Fingerprints of an early matter-dominated era

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DM Genesis in the early universe

Early Matter Domination Early matter domination

Generalized Dissipation Rate

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

*T*3 **Example:** $\Gamma_{\phi}\propto$ $\frac{1}{\phi} \propto \frac{1}{M^2}$ [Bodeker '06] M_p^2 **Moduli decay Example:** \bullet **oscillating scalar field** ϕ **with** $V(\phi) \sim \phi^p$ $\left(\frac{T}{T_{eq}}\right)^n \left(\frac{a}{a_{eq}}\right)^k$ **potential** $\Gamma_\phi = \hat{\Gamma}$ $\Gamma_{\phi\to f\bar{f}} \propto m_\phi(t) \propto a^{-3(p-2)/(p+2)}$ Fermionic decay **Examples: More Examples: Bosonic decay** $\Gamma_{\phi \to \eta \eta} \propto m_{\phi}^{-1}(t) \propto a^{3(p-2)/(p+2)}$ **Oscillating scalar 4elds** Γ_{ϕ} (n, k, ω) $T(z)$ during EMD_{NA} $m_{\phi}(t) \propto \langle \phi(t) \rangle^{(p-2)/2}$ $(0, 0, 0)$ decreases with z const. T $(1,0,0)$ decreases with z $\langle \phi(t) \rangle \sim a^{-6/p+2}$ $\langle \phi \rangle^{-2}$ $(0, 3, 0)$ 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 **Shtanov et See the See talk by Shtanov et See the See talk by Shtanov et See 1918** $\frac{T^2}{\langle \phi \rangle}$ al. '95; Kofman et al. '97; Garcia et $(2,6/5,1/5)$ decreases with z al. '12, ...]

Bodeker, hep-ph/0605030

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

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during non-adiabatic EMD

What are the signatures of an EMDE?

DM thermal decoupling in EMDE \triangleright **In an EMD: 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 $H \propto T^4$. \triangleright **For s-wave elastic scattering, ,** ⟨*σv*⟩el ∼ const \triangleright **As a result, DM cannot kinetically decouple before the onset of RD. SM SM DM DM SM DM SM DM** $\gamma_{\rm el} \sim T^4$ and $H \propto T^4$. [Gelmini et al. '08, Visinelli et al. '15, Waldstein et al. '16, Erickcek et al. '11, '15]

DM thermal decoupling in EMDE

SM

SM

DM

DM

DM

SM

DM

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

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

 \triangleright **DM kinetically decouples partially, before the onset of RD.**

 \triangleright **As a result, DM cools faster than the plasma during EMDE.**

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

 \triangleright **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:** Γ*^ϕ* ∼ *T*
- **In this case:** $T \propto a^{-1/2}$, 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.**
- **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.**

F Kinetic decoupling of DM where C and C and C denote the collision terms corresponding to the annihilation terms corresponding to the annihilation C Here (!*,* ^k) represents the momentum of the incoming bath particle, *^k* ⌘ *[|]*k*[|]* and *^M*² is the etic decoupling of DM the distribution functions of the relativistic bath particles. For *s*-wave elastic scatterings **The Linetic decoupling of DM temperature constants and the United States and Temperature constants and the United States and Temperature constants and the United States and Temperature constants and the United States and** situation becomes more involved if the thermal history of the universe during the decoupling Kinetic decoupling in non-standard cosmological scenario decoupling in non-standard cosmological scenario de where the scale of the the the scale bath evolves with the solution to the general solution to the general solution to the general solution to the Eq. (2.7) h factor as *^T* / *^a*↵ with parameter ↵ 0, and the Hubble expansion rate varies with tem-

subsequent sections. In a radiation-dominated universe, the bath temperature evolves as \sim

el(*T*) / *^T*(4+*n*)

^h*M*2i*^t* = const*.*, while for *^p*-wave ^h*M*2i*^t* / !2. After chemical decoupling, the evolution of

, (2.8)

*^T*dec ◆(4+*n*)

∪ a
∕ an ainm an ainm

*^a*dec ◆²

#

. (2.10)

i.e., el(*T*)*T* ⌧ *HT*. We will explore the implications of relaxing this condition in the

✓ *T*

H(*T*)

*^ess*dec ⁺ *T s ^e^s* [(1 *, s*) (1 *, s*dec)] *,* (2.9)

BB) and the elastic scatterings (*B* ! *B*) of the DM with the bath particles (*B*), respec**the number of the Standard RD scenario:**
temperature of the Bath as [78, 79] the temperature of the DM T_amario: The DM Taylor is obtained from Eq. (2.1) as a second from Eq. (2.1) as a seco is die rent from the usual radiation of the usual radiation in the following we include the following we include the total radiation \mathbb{R}^n kinetic decoupling of the DM for non-standard cosmological backdrops. perature as *^H* / *^T* . The momentum transfer rate in the elastic scattering depends on the

✓ *s*

of the DM (*f*(p*, t*)) is given by [99, 100]

the second and third moments of the phase space distribution as [78, 101]

Z *d*3*p*

 \overline{a}

1

(2⇡)³

 $(2 - 1)$

where *n,*eq denotes the equilibrium number density of the DM. The integration over *C*el[*f*]

T(*a*) = *T*

The collision term corresponding to the elastic scattering of the non-relativistic DM has the

T(*a*) = *T*

The Contract of Second

of *n*(*t*) is obtained by integrating both sides of Eq. (2.1) as

T(*a*) = *T*

 $T_{\chi}(t) \equiv$ g_χ $3n_\chi$ $\int d^3p$ $(2\pi)^3$ p^2 $\int_E f_\chi(\mathbf{p},t)$, \int $\frac{d\ln t}{d\ln t}$ $dT_{\boldsymbol{\chi}}$ *d* ln *a* $+2T_\chi(a)$ $\left[1+\frac{\gamma_{\rm el}(a)}{H(a)}\right]$ *H*(*a*) $= 2 \frac{\gamma_{\rm el}(a)}{H(a)}$ *H*(*a*) $\frac{d}{dx}\int \frac{d}{(2\pi)^3} \frac{d}{E} f_\chi(\mathbf{p},t)$ $\frac{d}{dx}\left[\ln a + 2T_\chi(a)\left[1 + \frac{\ln(a)}{H(a)}\right]\right] = 2\frac{\ln(a)}{H(a)}T(a)$ $K^{(0)} = 3n_{\chi} \int (2\pi)^3 E^{J\chi(\mathbf{P},\mathfrak{D})} d\ln a$ and $H(a)$ is $H(a)$ el(*T*) / *^T*(4+*n*) $T_{\chi}(t) \equiv \frac{3\chi}{2} \int \frac{d^{2}F}{(2-x^{2})^{2}} f_{\chi}(\mathbf{p},t)$ $\frac{1}{2\ln x} + 2T_{\chi}(a) \left[1 + \frac{2T_{\chi}(a)}{T_{\chi}(a)}\right] =$ the form [78] $T_{\chi}(t) \equiv \frac{g}{3\eta}$

where p and p denotes the number of internal degrees of \mathcal{P} and \mathcal{P} . The evolution of \mathcal{P} $\gamma_{el}(I)I \ll H(I)I_{\chi}$ To arrive at this equation, we specifically assume that the DM is non-relativistic below $\gamma_{el}(T) \ll H(T)$ $T_{\gamma} \sim a^{-2}$ T is the temperature of the plasma $\frac{\lambda}{\lambda}$ $\gamma_{\rm el}(T)T \ll H(T)T_{\chi}$ $T \sim a^{-1}$ that *^T* redshifts as *^T* ⇠ *^a*2. This solution additionally necessitates another condition, perature as *^H* / *^T* . The momentum transfer rate in the elastic scattering depends on the γ $T_v \sim a^{-2}$ el(*T*) ✓ *T ^T*dec ◆(4+*n*) $T_{\gamma} \sim a^{-2}$ $\gamma_{el}(T) \ll H(T)$ $T_{\chi} \sim a^{-2}$ $T \sim a^{-1}$

vanishes standard accredit. and into bath particles is given by \mathbf{r}_1 subsequent sections. In a radiation of the bath temperature evolves as respectively. In a radiation of the bath temperature of the bath as a final property **■ Non-standard scenario:**
■ *Non-standard scenario:*

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""

✓ *a*

 $\overline{}$ α ^{- α} $H \sim T^\beta \quad \gamma_{\rm el}(T) \propto T$ **Thance**
The DM temperature cools as a function of the DM temperature cools as a function of the DM temperature cools as
The DM temperature cools as a function of the DM temperature cools as a function of the DM temperatur σ is the universe more involved in the universe during the $\gamma \cdot \gamma_{\rm el}(T) \propto T^{(4+n)} \quad \gamma_{\rm el}(T_{\rm dec}) = H(T_{\rm dec}) \quad ,$ earlier, the condition for kinetic decoupling, el(*T*) ⌧ *H*, does not necessarily imply that the $T_{\text{max}} - \alpha$ is T_{max} α , $(T) \propto T^{(4+n)}$ γ , (T_{max}) $\mathbf{H} \sim \mathbf{H} \sim \mathbf{H}$, $\mathbf{H} \sim \mathbf{H}$, but $\mathbf{H} \sim \mathbf{H}$ $T \sim a^{-\alpha}$ $H \sim T^{\beta}$ $\gamma_{\text{el}}(T) \propto T^{(4+n)}$ $\gamma_{\text{el}}(T_{\text{dec}}) = H(T_{\text{dec}})$

H(*T*)

↵(4 + *n*)

 T_{dec} and T_{dec} are the second second second T_{dec} (and $\sqrt{\frac{-\alpha(5+n-\beta)}{n}}$ $\frac{d^2x(\omega)}{2-\alpha(5+n-\beta)}$ $\int^2 \left(a_{\text{dec}} \right) \frac{\alpha(\omega)}{n}$ At a temperature *T* after chemical decoupling of the DM, the annihilation rate becomes negligible compared to the Hubble expansion rate. So, one can drop *C*ann[*f*] from Eq. (2.1). kinetic decoupling of the DM for non-standard cosmological backdrops. $T_{\chi}(a) \simeq \frac{I_{\text{dec}}}{2 - \alpha(5 + n - \beta)} \left[2\left(\frac{a}{a_{\text{dec}}}\right) \right]$ $-\alpha(5 + n - \beta) \left(\frac{a}{a_{\text{dec}}}\right)$ $\gamma_{\text{el}}(I) \ll H(I)$ $\gamma_{\text{el}}(T)T \nless H(T)T \times H(T)T$ _x factor as *^T* / *^a*↵ with parameter ↵ 0, and the Hubble expansion rate varies with temperature as *^H* / *^T* . The momentum transfer rate in the elastic scattering depends on the ✓ *s ^s*dec ◆ $T_{\rm dec}$ $2 - \alpha(5 + n - \beta)$ $\overline{ }$ 2 $\left(\frac{a}{a_{\text{dec}}}\right)^{-\alpha(5+n-\beta)}$ $-\alpha(5 + n - \beta)$ $\left(\frac{a}{a_{\text{dec}}}\right)^{-2}$ γ_{el} ¹(*q, s*) is the upper incomplete gamma function: (*q, s*) = R ¹ *dt t^q*¹*e^t* $\begin{array}{cc} T_{\text{dec}} & \left[\begin{array}{cc} a & \end{array} \right]^{-(\alpha(5+n-\beta))} & \alpha(5+n-\beta) & \alpha & \end{array}$ $\begin{array}{cc} a & \end{array}$ $^{-2} & \gamma$, $(T) \ll H(T)$ $r(x) \approx \frac{1}{2 - \alpha(5 + n - \beta)} \left[\frac{2(\overline{a_{\text{dec}}})}{a_{\text{dec}}} \right]$ $-\alpha(5 + n - \beta) (\overline{a_{\text{dec}}}$ $\gamma_{el}(T) \ll H(T)$ $\gamma_{\text{el}}(T)T \nless H(T)T_{\chi}$

*^a*dec ◆↵(5+*n*)

Kinetic decoupling of DM factor as *^T* / *^a*↵ with parameter ↵ 0, and the Hubble expansion rate varies with tem-**Exinet** ↵(4 + *n*) *,* and*, s* = $\overline{1}$ ↵(4 + *n*) el(*T*) *H*(*T*) $\bf g$ of **1** *.* (2.10) Clearly, the first term in the Eq. (2.11) dominates at *a a*dec, i↵ ↵ (5 + *n*) *<* 2. The

the bath as in the bath as in the bath as ESS of the bath and the bath as ESS of the bath as a fragmental second series of the bath and the bath as \mathbf{r} Non-standard scenario: **Home el** *Toelenario:*

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

¹(*q, s*) is the upper incomplete gamma function: (*q, s*) = R ¹

where *n*partial ⌘ (2*/*↵) + 5. Hence, the kinetic decoupling of dark matter significantly

d⇢

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

–5–

depends on the specific dark matter model via the nature of elastic scattering, as well as on **the unitary injection:**

Partial decoupling during entropy injection

summarize the dividends the dividends of t

 $\propto a^{\sim}$

 $\Gamma_{\phi} \propto a^k T^n$

↵(4 + *n*)

cosmological scenarios with entropy injection. In the last two columns we specifically consider

Partial decoupling during entropy injection

*dt t^q*¹*e^t*

, (2.8)

*n n*dec: no kinetic decoupling,

d⇢

dt + 4*H*⇢ = (1 + !)⇢ *.* (2.13)

necessary requirement to satisfy the first decoupling condition el(*T*) ⌧ *H* is *n* = *n*dec *>*

 r_{rel} and r_{rel} are given by r_{rel} Islam, 2408.xxxx]

with the contract of

d⇢

the form [78]

Kinetic decoupling of DM 1 10 100 *T*dec*/T*RH 0*.*1 1 10 100 $T_{\rm kds}/T_{\rm RH}$ 100 λ ⁰*.*01 $|\gamma \propto \overline{T^6}|$ partial decoupling with $\Gamma_{\phi} \sim \text{const.}$ 1 10 100 *T*dec*/T*RH 100 Λ ⁰*.*01 $|\gamma \propto T^4|$ partial decoupling with $\Gamma_{\phi} \sim T$ 1 10 100 *T*dec*/T*RH 100 λ ⁰*.*01 $\gamma \propto T^6$ full decoupling with $\Gamma_{\phi} \sim T$ 0*.*0010 0*.*1437 0*.*2864 0*.*4291 0*.*5719 0*.*7146 0*.*8573 1*.*0000 $\lambda_{\rm fsh}^{\rm EMD} /$ $\lambda_{\text{fsh}}^{\text{RD}}$ Figure 1: *The ratios of dark matter free-streaming horizon in presence of an EMDE and in* \int_{R} $\int_{R}^{t_0}$ $\int_{\mathcal{H}} v_\chi(t)$ $\sqrt{3}$ $\int_{R}^{a_{\text{RH}}} \int_{R}^{a_{\text{RH}}} \int_{a}^{a_0} \int_{d} \sqrt{T_\chi(a)}$ $\int_{R} \sim a^{-\alpha}$, $f_{fsh} = \int_{t_1}^{t_2} dt \frac{dt}{a(t)} = \sqrt{\frac{1}{m_v}} \left[\int_{a_1}^{t_2} \frac{dt}{dt} \right]_{t_2}^{t_3} + \int_{a_2}^{t_3} \frac{dt}{a^2 H(a)}, \quad \sum_{i=1}^{\infty} \frac{1}{i} \frac{dt}{a} \sim T^{\beta}$ *the ratio r. For r <* 1*, the free-streaming horizon in an EMDE is always smaller than its counterpart in RD era. The change in the slope of the isocontours of r around T*dec*/T*RH ⇠ 20 $\lambda_{\text{fsh}}^{\text{RD}} = \int_{0}^{t_0} dt \frac{v_{\chi}(t)}{a(t)} = \sqrt{\frac{3}{m}} \left| \int_{0}^{a_{\text{eq}}} + \int_{0}^{a_0} \right| da \frac{\sqrt{T_{\chi}(a)}}{a^2 H(a)}$ • Right panel: ⇠ *^T*, leading to *^T* ⇠ *^a*1*/*² , *^H* ⇠ *^T*3, and full decoupling due to *^p*-wave \mathbf{L} $\frac{1}{2}$) and $\frac{1}{2}$, and $\frac{1}{2}$, and $\frac{1}{2}$, and $\frac{1}{2}$ partial full full function $\frac{1}{2}$ P 1 2 1/2 0 3 – partial $\mathcal{L}(\mathcal{L})$ The decoupling with $\Gamma_{\ell} \sim T$ full decoupling with $\Gamma_{\ell} \sim T$ $\sim T^4$ Table 1: *Conditions for kinetic decoupling of the DM are shown for di*↵*erent non-standard cosmological scenarios with entropy injection. In the last two columns we specifically consider the cases where s-wave (n* = 0*) and p-wave (n* = 2*) scatterings are dominant.* 2.1 Free-streaming of partially decoupled dark matter Once chemically and kinetically decoupled from the thermal bath, the dark matter starts to free-stream with a velocity *^v*(*a*) / ^p*T*(*a*). The free-streaming horizon fsh of the DM sets the structures will be well below which the structures will be washed out due to the large 0.0010 scaling of *T*(*a*) with the scale factor(*a*) plays a crucial role to determine fsh. We compute $\frac{1}{\text{dec}}$ in two cases $\frac{1}{\text{dec}}$ in $\frac{1}{\text{dec}}$ in presence of an EMDE, and in purely radiation dominated (RD) is an EMDE, and in purely radiation dominated (RD) is an EMDE, and in purely radiation dominated (RD) i universe using the general solution (2.9) for *T*(*a*) and the following expressions $\lambda_{\rm fsh}^{\rm EMD} =$ \int_0^t $t_{\rm dec}$ $dt \frac{v_{\chi}(t)}{v_{\chi}(t)}$ *a*(*t*) = $\overline{}$ 3 m_χ $\int f^{a}$ RH *a*dec $+$ $\int^{a_{\text{eq}}}$ *a*RH $+$ $\int_{a_{\rm eq}}^{a_0}$ *da* $\sqrt{T_{\chi}(a)}$ $\frac{\sqrt{2\pi}\chi(a)}{a^2H(a)}$ $\int T \sim a^{-\alpha}$, $H \sim T^{\beta}$ \int_0^t $t_{\rm kds}$ $dt \frac{v_{\chi}(t)}{\sqrt{2}}$ *a*(*t*) = \vert 3 m_χ $\int f^{a_{\rm eq}}$ *a*kds $+$ $\int_{a_{\rm eq}}^{a_0}$ *da* $\sqrt{T_{\chi}(a)}$ $\frac{\sqrt{2}}{a^2H(a)}$, $\int T \sim a^{-1}$, $H \sim T^2$. such that electronic that electronic corresponds to the decoupling temperature in the decoupling temperature in
The decoupling temperature in the decoupling temperature in the decoupling temperature in the decoupling tempe

0 1 1/2 -1 2 partial full

(Matter)

We observe that in all three cases, the free-streaming horizon is smaller in the cases, the free-streaming horizon is smaller in the cases, the free streaming horizon is smaller in the case of EMDE

[Banerjee, DC, Hait,
Islam, 2408.xxxx] the EMDE when el(*T*dec) = *H*EMD(*T*dec). [Banerjee, DC, Hait,

Matter power spectrum

*and ^k*RH = 1*.*⁷ ⇥ ¹⁰⁷ *^k*eq*. We use the same set of benchmark points as mentioned in Fig. 3.*

[Banerjee, DC, Hait, Islam, 2408.xxxx]

Halo mass fraction

redshifts values. For the benchmark points as mentioned in the caption of Fig. 3, the free-

Freeze-in DM in an EMD era

$$
\rho_{\phi}(z) \simeq \rho_{\gamma}(T_{\text{eq}})z^{-3(1+\omega)},
$$
\n
$$
\rho_{\gamma}(z) = z^{-4} \left[\rho_{\gamma}(T_{\text{eq}})^{\frac{4-\gamma}{4}} + \frac{\sqrt{3}M_{p}\hat{\Gamma}(4-n)(1+\omega)}{2\delta\rho_{\gamma}(T_{\text{eq}})^{\frac{(n-2)}{4}}} (z^{\delta/2} - 1) \right]^{\frac{4}{4-n}}
$$
\n**Sci|Post**\n
$$
z_{\text{NA}} = \left[1 + \frac{2\delta\rho_{\gamma}(T_{\text{eq}})^{\frac{1}{2}}}{\sqrt{3}M_{p}\hat{\Gamma}(4-n)(1+\omega)} \right]^{2/\delta}
$$
\n
$$
z_{\text{RI}} = \left[\frac{2\delta\rho_{\gamma}(T_{\text{eq}})^{\frac{1}{2}}}{\sqrt{3}M_{p}\hat{\Gamma}(4-n)(1+\omega)} \right]^{\frac{4}{2\delta - (4-n)(1-3\omega)}} = \left(\frac{T_{\text{RI}}}{T_{\text{eq}}} \right)^{-\frac{4}{3(1+\omega)}}
$$
\n
$$
z_{0} = (T_{\text{eq}}/T_{0})(T_{\text{RI}}/T_{\text{eq}})^{\frac{(3\omega - 1)}{3(1+\omega)}}
$$

the temperature (EMDA), followed by an entropy production phase where the thermal plasma

3*M*2

z ³

*z*RH ä

EMDNA *^z*NA *< ^z < ^z*RH *^T*RH ^Ä *^z*

