Production of dark photons and dark fermions during inflation

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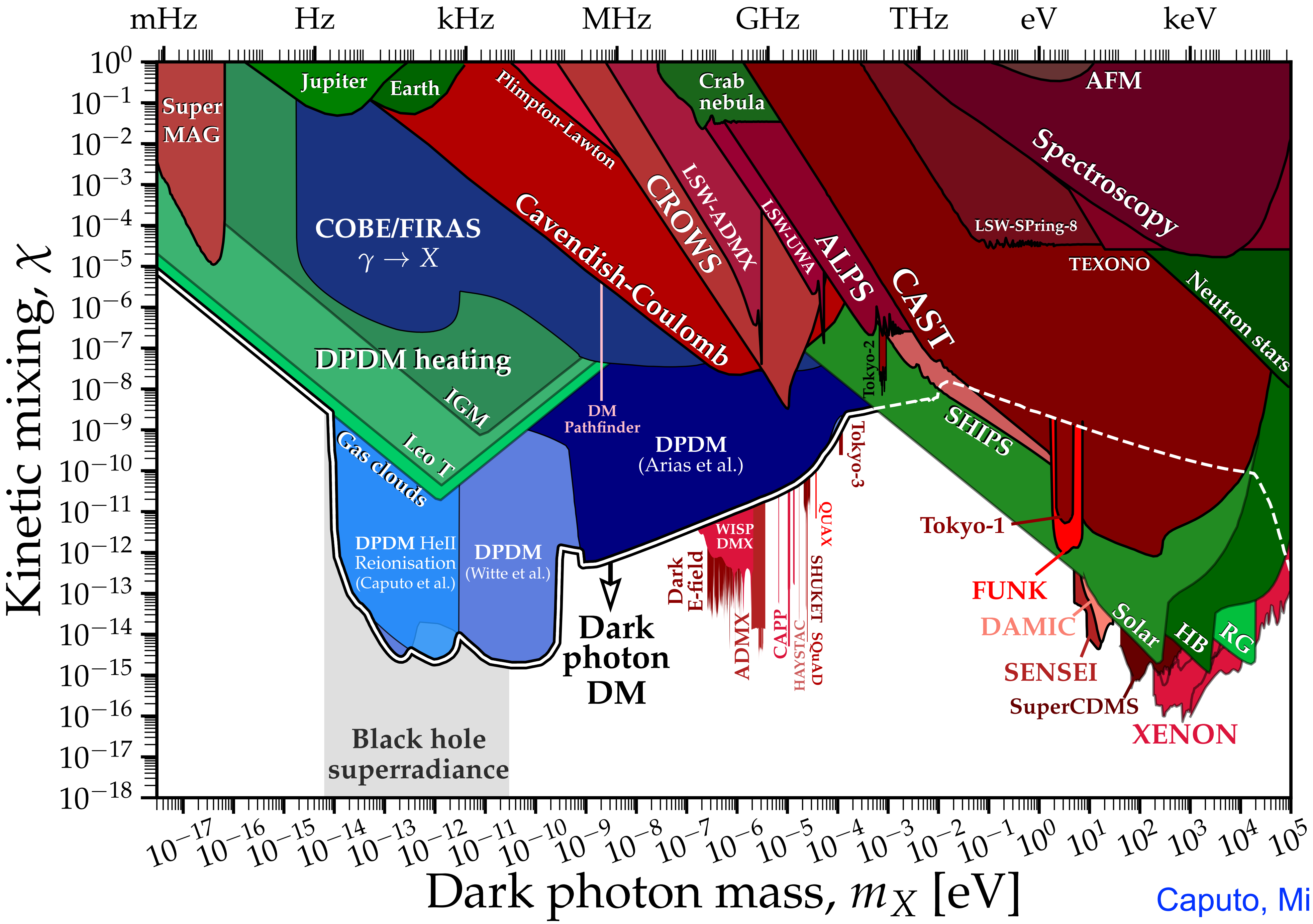


$$\mathcal{L} \supset \chi F_{\mu\nu} F'^{\mu\nu}$$

Caputo, Millar, O'Hare, Vitagliano (2021)

Some regions of parameter space rely on the assumption that the dark photon is the dark matter

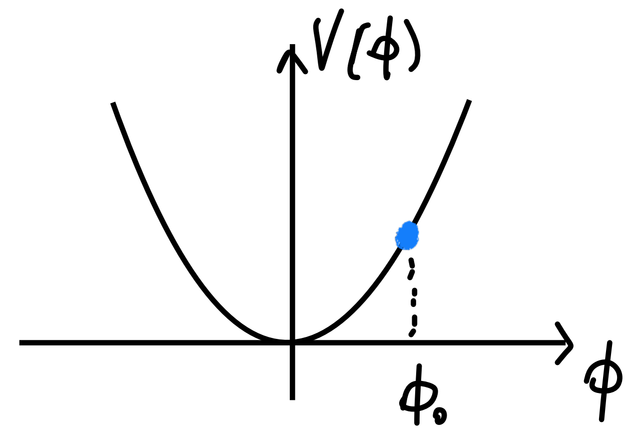
Dark photon dark matter

Misalignment?

Scalar field

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 \right)$$

$$\ddot{\phi} + 3H\dot{\phi} + m^2 \phi = 0$$



$$\rho_\phi = \frac{1}{2} m^2 \phi_0^2 = \text{const}$$

$$H \gg m$$

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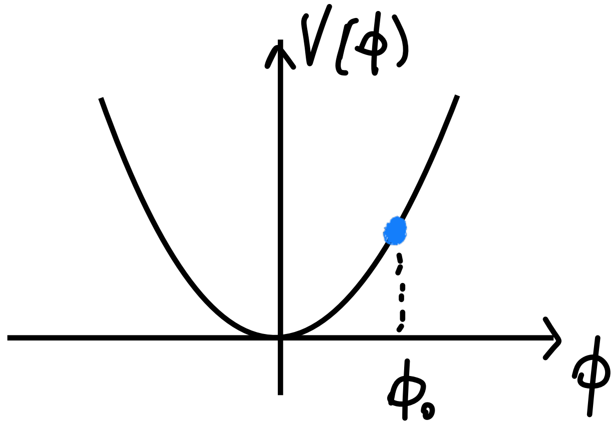

$$\rho_\phi = \frac{1}{2} m^2 \phi_0^2 = \text{const}$$

$$H \gg m$$

Vector field

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu \right)$$

$$\ddot{A}_i + H\dot{A}_i + m^2 A_i = 0$$

$$A_i \approx \text{const}$$

$$\rho_A \propto a^{-2}$$

Nelson, Scholtz (2011)

Misalignment? (continued)

$$\bar{A}_i = \frac{A_i}{a} \qquad \ddot{\bar{A}}_i + 3H\dot{\bar{A}}_i + \left(m^2 + \frac{1}{6}R\right)\bar{A}_i = 0 \qquad R = 6(H^2 + \dot{H})$$

$$\mathcal{L} \supset +\frac{1}{2}\xi\ R\ g^{\mu\nu}A_\mu A_\nu \qquad \xi = 1/6 \qquad m^2 \to m^2 - \xi R$$

Arias et al. (2012)

Fixes transverse modes but introduces a ghost instability for the longitudinal mode

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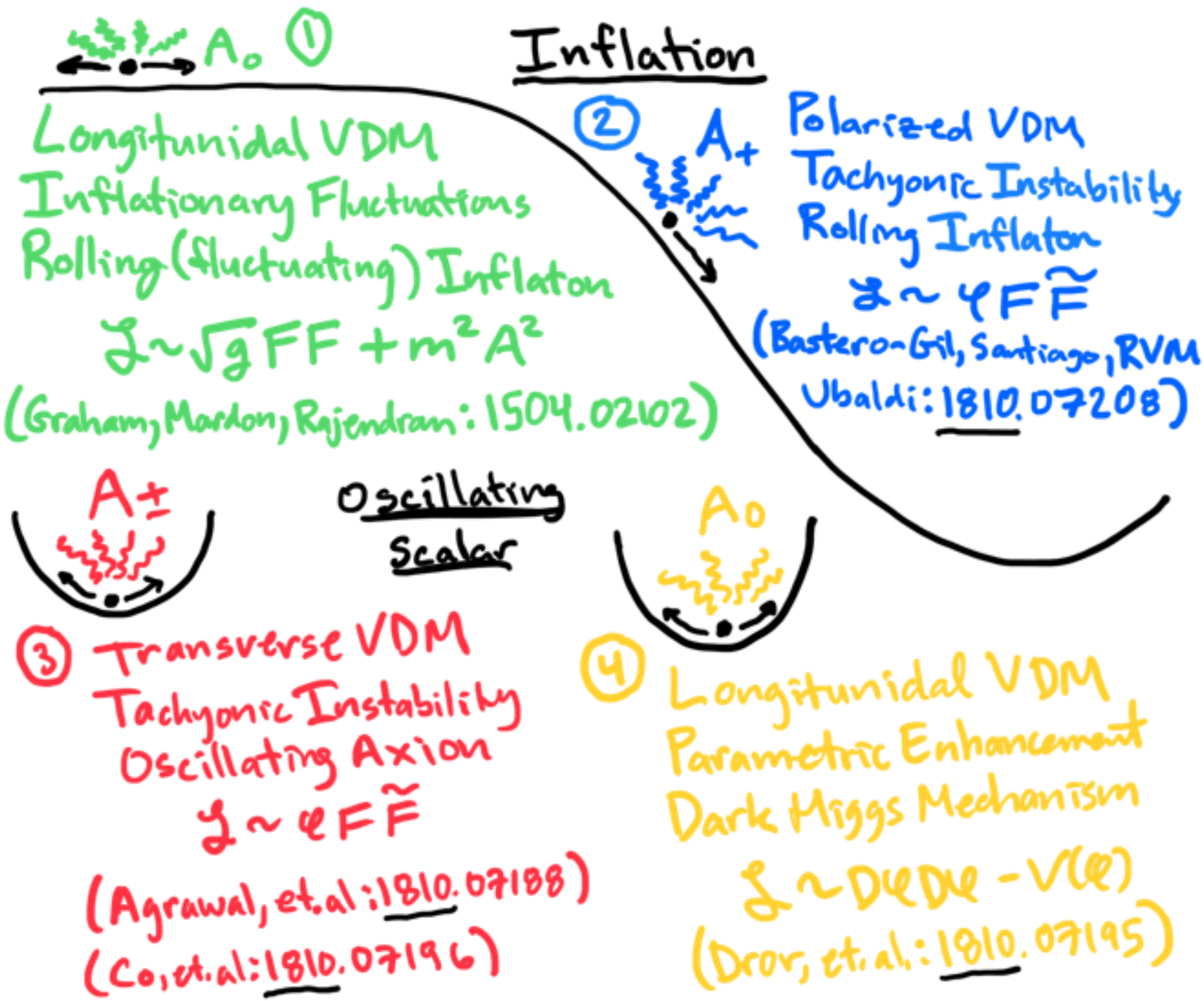
Fixes transverse modes but introduces a ghost instability for the longitudinal mode

$$S = \int d^4x \sqrt{-g}\left(-\frac{1}{4}f^2(\phi)F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2 g^{\mu\nu}A_\mu A_\nu\right) \qquad f(\phi) = \mathrm{Exp}\left(-\frac{\gamma}{8}\frac{\phi^2}{M_P^2}\right)$$

Nakayama (2019)

Kitajima, Nakayama (2023)

Constraints from isocurvature, anisotropic curvature perturbations



VDM = Vector Dark Matter = Dark Photon Dark Matter

Field content and equations of motion

$$S = -\int d^4x\,\sqrt{-g}\Big[\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi) + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2A_\mu A^\mu + \frac{\alpha}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\Big]$$

$$\ddot{\phi} + 3H\dot{\phi} + V' = \frac{\alpha}{f}F\tilde{F} \approx 0,$$

$$\ddot{A}_\pm + H\dot{A}_\pm + \left(\frac{k^2}{a^2} \pm \frac{k}{a}\frac{\alpha\dot{\phi}}{f} + m^2\right)A_\pm = 0\,,$$

$$\ddot{A}_L + \frac{3k^2 + a^2m^2}{k^2 + a^2m^2}H\dot{A}_L + \left(\frac{k^2}{a^2} + m^2\right)A_L = 0$$

for the transverse modes $\qquad \xi \equiv \frac{\alpha\dot{\phi}}{2Hf}$

$\omega_k^2 \simeq \frac{k^2}{a^2} \pm \frac{k}{a}2H\xi < 0 \qquad \frac{k}{a} < 2H\xi \qquad$ long wavelength tachyonic modes

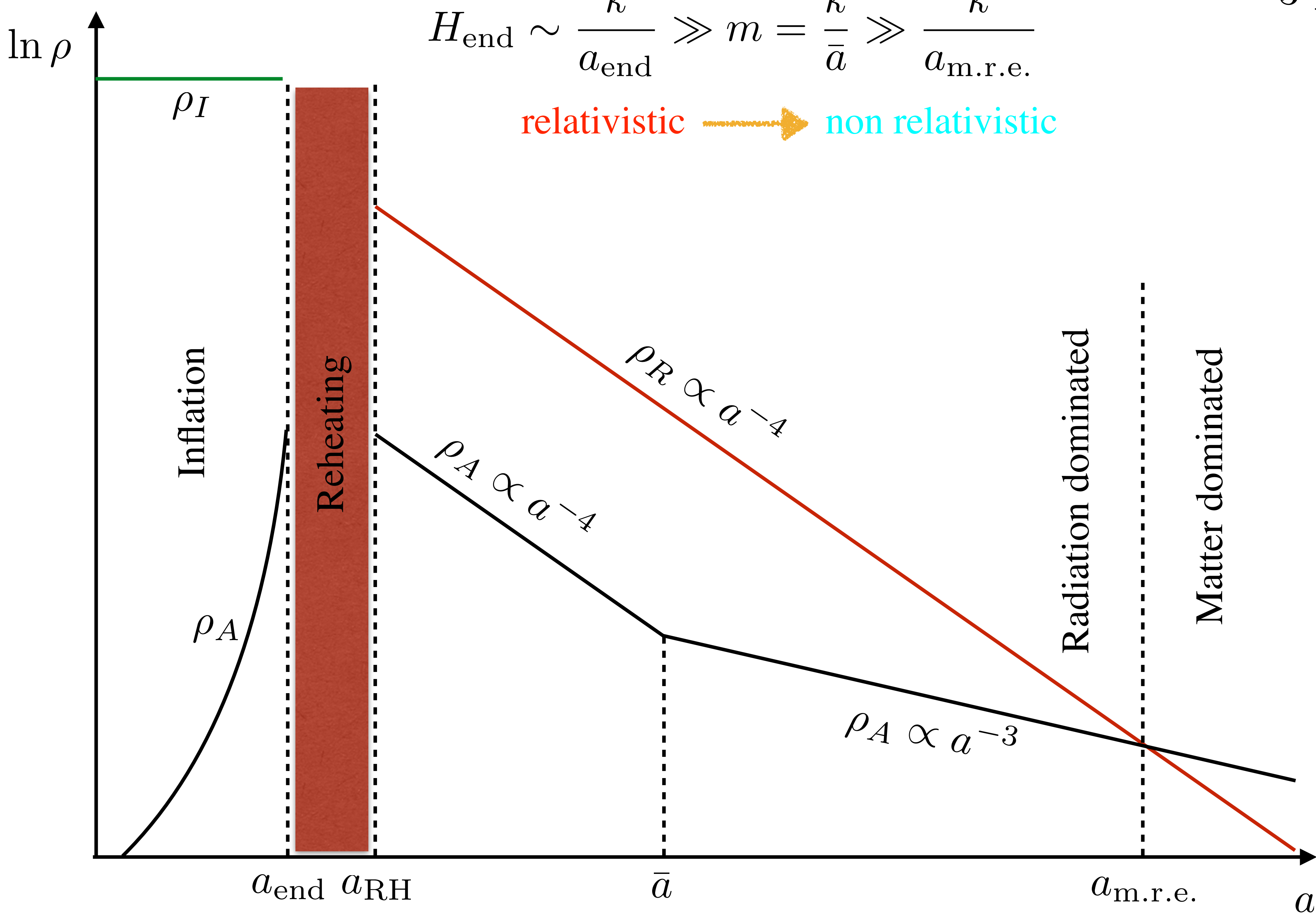
Evolution of the energy densities

$\rho_I = V(\phi) = 3H^2 M_P^2$ $\qquad \rho_R(T_{\rm RH}) = 3\epsilon_R^4 H^2 M_P^2$ $\qquad \rho_D(T_{\rm RH}) \approx 10^{-4} \frac{\epsilon_H^4 H^4}{\xi_{\rm end}^3} e^{2\pi\xi_{\rm end}}$

$3 \leq \xi_{\rm end} < 10$

$$H_{\rm end} \sim \frac{k}{a_{\rm end}} \gg m = \frac{k}{\bar{a}} \gg \frac{k}{a_{\rm m.r.e.}}$$

relativistic → non relativistic



Relic abundance

$$\frac{\Omega_T}{\Omega_{\rm CDM}} = 7\times 10^{-6}\,\frac{m}{\rm GeV}\left(\frac{H}{10^{11}\ {\rm GeV}}\right)^{3/2}\left(\frac{\epsilon_H}{\epsilon_R}\right)^3 \frac{e^{2\pi\xi_{\rm end}}}{\xi_{\rm end}^3}$$

$$\Omega_{\rm CDM}h^2 = 0.12$$

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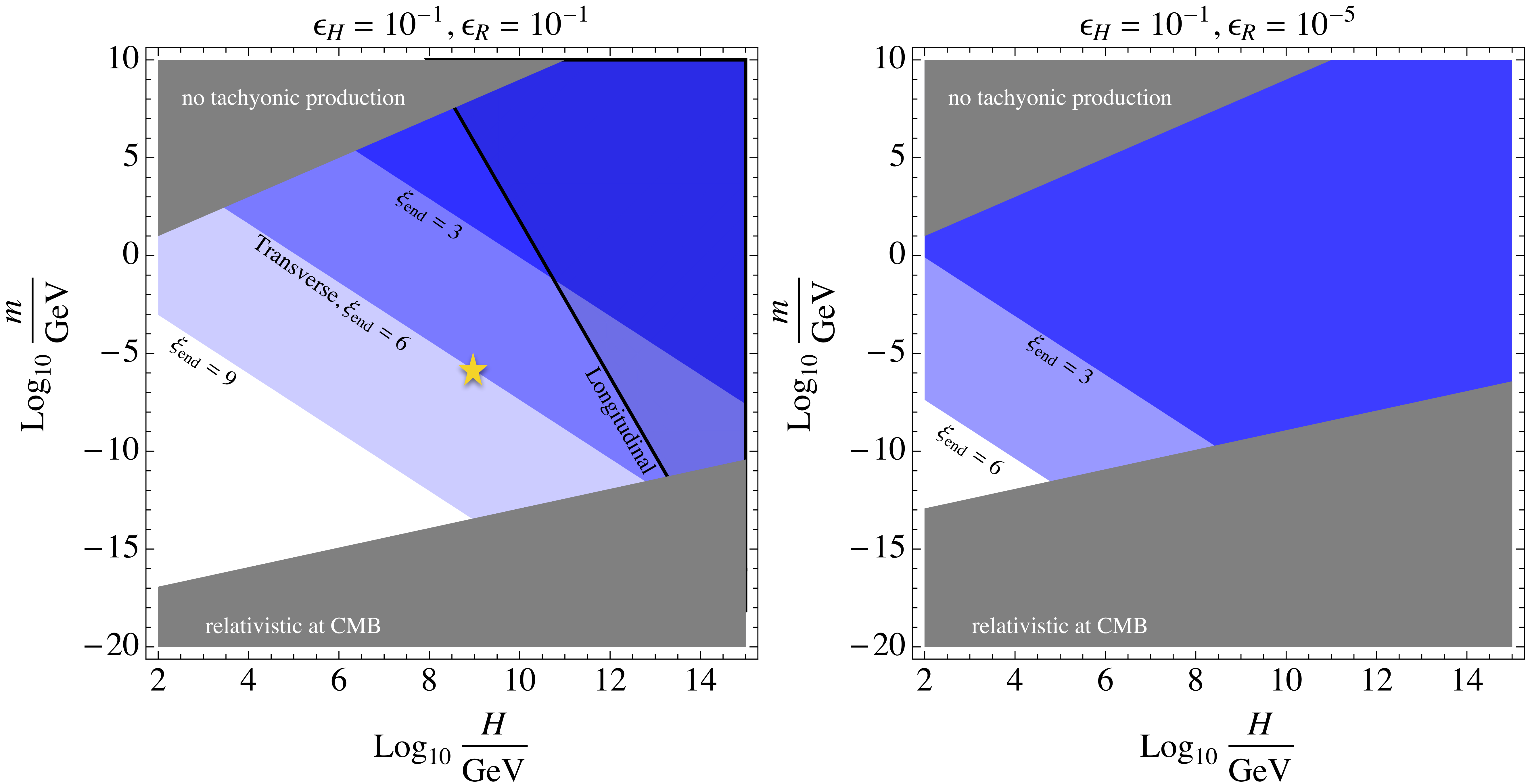
$$\frac{\Omega_L}{\Omega_{\rm CDM}} = \left(\frac{m}{6\times 10^{-15}\ {\rm GeV}}\right)^{1/2}\left(\frac{H}{10^{14}\ {\rm GeV}}\right)^2$$

Graham, Mardon, Rajendran 1504.02102

Constraints

- $k/a_{\rm end} \gg m$ for efficient tachyonic production
- VDM must NOT thermalize with the visible sector: $\xi_{\rm end} < 10$ and SMALL KINETIC MIXING
- negligible back reaction effect on inflaton dynamics: $\xi_{\rm end} < 10$
- start with a universe dominated by visible radiation: $\rho_R(T_{\rm RH}) \gg \rho_D(T_{\rm RH})$
- $a_* < a_{\rm m.r.e.}$: VDM becomes non relativistic (cold) before m.r.e.



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Do vortices kill all the scenarios?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}|D_\mu\Phi|^2 - \frac{\lambda}{4}(|\Phi|^2 - v^2)^2$$

$$D_\mu = \partial_\mu - ig_D A_\mu$$

$$\Phi = (\rho + v)e^{i\Pi/v} \qquad\qquad m_A = g_D v$$

Roughly when $\rho_A \sim \lambda v^4$ the U(1) is restored, vortices form, and the dark photon energy density is dissipated. East, Huang (2022)

Take $\lambda \to \infty$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(m_A A_\mu - \partial_\mu\Pi)(m_A A^\mu - \partial^\mu\Pi)$$

The longitudinal mode inherits the periodicity $\Pi \to \Pi + 2\pi v$

The same mode has fluctuations of order H during inflation.
If H > v vortices form, implying the bound:

$$g_D = \frac{m_A}{v} \leq \frac{m_A}{H} = 2\times 10^{-22}\left(\frac{m_A}{\text{eV}}\right)^{5/4}$$

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Kinetic mixing with the Standard Model

$$\chi \sim \frac{e\ g_D}{16\pi^2} < 10^{-24}$$

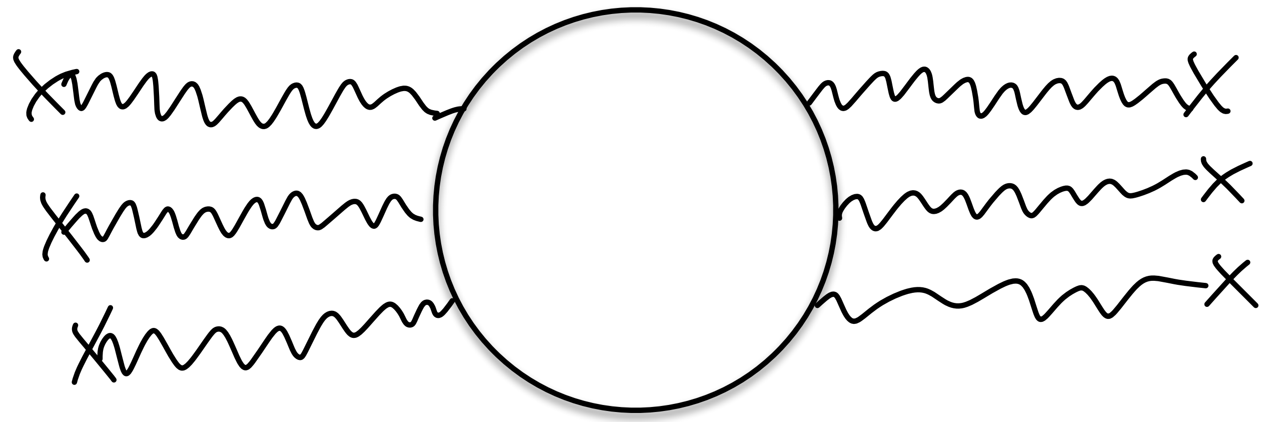
The longitudinal mode of the dark photon can still be the dark matter but it could be undetectable.

For the transverse modes, produced via the mechanism I discussed above, the impact of vortices is less clear to me.

Dark charged particles

Add dark fermions charged under U(1)$_D$

$$\mathcal{L} \supset \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi$$

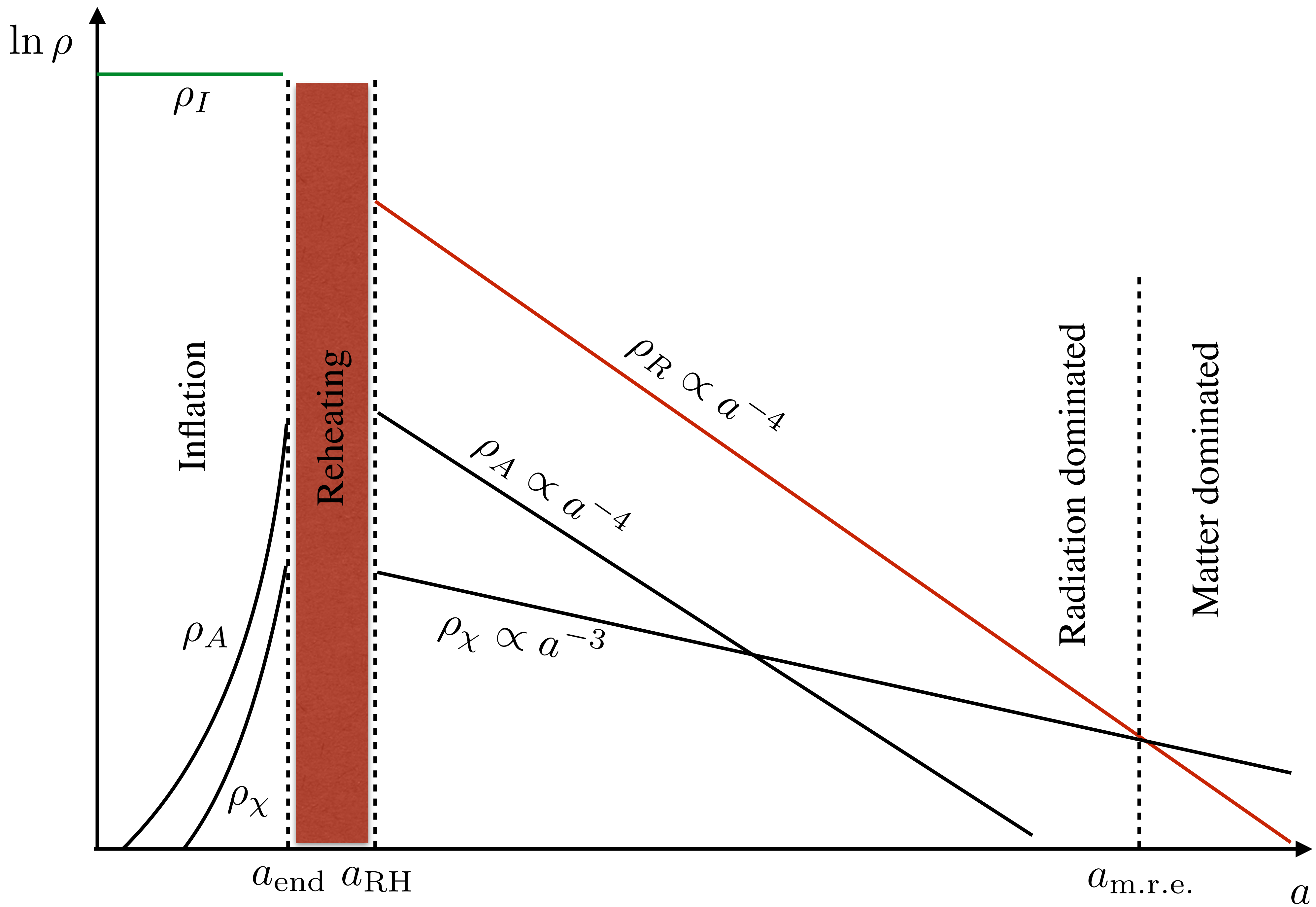


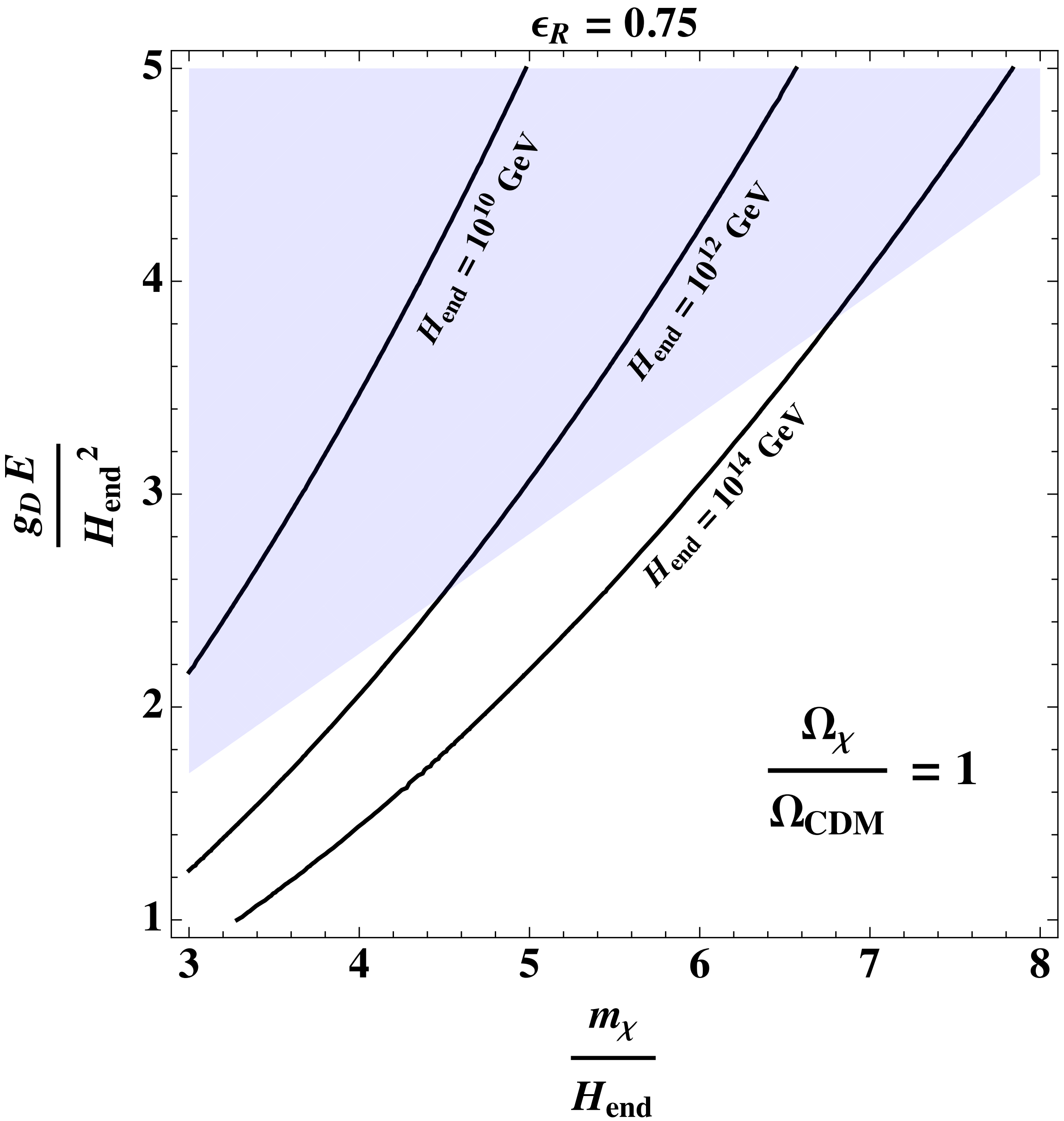
$$\dot{\rho}_\chi + 3H\rho_\chi = EJ = \sigma E^2$$

$$\bar{\sigma} \equiv \frac{\sigma}{H} \propto \text{Exp}\left[-\pi\frac{m_\chi^2}{g_D E}\right]$$

$$\rho_\chi^{\text{end}} \simeq \frac{\bar{\sigma}_{\text{end}}}{3}E^2$$

$$\frac{\Omega_\chi}{\Omega_{\rm CDM}} = \frac{8.2\cdot 10^{13}}{\epsilon_R^3}\left(\frac{g_D E}{H_{\rm end}^2}\right)^3 e^{-\pi\frac{m_\chi^2}{g_D E}}\left(\frac{H_{\rm end}}{10^{14}\ {\rm GeV}}\right)^{5/2}$$





Constraints:

- the dark fermions must remain non-relativistic
- they don't thermalize with the dark photons

Back of the envelope estimates indicate that the screened Coulomb force can have interesting implication in structure formation.

Conclusions

- Dark photon dark matter is not easy to make
- The scenario with superheavy dark fermions with a (massless) dark photon mediator has not been killed yet. Maybe interesting to study LSS implications.