Excited bound states and their role in dark matter production

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<u>in collaboration with</u>:

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<u>based on</u>:

arXiv:2308.01336
arXiv:2411.08737

Outline

1. Introduction: Thermal Production and Freeze-out
2. Theory background: bound states in PNREFT
3. Bound state formation: semi-classical picture
4. Intermezzo: Perturbative Unitarity Violation in BSF
5. Toy model: Bound States in dark gauge sectors
6. Realistic model: colored + charged t-channel mediator

Dark Matter Phenomenology – crash course

Dark Matter:

Key ingredient in modern cosmology

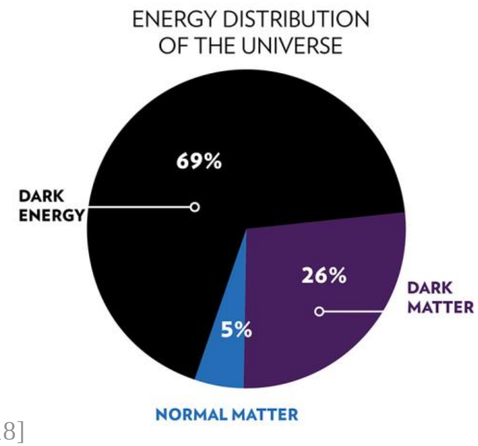
(gravitational evidence from all length scales)

- Dark
- Abundant
- Cold (probably)

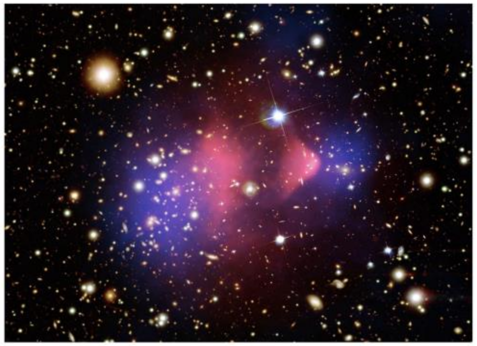
- Some strong constraints from cosmology:
  - Cosmic Microwave Background $\Omega_{DM}h^2 = 0.120 \pm 0.001$ [Planck, 2018]
  - Baryogenesis (must not be altered)
  - Structure formation (no warm / hot DM)

  ...

- else: No evidence from SM physics! (in)direct detection / collider searches / ...



→ *How is DM produced in the early Universe?*

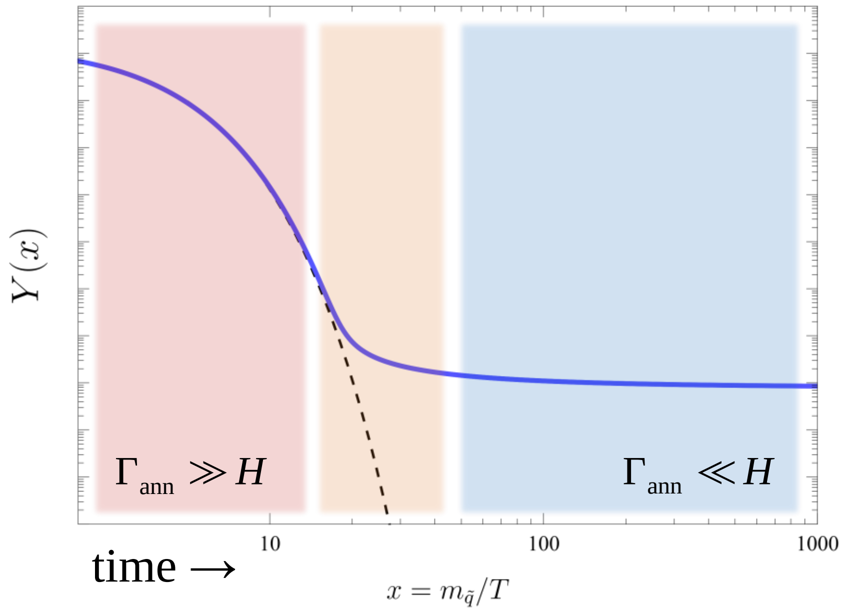

[Bullet Cluster; X-ray: NASA/CXC/CfA/]

Freeze-Out mechanism

Boltzmann equation: $$\frac{dY}{dx} = \frac{1}{3\,H\,s}\frac{ds}{dx}\,\frac{1}{2}\,\langle\sigma\,v\rangle\left(Y^2 - Y^{eq2}\right)$$

"time" coordinate: $x = \frac{m_\chi}{T}$

particle abundance: $Y = \frac{n}{s} = \frac{\text{particle number}}{\text{entropy}}$



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Thermally averaged annihilation cross-section

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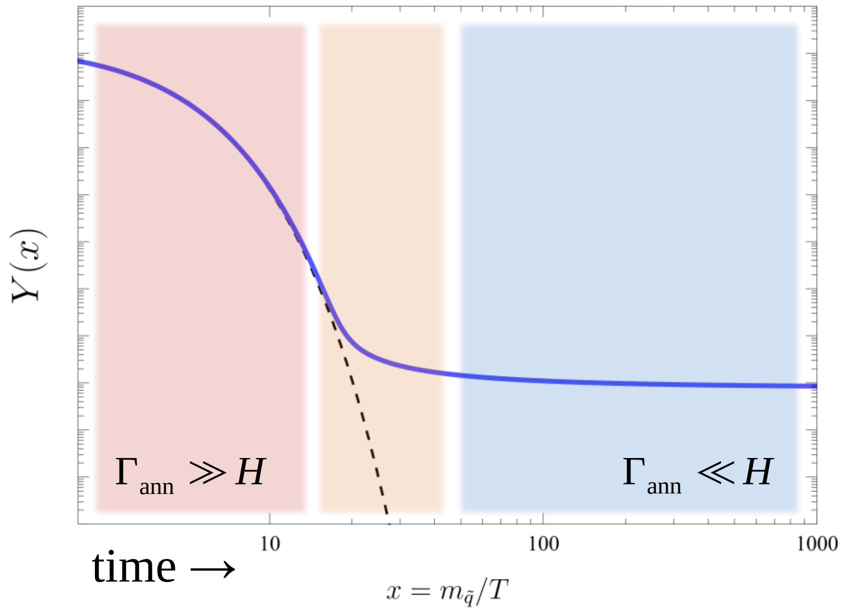

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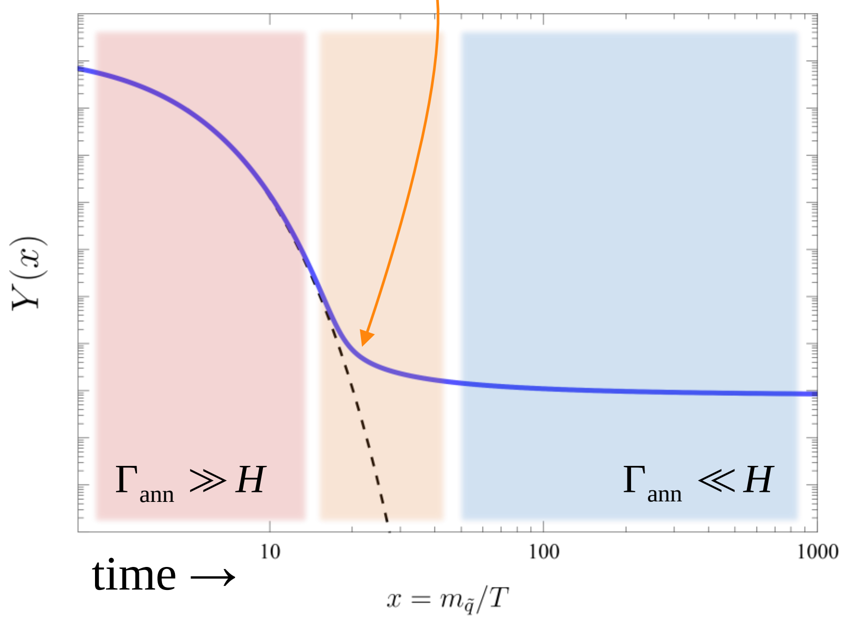
Thermally averaged annihilation cross-section

➡ $\frac{\Gamma_{annh}}{H} = \frac{n\cdot\langle\sigma v\rangle}{H} \sim T\cdot\langle\sigma v\rangle$ with $n \sim T^3$, $H \sim T^2$

annihilation turns inefficient: „Freeze Out“ when $\langle\sigma v\rangle < T^{-1} \sim x$



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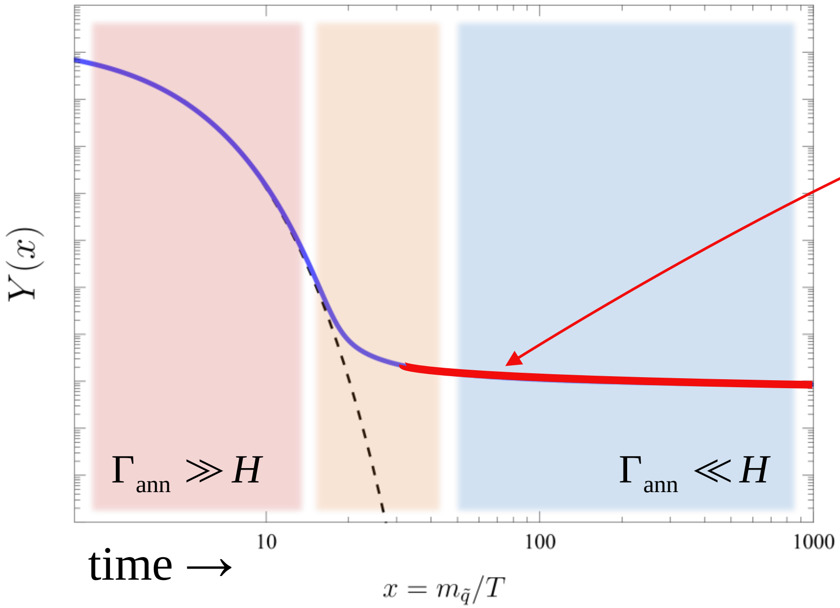
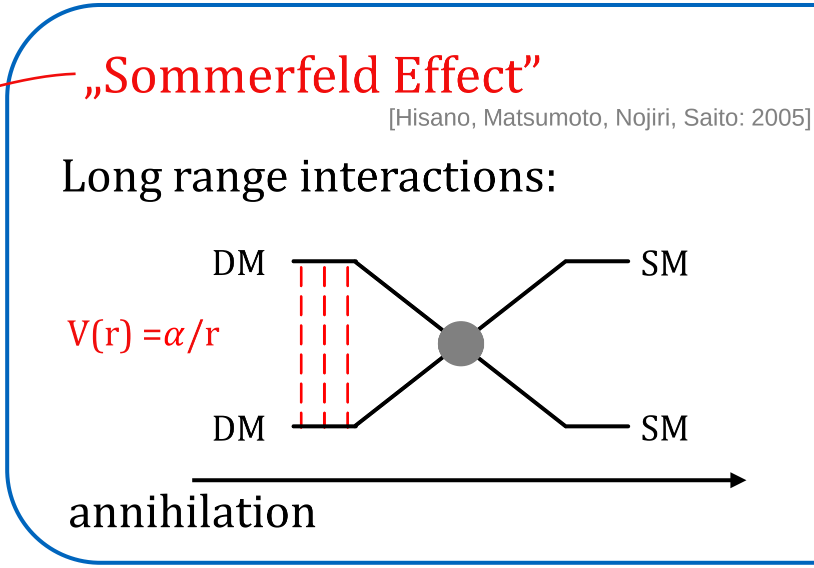
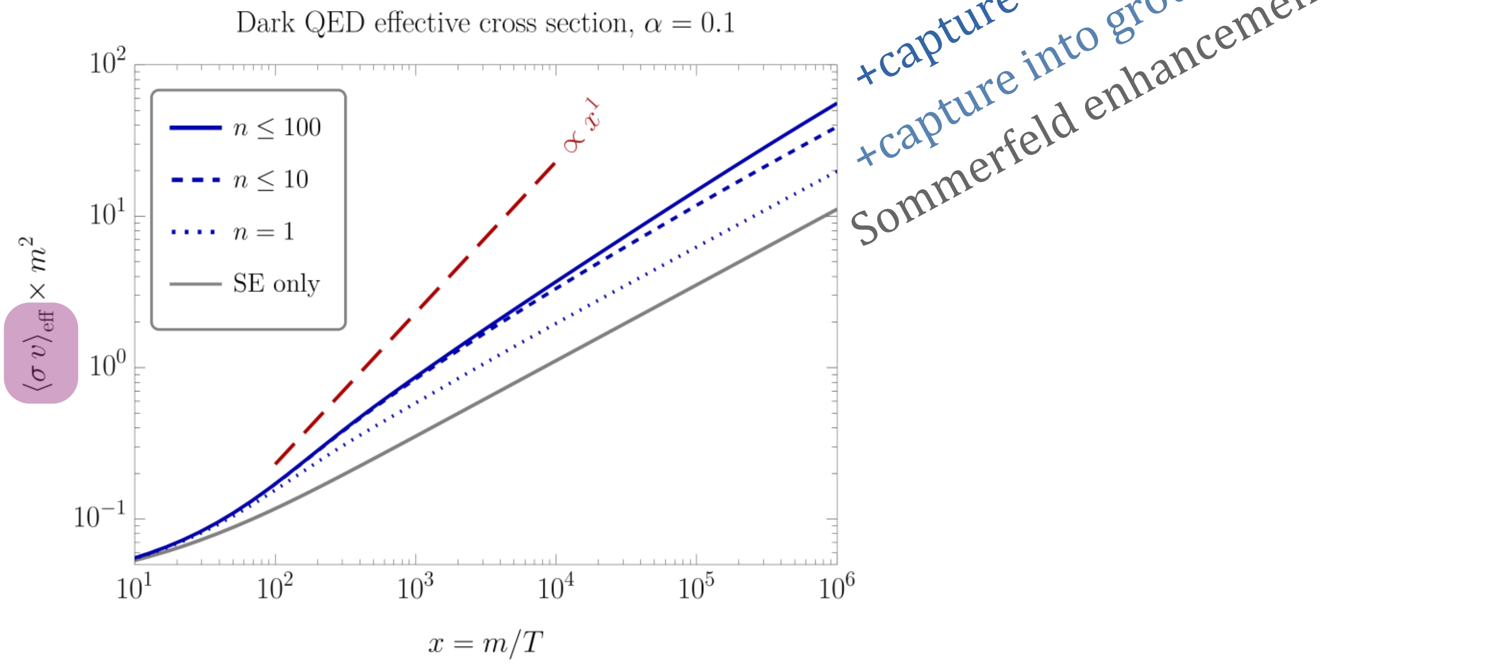




Effective cross-section: U(1) vs SU(N)

$$\frac{dY}{dx} = \frac{1}{3Hs}\frac{ds}{dx}\,\frac{1}{2}\langle\sigma v\rangle\left(Y^2 - Y^{eq2}\right)$$

dark U(1)



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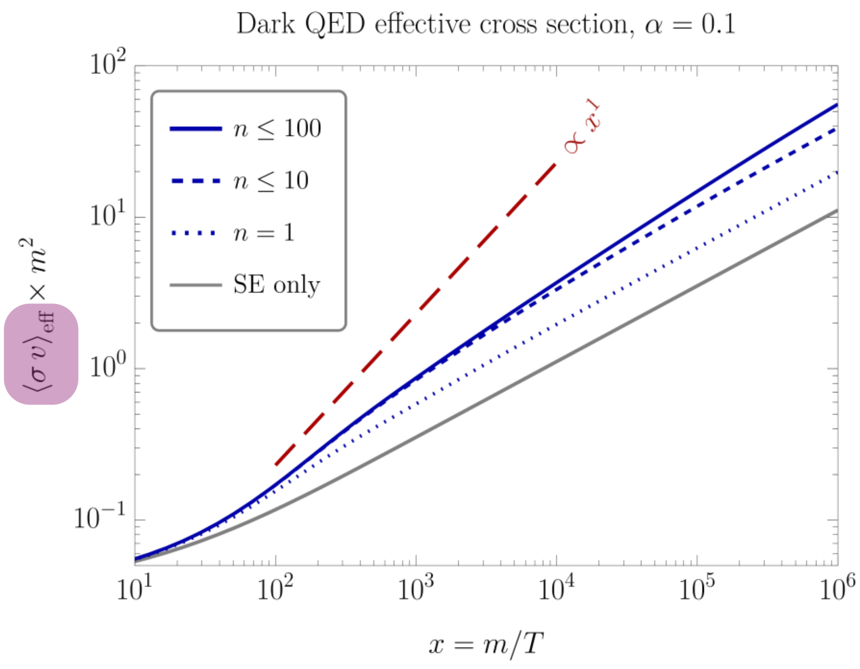
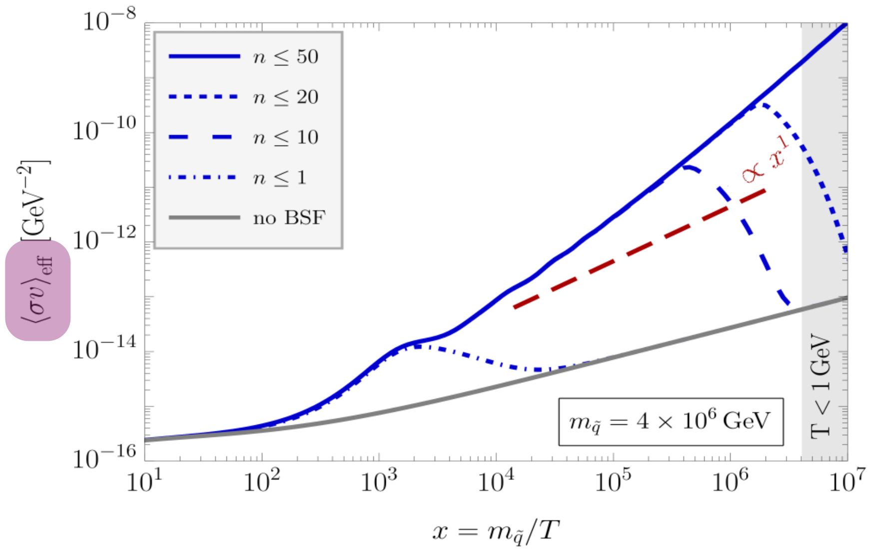


SU(3)c x U(1)Y



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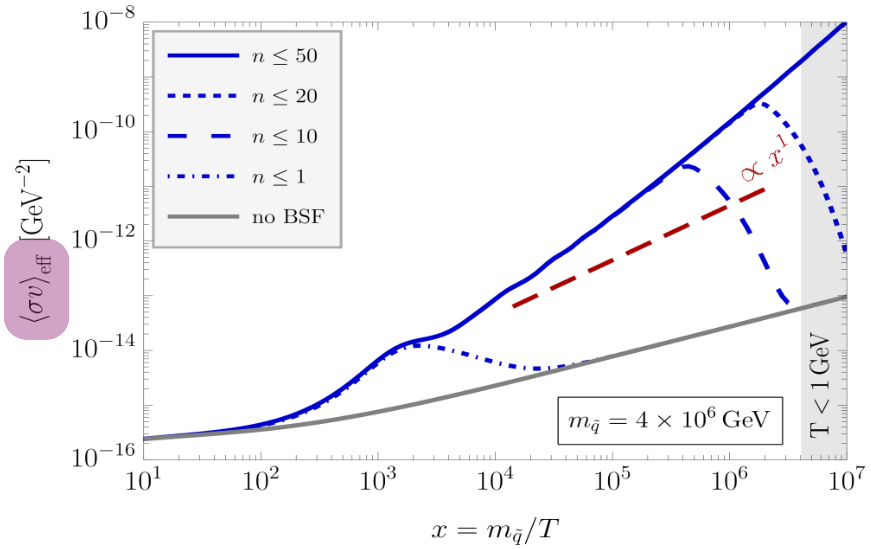


Efficient BSF prevents Chemical Decoupling !

Theory background

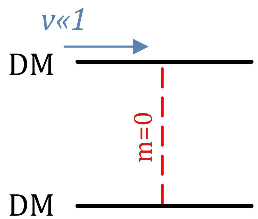
PNREFT

Potential **N**on-**R**elativistic **E**ffective **T**heory

Theory Background: long-range Potentials

For interactions with **light mediators**, perturbation theory breaks down:

- $1 \gg \alpha$ perturbative QFT
- $1 \gg v$ NREFT
- $\alpha \gtrsim v$ PNREFT

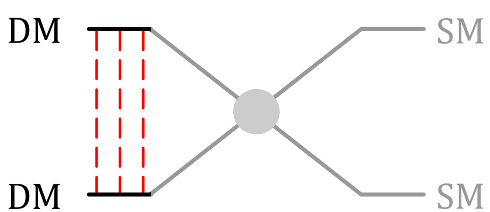


$$\sim \frac{\alpha}{p_{DM}} \sim \frac{\alpha}{v} \sim O(1)$$

→ Resum interaction to **all orders**
⇒ Coulomb-potential.

„Sommerfeld Effect" = long-range potentials between heavy particles

V(r) = α/r

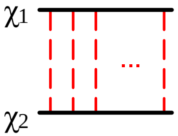


$$(\sigma v) = |\psi(0)|^2 \, (\sigma v)_{\text{Born}} \sim \frac{1}{v_{\text{rel}}} (\sigma v)_{\text{Born}}$$

for DM: [Hisano et al.: 2005]

Theory background: bound states in SU(N)

$$V(r) = \frac{\alpha_{\text{eff}}}{r}$$



Attractive, potentials can also host **bound states**!

$\longrightarrow$ What is the potential strength?

QED (or *U(1)*): $\alpha_{\text{eff}} = -Q_{\chi_1} Q_{\chi_2} \alpha_{\text{em}}$

QCD (or *SU(N)*): quarks = **3** in SU(3)

$$q \otimes \bar{q} \simeq \mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

$$\alpha_{[8]} = -\frac{1}{6}\alpha_3$$

$$\alpha_{[1]} = +\frac{4}{3}\alpha_3$$

(For DM, representations may differ from **F⊗F***.)

$\longrightarrow$ 2-body states exist in different eigenstates of the potential.

$\Rightarrow$ SU(N) gauge interactions can yield **different** & repulsive potentials.

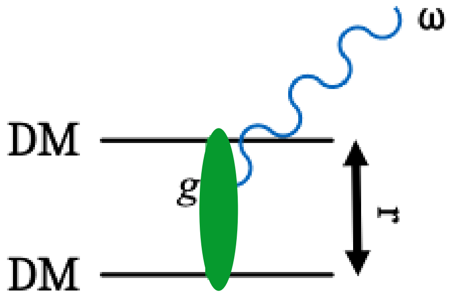
Theory background: Multipole interactions

~ *„Which process forms bound states ?“*

Scales in PNREFT:

- M_χ mass
- $p \sim Mv$ momentum
- $E \sim M\alpha^2, Mv^2$ energy

„Ultra-soft“ emissions, $\omega \sim M_\chi \alpha^2$, can be expanded in multipole orders **L**:



$|\mathbf{r}_1-\mathbf{r}_2| = r \sim 1/p_{rel} \sim 1/v$,

$\mathbf{r} \cdot \mathbf{p}_\omega \sim r\,\omega \sim \alpha$,

$$\mathcal{L} \supset g\,(\mathbf{r} \cdot \mathbf{p}_\omega)^L \propto g\alpha^L \ll 1$$

These provide **bound-state formation**, Bremsstrahlung & bound-to-bound transitions.

Theory background: PNREFT Lagrangian

We are interested in **annihilation** and **bound states**.

$\Rightarrow$ project into 2-particle space:

$\rightarrow$ 2 separate species (S, B) for scattering & bound states.

$\rightarrow$ independent potentials!

$\rightarrow$ include only the leading multipole operator.

$$\mathcal{L}_{\rm BSF} = \mathcal{S}^\dagger(R,\vec{r})\left(\mathrm{i}\partial^0 + \frac{\vec{\partial}_{\vec{r}}^2}{M_\chi} - \delta M_\mathcal{S} + \frac{\alpha_s}{r}\right)\mathcal{S}(R,\vec{r})$$

$$+\mathcal{B}^\dagger(R,\vec{r})\left(\mathrm{i}\partial^0 + \frac{\vec{\partial}_{\vec{r}}^2}{M_\chi} - \delta M_\mathcal{B} + \frac{\alpha_b}{r}\right)\mathcal{B}(R,\vec{r})$$

$$+ g_a^{\rm eff}\, p_\phi^a\, r^a P_a(\hat{p}_\phi\cdot\hat{r})\; \mathcal{B}^\dagger(R,\vec{r})\,\phi^\dagger(R)\,\mathcal{S}(R,\vec{r})$$

+ „h.c.“

+ „iδ(r) annihilation operators“

think „S = scattering state“.
if $\alpha_s > 0$, also bound states S exist

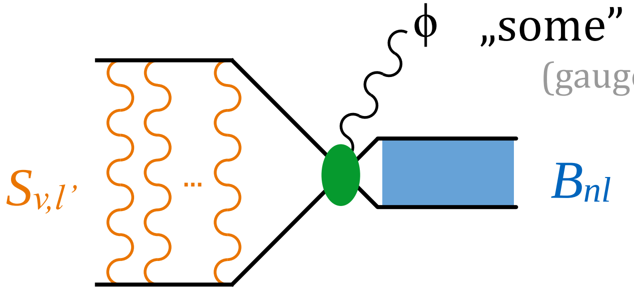
think „B = bound state“.
also B scattering-states exist

The equations of motion are simply the *Schrödinger equation.*

radiative **B**ound **S**tate **F**ormation

„Seeing the formula“ ≠ „Undestanding the physics“

General **BSF** expression



Some notation

n = major quantum number

l', l = partial-wave numbers

$$\kappa \equiv \frac{\alpha_s}{\alpha_b} ,$$

$$\zeta_n \equiv \frac{\alpha_b}{nv} , \quad \zeta_s \equiv \frac{\alpha_s}{v}$$

The computation is basically Quantum Mechanics.
General result for all $\{n, l, p, l', L, \alpha_s, \alpha_b\}$:

[Gordon: 1929]
[Beneke, Binder, Garny, **SL**, De Ros: 2024]

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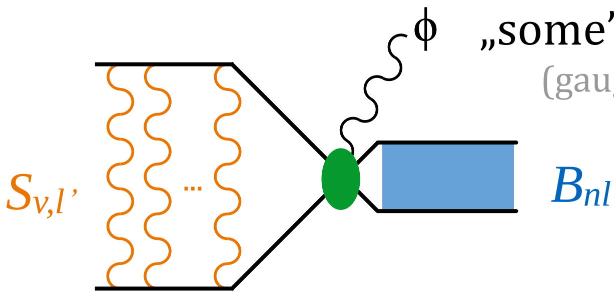

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amplitude

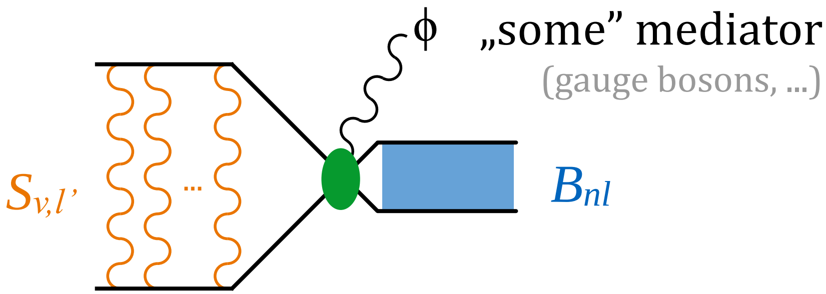
$$|M|^2 \propto \Sigma_m |\langle nlm|\, r^L \,|\vec{p}, l'\rangle|^2 \propto I_A \times I_R$$

radial overlap

$$I_R = \frac{2^{4\ell+2}\zeta_n^{2\ell+3}}{(\mu v)^{3+2L}\left(1+\zeta_n^2\right)^{2\ell+4}} \frac{\Gamma(\ell'+1)^2\Gamma(n+\ell+1)}{n\Gamma(2\ell+2)^2\Gamma(n-\ell)} S_{\ell'}(\zeta_s)\, \mathrm{e}^{-4\zeta_s\gamma_n}$$

$$\times \left|\frac{1-\mathrm{e}^{2\mathrm{i}(2(n-\ell)\gamma_n-\gamma_F-\gamma_R)}}{n\kappa\zeta_n\left(\zeta_n^2-1+\frac{2}{\kappa}\right)}\right|^2 \left|F_+(0)\right|^2 \left|R^L_{\ell'-\ell}\right|^2 ,$$

General **BSF** expression



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$$\times \underbrace{\left|\frac{1-e^{2i(2(n-\ell)\gamma_n-\gamma_F-\gamma_R)}}{n\kappa\zeta_n\left(\zeta_n^2-1+\frac{2}{\kappa}\right)}\right|^2}_{\sin^2(\textit{phase})} \underbrace{|F_+(0)|^2}_{\text{a single hypergeometric}} \underbrace{|R^L_{\ell'-\ell}|^2}_{\text{a rational polynomial}},$$

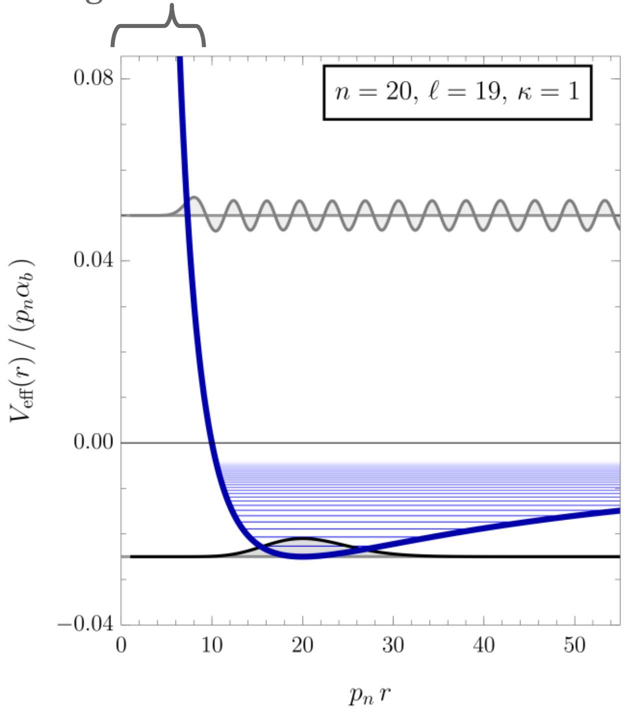
radiative **B**ound **S**tate **F**ormation

„Seeing the formula“ ≠ „Undestanding the physics“

Abelian scenario: $\alpha_b = \alpha_s$

<u>Attractive initial state</u>: $V_{\text{initial}}(r) = V_{\text{final}}(r)$

centrifugal barrier for $l > 0$



$$K = \frac{M_\chi}{4} v^2$$

$$E_n = \frac{M_\chi \alpha_b^2}{4n^2}$$

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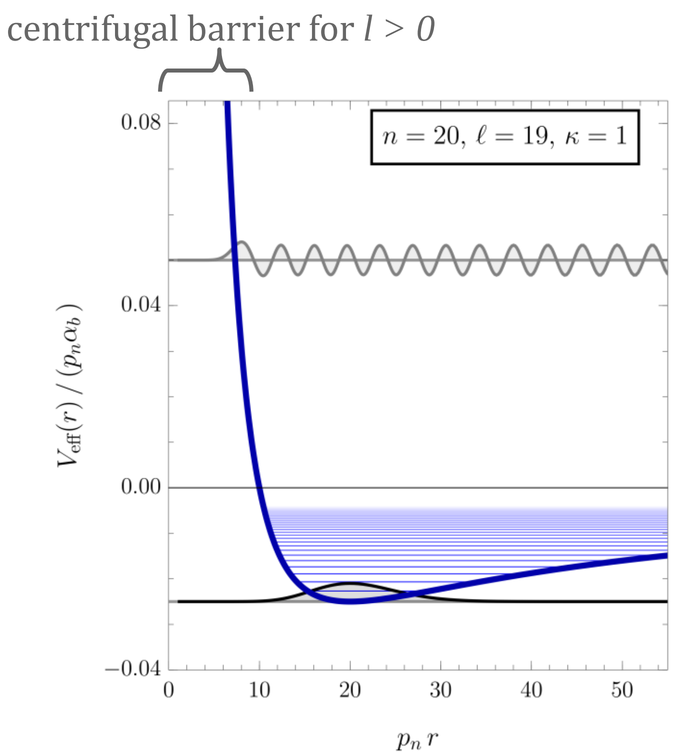

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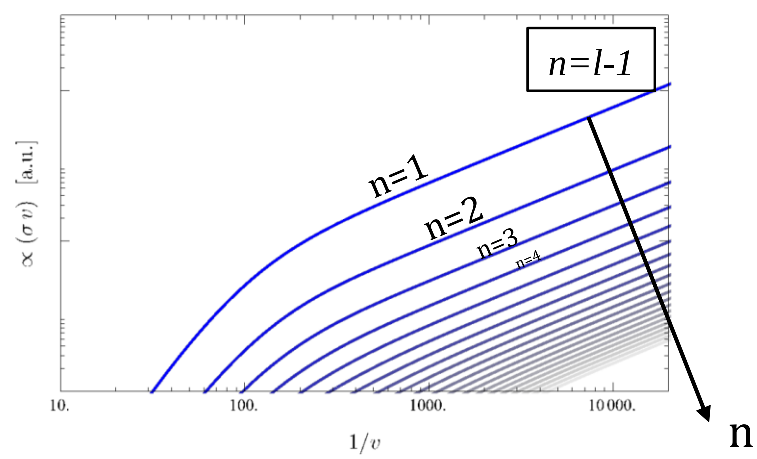
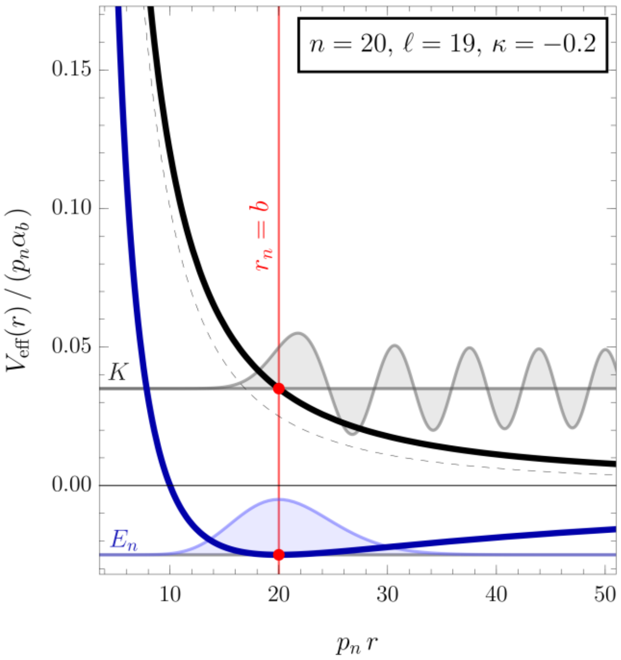


⇒ Higher n are suppressed.

Non-abelian scenario: $\alpha_b \neq \alpha_s$

Repulsive initial state: $V_{\text{initial}}(r) < 0$



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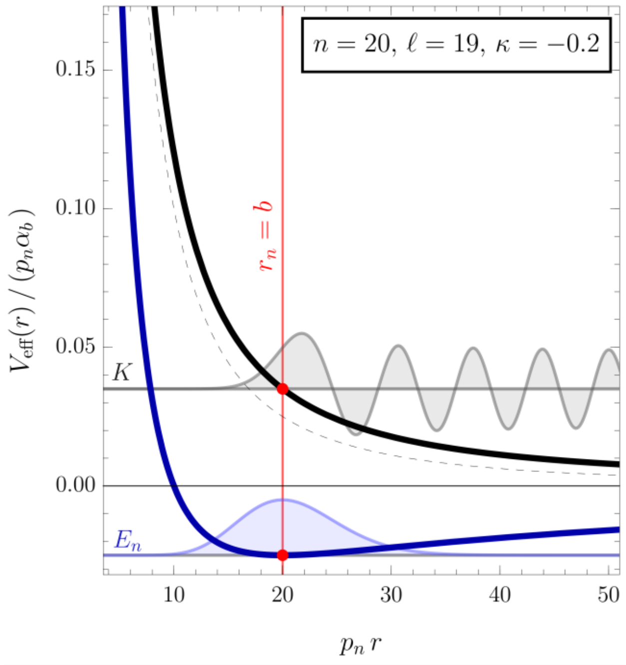

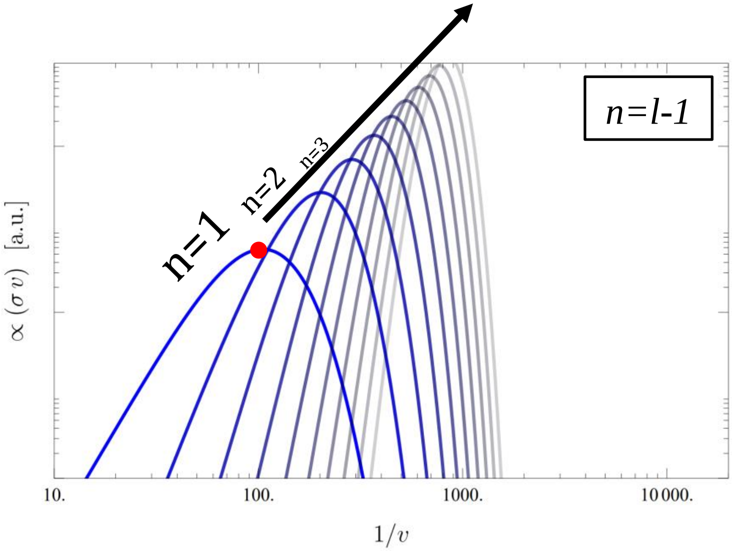

⇒ Higher n are enhanced !
BSF stronger than in the attractive case !

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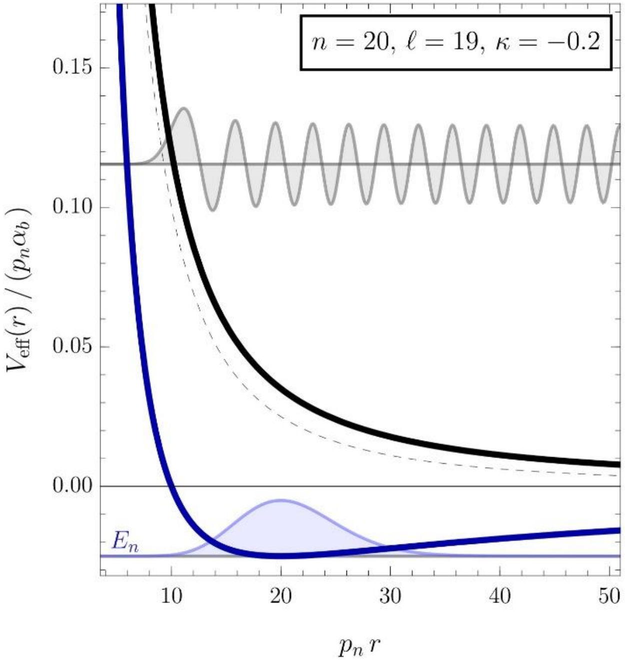
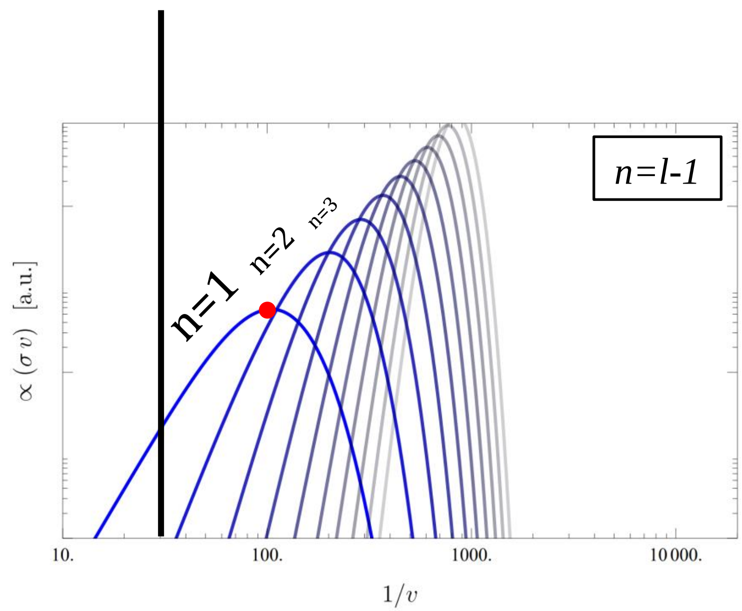


Too large *v*:

particles fly past each other



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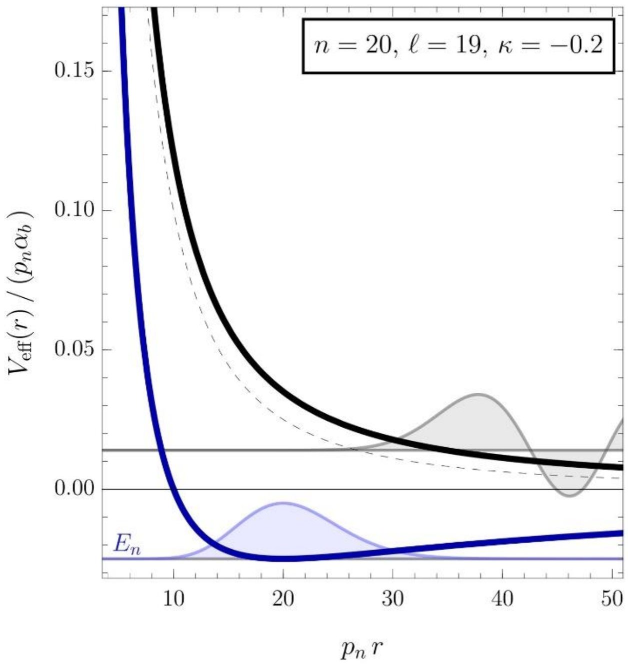
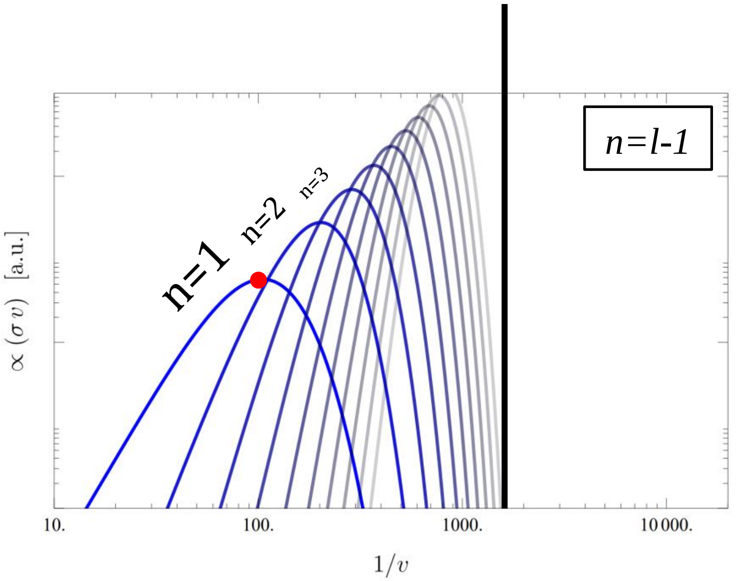


Too low *v*:
particles bounce off each other



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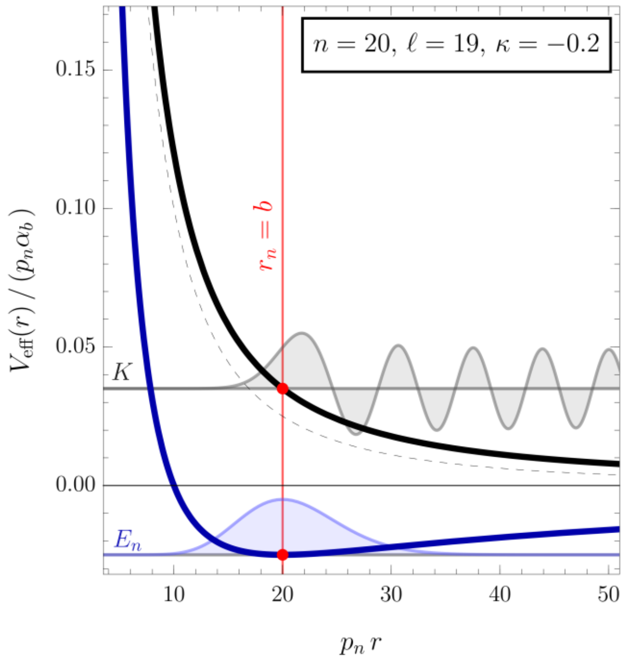
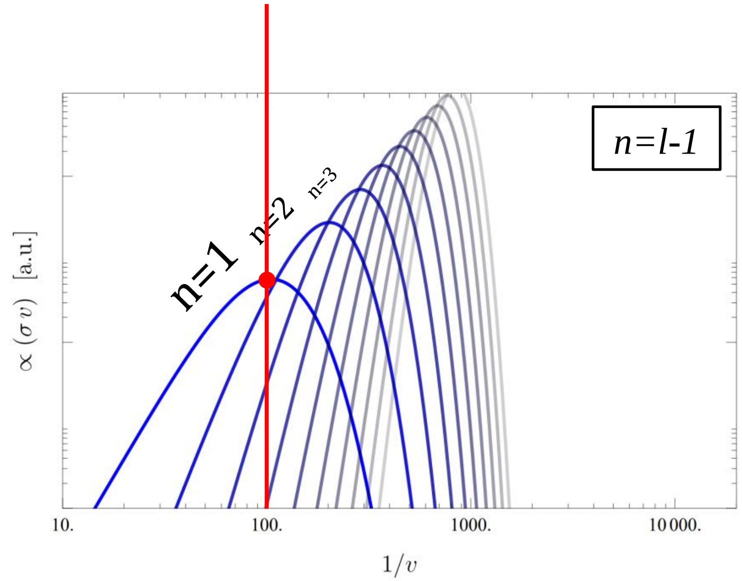


Maximum overlap



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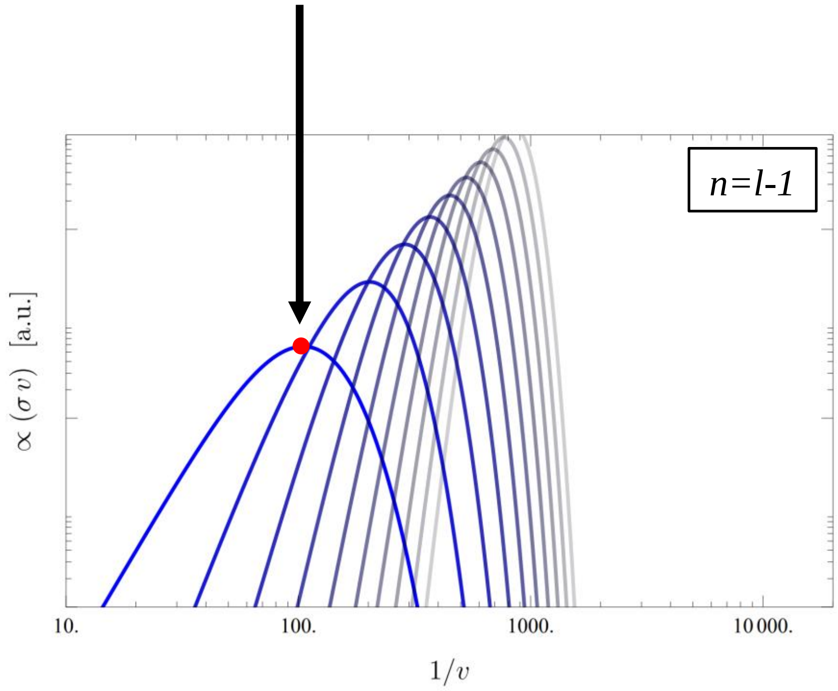
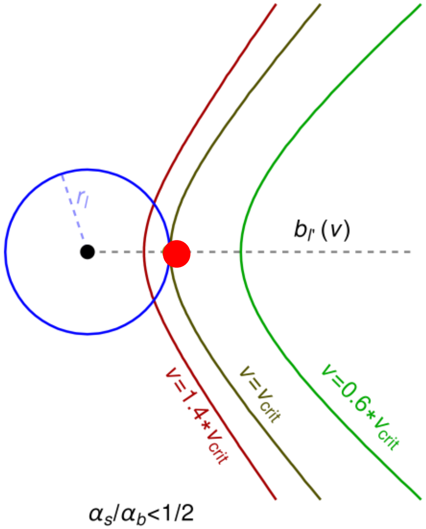
Non-abelian scenario: $\alpha_b \neq \alpha_s$

Anomalous **enhancement over the „Abelian" case** of identical potentials.



Classical analogy:
smooth matching of orbits

$$r_n = b_l \, ,$$
$$p_n = p(r = b_l)$$



The enhancement grows strongly with n !

Intermezzo:

perturbative **U**nitarity **Vi**olation

$2 \longrightarrow 2$ scattering bound from S-matrix unitarity:

$$(\sigma_{2\to 2} v)_{l'} \;\leq\; (\sigma v)^{uni}_{l'} \;\equiv\; \frac{4\pi\,(2l'+1)}{m^2 v} \sim \frac{1}{v}$$

Perturbative **U**nitarity **Vi**olation in BSF

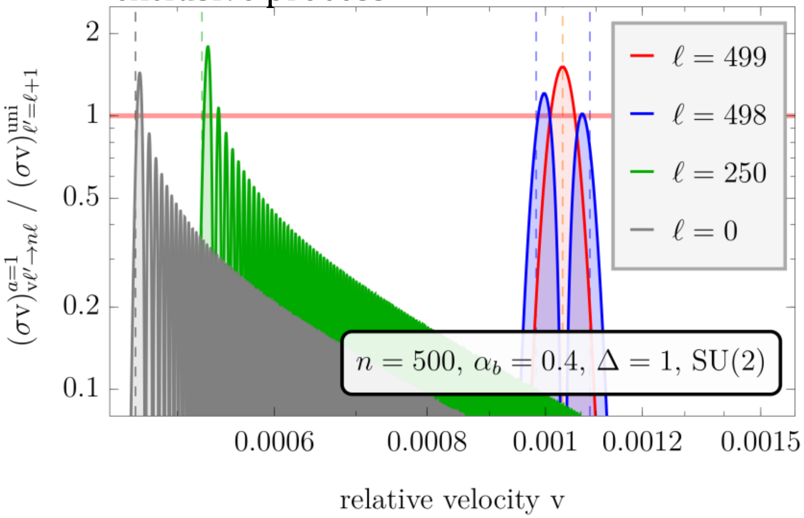
- Proven: for maximal angular momentum *l=n-1*

$$\max_v \left\{ (\sigma v)^{BSF}_{l' \to l=n-1} \right\} \propto \sqrt{n} \times (\sigma v)^{\text{uni}}_{l'}$$

- Proven: When summed in *n*, there will always be UVi below some critical velocity.
- Proven: The UVi depends on the coupling ratio κ < 1.

For any small coupling, high n violate unitarity !

exclusive process



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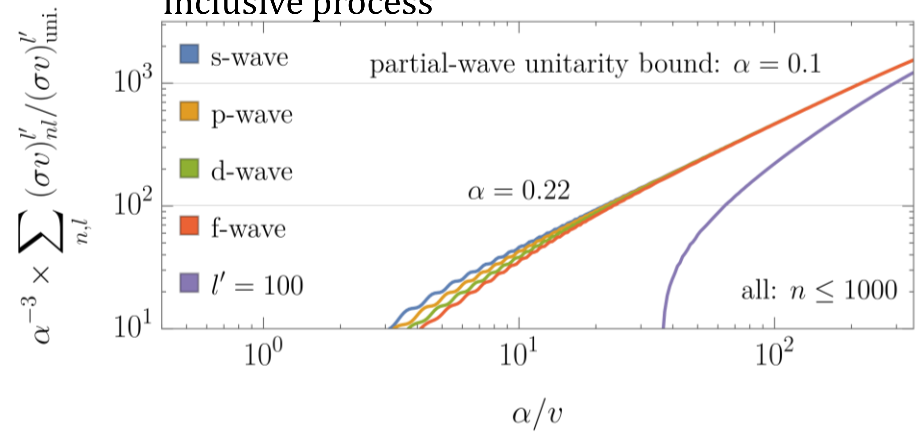
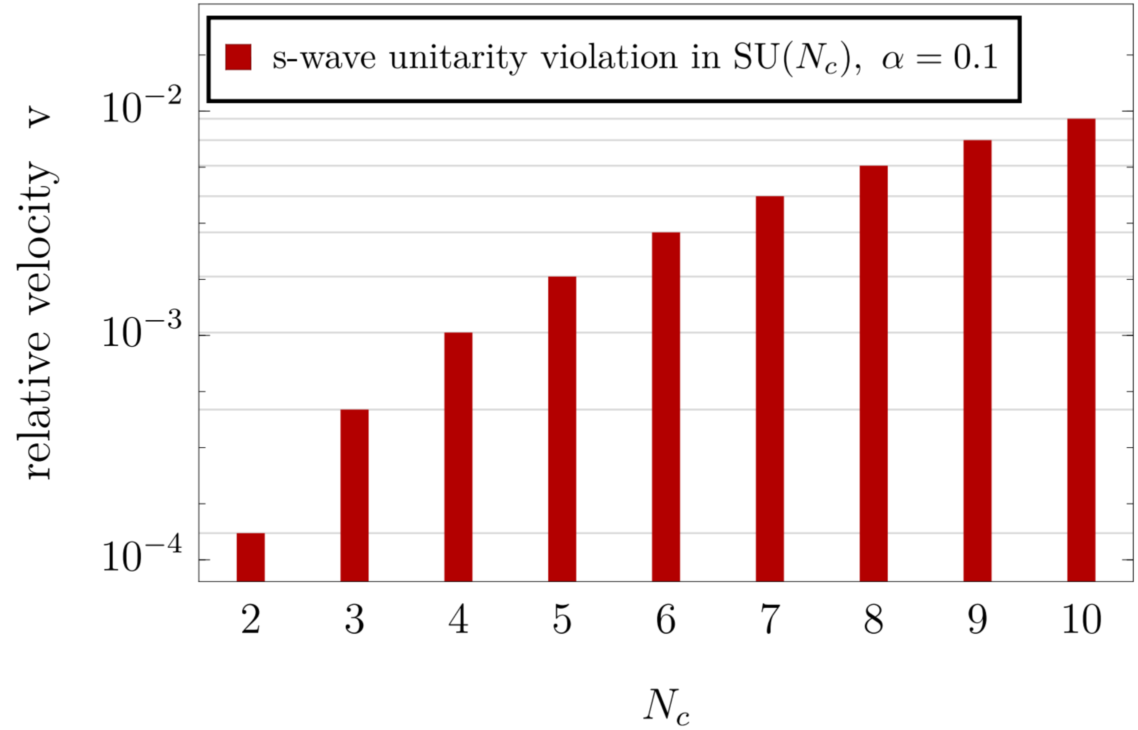


Unitarity violation in dark SU(N)

$$\kappa = \kappa(N_C) = \frac{-1}{N_C^2 - 1}$$

⇒ for every N_C, at fixed α, find the velocity where UVi first occurs:



Intermezzo end.

Bound states in thermal production

1. dark-sector toy models

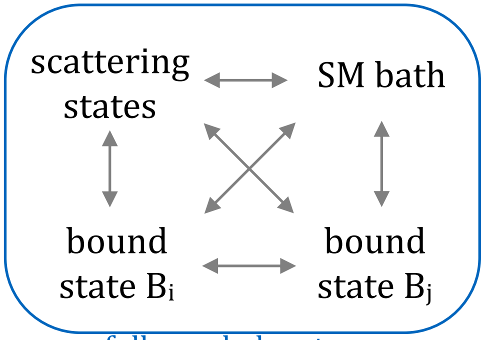
χ = DM: charged under a *new* (dark) symmetry U(1) or SU(N)

Quasi-steady state approximation

Every bound state = one species in the BME. → huge system of equations!

coupled system

$$\begin{cases} \dfrac{dY_\chi}{dx} = \dfrac{1}{3Hs}\dfrac{ds}{dx}\left[\dfrac{1}{2}\langle\sigma^{annh}_{\bar{\chi}\chi} v\rangle\left(Y_\chi^2 - Y_\chi^{eq2}\right) + \sum_i \dfrac{1}{2}\langle\sigma_{BSF,i} v\rangle\left(Y_\chi^2 - Y_\chi^{eq2}\dfrac{Y_i}{Y_i^{eq}}\right)\right] \\[2ex] \dfrac{dY_i}{dx} = \dfrac{1}{3Hs}\dfrac{ds}{dx}\left[\Gamma^B_{dec}\left(Y_i - Y_i^{eq}\right) - \sum_{j\neq i}\Gamma^{j\to i}_{trans}\left(Y_j - Y_j^{eq}\dfrac{Y_i}{Y_i^{eq}}\right) + \Gamma_{ion}\left(Y_i - Y_i^{eq}\dfrac{Y_\chi^2}{Y_\chi^{eq2}}\right)\right] \end{cases}$$



full coupled system

[Redi et al.: 1702.01141]
[Petraki et al.: 2112.00042]
[Garny, Heisig: 2112.01499]

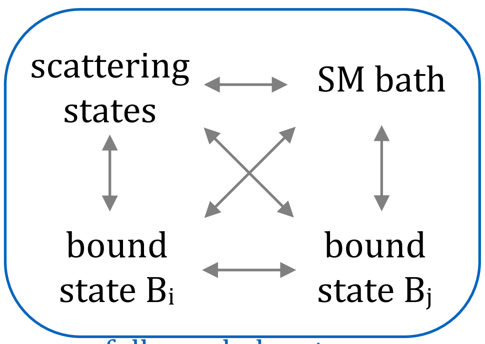
Quasi-steady state approximation

Every bound state = one species in the BME. → huge system of equations!

$$\frac{dY_\chi}{dx} = \frac{1}{3Hs}\frac{ds}{dx}\left[\frac{1}{2}\langle\sigma^{annh}_{\bar{\chi}\chi} v\rangle\left(Y_\chi^2 - Y_\chi^{eq2}\right) + \sum_i \frac{1}{2}\langle\sigma_{BSF,i} v\rangle\left(Y_\chi^2 - Y_\chi^{eq2}\frac{Y_i}{Y_i^{eq}}\right)\right]$$

$$0 = \frac{dY_i}{dx} = \frac{1}{3Hs}\frac{ds}{dx}\left[\Gamma^B_{dec}\left(Y_i - Y_i^{eq}\right) - \sum_{j\neq i}\Gamma^{j\to i}_{trans}\left(Y_j - Y_j^{eq}\frac{Y_i}{Y_i^{eq}}\right) + \Gamma_{ion}\left(Y_i - Y_i^{eq}\frac{Y_\chi^2}{Y_\chi^{eq2}}\right)\right]$$

“quasi steady-state“ approximation



full coupled system

$$\frac{dY_\chi}{dx} = \frac{1}{3Hs}\frac{ds}{dx}\frac{1}{2}\underbrace{\langle\sigma v\rangle^{\mathrm{eff}}_{\mathrm{ann}}}\left(Y_\chi^2 - Y_\chi^{eq2}\right)$$

effective annihilation cross-section

[Redi et al.: 1702.01141]
[Petraki et al.: 2112.00042]
[Garny, Heisig: 2112.01499]

Effective cross-section

$$\frac{dY_\chi}{dx} = \frac{1}{3Hs}\frac{ds}{dx}\frac{1}{2}\langle\sigma v\rangle_{\text{ann}}^{\text{eff}}\left(Y_\chi^2 - Y_\chi^{\text{eq}2}\right)$$

Includes scattering **and** bound states:

$$\langle\sigma v\rangle_{\text{ann}}^{\text{eff}} = \langle\sigma_{\chi\chi}^{\text{ann}} v\rangle + \sum_i R_i \langle\sigma_{\text{BSF,i}} v\rangle$$

direct annihilation

bound state formation

depletion efficiency $\in [0, 1]$

(includes transition, ionisation & decay)

recall:

„**Critical scaling**” for freeze-out: $\langle\sigma v\rangle_{\text{ann}}^{\text{eff}} \propto \frac{1}{T} \propto x$

Effective cross-section

$$\frac{dY_\chi}{dx} = \frac{1}{3Hs}\frac{ds}{dx}\frac{1}{2}\langle\sigma v\rangle_{\text{ann}}^{\text{eff}}\left(Y_\chi^2 - Y_\chi^{\text{eq}2}\right)$$

Includes scattering **and** bound states:

$$\langle\sigma v\rangle_{\text{ann}}^{\text{eff}} = \langle\sigma_{\chi\chi}^{\text{ann}} v\rangle + \sum_i R_i \langle\sigma_{\text{BSF,i}} v\rangle$$

direct annihilation

bound state formation

depletion efficiency $\in [0\,,1]$

(includes transition ✔, ionisation ✔ & decay ✔)

similar *Milne* *known*

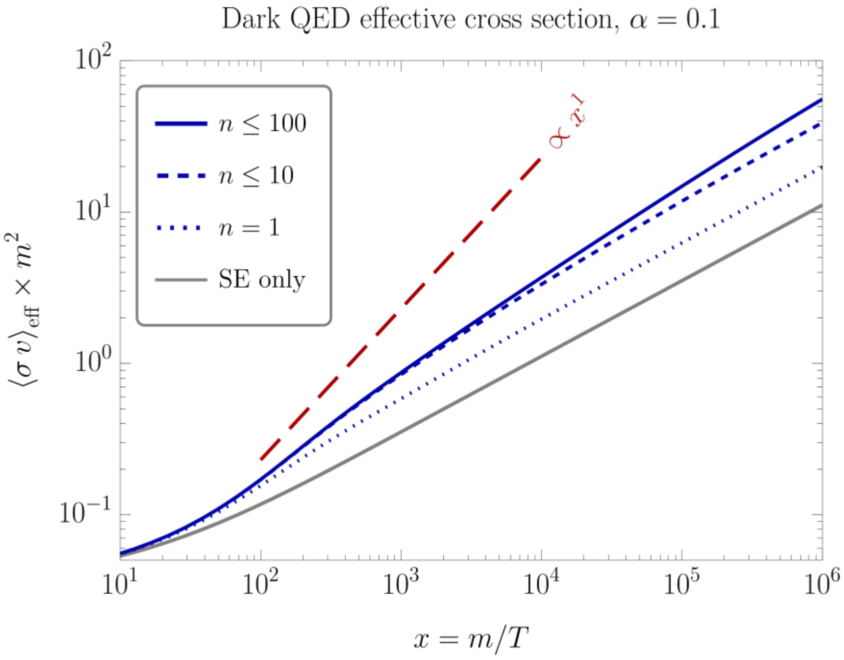
[Garny, Heisig: 2112.01499]

recall:

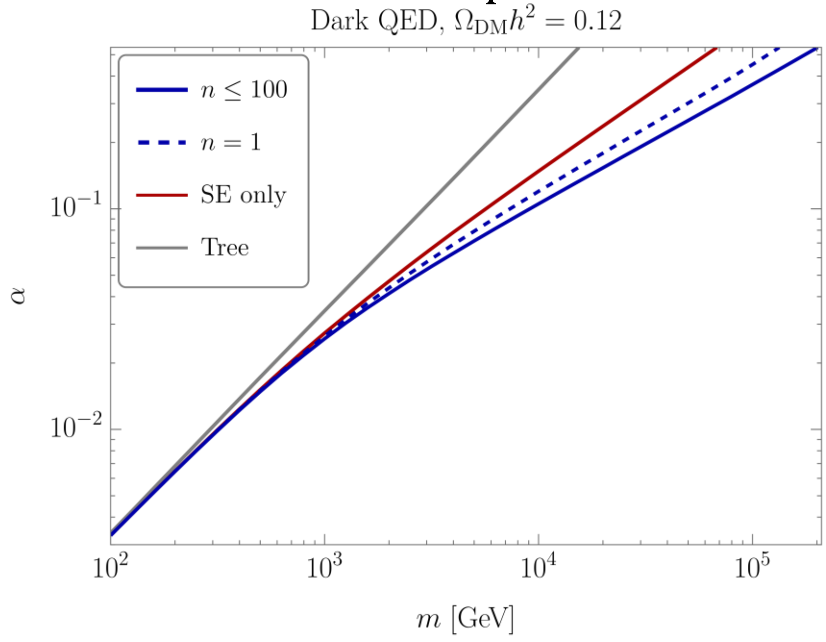
„**Critical scaling**" for freeze-out: $\langle\sigma v\rangle_{\text{ann}}^{\text{eff}} \propto \frac{1}{T} \propto x$

Effective cross-section: **dark U(1)**

effective cross-section



mass-coupling relation
from thermal production

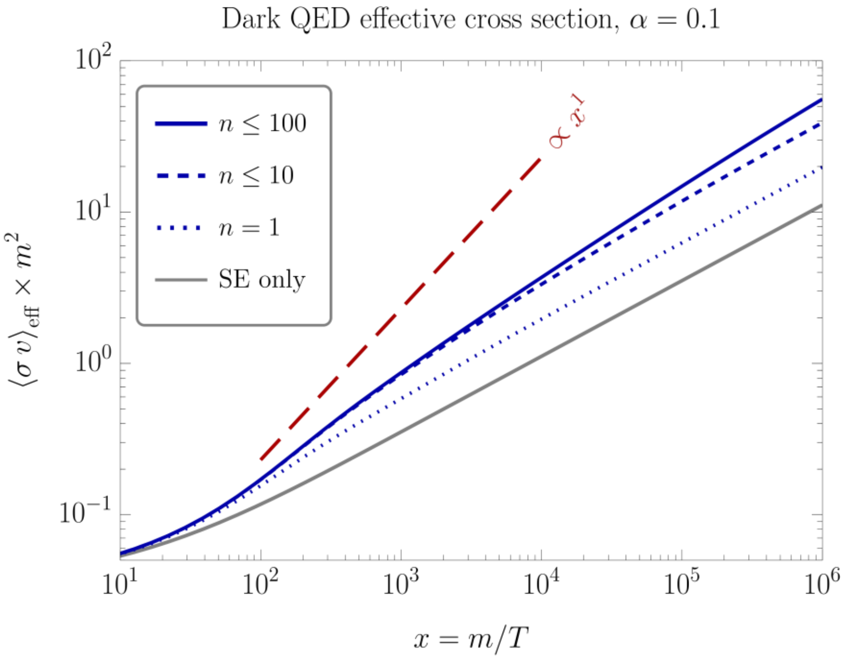


[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

Effective cross-section: **U(1)** vs **SU(N)**

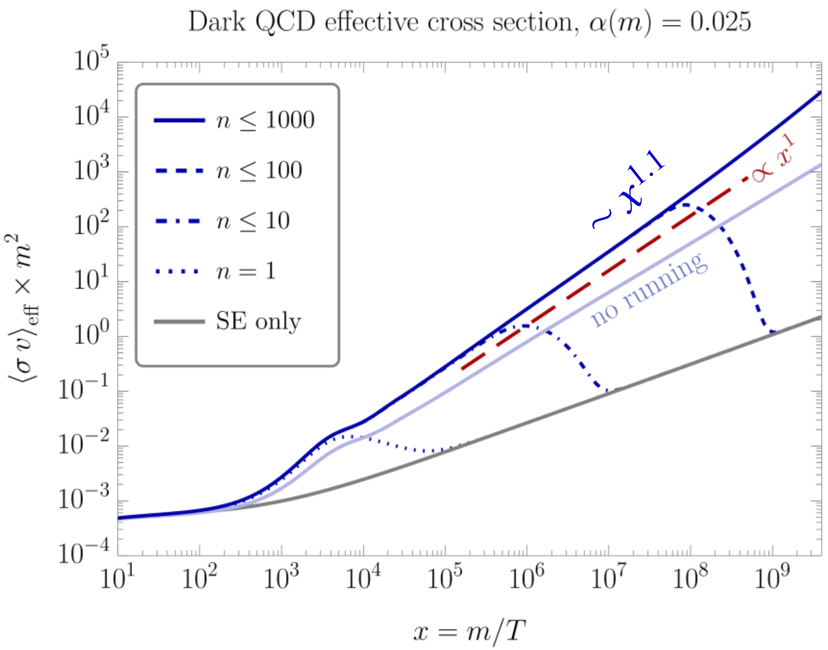
Includes bound-to-bound transitions.

dark U(1)



No bound-to-bound transitions allowed.

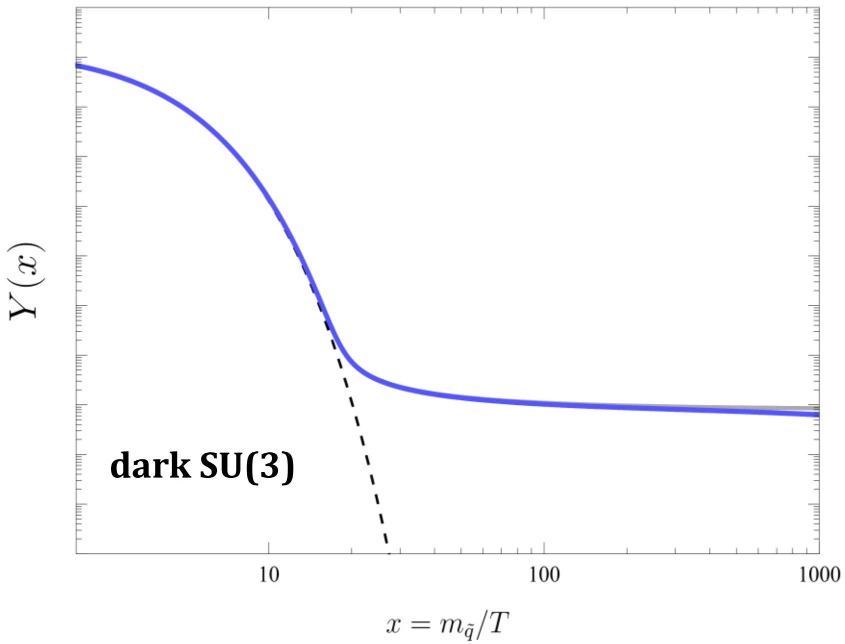
dark SU(3)



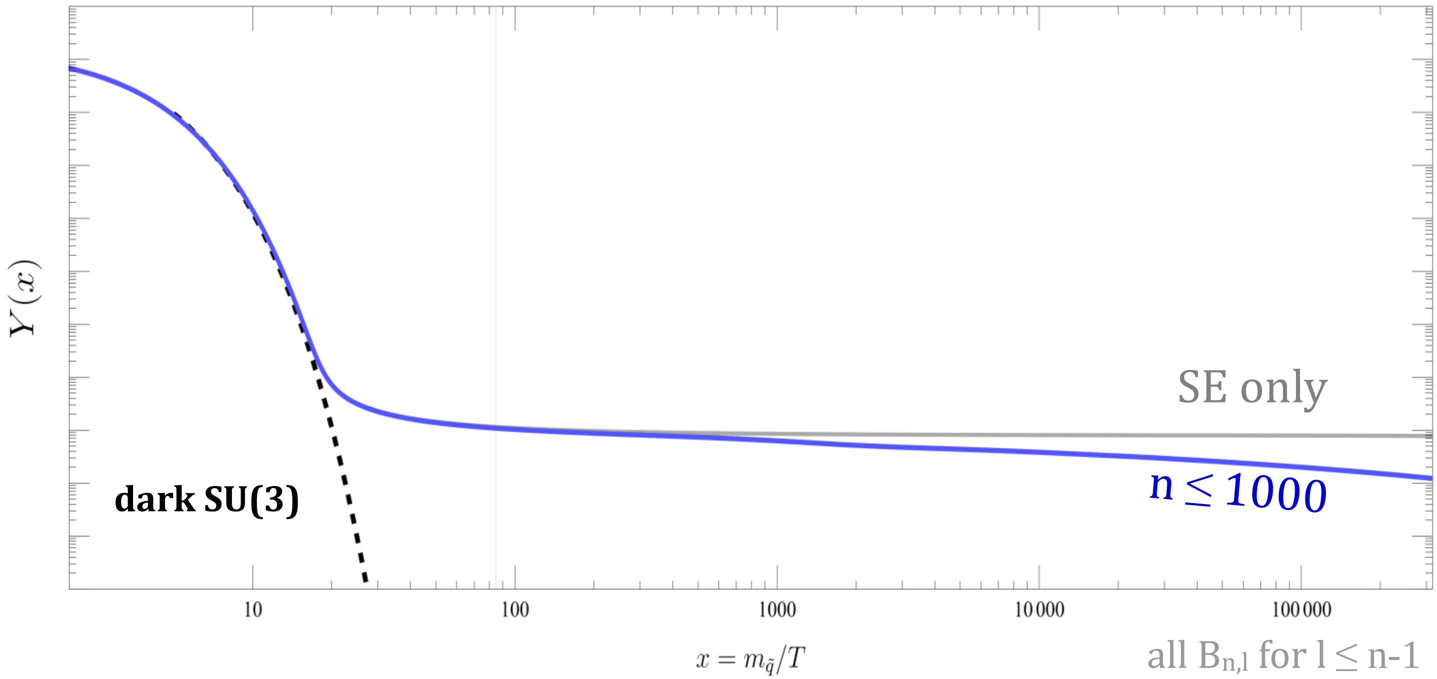
Efficient BSF prevents Chemical Decoupling !

[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

„Freeze-Out“ including BSF – dark SU(3)



„Freeze-Out“ including BSF – dark SU(3)



all $B_{n,l}$ for $l \leq n-1$

(~ 1 million bound states)

Bound states in thermal production

2. t-channel superWIMP

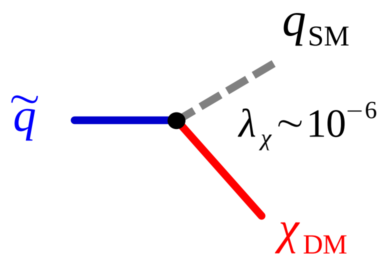
χ = DM: complete gauge singlet

$\tilde{q}$ = mediator: heavy colored & charged scalar

Including transitions: „add an additional U(1)“

Assume a <u>colored</u> **&** <u>charged</u> heavy scalar: $\tilde{q} \in (\mathbf{3},\mathbf{1})_{1/3}$ („b-squark“)

$$\mathscr{L} \supset \lambda_\chi \, \bar{q}\,\tilde{q}\,\chi + \text{h.c.}$$



→ QCD dominates the potential and BSF $(\tilde{q}^\dagger \tilde{q})^{[8]} \to B_i^{[1]} + g$

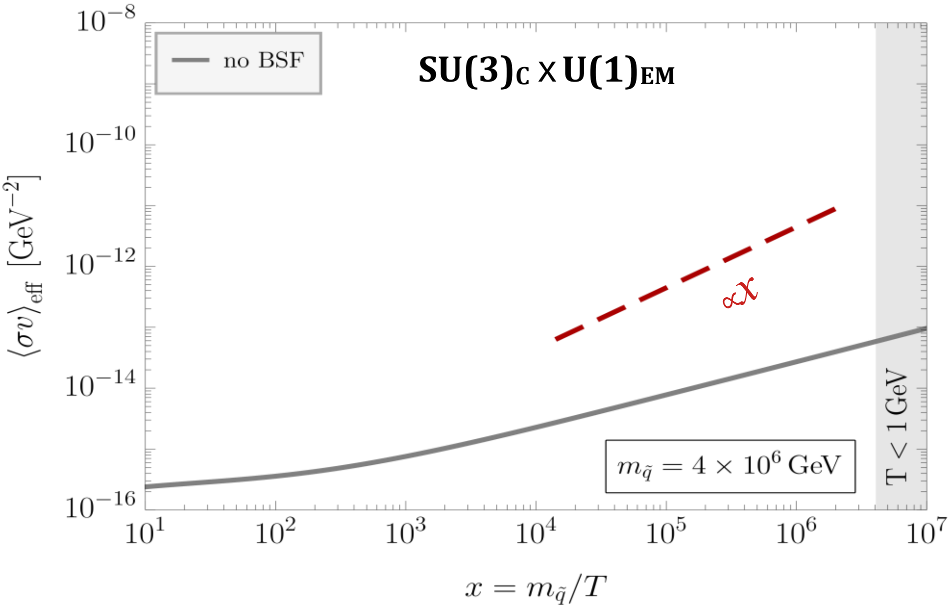
$$\kappa \equiv \frac{V_{[8]}}{V_{[1]}} = -\frac{1}{8}$$

→ QED allows transitions $B_i \to B_j$

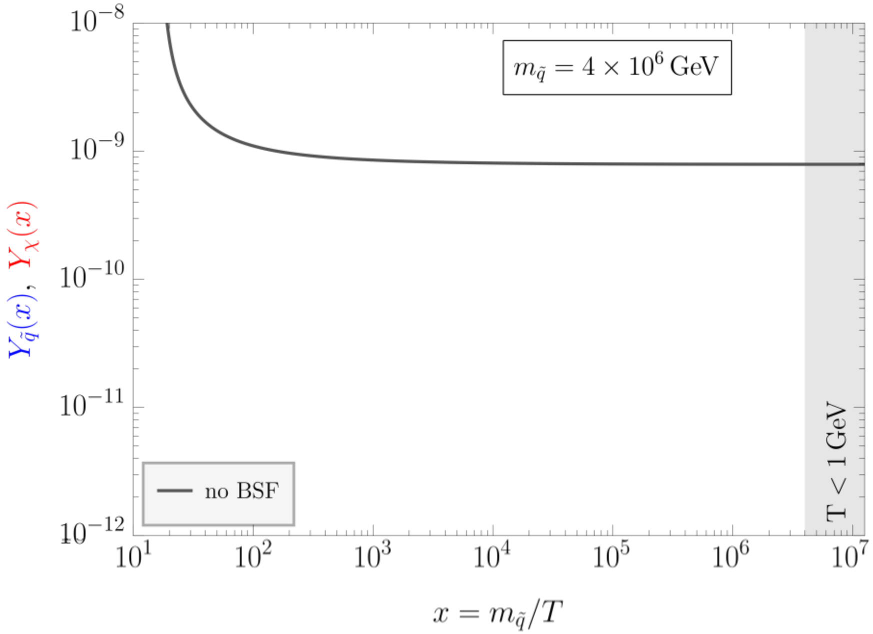
Abundance without excited states

cross section

(thermally averaged, incl. transitions)



mediator Yield

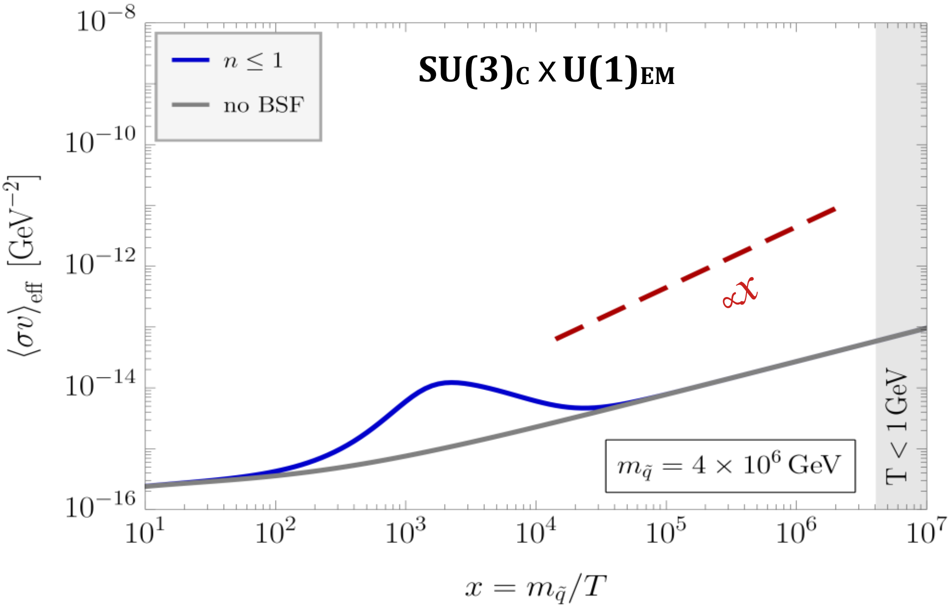


[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

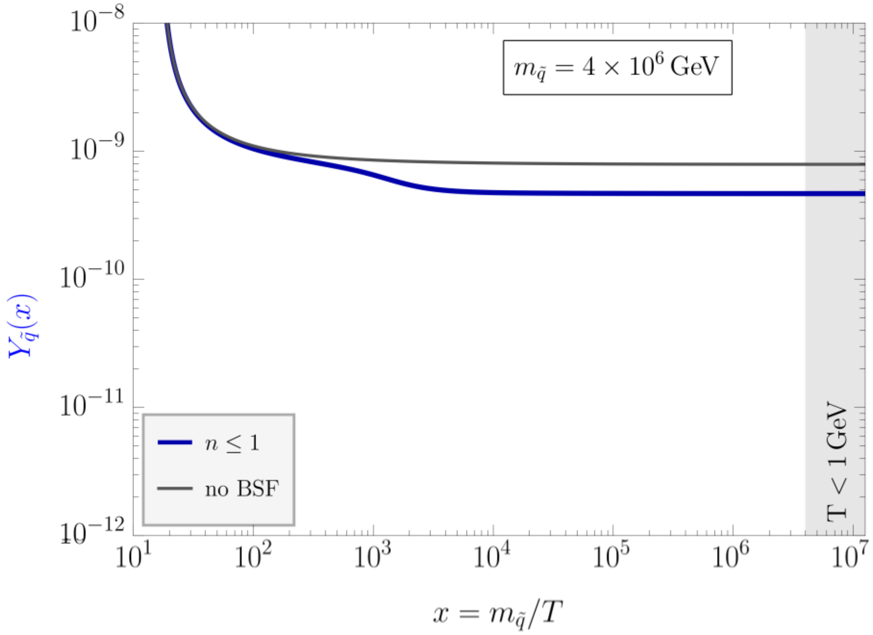
Abundance with an excited state (n=1)

effective cross section

(thermally averaged, incl. transitions)



mediator Yield

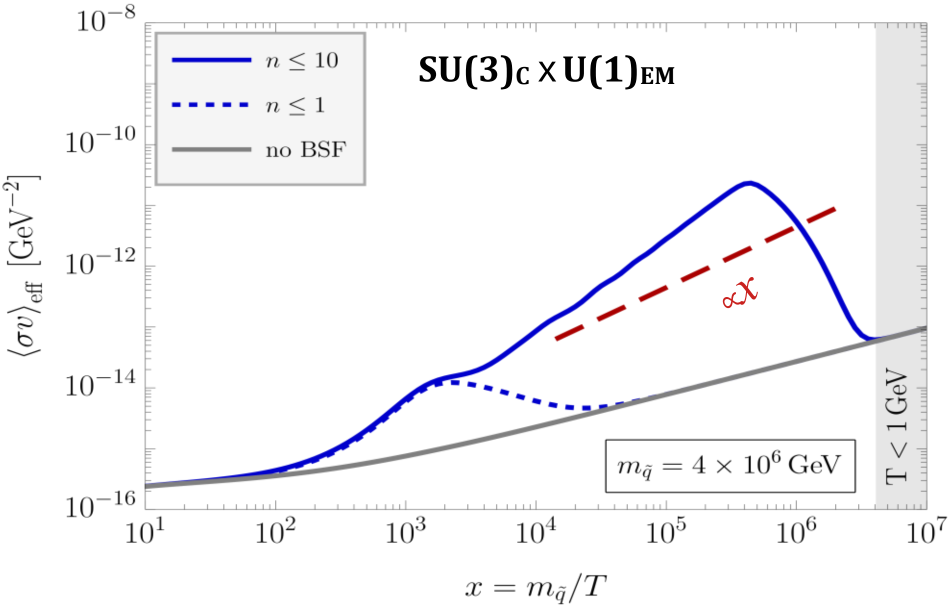


[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

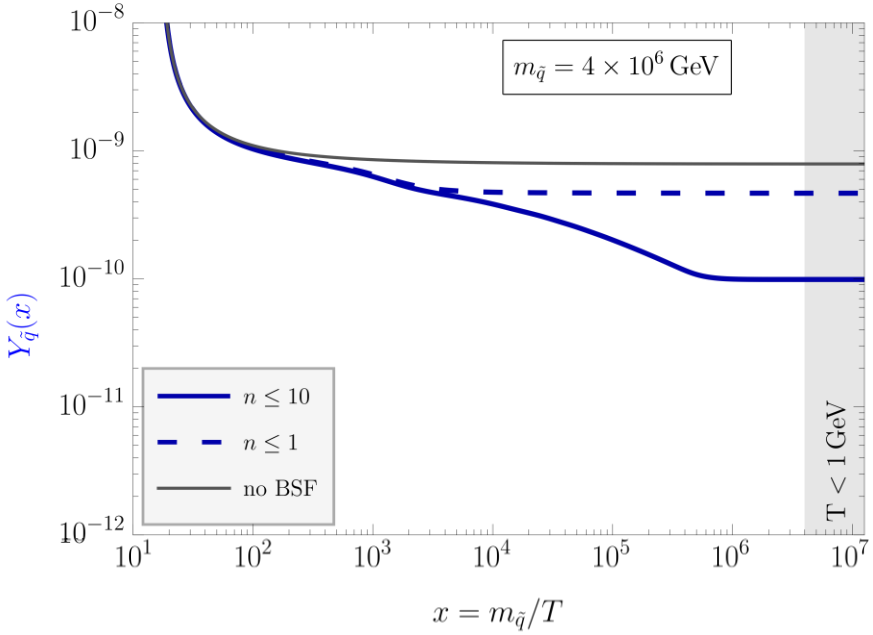
Abundance with some excited states

effective cross section

(thermally averaged, incl. transitions)



mediator Yield

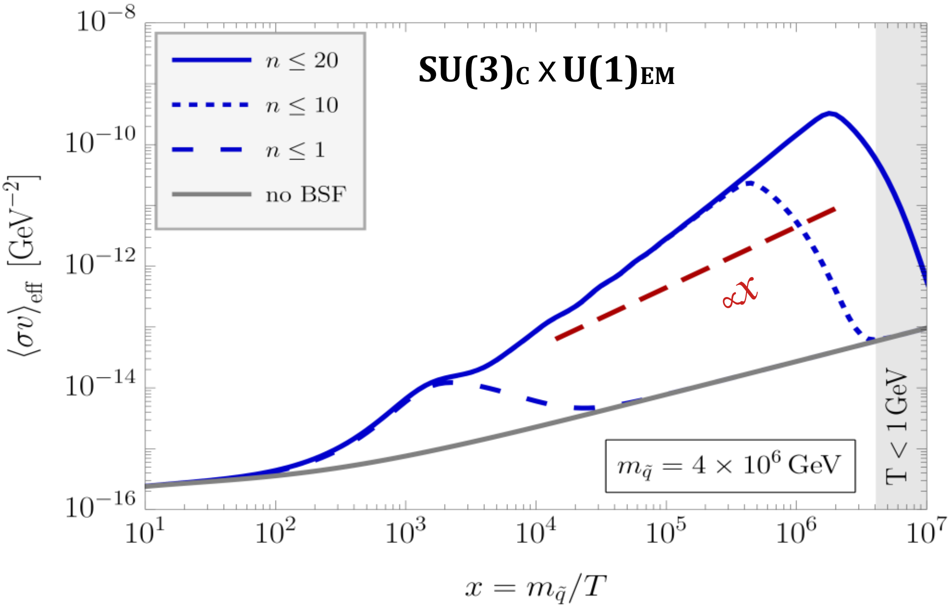


[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

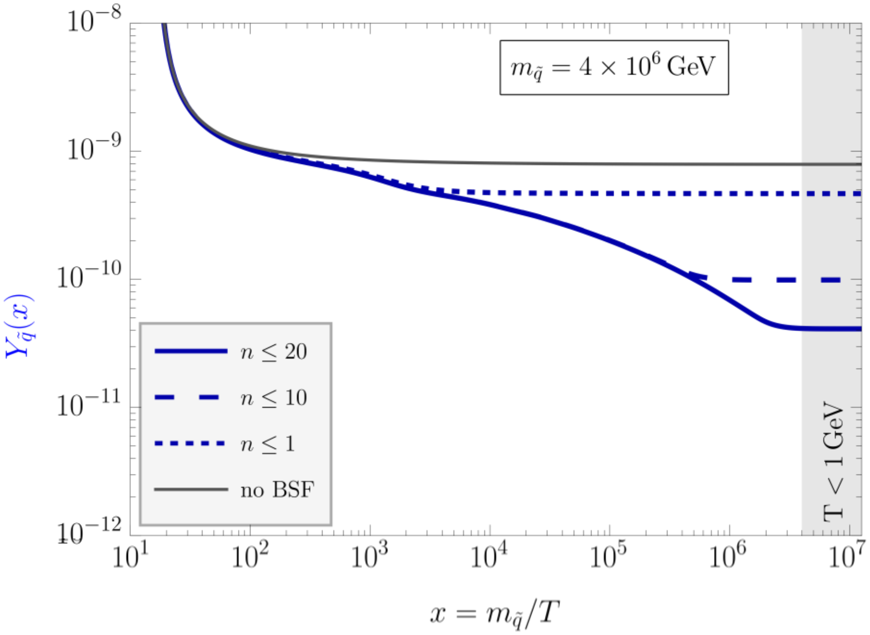
Abundance with many excited states

effective cross section

(thermally averaged, incl. transitions)



mediator Yield

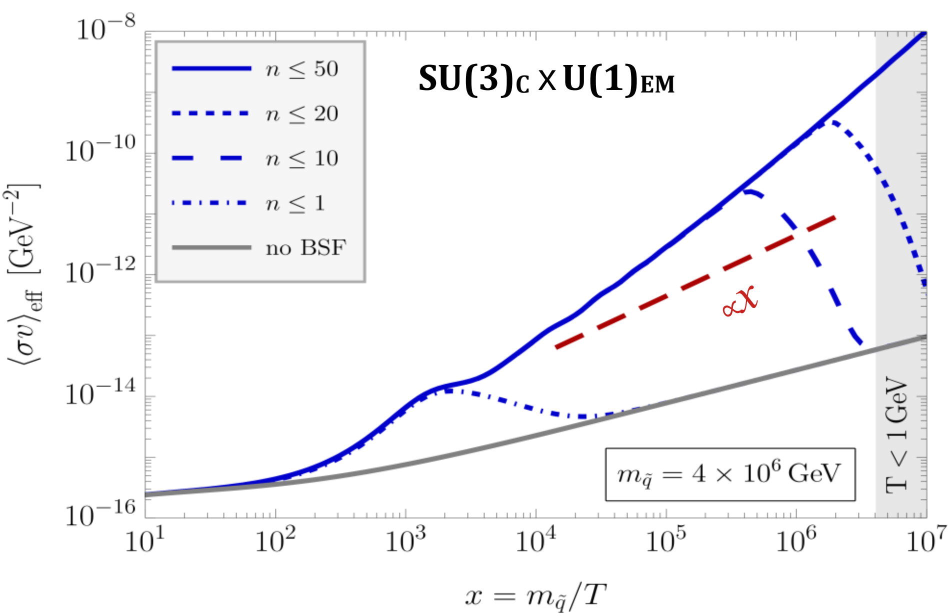


[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

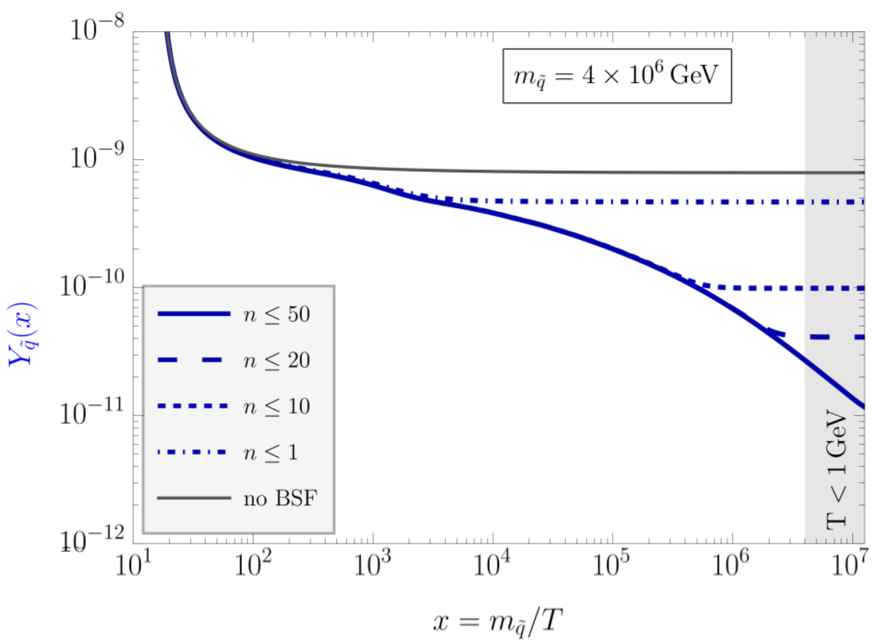
Abundance with enough excited states

effective cross section

(thermally averaged, incl. transitions)



mediator Yield



[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

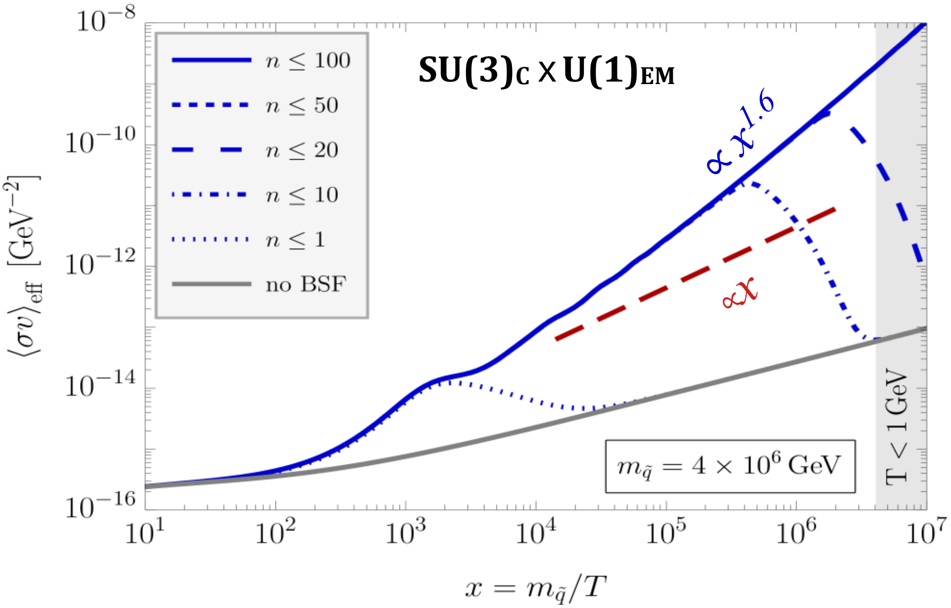
Abundance with too many excited states

- Cross-section converged in the pertubative regime.

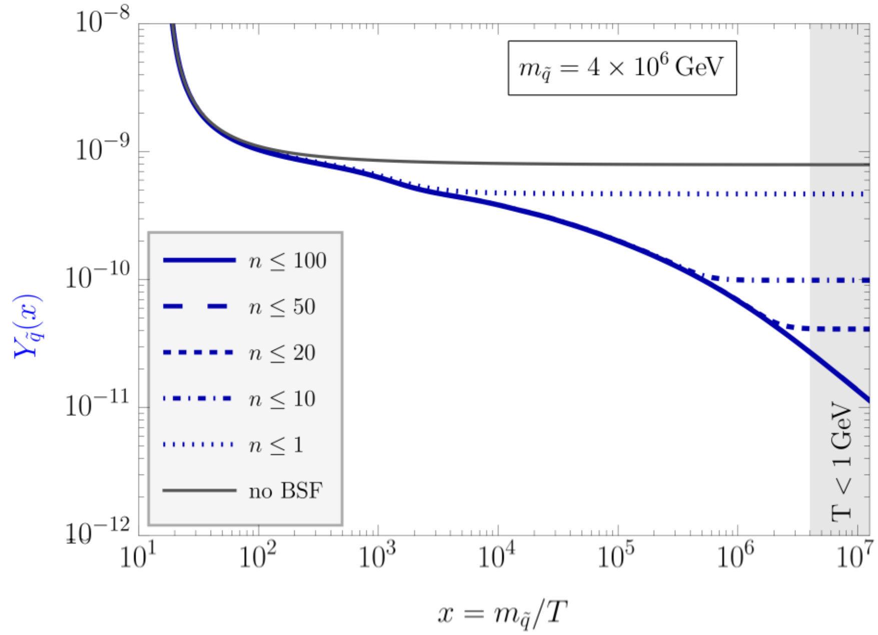
- Bound-to-bound transitions give strong enhancement: $x^{1.1} \longrightarrow x^{1.6}$

effective cross section

(thermally averaged, incl. transitions)



mediator Yield



[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

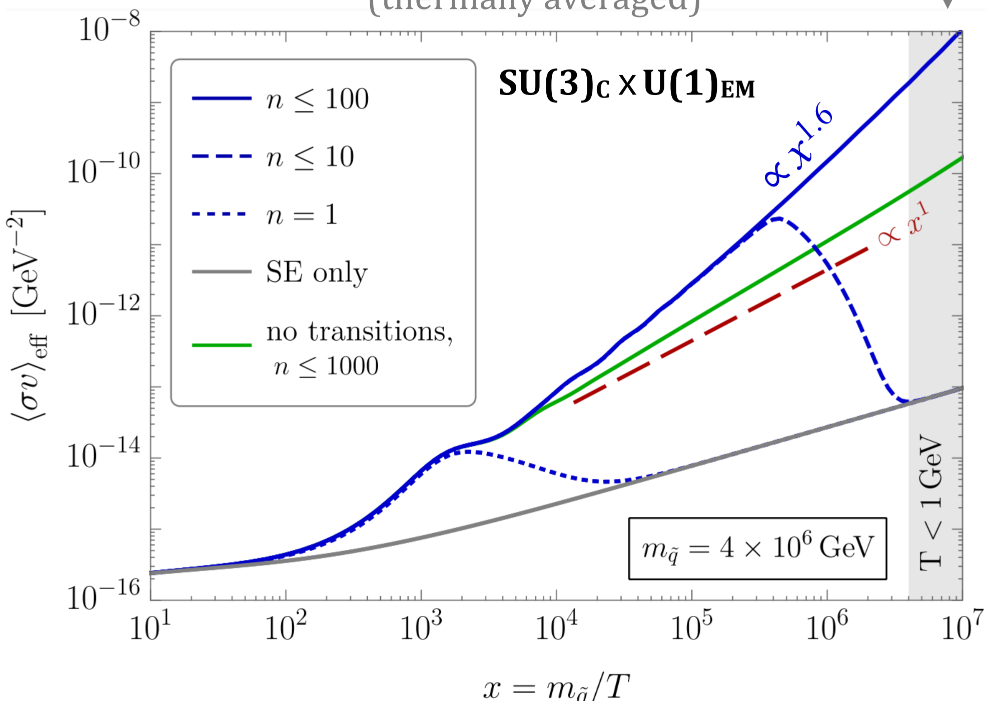
Eternal annihilation – how does it end?

- Respect unitarity bounds ✔
- Avoid non-perturbative regime α ~ 1 **?!**

effective cross section

(thermally averaged)

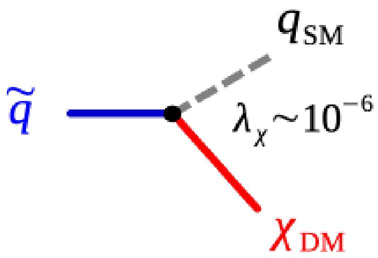
confinement phase

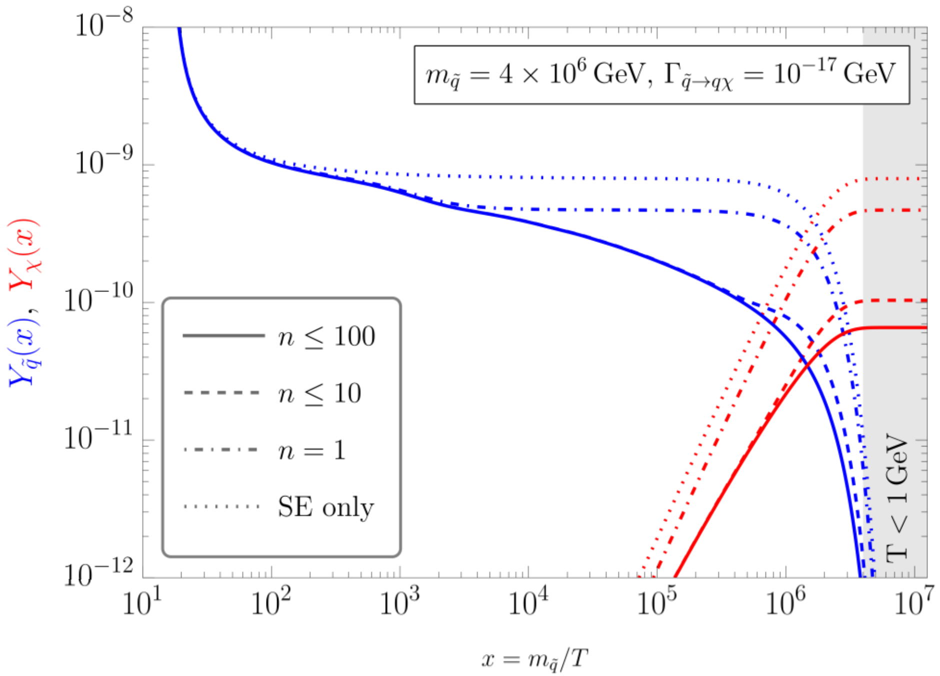


[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

superWIMP production with bound states

Adds a finite life-time: χ = DM,
$\tilde{q}$ = „t-channel mediator"





[Garny, Heisig: 2112.01449]
[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

superWIMP production with bound states

Adds a finite life-time: χ = DM,

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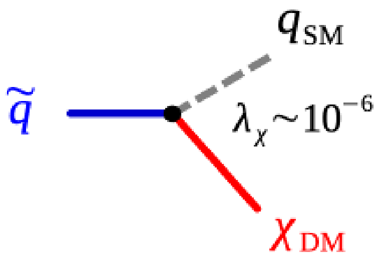

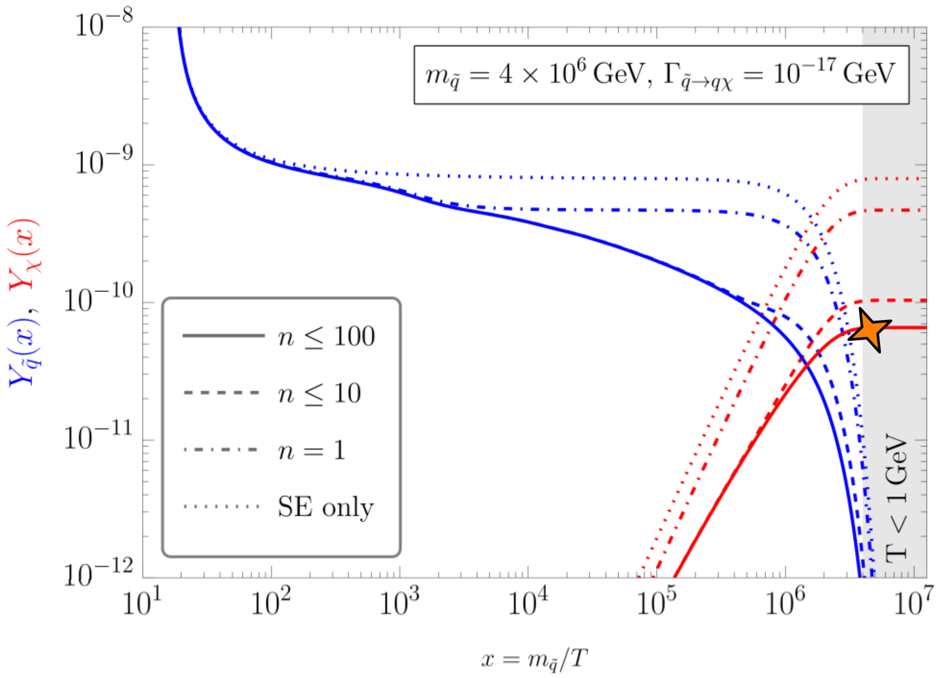

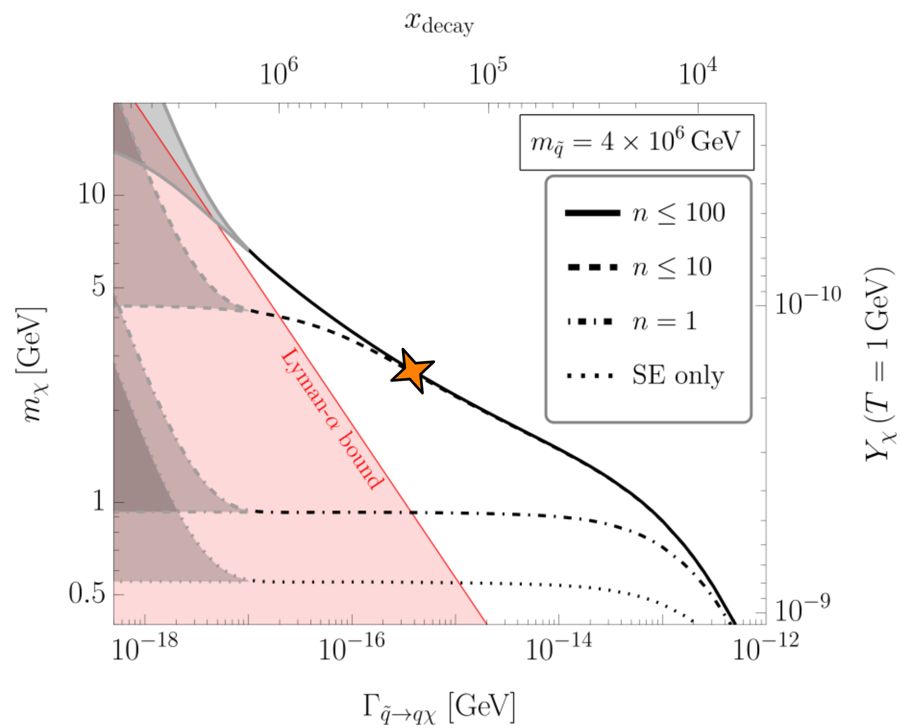

[Garny, Heisig: 2112.01449]

[Binder, Garny, Heisig, **SL**, Urban: 2308.01336]

Summary

Importance of **bound states** for dark matter:

1. Repulsive potentials show **enhanced** BSF.
2. Dominant effect at small temperatures.
3. Non-Abelian excited states can not be neglected.
4. Large effects from transitions between bound states.
5. Bound state formation can source eternal depletion.
6. Unitarity is systematically violated in BSF at leading order.

Using intuition from QED is dangerous
& bound states are exciting!