CosPA2017 parallel Session K: GW 2 14:15 - 14:30 at K206, YITP, Kyoto Univ., JAPAN

Exploring the string axiverse and parity violation in gravity with gravitational waves

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Daiske Yoshida and Jiro Soda

arXiv: 1708.09592

“Electromagnetic waves propagating in the string axiverse”

Daiske Yoshida and Jiro Soda

arXiv: 1710.09198

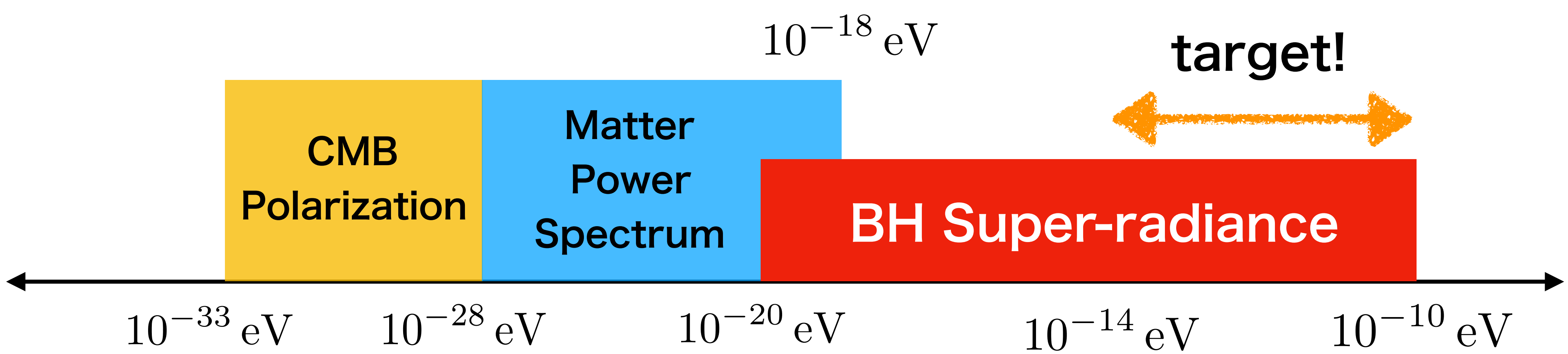
String axiverse and Axion dark matter

- String theory gives the massive pseudo-scalar fields (Axion).

  P. Svrcek and E. Witten (2006)

  A. Arvanitaki, et al (2010),

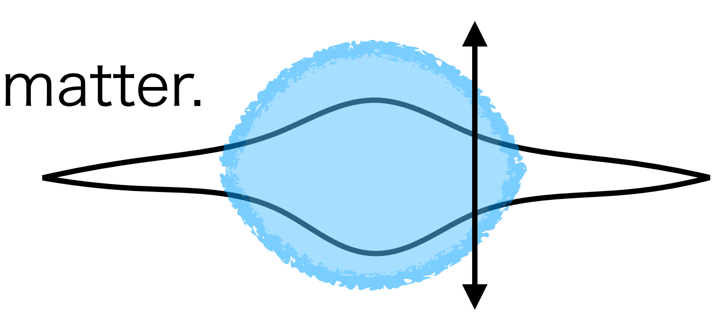
- Their mass is $10^{-33} \sim 10^{-10}\,\mathrm{eV}$. Its range is the very wide.



- Compactification of the extra dimensions $\rightarrow\ \Phi\tilde{F}F,\ \Phi\tilde{R}R$

- It is indicated that the axion can behave as the cold dark matter.

  W. Hu, R. Barkana, and A. Gruzinov (2000)



- To challenge the ultimate theory, **we must detect them!**

Dynamical Chern-Simons gravity

- This theory contains the coupling of the gravitational field and the scalar field. R. Jackiw and S. Y. Pi (2003)

- If we believe the string axiverse, this theory suggests the coupling with the gravitational field and axion.

- Its interaction is given by

$$\alpha = \sqrt{\frac{\kappa}{2}}\ell^2 \qquad l \sim 10^8\mathrm{km}$$

$$S_{\mathrm{CS}} = \frac{1}{4}\alpha \int_{\mathcal{V}} dx^4 \sqrt{-g}\,\Phi \tilde{R}R$$

$$\tilde{R}R \equiv \underbrace{\frac{1}{2}\epsilon^{\gamma\delta\rho\sigma} R^{\alpha}{}_{\beta\rho\sigma}}_{\equiv \tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta}} R^{\beta}{}_{\alpha\gamma\delta}$$

- This theory generates the parity-violated GW for circular polarization, h_{R}, h_{L} .

System

- Action

$$S = \kappa \int_{\mathcal{V}} dx^4 \sqrt{-g}\, R + \frac{1}{4}\alpha \int_{\mathcal{V}} dx^4 \sqrt{-g}\, \Phi \tilde{R} R$$

$$- \frac{1}{2} \int_{\mathcal{V}} dx^4 \sqrt{-g}\, \left[g^{\mu\nu} (\nabla_\mu \Phi)(\nabla_\nu \Phi) + 2V(\Phi) \right]$$

- Equations of motion

→ Gravitational field :

$$G_{\mu\nu} + \frac{\alpha}{\kappa} C_{\mu\nu} = \frac{1}{2\kappa} T_{\mu\nu}$$

$$C^{\mu\nu} \equiv (\nabla_\alpha \Phi) \epsilon^{\alpha\beta\gamma(\mu} \nabla_\gamma R^{\nu)}{}_\beta + (\nabla_\alpha \nabla_\beta \Phi) \tilde{R}^{\beta(\mu\nu)\alpha}$$

→ Axion :

$$\nabla_\mu \nabla^\mu \Phi - \frac{dV(\Phi)}{d\Phi} = -\frac{\alpha}{4} \tilde{R} R$$

Settings

- We set the spacetime as follows,

$$ds^2 \simeq a(\eta)^2(-d\eta^2 + \delta_{ij}dx^i dx^j + h_{ij}dx^i dx^j).$$

- We give some assumptions to solve this system.
  $\rightarrow$ The axion has the time-dependence only. $\Phi(x^\mu) = \Phi(\eta)$

  $\rightarrow$ Its potential is given by $V(\Phi) = \frac{1}{2}m^2\Phi^2$.

  $\rightarrow$ The expansion of Universe can be neglected in the scale of the time when the GWs through the core of Galaxy for 1 pc.

$$a(\eta) \simeq 1 \quad \rightarrow \quad \Phi(\eta) \simeq \Phi_0 \cos(m\eta)$$

- The EoM of GW

$$h''_A + \frac{\epsilon_A \delta \cos(m\eta)}{1 + \epsilon_A \frac{k}{m}\delta \sin(m\eta)} k\, h'_A + k^2 h_A = 0$$

$$\delta \equiv \frac{\alpha}{\kappa} m^2 \Phi_0$$

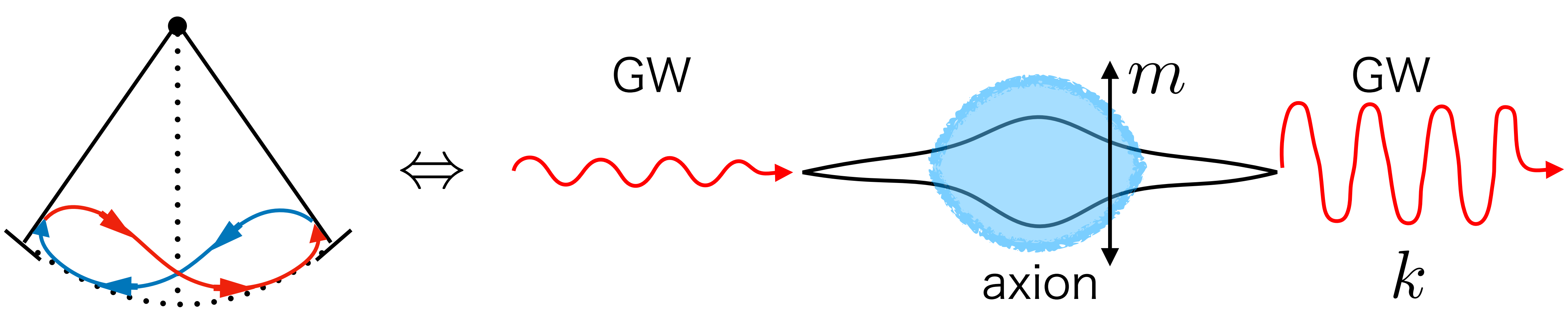
$$\epsilon_A \equiv \begin{cases} 1 & : \quad A = \mathrm{R} \\ -1 & : \quad A = \mathrm{L} \end{cases}$$

Parametric resonance

- The EoM of parametric resonance $$\frac{d^2x}{dt^2}+\beta(t)\frac{dx}{dt}+\omega^2(t)x=0$$

  The condition of parametric resonance
  → $\beta(t)$ and $\omega^2(t)$ can have the dependence of time only.
  → $\beta(t)$ and\or $\omega^2(t)$ are assumed to vary periodically, with the same period T.

- The Swings
  → The parameters vary at roughly twice the natural frequency of the arms of the swing, the amplitude of it will grow.



Estimation of the Growth rate

- Estimation of the resonance frequency

→ Resonance frequency $k_{\rm r} = \frac{m}{2}$ $\Rightarrow$ $f_{\rm r} = \frac{k_{\rm r}}{2\pi} \simeq 1.2 \times 10^4\,{\rm Hz}\left(\frac{m}{10^{-10}\,{\rm eV}}\right)$

→ Band of the resonance frequency $\frac{m}{2} - \frac{m}{8}\delta \lesssim k_{\rm r} \lesssim \frac{m}{2} + \frac{m}{8}\delta$

- Growth rate of the amplitude of GW

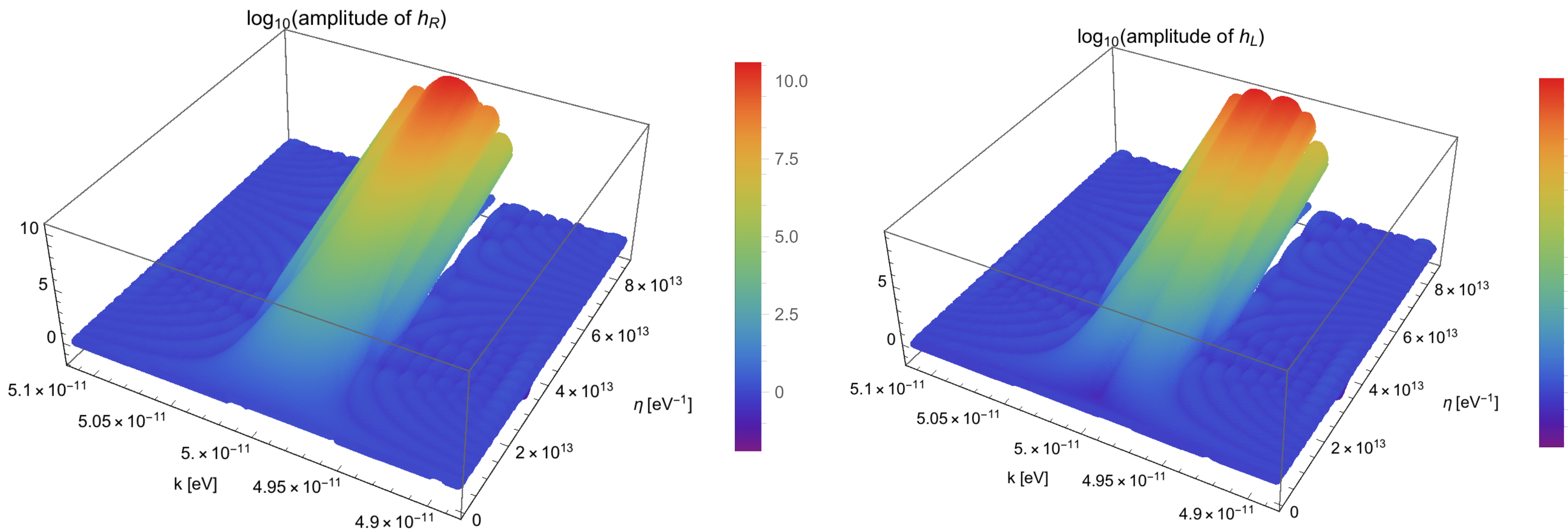
$$\Gamma_{\rm max} = \frac{m}{8}\delta$$
$$\simeq 2.8 \times 10^{-16}\ {\rm eV}$$
$$\times \left(\frac{m}{10^{-10}\ {\rm eV}}\right)^2 \left(\frac{\ell}{10^8\ {\rm km}}\right)^2 \sqrt{\frac{\rho}{0.3\ {\rm GeV/cm^3}}}$$

$$\Rightarrow t_{\times 10} \simeq 8.1 \times 10^{15}\ {\rm eV}^{-1} \times \left(\frac{10^{-10}\ {\rm eV}}{m}\right)^2 \left(\frac{10^8\ {\rm km}}{\ell}\right)^2 \sqrt{\frac{0.3\ {\rm GeV/cm^3}}{\rho}}$$

Numerical results: 1/2

- Plots of the growth of the amplitude of GW

$$\ell = 10^8\,\mathrm{km},\ m = 10^{-10}\,\mathrm{eV},\ \rho = 0.3 \times 10^6\,\mathrm{GeV/cm^3}$$
$$\delta \simeq 0.02$$



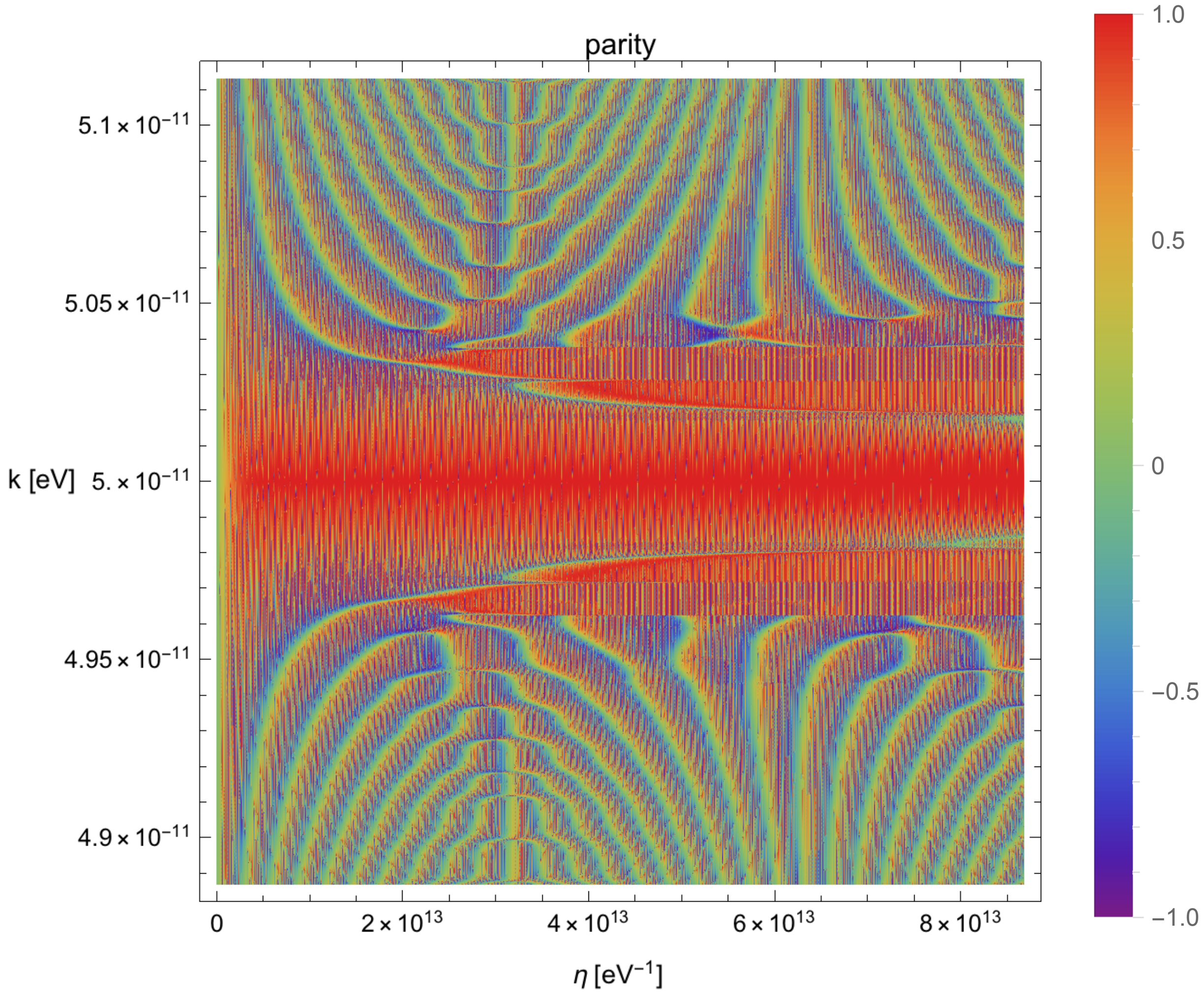
→ In the circular polarization basis, each of the amplitudes grows asymmetrically.

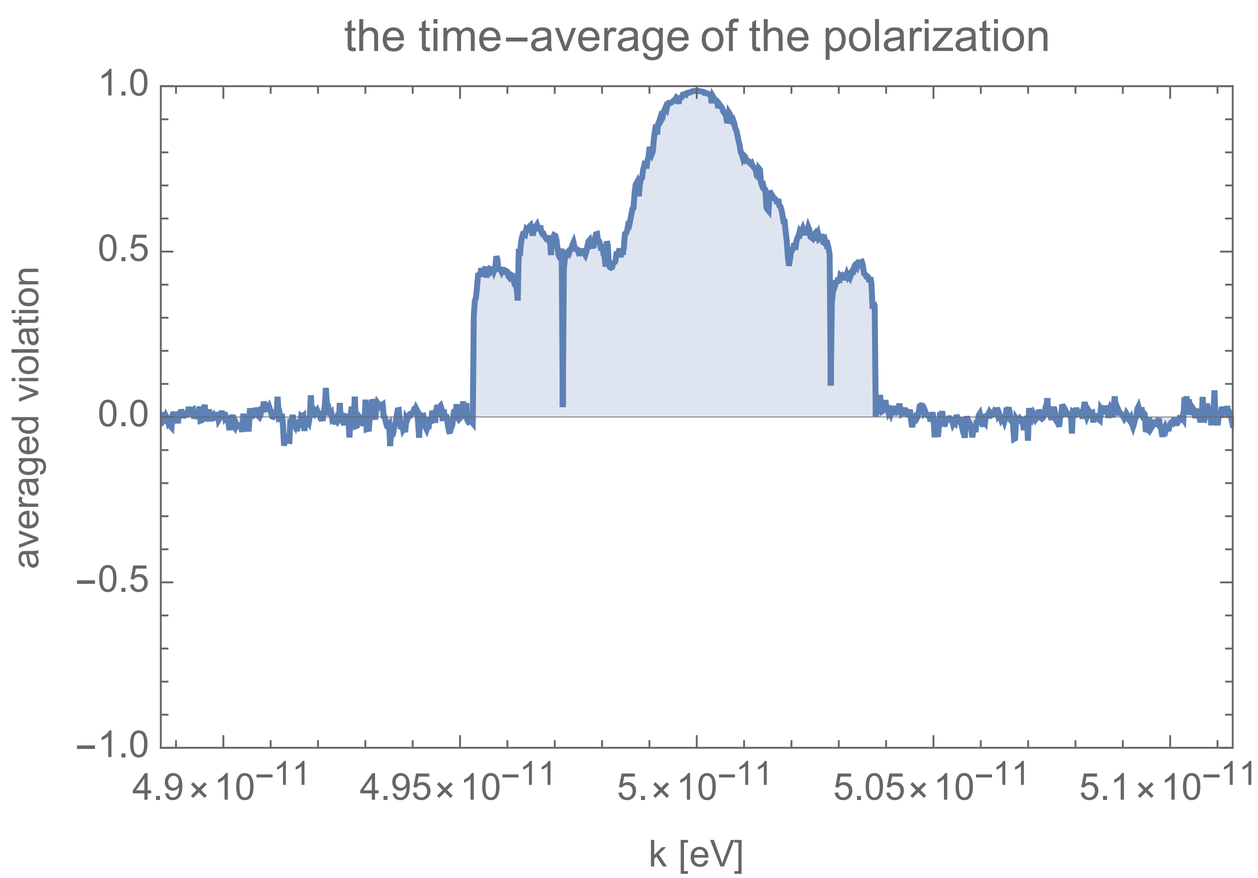
→ In this situation, h_R becomes 10^4 times as large as h_L.

Numerical results: 2/2

- The plot of the time evolution of the parity violation is below.

$$\text{parity}(\eta) = \frac{|h_R|^2 - |h_L|^2}{|h_R|^2 + |h_L|^2}$$





- The color indicates the level of the polarization.
  → The strong polarization near the resonance frequency.

Discussion

- Let's assume the growth rate of the amplitude of GW is true.

  $\rightarrow$ If, in the core of Galaxy, $\sim 1[\mathrm{pc}]$, you believe the NFW profile, $\rho_a \gg 0.3[\mathrm{GeV/cm^3}]$, and the dCS coupling constant today, $l \sim O(10^8)[\mathrm{km}]$, the amplitude of the GW becomes $10^{10^{12}}$ times bigger when the GW travel for $10[\mathrm{kpc}]$.

  $\rightarrow$ **This is the astonishing result!**

- This estimation, of course, implies **the stronger constraint** to the coupling constant of dCS gravity, l, or the energy density of the axion dark matter, ρ.

  Example)

  If you believe the value of $l \sim 10^8[\mathrm{km}]$, ρ satisfies $\rho \lesssim 10^{-26}[\mathrm{GeV/cm^3}]$.

  If you believe the value of $\rho \sim 0.3[\mathrm{GeV/cm^3}]$, l satisfies $l \lesssim 10[\mathrm{km}]$.

  Of course, there is room for more precise discussion.

Conclusion

- String axiverse generates **the axions** which have the light mass and **the Chern-Simons coupling** between the axion field and the gravitational/electromagnetic field.

- The light and coherently oscillating axion can behave as the cold dark matter well, so, through the above coupling, **the strong and parity violated gravitational waves are generally induced**.

- **This effect may use to detect the counterpart of the GR.**
  → They might give the new constraint to the abundance of the axion dark matter or the CS-coupling.