Vector Dark Matter at the end of inflation

- Dark Matter: evidence & candidates
- Inflation
- Dark photons as dark matter: non-thermal relic

M. Bastero-Gil
with J. Santiago, L. Ubaldi, R. Vega-Morales
- (JCAP1904(2019)015 [Arxiv:1810.07208])

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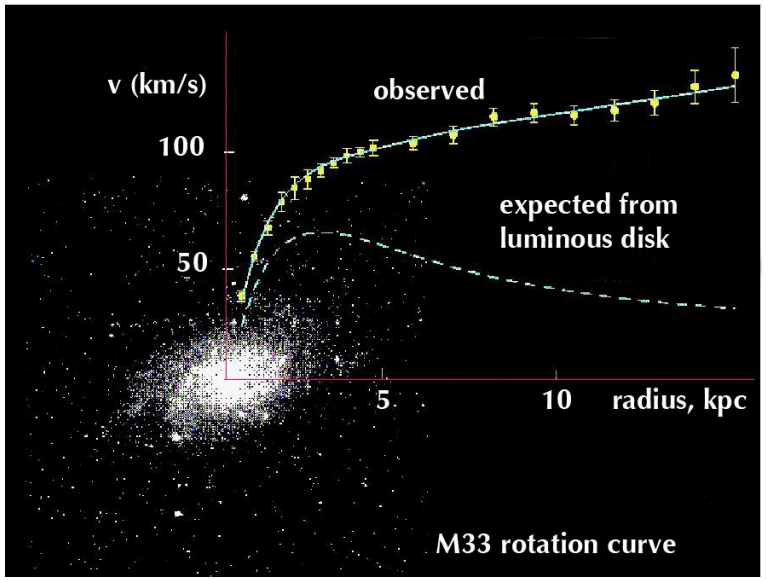
Dark Matter ~ 26 % total energy density
(gravitational evidence)

- Galaxy rotation curves

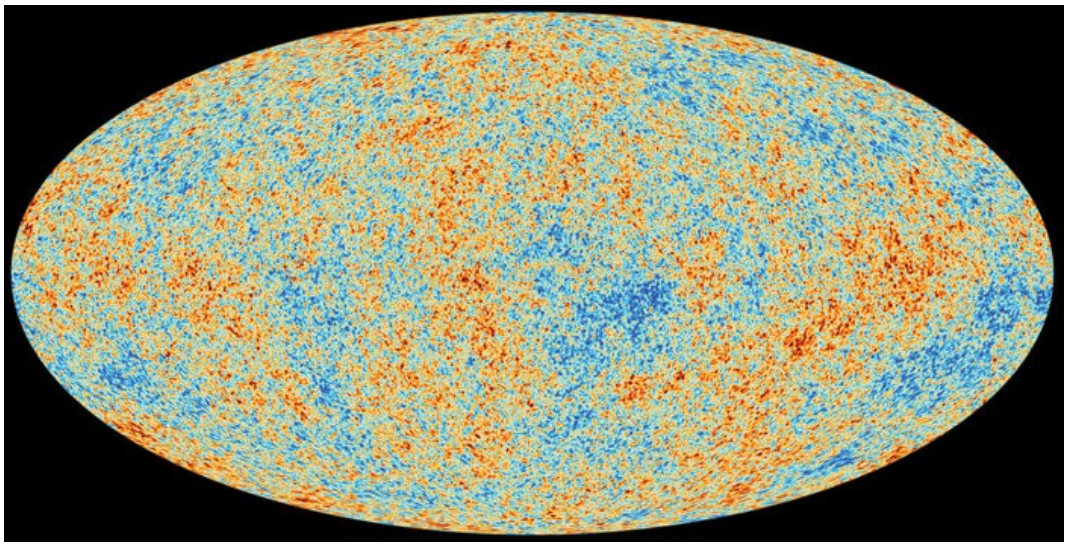


[Fritz Zwicky 1933; Vera Rubin 1975]

- Gravitational lensing

[Abell 2218 cluster, HST]

- Cosmic microwave background radiation



[Planck 2018: astro-ph/1807.06211]

Dark Matter candidates: Beyond the Standard Model

Axion like particles (ALP)

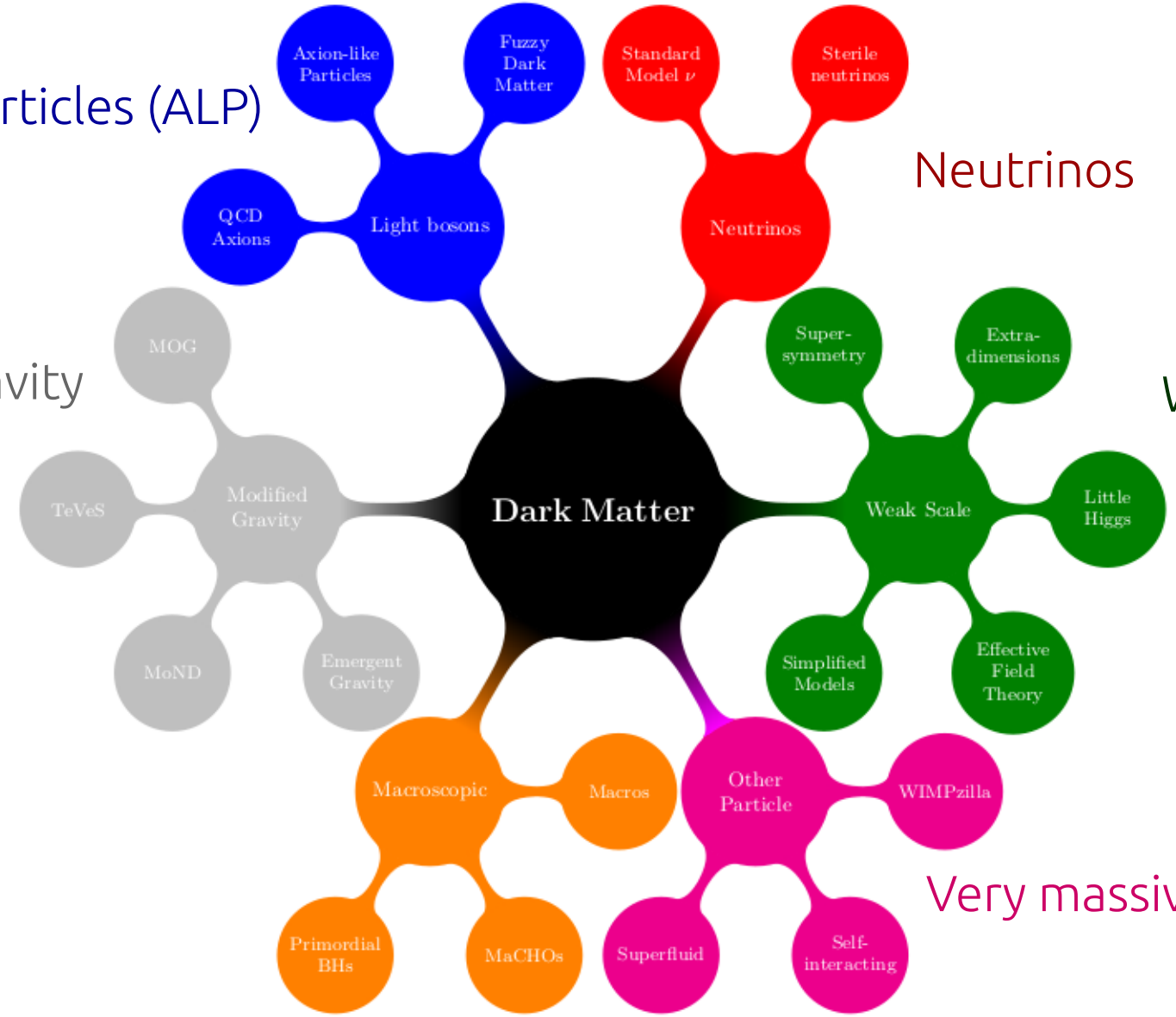
Modified gravity

Neutrinos

WIMPs

Very massive relics

MaCHOs, PBH



[Bertone & Tait, Nature 2018]

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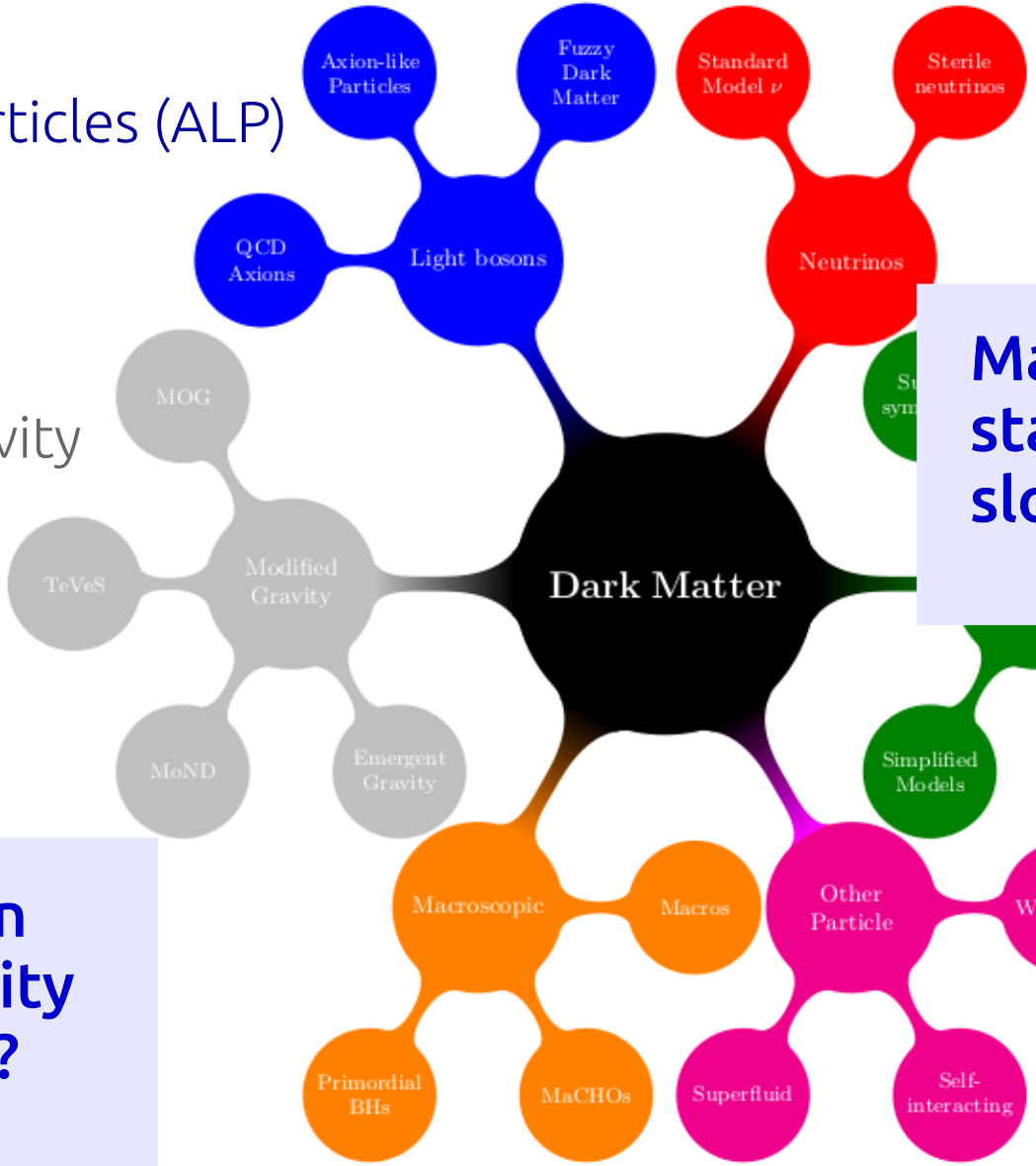


Neutrinos

Massive, neutral, stable particle, slow-moving ("cold")?

- **Production**
- **Relic density**
- **Detection?**

Very massive relics

MaCHOs, PBH

[Bertone & Tait, Nature 2018]

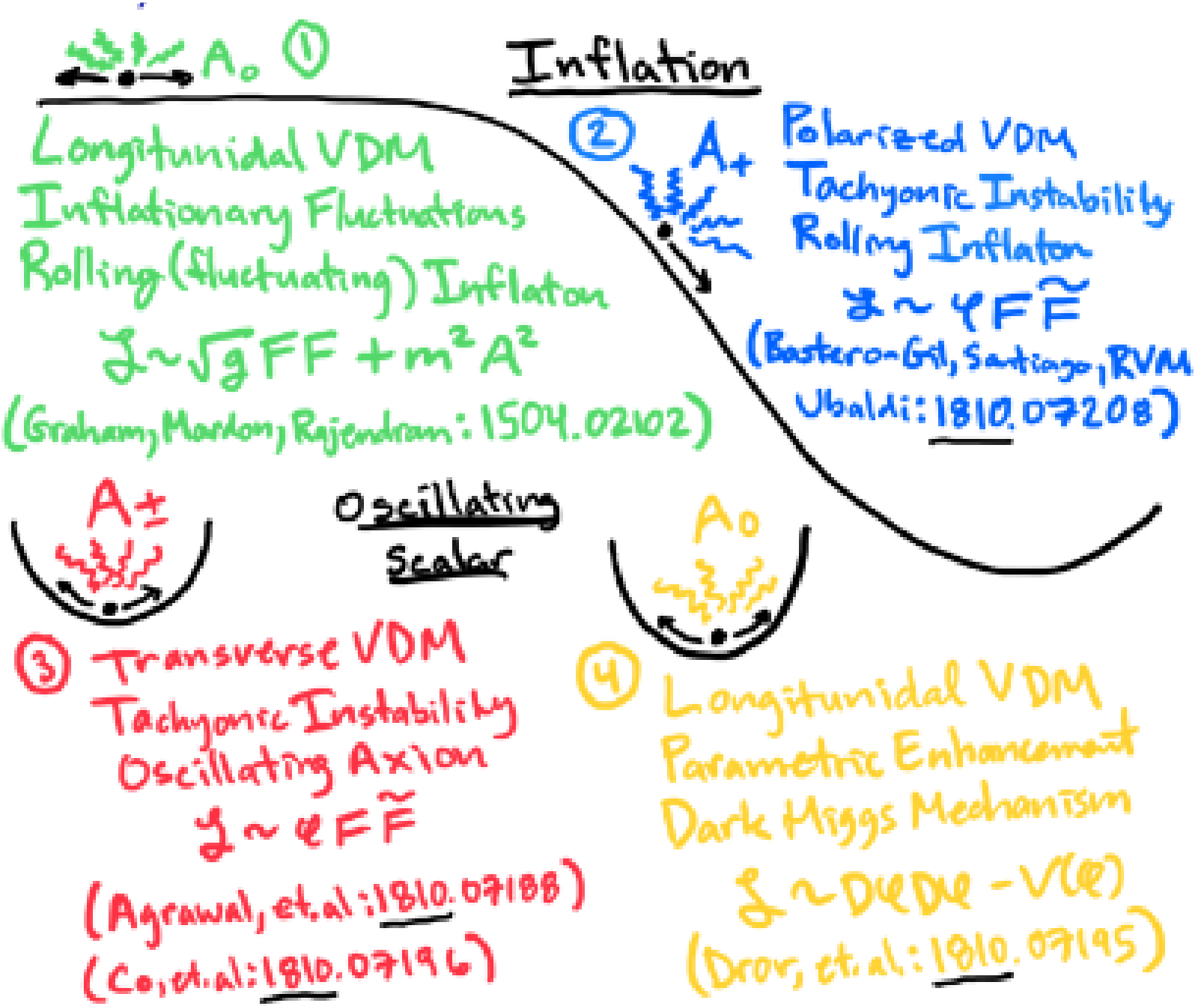
Dark photons (vector) as Dark Matter

$$L=\frac{1}{2}(\partial_\mu\phi)^2-V(\phi)-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{1}{2}m_A^2A_\mu A^\mu-\frac{\alpha}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- SM+ ”hidden” U(1) : massive (light) vector (”dark photon”)
- ϕ : scalar singlet (axion like, inflaton,...)
- **”Freeze-out” mechanism during inflation**

[Graham et al., Phys. Rev. D93 2015]

- After inflation, $H > m_A$ ➡ Radiation
- Before Matter-Radiation equality $H < m_A$ ➡ Matter


A₀ ①
Inflation
Longitunidal VDM
Inflationary Fluctuations
Rolling (fluctuating) Inflaton
$\mathcal{L} \sim \sqrt{g} FF + m^2 A^2$
(Graham, Mardon, Rajendran: 1504.02102)
② A_+
Polarized VDM
Tachyonic Instability
Rolling Inflaton
$\mathcal{L} \sim \phi F\tilde{F}$
(Bastero-Gil, Santiago, RVM Ubaldi: 1810.07208)
$A_\pm$
Oscillating Scalar
A_0
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Dark Higgs Mechanism
$\mathcal{L} \sim D_\mu\phi D^\mu\phi - V(\phi)$
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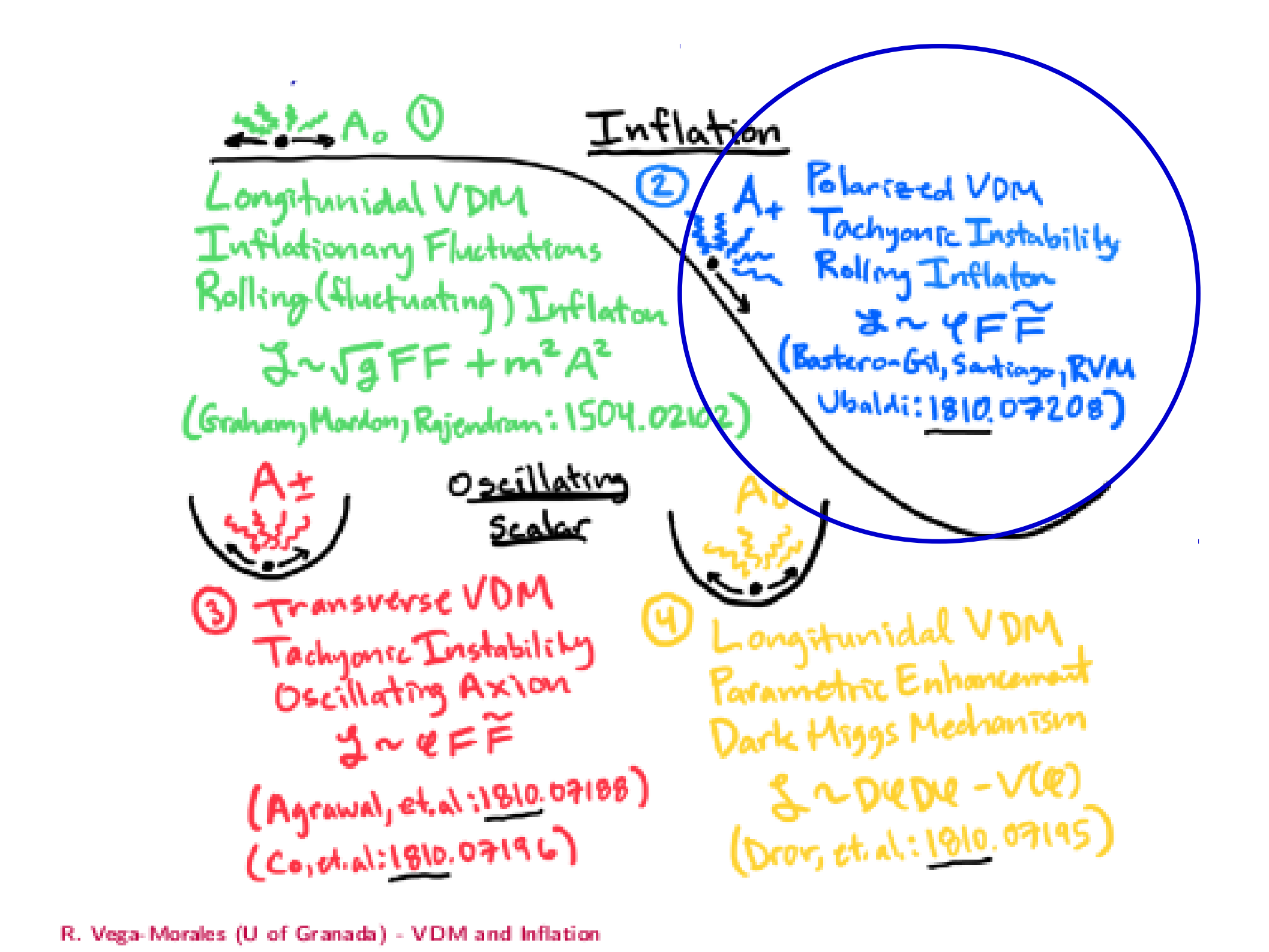
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Dark photons (vector) as Dark Matter

$$L=\frac{1}{2}(\partial_\mu\phi)^2-V(\phi)-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{1}{2}m_A^2A_\mu A^\mu-\frac{\alpha}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

- Evolution equations during inflation

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

[Graham et al., Phys. Rev. D93 2015]

- Light field during inflation, superhorizon fluctuations, k/aH <<1, are "frozen"

$$\ddot{A}_L+H\dot{A}_L\simeq 0$$

- Constant amplitude of the spectrum by the end of inflation $\rho_{A_L}\sim m_A^2A_L^2/a^2\propto a^{-2}$
- Re-entry, k/a > H, m : $\rho_{A_L}\sim m_A^2A_L^2/a^2\propto a^{-4}$
- Late-time, k/a, H < m : $\rho_{A_L}\sim m_A^2A_L^2/a^2\propto a^{-3}$

Matter

$$\frac{\Omega_L}{\Omega_c}=\sqrt{\frac{m}{6\times10^{-6}\,eV}}\left(\frac{H_I}{10^{14}\,GeV}\right)^2$$

Dark photons (vector) as Dark Matter

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- Evolution equations during inflation

Transverse A: $\ddot{A}_T+H\dot{A}_T+\left(\frac{k^2}{a^2}\mp\frac{k}{a}\frac{\alpha\dot{\phi}}{f}+m_A^2\right)A_T=0$

[Anber & Sorbo., Phys. Rev. D81 2010]

Negative squared frequency when $k/a<\alpha\dot{\phi}/f, m_A\ll H$

➡ "Tachyonic" production: exponential enhancement of vector fluctuations

$$A_T\simeq\frac{e^{\pi\xi}}{2\sqrt{2\pi k\xi}}$$

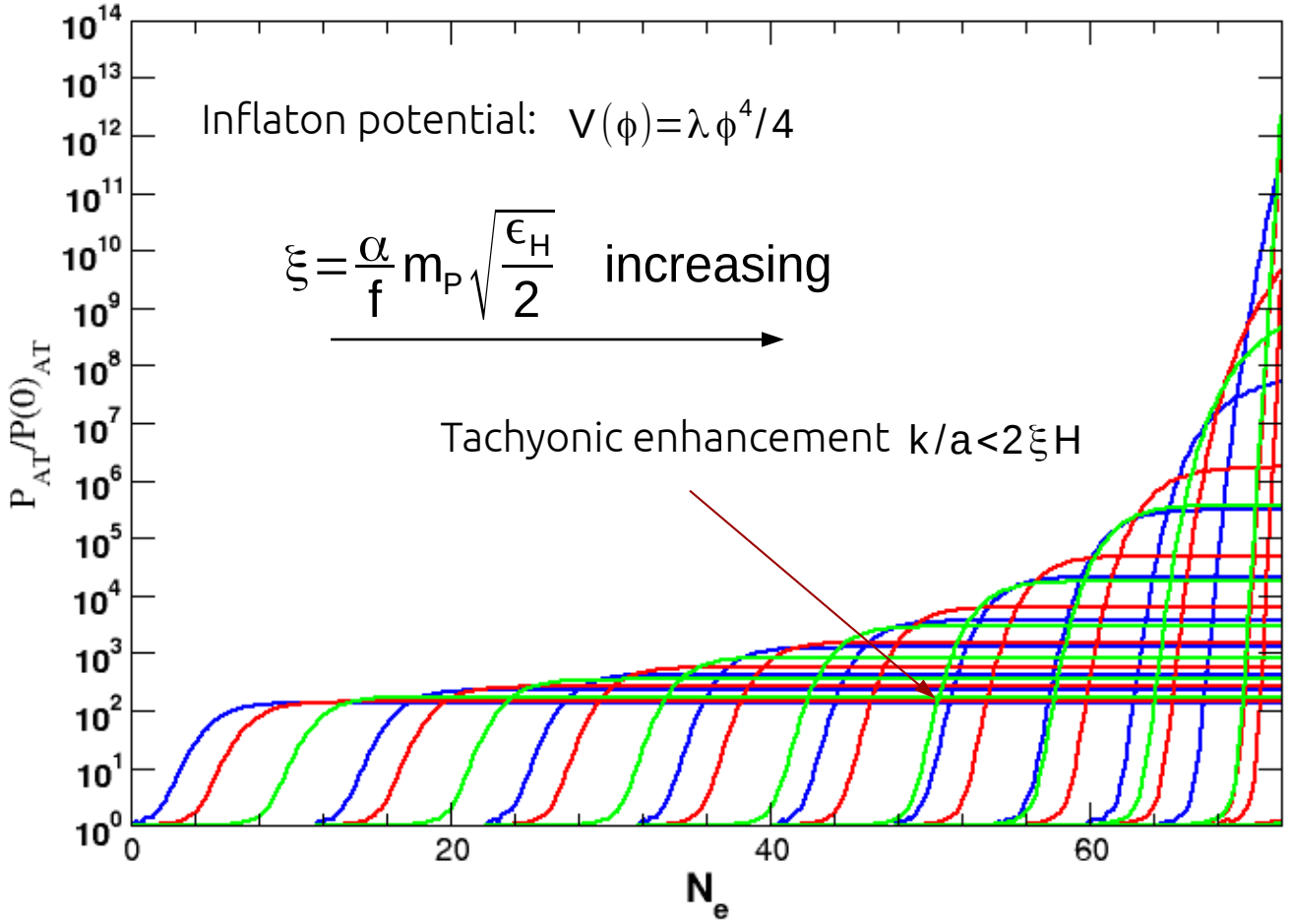
$$\xi=\frac{\alpha\dot{\phi}}{2Hf}=\sqrt{\frac{\epsilon}{2}}\frac{\alpha}{f}m_P$$

Larger enhancement by the end of inflation when $\epsilon_H\simeq 1$

Mass can be Stueckelberg OR Higgsed type and has negligible effects on tachyonic production mechanism as long as m << H

Dark photons (transverse) as Dark Matter

- Power spectrum: $P_{A_T}(k)=\frac{k^3}{2\pi^2}|A_T(k)|^2$
- Initial Power spectrum (Bunch-Davies vacuum): $P_{A_T}(k)=\frac{k^2}{4\pi^2}$



Dark photons (transverse) as Dark Matter

- Energy density power spectrum:

$$\frac{d\rho_{A_T}}{d\ln k}=\frac{1}{2a^4}\left(a^2 P_{\dot{A}_T}(k)+k^2 P_{A_T}(k)\right)$$

"Electric" "Magnetic"

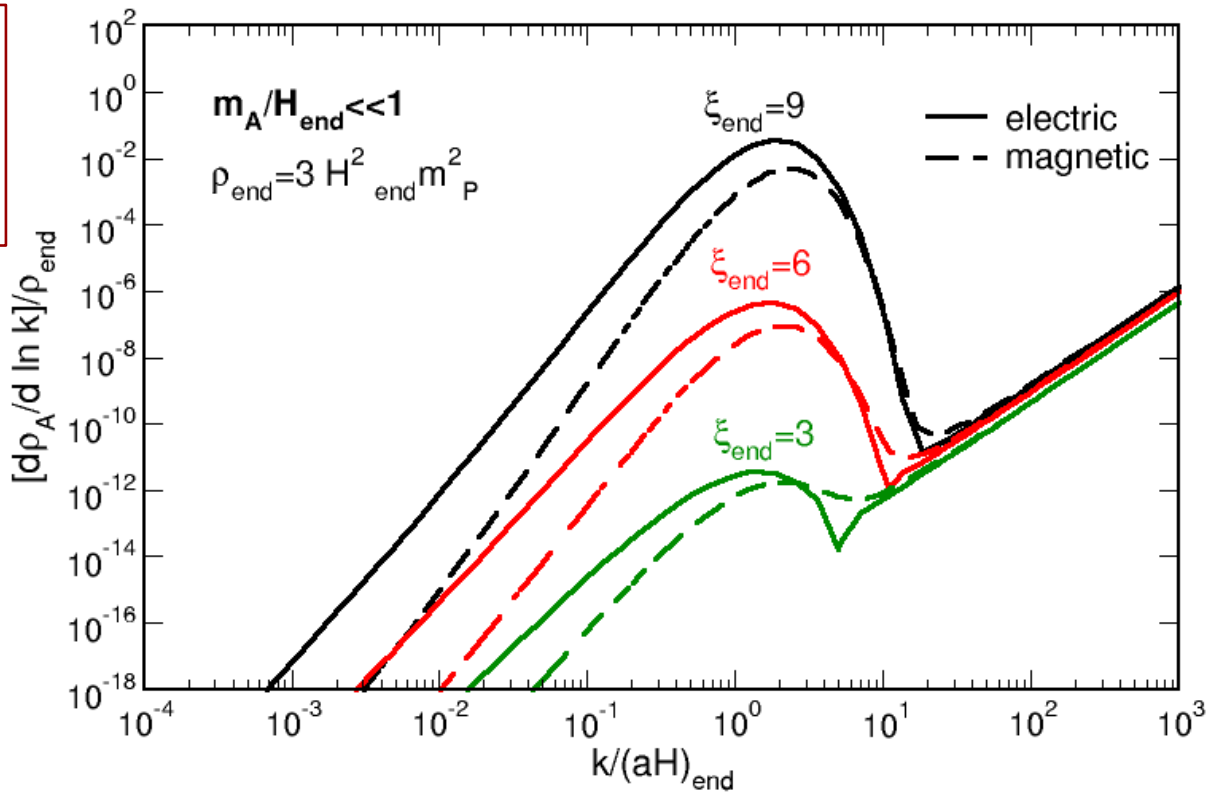
[Inflaton potential: $V(\phi)=\lambda\phi^4/4$ **]**

- Peaked structure at $k\sim a_{end}H$

$$\rho_{AT}(end)\simeq 10^{-4}\frac{H_{end}^4}{\xi_{end}}e^{2\pi\xi_{end}}$$

- Suppressed contribution at CMB scales

- No backreaction on inflaton dynamics for $\xi_{end}<O(10)$



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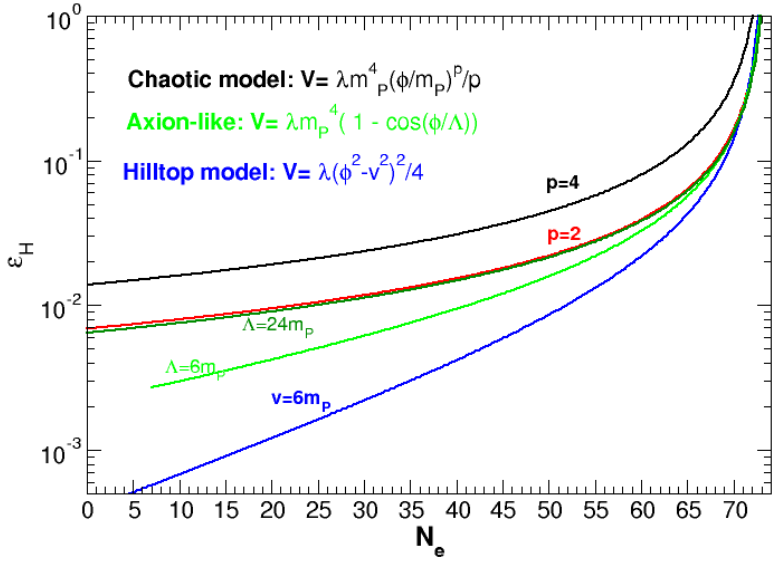
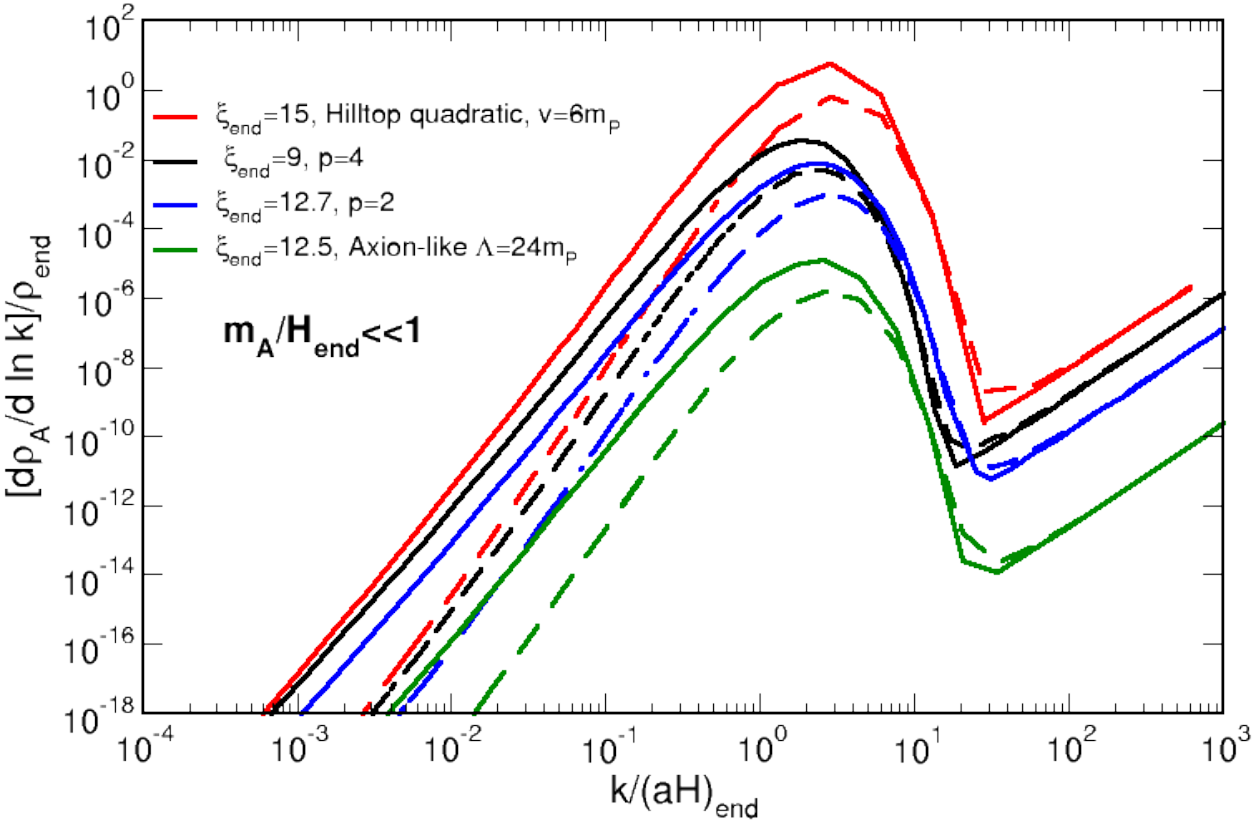
Slow-roll parameter $\epsilon = -\dot{H}/H^2 \leq 1$



Similar results for other
"large" field models of inflation



After Inflation ends...

$$\rho_I = 3H^2 m_P^2 \simeq V(\phi)$$

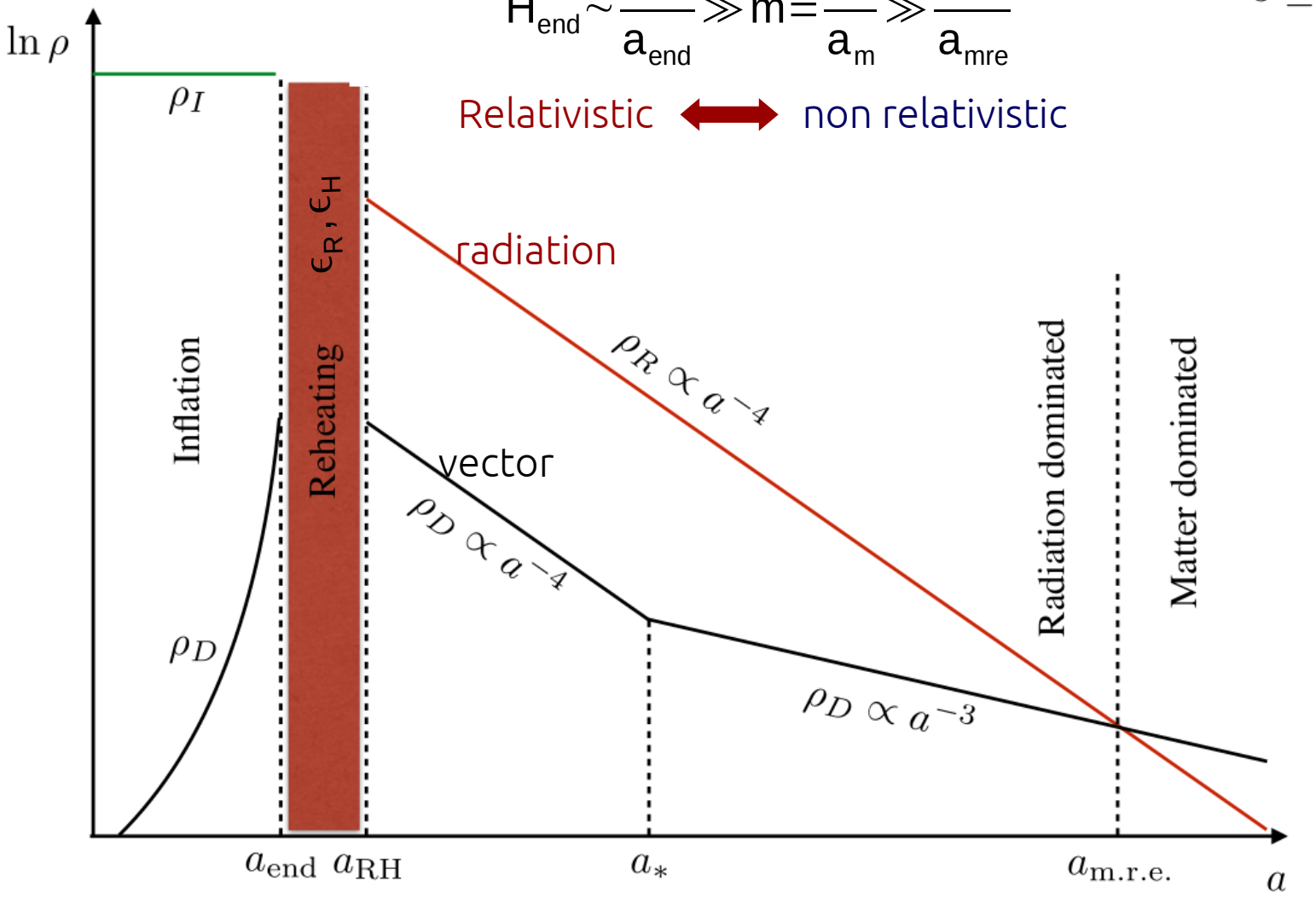
$$\rho_R(T_{RH}) = 3\epsilon_R^4 H^2 m_P^2$$

$$\rho_D(T_{RH}) \simeq 10^{-4} \frac{\epsilon_H^4 H^4}{\xi_{end}^3} e^{2\pi\xi_{end}}$$

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

$$H_{end} \sim \frac{k}{a_{end}} \gg m = \frac{k}{a_m} \gg \frac{k}{a_{mre}}$$

Relativistic ⟷ non relativistic



Relic abundance

•"reheating" (transition from inflation to a RD Universe)

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

$$\rho_R = \frac{\pi^2}{30} g_R T_{RH}^4 = 3\epsilon_{RH}^4 3H^2 m_P^2$$

ϵ_H, ϵ_{RH}<1

- While $q=k/a > m_A$: $\rho_{AT}(T) = \rho_{AT}(RH)\left(\frac{T}{T_{RH}}\right)^4$ Radiation (T ~ 1/a)

- When $q=k/a < m_A$: $\rho_{AT}(T) = \rho_{AT}(T_0)\left(\frac{\bar{T}}{T_0}\right)^3$ Matter

$$\left(q(\bar{T}) = m_A,\ T_0 = T_{CMB} = 10^{-13}\,\text{GeV}\right)$$

$$\frac{\Omega_T}{\Omega_c} = 7 \times 10^{-6} \frac{m_A}{\text{GeV}} \left(\frac{H}{10^{11}\,\text{GeV}}\right)^{3/2} \left(\frac{\epsilon_H}{\epsilon_{RH}}\right)^3 \frac{e^{2\pi\xi_{end}}}{\xi_{end}^3}$$

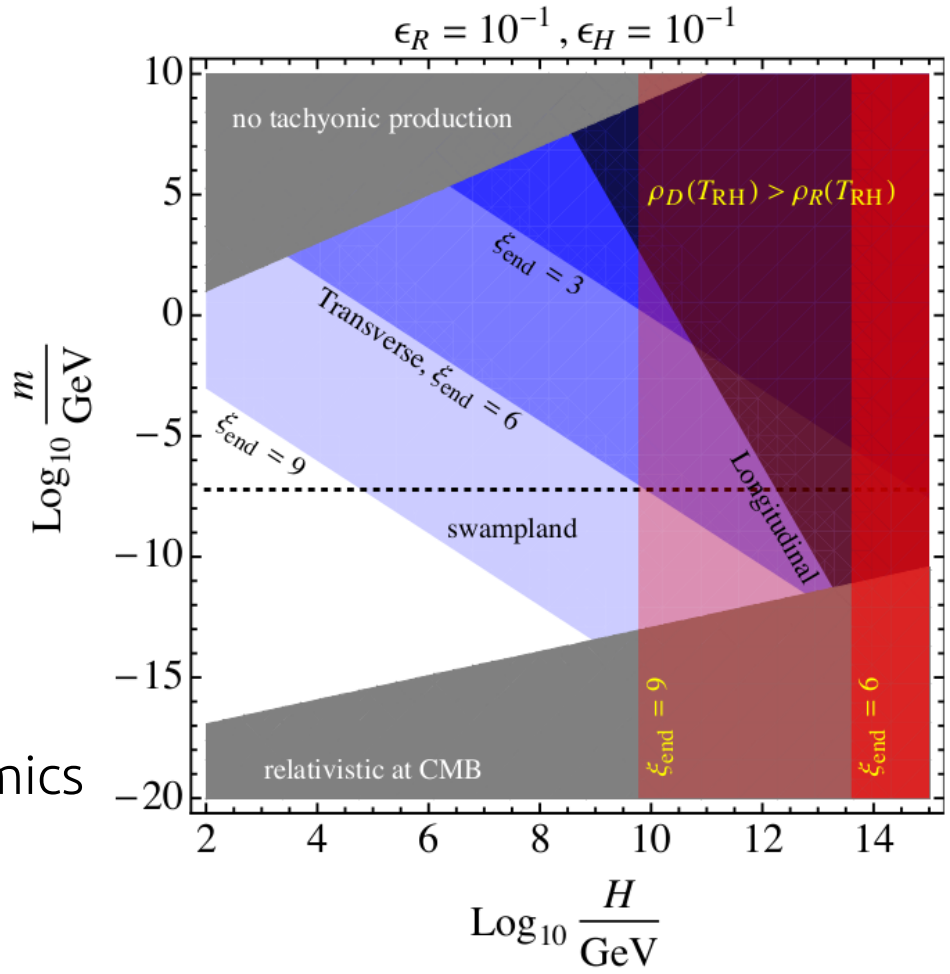
Relic abundance: parameter space

- m_A light enough for tachyonic production but large enough to become massive before T_{EQ}
- Energy density in radiation larger than that of vector at reheating
- Inflaton-dark photon coupling not too large to avoid thermalization

$$\xi_{end} < 0.44 \ln\left(\frac{m_P}{\sqrt{2}\,\xi_{end}}\right) + 3.4$$

- No backreaction effects on inflaton dynamics

$$\frac{\epsilon_H H}{m_P} \ll 10^2\, \xi_{end}^{3/2}\, e^{-\pi \xi_{end}}$$



- No "preheating" effecs (tachyonic enhancement during reheating due to oscillating inflaton)

[Preheating due to oscillating axion/dark Higgs:
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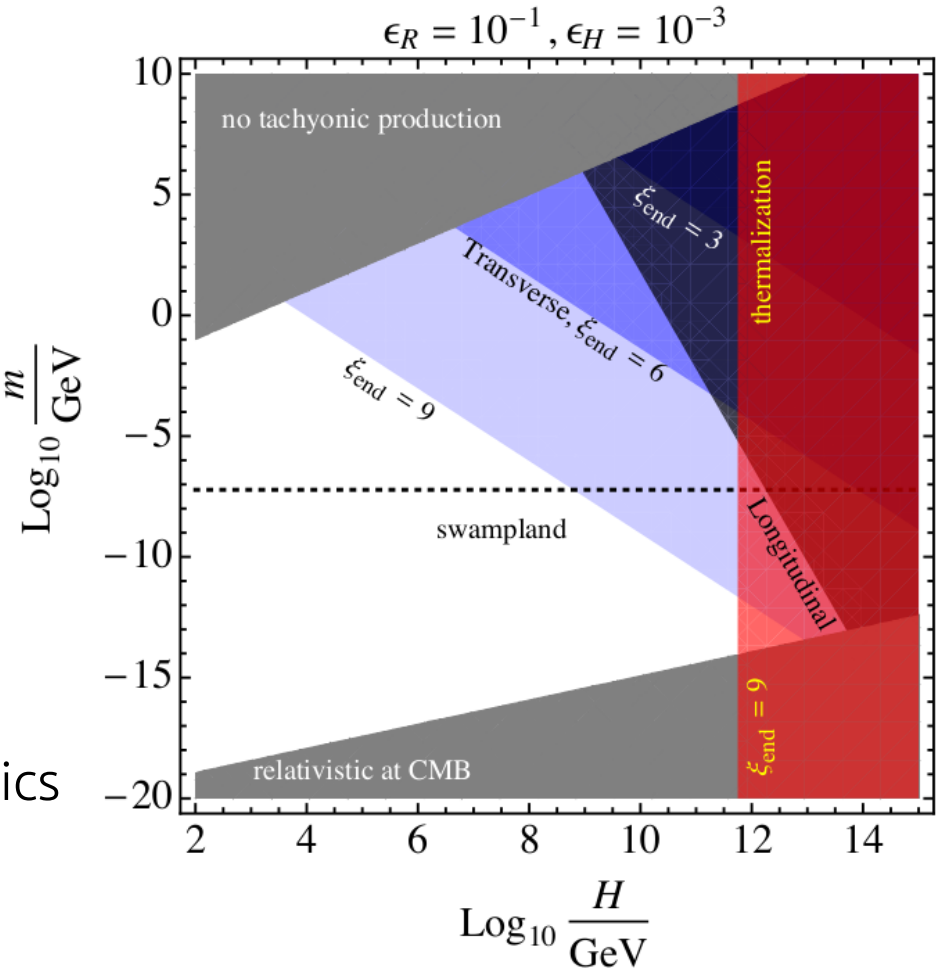

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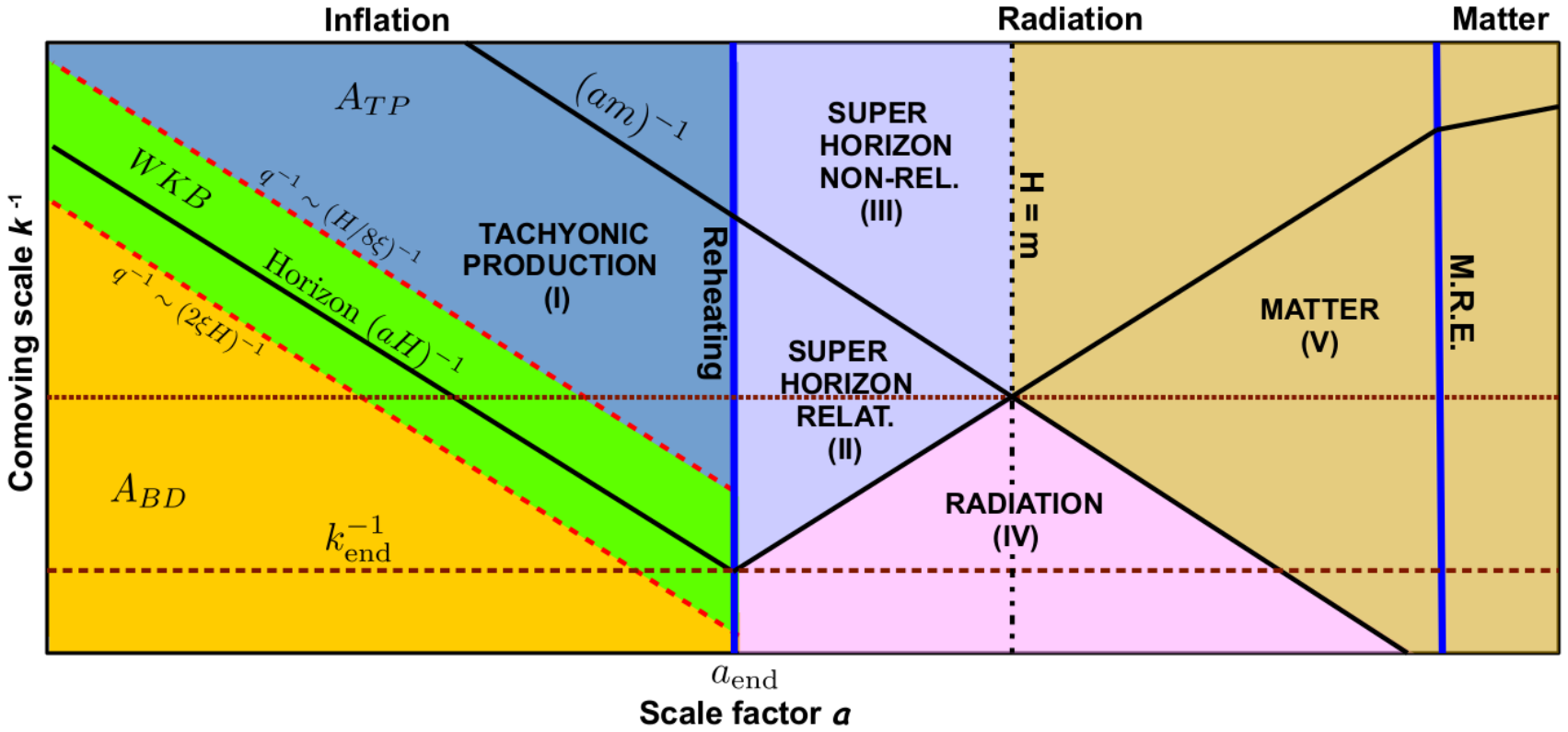
Cosmological evolution: Late time energy density spectrum

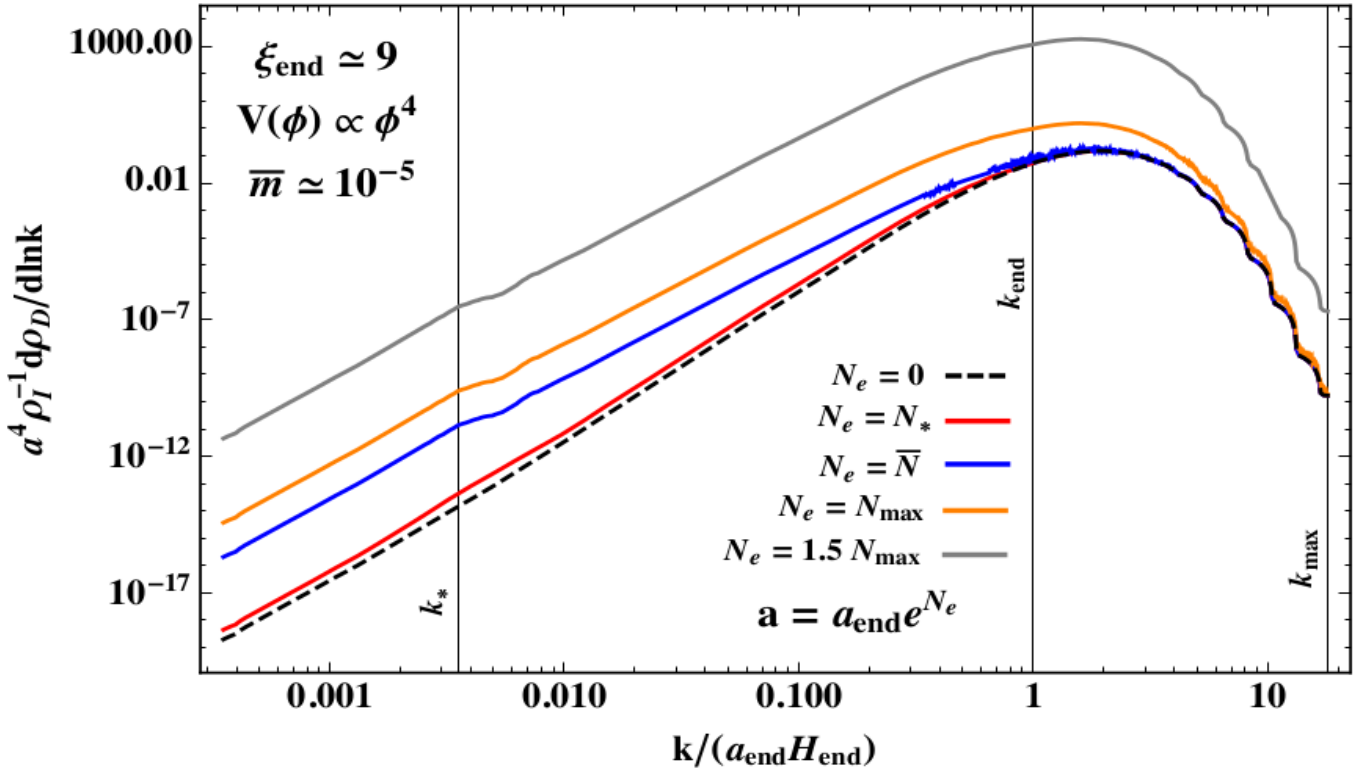


We need to solve EOMs for different modes in different regions after inflation

$$\ddot{A}_T + H\dot{A}_T + \left(\frac{k^2}{a^2} + m_A^2\right) A_T = 0$$

Cosmological evolution: Late time energy density spectrum

$$\frac{d\rho_{A_T}}{d\ln k} = \frac{k^3}{4\pi^2 a^2}\left(H^2 a^2 |\partial_a A_T(k)|^2 + \left(\frac{k^2}{a^2} + m^2\right)|A_T(k)|^2\right)$$



[Preliminary]

$N_* : k_*$ NR

$\overline{\mathbf{N}} : k_{end}$ NR

$N_{max} : k_{max}$ NR

- We have a **peak** at late times → Implications for structure/clumping?
- Scale at the end of inflation → scale of VDM clumping (coherence)

Summary

•The nature of DM still remains ellusive….

• Inflation needed in order to solve the standard cosmological problems and generate the seeds for large scale structure, but no much information on the detailed mechanism (inflationary scale? scalar field potential?)

• An Abelian (massive) vector field coupled to the inflaton and exponentially produced during inflation could account for the dark matter abundace

$$O(\mu eV) \leq m_A \leq O(GeV)$$

• Production of vector fluctuations takes place during inflation, with a characteristic spectrum peaked at the end of inflation: **signal in the matter power spectrum today?**

• Only one of the polarized states is produced : **polarized DM?**

• Small kinetic mixing with visible photon? : **Detection?**