Dark photon dark matter from a rolling inflation

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[arXiv:1810.07208] JCAP 1904 (2019) no.04, 015
[arXiv:2103.12145]

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MAINZ, May 11th, 2021

Beyond WIMPs

- No WIMP 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

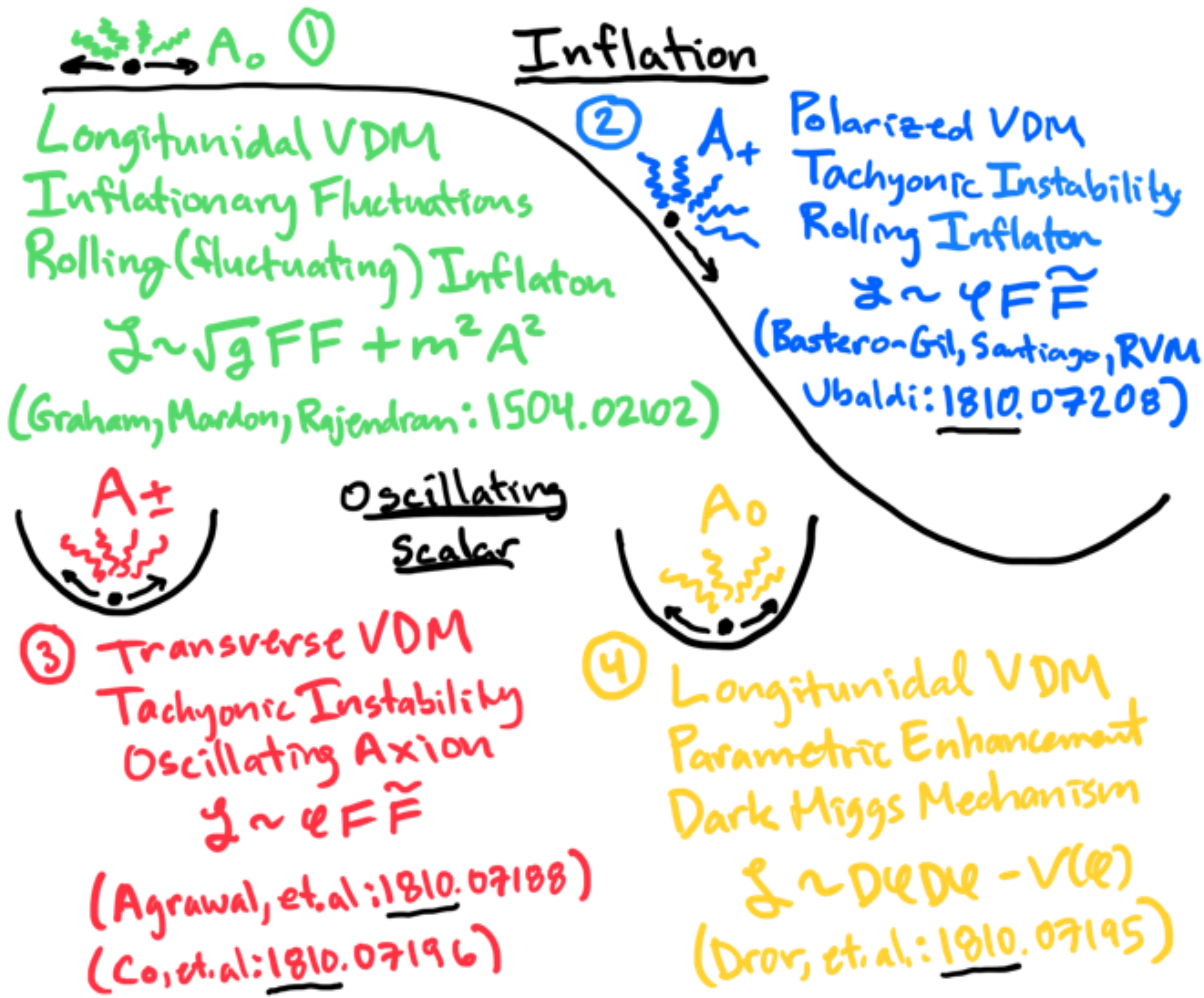
Raymond T. Co, Aaron Pierce, Zhengkang Zhang, Yue Zhao

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

R. Vega-Morales (U of Granada) - VDM and Inflation

Some equations

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

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

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

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

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

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

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

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

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

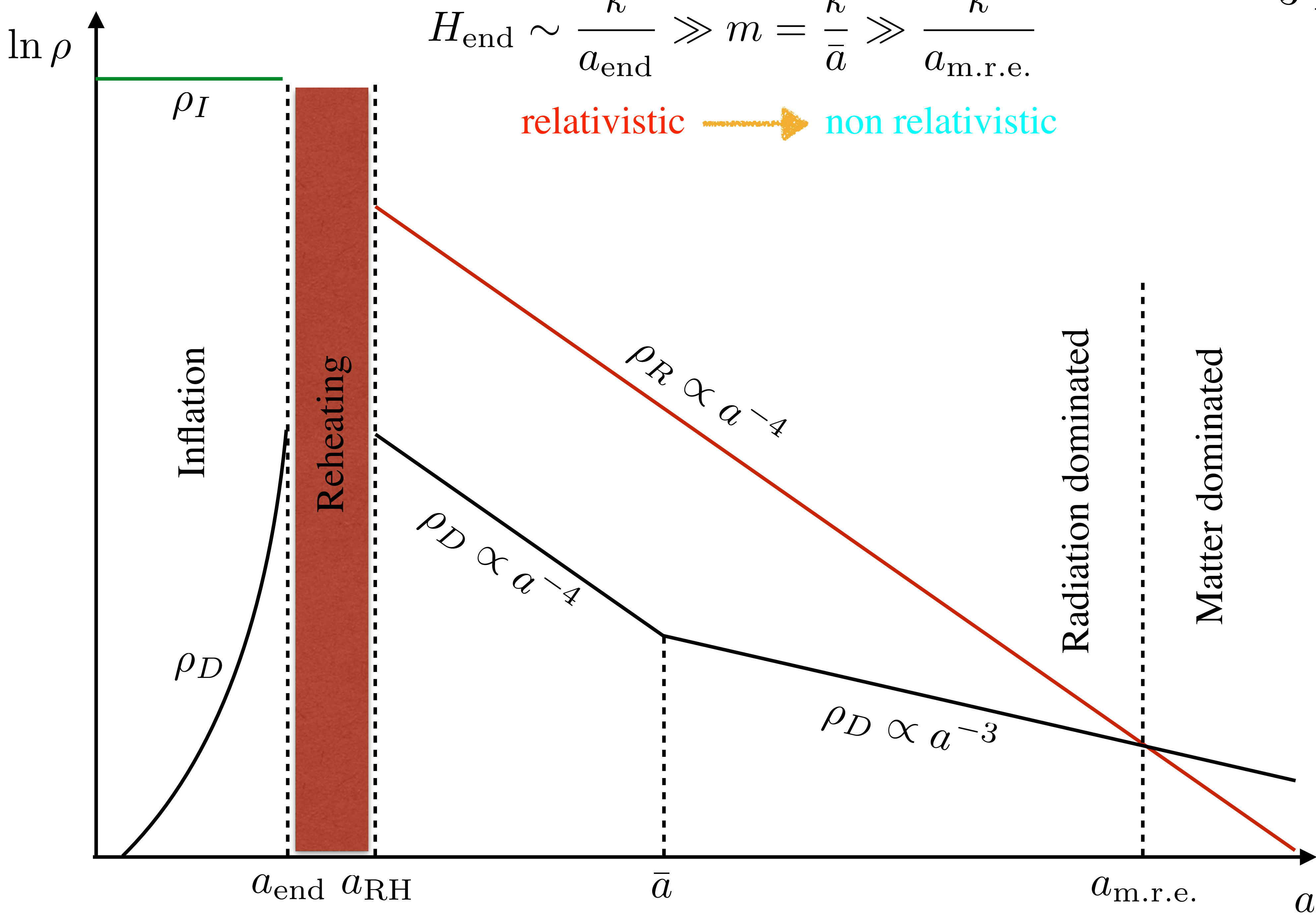
Evolution of the energy densities

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

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

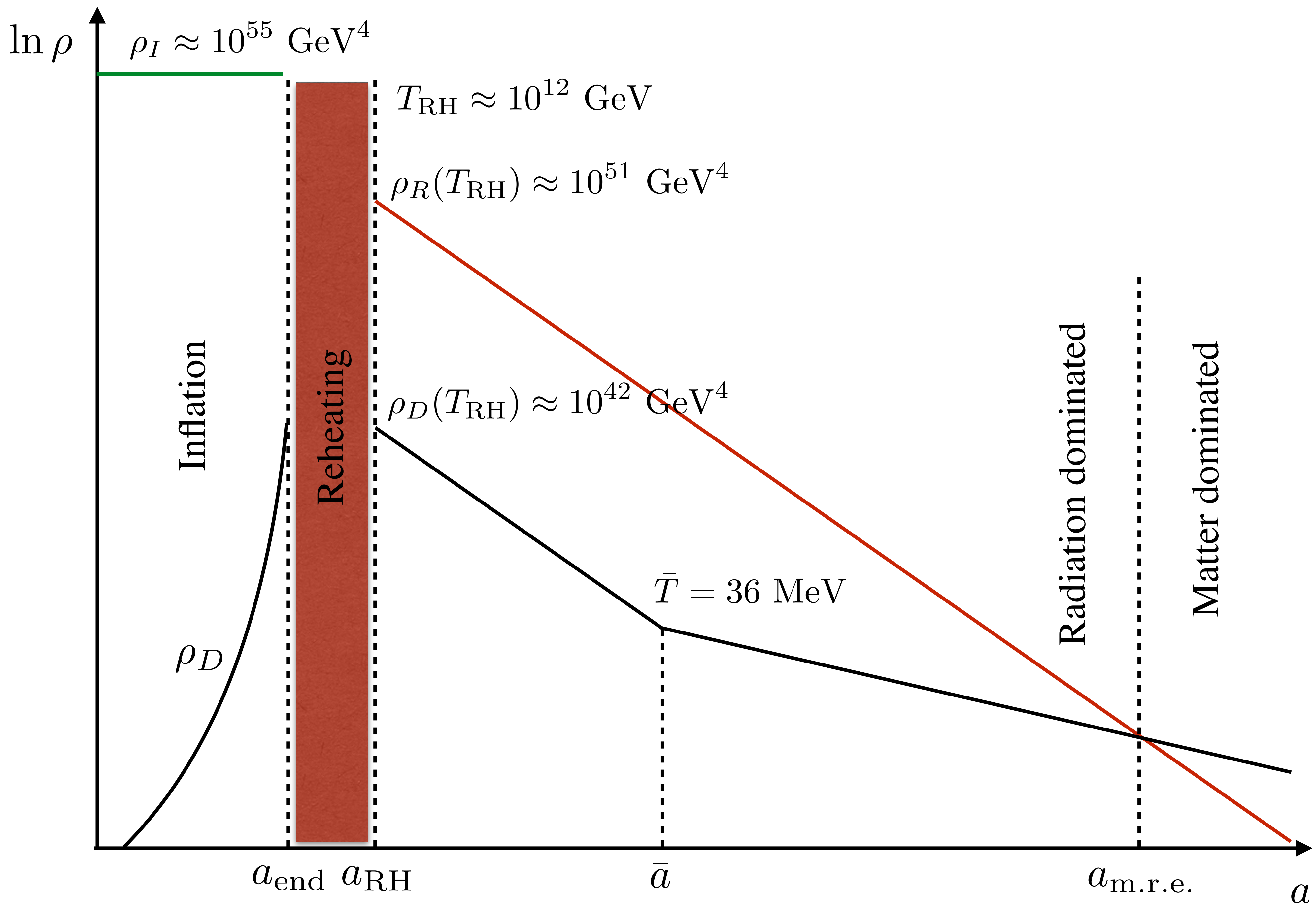
$$3 \leq \xi_{\rm end} < 10$$

relativistic → non relativistic



A benchmark

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



Relic abundance

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

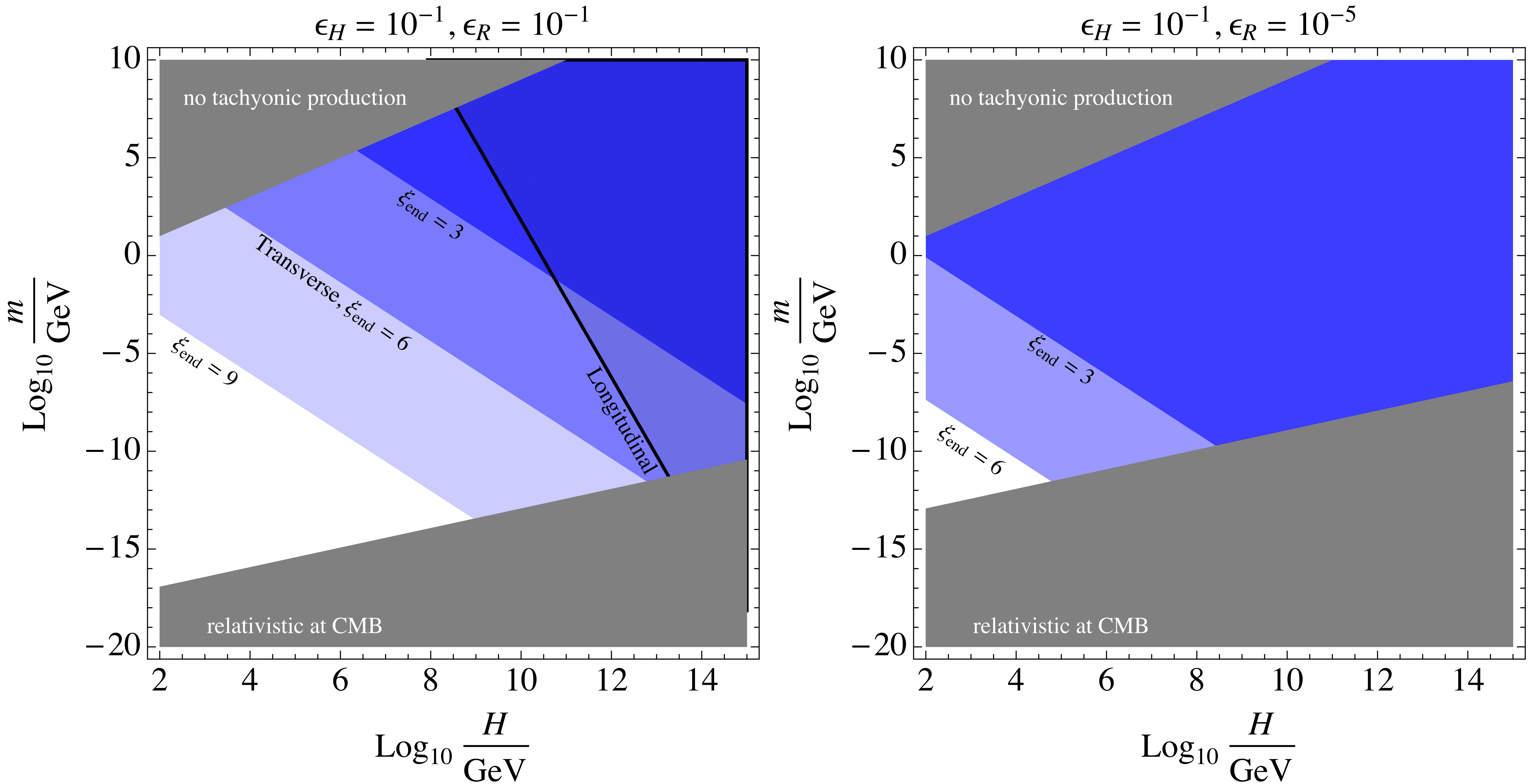
$$\Omega_{\rm CDM} h^2 = 0.12$$

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

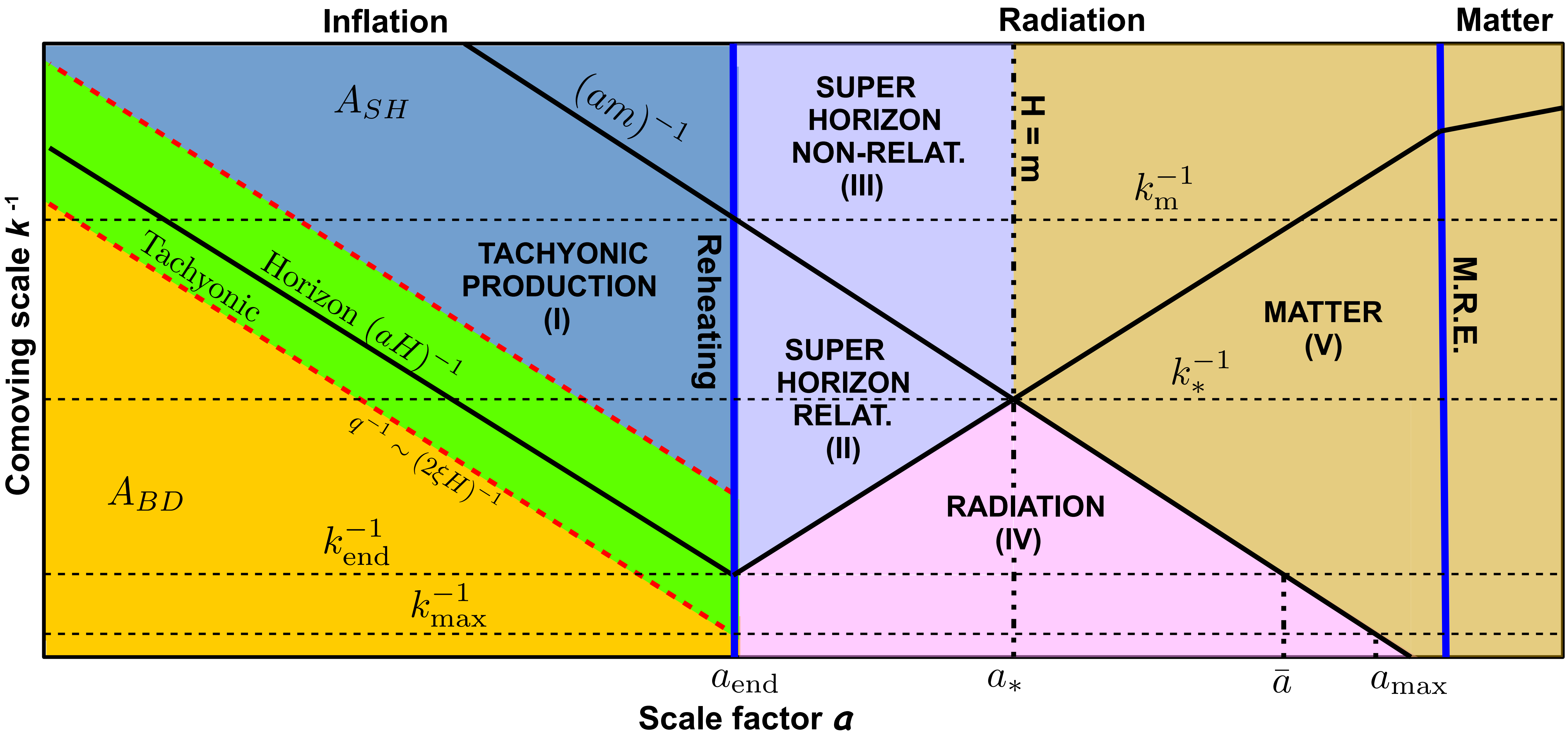
Graham, Mardon, Rajendran 1504.02102

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.



$\epsilon_H = 10^{-1}, \epsilon_R = 10^{-1}$
no tachyonic production
$\xi_{end} = 3$
Transverse, $\xi_{end} = 6$
$\xi_{end} = 9$
Longitudinal
relativistic at CMB
$\mathrm{Log}_{10}\frac{m}{\mathrm{GeV}}$
$\mathrm{Log}_{10}\frac{H}{\mathrm{GeV}}$
$\epsilon_H = 10^{-1}, \epsilon_R = 10^{-5}$
no tachyonic production
$\xi_{end} = 3$
$\xi_{end} = 6$
relativistic at CMB
$\mathrm{Log}_{10}\frac{m}{\mathrm{GeV}}$
$\mathrm{Log}_{10}\frac{H}{\mathrm{GeV}}$



$$k_{end} = a_{end} H_{end}$$

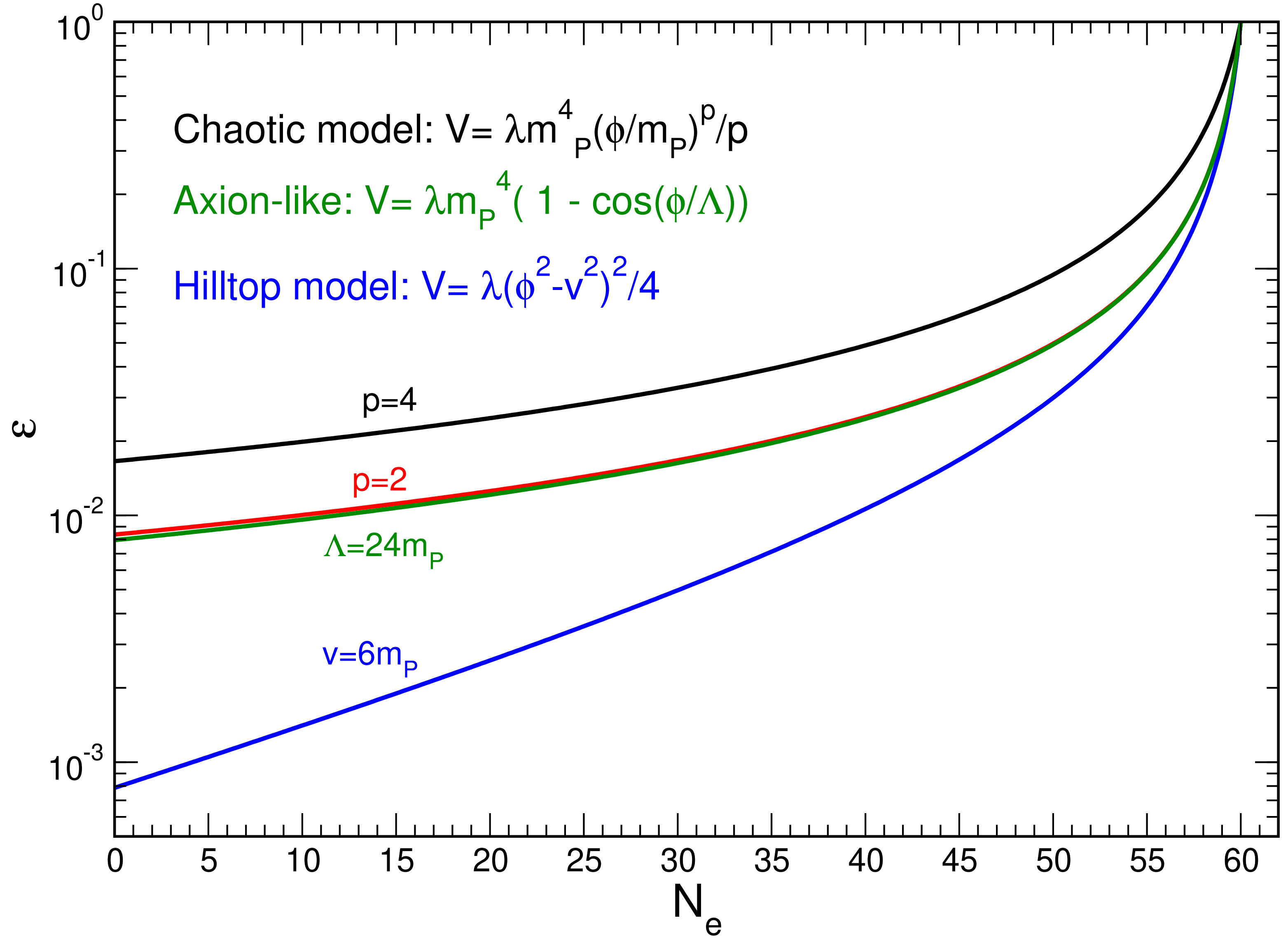
$$\frac{k_m}{k_{end}} = \frac{m}{H_{end}}$$

$$\frac{k_{max}}{k_{end}} = 2\xi_{end} + \mathcal{O}\left(\frac{m^2}{H_{end}^2}\right)$$

$$\frac{k_*}{k_{end}} = \sqrt{\frac{m}{H_{end}}}$$

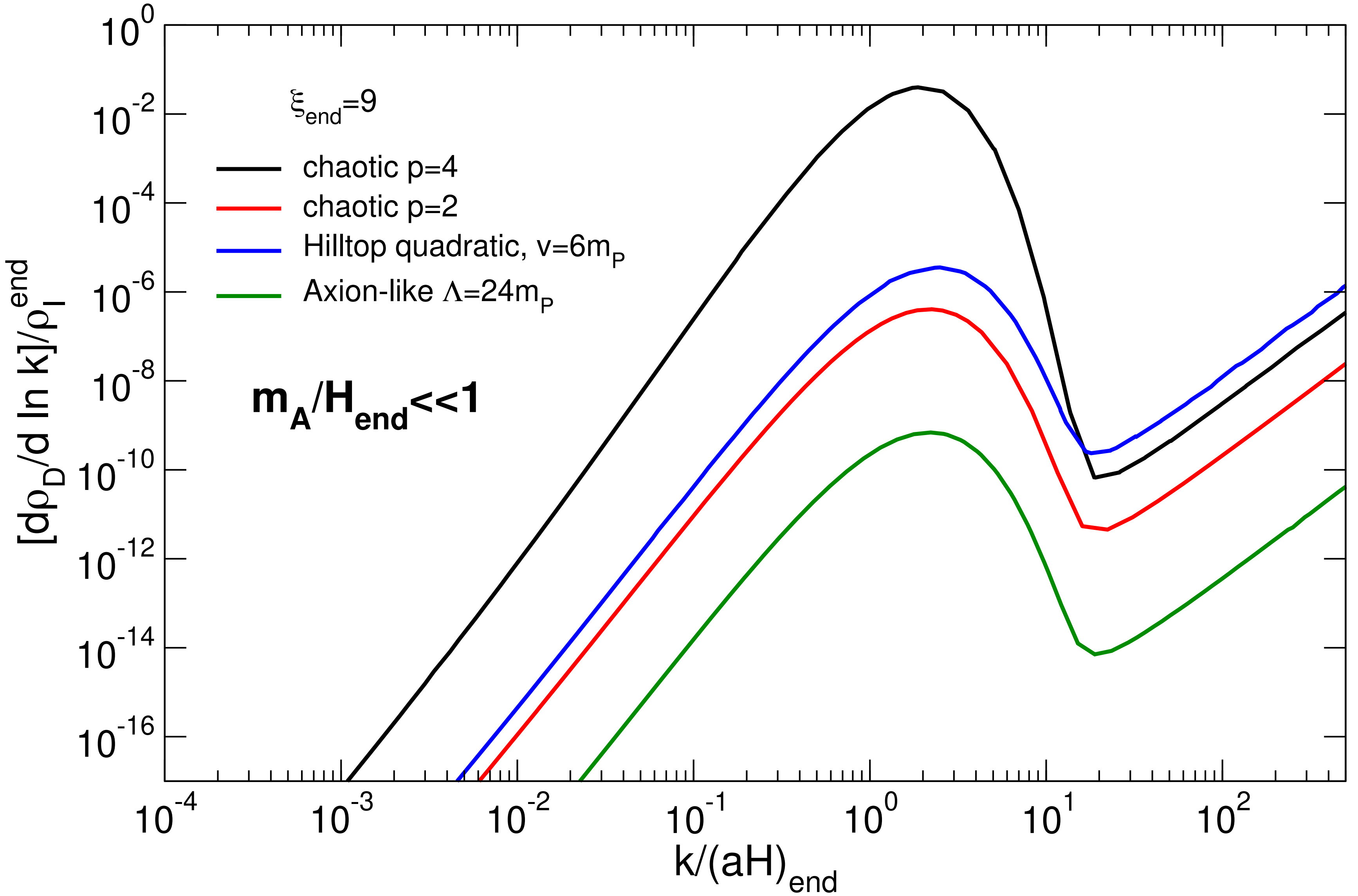
The inflaton speed is not constant

$$\varepsilon = -\frac{\dot{H}}{H^2}$$



The energy density spectrum

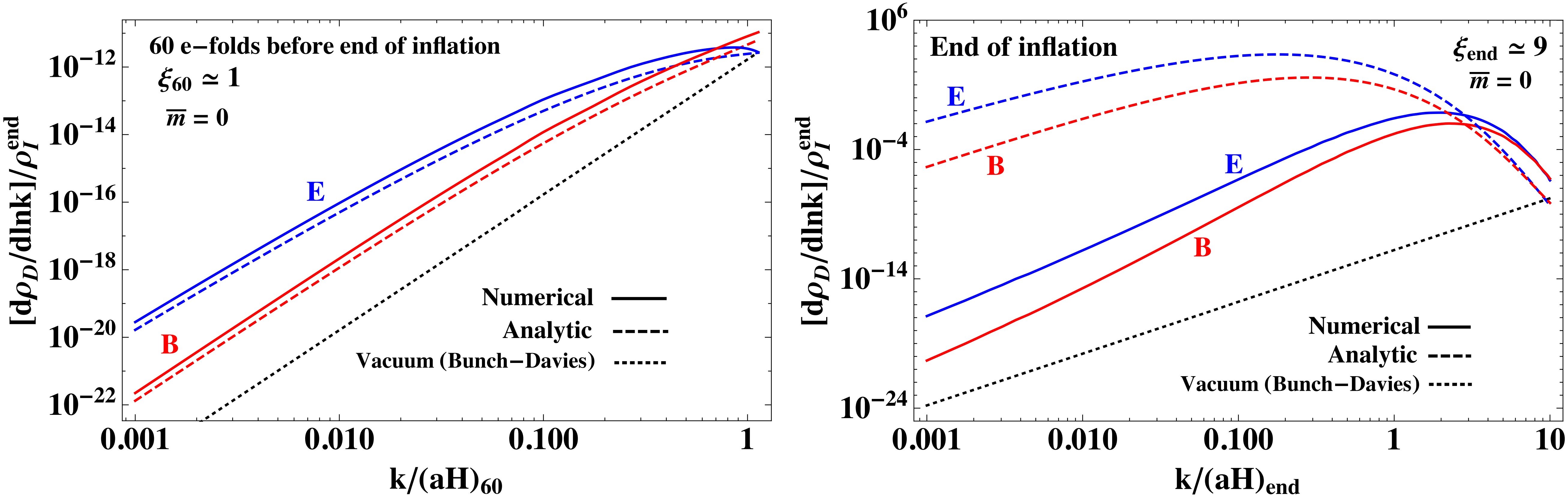
$$\frac{d\rho_D}{d\ln k} = \frac{1}{2a^4}\frac{k^3}{2\pi^2}\left(|\partial_\tau A_+(k,\tau)|^2 + (k^2 + a^2 m^2)|A_+(k,\tau)|^2\right)$$



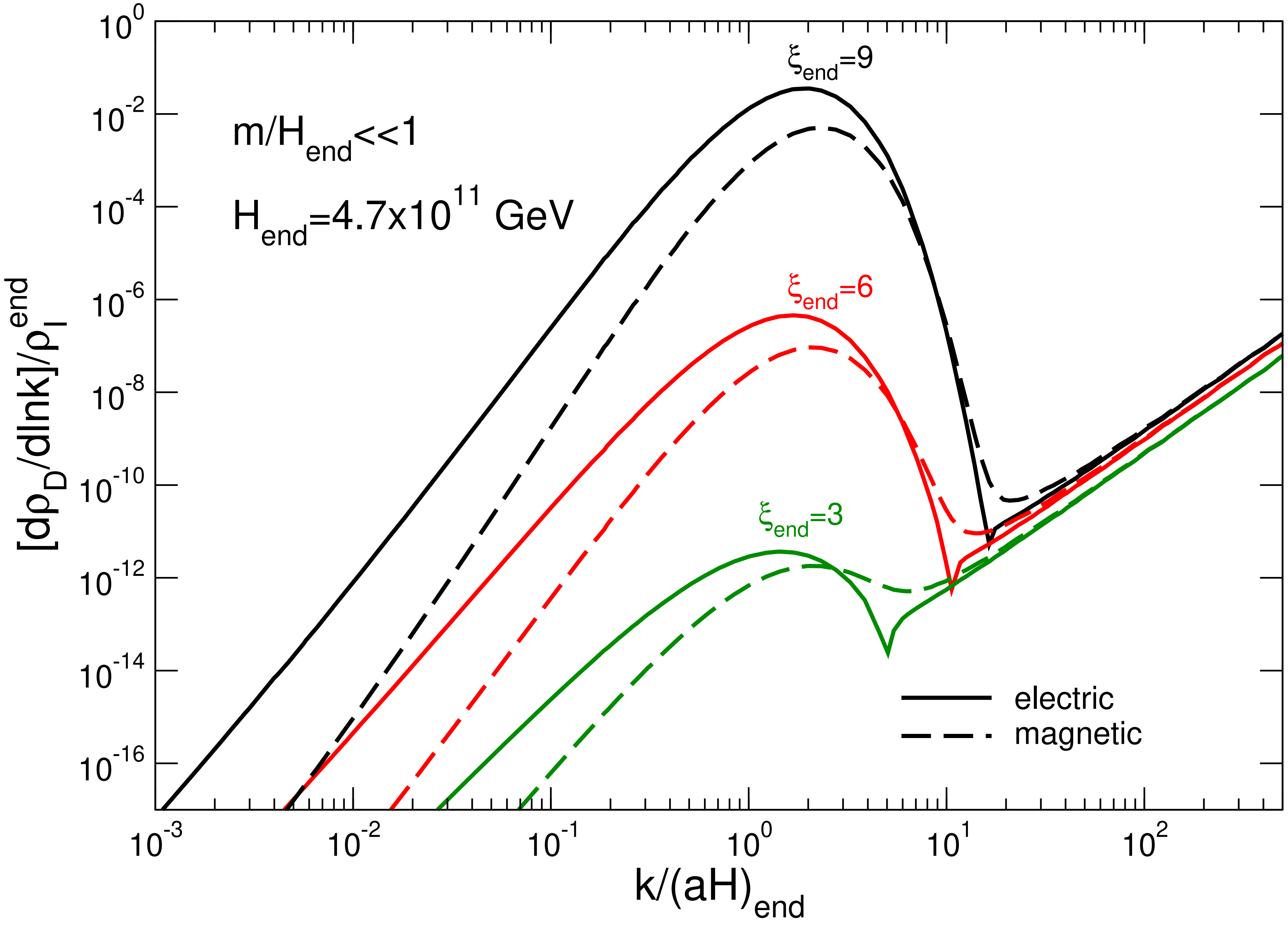
$$\mathcal{P}_X(k,\tau) = \frac{k^3}{2\pi^2}|X(k,\tau)|^2 \qquad X = A_+ \text{ or } \partial_\tau A_+$$

$$\frac{d\rho_E}{d\ln k} = \frac{1}{2a^4}\mathcal{P}_{\partial_\tau A_+}(k,\tau), \qquad \frac{d\rho_B}{d\ln k} = \frac{1}{2a^4}(k^2 + a^2 m^2)\mathcal{P}_{A_+}(k,\tau)$$

electric magnetic

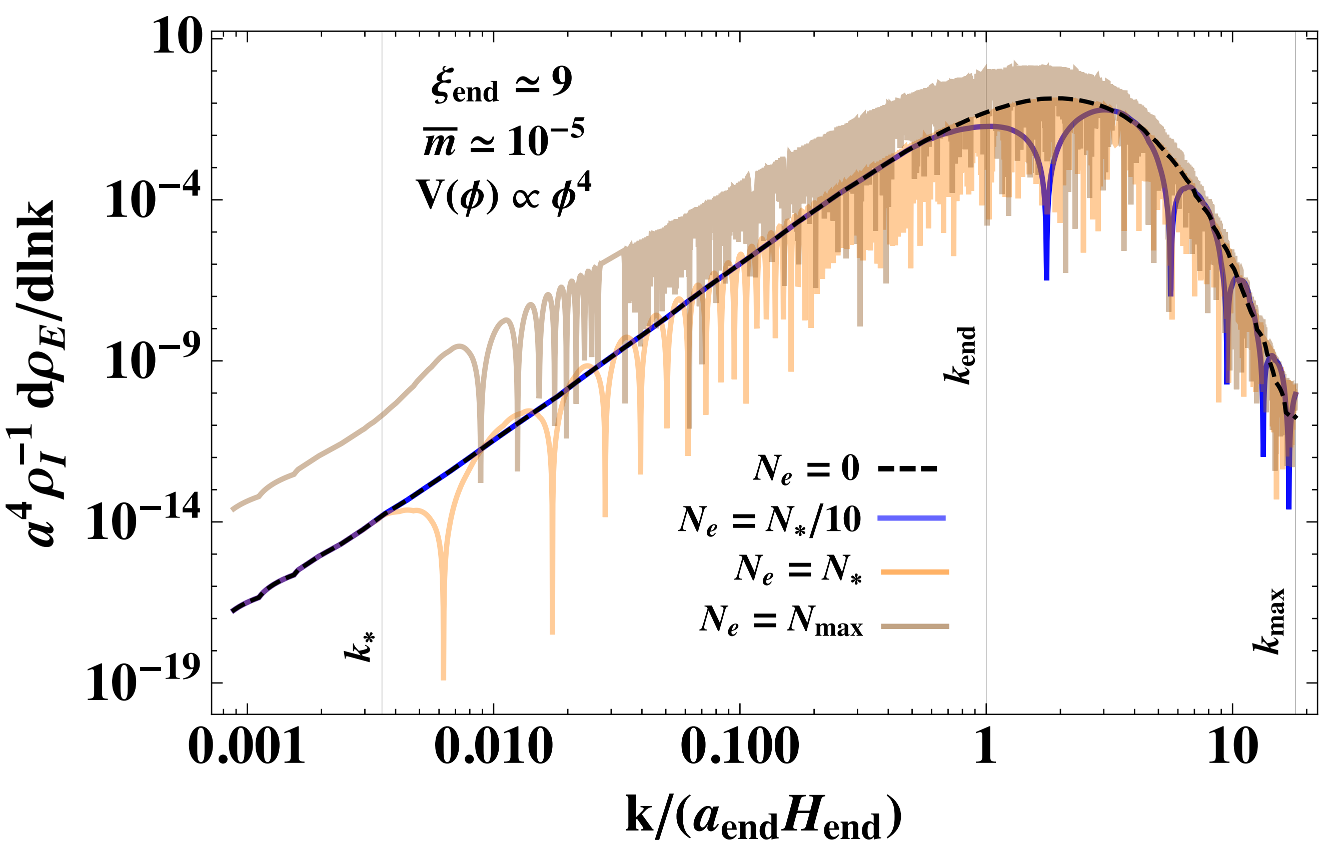


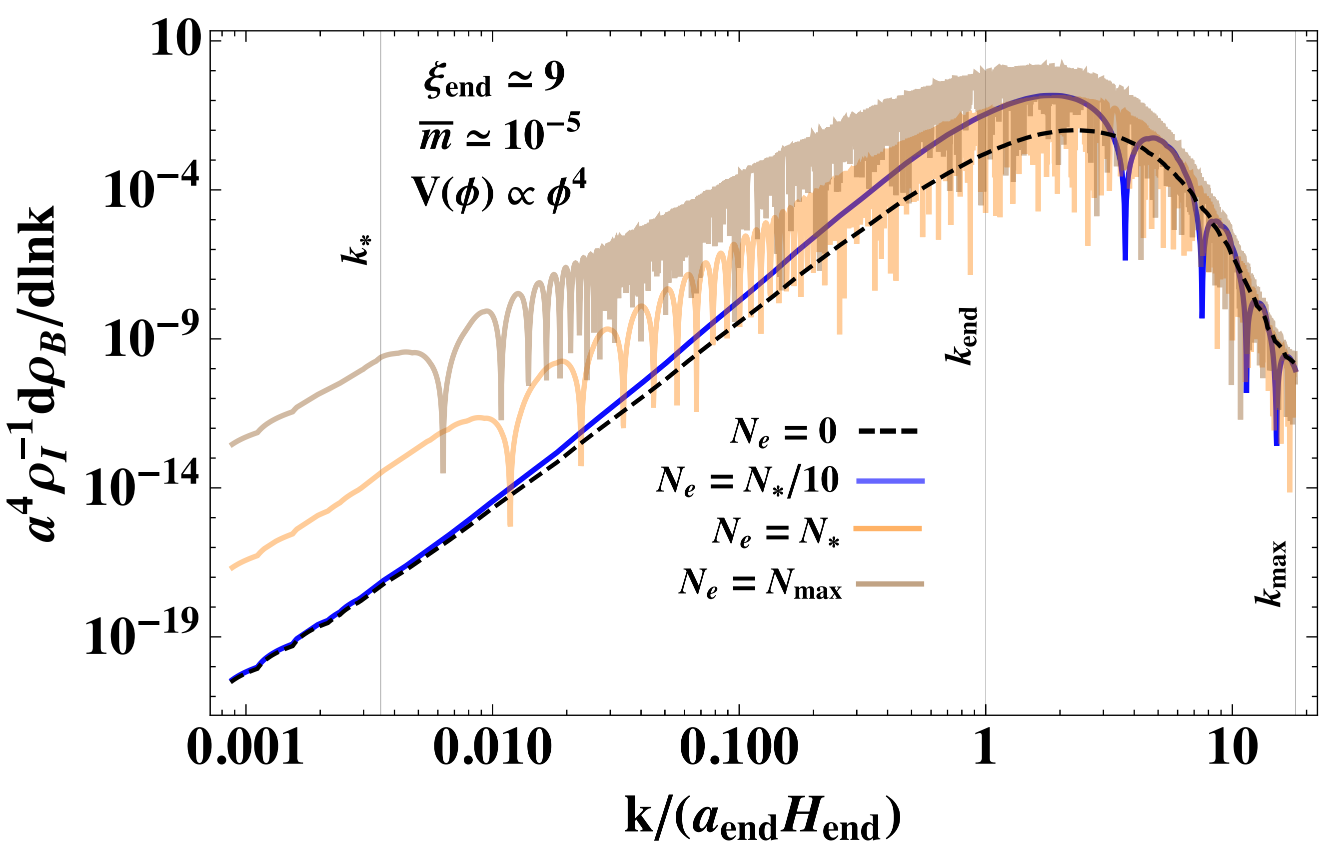
$$\xi \equiv \frac{\alpha\dot{\phi}}{2Hf} > 0$$

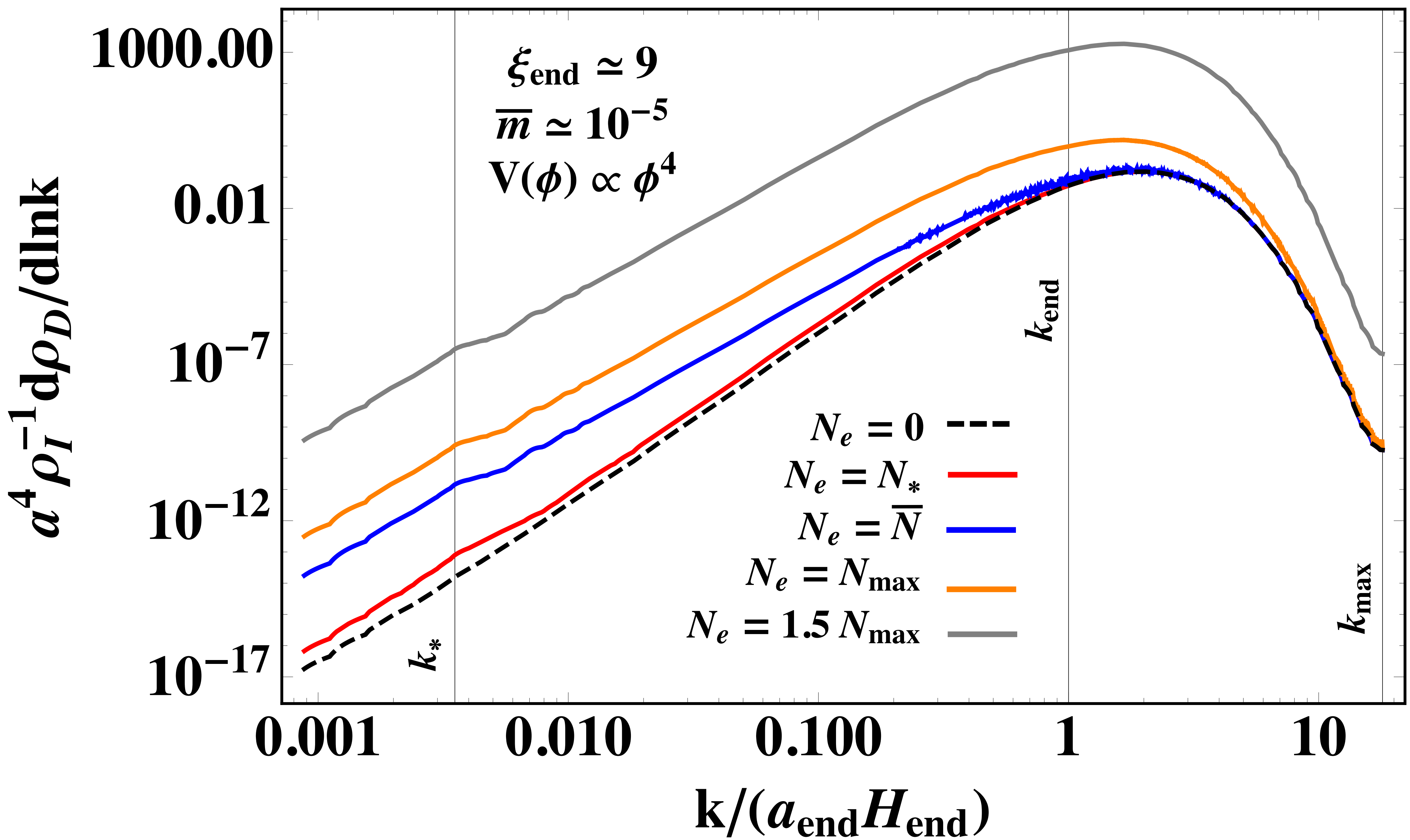


m/H_end<<1
H_end=4.7x10^11 GeV
ξ_end=9
ξ_end=6
ξ_end=3
electric
magnetic
[dρ_D/dlnk]/ρ_I^end
k/(aH)_end

Evolution of the power spectrum



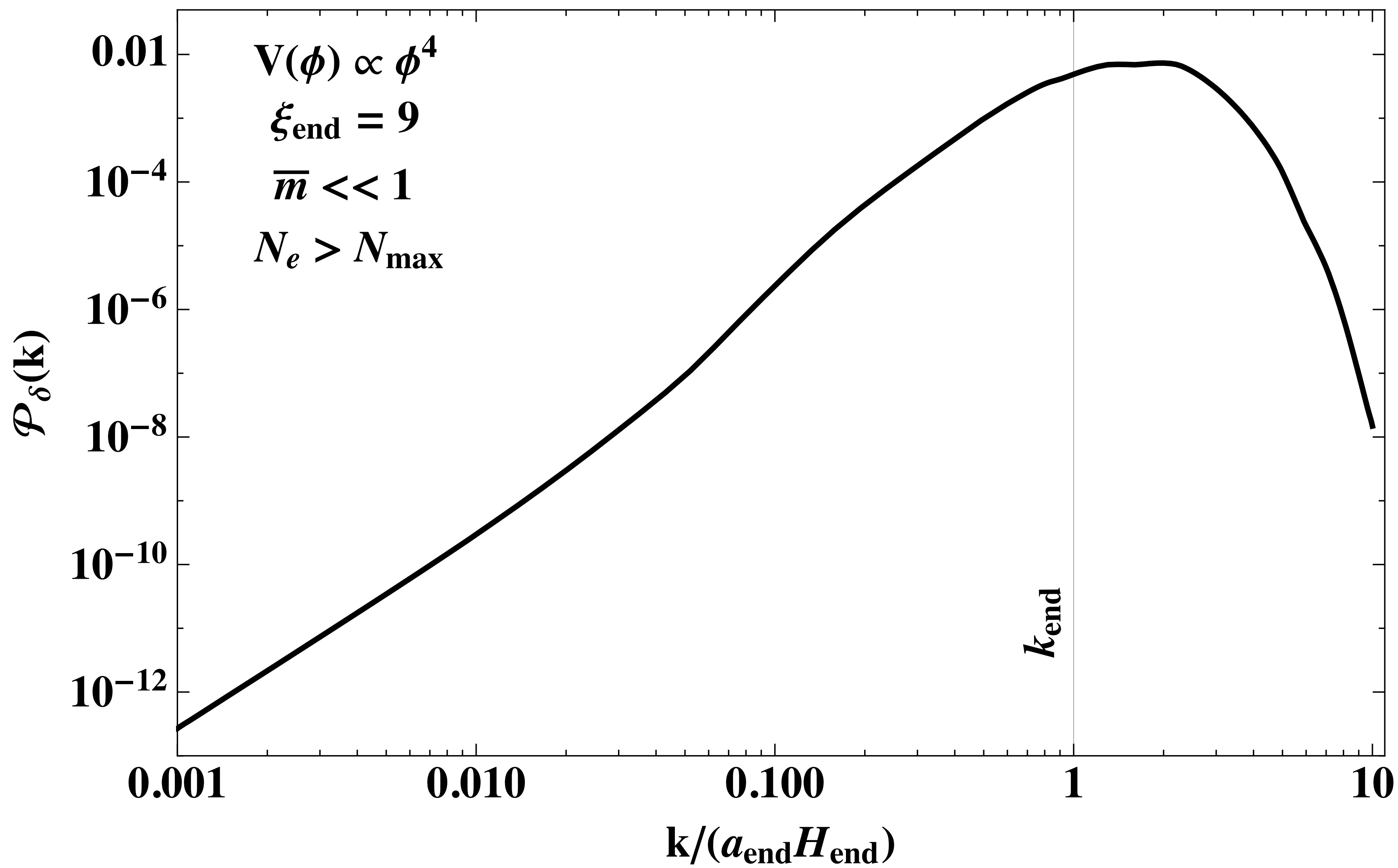



$\xi_{\rm end} \simeq 9$
$\overline{m} \simeq 10^{-5}$
$V(\phi) \propto \phi^4$
$a^4 \rho_I^{-1} d\rho_D/d\ln k$
1000.00
0.01
10^{-7}
10^{-12}
10^{-17}
k_*
$k_{\rm end}$
$k_{\rm max}$
$N_e = 0$
$N_e = N_*$
$N_e = \overline{N}$
$N_e = N_{\rm max}$
$N_e = 1.5\, N_{\rm max}$
0.001
0.010
0.100
1
10
$k/(a_{\rm end} H_{\rm end})$

Density contrast power spectrum

$$\rho(\vec{x}) = \langle\rho\rangle(1+\delta(\vec{x}))$$

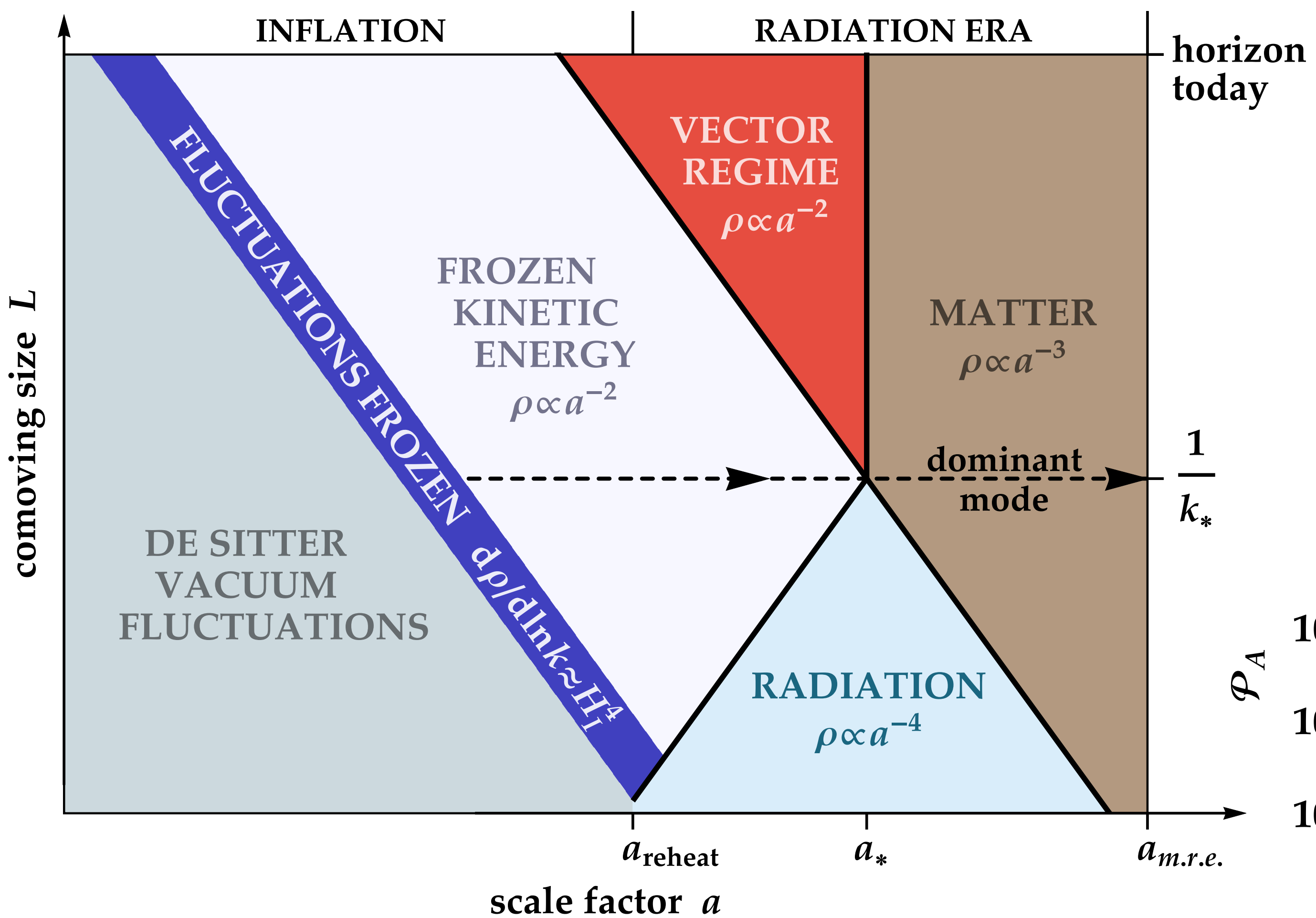
$$\langle\delta(\vec{k})\delta(\vec{k}')\rangle = (2\pi)^3\delta^3(\vec{k}+\vec{k}')\frac{2\pi^2}{k^3}\mathcal{P}_\delta(k)$$



$$k_{\rm end}^{-1} \approx 10\ {\rm km}\ \frac{\epsilon_R}{\epsilon_H}\left(\frac{100\ {\rm GeV}}{H}\right)^{1/2}$$

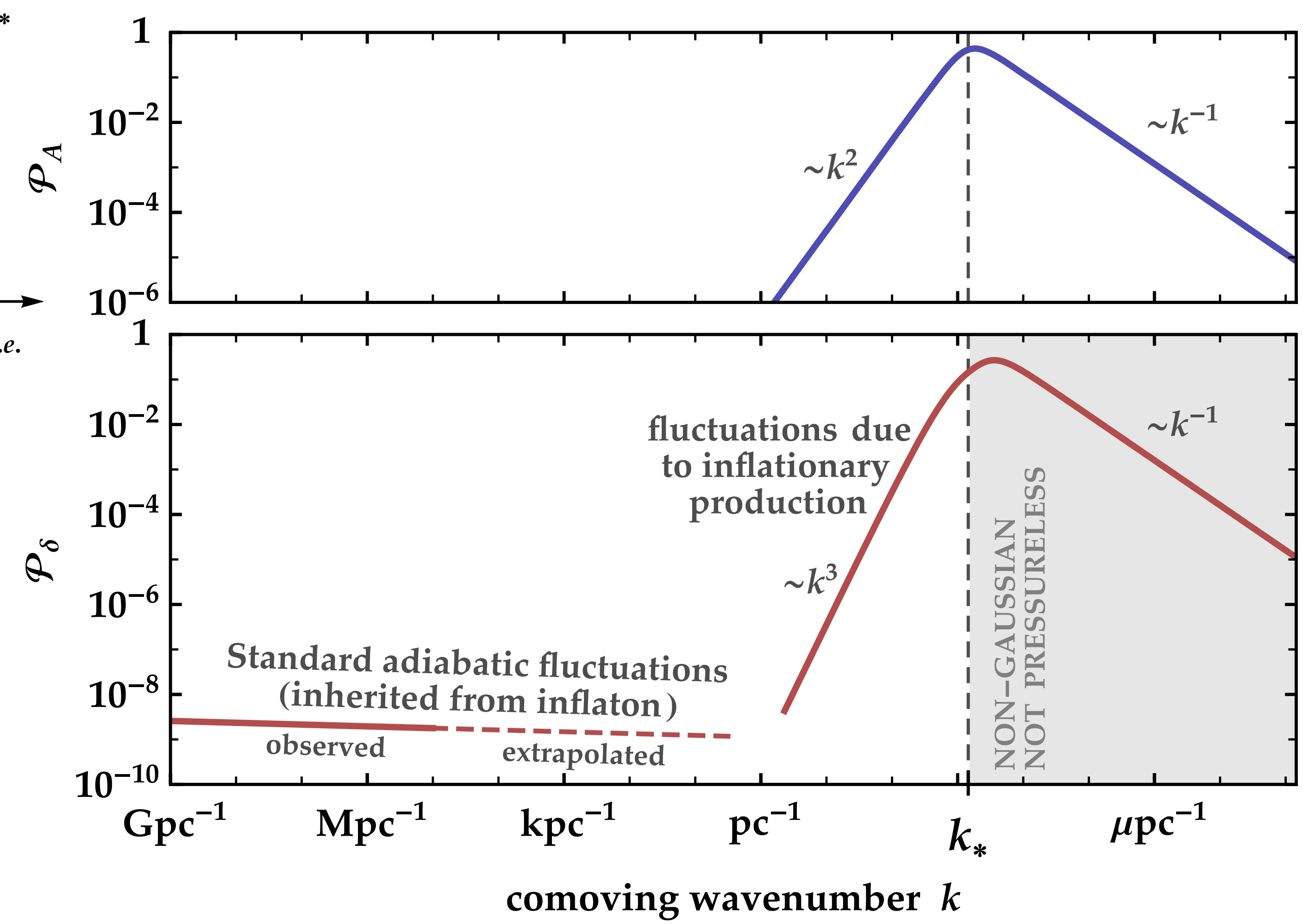
The longitudinal mode

GRAHAM, MARDON, and RAJENDRAN



$$k_*^{-1} \approx 10^{10}\ \text{km}\ \sqrt{\frac{10^{-5}\ \text{eV}}{m}}$$

Graham, Mardon, Rajendran 1504.02102



Conclusions

- I have presented a non-thermal mechanism for producing dark photon dark matter
- Large regions of parameter space available, several decades in mass and Hubble scale of inflation
- This dark matter candidate clumps at scales much smaller than those probed by CMB

Outlook

- Clumpy nature: Implications for structure formation? Opportunities for indirect detection?
- Turn on a SMALL kinetic mixing with the visible photon: Opportunities for direct detection?