Higgs-mediated bound states in dark matter models

Julia Harz

in collaboration with

Kalliopi Petraki

based on

submitted to JHEP, [arXiv:1901.10030]
JHEP 1902 (2019) 186, [arXiv:1811.05478]
Phys. Rev. D97 (2018) no.7, 075041, [arXiv:1711.03552]

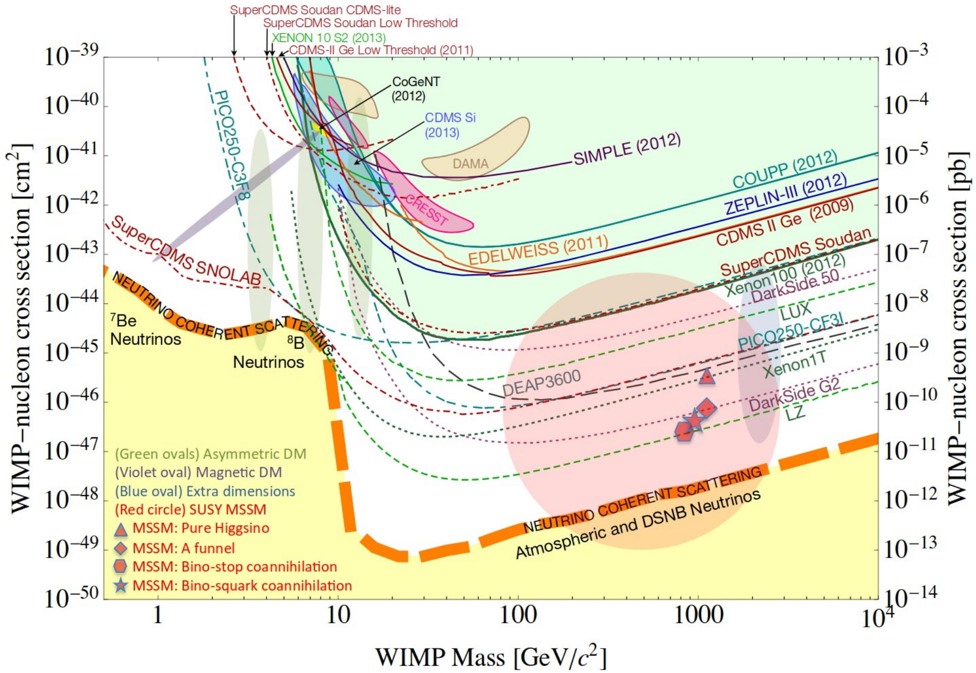
Technische Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

WIMP miracle?

$$\Omega h^2 \sim \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \sim 0.1$$

$$\Rightarrow \quad \langle \sigma v \rangle \sim \frac{g^4}{m_\chi^2} \sim 10^{-9}\mathrm{GeV}^{-2}$$

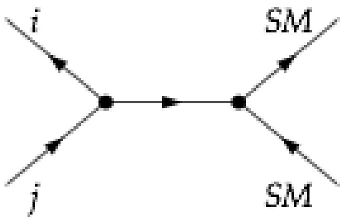


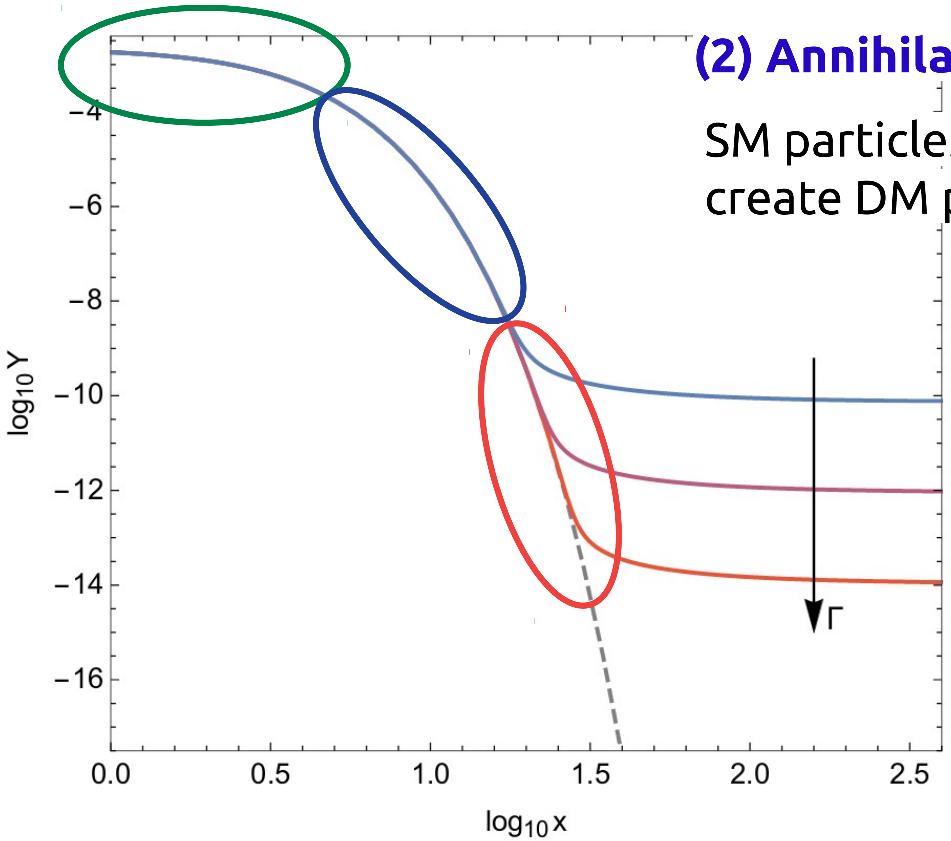
- *Minimal* WIMP models are currently under tension due to no observations at the LHC, direct or indirect detection
- Reason could be the realisation of a complex WIMP model that can evade bounds, *e.g. higher DM mass, complex dark sector, coannihilation scenarios etc.*

Freeze-out with co-annihilation

(1) Thermal equilibrium regime (T >> m)

annihilation and production of DM
in thermal equilibrium $Y \approx \text{const.}$





$x = m_\chi/T$

cooling down

(2) Annihilation regime (T ~ m/10)

SM particles not energetic enough to
create DM particles $Y \approx \exp(-m_{DM}/T)$

(3) Freeze-out (T ~ m/30)

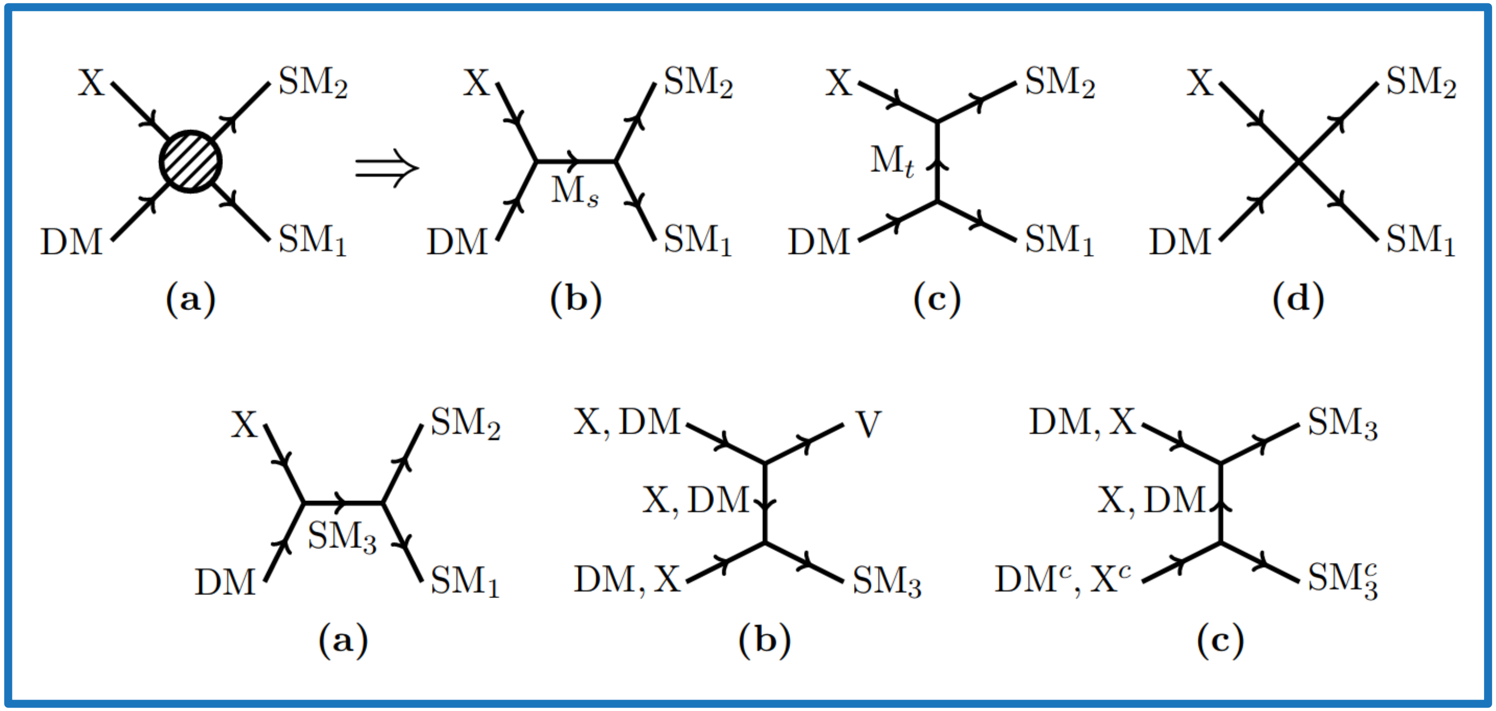
Annihilation rate falls
behind expansion rate
→ DM abundance

$$\Omega_\chi h^2 = \frac{n_\chi m_\chi}{\rho_{\text{crit}}} \propto \frac{1}{< \sigma_{\text{eff}} v >}$$

$$\langle \sigma_{\text{eff}} v \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{eq}}{n^{eq}} \frac{n_j^{eq}}{n^{eq}}$$

$$\frac{n_i^{eq}}{n^{eq}} \propto \exp^{\frac{-(m_i - m_\chi)}{T}}$$

Recent specific focus on (colored) Coannihilation



Coloured coannihilations: Dark matter phenomenology meets non-relativistic EFTs, Biondini et al (2018)

Cornering Colored Coannihilation, El Hedri et al (2018)

Stop Coannihilation in the CMSSM and SubGUT Models, Ellis et al (2018)

Simplified Phenomenology for Colored Dark Sector, El Hedri et al (2017)

The Coannihilation Codex, Baker et al (2016)

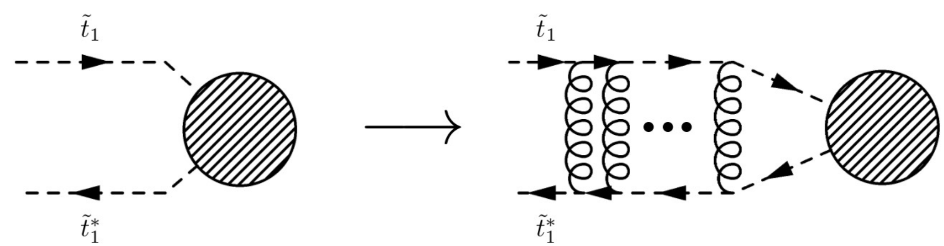
Anatomy of Coannihilation with a Scalar Top Partner, Ibarra et al (2015)

To name a few examples…

Non-perturbative effects

Sommerfeld enhancement

$\alpha \sim v_{\mathrm{rel}}$

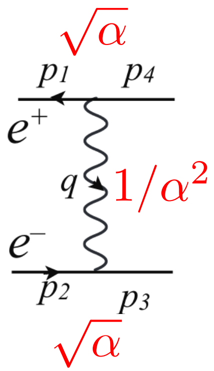


$\mu = \frac{m_1 m_2}{m_1 + m_2}$

Momentum transfer: $|\,\mathbf{q}\,| \sim \alpha\mu$

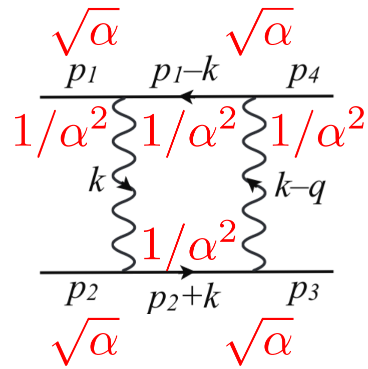
Energy transfer: $\mathrm{q}^0 \sim \mathbf{q}^2/2\mu \sim 1/2\alpha^2\mu$

one boson exchange:



$$\sim \alpha \frac{1}{q^2} \sim \alpha \frac{1}{(\mu\alpha)^2} \propto \frac{1}{\alpha}$$

each added loop:



$\int \to \alpha^5$

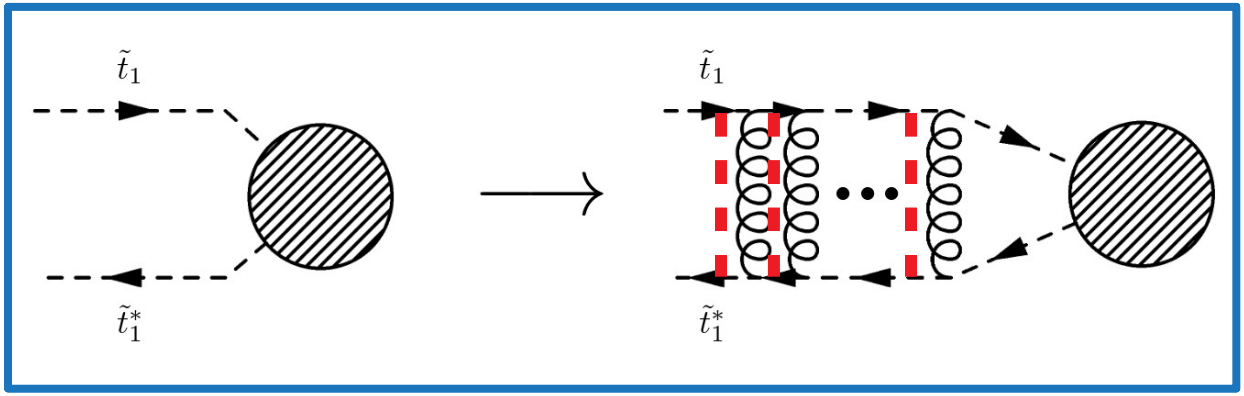
$$\sim \alpha \int dp^0 d^3p \frac{1}{p_\gamma^2} \frac{1}{p_1' - m_1} \frac{1}{p_2' - m_2}$$

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

$$\propto 1$$

Sommerfeld resummation!

Higgs enhancement?



What is the effect of *light scalars* such as the Higgs boson?

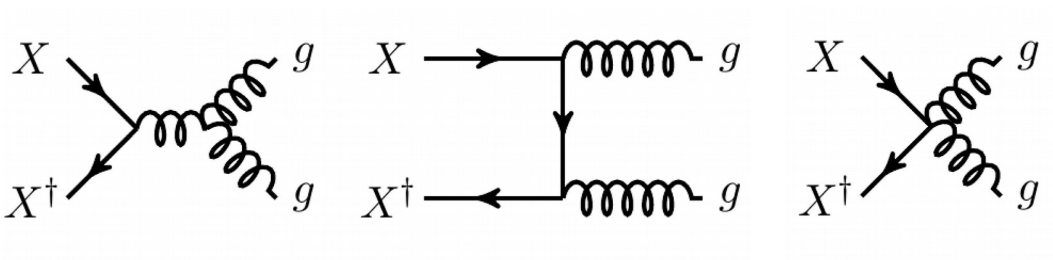
Higgs enhancement

- **Simplified model:**

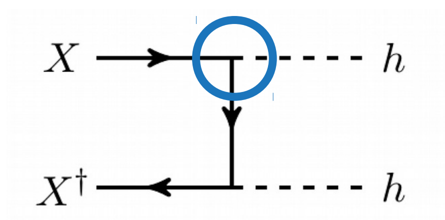
DM Majorana fermion χ; co-annihilating with complex scalar X charged under SU(3)$_c$

$$\delta\mathcal{L} = (D_{\mu,ij}X_j)^\dagger\,(D^{\mu}_{ij'}X_{j'}) - m_X^2\,X_j^\dagger X_j$$
$$+\frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \frac{1}{2}m_h^2 h^2 - g_h m_X\; h\, X_j^\dagger X_j$$

- **Annihilation processes:**



$$(\sigma v_{\rm rel})^{\rm pert}_{XX^\dagger\to gg} = \frac{14}{27}\frac{\pi\alpha_s^2}{m_X^2}$$

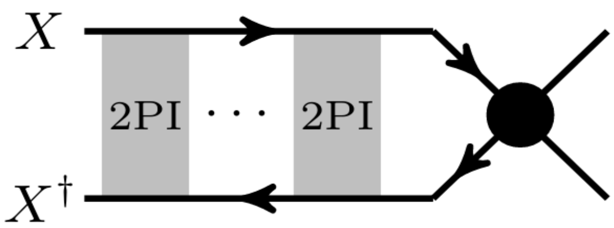


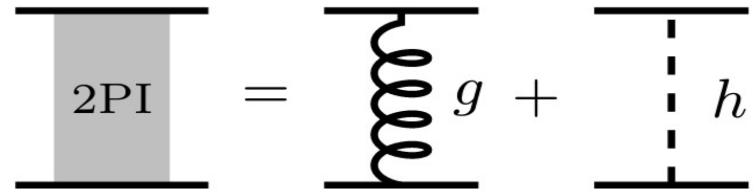
$$\alpha_h = \frac{g_h^2}{16\pi}$$

$$(\sigma v_{\rm rel})^{\rm pert}_{XX^\dagger\to hh} = \frac{4\pi\alpha_h^2}{3m_X^2}\frac{(1-m_h^2/m_X^2)^{1/2}}{[1-m_h^2/(2m_X^2)]^2}$$

we neglect p-wave suppressed contributions $X\bar{X}\to q\bar{q},\, X\bar{X}\to gh$

Higgs as mediator of long-range interactions





$$\left[-\frac{\nabla^2}{2\mu}+V_{\mathrm{scatt}}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r})=\mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r}) \quad \text{with} \quad \mathrm{V}_{\mathrm{scatt}}(r)=-\frac{\alpha_g^S}{r}-\frac{\alpha_h}{r}\,e^{-m_h r}$$

Characteristic parameters:

$$\zeta_{g,h}\equiv\frac{\mu\alpha_{g,h}}{\mu v_{\mathrm{rel}}}=\frac{\alpha_{g,h}}{v_{\mathrm{rel}}}$$

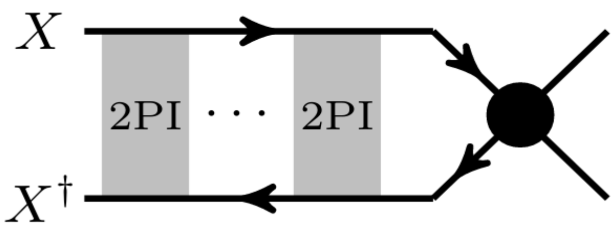
$$\frac{\text{Bohr momentum}}{\text{momentum exchange of unbound particles}} > 1$$

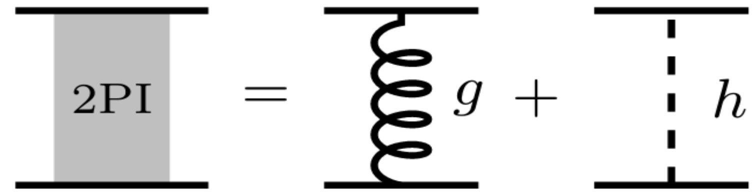
$$\mathrm{d}_h\equiv\frac{\mu\alpha_h}{m_h}$$

$$\frac{\text{Interaction range}}{\text{Bohr radius}} > 1$$

$$\left\{\nabla_{\mathbf{z}}^2+1+\frac{2}{z}\left[\zeta_g+\zeta_h\,\exp\left(-\frac{\zeta_h z}{d_h}\right)\right]\right\}\phi_{\mathbf{k}}=0 \quad \Rightarrow \quad \boxed{S_0(\zeta_g,\zeta_h,d_h)\equiv|\phi_{\mathbf{k}}(0)|^2}$$

Higgs as mediator of long-range interactions





$$\left[-\frac{\nabla^2}{2\mu} + V_{\rm scatt}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r}) \qquad \text{with} \qquad \mathrm{V}_{\rm scatt}(r) = -\frac{\alpha_g^S}{r} - \frac{\alpha_h}{r}\,e^{-m_h r}$$

Color decomposition: $\mathbf{3}\otimes\bar{\mathbf{3}} = \mathbf{1}\oplus\mathbf{8}$

$$C_{\mathbf{1},\mathbf{8}} = -T_1^a T_2^a = 1/2[(T_1^a)^2 + (T_2^a)^2 - (T_1^a + T_2^a)^2] = 1/2(C_2^{\mathbf{3}} + C_2^{\bar{\mathbf{3}}} - C_2^{\mathbf{1},\mathbf{8}})$$

with $C_2^{\bar{\mathbf{3}}} = C_2^{\mathbf{3}} = C_F = 4/3$

$C_2^{\mathbf{1}} = 0$

$C_2^{\mathbf{8}} = C_A$

$$\Rightarrow \quad \alpha_g^S \equiv \alpha_s^S \times \begin{cases} C_{\mathbf{1}} = C_F = 4/3 \\ C_{\mathbf{8}} = C_F - C_A/2 = -1/6 \end{cases}$$

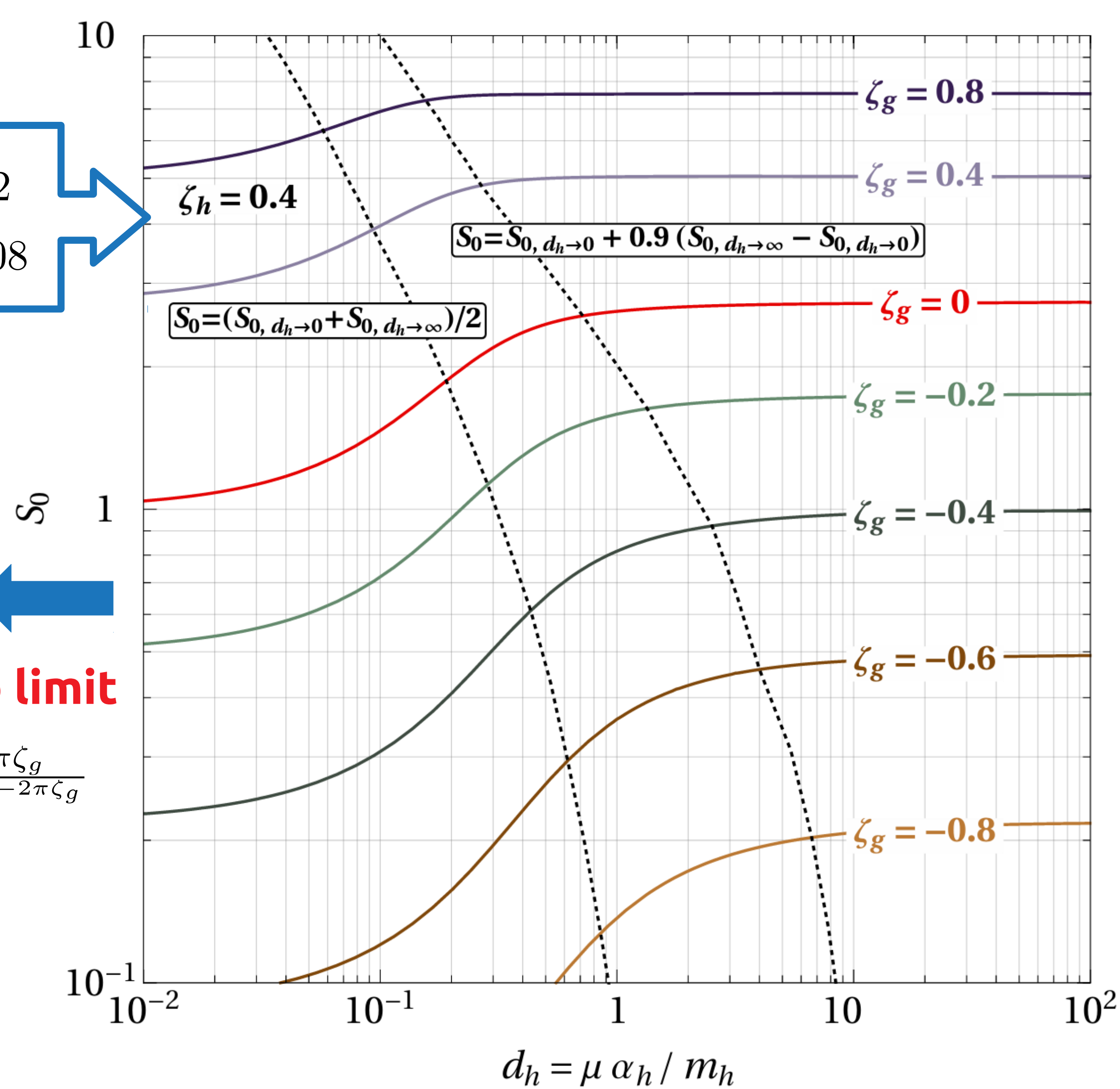
$$(\sigma v_{\rm rel})_{XX^\dagger\to gg} = (\sigma v_{\rm rel})^{\rm pert}_{XX^\dagger\to gg} \times \left(\frac{2}{7}S_0^{[\mathbf{1}]} + \frac{5}{7}S_0^{[\mathbf{8}]}\right) \qquad S_0^{[\mathbf{1}]} = S_0[\zeta_g^{[\mathbf{1}]},\,\zeta_h,\,d_h]$$

$$(\sigma v_{\rm rel})_{XX^\dagger\to hh} = (\sigma v_{\rm rel})^{\rm pert}_{XX^\dagger\to hh} \times S_0^{[\mathbf{1}]} \qquad S_0^{[\mathbf{8}]} = S_0[\zeta_g^{[\mathbf{8}]},\,\zeta_h,\,d_h]$$

Higgs enhancement

$v_{\rm rel} \approx 0.2$

$\alpha_h \approx 0.08$



$$\zeta_{g,h} \equiv \frac{\mu \alpha_{g,h}}{\mu v_{\rm rel}} = \frac{\alpha_{g,h}}{v_{\rm rel}}$$

$$d_h \equiv \frac{\mu \alpha_h}{m_h}$$

Coulomb limit

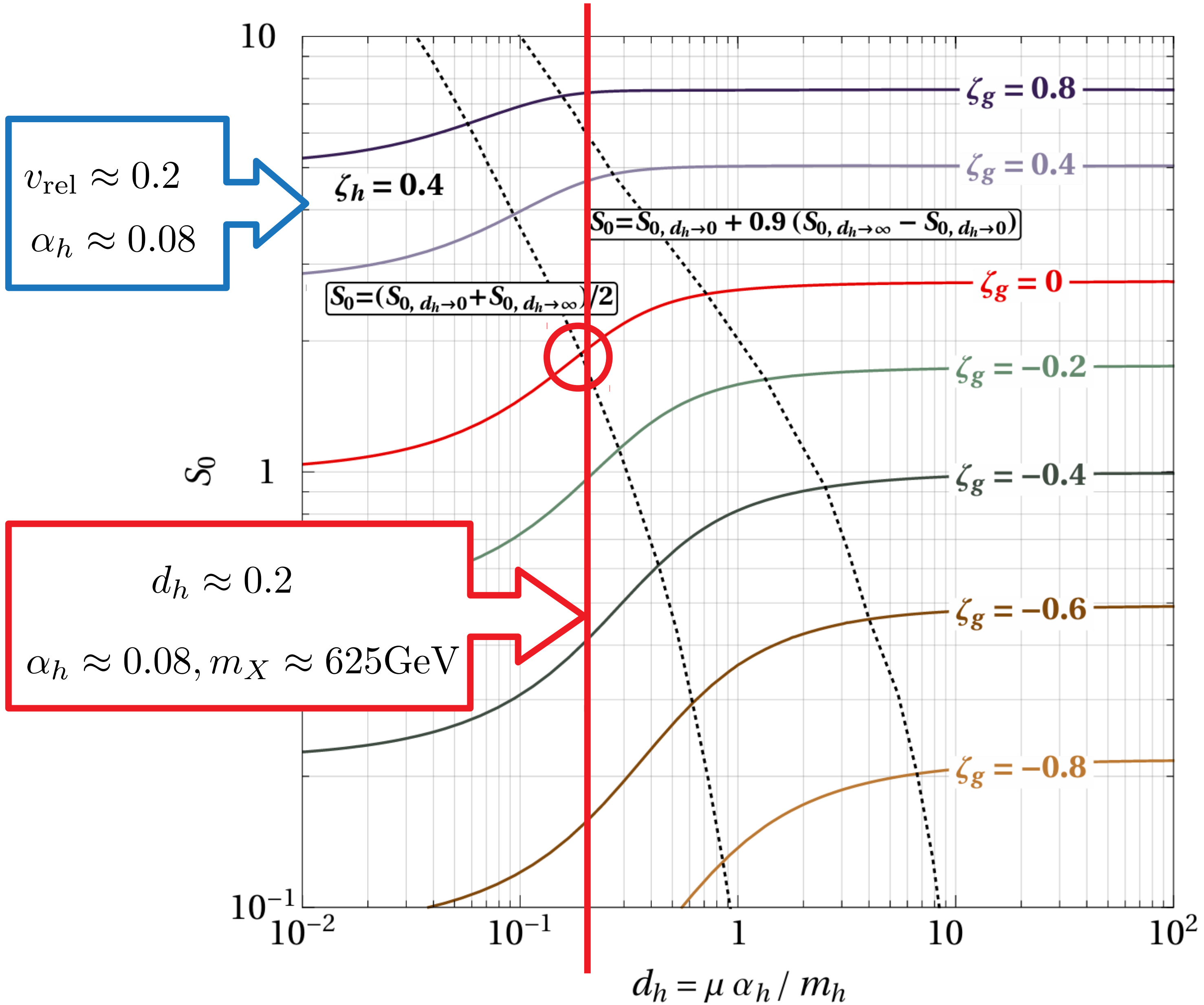
$$S_0 \simeq \frac{2\pi(\zeta_g+\zeta_h)}{1-e^{-2\pi(\zeta_g+\zeta_h)}}$$

Coulomb limit

$$S_0 \simeq \frac{2\pi\zeta_g}{1-e^{-2\pi\zeta_g}}$$

JH, Petraki, (2018)

Higgs enhancement



$$\zeta_{g,h} \equiv \frac{\mu \alpha_{g,h}}{\mu v_{\rm rel}} = \frac{\alpha_{g,h}}{v_{\rm rel}}$$

$$d_h \equiv \frac{\mu \alpha_h}{m_h}$$

d_h << 1 has already a significant impact!

JH, Petraki, (2018)

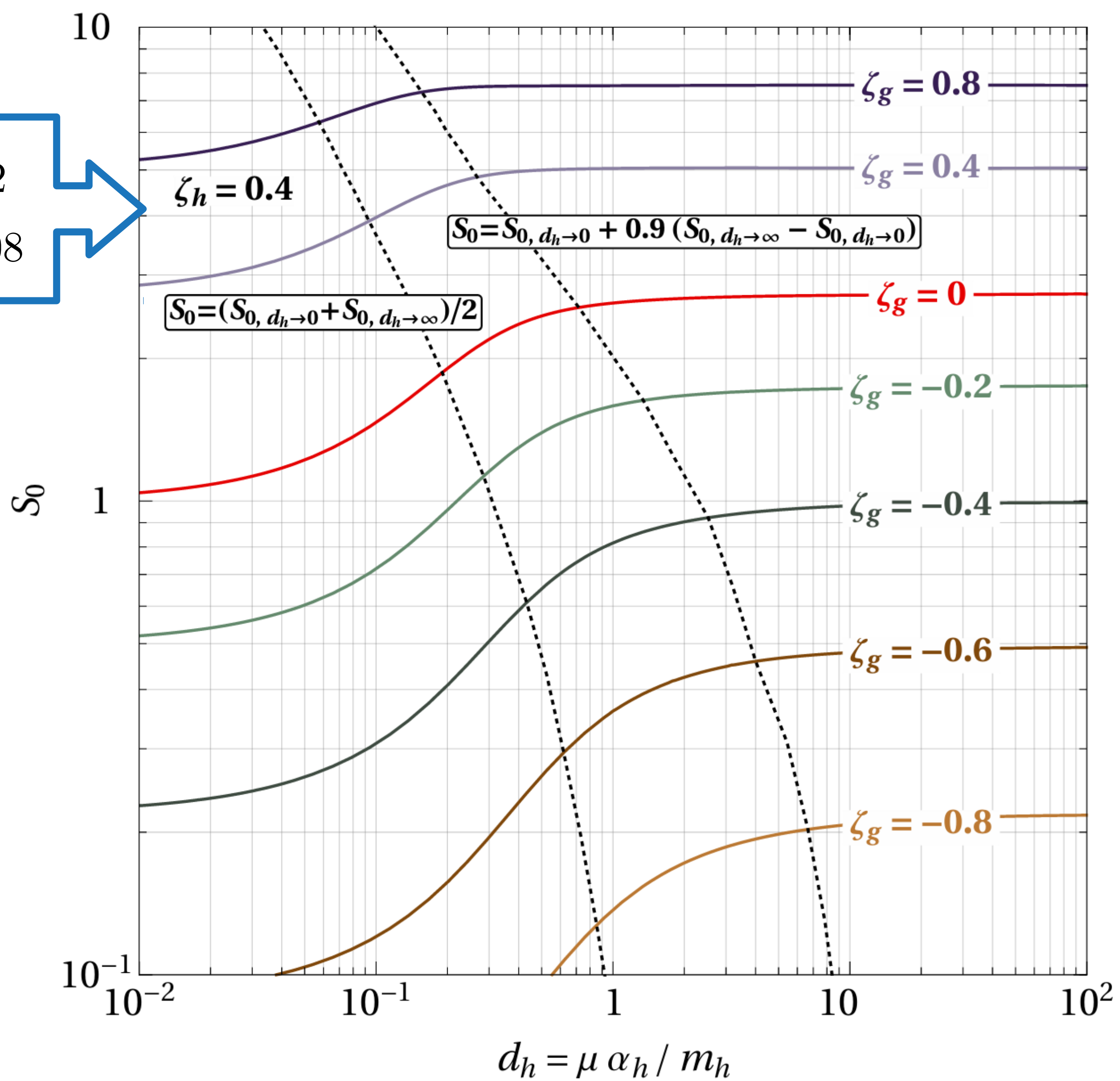
Higgs enhancement

$$\zeta_{g,h} \equiv \frac{\mu\alpha_{g,h}}{\mu v_{\rm rel}} = \frac{\alpha_{g,h}}{v_{\rm rel}};$$

$$d_h \equiv \frac{\mu\alpha_h}{m_h}$$

$v_{\rm rel} \approx 0.2$

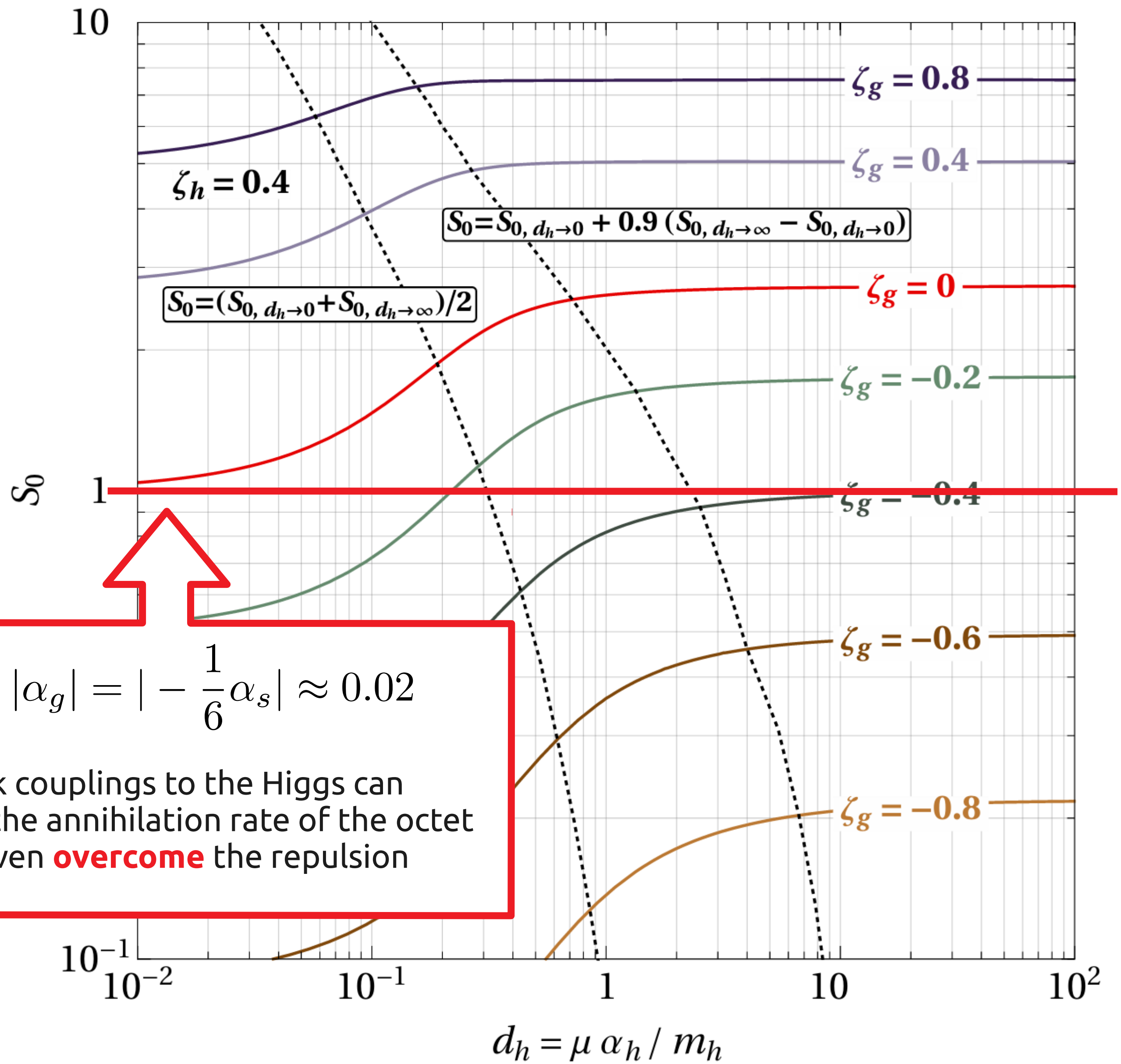
$\alpha_h \approx 0.08$



Higgs enhances the attraction of the singlet state

JH, Petraki, (2018)

Higgs enhancement



$$\alpha_h \approx |\alpha_g| = |-\frac{1}{6}\alpha_s| \approx 0.02$$

Even weak couplings to the Higgs can **enhance** the annihilation rate of the octet state or even **overcome** the repulsion

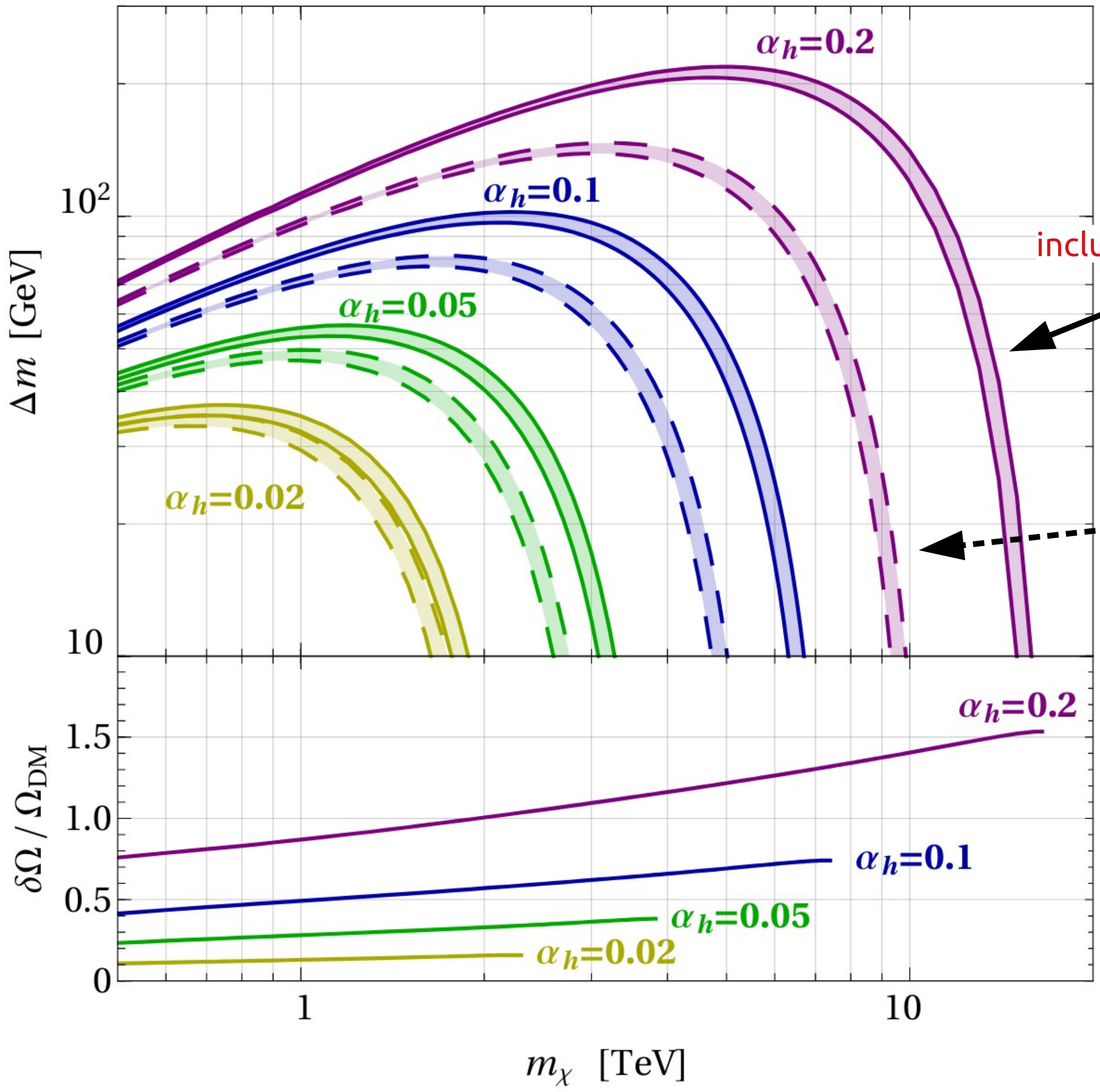
$$\zeta_{g,h} \equiv \frac{\mu\alpha_{g,h}}{\mu v_{\rm rel}} = \frac{\alpha_{g,h}}{v_{\rm rel}},$$

$$d_h \equiv \frac{\mu\alpha_h}{m_h}$$

Higgs reduces the repulsion of the octet state

JH, Petraki, (2018)

Impact of Higgs enhancement on the relic density

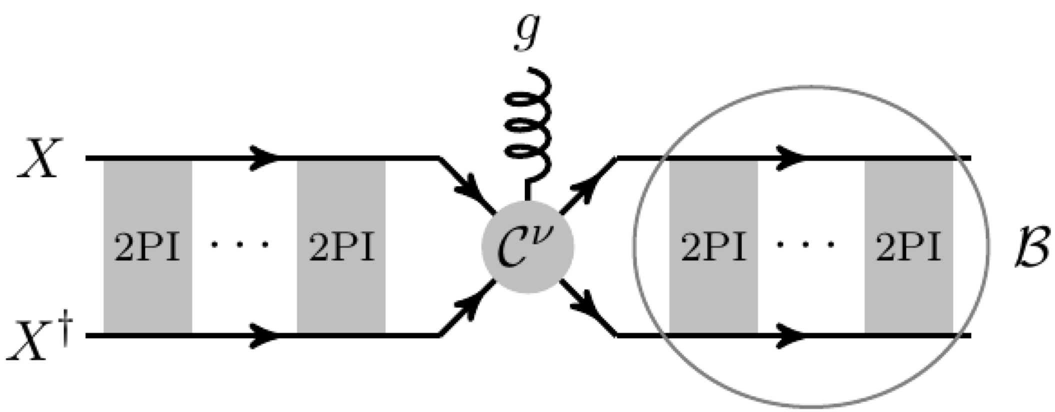


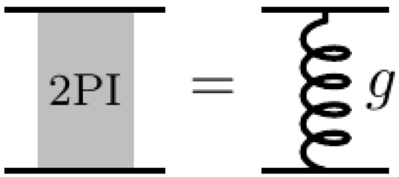
including Higgs exchange

gluon exchange only

JH, Petraki, (2018)

Bound states with gluon exchange





$$(X + X^\dagger)_{[\mathbf{8}]} \rightarrow \mathcal{B}(XX^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]}$$ **bound state formation**

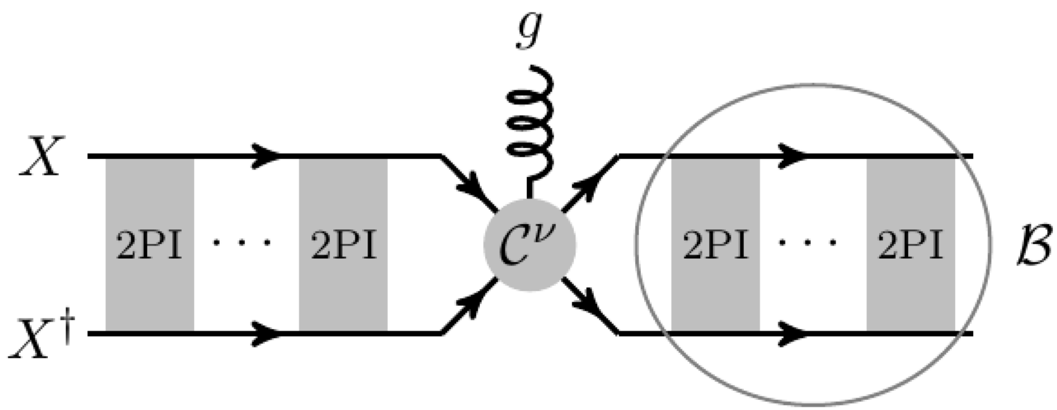
$$(\mathrm{XX}^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]} \rightarrow (X + X^\dagger)_{[\mathbf{8}]}$$ **bound state ionisation**

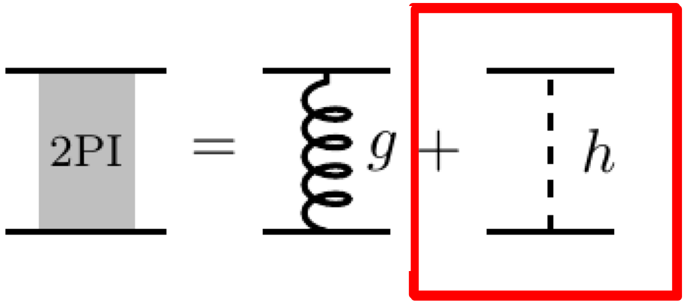
$$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \rightarrow g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$$ **bound state decay**

$$\boxed{\langle\sigma_{\mathrm{BSF}} v_{\mathrm{rel}}\rangle_{\mathrm{eff}} = \langle\sigma_{\mathrm{BSF}} v_{\mathrm{rel}}\rangle \times \left(\frac{\Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{dec}} + \Gamma_{\mathrm{ion}}}\right)}$$

→ additional “annihilation” channel alters the relic density prediction

Bound states with gluon and Higgs exchange





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

$$(X + X^\dagger)_{[\mathbf{1}]} \to \ \{\mathcal{B}(XX^\dagger)_{[\mathbf{8}]} + g_{[\mathbf{8}]}\}_{\mathbf{1_S}}$$

$$(X + X^\dagger)_{[\mathbf{8}]} \to \ \{\mathcal{B}(XX^\dagger)_{[\mathbf{8}]} + g_{[\mathbf{8}]}\}_{\mathbf{8_S}\text{ or }\mathbf{8_A}}$$

$$(X + X^\dagger)_{[\mathbf{1}]} \to \mathcal{B}(XX^\dagger)_{[\mathbf{1}]} + h$$

$$(X + X^\dagger)_{[\mathbf{8}]} \to \mathcal{B}(XX^\dagger)_{[\mathbf{8}]} + h$$

bound state formation

Higgs may allow

(1) to form tighter bound states

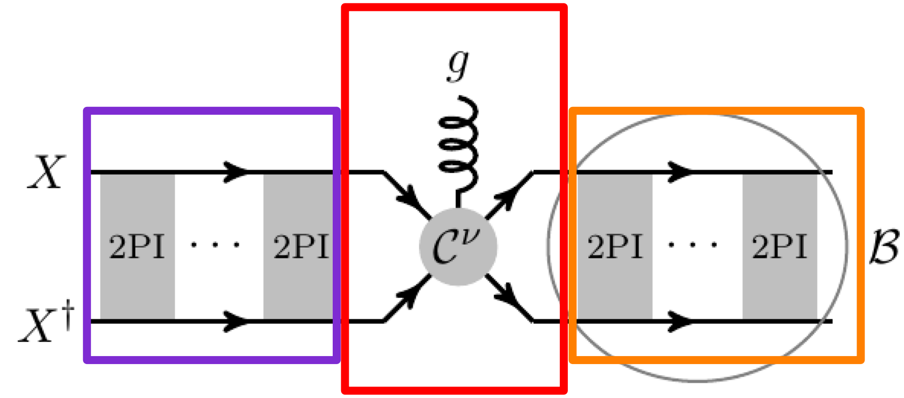
(2) to form color octet bound states

(3) *to form bound states via emission of a Higgs*

$$\boxed{\langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}} = \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle \times \left(\frac{\Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{dec}} + \Gamma_{\mathrm{ion}}} \right)}$$

Bound state formation

$$\left[-\frac{\nabla^2}{2\mu} + V_{\rm scatt}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r})$$



scattering state **radiative transition** **bound state**

Kinetic energy

$$\mathcal{E}_{\mathbf{k}} \equiv \frac{\mathbf{k}^2}{2\mu} = \frac{\mu v_{\rm rel}^2}{2} > 0$$

Scattering potential

$$\mathrm{V}_{\rm scatt}(r) = -\frac{\alpha_g^S}{r} - \frac{\alpha_h}{r}\,e^{-m_h r}$$

with $\alpha^S_{g,[\mathbf{1}]} = \frac{4\alpha_s^S}{3}$ and $\alpha^S_{g,[\mathbf{8}]} = -\frac{\alpha_s^S}{6}$

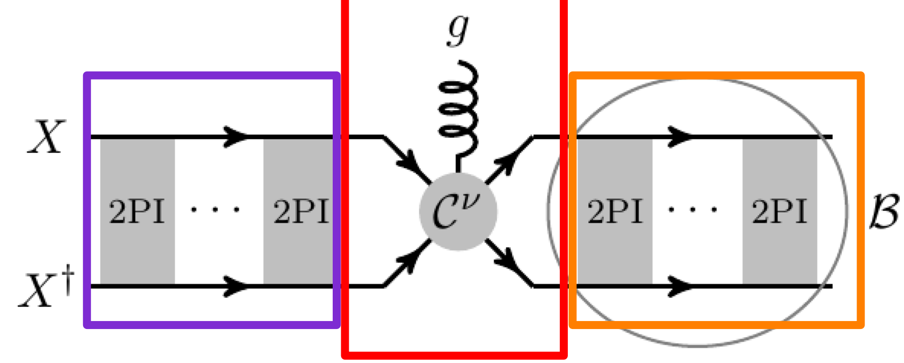
at scale $Q = \frac{m_X v_{\rm rel}}{2}$

scattering state

Bound state formation

$$\left[-\frac{\nabla^2}{2\mu}+V_{\rm scatt}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r})=\mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r})$$

$$\left[-\frac{\nabla^2}{2\mu}+V_{\rm bound}(\mathbf{r})\right]\psi_{n\ell m}(\mathbf{r})=\mathcal{E}_{n\ell}\,\psi_{n\ell m}(\mathbf{r})$$



scattering state

radiative transition

bound state

Binding energy

$$\mathcal{E}_{n\ell}\equiv-\gamma_{n\ell}^2\times\frac{\kappa^2}{2\mu}=-\frac{1}{2}\mu\,(\alpha_g^B+\alpha_h)^2\,\gamma_{n\ell}^2<0$$

$$V_{\rm bound}(r)=-\frac{\alpha_g^B}{r}-\frac{\alpha_h}{r}\,e^{-m_h r}$$

with Bohr momentum:

$$\kappa\equiv\mu\alpha$$

with $\alpha^B_{g,[\mathbf{1}]}=\frac{4\alpha_s^B}{3}$ and $\alpha^B_{g,[\mathbf{8}]}=-\frac{\alpha_s^B}{6}$

at scale

Coulomb limit: $\gamma^C=\frac{1}{n}$

$$Q=\mu\alpha\gamma_{nl}$$

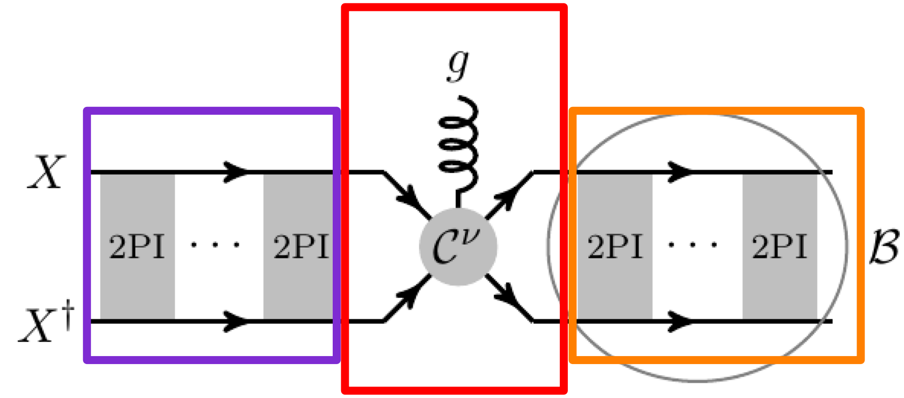
$$=\frac{m_X}{2}\left(\alpha_h+\alpha^B_{g,\{[\mathbf{1}],[\mathbf{8}]\}}\right)\times\gamma_{n\ell}\left(\frac{\alpha_{g,\{[\mathbf{1}],[\mathbf{8}]\}}}{\alpha_h},\;d_h\right)$$

bound state

Bound state formation

$$\left[-\frac{\nabla^2}{2\mu}+V_{\mathrm{scatt}}(\mathbf{r})\right]\phi_{\mathbf{k}}(\mathbf{r})=\mathcal{E}_{\mathbf{k}}\,\phi_{\mathbf{k}}(\mathbf{r})$$

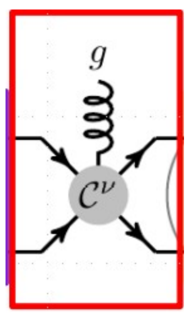
$$\left[-\frac{\nabla^2}{2\mu}+V_{\mathrm{bound}}(\mathbf{r})\right]\psi_{n\ell m}(\mathbf{r})=\mathcal{E}_{n\ell}\,\psi_{n\ell m}(\mathbf{r})$$



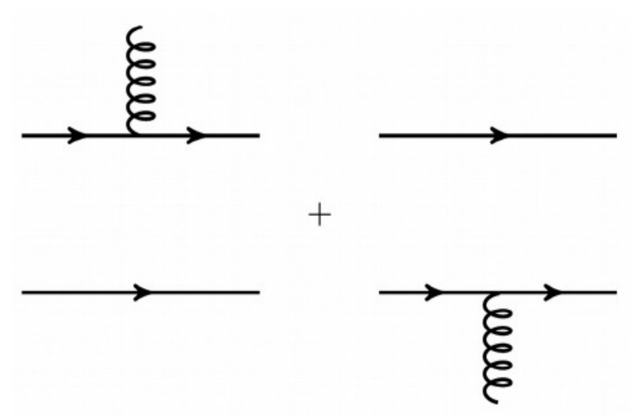
scattering state

radiative transition

bound state



=



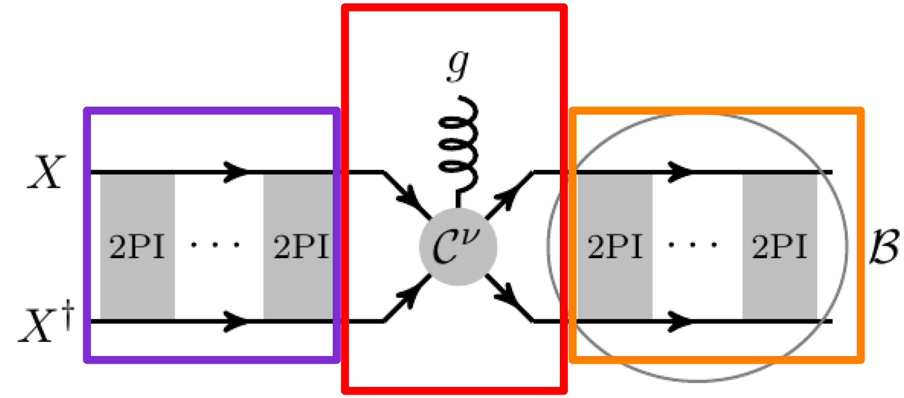
Effects of QCD bound states on dark matter relic abundance, Liew, Luo (2017)
Simplified Phenomenology for Colored Dark Sectors, El Hedri, Kaminska, de Vries, Zurita (2017)

transition amplitude

Bound state formation

$$\left[-\frac{\nabla^2}{2\mu} + V_{\text{scatt}}(\mathbf{r})\right] \phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\, \phi_{\mathbf{k}}(\mathbf{r})$$

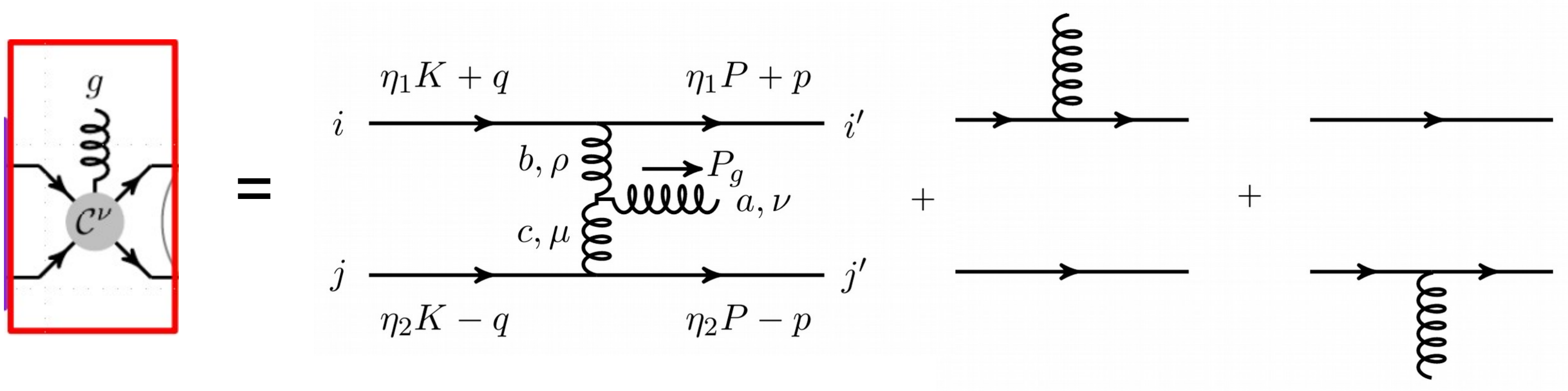
$$\left[-\frac{\nabla^2}{2\mu} + V_{\text{bound}}(\mathbf{r})\right] \psi_{n\ell m}(\mathbf{r}) = \mathcal{E}_{n\ell}\, \psi_{n\ell m}(\mathbf{r})$$



scattering state

radiative transition

bound state



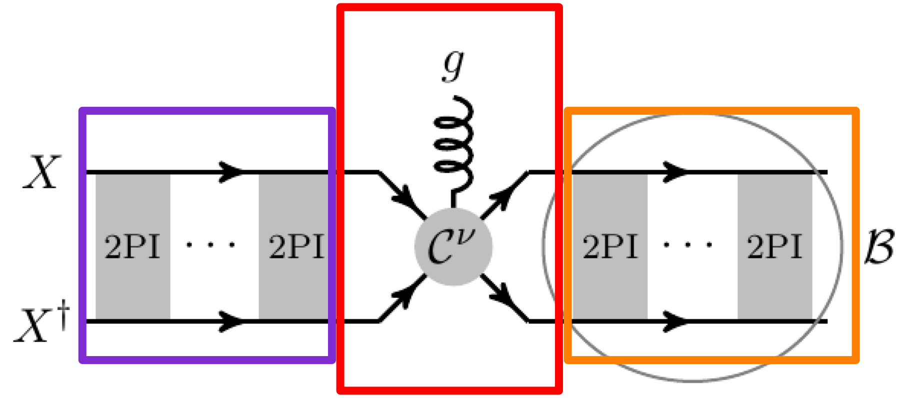
Cosmological Implications of Dark Matter Bound States, Mitridate, Redi, Smirnov, Strumia (2017)
Reappraisal of dark matter co-annihilating with a top or bottom partner, Keung, Low, Zhang (2017)
Capture and Decay of Electroweak WIMPonium, Asadi, Baumgart, Fitzpatrick, Krupczak, Slatyer (2016)

transition amplitude

Bound state formation

$$\left[-\frac{\nabla^2}{2\mu} + V_{\text{scatt}}(\mathbf{r})\right] \phi_{\mathbf{k}}(\mathbf{r}) = \mathcal{E}_{\mathbf{k}}\, \phi_{\mathbf{k}}(\mathbf{r})$$

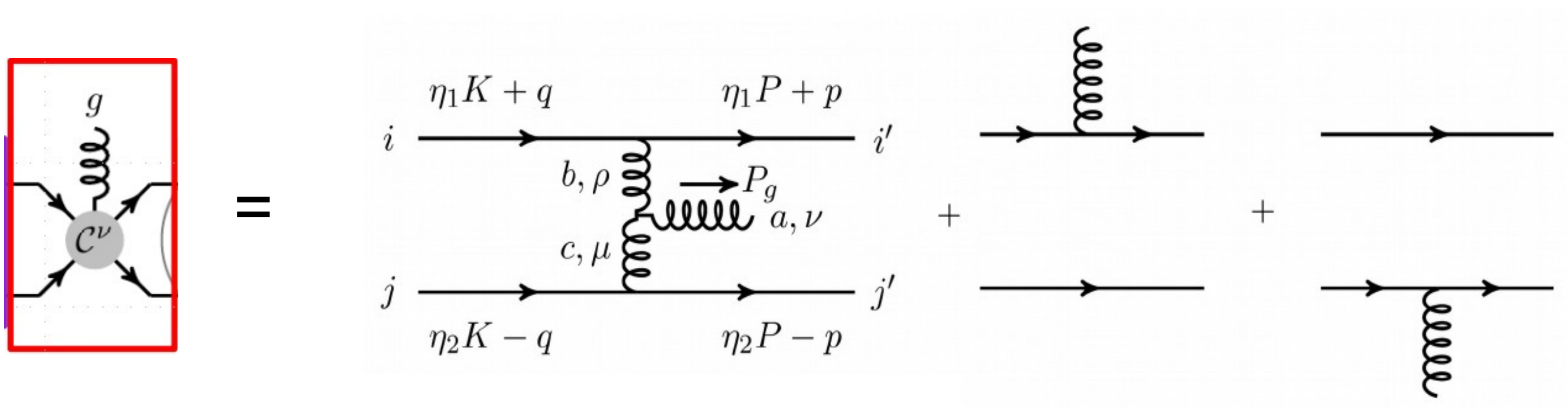
$$\left[-\frac{\nabla^2}{2\mu} + V_{\text{bound}}(\mathbf{r})\right] \psi_{n\ell m}(\mathbf{r}) = \mathcal{E}_{n\ell}\, \psi_{n\ell m}(\mathbf{r})$$



scattering state

radiative transition

bound state



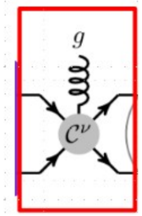
Derivation from Feynman diagrammatic approach, see
DM bound states from Feynman diagrams, Petraki et al. JHEP 1506 (2015) 128

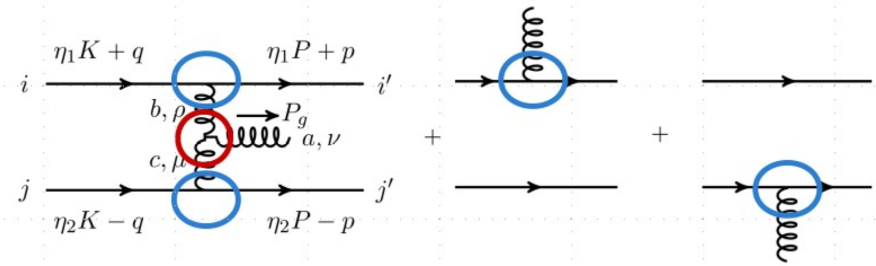
$$[\mathcal{M}^\nu_{\mathbf{k}\to\{n\ell m\}}]^a_{ii',jj'} = \frac{1}{\sqrt{2\mu}} \int \frac{d^3q}{(2\pi)^3} \frac{d^3p}{(2\pi)^3}\; \tilde{\psi}^*_{n\ell m}(\mathbf{p})\; \tilde{\phi}_{\mathbf{k}}(\mathbf{q})\; [\mathcal{M}^\nu_{\text{trans}}(\mathbf{q},\mathbf{p})]^a_{ii',jj'}$$

transition amplitude

Bound state formation

transition amplitude





$$\frac{1}{d_{\mathbf{R}}^2}\,|\,\mathcal{M}^{[\mathbf{adj}]\to[\mathbf{1}]}_{\mathbf{k}\to 100}\,|^2 = \left(\frac{2^5\pi\alpha_s^{\rm BSF}\,M^2}{\mu}\right)\times\frac{C_2(\mathbf{R})}{d_{\mathbf{R}}^2}\left[1+\frac{C_2(\mathbf{G})}{2}\left(\frac{\alpha_s^B}{\alpha_h+\alpha_g^B}\right)\right]^2 |\,\mathcal{J}^{[\mathbf{adj},\mathbf{1}]}_{\mathbf{k},100}\,|^2$$

with: $\mathbf{3}\otimes\bar{\mathbf{3}}=\mathbf{1}\oplus\mathbf{8}$

$$\frac{1}{9}\,|\,\mathcal{M}^{[\mathbf{8}]\to[\mathbf{1}]}_{\mathbf{k}\to 100}\,|^2 = \left(\frac{2^5\pi\alpha_s^{\rm BSF}\,M^2}{\mu}\right)\times\frac{4}{27}\left[1+\frac{3}{2}\left(\frac{\alpha_s^B}{\alpha_h+\alpha_g^B}\right)\right]^2 |\,\mathcal{J}^{[\mathbf{8},\mathbf{1}]}_{\mathbf{k},100}\,|^2$$

$$\text{for}\quad \alpha_h\to 0:\qquad \to\left[1+\frac{9}{8}\right]^2$$

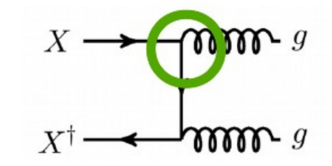
expected to have significant effect!

Comparison with Quarkonium literature:

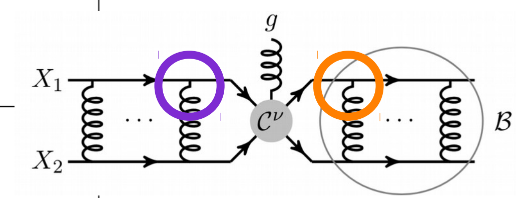
Perturbative heavy quark - anti-quark systems, M. Beneke, hep-ph/9911490
Running of the heavy quark production current and 1 / v potential in QCD, A. V. Manohar and I. W. Stewart, Phys. Rev. D63 (2001) 054004
*Renormalization group analysis of the QCD quark potential to order v**2*, A. V. Manohar and I. W. Stewart, Phys. Rev. D62 (2000) 014033
Thermal width and gluo-dissociation of quarkonium in pNRQCD, N. Brambilla, et al, JHEP 12 (2011) 116

Running of the strong coupling

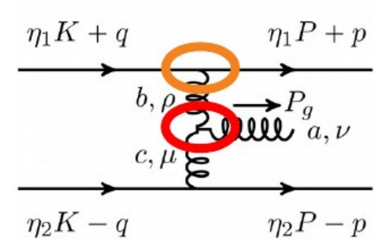
Vertices	α_s	α_g	Average momentum transfer Q
Annihilation: gluon emission	α_s^{ann}		m_X
Scattering-state wavefunction (ladder diagrams)	α_s^S	Colour-singlet $\alpha_{g,[1]}^S = \frac{4\alpha_s^S}{3}$	$\frac{m_X\, v_{\mathrm{rel}}}{2}$
		Colour-octet $\alpha_{g,[8]}^S = -\frac{\alpha_s^S}{6}$	
Colour-singlet bound-state wavefunction (ladder diagrams)	$\alpha_{s,[1]}^B$	$\alpha_{g,[1]}^B = \frac{4\alpha_{s,[1]}^B}{3}$	$\kappa_{[1]}\ \gamma_{n\ell}\left(\lambda_{[1]}, d_h\right) = \frac{m_X}{2}\left(\alpha_h + \frac{4\alpha_{s,[1]}^B}{3}\right) \times \gamma_{n\ell}\left(\frac{4\alpha_{s,[1]}^B}{3\alpha_h},\ d_h\right)$
Colour-octet bound state wavefunction (ladder diagrams)	$\alpha_{s,[8]}^B$	$\alpha_{g,[8]}^B = -\frac{\alpha_{s,[8]}^B}{6}$	$\kappa_{[8]}\ \gamma_{n\ell}\left(\lambda_{[8]}, d_h\right) = \frac{m_X}{2}\left(\alpha_h - \frac{\alpha_{s,[8]}^B}{6}\right) \times \gamma_{n\ell}\left(-\frac{\alpha_{s,[8]}^B}{6\alpha_h},\ d_h\right)$
Formation of colour-singlet bound states: gluon emission	$\alpha_{s,[1]}^{\mathrm{BSF}}$		$\frac{m_X}{4}\left[v_{\mathrm{rel}}^2 + \left(\alpha_h + \frac{4\alpha_{s,[1]}^B}{3}\right)^2 \times \gamma_{n\ell}^2\left(\frac{4\alpha_{s,[1]}^B}{3\alpha_h},\ d_h\right)\right]$
Formation of colour-octet bound states: gluon emission	$\alpha_{s,[8]}^{\mathrm{BSF}}$		$\frac{m_X}{4}\left[v_{\mathrm{rel}}^2 + \left(\alpha_h - \frac{\alpha_{s,[8]}^B}{6}\right)^2 \times \gamma_{n\ell}^2\left(-\frac{\alpha_{s,[8]}^B}{6\alpha_h},\ d_h\right)\right]$



μv_{rel}



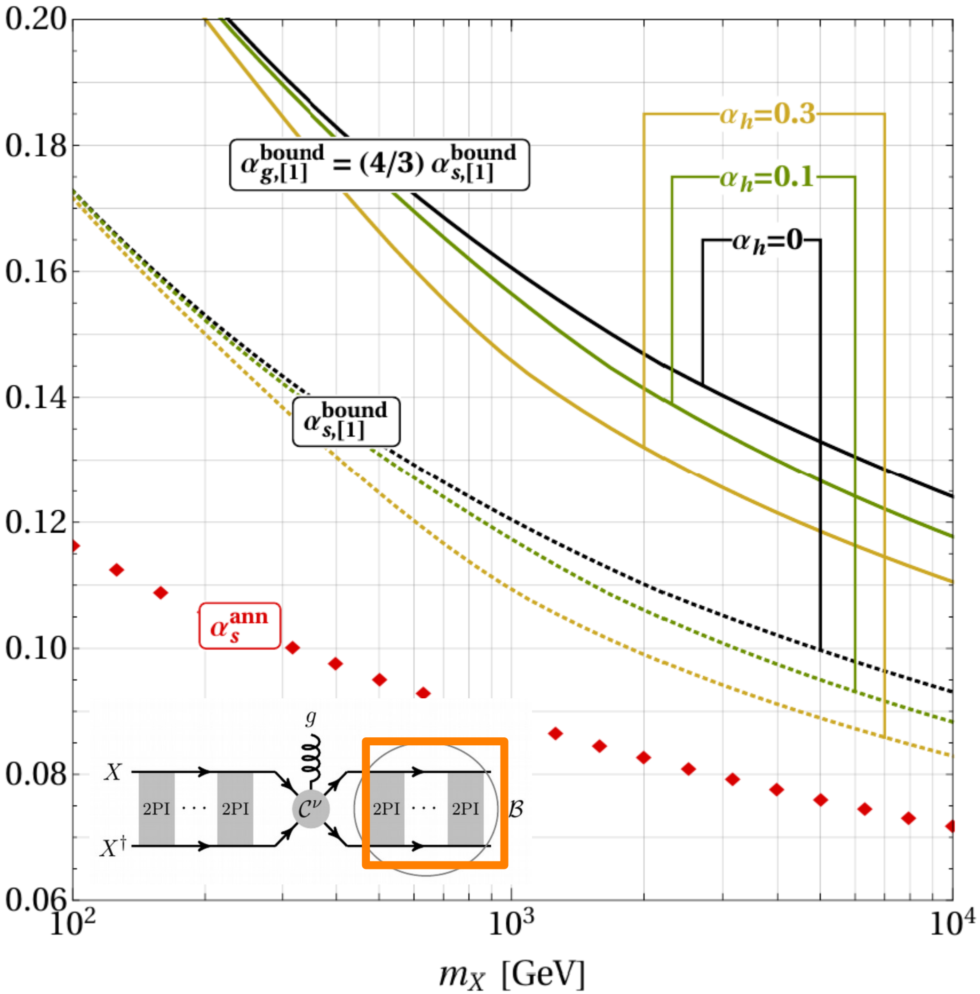
$\mu \alpha_g^B$



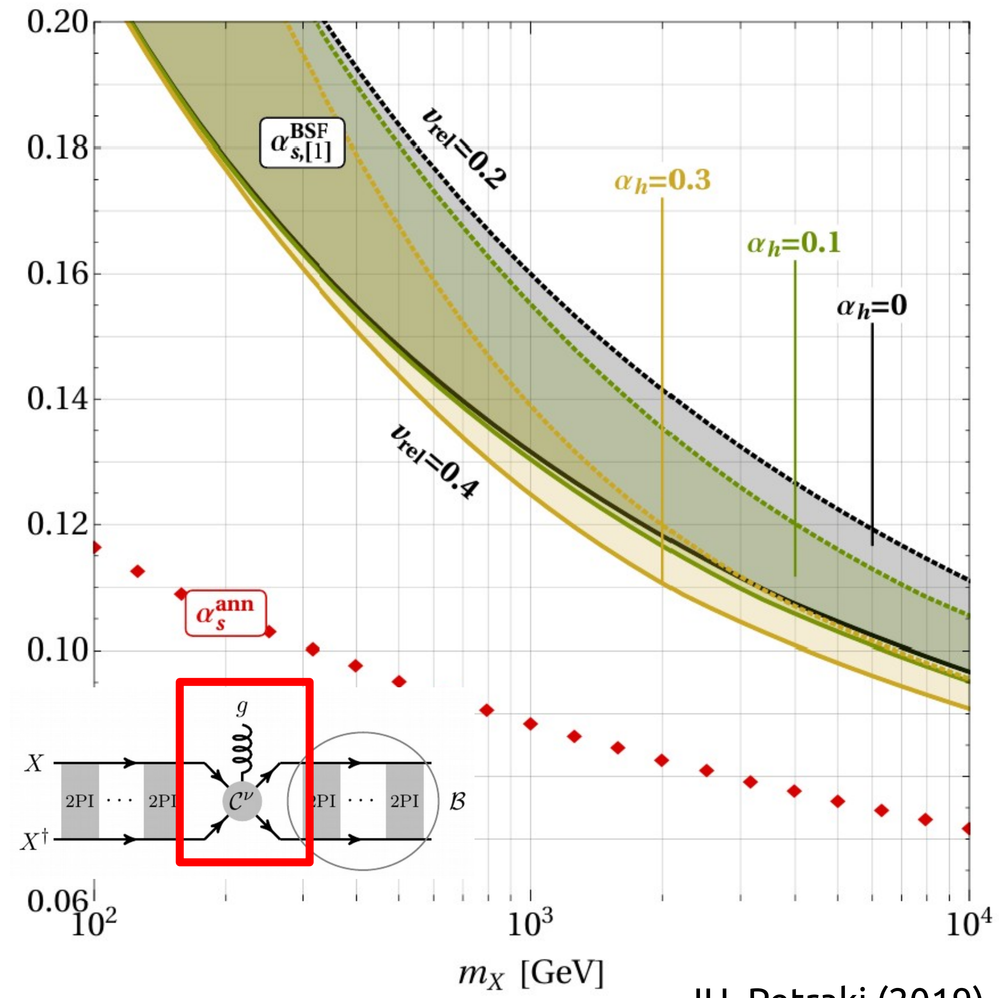
$|\,\mathbf{P_g}\,| = \mathcal{E}_{\mathbf{k}} - \mathcal{E}_{\mathbf{n}\ell}$

Running of the strong coupling – bound state

Colour–singlet bound states



Colour–singlet bound-state formation

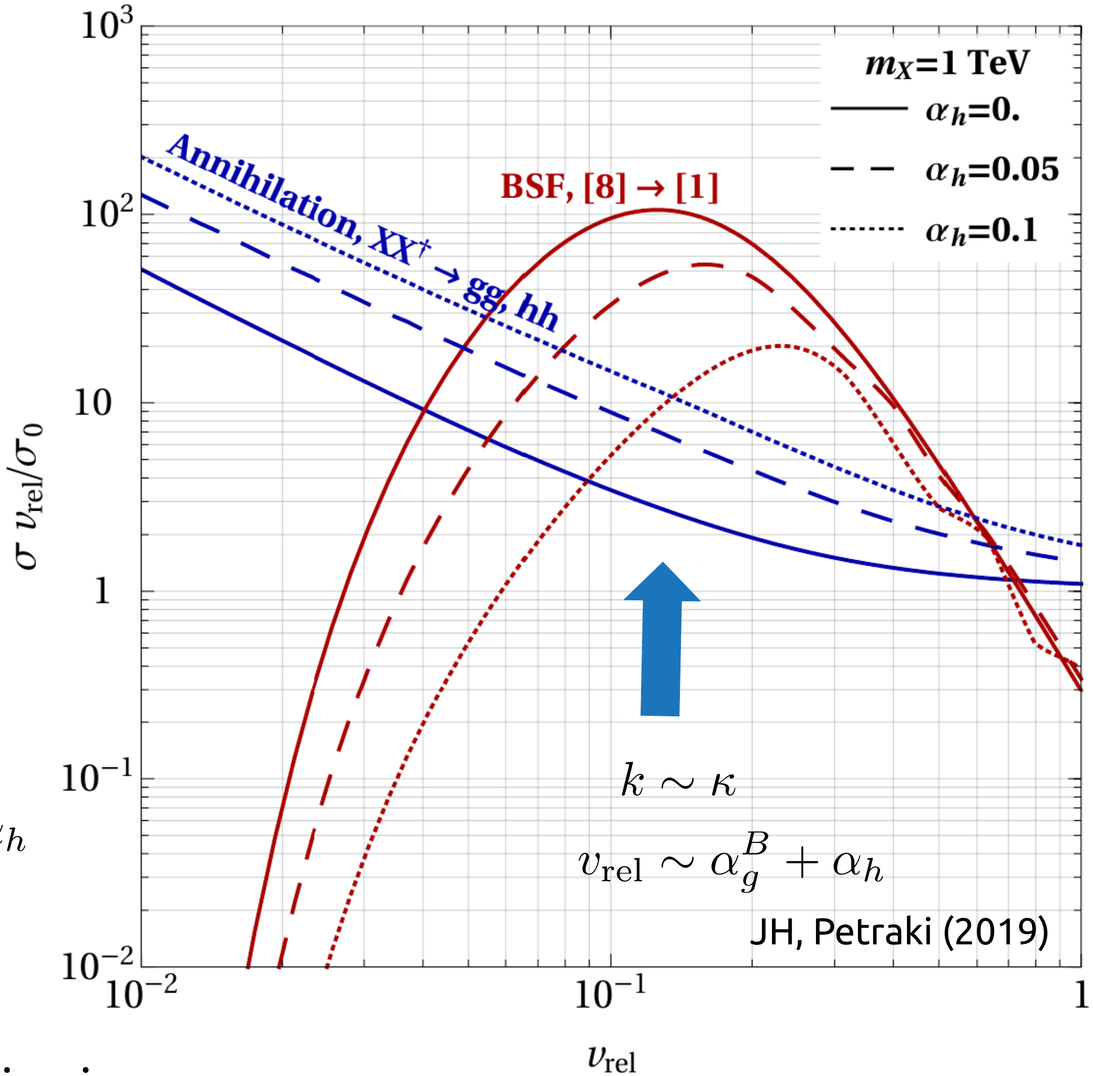


JH, Petraki (2019)
JH, Petraki (2018)

→ Higgs interaction decreases α_g considerably

Annihilation vs. BSF cross section

with Higgs exchange



$v_{\rm rel} \lesssim \alpha_g^S + \alpha_h$

Coulomb repulsion in

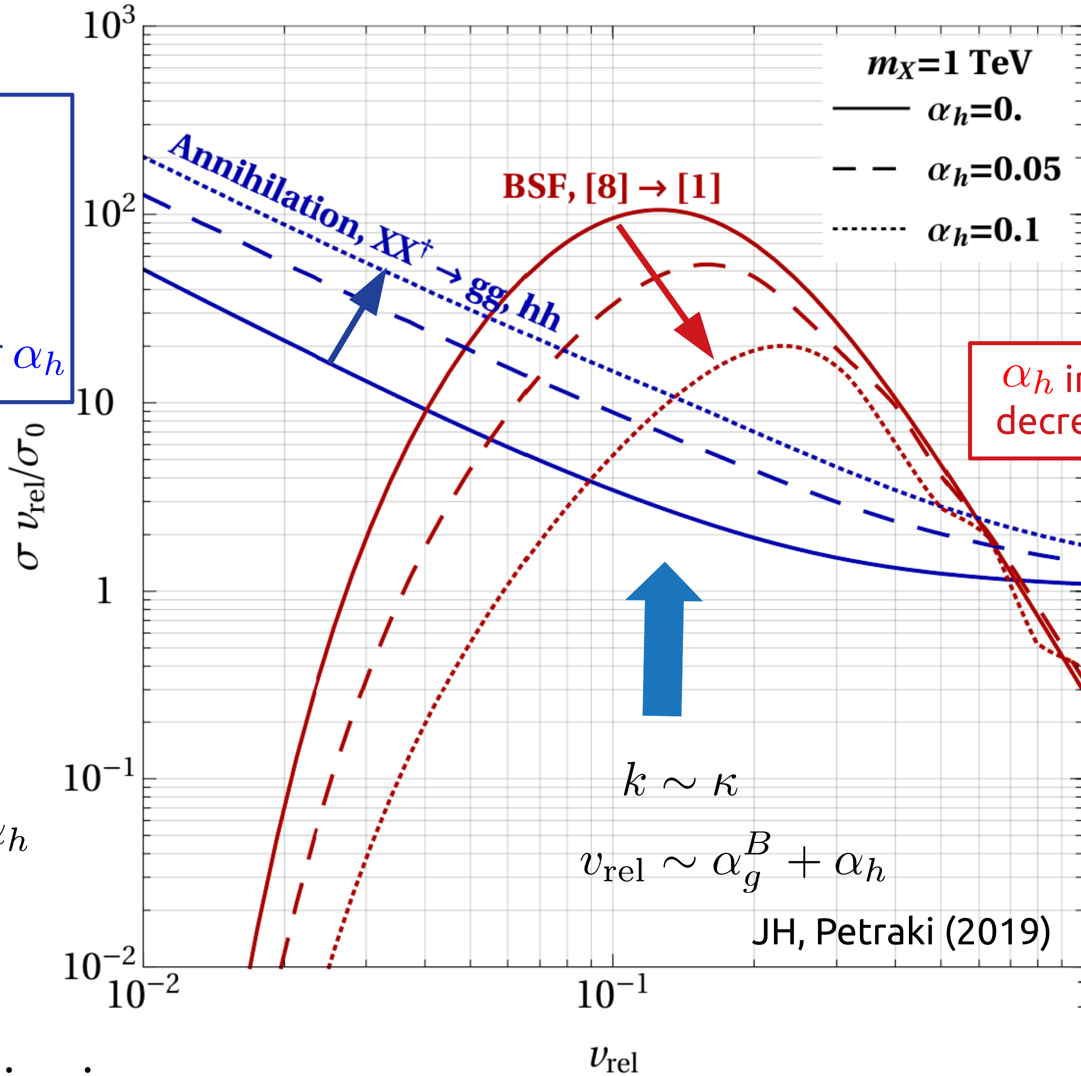
the scattering state

$$\sigma_{\rm BSF} v_{\rm rel} \propto (\kappa/k)^4$$
$$\approx [(\alpha_g^B + \alpha_h)/v_{\rm rel}]^4$$

Annihilation vs. BSF cross section

new annihilation channel

pert. annihilation + Sommerfeld effect increases with larger α_h



with Higgs exchange

α_h increases scale and decreases α_g

$v_{\rm rel} \lesssim \alpha_g^S + \alpha_h$

Coulomb repulsion in the scattering state

$$\sigma_{\rm BSF} v_{\rm rel} \propto (\kappa/k)^4$$
$$\approx [(\alpha_g^B + \alpha_h)/v_{\rm rel}]^4$$

→ relative strength of BSF seems to diminish, however, BSF peaks at later times!

Contributions to the effective BSF cross section

Remember:

$$(X+X^\dagger)_{[\mathbf{8}]} \to \mathcal{B}(XX^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]}$$ bound state formation

$$(\mathrm{XX}^\dagger)_{[\mathbf{1}]} + g_{[\mathbf{8}]} \to (X+X^\dagger)_{[\mathbf{8}]}$$ bound state ionisation

$$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$$ bound state decay

$$\langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle_{\mathrm{eff}} = \langle \sigma_{\mathrm{BSF}} v_{\mathrm{rel}} \rangle \times \left(\frac{\Gamma_{\mathrm{dec}}}{\Gamma_{\mathrm{dec}} + \Gamma_{\mathrm{ion}}} \right)$$

bound state ionisation

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

$$\Gamma_{\mathrm{ion}} = g_g \int_{\omega_{\min}}^{\infty} \frac{d\omega}{2\pi^2} \frac{\omega^2}{e^{\omega/T}-1}\, \sigma_{ion}$$

$$\sigma_{ion} = \frac{g_X^2}{g_g g_{\mathcal{B}}} \frac{\mu^2 v_{rel}^2}{\omega^2}\, \sigma_{\mathrm{BSF}}$$ Milne relation

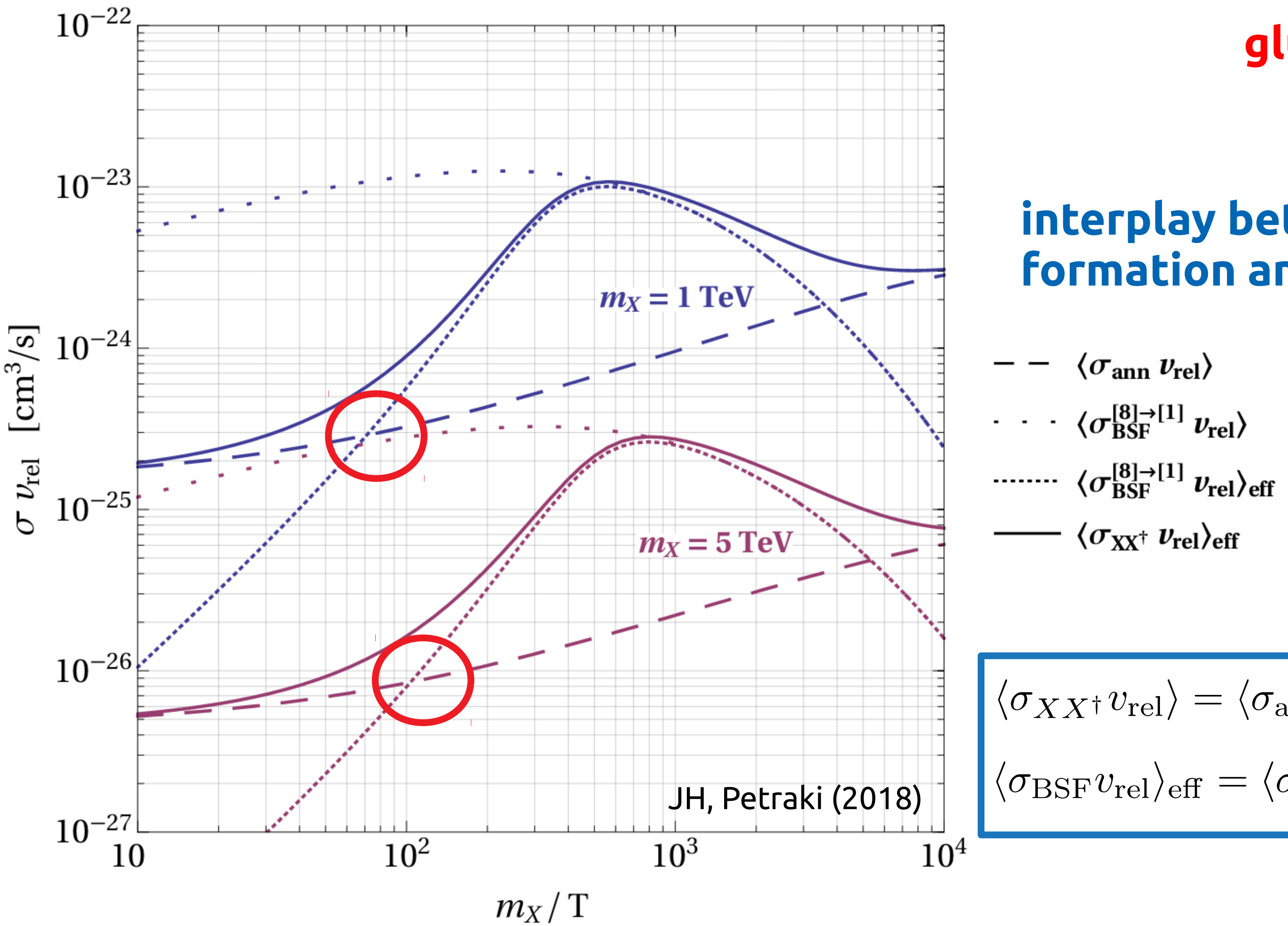
bound state decay

$$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$$

$$\Gamma_{\mathrm{dec}} = (\sigma^{s-\mathrm{wave}}_{\mathrm{ann},[\mathbf{1},\mathbf{8}]} v_{\mathrm{rel}})\ |\psi^{[\mathbf{1},\mathbf{8}]}_{n\ell m}(0)|^2$$

$$|\psi^{[\mathbf{1},\mathbf{8}]}_{1,0,0}(0)|^2 = \frac{\mu^3(\alpha_h + \alpha^B_{g\ ,[\mathbf{1},\mathbf{8}]})^3}{\pi}$$

Annihilation vs. effective BSF cross section



gluon exchange only

interplay between bound state formation and ionisation

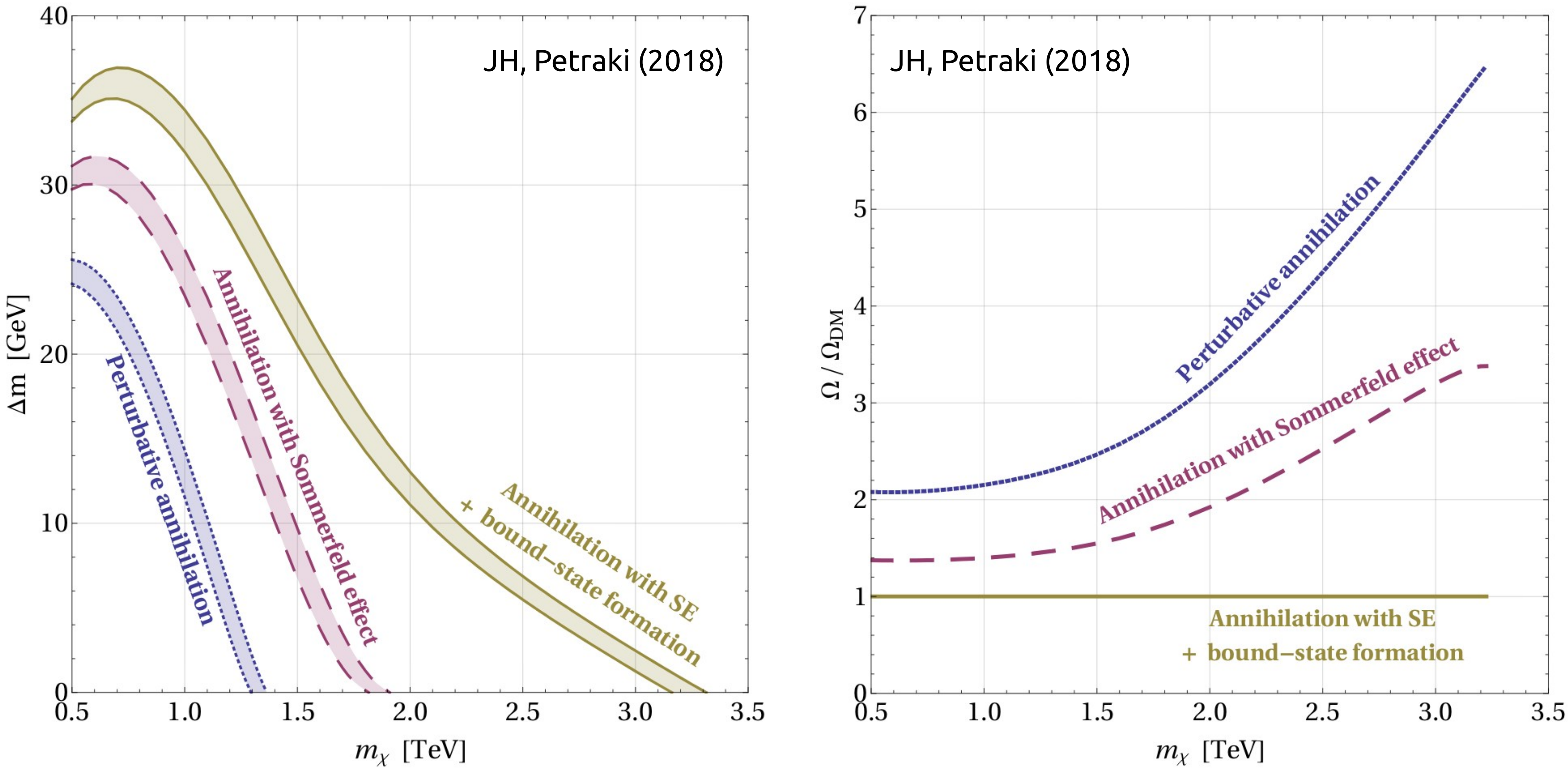
$$\langle \sigma_{XX^\dagger} v_{\rm rel} \rangle = \langle \sigma_{\rm ann}\, v_{\rm rel} \rangle + \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff}$$

$$\langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff} = \langle \sigma_{\rm BSF} v_{\rm rel} \rangle \times \left(\frac{\Gamma_{\rm dec}}{\Gamma_{\rm dec} + \Gamma_{\rm ion}} \right)$$

→ BSF becomes more important than direct annihilation at z > 70

Impact on the relic density

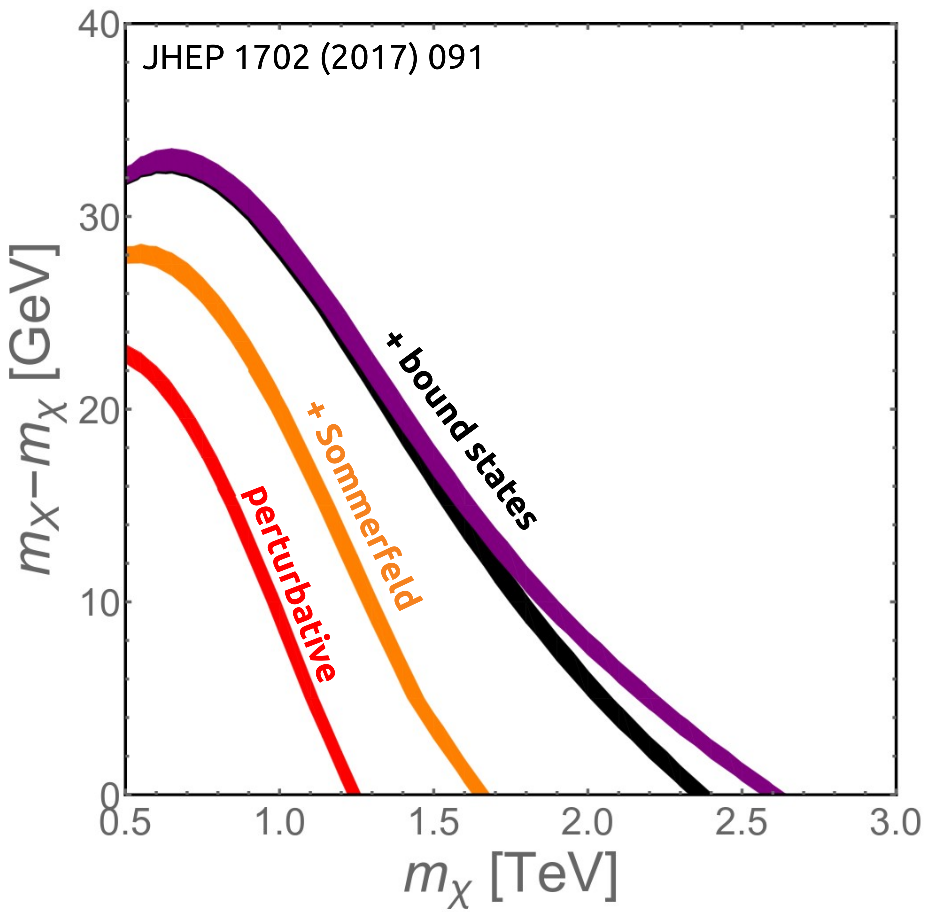
gluon exchange only

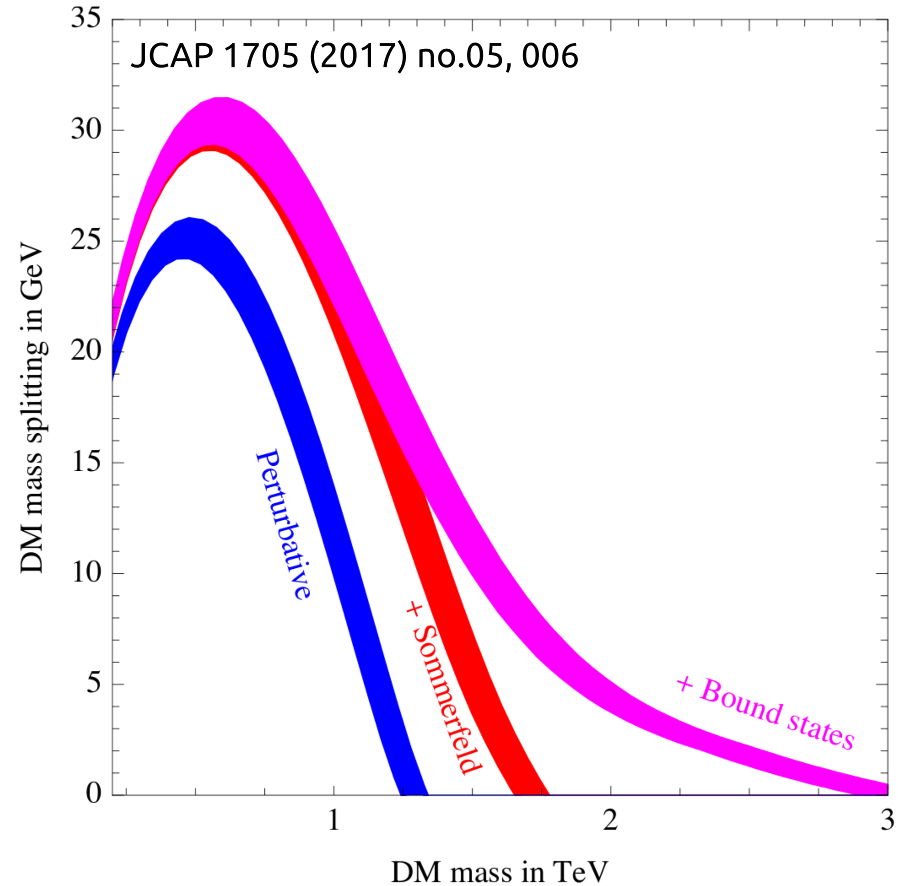


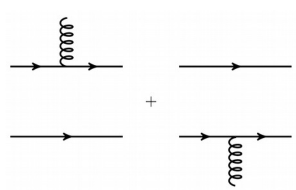
→ neglecting BSF and Sommerfeld enhancement would lead to a wrong relic density prediction by a factor 2 to 7

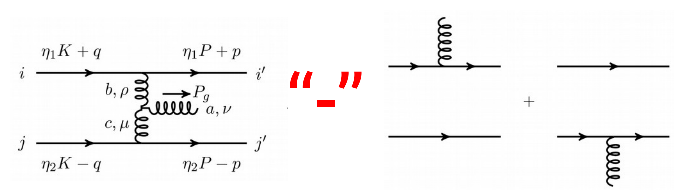
Comparison with previous results

gluon exchange only

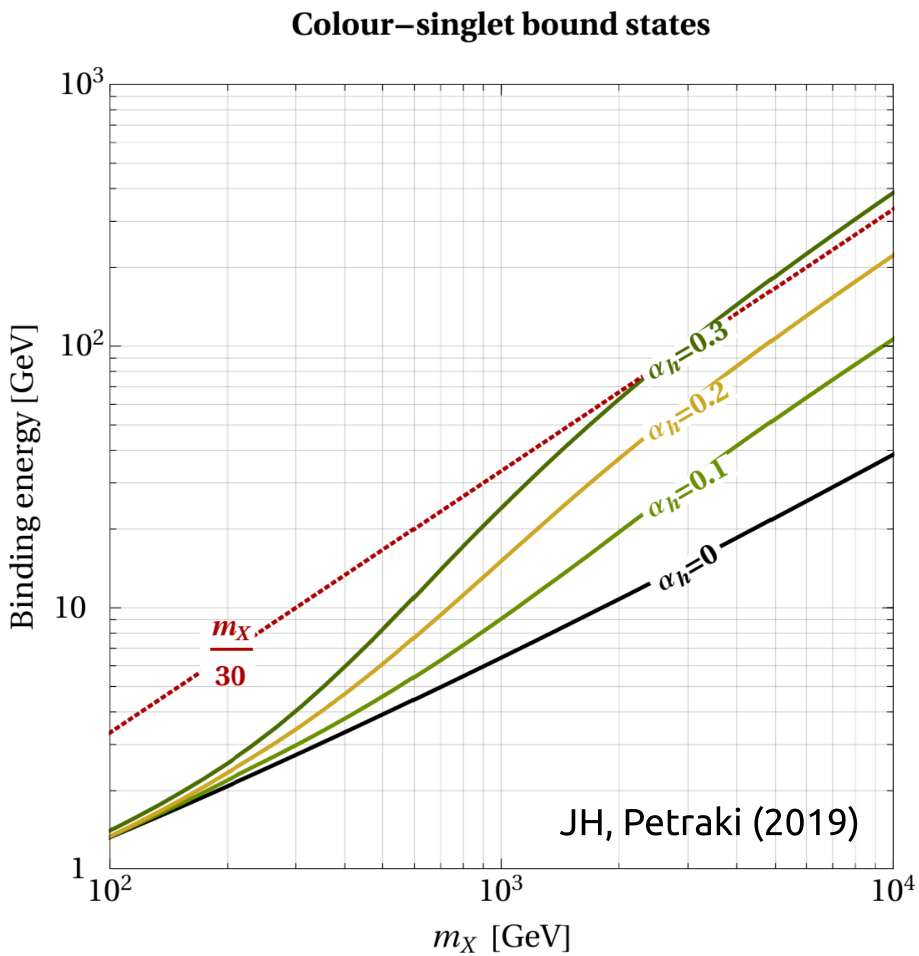






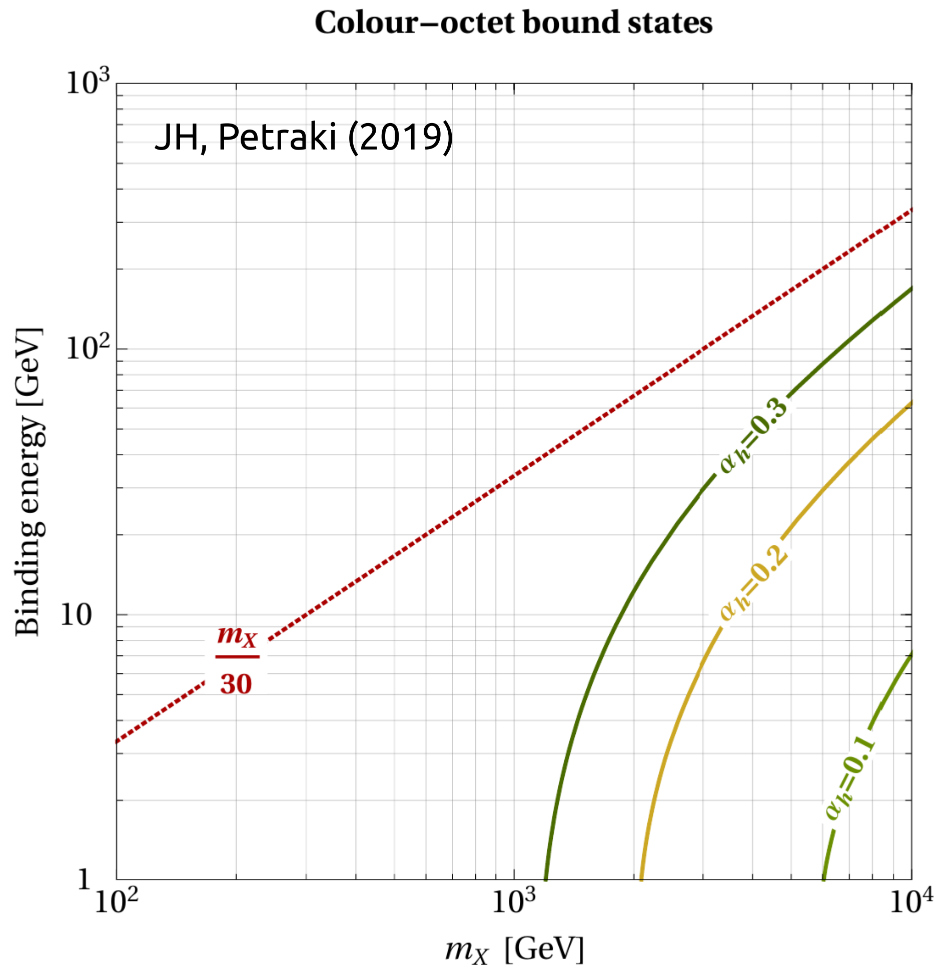


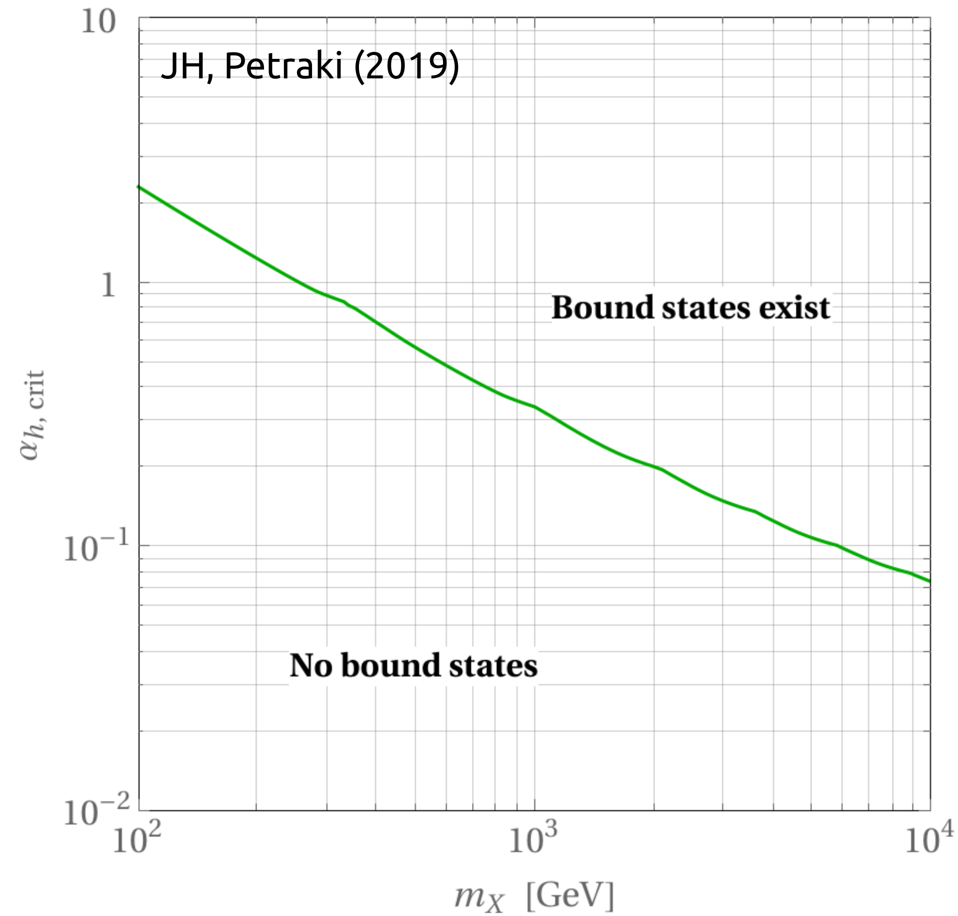
Impact of the Higgs on the formation of bound states



tighter bound states

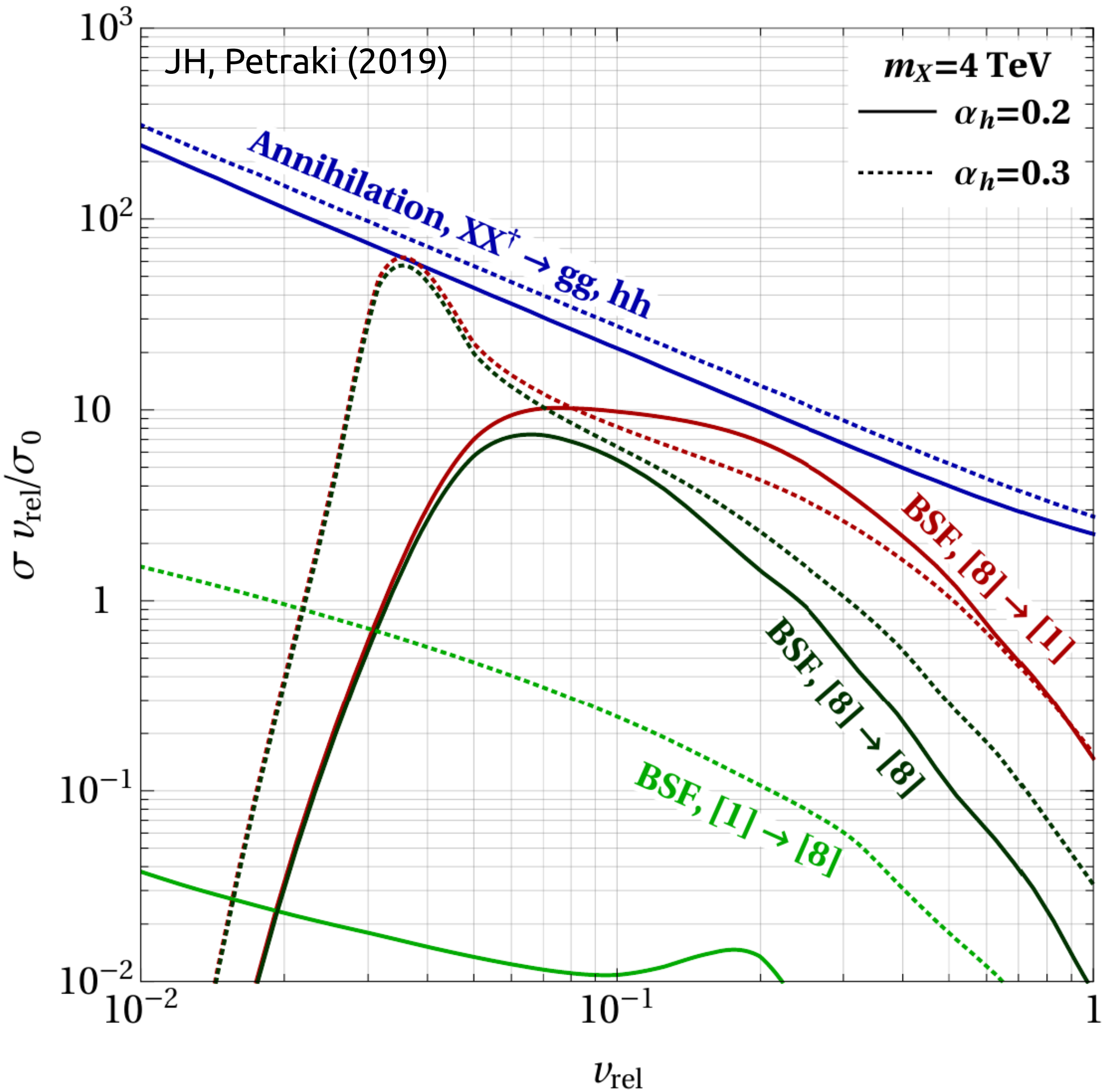
Impact of the Higgs on the existence of BS





additional bound states (color octet)

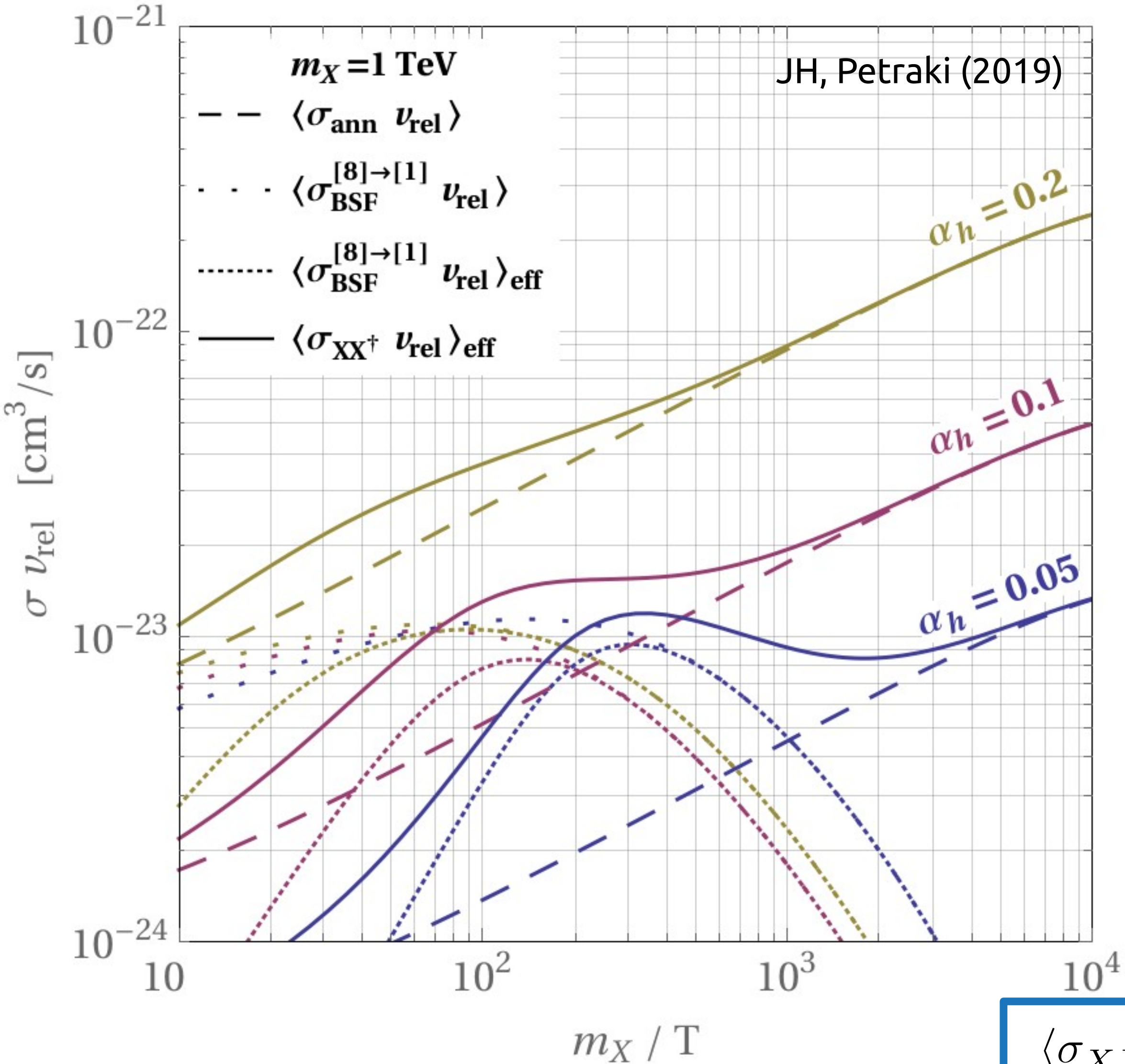
Impact of the Higgs on the BSF cross section



with Higgs exchange

at a certain mass and coupling, the formation of octets are possible

Impact of the Higgs on the effective BSF cross section



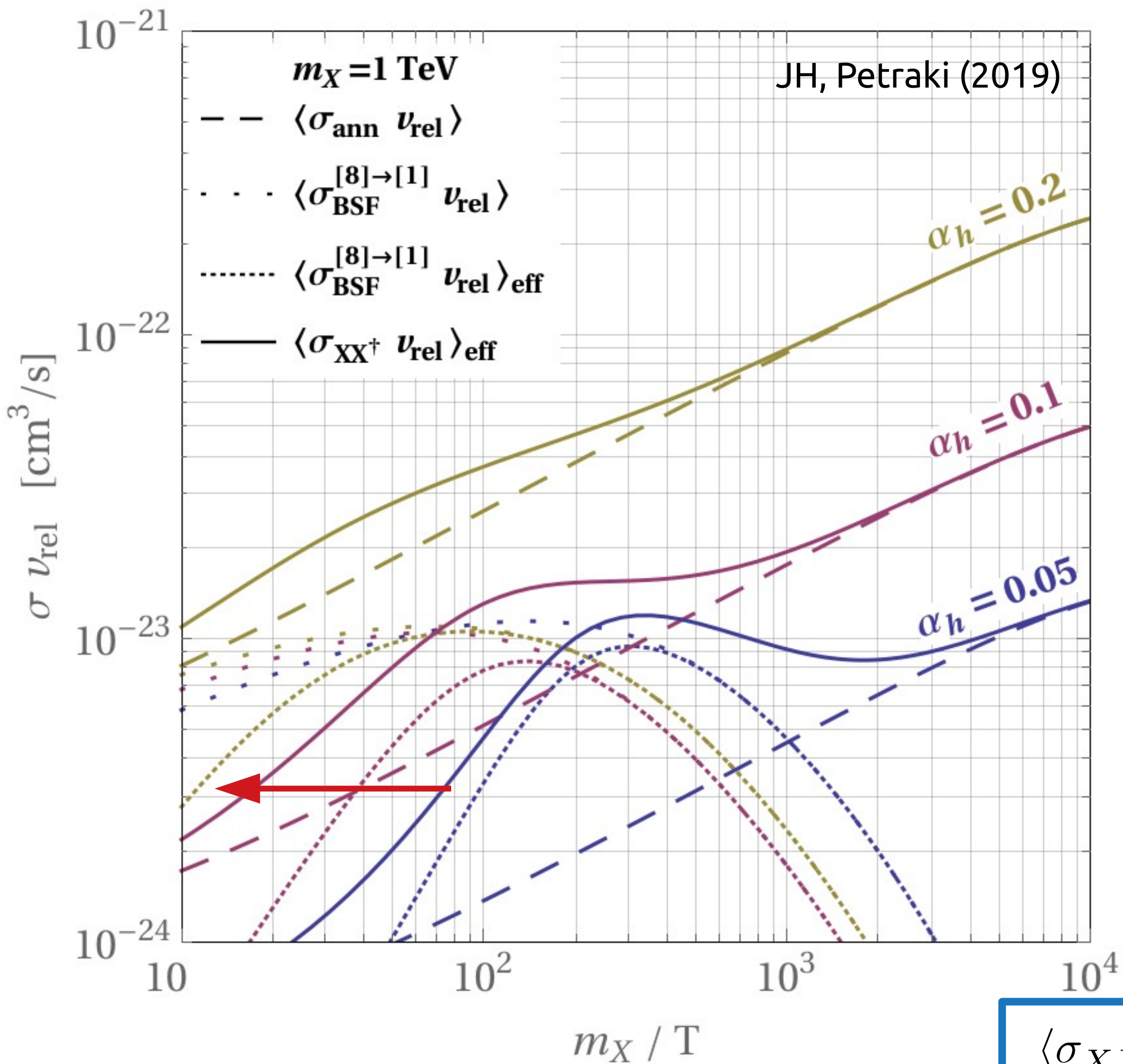
with Higgs exchange

- **Higgs coupling increases the binding energy**
- **a larger binding energy renders bound-state dissociation inefficient earlier, when the DM density is larger**
- **this enhances the efficiency to deplete DM**

$$\langle \sigma_{XX^\dagger} v_{rel} \rangle = \langle \sigma_{ann}\, v_{rel} \rangle + \langle \sigma_{BSF} v_{rel} \rangle_{eff}$$

$$\langle \sigma_{BSF} v_{rel} \rangle_{eff} = \langle \sigma_{BSF} v_{rel} \rangle \times \left(\frac{\Gamma_{dec}}{\Gamma_{dec} + \Gamma_{ion}} \right)$$

Impact of the Higgs on the effective BSF cross section



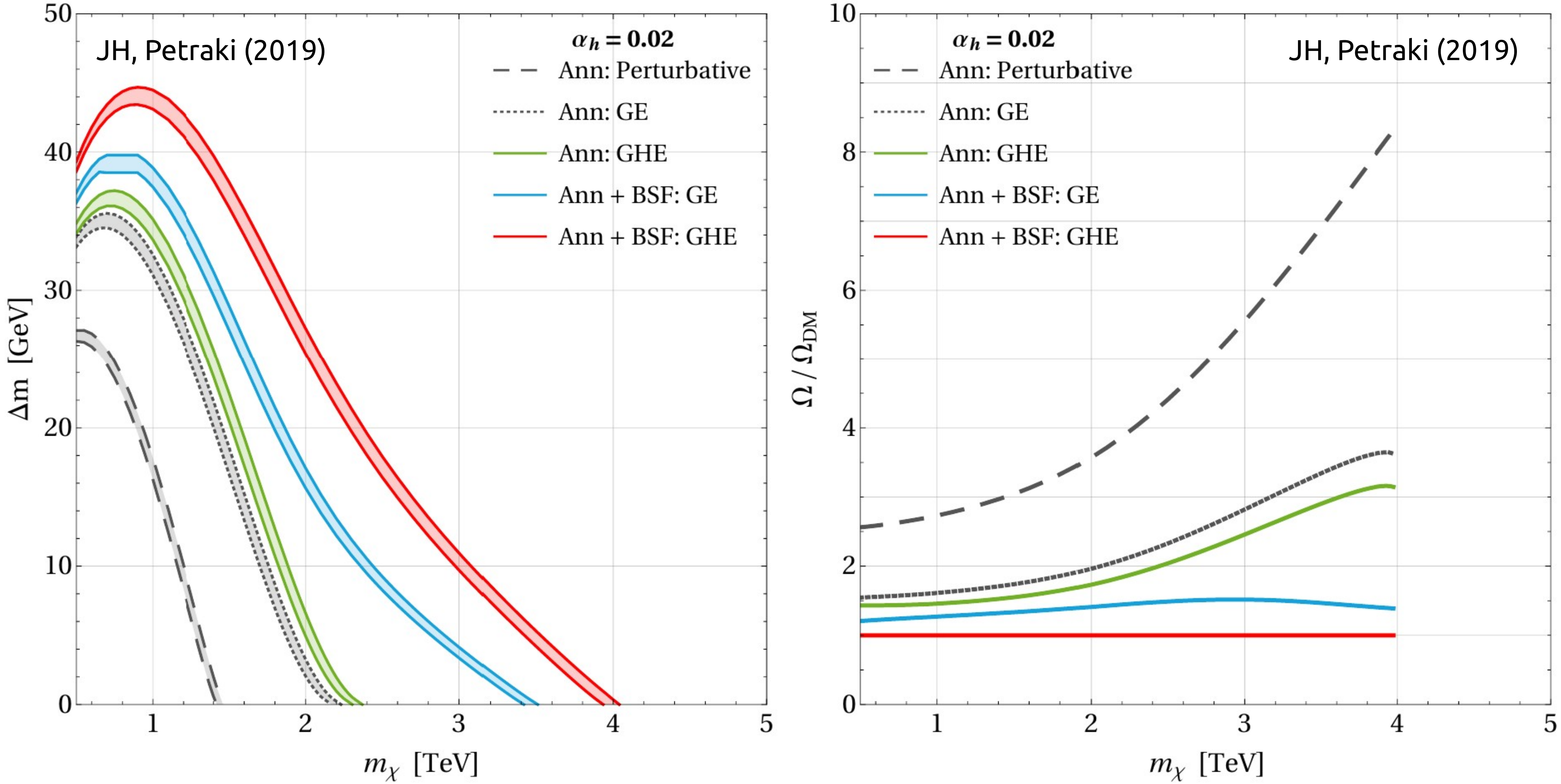
with Higgs exchange

- **Higgs coupling increases the binding energy**
- **a larger binding energy renders bound-state dissociation inefficient earlier, when the DM density is larger**
- **this enhances the efficiency to deplete DM**

$$\langle \sigma_{XX^\dagger} v_{rel} \rangle = \langle \sigma_{ann}\, v_{rel} \rangle + \langle \sigma_{BSF} v_{rel} \rangle_{eff}$$

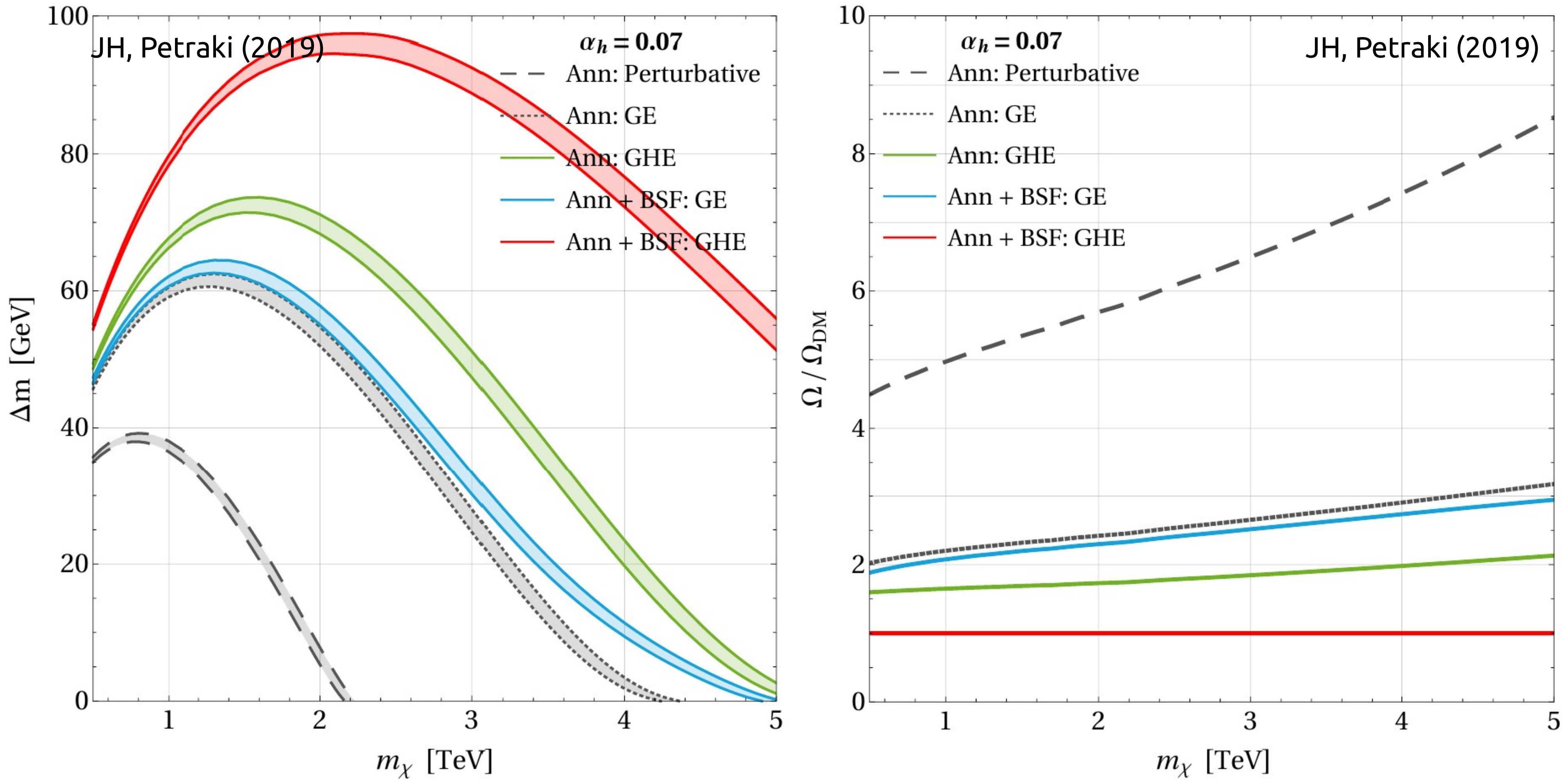
$$\langle \sigma_{BSF} v_{rel} \rangle_{eff} = \langle \sigma_{BSF} v_{rel} \rangle \times \left(\frac{\Gamma_{dec}}{\Gamma_{dec} + \Gamma_{ion}} \right)$$

Impact on the relic density (with Higgs exchange)



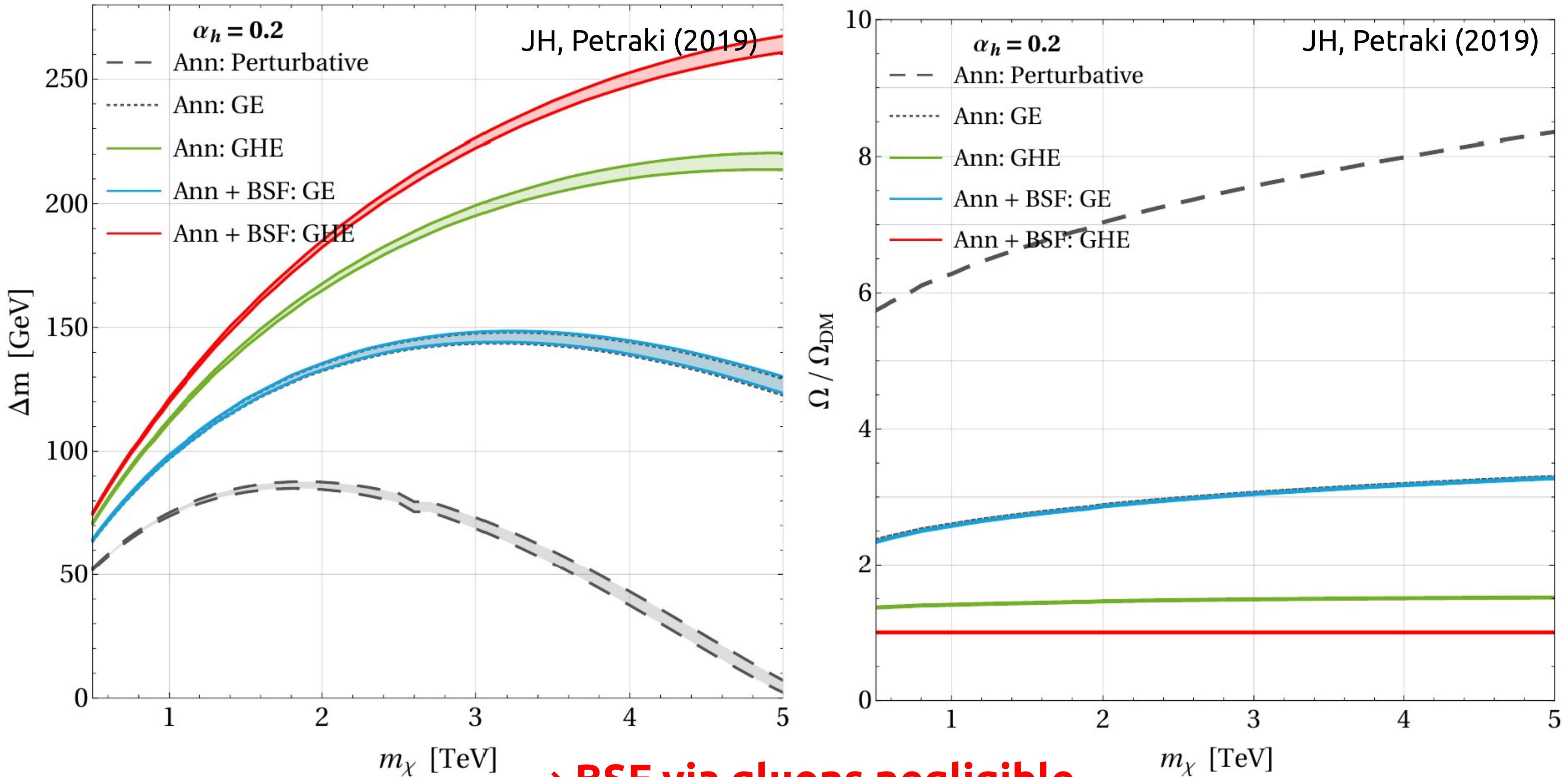
→ impact of gluon dominant for small Higgs couplings

Impact on the relic density (with Higgs exchange)



→ effect of gluon less prominent
→ main impact from Higgs enhancement and BSF

Impact on the relic density (with Higgs exchange)



→ **BSF via gluons negligible**
→ **Higgs enhancement most prominent**
→ **Higgs mediated BSF still sizable**

Conclusions

- Higgs boson can have significant effect on annihilation cross section ("Higgs enhancement") as well as on bound state formation process

- Capture of gluon mediated bound states was underestimated

- Sommerfeld effect and BSF via gluon and Higgs lead to significant effect on the theoretically predicted dark matter relic density

- In order to obtain the correct relic density, the mass gap between lightest and next-to-lightest particle is larger than previously predicted

- Increased values for the predicted DM mass strengthens the motivation for indirect searches in the multi-TeV regime

Thank you for your attention!