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Quantum Interferometry in Chern-Simons modified gravity

Hiroki Okawara

Hirosaki University, Japan

with K. Yamada, and H. Asada (Hirosaki)

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Abstract

Possible effects of Chern-Simons (CS) gravity on a quantum interferometer turn out to be dependent on the latitude and direction of the interferometer on the Earth in orbital motion around the Sun.

1 Chern-Simons (CS) gravity

CS gravity modifies GR via the addition of a correction

$$S_{CS} = \frac{1}{16\pi G}\int d^4x \frac{1}{4} f R^* R, \tag{1}$$

Following [1], let us consider a system of nearly spherical bodies in the standard PPN point-particle approximation. The CS correction to the metric becomes

$$\delta_{CS} g_{0i} = \frac{2G}{c^3}\sum_A \frac{\dot{f}}{r_A}\left[\frac{m_A}{r_A}(\vec{v}_A \times \vec{n}_A)^i - \frac{J_A^i}{2r_A^2} + \frac{3}{2}\frac{(\vec{J}_A\cdot\vec{n}_A)}{r_A^2} n_A^i\right]. \tag{2}$$

2 Phase shifts in a quantum interferometer

We consider a quantum interferometer that consists of a closed path C (its area S) on the Earth, as shown by Fig 1. Δ is a phase difference induced by g_{0i}.
By using Stokes theorem, Δ is rewritten in the surface integral form over S

$$\Delta = \frac{mc}{\hbar}\oint_C \vec{g}\cdot d\vec{r} = \frac{mc}{\hbar}\int_S (\vec{\nabla}\times\vec{g}). \tag{3}$$

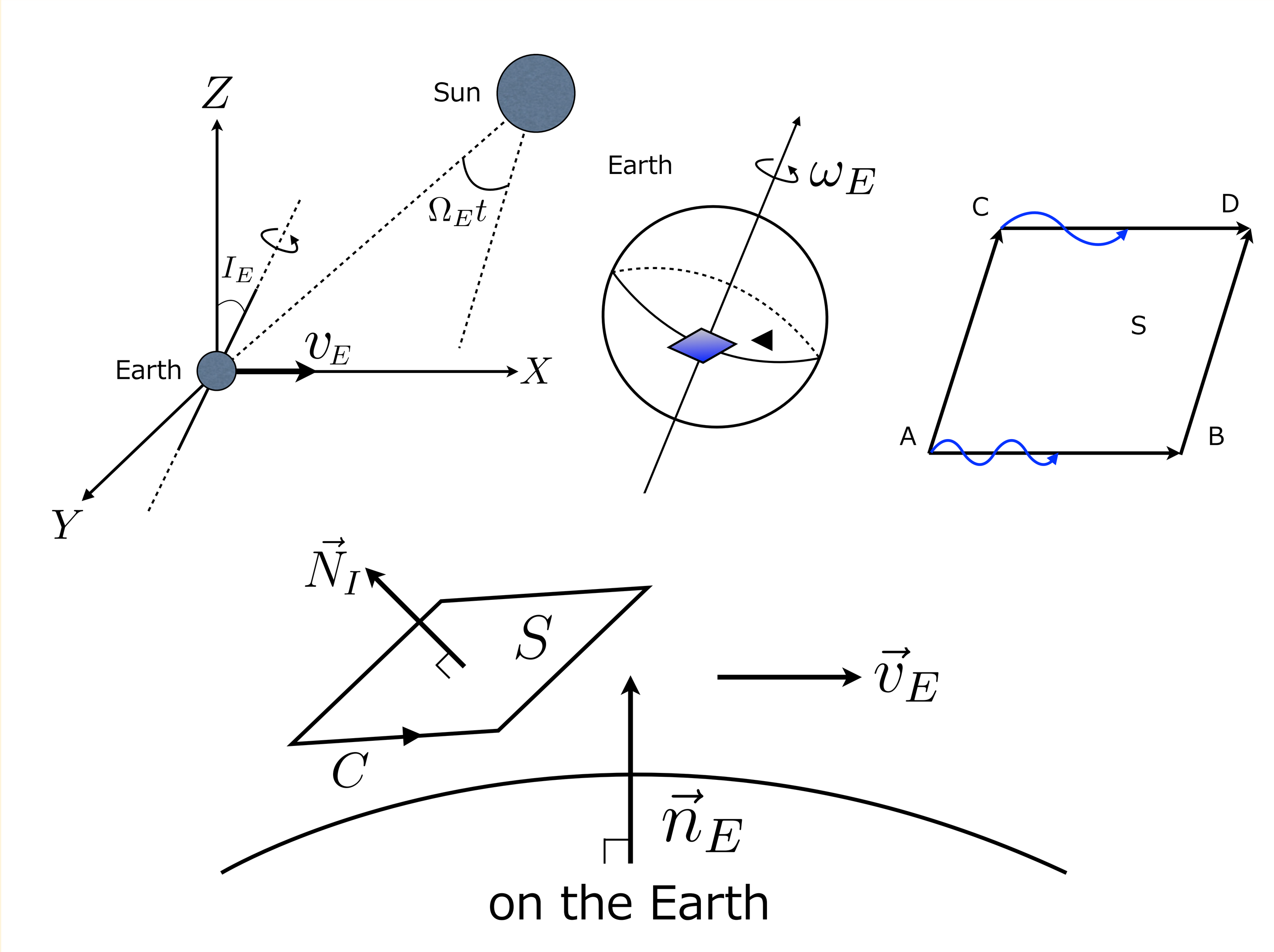

Figure 1: Quantum interferometer on the Earth orbiting around the Sun.

3 Phase shifts for Chern-Simons (CS) gravity

Let us substitute the CS term of Eq. (2) into Eq. (3) to obtain Δ for CS gravity. We focus on the Earth mass in CS gravity and use $r_E \gg \sqrt{S}$. Hence,

$$\Delta_{CS} = 2\dot{f}\frac{mGM_E S}{\hbar c^2 r_E^3}\tilde{\Delta}_{CS}, \tag{4}$$

$$\tilde{\Delta}_{CS} = [3(\vec{v}_E\cdot\vec{n}_E)\vec{n}_E - \vec{v}_E]\cdot\vec{N}_I. \tag{5}$$

Eq. (5) depends on the latitude and direction, and changes with the Earth's spin and orbital motion.

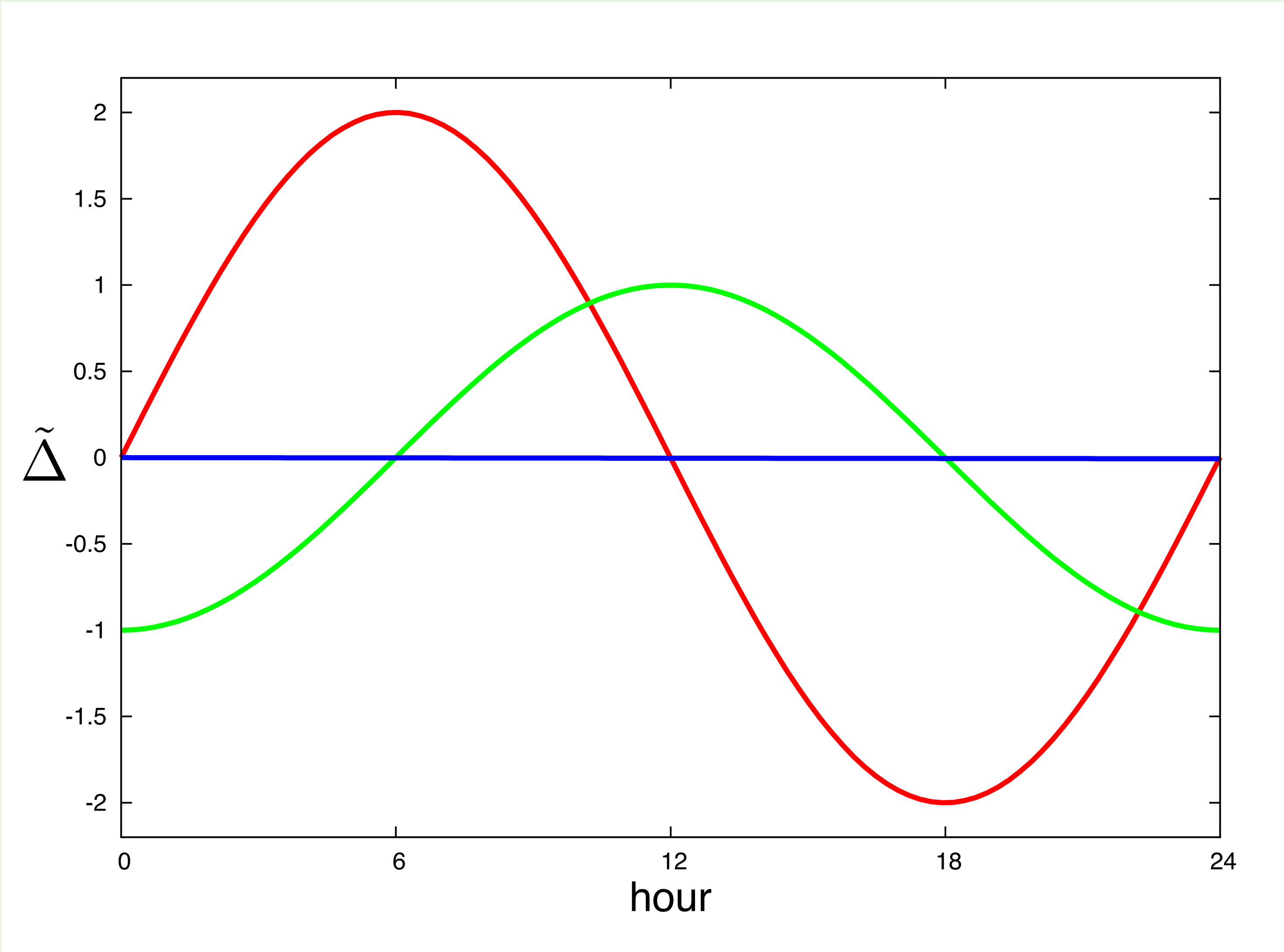

Figure 2: Daily variation in phase differences by CS effects. The red, green, and blue curves correspond to $\vec{N}_I$ for a horizontal plane and two vertical ones (one facing the East and the other facing the North), respectively.

4 Time variation and the latitude

By using the coordinate rotation $\vec{N}_I(t) = R(\omega_E t)\vec{N}_{I0}, \vec{n}_E(t) = R(\omega_E t)\vec{n}_{E0}$, $\tilde{\Delta}_{CS}$ is rewritten in the rotating matrix $R(t)$

$$\tilde{\Delta}_{CS} = \left(R(t)^{-1}\vec{v}_E\right)^{\mathrm{T}}\left[3(\vec{n}_{E0}\cdot\vec{N}_{I0})\vec{n}_{E0} - \vec{N}_{I0}\right], \tag{6}$$

$$R(t)^{-1}\vec{v}_E = \{R(\phi)\}^{-1}\{R(\omega_E t)\}^{-1}\{R(\Omega_E t)\}^{-1}R(I_E)R(\Omega_E t)\begin{pmatrix} v_E \\ 0 \\ 0 \end{pmatrix}. \tag{7}$$

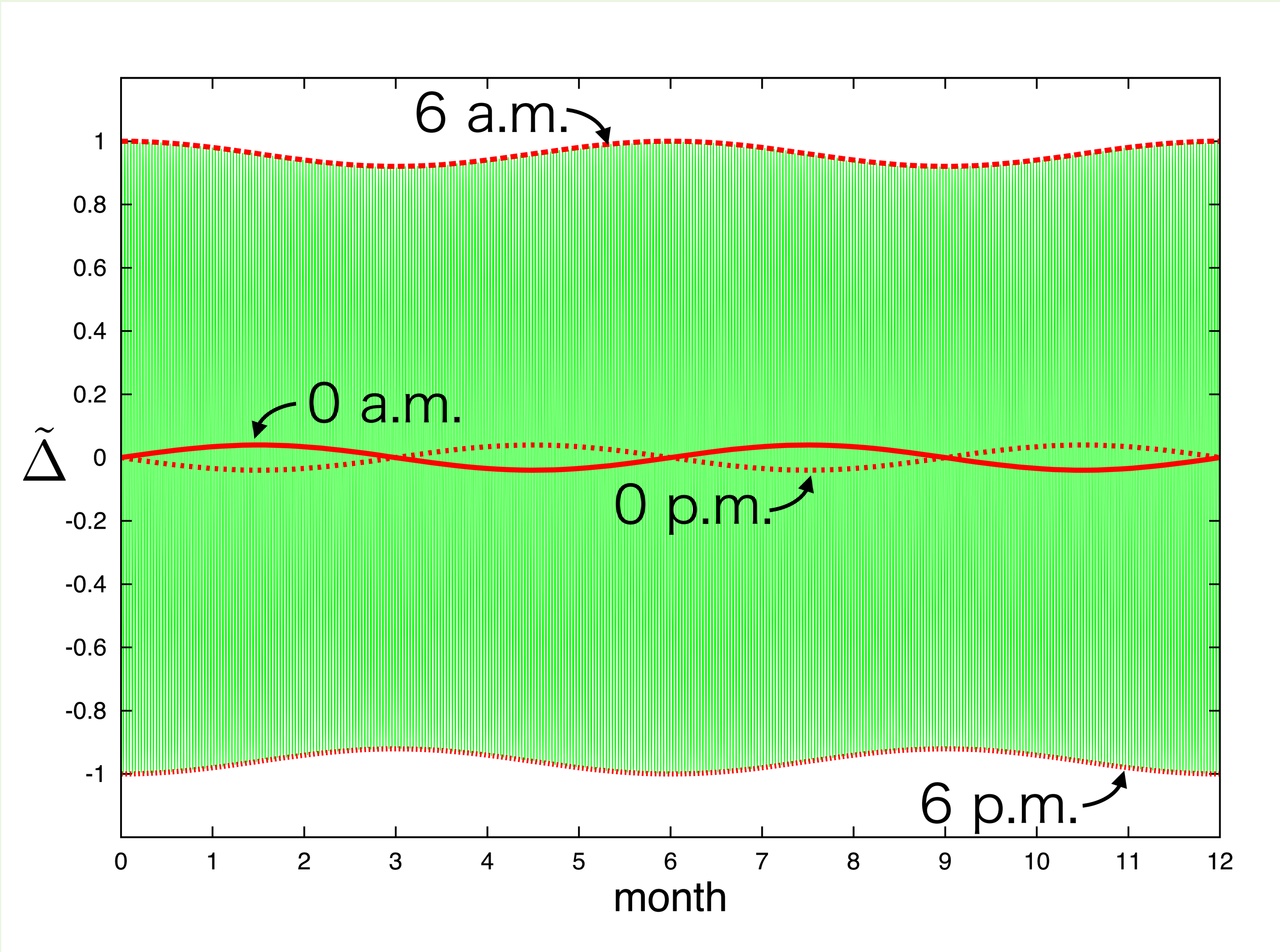

Figure 3: Seasonal variation in phase differences by CS effects. The green solid is full data points.

5 Possible constraint on $\dot{f}$

$\dot{f}$ induces the phase shift

$$|\Delta_{CS}| \sim 10^{-3}\mathrm{s}^{-1} \times \left(\frac{mc^2}{1\mathrm{GeV}}\right)\left(\frac{\dot{f}}{c}\right)\left(\frac{S}{0.4\mathrm{m}^2}\right). \tag{8}$$

Current phase mesurement accuracy at $O(10^{-3}) \to \dot{f}c^{-1} < 10^0$s bound.
GPB (Gravity Probe B), LAGEOS space mission $\to \dot{f}c^{-1} < 10^{-3}$s.

6 Conclusion

We considered effects of CS gravity on a quantum interferometer.

- Daily and seasonal variations in phase shifts are predicted with an estimate of the size of the effects.
- Neutron interferometry with ~ 5 meters arm length and $\sim 10^{-4}$ phase measurement accuracy would place a bound on a CS parameter comparable to Gravity Probe B satellite [2].

References

[1] S. Alexander and N. Yunes, Phys. Rev. Lett. **99**, 241101 (2007). [2] H. Okawara, K. Yamada, H. Asada, accepted Phys. Rev. Lett. (2012) (arXiv: **1210.4628**).