Precise dark matter relic abundance in decoupled sectors

Based on 2007.03696

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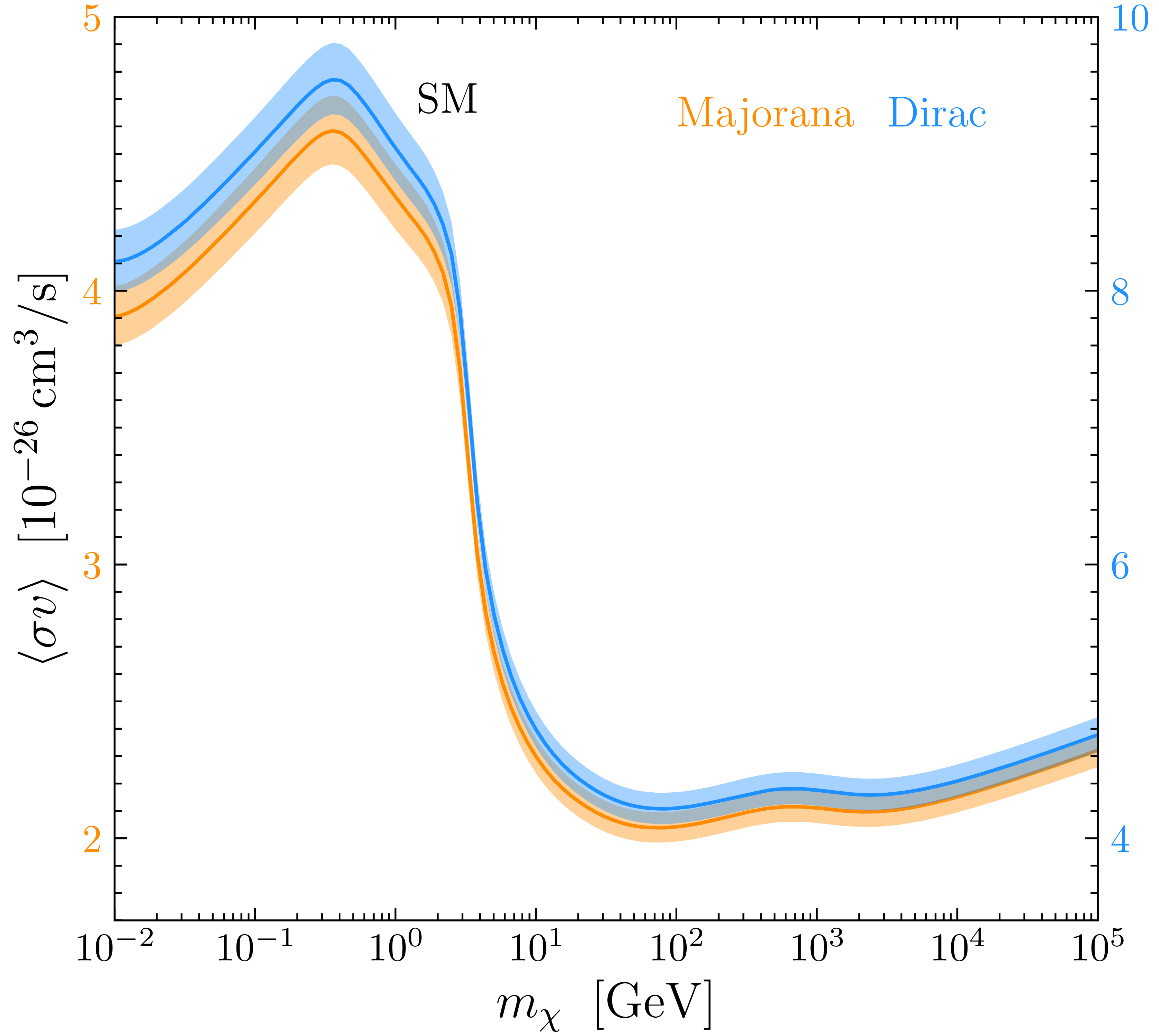


[arXiv: 2007.03696]

Outline

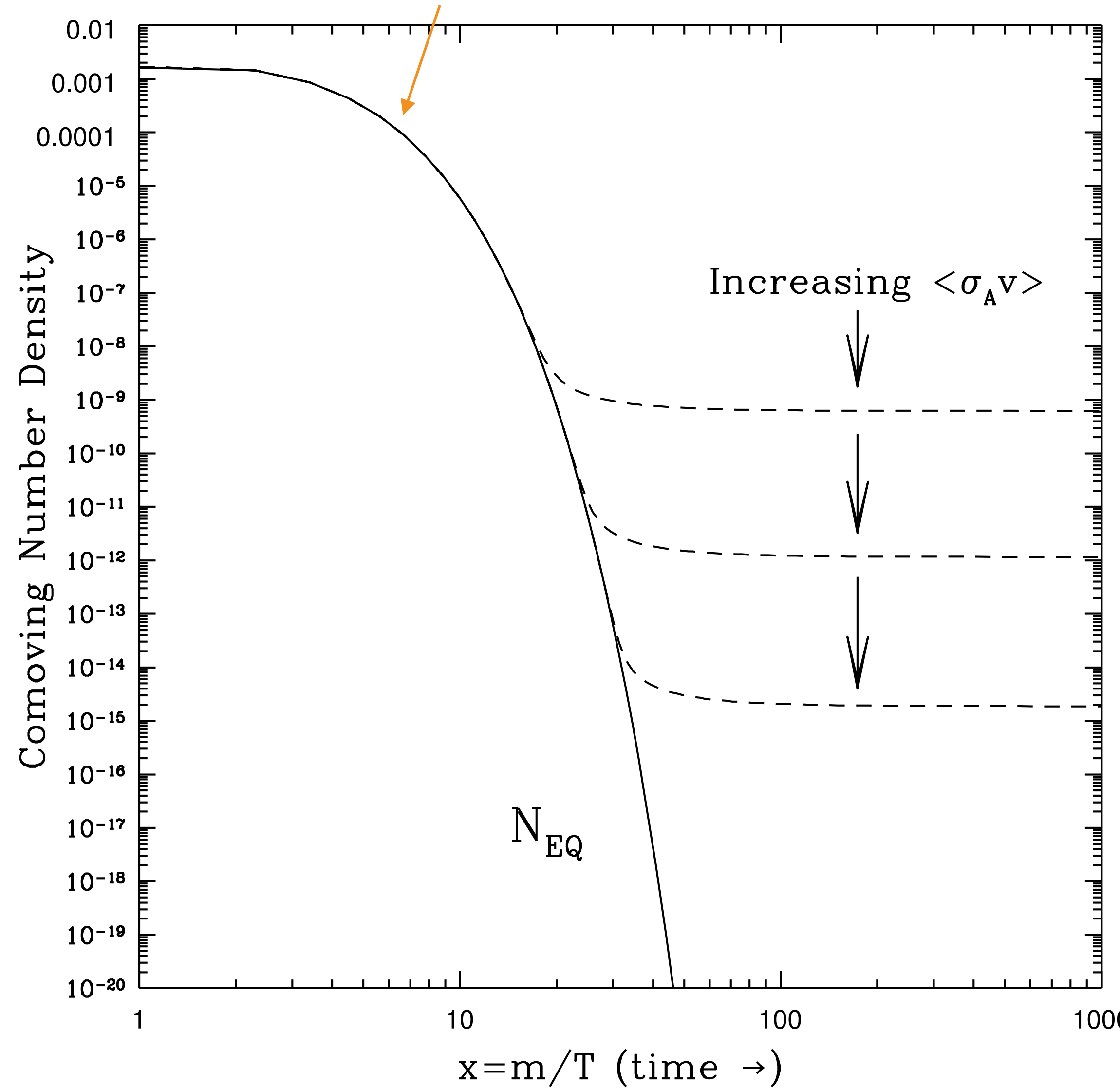
- Standard freeze-out
- Freeze-out in dark sector with massless states
- Freeze-out in dark sector with massive states
- Summary

Standard freeze-out

- DM annihilations $\chi\bar{\chi} \leftrightharpoons f\bar{f}$ into SM
- Boltzmann equation $(i \in \chi, \bar{\chi})$
  - $\dot{n}_i + 3Hn_i = \langle\sigma v\rangle(n_{\chi,\mathrm{eq}}n_{\bar{\chi},\mathrm{eq}} - n_\chi n_{\bar{\chi}})$
  - $n_{\chi,\mathrm{eq}} = n_{\bar{\chi},\mathrm{eq}} \simeq g_\chi \left(\frac{m_\chi T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_\chi}{T}\right)$

    for $m_\chi < T/3$
- DM initially in equilibrium with SM

$0 \simeq \mu_f + \mu_{\bar{f}} = \mu_\chi + \mu_{\bar{\chi}} = 2\mu_\chi$



[arXiv: 0901.4090]

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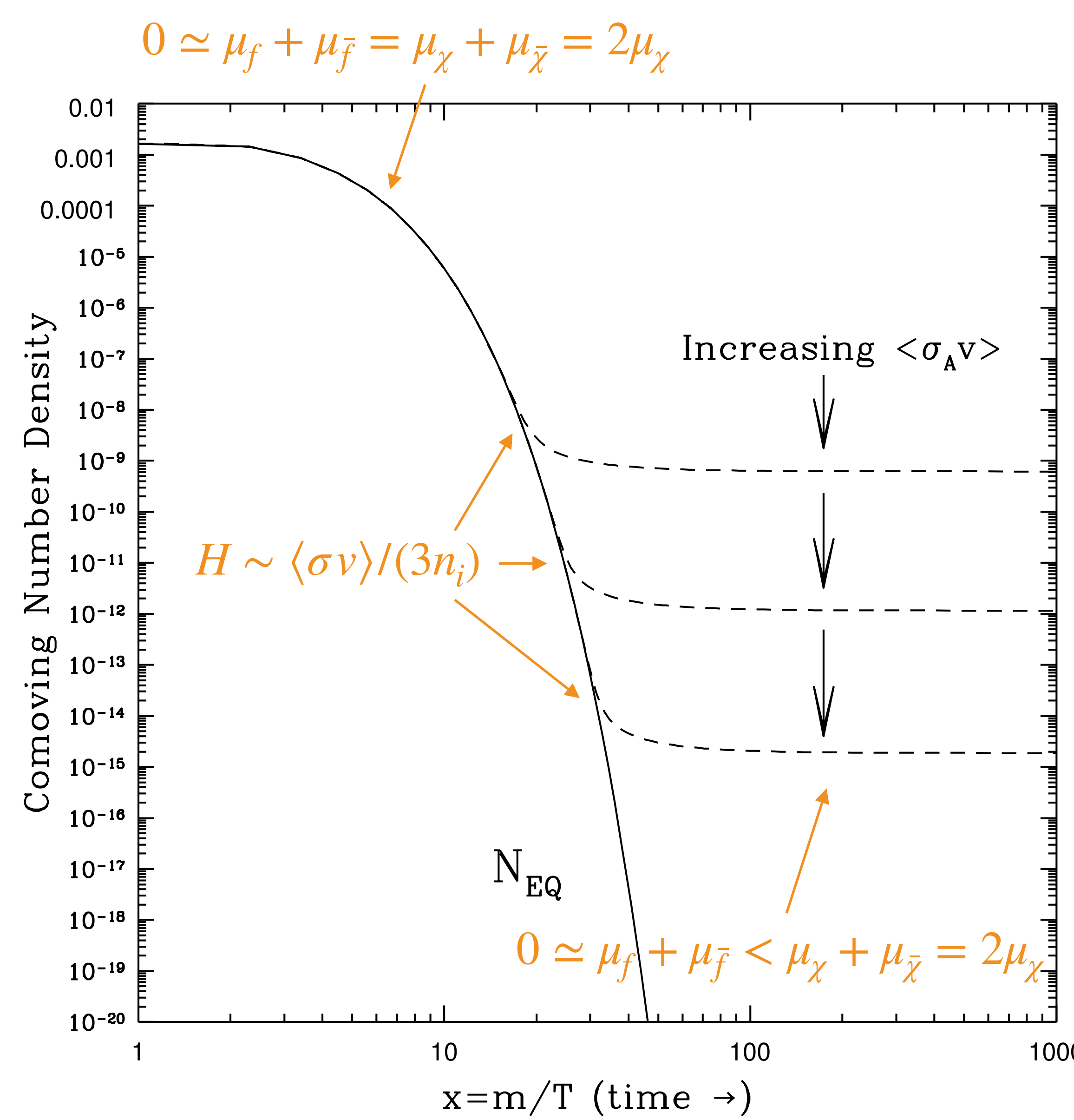
    for $m_\chi < T/3$
- DM initially in equilibrium with SM
- Annihilations freeze out when $H \sim \langle \sigma v \rangle / (3n_i)$
  - Chemical decoupling, still the same temperature (kinetic equilibrium)
  - Chemical potential develops for $\chi, \bar{\chi}$



[arXiv: 0901.4090]

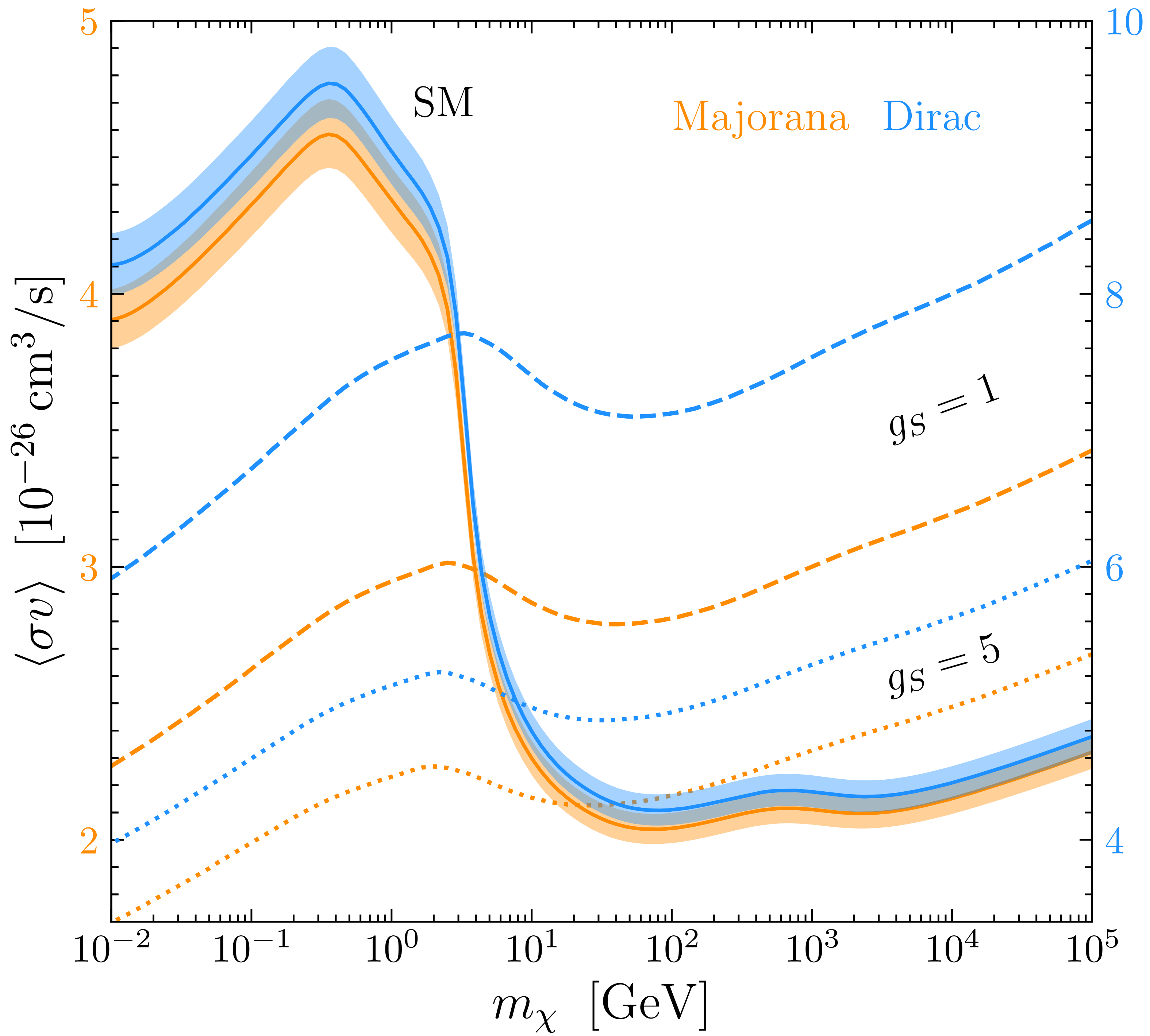
Freeze-out in dark sector with massless states

- Assume massless scalar S, g_S degrees of freedom, chemical potential $\mu_S = 0$
- DS in equilibrium with SM until decoupling temperature T_{dec}
- Temperature in dark sector T_χ evolves according to entropy conservation
- DM annihilations $\chi\bar{\chi} \leftrightharpoons SS$
- Boltzmann equation needs to be changed in the following way:
  - $\dot{n}_i + 3\boxed{H}n_i = \boxed{\langle\sigma v\rangle(n_{\chi,\text{eq}}n_{\bar{\chi},\text{eq}} - n_\chi n_{\bar{\chi}})}$

    Include DS Evaluate at T_χ

Freeze-out in dark sector with massless states

Results for $\langle \sigma v \rangle$ s-wave



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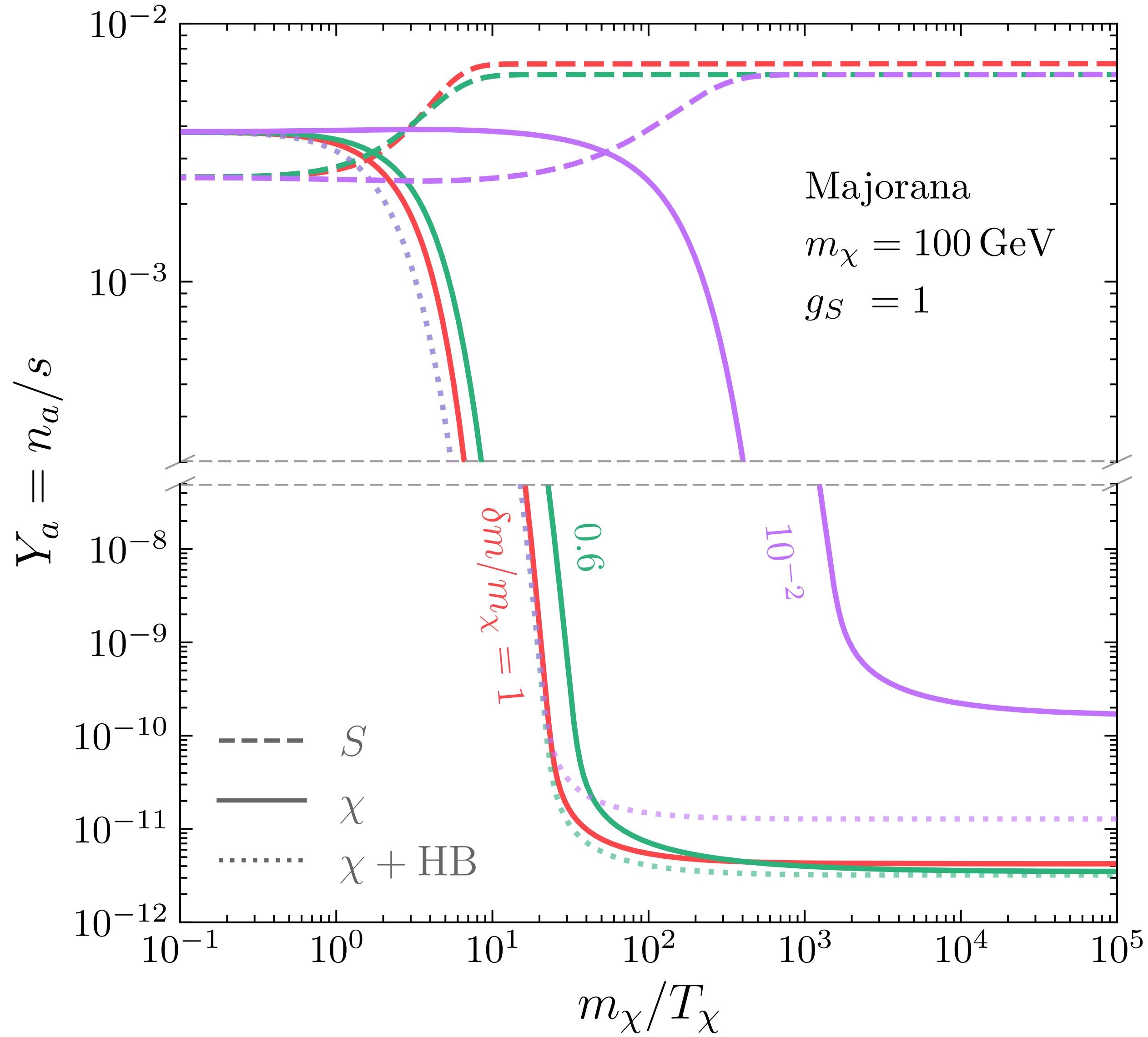
Freeze-out in dark sector with massive states

- $m_S = 0 \Rightarrow$ number-changing interactions in equilibrium, e.g. $\chi\bar{\chi} \leftrightharpoons \chi\bar{\chi}S \Rightarrow \mu_S = 0$
- $m_\chi \gtrsim m_S > 0 \Rightarrow$ number-changing interactions decouple $\Rightarrow$ all particles build up chemical potential
- Kinetic equilibrium $\Rightarrow$ Fermi-Dirac and Bose-Einstein distribution functions with temperature T_χ and chemical potentials $\mu_\chi = \mu_{\bar{\chi}}, \mu_S$
- Temporal evolution governed by ($N_\chi = 1(2)$ for Majorana (Dirac)):
    - $\dot{n}_i + 3Hn_i = \mathfrak{C}/N_\chi, \;\; \dot{n}_S + 3Hn_S = -\,\mathfrak{C}$
    - $\mathfrak{C} \sim \int |\overline{\mathcal{M}}_{\chi\bar{\chi}\to SS}|^2 [f_S f_{S'}(1-f_\chi)(1-f_{\bar{\chi}}) - f_\chi f_{\bar{\chi}}(1+f_S)(1+f_{S'})] \times \ldots$
    - $\dot{\rho}_{\mathrm{DS}} + 3H(\rho_{\mathrm{DS}} + P_{\mathrm{DS}}) = 0$
- In the following $|\overline{\mathcal{M}}_{\chi\bar{\chi}\to SS}|^2 = \mathrm{const}$ as benchmark

Freeze-out in dark sector with massive states

Evolution of particle abundances

- Different $\delta m/m_\chi = (m_\chi - m_S)/m_\chi$, same $|\overline{\mathscr{M}}_{\chi\bar{\chi}\to SS}|^2$
- Rise in chemical potentials compensates would-be Boltzmann suppression when χ, $\bar{\chi}$, and S become non-relativistic
- Boltzmann suppression of $\chi, \bar{\chi}$ only once $T_\chi \sim \delta m$
- Combination of different effects (n_S smaller, evolution of μ_S, kinematic impact of m_S on $\mathfrak{C}$, "late" freeze-out) leads to small decrease in Y_χ up to $\delta m/m_\chi \sim 0.6$ and increase for smaller $\delta m/m_\chi$



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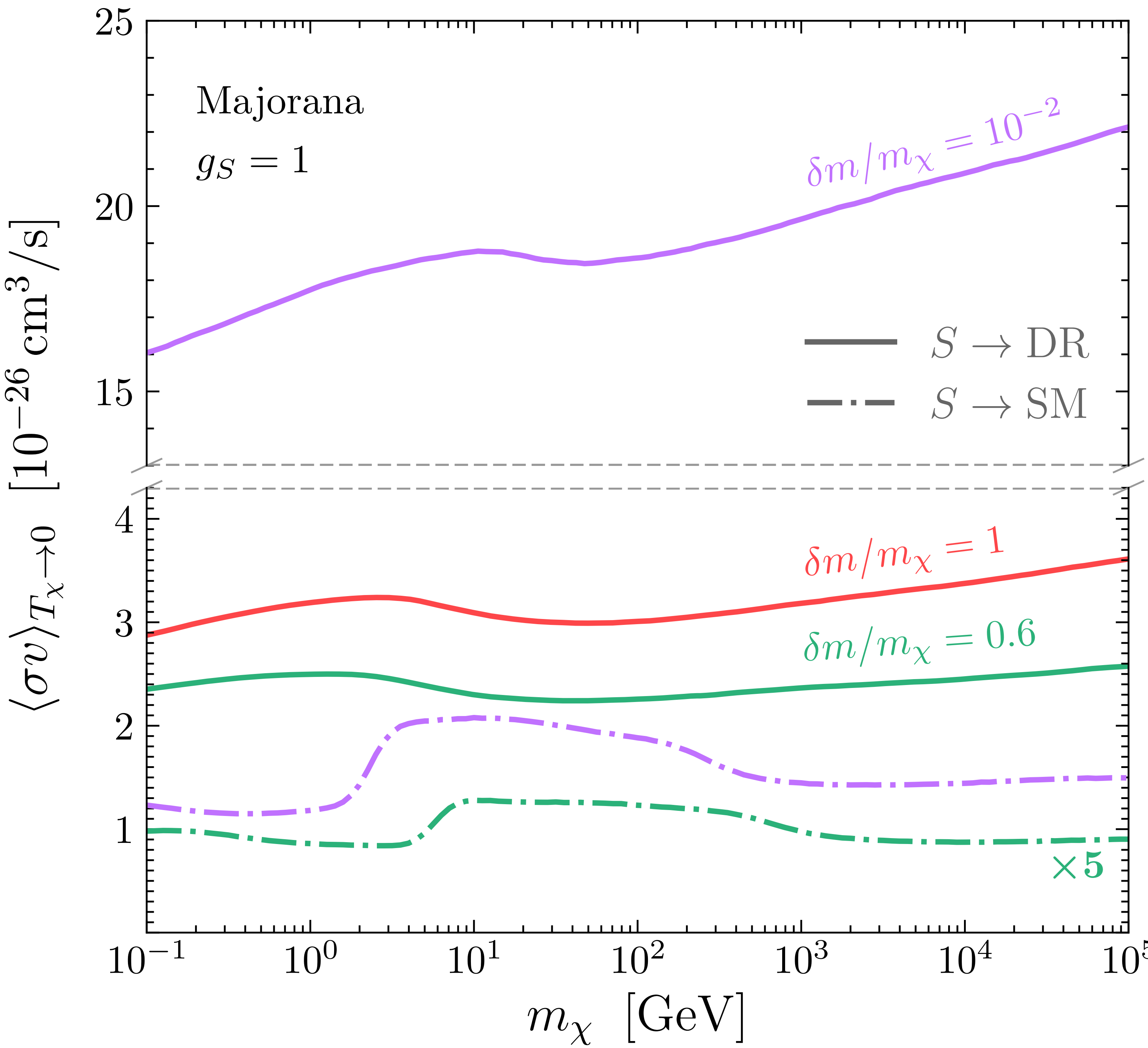
Freeze-out in dark sector with massive states

Results for $\langle \sigma v \rangle_{T_\chi \to 0}$



$\tau_S = 1\, s \times (1\,\mathrm{GeV}/m_S)^2$

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Summary

- Framework for precision calculations of DM freeze-out in decoupled sectors
- Benchmark lines for massless S
- Large difference to standard treatment for massive S, but model dependent

Thank you