Sterile neutrino dark matter from dark thermal bath

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Scalars 2023 @ University of Warsaw

JHEP 05 (2023) 108 [arXiv:2302.09515 [hep-ph]]

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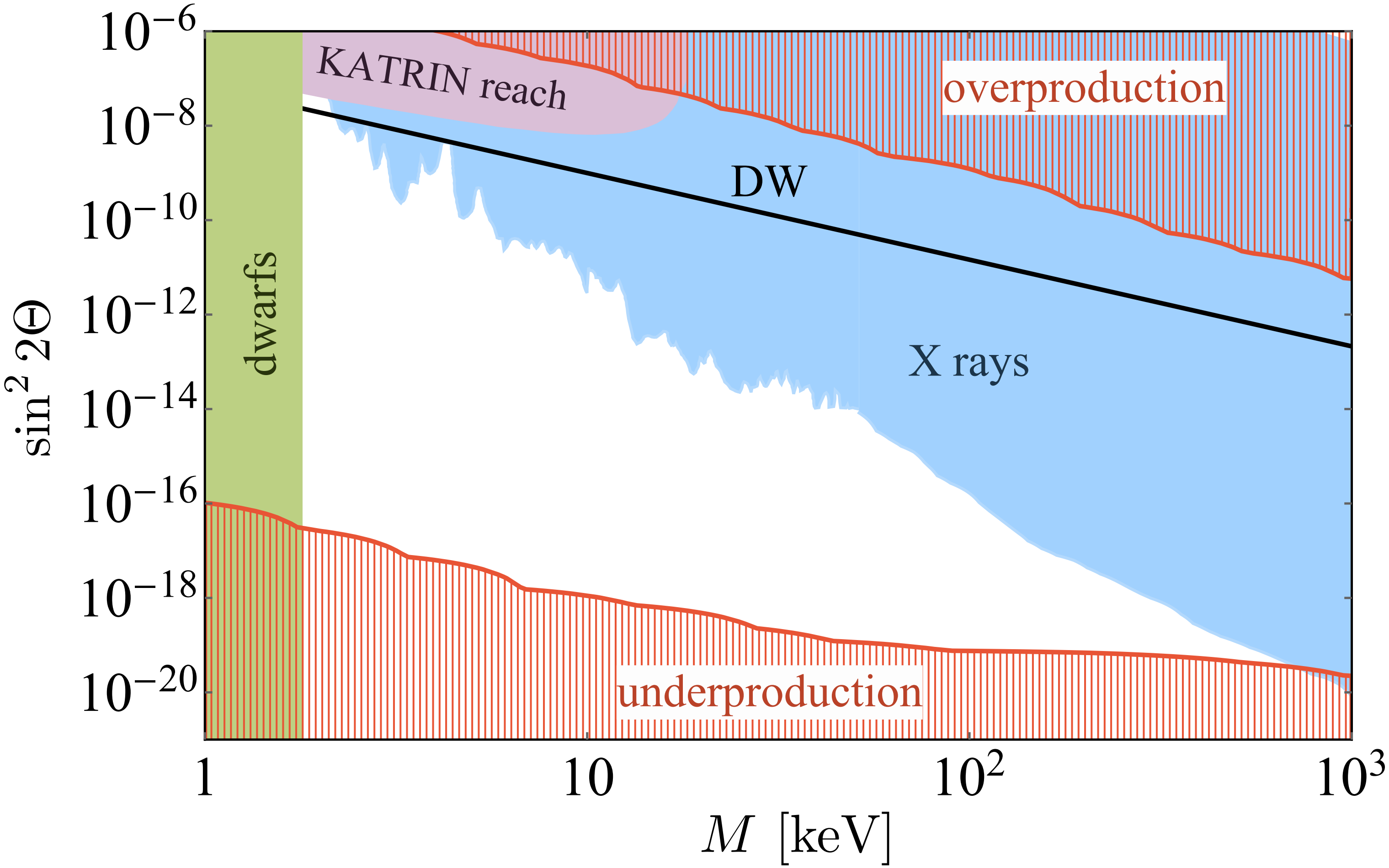
Introduction

- Sterule ν is a strong DM candidate.
- But the production mechanism is unknown.
- Dodelson-Widrow? $\quad W\nu_a \leftrightarrow W\nu$



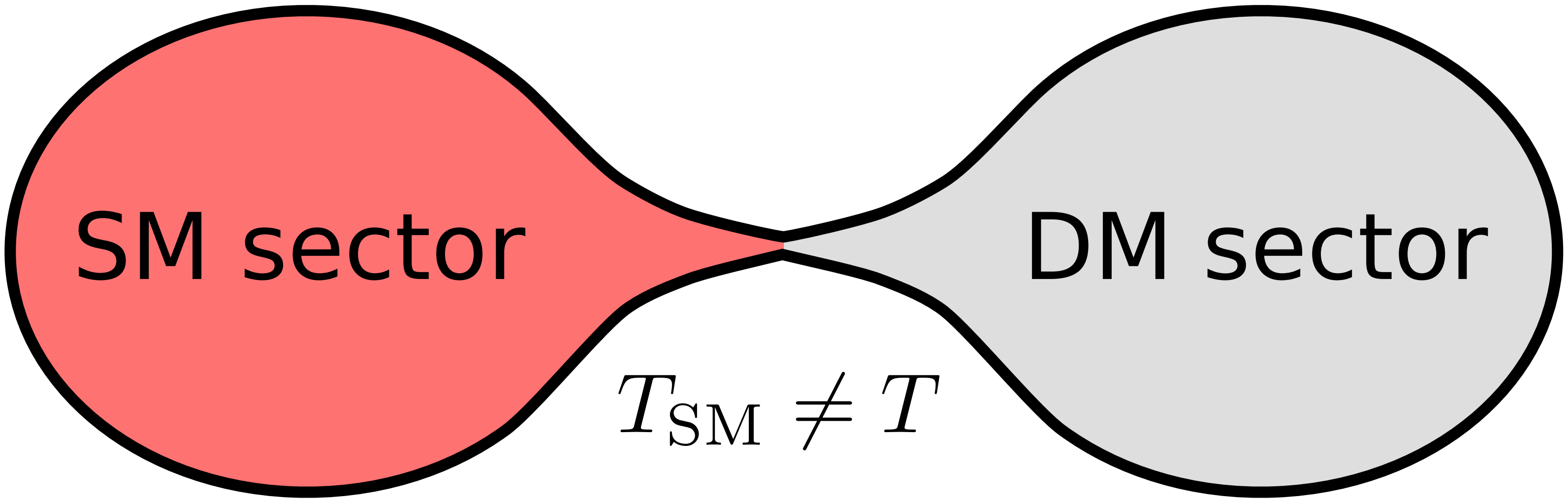
Gouvea et al.,
PRL 124 (2020) 8, 081802
arXiv:1910.04901

Introduction

- We consider a dark sector made from sterile ν and a scalar field s.

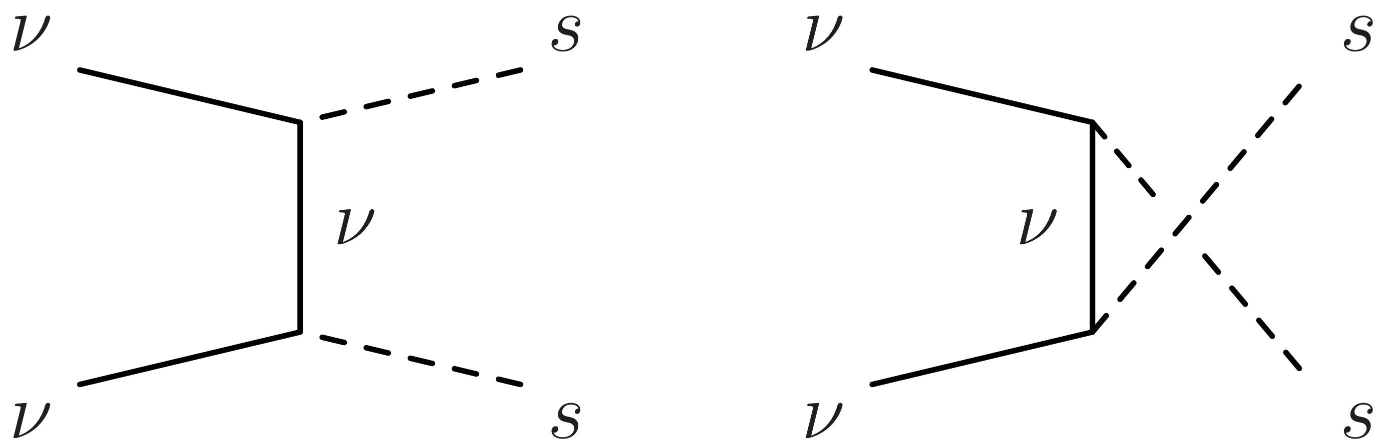
  $\Rightarrow$ dark matter is produced from dark thermal bath.

1. Quantum statistics: $f = \left(e^{(E-\mu)/T} \pm 1\right)^{-1}$
2. Thermal mass: $\Delta m_s^2 = \dfrac{\lambda_s}{4} T^2$, $\Delta M^2 = \dfrac{\lambda^2 T^2}{16}$



Model (setup)

- Particles in dark sector: ν (DM) and s (real scalar)
- Lagrangian: $\mathcal{L} = -y_\nu L H \nu - \frac{\lambda}{2} s\nu\nu - \frac{M}{2}\nu\nu$
- Relic abundance is determined by $\nu\nu \to ss$ freeze-out $(M > m_s)$



- But SM sector is decoupled from dark sector $(T_{\rm SM} \neq T)$

  Temperature of dark sector: T Temperature of SM sector: $T_{\rm SM}$

  $T < T_{\rm SM} \Leftarrow$ SM sector dominates energy density in the universe.

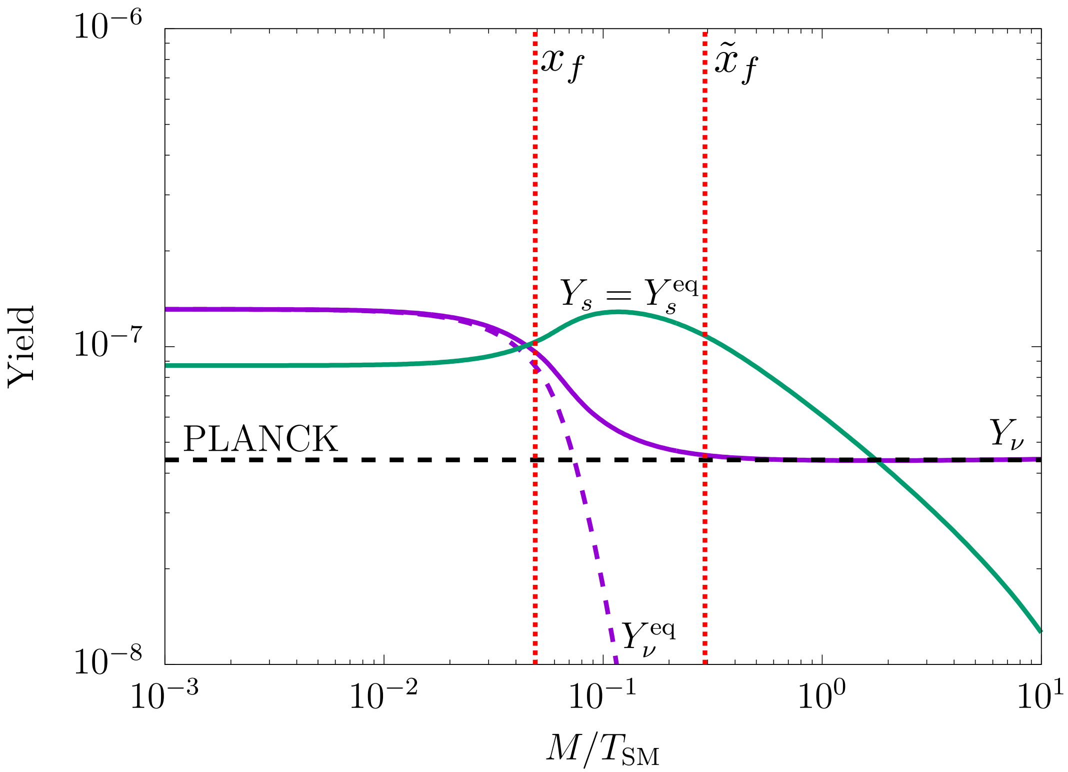
DM relic abundance

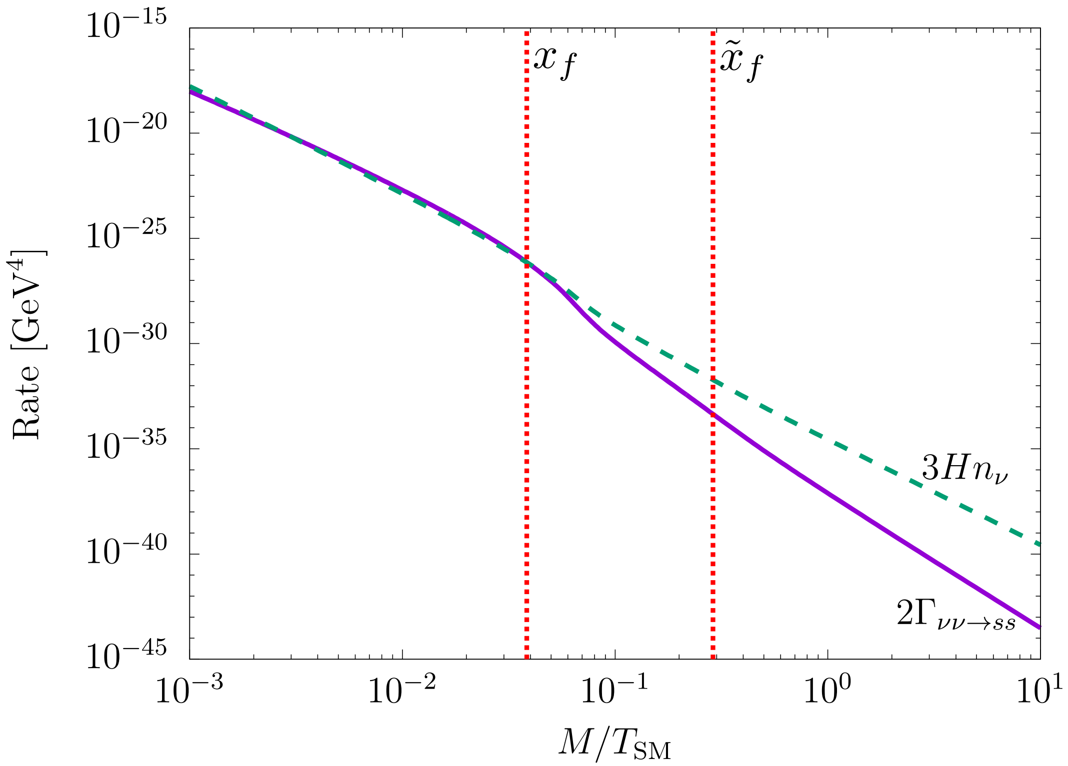
- Boltzmann equation
  $$\frac{dn_\nu}{dt} + 3Hn_\nu = 2\left(\Gamma_{ss\to\nu\nu} - \Gamma_{\nu\nu\to ss}\right)$$
  Reaction rate for inverse process $\Gamma_{ss\to\nu\nu} = \Gamma_{\nu\nu\to ss} e^{-2\mu/T}$

- Entropies in each sector independently conserve.
  $$\frac{s_\nu + s_s}{s_{\rm SM}} = \text{const}$$

- Solve the coupled equations

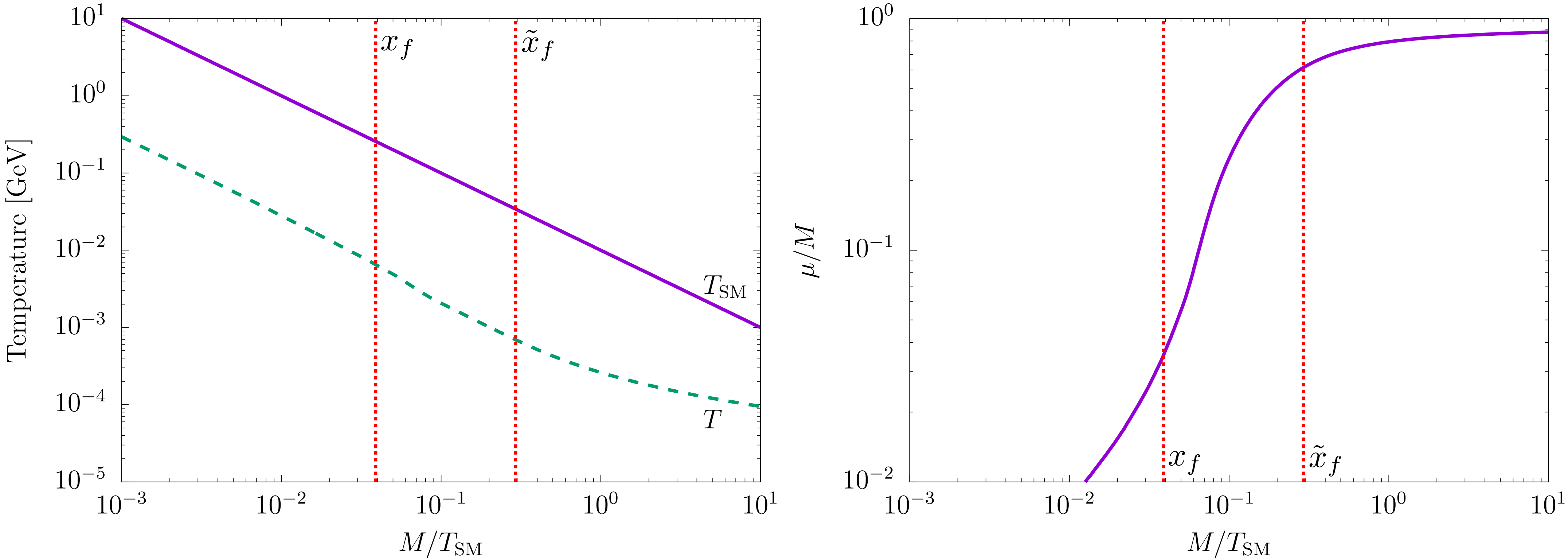
Example of numerical solution





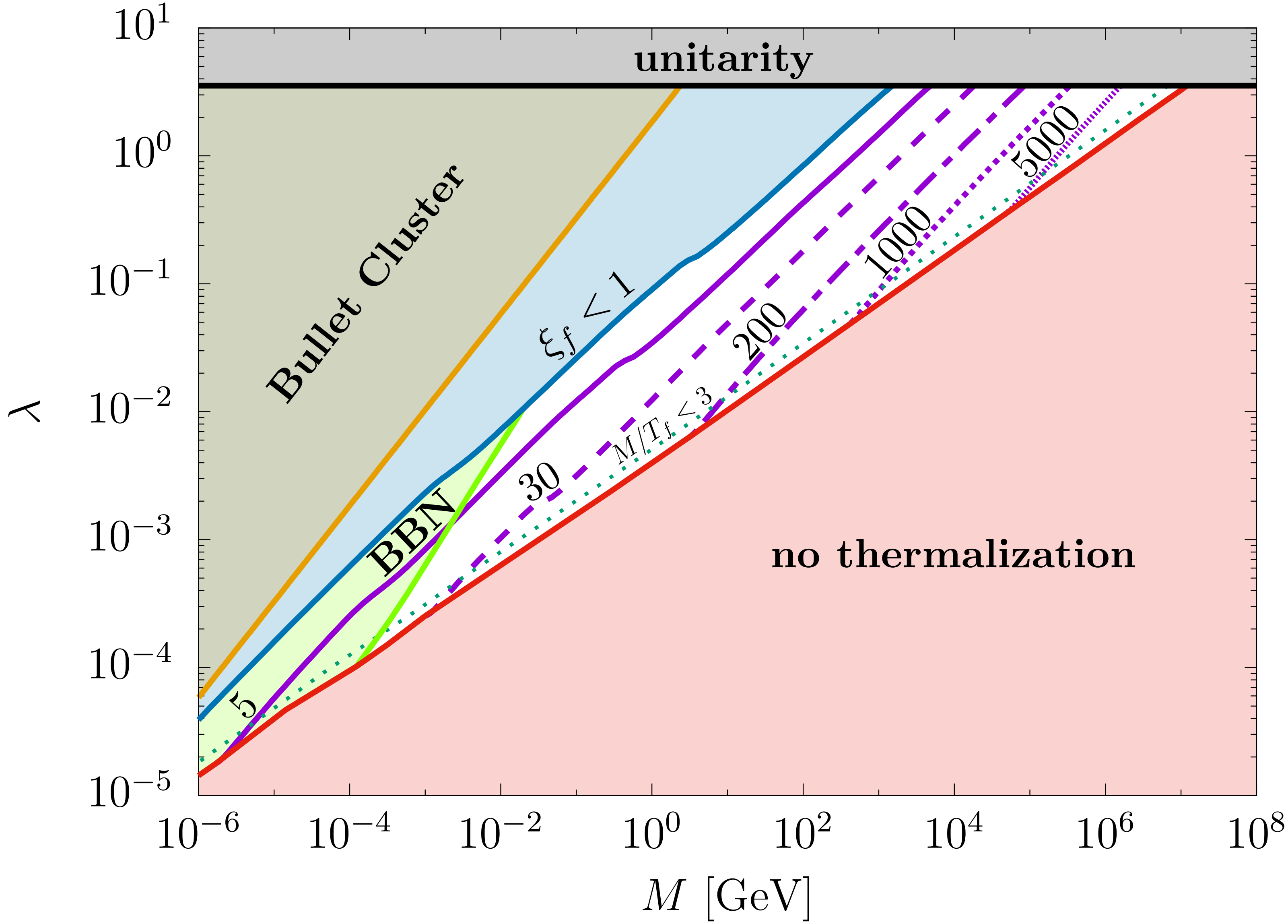
- $M = 10$ MeV, $\lambda = 6.5 \times 10^{-4}$
- Initial condition: $T_{\rm SM}/T = 34$ at $M/T_{\rm SM} = 10^{-3}$
- Yield $= Y_i = \dfrac{n_i}{s_{\rm SM}}$ where $s_{\rm SM} = \dfrac{2\pi^2}{45} g_{*s} T_{\rm SM}^3$
- $M/T_f = 1.54 \Rightarrow$ relativistic freeze-out

Example of numerical solution



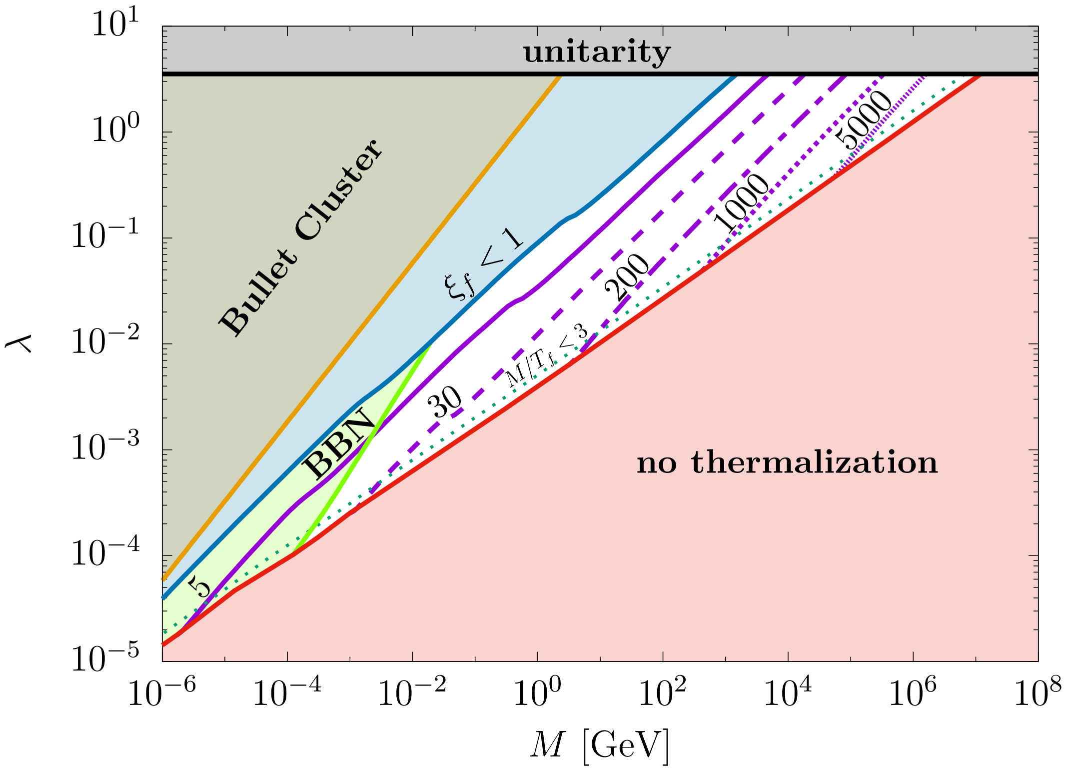
- Temperature starting decoupling: $x_f = M/T_f$
  Temperature fixing relic abundance: $\tilde{x}_f = M/\tilde{T}_f$
- Relation between x_f and $\tilde{x}_f$: $\tilde{x}_f/x_f = 2.6x_f^{-1.04} - 3.0x_f^{-0.024} + 3.6$
- Final DM abundance: $Y_\infty = 4.4 \times 10^{-10} \left(\dfrac{\mathrm{GeV}}{M}\right)$

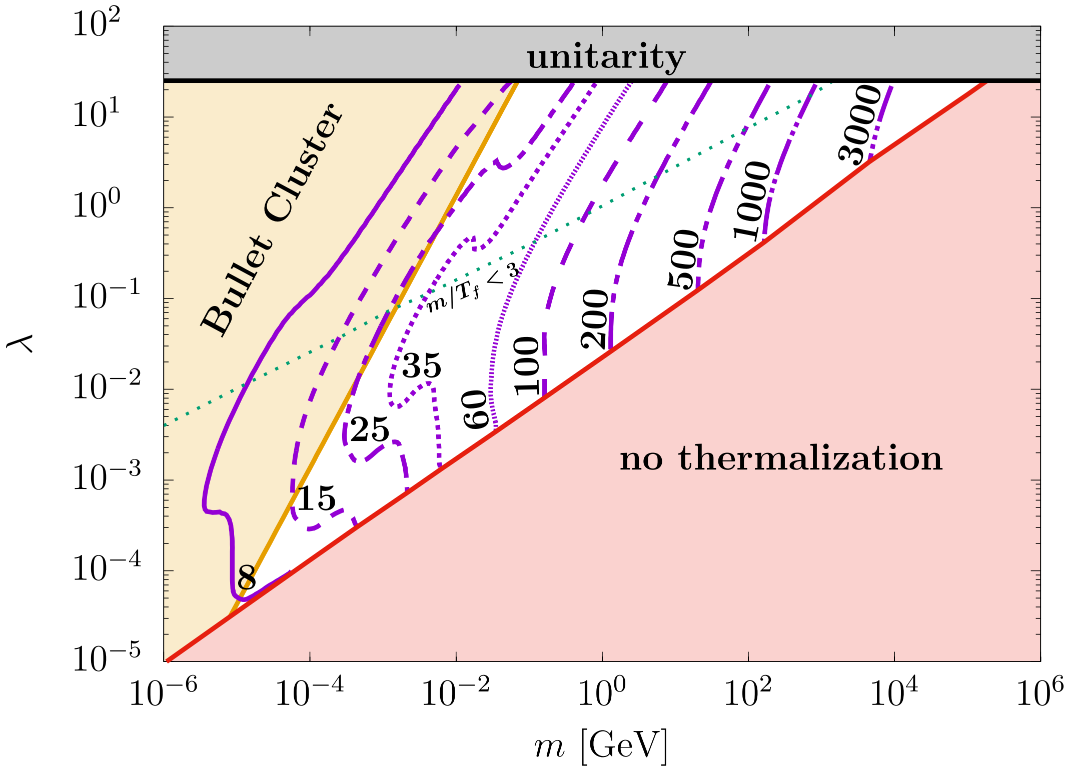
Summary plot



- $\xi_f = T_{\rm SM}/T$ at freeze-out $= 5, 30, 200, 1000, 5000$

Comparison with previous work (different process)





Arcadi, Lebedev, Pokorski, TT, JHEP 08 050 (2019)

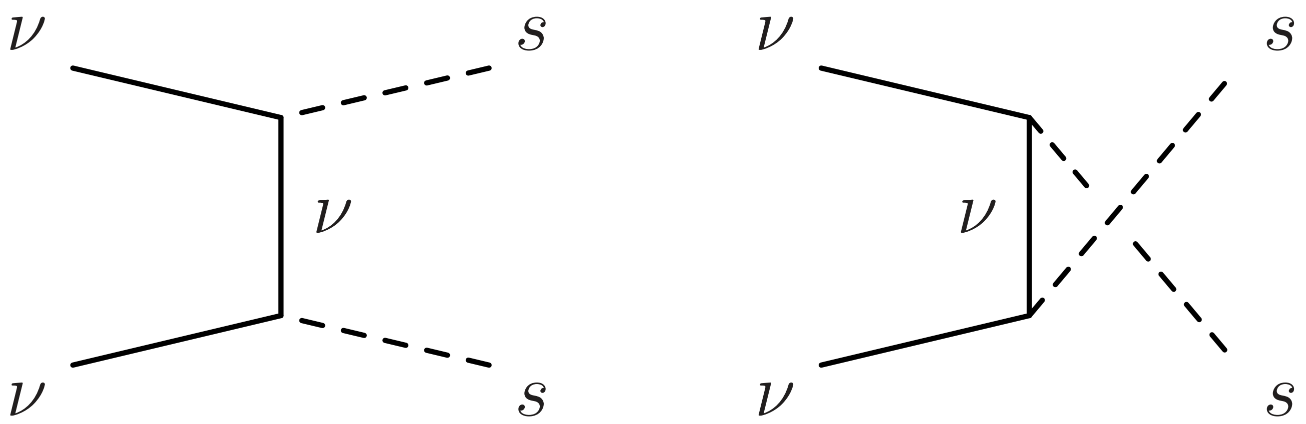
- Scalar DM (S) is produced via $SSSS \to SS$ in dark sector.
- For the scalar S, large parameter space inducing relativistic freeze-out due to BE enhancement
  $\Rightarrow$ This is because of large enhancement due to $f^4(1+f)^2$.

Summary

1. Sterile ν is a strong DM candidate.
2. But the production mechanism is unknown.
3. Here we considered a production from dark sector freeze-out.
4. Most of parameter space induces non-relativistic freeze-out.
   (large relativistic parameter space for $SSSS \to SS$)

Back Up

$\nu\nu \to ss$ freeze-out



- Freeze-out in dark sector: $\nu\nu \to ss$

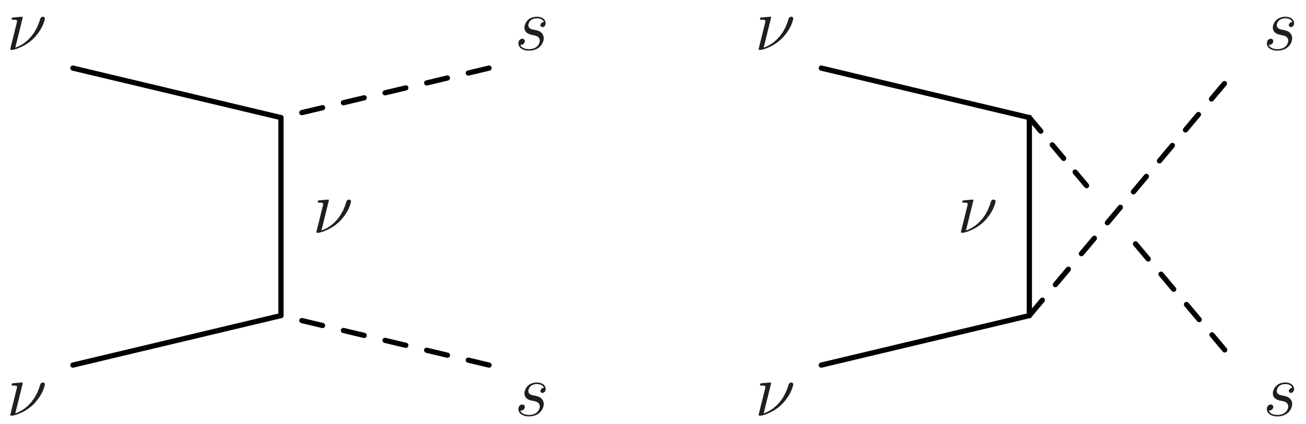
$$12 \to 34$$

- Reaction rate: $\Gamma_{\nu\nu\to ss} = \int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}$

$$\times f_1 f_2 (1+f_3)(1+f_4) \left|\mathcal{M}_{\nu\nu\to ss}\right|^2 (2\pi)^4 \delta^4(p_1+p_2-p_3-p_4)$$

- $1+f$: Bose-Einstein factor
- $f_\nu = \left(e^{\frac{E-\mu}{T}}+1\right)^{-1}, \qquad f_s = \left(e^{\frac{E}{T}}-1\right)^{-1}$

$\nu\nu \to ss$ freeze-out 2



- Modify the reaction rate: $\Gamma_{\nu\nu\to ss} =$

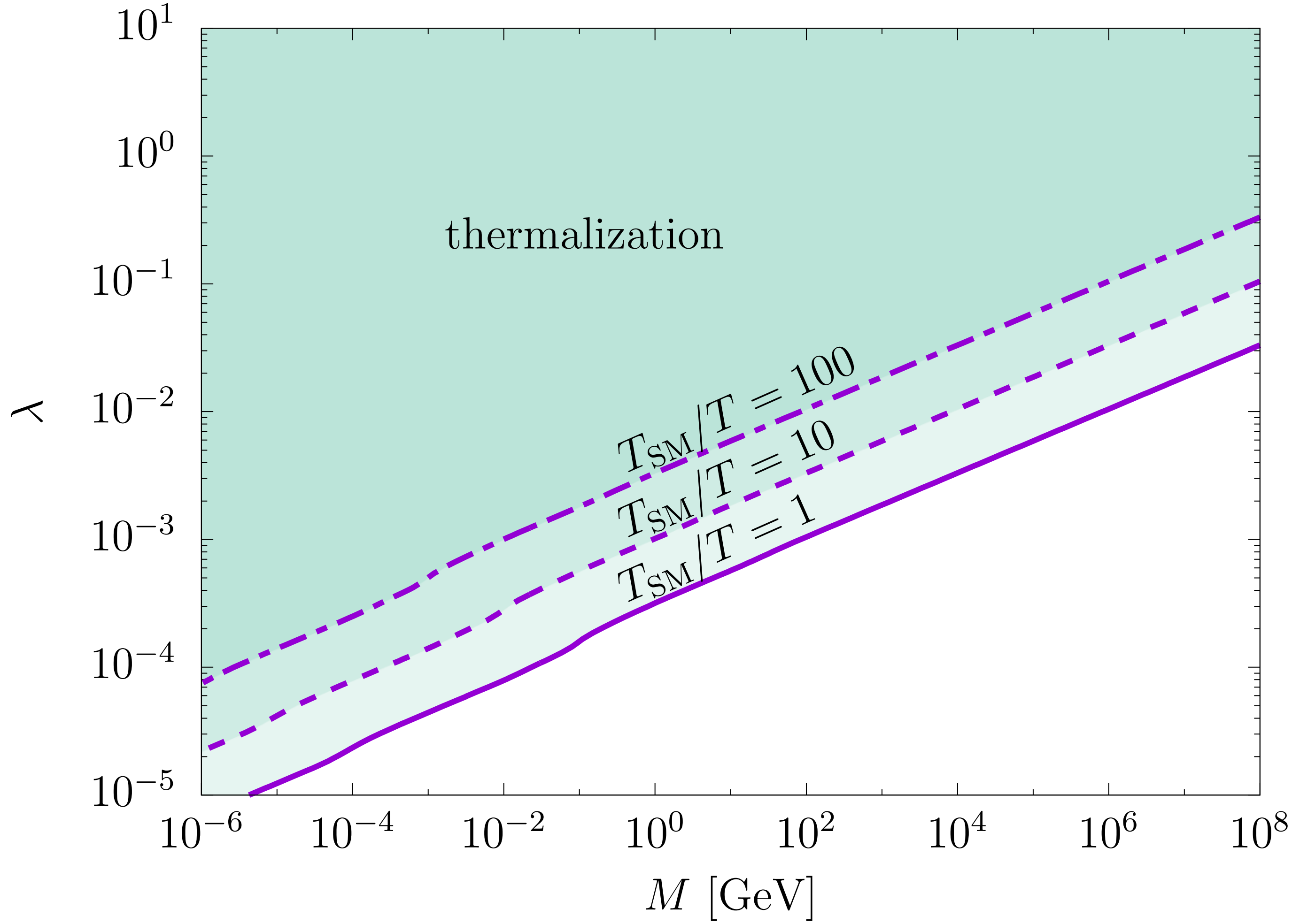
$$\frac{16T}{\pi^4}\int_M^\infty \frac{d\eta\ \sinh\eta\ \sigma_{\rm CM}(E,\eta)}{e^{2(E\cosh\eta-\mu)/T}-1}\log\left(\frac{\cosh\left(\frac{E}{2T}\cosh\eta+\frac{\sqrt{E^2-M^2}}{2T}\sinh\eta-\frac{\mu}{2T}\right)}{\cosh\left(\frac{E}{2T}\cosh\eta-\frac{\sqrt{E^2-M^2}}{2T}\sinh\eta-\frac{\mu}{2T}\right)}\right)$$

where $\sigma_{\rm CM}(E,\eta) = \dfrac{1}{4E_3E_4v_{\rm CM}}$

$$\times\int\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}(2\pi)^4\overline{|\mathcal{M}_{\nu\nu\to ss}|^2}(1+f_3)(1+f_4)\delta^4(p_1+p_2-p_3-p_4)$$

- Possible to numerically calculate $\sigma_{\rm CM}$ by CalcHEP

Parameter space that dark sector is thermalized

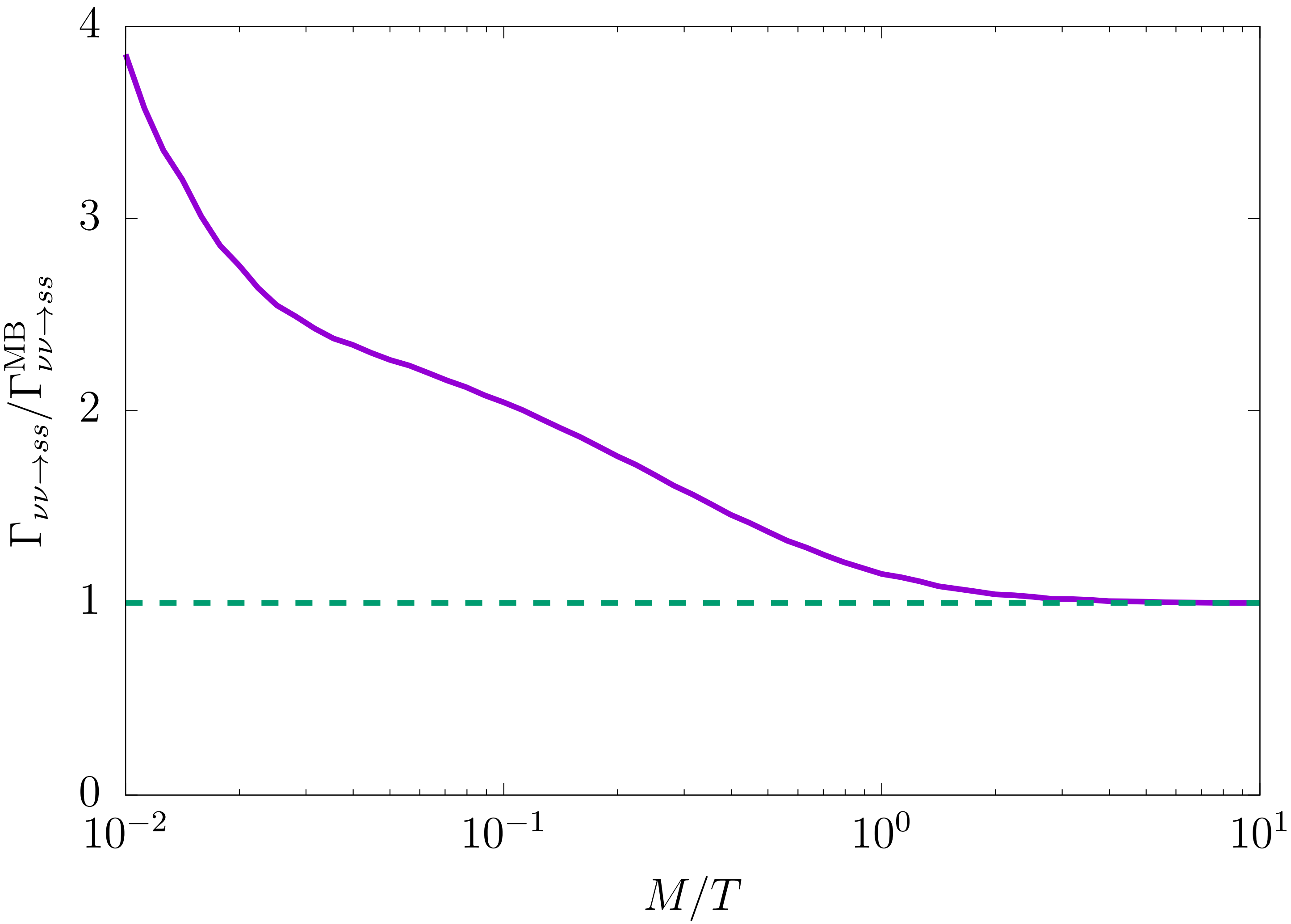


$\Gamma_{\nu\nu\to ss}(T) \approx H(T_{\rm SM}) n_\nu(T)$

$\Gamma_{\nu\nu\to ss}/n_\nu$ is maximum at $M/T \approx 0.6$

- $\lambda \approx 2 \times 10^{-4} \left(\frac{T_{\rm SM}}{T}\right)^{1/2} \left(\frac{M}{\rm GeV}\right)^{1/4}$

Effect of quantum statistics



- Ratio of reaction rates with quantum and Boltzmann (app.) statistics
- When $M/T \ll 1$, a few factor enhancement due to BE factor

Constraints

- The scalar s eventually decays into SM particles.

  BBN: $\tau_s < 1$s

  Ex: decay via the mixing with the SM Higgs

  $\tau_s < 1$s $\Leftrightarrow$ mixing angle $\sin\theta \gtrsim 10^{-9}$

  Decoupling temperature: $T_{\rm SM}$ at freeze-out > 1 MeV

- Self-interaction of sterile ν DM ($\nu\nu \to \nu\nu$)
  $$\frac{\sigma_{\rm self}}{M} = \frac{\lambda^4}{8\pi}\frac{M}{m_s^4} < 1\ {\rm cm}^2/{\rm g}$$

- $\xi_f = T_{\rm SM}/T$ at freeze-out
  Required condition: $\xi_f > 1$ ($\rho_{\rm SM} \gg \rho_{\rm DM}$)

- Perturbative unitarity bound: $\lambda < \sqrt{4\pi}$

- Dark sector thermalization condition: $\Gamma_{\nu\nu\to ss} > Hn_\nu$ at $M/T = 0.6$