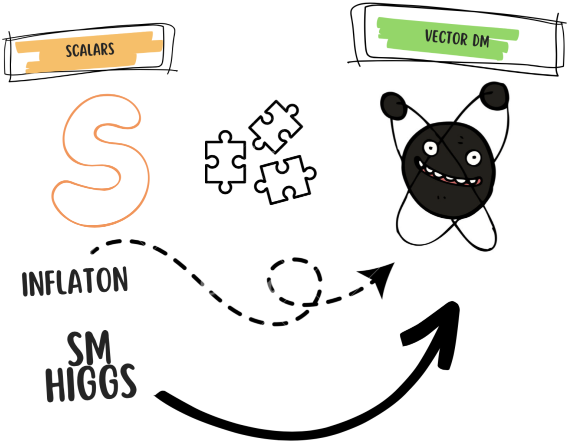
Role of scalars in gravitational production of vector dark matter

Anna Socha

University of Warsaw

based on: A. Ahmed, B. Grządkowski, AS 2005.01766, 2111.06065, 2207.11218


SCALARS
VECTOR DM
S
INFLATON
SM
HIGGS

Purely gravitational DM

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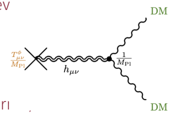

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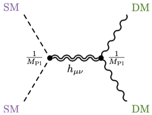

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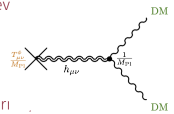

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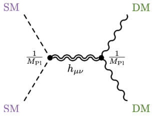

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- All these phenomena are universal and inevitable. However, they occur at slightly different moments and have distinct origins.

The action for a massive spin-1 DM spectator field X_μ in a background metric $g_{\mu\nu}$ is given by

$X_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu$

$$S_{\rm DM} = \int d^4x \sqrt{-g}\,\mathcal{L}_{\rm DM}, \quad \mathcal{L}_{\rm DM} = -\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} X_{\mu\nu} X_{\alpha\beta} - \frac{1}{2} m_X^2 g^{\mu\nu} X_\mu X_\nu .$$

FLRW spacetime

$$ds^2 = dt^2 - a^2(t) d\vec{x}^{\,2}, \quad dt = a(\tau) d\tau$$

Gravitational coupling

only through $g^{\mu\nu}$, $\sqrt{-g}$ without non-minimal coupling, i.e., $\xi_1 R\, g^{\mu\nu} X_\mu X_\nu, \xi_2 R^{\mu\nu} X_\mu X_\nu$

Non-zero mass

generated e.g. via the Stueckelberg mechanism

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Remarks

- X_0 does not have a kinetic term; it is an auxiliary field.

$$\boxed{\mathcal{X}_0 = \frac{-i\vec{k}\cdot\vec{\mathcal{X}}'}{k^2 + a^2 m_X^2}}$$

Not populated by expansion

- Massless vectors with a minimal coupling to gravity, i.e., $\xi_1 = 0 = \xi_2$ are conformally coupled to gravity.

EoMs for DM fields

$$[\hat{a}_\lambda(\vec{p}), \hat{a}^\dagger_\sigma(\vec{q})] = (2\pi)^3 \delta_{\lambda,\sigma} \delta^{(3)}(\vec{p} - \vec{q})$$

Fourier decomposition

$$\hat{\vec{X}}(\tau, \vec{x}) = \sum_{\lambda=\pm,L} \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\cdot\vec{x}} \vec{\epsilon}_\lambda(\vec{k}) \{\mathcal{X}_\lambda(\tau, k) \hat{a}_\lambda(\vec{k}) + \mathcal{X}^*_\lambda(\tau, k) \hat{a}^\dagger_\lambda(\vec{k})\}$$

Harmonic oscillator equation, Wronskian

$$\mathcal{X}''_\lambda + \omega^2_\lambda(\tau)\mathcal{X}_\lambda = 0, \qquad \mathcal{X}'_\lambda \mathcal{X}^*_\lambda - \mathcal{X}^{*\prime}_\lambda \mathcal{X}_\lambda = -\mathrm{i}$$

Time-dependent frequencies

Transverse modes

$$\omega^2_\pm(\tau) \equiv k^2 + a^2(\tau) m^2_X,$$

Redefined longitudinal mode*

$$\omega^2_L(\tau) \equiv k^2 + a^2(\tau) m^2_X - \frac{k^2}{k^2 + a^2(\tau) m^2_X} \left[\frac{a''(\tau)}{a(\tau)} - \frac{3a^2(\tau) m^2_X}{k^2 + a^2(\tau) m^2_X} \left(\frac{a'(\tau)}{a(\tau)} \right)^2 \right]$$

Longitudinal mode $\mathcal{A}_L$ is not canonically normalized

$$\mathcal{X}_L \equiv \frac{a m_X}{\sqrt{k^2 + a^2 m^2_X}} \mathcal{A}_L$$

The vacuum expectation value of the total energy density of the spin-1 DM decomposes as,

$$\langle \hat{\rho}_X \rangle \equiv \langle 0| \hat{\rho}_X |0\rangle = \langle \hat{\rho}_L \rangle + \langle \hat{\rho}_\pm \rangle,$$

Bunch-Davies vacuum

with

Transverse modes

$$\langle \hat{\rho}_\pm \rangle = \frac{1}{2a^4} \int \frac{d^3k}{(2\pi)^3} \left\{ |\mathcal{X}_\pm'|^2 + |\mathcal{X}_\pm|^2 \left[k^2 + a^2 m_X^2 \right] \right\},$$

Redefined longitudinal mode

$$\langle \hat{\rho}_L \rangle = \frac{1}{2a^4} \int \frac{d^3k}{(2\pi)^3} \left\{ |\mathcal{X}_L'|^2 + |\mathcal{X}_L|^2 \left[k^2 + a^2 m_X^2 + \left(\frac{a'}{a} \right)^2 \frac{k^4}{(k^2 + a^2 m_X^2)^2} \right] - (\mathcal{X}_L' \mathcal{X}_L^* + \mathcal{X}_L^{*\prime} \mathcal{X}_L) \frac{k^2}{k^2 + a^2 m_X^2} \frac{a'}{a} \right\}.$$

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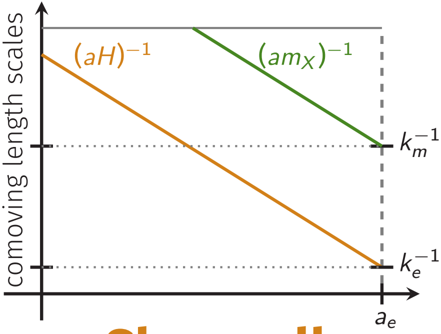
$$\left.-(\mathcal{X}'_L\mathcal{X}^*_L+\mathcal{X}^{*\prime}_L\mathcal{X}_L)\frac{k^2}{k^2+a^2m_X^2}\frac{a'}{a}\right\}.$$

Note that $\langle\hat{\rho}_L\rangle \gg \langle\hat{\rho}_\pm\rangle$

This could change if one considers direct X_μ coupling to the inflaton ϕ of the form $\phi X_{\mu\nu}\tilde{X}^{\mu\nu}$, see e.g. arXiv:1810.07208

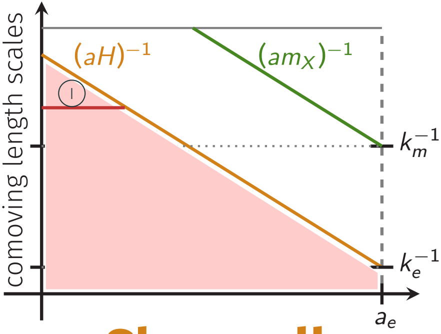
Evolution of the longitudinal modes during inflation



Slow-roll

$$H_{\mathrm{I}} \simeq H_e,$$

$$\left(\frac{a'}{a}\right)^2 = a_{\mathrm{I}}^2 H_e^2, \quad \frac{a''}{a} = 2a_{\mathrm{I}}^2 H_e^2.$$



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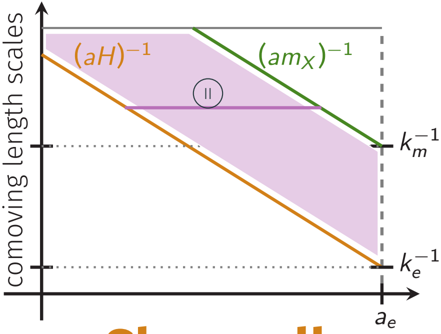
I **Sub-horizon**

$$\omega_L^2 \simeq k^2,$$

Bunch-Davies vacuum

$$\mathcal{X}_L^{\mathrm{I}} \simeq \frac{1}{\sqrt{2k}} e^{-ik\tau},$$

Evolution of the longitudinal modes during inflation



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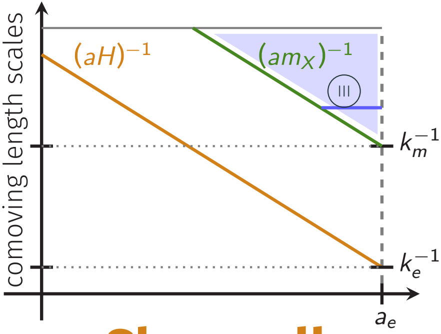
II **Super-horizon R**

$$\omega_L^2 \simeq k^2 - 2a_{\mathrm{I}}^2 H_e^2 < 0,$$

tachyonic enhancement

$$\boxed{\mathcal{X}_L^{\mathrm{II}} \simeq \frac{i}{2\sqrt{k}} \frac{a_{\mathrm{I}} H_e}{k} e^{-ik\tau} ,}$$

Evolution of the longitudinal modes during inflation



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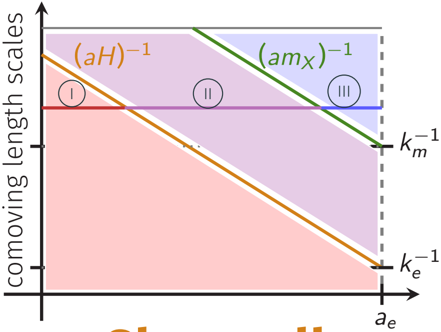
III **Super-horizon NR**

$$\omega_L^2 \simeq a_{\mathrm{I}}^2 m_X^2 + k^2 \frac{H_I^2}{m_X^2},$$

constant solution

$$\mathcal{X}_L^{(\mathrm{III})} \simeq \mathrm{const.}$$



Slow-roll

$$H_{\rm I} \simeq H_e,$$

$$\left(\frac{a'}{a}\right)^2 = a_{\rm I}^2 H_e^2, \quad \frac{a''}{a} = 2a_{\rm I}^2 H_e^2.$$

I Sub-horizon

$$\omega_L^2 \simeq k^2,$$

Bunch-Davies vacuum

$$\mathcal{X}_L^{\rm I} \simeq \frac{1}{\sqrt{2k}} e^{-ik\tau},$$

II Super-horizon R

$$\omega_L^2 \simeq k^2 - 2a_{\rm I}^2 H_e^2 < 0,$$

tachyonic enhancement

$$\mathcal{X}_L^{\rm II} \simeq \frac{i}{2\sqrt{k}} \frac{a_{\rm I} H_e}{k} e^{-ik\tau},$$

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$$\mathcal{X}_L^{\rm (III)} \simeq \text{const.}$$

Post-inflationary evolution

Boltzmann equations

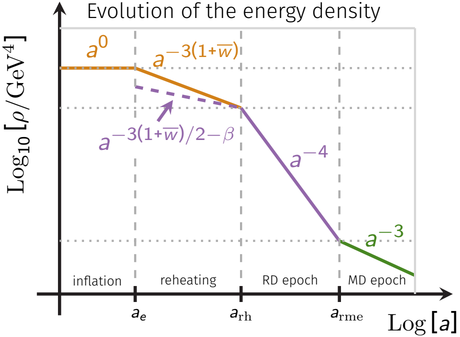
$$\dot{\rho}_\phi + 3H(1+\overline{w})\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \Gamma_\phi \rho_\phi$$

$$\Gamma_\phi \propto a^{-\beta}$$

Friedmann equation

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left(\rho_\phi + \rho_{\rm SM}\right)$$



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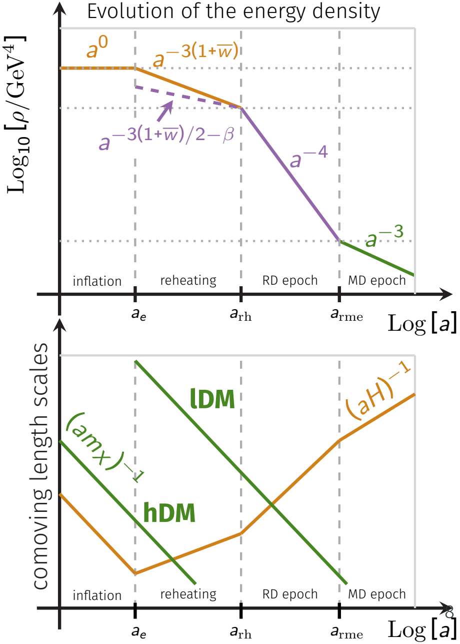
Evolution of a, H and the Hubble radius

Reheating

$$H(a) = H_e(a/a_e)^{-\frac{3(1+\overline{w})}{2}}$$

RD epoch

$$H(a) = H_{\mathrm{rh}}(a/a_{\mathrm{rh}})^{-2}$$



DM production strongly depends on reheating dynamics

Expansion history $\overline{w}$

Form of the inflaton potential $V(\phi) \sim \phi^{2n}$ $\boxed{\overline{w} = \frac{n-1}{n+1}}$

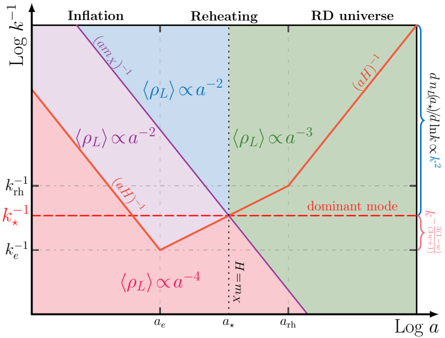
Reheating duration $\gamma^2 = H_{\rm rh}/H_e$

Form of the interactions $\boxed{\Gamma_\phi \propto a^{-\beta}}$

$$\text{e.g.,} \quad \phi \to SS \quad \begin{cases} \xrightarrow{\text{quadratic}} \beta = 0 \\ \xrightarrow{\text{quartic}} \beta = -1 \end{cases}$$

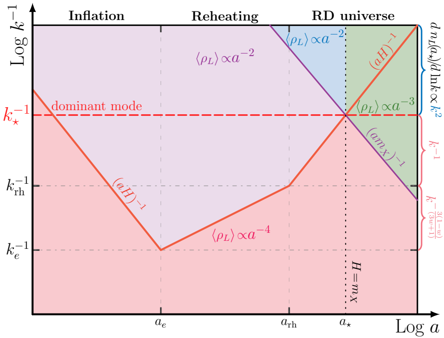
heavy DM vectors (hDM)

$m_X > H_{\rm rh}$



light DM vectors (lDM)

$m_X < H_{\rm rh}$



dominant mode

$$k_\star \equiv a_\star m_X\,, \qquad H(a_\star) = m_X$$

- hDM: $H_{\rm rh} \le m_X < H_e$,

$$\frac{d\langle n_{\rm L}^{\rm hDM}(a_\star)\rangle}{d\ln k} = \frac{H_e^3}{8\pi}\begin{cases}\left(\frac{m_X}{H_e}\right)^{\frac{2}{1+\overline{w}}}\left(\frac{k_e}{k}\right)^{\frac{3(1-\overline{w})}{(1+3\overline{w})}}, & k_\star < k < k_e,\\ \left(\frac{m_X}{H_e}\right)^{\frac{1-3\overline{w}}{3(1+\overline{w})}}\left(\frac{k}{k_e}\right)^2, & k < k_\star.\end{cases}$$

- lDM: $m_X < H_{\rm rh}$,

$$\frac{d\langle n_{\rm L}^{\rm lDM}(a_\star)\rangle}{d\ln k} = \frac{H_e^3}{8\pi}\begin{cases}\left(\frac{m_X}{H_e}\right)^{3/2}\gamma^{\frac{1-3\overline{w}}{1+\overline{w}}}\left(\frac{k_e}{k}\right)^{\frac{3(1-\overline{w})}{1+3\overline{w}}}, & k_{\rm rh} < k < k_e,\\ \left(\frac{m_X}{H_e}\right)^{3/2}\gamma^{\frac{-1+3\overline{w}}{3(1+\overline{w})}}\frac{k_e}{k}, & k_\star < k < k_{\rm rh},\\ \gamma^{\frac{2(1-3\overline{w})}{3(1+\overline{w})}}\left(\frac{k}{k_e}\right)^2, & k < k_\star.\end{cases}$$

$k_{\rm e} \equiv a_e H_e$

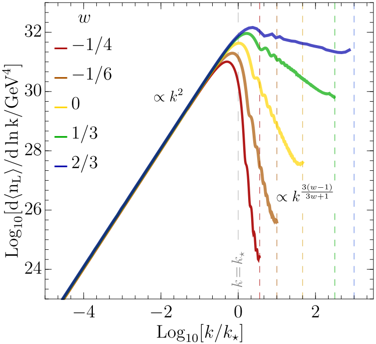
$k_\star \equiv a_\star m_X$

reheating efficiency

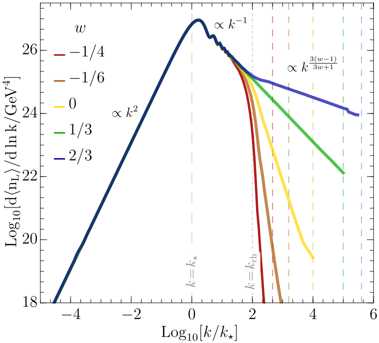
$\gamma^2 \equiv H_{\rm rh}/H_e$

$k_{\rm rh} \equiv a_{\rm rh} H_{\rm rh}$

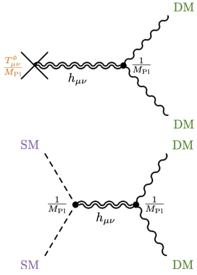
$\frac{d\langle n_{\rm L}(a_\star)\rangle}{d\ln k}(k)$ for $H_{\rm rh} < m_X < H_I$



$\frac{d\langle n_{\rm L}(a_\star)\rangle}{d\ln k}(k)$ for $m_X < H_{\rm rh}$



Graviton-mediated DM production



$$\mathcal{L}_{\rm int} = \frac{h^{\mu\nu}}{M_{\rm Pl}} \left(T^{\rm DM}_{\mu\nu} + T^{\phi}_{\mu\nu} + T^{\rm SM}_{\mu\nu} \right)$$

Boltzmann equation

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = \mathcal{R}_{\phi} + \mathcal{S}_{\rm SM}$$

$$\mathcal{R}_{\phi} \propto \frac{\rho_{\phi}^2}{M_{\rm Pl}^4}$$

$$\mathcal{S}_{\rm SM} \propto \begin{cases} T^8/M_{\rm Pl}^4, & m_X \ll T, \\ \left(m_X^5\, T^3/M_{\rm Pl}^4\right)\ e^{-2m_X/T}, & m_X \gg T, \end{cases}$$

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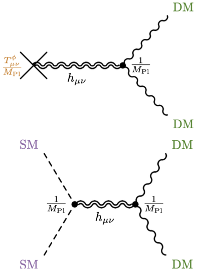

Boltzmann equation

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = \mathcal{R}_{\phi} + \mathcal{S}_{\rm SM}$$

$$\mathcal{R}_{\phi} \propto \frac{\rho_{\phi}^2}{M_{\rm Pl}^4} \xrightarrow{\text{Inflaton potential}} \rho_e, \quad T_{\rm max}$$

UV sensitive

$$\mathcal{S}_{\rm SM} \propto \begin{cases} T^8/M_{\rm Pl}^4, & m_X \ll T, \\ \left(m_X^5\, T^3/M_{\rm Pl}^4\right)\; e^{-2m_X/T}, & m_X \gg T, \end{cases}$$

Interactions

1. Specify the inflaton evolution

The α-attractor T-model

$$V(\phi) = \Lambda^4 \tanh^{2n}\left(\frac{\phi}{M}\right)$$

R. Kallosh et al. , arXiv:1306.5220
R. Kallosh et al. , arXiv:1311.0472

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2. Determine the reheating dynamics

Bosonic, perturbative reheating

$$\phi \to SS$$

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$$\left(\Omega_X^{\mathrm{GP}} + \Omega_X^{\mathrm{IG}} + \Omega_X^{\mathrm{SMG}}\right) h^2$$

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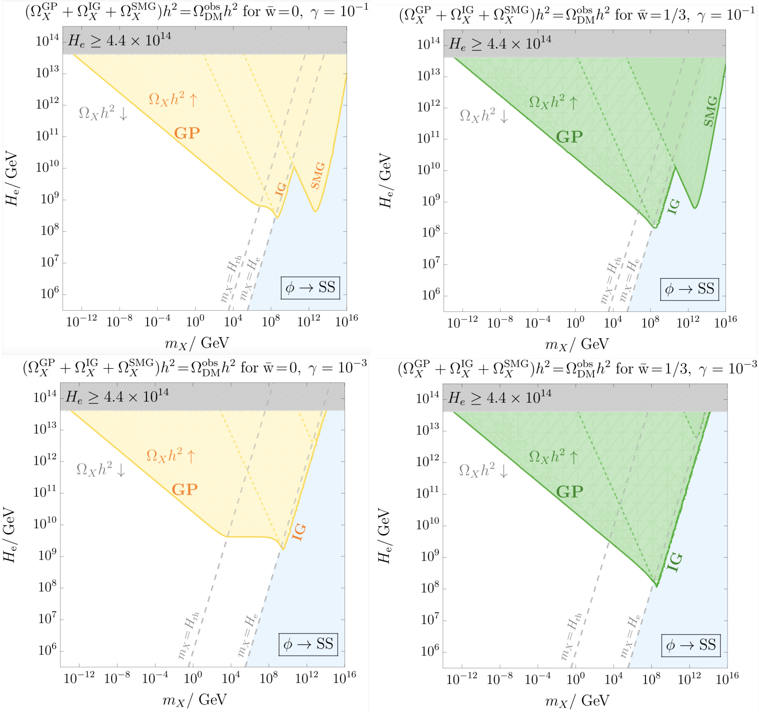
$$\left(\Omega_X^{\mathrm{GP}} + \Omega_X^{\mathrm{IG}} + \Omega_X^{\mathrm{SMG}}\right) h^2$$

4. Compare with the observed value

$$\Omega_X^{\mathrm{obs}} h^2 \simeq 0.1198 \pm 0.0012$$



$(\Omega_X^{\rm GP}+\Omega_X^{\rm IG}+\Omega_X^{\rm SMG})h^2=\Omega_{\rm DM}^{\rm obs}h^2$ for $\bar{\rm w}=0,\ \gamma=10^{-1}$
$(\Omega_X^{\rm GP}+\Omega_X^{\rm IG}+\Omega_X^{\rm SMG})h^2=\Omega_{\rm DM}^{\rm obs}h^2$ for $\bar{\rm w}=1/3,\ \gamma=10^{-1}$
$(\Omega_X^{\rm GP}+\Omega_X^{\rm IG}+\Omega_X^{\rm SMG})h^2=\Omega_{\rm DM}^{\rm obs}h^2$ for $\bar{\rm w}=0,\ \gamma=10^{-3}$
$(\Omega_X^{\rm GP}+\Omega_X^{\rm IG}+\Omega_X^{\rm SMG})h^2=\Omega_{\rm DM}^{\rm obs}h^2$ for $\bar{\rm w}=1/3,\ \gamma=10^{-3}$
$H_e \geq 4.4\times10^{14}$
$\Omega_X h^2\uparrow$
$\Omega_X h^2\downarrow$
GP
IG
SMG
$m_X=H_{\rm rh}$
$m_X=H_{\rm e}$
$\phi\to SS$
$H_{\rm e}/$ GeV
$m_X/$ GeV

Summary

- Purely Gravitational DM model could be considered as a minimal, albeit viable scenario for the dark sector.
- It has been established that the spectrum of dark vectors produced gravitationally has a peak structure. In particular, it is centered around a characteristic comoving momentum $k_\star$.
- We have demonstrated that accounting for the finite duration of reheating has a significant impact on the production of heavy DM vectors, i.e., with mass $m_X > H_{\rm rh}$.
- VDM particles with mass $m_X < H_e$ are abundantly produced in the inflationary era due to the tachyonic enhancement of the longitudinal momentum modes.
- Superheavy DM vectors ($m_X > H_e$) can be created thermally by the SM bath in an (almost) instantaneous reheating scenario.

Thank you for your attention!

Back-up slides

The isocurvature constraints are suppressed if

$$k_\star \ll k_{\rm CMB} \approx 0.05\mathrm{Mpc}^{-1}.$$

$$k_\star \approx 1400\,\mathrm{pc}^{-1}\sqrt{\frac{m_X}{10^{-14}\mathrm{GeV}}}\begin{cases}\left(\frac{H_{\rm rh}}{m_X}\right)^{\frac{1-3\overline{w}}{6(1+\overline{w})}}, & H_{\rm rh}\leq m_X < H_e\,,\\ 1\,, & H_{\rm mre}\leq m_X < H_{\rm rh}\,.\end{cases}$$

lDM vectors with mass $m_X \geq 10^{-14}\mathrm{GeV}$ are safe

$$\left(\frac{H_{\rm rh}}{m_X}\right)^{\frac{1-3w}{6(1+w)}} = \begin{cases}\left(\frac{m_X}{H_{\rm rh}}\right)^{[0,1/6)} \geq 1\,, & w=[1/3,\ 1)\,,\\ \left(\frac{H_{\rm rh}}{m_X}\right)^{(1/2,0)} < 1\,, & w=(-1/3,\ 1/3)\,.\end{cases}$$

lower bound on the reheating scale

$$m_X \geq H_{\rm rh} \geq 10^{-14}\mathrm{GeV}\left(\frac{10^{-14}\mathrm{GeV}}{\mathrm{m_X}}\right)^{\frac{2(1+3\mathrm{w})}{(1-3\mathrm{w})}}, \qquad w = (-1/3, 1/3).$$

Expansion | **Interactions**

$$\dot{\rho}_\phi + 3(1+\overline{w})H\rho_\phi = -\langle \Gamma_\phi \rangle \rho_\phi$$

$$\dot{\rho}_\mathcal{R} + 4H\rho_\mathcal{R} = \langle \Gamma_\phi^\mathcal{R} \rangle \rho_\phi$$

$$\overline{w} \equiv \langle p_\phi \rangle / \langle \rho_\phi \rangle$$

$$H^2 = \frac{\rho_\phi + \rho_\mathcal{R}}{3M_{pl}^2}$$

Time-dependent decay rate

$$\langle \Gamma_\phi^\mathcal{R} \rangle \simeq \langle \Gamma_\phi \rangle = \Gamma_\phi^e \left(\frac{a_e}{a}\right)^\beta$$

constant parameter

Non-instantaneous reheating

$$\boxed{\rho_\phi(a) \overset{H\gg\Gamma_\phi}{\simeq} 3M_{\rm Pl}^2 H_e^2 \left(\frac{a_e}{a}\right)^{3(1+\overline{w})}}$$

$$\boxed{\rho_{\mathcal{R}}(a) = \frac{6M_{Pl}^2 H_e \Gamma_\phi^e}{5-3\overline{w}-2\beta}\left[\left(\frac{a_e}{a}\right)^{\beta+3(1+\overline{w})/2} - \left(\frac{a_e}{a}\right)^4\right]}$$

the dominant term
for $\beta \leq (n+4)/(n+1)$