The Imprint of Ultralight Vector DM on Gravitational-Wave Propagation

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Phys.Rev.D 103 (2021) 12, 123546 · arXiv:2012.07505

Workshop on Very Light Dark Matter · September 2021

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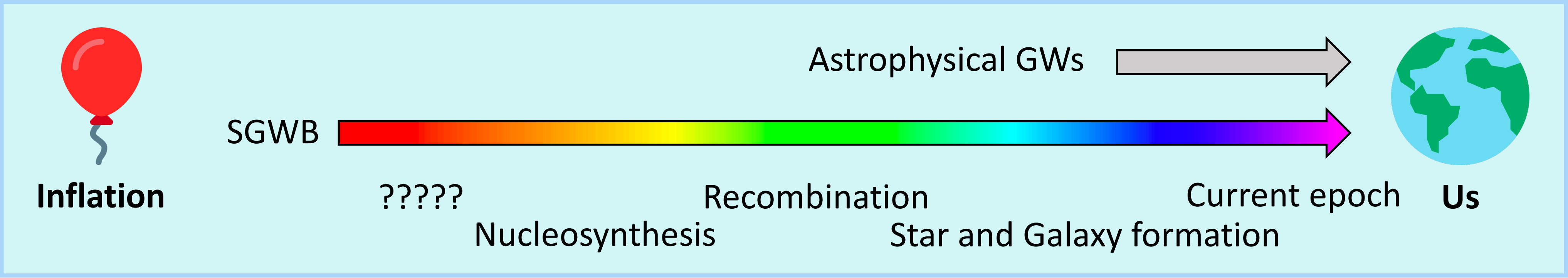
INTRODUCTION – GWS AND COSMOLOGY

- GWs have opened a window of opportunity for new observations.
- Stochastic GW Background is predicted by all models of inflation:
  - **Primordial**: Carries information from remote epochs.
  - **Spectrum**: Wide range of frequencies.

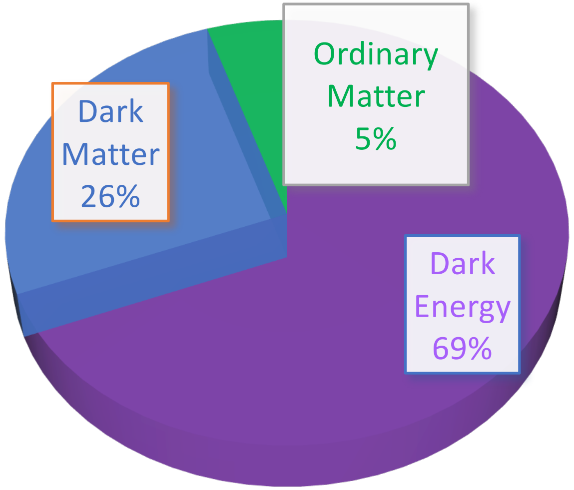


- Expected to be detected in 2020s? → CMB B-mode polarization (LiteBIRD, BICEP array…).
- Powerful tool to explore new physics. In our case, ultra light vector dark matter.

INTRODUCTION – ULTRALIGHT VECTOR DARK MATTER

- We do not know the nature of most of the content in our Universe.
- Ultralight fields ($m \ll 1\text{eV}$) are a possibility for dark matter (Nelson&Scholtz, 2011; Cembranos et al., 2017)
- Vectors growing in popularity.
- Described as classical fields (BE condensate)
- Production: Misalignment, at the end of inflation…
- Can have a different impact on some observables.

OUR UNIVERSE



Our Model: The Dynamics

- Ultralight vector dark matter.

$$S = \int dx\sqrt{g}\left(-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{m^2}{2}A_\mu A^\mu\right)$$

- Linearly polarised $A_\mu = (A_0, 0, 0, A_z)$

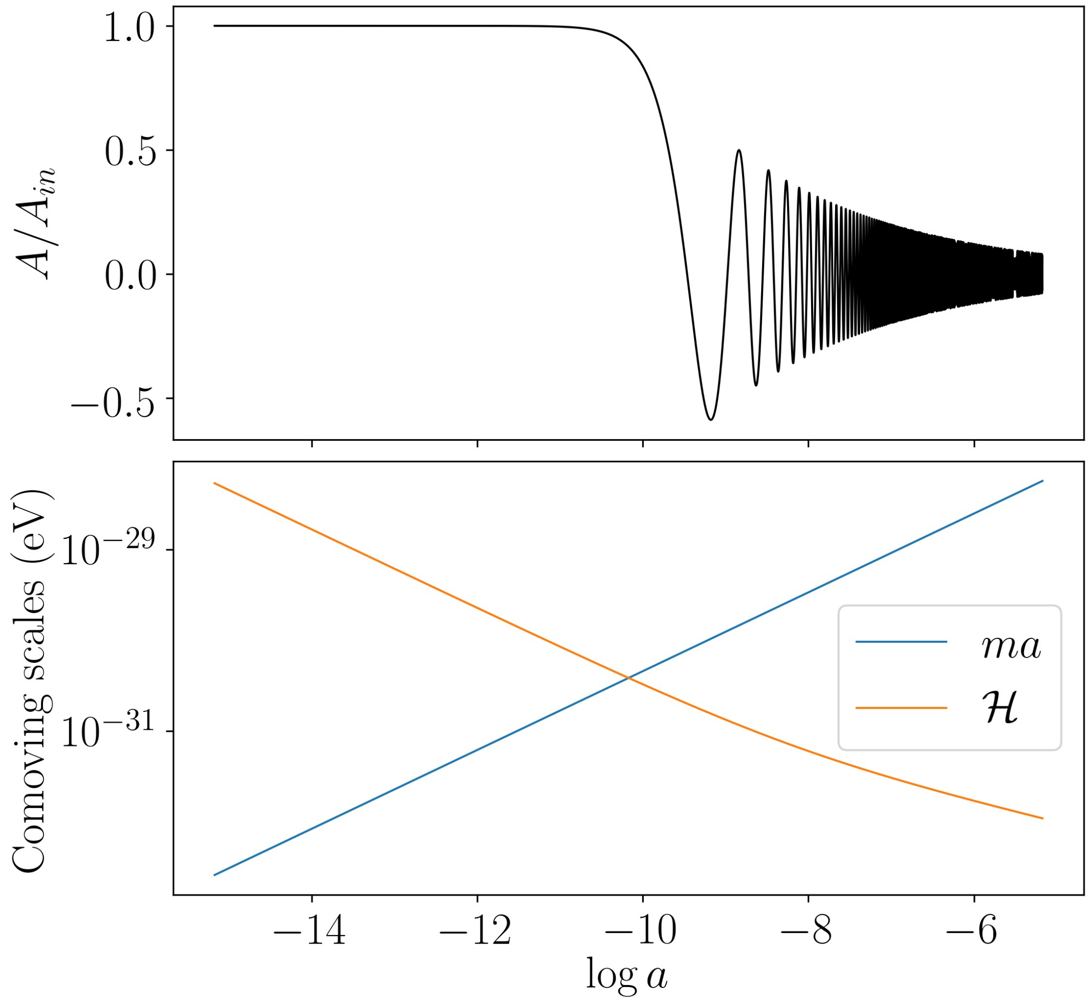
$$F^{\mu\upsilon}{}_{;\upsilon} - m^2 A^\mu = 0 \begin{cases} m^2 A_0 = 0, \\ A_z'' + m^2 a^2 A_z = 0 \end{cases}$$

- WKB ($ma \gg \mathcal{H}$) valid solution:

$$A_z(\eta) = A_0 a^{-1/2}(\eta)\cos\int^{\eta} ma(\eta')d\eta'$$

Primordial
Constant regime
Behaves as $\rho \propto a^{-2}$

Current
WKB regime
Behaves as matter
$\rho \propto a^{-3}, \langle p \rangle = 0$



Our Model: it is Matter, indeed

- Energy density:

$$\rho_A = T^0_0 = \frac{A_z'^2}{2a^4} + \frac{m^2}{2a^2}A_z^2$$

- In WKB regime, $\rho_A \propto a^{-3}$.
- Anisotropic pressures average out, $\langle p \rangle = 0$
- Satisfies the isotropy theorem for coherent oscillating vector fields (Cembranos et al., 2012)
- We want the MR equality to remain unaffected $\rightarrow m \geq 10^{-27}$eV.

Primordial
Constant regime
Behaves as $\rho \propto a^{-2}$

Current
WKB regime
Behaves as matter
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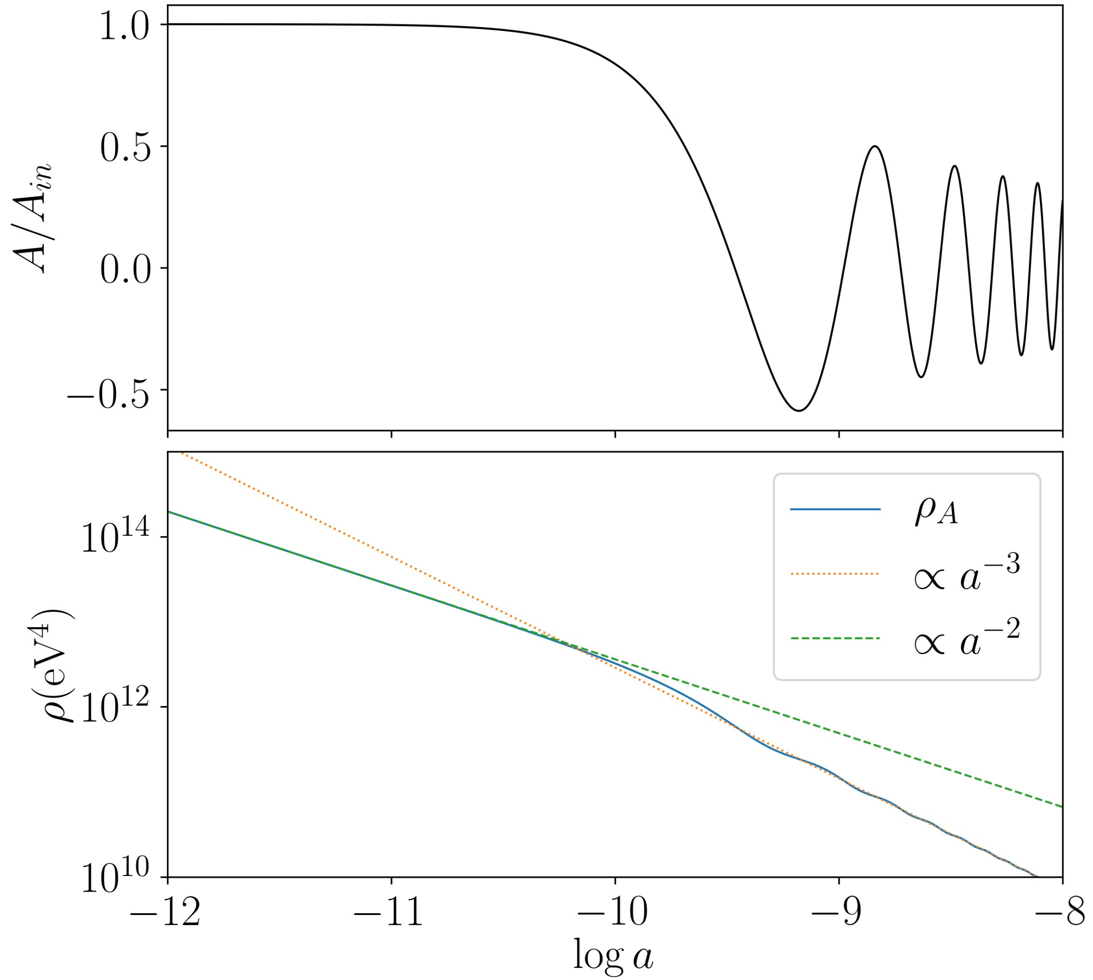


GW-Propagation Modification

$$\delta G_{ij}^{(TT)} = 8\pi G\, \delta T_{ij}^{(TT)}$$

Geometric Side

$$\delta G_{ij}^{(TT)} = -\frac{1}{2a^2}\left(h_{ij}'' + 2\mathcal{H} h_{ij}' + k^2 h_{ij}\right)$$

- h_{ij} describes tensorial perturbations (GWs)
- Two degrees of freedom: (+, x) polarizations.

Content of the Universe Side

$T_{ij}^{(TT)}(g_{\mu\nu}, A_\mu)$, with A_μ the new vector field

$$\Downarrow$$

$$\delta T_{ij}^{(TT)} \propto \begin{cases} \delta A & \Rightarrow \text{~~Source terms~~} \\ \delta g \equiv h_{ij} & \Rightarrow \text{Propagation!} \end{cases}$$

~~Source terms~~ (Cembranos et al. 2017)

Propagation!

Our Model: The Effect on GWs

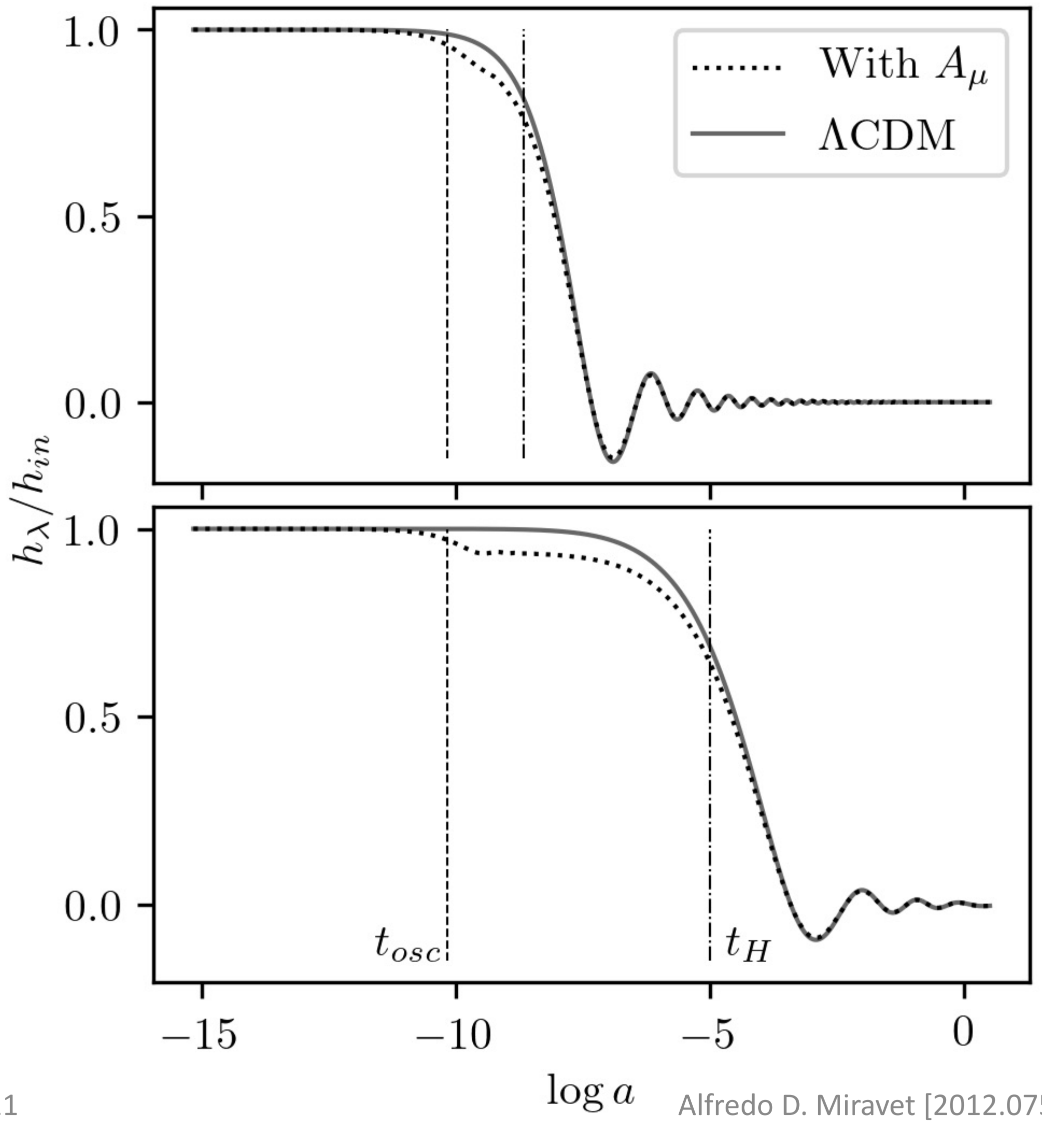
- The propagation equation is modified

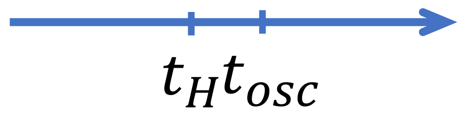
$$h_\lambda'' + 2\mathcal{H} h_\lambda' + \left[k^2 - 8\pi G \sin^2\vartheta \left(\frac{A'^2}{2a^2} - \frac{m^2}{2} A^2\right)\right] h_\lambda = 0$$

- Anisotropic effect: $\cos\vartheta = \hat{k} \cdot \hat{A}$
- The evolution is governed by two events:
  - The mode enters the Hubble horizon ($k = \mathcal{H}$) at $t = t_H$.
  - The fields starts oscillating ($ma = \mathcal{H}$) at $t = t_{osc}$.

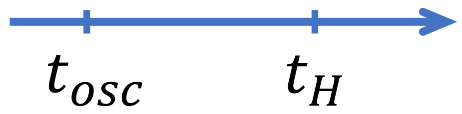
$t_H \ll t_{osc}$ No effect	$t_H \gg t_{osc}$ GW are affected	$t_H \approx t_{osc}$ Max. effect

OUR MODEL: THE EFFECT ON GWS (EXAMPLE)





$t_H \approx t_{osc}$
Max. effect



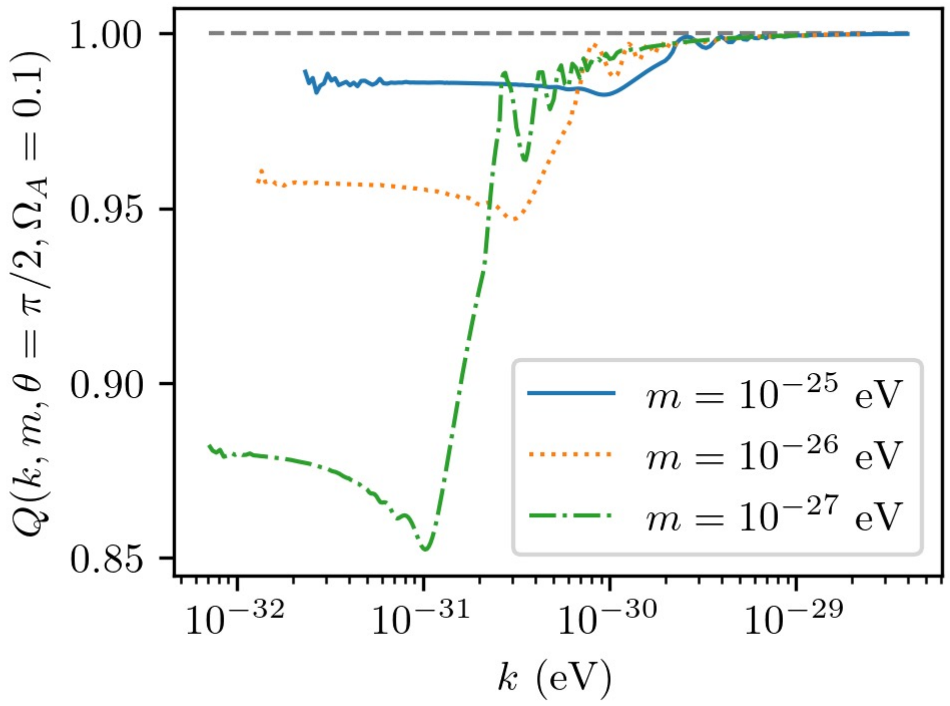
$t_H \gg t_{osc}$
GW are affected

Our Model: Results

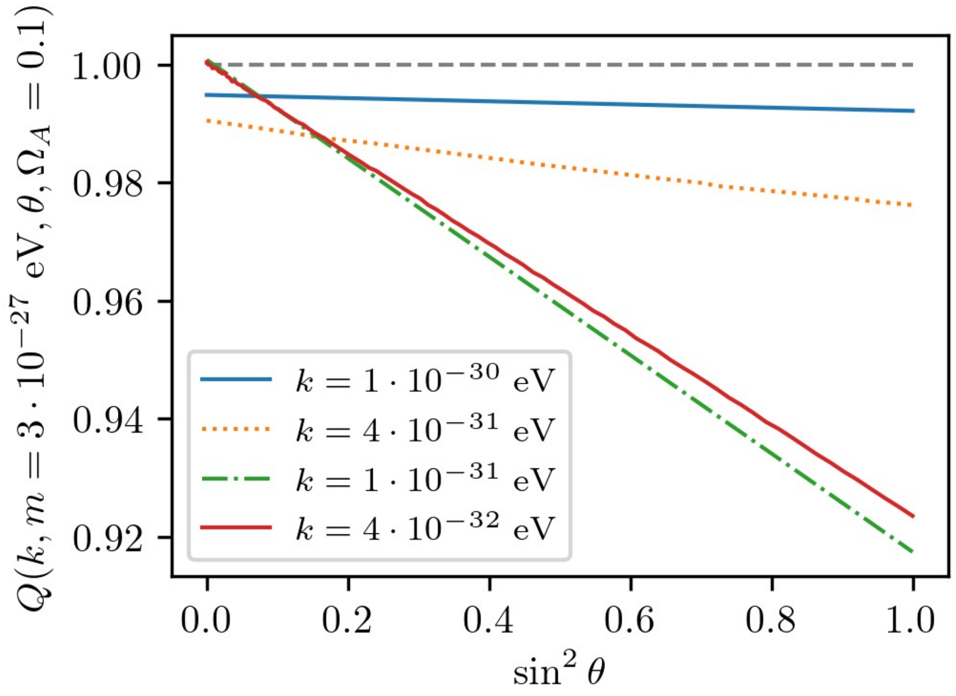
$$Q = \frac{|h(A \neq 0)|}{|h(A = 0)|}$$

Free parameters: (k, m, Ω_A, θ)

- For different masses: The suppression is larger for smaller masses.



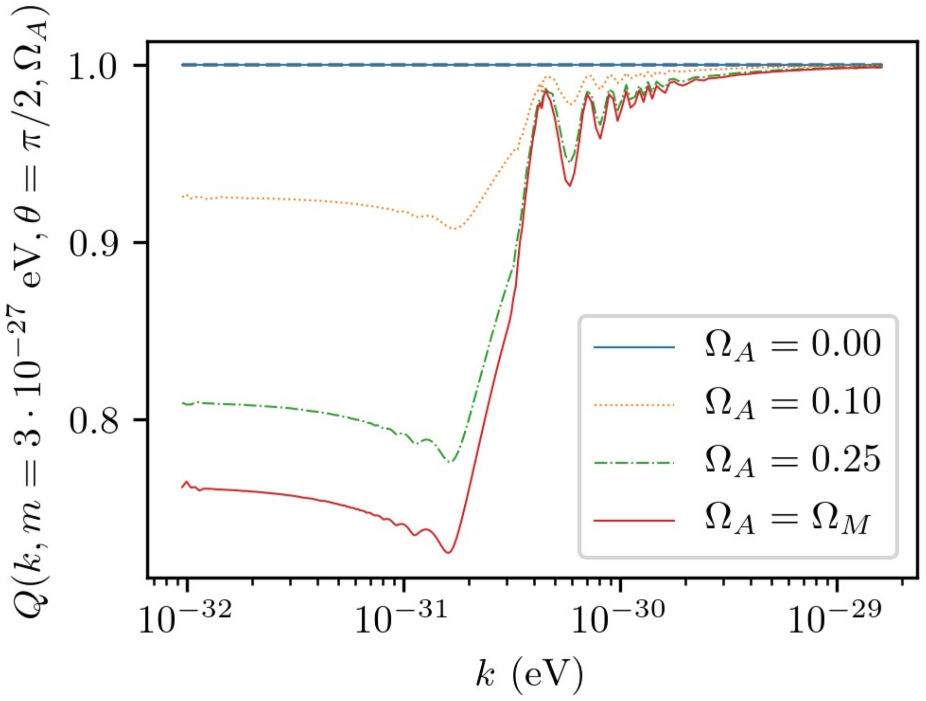
- For different angles: The suppression is anisotropic, highly correlated to $\sin^2\theta$.

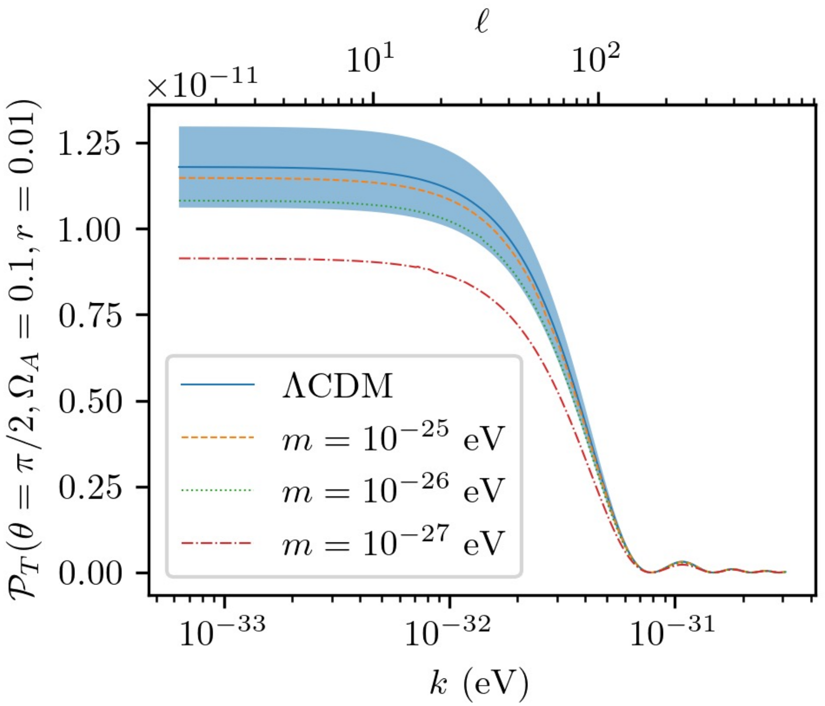


OUR MODEL: RESULTS (II)

- For <u>different abundances</u>: The suppression is larger for larger abundancies.

- There are some regions in the parameter space distinguishable from standard cosmology, with $\sigma(r) = 10^{-3}$ (LiteBIRD).





Discussion and Conclusions

- Ultralight vector dark matter produces a slight diminution in primordial GW amplitude.
- The effect is anisotropic.
- Possibility to be detected in the low multipole region of the CMB B-mode power spectrum.
- Little to no effect on astrophysical GWs.

Further (ongoing) work

SOON

$$V(A) = \lambda A^4$$

- Quartic potential
- Vector dark radiation
- Interesting phenomenology.

Thank you for your attention!

Questions?