Traces of early matter domination:

Dark matter cooling boosts sub-earth halo population

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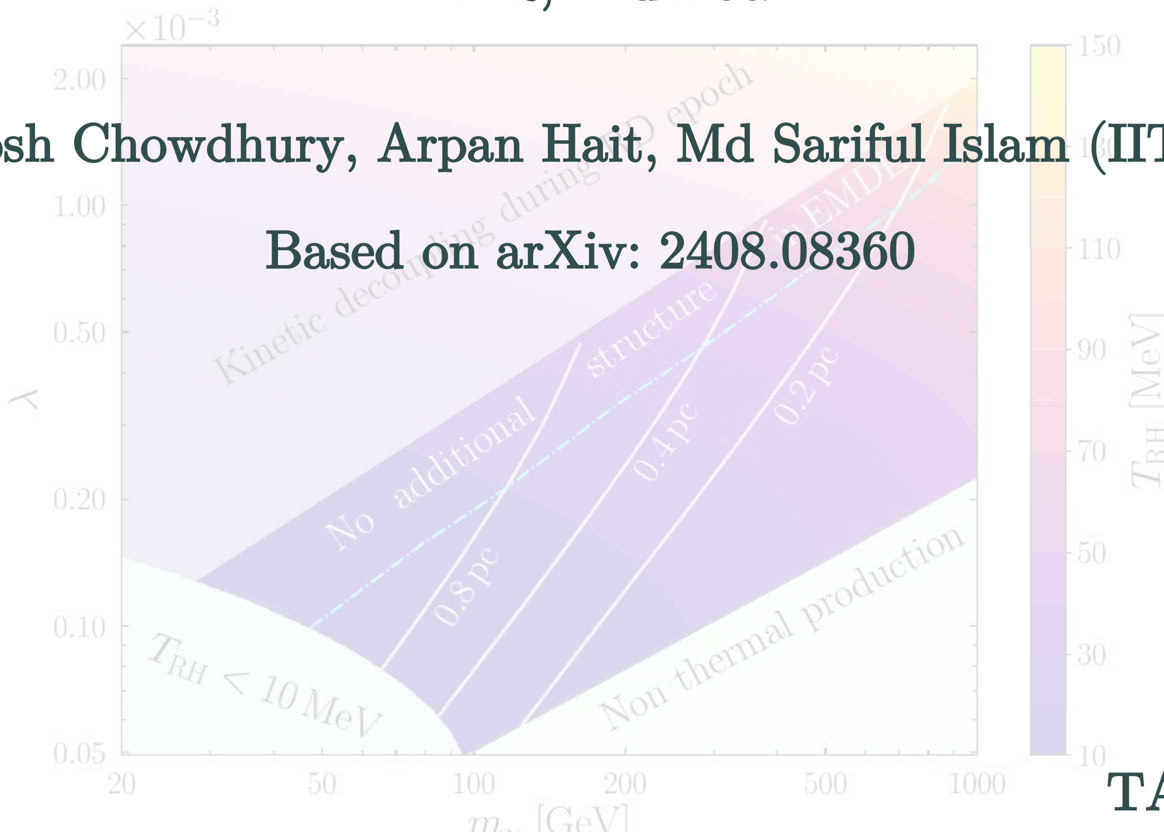
Based on arXiv: 2408.08360



TAPP 2024, IMSC

Overview

A pre-BBN early matter dominated epoch impacts thermal decoupling of dark matter

Additional cooling of DM, reduced free streaming horizon

Cooling rate depends on the rate of entropy injection during reheating

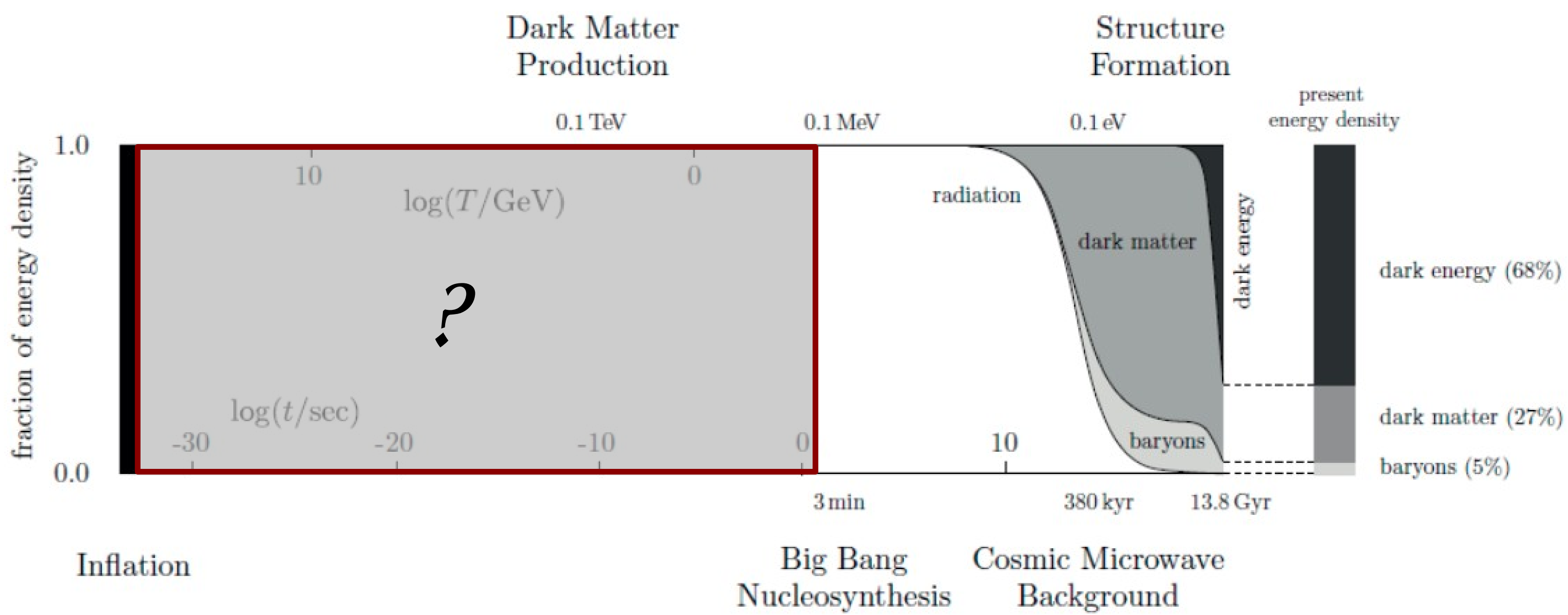
Matter perturbations grow linearly during EMDE

Boosts in sub-earth mass halo populations

Amplification of DM annihilation rate at the galactic centers

AB, D Chowdhury, A Hait, Md S Islam, [2408.08360]

How was the Universe prior to BBN?



Credits: **Daniel Baumann, *Cosmology, Part III Math Tripos***

- Little to no constraints from inflation to BBN

  Universe must be radiation dominated around T > 5 MeV

- Most important particle physics events have happened during this time:
  - EW phase transition, QCD phase transition, Baryogenesis
  - Dark matter production…

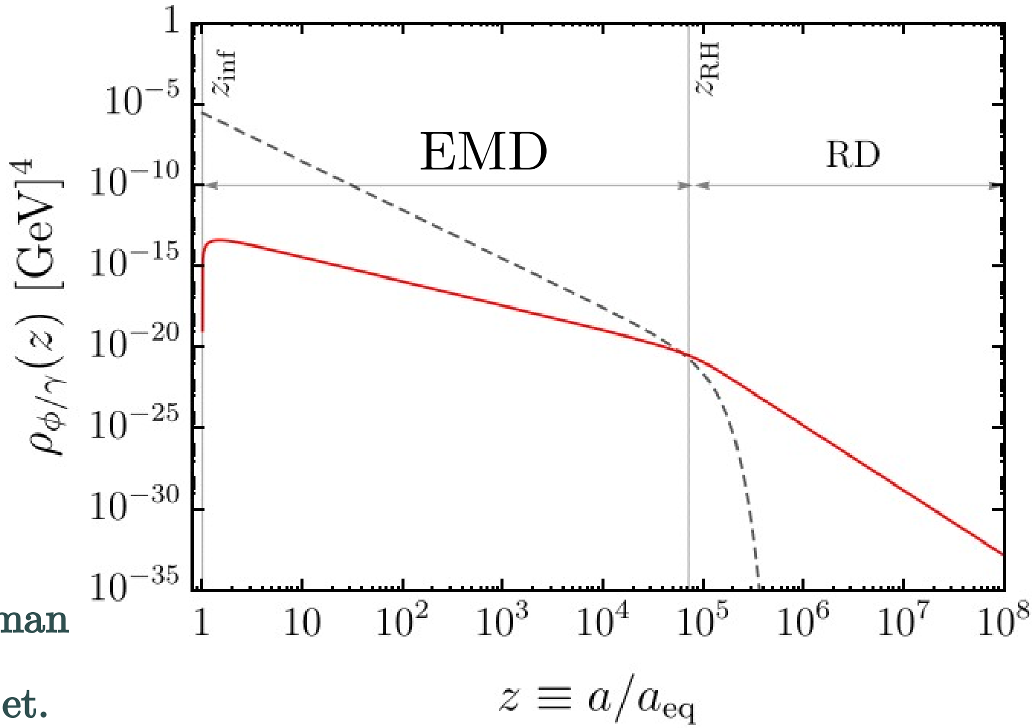
Early matter dominated epoch

Motivated BSM scenarios predict: meta-stable / long-lived particles dominating the energy density of the universe

Example: Dilaton, Moduli, Curvaton ...

- Rate of dissipation depends on
- Perturbative decay: $\Gamma_\phi \sim \text{const.}$
- Thermally dominated: $\Gamma_\phi \sim T^m$
- Field dependent: $\Gamma_\phi \sim \phi^k$

[Scherrer, Turner ’85; Shtanov et al. ’95; Kofman et al. ’97; Garcia et al. ’12, Mukaida et. al. 1208.3399, 1212.4985; Drewes, 1406.6243; Co et. al. 2007.04328; ...]

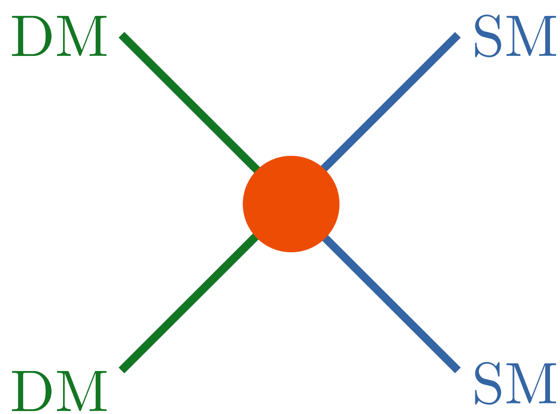


Evolution of plasma temperature depends on the entropy injection rate $T \propto a^{\alpha(k,m)}$

What are the cosmological fingerprints of EMDE?

Dark matter decoupling

Thermal decoupling = Chemical decoupling + Kinetic decoupling



$$\Gamma_{\rm ann} = n_{\rm DM}^{\rm eq} \langle \sigma v \rangle_{\rm ann}$$

$$T^{3/2} e^{-m_\chi / T}$$

Sets relic density

$g/g_{\rm standard}$	early MD era	fast-expanding universe
DM freeze-out	smaller	larger
DM freeze-in	larger	larger

Dilution of relic due to entropy injection

Dark matter decoupling

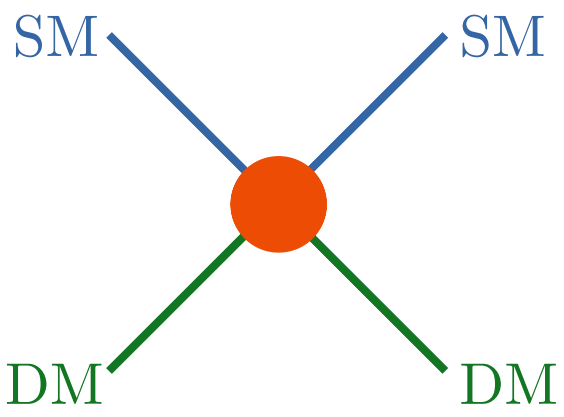
Thermal decoupling = Chemical decoupling + Kinetic decoupling

In RD: DM cools faster than radiation after decoupling

$$T_\chi \sim \begin{cases} T_{\rm rad}\,, & T > T_{\rm kds} \\ a^{-2}\,, & T < T_{\rm kds} \end{cases}$$

Free-streaming horizon: fixed by the decoupling

$$\lambda_{\rm fsh}^{\rm RD} = \int_{t_{\rm kds}}^{t_0} dt\, \frac{v_\chi(t)}{a(t)} = \int_{a_{\rm kds}}^{a_0} da\, \frac{\sqrt{T_\chi(a)}}{a^2 H(a)}$$



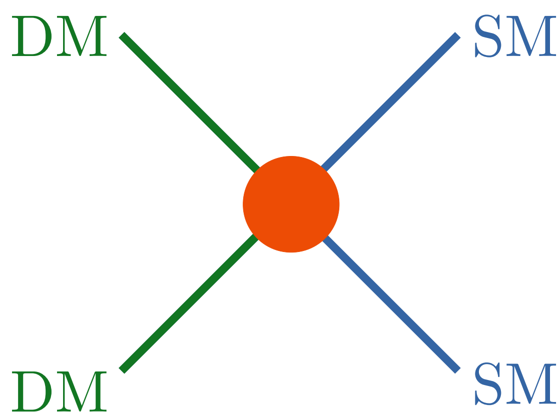
$$\Gamma_{\rm el} = n_{\rm SM}^{\rm eq} \langle \sigma v \rangle_{\rm el}$$

$$T^3$$

Sets free streaming horizon

Dark matter decoupling

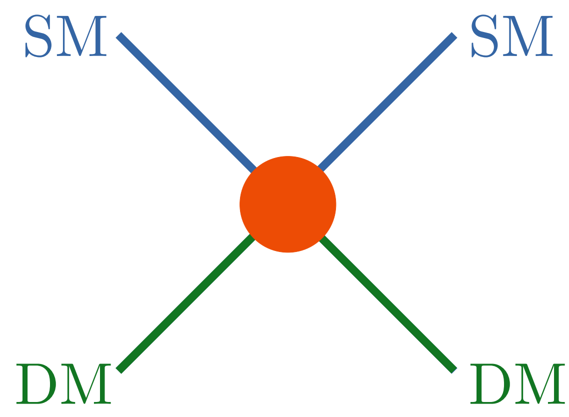
Thermal decoupling = Chemical decoupling + Kinetic decoupling



$$\Gamma_{\rm ann} = n_{\rm DM}^{\rm eq} \langle \sigma v \rangle_{\rm ann}$$

$$n_{\rm DM}^{\rm eq} \rightarrow T^{3/2} e^{-m_\chi / T}$$

Sets relic density



$$\Gamma_{\rm el} = n_{\rm SM}^{\rm eq} \langle \sigma v \rangle_{\rm el}$$

$$n_{\rm SM}^{\rm eq} \rightarrow T^3$$

Sets free streaming horizon

For cold dark matter in RD:
Chemical decoupling precedes kinetic decoupling

$$H_{\rm RD} \sim T^2$$

Kinetic decoupling during EMDE

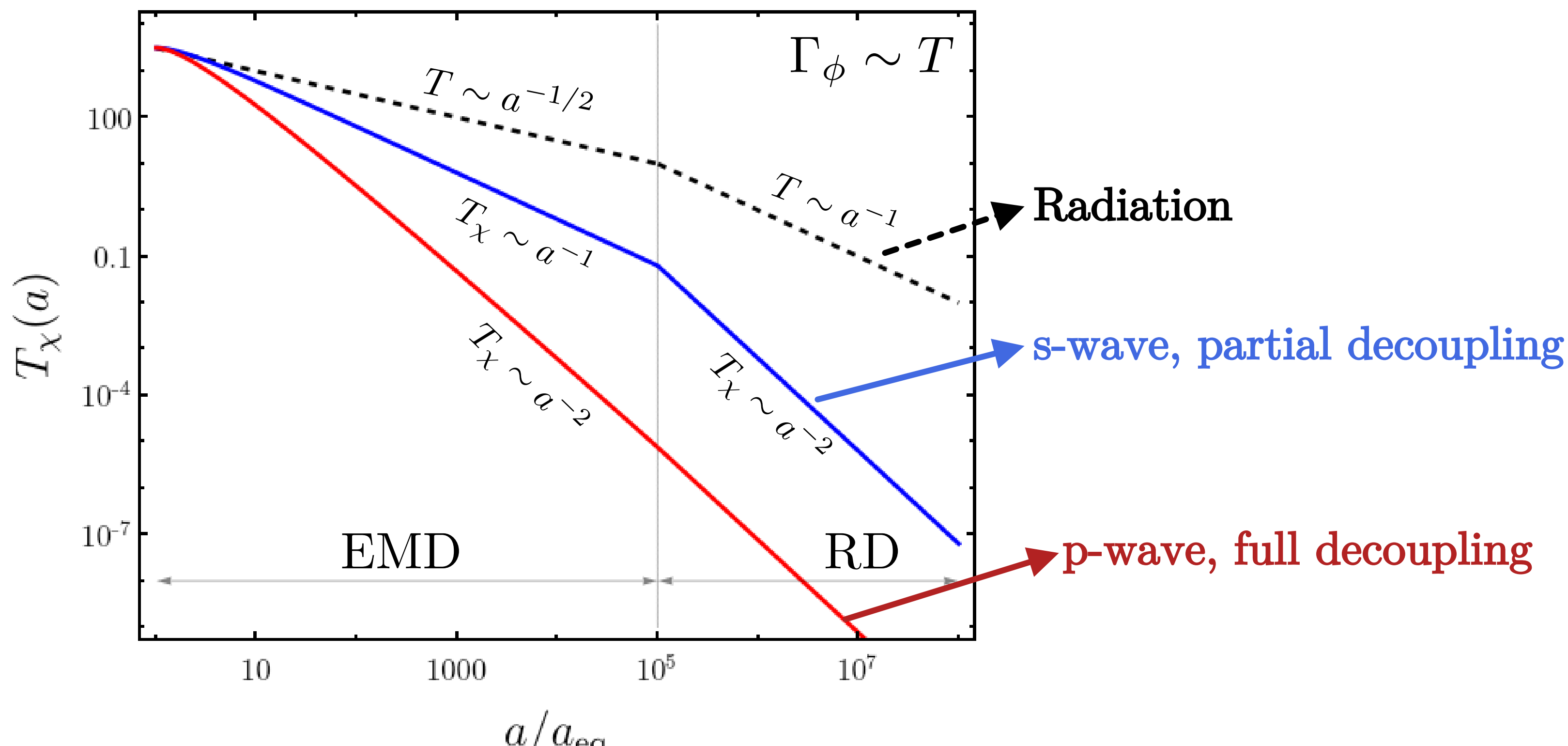
$$\frac{dT_\chi}{d\ln a} + 2T_\chi(a)\left[1 + \frac{\gamma_{\rm el}(a)}{H(a)}\right] = 2\frac{\gamma_{\rm el}(a)}{H(a)}T(a)$$

Momentum transfer in elastic scattering

$$\gamma_{\rm el} \sim \begin{cases} T^4, (\mathrm{s-wave}) \\ T^6, (\mathrm{p-wave}) \end{cases}$$

$$T_\chi(a) \propto C_1 \left(\frac{a}{a_{\rm dec}}\right)^{-p} + C_2 \left(\frac{a}{a_{\rm dec}}\right)^{-2}$$

p **depends on the expansion history and elastic scattering rate**



Kinetic decoupling during EMDE

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p **depends on the expansion history and elastic scattering rate**

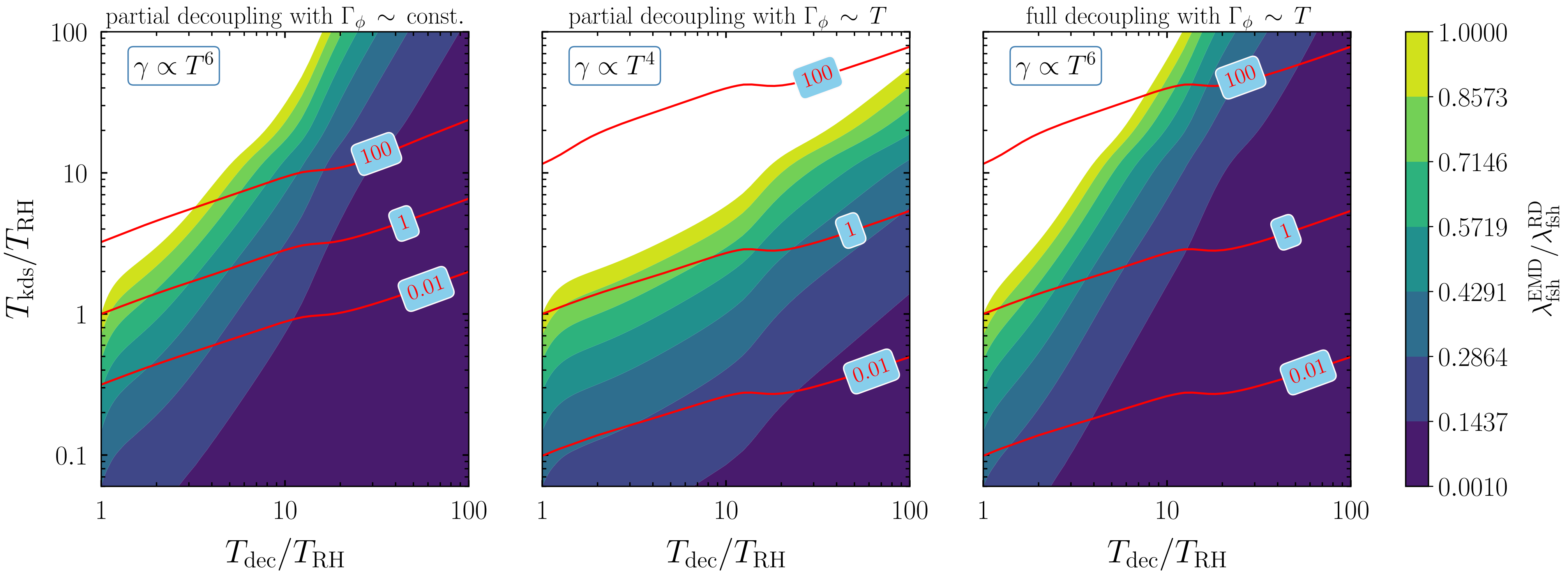
$$\Gamma_\phi \sim \mathrm{const.} \implies T \sim a^{-3/8} \qquad T_\chi \sim \begin{cases} a^{-3/8}, & (\mathrm{s-wave}) \\ a^{-9/8}, & (\mathrm{p-wave}) \end{cases}$$

- s-wave: **No decoupling**
- p-wave: **Partial decoupling**

$$\Gamma_\phi \sim T \implies T \sim a^{-1/2} \qquad T_\chi \sim \begin{cases} a^{-1}, & (\mathrm{s-wave}) \\ a^{-2}, & (\mathrm{p-wave}) \end{cases}$$

- s-wave: **Partial decoupling**
- p-wave: **Full decoupling**

Kinetic decoupling during EMDE

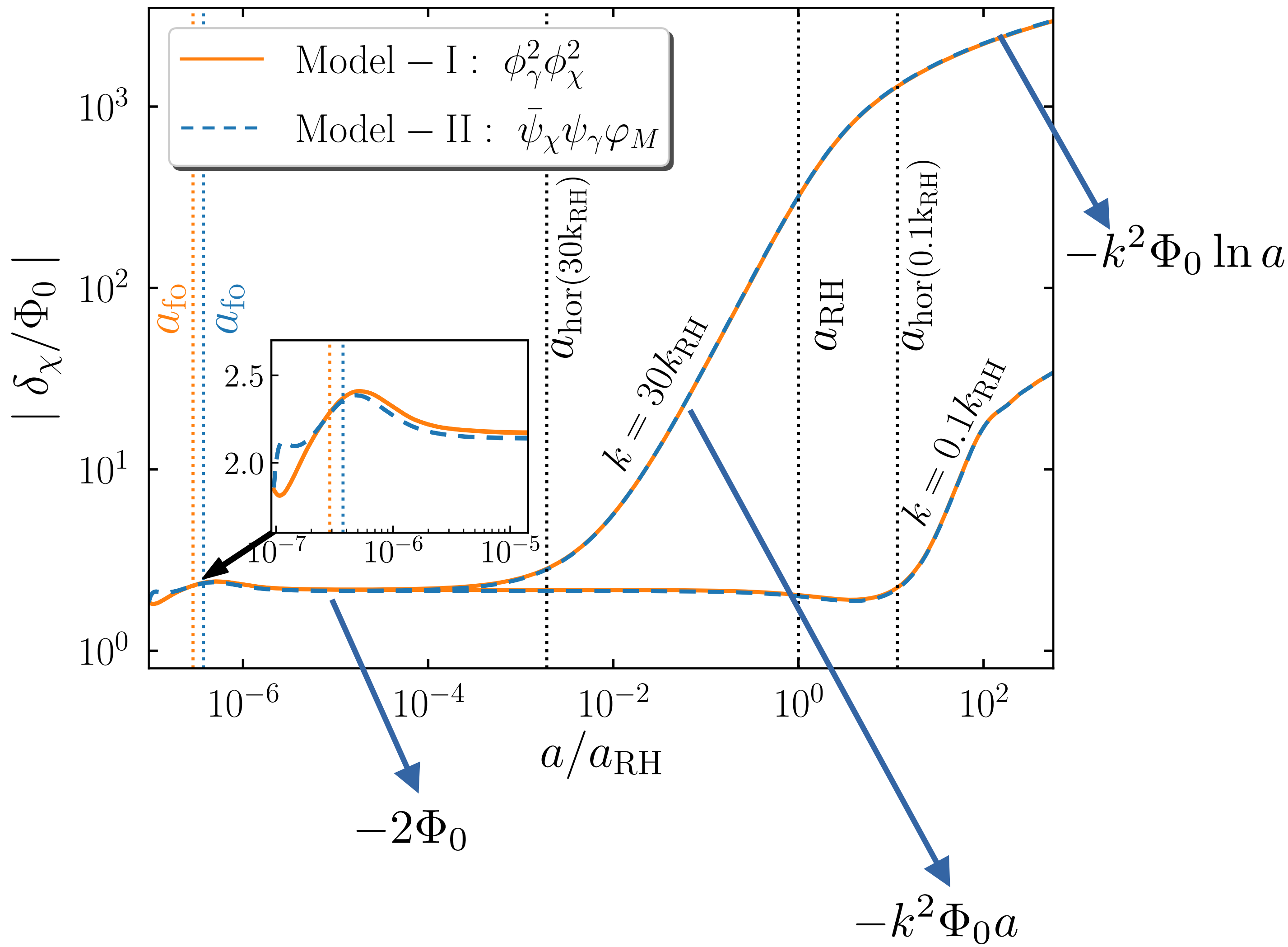


$\Gamma_\phi \sim$ const.	$\Gamma_\phi \sim T$	$\Gamma_\phi \sim T$
s-wave: no decoupling **p-wave: partial decoupling**	**s-wave: partial decoupling**	**p-wave: full decoupling**

Free streaming horizon is reduced if DM decouples (partial / full) during EMDE

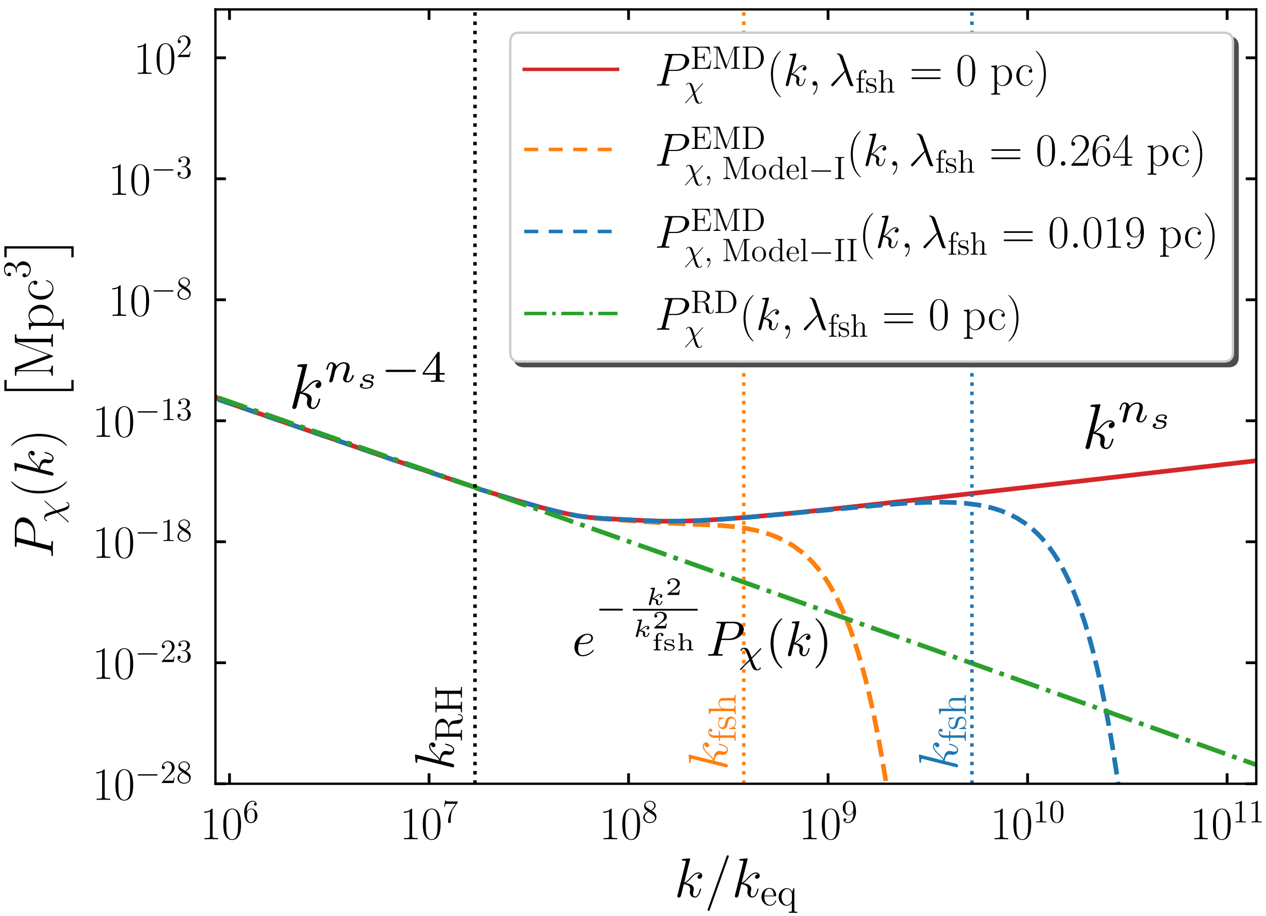
Unless: multiple annihilation and elastic scattering channels are present

Boost in sub-earth halo population



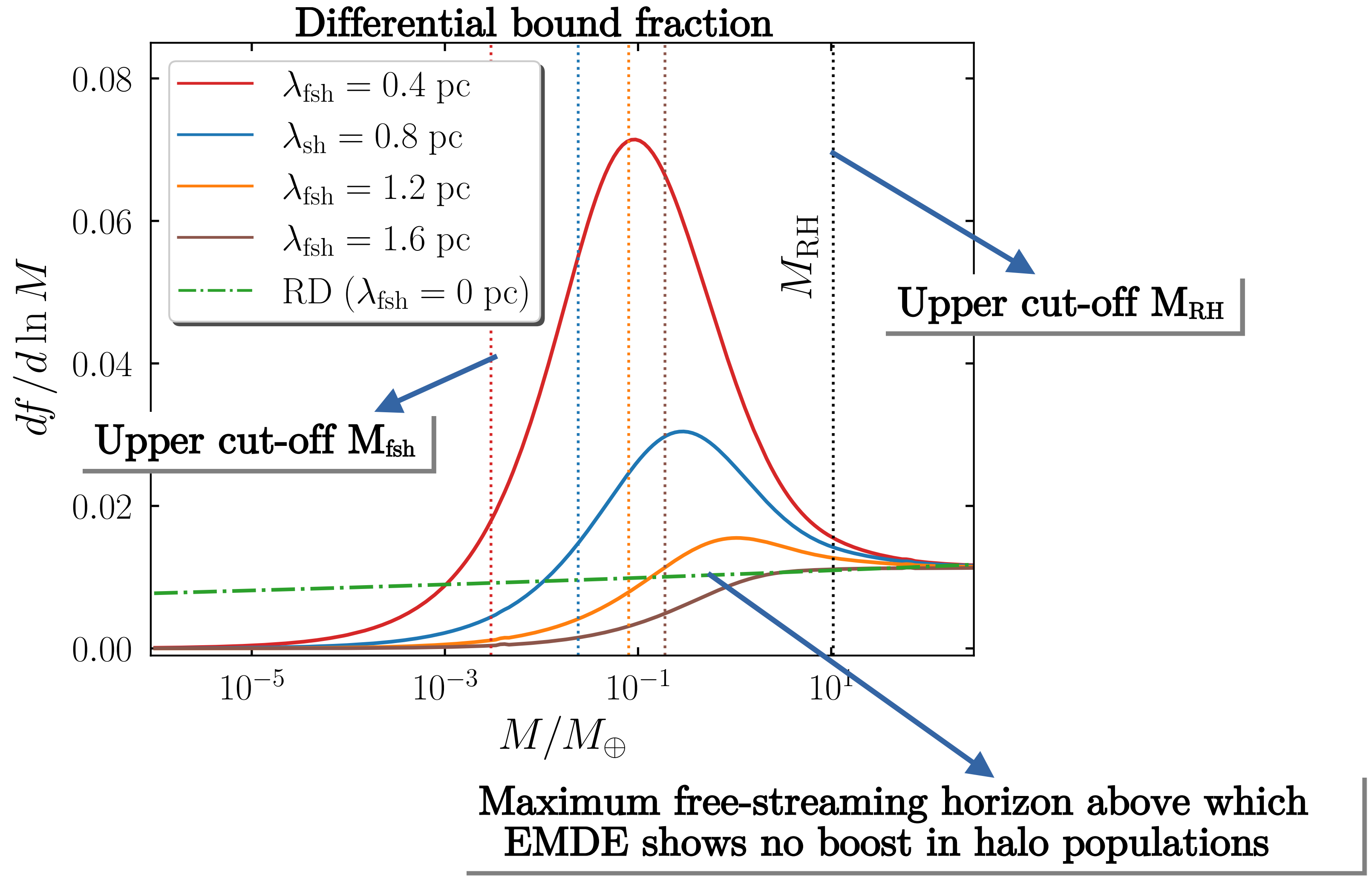
Linear growth of matter perturbations till the end of reheating for modes entering horizon during EMDE

Boost in sub-earth halo population

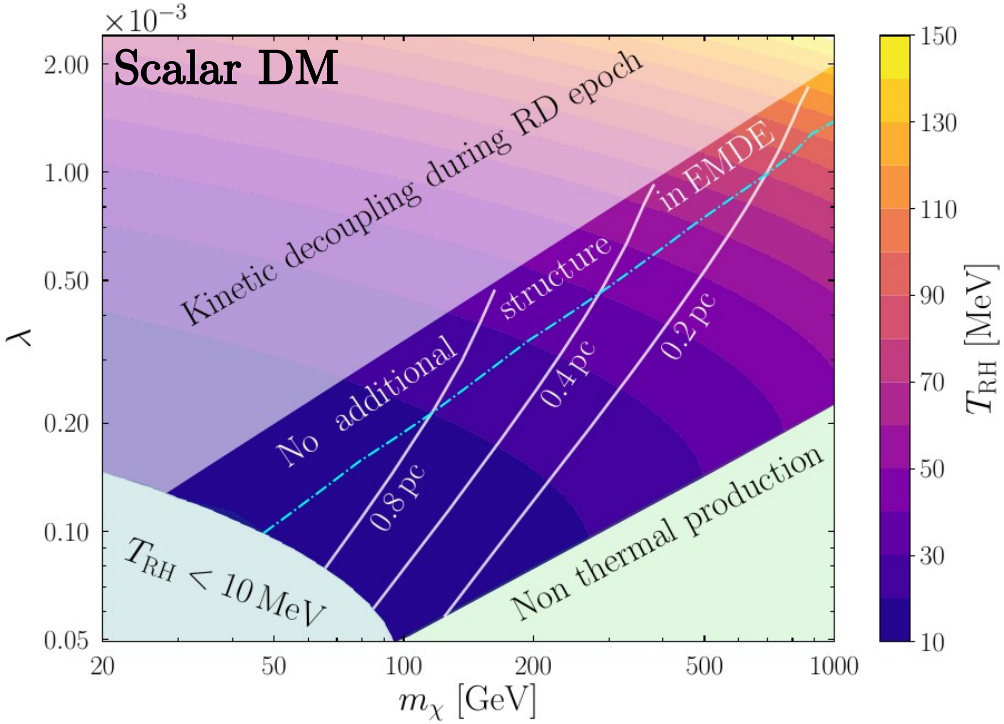


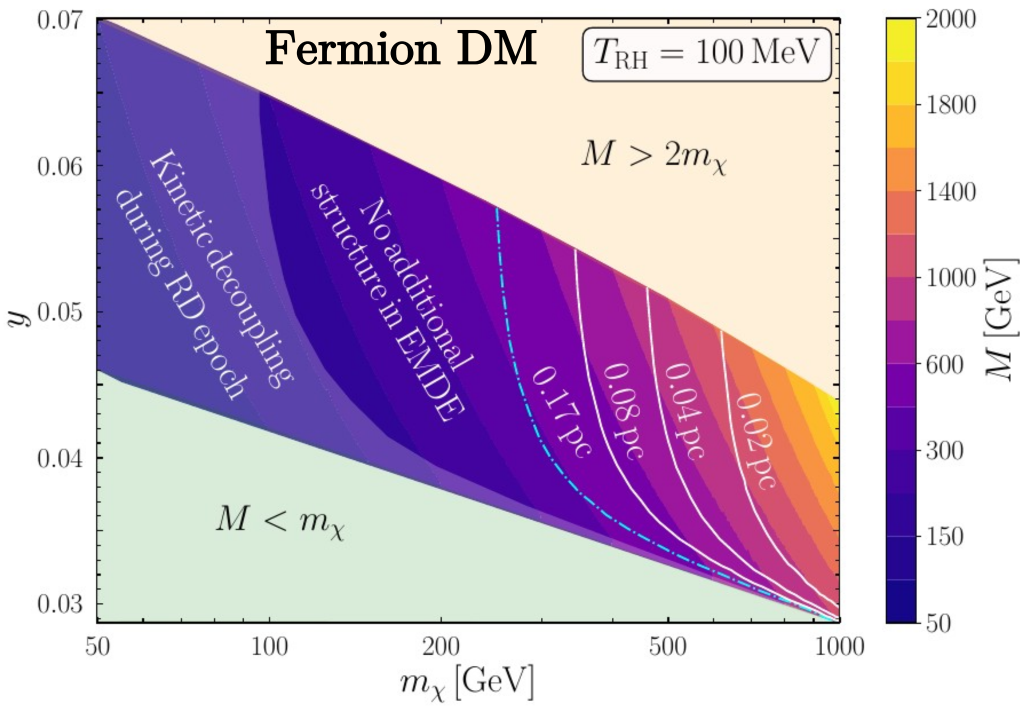
Enhanced matter power spectrum during EMDE in the range $k_{\rm RH} < k < k_{\rm fsh}$

Boost in sub-earth halo population



Distinguishing dark matter models





$$\text{Model} - \text{I}: \ \mathcal{L} \sim \lambda \phi_\chi^2 \phi_\gamma^2$$

s-wave elastic scattering

$$\gamma_{\rm el} \sim T^4$$

Partial decoupling in EMDE

$$\text{Model} - \text{II}: \ \mathcal{L} \sim y \bar{\psi}_\chi \psi_\gamma \phi_M$$

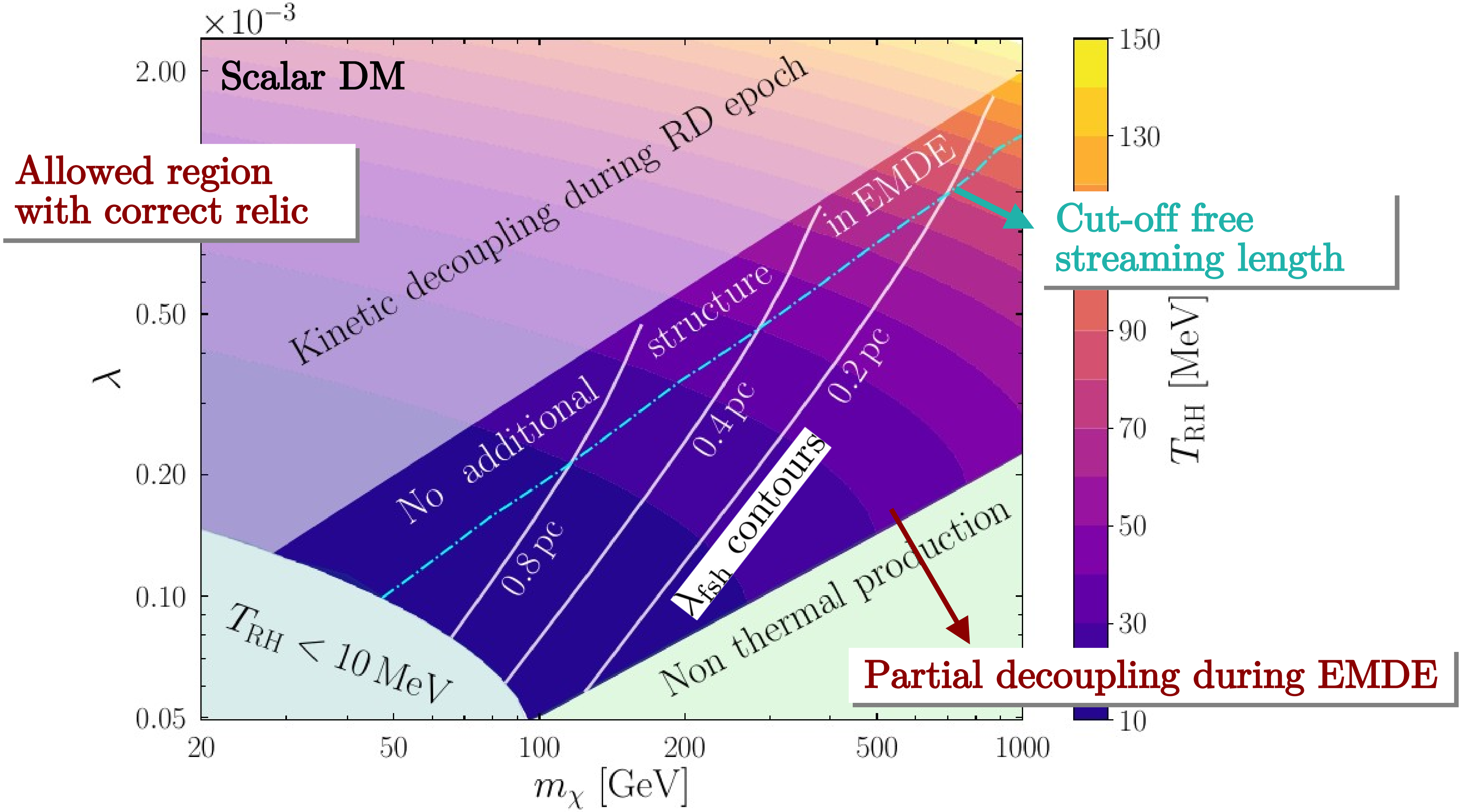
p-wave elastic scattering

$$\gamma_{\rm el} \sim T^6$$

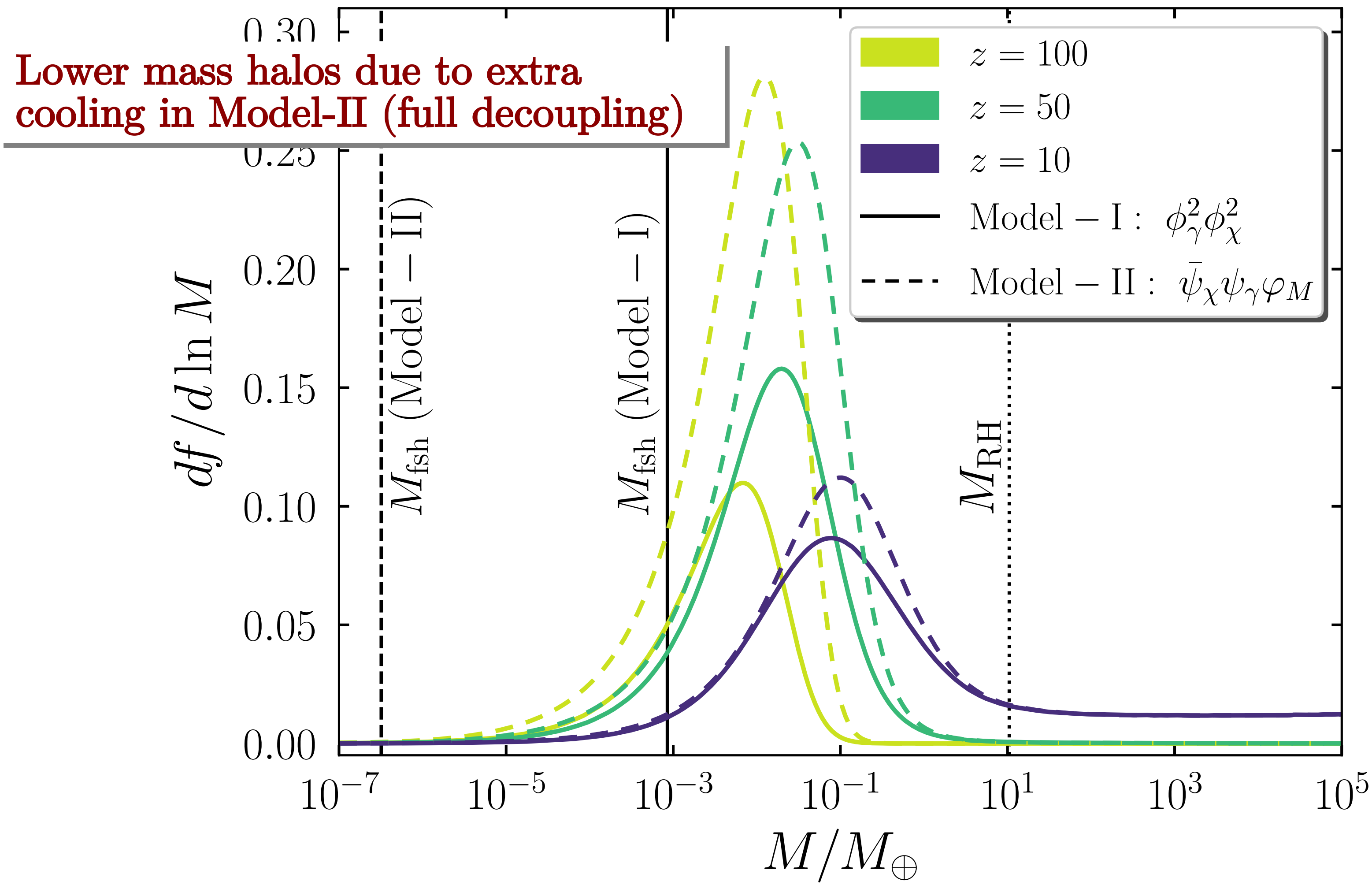
Full decoupling in EMDE

Larger population of sub-earth halos in the fermionic DM case

Distinguishing dark matter models



Distinguishing dark matter models



Larger population of sub-earth halos in the fermionic DM case

Implications of boost in small scale structures

Competing effects in DM annihilation rate:

$$\Gamma_{\rm ann} = \frac{\langle \sigma v \rangle_{\rm ann}}{2 m_\chi^2} \int \rho_\chi^2(\vec{r}) d^3\vec{r}$$

- Lower annihilation cross-section
- Higher microhalo population

Advantage of T-dependent entropy injection: allows larger cross-section compared to usual EMDE

$$\frac{\langle \sigma v \rangle_{\rm ann}^{\Gamma_\phi \sim T}}{\langle \sigma v \rangle_{\rm ann}^{\Gamma_\phi \sim {\rm const.}}} \sim \frac{m_\chi}{10\,{\rm GeV}} \frac{10\,{\rm MeV}}{T_{\rm RH}} \frac{10^3}{x_{\rm fo}^c} \left(\frac{x_{\rm fo}^T}{x_{\rm fo}^c} \right)^3 \gg 1$$

[ONGOING WORK]

Summary

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Thank you