Dark photon dark matter from inflation

Lorenzo Ubaldi
Jožef Stefan Institut, Ljubljana

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

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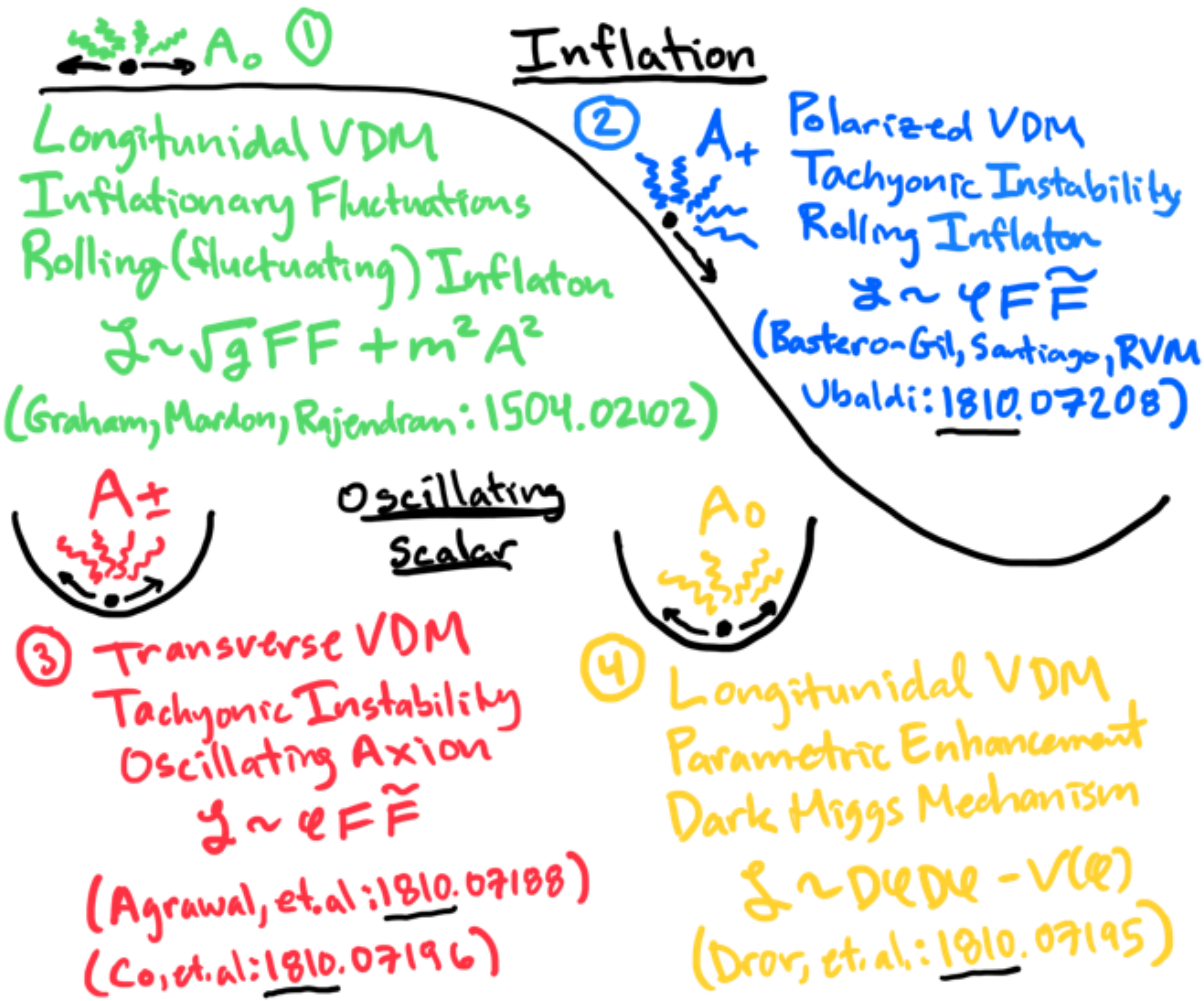
Field content

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

ϕ	inflaton
A_μ	dark photon



VDM = Vector Dark Matter = Dark Photon Dark Matter

Equations of motion

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

no back reaction on the inflaton

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

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

Tachyonic growth

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

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

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

$\omega_+^2 < 0$ 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

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

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

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

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

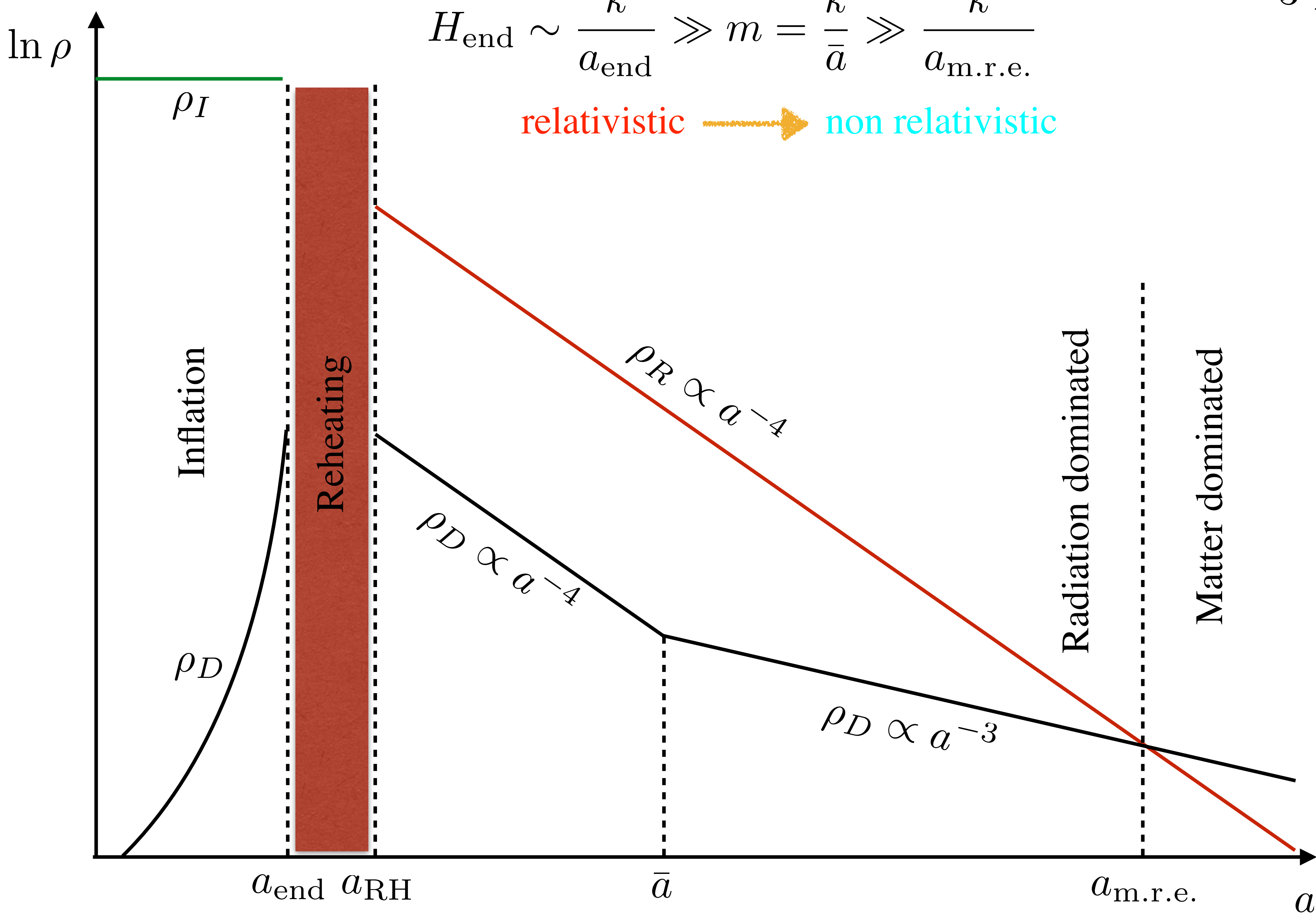
Evolution of the energy densities

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

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

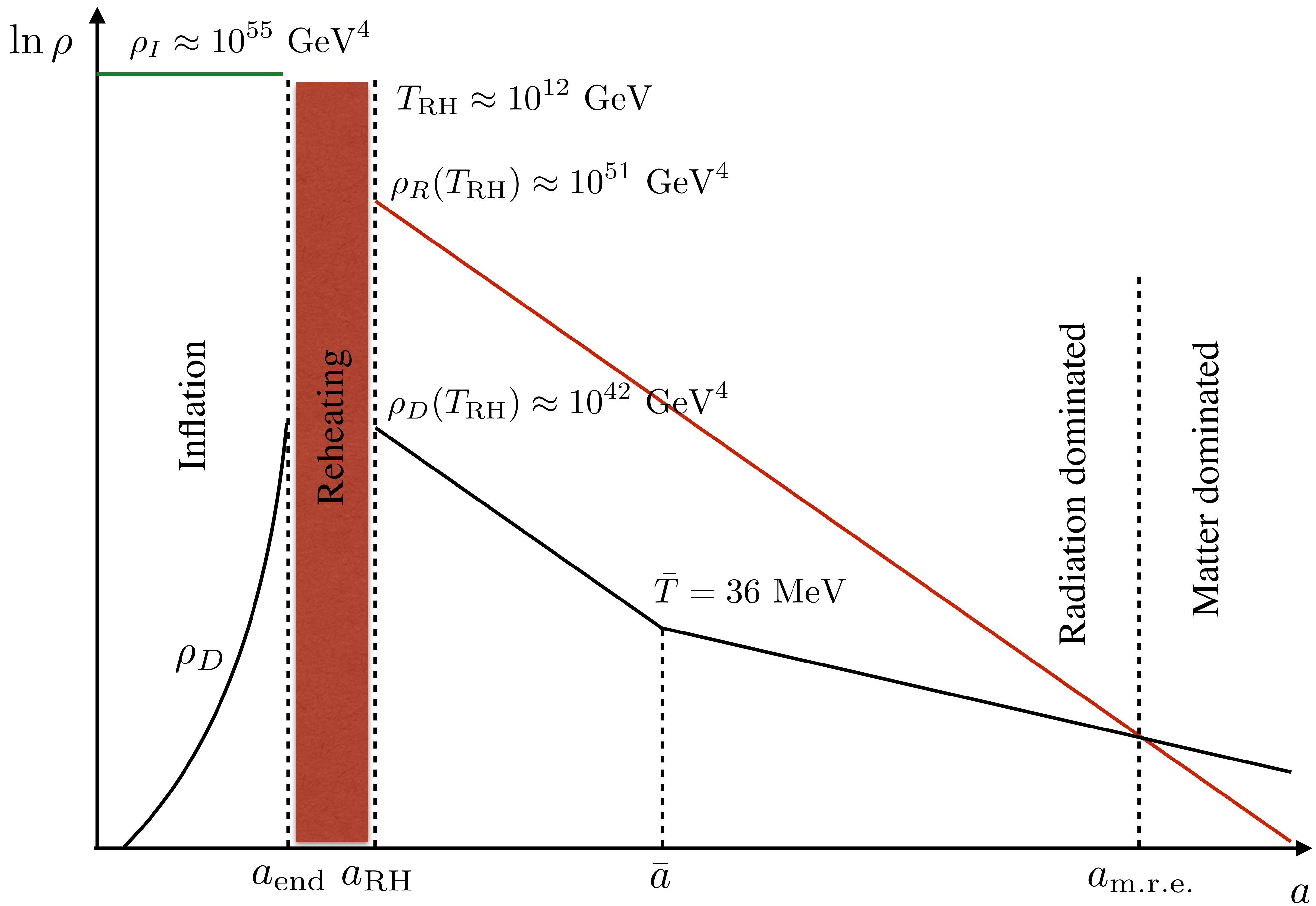
$$H_{\rm end} \sim \frac{k}{a_{\rm end}} \gg m = \frac{k}{\bar{a}} \gg \frac{k}{a_{\rm m.r.e.}}$$

relativistic → non relativistic



A benchmark

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



Relic abundance

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

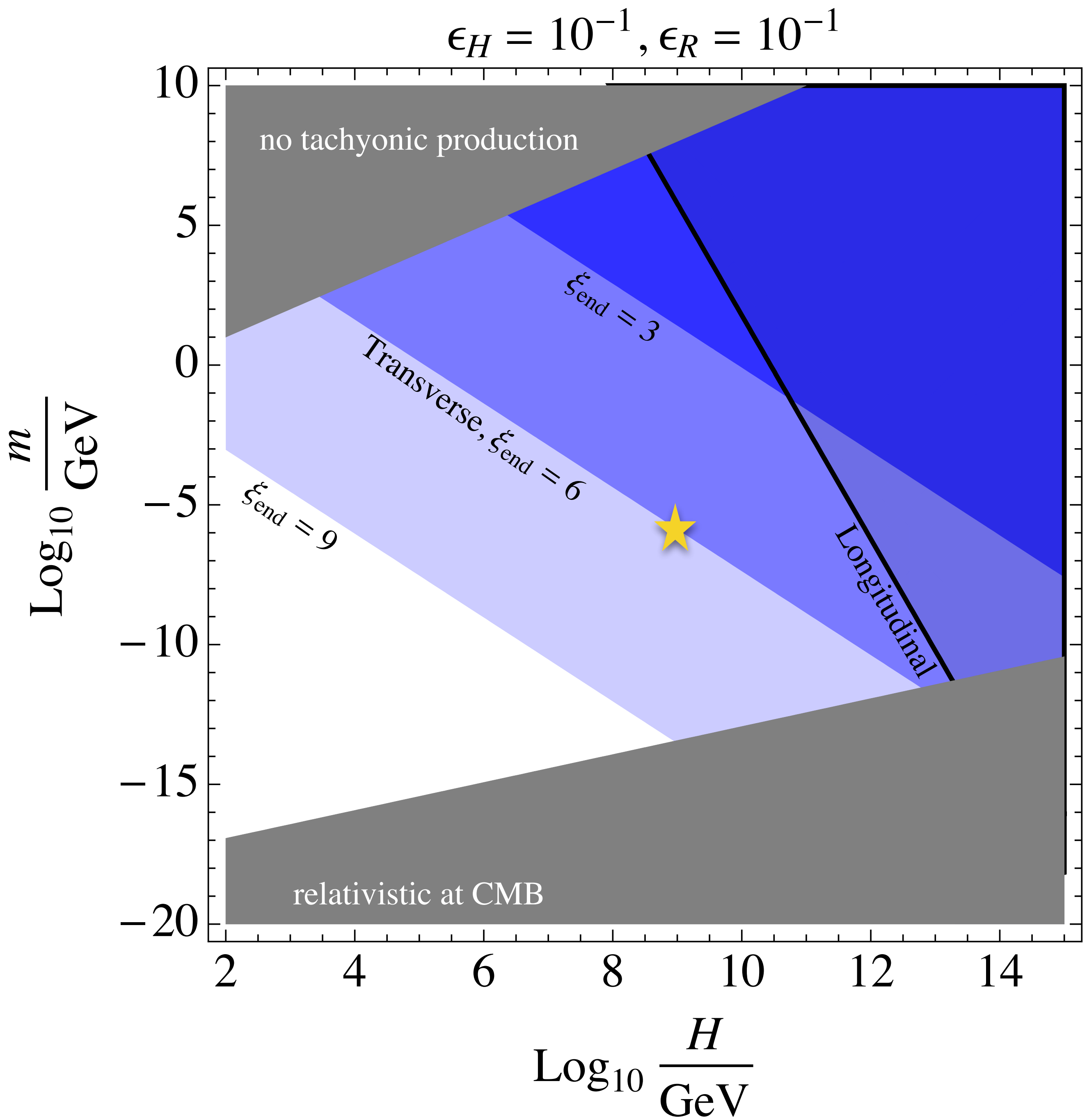
$$\Omega_{\rm CDM}h^2 = 0.12$$

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

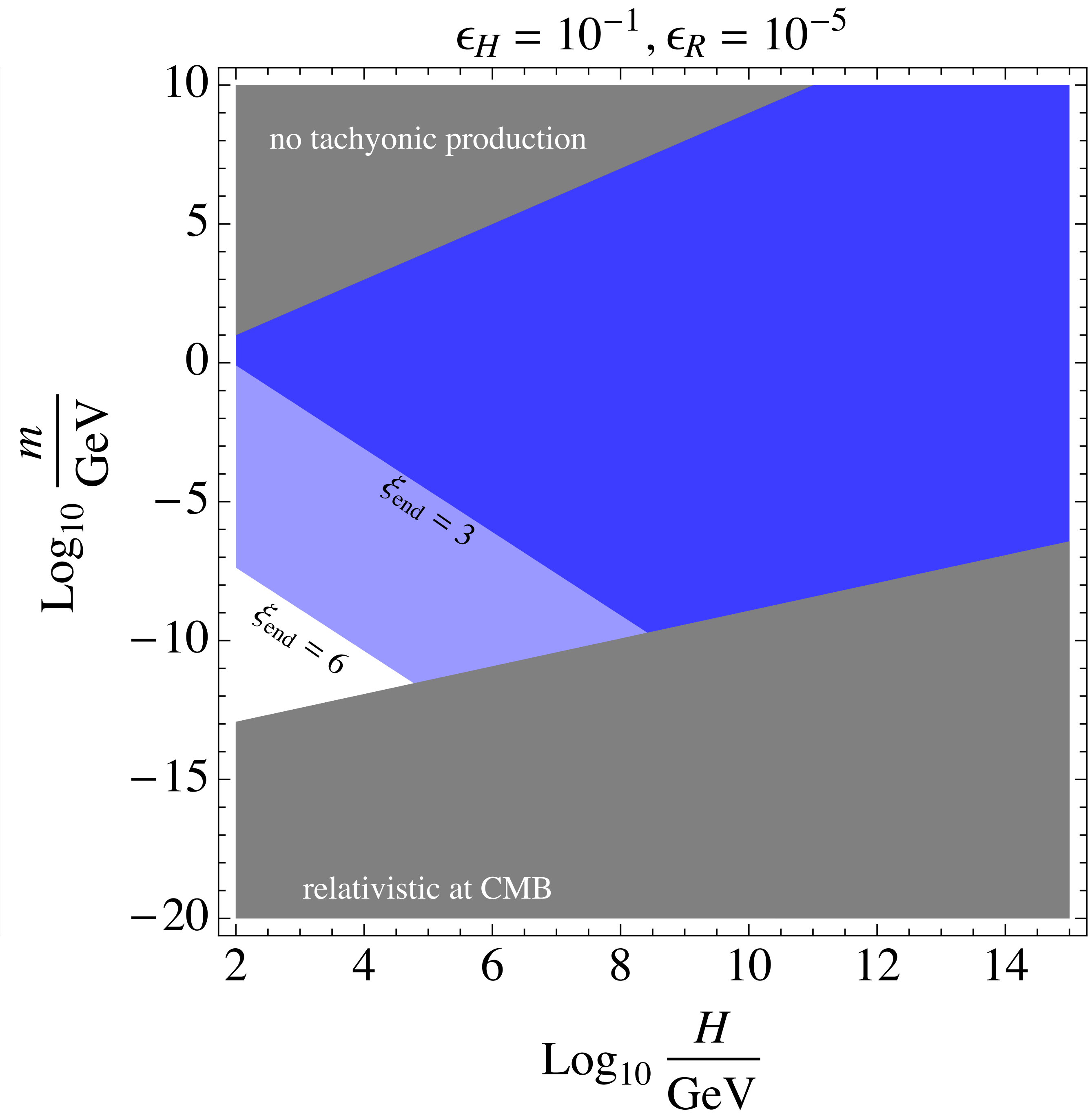
Graham, Mardon, Rajendran 1504.02102

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.

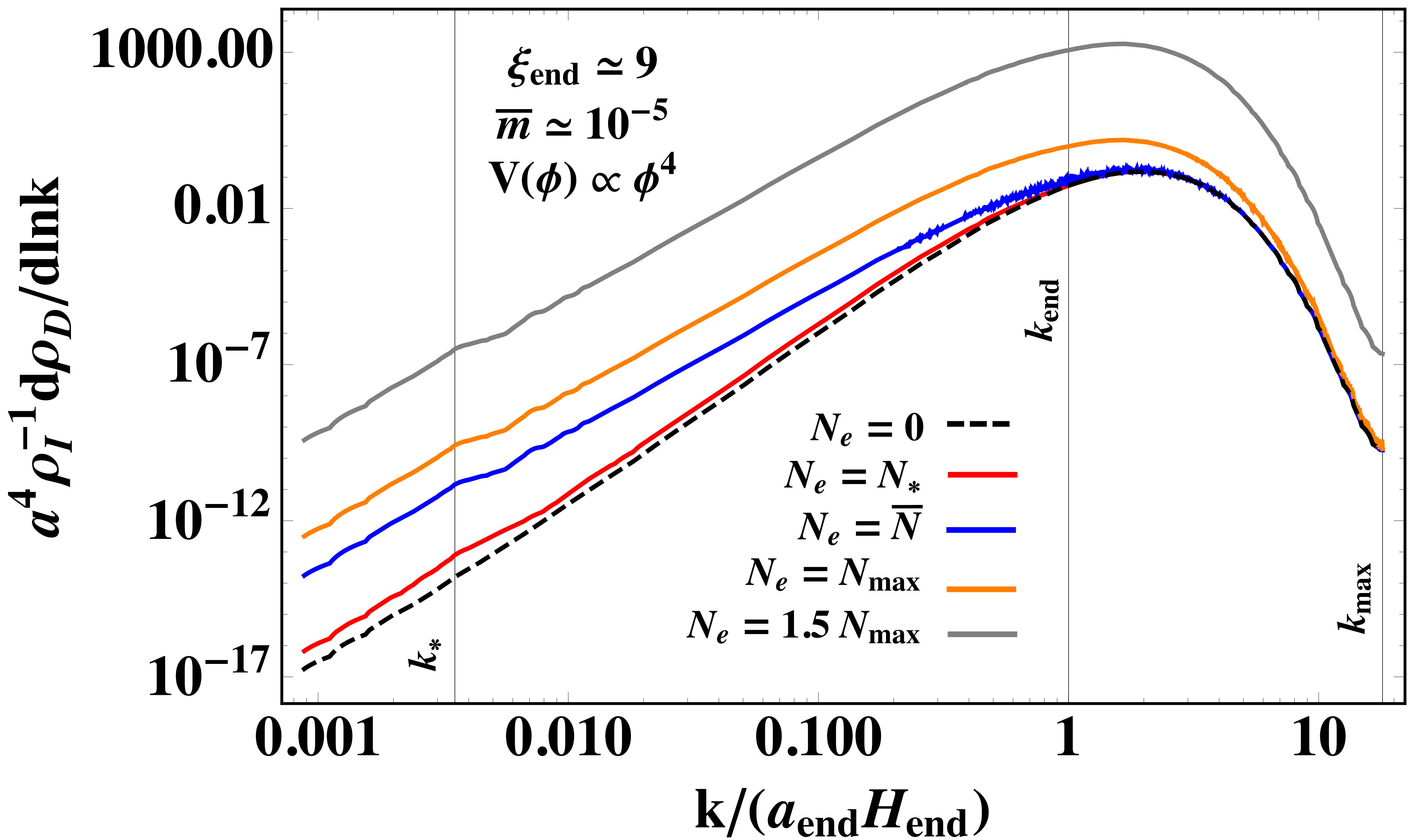


$\epsilon_H = 10^{-1}, \epsilon_R = 10^{-1}$
no tachyonic production
$\xi_{\rm end} = 3$
Transverse, $\xi_{\rm end} = 6$
$\xi_{\rm end} = 9$
Longitudinal
relativistic at CMB
$\mathrm{Log}_{10}\,\frac{m}{\mathrm{GeV}}$
$\mathrm{Log}_{10}\,\frac{H}{\mathrm{GeV}}$



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

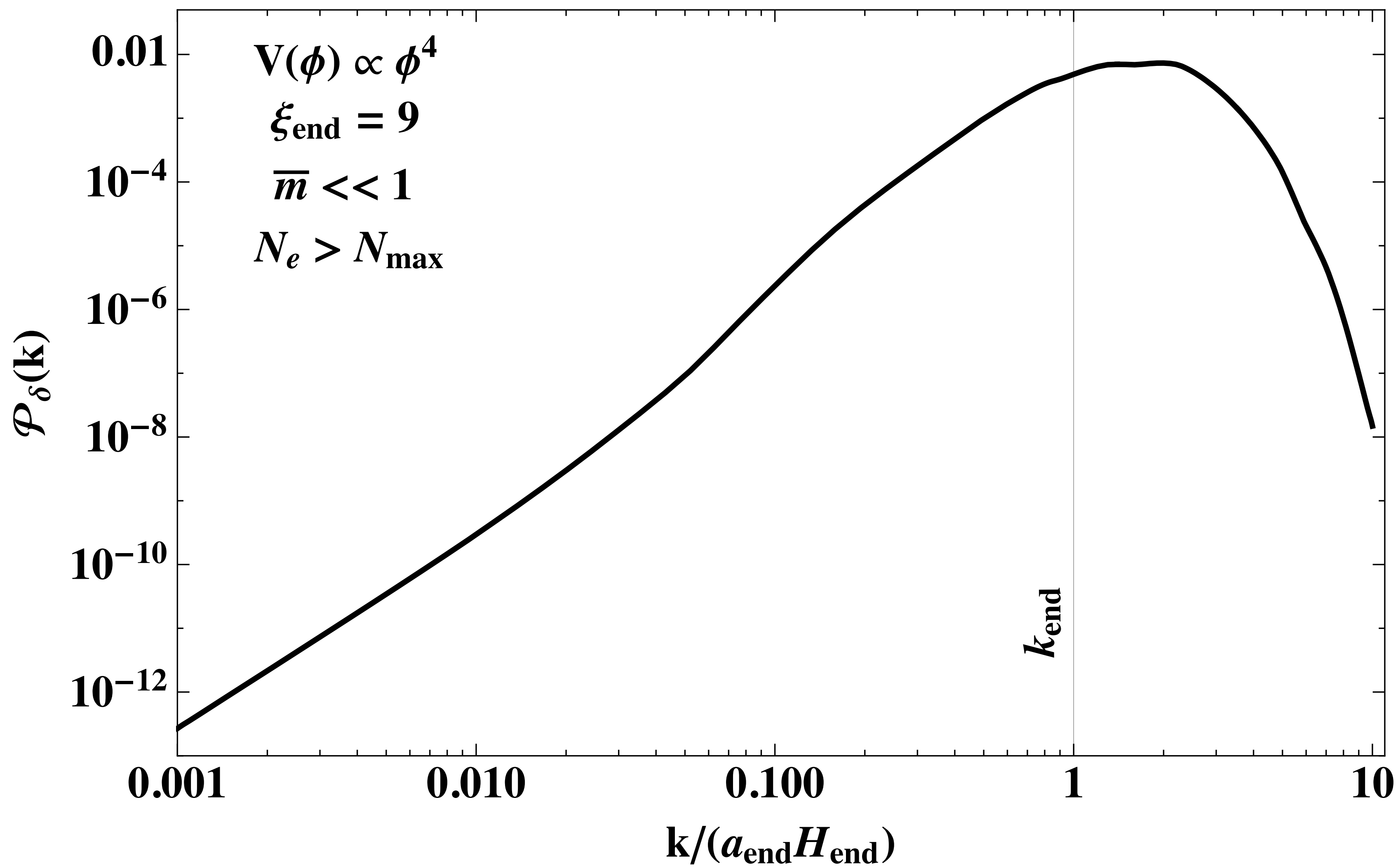
Evolution of the power spectrum



Density contrast power spectrum

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

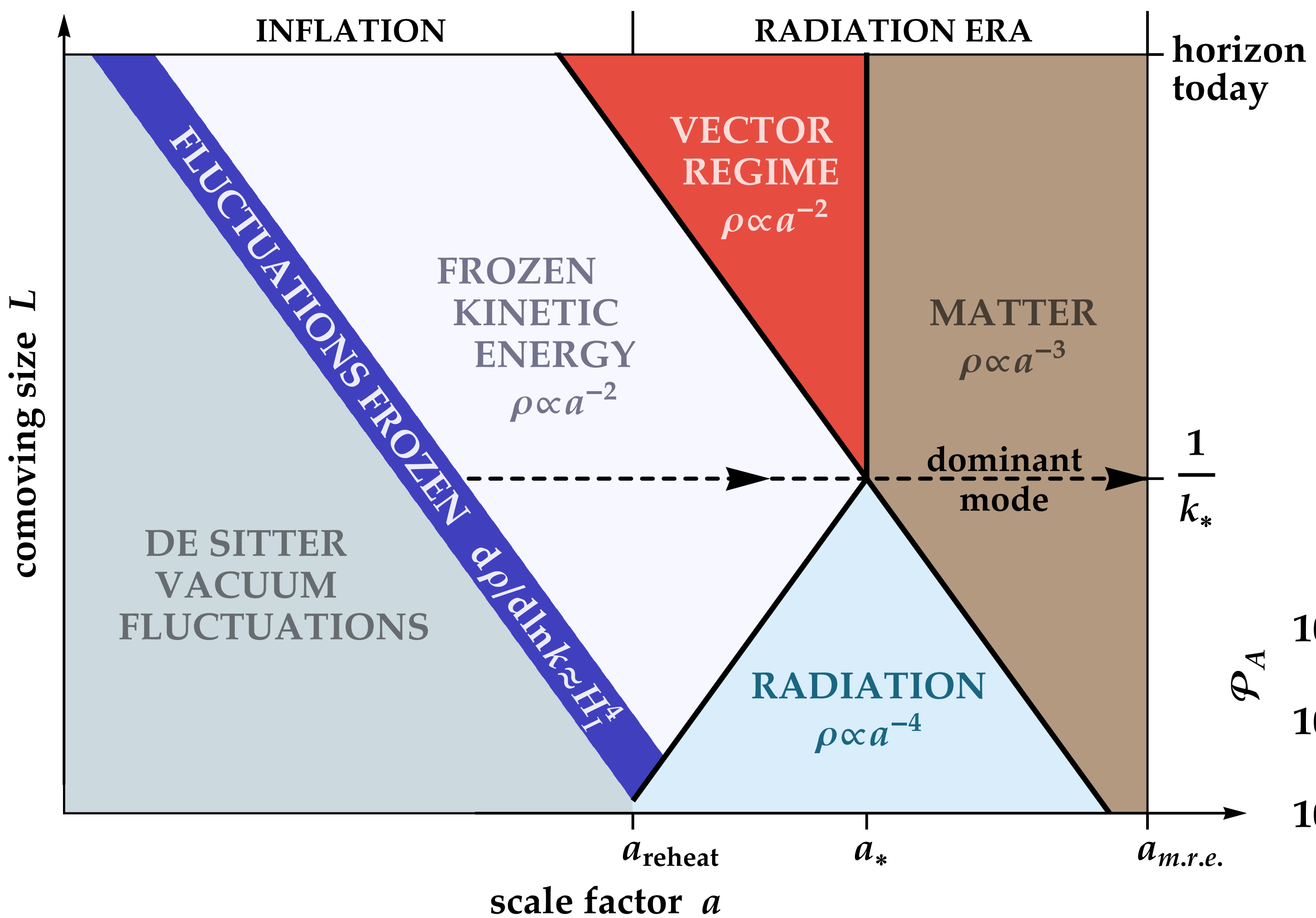
$$\langle\delta(\vec{k})\delta(\vec{k}')\rangle = (2\pi)^3\delta^3(\vec{k}+\vec{k}')\frac{2\pi^2}{k^3}\mathcal{P}_\delta(k)$$



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

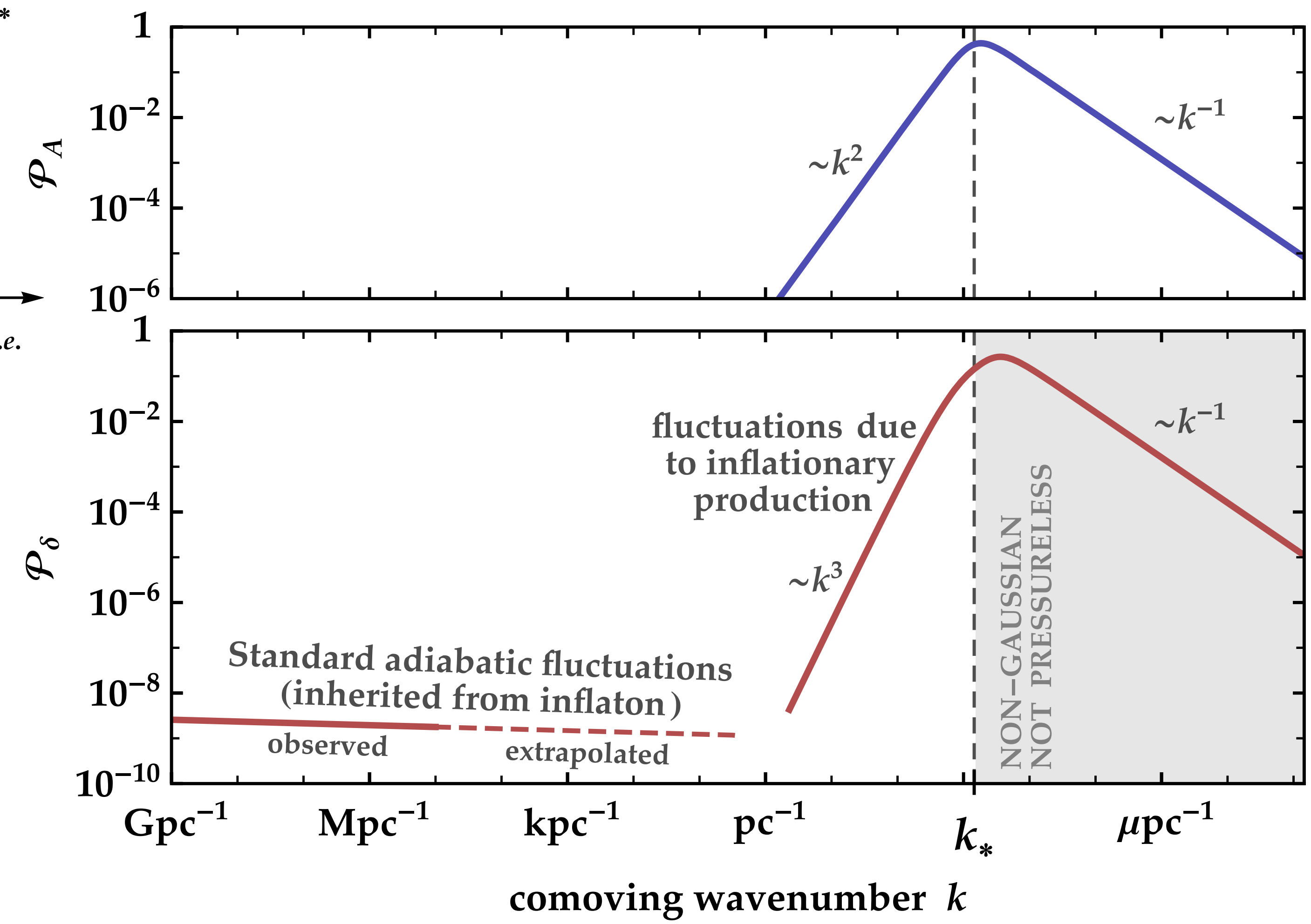
The longitudinal mode

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