The imprint of ultralight vector fields on gravitational wave propagation

Alfredo D. Miravet
alfrdelg@ucm.es

Departamento de Física Teórica and IPARCOS.
Universidad Complutense de Madrid

Based on 2012.07505 in collaboration with Antonio L. Maroto

17th MultiDark Consolider Workshop
January 26th, 2021

Ultralight vector dark matter

- Ultralight DM: Bosonic fields with very small masses $m \ll 1$ eV.
- Can be described as classical fields (B-E condensate).
- Interparticle separation $< \lambda_{\text{Compton}} \Rightarrow$ Alleviate some CDM small-scale issues.
- Scalars are the most common choice, but ULVF have been growing in popularity:
  - Spin-1 fields, $m \lesssim 10^{-20}$ eV.
  - Production at the end of inflation or by misalignment mechanism.
  - Can have an different impact on the CMB and pulsar timing signals.

Primordial Gravitational Waves

- Detection and confirmation in the last years.
- All detected sources are astrophysical, but cosmological GWs are expected.
- Observable not directly, but through low multipole ($\ell < 200$) region of CMB B-mode power spectrum.
- Have travelled from the end of inflation $\Rightarrow$ Sensitive to cosmological model changes.
- ULVF introduces a non-zero anisotropic stress $\delta T^i{}_j$ in the propagation equation.

ULVF dynamics in Cosmology

- Abelian VF action in RW background:

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

- Equation of motion: $F^{\mu\nu}{}_{;\nu} - m^2 A^\mu = 0.$
- Homogeneous field, linear polarization:

$$A_\mu(\eta) = (A_0(\eta), 0, 0, A_z(\eta))$$

$$m^2 A_0 = 0, \qquad A_z'' + m^2 a^2 A_z = 0.$$

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

$$A_z(\eta) = A_{z,0} a^{-1/2}(\eta) \cos \int^\eta m a(\eta') \, \mathrm{d}\eta' ,$$

- For earlier periods ($ma \ll \mathcal{H}$) $\Rightarrow A_z =$const.

ULVF evolution example

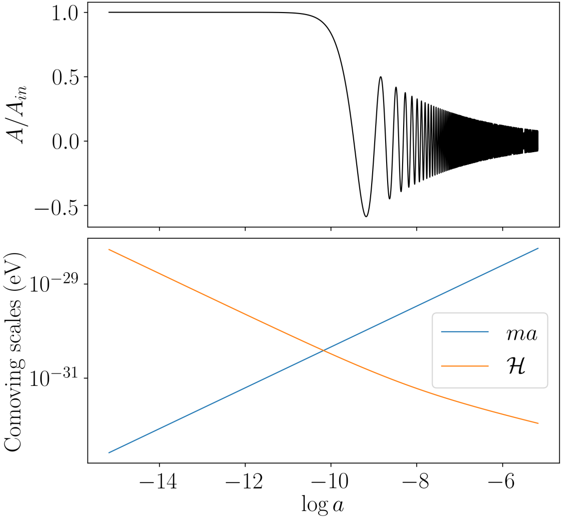


Figure: ULVF evolution with $m = 10^{-26}$ eV, $\Omega_A = 0.1$. Relevant comoving scales plotted below.

ULVF energy density

- The energy density:

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

  - For $ma \ll \mathcal{H}$ (earlier)$\Rightarrow \rho_A \propto a^{-2} \Rightarrow$ Curvature-like.
  - For $ma \gg \mathcal{H}$ (WKB)$\Rightarrow \rho_A \propto a^{-3} \Rightarrow$ Matter. Anisotropic pressures average to zero in the WKB regime. [Cembranos et al, 1311.1402]

- We want the M-R equality to remain unaffected$\Rightarrow m \gtrsim 10^{-27}$ eV.

- Abundance parameter today:

$$\Omega_A = \frac{\rho_{A,0}}{\rho_c}.$$

ULVF energy density example

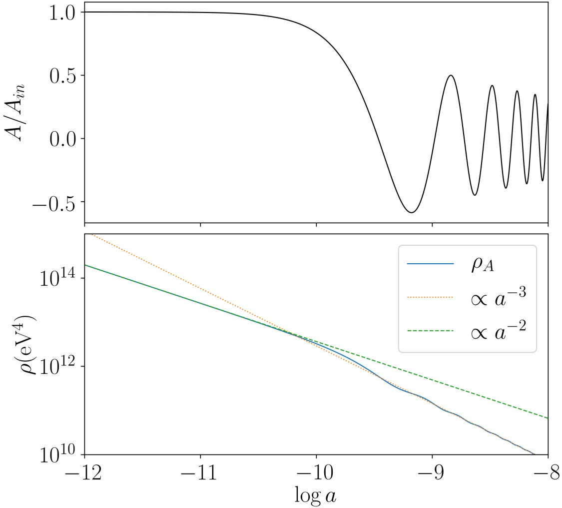


Figure: ULVF evolution with $m = 10^{-26}$ eV, $\Omega_A = 0.1$ and its energy density. Different scalings are shown for comparison.

The effect on GW propagation

- TT projection of metric-perturbed Einstein equation:

$$\Lambda_{ij,lm}(\delta G^l{}_m - 8\pi G \delta T^l{}_m) = 0$$

- We omit source terms and focus on propagation:

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

- $\cos\theta \equiv \hat{k} \cdot \hat{A}$. Anisotropic effect.
- The new term is constant early on; oscillates in WKB regime.
- Interest on modes with $k^2 = H_0^2/a_*$ with $m a_* = \mathcal{H}(a_*) \Rightarrow$ Depends on mass.

GW propagation example

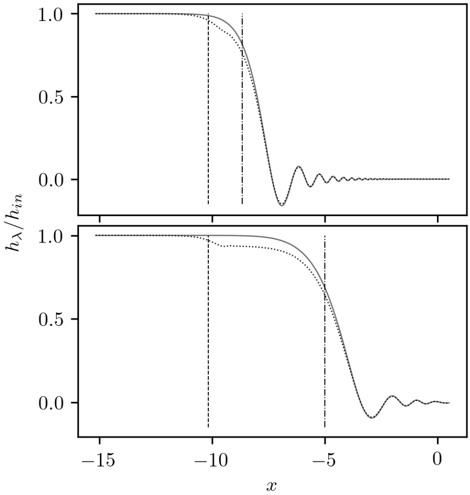


Figure: GW evolution with and without ULVF for $k = 10^{-31}$ eV (above) and $k = 10^{-32}$ eV (below). Parameters are $m = 10^{-26}$ eV, $\Omega_A = 0.25$, $\theta = \pi/3$

Transfer functions and Power Spectrum

- The change from ΛCDM is quantified with the quotient function:

$$Q(k, m, \theta, \Omega_A) = \frac{|h_{\lambda,\Lambda\mathrm{CDM+A}}(k, m, \theta, \Omega_A)|}{|h_{\lambda,\Lambda\mathrm{CDM}}(k)|}.$$

- The today-primordial ratio within ΛCDM is the transfer function:

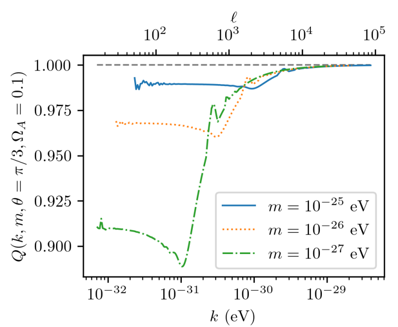
$$h_{\lambda,\Lambda\mathrm{CDM}}(k, \eta_0) = T(k) h_{\lambda,\Lambda\mathrm{CDM}}(k, \eta_{in})$$

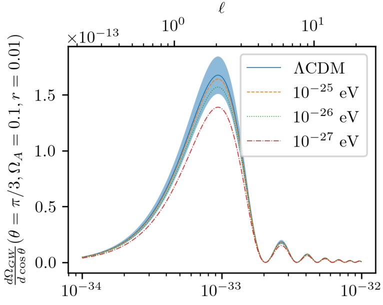
- GW abundance today (anisotropic):

$$\frac{\mathrm{d}\Omega_{GW}}{\mathrm{d}\cos\theta} = \frac{k^2}{24H_0^2} r(k_*) A_{\mathcal{R}}(k_*) \left(\frac{k}{k_*}\right)^{n_T} |T(k)|^2 |Q(k, m, \theta, \Omega_A)|^2.$$

Results: Suppression

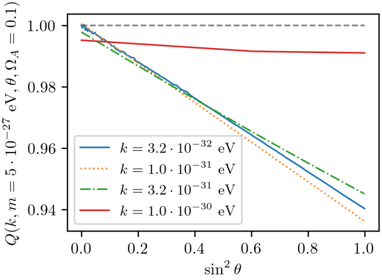
- For different masses:
  - The suppression effect is larger for smaller masses.
  - The k with maximum deviation $k_{\min}$ depends on mass, and increases with m.
- Clear asymptotic behaviour.
- Some regions in the parameter space are distinguishable from ΛCDM with typical r, $\sigma(r) = 10^{-3}$ (LiteBIRD).

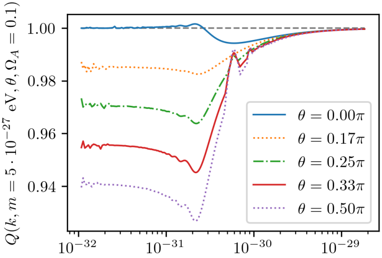




Results: Anisotropy

- Anisotropic effect, highly correlated to $\sin^2\theta$ (quadrupolar modulation).
- $\theta = 0$ means no coupling in the propagation Eq., but ULVF still present in the background $\Rightarrow$ Non-zero small effect.
- Making θ closer to $\pi/2$ makes the deviation larger. No displacement in k.





Discussion and conclusions

- ULVF produce a slight diminution in primordial GW amplitudes in a certain region in k.
- The effect depends on θ, it is anisotropic. Quadrupolar modulation.
- Possibility to detect for smaller masses ($m \lesssim 10^{-26}$ eV) in low-multipole region $\ell \leq 200$ with current and forthcoming B-mode detectors $\sigma(r) < 0.001 \sim 0.006$ (BICEP, Simons, LiteBIRD...) given typical inflationary $r = 0.01$.
- Direct observation from interferometers and PTAs is far from possible currently. Only B modes.
- No effect on astrophysical GWs.
- Extensions and prospects:
    - Computation of B-mode power spectrum with Boltzmann code.
    - Analyse more complicated potentials.

Thank you for your attention!
Questions?