# Probing Non-standard Cosmology Through Sub-earth Mass Halos

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**Abstract**

The existence of an early matter-dominated epoch prior to the big bang nucleosynthesis may lead to a scenario where the thermal dark matter cools faster than plasma before the radiation-dominated era begins. Our study shows that the $s$-wave scattering is sufficient to partially decouple the dark matter from the plasma if the entropy injection during the reheating era depends on the bath temperature. In contrast, $p$-wave scattering leads to full decoupling in such cosmological backdrop. A combination of enhanced matter perturbations and reduced free-streaming horizon results in an increase in the number density of sub-earth mass halos. The resulting boost in the dark matter annihilation signatures could offer an intriguing probe to differentiate pre-BBN non-standard cosmological epochs.

## Early matter dominated epoch

A meta-stable scalar field $\phi$ with an equation of state $\omega_\phi$ dominates the energy density of the universe prior to the onset of BBN. The field $\phi$ coherently oscillates around the minima of its potential and dissipates its energy via decaying into radiation. The radiation then annihilates to dark matter and vice versa. The Boltzmann equations are given by:

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi\,, \tag{1}$$

$$\frac{d\rho_\gamma}{dt} + 4H\rho_\gamma = \Gamma_\phi \rho_\phi + 2\langle E\rangle \langle\sigma v\rangle_{\rm ann}\left(n_\chi^2 - n_{\chi,{\rm eq}}^2\right), \tag{2}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\rm ann}\left(n_\chi^2 - n_{\chi,{\rm eq}}^2\right). \tag{3}$$

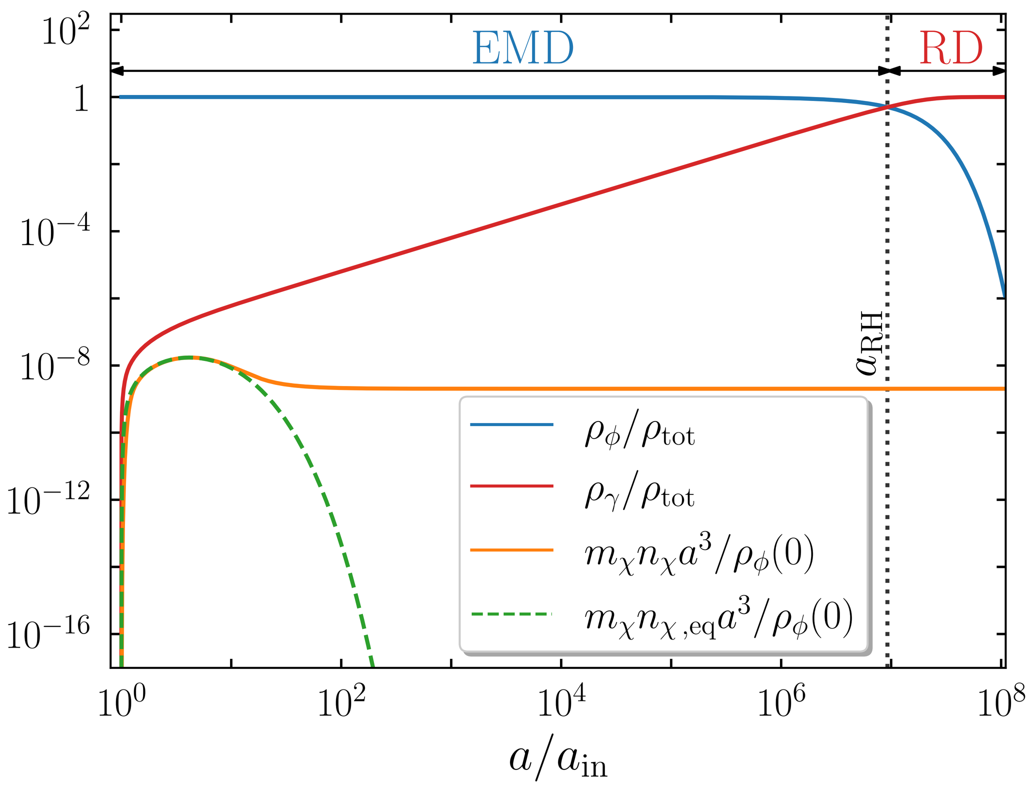



**Figure 1:** Evolution of the background energy densities $\rho_\phi$ (blue) and $\rho_\gamma$ (red), normalized by the total energy density, as well as the comoving number density of the DM.

The dissipation rate of $\phi$ has non-trivial dependence on the scale factor and the temperature of the plasma as

$$\Gamma_\phi \propto a^k T^m \tag{4}$$

The background plasma evolves with scale factor as $T \propto a^{-\alpha}$.

## Partial kinetic decoupling of dark matter

DM chemically decouples when the interaction rate falls below the Hubble expansion rate. After chemical decoupling, the evolution of the temperature of the DM, i.e., $T_\chi$ with respect to the scale factor is given by

$$T_\chi(a) \simeq \frac{T_{\rm dec}}{(2-q)}\left[2\left(\frac{a}{a_{\rm dec}}\right)^{-q} - q\left(\frac{a}{a_{\rm dec}}\right)^{-2}\right]. \tag{5}$$

| $\phi$ domination | $k$ | $m$ | $\alpha$ | Conditions for kinetic decoupling | | | |
|---|---|---|---|---|---|---|---|
| | | | | $n_{\rm dec}$ | $n_{\rm partial}$ | $s$-wave | $p$-wave |
| $\omega_\phi = 0$ | 0 | 0 | 3/8 | 0 | 13/3 | – | partial |
| (Matter) | 0 | 1 | 1/2 | -1 | 2 | partial | full |

**Table 1:** Conditions for kinetic decoupling of the DM are shown for different non-standard cosmological scenarios with entropy injection.

## Implications of Early matter domination

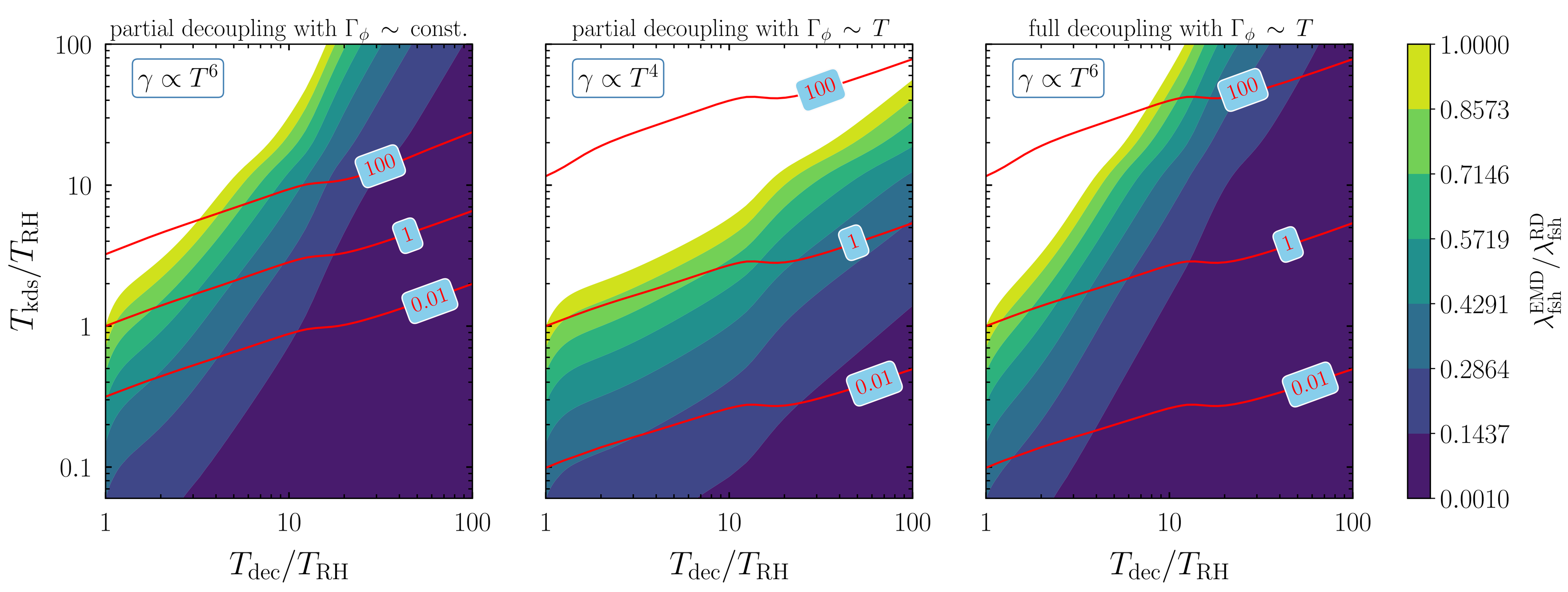



**Figure 2:** The ratios of dark matter free-streaming horizon in the presence of an EMDE and in standard radiation dominated epoch are shown in $T_{kds} - T_{dec}$ plane in the units of $T_{RH}$.

The free-streaming horizon is smaller in the case of EMDE if $r \leq 1$.
**Caveat:**If, the primary interaction governing the relic density of the DM also maintains it in kinetic equilibrium with the bath, one typically needs $r < 1$ to match the observed relic density.

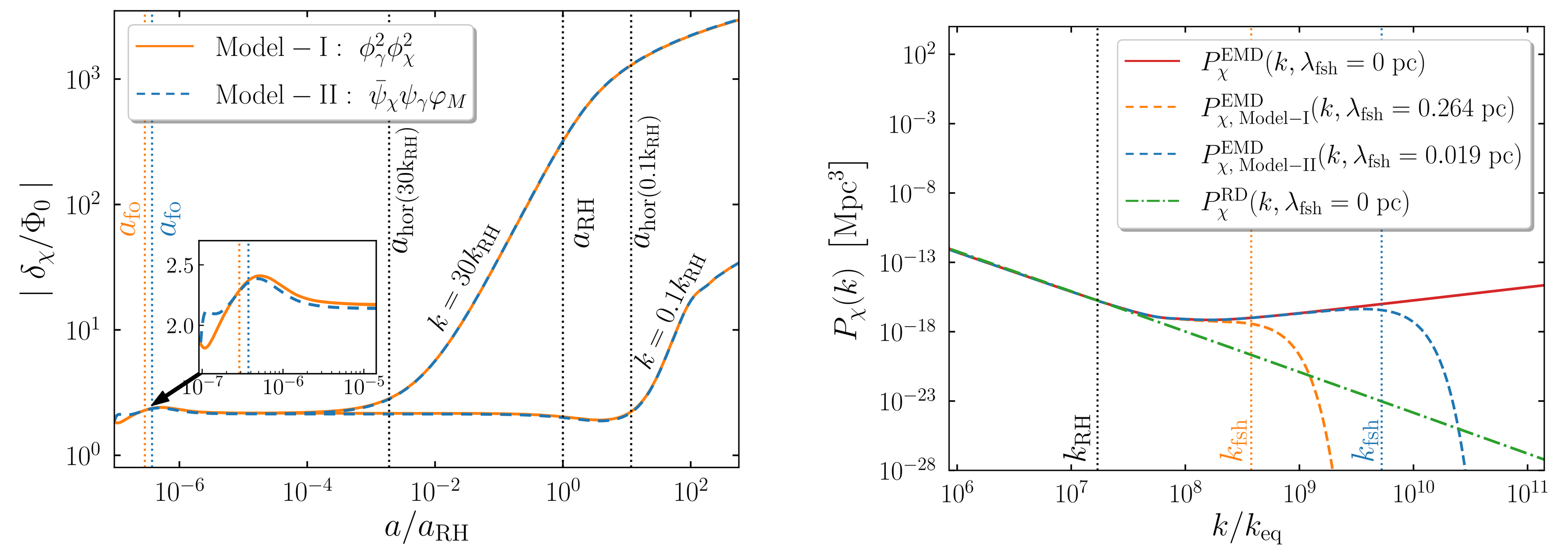
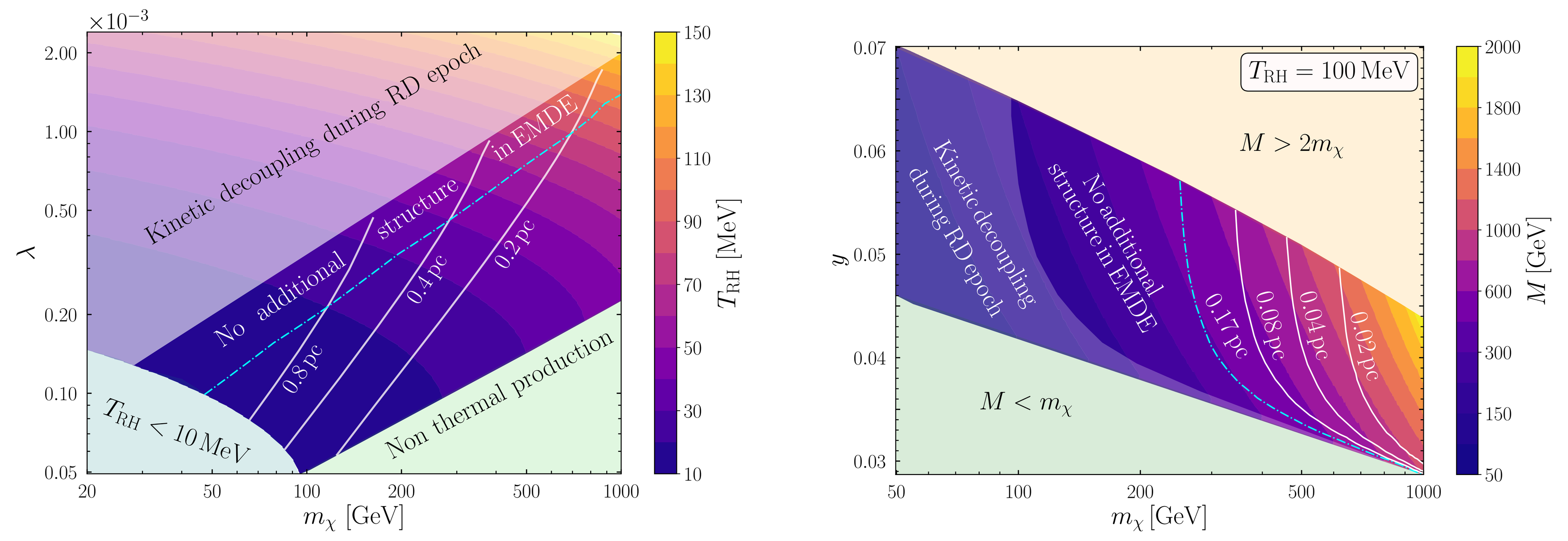



**Figure 3:** The evolution of $\delta_\chi$ is presented for two modes: one entering during an EMDE ($k = 30k_{RH}$) and the other during RD ($k = 0.1k_{RH}$). After the horizon entry of the mode ($a > a_{hor}$), $\delta_\chi$ grows linearly until reheating, followed by a logarithmic scaling during radiation domination. The matter power spectrum $P_\chi(k)$ for different values of $\lambda_{fsh}$, evaluated at $z = 50$, in case of an EMDE with a temperature-dependent entropy injection.

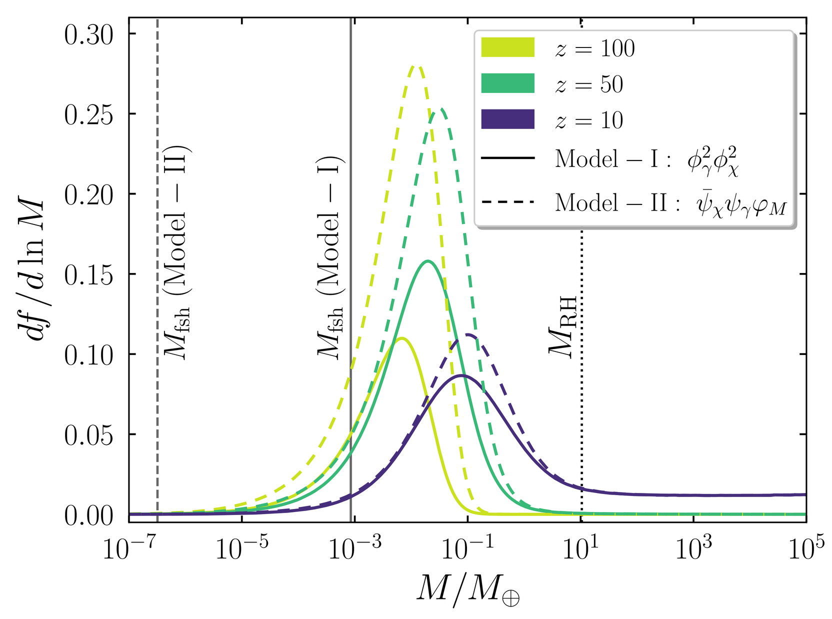
## Particle physics realization




(a) Scalar dark matter

(b) Fermionic dark matter

**Figure 4:** The allowed parameter space satisfying the present-day relic density of the DM is presented by coloured bands. The DM shows partial kinetic decoupling during the EMDE in the dark-shaded region, while in the light-shaded region, DM kinetically decouples after reheating.




Differential halo mass fraction for both models

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The differential halo mass function peaks around $M = 0.1\,M_\oplus$ for both models, while the absolute value is higher in Model II due to the reduced $\lambda_{\rm fsh}$.

## Conclusions

- Due to entropy injection during EMDE, the annihilation cross-section requires to be smaller than in a purely radiation dominated universe.
- The DM gets fully kinetically decoupled in EMDE with $\Gamma_\phi \sim T$ in contrast with the case of $\Gamma_\phi \sim$ const., where $p$-wave elastic scattering is able to partially decouple the DM during EMDE.
- This results in a comparatively reduced free-streaming horizon of the DM, provided the decoupling temperature is same.
- Therefore, the boost in the sub-earth halo population is expected to be more in the $\Gamma_\phi \sim T$, putting it in an advantageous situation in terms of observational probes.

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## References

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