Ultralight dark photon can resolve the Hubble tension problem

Igor Samsonov

UNSW

3 December 2019, TeVPA 2019

Based on: V.V. Flambaum, I.B. Samsonov, Phys.Rev. D100 (2019) 063541.

Hubble constant

$$H_0 \approx 70 \frac{\text{km}}{\text{s} \cdot \text{Mpc}}$$

Hubble constant tension problem

- Local measurement
(Supernovae & Cephidae)
[Riess et al. 2016, 2018]

- *Planck* measurement
(CMB+BAO)
[Planck Collaboration 2018]

$$H_0 = 73.24 \pm 1.74 \frac{\text{km}}{\text{s} \cdot \text{Mpc}}$$

Vs

$$H_0 = 66.93 \pm 0.62 \frac{\text{km}}{\text{s} \cdot \text{Mpc}}$$

Disagreement is more than 3σ !

Axion field evolution

[V. Poulin, T. L. Smith, D. Grin, T. Karwal, M. Kamionkowski, 2019]

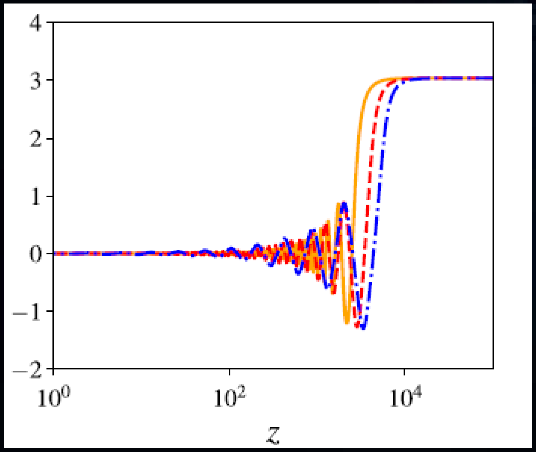
Homogeneous scalar field evolution

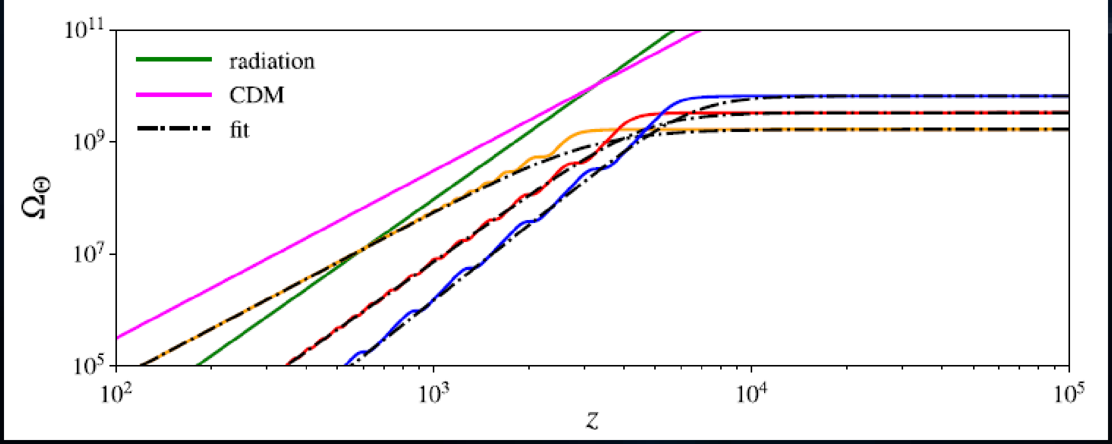
$$\ddot{\phi} + 3H\dot{\phi} + V_n' = 0$$

Axion potential

$$V_n(\phi) = \Lambda^4 \left(1 - \cos\frac{\phi}{f}\right)^n$$

Energy density evolution





Axion field solution of the Hubble tension problem

[V. Poulin, T. L. Smith, D. Grin, T. Karwal, M. Kamionkowski, 2019]

Extension of the ΛCDM model:

$$H(a) = H_0 \sqrt{\Omega_{\text{mat}}(a) + \Omega_{\text{rad}}(a) + \Omega_\Lambda + \Omega_\phi(a)}$$

Sound horizon of BAO:

$$r_s = \int_0^{a_*} \frac{c_s(a)da}{H(a)} \overset{!}{=} 146.8 \pm 1.8 \text{ Mpc}$$

- a_* =1/(z_* – 1), z_* =1090 is the redshift at recombination time;
- c_s is the sound speed in primordial plasma
- Scalar field ϕ behaves as radiation and amends the size of sound horizon of BAO (similar to N_{eff} effect).
- For certain values of the parameters this resolves the Hubble tension problem.

Dark photon as dark matter candidate

[Holdom & Galison, Manohar 1984]

- Visible photon γ

$$A_\mu: \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- Dark photon γ'

$$A'_\mu: \qquad F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$$

- Lagrangian

$$L = -\tfrac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{m^2}{2} A'^{\mu} A'_\mu + \chi \cdot F'^{\mu\nu} F_{\mu\nu}$$

- χ is small, A' is almost unobservable
- m is small, no spontaneous decay

Massive vector field in expanding universe

- Homogeneous vector field in FRW universe

$$\ddot{\vec{A}} + \frac{\dot{a}}{a}\dot{\vec{A}} + m^2\vec{A} = 0$$

- In the radiation-dominated epoch, $a \sim \sqrt{t}$

$$\vec{A}(t) = \vec{A}_0 \cdot (mt)^{\frac{1}{4}}\left(c_1 J_{\frac{1}{4}}(mt) + c_2 Y_{\frac{1}{4}}(mt)\right)$$

- Energy density for this solution

$$\Omega_A(a) \sim \begin{cases} a^{-4} & \text{for} \quad t < m^{-1} \\ a^{-3} & \text{for} \quad t > m^{-1} \end{cases}$$

(Radiation)

(CDM)

Anisotropy

- Single homogeneous vector field creates anisotropy of the universe
- A triplet of mutually orthogonal vector fields (A_1, A_2, A_3) with the same mass and magnitude preserves isotropy
- Alternatively, large number N of randomly oriented vector fields also preserve approximate isotropy (see e.g. vector inflation, [Golovnev, Mukhanov, Vanchurin, 2008]). Anisotropy $\sim N^{-1/2}$
- Further we assume one of these scenarios

Vector field extension of the ΛCDM model

- Assume that some (small) fraction of Dark Matter is represented by the massive vector field A with equation of state w and energy density Ω_A

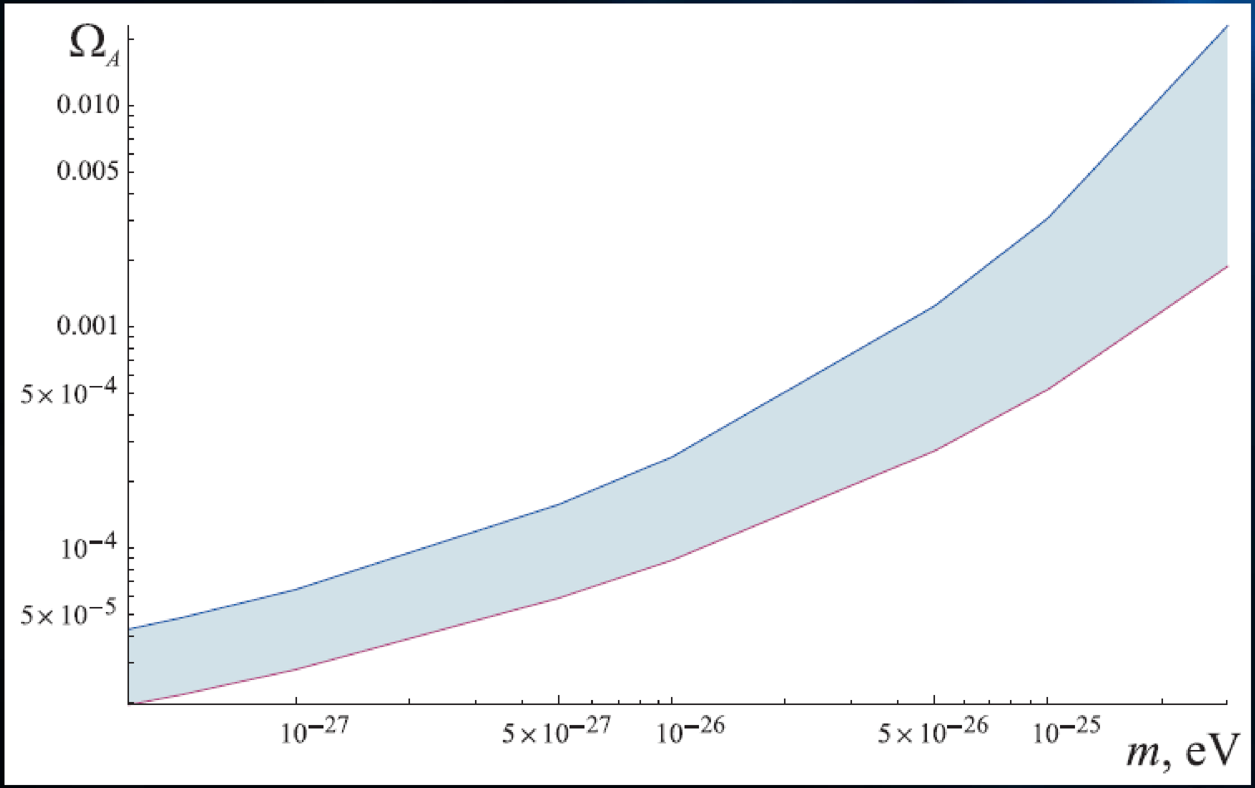
$$H(a) = H_0 \sqrt{\Omega_{\text{rad}} a^{-4} + (\Omega_{\text{matt}} - \Omega_A) a^{-3} + \Omega_A a^{3(w+1)} + \Omega_\Lambda}$$

- This changes the size of the sound horizon unless the Hubble constant is amended

$$r_s = \int_0^{a_*} \frac{c_s(a)\,da}{H(a)} \overset{!}{=} 146.8 \pm 1.8\ \text{Mpc}$$

Resolution of the Hubble tension problem

- It is possible to fit the parameters of the model to satisfy H_0=73 km s^{-1} Mpc^{-1} and r_s=146.8±1.8 Mpc



Summary

- A (small) fraction of Dark Matter may be represented by the massive vector field (dark photon)
- The massive vector field may be produced non-thermally in the early universe. It behaves as radiation for $t<m^{-1}$, but is for $t>m^{-1}$ it becomes CDM
- When it behaves as radiation, it changes the expansion rate of the universe and affects the sound horizon of BAO.
- This resolves the Hubble tension problem for certain values of the parameters.