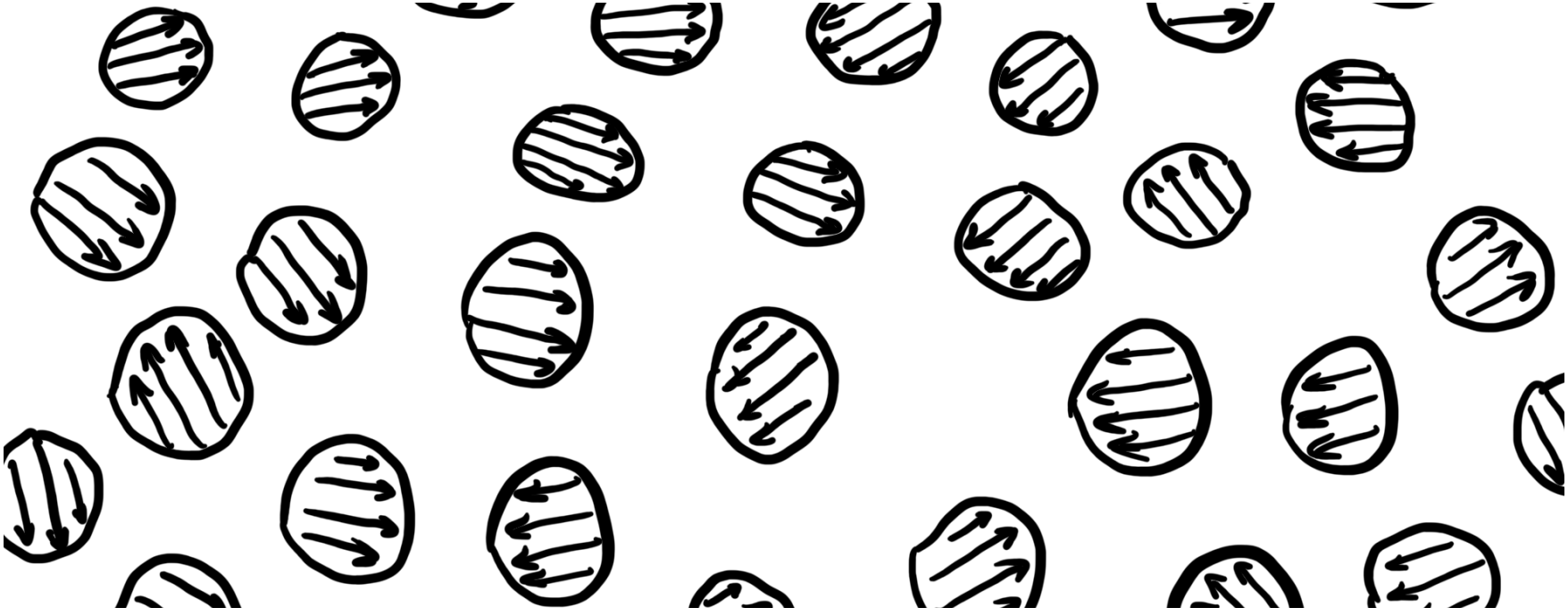
Clumpy Polarized Vector Dark Matter and the end of inflation



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ZPW2019 Workshop - A New Look at Dark Matter

University of Zurich, January 9, 2019

Mar Bastero-Gil, Jose Santiago, Lorenzo Ubaldi, RVM: 1810.07208 + ongoing

Overview

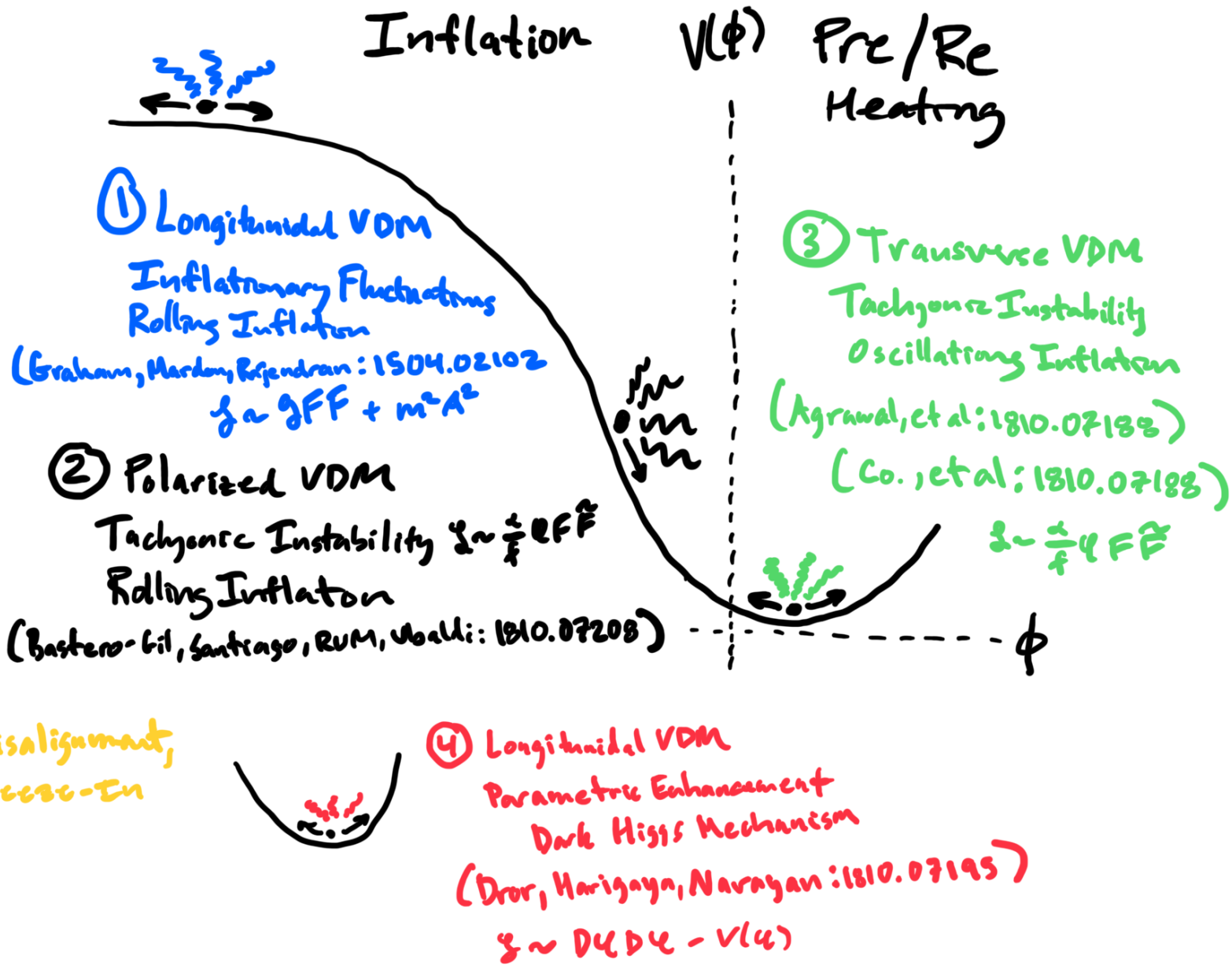
- Context and motivation
- Polarized VDM production
- Energy density spectrum
- Ongoing/Future directions
- Summary and Conclusions

Vector Dark Matter (VDM) Models & Pheno

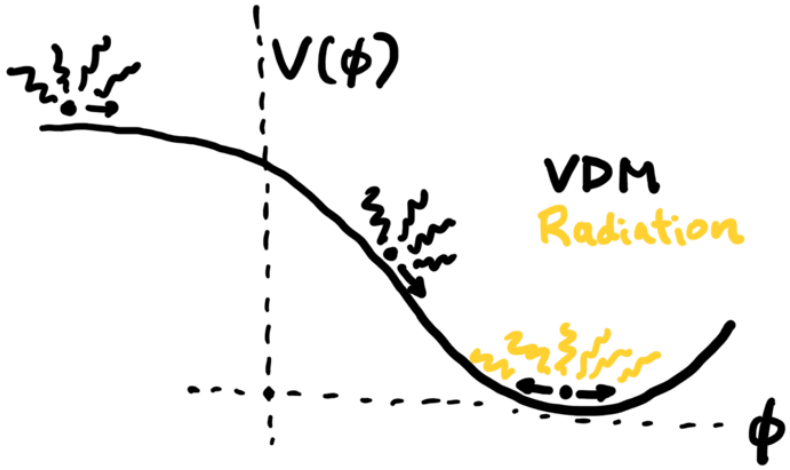
- VDM an exciting topic due to recent progress
- Interesting for pheno reasons: dark photon experiments, indirect/direct detection, lensing, GWs, super radiance, etc.
- Can appear in many models: pseudo scalar inflation, QCD axion mechanisms, dark Gauge/Higgs sectors, relaxions
- (So far) generically five VDM production mechanisms:
  - freeze-in: 0811.0326
  - mis-alignement: 1105.2812, 1201.5902
  - parametric enhancement: 1810.07195
  - inflationary fluctuations: 1504.02102
  - tachyonic instability: 1810.07196, 1810.07195, 1810.07208
- Tachyonic instability well studied in many contexts

(axion inflation, dissipation in inflation and relaxion mechanisms, primordial magnetic fields, baryo/lepto genesis, chiral gravitational waves during inflation, preheating, decreasing abundance of QCD axion DM)

Recent VDM Production Mechanisms



Clumpy Polarized Vector DM Production



The coupling $\phi F\tilde{F}$ leads to a tachyonic instability and exponential production of one transverse polarization

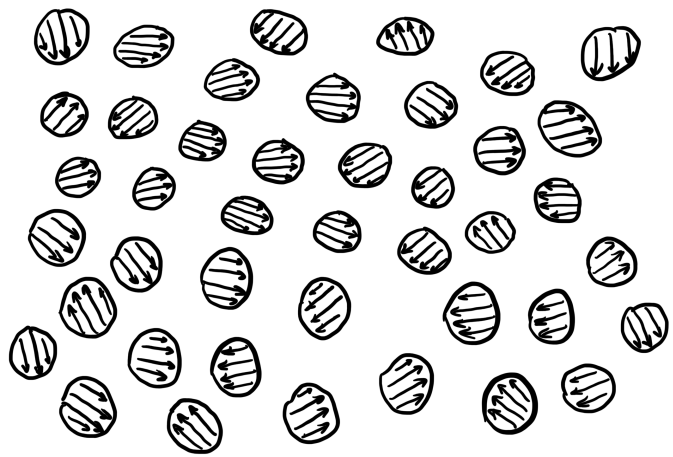
Reaches its maximum near the end of inflation

Inflaton decays perturbitavely into radiation $\Rightarrow$ reheating

Can account for observed DM for masses $\sim 10^{-15} - 10^{6}\,\mathrm{GeV}$

This mechanism naturally leads to various novel features:

- Energy density spectrum contains information on inflaton potential
- Typical scale at which VDM 'clumps' directly tied to scale at end of inflation $\Rightarrow$ peak in energy density spectrum
- Only one polarization produced tachyonically during slow roll of inflaton $\Rightarrow$ VDM is polarized



Action and Equations of Motion

Starting point is the action for a (massive or massless) vector boson coupled to the inflaton via a pseudo scalar coupling:

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

(Mass can be Stuckelberg OR Higgsed. Neglect possible $U(1)$ kinetic mixing with hypercharge)

Inflaton potential is generic & defines the Hubble scale: $H = \frac{\sqrt{V(\phi)}}{\sqrt{3}M_{\rm Pl}}$

Gives EOM for inflaton, longitudinal, & transverse VDM modes:

$$\begin{aligned} \ddot{\phi} &+ 3H\dot{\phi} + V' = \frac{\alpha}{f}F\tilde{F} \approx 0, \\ \ddot{A}_\pm &+ H\dot{A}_\pm + \left(\frac{k^2}{a^2} \pm \frac{k}{a}\frac{\alpha\dot{\phi}}{f} + m^2\right)A_\pm = 0\,, \\ \ddot{A}_L &+ \frac{3k^2 + a^2m^2}{k^2 + a^2m^2}H\dot{A}_L + \left(\frac{k^2}{a^2} + m^2\right)A_L = 0 \end{aligned}$$

(P. W. Graham, J. Mardon, S. Rajendran: 1504.02102)

Tachyonic instability during slow roll

Customary to define the tachyonic enhancement parameter:

$$\xi \equiv \frac{\alpha\dot{\phi}}{2Hf} = \sqrt{\frac{\epsilon}{2}}\frac{\alpha}{f}M_{\rm Pl}, \quad \delta\xi = \mathcal{O}(10) \text{ over } 60 \text{ e} - \text{folds}$$

(Increases with increasing $\dot{\phi}$ and decreasing H until end of inflation)

Controls exponential enhancement and related to potential via

$$\epsilon \equiv -\dot{H}/H^2, \quad |\dot{\phi}| \approx V'/3H, \quad \epsilon = \frac{\dot{\phi}^2}{2H^2M_{Pl}^2}$$

Defining $\bar{m} \equiv m/H$ and using $\tau < 0$, $\tau \simeq -\frac{1}{aH}$ during inflation, obtain transverse mode EOM in conformal time ($ad\tau = dt$):

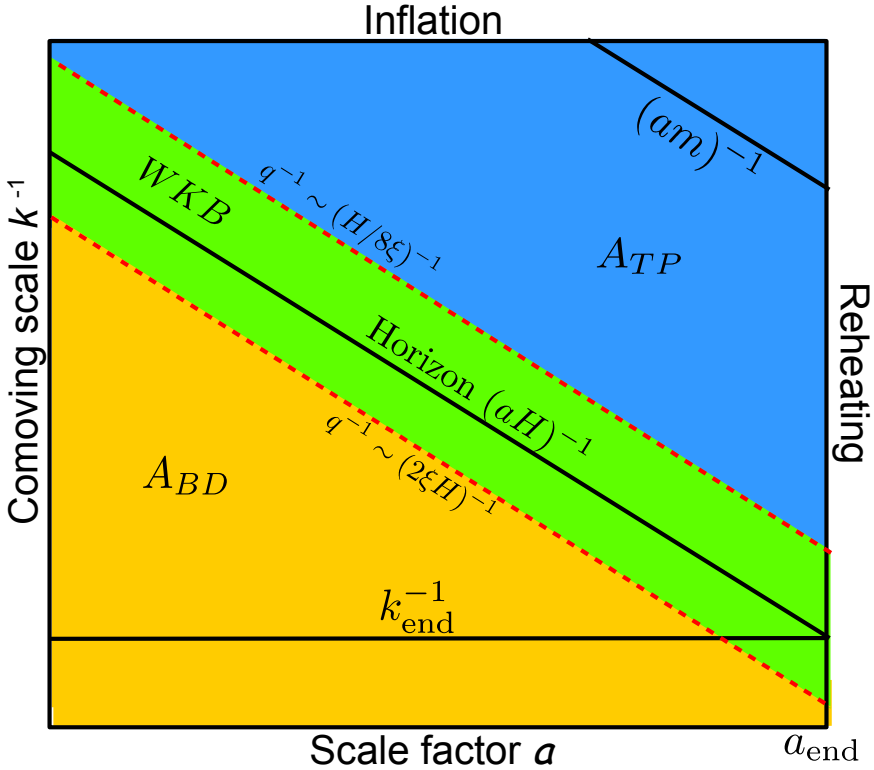
$$\Big[\frac{\partial^2}{\partial\tau^2} + k^2 \pm 2\,k\,\frac{\xi}{\tau} + \frac{\bar{m}^2}{\tau^2}\Big]A_\pm(k,\tau) = A_\pm'' + \omega^2(k,\tau)A_\pm = 0$$

With convention $\dot{\phi} > 0$ we have $\xi > 0 \Rightarrow$ ONLY the A_+ mode experiences tachyonic enhancement when frequency satisfies:

$$\Omega^2(k,\tau) = -\omega^2(k,\tau) = -(k^2 + 2k\frac{\xi}{\tau} + \frac{\bar{m}^2}{\tau^2}) > 0 \ \ (\text{note}: -\infty < \tau < 0)$$

Exponentially Enhanced Tachyonic Mode ($\bar{m} \ll 1$)

Tachyonic instability ($\Omega^2 > 0$) **triggered when physical momenta satisfy** $q = k/a < 2\xi H \Rightarrow$ **wavelength of order horizon** $q^{-1} \sim H^{-1}$



Conformal diagram gives intuition on amplitudes:

$$\lim_{-k\tau\to\infty} A_{\pm}(k,\tau) = \frac{e^{-ik\tau}}{\sqrt{2k}} \equiv A_{\rm BD}$$

$$A_{+}(k,\tau) \simeq \sqrt{\frac{-2\tau}{\pi}}\, e^{\pi\xi} K_{\mathbf{1}}\left[2\sqrt{-2\xi k\tau}\right]$$

$(-k\tau < 2\xi, K_{\mathbf{1}} \equiv$ modified Bessel 2nd kind$)$

$$\lim_{-k\tau\to\mathbf{0}} A_{+}(k,\tau) = \frac{e^{\pi\xi}}{2\sqrt{2\pi k\xi}} \equiv A_{\rm TP}$$

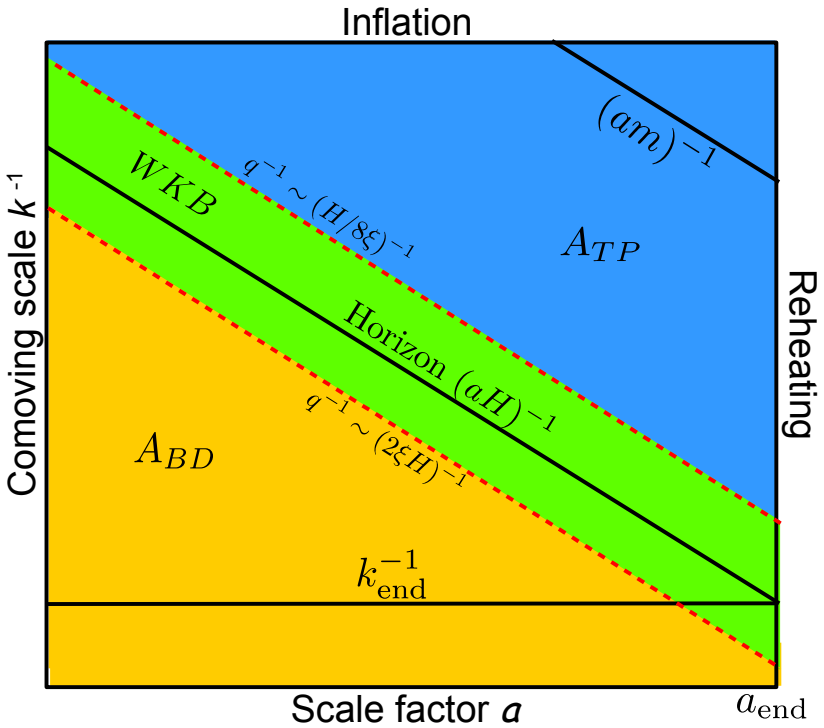
[Well known solutions (constant ξ) from gauge field production mechanisms: Anber & Sorbo: 0606534]

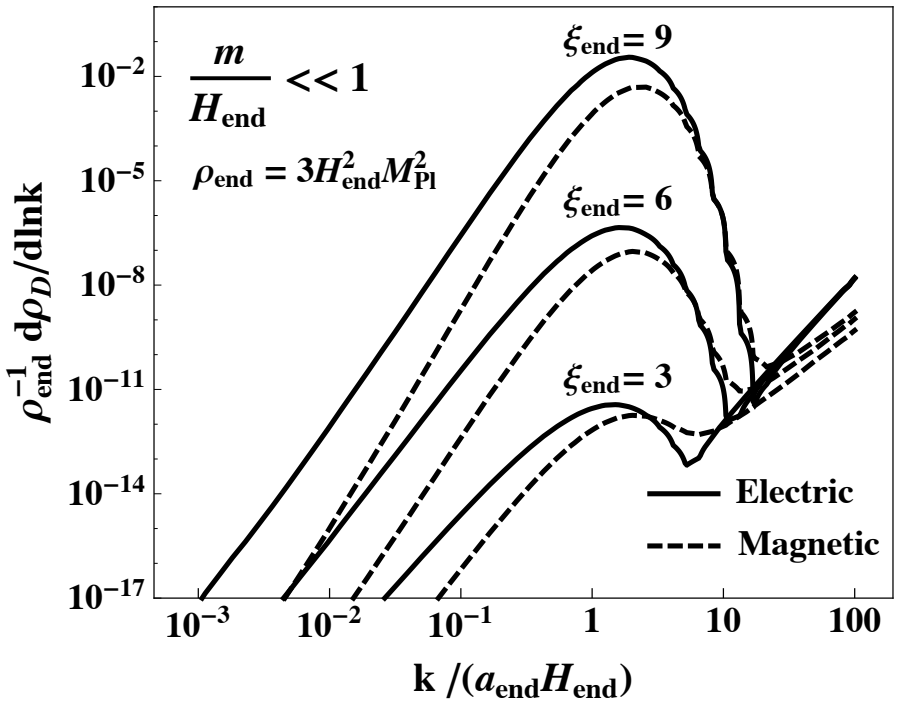
The amplitude at horizon crossing (where most of the power is) is well approximated by WKB in the range $H/8\xi < q < 2\xi H$

$$A_{+}(k,\tau)_{\rm WKB} \simeq \frac{1}{\sqrt{2k}}\left(\frac{-k\tau}{2\xi}\right)^{1/4} e^{\pi\xi - 2\sqrt{-2\xi k\tau}}$$

Input energy spectrum at end of inflation

While WKB is useful for intuition, since ξ is time dependent, need to numerically solve EOM to obtain accurate spectrum





VDM has dark 'magnetic' & 'electric' energy density contribution

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

Peak at $k^{-1} \sim k_{\rm end}^{-1} \ll k_{\rm CMB}^{-1} \Rightarrow$ power suppressed at CMB scales

Estimating the VDM Relic Abundance

Inflaton energy converted to VDM and radiation:

$$\rho_I = V(\phi) = 3H^2 M_{\rm Pl}^2$$

Energy stored in radiation:

$$\rho_R(T_{\rm RH}) = \frac{\pi^2}{30} g_*(T_{\rm RH}) T_{\rm RH}^4$$
$$= \epsilon_R^4 3H^2 M_{\rm Pl}^2 = \epsilon_R^4 \rho_I$$

Defines reheat temperature:

$$T_{\rm RH} = \epsilon_R \left(\frac{90}{\pi^2 g_*(T_{\rm RH})}\right)^{1/4} \sqrt{H M_{\rm Pl}}$$

We assume instant reheating:

$$\Rightarrow a_{\rm end} = a_{\rm RH}$$

Initial VDM energy density produced at end of inflation is estimated using WKB

$$\rho_D \approx 10^{-4} \frac{H_{\rm end}^4}{\xi_{\rm end}^3} e^{2\pi\xi_{\rm end}}$$

Hubble parameter decreases (slowly) until inflation ends:

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

To estimate relic abundance today, must track redshift of VDM energy density

We parametrize ignorance of potential $V(\phi)$ with ϵ_R, ϵ_H

Redshift of energy density

At end of inflation, energy density peaked at $k \sim a_{\rm end} H_{\rm end}$

Modes contributing most to $\rho_D(T_{\rm RH})$ have physical momentum:

$$q(T_{\rm RH}) \equiv \frac{k}{a_{\rm end}} \sim H_{\rm end}$$

At reheating we have $q(T_{\rm RH}) \gg m$ and $q(T)$ then redshifts as,

$$q(T) = q(T_{\rm RH}) \frac{T}{T_{\rm RH}}$$

VDM becomes non-relativistic at temperature $\bar{T}$ defined by,

$$q(\bar{T}) = m \quad \Rightarrow \quad \bar{T} = m \left(\frac{90}{\pi^2 g_*(T_{\rm RH})} \right)^{1/4} \frac{\epsilon_R}{\epsilon_H} \left(\frac{M_{\rm Pl}}{H} \right)^{1/2}$$

Above (below) $\bar{T}$ energy density redshifts like radiation (matter)

Relic Density of Polarized VDM

VDM relic density today normalized to observed amount of CDM:

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

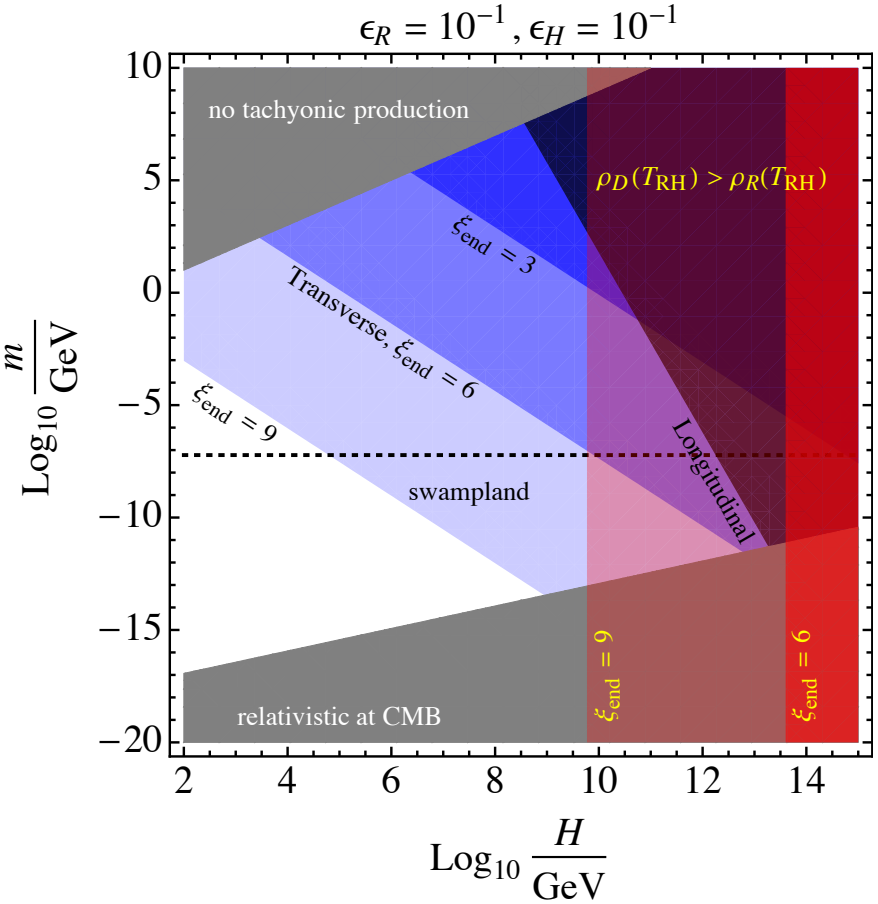
We see $\Omega_T/\Omega_{\rm CDM}$ depends on 5 parameters: m, H, $\xi_{\rm end}$, ϵ_H, ϵ_R

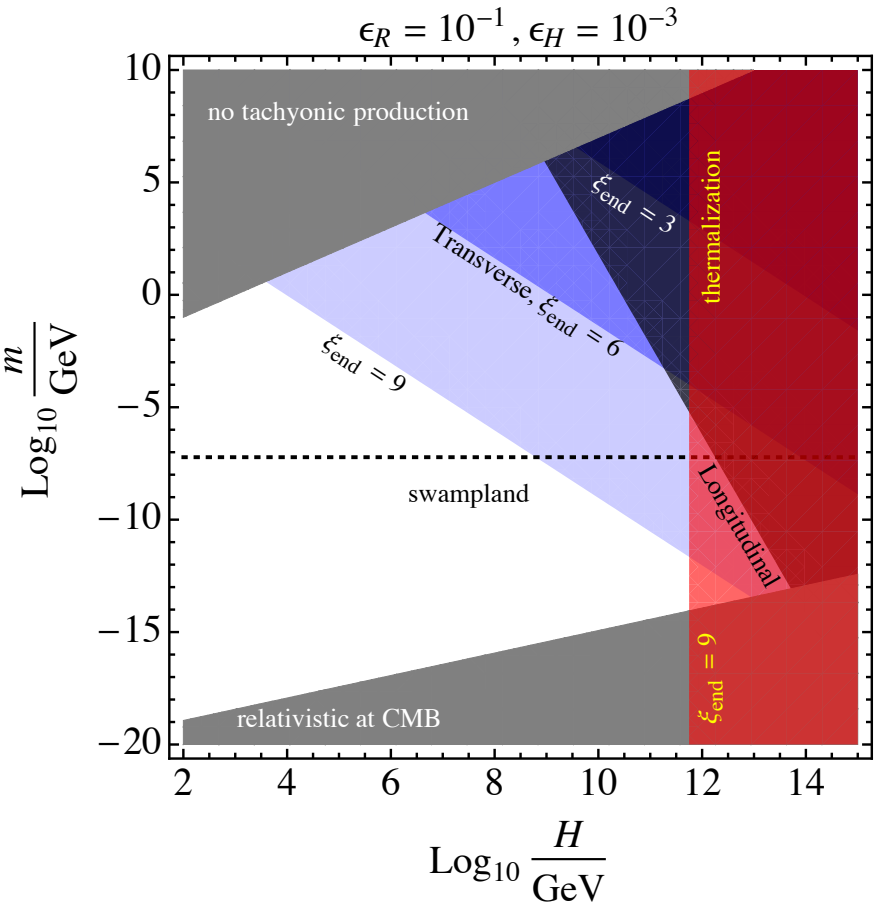
Various constraints must be satisfied for a viable VDM candidate:

- $m \ll q(T_{\rm RH})$ for efficient tachyonic production at end of inflation
- VDM becomes (cold) non-relativistic before MRE $\Rrightarrow \bar{T} > T_{\rm CMB}$
- At RH, energy in radiation greater than VDM $\Rrightarrow \rho_R(T_{\rm RH}) > \rho_D(T_{\rm RH})$
- Inflaton & VDM must not thermalize $\Rrightarrow$ upper bound on ξ (& kinetic mixing)
  (no other light fields in the dark sector which couple to VDM $\Rrightarrow$ Schwinger effect: 1706.03072)
- Assume negligible back-reaction effects on the inflaton dynamics
  (neglect VDM production from inflaton oscillations after inflation: 1810.07188, 1810.07188)

Imposing constraints $\Rrightarrow$ allowed parameter space in $m - H$ plane

Parameter Space for VDM Relic Abundance





We have also included relic density of longitunidal component:

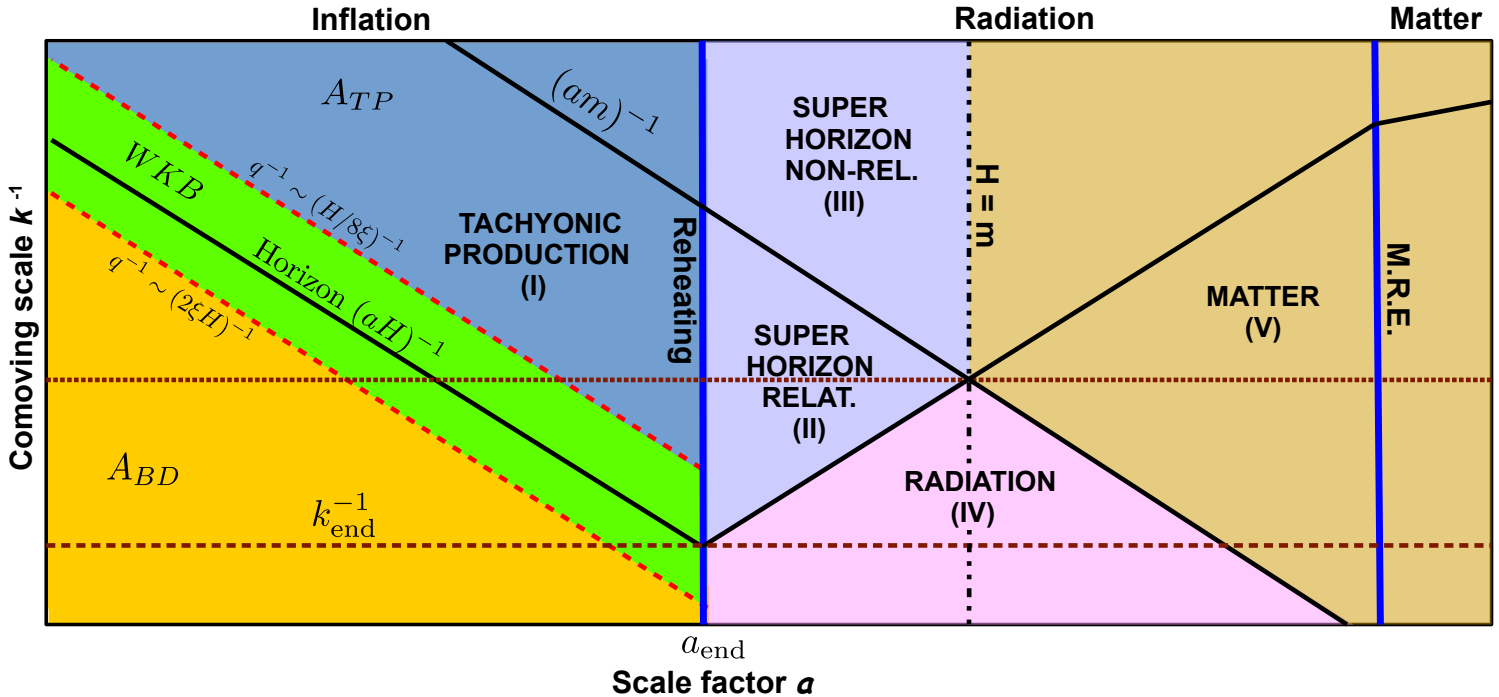
$$\frac{\Omega_L}{\Omega_{\text{CDM}}} = \left(\frac{m}{6 \times 10^{-15}\ \text{GeV}}\right)^{1/2} \left(\frac{H}{10^{14}\ \text{GeV}}\right)^{2}$$

(P. W. Graham, J. Mardon, S. Rajendran: 1504.02102)

Cosmological Evolution of Tachyonic Modes

Energy density spectrum has implications for how VDM clumps

Relevant quantity is late time energy density spectrum



Can analytically solve approximate EOMs in different regions

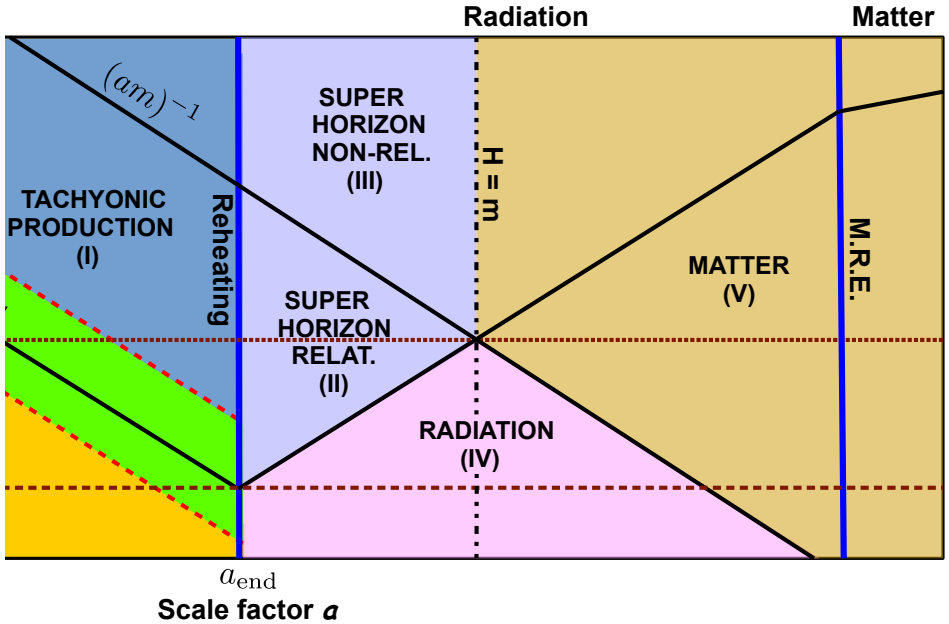
$$\ddot{A}_{\pm} + H\dot{A}_{\pm} + \left(\frac{k^2}{a^2} + m^2\right) A_{\pm} = 0 \quad \text{(after inflation)}$$

Must track evolution of 'electric' and 'magnetic'energy density

$$\frac{d\rho}{d\ln k} = \left(\frac{k^3}{2\pi^2}\right)\left(\frac{H^2}{2}|\partial_a A(k,a)|^2 + \frac{1}{2a^2}\left(\frac{k^2}{a^2} + m^2\right)|A(k,a)|^2\right) = \frac{d\rho_E}{d\ln k} + \frac{d\rho_B}{d\ln k}$$

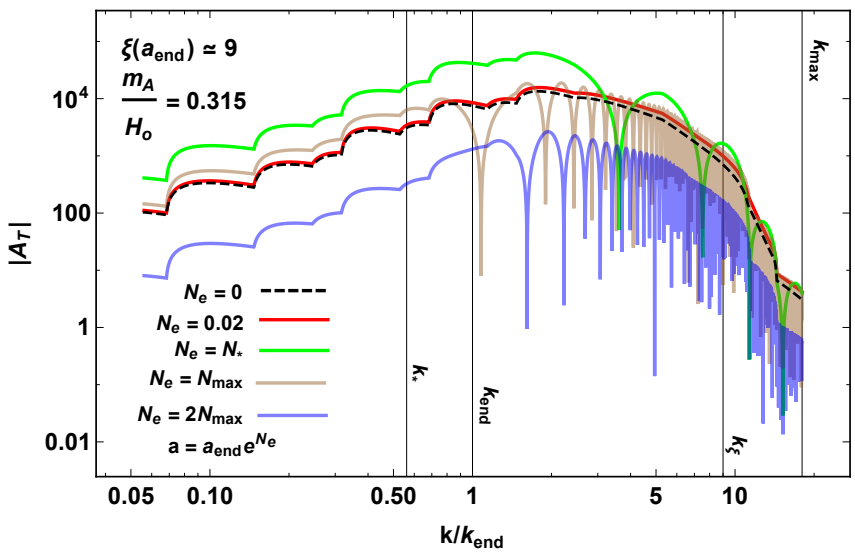
Cosmological Evolution of 'Magnetic' Modes

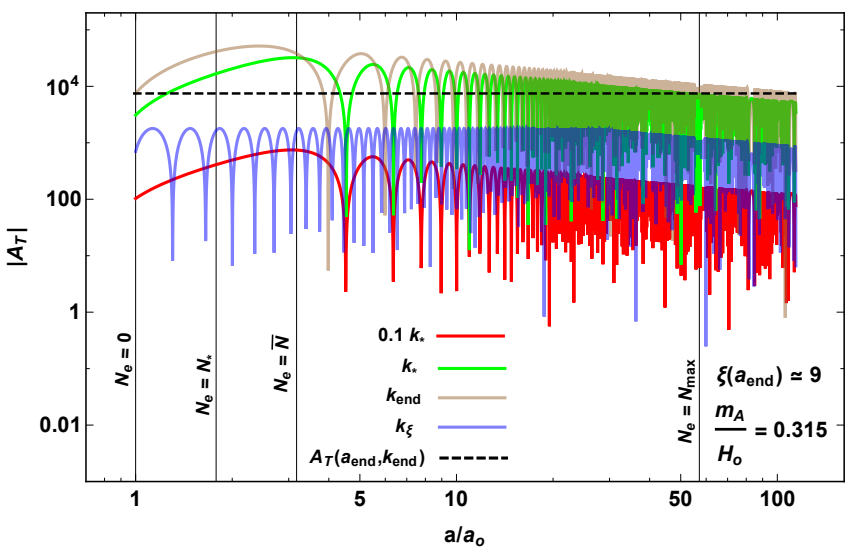
(PRELIMINARY)



'Glue' approx. solutions together at boundaries:

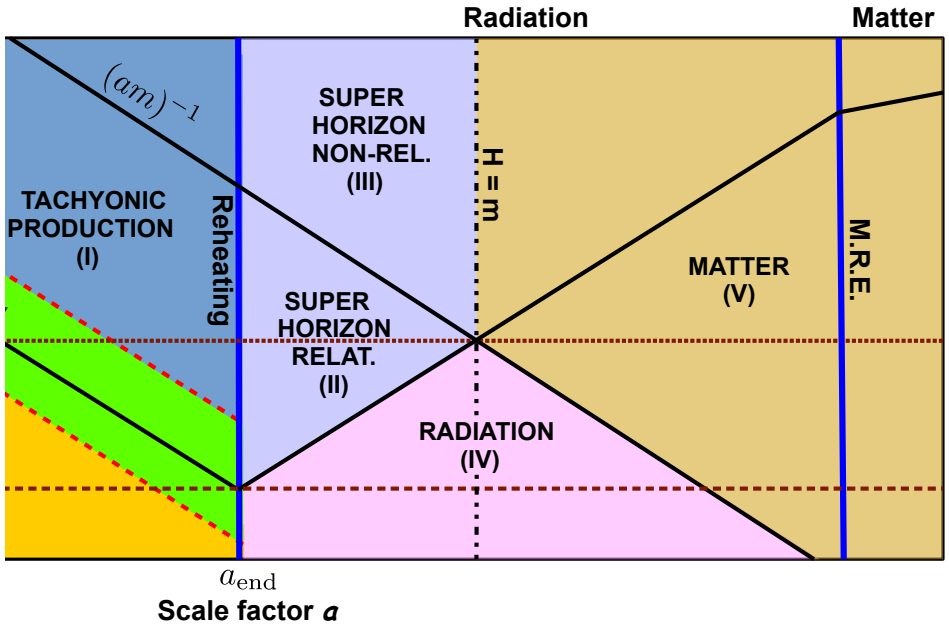
$$
\begin{aligned}
(I)\ A_+ &= A_{\rm TP} \\
(II)\ A_+ &= c_1 + c_2 a \\
(III)\ A_+ &= c_1 + c_2 a \\
(IV)\ A_+ &= (a_4 e^{ik\tau} + b_4 e^{-ik\tau}) \\
(V)\ A_+ &= \frac{1}{\sqrt{a}}(a_5 e^{imt} + b_5 e^{-imt})
\end{aligned}
$$





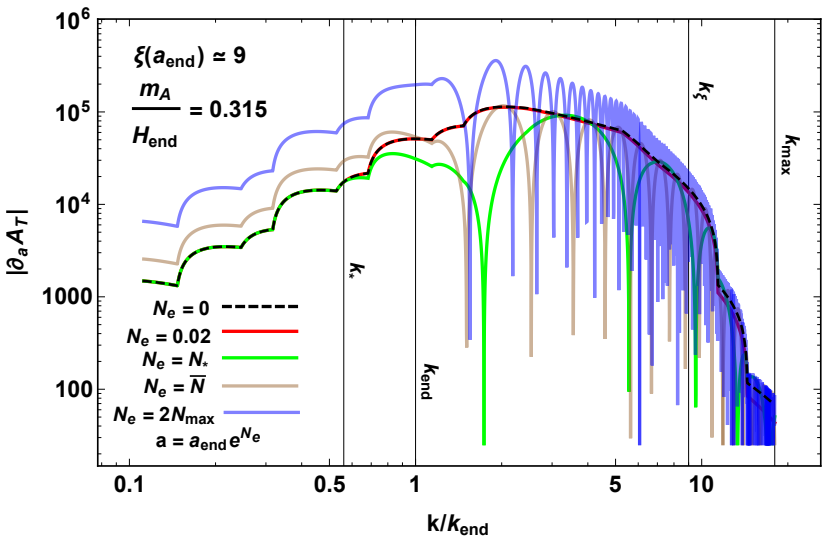
Cosmological Evolution of 'Electric' Modes

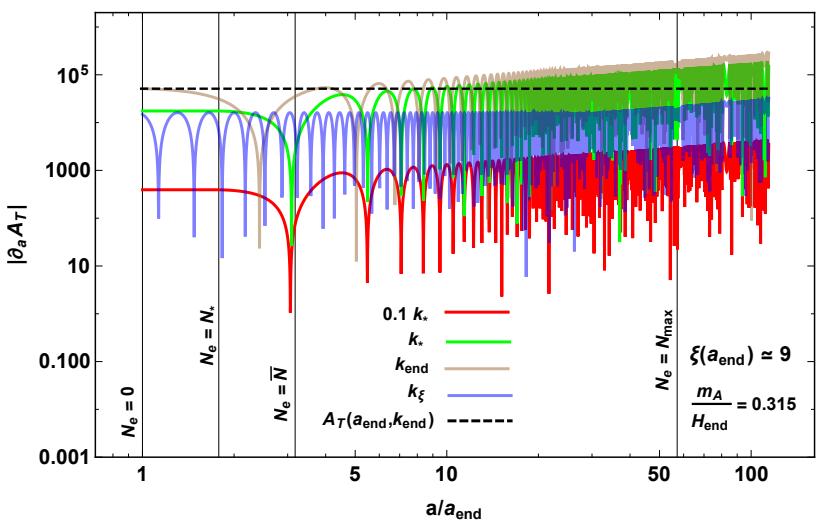
(PRELIMINARY)



'Glue' approx. solutions together at boundaries:

$$
\begin{aligned}
(I)\ \partial_a A_+ &= A'_{\rm TP} \\
(II)\ \partial_a A_+ &= c_1 \\
(III)\ \partial_a A_+ &= c_1 \\
(IV)\ \partial_a A_+ &= \frac{ik}{a_{\rm end}^2 H_{\rm end}}\left(a_4 e^{ik\tau} - b_4 e^{-ik\tau}\right) \\
(V)\ \partial_a A_+ &= \frac{im\sqrt{a}}{a_{\rm end}^2 H_{\rm end}}\left(a_5 e^{imt} - b_5 e^{-imt}\right)
\end{aligned}
$$

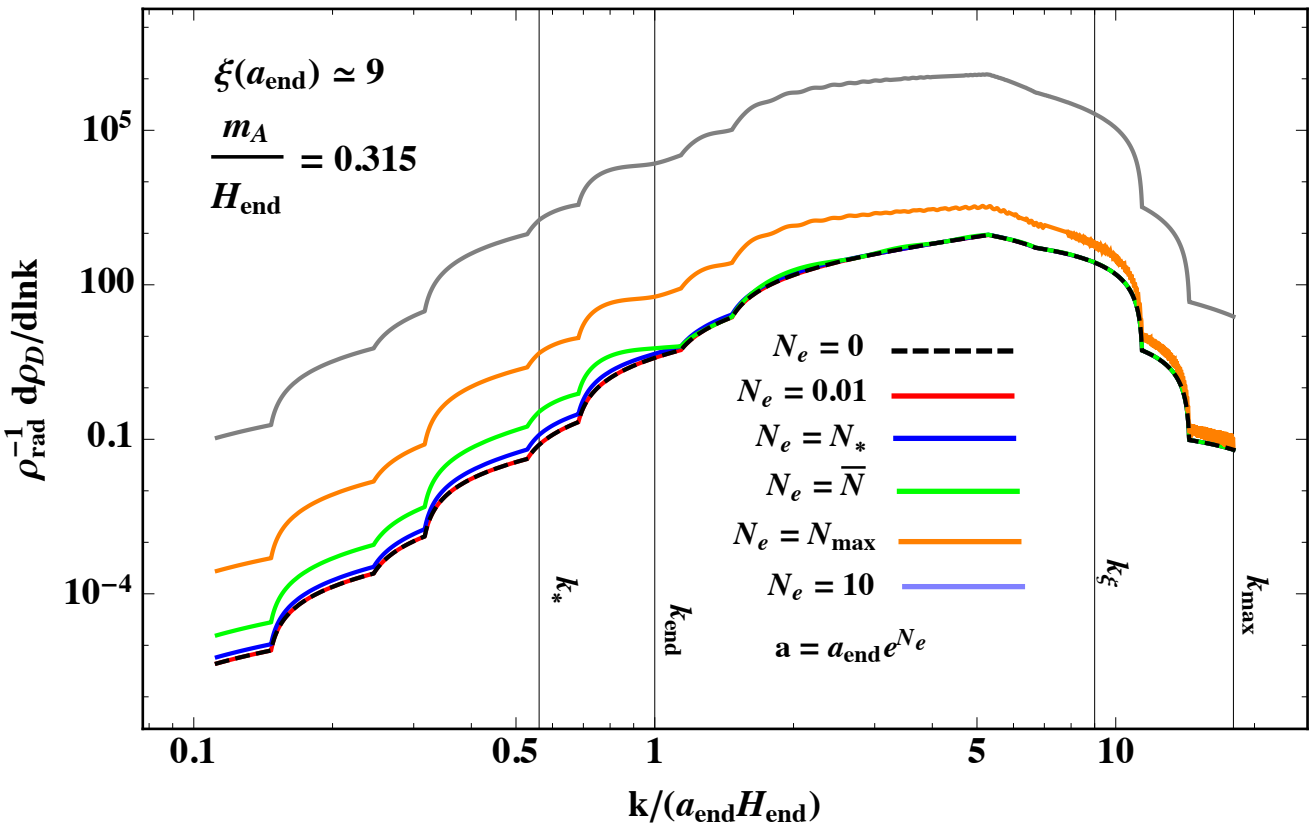




Late Time Energy Density Spectrum (PRELIMINARY)

$$\frac{d\rho}{d\ln k} = \left(\frac{k^3}{2\pi^2}\right)\left(\frac{H^2}{2}|\partial_a A(k,a)|^2 + \frac{1}{2a^2}\left(\frac{k^2}{a^2} + m^2\right)|A(k,a)|^2\right)$$

Have a peak at late times $\Rightarrow$ implications for structure/clumping



Scale at end of inflation connected to scale of VDM clumping

Scale of clumping is $\sqrt{\bar{m}}$ smaller than for longitudinal mode

Ongoing/Future Work & Summary/Conclusions

- Ongoing/Future work:
  - Explore implications of energy density spectrum on VDM clumping and structure formation
  - Examine regions of parameter space where both longitudinal and transverse modes give comparable contributions
  - Study energy density spectrum for different inflation models
  - Explore phenomenology associated with polarization
  - Explore effects of Stueckelberg vs Higgsed VDM mass
- Summary and Conclusions:
  - We have presented a new VDM production mechanism
  - Relic abundance obtained for VDM masses $10^{-15} - 10^{6}$ GeV
  - VDM is polarized with peak in energy density spectrum
  - Clumping scale (peak) connected to scale at end of inflation
  - Mechanism works for Stuckelberg or Higgsed VDM mass
  - Much phenomenology yet to explore!

THANKS!