Excited dark states matter

Graham White (with Tobias Binder)

Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan

Abstract

- In many dark matter models bound state transitions are fast.
- In a thermal bath, excited states contribute significantly to the effective annihilation cross section.
- Preliminary results indicate a dramatic change to the unitarity bound.

Introduction

- Solving full chemical network in Fig. 1 is daunting
- When transitions amongst bound states are fast compared to the decay of the ground state, the effective annihilation rate is controlled by

$$\langle\sigma^{\rm bsf}v\rangle_{\rm eff} \equiv \frac{\left(\sum_{ij,\mathcal{B}}\langle\sigma_{ij}^{\rm bsf}v\rangle_{\mathcal{B}}\right)\left(\sum_{\mathcal{B}}\Gamma^{\rm dec}_{\mathcal{B}}n^{\rm eq}_{\mathcal{B}}\right)}{\sum_{\mathcal{B}}[\Gamma^{\rm dec}_{\mathcal{B}}+\Gamma^{\rm dis}_{\mathcal{B}}]n^{\rm eq}_{\mathcal{B}}}. \qquad (1)$$

- Excited states make a contribution.

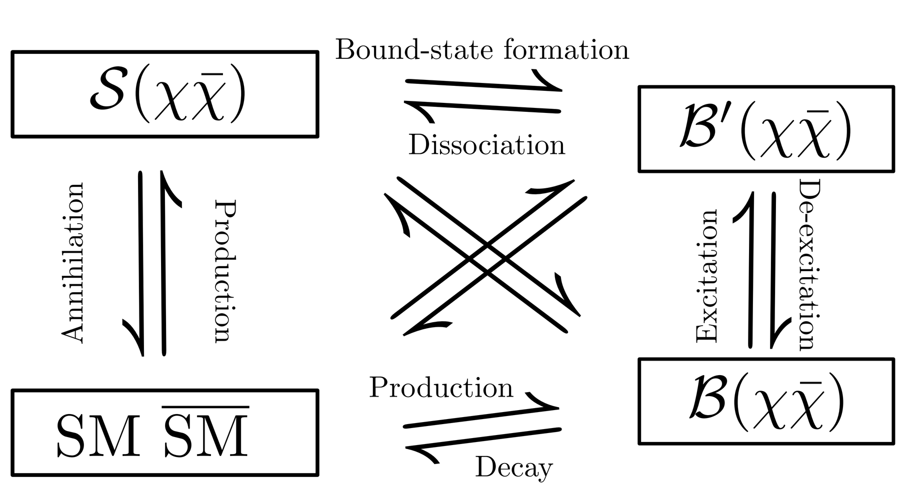

Figure 1:Full chemical network including excited states

Infrared enhancements

- At next to leading order include self energy diagram Fig. 2
- For dark U(1) in a thermal bath

$$(\sigma^{\rm bsf}_{\chi\bar{\chi}}v)^{\rm NLO}_{\mathcal{B}} = (\sigma^{\rm bsf}_{\chi\bar{\chi}}v)^{\rm LO}_{\mathcal{B}}\left[1+\alpha n_f R(\Delta E/T)\right]. \quad (2)$$

- The function R gets large in the infrared, meaning excited states make a major contribution

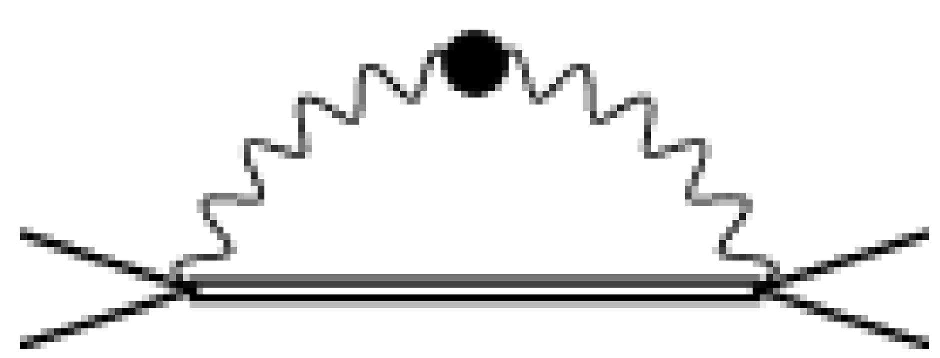

Figure 2:Self energy diagram to calculate NLO corrections

Dark U(1)

- For dark U(1) the effective cross section is approximately the ionization equilibrium x-section until the temperature reaches the binding energy

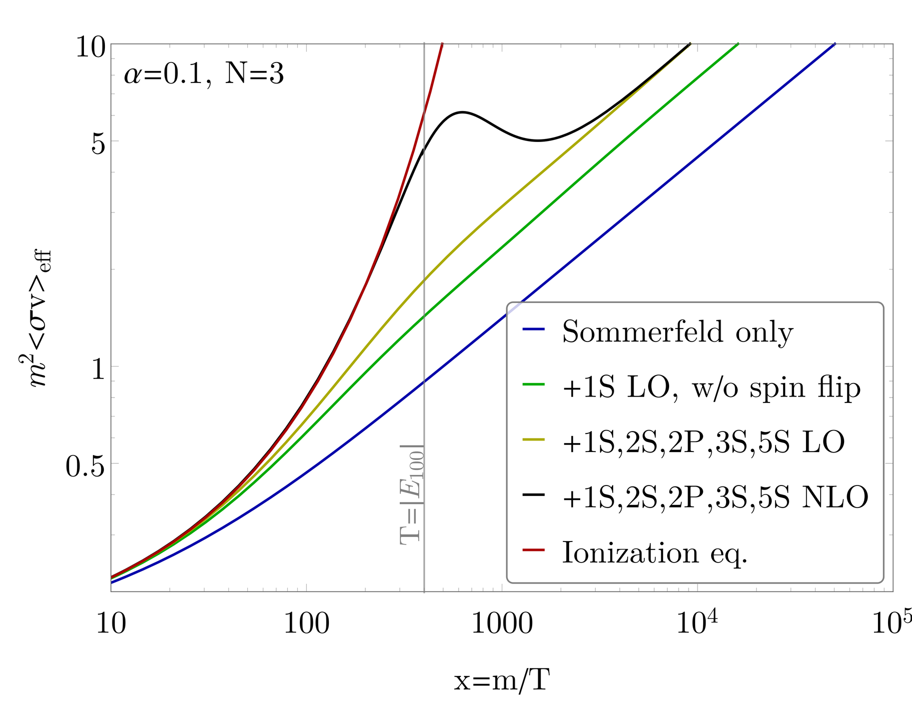

Figure 4:Dark U(1) in a bath

Squark coannihilation

- For squark co-annihilation transitions yet to be calculated but assumed to be fast through photon exchange
- For squarks in a thermal bath

$$(\sigma^{\rm bsf}_{\chi\bar{\chi}}v)^{\rm NLO}_{\mathcal{B}} \approx (\sigma^{\rm bsf}_{\chi\bar{\chi}}v)^{\rm LO}_{\mathcal{B}}\left[1+\alpha\left(N_c+\frac{n_f}{2}\right)R(\Delta E/T)\right] \quad (3)$$

- preliminary results: amplification even more dramatic!

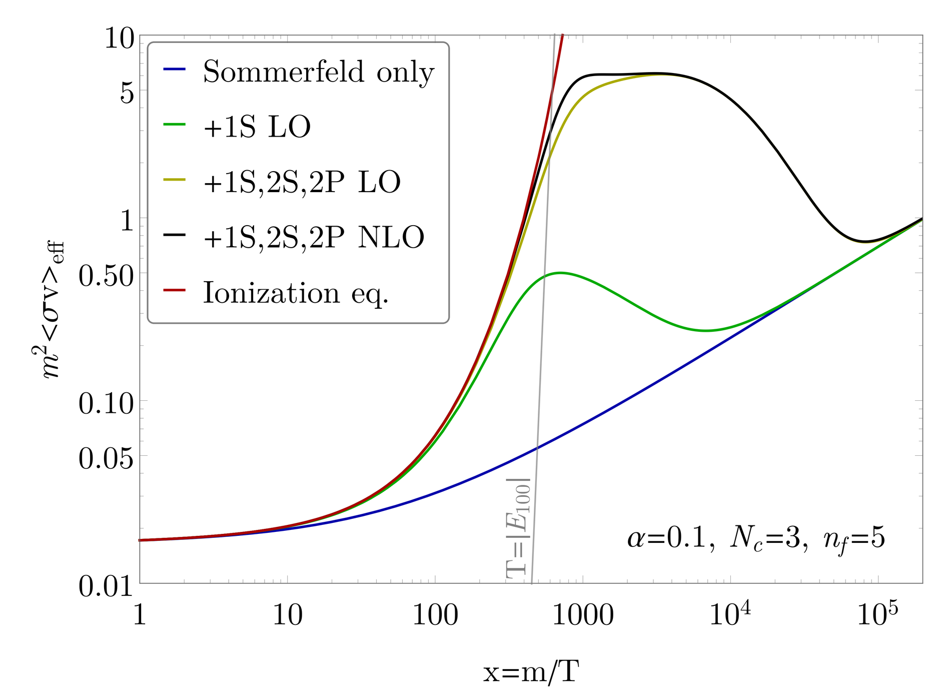

Figure 3:Squark co-annihilation effective cross section

Melted bound states

- Remaining mystery: how to treat melted bound states.
- See Fig. 5 for example where first 3 energy levels exist but then the energy spectrum becomes continuous.

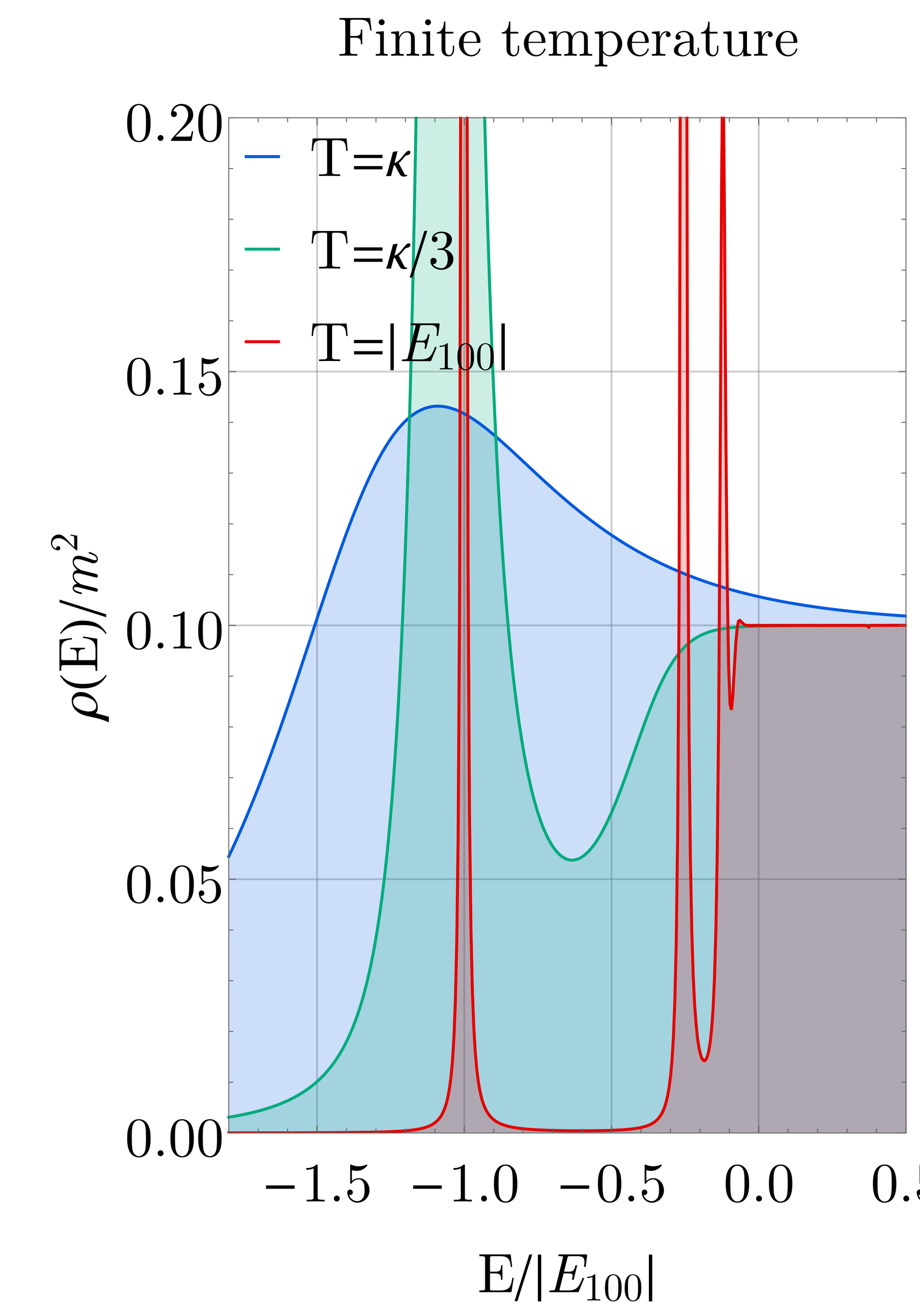

Figure 5:Melted bound states

Conclusion

- Excited states matter
- Thermal field theory effects at NLO matter
- Potentially large consequences in some models, particularly in calculating the unitarity bound