Dark-matter bound states: overhauling thermal decoupling at the TeV scale

Kallia Petraki

Sorbonne University, LPTHE, Paris and Nikhef, Amsterdam

TeVPA

Sydney, 02 December 2019

Classification schemes
of dark matter candidates

Interaction with the SM

Portal operators	SM interactions	Heavy mediators
$\epsilon\, F_Y^{\mu\nu} F_{D\,\mu\nu}$ $(\mu\phi + \lambda\phi^2)\lvert H\rvert^2$ $yLHN$	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 Heavy meds Light meds

Classification schemes
of dark matter candidates

most of DM research

Interaction with the SM

Portal operators	SM interactions	Heavy mediators
$\epsilon F_Y^{\mu\nu} F_{D\,\mu\nu}$ $(\mu\phi + \lambda\phi^2)\|H\|^2$ $yLHN$	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 Heavy meds Light meds

Classification schemes
of dark matter candidates

this talk

Interaction with the SM

Portal operators	SM interactions	Heavy mediators
$\epsilon F_{Y}^{\mu\nu} F_{D\,\mu\nu}$ $(\mu\phi + \lambda\phi^2)\|H\|^2$ $yLHN$	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 Heavy meds Light meds

Long-range interactions
Motivation

Long-range interactions appear in a variety of DM theories

- 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.

Long-range interactions
mediated by
massless or light particles

→ **Bound states**

Bound states

Phenomenological implications

- **Stable bound states**
  - DM self-scattering in halos: Screening
  - Indirect detection signals: Radiative level transitions
  - Direct detection signals: Screening, inelastic scattering

- **Unstable (positronium-like) bound states**
  formation + decay = extra annihilation channel
  - Relic abundance
  - Indirect detection

Outline

Bound states and density of thermal relic DM

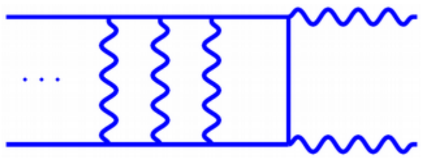
- Dark U(1) sector
- Neutralino-squark coannihilation scenarios
- The 125 GeV Higgs as a light mediator
- Bound-state formation via emission of a charged scalar
- Bound-state formation inside a relativistic thermal bath

Thermal freeze-out with long-range interactions

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

Direct annihilation

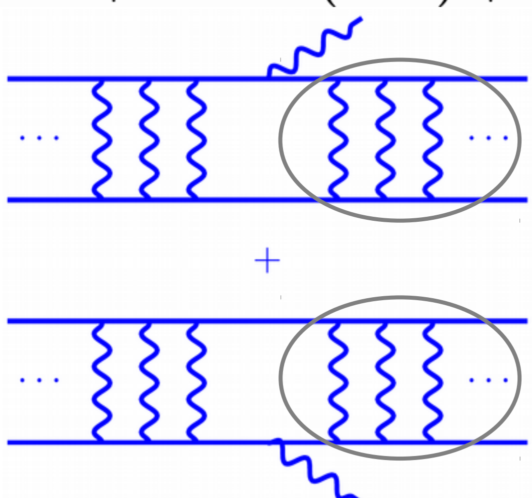
$$X + \bar{X} \to 2\gamma_D$$



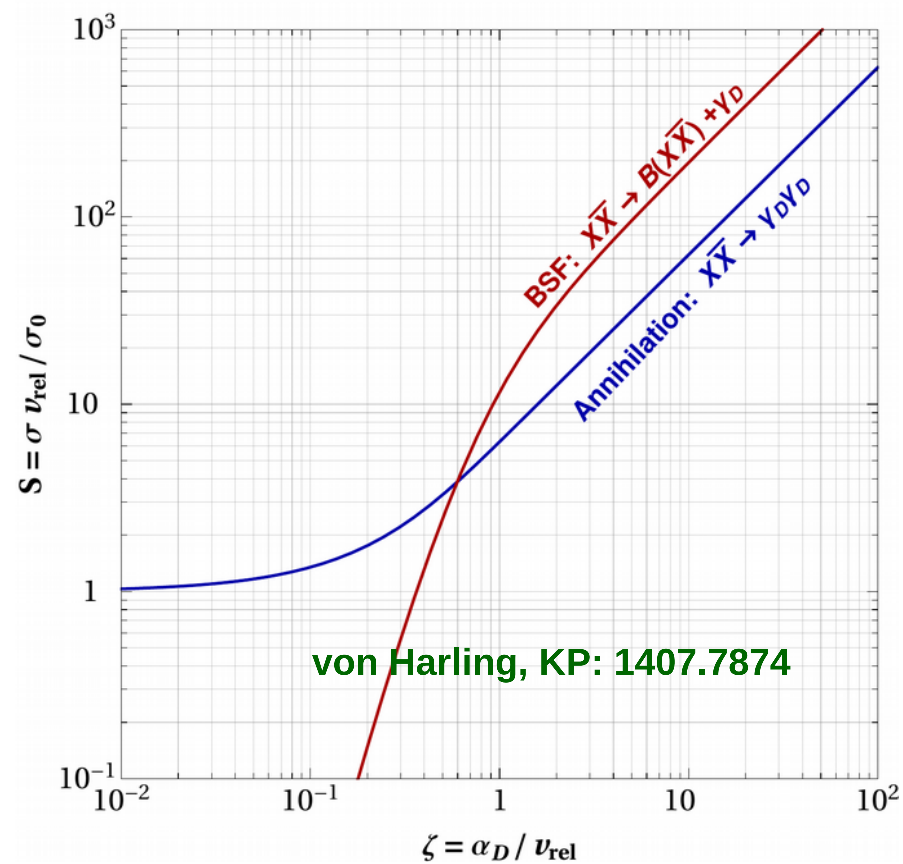
$$\sigma_{\rm ann} v_{\rm rel} = \frac{\pi \alpha_D^2}{m_X^2} \times S_{\rm ann}(\alpha_D / v_{\rm rel})$$

Radiative bound-state formation

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



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



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

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

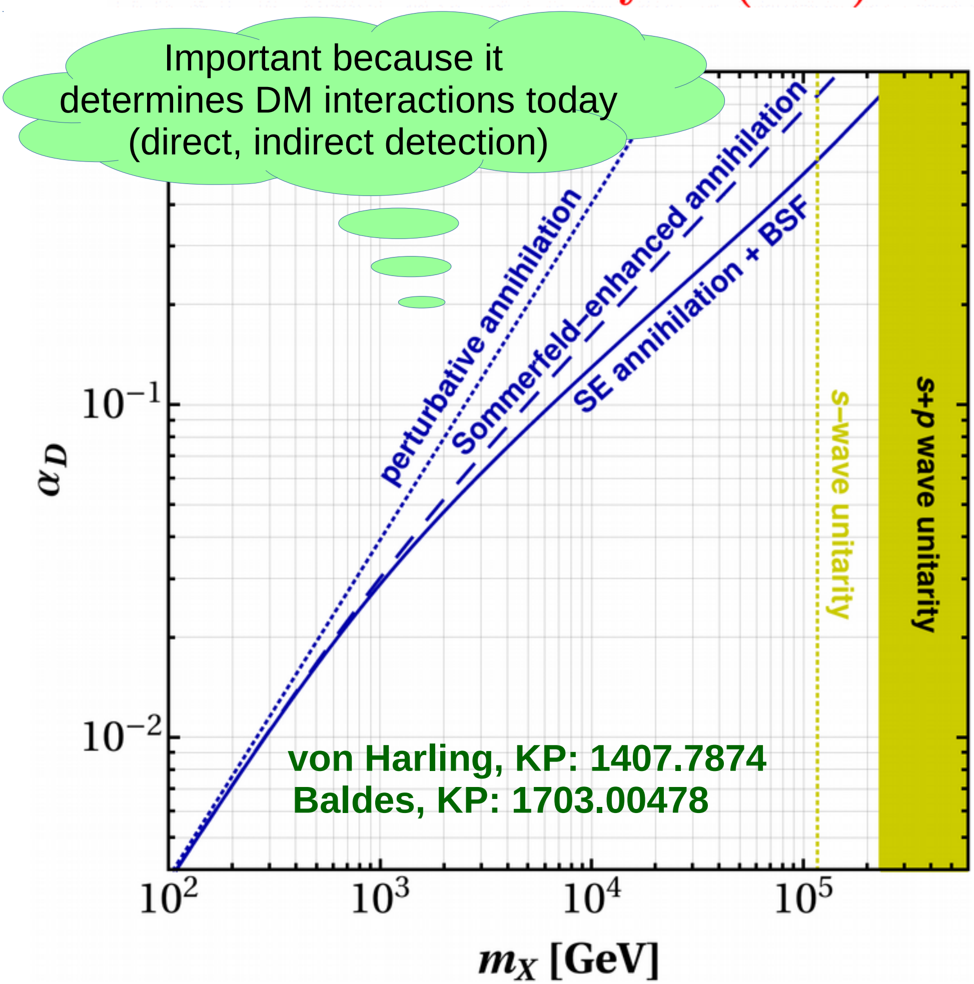
Thermal freeze-out with long-range interactions

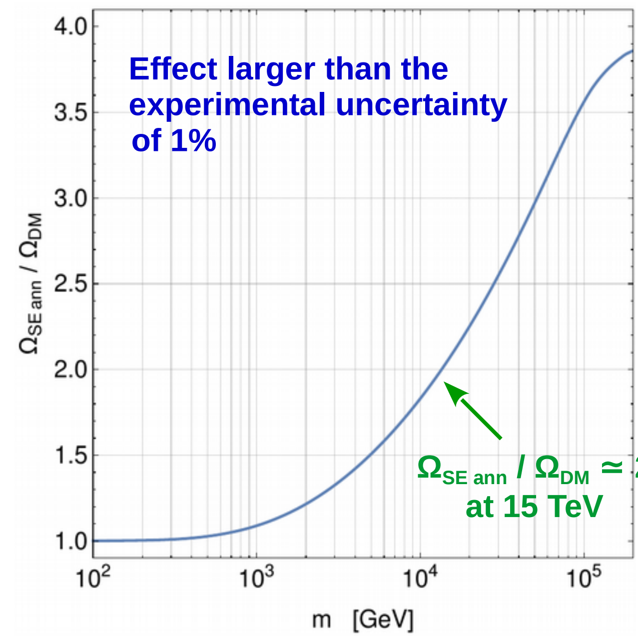
Dark U(1) model: Dirac DM $X,\bar{X}$ coupled to γ_D

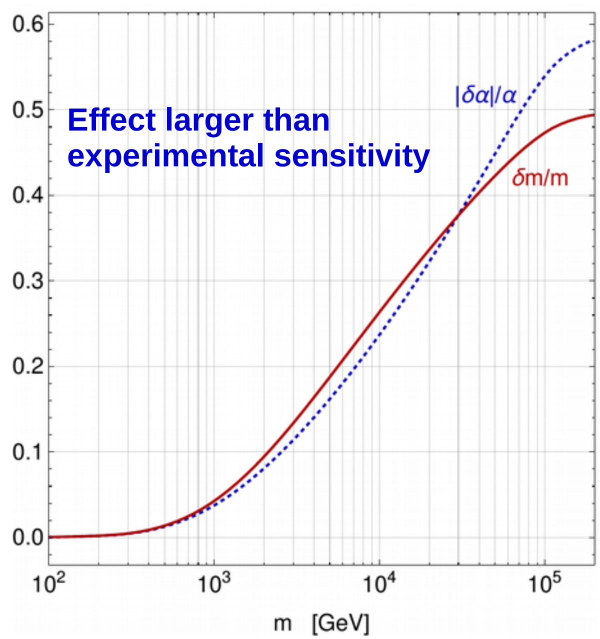
Direct Annihilation $X\bar{X} \to \gamma_D \gamma_D$

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 $3\gamma_D$







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

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

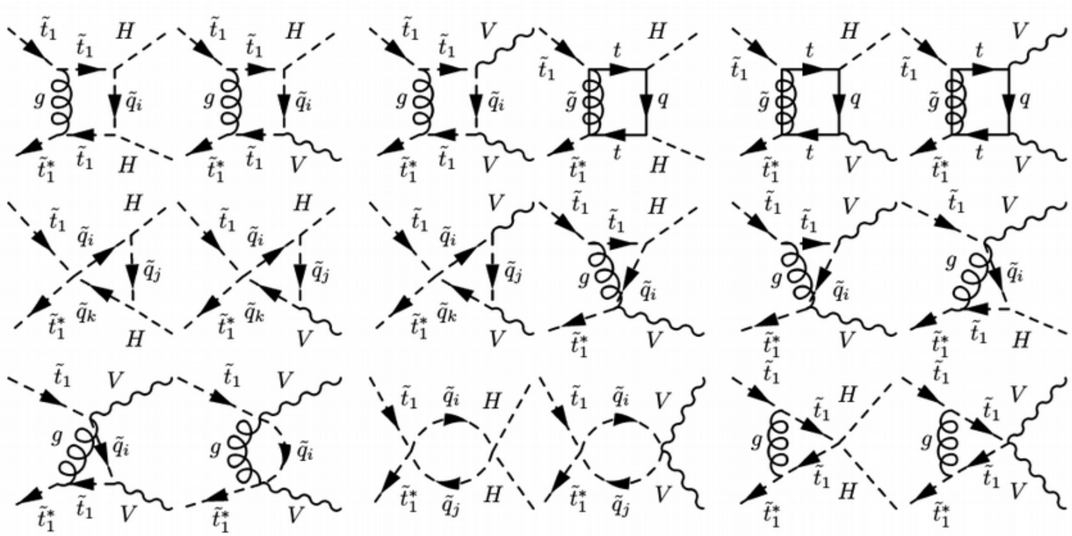
$$\sigma^{\rm eff}_{\rm ann} = [\, n^2_{\rm LSP}\, \sigma^{\rm LSP}_{\rm ann} + n^2_{\rm NLSP}\, \sigma^{\rm NLSP}_{\rm ann} + n_{\rm LSP}\, n_{\rm NLSP}\, \sigma^{\rm LSP-NLSP}_{\rm ann}\,]/n^2_{\rm tot}$$

Important to compute accurately!
→ QCD corrections

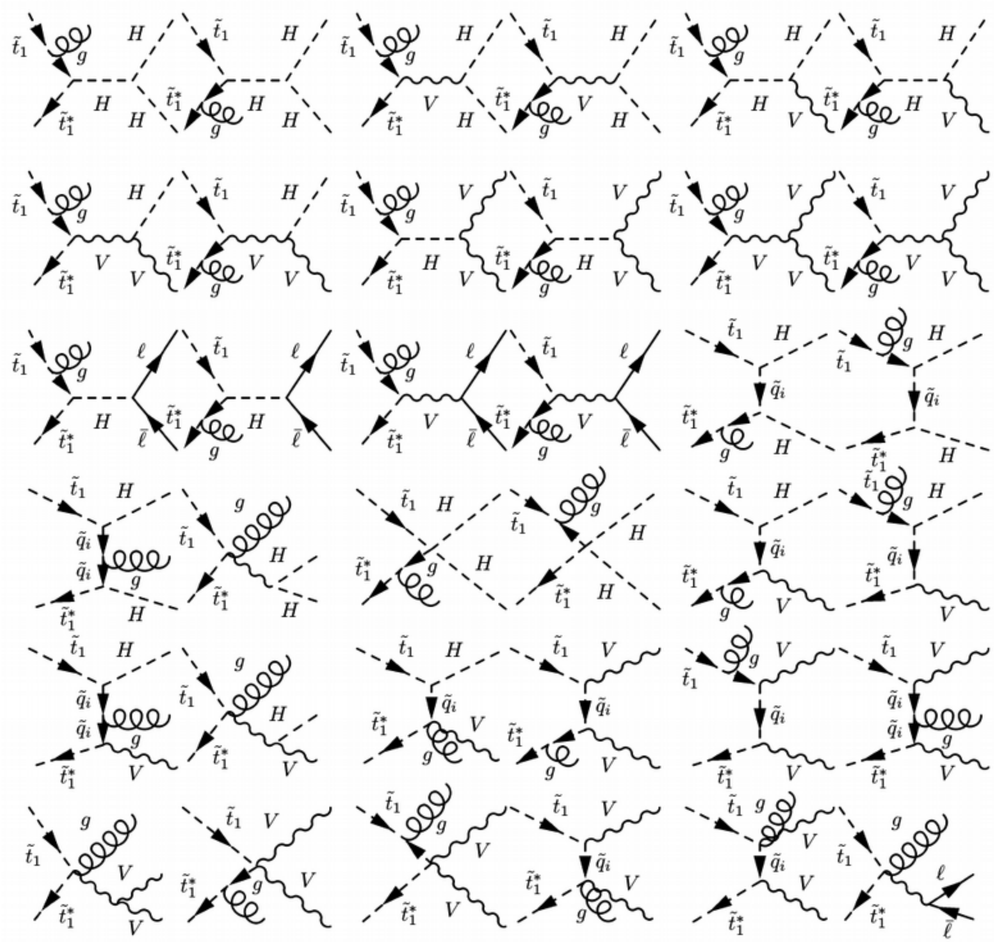
QCD corrections to stop annihilation

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

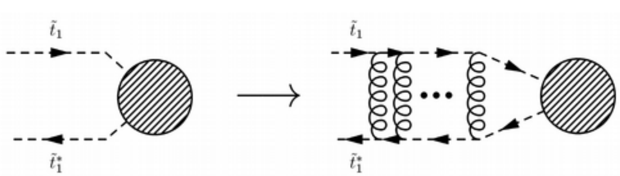
QCD loop corrections



Gluon emission



Sommerfeld effect

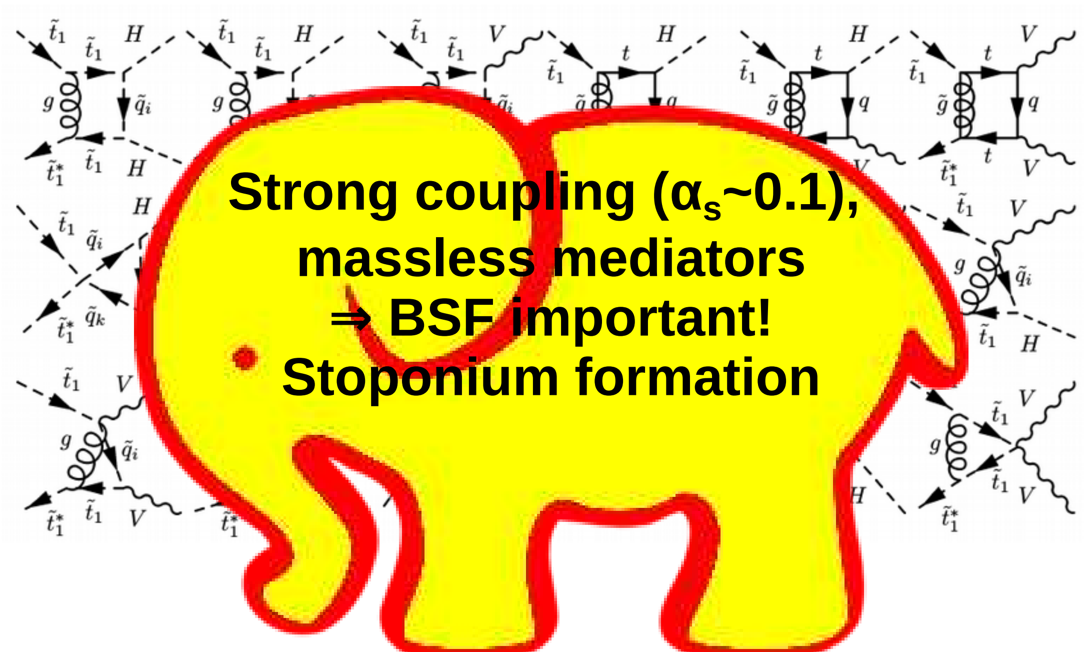


broadly, the most important

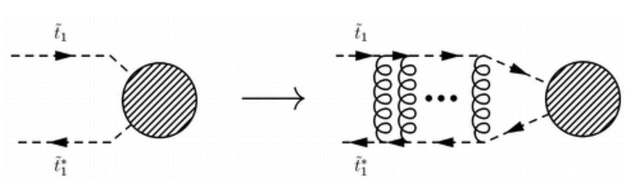
QCD corrections to stop annihilation

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

QCD loop corrections

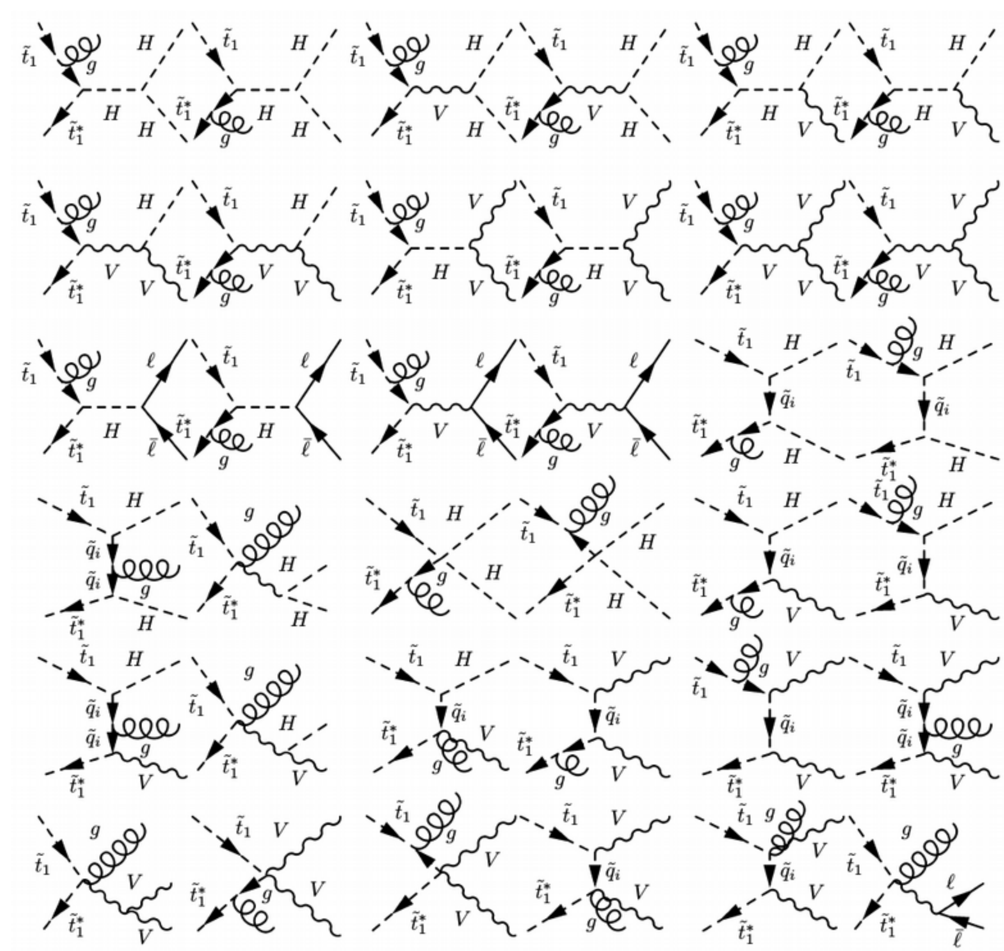


Sommerfeld effect



broadly, the most important

Gluon emission



DM coannihilation with scalar colour triplet

MSSM-inspired toy model

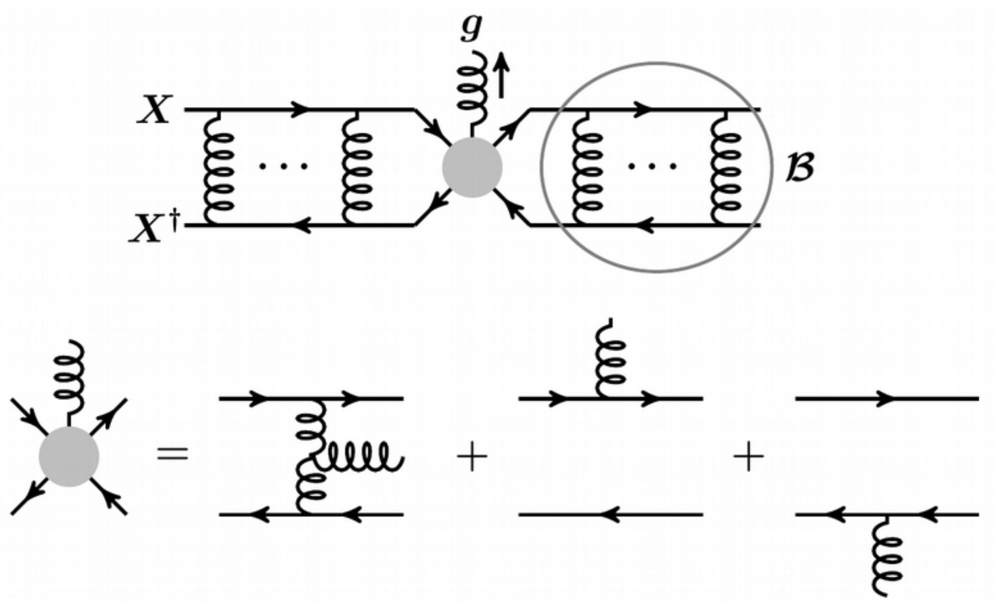
$$\begin{aligned}\mathcal{L} \supset\ & \frac{1}{2}\overline{\chi^c}\, i\partial\!\!\!/\chi - \frac{1}{2}m_\chi\,\overline{\chi^c}\chi \\ +\ & \left[(\partial_\mu + ig_s G^a_\mu T^a)X\right]^\dagger \left[(\partial^\mu + ig_s G^{a,\mu}T^a)X\right] - m_X^2|X|^2 \\ +\ & (\chi \leftrightarrow X, X^\dagger)\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

Harz, KP: 1805.01200

DM coannihilation with scalar colour triplet

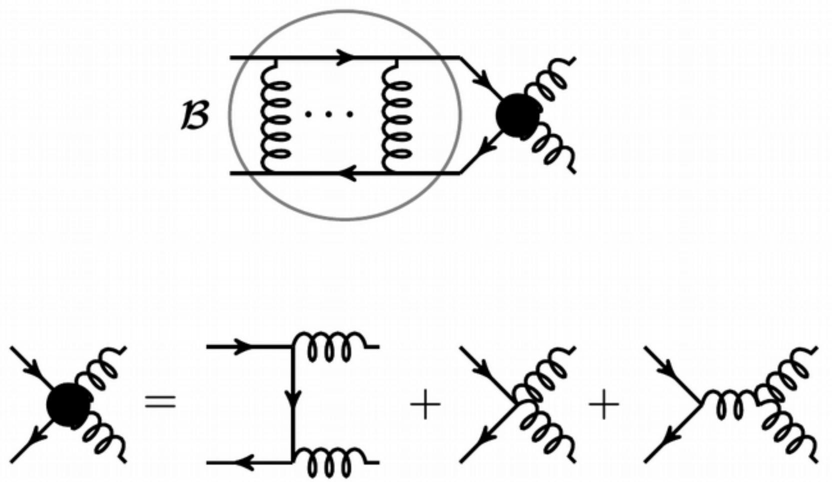
MSSM-inspired toy model

Bound-state formation and decay



Allowed transitions

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

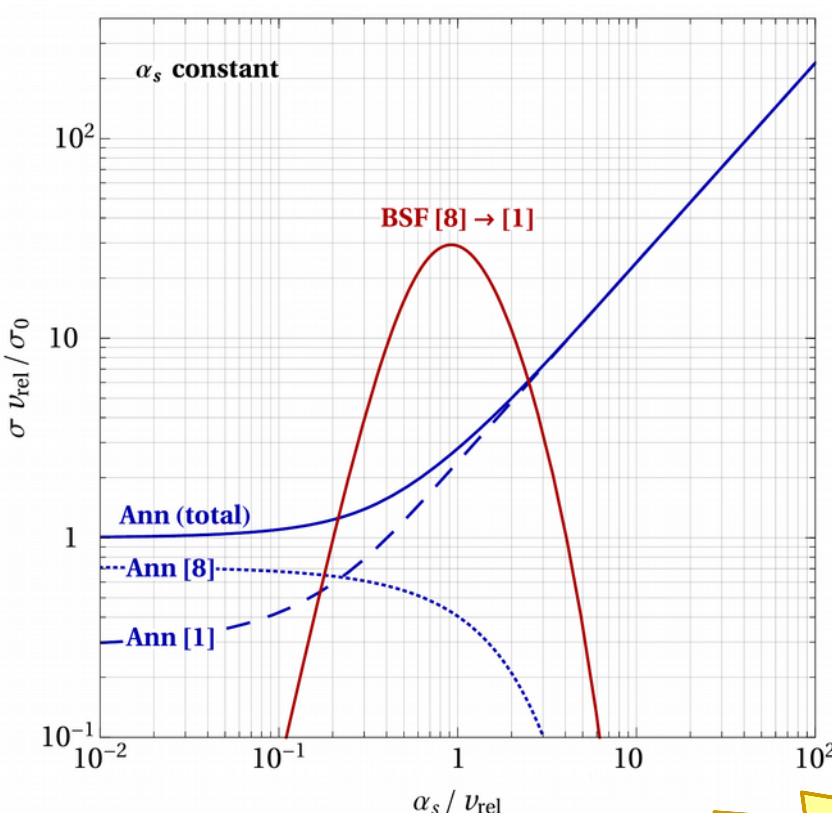


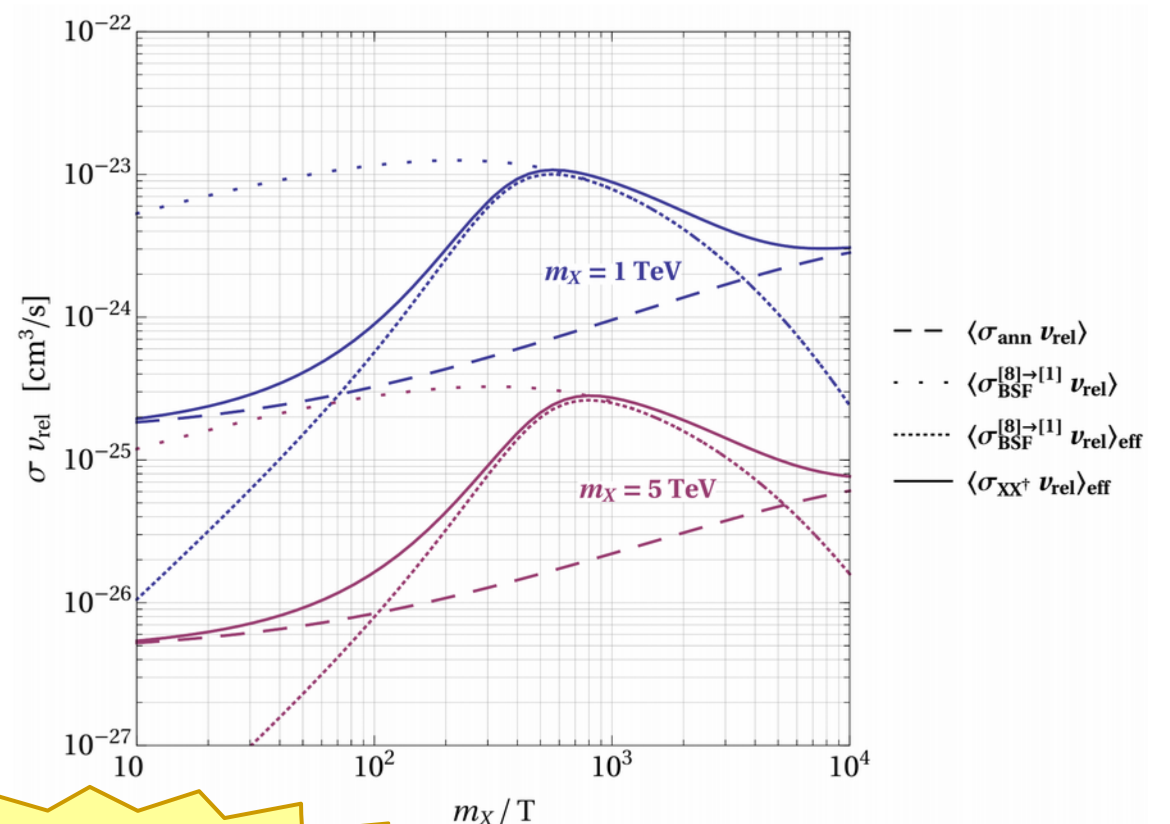
Harz, KP: 1805.01200

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

Bound-state formation *vs* Annihilation





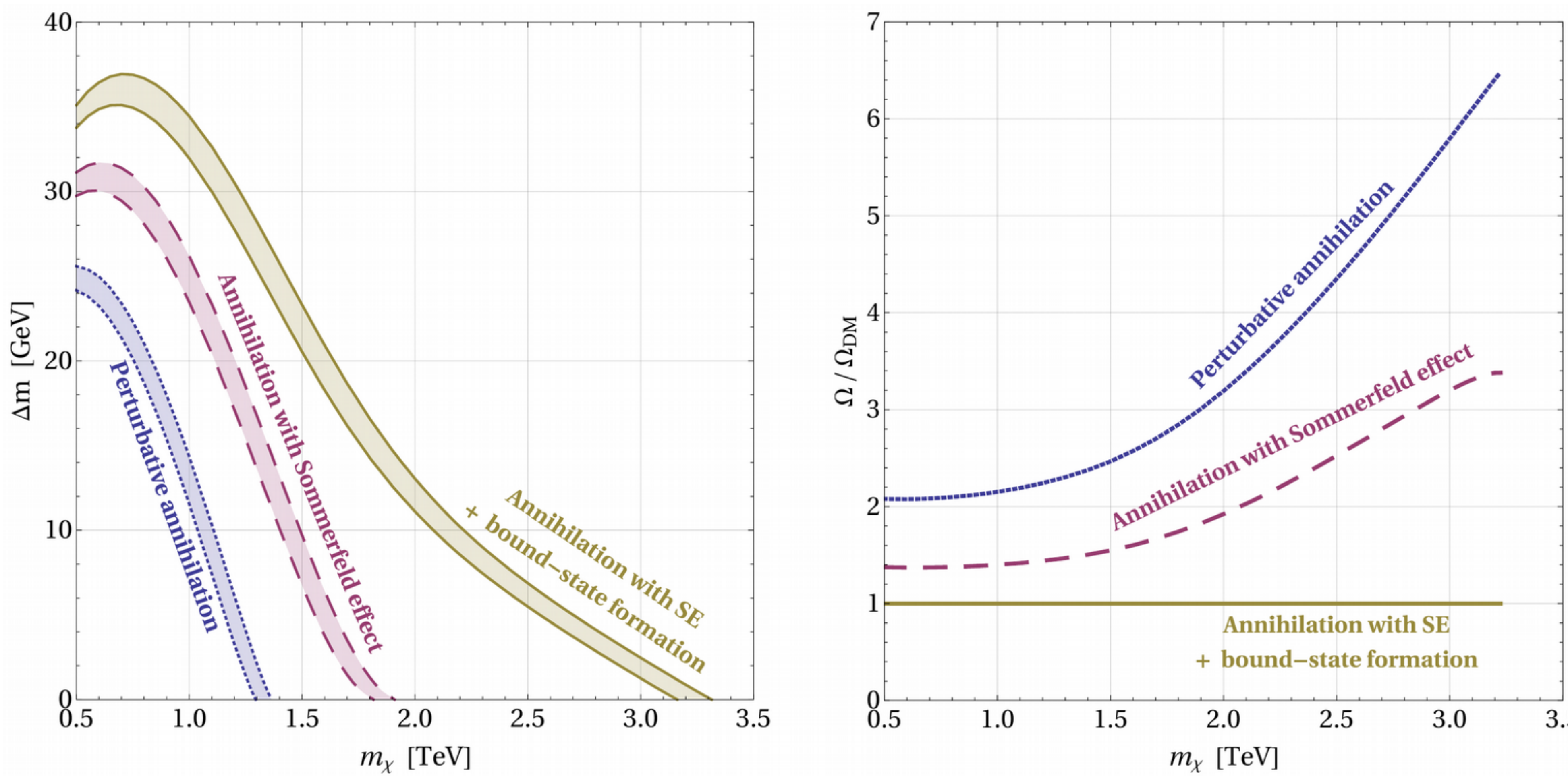
BSF can exceed Ann
by more than
an order of magnitude!

Harz, KP: 1805.01200

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

Relic density

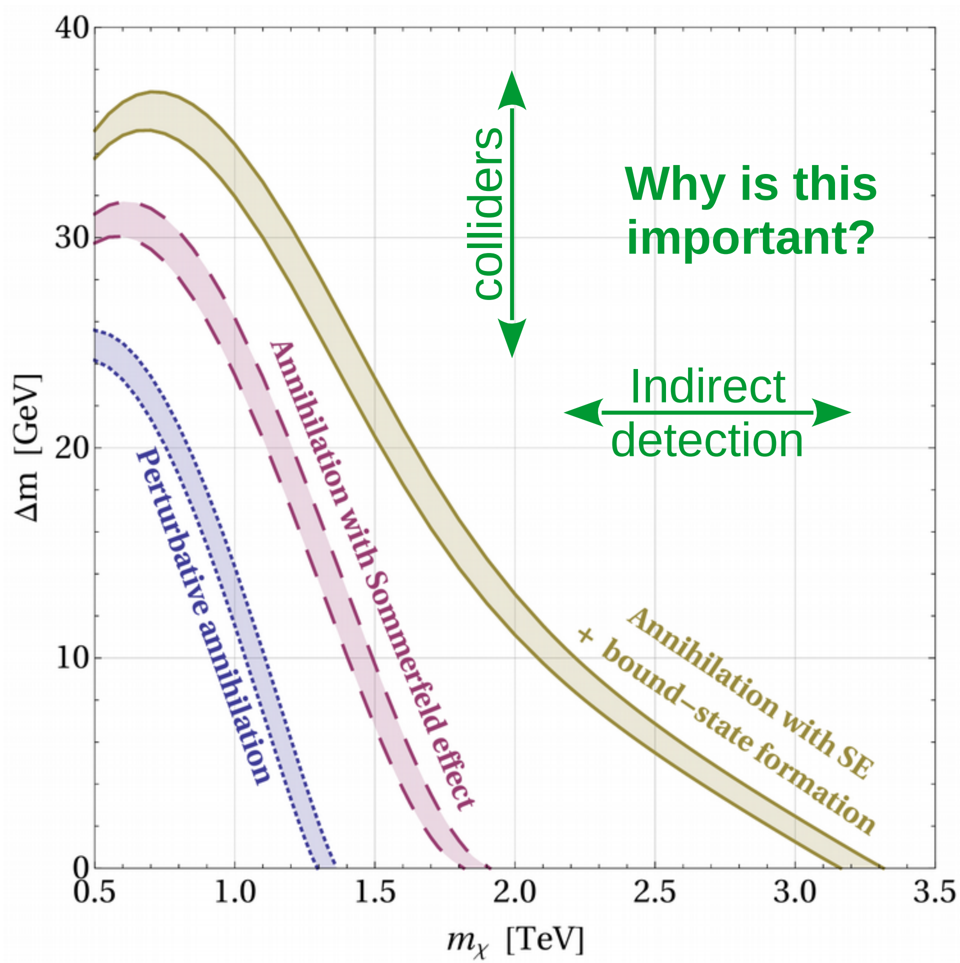


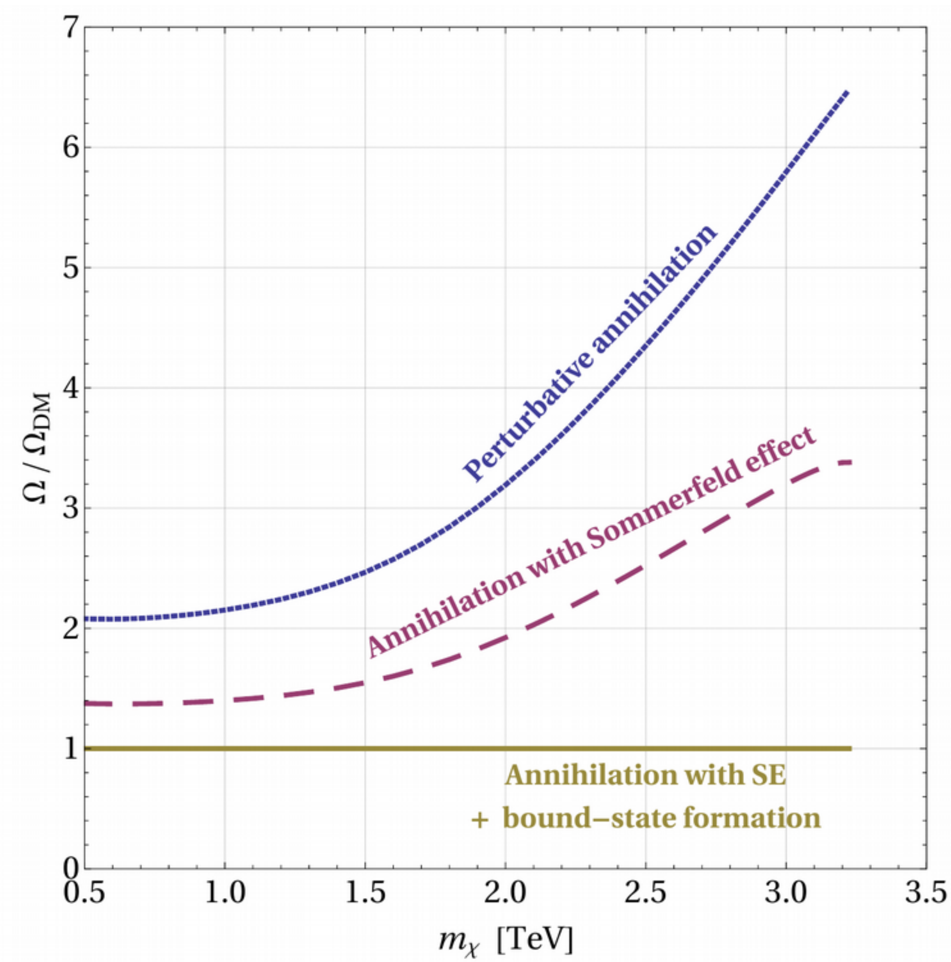
Harz, KP: 1805.01200

DM coannihilation with scalar colour triplet

MSSM-inspired toy model

Relic density





Harz, KP: 1805.01200

Can the Higgs mediate a long-range force?

Common reactions

YES

if DM is heavy enough

NO

- The Higgs is quite heavy, and certainly heavier than all SM gauge bosons.
- The coupling of DM to the Higgs is not expected or allowed to be very large.

Can the Higgs mediate a long-range force?

Common reactions

YES

if DM is heavy enough

NO

- The Higgs is quite heavy, and certainly heavier than all SM gauge bosons.
- The coupling of DM to the Higgs is not expected or allowed to be very large.

Not obvious

Doesn’t happen in the simplest cases

Not true

- For multi-TeV DM, the Higgs is light
- In coannihilation scenarios, the coupling to the Higgs can be sizable.
- Interference effect between Higgs and other (SM) mediators

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

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

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

Important to compute 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

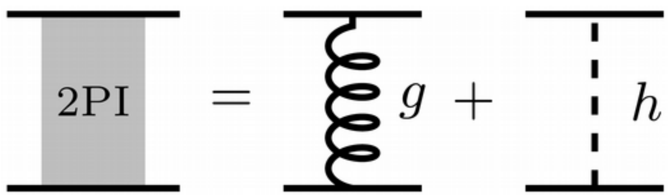
$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{1}{2}\overline{\chi^c}\, i\partial\!\!\!/ \chi - \frac{1}{2} m_\chi\, \overline{\chi^c}\chi \\
& + \left[(\partial_\mu + i g_s G^a_\mu T^a) X\right]^\dagger \left[(\partial^\mu + i g_s G^{a,\mu} T^a) X\right] - m_X^2 |X|^2 \\
& + \frac{1}{2}\partial_\mu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

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

Harz, KP: 1711.03552, 1901.10030

Higgs enhancement and relic density

MSSM-inspired toy model

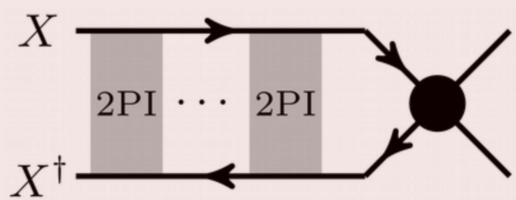


$$V(r) = -\frac{\alpha_g}{r} - \frac{\alpha_h}{r} e^{-m_h r}$$

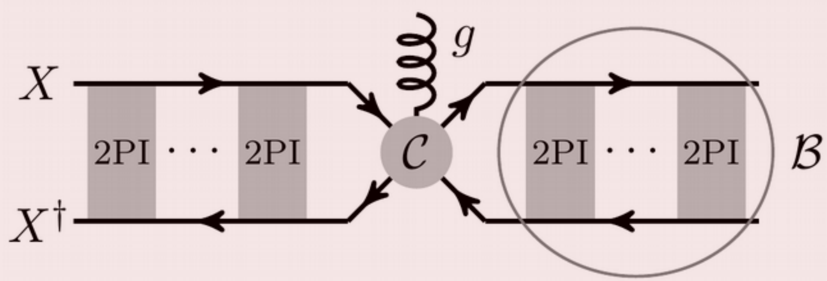
gluon exchange

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

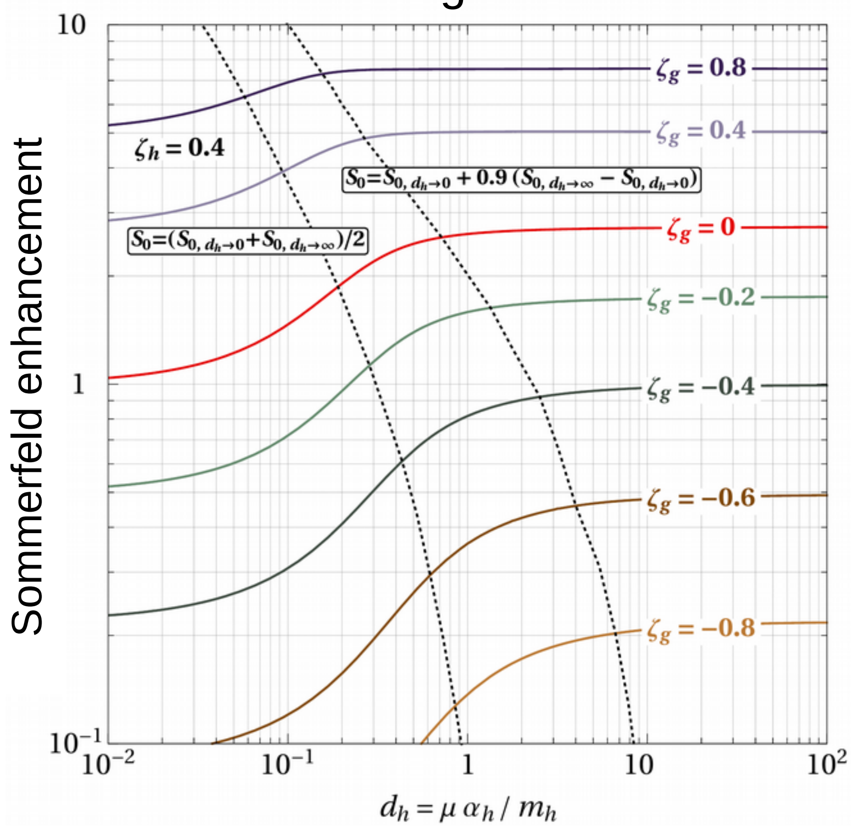
Higgs enhancement

interference between Coulomb & Yukawa potentials

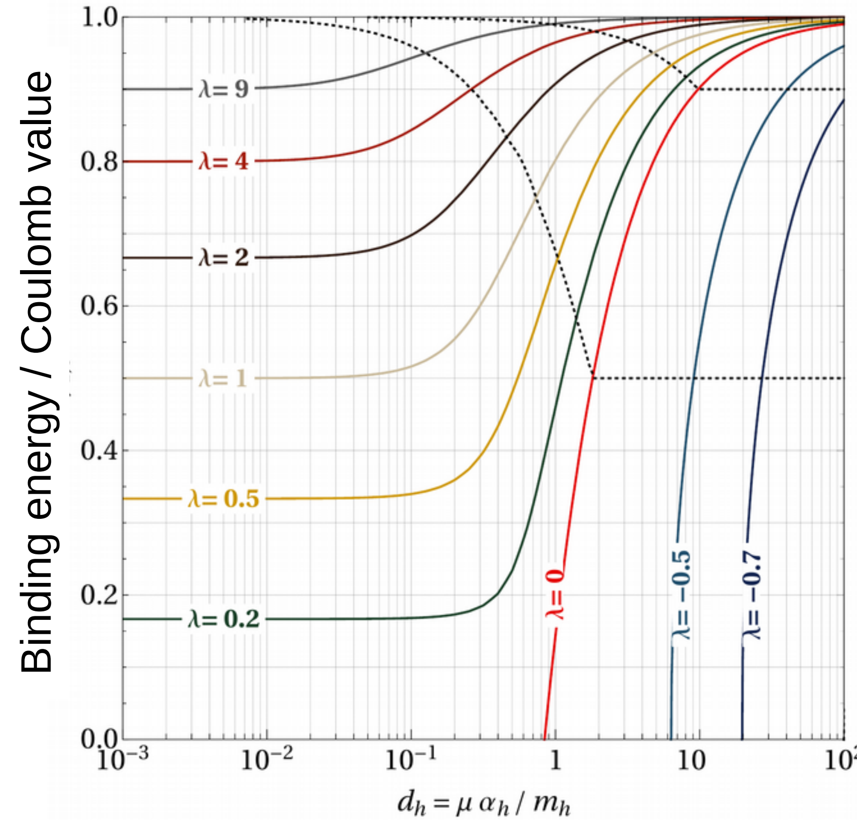
$$\zeta_g \equiv \frac{\mu\alpha_g}{\mu v_{\rm rel}}, \qquad \zeta_h \equiv \frac{\mu\alpha_h}{\mu v_{\rm rel}}, \qquad d_h \equiv \frac{\mu\alpha_h}{m_h}, \qquad \lambda \equiv \frac{\alpha_g}{\alpha_h}$$

Parametrises how “long-range” the interaction is.

Scattering states



Bound states



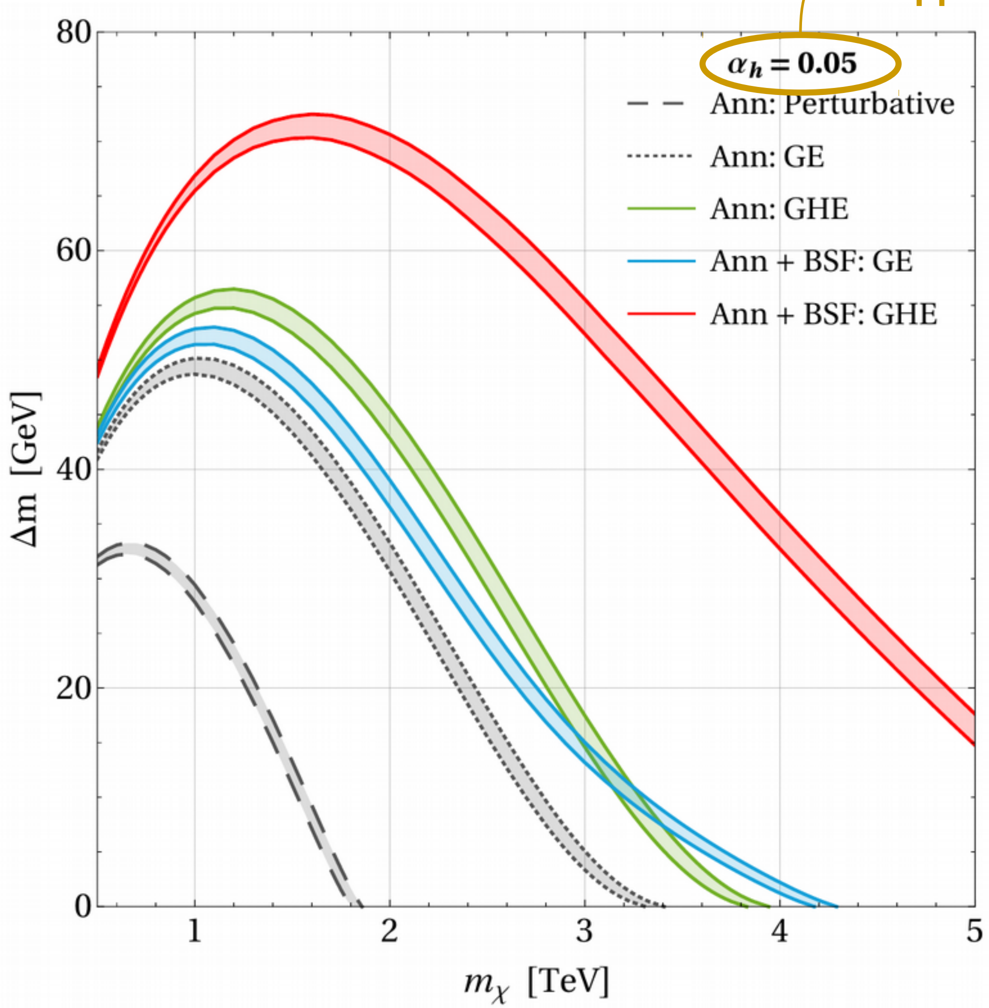
How “long-range” the Higgs exchange is depends on the other mediators, here the gluons!

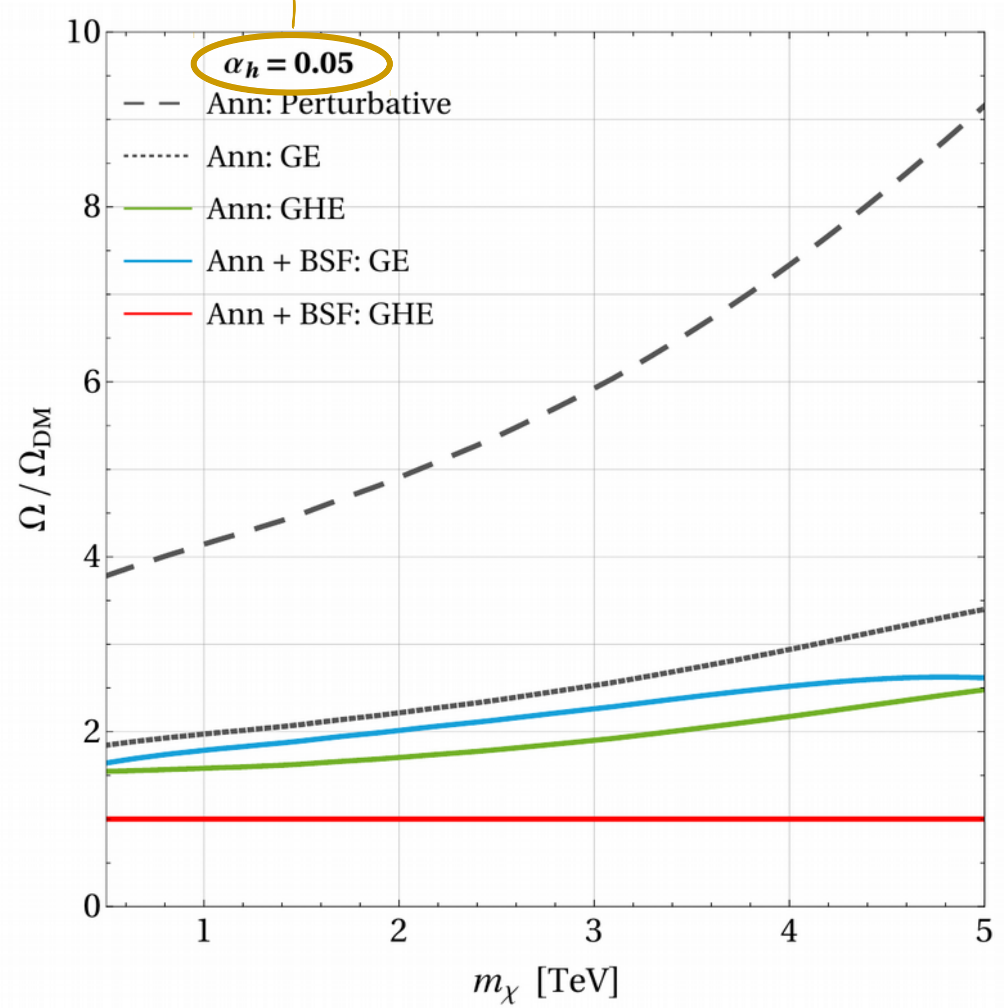
Harz, KP: 1711.03552, 1901.10030

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 emission ?

Capture via emission of neutral scalar suppressed, due to cancellations in amplitude.

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 !

Ko,Matsui,Tang:1910:04311
Oncala, KP: 1911.02605

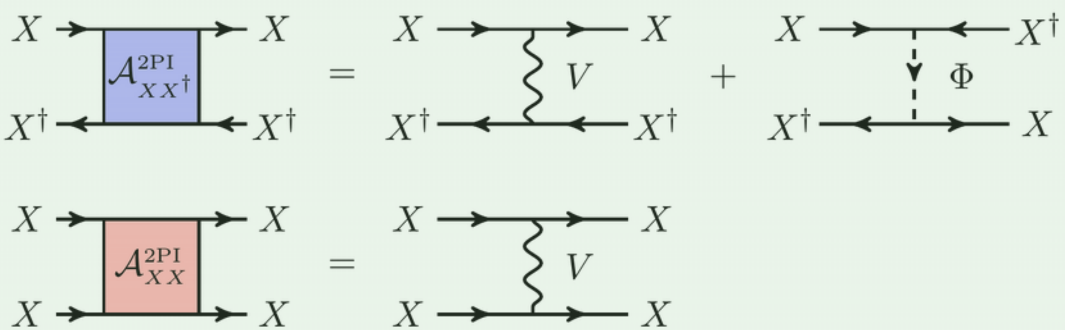
Sudden change in effective Hamiltonian precipitates transitions.
Akin to atomic transitions precipitated by β decay of nucleus.

BSF via emission of a *charged* scalar

U(1) model with scalar DM

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

$$m_X \gg m_\Phi$$

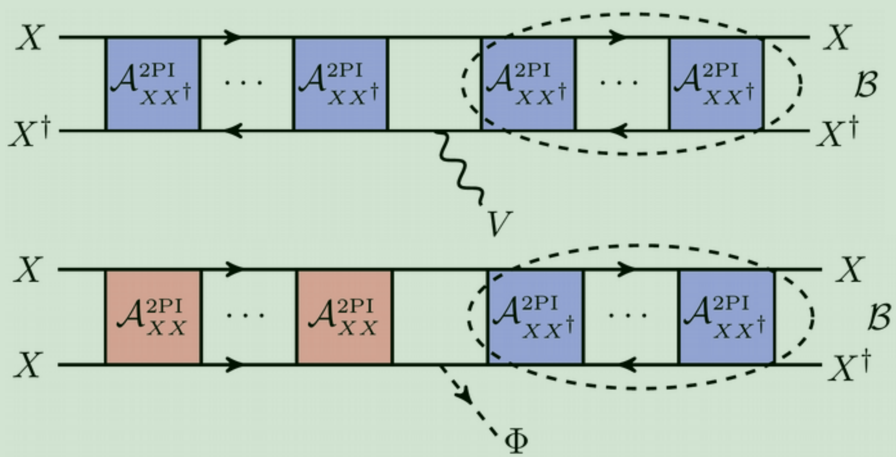


$$U_{XX^\dagger}(r) = -\frac{\alpha_V}{r} - (-1)^\ell \frac{\alpha_\Phi}{r} e^{-m_\Phi r}$$

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

BSF$_V$

BSF$_\Phi$

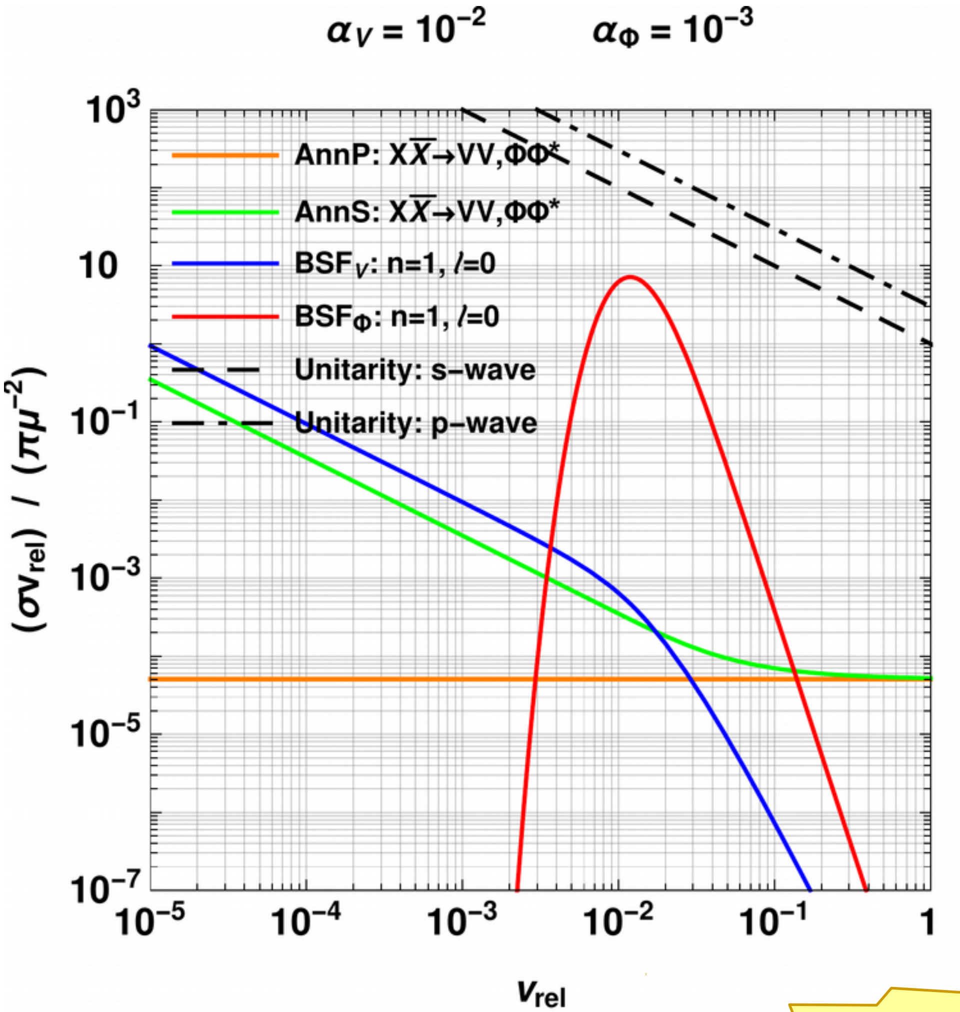


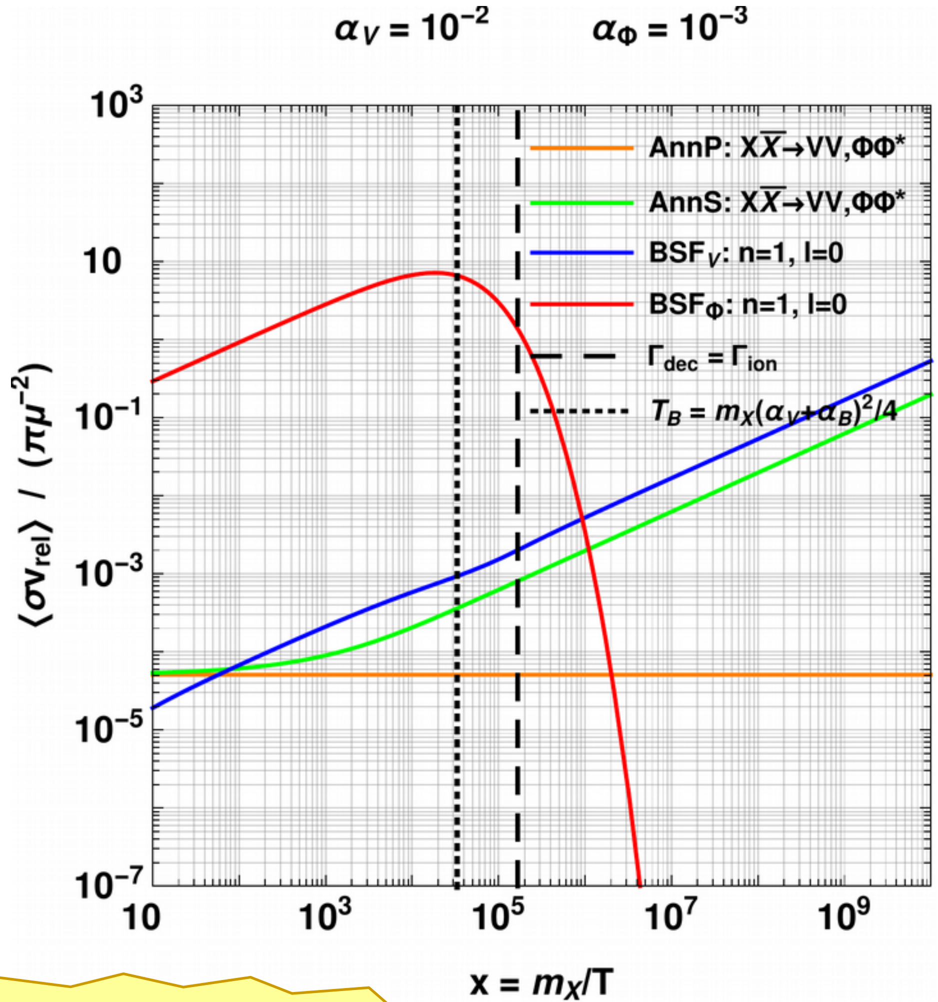
Change in effective Hamiltonian.
Very fast transition!

Oncala, KP: 1911.02605

BSF via emission of a *charged* scalar

U(1) model with scalar DM



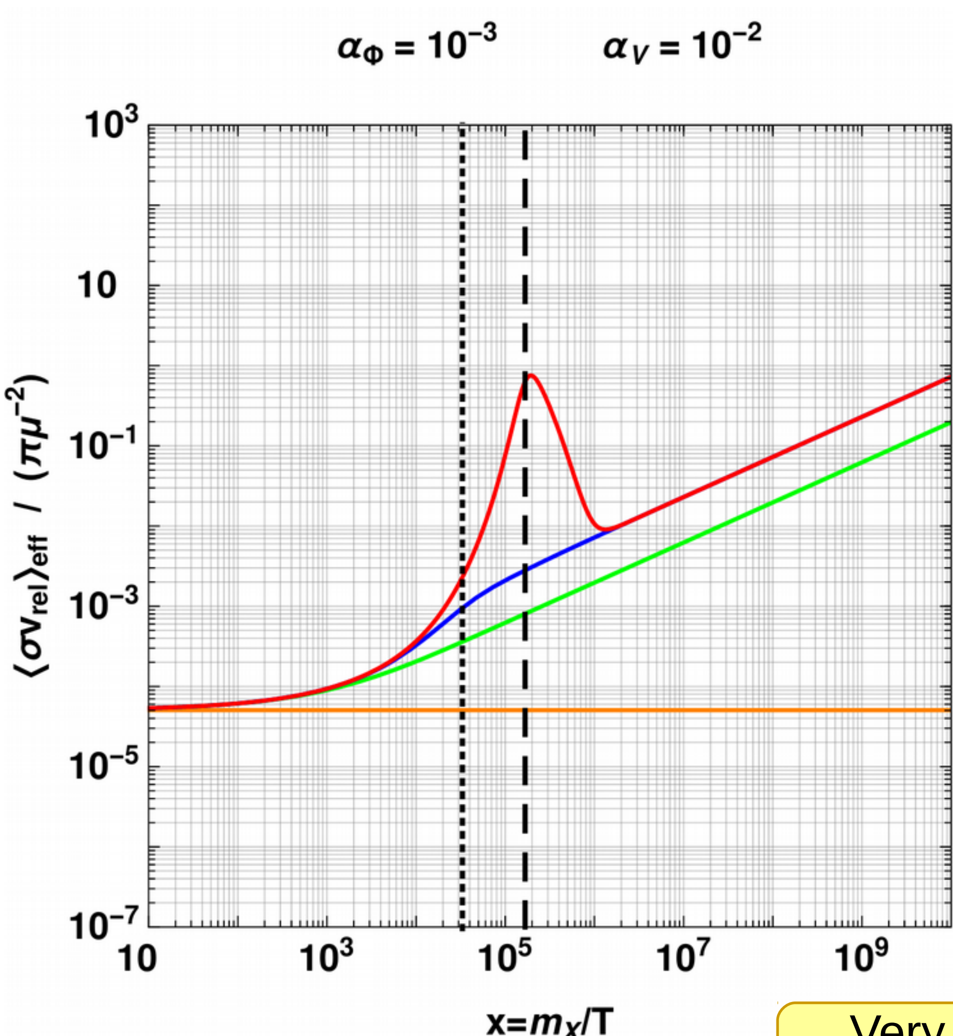


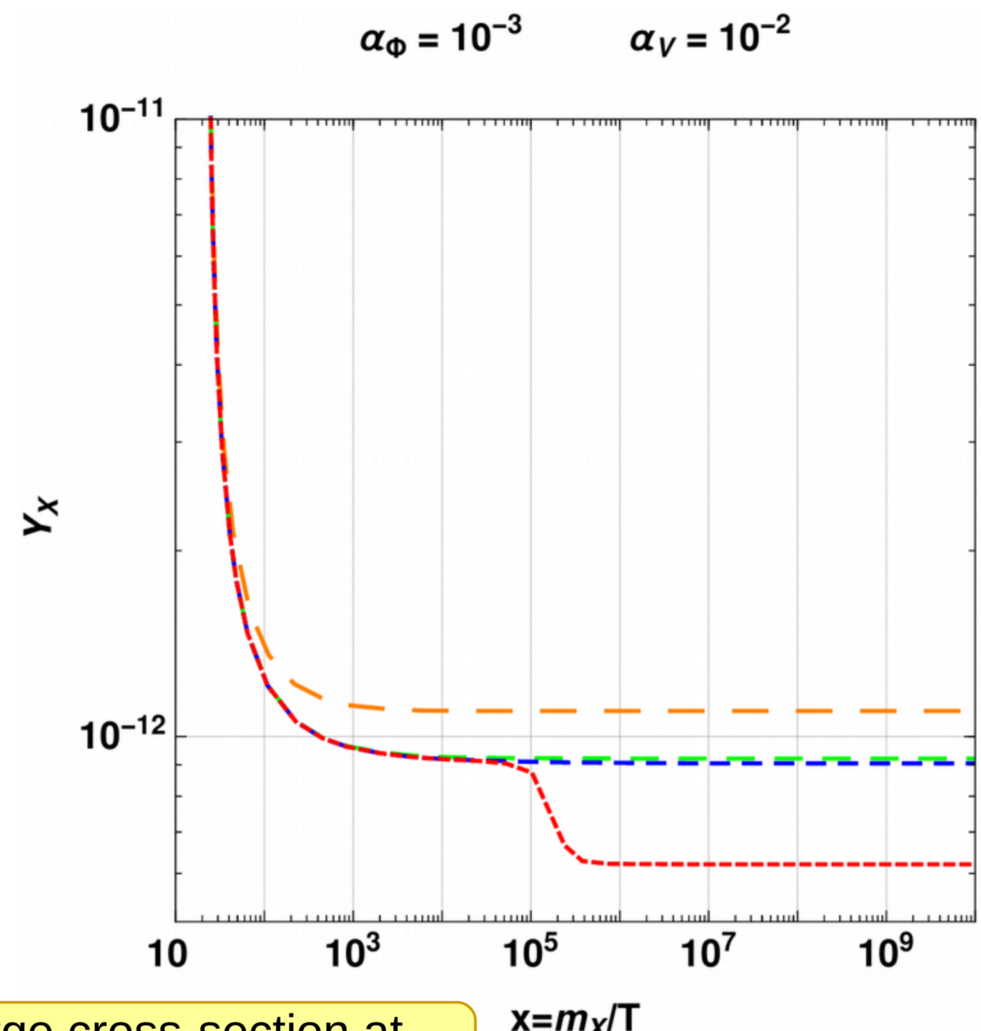
Oncala, KP: 1911.02605

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

BSF via emission of a *charged* scalar

U(1) model with scalar DM





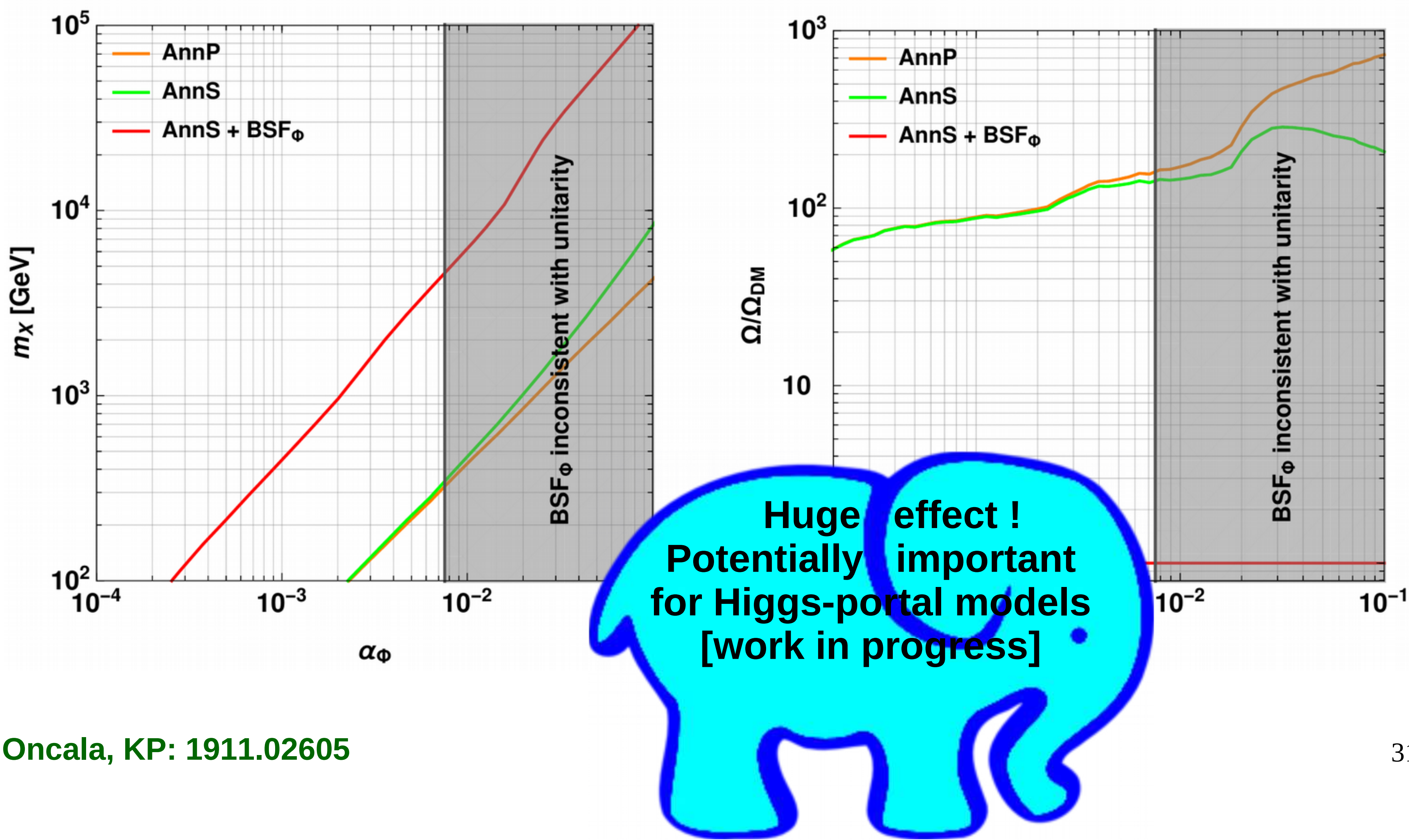
Very large cross-section at
$T \sim m_X (\alpha_\Phi+\alpha_V)^2 / 4 \ll m_X/30$
⇒ recoupling of DM depletion

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

BSF via emission of a *charged* scalar

U(1) model with scalar DM

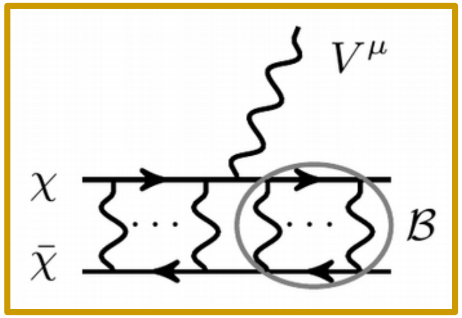
$\alpha_V = 0$ ← Limit of global symmetry → $\alpha_V = 0$



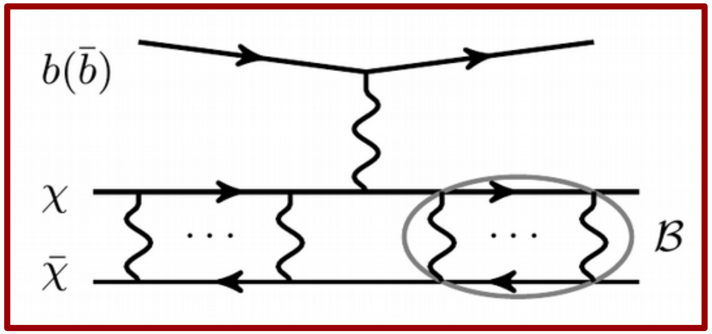
Oncala, KP: 1911.02605

Bound-state formation
via scattering on relativistic bath particles

Radiative capture



Capture via bath scattering



Dissipation of energy may occur:

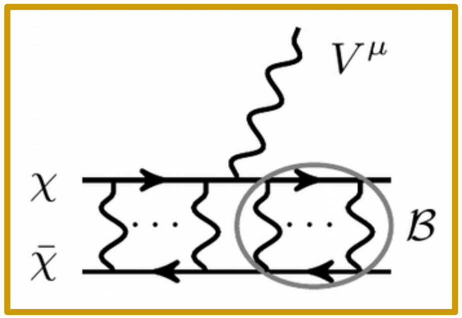
- Radiatively (usually emission of force mediator)
- Via scattering, if mediator couples to light species
  - Suppressed by extra α.
  - Enhanced by large number density of relativistic particles, $\mathbf{(T/\omega)^3}$, where $\boldsymbol{\omega = m_X (\alpha^2+v_{rel}^2) / 4}$ is the dissipated energy.
  - **Kinematically accessible even if $\mathbf{m_{mediator} > \omega}$.**

Binder, Mukaida, KP: 1910.11288

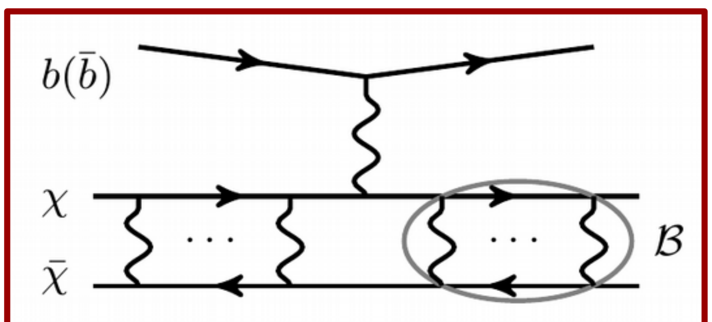
Bound-state formation via scattering on relativistic bath particles

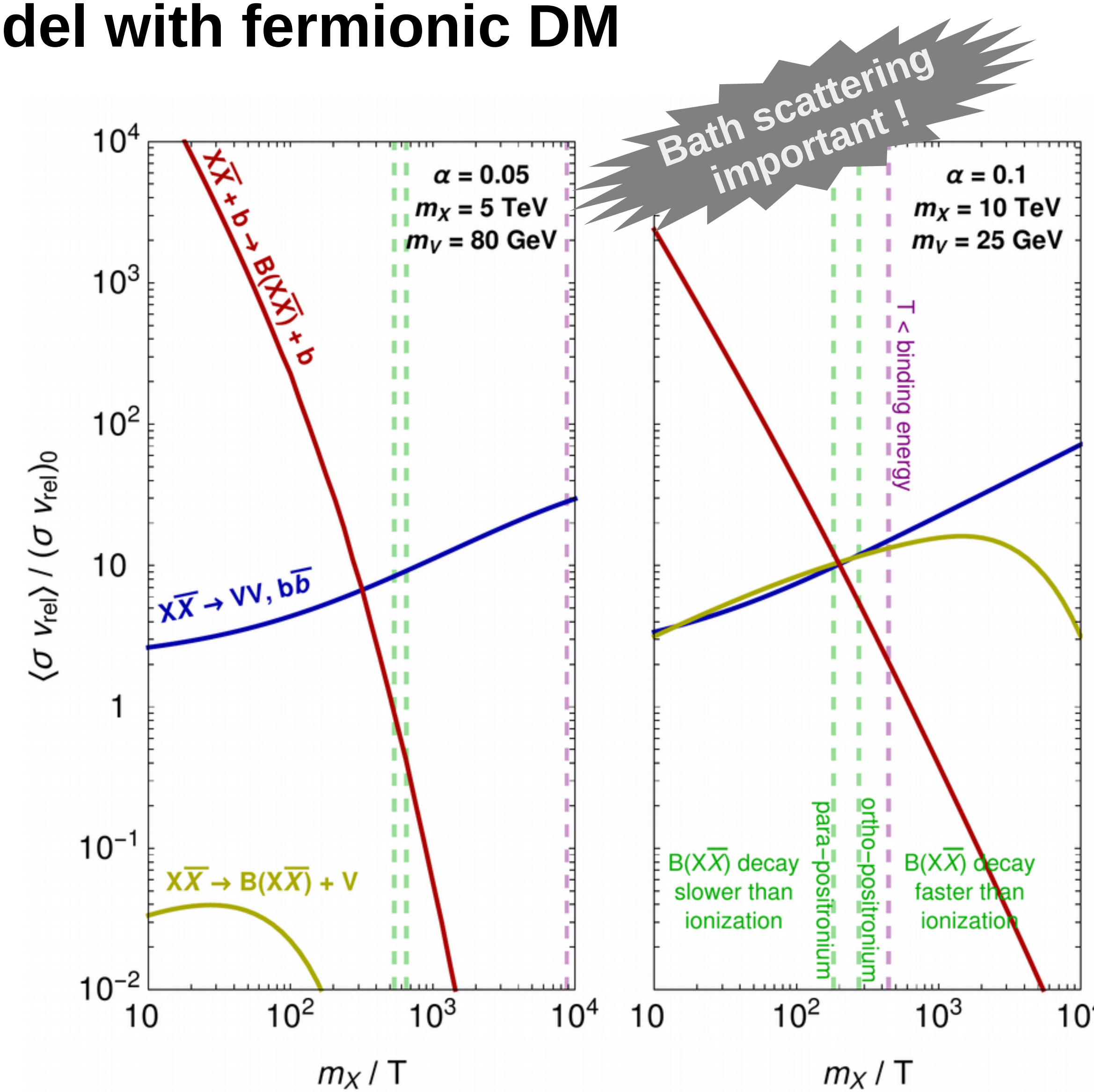
U(1) model with fermionic DM

Radiative capture



Capture via bath scattering



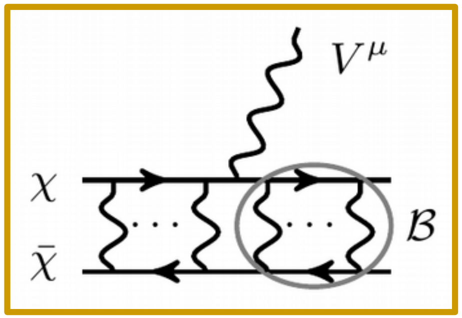


Binder, Mukaida, KP: 1910.11288

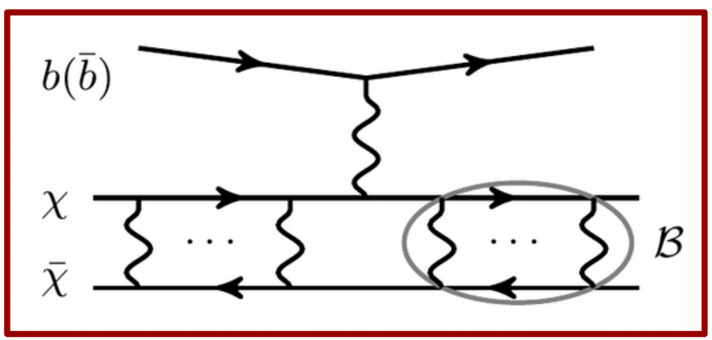
Bound-state formation via scattering on relativistic bath particles

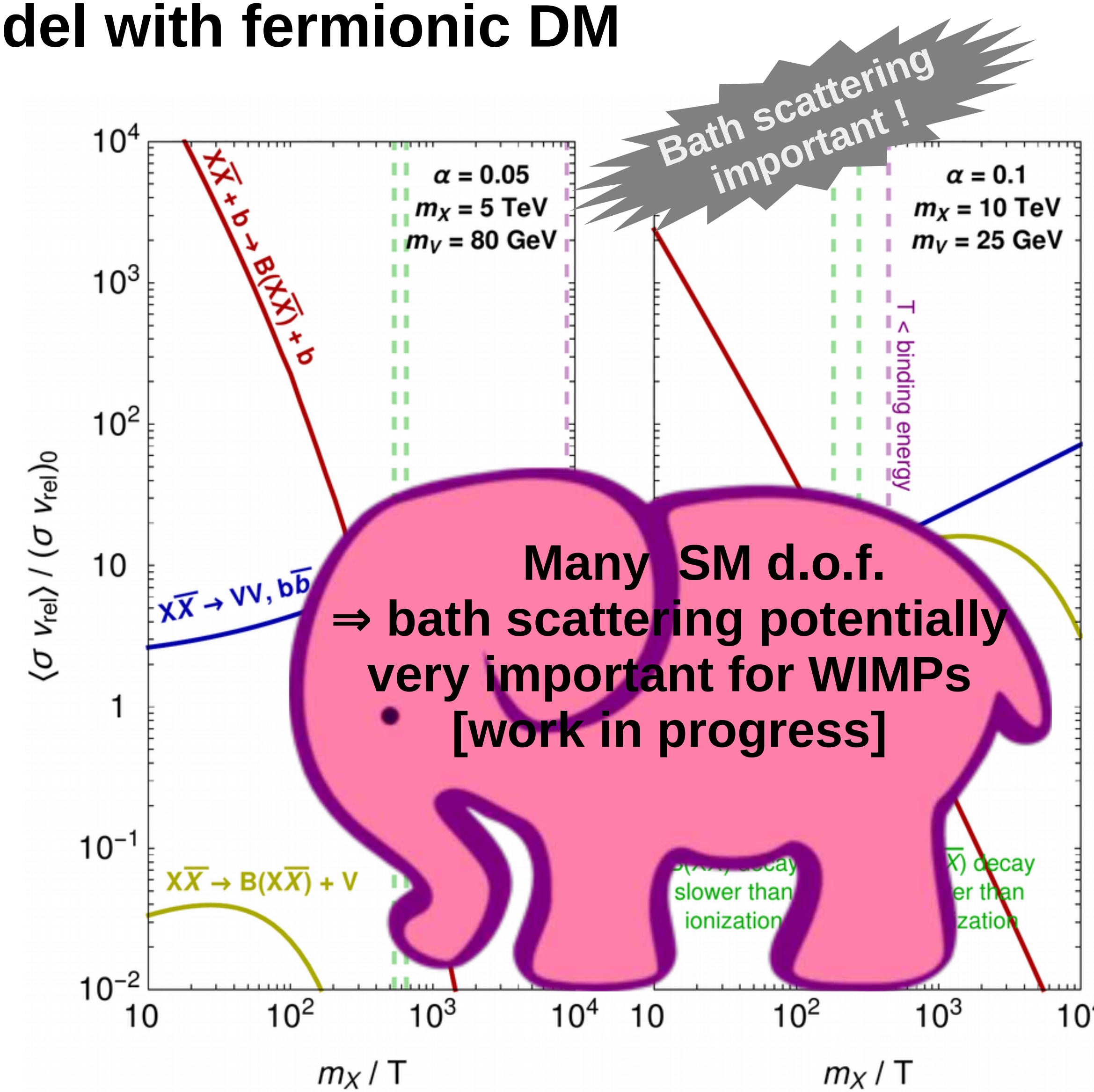
U(1) model with fermionic DM

Radiative capture



Capture via bath scattering





Binder, Mukaida, KP: 1910.11288

Conclusion

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

  In fact, the unitarity limit can be approached / realised only by attractive long-range interactions $\Rightarrow$ 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