Fingerprints of freeze-in dark matter in an early matter-dominated era

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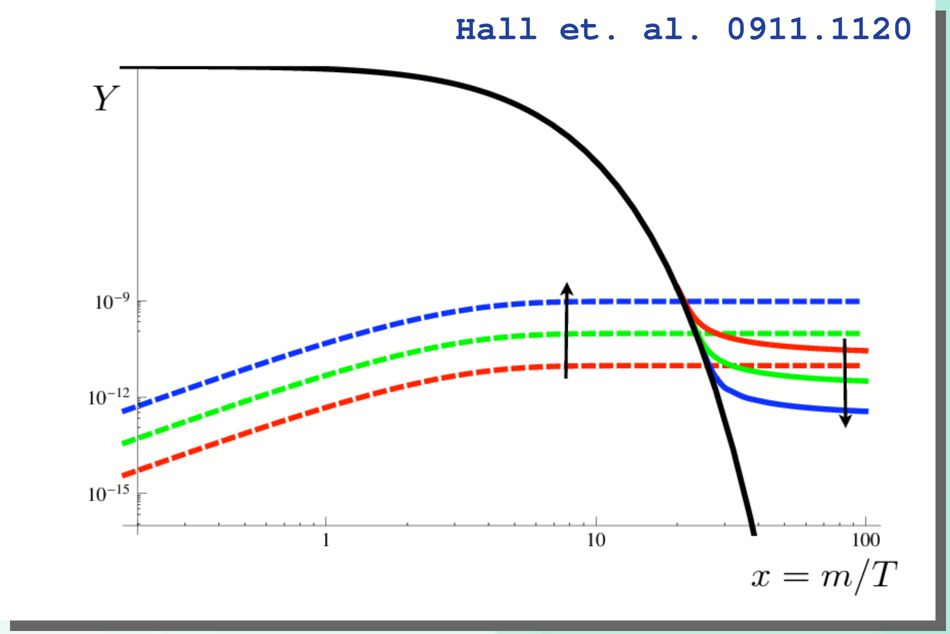
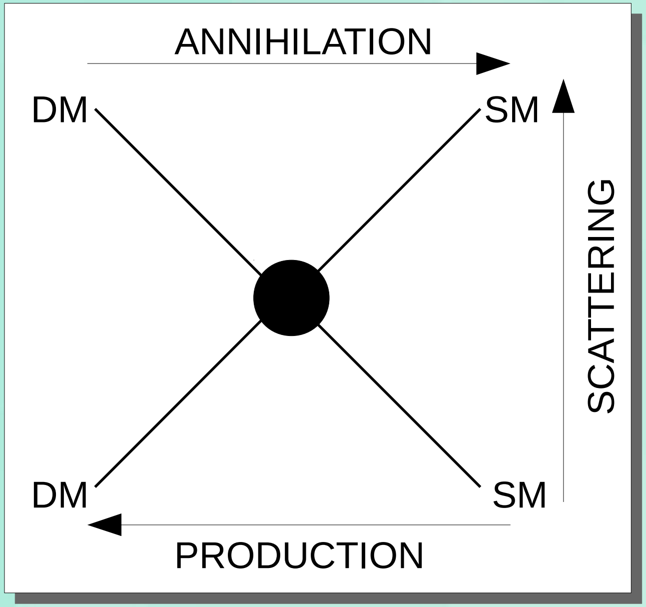
Freeze-out vs. Freeze-in





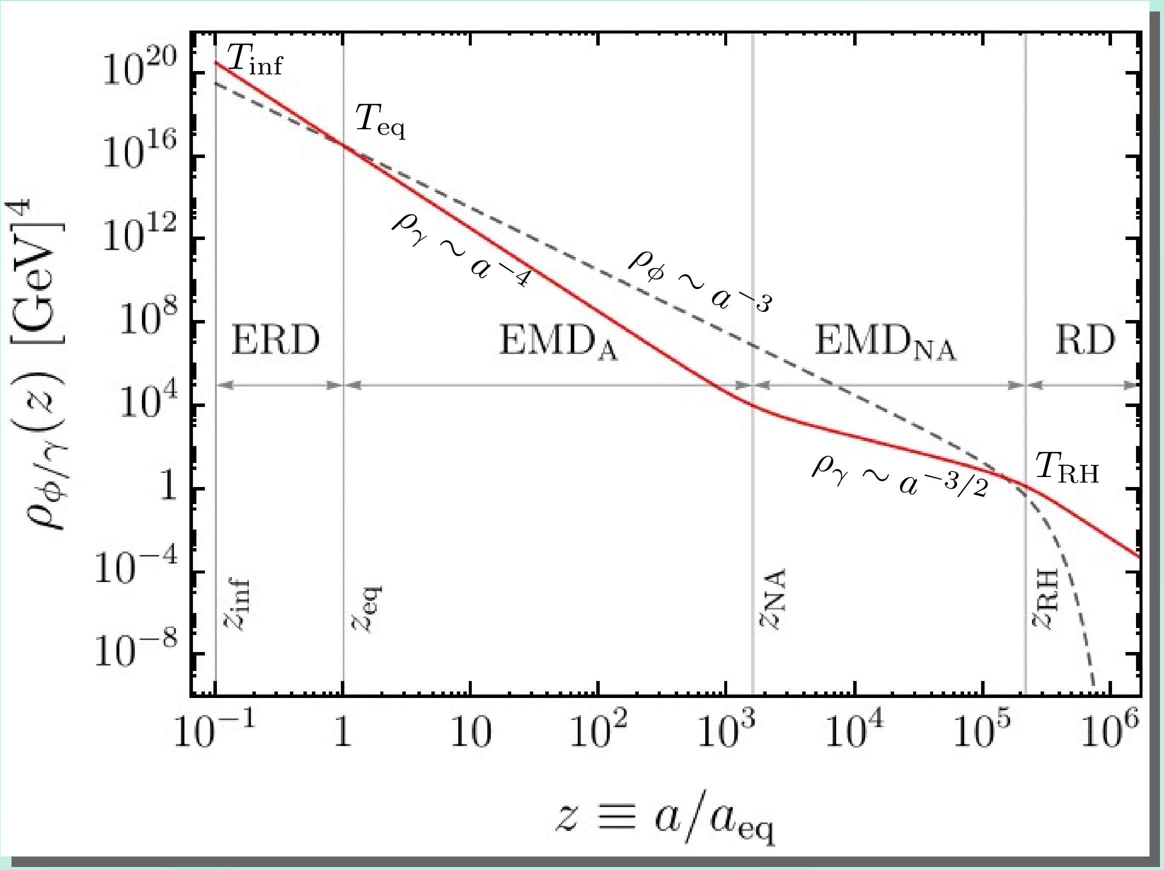
Freeze-out	Freeze-in
DM-SM in thermal equilibrium, Large coupling required	DM-SM never in thermal equilibrium, Extremely small coupling
At high temperature DM has thermal abundance	Initial abundance of DM at the end of inflation is negligible
Cosmology at high temperature is irrelevant	Cosmology from the end of inflation till today impacts relic

Early matter domination

BSM motivations for EMD

- Meta-stable matter fields
- Oscillating scalar fields
- Moduli
- SUSY condensates
- Dilaton
- Q-balls
- Curvaton

$$\dot{\rho}_\phi + 3(1+\omega)H\rho_\phi = -(1+\omega)\Gamma_\phi\rho_\phi$$
$$\dot{\rho}_\gamma + 4H\rho_\gamma = (1+\omega)\Gamma_\phi\rho_\phi$$
$$H = \frac{1}{\sqrt{3}M_p}\sqrt{\rho_\phi + \rho_\gamma}$$



Constraints from BBN: $T_{\rm RH} \gtrsim$ few MeV

Evolution is dependent on the dissipation rate

1711.05007,1803.08064,1910.06319,2003.01723...
vast literature on effect of EMD on DM production

See also, talk by Catarina Cosme
(neutrino session)

Matter dissipation rate

In general depends on the temperature and the expansion of the universe

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

Examples:

Oscillating scalar fields with $V(\phi) \sim \phi^p$ potential

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

$$\Gamma_{\phi\to bb} \propto m_\phi^{-1}(t) \propto a^{3(p-2)/(p+2)}\,, \ \text{(for bosonic decay)},$$

Garcia et. al. 2012.10756
See talk by Keith Olive

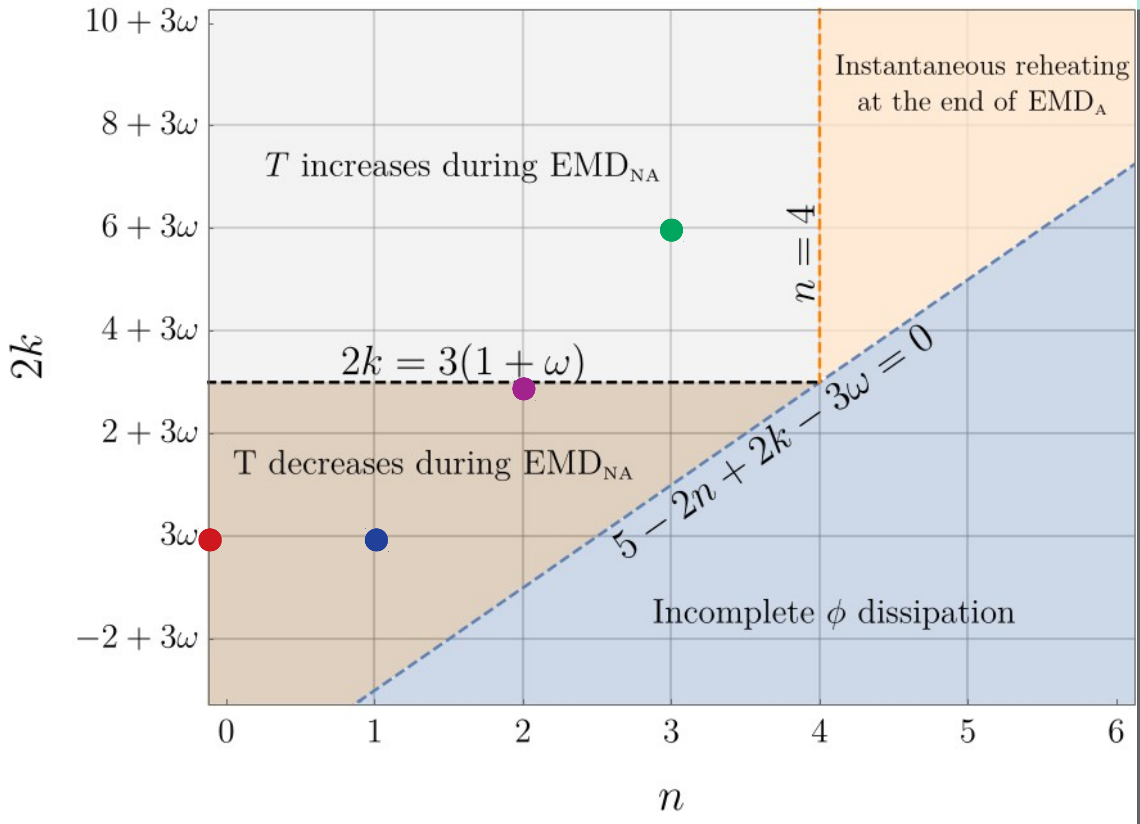
Moduli decay: $\Gamma_\phi \propto \frac{T^3}{M_p^2}$

Bodeker, hep-ph/0605030

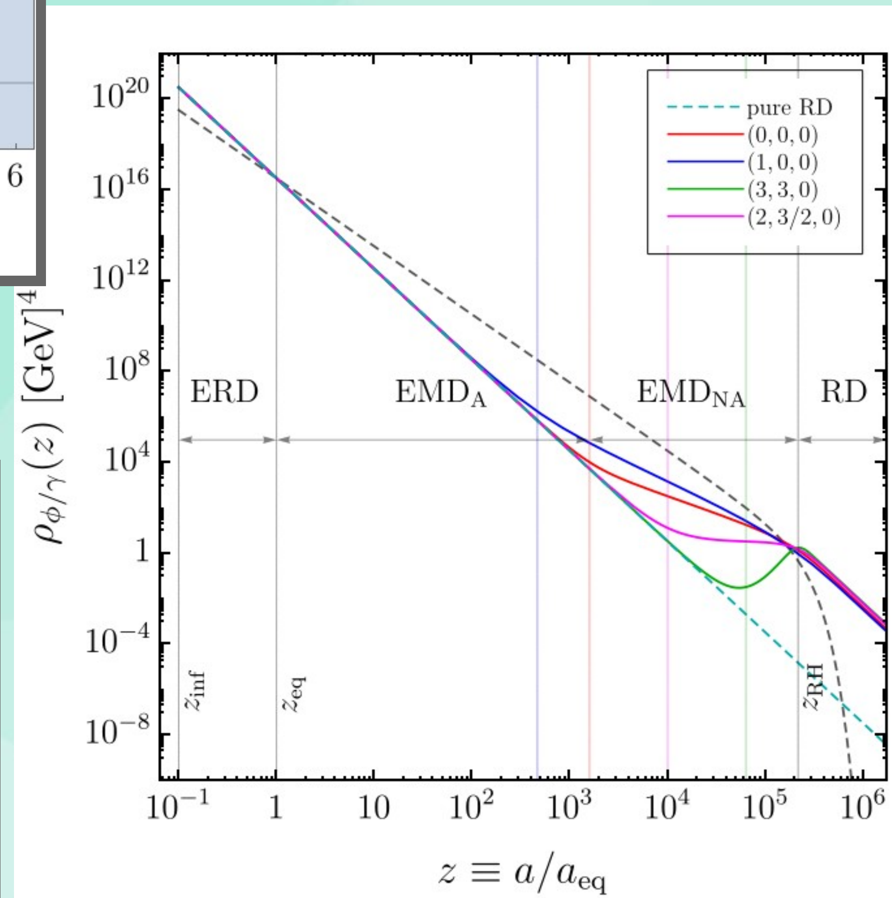
More Examples:

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



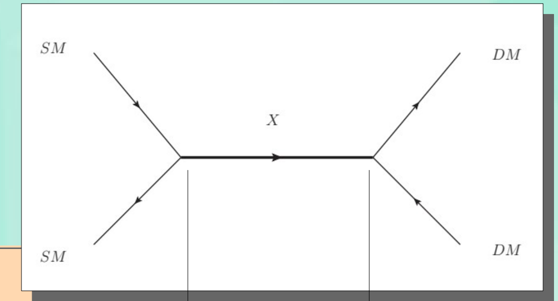
$$\Gamma_\phi = \hat{\Gamma}\left(\frac{T}{T_{\mathrm{eq}}}\right)^{n}\left(\frac{a}{a_{\mathrm{eq}}}\right)^{k}$$



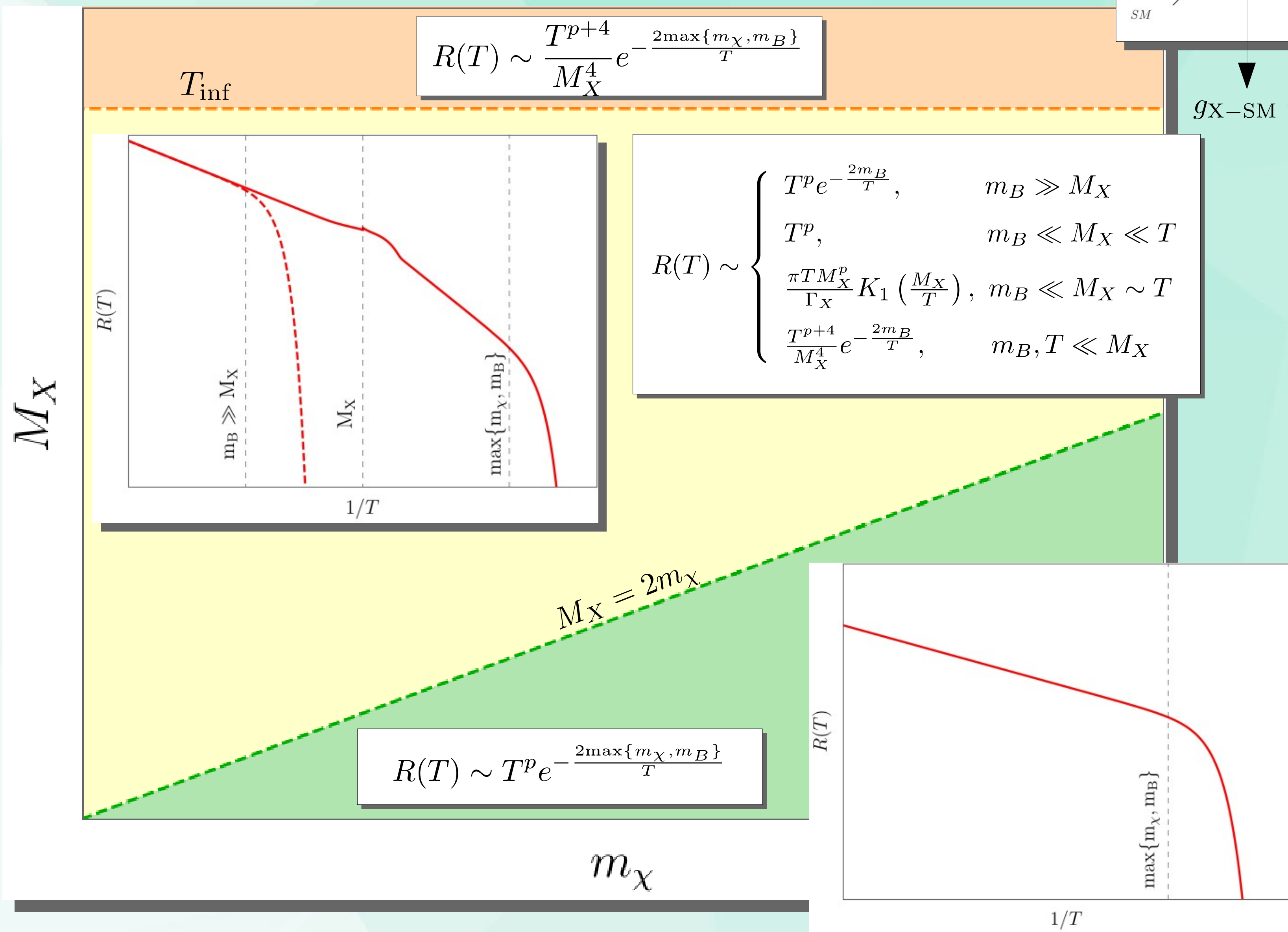
Epoch	z	$T(z)$	$H(z)$
ERD	$z_{\mathrm{inf}} < z < 1$	$\frac{T_{\mathrm{eq}}}{z}$	$\sqrt{\frac{\rho_\gamma(T_{\mathrm{eq}})}{3M_p^2}}\,z^{-2}$
$\mathrm{EMD_A}$	$1 < z < z_{\mathrm{NA}}$	$\frac{T_{\mathrm{eq}}}{z}$	$\sqrt{\frac{\rho_\gamma(T_{\mathrm{eq}})}{3M_p^2}}\,z^{-\frac{3}{2}(1+\omega)}$
$\mathrm{EMD_{NA}}$	$z_{\mathrm{NA}} < z < z_{\mathrm{RH}}$	$T_{\mathrm{RH}}\left(\frac{z}{z_{\mathrm{RH}}}\right)^{\frac{\delta-8+2n}{8-2n}}$	$\sqrt{\frac{\rho_\gamma(T_{\mathrm{eq}})}{3M_p^2}}\,z^{-\frac{3}{2}(1+\omega)}$
RD	$z_{\mathrm{RH}} < z$	$T_{\mathrm{eq}}z_{\mathrm{RH}}^{\frac{1-3\omega}{4}}\,z^{-1}$	$\frac{\sqrt{\rho_\gamma(T_{\mathrm{RH}})}}{\sqrt{3}M_p}\left(\frac{z}{z_{\mathrm{RH}}}\right)^{-2}$

Freeze-in production rate

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_\chi^{\text{eq}2}\right) = R(T)$$



$g_{\text{X}-\text{SM}} \ll 1$ $g_{\text{X}-\text{DM}} \sim \mathcal{O}(1)$



$$R(T) \sim \frac{T^{p+4}}{M_X^4} e^{-\frac{2\max\{m_\chi, m_B\}}{T}}$$

$$R(T) \sim \begin{cases} T^p e^{-\frac{2m_B}{T}}, & m_B \gg M_X \\ T^p, & m_B \ll M_X \ll T \\ \frac{\pi T M_X^p}{\Gamma_X} K_1\left(\frac{M_X}{T}\right), & m_B \ll M_X \sim T \\ \frac{T^{p+4}}{M_X^4} e^{-\frac{2m_B}{T}}, & m_B, T \ll M_X \end{cases}$$

$$R(T) \sim T^p e^{-\frac{2\max\{m_\chi, m_B\}}{T}}$$

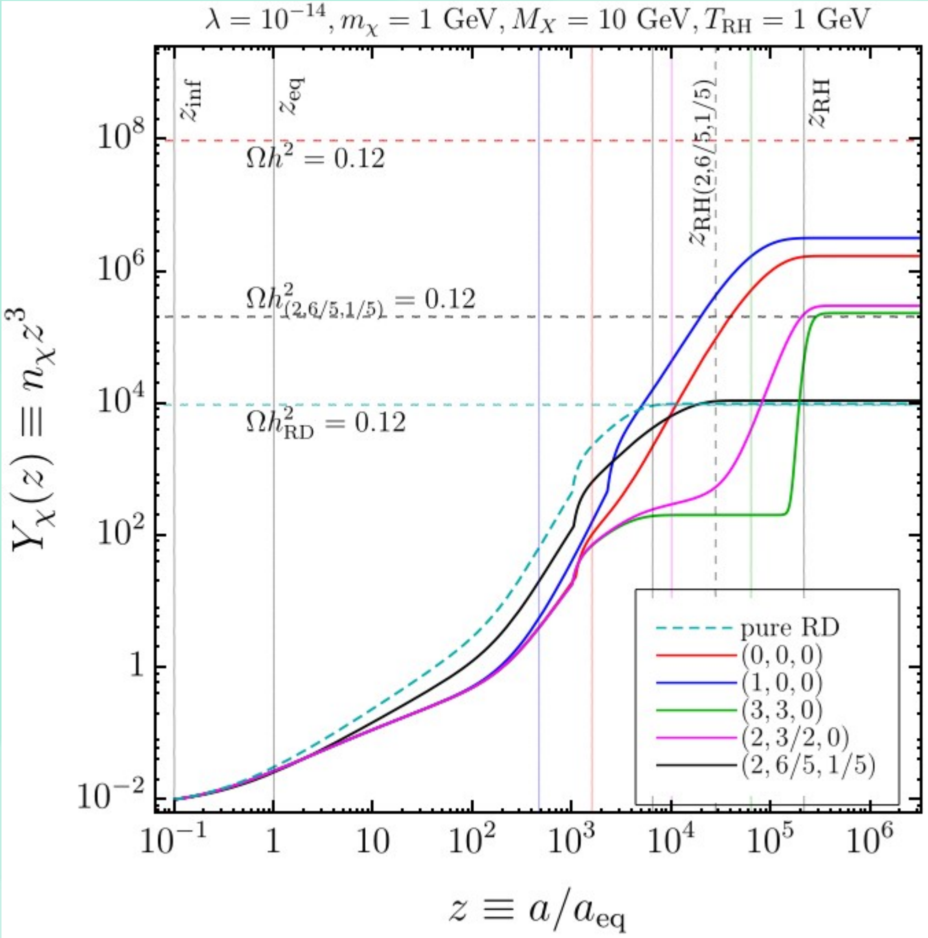
Freeze-in DM yield during EMD

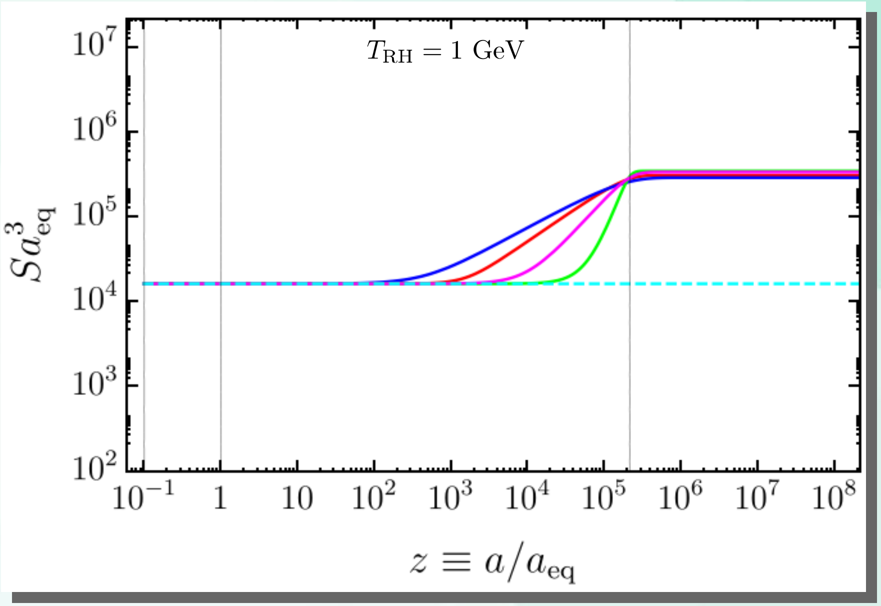
- DM yield dilutes due to entropy production
- Non-trivial temperature evolution also changes the DM production rate during non-adiabatic EMD

$$\frac{\Omega h^2}{\Omega h^2_{\rm RD}} = \frac{Y_\chi(z_0)}{Y_\chi^{\rm RD}(z_0)}\left(\frac{z_0^{\rm RD}}{z_0}\right)^3 = \frac{Y_\chi(z_0)}{Y_\chi^{\rm RD}(z_0)}\left(\frac{T_{\rm RH}}{T_{\rm eq}}\right)^{\frac{1-3\omega}{1+\omega}}$$

$$\sim 10^{-2} - 10^{-3}$$

$$\frac{dY_\chi(z)}{dz} = \frac{z^2 R(T(z))}{H(z)}$$





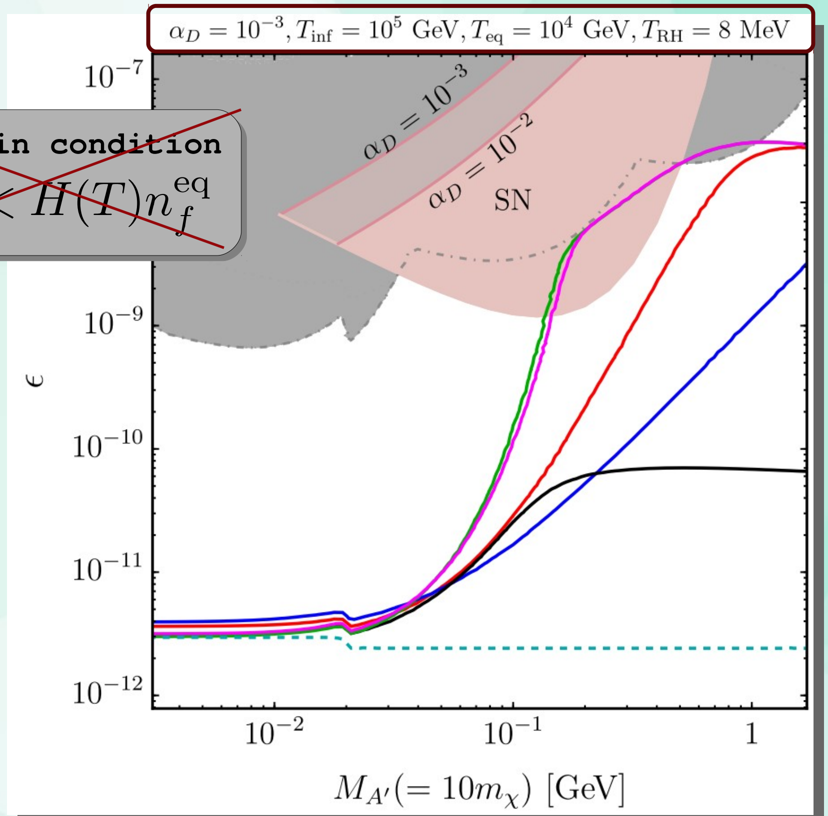
Larger coupling is required to saturate freeze-in relic in presence of EMD epoch

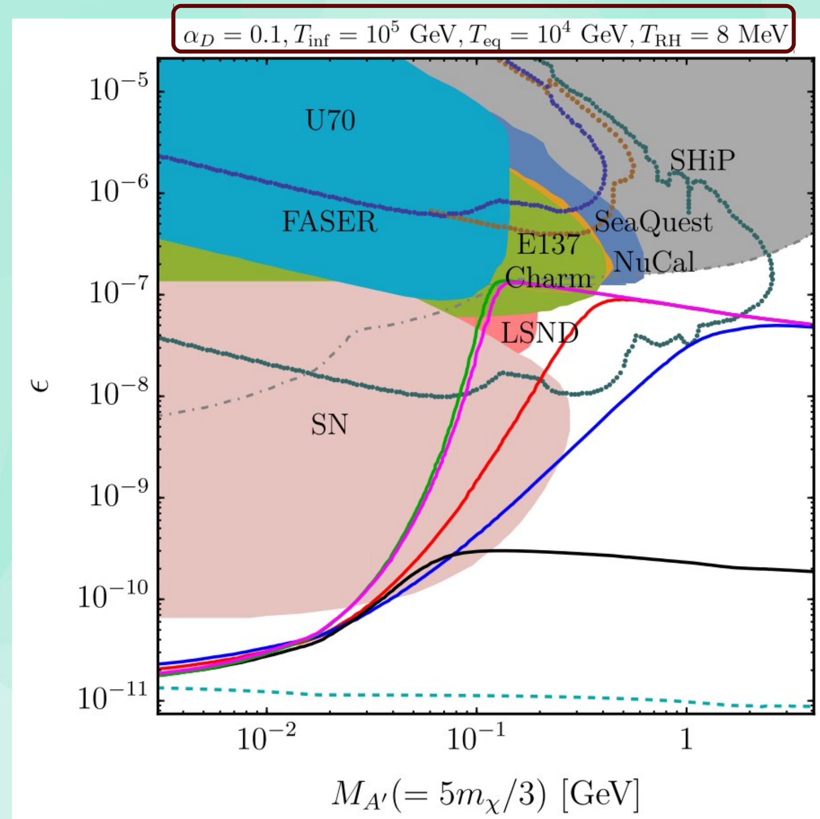
AB, D Chowdhury, 2204.03670

Dark photon portal

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

~~**Freeze-in condition** $R(T) \ll H(T)n_f^{\rm eq}$~~





Parameter space staisfying observed relic is accessible to experiments in the presence of an early matter dominated era

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Summary

- **Freeze-in DM relic depends on the non-standard epochs of cosmology at high temperatures**
- **An epoch of pre-BBN early matter domination leads to freeze-in with larger couplings**
- **Details depend crucially on the temperature and expansion dependent dissipation rate of the dominating matter field**
- **Dark photon portal dark matter model may come under the experimental radar in presence of early matter domination**

THANK YOU