Cosmic Stability of Dark Matter from Pauli Blocking

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Motivation

- The evidence for dark matter (DM) is substantial and varied, yet we know little about its fundamental properties.
- Among the few things we do know is that DM is **stable** on cosmic time scales.
- The (meta)stability of DM may provide an important clue to its fundamental nature, e.g.,
    - New stabilizing symmetry for DM (e.g. WIMP DM),
    - DM has feeble interactions and/or is very light (e.g., axion DM),
    - As in these examples, the origin of DM stability may suggest correlated observational signals.
- Here I wish to explore the idea that DM is long-lived in our Universe as a consequence of the **Pauli exclusion principle.**

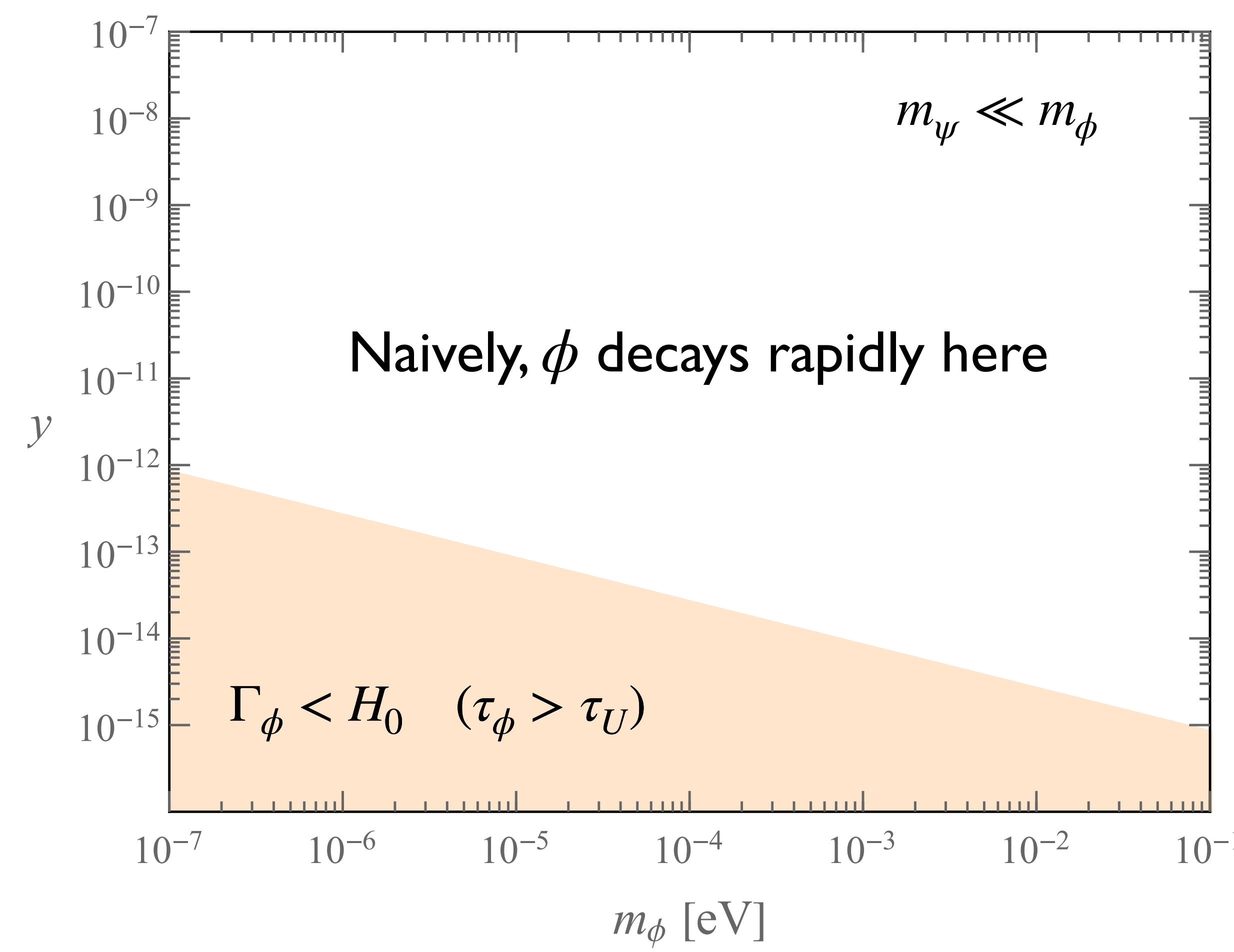
Basic setup

- DM is a light scalar field ϕ, which interacts with a lighter Majorana fermion ψ

$$-\mathscr{L} \supset \frac{1}{2} m_\phi^2 \phi^2 + \left(\frac{1}{2} m_\psi \psi \psi + \frac{1}{2} y \phi \psi \psi + \mathrm{h.c.} \right)$$

- The $\phi \to \psi\psi$ decay rate in vacuum is

$$\Gamma_\phi \simeq \frac{y^2 m_\phi}{16\pi} \quad \text{for} \quad m_\psi \ll m_\phi$$



- Naively, ϕ decays rapidly on cosmological time scales unless the Yukawa coupling is minuscule .

DM stability from Pauli blocking

- Suppose at some early redshift $z = z_{\rm ini}$ there is a population of non-relativistic ϕ particles, $n_\phi \neq 0$, and negligible population of ψ particles. Then ϕ decays via $\phi \to \psi\psi$.

- If the decay is fast, the states of ψ in a spherical shell of momentum around $E_\psi = m_\phi/2$ are quickly occupied ("Fermi shell"). The effective decay rate is then

$$\Gamma_\phi^{\rm eff} = \Gamma_\phi \left(1 - 2 f_\psi [E_\psi = m_\phi/2]\right)$$

  Here f_ψ is the fermion phase space distribution function. This says that f_ψ cannot increase beyond $f_\psi = 1/2$, at which point the decay is Pauli blocked.

- Since the Universe expands, the ψ energy redshift as $E \propto a^{-1}$. Thus, the original shell shrinks while the DM decays continuously replenishes the shell near $E_\psi = m_\phi/2$. For $z \ll z_{\rm ini}$, ψ forms a Fermi sea, with Fermi energy $E_F = m_\phi/2$:

$$f_\psi = \frac{1}{2}\Theta\left[\frac{m_\phi}{2} - p\right]\Theta\left[p - \frac{m_\phi}{2}\frac{1+z}{1+z_{\rm ini}}\right] \to \frac{1}{2}\Theta\left[\frac{m_\phi}{2} - p\right]$$

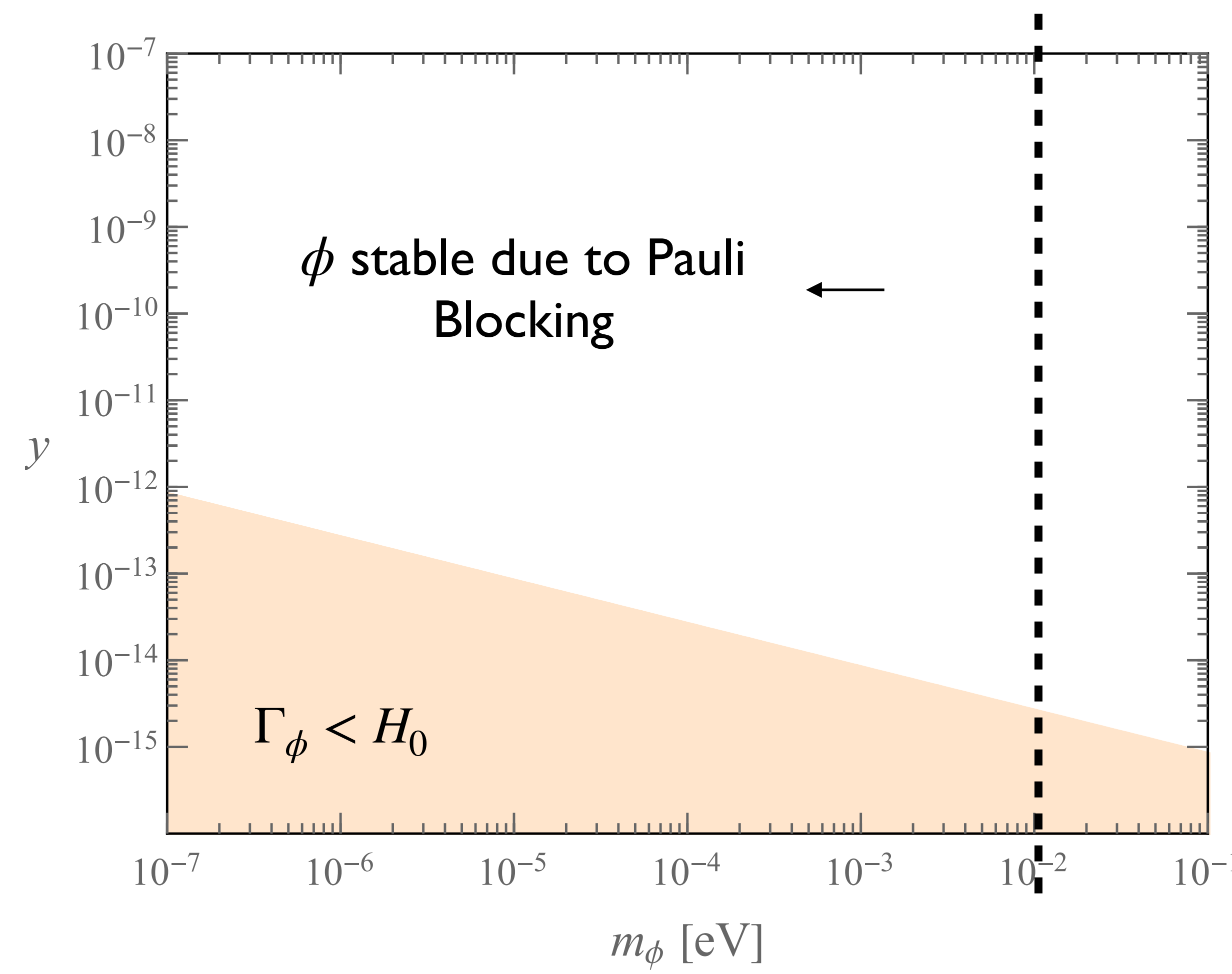
DM stability from Pauli blocking

- The energy transferred to the Fermi sphere is negligible if

$$\rho_\phi \gg \rho_\psi = g_\psi \int \frac{d^3 p_\psi}{(2\pi)^3} E_\psi f_\psi = \frac{g_\psi}{2\pi^2} \int_0^{E_F} dE_\psi E_\psi^3 \frac{1}{2} = \frac{g_\psi E_F^4}{16\pi^2} = \frac{g_\psi m_\phi^4}{256\pi^2}$$

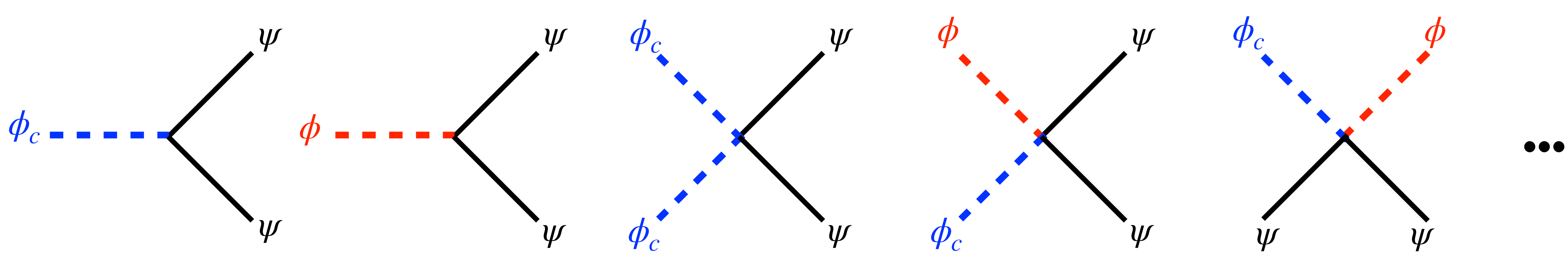
- If ϕ is to account for DM, this bound should at least be satisfied today, with $\Omega_{\phi,0} \simeq 0.26$ [$\rho_\phi \sim (2\,\mathrm{meV})^4$]

- This leads to the bound $m_\phi \ll 0.01\,\mathrm{eV}$



Thermalization and Evaporation

- Thus far we have shown that scalar DM is stable against decays due to Pauli blocking, provided it is lighter than about 10 meV. However, we have not accounted for scattering processes.
- The scalar condensate may still "evaporate" if 2-to-2 scattering processes are fast.
- For large enough couplings y, we anticipate that the scalar-fermion system will eventually reach a quasi-equilibrium state comprised of a DM condensate $\phi_{\rm c}$ and a thermal dark radiation component $(\phi_{\rm th}, \psi)$.
- Thus we must therefore study the evolution of the scalar-fermion fluid accounting for decay / inverse decay and scattering involving $\phi_c, \phi_{\rm th}, \psi$.



Approach to thermalization

- At early times, after ϕ starts oscillating, parametric resonance (see below) populates ψ with number density $\mathcal{O}(m_\phi^3)$ and typical particle momentum of $p_{\rm typ} \gtrsim m_\phi$.

- The decay-inverse decay $\phi \leftrightarrow \psi\psi$ is isotropic in the parent rest frame, but in the cosmic frame the decay products will have directions with angle $\theta \sim 1/\gamma \sim m_\phi/p_{\rm typ}$.

- To isotropize particle momenta requires a random walk of N reactions such that $\theta_{eff}^2 \approx (m_\phi/p_{\rm typ})^2 N \approx 1$.

- The time scale for isotropization is

$$t_{\rm iso} \simeq \Gamma_\phi^{-1} \times N \approx \left[\frac{y^2 m_\phi}{16\pi}\left(\frac{m_\phi}{p_{\rm typ}}\right)^2\right]^{-1}$$

- At this time scale, the system consists of the nearly homogeneous and isotropic dark radiation plasma and the DM condensate

Boltzmann equations

- To study the evolution of the dark sector we employ the Boltzmann equations:

$$\frac{\partial f_\phi[p_\phi, t]}{\partial t} - p_\phi H \frac{\partial f_\phi[p_\phi, t]}{\partial p_\phi} = C^\phi[p_\phi, t],$$
$$\frac{\partial f_\psi[p_\psi, t]}{\partial t} - p_\psi H \frac{\partial f_\psi[p_\psi, t]}{\partial p_\psi} = C^\psi[p_\psi, t],$$

- Solving directly for the phase space distributions is challenging (coupled partial integro-differential equations). To make progress, we make the following ansatz:

$$f_\phi[p_\phi, t] = \hat{f}_\phi[p_\phi, t] + f_\phi^{\rm th}[p_\phi, t], \qquad f_\psi[p_\psi, t] = f_\psi^{\rm th}[p_\psi, t],$$

$$\hat{f}_\phi[p_\phi, t] = (2\pi)^3 \hat{n}_\phi[t] \delta^3(\vec{p}_\phi) \qquad f_{\phi,\psi}^{\rm th}[p, t] = \left\{\exp\left[\frac{E_{\phi,\psi} - \mu_{\phi,\psi}[t]]}{T[t]}\right] \mp 1\right\}^{-1}$$

Condensate

Thermal component (equilibrium form)

Integrated Boltzmann equations

- With the ansatz above we study the evolution of the bulk quantities (number densities, energy densities, pressure):

$$n_i[t] = g_i \int \frac{d^3p_i}{(2\pi)^3}\, f_i[p_i,t], \qquad \rho_i[t] = g_i \int \frac{d^3p_i}{(2\pi)^3}\, E_i\, f_i[p_i,t], \qquad P_i[t] = g_i \int \frac{d^3p_i}{(2\pi)^3}\, \frac{p_i}{3E_i}\, f_i[p_i,t],$$

- We can isolate the condensate and thermal components via a projection operator $\hat{P}$ that excludes a small region around $p_\phi = 0$ in the integrals:

$$\hat{P} \int \frac{d^3p_\phi}{(2\pi)^3} \equiv \frac{1}{(2\pi)^3} \int d\Omega_\phi \int_\epsilon^\infty p_\phi^2\, dp_\phi \qquad [1-\hat{P}] \int \frac{d^3p_\phi}{(2\pi)^3} \equiv \frac{1}{(2\pi)^3} \int d\Omega_\phi \int_0^\epsilon p_\phi^2\, dp_\phi,$$

➡

$$[1-\hat{P}] \int \frac{d^3p_\phi}{(2\pi)^3}\, f_\phi[p_\phi,t] = [1-\hat{P}] \int \frac{d^3p_\phi}{(2\pi)^3}\, \hat{f}_\phi[p_\phi,t] = \hat{n}_\phi[t],$$

Condensate

$$\hat{P} \int \frac{d^3p_\phi}{(2\pi)^3}\, f_\phi[p_\phi,t] = \hat{P} \int \frac{d^3p_\phi}{(2\pi)^3}\, f_\phi^{\rm th}[p_\phi,t] = n_\phi^{\rm th}[t]$$

Thermal component

Integrated Boltzmann equations

- With the projection operators, we can write the Boltzmann equations for the number and energy densities:

$$\dot{\hat{n}}_\phi + 3H\hat{n}_\phi = \mathcal{C}^{\phi_c}, \qquad \dot{\hat{\rho}}_\phi + 3H(\hat{\rho}_\phi + \hat{P}_\phi) = \mathcal{E}^{\phi_c},$$

$$\dot{n}_\phi^{\rm th} + 3Hn_\phi^{\rm th} = \mathcal{C}^{\phi}, \qquad \dot{\rho}_\phi^{\rm th} + 3H(\rho_\phi^{\rm th} + P_\phi^{\rm th}) = \mathcal{E}^{\phi},$$

$$\dot{n}_\psi + 3Hn_\psi = \mathcal{C}^{\psi}. \qquad \dot{\rho}_\psi + 3H(\rho_\psi + P_\psi) = \mathcal{E}^{\psi}.$$

- Summing the equations for the energy densities, we have

$$\dot{\rho}_{\rm tot} + 3H(\rho_{\rm tot} + P_{\rm tot}) = \mathcal{E}^{\phi_c} + \mathcal{E}^{\phi} + \mathcal{E}^{\psi} = 0,$$

- The condensate (thermal components) are non-relativistic (typically relativistic), leading to

$$\hat{\rho}_\phi = m_\phi \hat{n}_\phi, \qquad \hat{P}_\phi = 0. \qquad\qquad P_\phi^{\rm th} \simeq \rho_\phi^{\rm th}/3, \qquad P_\psi \simeq \rho_\psi/3.$$

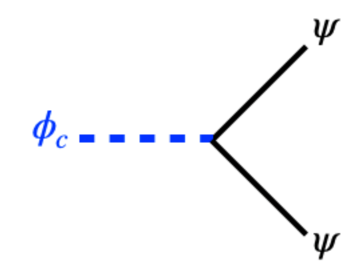
Condensate — Thermal component

Collision term example - DM decay / inverse decay

- Unintegrated collision term for decay / inverse decay:

$$C^{\phi}_{\phi\leftrightarrow\psi\psi} = -\frac{1}{S_\psi}\frac{1}{g_\phi}\frac{1}{2E_\phi}\sum_{\rm spins}\int d\Pi_1\, d\Pi_2\,(2\pi)^4\delta^4(p_\phi - p_1 - p_2)|\mathcal{M}_{\phi\to\psi\psi}|^2$$
$$\times\{f_\phi[p_\phi](1-f_\psi[p_1])(1-f_\psi[p_2]) - (1+f_\phi[p_\phi])f_\psi[p_1]f_\psi[p_2]\}\,.$$

- Use projector to isolate condensate and thermal pieces:
  - Condensate ϕ_c :



$$\mathcal{C}^{\phi_c}_{\phi_c\leftrightarrow\psi\psi} = g_\phi[1-\hat{P}]\int\frac{d^3p_\phi}{(2\pi)^3}C^{\phi}_{\phi\leftrightarrow\psi\psi}$$
$$= -\frac{1}{S_\psi}\sum_{\rm spins}[1-\hat{P}]\int d\Pi_\phi\, d\Pi_1\, d\Pi_2\,(2\pi)^4\delta^4(p_\phi - p_1 - p_2)|\mathcal{M}_{\phi\to\psi\psi}|^2\;\hat{f}_\phi[p_\phi](1-f_\psi[p_1]-f_\psi[p_2]).$$

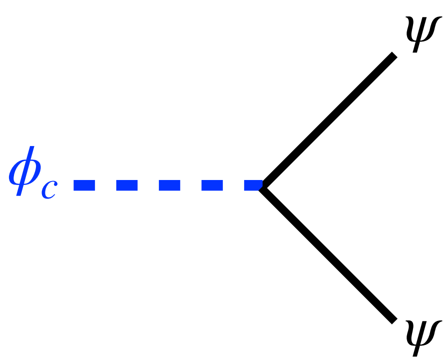
- The integrals can be carried out analytically:

$$\mathcal{C}^{\phi_c}_{\phi_c\leftrightarrow\psi\psi} = -\Gamma_{\phi\to\psi\psi}\,(1-2f_\psi[E_\psi = m_\phi/2])\,\hat{n}_\phi,$$

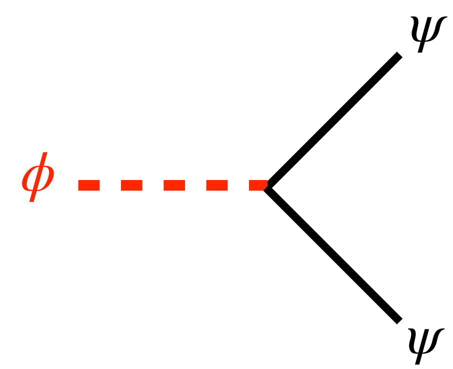
effective DM decay rate advertised earlier

  - The phase space factor is proportional to $e^{m_\phi/2T} - e^{\mu_\psi/T}$ and biases $\mu_\psi \to m_\phi/2$, at which point the DM condensate decay is Pauli blocked.

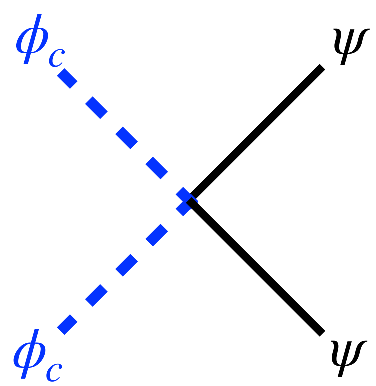
Collision terms:



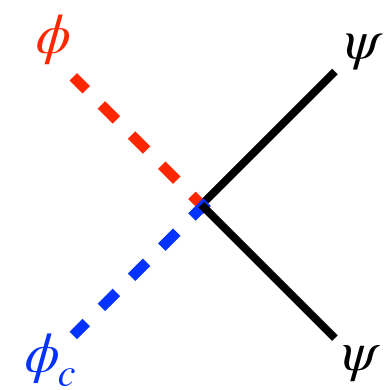
$\sim \quad \mu_\psi \to m_\phi/2$



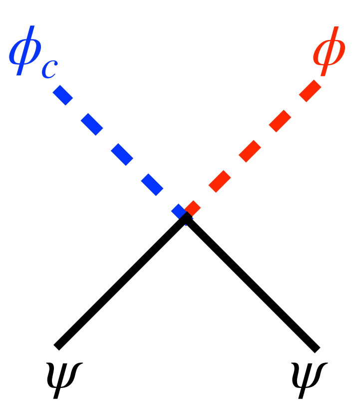
$\sim \quad \mu_\phi \to 2\mu_\psi \to m_\phi$



$\sim \quad \mu_\psi \to m_\phi$



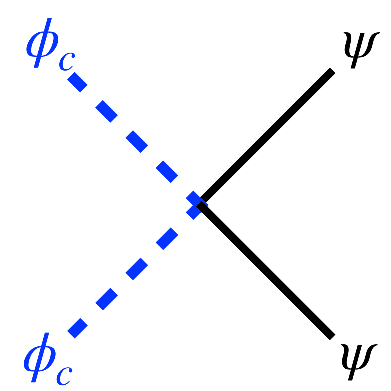
$\sim \quad \mu_\psi \to (\mu_\phi + m_\phi)/2$



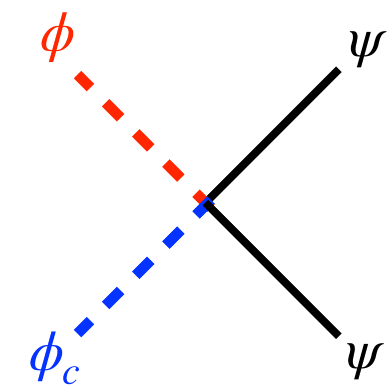
$\sim \quad \mu_\phi \to m_\phi$

When both (inverse) decay and scattering are fast, number conservation no longer hold, and the temperature starts to grow

Chirality suppressed case, $m_\psi \to 0$



$\to 0$



$\neq 0$

Evolution for benchmark model:

$$n_\phi[0]/m_\phi^3 = 10^8,$$

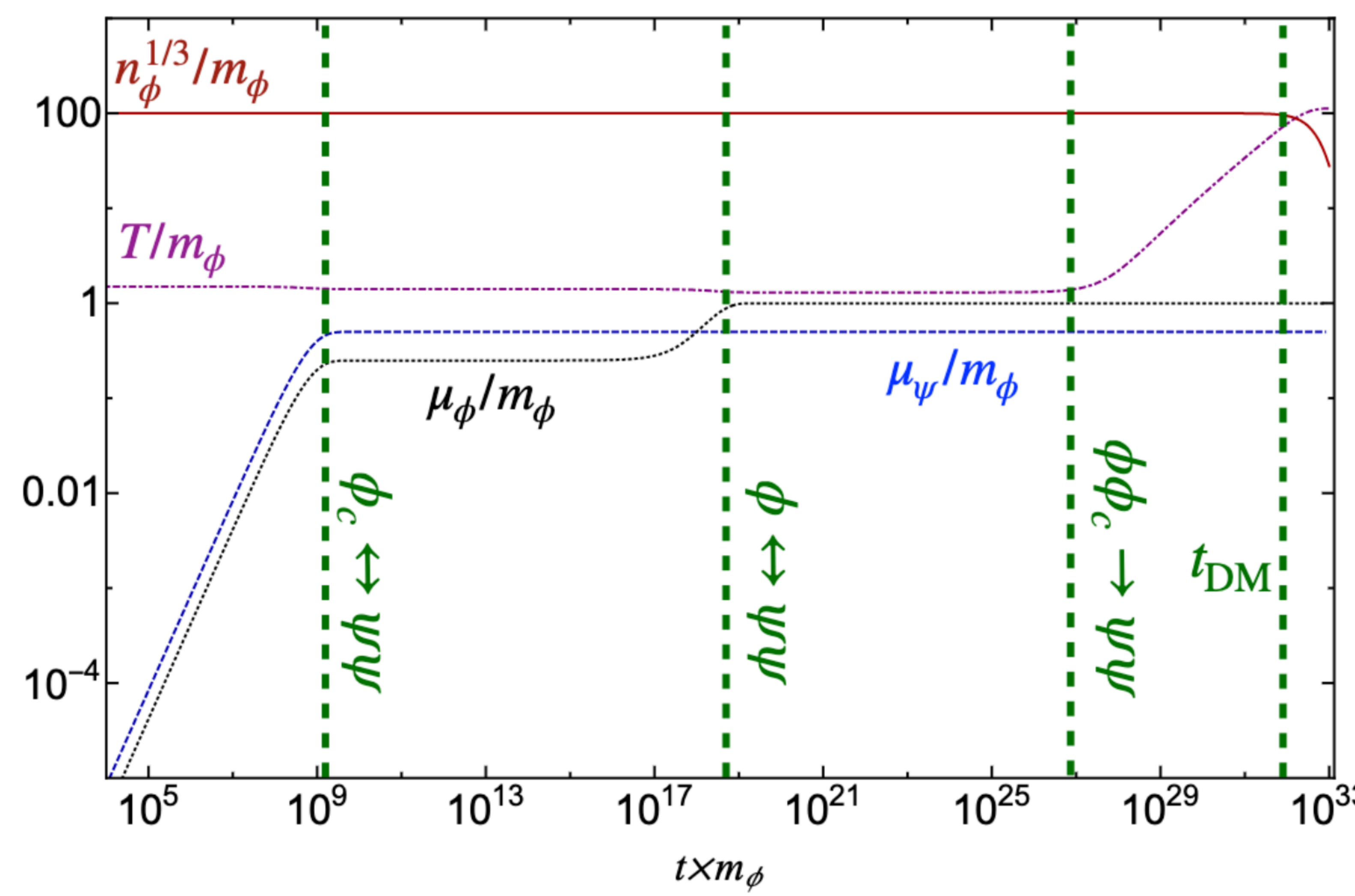
$$T[0] = 3/2 m_\phi,$$

$$\mu_\phi[0] = \mu_\psi[0] = 0,$$

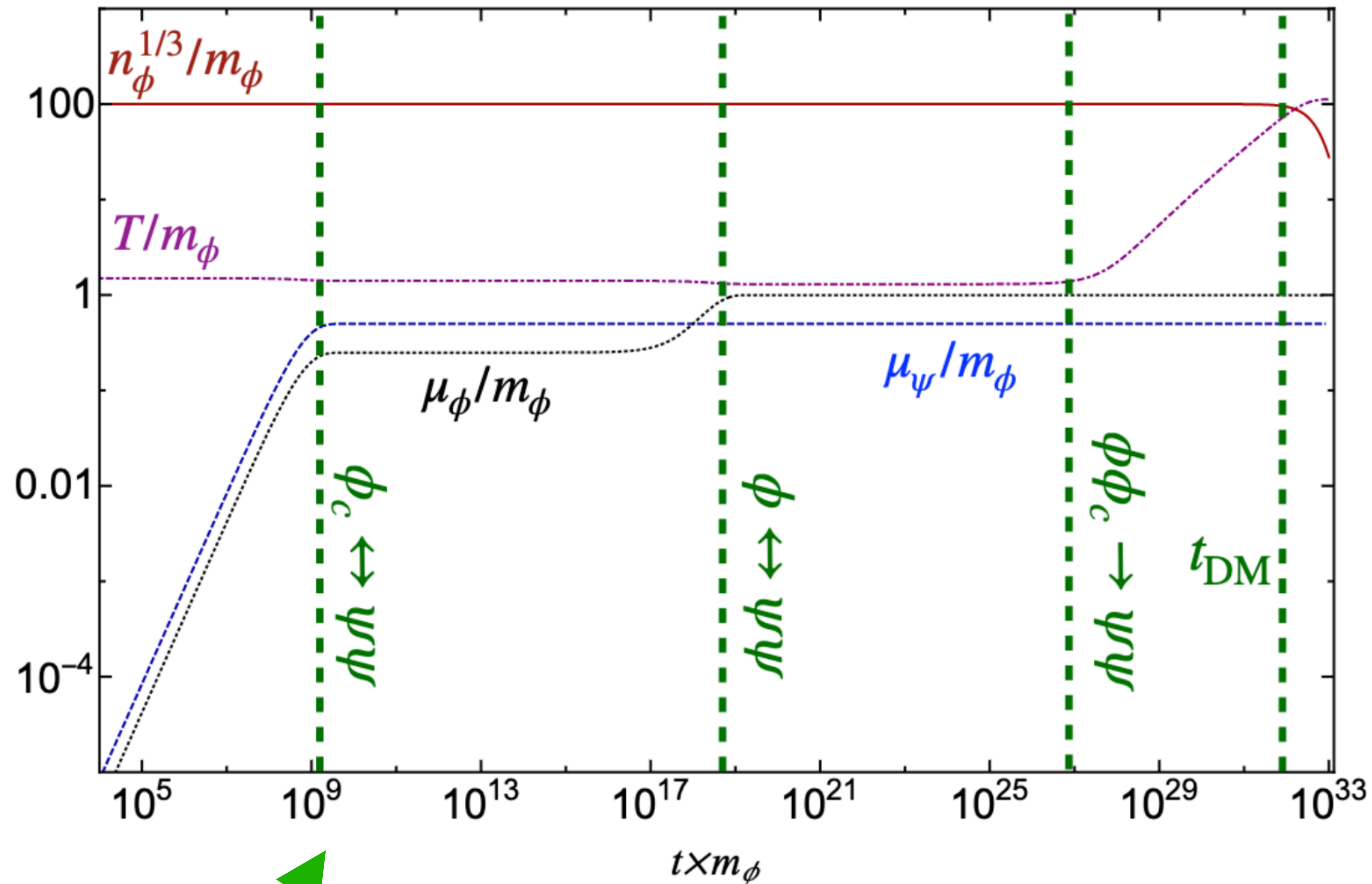
$$y = 10^{-8}$$

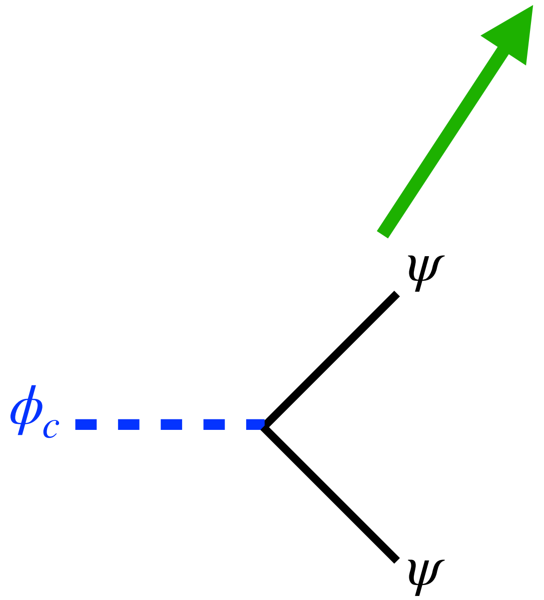
$$m_\psi = 0,$$

Neglect Hubble expansion



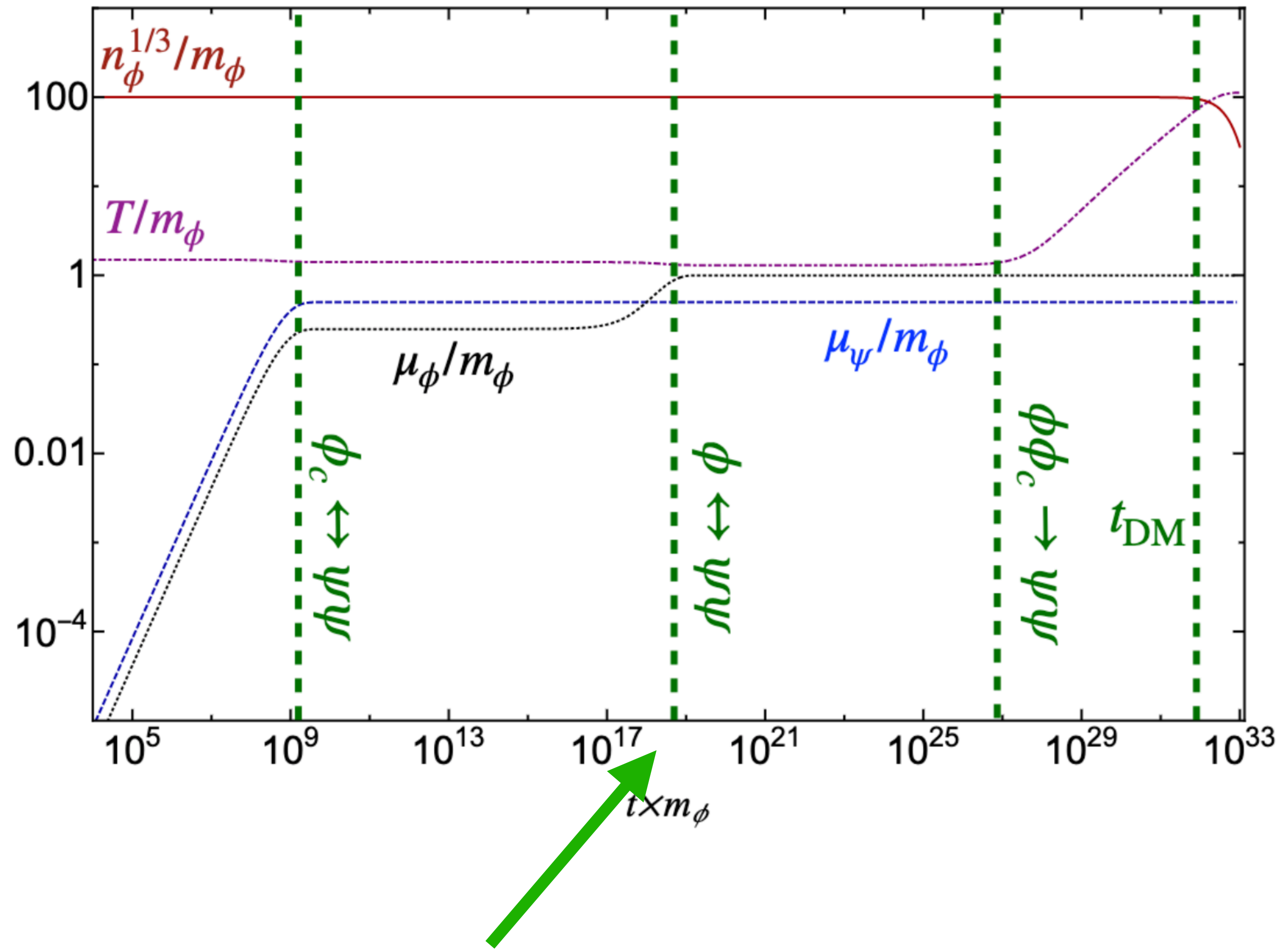
Chirality suppressed case, $m_\psi \to 0$

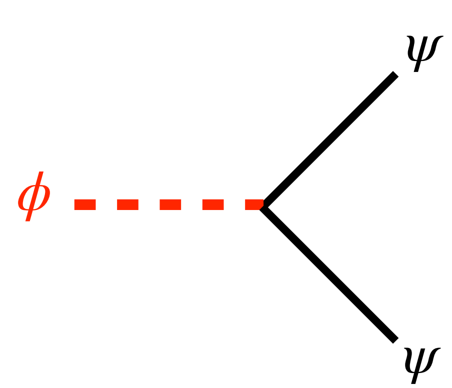




$\sim \quad \mu_\psi \to m_\phi/2$

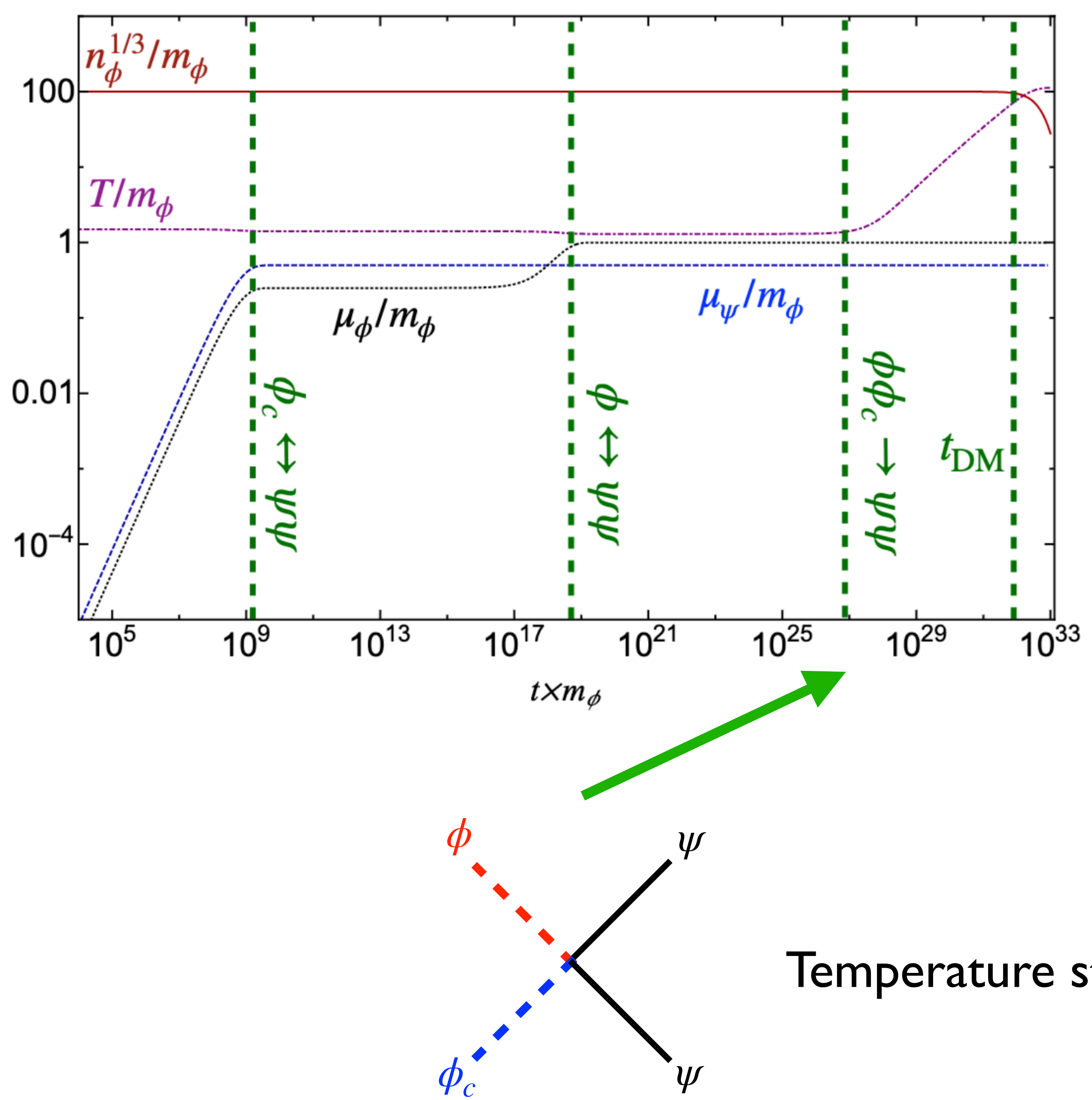
Chirality suppressed case, $m_\psi \to 0$





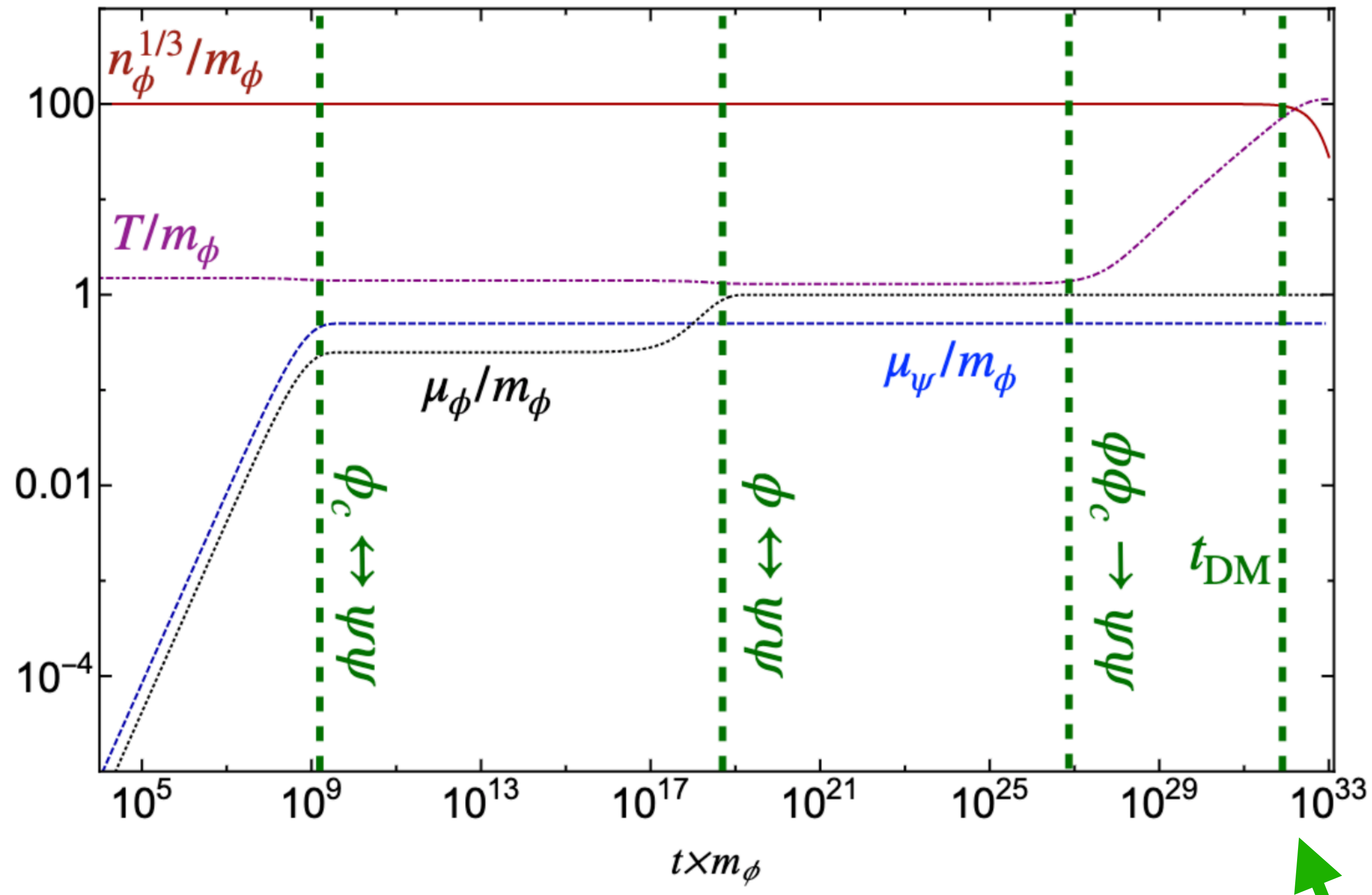
$\sim \quad \mu_\phi \to 2\mu_\psi \to m_\phi$

Chirality suppressed case, $m_\psi \to 0$



Temperature starts to grow

Chirality suppressed case, $m_\psi \to 0$



DM condensate "decays" or evaporates due to annihilation

Chirality suppressed case, $m_\psi \to 0$

- Boltzmann equation:

$$\frac{d}{dt}(\rho_\phi^{\rm th} + \rho_\psi) = (g_\phi + \frac{7}{8}g_\psi)\frac{\pi^2}{30}\frac{d}{dt}T^4 \approx \Gamma_{\rm th} m_\phi n_\phi^{\rm th}, \qquad \Gamma_{\rm th} \equiv \frac{y^4 \hat{n}_\phi}{32\pi T^2}, \qquad n_\phi^{\rm th} \approx \frac{T^3}{\pi^2}$$

➡ $$t \sim \frac{1}{y^4 m_\phi \hat{n}_\phi} T^3$$

- DM condensate evaporates when $(g_\phi + \frac{7}{8}g_\psi)\frac{\pi^2}{30}T^4[t_{\rm DM}] = m_\phi \hat{n}_\phi[z=0]$

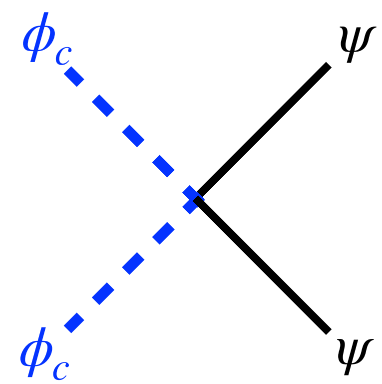
➡ $$(y^4 m_\phi \hat{n}_\phi t_{\rm DM})^{4/3} \sim m_\phi \hat{n}_\phi$$

➡ DM lifetime: $$t_{\rm DM} \sim \frac{1}{y^4 (m_\phi \hat{n}_\phi)^{1/4}},$$

Requiring $t_{\rm DM} \lesssim t_U = 13.8$ Gyr, we obtain the constraint $y \lesssim 10^{-7}$

DM condensate is stable against evaporation provided coupling is not too large.

Chirality unsuppressed case, $m_\psi \to 0$



$\neq 0$

Evolution for benchmark model:

$n_\phi[0]/m_\phi^3 = 10^8,$

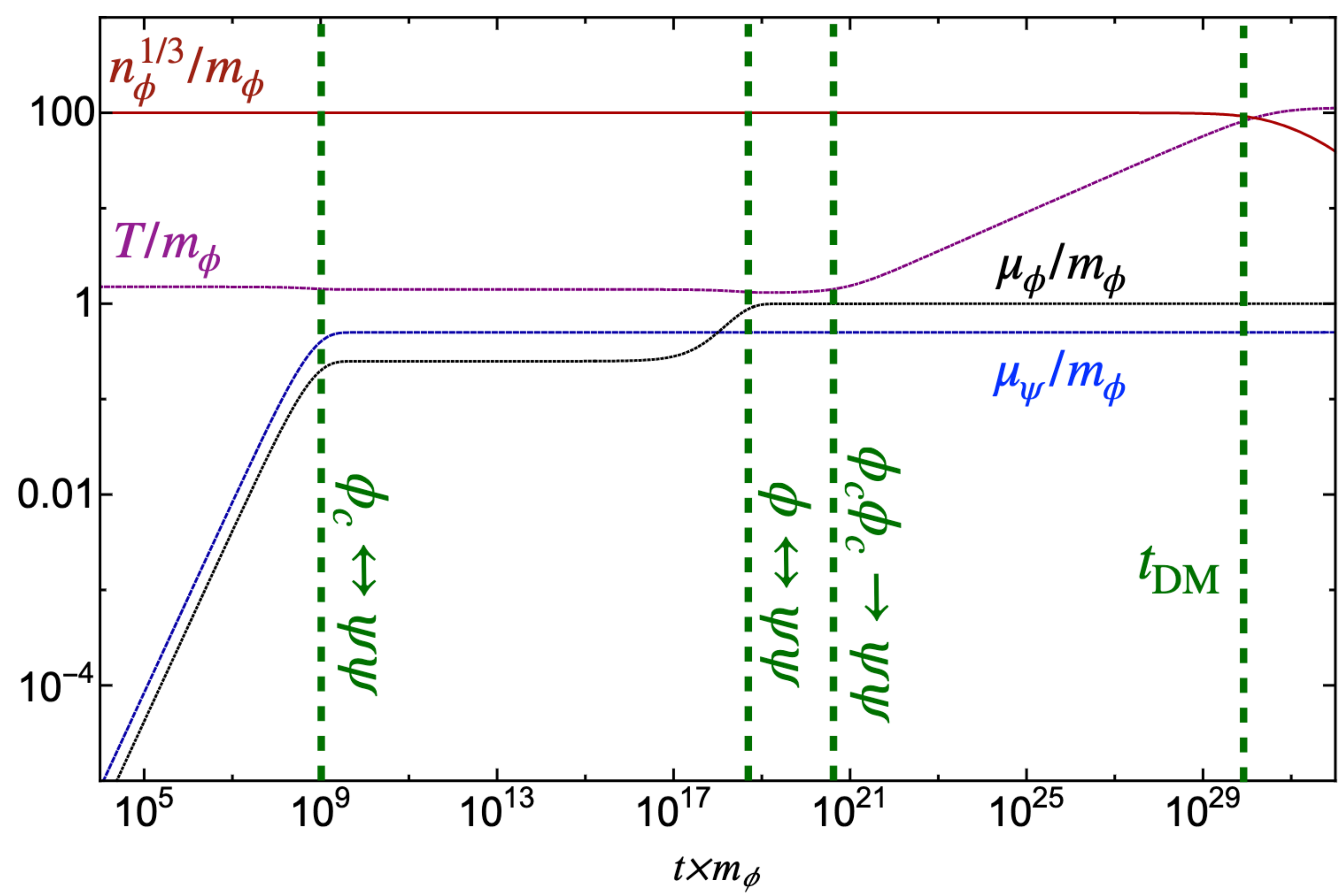
$T[0] = 3/2 m_\phi,$

$\mu_\phi[0] = \mu_\psi[0] = 0,$

$y = 10^{-8}$

$m_\psi = m_\phi/50$

Neglect Hubble expansion



Chirality unsuppressed case, $m_\psi \neq 0$

- As in the previous case, the evolution is first marked by Pauli blocking of condensate decay, followed by kinetic equilibration due to decays and inverse decays.

- Eventually, the process $\phi_c\phi_c \leftrightarrow \psi\psi$ will come into equilibrium, at which point the temperature of the dark sector grows,

$$\frac{d}{dt}(\rho_\phi^{\rm th} + \rho_\psi) = (g_\phi + \tfrac{7}{8} g_\psi)\frac{\pi^2}{30}\frac{d}{dt}T^4 \approx \Gamma_{\rm th} m_\phi \hat{n}_\phi, \qquad \Gamma_{\rm th} \equiv \frac{y^4 m_\psi^2}{\pi m_\phi^4}\frac{m_\phi}{T}\hat{n}_\phi,$$

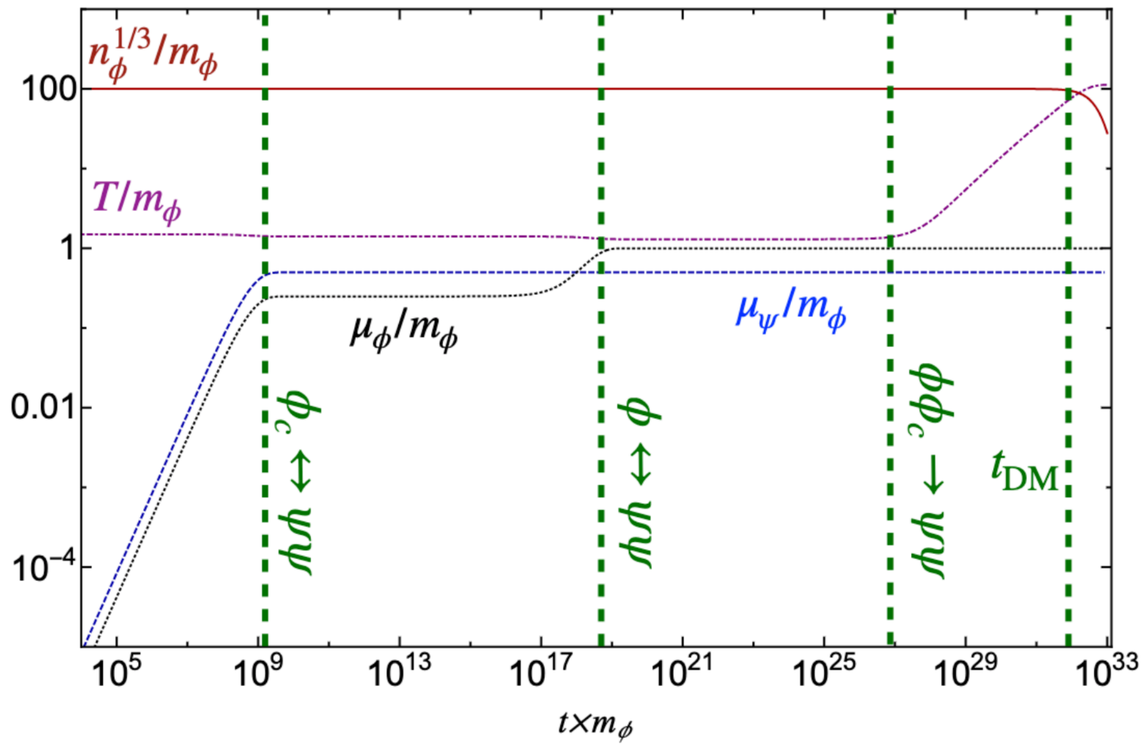
- Dark matter condensate evaporates when $(g_\phi + \tfrac{7}{8} g_\psi)\frac{\pi^2}{30}T^4 = m_\phi n_\phi[z=0]$

➡ DM lifetime: $t_{\rm DM} \sim \dfrac{m_\phi^4}{y^4 m_\psi^2 (m_\phi \hat{n}_\phi)^{3/4}},$

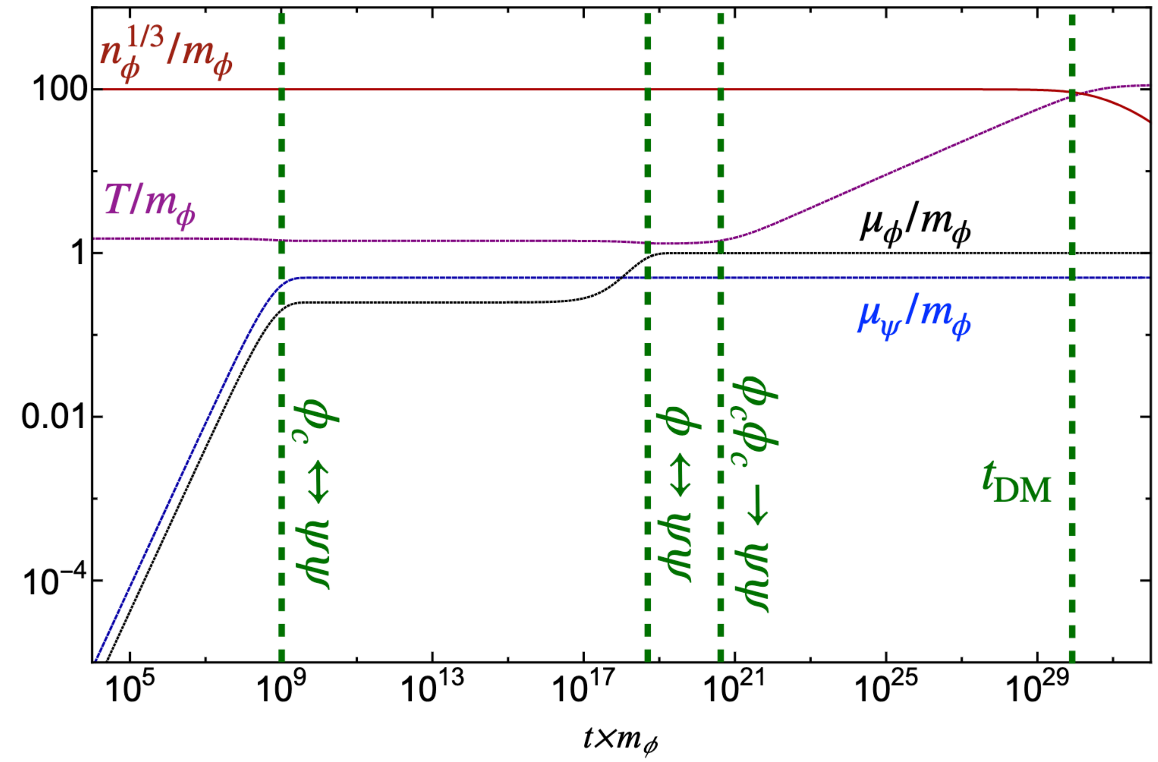
Requiring $t_{\rm DM} \lesssim t_U = 13.8$ Gyr, we obtain the constraint

$$\frac{m_\psi}{m_\phi} \lesssim 0.8 \left(\frac{10^{-9}}{y}\right)^2 \left(\frac{m_\phi}{10^{-6}\,{\rm eV}}\right)$$

Chirality suppressed



Chirality unsuppressed



- Temperature growth is much slower in the chirality unsuppressed case ($T \sim t^{1/5}$) than in the chirality suppressed case ($T \sim t^{1/3}$).

- This leads to a novel mechanism for slow production of dark radiation in the chirality unsuppressed case.

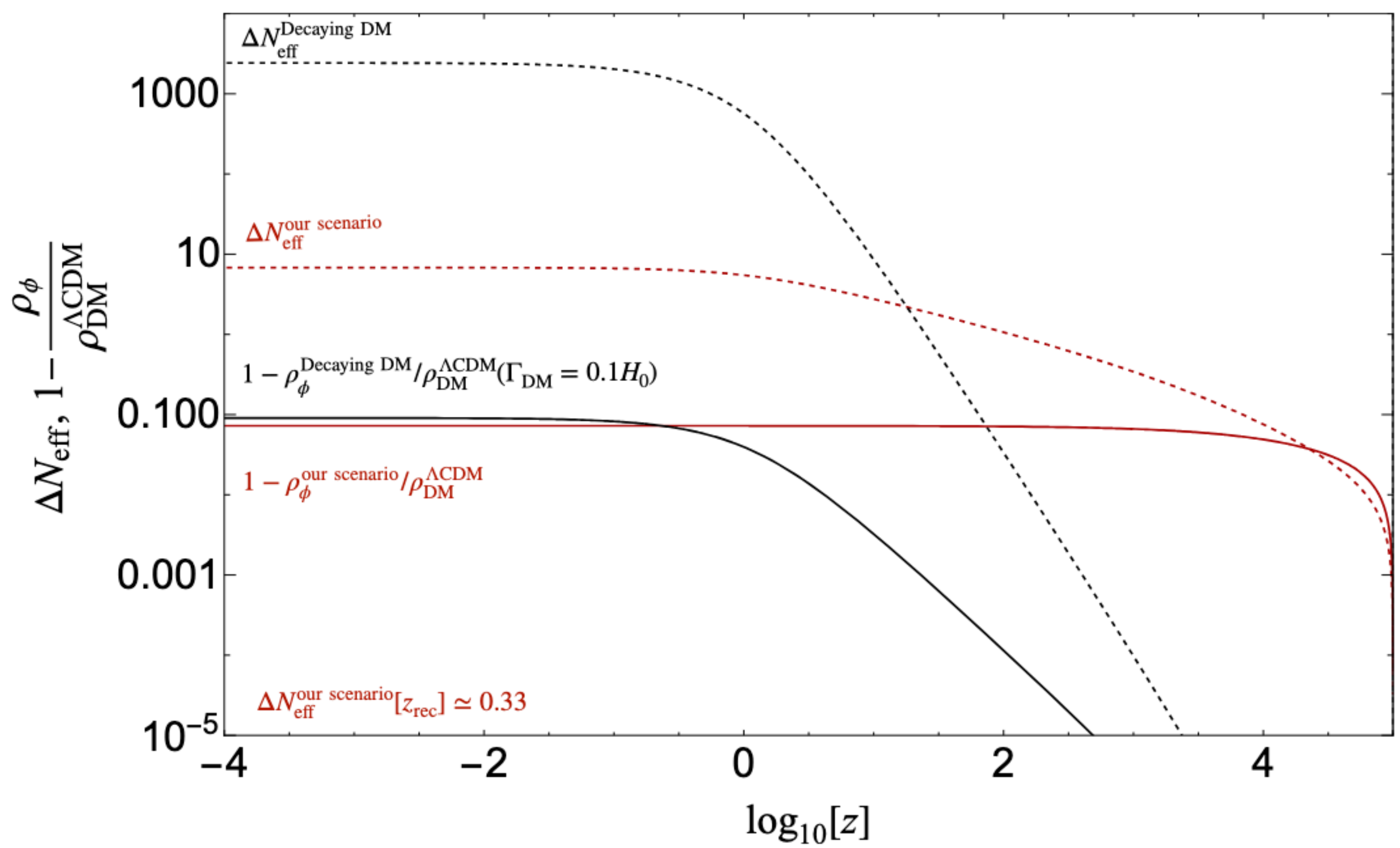
Slow production of dark radiation

- Solve Boltzmann equations for DM condensate and dark radiation

$$\dot{\hat{n}}_\phi + 3H\hat{n}_\phi \simeq -\frac{y^4 m_\psi^2 \hat{n}_\phi^2}{2\pi m_\phi^3 T} \qquad \dot{\rho}_{\rm DS} + 4H\rho_{\rm DS} \simeq \frac{y^4 m_\psi^2 \hat{n}_\phi^2}{2\pi m_\phi^2 T}$$

- Our scenario predicts a sizable ($\Delta N_{\rm eff} \approx 0.33$ for this benchmark) at recombination, while being consistent with observed DM density today.

- For comparison, we show the evolution for a standard decaying DM scenario. For a decay width $\Gamma = 0.1 H_0$, consistent with observations, there is negligible $\Delta N_{\rm eff}$ at recombination.



$$y = 10^{-9}, \quad m_\phi = 10^{-4}\,{\rm eV}, \quad m_\psi = m_\phi/5$$

Estimate of dark radiation production

- Production of dark radiation in a Hubble time: $$\delta\rho_{DS} a^4 \sim \frac{y^4 m_\psi^2 \hat{n}_\phi^2}{2\pi m_\phi^2 T H} a^4$$

- During radiation and matter eras, dark radiation dominantly produced at late times: $$\rho_{DS}[z] = g_{\rm DS}\frac{\pi^2}{30}T^4[z] \sim \frac{y^4 m_\psi^2 \hat{n}_\phi^2}{2\pi m_\phi^2 T[z] H[z]}$$

- The temperature of the dark sector during these eras is $$T[z] \sim \left(\frac{y^4 m_\psi^2 \hat{\rho}_\phi^2[z]}{m_\phi^4 H[z]}\right)^{1/5}$$

- Requiring $\Delta N_{\rm eff}[z_{\rm rec}] \lesssim 1$ leads to a stronger bound on the coupling:

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_{DS}}{\rho_\gamma} \implies T[z_{\rm rec}] \lesssim T_\gamma[z_{\rm rec}] \implies \frac{y^4 m_\psi^2}{m_\phi^4} \lesssim \frac{H[z_{\rm rec}] T_\gamma[z_{\rm rec}]^5}{\hat{\rho}_\phi^2[z_{\rm rec}]}$$

➡ $$y \lesssim 10^{-10}\left(\frac{m_\phi}{10^{-6}\,{\rm eV}}\right)^{1/2}\sqrt{\frac{m_\phi}{m_\psi}}$$

Estimate of dark radiation production

- During dark energy era (late times), dark radiation production is decreasing, Thus

$$T[z] \sim \frac{1+z}{1+z_{\rm DE}} \left(\frac{y^4 m_\psi^2 \hat{\rho}_\phi^2[z_{\rm DE}]}{m_\phi^4 H[z_{\rm DE}]} \right)^{1/5}$$

- This gives a relation between the dark radiation today and at early times,

$$\frac{\Delta N_{\rm eff}[0]}{\Delta N_{\rm eff}[z_{\rm rec}]} = \frac{T^4[0]}{T^4[z_{\rm rec}]} = \left(\frac{H[z_{\rm rec}]}{H[z_{\rm DE}]} \frac{1+z_{\rm DE}}{1+z_{\rm rec}} \right)^{4/5} \sim 10$$

- This is much smaller than a standard decaying dark matter scenario.

Parametric resonance

- So far we have been implicitly considering the perturbative regime

$$\Gamma_{\phi\to\psi\psi}\frac{m_\phi}{E} \gg \sigma v n_\phi \quad \Longrightarrow \quad Q \equiv \frac{y^2\rho_\phi}{m_\phi^4} \ll 1$$

- Instead, in the regime $Q \gg 1$, which will typically occur at early times since $Q \sim a^{-3}$ in the expanding universe, the fermion acquires a large oscillating mass, $M_{\rm eff} \simeq y\,\phi(t)$. It's typical size is set by the oscillation amplitude,

$$\overline{M}_{\rm eff} \sim y\,\phi_{\rm amp} \sim Q^{1/2} m_\phi \gg m_\phi$$

- In this regime the perturbative description using Boltzmann equations is not valid. A similar system has been studied in the context of inflationary preheating, where the phenomenon of broad parametric resonance is important.

- Here we will give a qualitative description of the dynamics in this regime, following the preheating literature.

Parametric resonance

- Consider the frequency ω_k of the fermion,

$$\omega_k = \sqrt{k^2 + y^2 \phi^2(t)}$$

- The particle description is valid when the adiabatic condition holds:

$$|\dot{\omega}_k| \lesssim \omega_k^2$$

- When this condition is violated, with $|\dot{\phi}|$ large, there is efficient ψ production. This will occur when $|\phi|$ is small and for small momentum k:

$$|\phi| \lesssim |\phi_*| \sim |m_\phi \phi_{\rm amp}/y|, \qquad k \lesssim y|\phi_*| \sim \sqrt{y m_\phi \phi_{\rm amp}}$$

- In this broad parametric resonance regime, a Fermi sphere of ψ with all modes $k \lesssim k_F \sim k_* \sim y|\phi_*|$ is produced.

Parametric resonance

- The Fermi momentum is much smaller than the effective ψ mass:

$$k_F \sim (y m_\phi \phi_{\rm amp})^{1/2} \sim Q^{1/4} m_\phi \sim \overline{M}_{\rm eff}/Q^{1/4} \ll \overline{M}_{\rm eff}$$

- Thus, the fermions are nonrelativistic while $Q \ll 1$ and the adiabatic condition (particle picture) holds.

- During most of the evolution the energy density of the fermions is given by

$$\rho_\psi \sim \bar{M}_{\rm eff} n_\psi \sim \bar{M}_{\rm eff} \frac{g_\psi}{2\pi^2} k_F^3 \sim \frac{g_\psi}{2\pi^2} Q^{5/4} m_\phi^4 \sim \frac{g_\psi}{2\pi^2} y^2 Q^{1/4} \rho_\phi$$

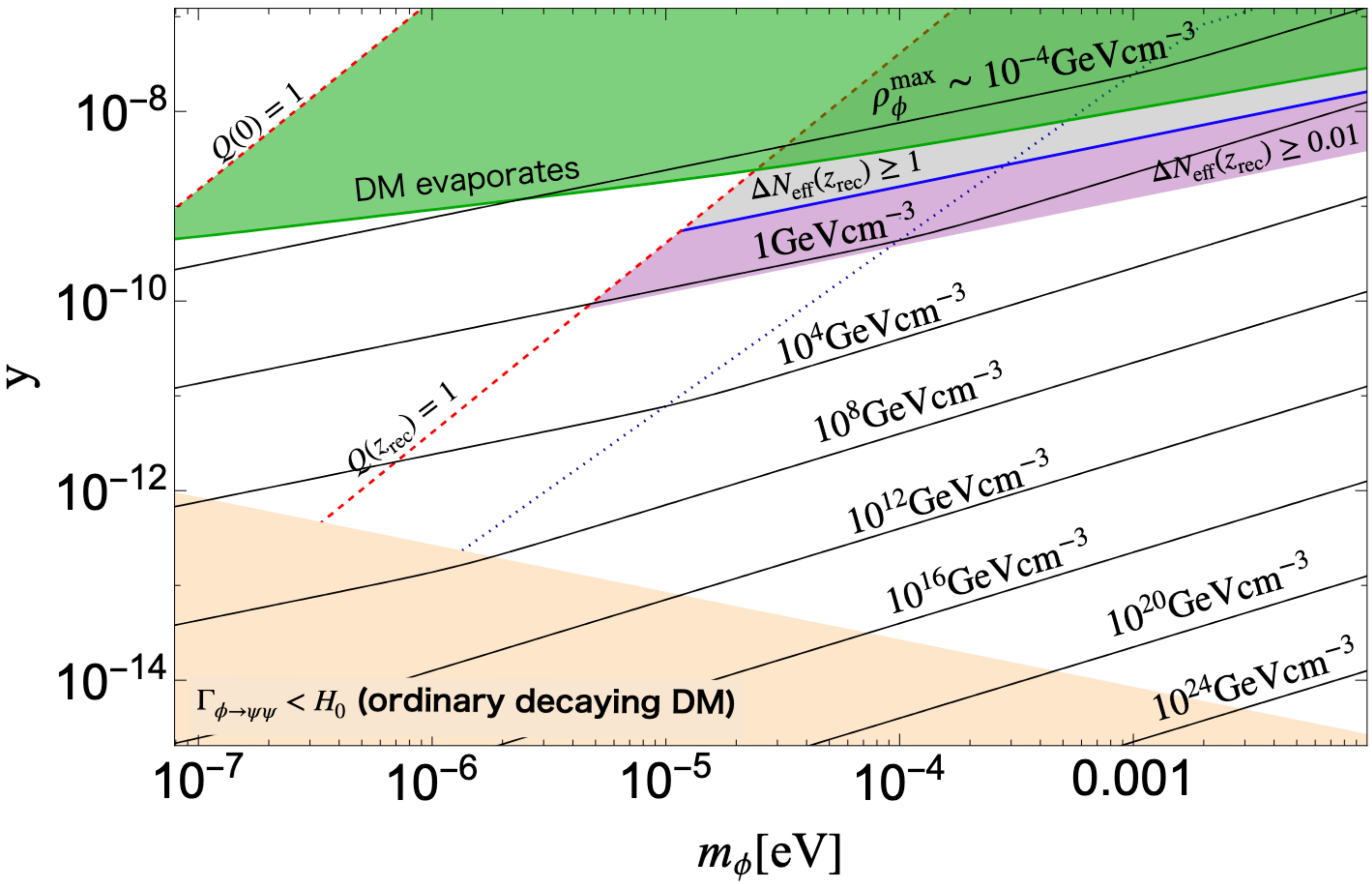
- Assuming DM is produced through the misalignment mechanism, one can show that over all of the parameter space we obtain $\rho_\psi \ll \rho_\phi$ from parametric resonance production of fermions.

- Since $Q \sim a^{-3}$ in the expanding universe, eventually at some late time Q becomes smaller than unity, at which point our perturbative Botlzmann equation analysis above will be valid.

Potential signatures and implications

- Dark radiation
  - We predict a novel kind of dark radiation which has self interactions and interactions with the DM condensate.
  - This is already constrained by CMB and BAO observations via $\Delta N_{\rm eff}$, and can be further probed by future missions, e.g., CMB-S4.
  - Such self interacting dark radiation may help to alleviate the Hubble tensions (see e.g., Blinov, Marques-Tavares, 2003.08387), however a detailed study of the cosmological perturbations is required.
- Absence of very dense DM structures
  - DM annihilation/evaporation is enhanced in regions with high DM density.
  - At large couplings, our scenario should predict, e.g., cored DM profiles, cutoff in (sub-)halo mass functions.
  - Requires more detailed studies (e.g., simulations of structure formation) and can potentially be probed with future observatories (e.g. Vera Rubin).

Summary



$Q(0)=1$
DM evaporates
$\rho_\phi^{max} \sim 10^{-4}$GeVcm^{-3}
$\Delta N_{eff}(z_{rec}) \geq 1$
$\Delta N_{eff}(z_{rec}) \geq 0.01$
1GeVcm^{-3}
10^4GeVcm^{-3}
10^8GeVcm^{-3}
10^{12}GeVcm^{-3}
10^{16}GeVcm^{-3}
10^{20}GeVcm^{-3}
10^{24}GeVcm^{-3}
$Q(z_{rec})=1$
$\Gamma_{\phi\to\psi\psi} < H_0$ (ordinary decaying DM)
y
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
0.001
m_ϕ[eV]

DM stabilized by neutrinos

- A natural candidate for the fermions in our scenario are the SM neutrinos

$$-\mathscr{L} \supset \frac{1}{2} y_{ij}\, \phi\, \nu_i \nu_j + \mathrm{h.c.}$$

- Here $i, j = 1,2,3$ are mass eigenstates, and we will mostly have in mind the normal hierarchy. We will also typically assume there is no special structure in the coupling matrix $y_{ij} \sim y$.

- We will assume the mass hierarchy $m_{\nu_1} < m_\phi/2, \;\; m_\phi \ll m_{\nu_{2,3}}$. Then the ϕ_c is stabilized due to the Pauli blocking of its decays to ν_1.

- There are several differences in this scenario, mainly due to the presence of the cosmic neutrino background (CνB). In particular,
  - Additional CνB interactions with ϕ can inhibit neutrino free streaming near recombination. This is not an issue if the couplings are small enough.
  - There can be important modifications to the CνB at late times, which may enhance the prospects for its detection.

CνB component from primordial νs (weak coupling)

- Let us first consider weak couplings, $y \lesssim 10^{-14}$. Then the heavy neutrino decays happen at temperatures $T_\nu \lesssim 0.05\,\mathrm{eV}$, i.e., the decays happen out of equilibrium. We have the following processes:

$$\nu_3 \to \phi(\mathrm{boosted}) + \nu_{1,2}.$$

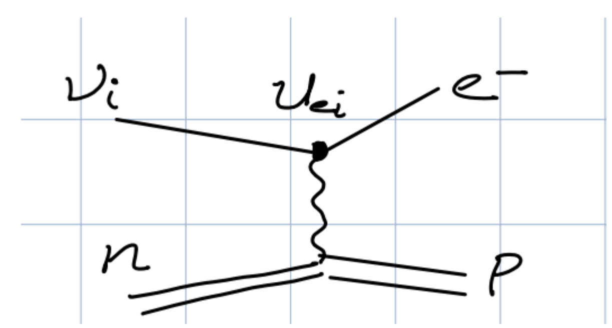
$$\nu_2 \to \phi(\mathrm{boosted}) + \nu_1, \quad \phi(\mathrm{boosted}) \to 2\nu_1$$

- Assuming these cascade decays occur at the same rate, the the comoving number density of light neutrinos increases

$$(n_{\nu,1} + n_{\nu,2} + n_{\nu,3})a^3 \to (8n_{\nu,1})a^3$$

- The CνB detection in a tritium capture experiment such as PTOLEMY can be enhanced. The detection rates depend on the PMNS elements, $|(U_{\mathrm{PMNS}})_{ei}|^2 = \{0.7, 0.3, 0.02\}$. The enhancement factor is

$$\frac{0.7 \times (1 + 3 + 0.5(3+5))}{(0.7 + 0.3 + 0.02)} \sim 6 \qquad (\mathrm{typical}\ E_\nu = \mathcal{O}(0.01)\,\mathrm{eV})$$



CνB component from primordial νs (moderate coupling)

- Next, consider moderate couplings, $10^{-14} \lesssim y \lesssim 10^{-9}$. Then the heavy neutrino decays happen thermally at higher temperatures, and neutrinos and thermal ϕs reach equilibrium. The comoving entropy stored in the neutrino-ϕ system is conserved, leading to the relation

$$(1+7/4)\frac{2\pi^2}{45}(T_\nu[0])^3 \simeq 3\times(7/4)\frac{2\pi^2}{45}(T_\nu^{\rm SM}[0])^3$$

- The final ν_1 number density is thus increased by a factor

$$\left(\frac{T_\nu[0]}{T_\nu^{\rm SM}[0]}\right)^3 \simeq \frac{21}{11}$$

- The CνB detection is enhanced by the factor

$$\frac{0.7\times(21/11)}{(0.7+0.3+0.02)} \sim 1.3 \qquad (\text{typical } E_\nu = \mathcal{O}(T_\nu^{\rm SM}[0])).$$

- This may be challenging to detect given the PTOLEMY energy resolution ~ 0.01 - 0.1 eV.

CνB component from DM decay

- Besides the components from heavier neutrino decays, there is the neutrino Fermi sea component produced from the Pauli-blocked DM decays.

- The ν_1 number density of this component is

$$n_{\nu_1} \sim \frac{1}{6\pi^2} E_F^3 \sim \frac{1}{6\pi^2} \left(\frac{m_\phi}{2} \right)^3$$

- This dominates over the other components when $m_\phi \gg T_\nu^{\rm SM}[0]$. The C$\nu$B detection rate is enhanced by a factor of

$$\sim 10^3 \left(\frac{m_\phi}{5\,\mathrm{meV}} \right)^3 \qquad (\text{typical } E_\nu = \mathcal{O}(m_\phi)),$$

- This component is particularly interesting as it provides a direct signature of the stabilization mechanism.

Outlook

- DM stability may provide an important clue to its basic nature and point the way towards its observational signatures.
- We have explored the hypothesis that DM stability is a consequence of the Pauli exclusion principle.
- For the minimal model of a scalar and a BSM fermion, the decay $\phi \to \psi\psi$ is Pauli blocked provided the DM is lighter than about 10 meV.
- Sizable interactions can populate an interacting dark radiation component, which can be probed through precision cosmology.
- If the DM decays to neutrinos, the cosmic neutrino background today can be modified, and its detection prospects could be enhanced.
- There is wide scope for further investigations: precision cosmology, CνB detection, model building, …