KOBE UNIVERSITY Graduate School of Science

新学術領域「加速宇宙」シンポジウム、東北大学、2018.2.11

String axions
in Chern-Simons gravity

with Daiske Yoshida

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Kobe University

Achievements in 2017

1) Anisotropic Constant-roll Inflation.
Asuka Ito, Jiro Soda. Eur.Phys.J. C78 (2018) no.1, 55
2) Electromagnetic waves propagating in the string axiverse.
Daiske Yoshida, Jiro Soda.[arXiv:1710.09198[hep-th]].
3) Cosmological imprints of string axions in plateau.
Jiro Soda, Yuko Urakawa.[arXiv:1710.00305[astro-ph.CO]].
4) Exploring the string axiverse and parity violation in gravity with gravitational waves.
Daiske Yoshida, Jiro Soda.[arXiv:1708.09592[gr-qc]].
5) Schwinger Pair Production by Electric Field Coupled to Inflaton.
Jia-Jia Geng, Bao-Fei Li, Jiro Soda, Anzhong Wang, Qiang Wu, Tao Zhu. to appear in JCAP
6) Infinite violation of Bell inequalities in inflation.
Sugumi Kanno, Jiro Soda. Phys.Rev. D96 (2017) no.8, 083501.
7) Electromagnetic Memory Effect Induced by Axion Dark Matter.
Daiske Yoshida, Jiro Soda. Phys.Rev. D96 (2017) no.6, 064005.
8) Nonlinear resonant oscillation of gravitational potential induced by ultralight axion in $f(R)$ gravity.
Arata Aoki, Jiro Soda. Phys.Rev. D96 (2017) no.2, 023534.
9) Photon-Axion Conversion, Magnetic Field Configuration, and Polarization of Photons.
Emi Masaki, Arata Aoki, Jiro Soda. Phys.Rev. D96 (2017) no.4, 043519.

The string axions

QCD axion

Resolve the Strong CP problem

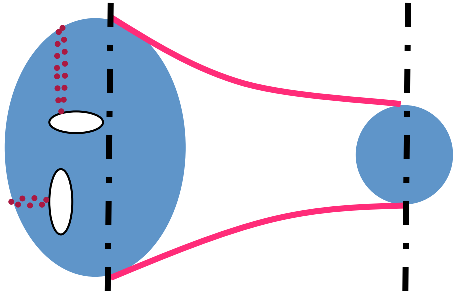
$$m_a \approx 6\times10^{-6}\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

f_a : decay constant

string axions

Model independent axion $H = dB = *d\theta$

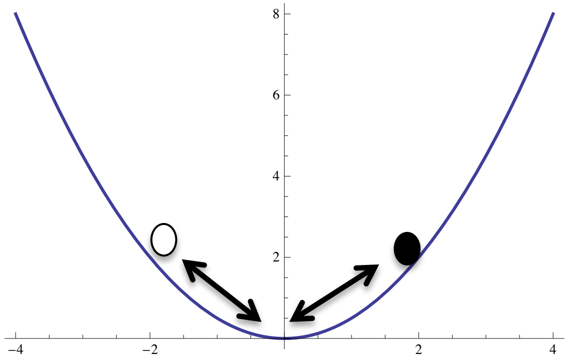
Model dependent axion $a_i = \int_{C_{p_i}} F_p$



$$m_a \approx \frac{\mu^2}{f_a} e^{-\#\mathrm{moduli}/2}$$

Mass distribution is logarithmically flat

Coherent axion oscillation



The model

$$S=\frac{1}{2}\int d^4x\sqrt{-g}\,R-\int d^4x\sqrt{-g}\left[\frac{1}{2}\nabla^{\mu}\phi\nabla_{\mu}\phi+\frac{1}{2}m^2\phi^2\right]$$

The axion is an coherently oscillating scalar field

$$\phi=\phi_0\cos mt$$

The energy density becomes

$$\rho_{DM}=\frac{1}{2}\dot{\phi}^2+\frac{1}{2}m^2\phi^2\approx\frac{1}{2}m^2\phi_0^2$$

The pressure is given by

$$p_{DM}=\frac{1}{2}\dot{\phi}^2-\frac{1}{2}m^2\phi^2\approx-\frac{1}{2}m^2\phi_0^2\cos(2mt)$$

The average value of the pressure over the oscillation period is zero.
Hence, the axion can be regarded as the dust matter on cosmological scales.

Gravitational waves propagating in the axion dark matter

$$10^{-14}\,\mathrm{eV} \quad \Leftrightarrow \quad 10^{-10}\,\mathrm{eV}$$

Axion search through Chern–Simons portal

In the presence of the axion, there arises the Chern-Simons term in the gravity sector.

$$S=\frac{M_p^2}{2}\int d^4x\sqrt{-g}\,R+\frac{M_p}{8}\underset{\uparrow}{\ell^2}\int d^4x\sqrt{-g}\,\phi\,\varepsilon^{\mu\nu\lambda\rho}R_{\alpha\beta\mu\nu}R^{\alpha\beta}{}_{\lambda\rho}-\int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2+\frac{1}{2}m^2\phi^2\right]$$

coupling constant

The Chern-Simons term appears in string theory.
It is also natural from the effective theory point of view.

Indeed, the Chern-Simons gravity has been investigated
as a modified theory of gravity for a long time.

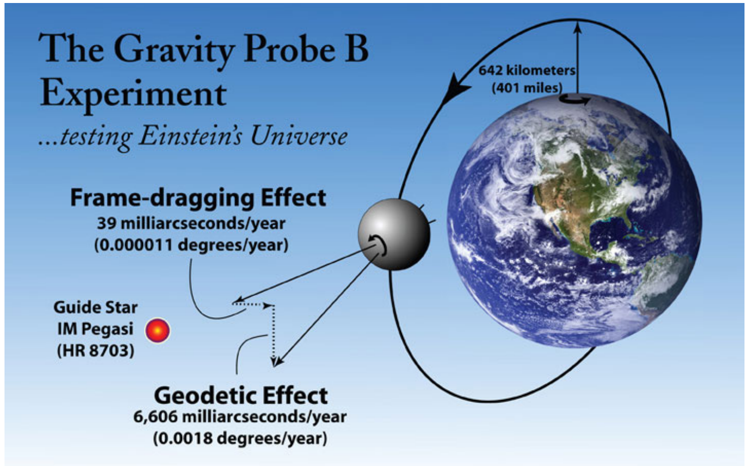
There already exists a Post-Newtonian constraint on the coupling
from the gravity probe B experiment.

The future observation of gravitational waves will also
give a constraint on the coupling constant.

Current constraint on CS coupling

Gravity probe B has measured the gyroscopic precession due to the frame dragging.
The result was in agreement with GR to an accuracy of 20%.

$$\left|\frac{\omega\left(1.1R_\oplus\right)}{\dfrac{2J}{\left(1.1R_\oplus\right)^3}}-1\right|\le 20\%$$



Y.Ali-Haimoud & Y.Chen 2011

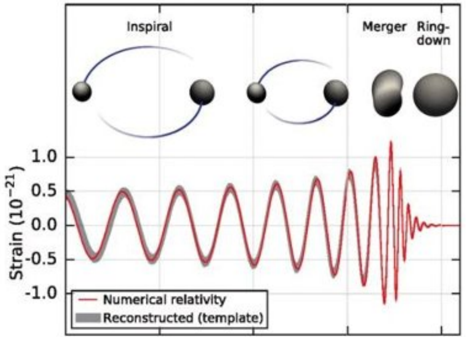
$$\ell \le 10^8\,\mathrm{km}$$

Future Constraint on CS coupling with GW

The gravitational waves emitted from the binary system can be calculated as

$$\tilde{h}(f) = A f^{-7/6} \exp\left[i \Psi(f) \right] \qquad A = 30^{-1/2} \pi^{-2/3} M^{5/6} D_L^{-1} \qquad M = \mu^{3/5} (m_1 + m_2)^{2/5}$$

$$\Psi(f) = \Psi_{\mathrm{GR}}(f) + \delta \Psi(f) \qquad \delta \Psi(f) = \frac{3}{128} (\pi M f)^{-5/3} \left(-10 \delta C (m\omega)^{4/3} \right)$$



Kerr parameter

$$\delta C = \frac{330845}{1107456} \frac{\ell^4}{(m_1 + m_2)^2 m_1^2} \chi_1^2 \left[1 - \frac{190107}{66169} \left(\hat{S}_1 \cdot \hat{L} \right)^2 \right] - \frac{41525}{158208} \frac{\ell^4}{(m_1 + m_2)^4} \frac{\chi_1 \chi_2}{\eta} \left[\left(\hat{S}_1 \cdot \hat{S}_2 \right) - \frac{4743}{1661} \left(\hat{S}_1 \cdot \hat{L} \right) \left(\hat{S}_2 \cdot \hat{L} \right) \right] + (1 \leftrightarrow 2)$$

In future, in principle, the ground-based detectors could constrain the CS coupling to be

$$\ell \leq (10 - 100)\,\mathrm{km}$$

or prove the presence of the CS term.

Yagi, Yunes,Tanaka 2012

Parametric amplification of GWs

Dynamical Chern-Simons gravity

$$S = \frac{M_p^2}{2}\int d^4x\sqrt{-g}\,R + \frac{M_p}{8}\ell^2\int d^4x\sqrt{-g}\,\phi\,\varepsilon^{\mu\nu\lambda\rho}R_{\alpha\beta\mu\nu}R^{\alpha\beta}{}_{\lambda\rho} - \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 + \frac{1}{2}m^2\phi^2\right]$$

$$h_{ij} = h_R e_{ij}^R(\mathbf{n}) + h_L e_{ij}^L(\mathbf{n})$$

$$i\varepsilon_{ilm}n_l e_{mj}^{R/L}(\mathbf{n}) = \pm e_{ij}^{R/L}(\mathbf{n})$$

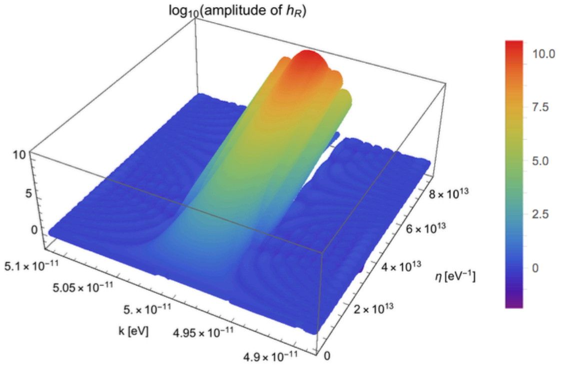
We can neglect the cosmic expansion

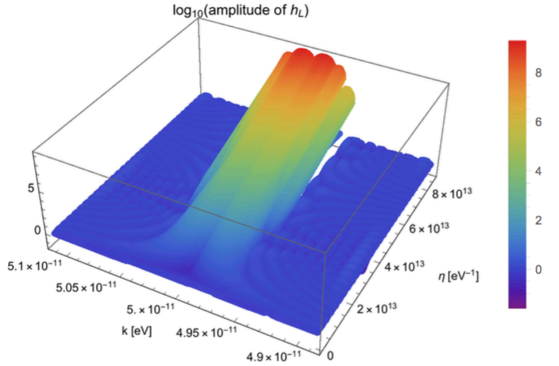
$$\phi = \phi_0 \cos mt$$

GWs in the axion background

$$\ddot{h}_A + \frac{m\varepsilon_A\delta\cos mt}{m + \varepsilon_A k\delta\cos mt}k\dot{h}_A + k^2 h_A = 0$$

$$\delta = m^2\ell^2\frac{\phi_0}{M_p} \qquad \varepsilon_A = \begin{cases} 1 & \text{for R} \\ -1 & \text{for L} \end{cases}$$



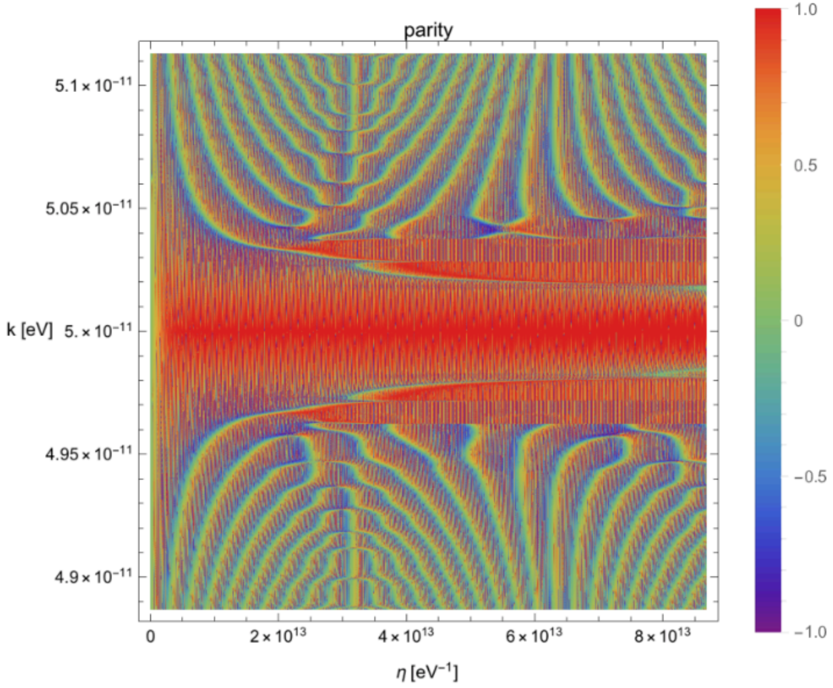


$$k_{\text{res}} = \frac{m}{2} = 1.2\times10^4\left(\frac{m}{10^{-10}\,\text{eV}}\right)\text{Hz}$$

Parity violation in gravity

Axion oscillation induces parity violation in gravity.

$$\text{parity\_violation} = \frac{|h_R|^2 - |h_L|^2}{|h_R|^2 + |h_L|^2}$$



If this parity violation pattern is observed, we can believe the axion dark matter.

A new constraint on Chern–Simons gravity

The current constraint provided by the Gravity Probe B is $\ell \leq 10^8\,\mathrm{km}$

Suppose the axion is the main component of the dark matter.

We can calculate the growth rate analytically as

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

$$c\,t_{\times 10} = 10^{-8}\left(\frac{10^{-10}\,\mathrm{eV}}{m}\right)\left(\frac{10^{8}\,\mathrm{km}}{\ell}\right)^2\sqrt{\frac{0.3\mathrm{GeV/cm}^3}{\rho}}\ \mathrm{pc}$$

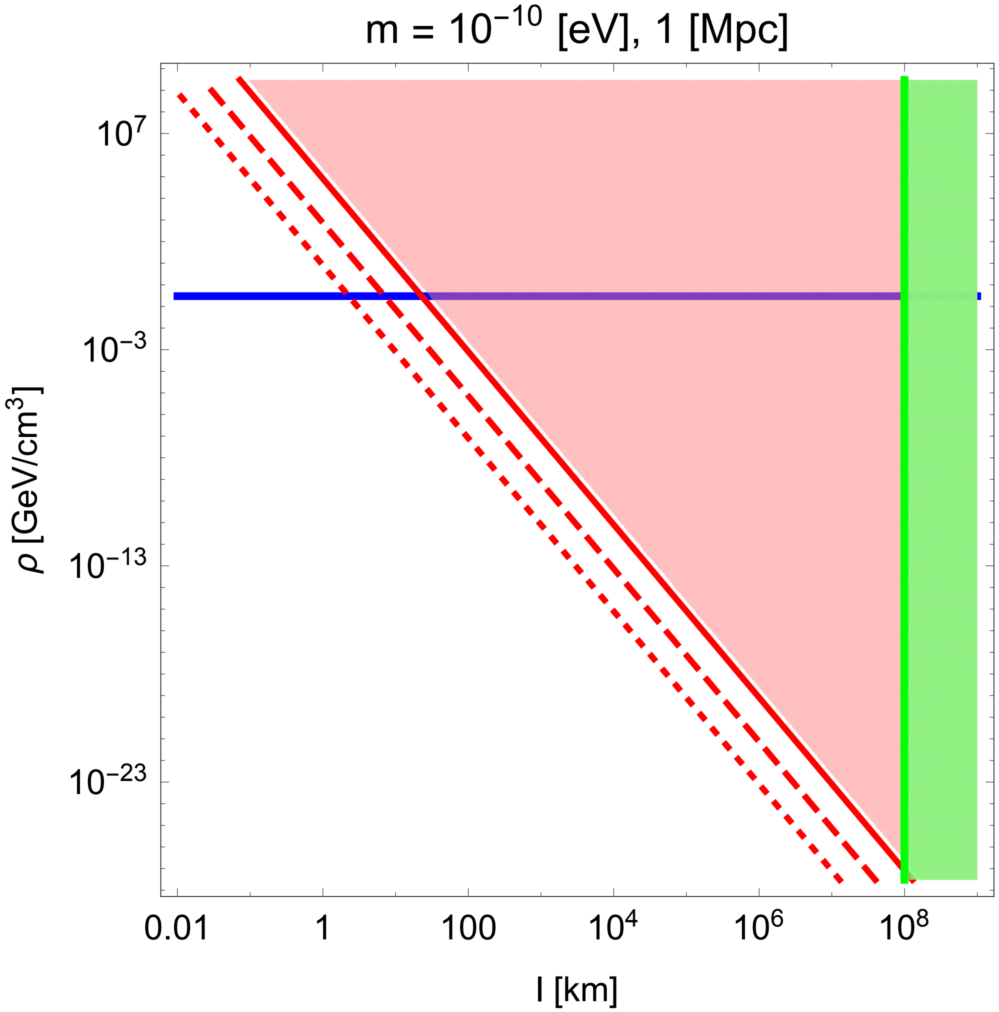
From this growth rate, we can say that
after 10kpc propagation the amplitude of 10kHz GWs is significantly enhanced.

However, we have never observed these phenomena.

Thus, taking $c\,t_{\times 10} = 10\mathrm{Mpc}$, we obtain a new stringent constraint

$$\ell \leq 10\mathrm{km}$$

Constraint from GW observations



Electromagnetic waves propagating in axion dark matter

$$10^{-13}\mathrm{eV} \quad \Leftrightarrow \quad 10^{3}\mathrm{eV}$$

A constraint on axion density

$$\ddot{A}+k^{2}\left[1+\varepsilon\lambda\frac{\sqrt{\rho}}{k}\sin mt\right]h_{A}=0 \quad , \quad \varepsilon=\pm 1$$

Suppose the axion is the main component of the dark matter.

We can calculate the growth rate analytically as $\Gamma=\frac{\lambda\sqrt{\rho}}{4}$ at $k_{r}=\frac{m}{2}$

From this growth rate, we can say that

$$c\,t_{\times 10}=30\frac{\left(10^{12}\,\mathrm{GeV}\right)^{-1}}{\lambda}\sqrt{\frac{0.3\mathrm{GeV/cm}^{3}}{\rho}}\ \mathrm{pc}$$

After 30Mpc propagation, there should not be significant growth.

Thus, we have obtained the constraint on the axion abundance

$$\frac{\rho_{axion}}{\rho_{DM}}\leq 10^{-12}$$

Summary

- We have shown that string dark matter and parity violation in gravity induced by the axion can be detected with ground laser interferometers.

- We can give a new stringent constraint on dynamical Chern-Simons gravity if the axion is the dark matter.