Dark photon dark matter from inflation

Lorenzo Ubaldi
SISSA & INFN, Trieste

[arXiv:1810.07208] JCAP 1904 (2019) no.04, 015

Mar Bastero-Gil, Jose Santiago, LU, Roberto Vega-Morales

Portorož, April 17th, 2019

Beyond WIMPs

- No WIMPs in direct detection so far
- Important to think about alternative dark matter candidates
- The dark photon, a massive vector from a dark U(1) gauge group, is a good candidate
- I will discuss a non-thermal mechanism for producing a relic density of cold massive dark photons
- It can lead to interesting phenomenology

Sociology and dark photon fest

1) Relic Abundance of Dark Photon Dark Matter   1810.07188

Prateek Agrawal, Naoya Kitajima, Matthew Reece, Toyokazu Sekiguchi, Fuminobu Takahashi

From: Prateek Agrawal

[v1] Tue, 16 Oct 2018 18:00:00 UTC (233 KB)

2) Parametric Resonance Production of Ultralight Vector Dark Matter   1810.07195

Jeff A. Dror, Keisuke Harigaya, Vijay Narayan

From: Vijay Narayan

[v1] Tue, 16 Oct 2018 18:00:05 UTC (531 KB)

3) Dark Photon Dark Matter Produced by Axion Oscillations   1810.07196

Raymond T. Co, Aaron Pierce, Zhengkang Zhang, Yue Zhao

From: Zhengkang Zhang

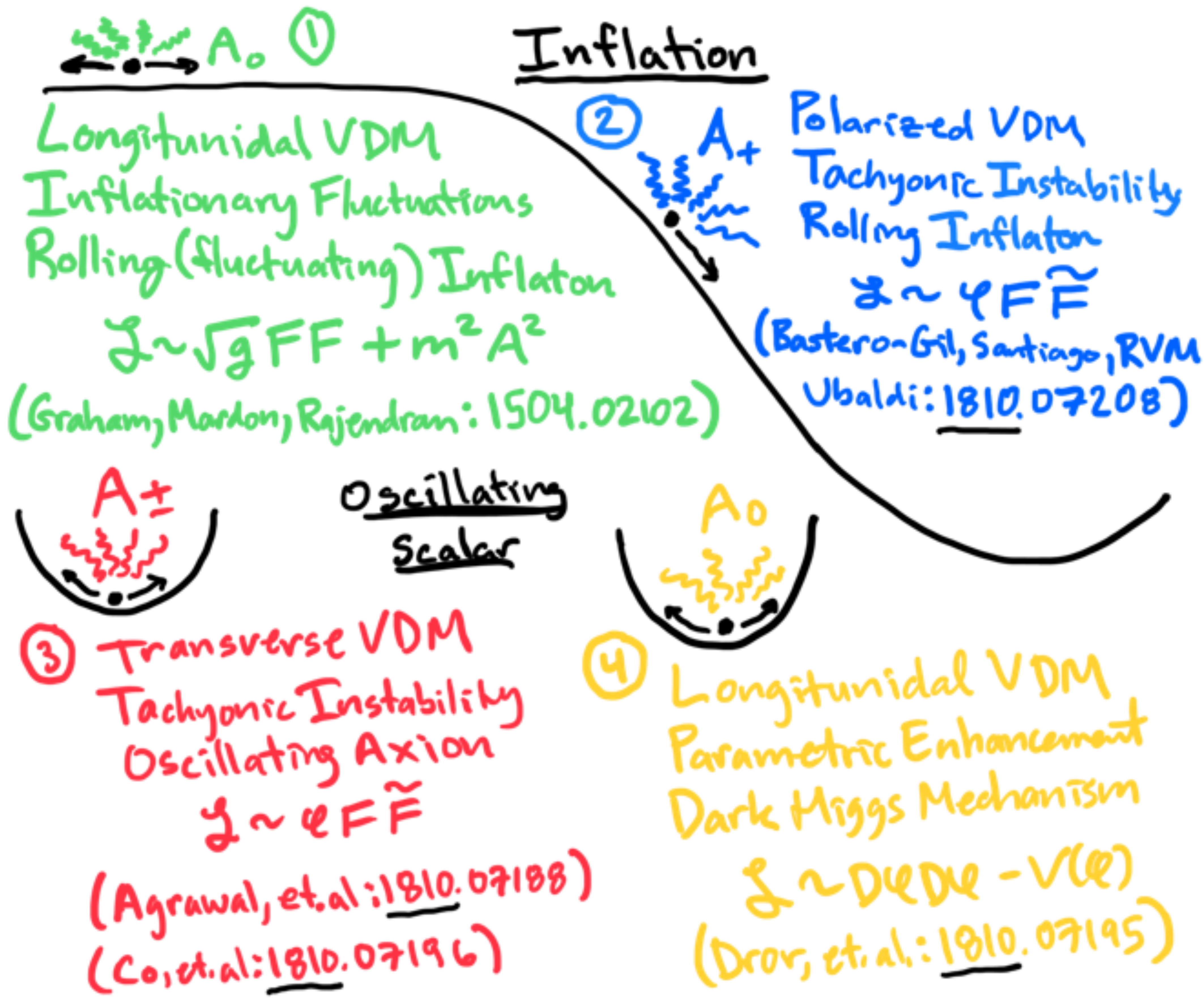
[v1] Tue, 16 Oct 2018 18:00:06 UTC (441 KB)

4) Vector dark matter production at the end of inflation   1810.07208

Mar Bastero-Gil, Jose Santiago, LU, Roberto Vega-Morales

From: Roberto Vega-Morales

[v1] Tue, 16 Oct 2018 18:04:45 UTC (870 KB)



VDM = Vector Dark Matter = Dark Photon Dark Matter

Some equations

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

$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2 \qquad \frac{\dot{a}^2}{a^2} \equiv H^2 = \frac{V(\phi)}{3M_P^2}$$

$$\hat{\vec{A}}(\vec{x},t) = \sum_{\lambda=\pm,L}\int\frac{d^3k}{(2\pi)^3}e^{i\vec{k}\cdot\vec{x}}\;\vec{\epsilon}_\lambda(\vec{k})[A_\lambda(k,t)a_\lambda(\vec{k}) + A_\lambda(k,t)^* a_\lambda^\dagger(-\vec{k})]$$

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

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

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

Some equations

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

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

$$\frac{\dot{a}^2}{a^2} \equiv H^2 = \frac{V(\phi)}{3M_P^2}$$

$$\hat{\vec{A}}(\vec{x},t) = \sum_{\lambda=\pm,L}\int\frac{d^3k}{(2\pi)^3}e^{i\vec{k}\cdot\vec{x}}\;\vec{\epsilon}_\lambda(\vec{k})[A_\lambda(k,t)a_\lambda(\vec{k}) + A_\lambda(k,t)^* a_\lambda^\dagger(-\vec{k})]$$

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

$$\dot{\phi} \simeq -\frac{V'}{3H}$$

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

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

Graham, Mardon, Rajendran 1504.02102

More equations

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

$$m^2 \ll \frac{k^2}{a^2}\,,\ H^2$$

$$\ddot{A}_\pm + H\dot{A}_\pm + \omega_\pm^2 A_\pm = 0 \qquad \omega_\pm^2 = \frac{k^2}{a^2} \mp 2\frac{k}{a}H\xi \qquad \xi \equiv \frac{\alpha\dot{\phi}}{2Hf} > 0$$

$\omega_+^2 < 0$ for $\frac{k}{a} < 2H\xi$

$$\lambda = k^{-1} \sim (aH)^{-1}$$

comoving wavelength of exponentially enhanced modes is roughly the size of the comoving horizon

$$A_+ \simeq \frac{1}{\sqrt{2k}}\left(\frac{k}{2\xi aH}\right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi k(aH)^{-1}}}$$

$$\vec{E} = \frac{1}{a}\frac{\partial\vec{A}}{\partial t}\,, \quad \vec{B} = \frac{1}{a^2}\nabla\times\vec{A}$$

$$\rho_D = \frac{1}{2}\langle 0|\vec{E}^2 + \vec{B}^2|0\rangle \approx 10^{-4}\frac{H_{\rm end}^4}{\xi_{\rm end}^3}e^{2\pi\xi_{\rm end}}$$

Energy density in dark photons at the end of inflation

$$H_{\rm end} = \epsilon_H H$$

$H_{\rm end}$ Hubble at the end of inflation

H Hubble during inflation

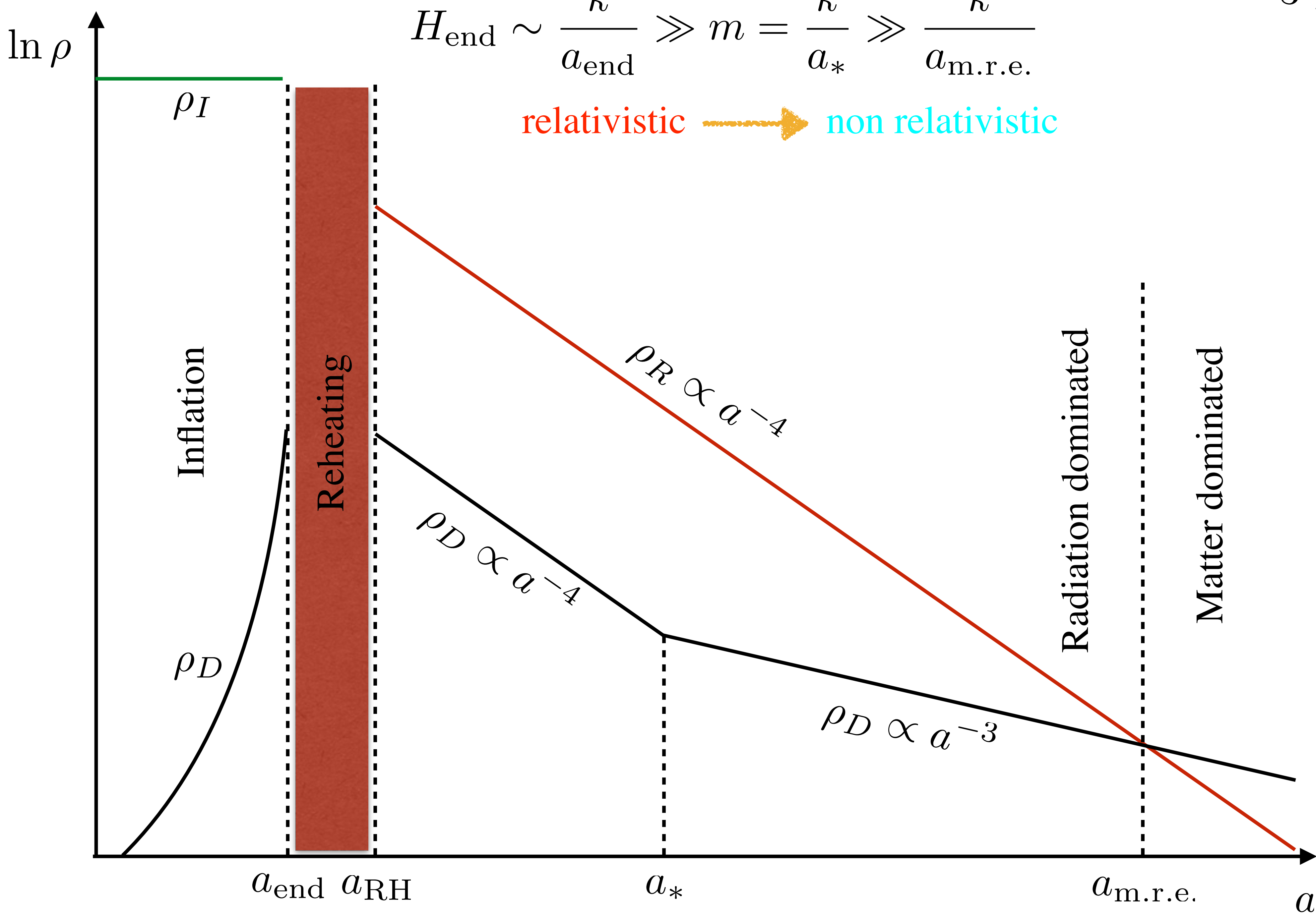
Evolution of the energy densities

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

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

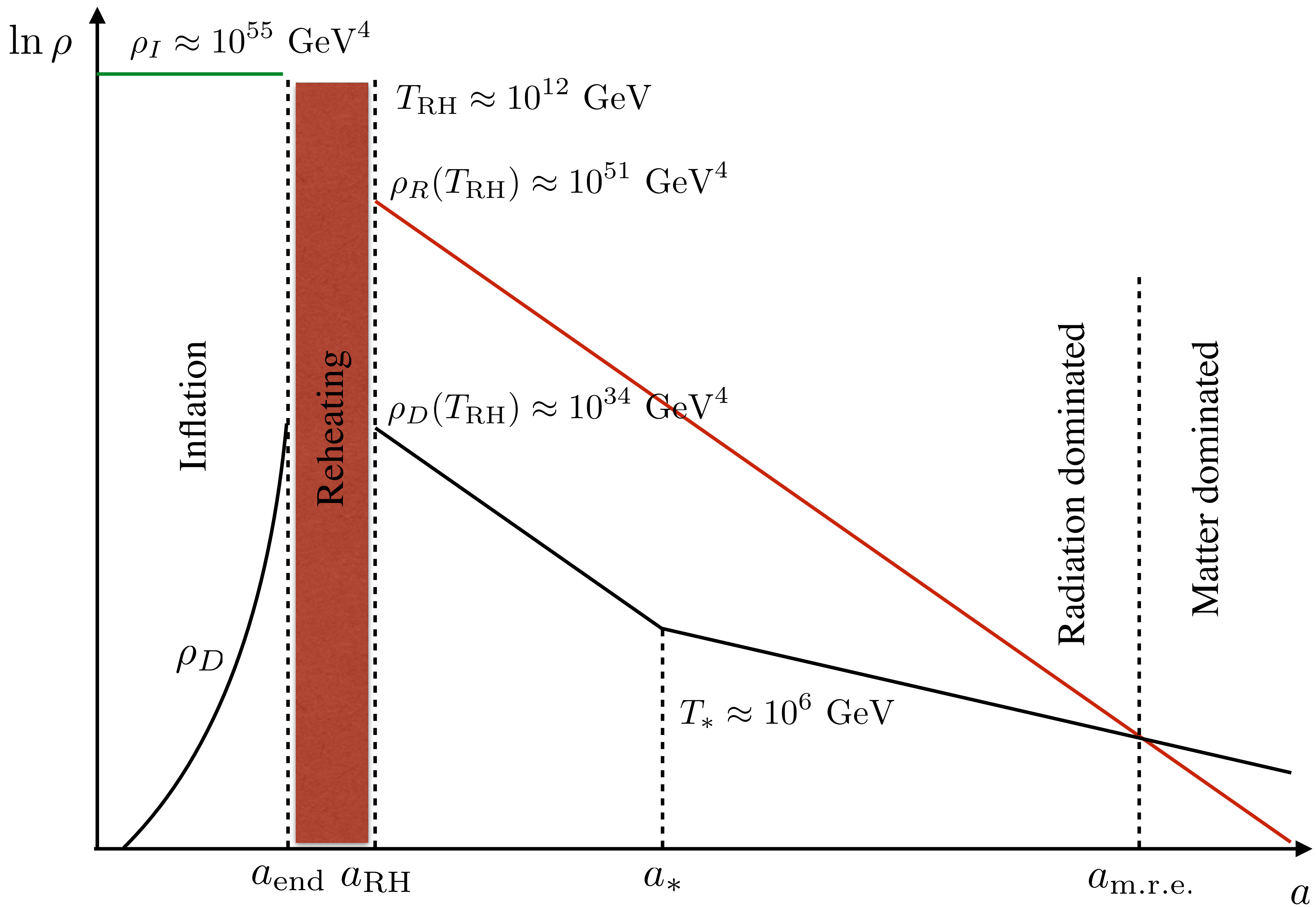
$$H_{\rm end} \sim \frac{k}{a_{\rm end}} \gg m = \frac{k}{a_*} \gg \frac{k}{a_{\rm m.r.e.}}$$

relativistic → non relativistic



A benchmark

$$m = 1.3 \text{ GeV}\,,\ H = 10^9 \text{ GeV}\,,\ \xi_{\text{end}} = 6\,,\ \epsilon_R = 10^{-1}\,,\ \epsilon_H = 10^{-3}$$



Relic abundance

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

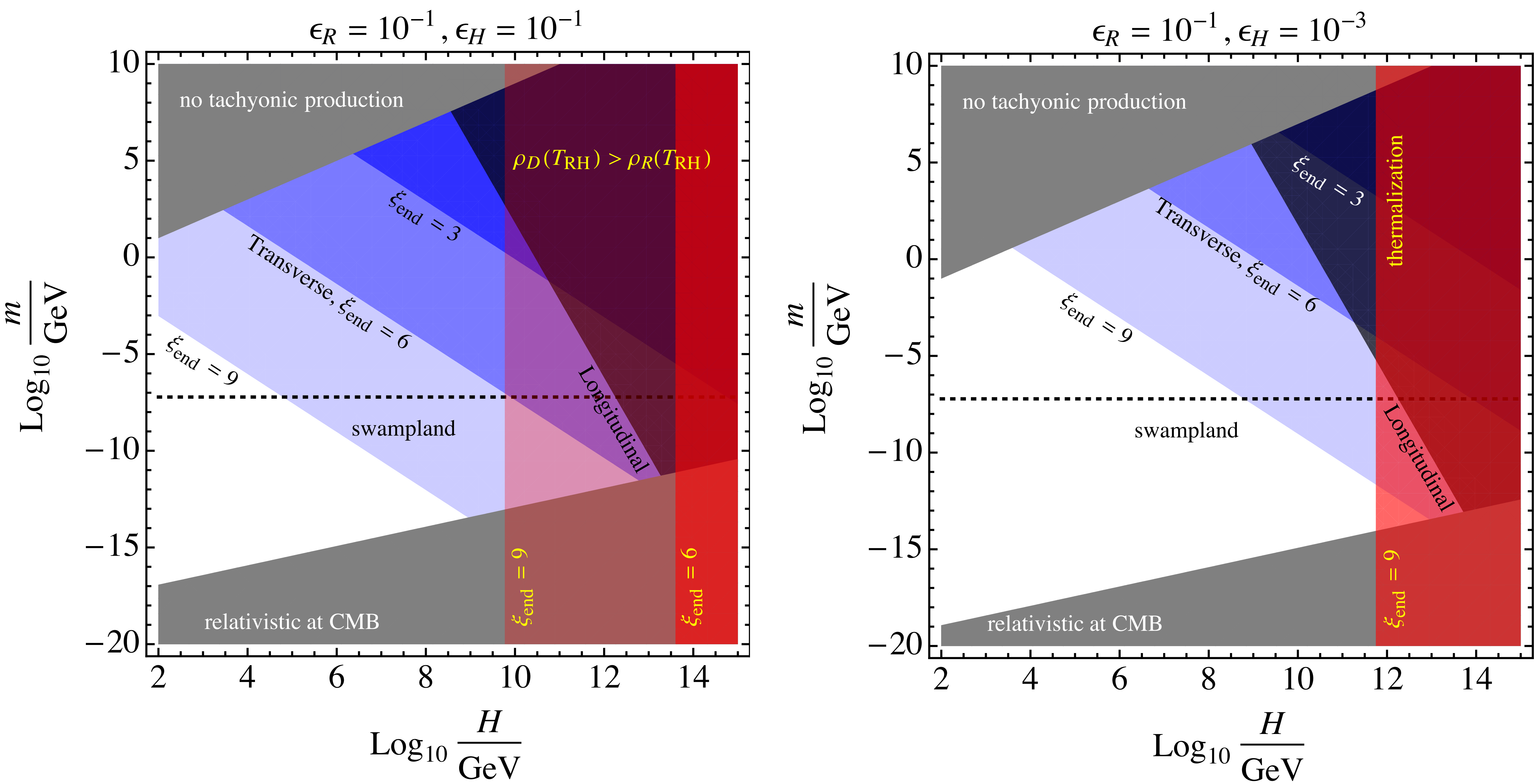
$$\Omega_{\rm CDM} h^2 = 0.12$$

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

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.



$\epsilon_R = 10^{-1}, \epsilon_H = 10^{-1}$
no tachyonic production
$\rho_D(T_{RH}) > \rho_R(T_{RH})$
$\xi_{end} = 3$
Transverse, $\xi_{end} = 6$
$\xi_{end} = 9$
Longitudinal
swampland
relativistic at CMB
$\xi_{end} = 9$
$\xi_{end} = 6$
$\text{Log}_{10} \frac{m}{\text{GeV}}$
$\text{Log}_{10} \frac{H}{\text{GeV}}$
$\epsilon_R = 10^{-1}, \epsilon_H = 10^{-3}$
no tachyonic production
$\xi_{end} = 3$
thermalization
Transverse, $\xi_{end} = 6$
$\xi_{end} = 9$
swampland
Longitudinal
relativistic at CMB
$\xi_{end} = 9$
$\text{Log}_{10} \frac{m}{\text{GeV}}$
$\text{Log}_{10} \frac{H}{\text{GeV}}$

Conclusions

- I have presented a new non-thermal mechanism for producing dark photon dark matter
- Large region of parameter space available, several decades in mass and Hubble scale of inflation

Outlook

- Clumpy dark matter? At what scale? Implications for structure formation?
- Is the non relativistic dark photon polarized?
- Turn on a small kinetic mixing with the visible photon. Opportunities for detection?