Breeding and cannibalism: The role of number-changing processes in the dark sector

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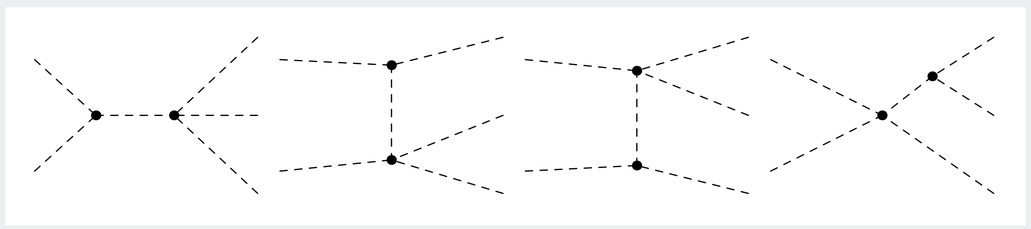
What it means to be "thermalised"

- ***"The dark matter species φ is thermalised."*** $\rightarrow$ The phase-space distribution f_φ is solely determined by a single temperature T
- This requires:
  - ▷ **Kinetic equilibrium:** Presence of efficient elastic scattering processes of φ
  - ▷ **Chemical equilibrium:** Absence of a chemical potential. Only possible, if number changing processes are present
- For a non-thermal production of φ (e.g. freeze-in mechanism), these two requirements might not be fulfilled
- Dark matter self interactions: Kinetic and chemical equilibrium can be maintained within the dark sector. The effect of number changing processes needs to be considered [1]

Number changing processes in unstable dark sectors

- Assume that the dark sector consist of a light scalar s with quartic self coupling λ_s. If the $\mathbb{Z}_2$-symmetry is spontaneously broken, $2 \rightarrow 3$ processes are possible (s behaves as a **"dark Higgs"**)



- Assume small mixing of s with the SM-Higgs h: s can decay
  - ▷ s might be only a component of an extended dark sector
  - ▷ s is long-lived for small mixing
- Moreover: Freeze-in production of s via Higgs decay $h \rightarrow ss$

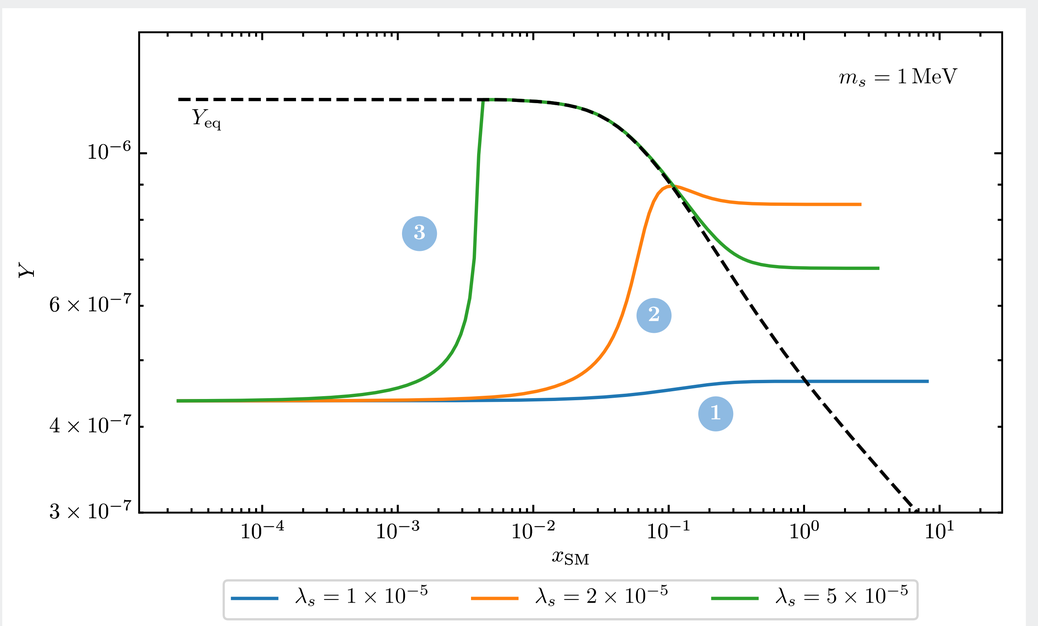
Boltzmann equation for $2 \rightarrow 3$ processes

- The Boltzmann equation describes the evolution of the number density n_s
- It is convenient to express this equation in terms of $Y_s = n_s / s_{\rm SM}$, where $s_{\rm SM}$ is the entropy density of the Standard Model, and $x_{\rm SM} = m_s / T_{\rm SM}$
- For $2 \rightarrow 3$ processes the Boltzmann equation reads

$$\frac{\mathrm{d}\, Y_s}{\mathrm{d}\log x_{\rm SM}} = \frac{s_{\rm SM}}{H}\langle \sigma v \rangle_{2\to 3} Y_s \left[1 - \frac{Y_s}{Y_s^{\rm eq}}\right], \qquad (1)$$

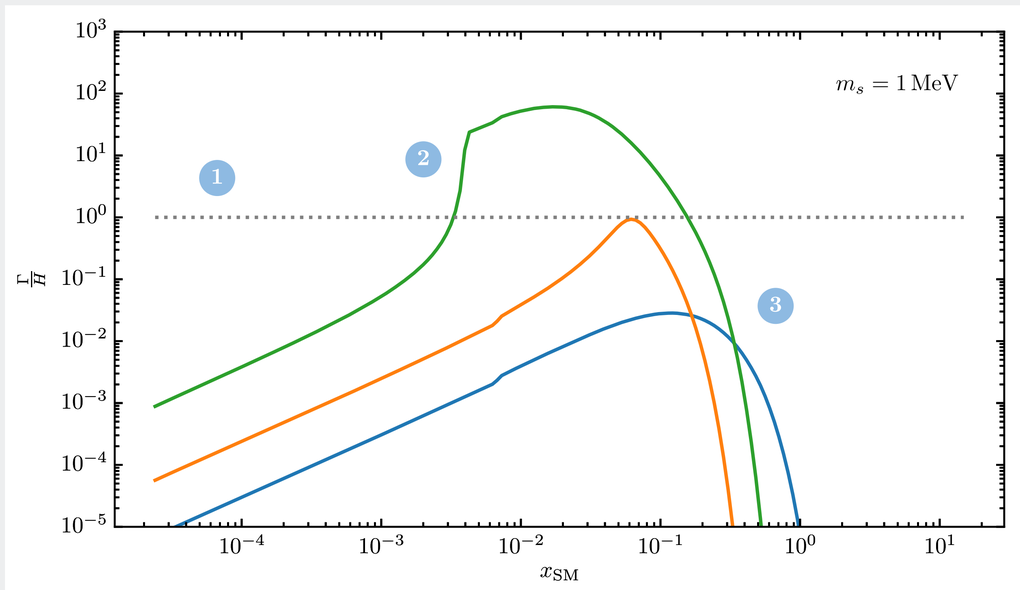
  where $Y_s^{\rm eq}$ denotes the yield in the case of chemical equilibrium
- The dark sector temperature $T_{\rm dark}$ has a non-trivial dependence on the SM temperature $T_{\rm SM}$ and is set by the assumption that the entropy densities of the visible and the dark sector are independently conserved [2]

Number changing processes and the evolution of Y



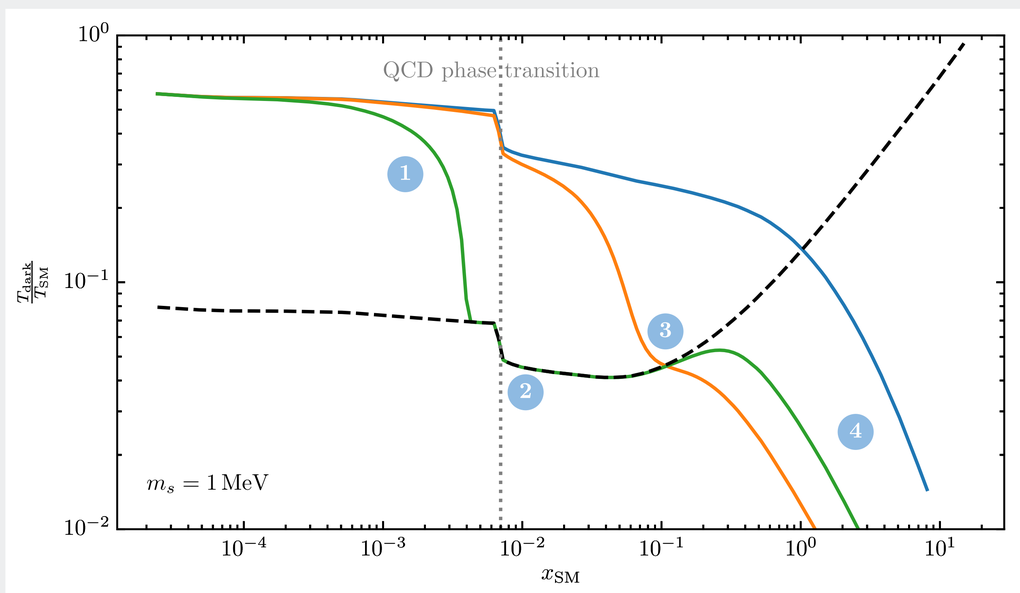
1. For small couplings number changing processes have (almost) no effect
2. For intermediate couplings $2 \rightarrow 3$ processes will enhance Y shortly before these prcocesses decouple due to the Boltzmann suppression of $Y_{\rm eq}$
3. For high couplings chemical equilibrium is reached earlier and Y will decouple at later times (c.f. freeze-out of WIMPs. *Here:* ***"dark freeze-out"***)

Interaction rate vs. Hubble rate



1. For $\Gamma / H \geq 1$, number changing processes are efficient and chemical equilibrium is maintained
2. For $Y_{\rm ini} < Y_{\rm eq}$, the $2 \rightarrow 3$ processes will increase the number density of s which in turn increases the interaction rate $\Gamma = \langle \sigma v \rangle n_s$
3. As the universe expands the dark sector cools adiabatically and s becomes non-relativistic. Hence the number density and the interaction rate become Boltzmann suppressed.

Evolution of the dark sector temperature



1. $2 \rightarrow 3$-processes will enhance the number density and cool down the dark sector **("Breeding")**
2. In chemical equilibrium: $T_{\rm dark}$ scales as $T_{\rm SM}$ **("Cohabitation")**
3. $3 \rightarrow 2$-processes will decrease the number density and heat up the dark sector to prevent the species from being non-relativistic **("Cannibalism")**
4. When the number changing processes become inefficient the dark sector becomes non-relativistic and $T_{\rm dark}$ scales accordingly

Summary

- In non-thermalised dark sectors, number changing processes may have a non-negligible effect and are especially important in unstable dark sectors
- The full thermal history of **"sub-GeV dark Higgs bosons"** with production via freeze-in, full details on the numerical treatment of the number changing processes and phenomenological consequences will be published soon [3]

References

[1] Matti Heikinheimo, Tommi Tenkanen, Kimmo Tuominen, and Ville Vaskonen
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[2] Eric D. Carlson, Marie E. Machacek, and Lawrence J. Hall
"Self-interacting dark matter" *Astrophys. J.*, 398:43–52, 1992

[3] Saniya Heeba, Felix Kahlhoefer, and Patrick Stöcker
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