

Ultra Light Dark Matter from Thermal Neutrinos

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Outline

- Ultralight boson with a huge population can be a cold dark matter candidate

$$\frac{n_\phi}{s} \sim 10^{19} \frac{10^{-20} \text{eV}}{m_\phi}$$

- It can be generated by a misaligned initial amplitude leading to a coherent oscillation: (ex) QCD axion with instanton potential.
- Thermal fermions (neutrinos) may be the origin of the misalignment.

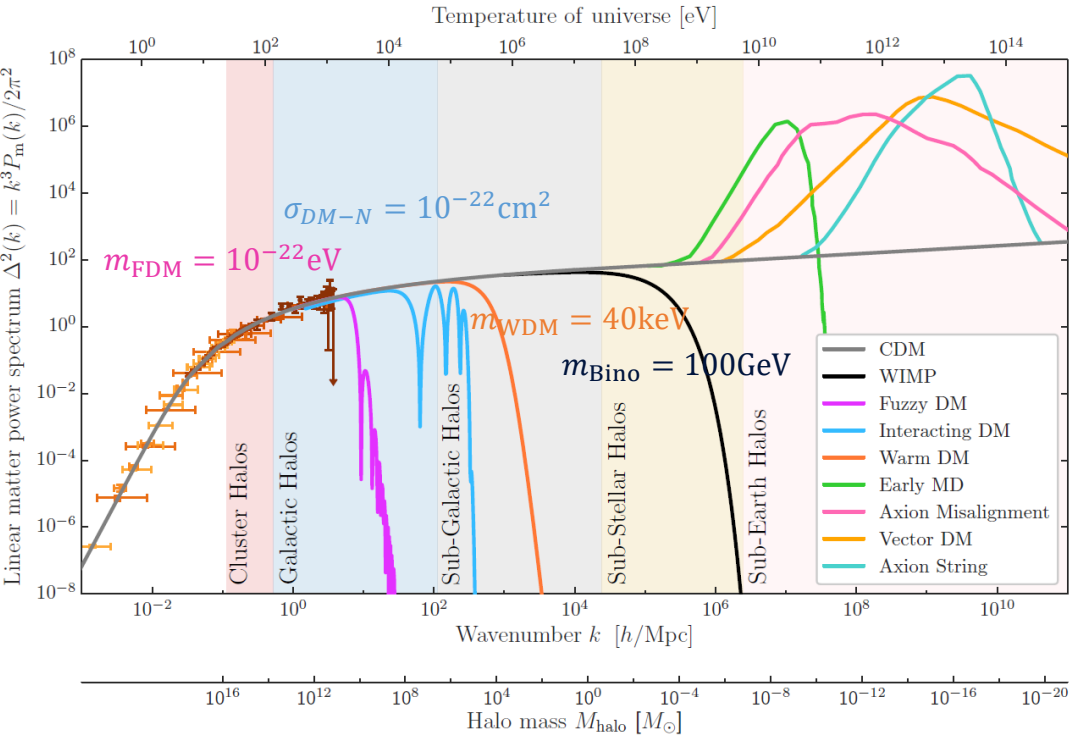
EJC, 2109.07423

- Medium correction to neutrino masses needs to be suppressed.

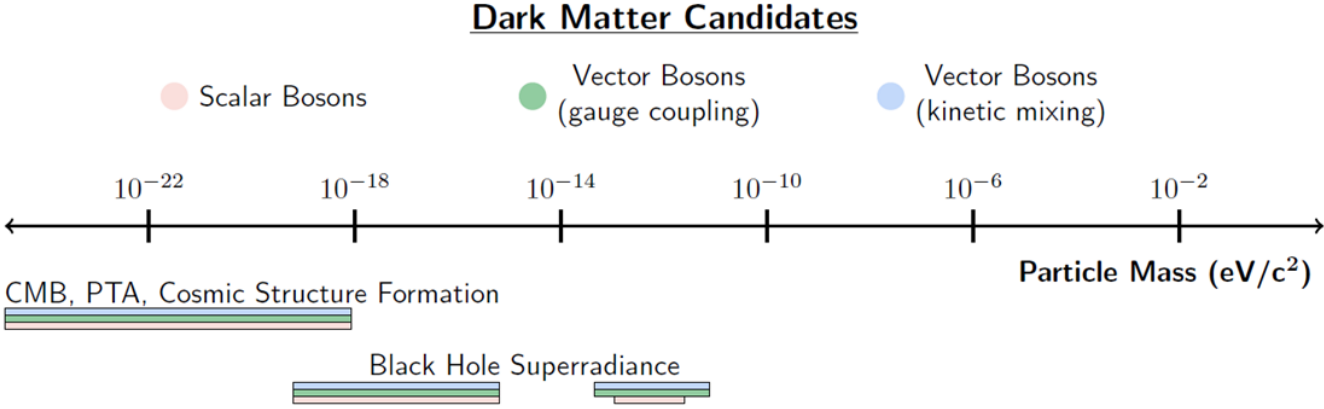
KY Choi, EJC, JK Kim, 2012.09474, 1909.10478

ULDM and cosmic structures

Snowmass, 2203.07354



Snowmass, 2203.14915



Misalignment mechanism

- Evolution in the FLRW universe:

$$\langle \hat{\phi}(x) \rangle_T = \phi(t)$$

$$\ddot{\phi}(t) + 3H\dot{\phi}(t) + V'(\phi) = 0$$

- For an approximately free field:

$$\phi''(x) + \frac{3}{2x}\phi'(x) + \phi(x) \approx 0$$

$$x \equiv m_\phi t$$

- Analytic solution

$$\phi(x) = C_1 \frac{J_{1/4}(x)}{x^{1/4}} + C_2 \frac{Y_{1/4}(x)}{x^{1/4}}$$

$$H \gg m_\phi \ (x \ll 1) : \phi = \phi_i; \dot{\phi} = 0$$

$$H \ll m_\phi \ (x \gg 1) : \phi \sim \phi_i \frac{\sin(m_\phi t + \frac{\pi}{8})}{(m_\phi t)^{3/4}}$$

$$m_\phi \gg H_{eq} \approx 3 \cdot 10^{-27} \text{ eV}$$

CDM density: $\rho_{DM}(x_{eq}) \approx 0.23 \text{ eV}^4$

$$\rho_\phi(x_{eq}) \sim \frac{m_\phi^2 \phi_i^2}{x_{eq}^{3/2}} \Rightarrow \phi_i \sim 0.01 M_p \left(\frac{10^{-20} \text{ eV}}{m_\phi} \right)^{\frac{1}{4}}$$

Scalar field in thermal background

- Scalar field interacting with thermal fermions:

$$\mathcal{L}' = y_\phi \hat{\phi} (\bar{f}_R f_L + \bar{f}_L f_R)$$

$$\rightarrow V_{T,\text{eff}}(\phi) = -\frac{g_f}{2\pi^2} T^4 J_F \left(\frac{(m_f + y_\phi \phi)^2}{T^2} \right)$$

Dolan+Jackiw, 1974

Weinberg, 1974

- Leading thermal effects in cosmological evolution:

$$\ddot{\phi}(t) + 3H\dot{\phi}(t) + (m_\phi^2 + m_T^2)\phi(t) \approx \frac{\partial}{\partial \phi} \langle \mathcal{L}' \rangle_T$$

$$m_T^2 = \frac{g_f}{24} y_\phi^2 T^2, \quad \langle \mathcal{L}' \rangle_T = y_\phi \phi \frac{g_f m_f T^2}{24}$$

$$g_f = 4N_c \quad (2) \quad \text{for } f = q, l (v)$$

Esteban+Salvado, 2101.05804

Batell+Ghalsasi, 2109.04476

General features

- Evolution from $T_{ew} \approx 100$ GeV down to $T_{eq} \approx 0.67$ eV:

$$\tilde{\phi}''(x) + \frac{3}{2x} \tilde{\phi}'(x) + \left(1 + \frac{x_1}{x}\right) \tilde{\phi}(x) = \frac{x_S}{x}$$

$$x_1 \equiv y_\phi^2 \frac{c_t^2 g_f M_P}{48 m_\phi}, \quad x_S \equiv y_\phi \frac{c_t^2 g_f m_f}{48 m_\phi}$$

- Vanishing initial condition at x_{ew} : $\phi = 0, \phi' = 0$.
- The resulting DM density will be

$$\rho_\phi(x_{eq}) \approx \frac{c_f^2 x_S^2 m_\phi^2 M_P^2}{\pi x_{eq}^{3/2}}$$

$$\rho_\phi = \rho_{DM} \Rightarrow c_f^2 x_S^2 \approx 2.5 \times 10^{-4} m_{20}^{-1/2}$$

(Notation) $T = c_t \sqrt{M_P/2t}$ $c_t = 1.74/g_*^{1/4}$

$$x = m_\phi t = \frac{c_t^2 m_\phi M_P}{2T^2},$$

$$\tilde{\phi} = \phi/M_P, \quad m_{20} \equiv m_\phi/10^{-20} \text{ eV}$$

$$x_{ew} \approx 10^{-15} m_{20} \quad x_{eq} \approx 2 \times 10^7 m_{20}$$

$$x_1 \approx 10^{47} y_\phi^2 m_{20}^{-1} \quad x_S \approx 2 \cdot 10^{24} y_\phi m_{20}^{-1} \left(\frac{m_f}{m_e}\right)$$

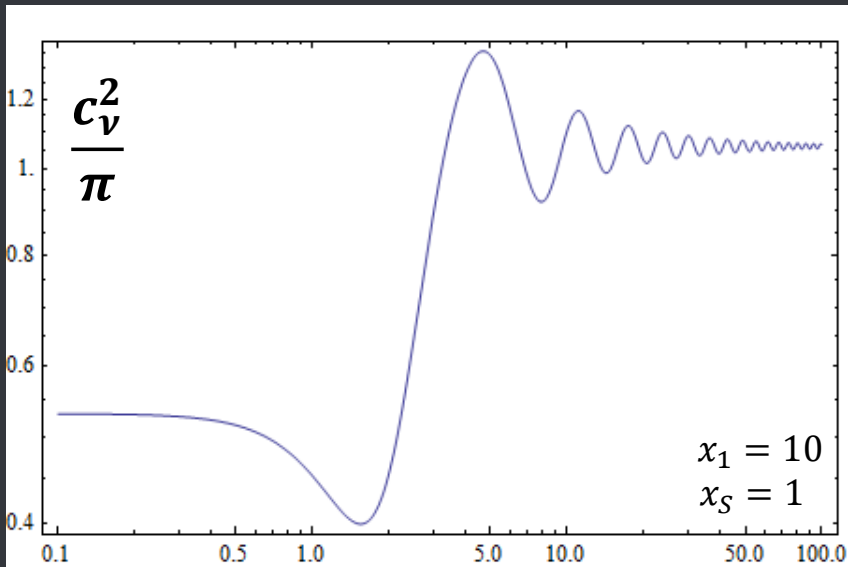
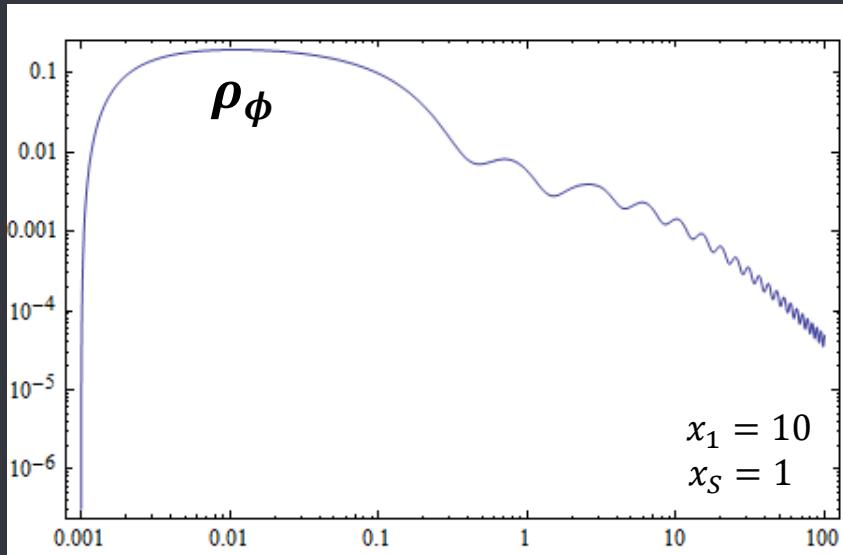
ULDM from thermal ν

- $x_{ew} < x_1 < x_{eq} < x_\nu$

$$\tilde{\phi}''(x) + \frac{3}{2x} \tilde{\phi}'(x) + \left(1 + \frac{x_1}{x}\right) \tilde{\phi}(x) = \frac{x_S}{x}$$

Analytic Solution

$$\tilde{\phi}(x) = \begin{cases} \frac{x_S}{x_1} \left(1 - \sqrt{\frac{x_{ew}}{x}} \cos[2(\sqrt{xx_1} - \sqrt{x_{ew}x_1})] - \frac{1}{2\sqrt{xx_1}} \sin[2(\sqrt{xx_1} - \sqrt{x_{ew}x_1})] \right) & x \ll x_1 \\ C_1 \frac{J_{1/4}(x)}{x^{1/4}} + C_2 \frac{Y_{1/4}(x)}{x^{1/4}} + \frac{x_S}{(2x)^{1/4}} \left(\frac{\pi}{\Gamma(\frac{3}{4})} J_{1/4}(x) G_1(x) - \frac{4\Gamma(\frac{3}{4})}{3} J_{-1/4}(x) G_2(x) \right) & x \gg x_1 \end{cases}$$



$$\rho_\phi(x_{eq}) \approx \frac{c_v^2 x_S^2 m_\phi^2 M_P^2}{\pi x_{eq}^{3/2}}$$

$$c_v^2 = \frac{\pi \Gamma\left(\frac{3}{4}\right)^2}{2\sqrt{2}} + \frac{2^{\frac{3}{4}} \pi^{\frac{3}{2}} C_1}{\Gamma\left(\frac{1}{4}\right) x_S} + \frac{C_1^2 + C_2^2}{x_S^2} \approx 3.34 \text{ for } x_1 \gg 1$$

$$y_\phi \approx 3 \cdot 10^{-20} m_{20}^{\frac{3}{4}} \left(\frac{0.05\text{eV}}{m_\nu}\right)$$

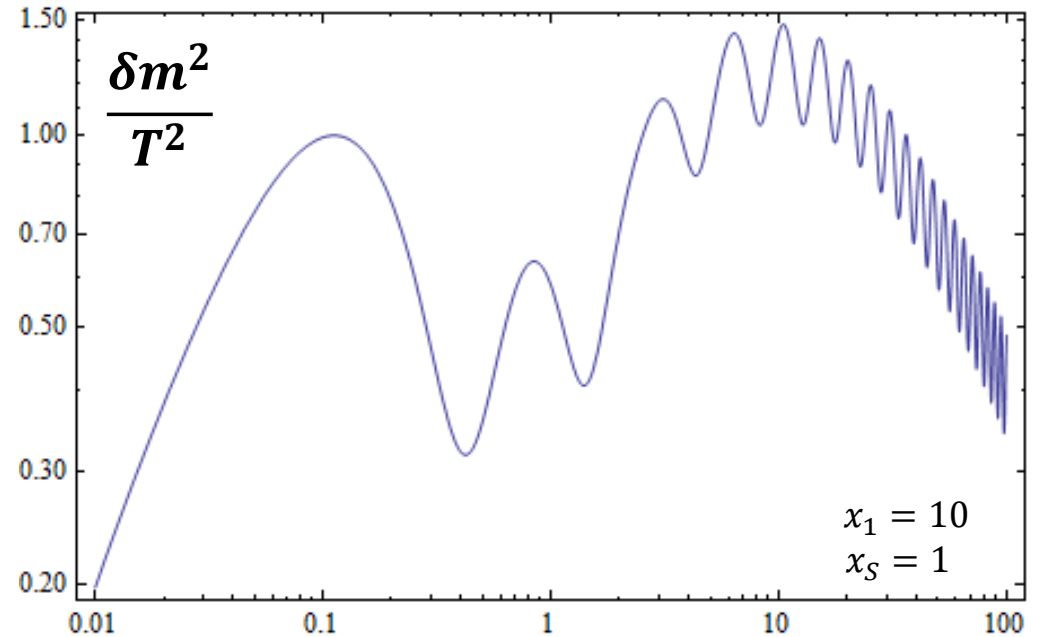
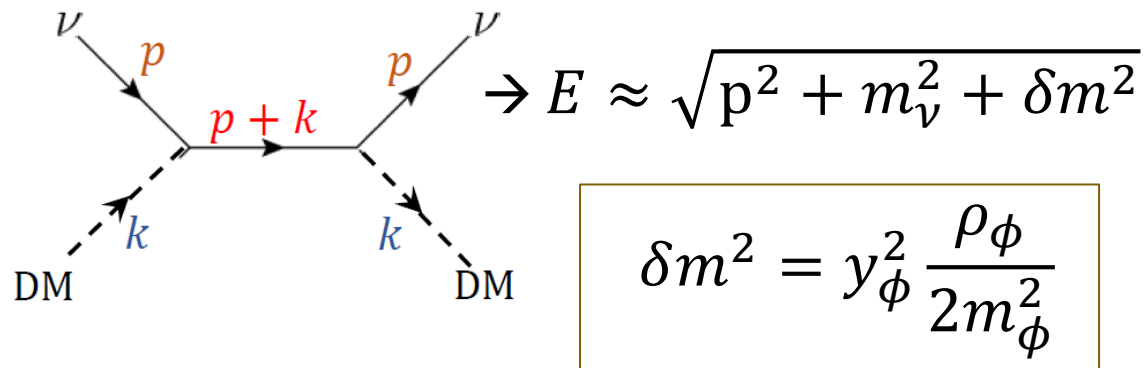
$$\frac{x_S}{x_1} \approx 6.8 \cdot 10^{-10} m_{20}^{-\frac{3}{4}} \left(\frac{m_\nu}{0.05\text{eV}}\right)^2$$

$$\frac{x_1}{x_{eq}} \sim 0.34 m_{20}^{-\frac{1}{2}} \left(\frac{0.05\text{eV}}{m_\nu}\right)^2 < 1$$

$$(*) \text{ BBN: } y_\phi \lesssim 7 \times 10^{-6} \quad m_\phi \lesssim 0.092 \text{ eV} \left(\frac{m_\nu}{0.05 \text{ eV}}\right)^{4/3}$$

Neutrinos propagating in ULDM

Dispersion relation of Neutrinos travelling through ULDM background gets modified \rightarrow the medium-induced mass-squared can be large.



Neutrino mass correction by ULDM

During DM genesis at $T_1(x_1)$

Demanding for the consistency:

$$\frac{\delta m^2(T)}{T^2} < 0.1 \text{ at } T = T_1$$

we get $m_{20} > 2.2 \times 10^6 \left(\frac{0.05\text{eV}}{m_\nu} \right)^4$

or $T_1 > 70 T_{eq}$

Now around us

Neutrinos around us get negligible corrections:

$$\delta m_{local}^2 = y_\phi^2 \frac{\rho_{\text{DM}}^{local}}{2m_\phi^2} < 7.2 \cdot 10^{-9} \text{eV}^2$$

($\rho_{\text{DM}}^{local} = 0.3 \text{GeV/cm}^3$)

Summary

- A huge population of ULDM can be originated from its tiny coupling to SM fermions. [Gravity bounds excludes u, d, s, e as the main source of the DM generation.]
- For the $\phi\nu\nu$ coupling, DM genesis requires $m_\phi \sim (10^{-11}, 10^{-2})\text{eV}$ and $y_\phi \sim (10^{-12}, 10^{-6})$, and can occur very late at around $T > 70T_{eq}$.
- Tiny correction to the neutrino mass-squared ($< 10^{-8} \text{ eV}^2$) at present.