Neutrinos and Ultra Light Dark Matter

20-Feb	310-B502	21-Feb	310-B502	22-Feb	310-312	23-Feb	310-B502	24-Feb	310-B502
9:30-10:30	Kaoru Hagiwara	9:30-10:30	Matthew Reece	9:30-10:30	Ben Safdi	9:30-10:30	Daniel Green	9:30-10:10	Pyungwon Ko
10:30-11:00	Break	10:30-11:00	Break	10:30-11:00	Break	10:30-11:00	Break	10:10-10:40	Simon Clery
11:00-11:40	Yeongduk Kim	11:00-11:40	Seung Joo Lee	11:00-11:40	SungWoo Youn	11:00-11:40	Hyung Mok Lee	10:40-11:10	Break
11:40-12:20	Jong Chul Park	11:40-12:20	Hyung Do Kim	11:40-12:20	Takeo Moroi	11:40-12:20	Youngmin Kim	11:10-11:40	Ki-Young Choi
12:20-14:00	Lunch	12:20-14:00	Lunch	12:20-14:00	Lunch	12:20-14:00	Lunch	11:40-12:00	Arpan Kar
14:00-14:40	Eung Jin Chun	14:00-14:40	Un-Ki Yang	14:00-14:40	Kiwoon Choi	14:00-14:40	Dumitru Ghilencea	12:00-12:20	Sougata Ganguly
14:40-15:10	Seung J. Lee	14:40-15:10	Jeonghyeon Song	14:40-15:10	Minho Son	14:40-15:40	David Weir	12:20-14:00	Lunch
15:10-15:40	Sunghoon Jung	15:10-15:40	Seong Youl Choi	15:10-15:40	Ryosuke Sato	15:40-16:10	Break	14:00-14:40	Motoi Endo
15:40-16:10	Break	15:40-16:10	Break	15:40-16:20	Deog Ki Hong	16:10-16:40	Kyungmin Kim	14:40-15:20	Youngjoon Kwon
16:10-16:50	Seong Chan Park	16:10-16:40	Myeonghun Park	16:20-18:00	discussion	16:40-17:10	Shuntaro Aoki	15:20-15:50	Chan Beom Park
16:50-17:10	Shu-Yu Ho	16:40-17:10	Sungwoo Hong	18:00-21:00	Banquet	17:10-17:30	Pankaj Saha	15:50-16:20	Break
17:10-17:30	Kiyoharu Kawana	17:10-17:40	Kimiko Yamashita			17:30-18:00	Ligong Bian	16:20-16:50	Sang Hui Im
		17:40-18:00	Liliana Velasco					16:50-17:10	Junichiro Kawamura
								17:10-17:30	Adil Jueid

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Eung Jin Chun

Outline

- A huge population of ultralight boson CDM can be generated by the misaligned initial amplitude.

- Thermal neutrinos may be the origin of the ULDM misalignment.

EJC, 2109.07423

- Its impact on the effective neutrino mass then and now. (*)

KY Choi, EJC, JK Kim, 2012.09474
1909.10478

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

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

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

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

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

CDM density: $\rho_{DM}(x_{eq}) \approx 0.23 \text{ eV}^4 \quad \rho_\phi(x) \sim \frac{m_\phi^2 \phi_i^2}{x^{3/2}} \Rightarrow \phi_i \sim 0.01\, M_p \left(\frac{10^{-20}\mathrm{eV}}{m_\phi}\right)^{1/4}$

Scalar field in thermal background

- Scalar field interacting with thermal fermions:

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

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

Dolan+Jackiw,
Weinberg, 1974

- Leading thermal effects in cosmological evolution:

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

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

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

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:

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

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

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

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

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

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

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

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

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

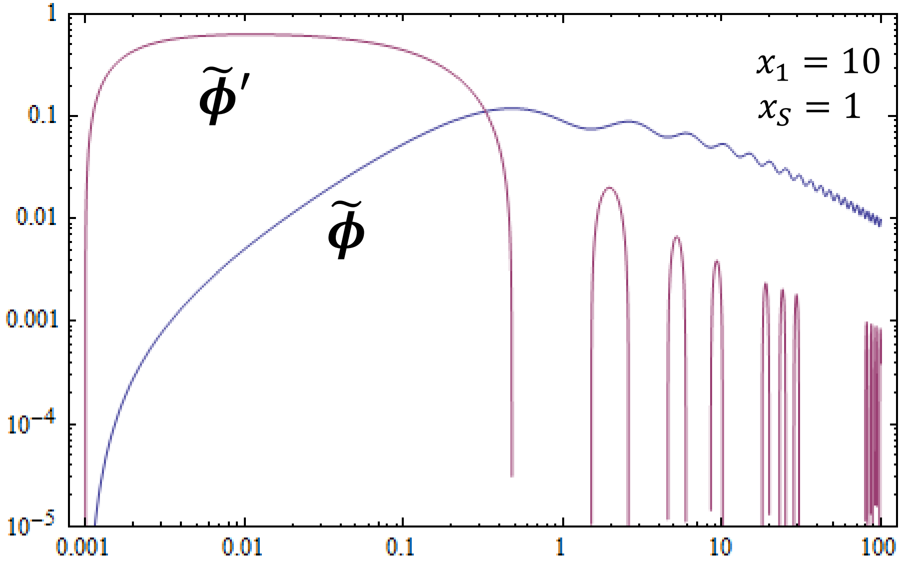
$$x_1 \approx 10^{47} y_\phi^2 m_{20}^{-1} \qquad x_S \approx 2 \cdot 10^{17}\, y_\phi\, m_{20}^{-1}\left(\frac{m_\nu}{0.05\mathrm{eV}}\right)$$

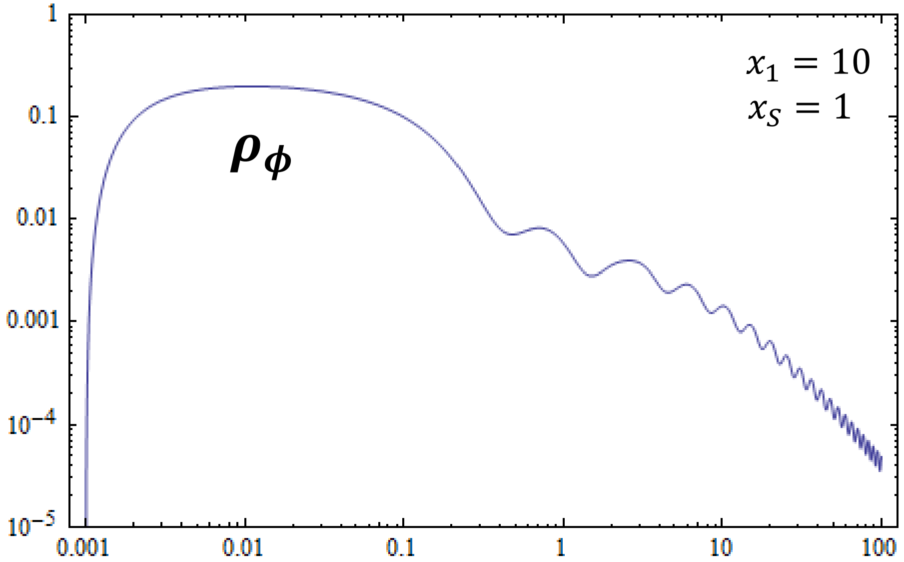
ULDM in thermal ν background

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

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

Numerical Solution





ULDM in thermal ν background

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

$x < x_1$

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

$x > x_1$

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

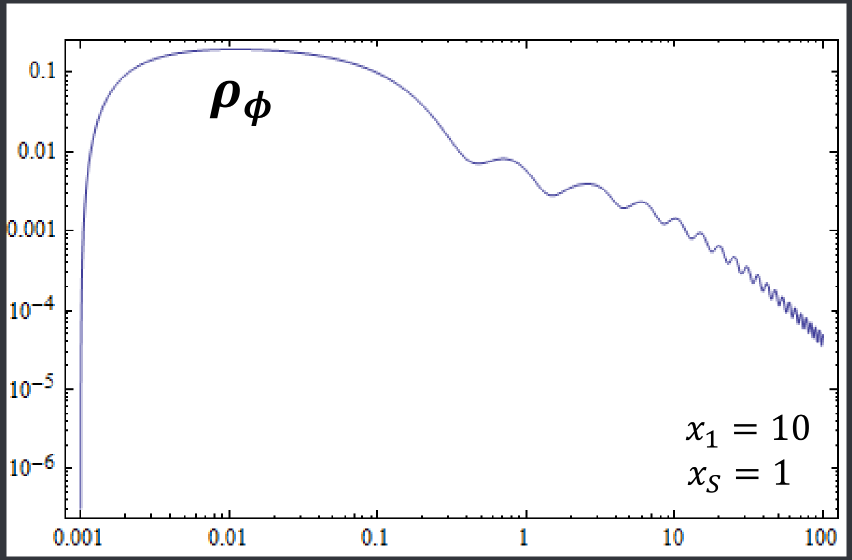
Analytic Solution

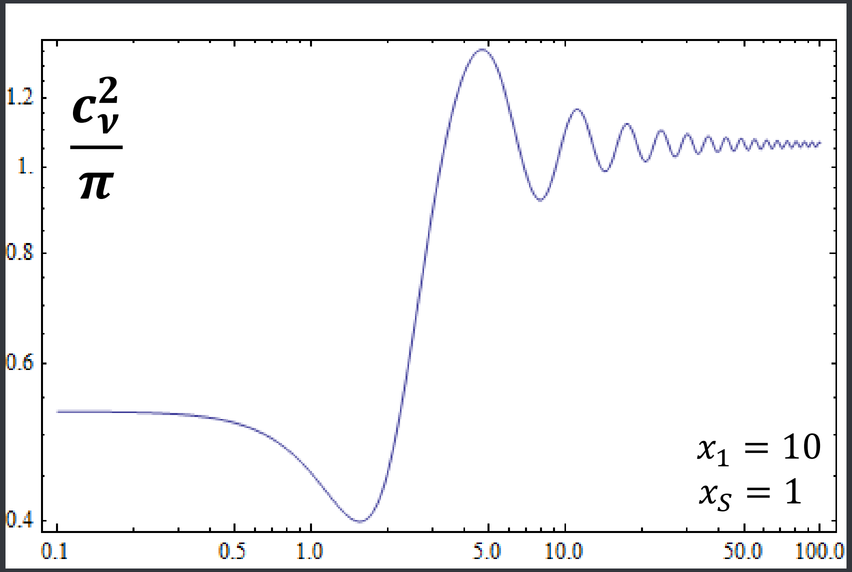
$$\tilde{\phi}(x) = \begin{cases} \frac{x_S}{x_1}\left(1 - \sqrt{\frac{x_{ew}}{x}}\cos[2(\sqrt{xx_1} - \sqrt{x_{ew}x_1})] - \frac{1}{2\sqrt{xx_1}}\sin[2(\sqrt{xx_1} - \sqrt{x_{ew}x_1})]\right) \\ C_1\frac{J_{1/4}(x)}{x^{1/4}} + C_2\frac{Y_{1/4}(x)}{x^{1/4}} + \frac{x_S}{(2x)^{1/4}}\left(\frac{\pi}{\Gamma\left(\frac{3}{4}\right)}J_{1/4}(x)G_1(x)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

$(*)\ G_{1,2}(x) \to$ constant for $x \to \infty$

$$\frac{C_1}{x_S} = -\frac{\pi}{2^{\frac{1}{4}}\Gamma(\frac{3}{4})}G_1(x_1) + \frac{2^{\frac{5}{4}}\Gamma(\frac{3}{4})}{3}G_2(x_1) - \frac{\pi}{2}\frac{Y_{\frac{1}{4}}(x_1)\sin^2(x_1) - Y_{-\frac{3}{4}}(x_1)[x_1 - \frac{1}{2}\sin(2x_1)]}{x_1^{3/4}}$$

$$\frac{C_2}{x_S} = -\frac{2^{\frac{5}{4}}\Gamma(\frac{3}{4})}{6}G_2(x_1) + \frac{\pi}{2}\frac{J_{\frac{1}{4}}(x_1)\sin^2(x_1) - J_{-\frac{3}{4}}(x_1)[x_1 - \frac{1}{2}\sin(2x_1)]}{x^{3/4}}$$





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

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

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

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

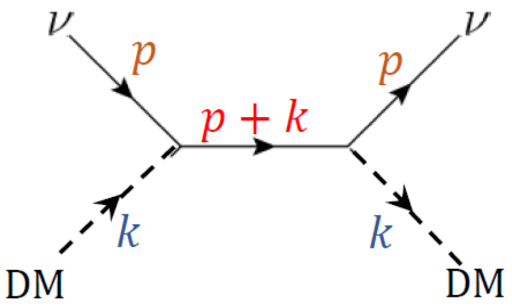
$$\frac{x_1}{x_{eq}} \sim 0.34\, m_{20}^{-\frac{1}{2}} \left(\frac{0.05\text{eV}}{m_\nu}\right)^2 < 1$$

(*) 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

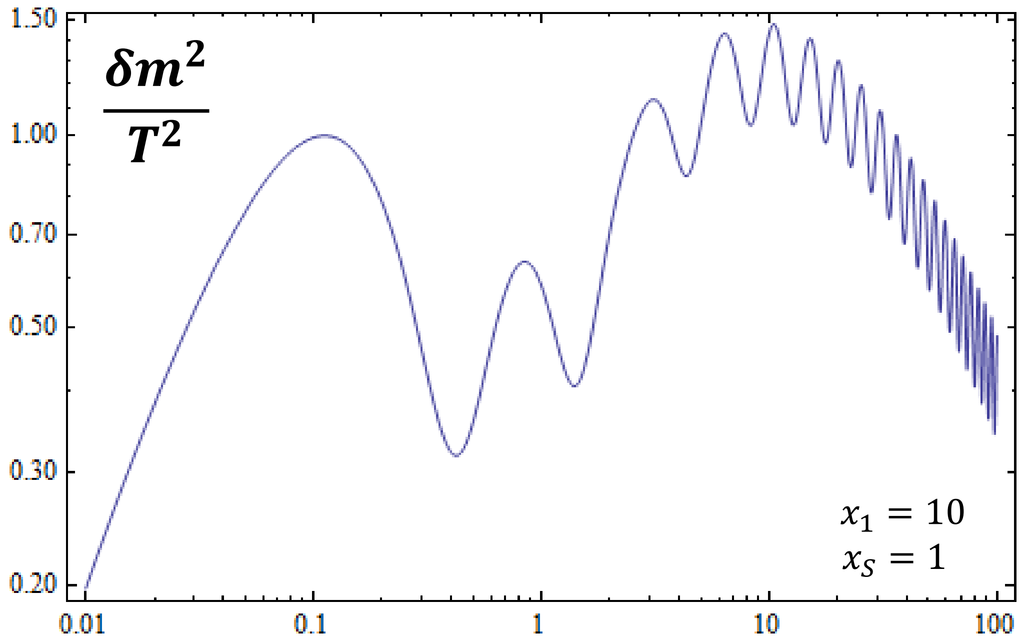
Wolfenstein:

Coherent forward scattering → Modification of neutrino dispersion relation



$$\rightarrow E \approx \mathrm{p} + \frac{m_\nu^2 + \delta m^2}{2\mathrm{p}}$$

$$\delta m^2 = y_\phi^2 \frac{\rho_\phi}{2 m_\phi^2}$$



Mass-squared 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:

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

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

Summary

- A huge population of ULDM can be originated from its tiny coupling to SM fermions.

- For the $\phi \nu \nu$ coupling, DM genesis requires $m_\phi \sim (10^{-11}, 10^{-2})\mathrm{eV}$ and $y_\phi \sim (10^{-12}, 10^{-6})$, and can occur very late at around $T > 70 T_{eq}$.

- No observable correction to the masses of neutrinos around us.