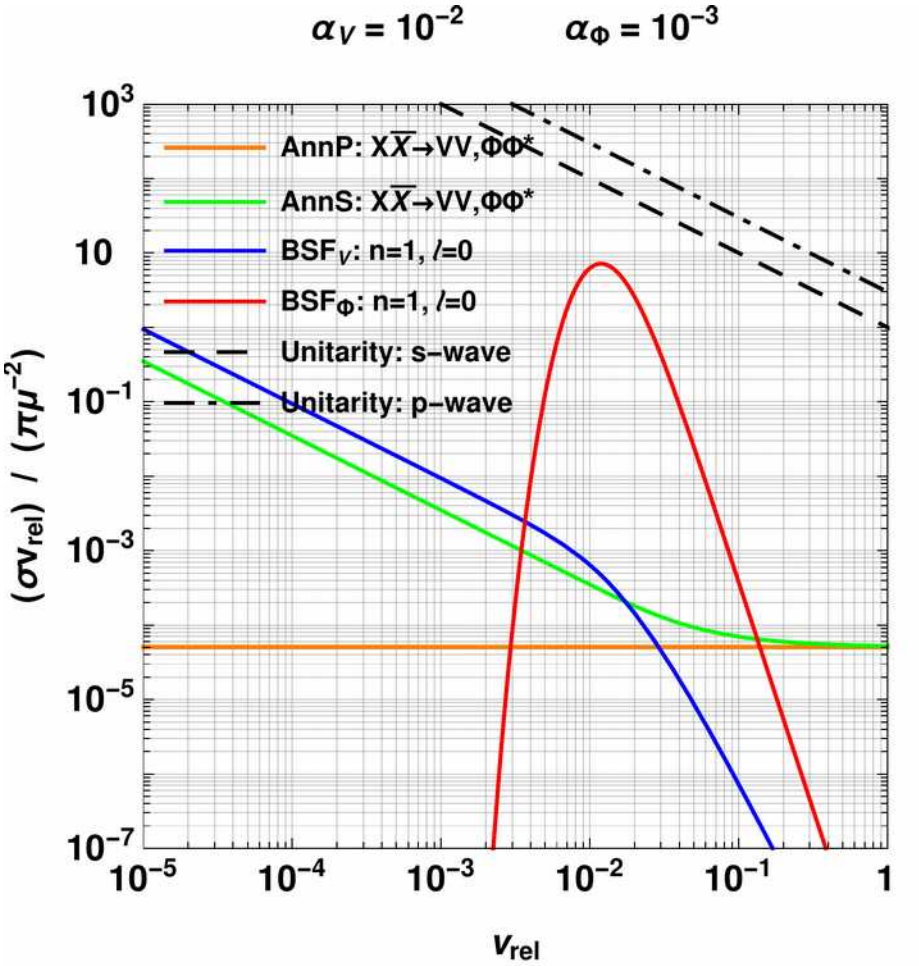


Change in effective Hamiltonian.
Very fast transition!

Oncala, KP: 1911.02605

BSF via emission of a *charged* scalar

U(1) model

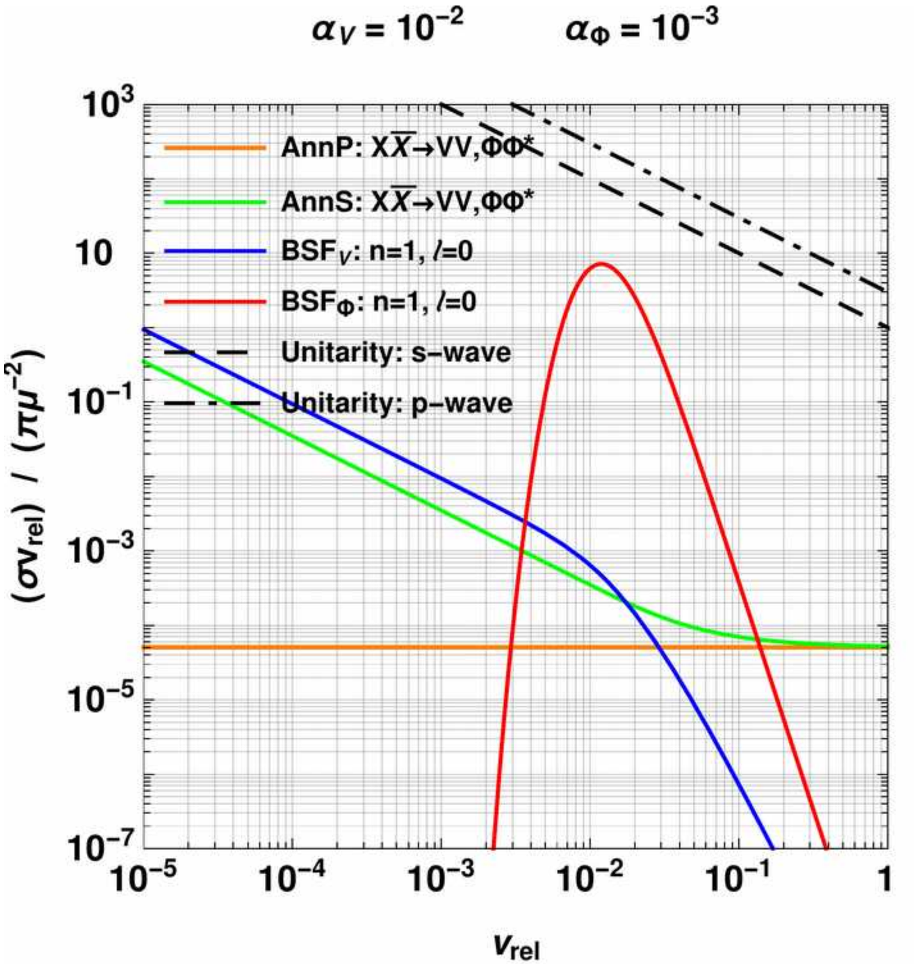


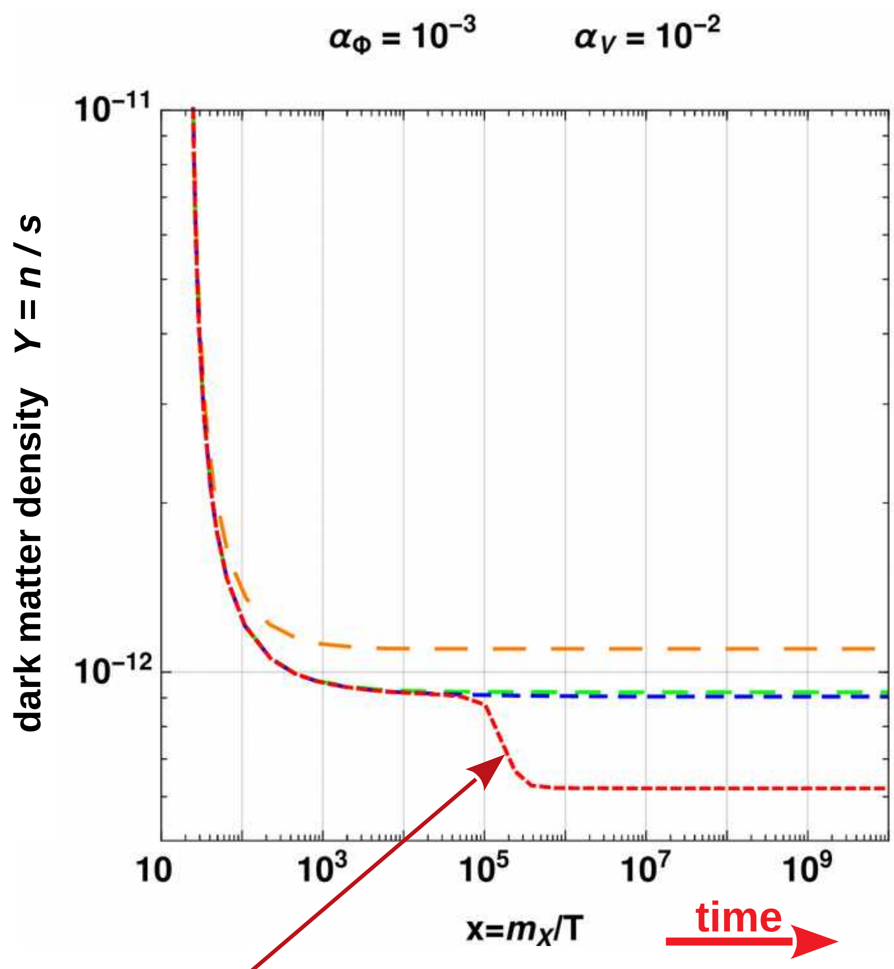
BSF_Φ very large, even for small values of α_Φ, α_V !

Oncala, KP: 1911.02605

BSF via emission of a *charged* scalar

U(1) model



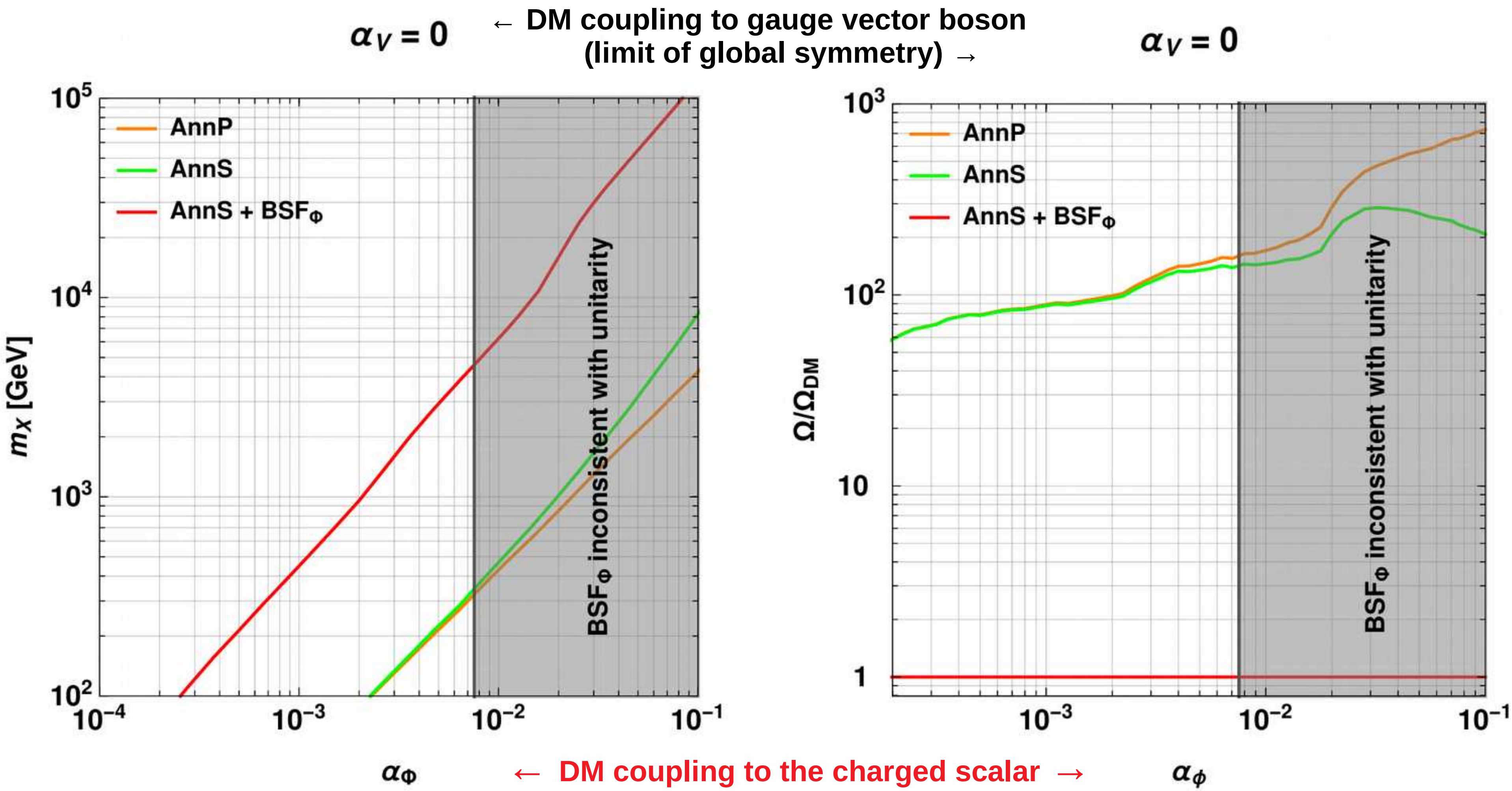


At T ~ binding energy << m_X/30
⇒ recoupling of DM destruction
when BSF via charged scalar emission considered

Oncala, KP: 1911.02605
(see also Ko,Matsui,Tang:1910:04311)

BSF via emission of a *charged* scalar

U(1) model

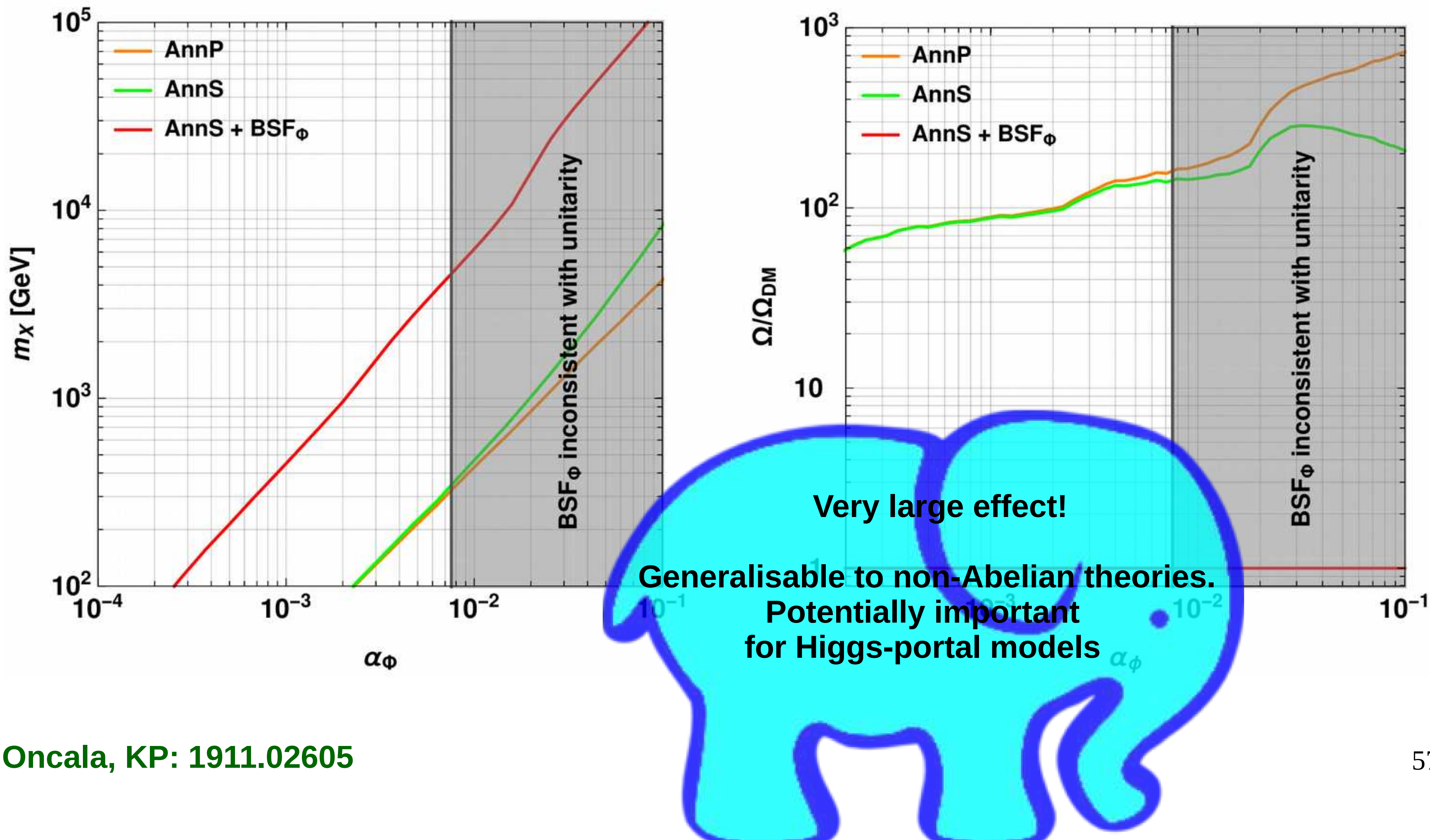


Oncala, KP: 1911.02605

BSF via emission of a *charged* scalar

U(1) model

$\alpha_V = 0$ ← DM coupling to gauge vector boson (limit of global symmetry) → $\alpha_V = 0$



Very large effect!

Generalisable to non-Abelian theories.
Potentially important
for Higgs-portal models

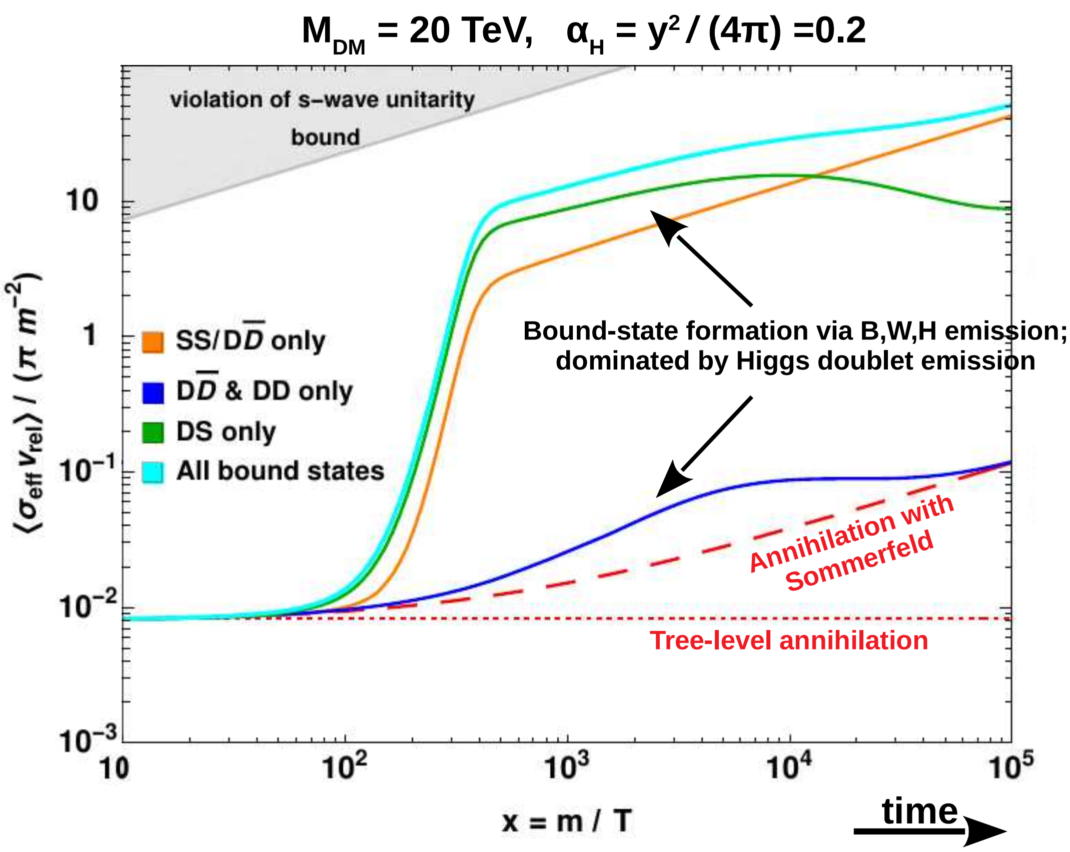
Oncala, KP: 1911.02605

6. Bound-state formation via Higgs-doublet emission

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

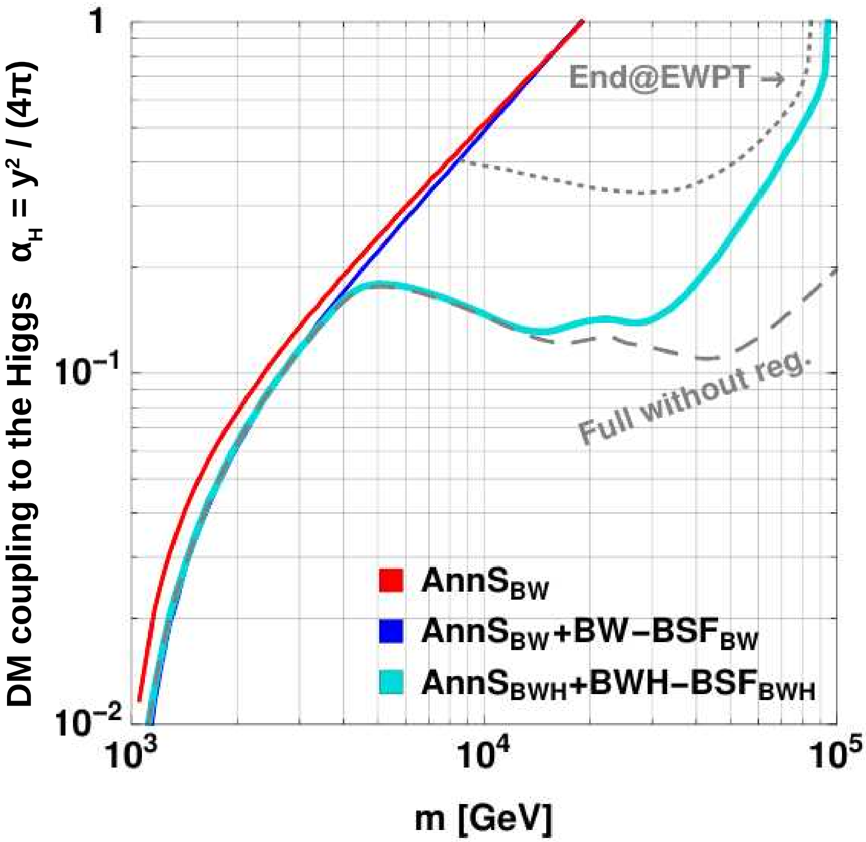


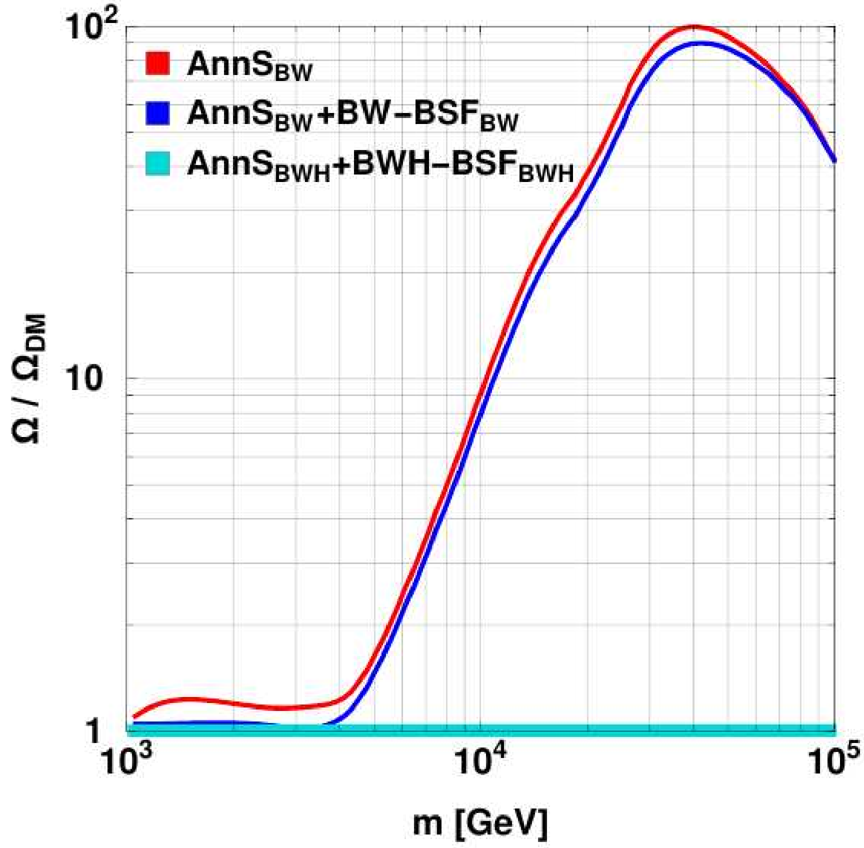
Oncala, KP: 2101.08666/7

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



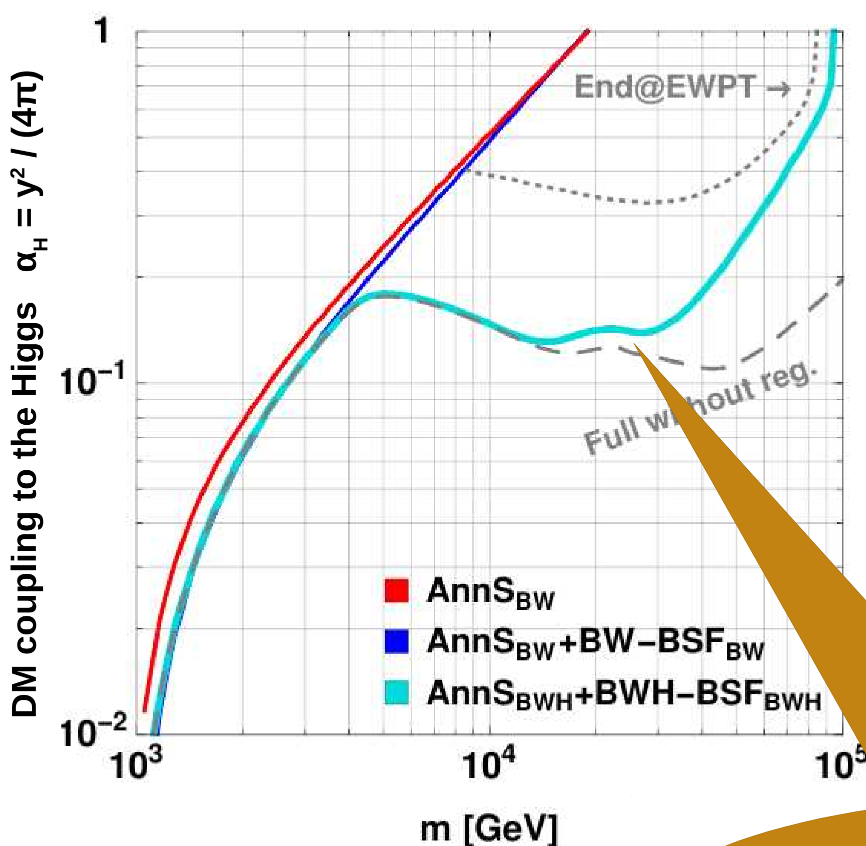


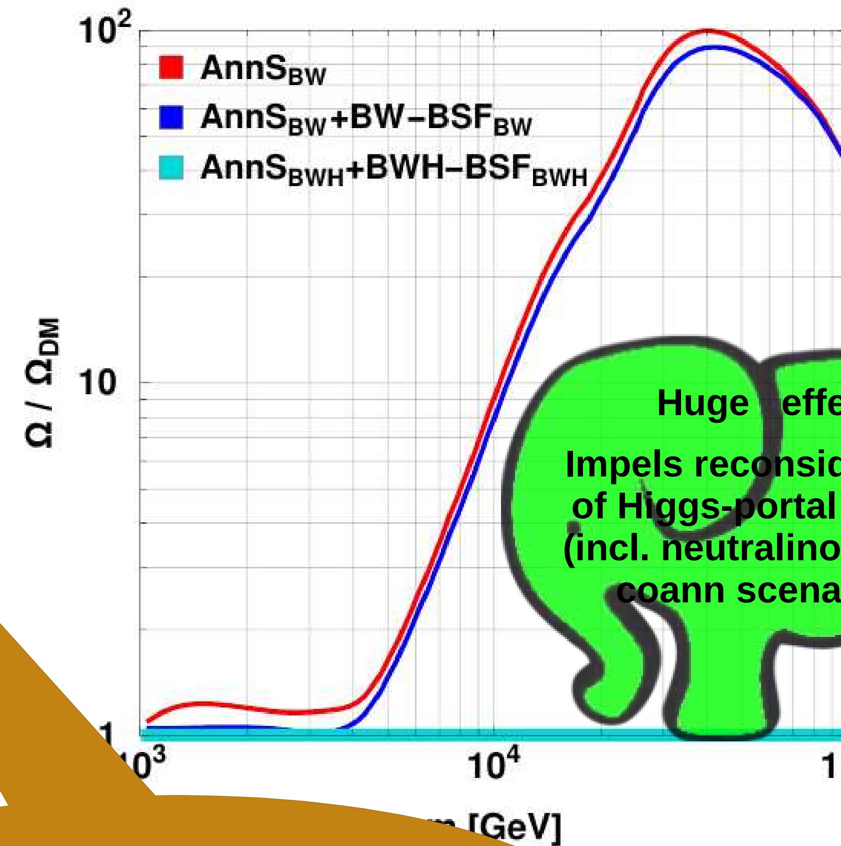
Oncala, KP: 2101.08666/7

Renormalisable Higgs-portal WIMP models

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

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





Huge effect!

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

Effect only at large α_H, due to phase-space suppression in Higgs emission.

For higher multiplets, important effect expected also at lower α_H.

Oncala, KP: 2101.08666/7

Conclusion
(*or my ten ~~cents~~ drachmas)*

Δημόκριτος

- **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