# Dark Matter bound states inside the early Universe plasma

Tobias Binder

@ EPS (online)
27th July 2021

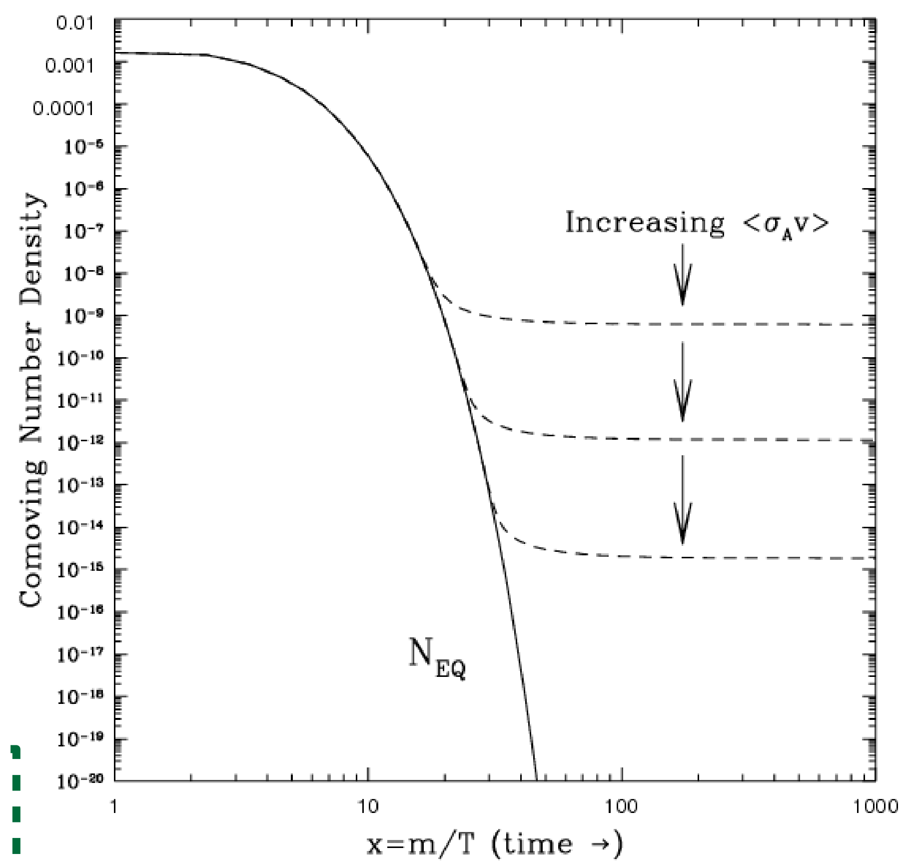
1808.06472 (PRD), 1910.11288 (PRL), 2002.07145 (JHEP), 2106.03629, **2107.03945**, ...

In collaboration w/:
B. Blobel, L. Covi, J. Harz, K. Petraki, **K. Mukaida**, **B. Hitschfeld**, **X. Yao**, ...

# Thermally produced dark matter

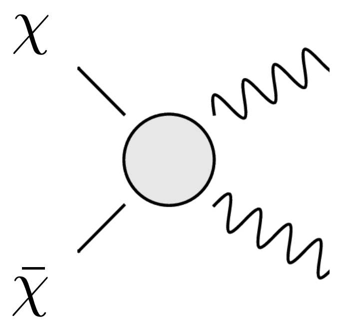

- One leading DM hypothesis:
  Thermally produced (~MeV-PeV).
- **Testable** and relic abundance **independent** of initial conditions.
- Strong constraints on coupling strength put many MeV-TeV mass realizations in thermal scenarios under tension. (However: see talk by A. Hryczuk)
- **Heavy WIMPs:** TeV-scale and above still remains attractive and much less constrained.
- Prediction of **heavy WIMPs** relic abundance challenging due to **long-range force effects**

Thermal production



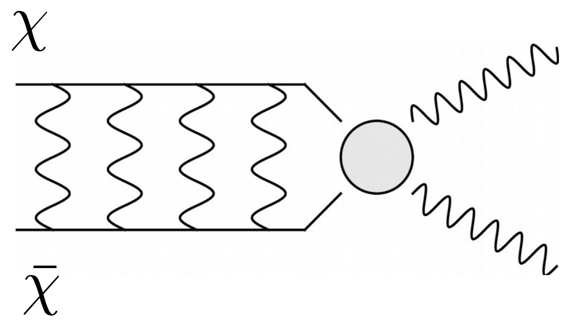
# Heavy WIMPs

**WIMP annihilation**




$m_{\text{mediator}} \gg \alpha m_\chi$

**Heavy WIMP annihilation**




$m_{\text{mediator}} \lesssim \alpha m_\chi$

## Long-range force effects:

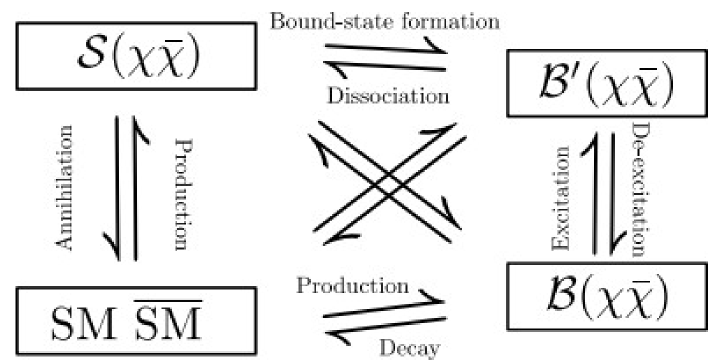
- Sommerfeld-enhanced annihilation
- (meta-stable) bound states
- **formation/dissociation of bound states**

These modify:

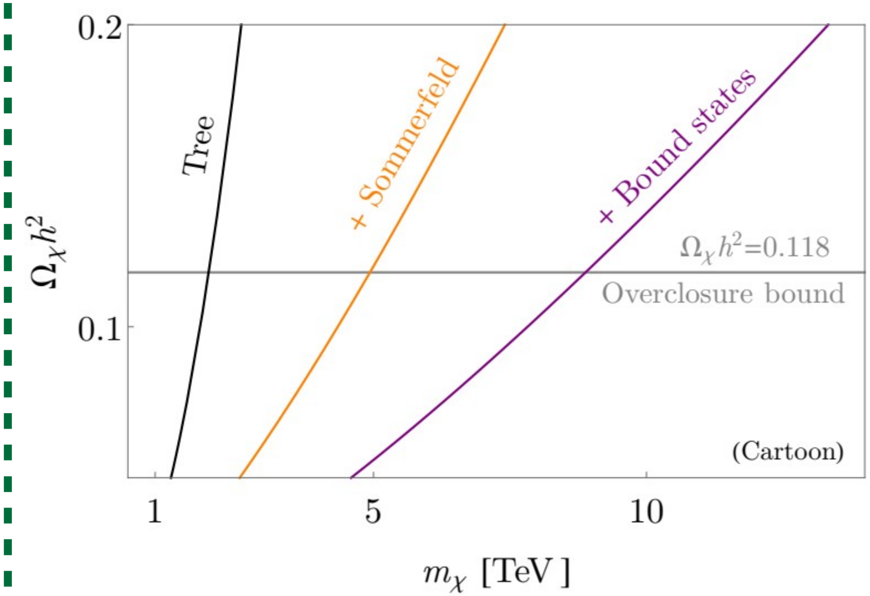
- **Prediction of relic abundance**
- Predicted flux of SM particles from annihilation in, e.g.,the galactic center (Indirect detection)

**[Seminal works by J. Hisano et al. 2006+]**

Chemical network:




Relic abundance implications:

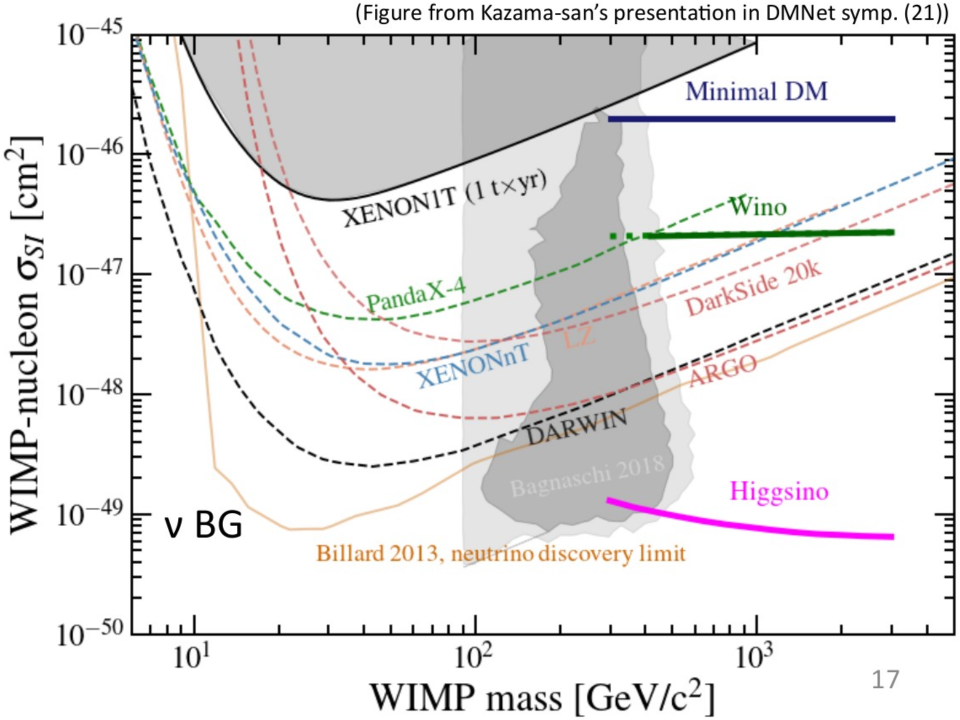


# Motivation for heavy WIMPs

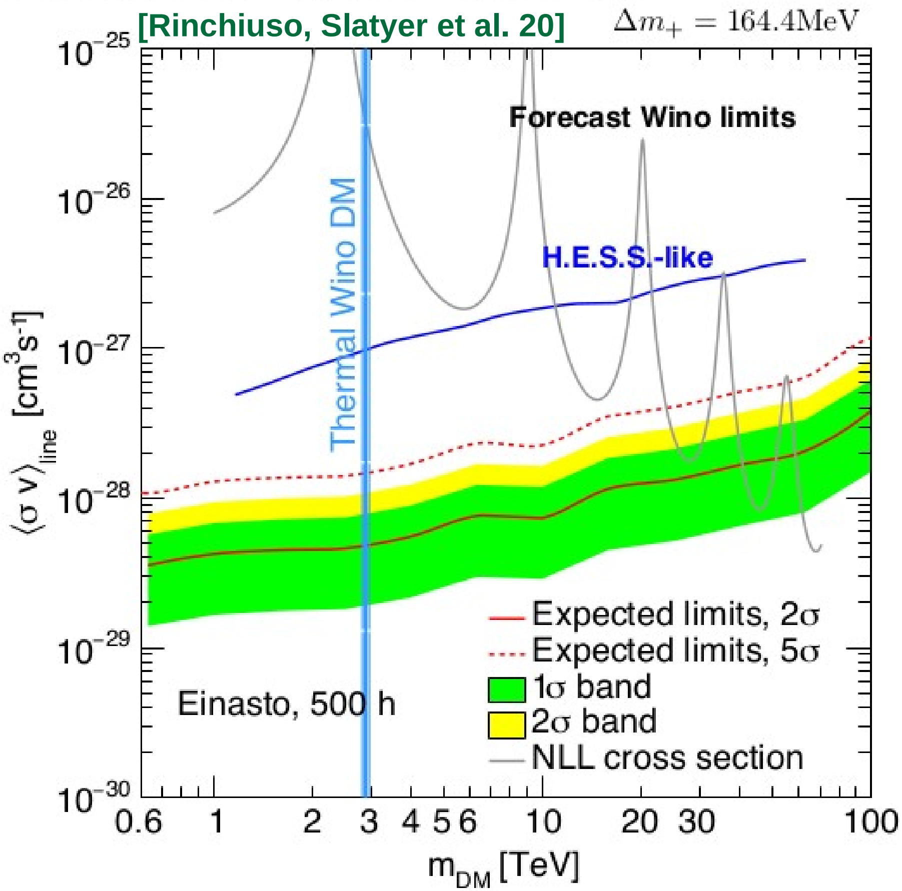
- ➢ **Many "well-motivated" new physics models at TeV scale or above: Supersymmetry, Minimal Dark Matter, ...**
- ➢ **Future experiments, mass sensitivity (indirect detection)**
- ➢ **Non-equilibrium QFT, Heavy Quarkonia**

Workshop: "Quarkonia meet Dark Matter"

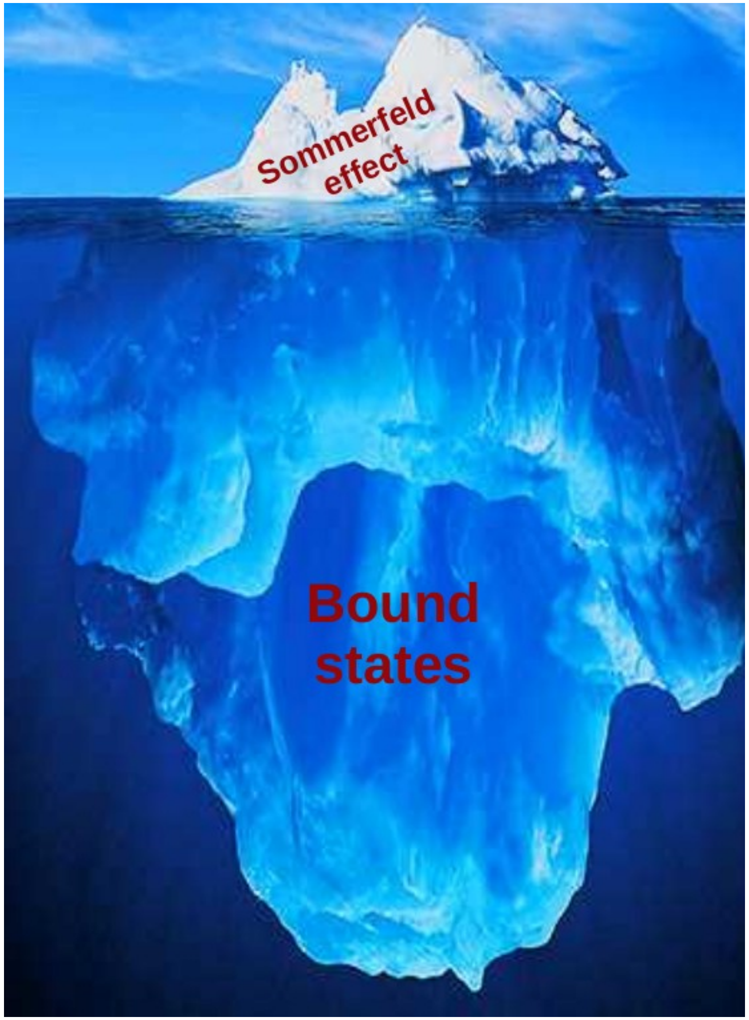
(Figure from Kazama-san's presentation in DMNet symp. (21))



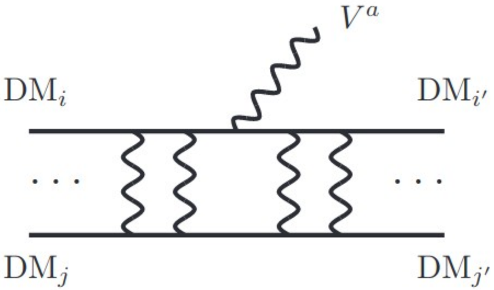

[Rinchiuso, Slatyer et al. 20]

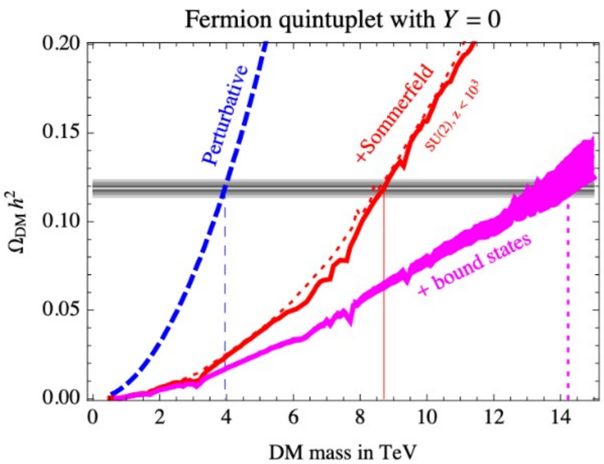


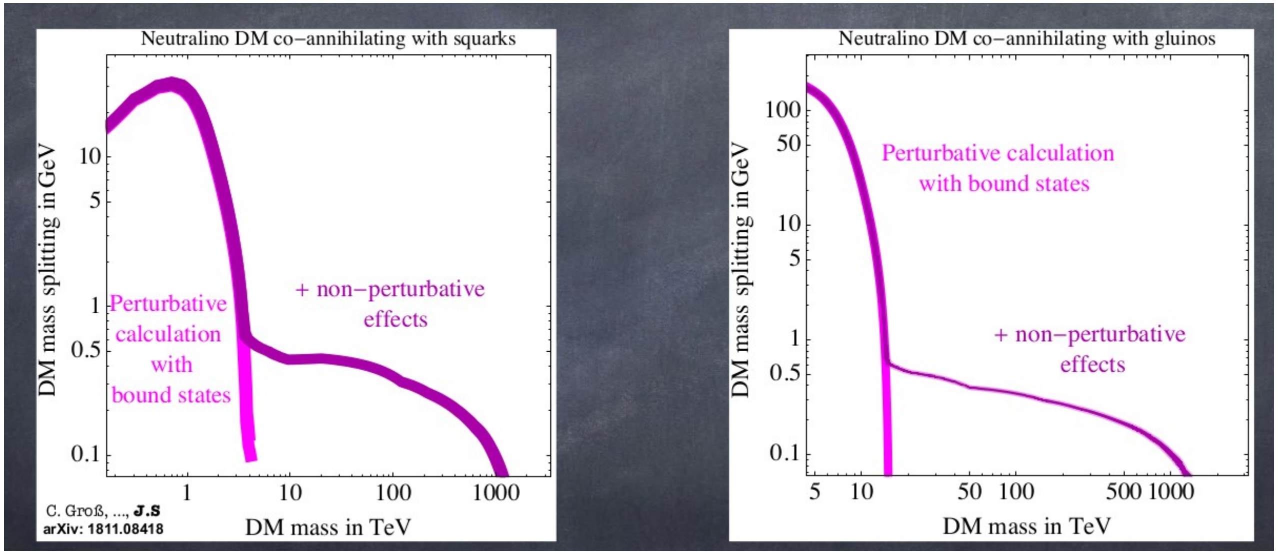
# Relic abundance with long-range force effects

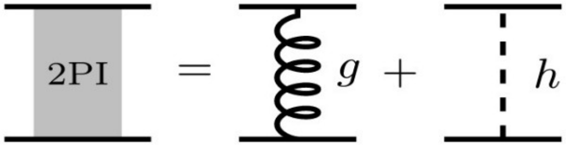



## Bound-state formation @ LO:




**[see talks by K. Petraki, J. Smirnov, J. Harz @** “Quarkonia meet Dark Matter”: **https://indico.ipmu.jp/event/389/overview ]**

# Heavy WIMP relic abundance status

- Lot of theoretical progress over past two decades

- Sommerfeld effect at zero temperature
  + BSF @ LO understood

[see works by Braaten et al, Beneke et al., Hisano et al., Slatyer et al., Petraki et al...]

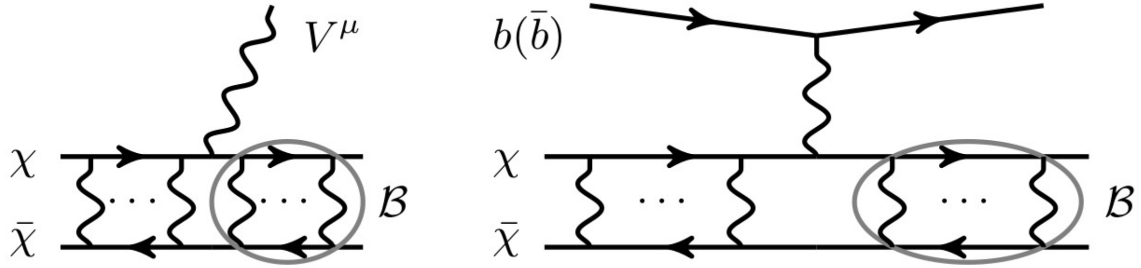
- Sommerfeld effect + bound state decay at finite temperature and in ionization equilibrium understood

[TB, L. Covi, K. Mukaida 18, see also Biondini, Laine et al.]

- Beyond ionization equilibrium, including BSF at finite temperature, very recently understood (new)

[TB 21]

- NLO BSF processes can entirely dominate over LO at T~E

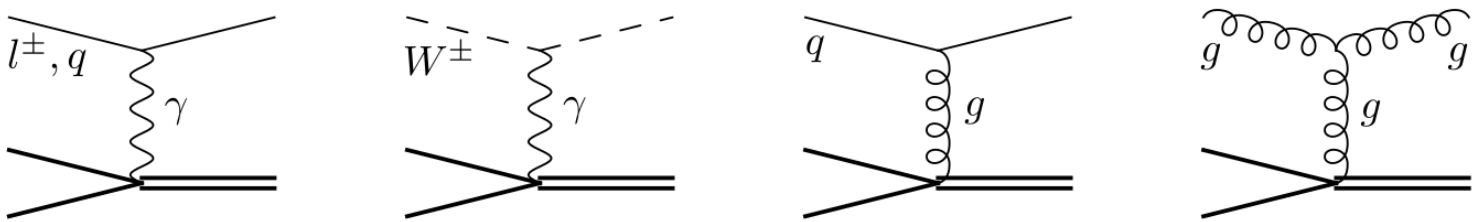



[TB, K. Mukaida, K. Petraki 19]

[This talk: non-abelian BSF at NLO: TB et al. 21]

# Massless mediators

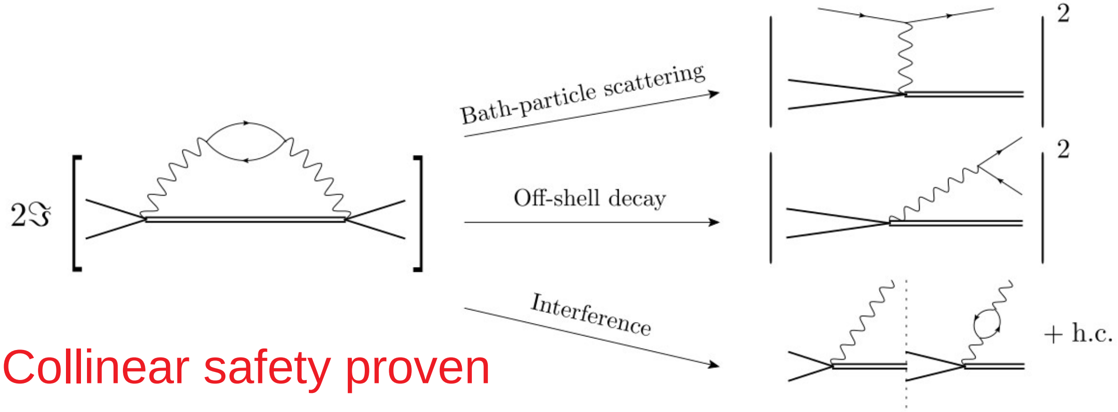
- **E.g., in co-annihilation scenarios:**




In "standard Boltzmann approach", these diagrams are all divergent in collinear direction of the bath particles.

- **Thermal field theory approach needed**

Derived BSF cross section for QED-like toy model:




Collinear safety proven

[TB, B. Blobel, J. Harz, K. Mukaida 20]

# Abelian Electric field correlator

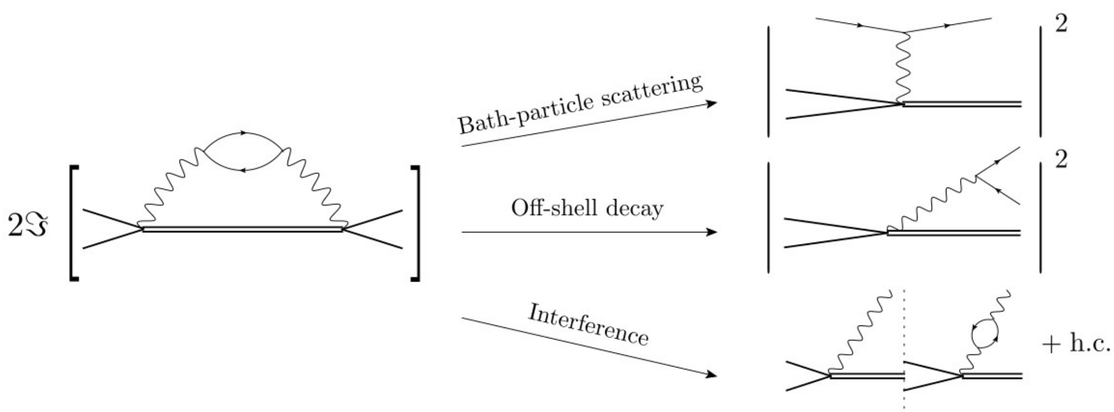
$$\mathcal{L}^{\text{pNR}} = \int \mathrm{d}^3 r \; \mathrm{Tr}\{O^\dagger(\mathbf{x},\mathbf{r},t)\,[i\partial_t - h + \; \mathbf{r}\cdot g\mathbf{E}(\mathbf{x},t) + \; \vec{\mu}\cdot g\mathbf{B}(\mathbf{x},t)]\,O(\mathbf{x},\mathbf{r},t)\}$$
$$- \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \mathcal{L}^{\text{env}}[A],$$

- **Derived evolution equation for number density in “open quantum system framework”**

- **Key quantity, entering collision term of number density equation, is the Electric Field Correlator:**

$$\langle E_i(x) E_j(y) \rangle_T$$

Includes NLO BSF corrections, factorizes from dipole overlap integral.




**[TB, B. Blobel, J. Harz, K. Mukaida 20]**

# Non-Abelian Electric Field Correlator

Consider

$$\boldsymbol{R} \otimes \bar{\boldsymbol{R}} = \boldsymbol{1} \oplus \boldsymbol{adj} \oplus \cdots ,$$

Singlet configuration has tightest bound state.

$$\mathcal{L}_{\mathrm{pNREFT}} \supset \int \mathrm{d}^3 r \; \mathrm{Tr} \Big[ \mathrm{S}^\dagger (i\partial_0 - H_s) \mathrm{S} + \mathrm{Adj}^\dagger (iD_0 - H_{\mathrm{adj}}) \mathrm{Adj} - V_A (\mathrm{Adj}^\dagger \boldsymbol{r} \cdot g\boldsymbol{E} \mathrm{S} + \mathrm{h.c.}) - \frac{V_B}{2} \mathrm{Adj}^\dagger \{ \boldsymbol{r} \cdot g\boldsymbol{E}, \mathrm{Adj} \} + \cdots \Big] .$$

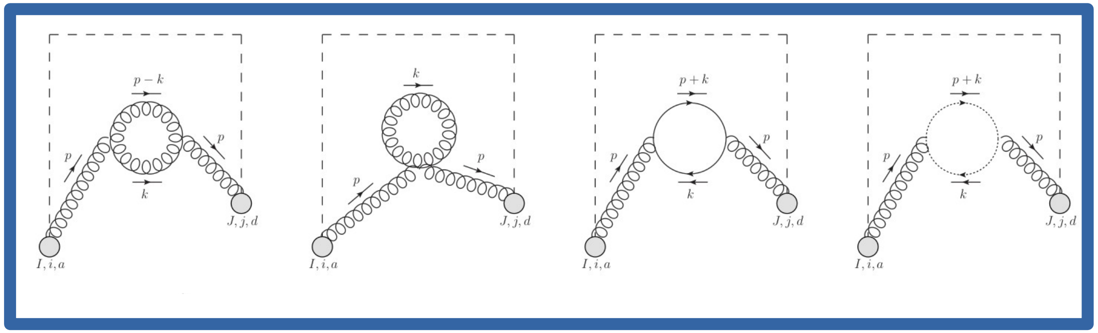
$$\mathcal{S}(\chi\bar{\chi})_{\mathrm{adj}} \rightleftharpoons \mathcal{B}(\chi\bar{\chi})_1 , \quad \mathcal{S}(\chi\bar{\chi})_1 \rightleftharpoons \mathcal{B}(\chi\bar{\chi})_{\mathrm{adj}} , \quad \mathcal{S}(\chi\bar{\chi})_{\mathrm{adj}} \rightleftharpoons \mathcal{B}(\chi\bar{\chi})_{\mathrm{adj}} ,$$

$$g^{E++}_{i_1 i_2}(t_1, t_2, \mathbf{R}_1, \mathbf{R}_2) = \Big\langle \mathrm{Tr}_{\mathrm{color}} \Big( E_{i_1}(\mathbf{R}_1, t_1) \mathscr{W}_{[(\mathbf{R}_1, t_1), (\mathbf{R}_1, +\infty)]} \mathscr{W}_{[(\mathbf{R}_2, +\infty), (\mathbf{R}_2, t_2)]} E_{i_2}(\mathbf{R}_2, t_2) \Big) \Big\rangle_T$$

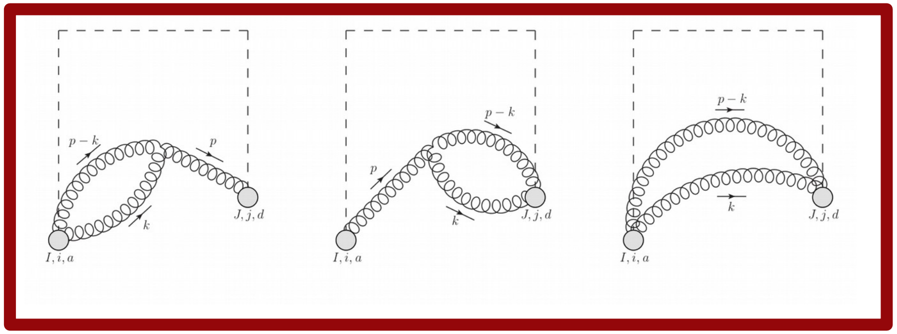
[TB et al. 21]

# Non-Abelian Electric Field Correlator at NLO

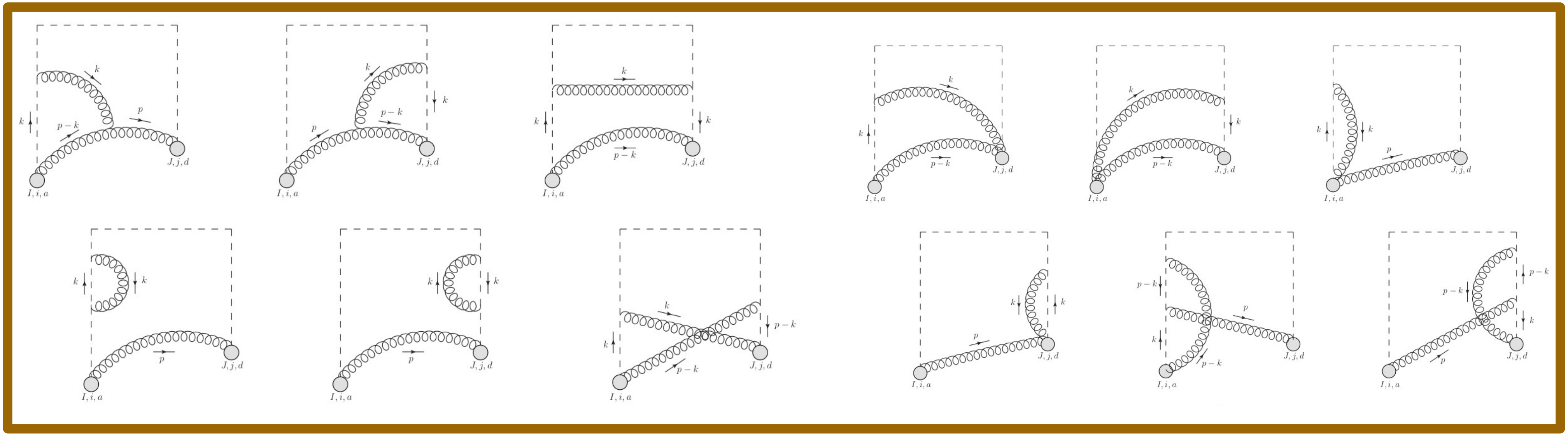
## Self-energy



## Non-linear



## Wilson lines



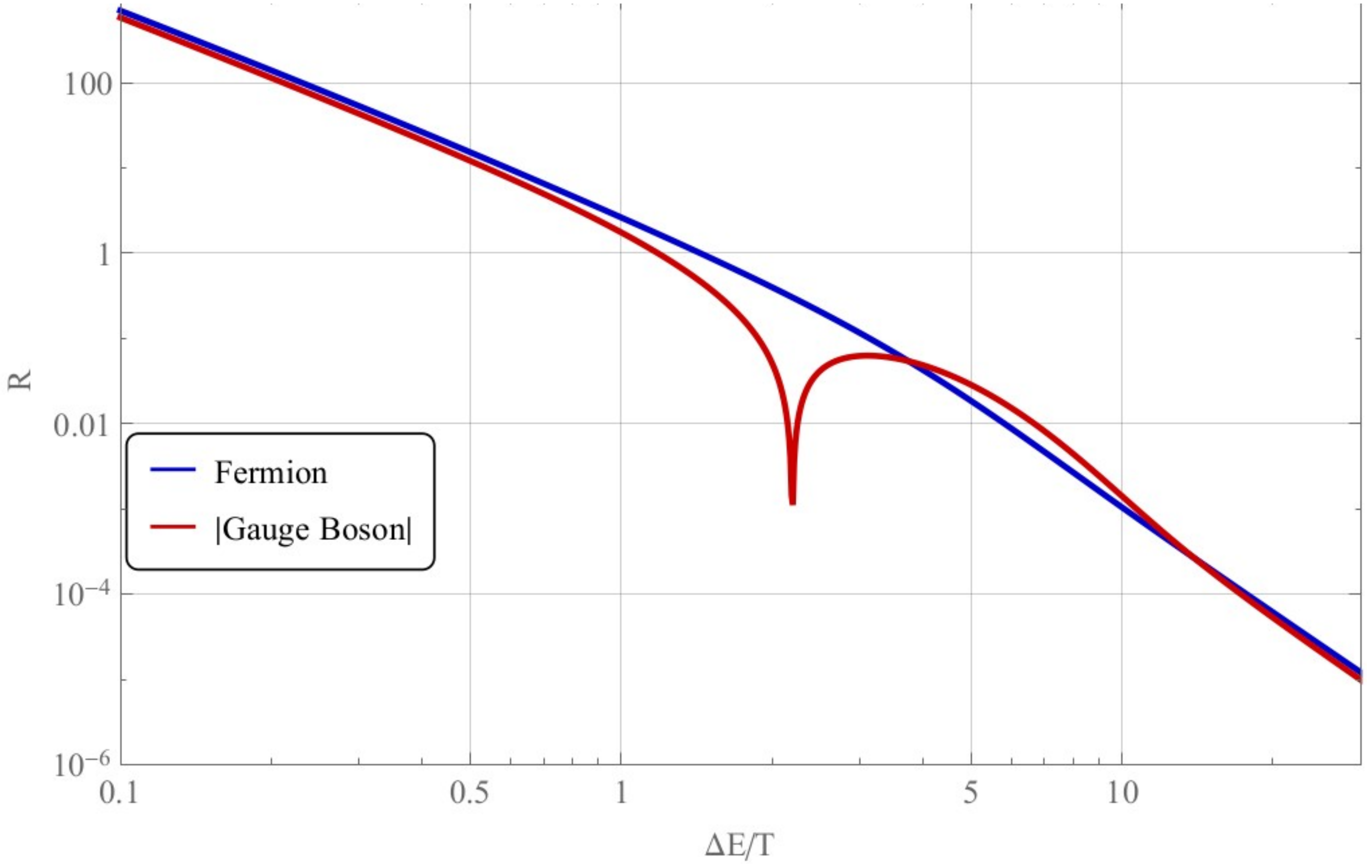
**Gauge invariance, infrared and collinear safety proven.**

[TB et al. 21]

# Enhanced rates inside plasma

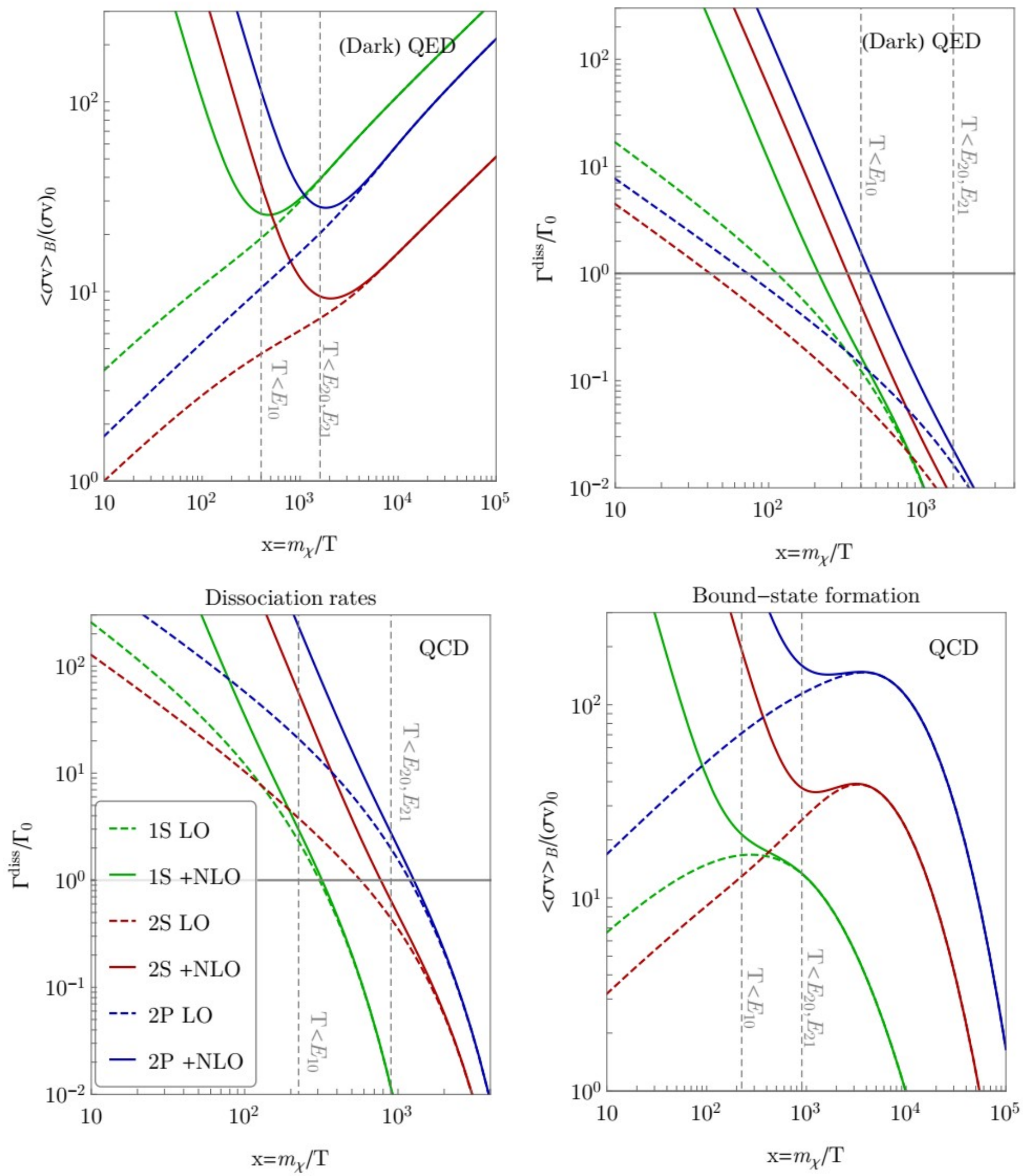
$$(\sigma v_{\mathrm{rel}})^{\mathrm{LO+NLO}}_{\mathcal{B}} = (\sigma v_{\mathrm{rel}})^{\mathrm{LO}}_{\mathcal{B}} \times \Big[1 + \alpha N_c R_g^{T=0}(\mu/\Delta E) + \alpha N_c R_g^{T\neq 0}(\Delta E/T) + \alpha N_f R_f^{T=0}(\mu/\Delta E) + \alpha N_f R_f^{T\neq 0}(\Delta E/T)\Big]$$

for any $\mathcal{B}$ .

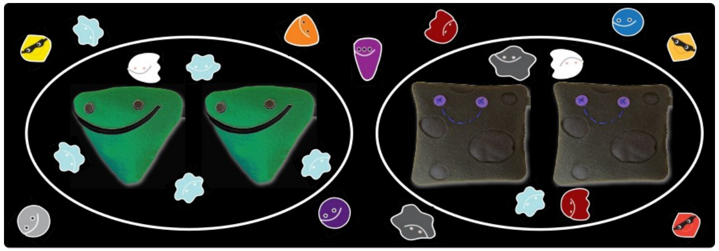



[TB et al. 21]

# Flipped hierarchy of rates inside plasma



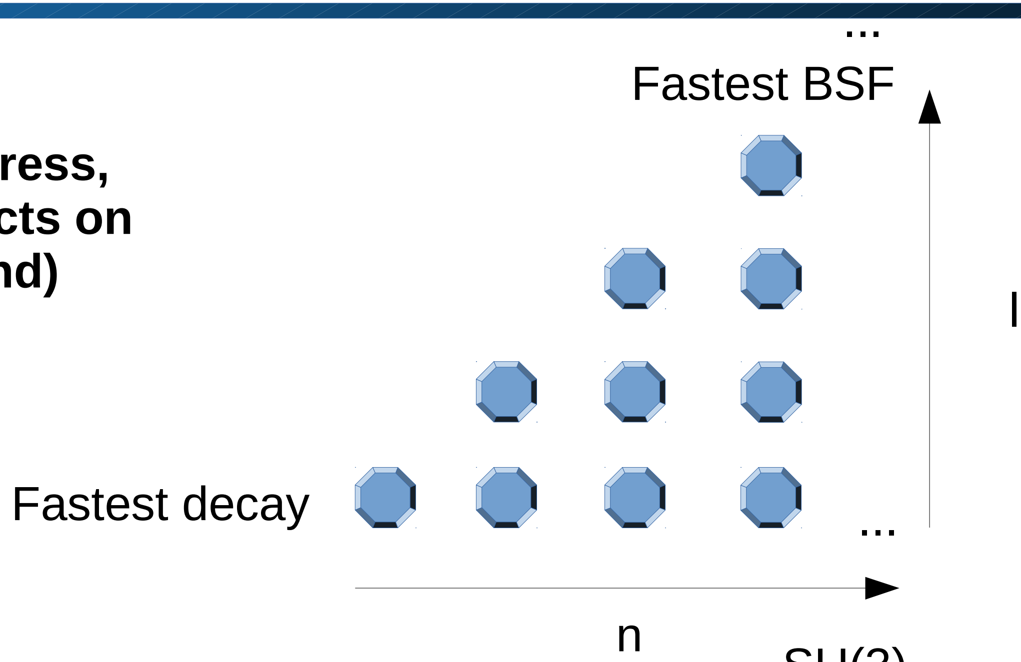

Includes SM process at NLO @ finite T (**new**)! Relevant for Quarkonia and DM transport.

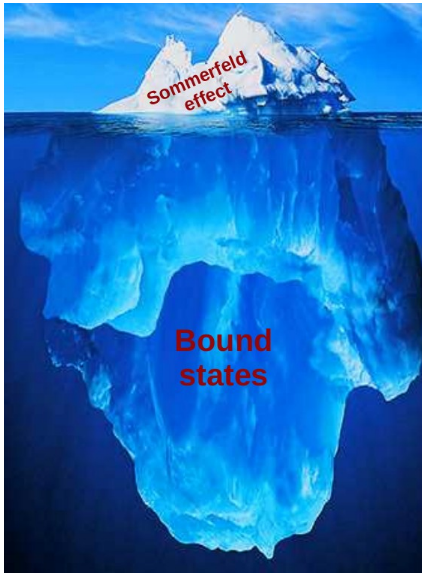


**[TB et al. 21]**

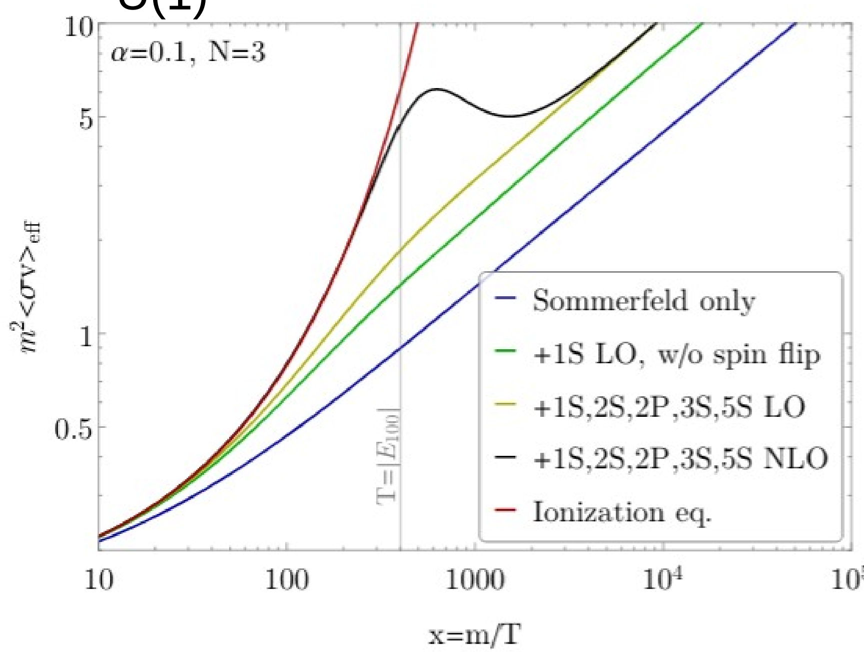
# Effective cross section (Preliminary)

**(work in progress, dramatic effects on unitarity bound)**

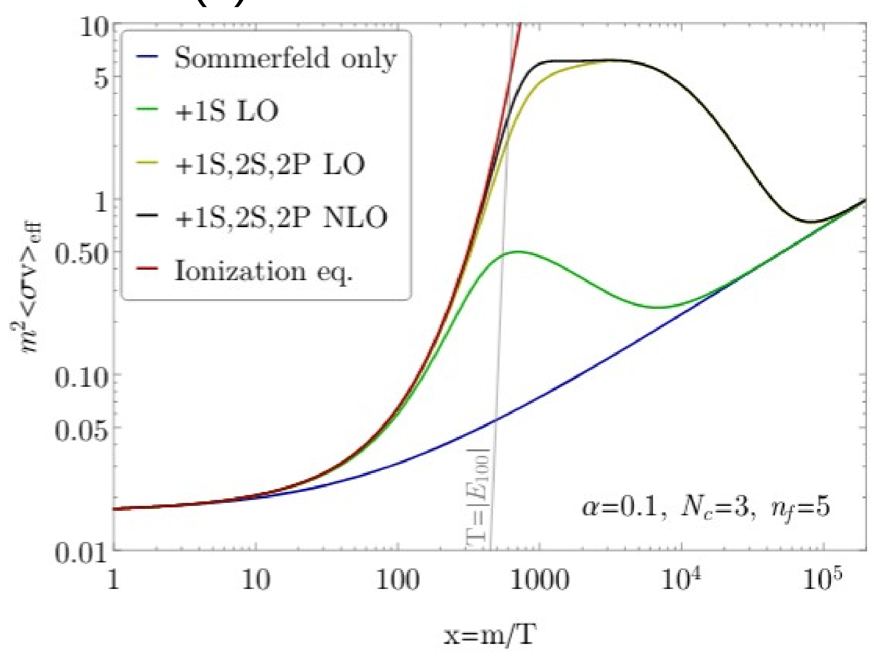



U(1)




SU(3)



# Summary and conclusion

- Heavy WIMPs experience long-range force effects, relic abundance computation more involved
- Meta-stable bound states contribute to relic abundance depletion on top of Sommerfeld effect
- NLO processes enhance ultra-soft transitions (bound-state formation, dissociation, level-transitions)
- Non-abelian electric field correlator at NLO gauge invariant, infrared and collinear finite. Results can be used for any singlet-adjoint transition with unbroken SU(N) gauge theory.
- Qualitatively, implications are that heavy WIMPs can be even heavier than expected.
- Results can be used to discuss transport of Quarkonia inside QGP

# (Dark) pNRQED

## **Relativistic** QED:

**[Dirac 1928]**

$$\mathcal{L} = i\bar{\chi}\gamma^\mu\partial_\mu\chi - m\bar{\chi}\chi - g\bar{\chi}\gamma^\mu\chi A_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \mathcal{L}^{\rm env}[A],$$

## **Non-relativistic** QED:

**[Caswell & Lepage 1986, Labelle 1992]**

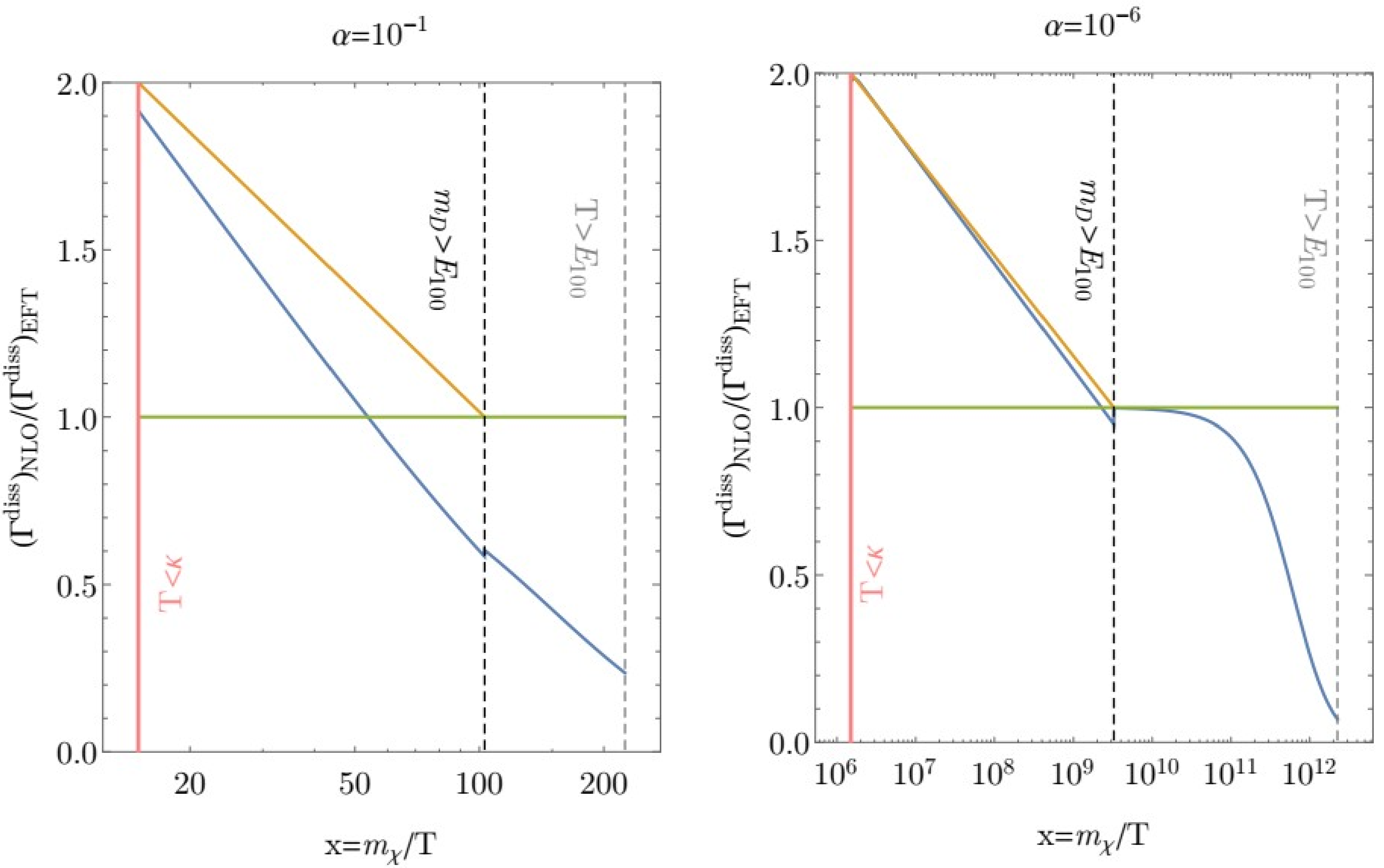
$$\mathcal{L}^{\rm NR} = \eta^\dagger\left[iD_0 + \frac{D^2}{2m_e}\right]\eta + \xi^\dagger\left[iD_0 - \frac{D^2}{2m_e}\right]\xi + \int \frac{g^2}{2}\underbrace{J^0 V J^0}_{\text{“potential”}} + \ldots$$

## **Potential** non-relativistic QED:

**[Brambilla et al. 2000 +]**

$$\mathcal{L}^{\rm pNR} = \int {\rm d}^3 r\ {\rm Tr}\{O^\dagger(\mathbf{x},\mathbf{r},t)\left[i\partial_t - h + \ \mathbf{r}\cdot g\mathbf{E}(\mathbf{x},t) + \ \vec{\mu}\cdot g\mathbf{B}(\mathbf{x},t)\right]O(\mathbf{x},\mathbf{r},t)\}$$
$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \mathcal{L}^{\rm env}[A],$$

# Fixed NLO vs. EFT treatment for fermion loop




**[For EFT treatment, see Brambilla et al.]**