State-of-the-art calculations of the dark matter abundance

Julia Harz

DM@LHC, Seattle

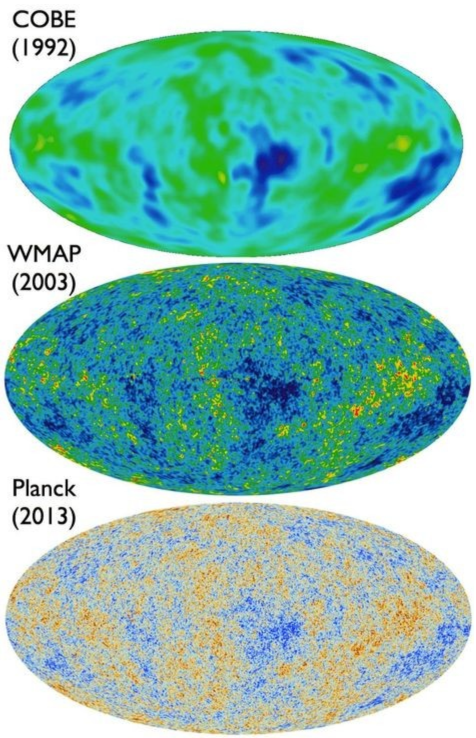
15.08.2019

Technische Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Unprecedented precision & powerful constraint

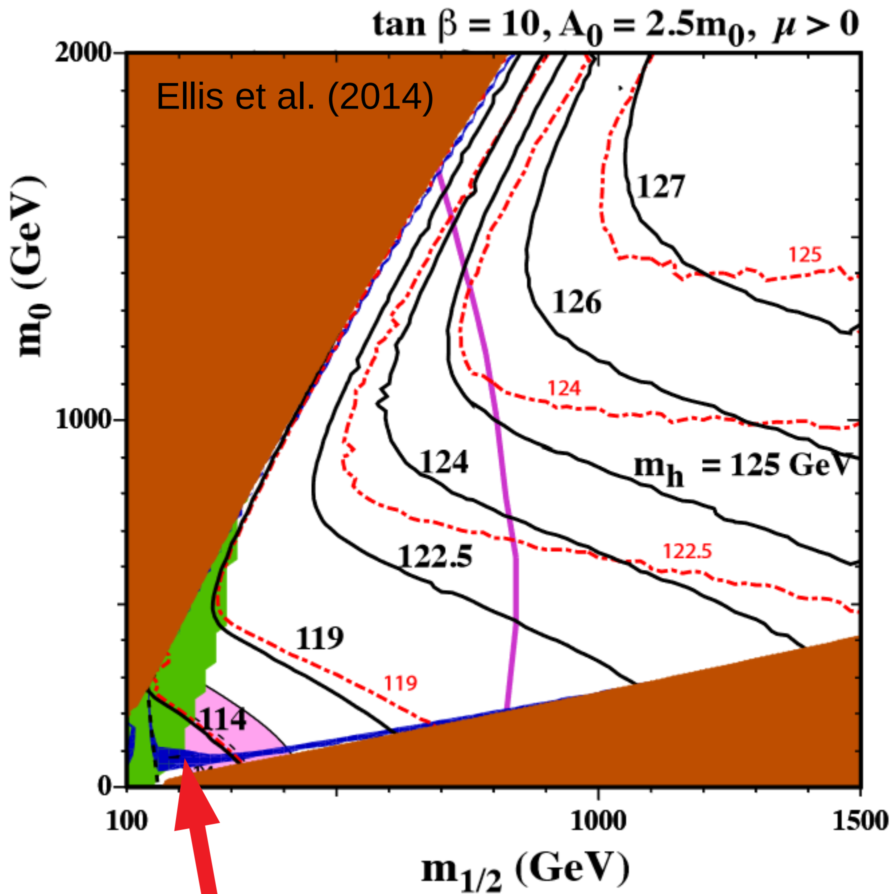
Cosmic Microwave Background (CMB)



dark matter density:

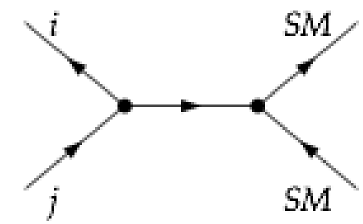
$$\Omega_{\mathrm{CDM}} h^2 = 0.120 \pm 0.001$$

N. Aghanim et al. [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO]



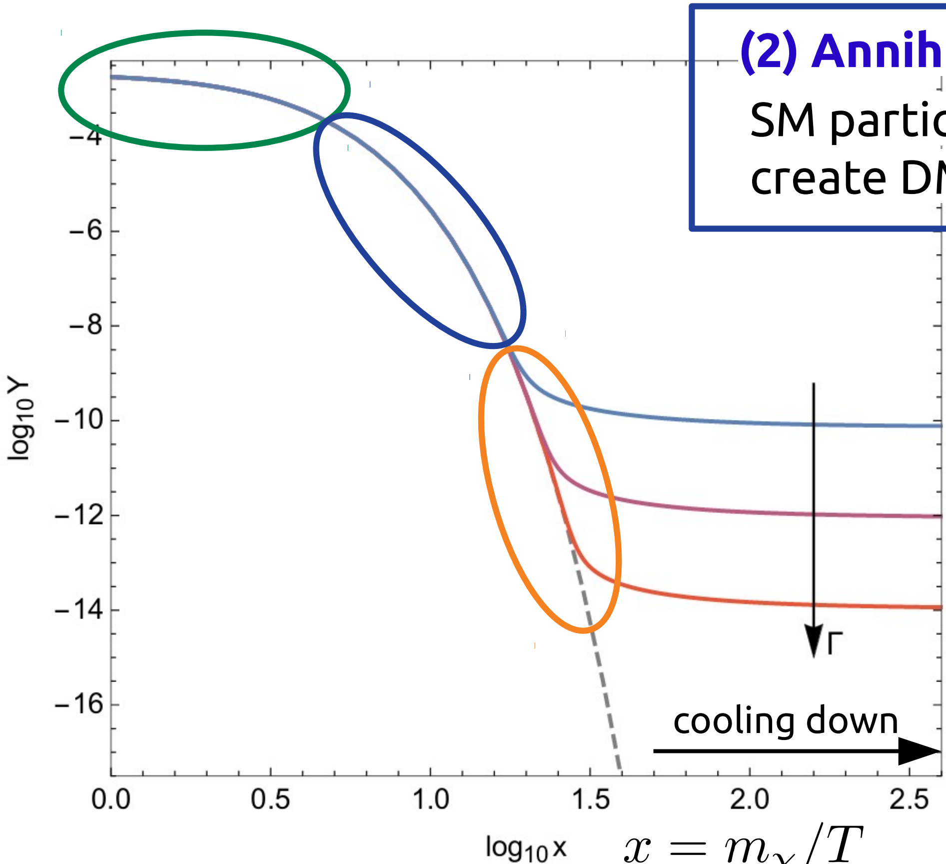
Relic abundance constraints the parameter space to a small strip under the assumption that DM is made out of one particle

Dark Matter Freeze-out



Thermal equilibrium regime (T >> m)

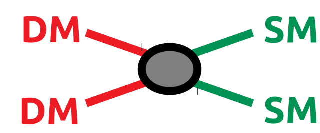
annihilation and production of DM in thermal equilibrium $Y \approx \text{const.}$



$x = m_\chi / T$

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

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

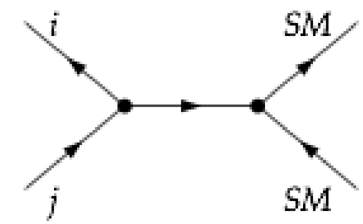


(3) Freeze-out (T ~ m/30)

Annihilation rate falls behind expansion rate

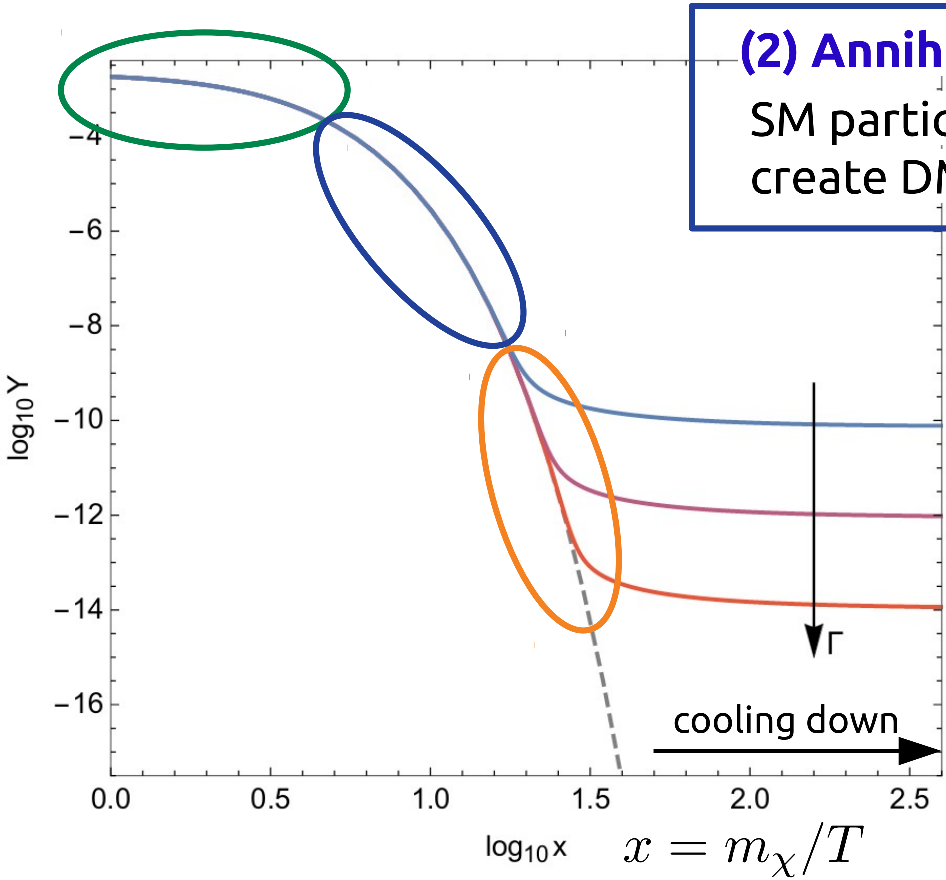
$$\frac{\Gamma}{H} < 1$$

Dark Matter Freeze-out



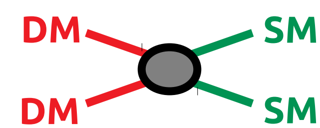
Thermal equilibrium regime (T >> m)

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



(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)

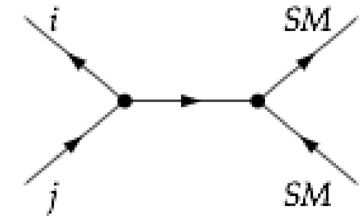
Annihilation rate falls behind expansion rate

$$\frac{\Gamma}{H} < 1$$

$$\dot{n} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

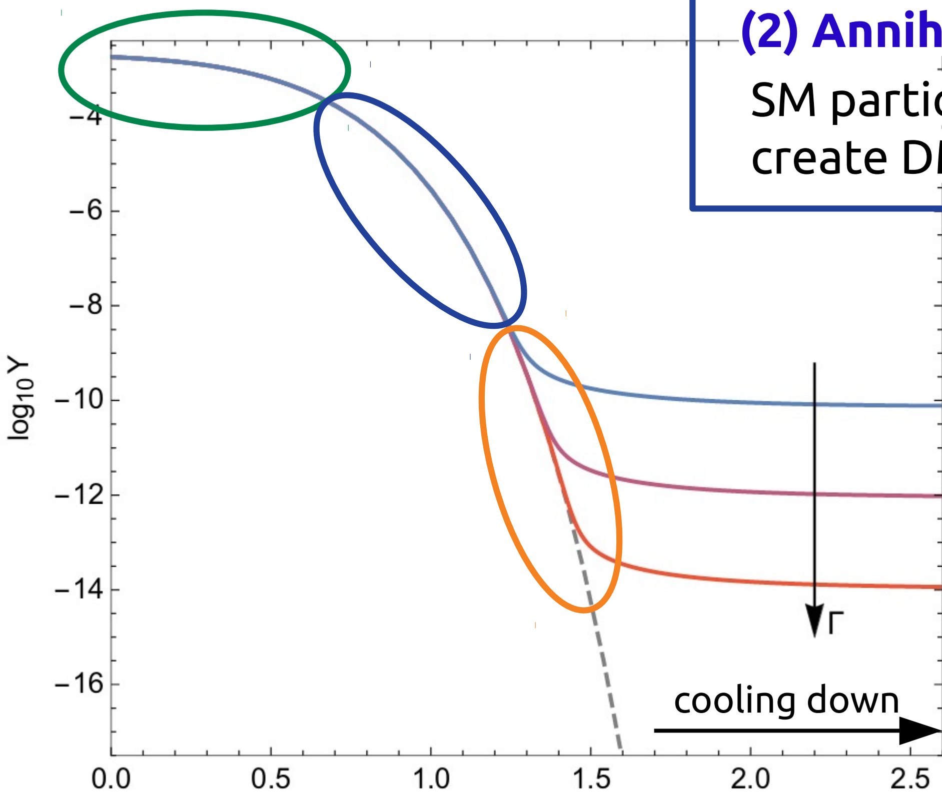
$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

Dark Matter Freeze-out



Thermal equilibrium regime (T >> m)

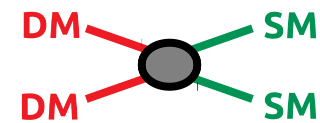
annihilation and production of DM
in thermal equilibrium $Y \approx \text{const.}$



$x = m_\chi / T$

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

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



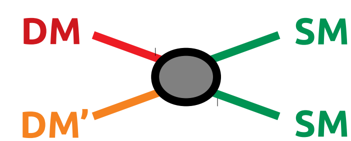
(3) Freeze-out (T ~ m/30)

Annihilation rate falls
behind expansion rate

$$\frac{\Gamma}{H} < 1$$

$$\dot{n} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

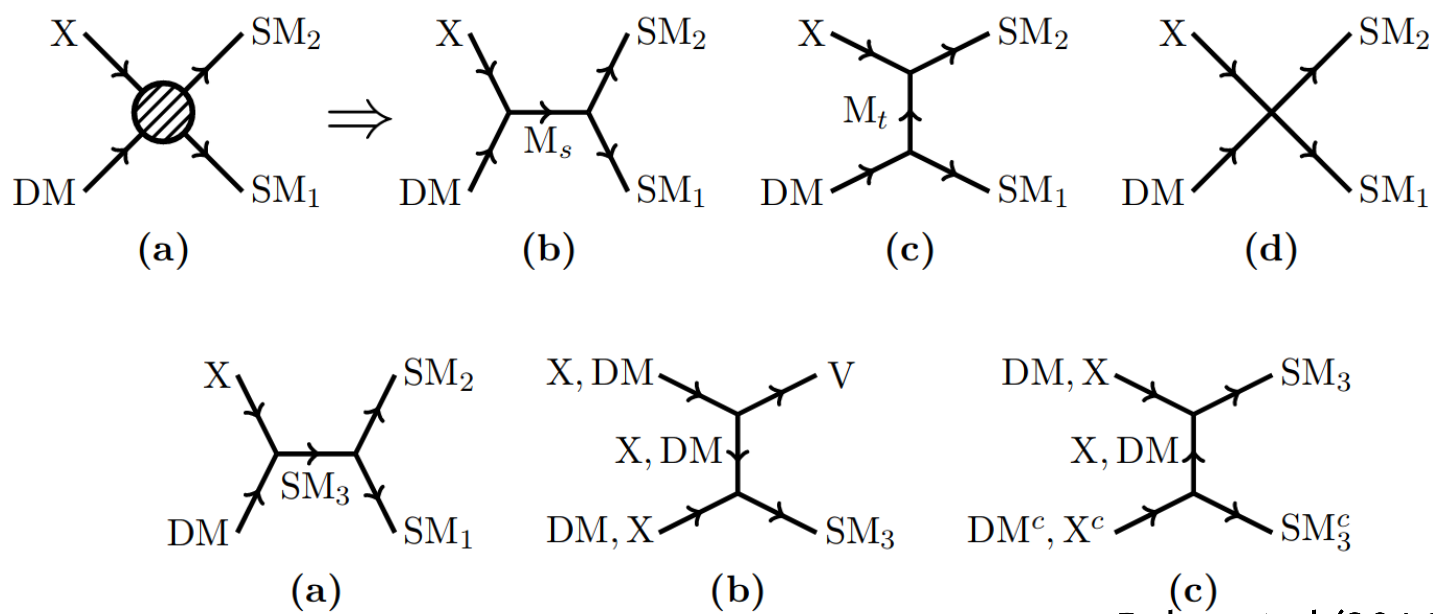


$$\langle \sigma_{\text{eff}} v \rangle = \sum_{ij} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{eq}}{n^{eq}} \frac{n_j^{eq}}{n^{eq}}$$

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

co-annihilation

Recent specific focus on (colored) Coannihilation



Baker et al (2016)

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 only few examples…

Exceptions in the calculation of the relic density

1990

Famous three exceptions:

(1) particles degenerate in mass to DM (*coannihilation*)

(2) annihilation in heavier states (*forbidden channels*)

(3) resonant enhancement

October 1990

CfPA-TH-90-001
BA-90-79

UNIVERSITY OF CALIFORNIA, BERKELEY

CENTER FOR PARTICLE ASTROPHYSICS

Three Exceptions
in the Calculation of Relic Abundances

KIM GRIEST

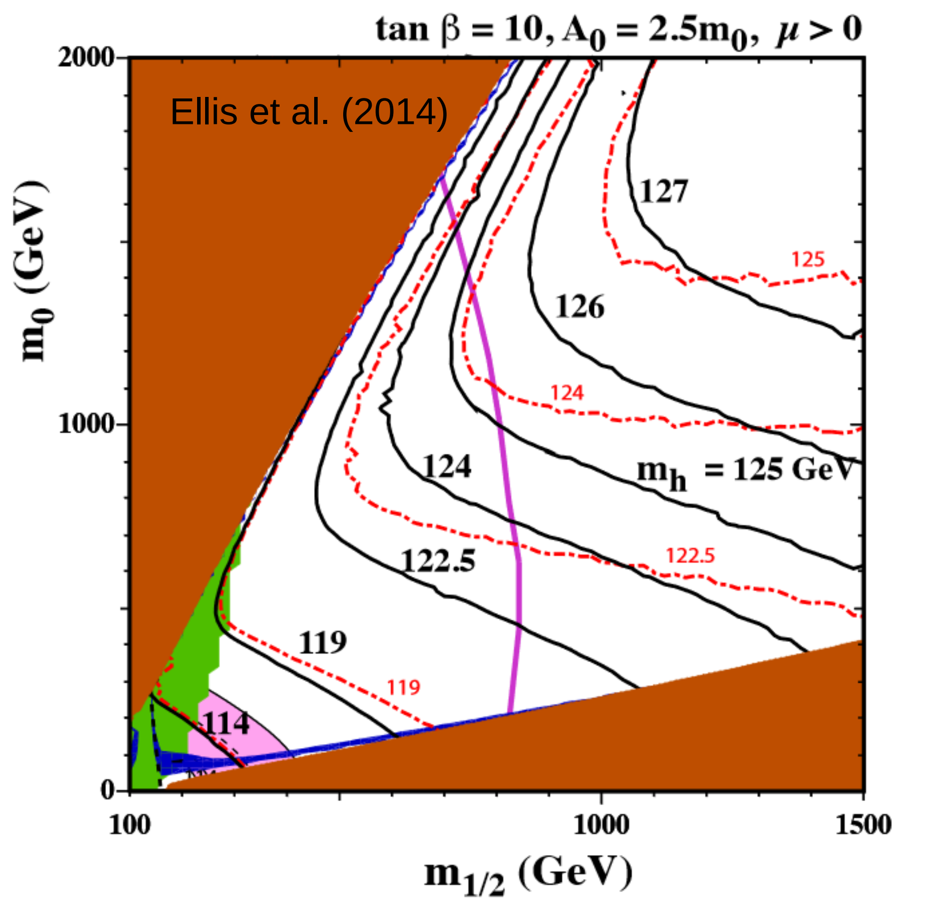
Center for Particle Astrophysics and Astronomy Department,
University of California, Berkeley, CA 94720

and

DAVID SECKEL

Bartol Research Institute,
University of Delaware, Newark, DE 19716

Test your favorite model in agreement with DM



Software tools are publicly available to constrain the parameter space, e.g.:

MicrOMEGAs, Belanger, Boudjema, Pukhov, Semenov et al. [2002-2018]

DarkSUSY, Bringmann, Edsjo, Gondolo, Ullio, Bergstrom [2002-2018]

MadDM, Ambrogio, Arina, Backovic, Heisig, Maltoni, Mantani, Mattelaer, Mohlabeng [2014-2019]

Everything settled and straightforward?

Exceptions in the calculation of the relic density

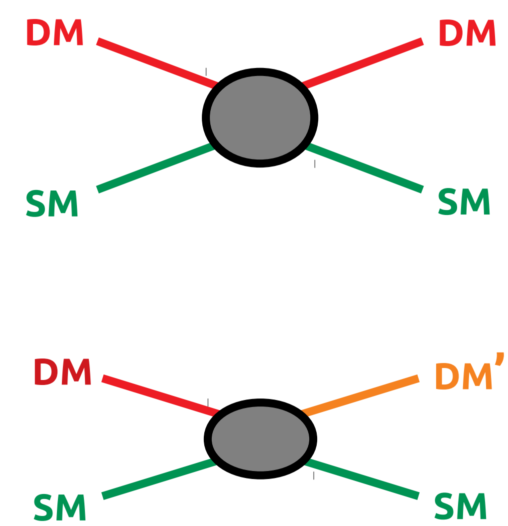
2019

modified Hubble expansion

$$\boxed{\dot{n} + 3Hn = -\langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)}$$

Break down of assumptions:

Kinetic equilibrium maintained by



modification of particle physics cross section

- NLO
- theoretical uncertainties
- Sommerfeld enhancement
- Boundstate formation

finite temperature effects?

Exceptions in the calculation of the relic density

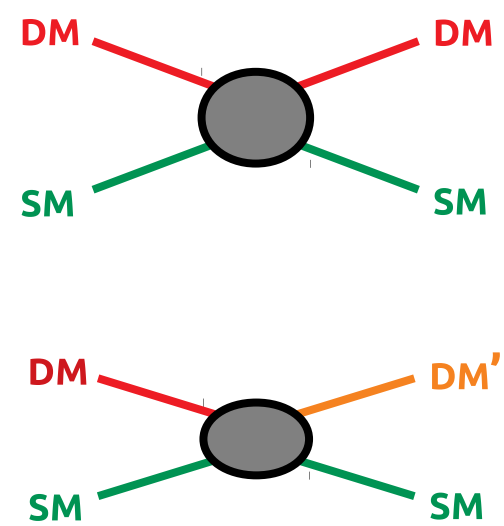
2019

1. **modified Hubble expansion**

$$\boxed{\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)}$$

2. **Break down of assumptions:**

Kinetic equilibrium maintained by



3. **modification of particle physics cross section**

- NLO
- theoretical uncertainties
- Sommerfeld enhancement
- Boundstate formation

finite temperature effects?

4.

Modified Hubble expansion

Modified Hubble expansion

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

Existence of another species Φ whose energy density red shifts according to

$$\rho_\phi \propto a^{-(4+n)}$$

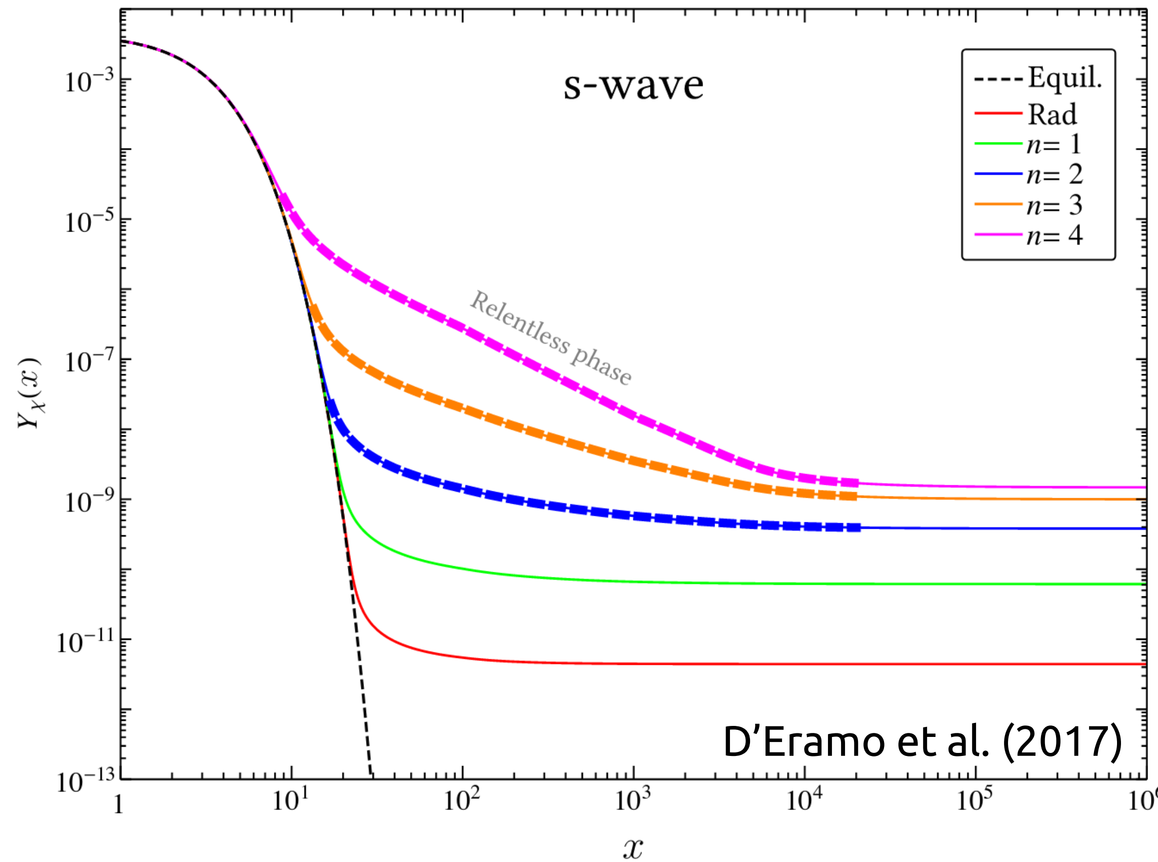
n = 0 radiation
n > 0 energy density dominates over radiation

Which leads to **modified Hubble expansion**

$$H(T) \simeq \frac{\pi \bar{g}_\star^{1/2}}{3\sqrt{10}} \frac{T^2}{M_{\rm Pl}} \left(\frac{T}{T_r}\right)^{n/2}$$

$$T_r = T\Big|_{\rho_\phi = \rho_r}$$

$$T_r > T_{\rm BBN}$$



"Relentless Dark Matter",
D'Eramo, Fernandez, Profumo (2017)

see also Arbey, Mahmoudi (2008)

Break down of assumptions

Early kinetic decoupling

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

In the usual Dark Matter calculation it is assumed that DM stays in thermal equilibrium at least until freeze-out

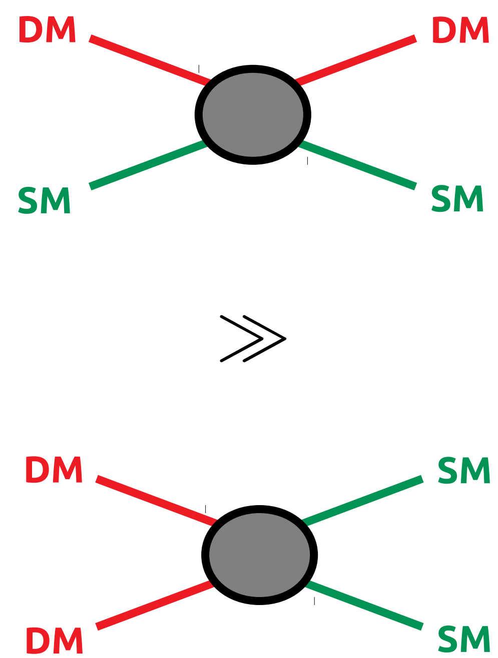
$$\frac{dn_\chi}{dt} + 3Hn_\chi = g_\chi \int \frac{d^3p}{(2\pi)^3 E} C_{\rm ann}[f_\chi]$$

$$C_{\rm ann} = g_\chi E \int \frac{d^3\tilde{p}}{(2\pi)^3} v\sigma_{\bar\chi\chi\to\bar f f}$$
$$\times \left[f_{\chi,\rm eq}(E) f_{\chi,\rm eq}(\tilde{E}) - \boxed{f_\chi(E) f_\chi(\tilde{E})} \right]$$

$$\boxed{f_\chi = A(T) f_{\chi,\rm eq} = \frac{n_\chi}{n_{\chi,\rm eq}} f_{\chi,\rm eq}}$$

$$\langle \sigma v \rangle \equiv \frac{g_\chi^2}{n_{\chi,\rm eq}^2} \int \frac{d^3p}{(2\pi)^3} \frac{d^3\tilde{p}}{(2\pi)^3} \sigma v_{\bar\chi\chi\to\bar f f} f_{\chi,\rm eq}(\mathbf{p}) f_{\chi,\rm eq}(\tilde{\mathbf{p}})$$

Hard-coded in common DM codes!



Early kinetic decoupling

In the usual Dark Matter calculation it is assumed that DM stays in thermal equilibrium at least until freeze-out

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

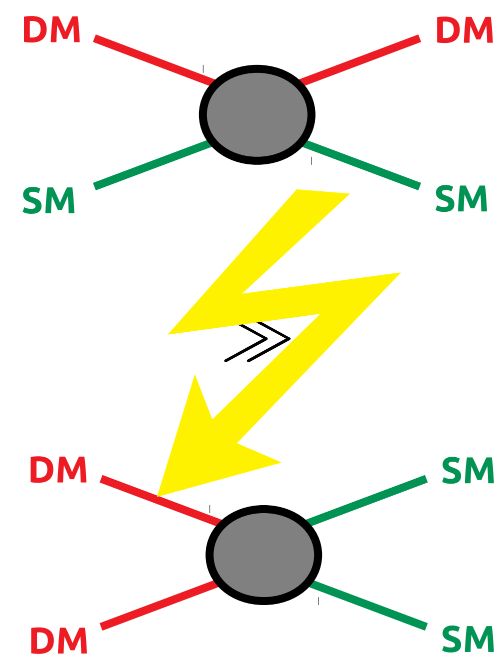
$$\frac{dn_\chi}{dt} + 3Hn_\chi = g_\chi \int \frac{d^3p}{(2\pi)^3 E} C_{\rm ann}[f_\chi]$$

$$C_{\rm ann} = g_\chi E \int \frac{d^3\tilde{p}}{(2\pi)^3} v\sigma_{\bar{\chi}\chi\to\bar{f}f} \times \left[f_{\chi,\rm eq}(E) f_{\chi,\rm eq}(\tilde{E}) - \boxed{f_\chi(E) f_\chi(\tilde{E})} \right]$$

$$\boxed{f_\chi = A(T) f_{\chi,\rm eq} = \frac{n_\chi}{n_{\chi,\rm eq}} f_{\chi,\rm eq}}$$

$$\langle \sigma v \rangle \equiv \frac{g_\chi^2}{n_{\chi,\rm eq}^2} \int \frac{d^3p}{(2\pi)^3} \frac{d^3\tilde{p}}{(2\pi)^3} \sigma v_{\bar{\chi}\chi\to\bar{f}f} f_{\chi,\rm eq}(\mathbf{p}) f_{\chi,\rm eq}(\tilde{\mathbf{p}})$$

Hard-coded in common DM codes!



In case of enhancement of the annihilation cross section this is not necessarily fullfilled!

→ phenomenologcial studies:

Duch, Grzadkowski (2017)
Feng, Kaplinghat, Yu (2010)
Dent, Dutta, Scherrer (2010)

→ Development of a rigorous numerical treatment + code:

Binder, Bringmann, Gustafsson, Hryczuk (2017)

Early kinetic decoupling

In the usual Dark Matter calculation it is assumed that DM stays in thermal equilibrium at least until freeze-out

$$\dot{n} + 3Hn = -\langle \sigma_{\mathrm{eff}} v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

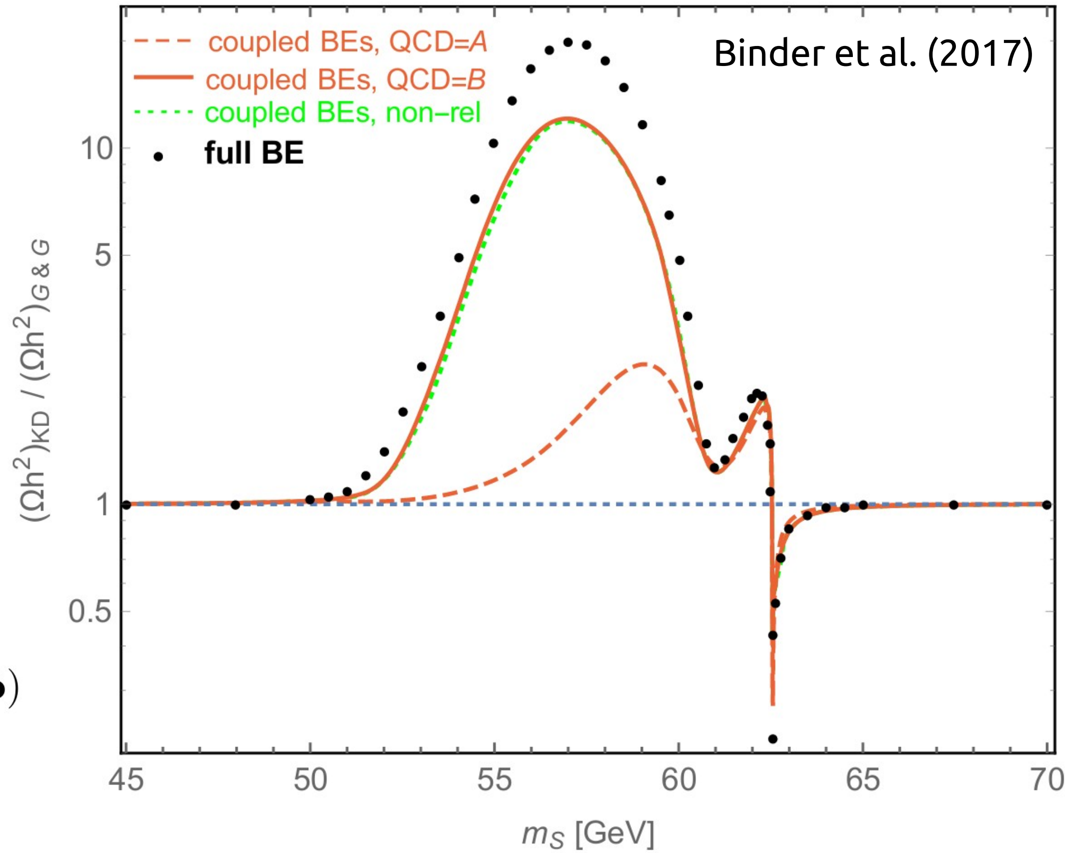
$$\frac{dn_\chi}{dt} + 3Hn_\chi = g_\chi \int \frac{d^3p}{(2\pi)^3 E} C_{\mathrm{ann}}[f_\chi]$$

$$C_{\mathrm{ann}} = g_\chi E \int \frac{d^3\tilde{p}}{(2\pi)^3} v\sigma_{\bar{\chi}\chi \to \bar{f}f} \times \left[f_{\chi,\mathrm{eq}}(E) f_{\chi,\mathrm{eq}}(\tilde{E}) - \boxed{f_\chi(E) f_\chi(\tilde{E})} \right]$$

$$\boxed{f_\chi = A(T) f_{\chi,\mathrm{eq}} = \frac{n_\chi}{n_{\chi,\mathrm{eq}}} f_{\chi,\mathrm{eq}}}$$

$$\langle \sigma v \rangle \equiv \frac{g_\chi^2}{n_{\chi,\mathrm{eq}}^2} \int \frac{d^3p}{(2\pi)^3} \frac{d^3\tilde{p}}{(2\pi)^3} \sigma v_{\bar{\chi}\chi \to \bar{f}f} f_{\chi,\mathrm{eq}}(\mathbf{p}) f_{\chi,\mathrm{eq}}(\tilde{\mathbf{p}})$$

Hard-coded in common DM codes!



→ Development of a rigorous numerical treatment + code:

Binder, Bringmann, Gustafsson, Hryczuk (2017)

→ phenomenologcial studies:

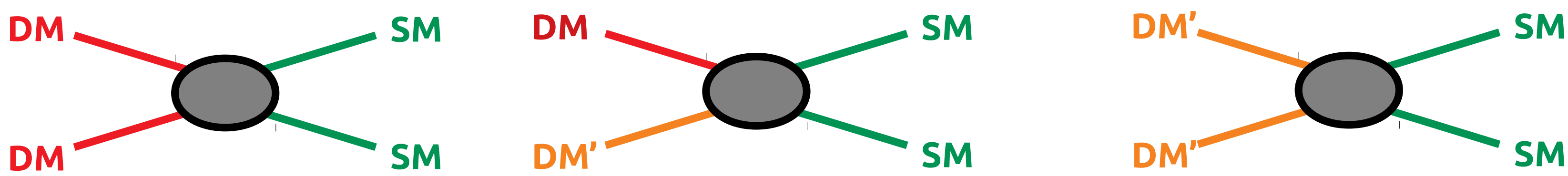
Duch, Grzadkowski (2017)
Feng, Kaplinghat, Yu (2010)
Dent, Dutta, Scherrer (2010)

Conversion driven freeze-out

Based on Gondolo & Gelmini's exception "coannihilation"

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

In **coannihilation** scenarios the following processes are present:



Kinetic equilibrium maintained by

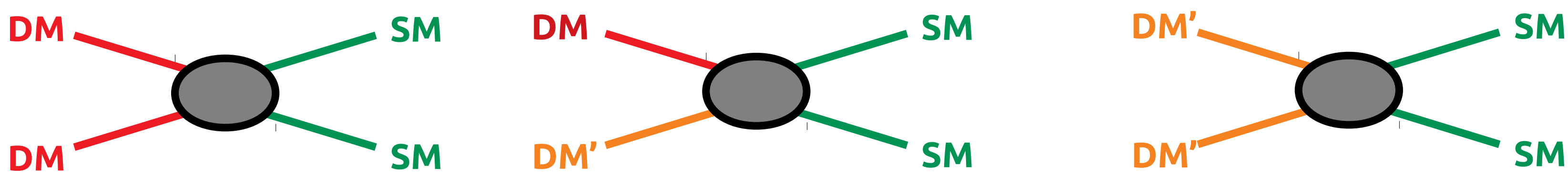
justifies the usage of **one** BEQ

Conversion driven freeze-out

Based on Gondolo & Gelmini's exception "coannihilation"

$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

In **coannihilation** scenarios the following processes are present:



Kinetic equilibrium maintained by

~~justifies the usage of **one** BEQ~~

If it falls out of equilibrium,
coupled BEQ are needed

"Coannihilation without chemical equilibrium",
Garny, Heisig, Lülf, Vogl (2017)

And more…

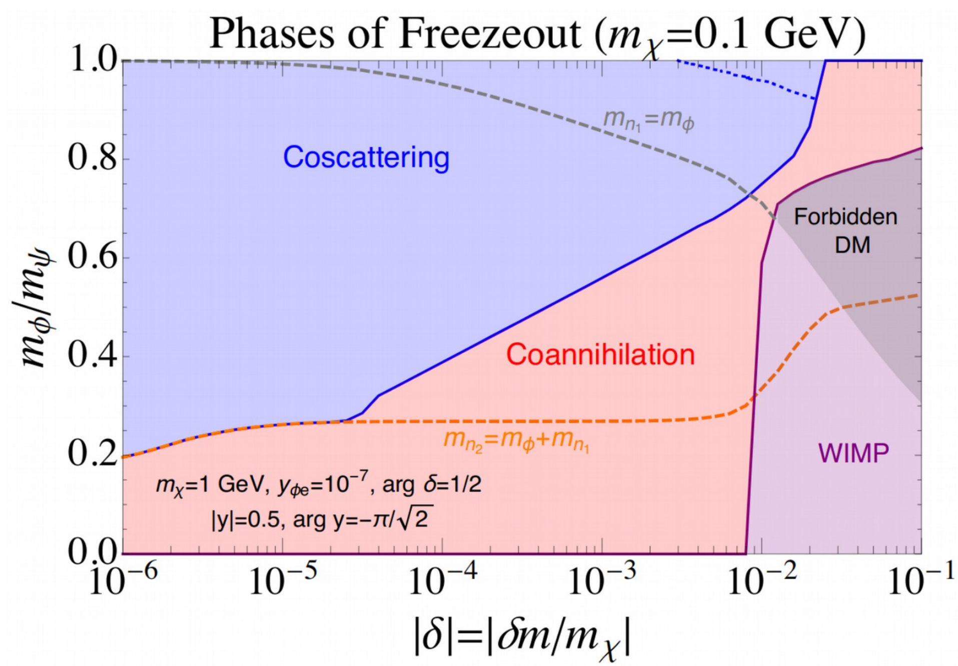
$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2)$$

Coscattering

D'Agnolo, Pappadopulo, Rudermann (2017)

Forbidden Dark Matter

D'Angelo, Rudermann (2015)



Re-annihilation

Binder, Gustafsson, Kamada (2018)

Cannibal Dark Matter

Pappadopulo, Rudermann, Trevisan (2016)

Semi-annihilation

D'Eramo, Thaler (2010)

… and more …

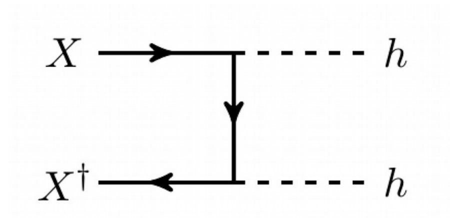
Effects impacting the particle cross section

Effects impacting the particle cross section

$$\dot{n} + 3Hn = -\langle \sigma_{\mathrm{eff}} v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\mathrm{eff}} v \rangle}$$

Born level annihilation



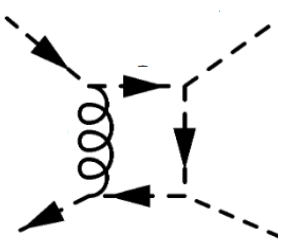
$$\sigma_{\mathrm{eff}} v_{\mathrm{rel}} = \sigma^{\mathrm{tree}} v_{\mathrm{rel}}$$

usually DM codes include *only* born level calculation

Effects impacting the particle cross section

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

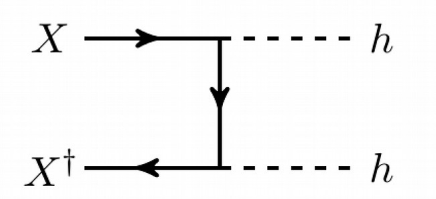
Higher order corrections



$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm NLO} v_{\rm rel}$$

can lead to sizeable corrections to the DM abundance

Born level annihilation



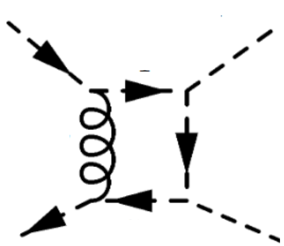
$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel}$$

usually DM codes include *only* born level calculation

Effects impacting the particle cross section

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

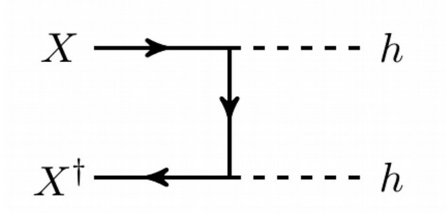
Higher order corrections



$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm NLO} v_{\rm rel}$$

can lead to sizeable corrections to the DM abundance

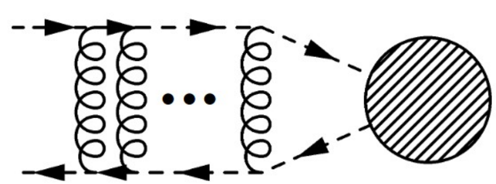
Born level annihilation



$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel}$$

usually DM codes include *only* born level calculation

Sommerfeld enhancement



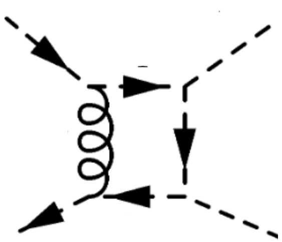
$$\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$$

$$\sigma_{\rm eff} v_{\rm rel} = \sigma^{\rm tree} v_{\rm rel} \times S_0$$

Effects impacting the particle cross section

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

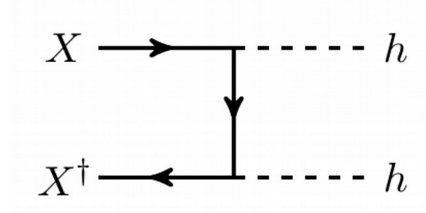
Higher order corrections



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{NLO}} v_{\text{rel}}$$

can lead to sizeable corrections to the DM abundance

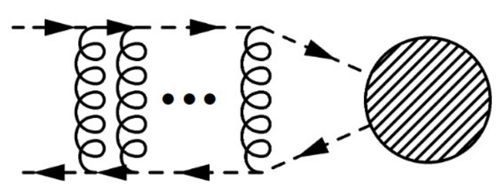
Born level annihilation



$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}}$$

usually DM codes include *only* born level calculation

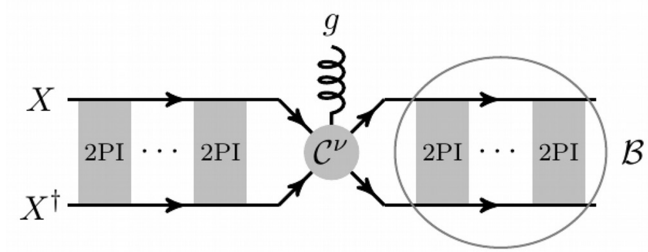
Sommerfeld enhancement



$$\left(\frac{\alpha}{v_{\text{rel}}}\right)^n \sim 1$$

$$\sigma_{\text{eff}} v_{\text{rel}} = \sigma^{\text{tree}} v_{\text{rel}} \times S_0$$

Bound state formation



$$\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle = \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle + \langle \sigma_{\text{BSF}} v_{\text{rel}} \rangle_{\text{eff}}$$

bound state formation and subsequent decay open up a new effective DM annihilation channel

Impact of higher order corrections

Impact of higher order corrections

non-exhaustive list!

QED:

- **Relic density calculations beyond tree-level, exact calculations versus effective couplings: the ZZ final state,** Boudjema, Drieu La Rochelle, Mariano (2014)
- **Radiative Corrections to the Neutralino Dark Matter Relic Density - an Effective Coupling Approach,** Chatterjee, Drees, Kulkarni (2012)
- **One-loop corrections, uncertainties and approximations in neutralino annihilations: Examples,** Boudjema, Drieu La Rochelle, Kulkarni (2011)
- **Relic density at one-loop with gauge boson pair production,** Baro, Boudjema, Chalons, Hao (2010)
- **Full one-loop corrections to the relic density in the MSSM: A Few examples,** Baro, Boudjema, Semenov (2008)
- **SUSY dark matter: Loops and precision from particle physics,** Boudjema, Semenov , Temes (2006)

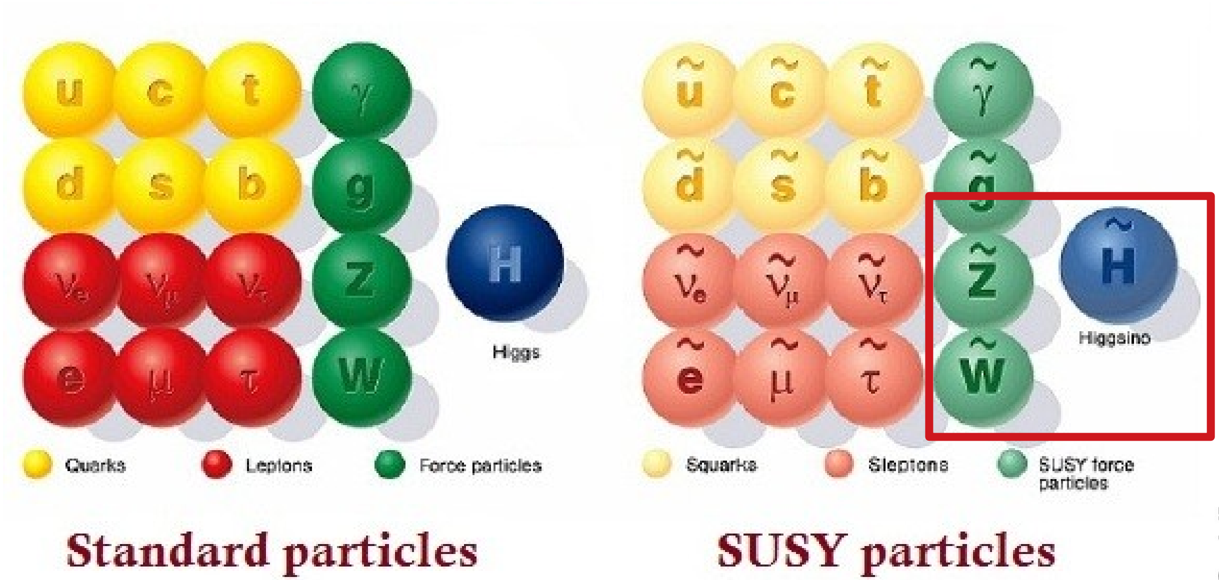
QCD:

- **Theoretical uncertainty of the supersymmetric dark matter relic density from scheme and scale variations,** JH, Herrmann, Klasen, Kovarik, Steppeler (2016)
- **SUSY-QCD corrections to stop annihilation into electroweak final states including Coulomb enhancement effects,** JH, Herrmann, Klasen, Kovařík, Meinecke (2015)
- **One-loop corrections to neutralino-stop coannihilation revisited,** JH, Herrmann, Klasen, Kovarik (2015)
- **One-loop corrections to gaugino (co)annihilation into quarks in the MSSM,** Herrmann, Klasen, Kovarik, Meinecke, Steppeler (2014)
- **Neutralino-stop coannihilation into electroweak gauge and Higgs bosons at one loop,** JH, Herrmann, Klasen, Kovarik, Le Boulc'h (2013)
- **SUSY-QCD effects on neutralino dark matter annihilation beyond scalar or gaugino mass unification,** Herrmann, Klasen, Kovarik (2009)
- **Neutralino Annihilation into Massive Quarks with SUSY-QCD Corrections**, Herrmann, Klasen, Kovarik (2009)

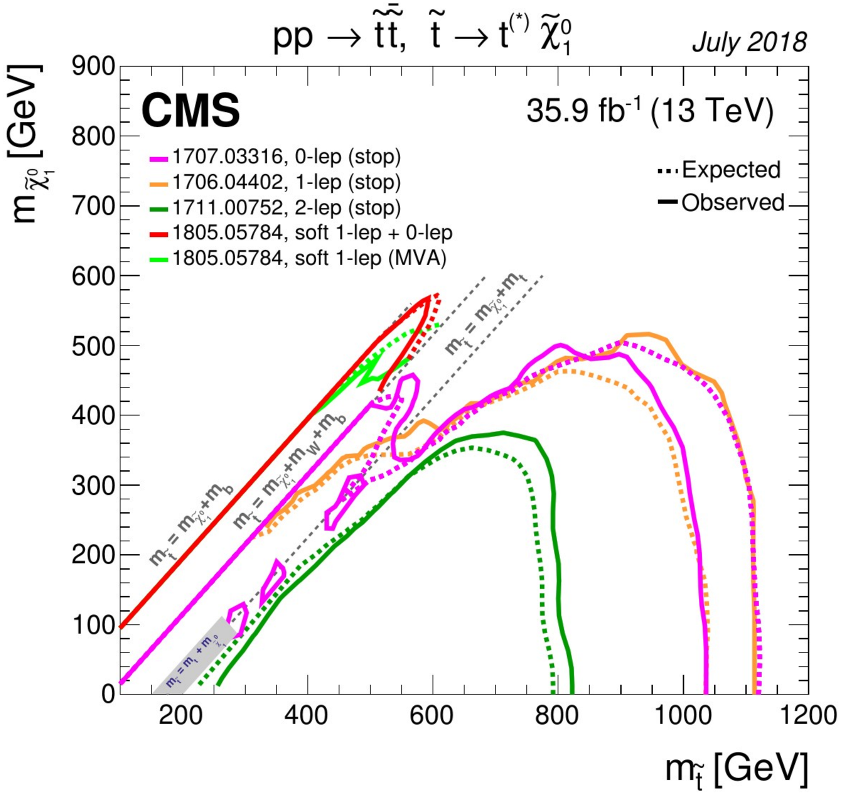
other observables:

- **Leading QCD Corrections for Indirect Dark Matter Searches: a Fresh Look,** Bringmann, Galea, Walia (2016)
- **SUSY-QCD corrections for direct detection of neutralino dark matter and correlations with relic density,** Klasen, Kovarik, Steppeler (2016)

Impact of higher order corrections

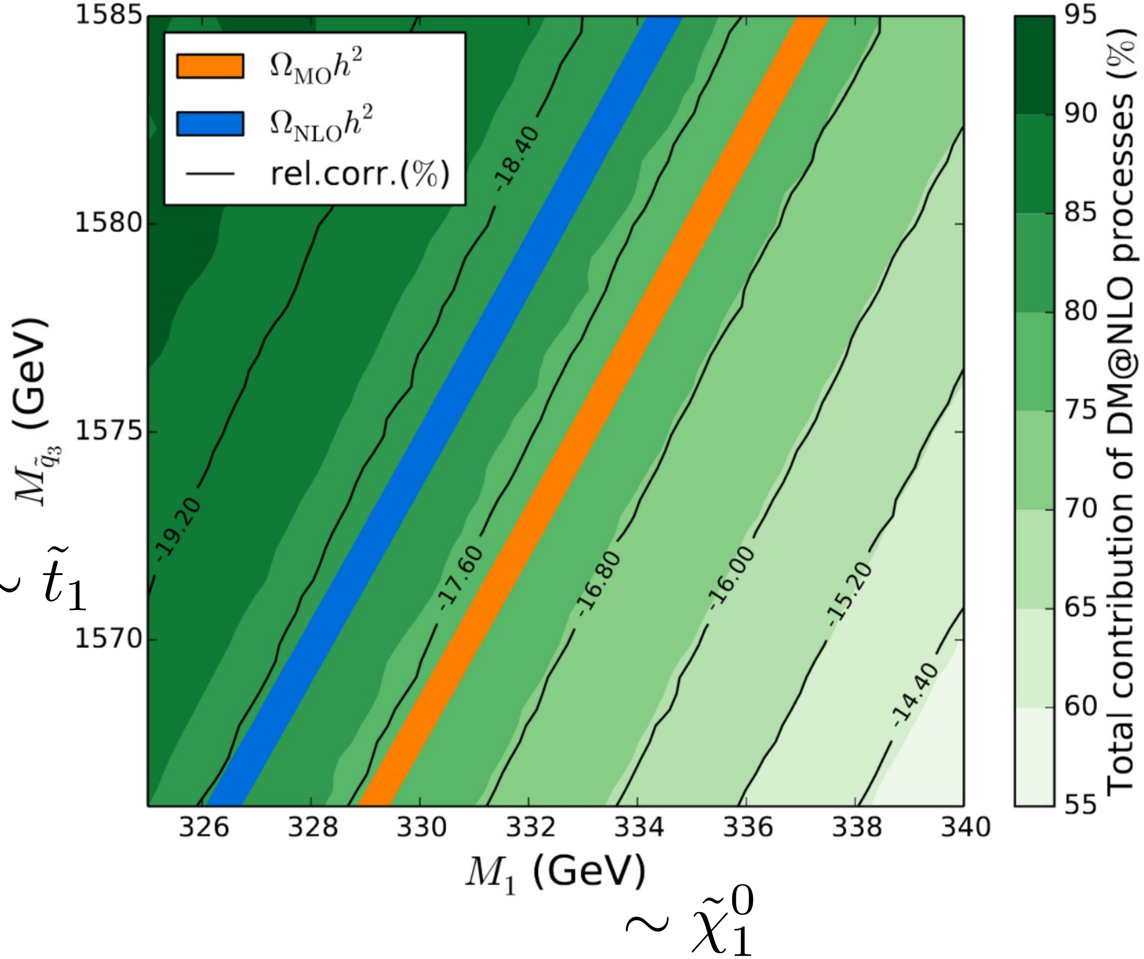


χ



Impact of higher order corrections

$$\chi_1^0 \tilde{t}_1 \to tX$$



$\tilde{\chi}_1^0\tilde{t}_1 \to tg$	23%
$\tilde{\chi}_1^0\tilde{t}_1 \to th^0$	23%
$\tilde{\chi}_1^0\tilde{t}_1 \to tZ^0$	5%
$\tilde{\chi}_1^0\tilde{t}_1 \to bW^+$	10%
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$	15%
$\sum_{\mathrm{corr}}$	76%

$$m_{\tilde{\chi}_1^0} = 338.3\mathrm{GeV}$$
$$m_{\tilde{t}_1} = 376.3\mathrm{GeV}$$

→ corrections of around 20% on the relic density

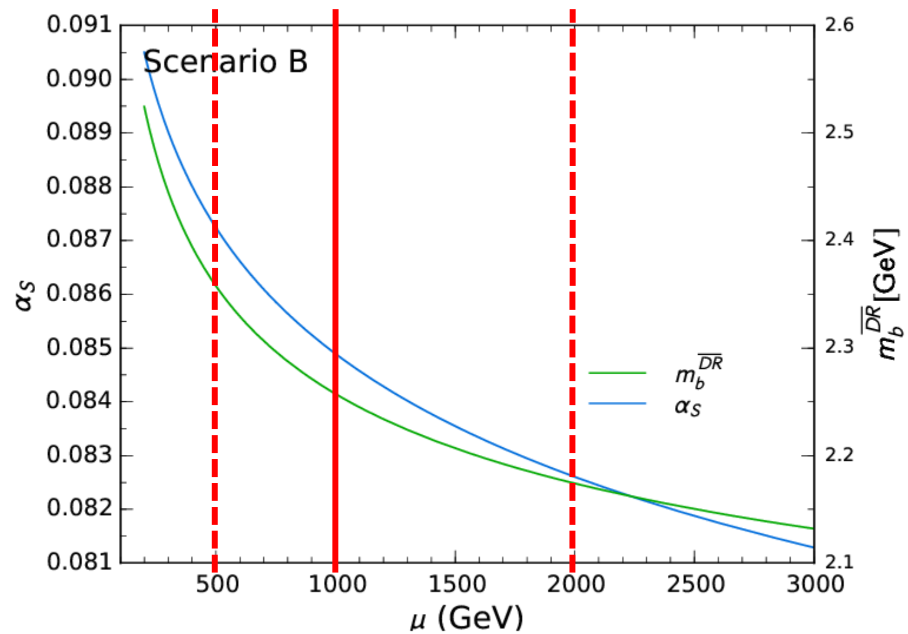
JH, B. Herrmann, M. Klasen, K. Kovařík and Q. Le Boulc'h, Phys. Rev. D 87, 054031 (2013)
JH, B. Herrmann, M. Klasen, and K. Kovařík, Phys. Rev. D 91, 034028 (2015)

Theoretical uncertainties

Theoretical uncertainties

There was no estimation of the theoretical uncertainty in the literature before!

→ scale variation $\mu_R/2 < \mu < 2\mu_R$ gives an estimate

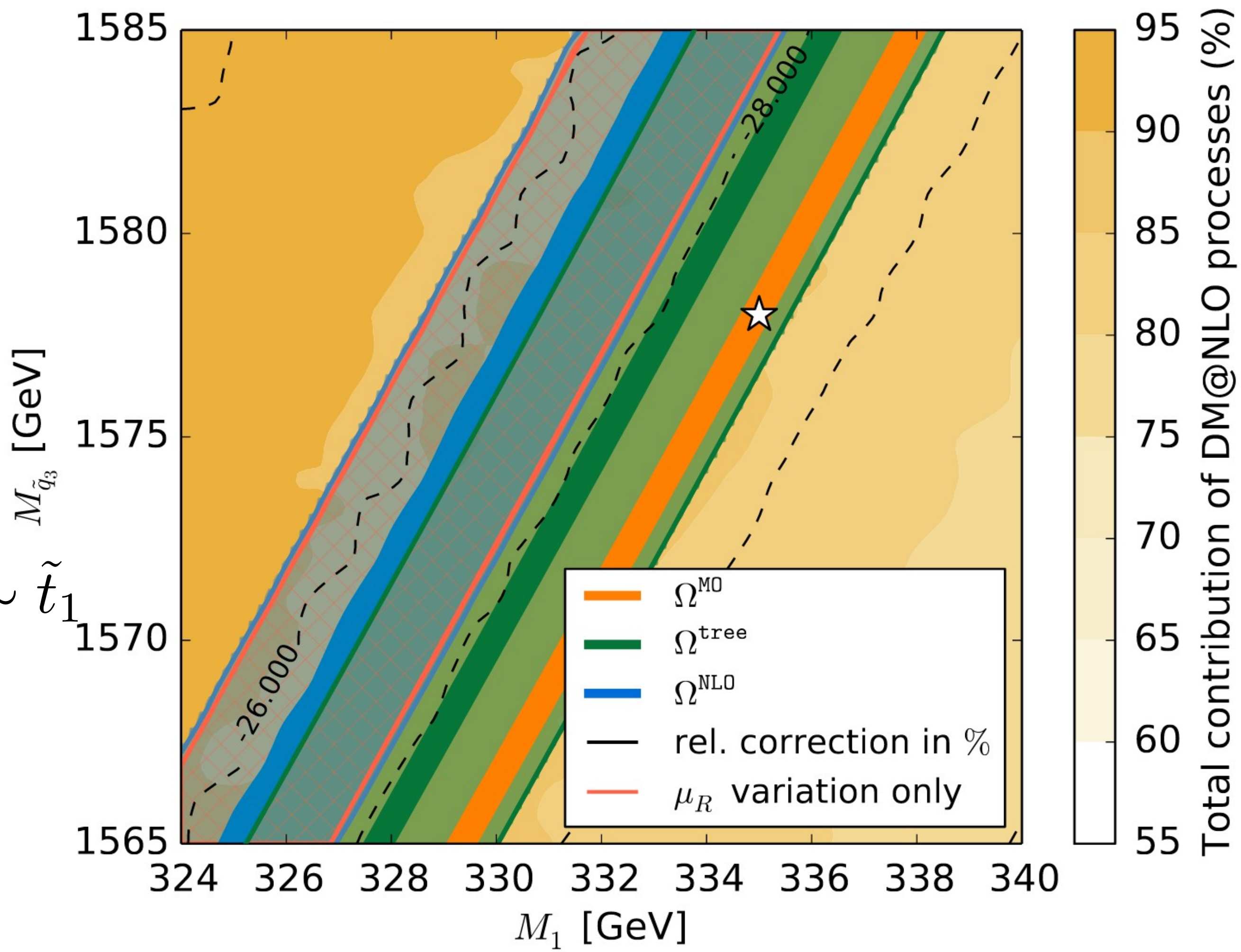


- Calculation contains explicit uncancelled logs of the renormalisation scale
- Depends implicitly on scale dependent parameters, such as $\alpha_s, \theta_{\tilde{t}}, \theta_{\tilde{b}} A_t, A_b, m_b, m_{\tilde{t}_2}$

→ first study of this kind in the context of DM

JH, B. Herrmann, M. Klasen, K. Kovařík, and P. Steppeler, Phys. Rev. D93, 114023 (2016)

Theoretical uncertainties



$\sim \tilde{t}_1$

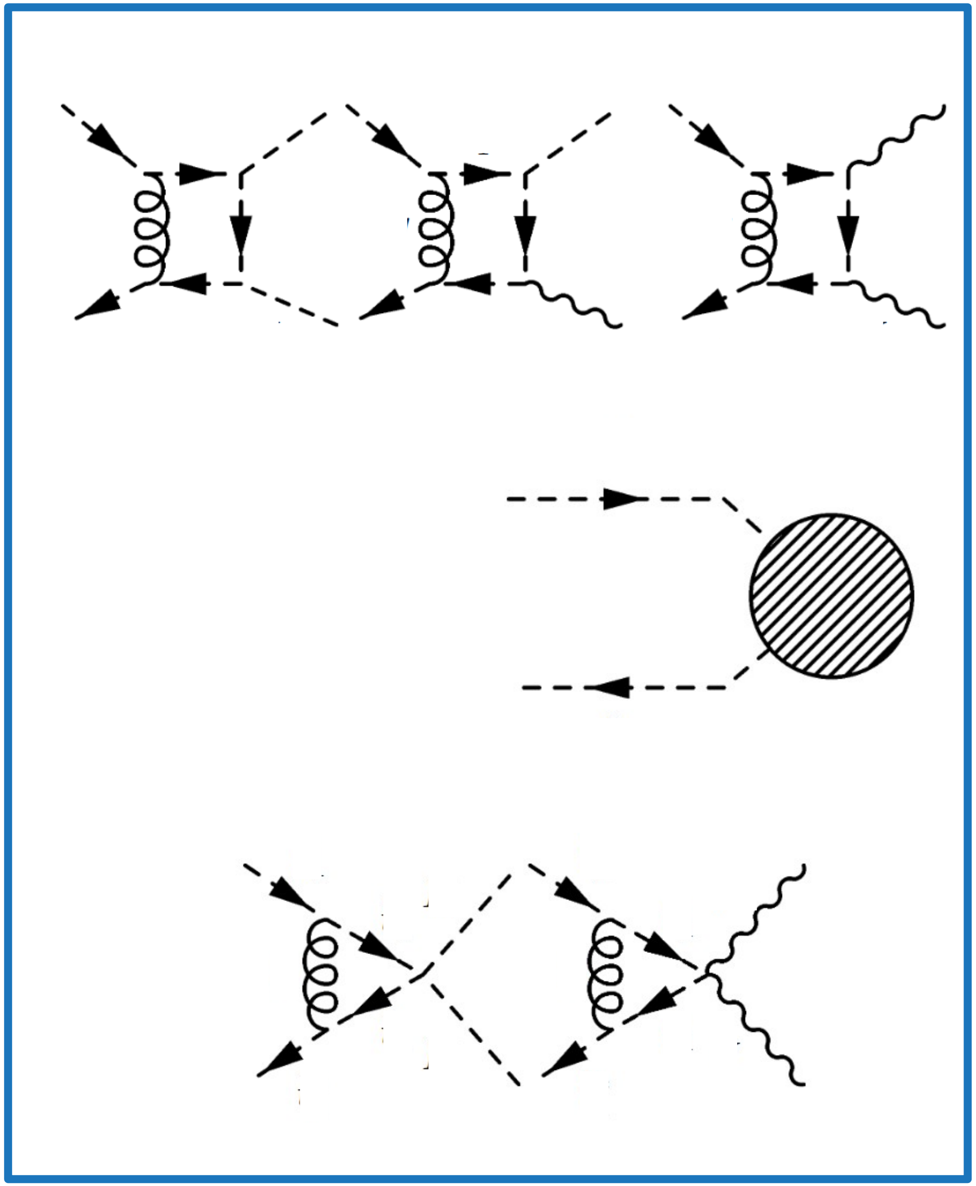
$\sim \tilde{\chi}_1^0$

		C
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to$	$t\bar{t}$	16%
$\tilde{\chi}_1^0\tilde{t}_1 \to$	th^0	23%
	tg	23%
	tZ^0	5%
	bW^+	11%
$\tilde{t}_1\tilde{t}_1^* \to$	h^0h^0	5%
	Z^0Z^0	2%
	W^+W^-	3%
Total		88%

JH, B. Herrmann, M. Klasen, K. Kovařík, and P. Steppeler, Phys. Rev. D93, 114023 (2016)
JH, B. Herrmann, M. Klasen, and K. Kovařík, Phys. Rev. D 91, 034028 (2015)
JH, B. Herrmann, M. Klasen, K. Kovařík, and M. Meinecke, Phys. Rev. D 91, 034012 (2015)
JH, B. Herrmann, M. Klasen, K. Kovařík, and Q. Le Boulc'h, Phys. Rev. D 87, 054031 (2013)

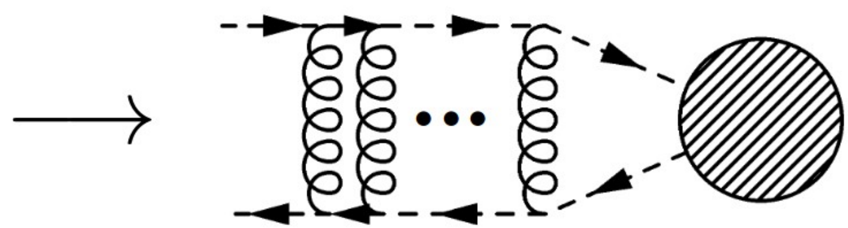
Sommerfeld effect

Sommerfeld effect



Important in the regime:

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

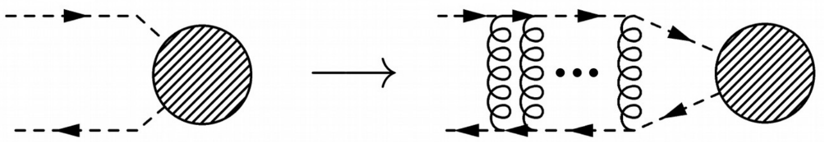


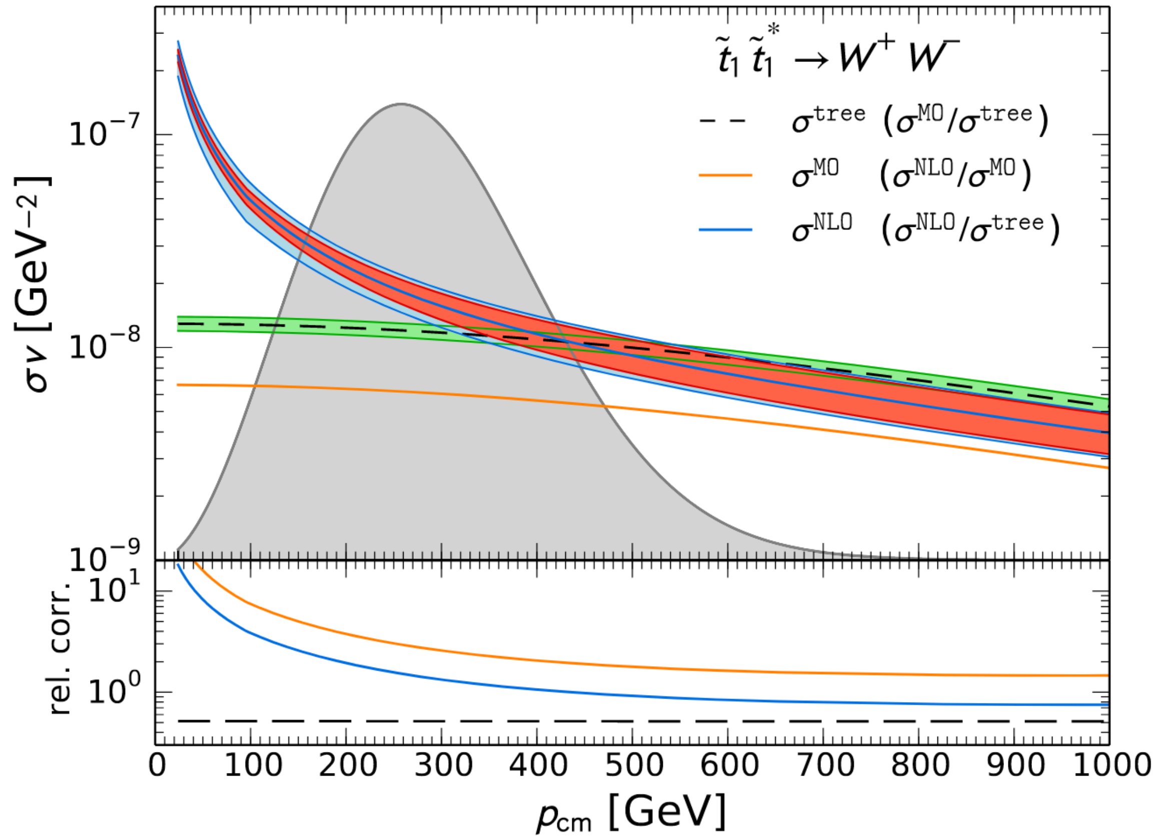
Exchange of n gluons contains a correction proportional to

$$\left(\frac{\alpha}{v_{\rm rel}}\right)^n \sim 1$$

Sommerfeld effect

Non-perturbative effects for small velocities





$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle}$$

→ Large K-factor in relevant region K=1-9

S. Schmiemann, JH, B. Herrmann, M. Klasen, K. Kovařík, Phys. Rev. D99 095015 (2019)
JH, B. Herrmann, M. Klasen, K. Kovařík, and P. Steppeler, Phys. Rev. D93, 114023 (2016)
JH, B. Herrmann, M. Klasen, K. Kovařík, and M. Meinecke, Phys. Rev. D 91, 034012 (2015)

Sommerfeld effect

non-exhaustive list!

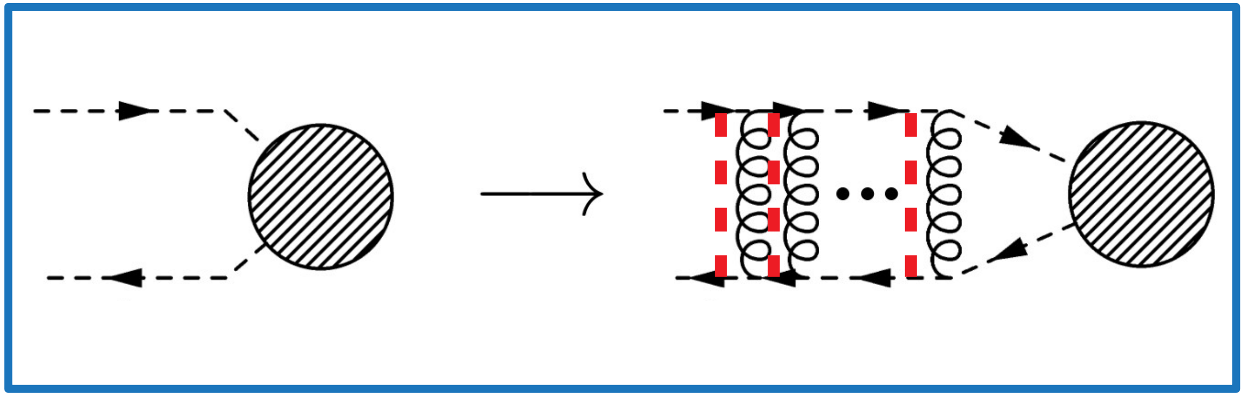
MSSM:

- **Relic density of wino-like dark matter in the MSSM**, Beneke, Bharucha, Dighera, Hellmann, Hryczuk, Recksiegel, Ruiz-Femenia (2016)
- **Heavy neutralino relic abundance with Sommerfeld enhancements - a study of pMSSM scenarios**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **SUSY-QCD corrections to stop annihilation into electroweak final states including Coulomb enhancement effects,** JH, B. Herrmann, M. Klasen, K. Kovařík, and M. Meinecke, Phys. Rev. D 91, 034012 (2015)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos III. Computation of the Sommerfeld enhancements**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos II. P-wave and next-to-next-to-leading order S-wave coefficients**, Hellmann, Ruiz-Femenía (2013)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos I. General framework and S-wave annihilation,** Beneke, Hellmann, Ruiz-Femenia (2013)
- **Enhanced One-Loop Corrections to WIMP Annihilation and their Thermal Relic Density in the Coannihilation Region**, Drees, Gu (2013)

Other Models:

- **Higgs Enhancement for the Dark Matter Relic Density**, JH, Petraki, (2018)
- **A Sommerfeld Toolbox for Colored Dark Sectors**, El Hedri, Kaminska, Vries (2017)
- **Asymmetric thermal-relic dark matter: Sommerfeld-enhanced freeze-out, annihilation signals and unitarity bounds**, Baldes, Petraki (2017)
- **The Sommerfeld Enhancement in the Scotogenic Model with Large Electroweak Scalar Multiplets,** Chowdhury, Nasri (2017)
- **Self-consistent Calculation of the Sommerfeld Enhancement**, Blum, Sato, Slatyer (2016)

Sommerfeld effect



What is the effect of a multiple exchange of Higgs boson?

Sommerfeld effect via massive scalar exchange

non-exhaustive list!

First conceptional studies before the Higgs discovery:

- **The Sommerfeld enhancement for scalar particles and application to sfermion co-annihilation regions**, Hryczuk (2011)
- **Sommerfeld Enhancements for Thermal Relic Dark Matter**, Feng, Kapling, Yu (2010)
- **Potentially Large One-loop Corrections to WIMP Annihilation**, Drees, Kim, Nagao (2009)

More specific studies after the Higgs discovery:

- **Relic density of wino-like dark matter in the MSSM**, Beneke, Bharucha, Dighera, Hellmann, Hryczuk, Recksiegel, Ruiz-Femenia (2016)
- **Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos III. Computation of the Sommerfeld enhancements**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **Heavy neutralino relic abundance with Sommerfeld enhancements - a study of pMSSM scenarios**, Beneke, Hellmann, Ruiz-Femenia (2015)
- **Higgs portal, fermionic dark matter, and a Standard Model like Higgs at 125 GeV**, Lopez-Honorez, Schwetz, Zupan (2012)

However, Higgs boson exchange has been neglected in recent studies of generic, (colored) coannihilation scenarios!

Higgs enhancement

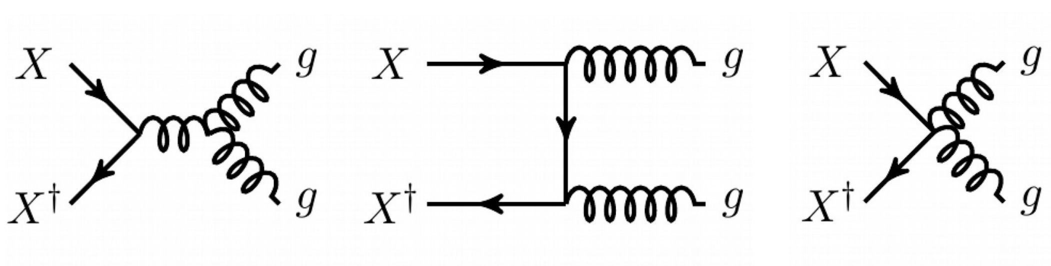
Higgs enhancement

- **Simplified model:**

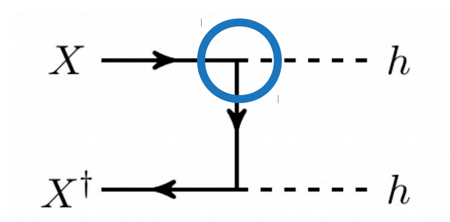
DM Majorana fermion χ; co-annihilating with complex scalar X charged under SU(3)$_c$

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

- **Annihilation processes:**



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

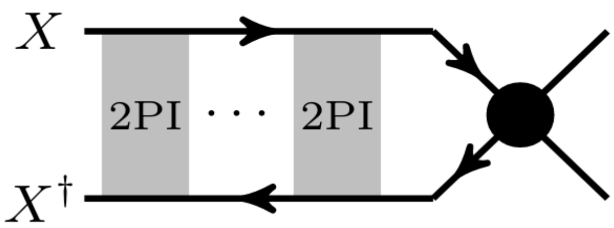


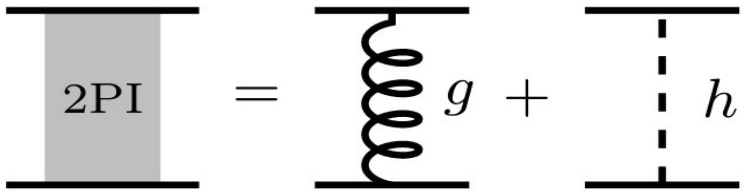
$$\alpha_h = \frac{g_h^2}{16\pi}$$

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

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





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

$$\boxed{S_0(\zeta_g, \zeta_h, d_h) \equiv |\phi_{\mathbf{k}}(0)|^2}$$

Color decomposition:

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

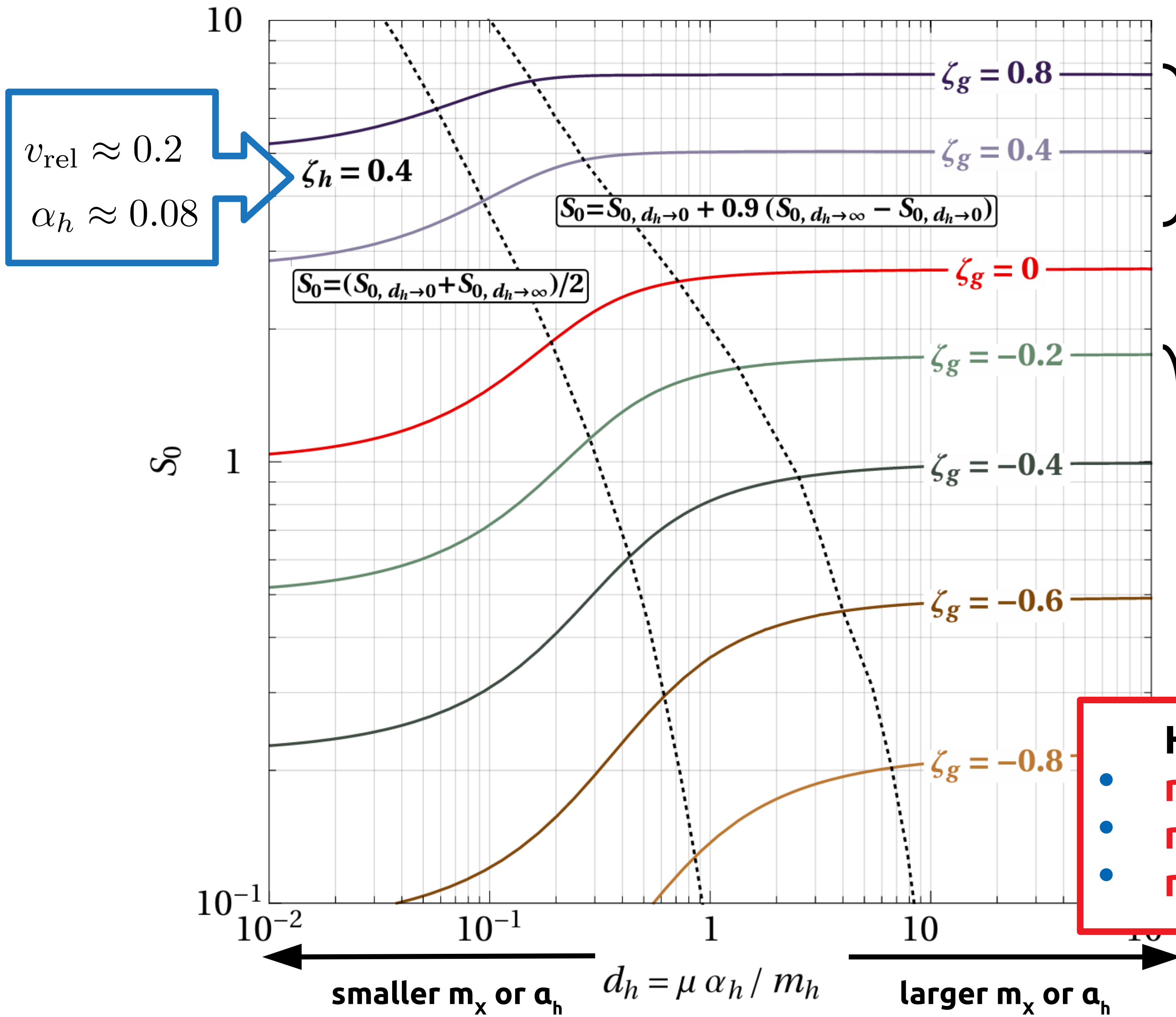
$$(\sigma v_{\mathrm{rel}})_{XX^\dagger \to gg} = (\sigma v_{\mathrm{rel}})^{\mathrm{pert}}_{XX^\dagger \to gg} \times \left(\frac{2}{7} S_0^{[\mathbf{1}]} + \frac{5}{7} S_0^{[\mathbf{8}]}\right)$$

$$(\sigma v_{\mathrm{rel}})_{XX^\dagger \to hh} = (\sigma v_{\mathrm{rel}})^{\mathrm{pert}}_{XX^\dagger \to hh} \times S_0^{[\mathbf{1}]}$$

Higgs enhancement

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

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



attractive gluon potential (singlet)

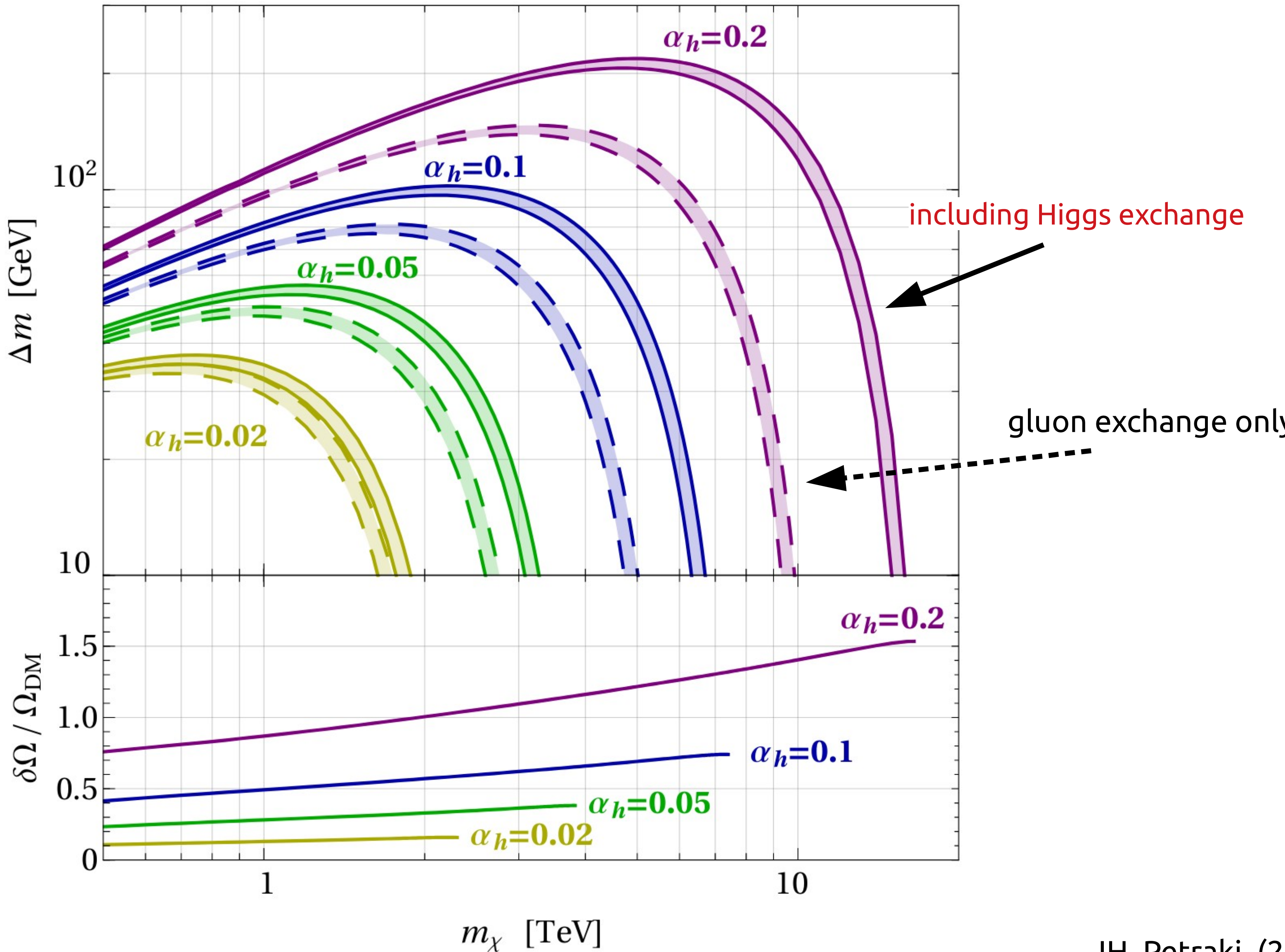
repulsive gluon potential (octet)

Higgs is able to

- **make singlet more attractive**
- **make octet less repulsive**
- **make octet attractive**

JH, Petraki, (2018)

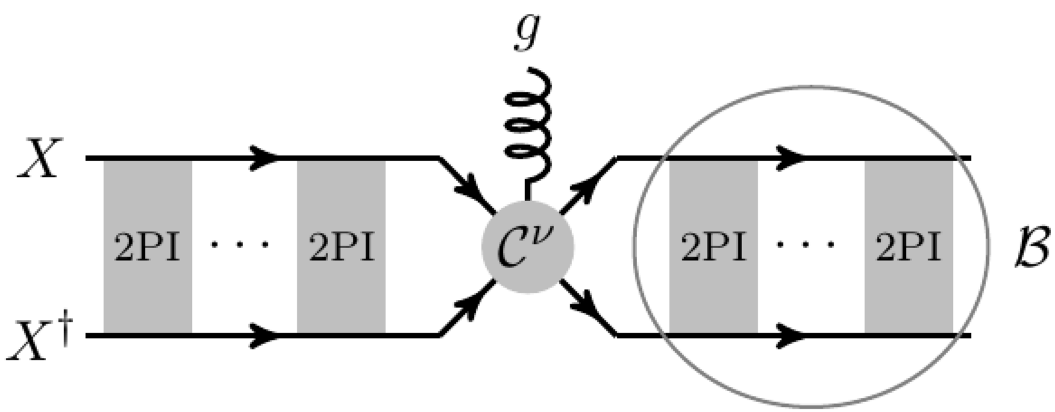
Impact of Higgs enhancement on the relic density

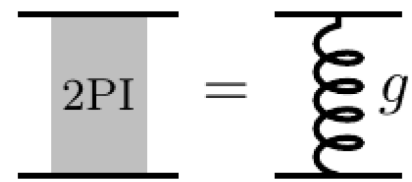


JH, Petraki, (2018)

Bound state formation

Bound states with gluon exchange





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

bound state formation

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

bound state ionisation

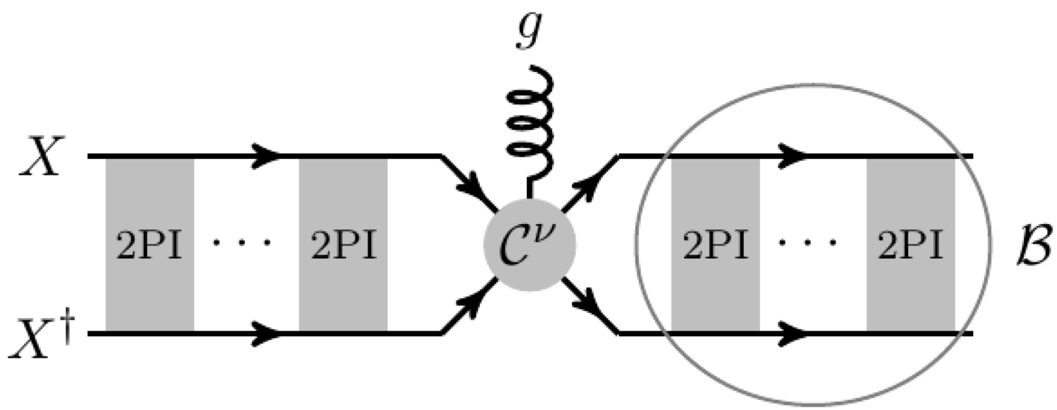
$$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\ g_{[\mathbf{8}]}$$

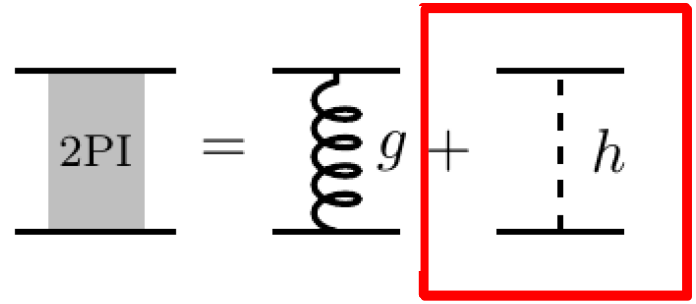
bound state decay

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

→ additional "annihilation" channel alters the relic density prediction

Bound states with gluon and Higgs exchange





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

bound state formation

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

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

Higgs may allow

(1) to form tighter bound states

(2) to form color octet bound states

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

Contributions to the effective BSF cross section

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\text{eff}} v \rangle}$$

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

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

bound state ionisation

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

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

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

Milne relation

bound state decay

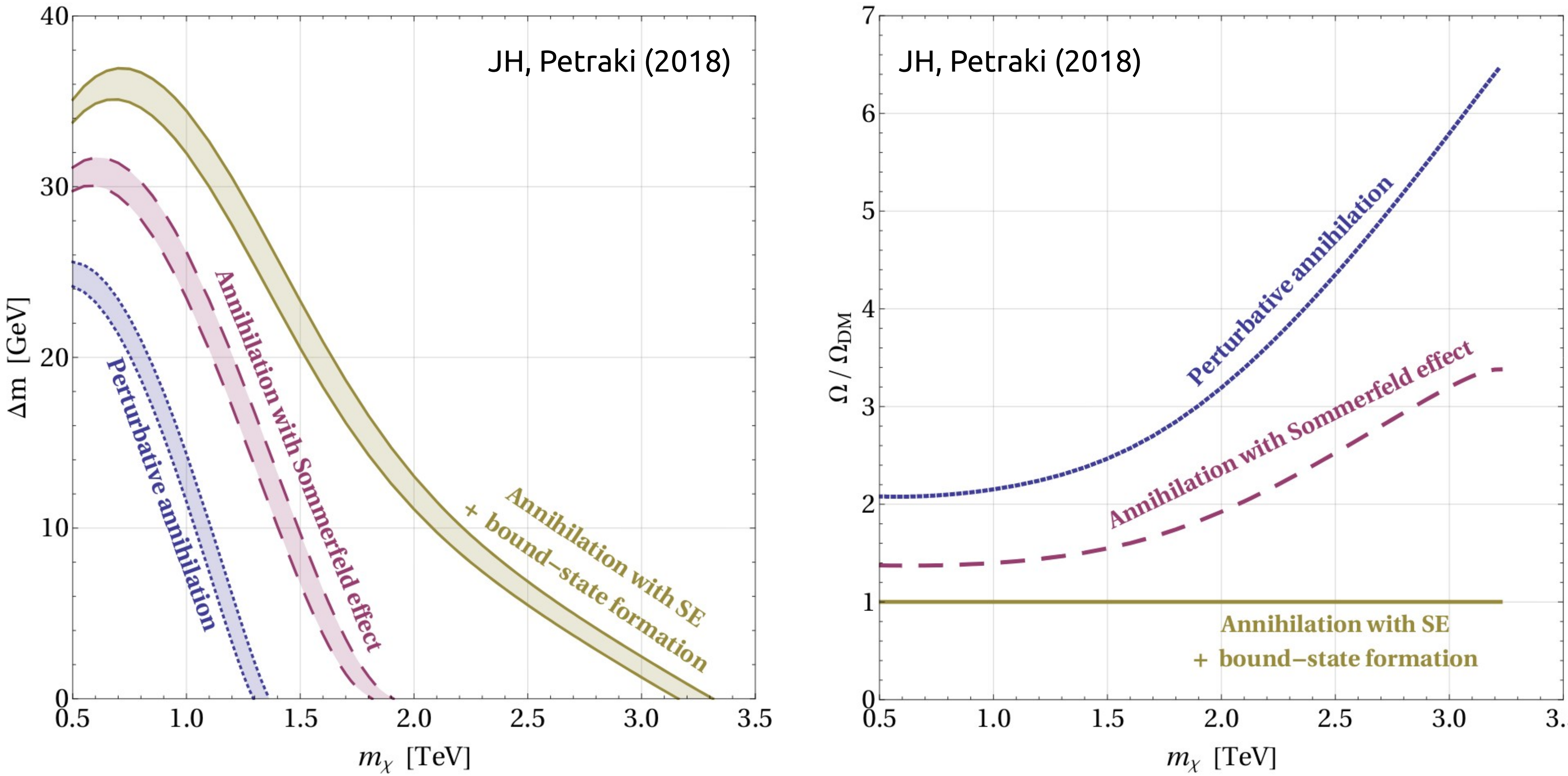
$$\mathcal{B}(XX^\dagger)_{[\mathbf{1}]} \to g_{[\mathbf{8}]}\; g_{[\mathbf{8}]}$$

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

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

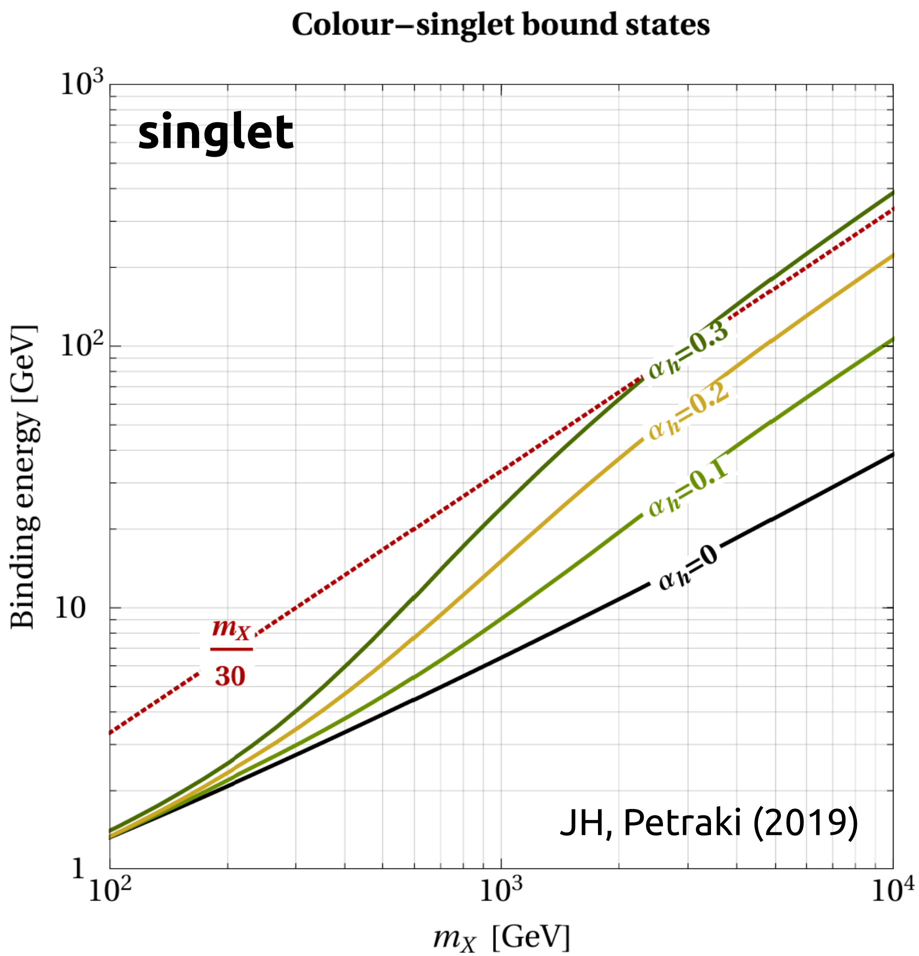
Impact on the relic density

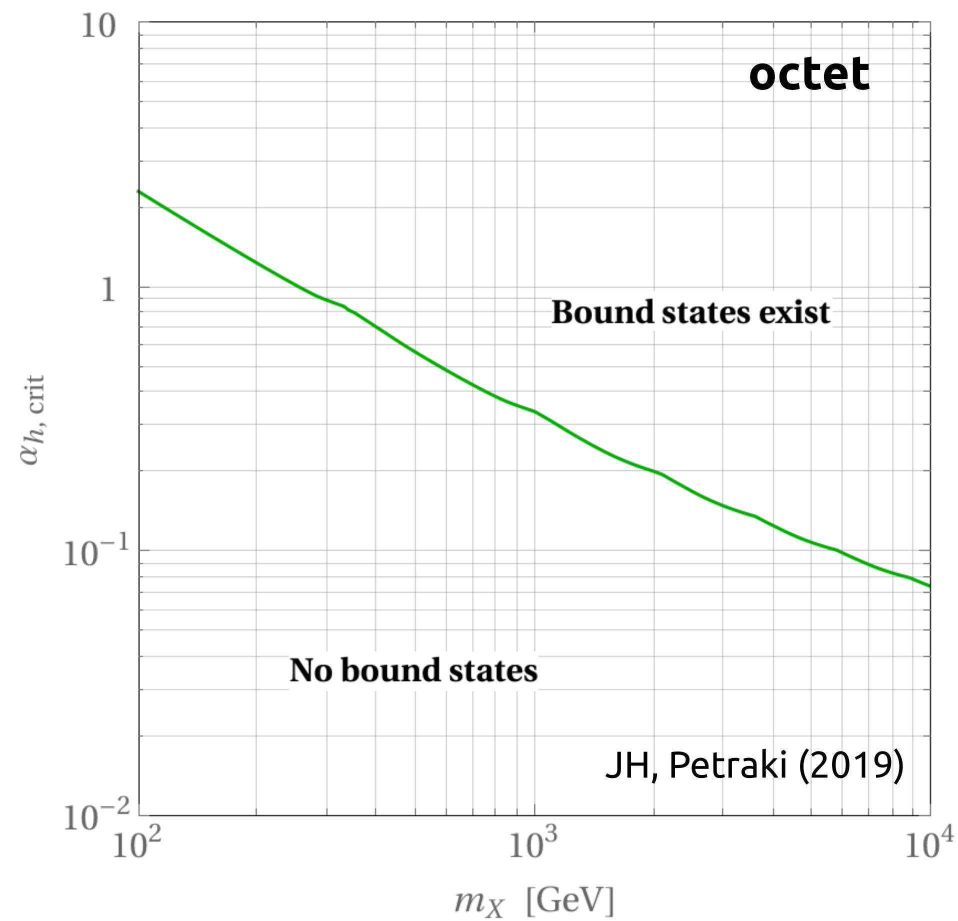
gluon exchange only



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

Impact of the Higgs on the formation of bound states

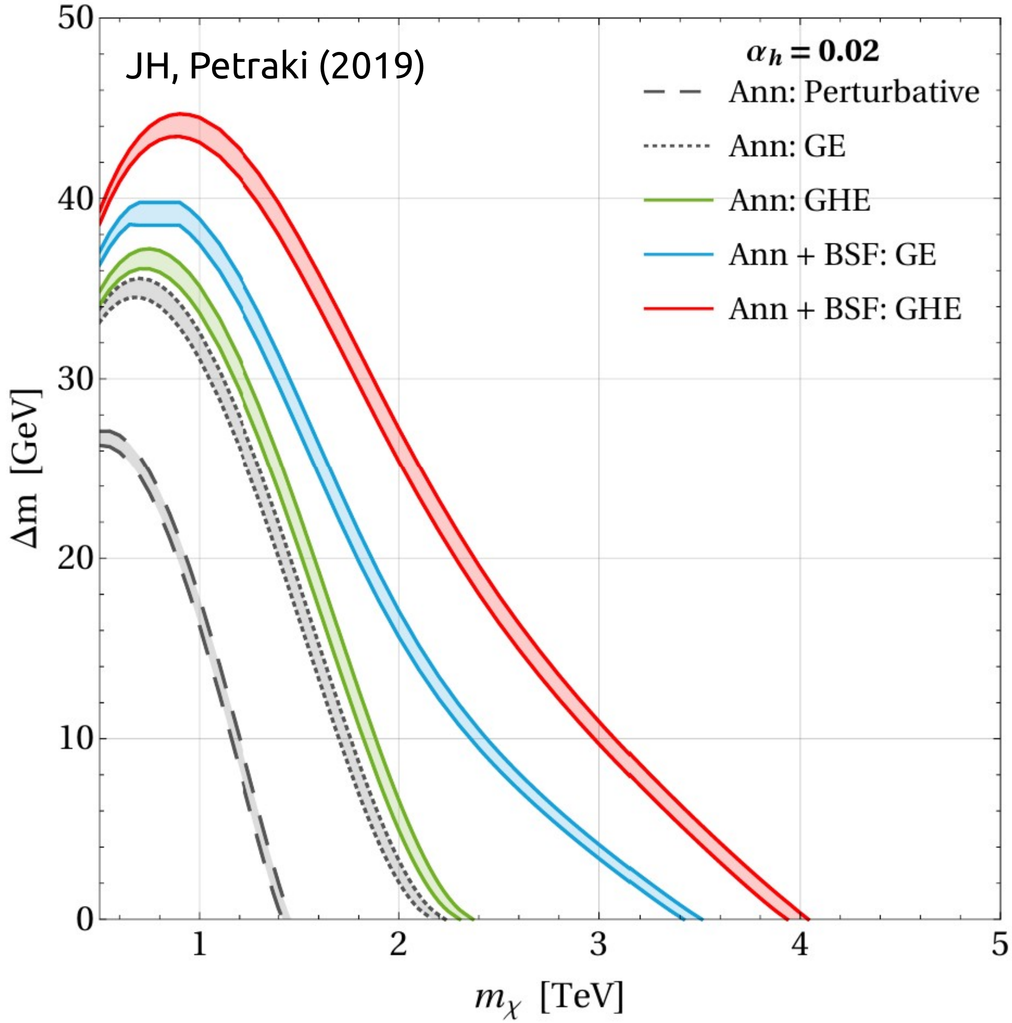


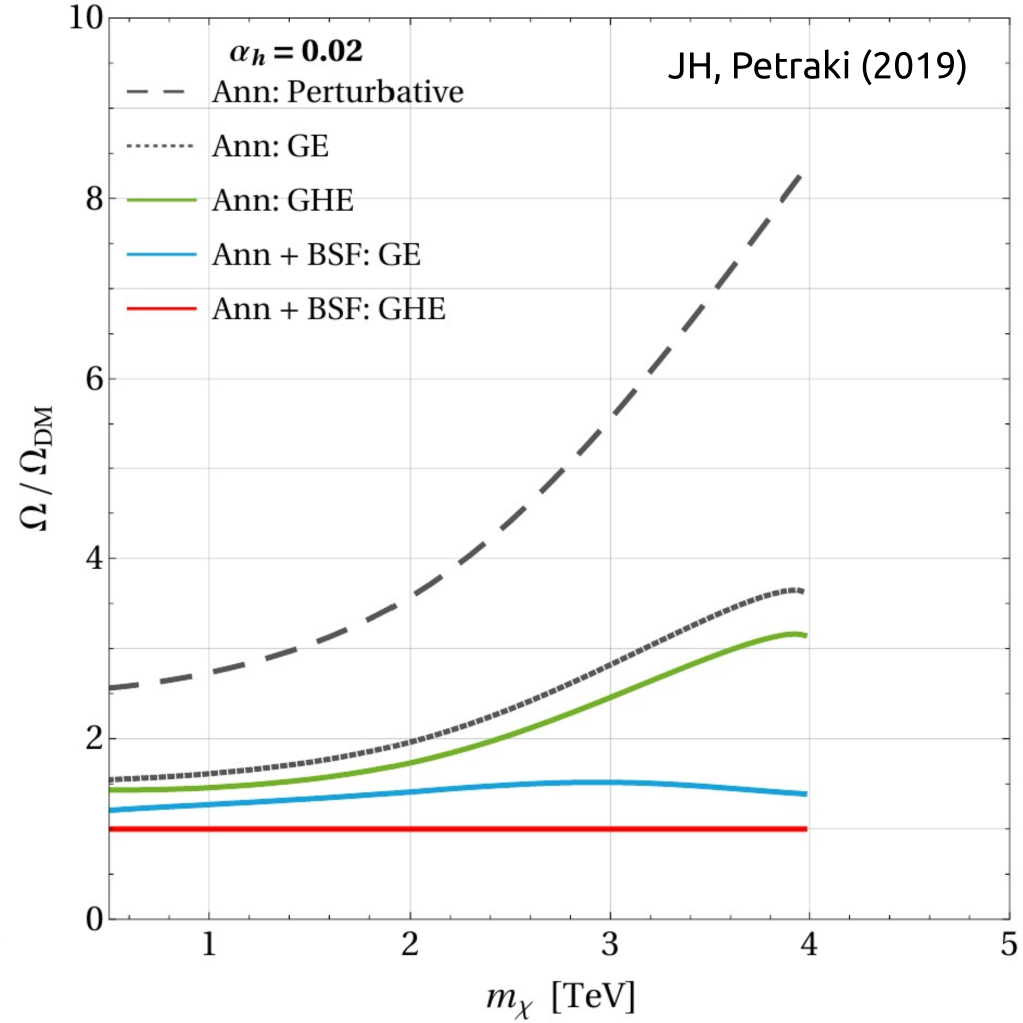


tighter bound states

additional bound states

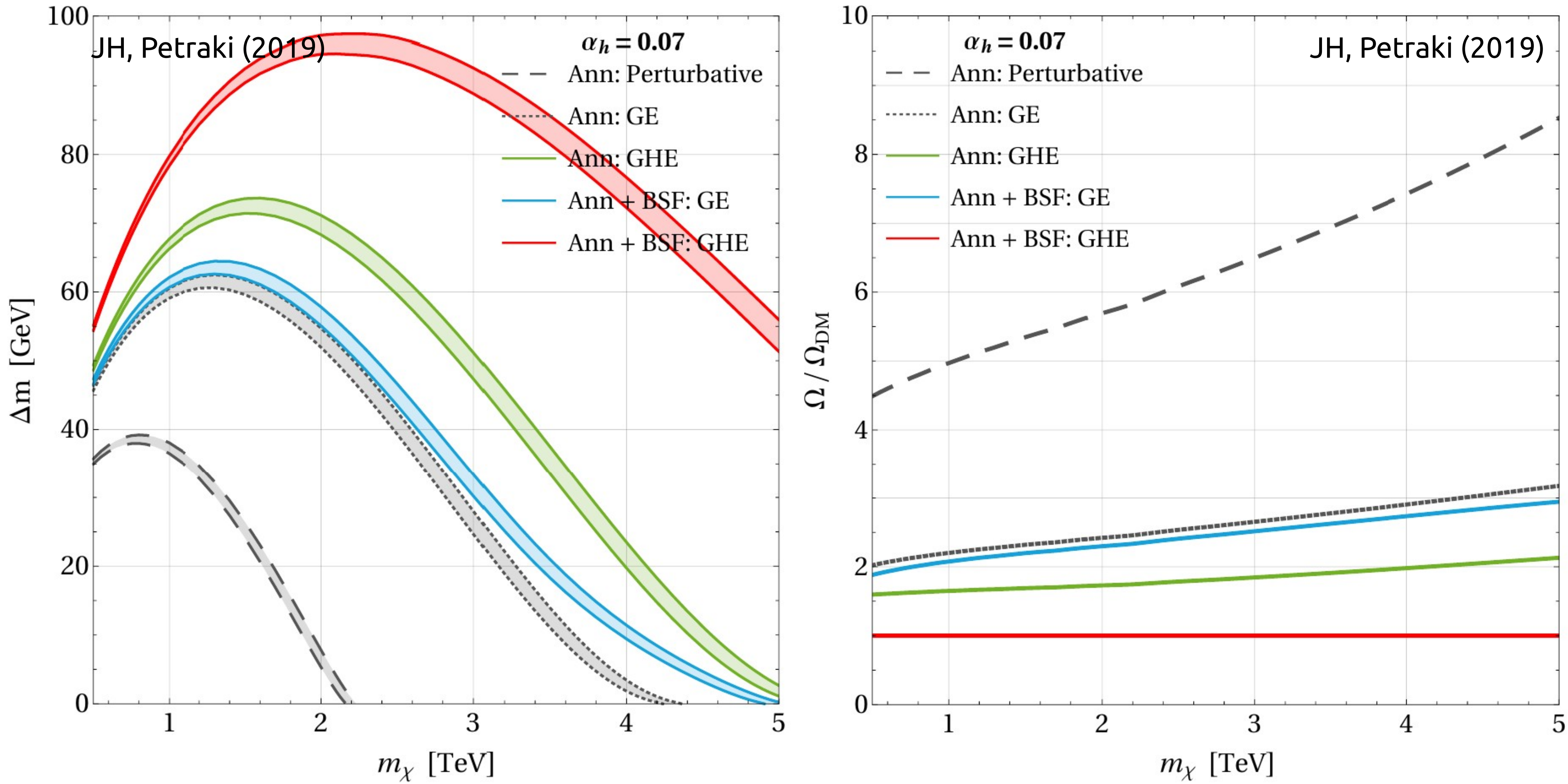
Impact on the relic density (with Higgs exchange)





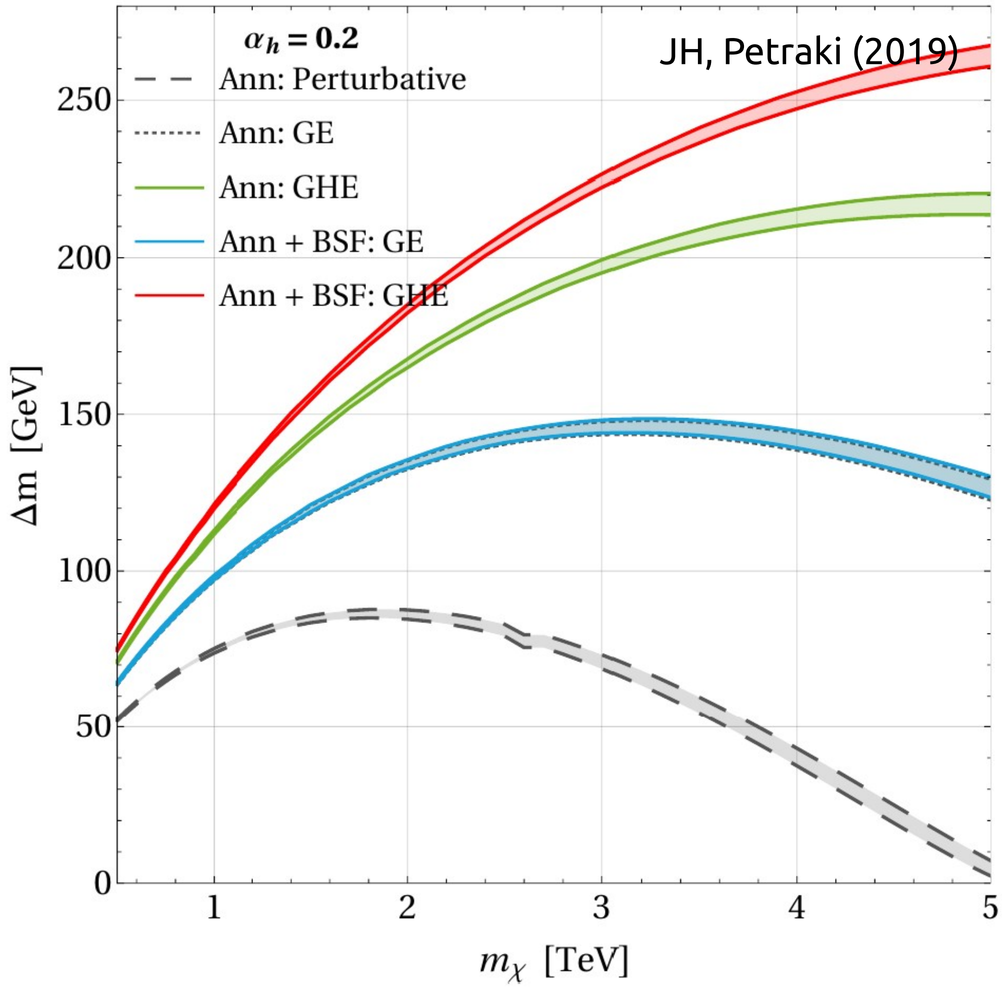
→ impact of gluon dominant for small Higgs couplings

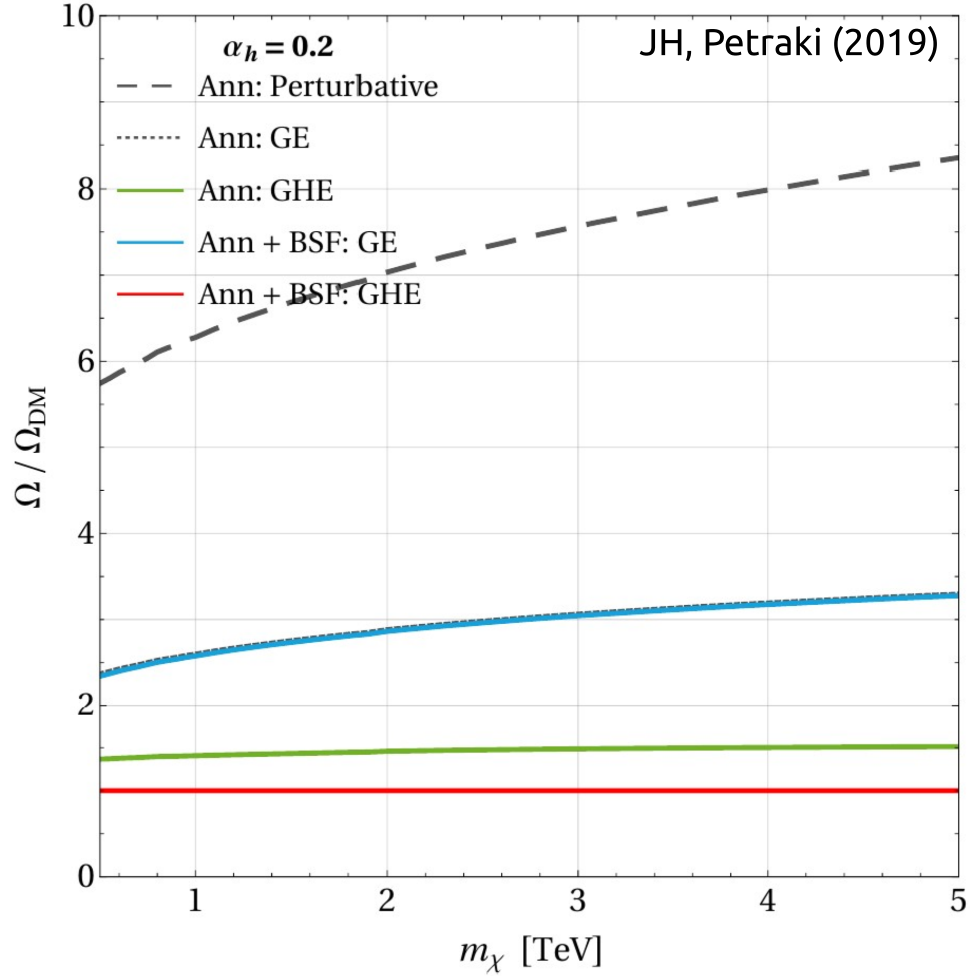
Impact on the relic density (with Higgs exchange)



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

Impact on the relic density (with Higgs exchange)

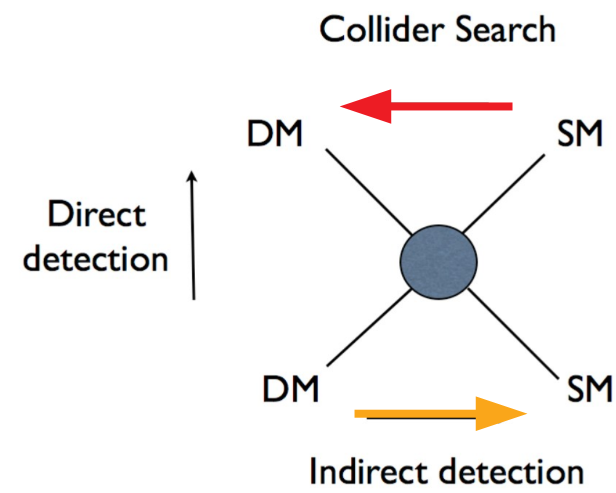


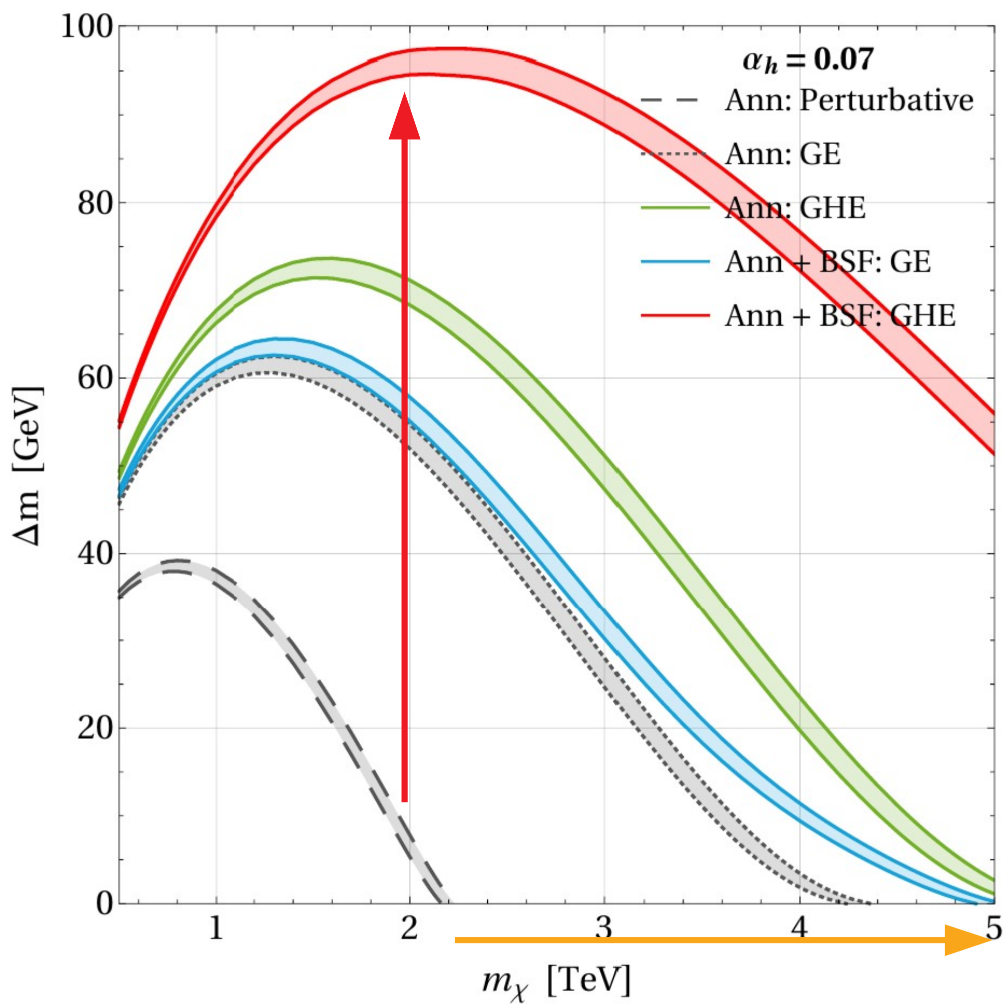


→ **Higgs enhancement most prominent**

→ **Higgs mediated BSF still sizable**

Why relevant?



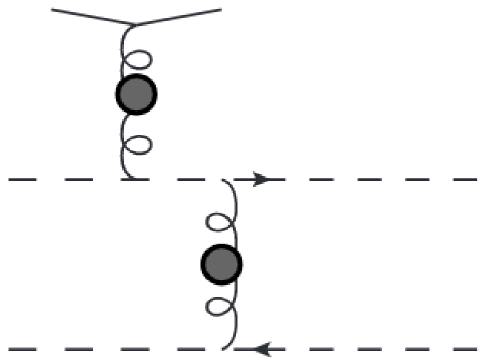


- More precise theoretical predictions
- Increased predicted mass splitting → **improved detection prospects with respect to multi-/mono-jet searches**
- DM can be heavier than anticipated → **interesting multi-TeV regime to be probed with indirect detection**

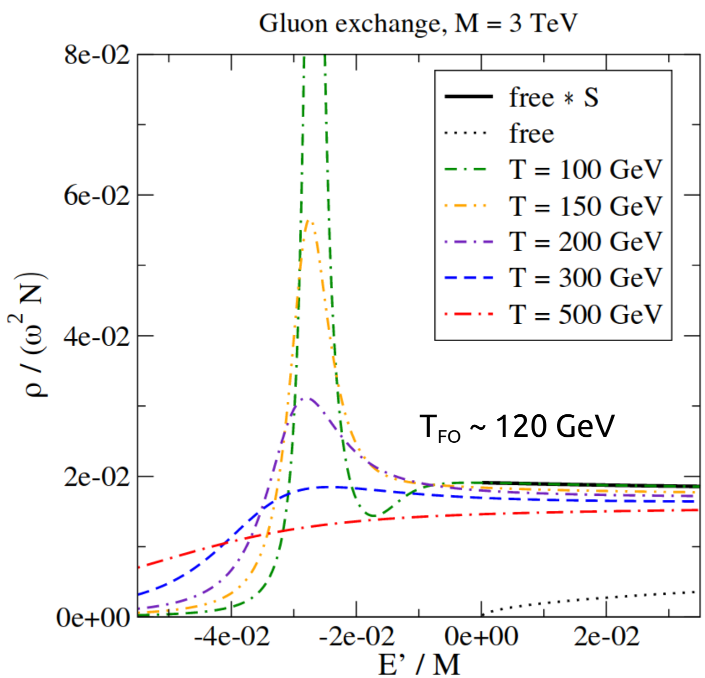
Finite temperature effects

Finite temperature effects

- Thermal masses – Deybe screening
- Scattering of heavy particles with light plasma constituents – Landau damping



Kim, Laine (2017)
Biondini, Laine (2018)
Biondini (2018)
Biondini, Vogl (2018)



Example: Gluino annihilation

Dark Matter Sommerfeld-enhanced annihilation and Bound-state decay at finite temperature

Tobias Binder,[1,*] Laura Covi,[1,†] and Kyohei Mukaida[2,‡]
[1] *Institute for Theoretical Physics, Georg-August University Göttingen, Friedrich-Hund-Platz 1, Göttingen, D-37077 Germany*
[2] *Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, Hamburg, D-22607 Germany*
(Dated: September 6, 2018)

Both approaches only valid in ionization equilibrium!

Conclusions

- *modified* Hubble expansion can play a role
- careful with underlying assumptions (*chemical/kinetic equilibrium*)
- *higher order corrections* can have sizable impact
- *theoretical uncertainties* shall be included
- *Sommerfeld enhancement* leads to huge corrective factors
- *formation of bound states* alters the relic abundance similarly
- *Higgs boson* can have an impact on previously studied scenarios
- important *implications on experimental studies* (collider, indirect detection)

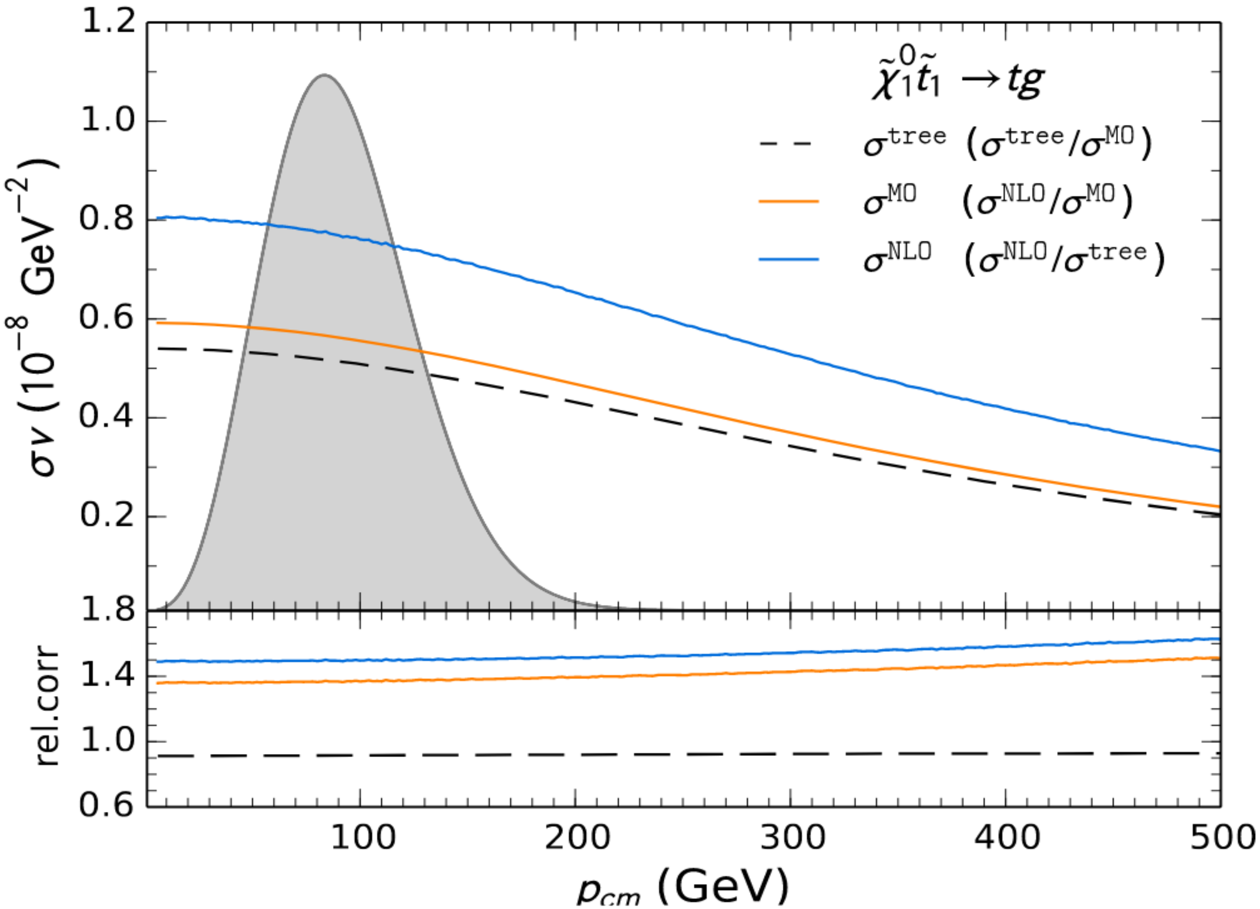
"Three exceptions" in 1990, but still an active research field!

Thank you for your attention!

Impact on the cross section

$$\Omega_\chi h^2 = \frac{n_\chi m_\chi}{\rho_{\text{crit}}} \propto \frac{1}{\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle}$$

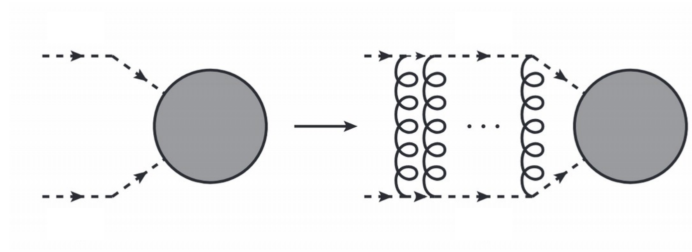
Coannihilation scenario on cross section level



→ Corrections of around 40% to the MicrOMEGAs cross section

JH, B. Herrmann, M. Klasen, K. Kovařík and Q. Le Boulc'h, Phys. Rev. D 87, 054031 (2013)
JH, B. Herrmann, M. Klasen, and K. Kovařík, Phys. Rev. D 91, 034028 (2015)

Sommerfeld effect



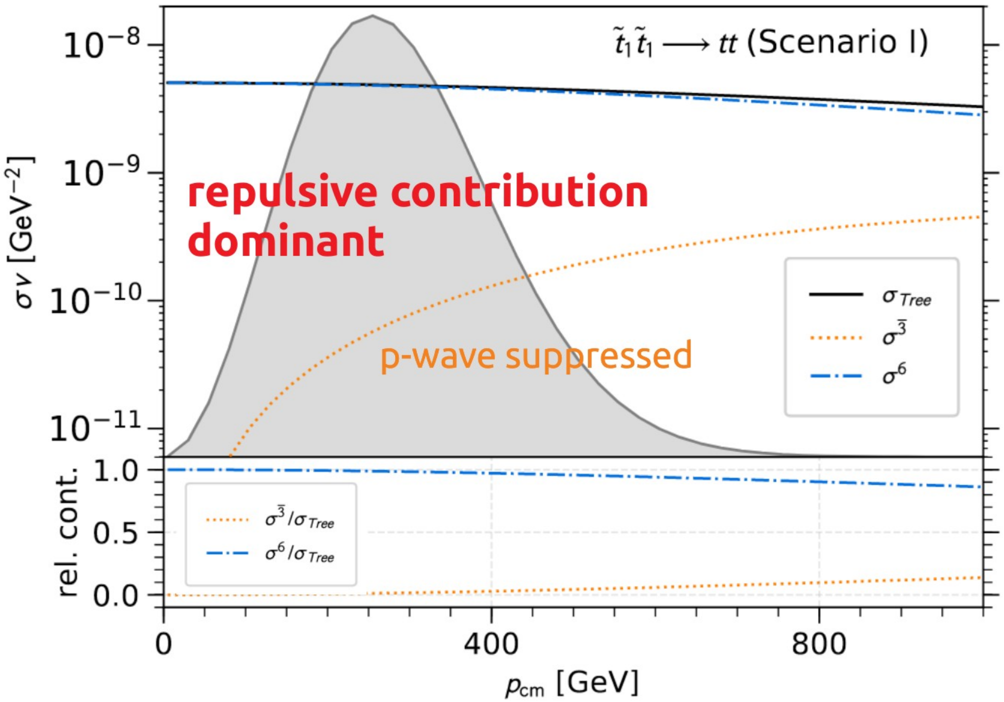
$$\mathbf{3} \otimes \mathbf{3} = \overline{\mathbf{3}} \oplus \mathbf{6}$$

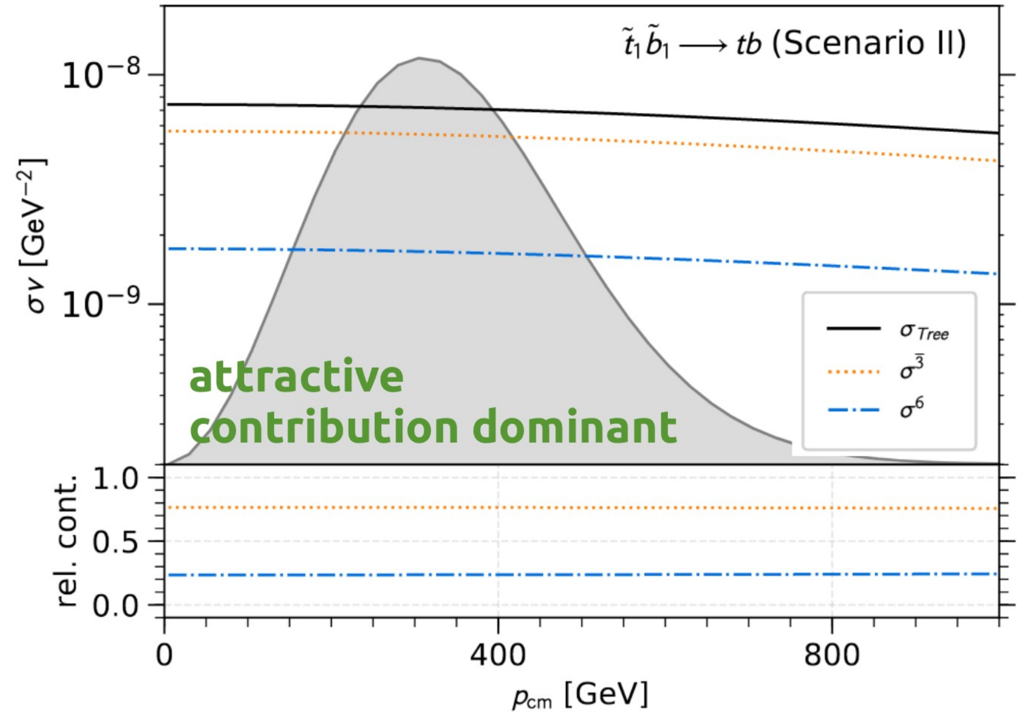
$$\mathrm{V}^{\mathbf{6}}_{\mathrm{QCD}}(r) \sim \left(+\tfrac{1}{3}\right) \frac{\alpha_s}{r}$$

repulsive

$$\mathrm{V}^{\overline{\mathbf{3}}}_{\mathrm{QCD}}(r) \sim \left(-\tfrac{2}{3}\right) \frac{\alpha_s}{r}$$

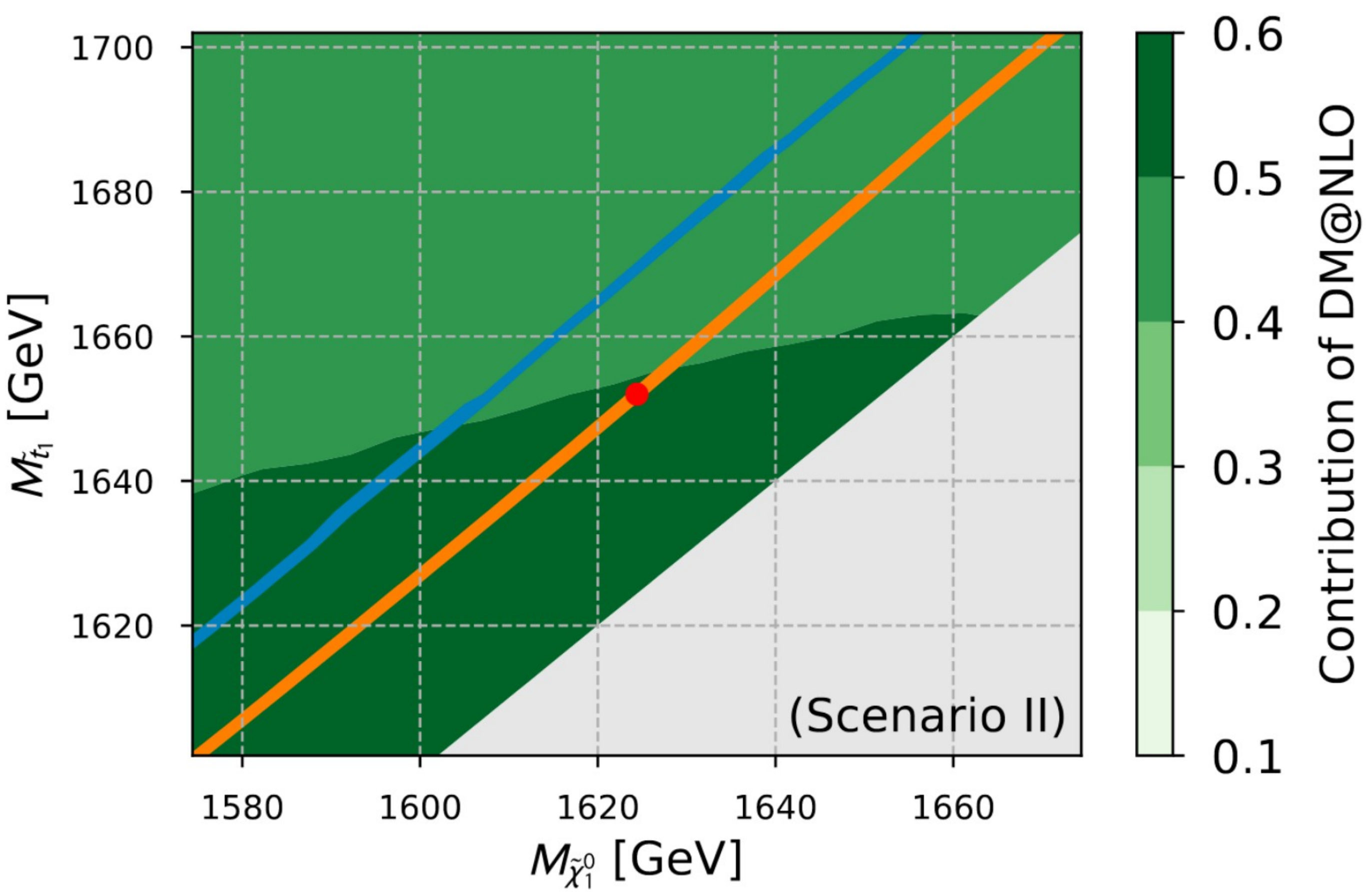
attractive





S. Schmiemann, JH, B. Herrmann, M. Klasen, K. Kovařík, Phys. Rev. D99 095015 (2019)

Sommerfeld effect



$$m_{\tilde{\chi}_1^0} = 1624.4\text{GeV}$$
$$m_{\tilde{t}_1} = 1652.0\text{GeV}$$

Contributing processes	Scenario II
$\tilde{t}_1\,\tilde{t}_1 \rightarrow t\,t$	8.8%
$\tilde{b}_1\,\tilde{b}_1 \rightarrow b\,b$	7.4%
$\tilde{t}_1\,\tilde{b}_1 \rightarrow t\,b$	34.0%
$\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \rightarrow q\,\bar{q}$	–
$\tilde{\chi}_1^0\,\tilde{t}_1 \rightarrow t\,g$	–
$\tilde{\chi}_1^0\,\tilde{t}_1 \rightarrow q\,V\,,q\,\phi$	–
$\tilde{\chi}_1^0\,\tilde{b}_1 \rightarrow q\,V\,,q\,\phi$	–
$\tilde{t}_1\,\tilde{t}_1^* \rightarrow g\,g$	9.8%
$\tilde{t}_1\,\tilde{t}_1^* \rightarrow q\,\bar{q}$	2.4%
$\tilde{t}_1\,\tilde{b}_1^* \rightarrow q\,\bar{q}'$	4.0%
$\tilde{b}_1\,\tilde{b}_1^* \rightarrow q\,\bar{q}\,,g\,g$	8.1%
$\tilde{\chi}_1^0\,\tilde{g} \rightarrow X$	–
$\tilde{g}\,\tilde{g} \rightarrow X$	–
DM@NLO current analysis	50.2%
DM@NLO total [15–18, 20–22]	50.2%

→ corrections of around 20 GeV on the physical masses

S. Schmiemann, JH, B. Herrmann, M. Klasen, K. Kovařík, Phys. Rev. D99 095015 (2019)

Higgs enhancement

- **Boltzmann equation:**

$$\boxed{\begin{gathered}\tilde{Y} \equiv Y_\chi + Y_X + Y_{X^\dagger} = Y_\chi + 2Y_X \\ \frac{d\tilde{Y}}{dx} = -\sqrt{\frac{\pi}{45}}\frac{M_{\rm Pl} m_X\, g_{*,\rm eff}^{1/2}}{x^2}\langle\sigma_{\rm eff}\, v_{\rm rel}\rangle\left(\tilde{Y}^2 - \tilde{Y}_{\rm eq}^2\right)\end{gathered}}$$

$$Y_\chi^{\rm eq} = \frac{90}{(2\pi)^{7/2}}\,\frac{g_\chi}{g_{*,S}}\; x^{3/2}\; e^{-x}$$

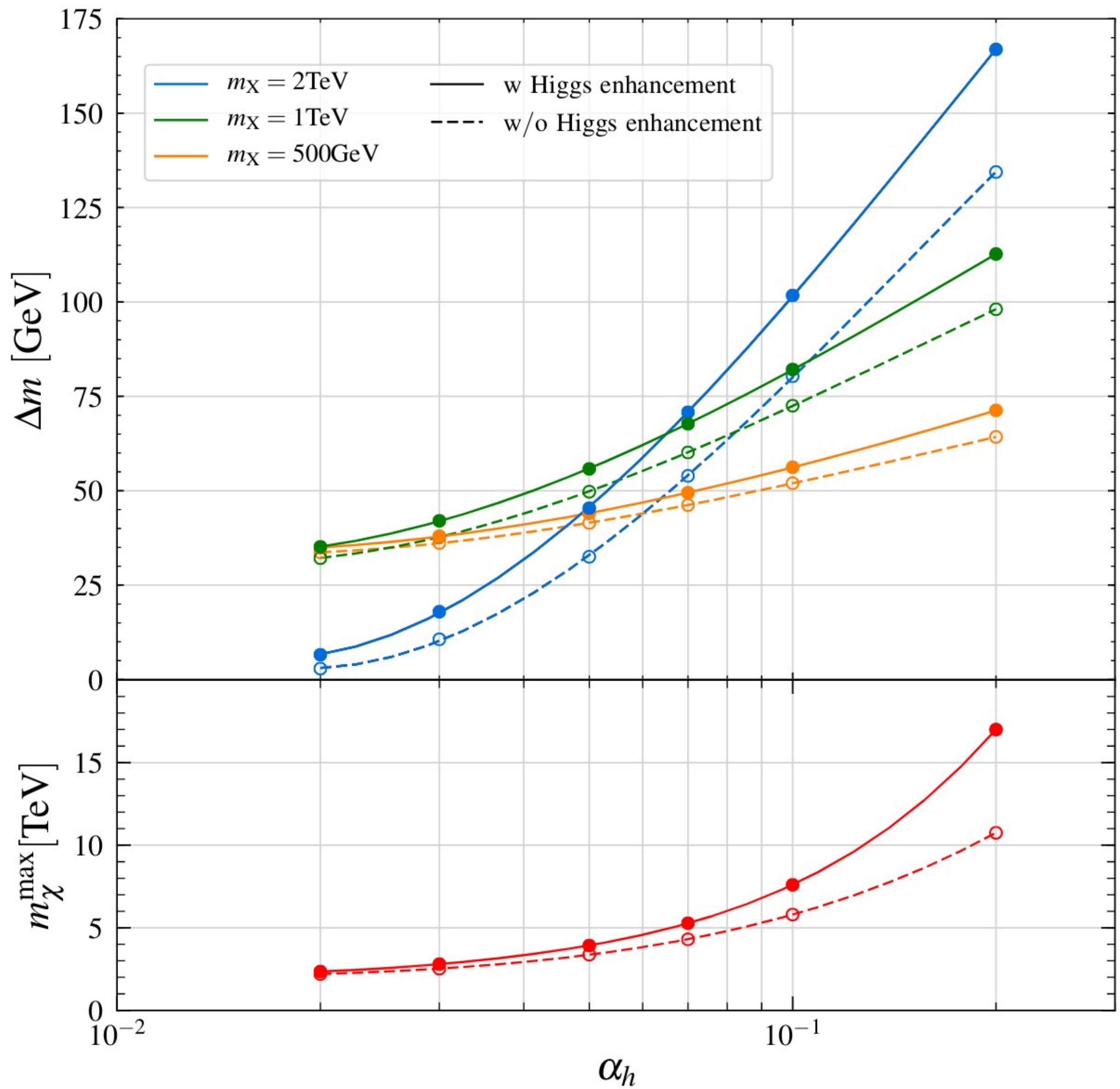
$$Y_X^{\rm eq} = Y_{X^\dagger}^{\rm eq} = \frac{90}{(2\pi)^{7/2}}\,\frac{g_\chi}{g_{*,S}}\;[(1+\Delta)x]^{3/2}\; e^{-(1+\Delta)x}$$

- **Assumption:**

$$\boxed{\begin{gathered}\Gamma(X + {\rm SM} \leftrightarrow \chi + {\rm SM}) \gg H \\ \sigma(X + {\rm SM} \leftrightarrow \chi + {\rm SM}) \gg \frac{17\, x_{\rm dec}}{m_\chi M_{\rm Pl}} \sim 6 \times 10^{-11}\ {\rm pb}\left(\frac{\rm TeV}{m_\chi}\right)\end{gathered}}$$

$$x_{\rm dec} = m_\chi / T_{\rm dec}$$

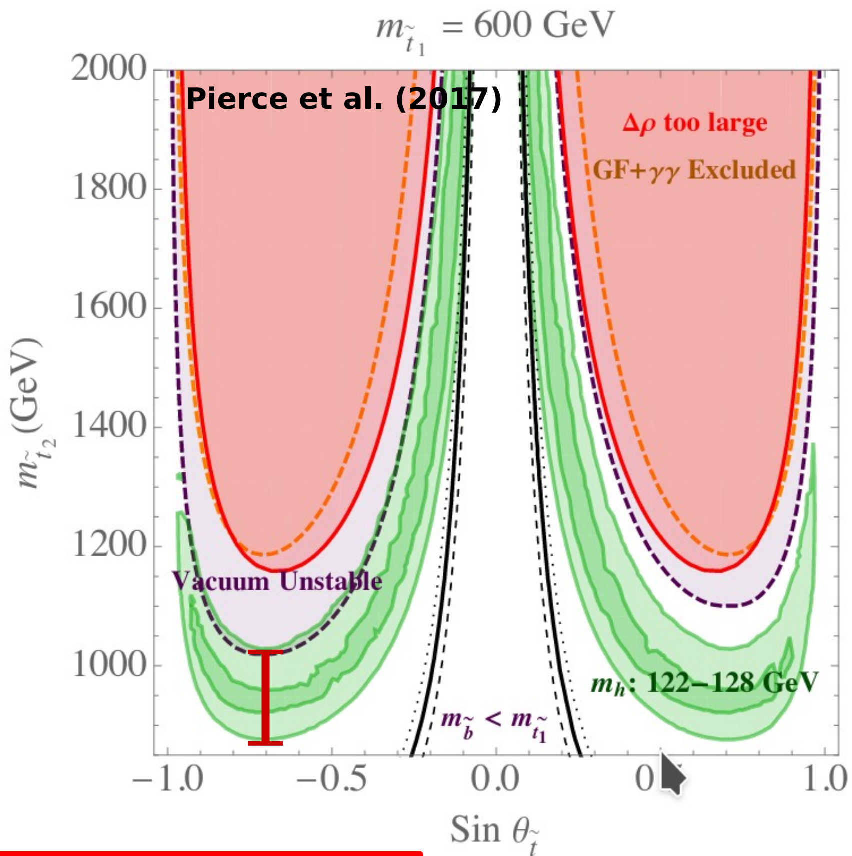
Impact of Higgs enhancement on the relic density

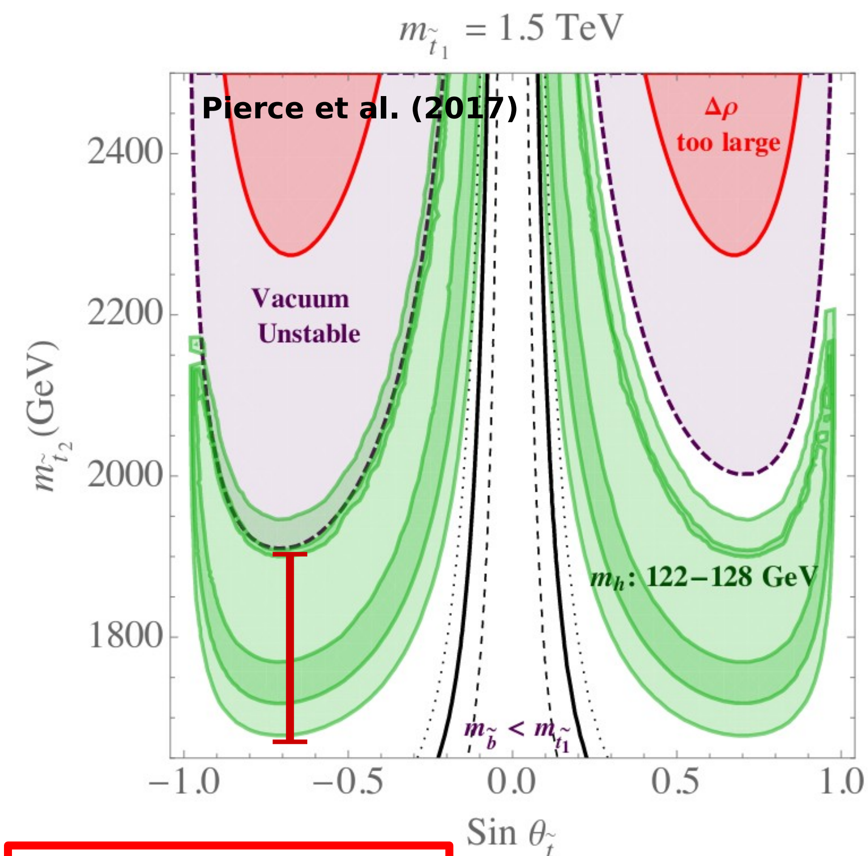


JH, Petraki, (2018)

Vacuum stability?

Example: realization within the MSSM:





$\boxed{\alpha_h \approx (0.02 - 0.07)}$

$\boxed{\alpha_h \approx (0.01 - 0.05)}$

We checked explicitly one MSSM scenario as example with *vevacious*

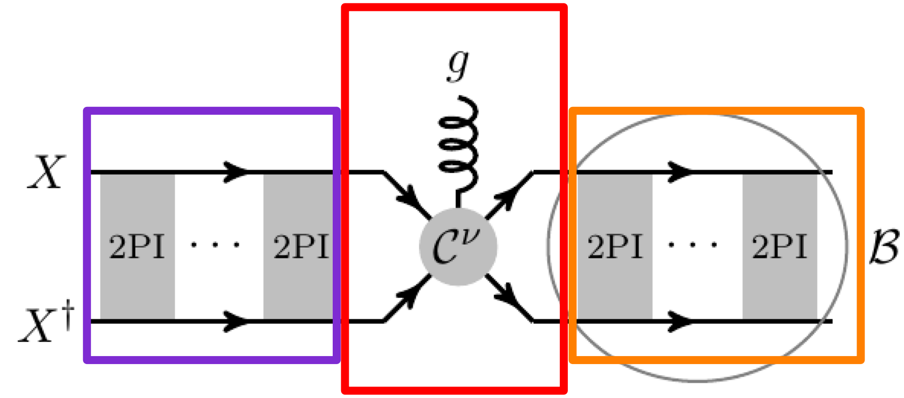
$\alpha_h \approx 0.15$

$m_{\tilde{\chi}_1^0} = 982.5$ GeV

$m_{\tilde{t}_1} = 1066.1$ GeV

Bound state formation

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



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 $\alpha^S_{g,[\mathbf{8}]} = -\frac{\alpha_s^S}{6}$

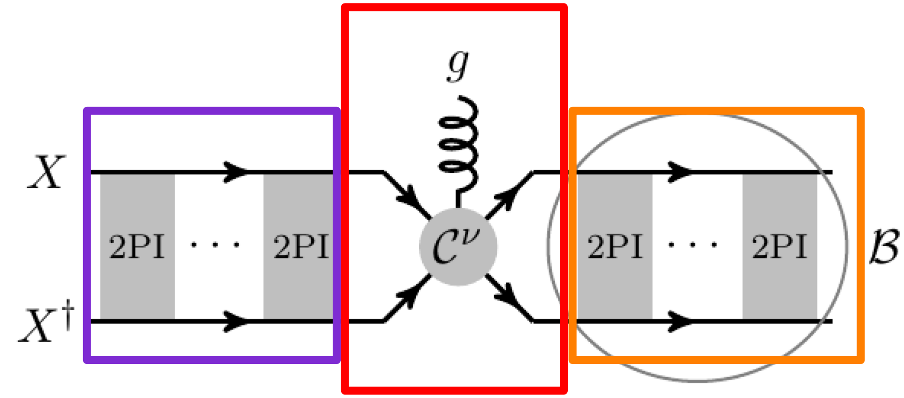
at scale $Q = \frac{m_X v_{\rm rel}}{2}$

scattering state

Bound state formation

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

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



scattering state

radiative transition

bound state

Binding energy

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

with Bohr momentum:

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

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

Bound state potential

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

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

at scale

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

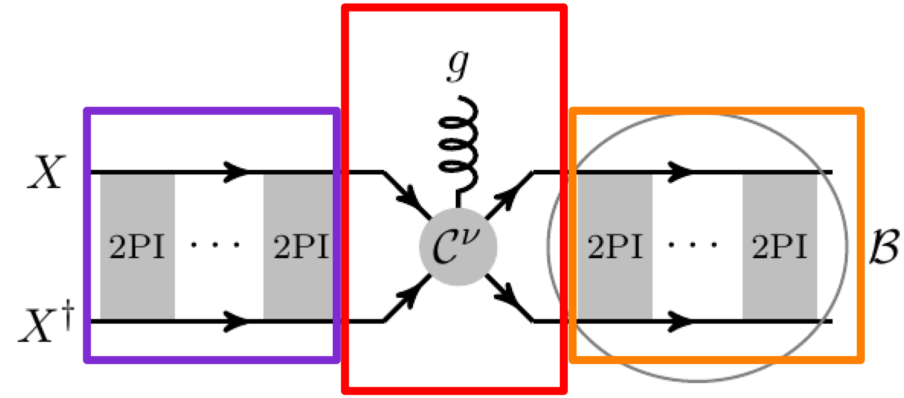
$$= \frac{m_X}{2}\left(\alpha_h + \alpha^B_{g,\{[\mathbf{1}],[\mathbf{8}]\}}\right) \times \gamma_{n\ell}\left(\frac{\alpha_{g,\{[\mathbf{1}],[\mathbf{8}]\}}}{\alpha_h},\ d_h\right)$$

bound state

Bound state formation

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

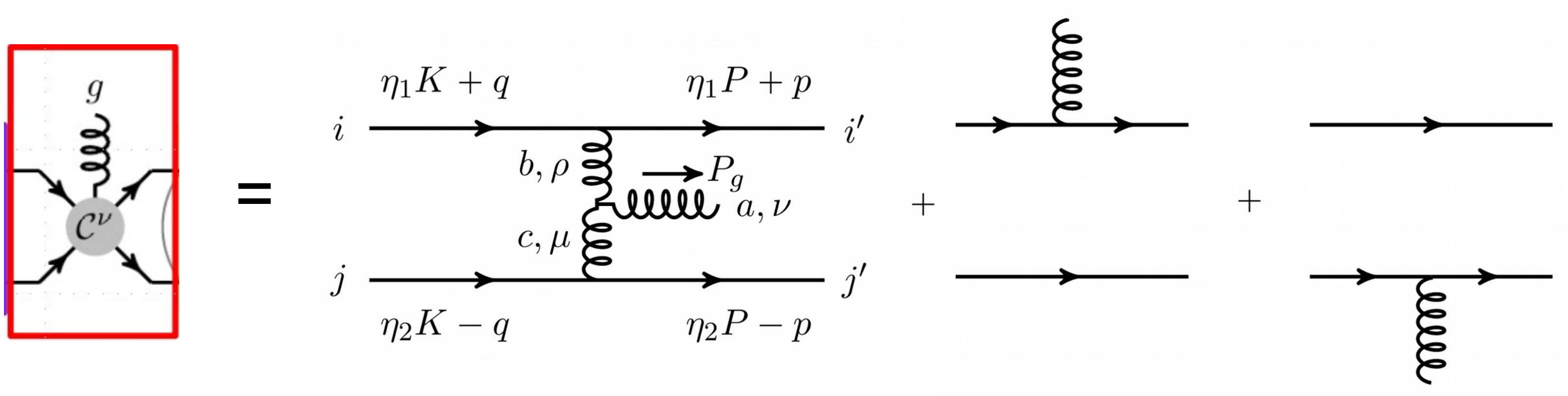
$$\left[-\frac{\nabla^2}{2\mu} + V_{\text{bound}}(\mathbf{r})\right] \psi_{n\ell m}(\mathbf{r}) = \mathcal{E}_{n\ell}\, \psi_{n\ell m}(\mathbf{r})$$



scattering state

radiative transition

bound state



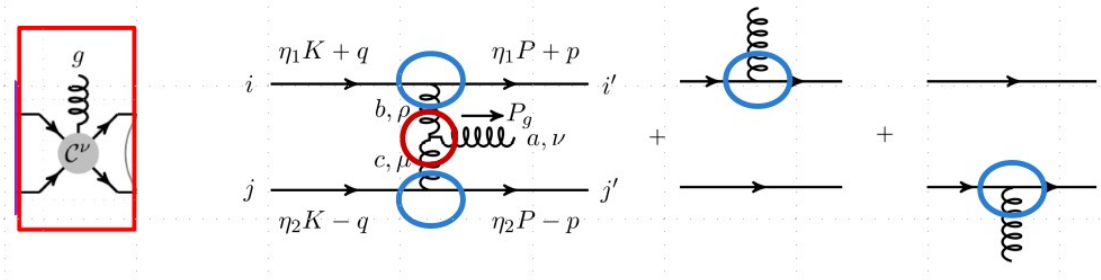
Derivation from Feynman diagrammatic approach, see
DM bound states from Feynman diagrams, Petraki et al. JHEP 1506 (2015) 128

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

transition amplitude

Bound state formation

transition amplitude



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

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

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

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

expected to have significant effect!

Comparison with Quarkonium literature:

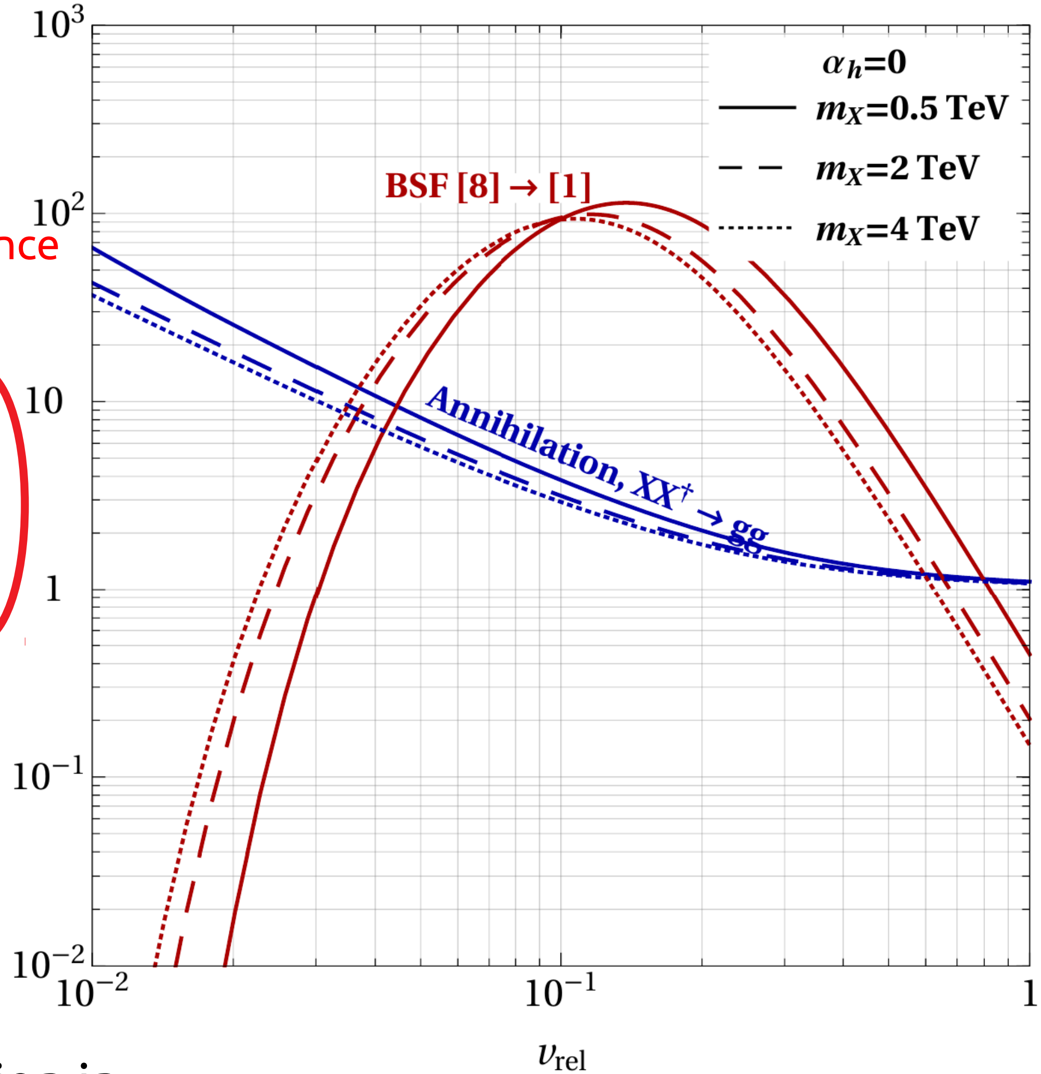
Perturbative heavy quark - anti-quark systems, M. Beneke, hep-ph/9911490

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

Annihilation vs. BSF cross section



gluon exchange only

direct mass dependence cancels
→ only indirect scale dependence

$\alpha_s/v_{\rm rel} << 1$

$\sigma_{\rm BSF}^{[\mathbf{8}]\to[\mathbf{1}]} \propto (\alpha_s/v_{\rm rel})^4$

$\alpha_s/v_{\rm rel} >> 1$

Coulomb repulsion in the scattering state

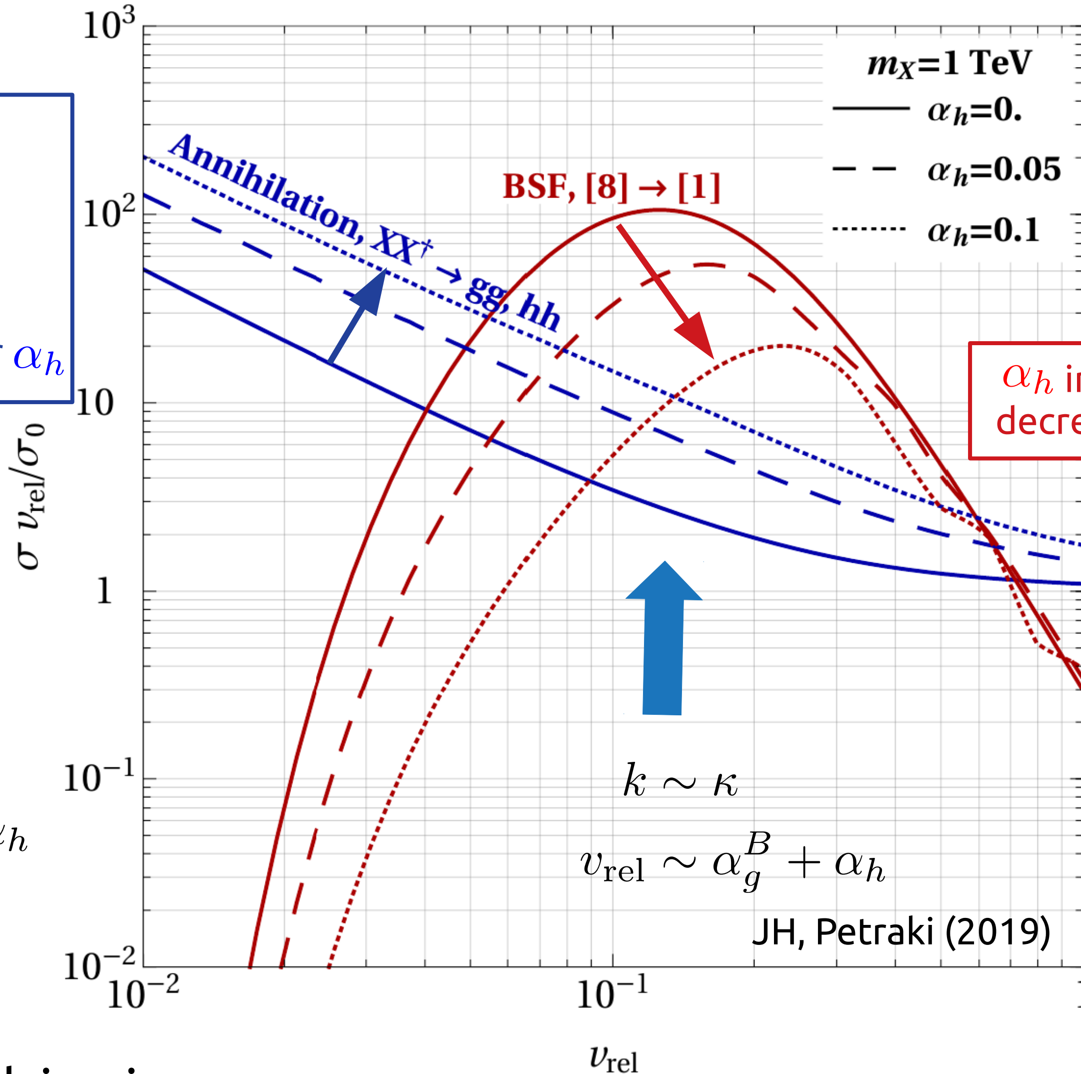
→ scale dependence has an strong impact on BSF and annihilation cross section!

Annihilation vs. BSF cross section

with Higgs exchange

new annihilation channel

pert. annihilation + Sommerfeld effect increases with larger α_h



α_h increases scale and decreases α_g

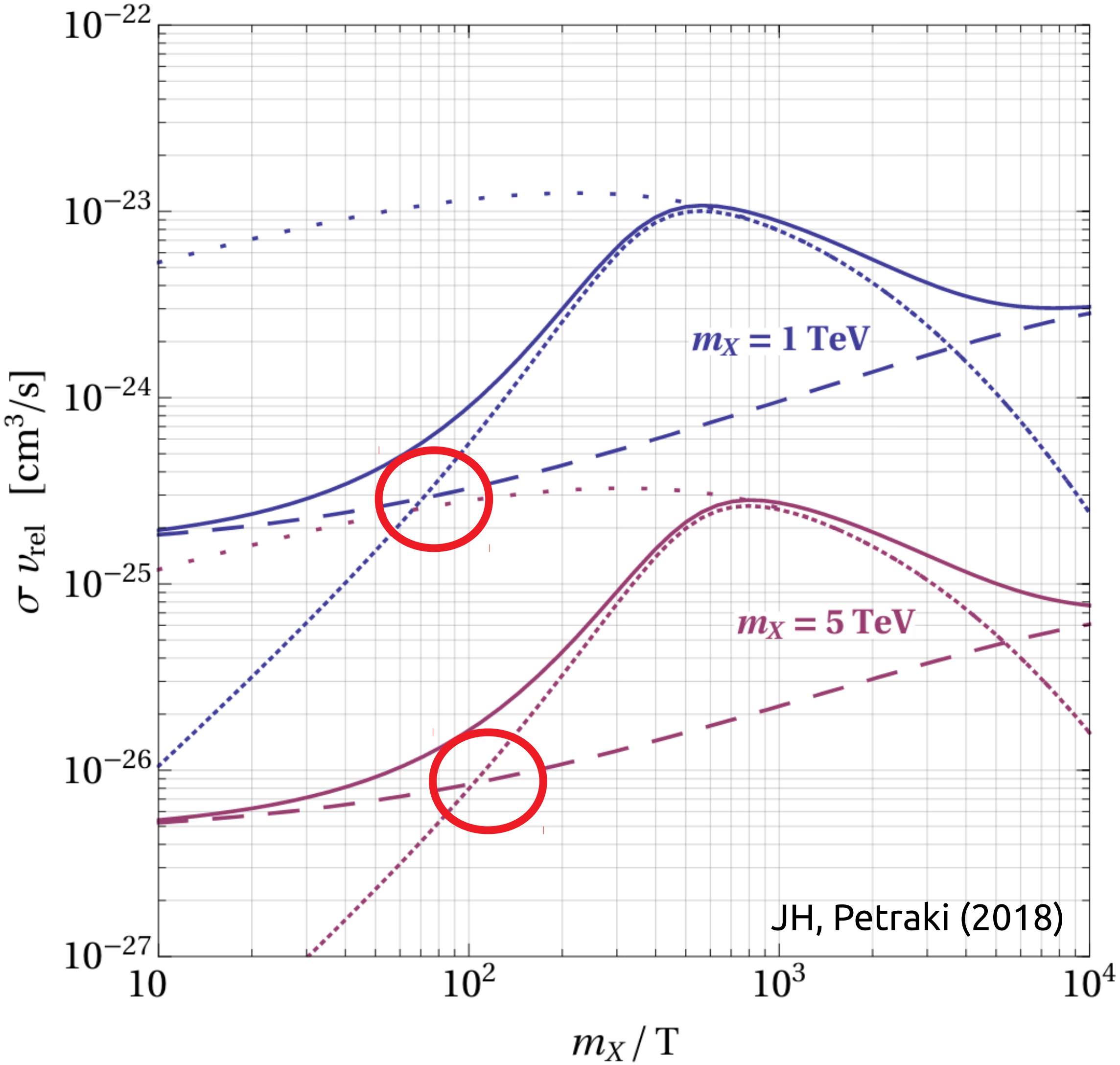
$v_{\rm rel} \lesssim \alpha_g^S + \alpha_h$

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

Coulomb repulsion in the scattering state

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

Annihilation vs. effective BSF cross section



gluon exchange only

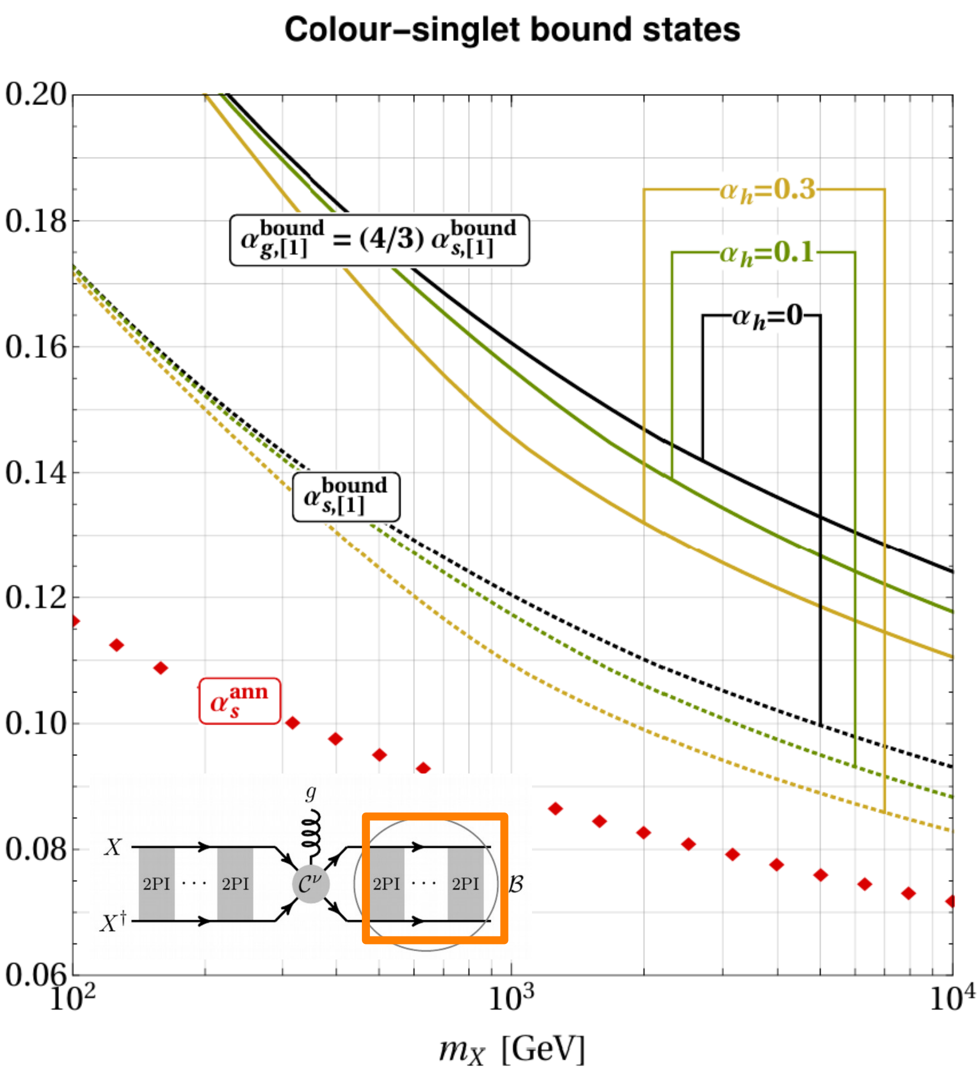
interplay between bound state formation and ionisation

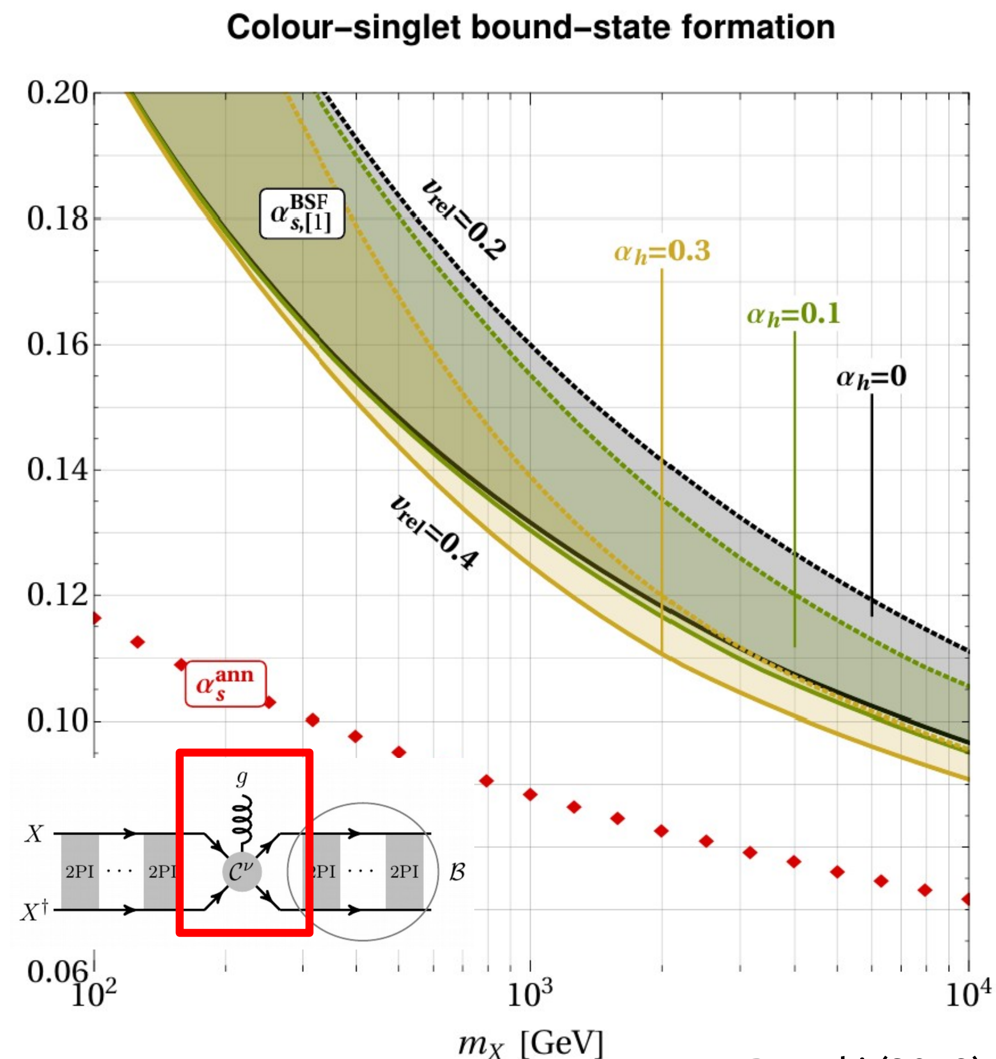
$$\langle \sigma_{XX^\dagger} v_{\rm rel} \rangle = \langle \sigma_{\rm ann}\, v_{\rm rel} \rangle + \langle \sigma_{\rm BSF} v_{\rm rel} \rangle_{\rm eff}$$

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

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

Running of the strong coupling – bound state

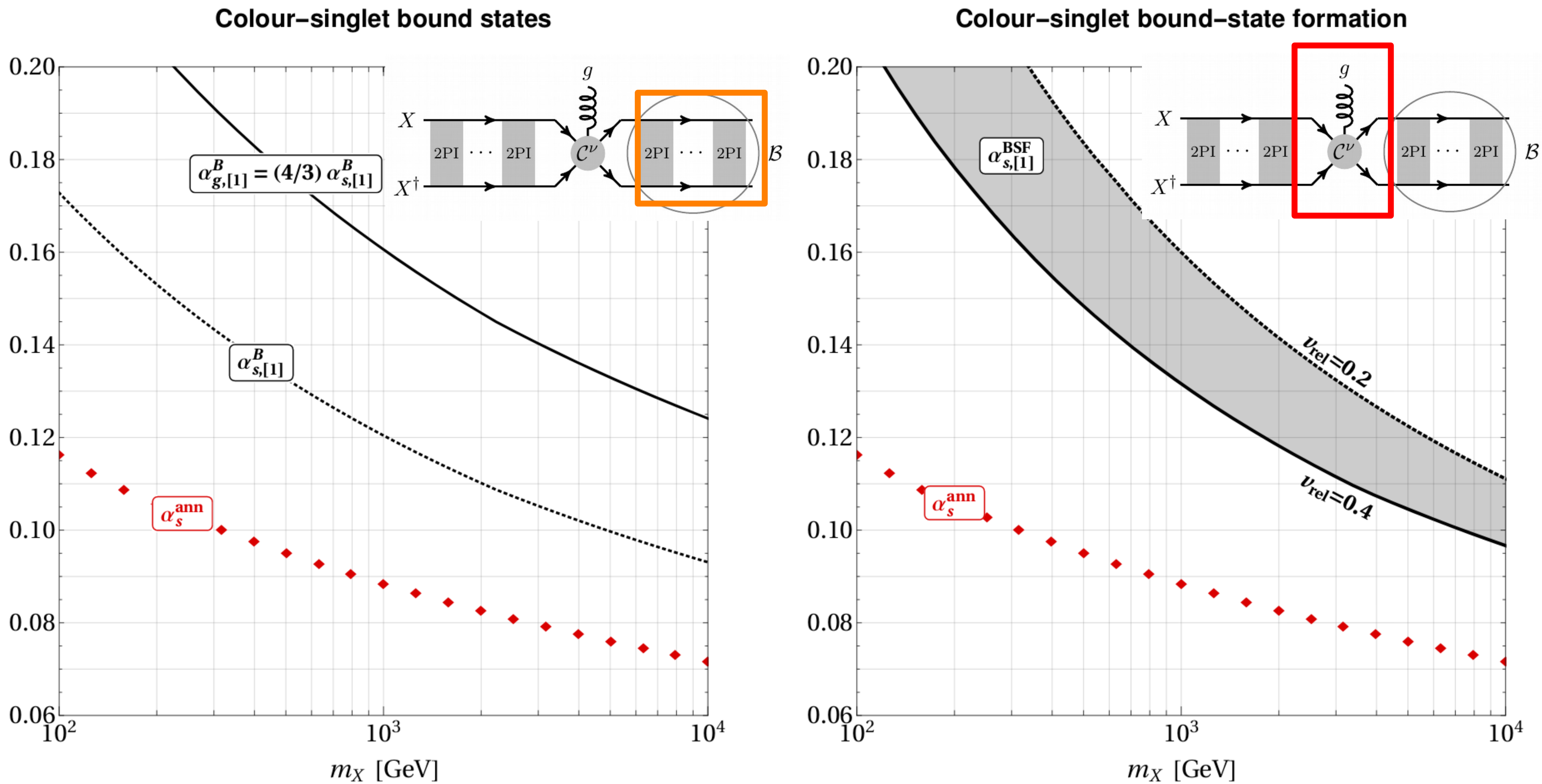




JH, Petraki (2019)
JH, Petraki (2018)

→ Higgs interaction decreases α_g considerably

Running of the strong coupling – bound state

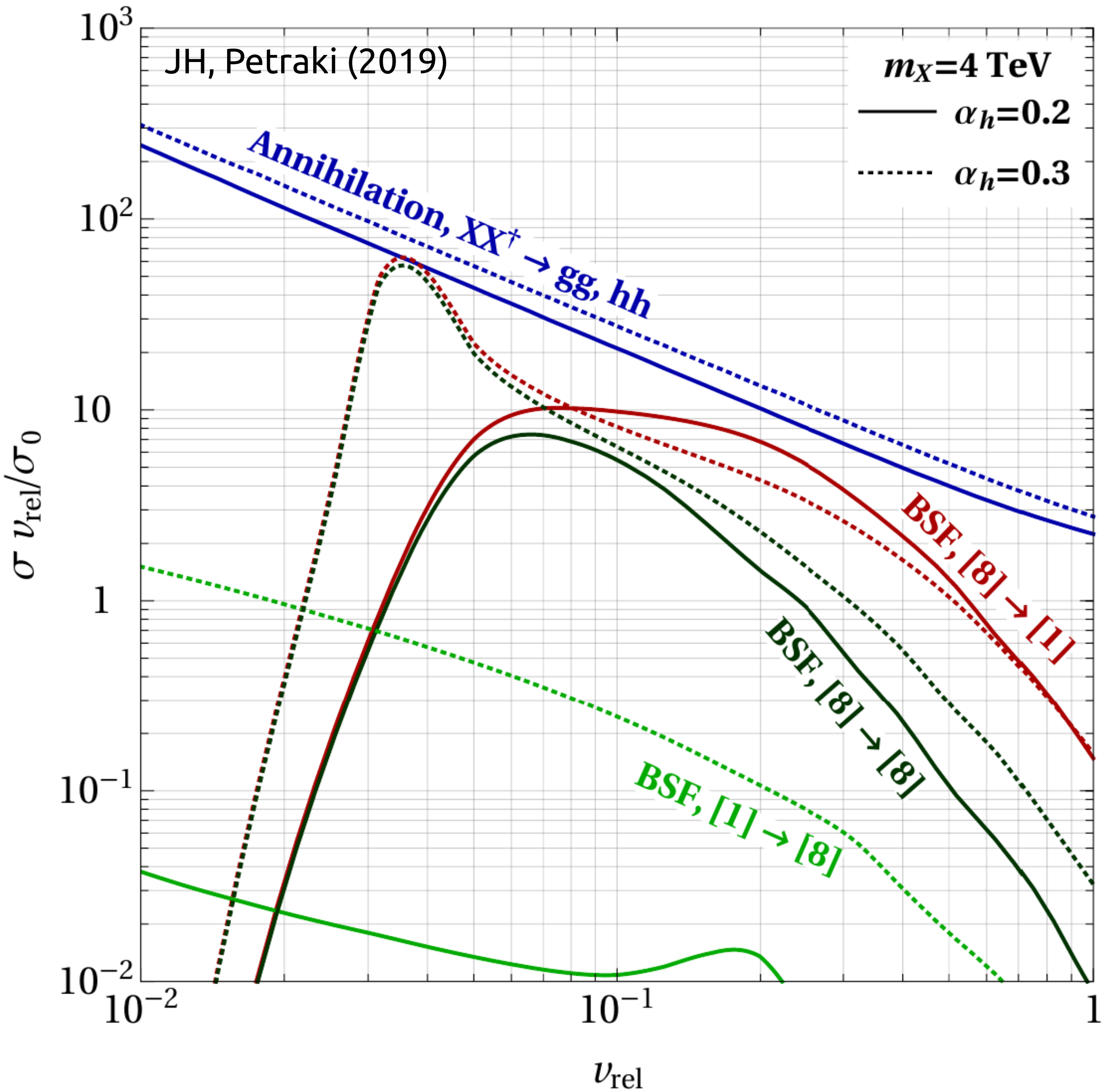


JH, Petraki (2018)

$\mu\alpha_g^B$

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

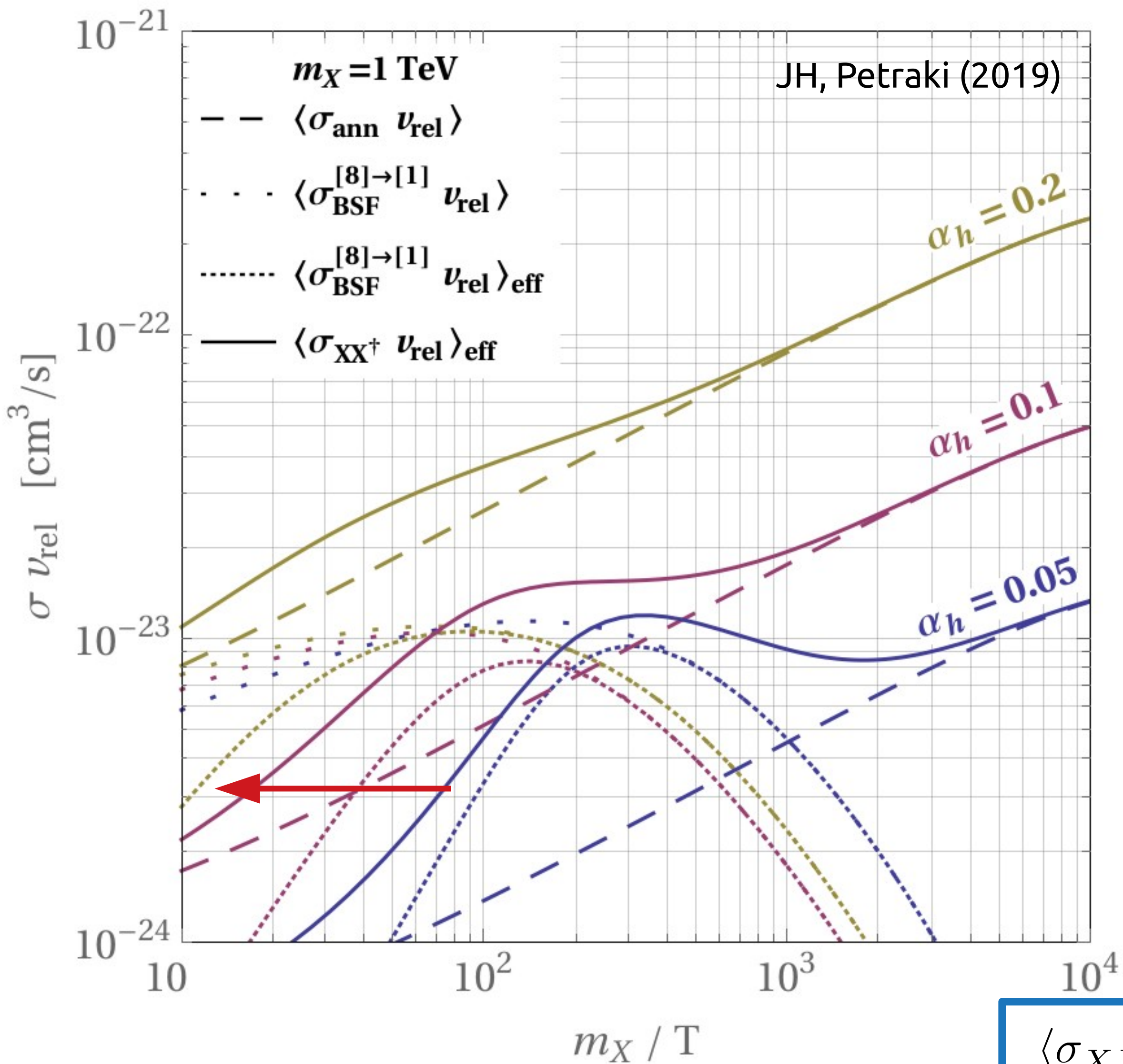
Impact of the Higgs on the BSF cross section



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**

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

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