A New Production Mechanism for Dark Photons

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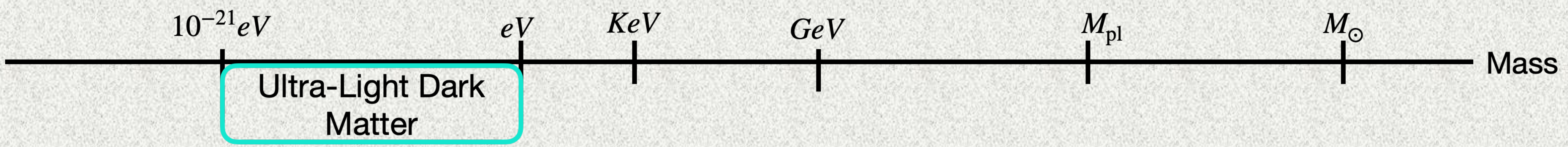
Introduction

Recent interest in ultra-light dark matter



Dark photons hard to produce non relativistically due to spin

Graham, Mardon, Rajendran, PhysRevD.93.103520
Co, Pierce, Zhang, Zhao, PhysRevD.99.075002
Agrawal, Kitajima, Reece, Sekiguchi, Takahashi, physletb.2019.135136

Single Derivative Coupling

Production of scalar DM is easy to achieve, by “Misalignment mechanism”.

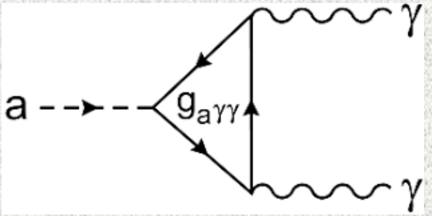
Is it possible to convert the scalar DM into a vector DM while keeping it cold?

$$\mathcal{L}_{\rm int} = \frac{\phi}{2f} F \tilde{F}_d$$

Massless U(1)

Massive U(1)

Cosmogenic Magnetic Field



$$\frac{\phi}{f_{a\gamma}} F\tilde{F} \qquad \frac{\phi}{f_D} F_D \tilde{F}_D \qquad \frac{\phi}{f} F \tilde{F}_d$$

On the other, EW phase transitions can create large scale Magnetic field

$$B^2 \sim 10^{-2} \rho_\gamma$$

$$\frac{B}{f} \gg H \sim \frac{\sqrt{\rho_\gamma}}{m_{pl}}$$

Baym, Bodeker, McLerran, PhysRevD.53.662

Homogeneous magnetic field

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = \frac{B(t)}{af} \dot{A}_D$$

$$\ddot{A}_D + H\dot{A}_D + m_A^2 A_D = -a\frac{B(t)}{f}\dot{\phi}$$

If the Magnetic field is homogeneous, the scalar and the dark vector do not source the electromagnetic field, so its dynamics can be completely ignored. The dynamics of the scalar and the vector remain homogeneous. Assume the scalar mass to be unchanging.

$$\left.\frac{B}{f}\right|_i \gg H, m_\phi, m_A \qquad m_\phi > m_A$$

Static universe

Ignoring the expansion of the universe, the instantaneous eigenmodes have

$$\omega_s^2 \approx \frac{m_\phi^2 m_A^2}{b^2 + m_\phi^2}$$

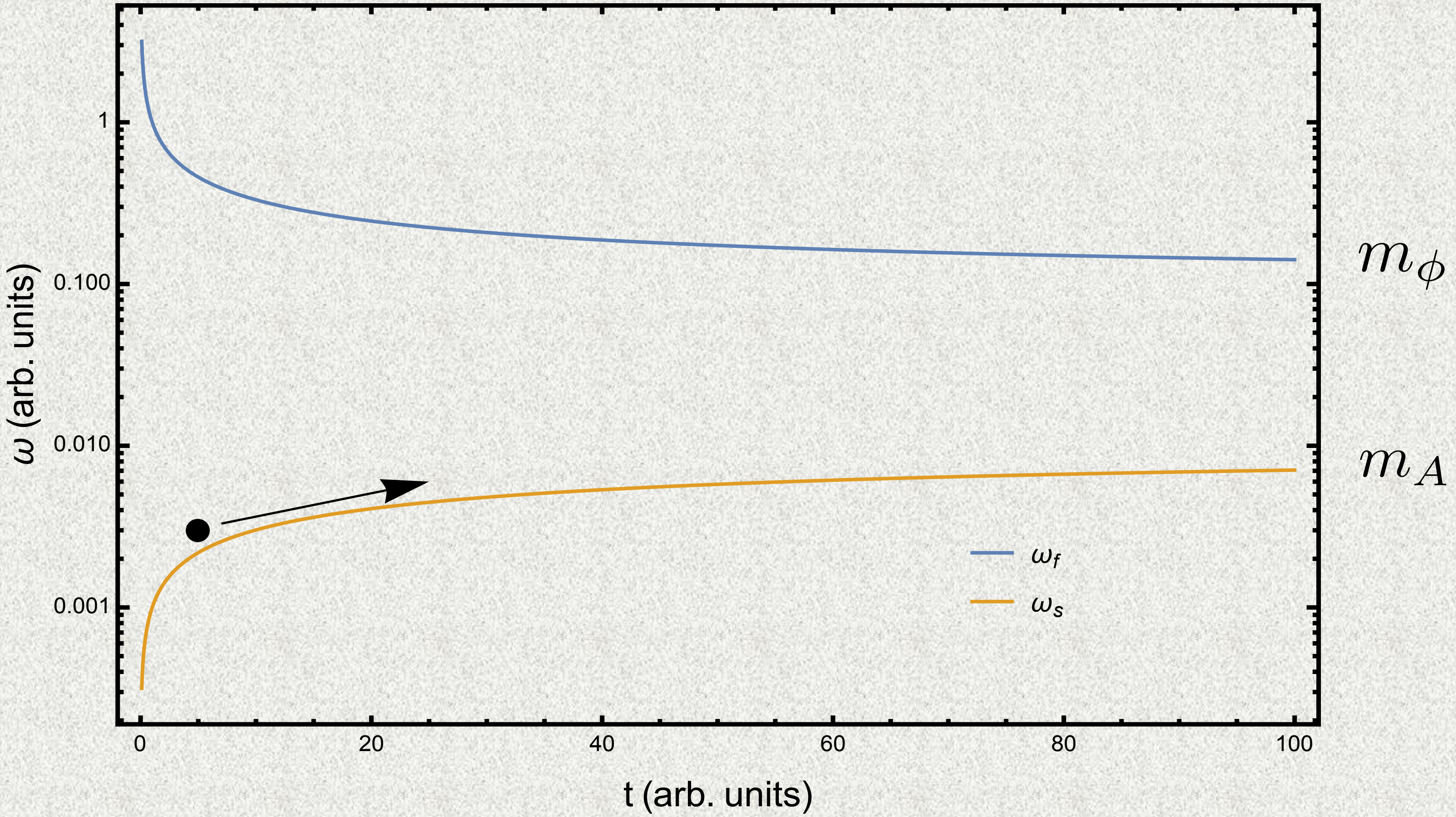
$$\omega_f^2 \approx b^2 + m_\phi^2$$

Where $b = B/f$ and we assumed $b, m_\phi \gg m_A$

The cosmological initial condition predominantly excite the slow mode

$$\dot{\phi} = A_D = \dot{A}_D = 0$$

Static universe



The state is adiabatically converted into vector

Expanding Universe

$$\frac{B}{f} \gg H \sim \frac{\sqrt{\rho_\gamma}}{m_{pl}}$$ Conversion is always efficient

Two important time scales:

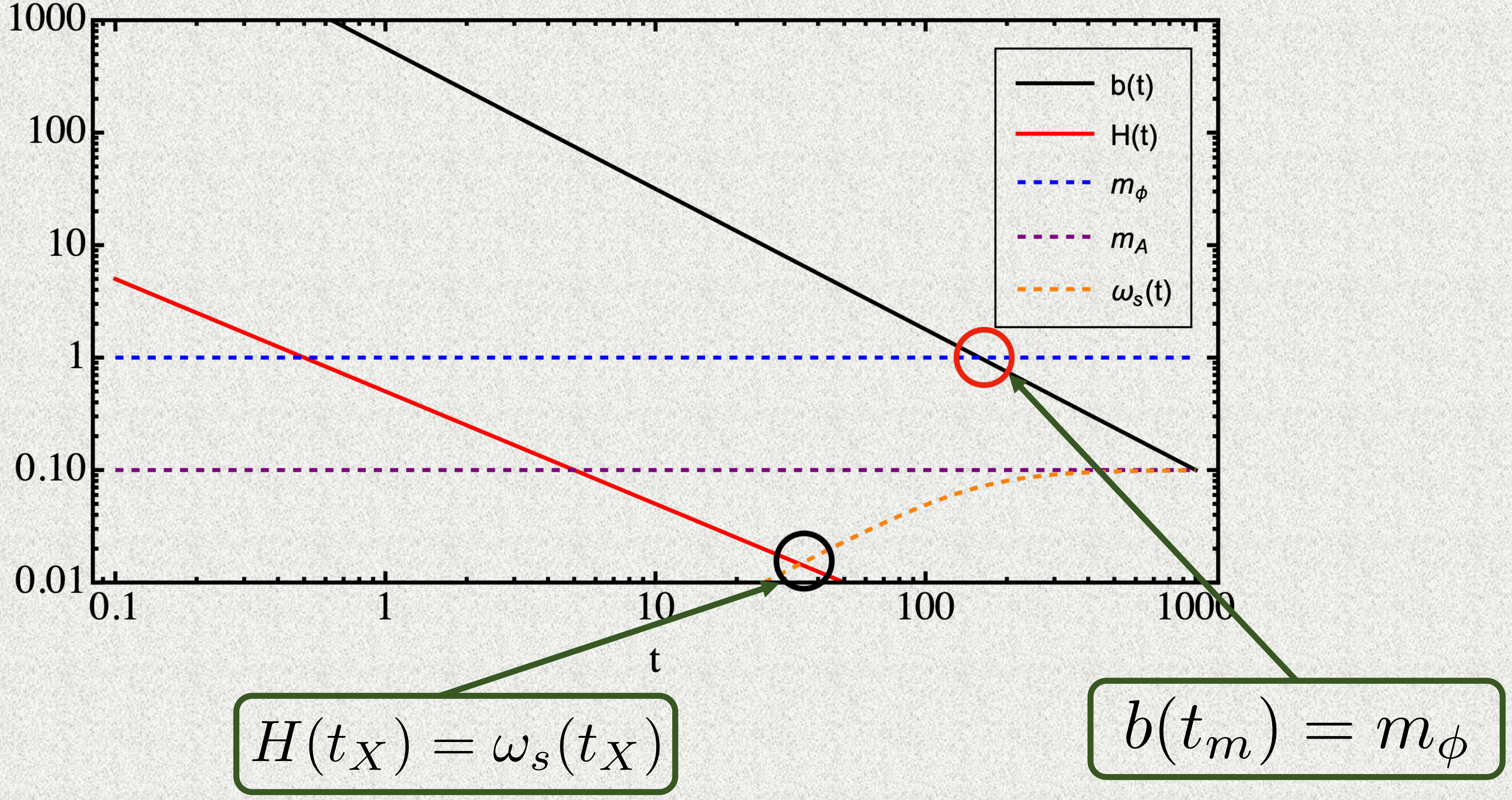
$H(t_X) = \omega_s(t_X)$: The slow mode begins to oscillate

$b(t_m) \equiv \frac{B(t_m)}{f} = m_\phi$: Mixing is unimportant. Slow mode becomes the vector mode

$t_X < t_m$: The vector glides

$t_m < t_X$: The vector behaves like radiation

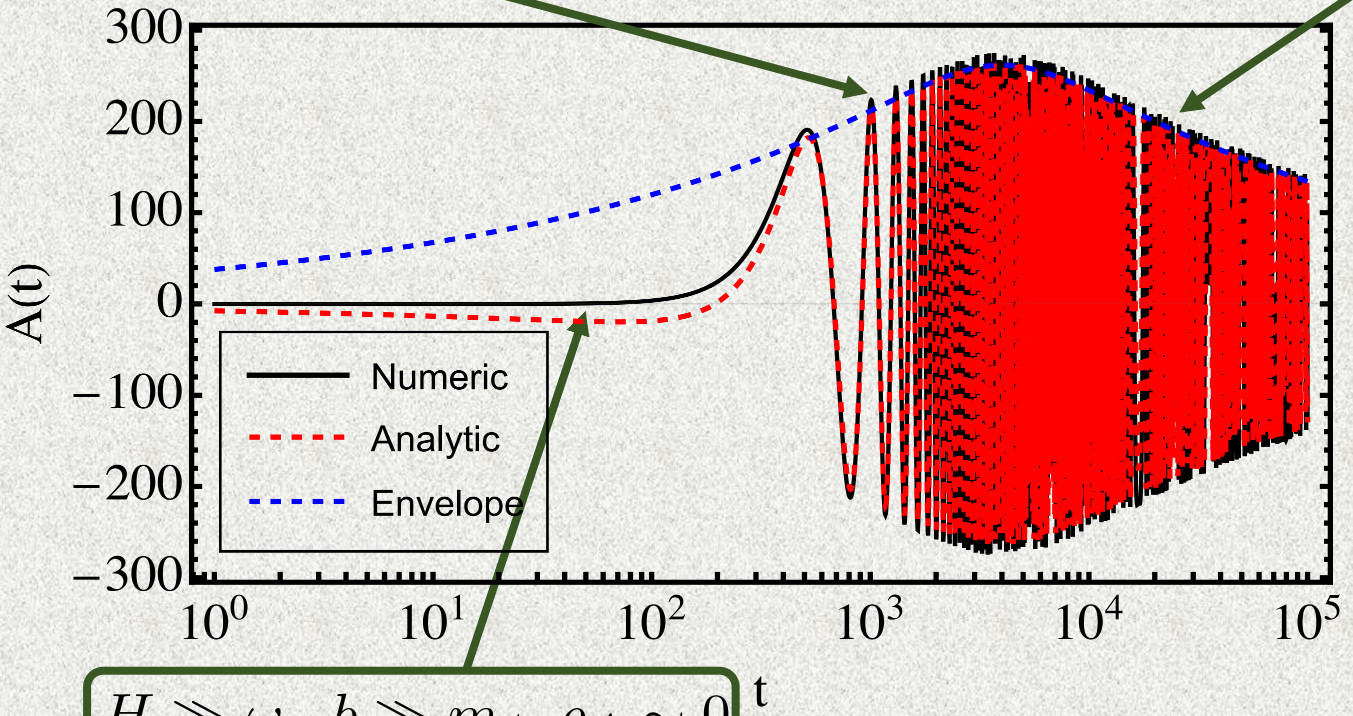
Gliding


1000
100
10
1
0.10
0.01
0.1
1
10
100
1000
t
b(t)
H(t)
m_ϕ
m_A
ω_s(t)
$H(t_X) = \omega_s(t_X)$
$b(t_m) = m_\phi$

Gliding

$H \ll \omega_s, b \gg m_\phi, A \sim \sqrt{a}, \rho_A \sim a^{-1}$

$H \ll \omega_s, b \ll m_\phi, A \sim a^{-1/2}, \rho_A \sim a^{-3}$

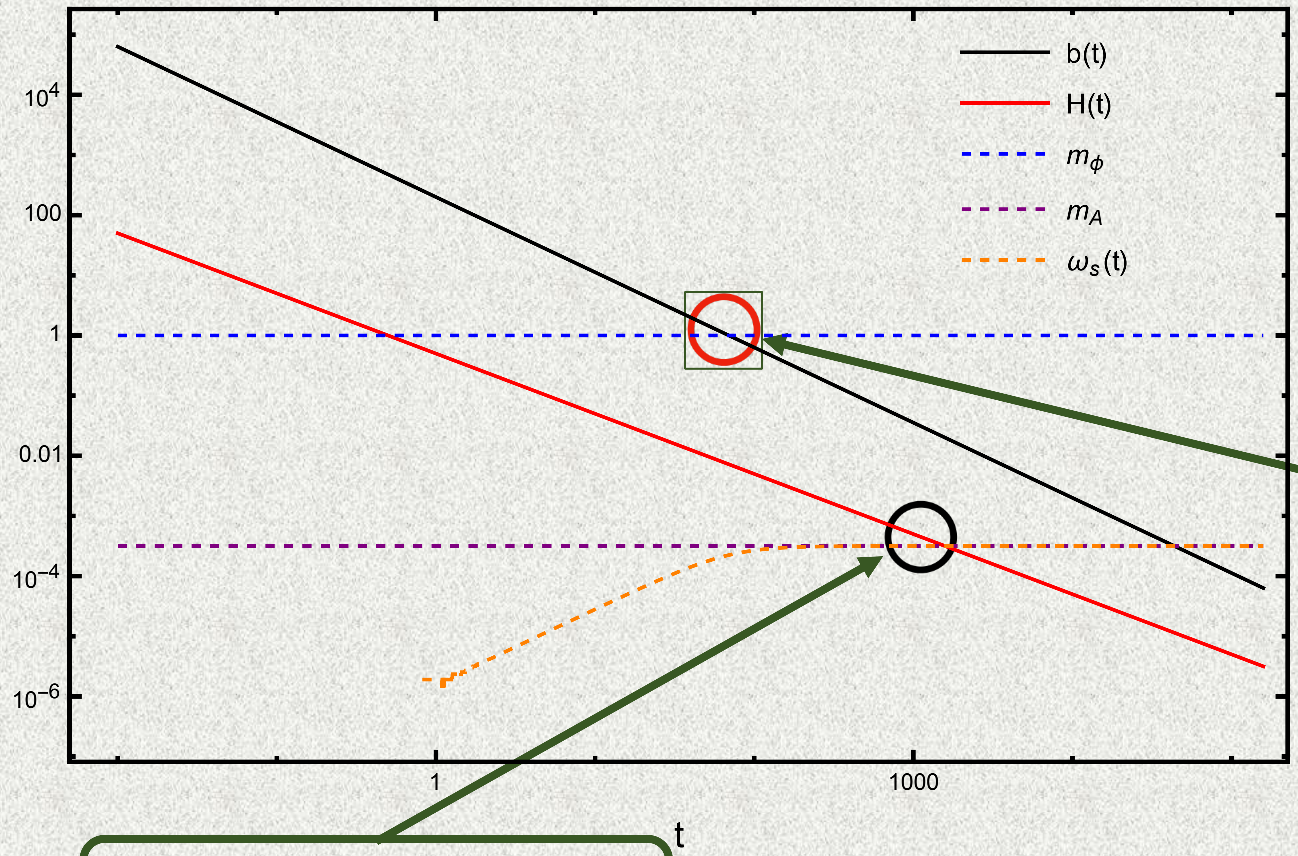


$H \gg \omega_s, b \gg m_\phi, \rho_A \sim 0$

The energy density redshifts slower than matter

Hook, Marques-Tavares, Tsai, PhysRevLett.124.211801

Radiation like behavior



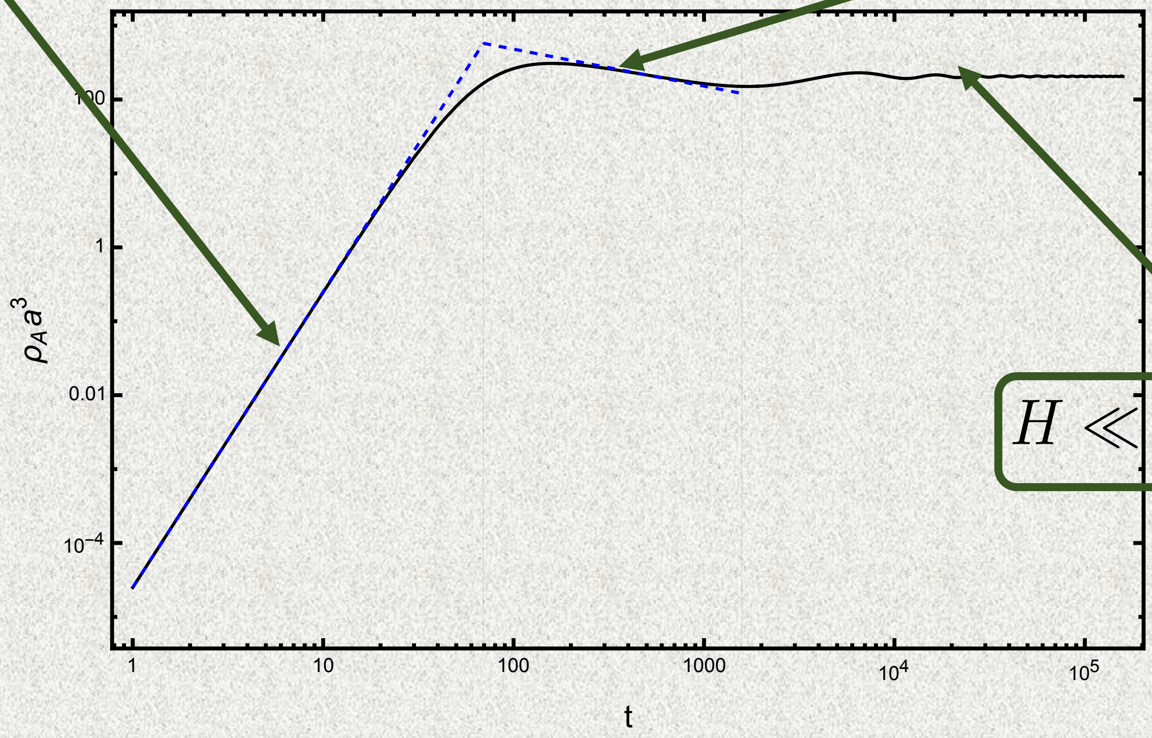
$$b(t_m) = m_\phi$$

$$H(t_X) = \omega_s(t_X)$$

Radiation like behavior

$H \gg \omega_s, b \gg m_\phi, \rho_A \sim 0$

$H \gg \omega_s, b \ll m_\phi, \rho_A \sim a^{-2}\dot{A}^2 \sim a^{-4}$



$H \ll \omega_s, b \ll m_\phi, \rho_A \sim a^{-3}$

The energy density redshifts like radiation.

Inhomogeneous Magnetic Field

Inhomogeneities in the Magnetic field can significantly decrease the conversion efficiency

$$k_B \sim a^{-3/2}$$

Both analytics and numerics are difficult.

Work in Progress

Summary

- A misaligned scalar can be fully converted to dark photons in the presence of a large homogeneous magnetic field.

- The dark photon behaves like nonrelativistic DM in the late Universe.

- The total amount of dark photon dark matter depends on the masses of both the scalar and the dark photon.

- The inhomogeneities in the magnetic field could decrease conversion.

Thank you

Back up slide

Possible parameter space