Fingerprints of an early matter-dominated era

mainly based on JCAP 03 (2025) 30 [arXiv: 2408.08360]

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The Frontier of Particle Physics: Exploring Muons, Quantum Science and the Cosmos

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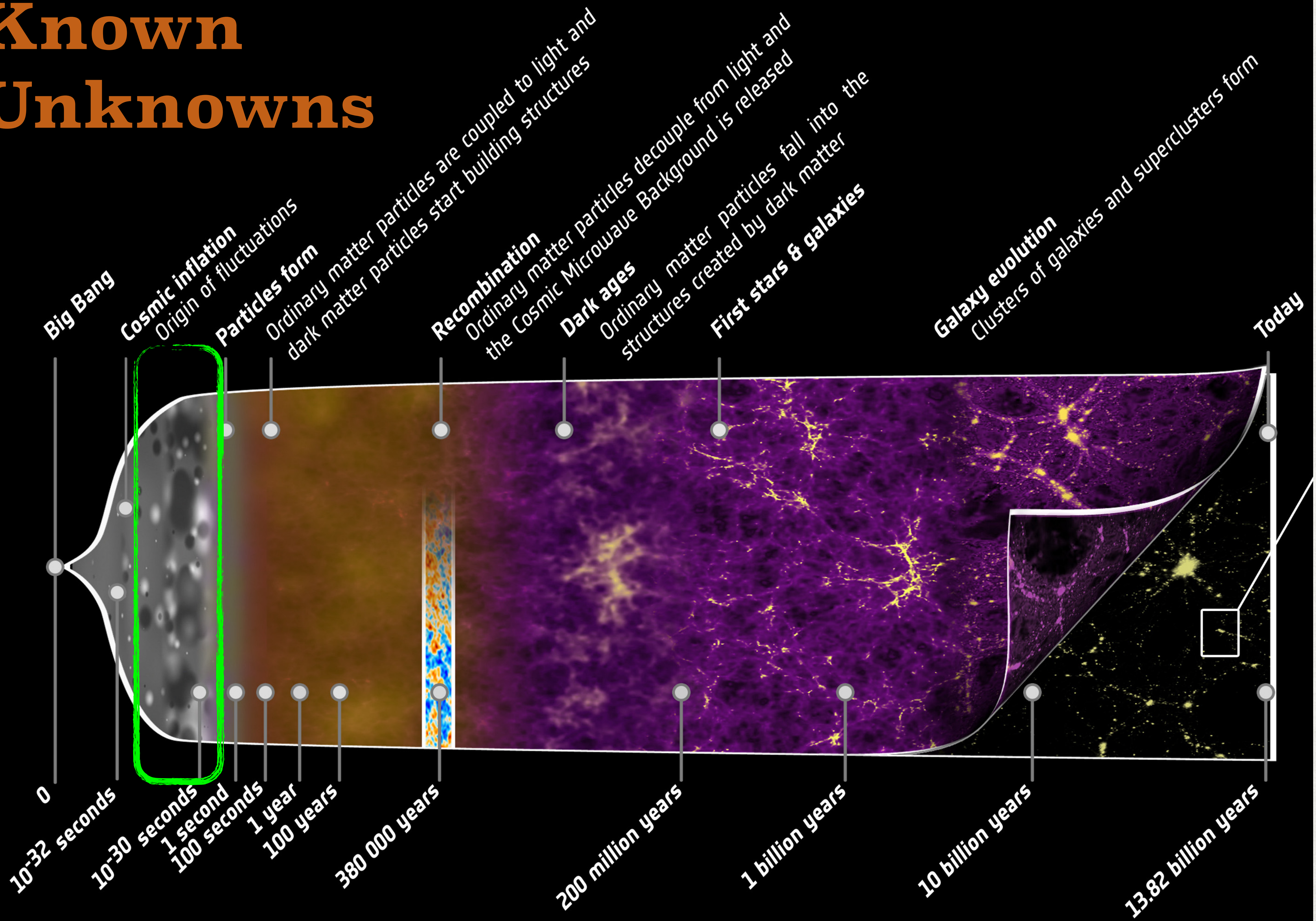
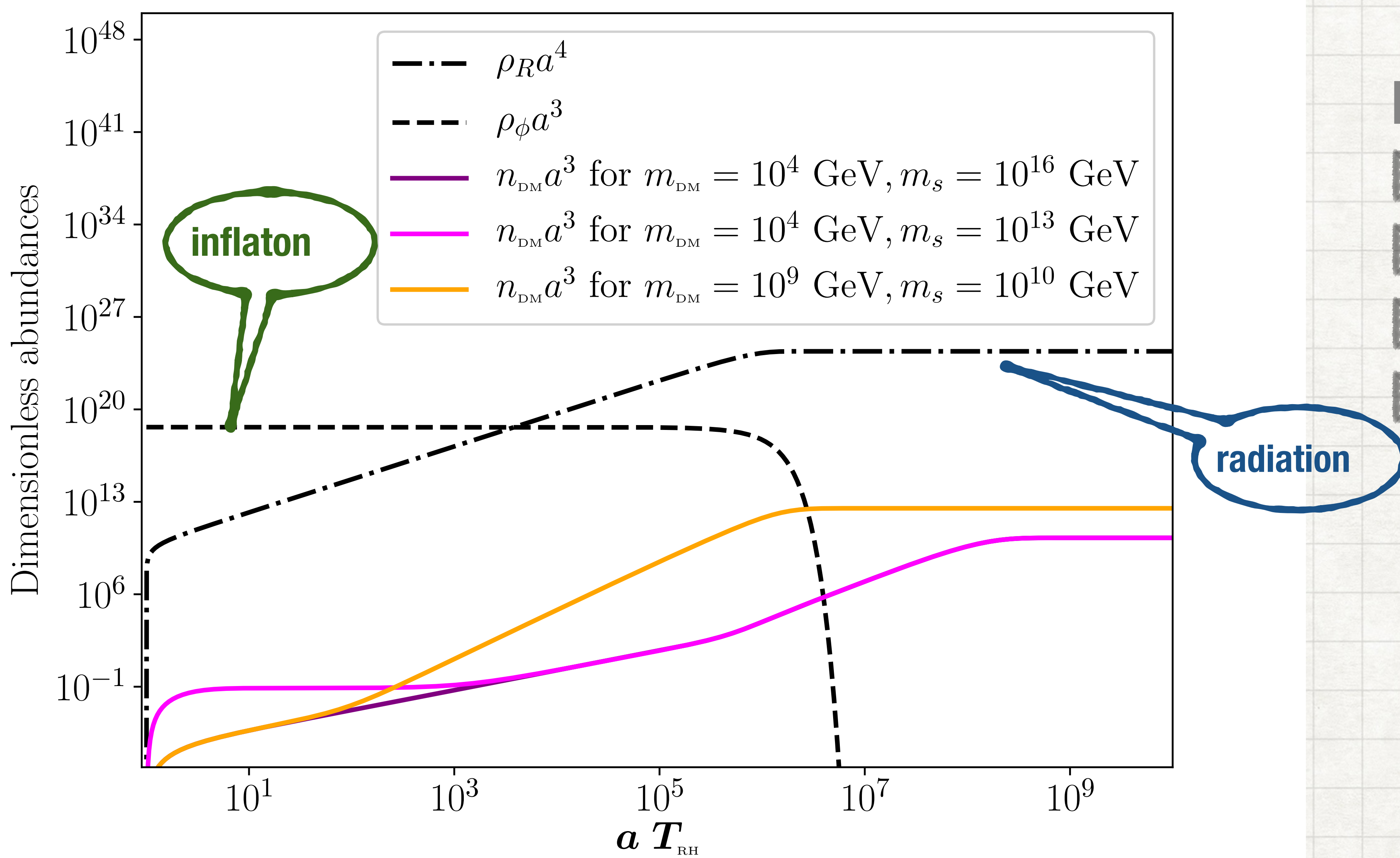
Known Unknowns



DM Genesis in the early universe



DM Portals

- Spin-2
- Spin-1
- Spin-1/2
- Spin-0

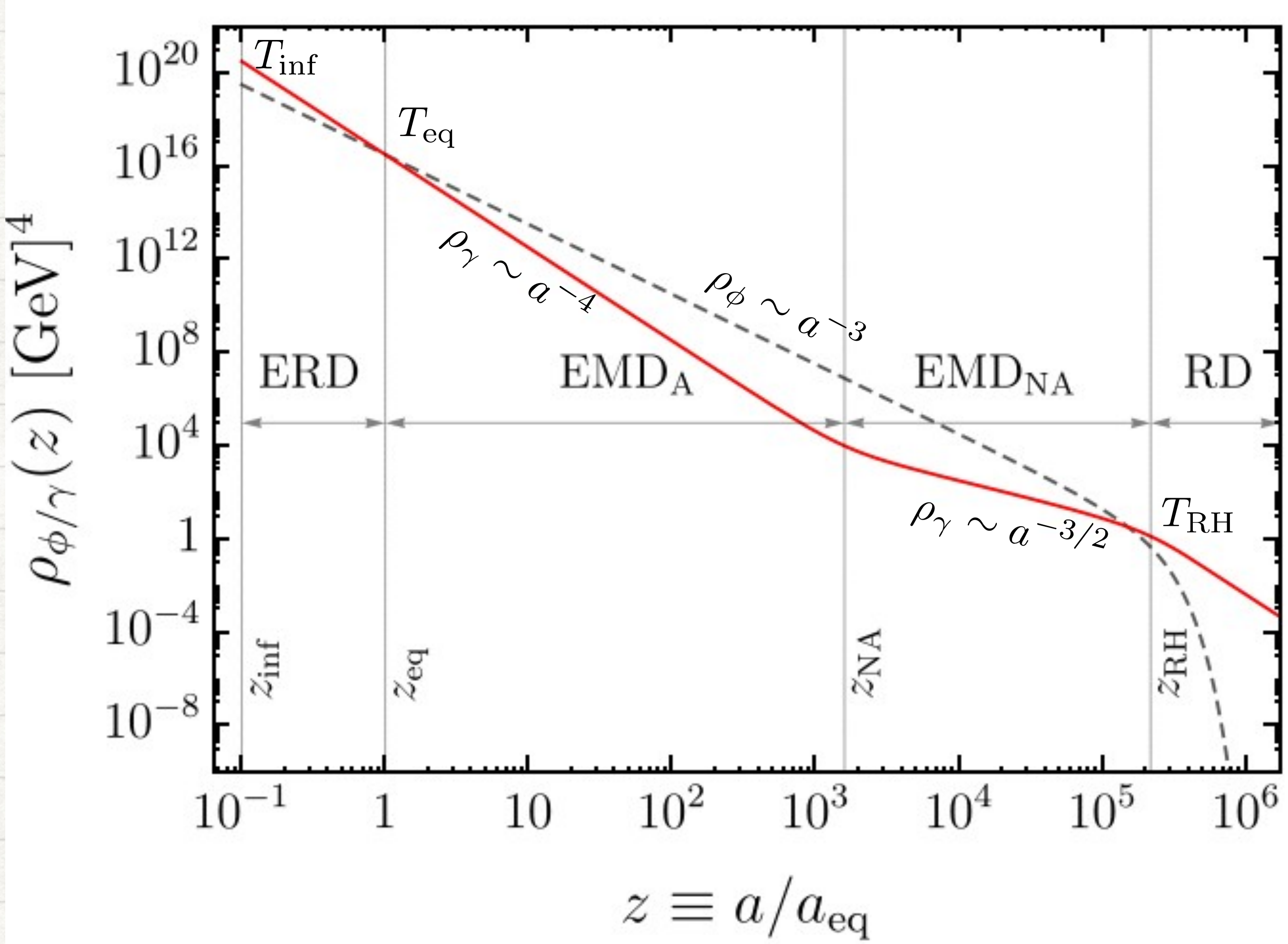
[1711.05007; 1803.08064; 1910.06319; 2003.01723; ….]

DC, Dudas, Dutra, Mambrini [1811.01947]

Early Matter Domination

$$\frac{\rho_\phi}{\rho_\gamma} \propto a$$

ϕ meta-stable field



BSM candidates of a meta-stable field

- Dilaton
- Moduli
- Curvaton …

[1711.05007; 1803.08064; 1910.06319; 2003.01723; ….]

Main constraint: $T_{RH} \gtrsim$ few MeV from BBN

$$\dot\rho_\phi + 3(1+\omega)H\rho_\phi = -(1+\omega)\Gamma_\phi\rho_\phi$$

$$\dot\rho_\gamma + 4H\rho_\gamma = (1+\omega)\Gamma_\phi\rho_\phi$$

$$H = \frac{1}{\sqrt{3}M_p}\sqrt{\rho_\phi+\rho_\gamma}$$

$\Gamma_\phi =$ Dissipation rate

Generalized Dissipation Rate

A generalized dissipation rate depends on temp. and scale factor.

- **Example:** Moduli decay $\Gamma_\phi \propto \frac{T^3}{M_p^2}$ [Bodeker '06]

$$\Gamma_\phi = \hat{\Gamma}\left(\frac{T}{T_{eq}}\right)^n \left(\frac{a}{a_{eq}}\right)^k$$

- **Example:** oscillating scalar field ϕ with $V(\phi) \sim \phi^p$ potential

$$\Gamma_{\phi\to f\bar{f}} \propto m_\phi(t) \propto a^{-3(p-2)/(p+2)}$$ Fermionic decay

$$\Gamma_{\phi\to\eta\eta} \propto m_\phi^{-1}(t) \propto a^{3(p-2)/(p+2)}$$ Bosonic decay

$$m_\phi(t) \propto \langle\phi(t)\rangle^{(p-2)/2}$$

$$\langle\phi(t)\rangle \sim a^{-6/p+2}$$

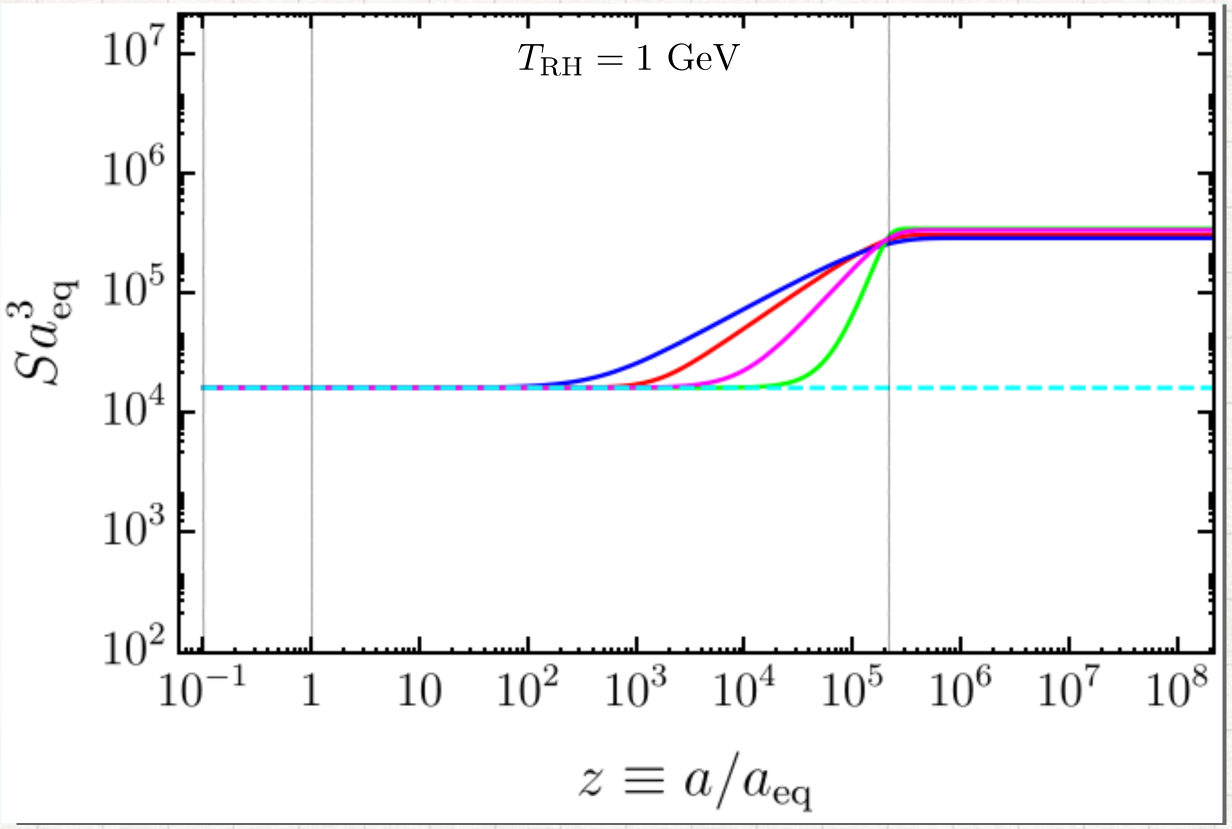
[Scherrer, Turner '85; Shtanov et al. '95; Kofman et al. '97; Garcia et al. '12, ...]

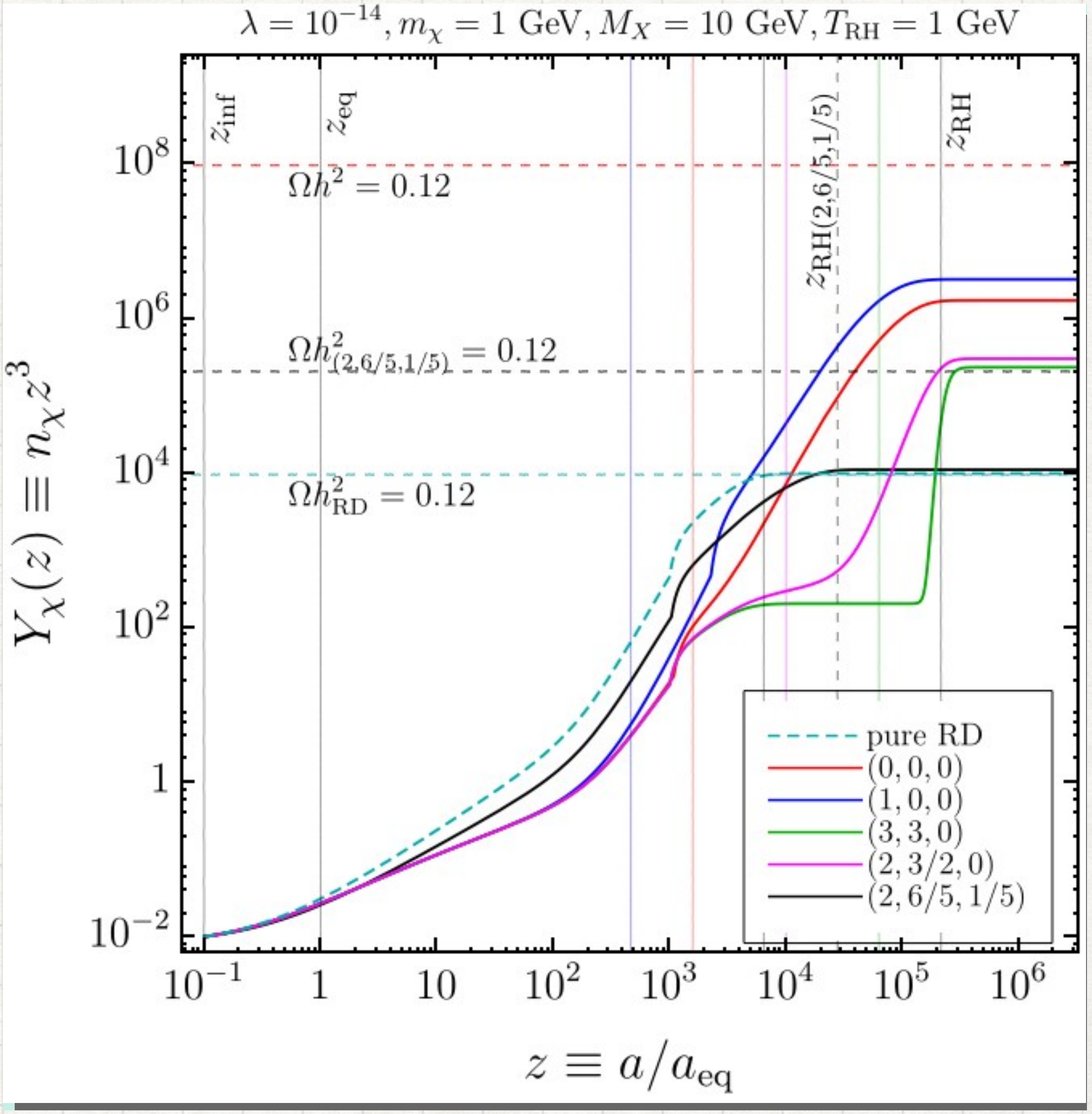
More Examples:

Γ_ϕ	(n,k,ω)	$T(z)$ during EMD$_{\rm NA}$
const.	$(0,0,0)$	decreases with z
T	$(1,0,0)$	decreases with z
$\langle\phi\rangle^{-2}$	$(0,3,0)$	increases with z
$\frac{T^3}{\langle\phi\rangle^2}$	$(3,3,0)$	increases with z
$\frac{T^2}{\langle\phi\rangle}$	$(2,3/2,0)$	remains constant
$\frac{T^2}{\langle\phi\rangle}$	$(2,6/5,1/5)$	decreases with z

Mukaida et. al. 1208.3399, 1212.4985
Drewes, 1406.6243
Co et. al. 2007.04328

Freeze-in DM in an EMD era





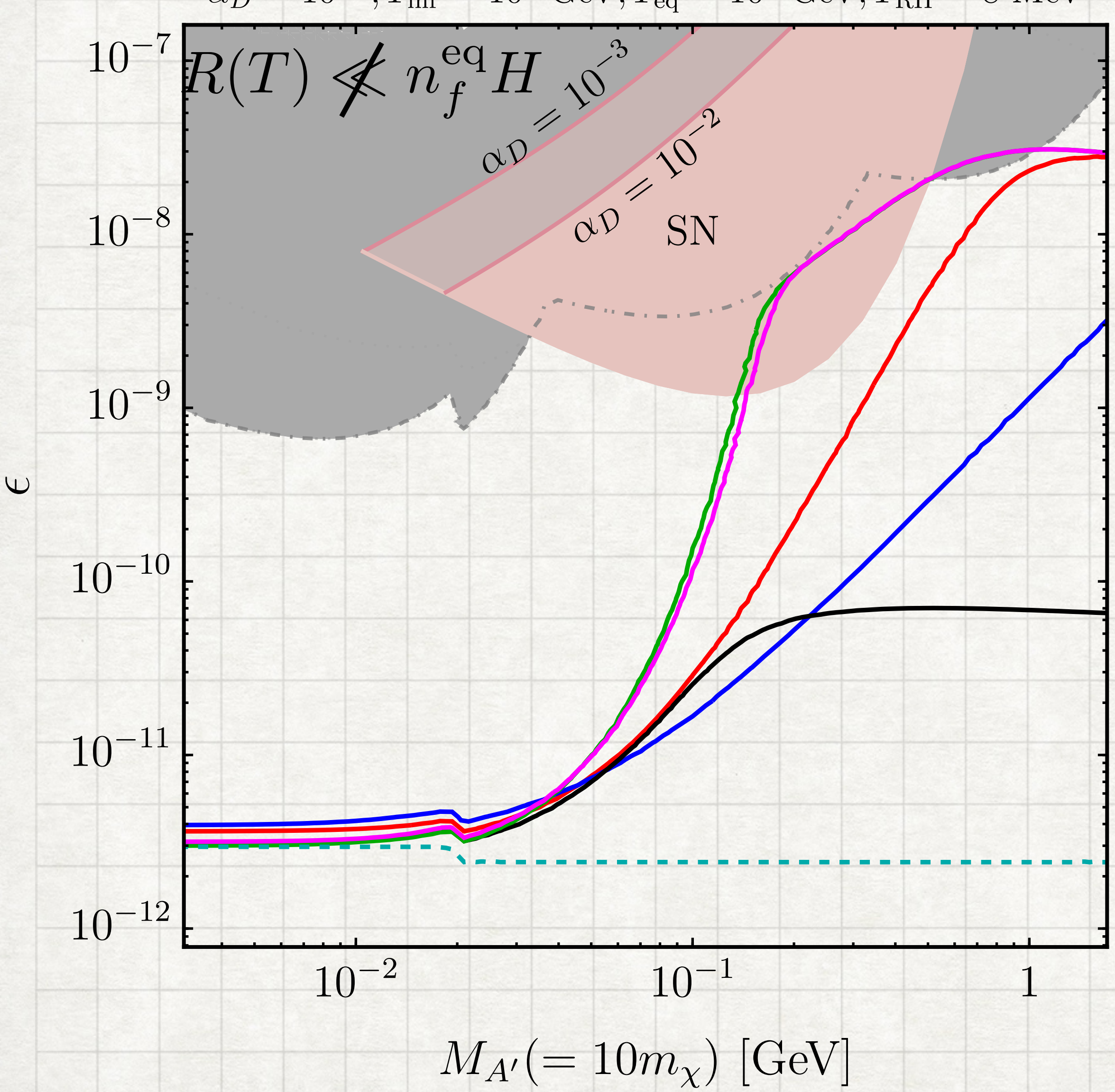
$$\Gamma_\phi = \hat{\Gamma}\left(\frac{T}{T_{eq}}\right)^n \left(\frac{a}{a_{eq}}\right)^k$$

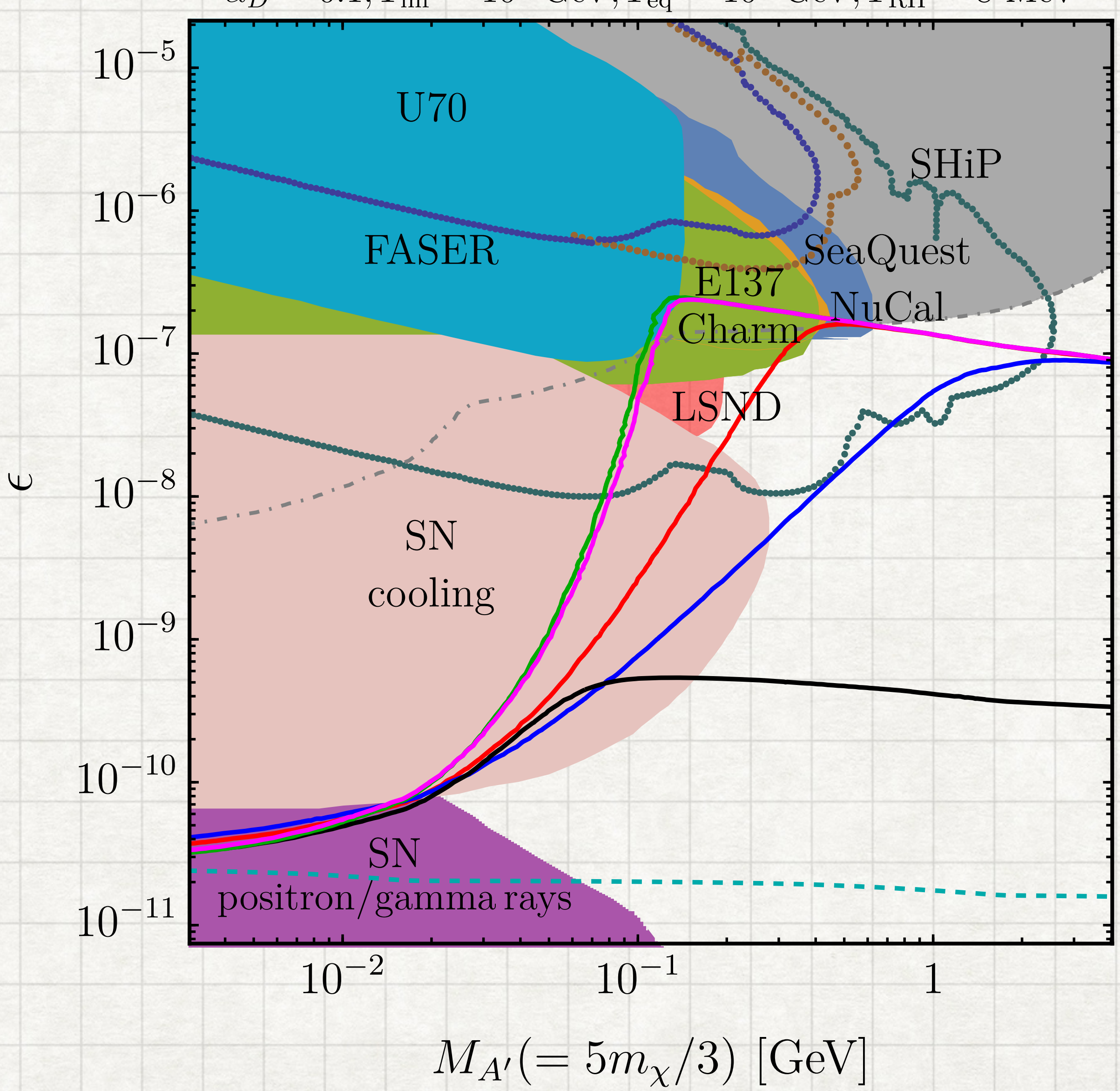
Larger coupling is required to saturate the DM relic in EMD

[Banerjee, DC, Sci. Post. '22]

Dark Photon Portal DM

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}M^2_{A'}A'_\mu A'^\mu + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + g_D\bar{\chi}\gamma^\mu A'_\mu\chi$$





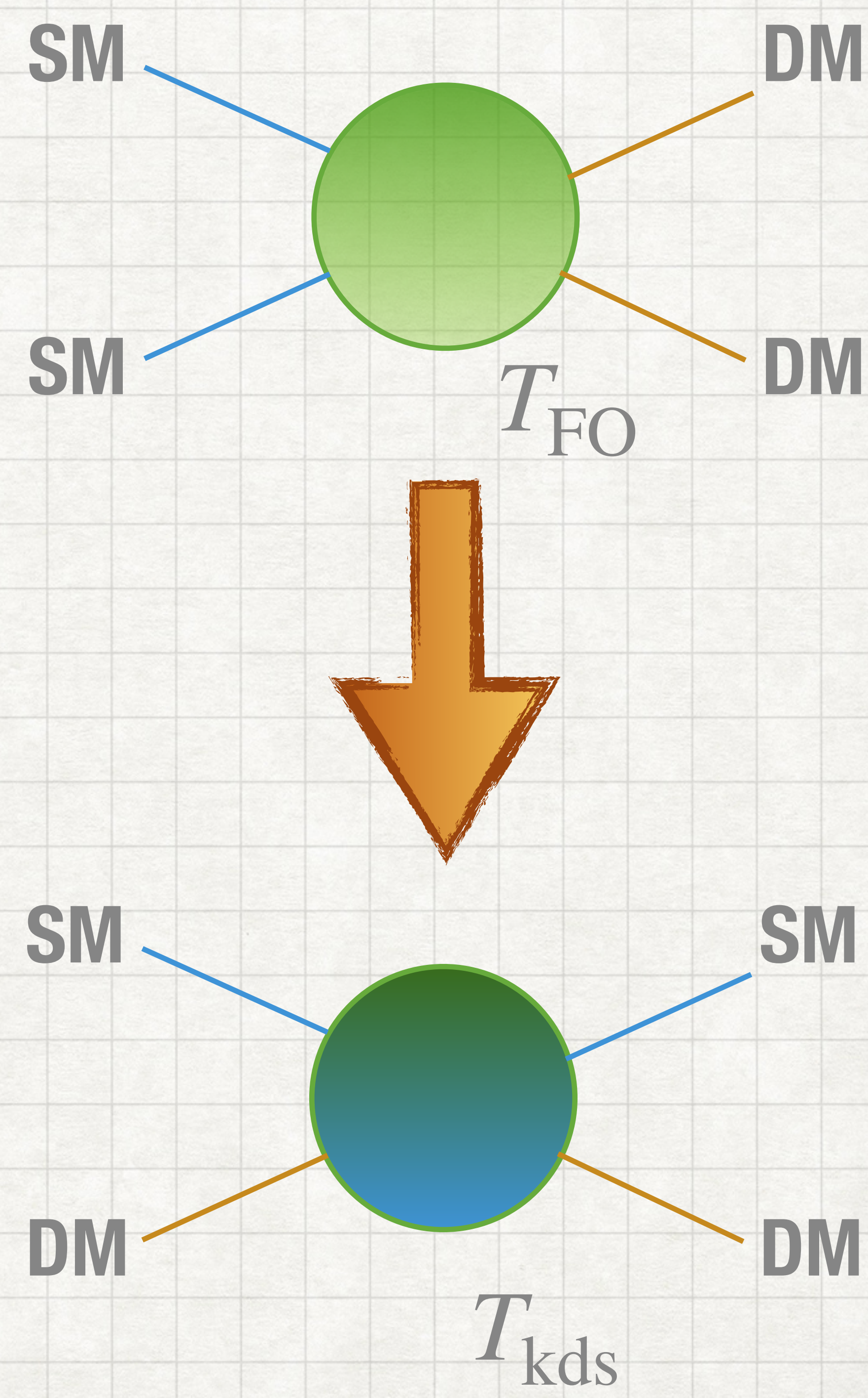
[Banerjee, DC, Sci. Post. '22]

What are the signatures of an EMDE?

DM Thermal decoupling in RD

- In the standard RD epoch, DM decouples first chemically the plasma: $\chi\chi \to BB$
- After this, DM kinetically decouples from the plasma: $\chi B \to \chi B$
- Then DM free streams.

$$\boxed{T_{\rm FO} > T_{\rm kds}}$$



DM thermal decoupling in EMDE

- In EMDE: kinetic decoupling is determined by how the elastic scattering XS and Hubble vary with the plasma temperature.

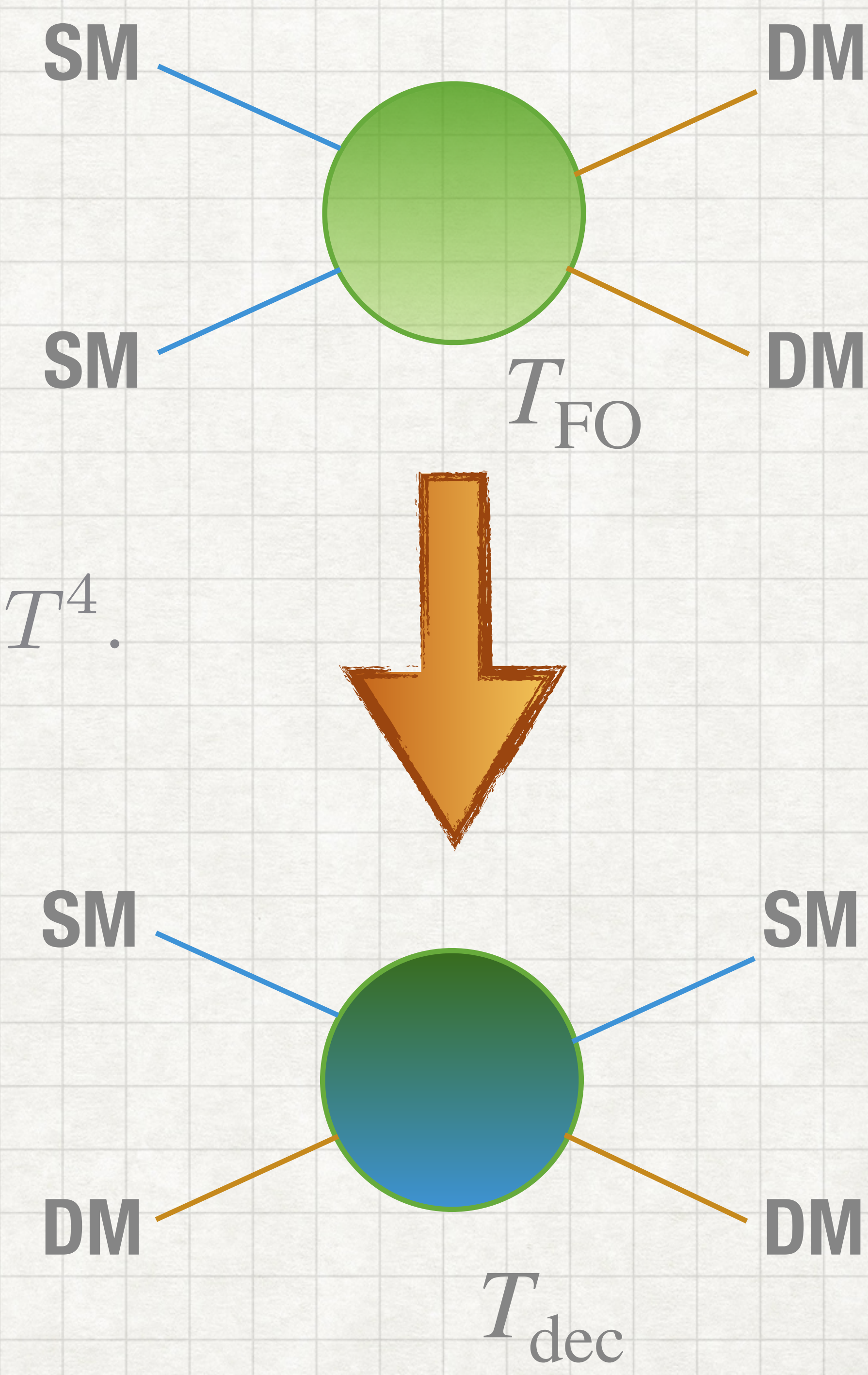
- Reheating initiates when $\Gamma_\phi > H$.

- For constant Γ_ϕ: $T \propto a^{-3/8}$, and $H \propto T^4$.

- For s-wave elastic scattering, $\langle \sigma v \rangle_{\rm el} \sim \text{const}$,

$$\gamma_{\rm el} \sim T^4 \text{ and } H \propto T^4.$$

- As a result, DM cannot kinetically decouple before the onset of RD.



[Gelmini et al. '08, Visinelli et al. '15, Waldstein et al. '16, Erickcek et al. '11, '15]

DM thermal decoupling in EMDE

- For p-wave elastic scattering, $\langle \sigma v \rangle_{\rm el} \sim T^2$

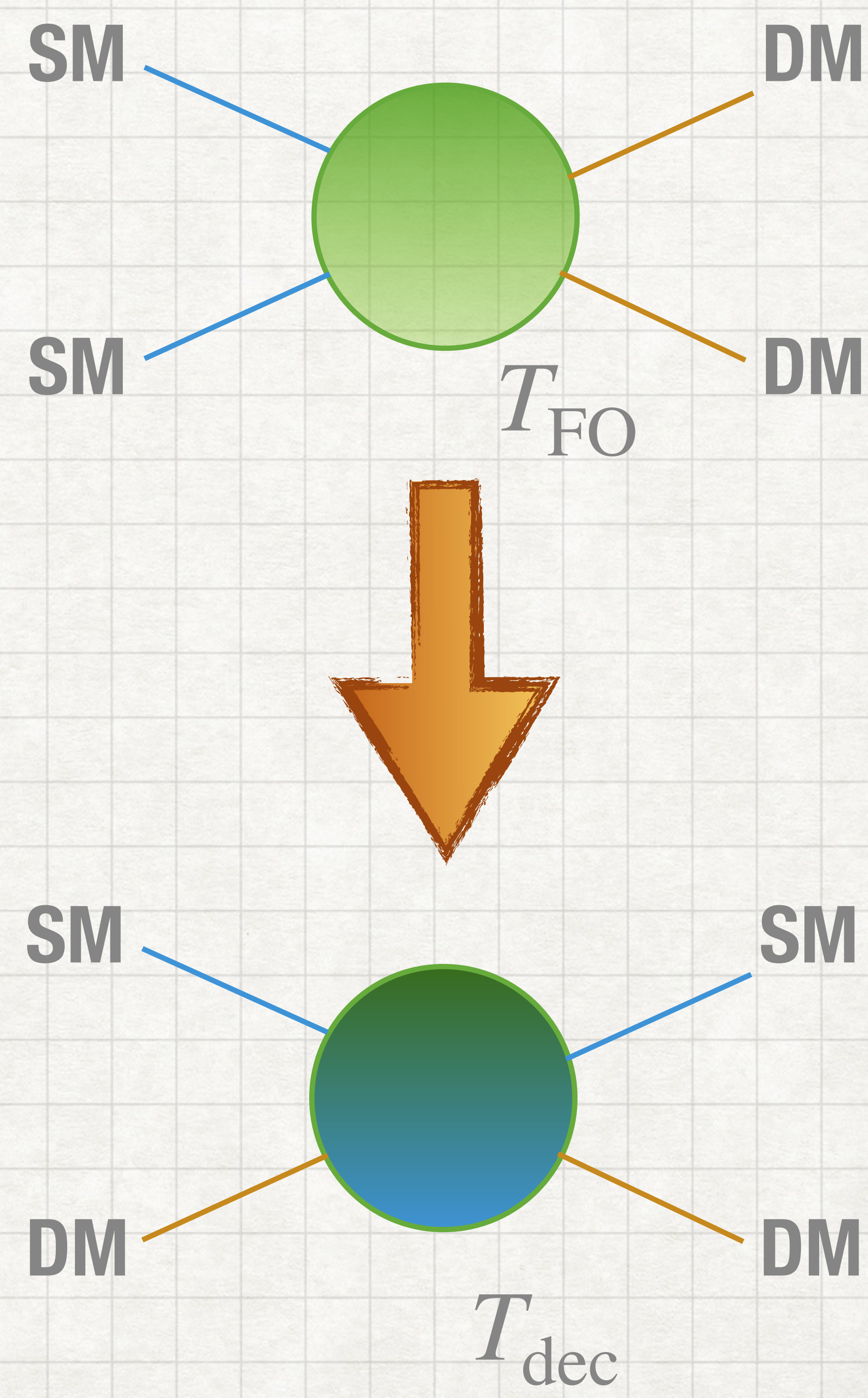
$$\gamma_{\rm el} \sim T^6 \text{ and } H \propto T^4$$

- DM kinetically decouples partially, before the onset of RD.

- As a result, DM cools faster than the plasma during EMDE.

- Due to this, the free-streaming horizon reduces in EMDE compared to the standard RD scenario.

- Small-scale structure are formed due to the scales entering the horizon before RD.



[Gelmini et al. '08, Visinelli et al. '15, Waldstein et al. '16, Erickcek et al. '11, '15]

DM thermal decoupling in EMDE

- Entropy injection during the EMDE depends on the plasma temperature: $\Gamma_\phi \sim T$
- In this case: $T \propto a^{-1/2}, \text{ and } H \propto T^3.$
- As a result, the s-wave scattering is enough to partially decouple the DM from the plasma.
- Whereas, p-wave scattering fully decouples it from the plasma before the onset of RD.
- Such extra cooling of the DM receives an extra kick from the enhanced matter perturbations during EMDE.
- As a result, a boost in the formation of structures at sub-earth scales.

Kinetic decoupling of DM

Standard RD scenario:

$$T_\chi(t) \equiv \frac{g_\chi}{3n_\chi}\int \frac{d^3p}{(2\pi)^3}\frac{p^2}{E}f_\chi(\mathbf{p},t) \qquad \frac{dT_\chi}{d\ln a} + 2T_\chi(a)\left[1+\frac{\gamma_{\rm el}(a)}{H(a)}\right] = 2\frac{\gamma_{\rm el}(a)}{H(a)}T(a)$$

$$\gamma_{\rm el}(T) \ll H(T) \qquad T_\chi \sim a^{-2}$$

$$\gamma_{\rm el}(T)T \ll H(T)T_\chi \qquad T \sim a^{-1}$$

Non-standard scenario:

$$T \propto a^{-\alpha} \quad H \propto T^\beta \quad \gamma_{\rm el}(T) \propto T^{(4+n)} \quad \gamma_{\rm el}(T_{\rm dec}) = H(T_{\rm dec})$$

$$T_\chi(a) \simeq \frac{T_{\rm dec}}{2-\alpha(5+n-\beta)}\left[2\left(\frac{a}{a_{\rm dec}}\right)^{-\alpha(5+n-\beta)} - \alpha(5+n-\beta)\left(\frac{a}{a_{\rm dec}}\right)^{-2}\right] \qquad \gamma_{\rm el}(T) \ll H(T)$$

$$\gamma_{\rm el}(T)T \not\ll H(T)T_\chi$$

Kinetic decoupling of DM

Non-standard scenario:

$$T \sim a^{-\alpha} \quad H \sim T^{\beta} \quad \gamma_{\rm el}(T) \propto T^{(4+n)}$$

$$T_\chi(a) \simeq \frac{T_{\rm dec}}{2-\alpha(5+n-\beta)}\left[2\left(\frac{a}{a_{\rm dec}}\right)^{-\alpha(5+n-\beta)} - \alpha(5+n-\beta)\left(\frac{a}{a_{\rm dec}}\right)^{-2}\right]$$

$n \leq n_{\rm dec}$: no kinetic decoupling,
$n_{\rm dec} < n < n_{\rm partial}$: partial kinetic decoupling,
$n > n_{\rm dec}$ and $n \geq n_{\rm partial}$: full kinetic decoupling,

$$n_{\rm partial} \equiv (2/\alpha) + \beta - 5.$$

$$n_{\rm dec} = \beta - 4$$

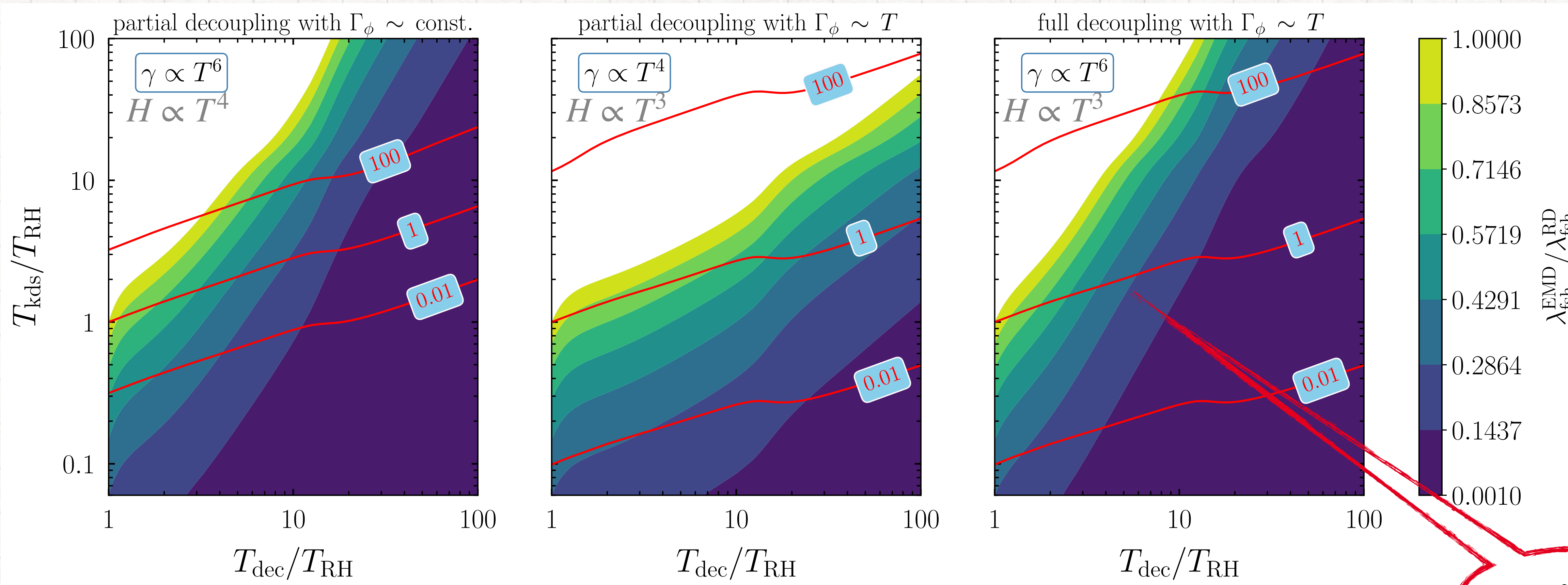
During entropy injection:

$$\Gamma_\phi \propto a^k T^m$$

ϕ domination	k	m	α	Conditions for kinetic decoupling: $n_{\rm dec}$	$n_{\rm partial}$	s-wave	p-wave
$\omega_\phi = 0$ (Matter)	0	0	3/8	0	13/3	–	partial
	0	1	1/2	-1	2	partial	full
$\omega_\phi = 1/3$ (Radiation)	-1	0	3/4	-4/3	1/3	partial	full
	1	0	1/4	4	11	–	–
	1	2	1/2	0	3	–	partial
$\omega_\phi = 1$ (Kination)	0	0	3/4	0	5/3	–	full
	0	1	1	-1	0	full	full

[Banerjee, DC, Hait, Islam, 2408.08360]

Kinetic decoupling of DM



$$r \equiv \frac{\gamma_0^{\rm EMD}}{\gamma_0^{\rm RD}}$$

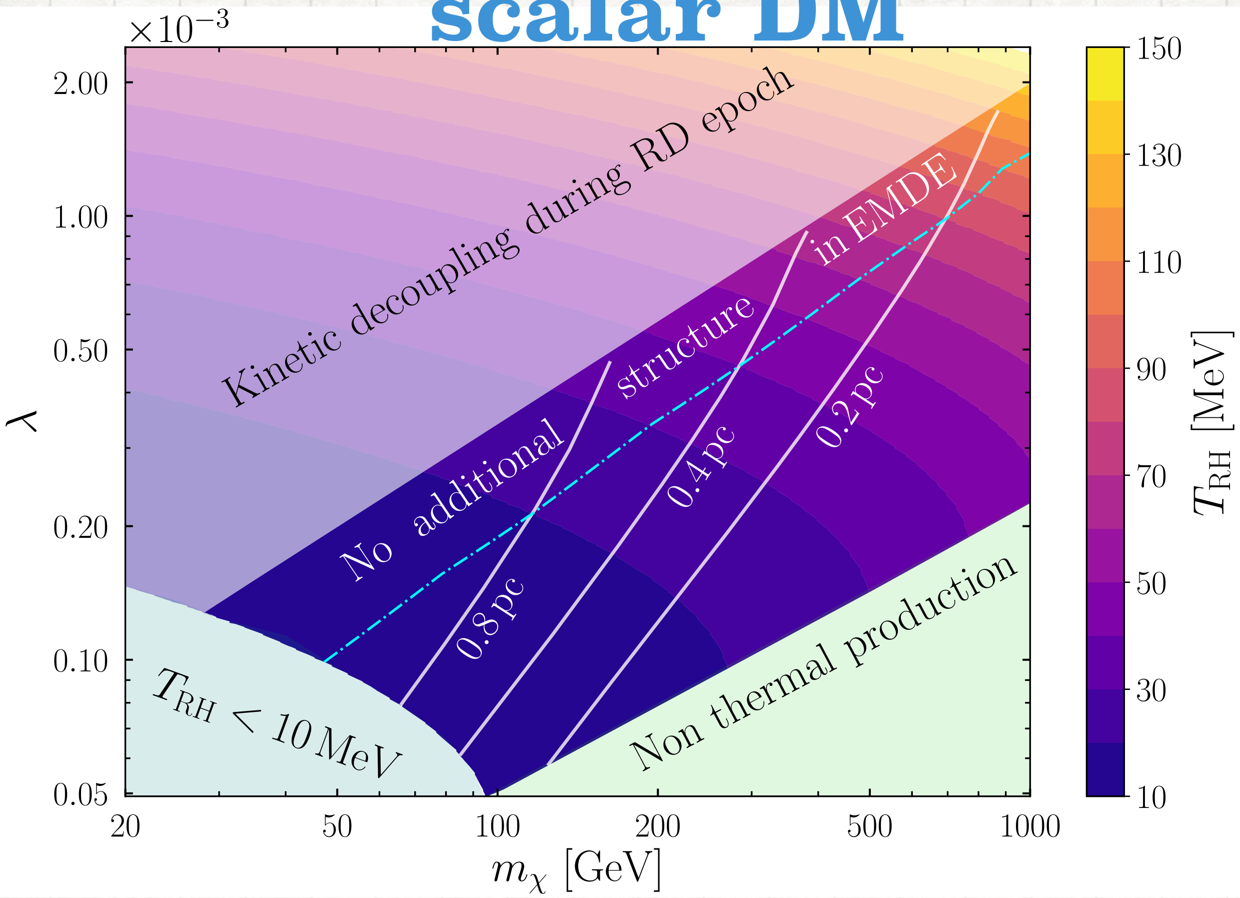
$$\lambda_{\rm fsh}^{\rm EMD} = \int_{t_{\rm dec}}^{t_0} dt\, \frac{v_\chi(t)}{a(t)} = \sqrt{\frac{3}{m_\chi}} \left[\int_{a_{\rm dec}}^{a_{\rm RH}} + \int_{a_{\rm RH}}^{a_{\rm eq}} + \int_{a_{\rm eq}}^{a_0}\right] da \frac{\sqrt{T_\chi(a)}}{a^2 H(a)}\,, \qquad \begin{cases} T \sim a^{-\alpha}, \\ H \sim T^{\beta} \end{cases}$$

$$\lambda_{\rm fsh}^{\rm RD} = \int_{t_{\rm kds}}^{t_0} dt\, \frac{v_\chi(t)}{a(t)} = \sqrt{\frac{3}{m_\chi}} \left[\int_{a_{\rm kds}}^{a_{\rm eq}} + \int_{a_{\rm eq}}^{a_0}\right] da\, \frac{\sqrt{T_\chi(a)}}{a^2 H(a)}\,, \qquad \begin{cases} T \sim a^{-1}, \\ H \sim T^{2}. \end{cases}$$

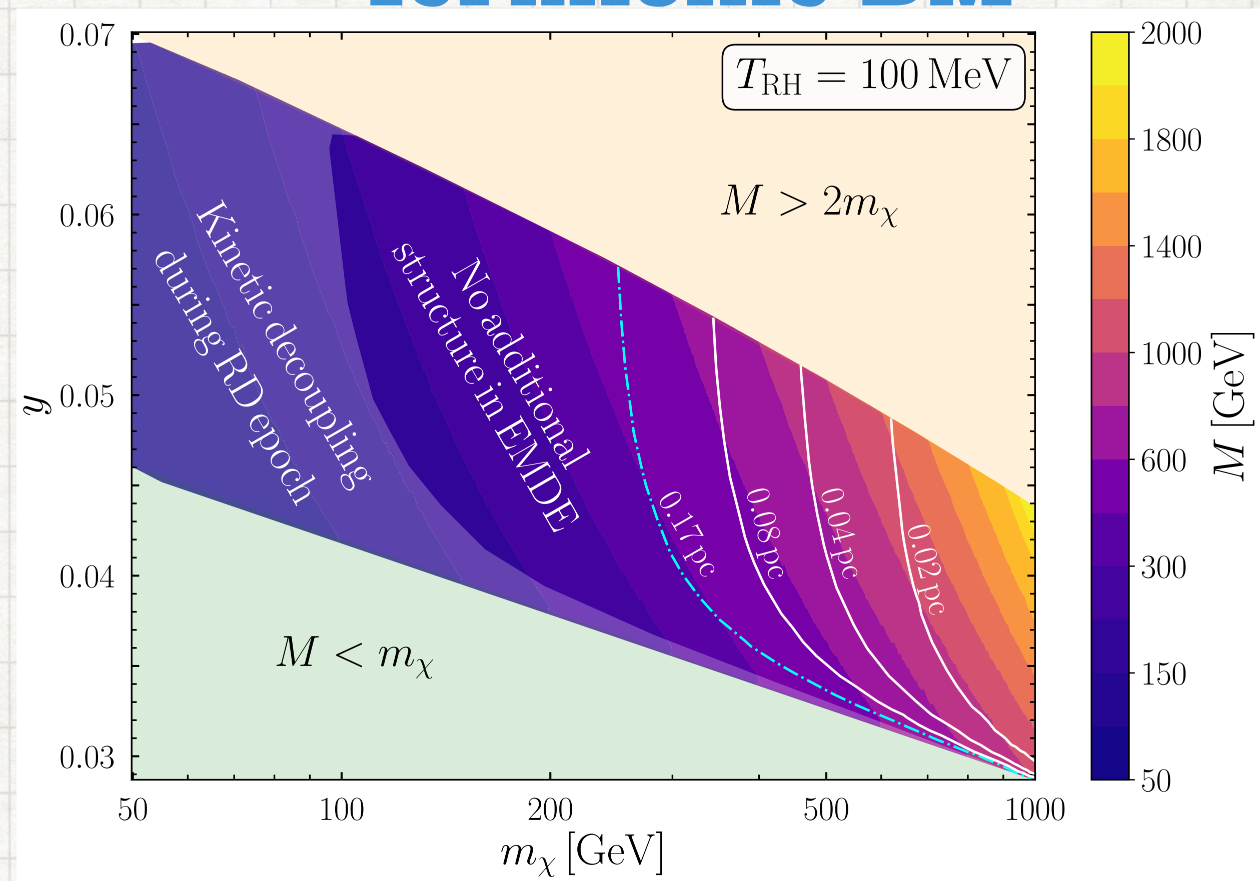
[Banerjee, DC, Hait, Islam, 2408.08360]

Case Studies

scalar DM



fermionic DM



s-wave elastic scattering

$$\mathcal{L} \supset \frac{\lambda}{4}\phi_\chi^2\varphi_\gamma^2$$

$$\gamma_{\rm el}(T) = \frac{\lambda^2\pi}{180} m_\chi \left(\frac{T}{m_\chi}\right)^4$$

p-wave elastic scattering

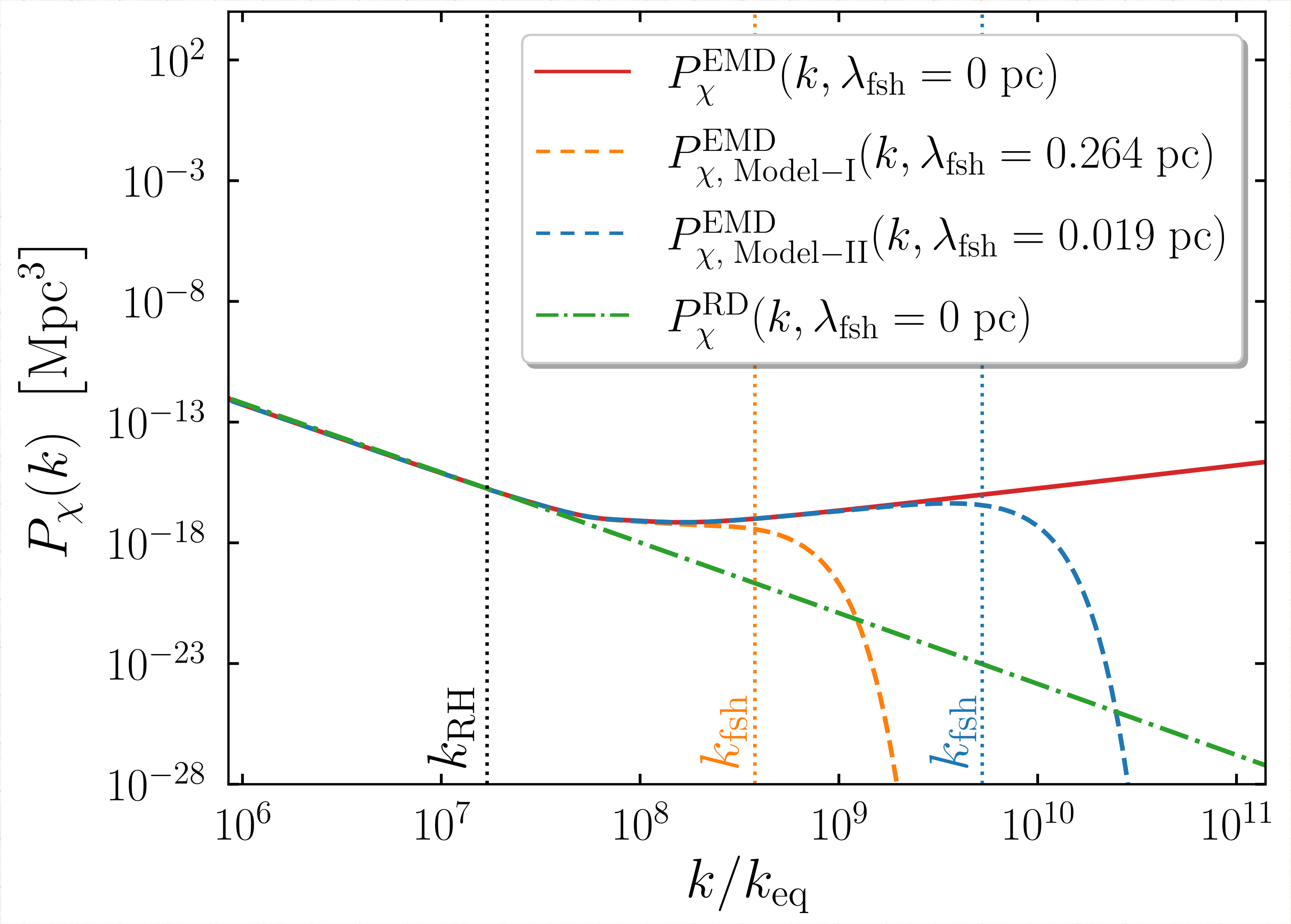
$$\mathcal{L} \supset y\bar{\psi}_\chi\psi_\gamma\varphi_M$$

$$\gamma_{\rm el}(T) = \frac{341}{756}\pi^3 y^4 \frac{m_\chi^3}{(M-m_\chi)^2}\left(\frac{T}{m_\chi}\right)^6$$

$$m_\chi < M \leq 2m_\chi$$

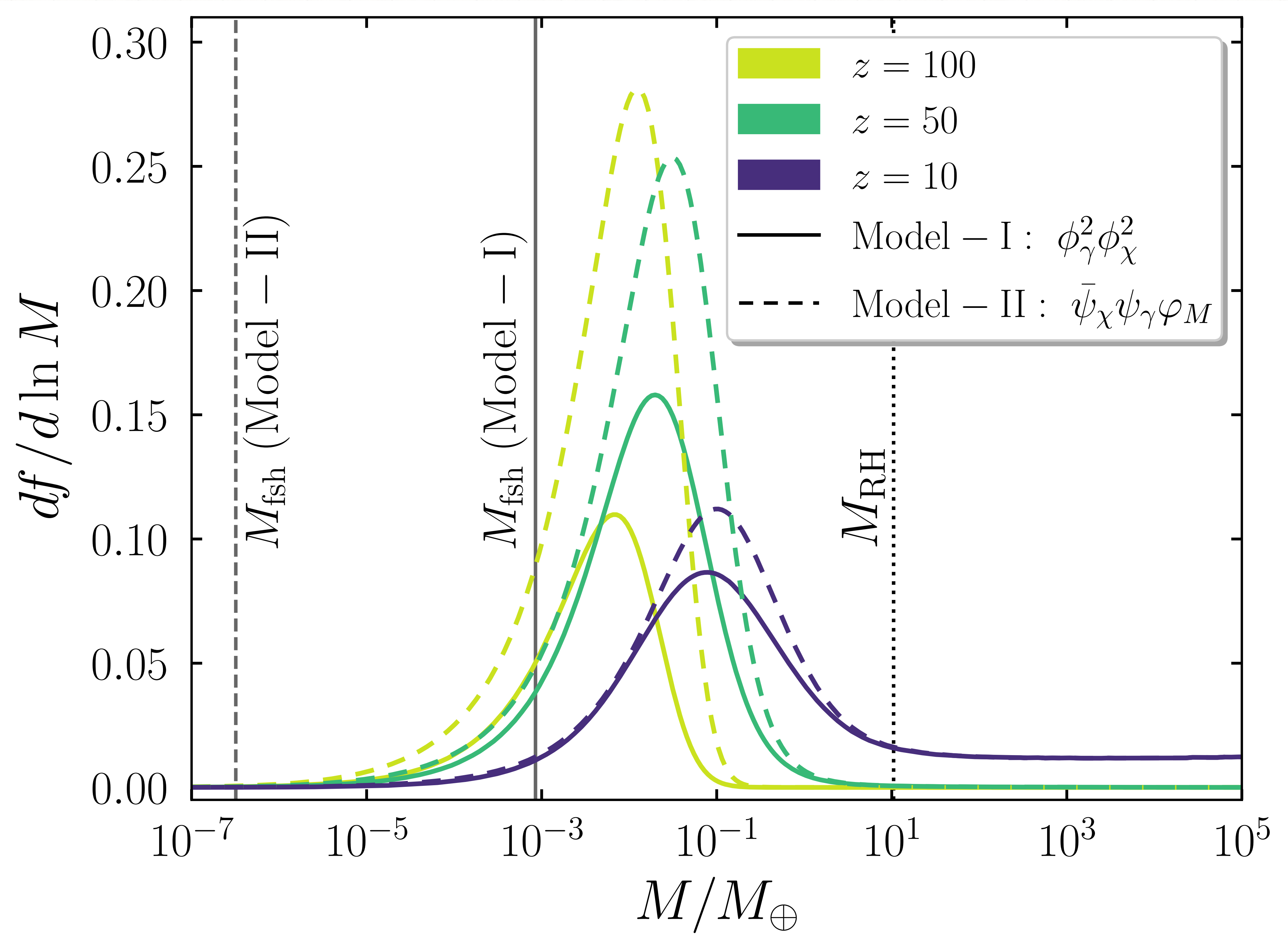
[Banerjee, DC, Hait, Islam, 2408.08360]

Matter power spectrum



[Banerjee, DC, Hait, Islam, 2408.08360]

Halo mass fraction



Summary

- Null results from thermal DM direct detection experiments give an impetus to consider other non-standard DM scenarios.
- Freeze-in DM relic depends on the non-standard epochs of cosmology at high temperatures.
- Early matter domination prior to BBN leads to a freeze-in scenario with larger coupling.
- Depending on the background, DM kinetically decouples from the thermal bath with either partial (s-wave) or full (p-wave).
- Such early decoupling leads to sub-earth mass halo formation.
- Such sub-earth mass halos can give rise to annihilation signatures.

Thank You!