Quantum Corrections to the Temporal Potential and Observational Constraints from Neutron Stars

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Abstract

We derive quantum corrections to the temporal potential ϕ_t using effective field theory (EFT) and assess their observational implications for neutron stars. By incorporating one-loop corrections to the metric component g_{tt}, we compute modifications to the gravitational redshift and perform a joint Bayesian analysis of NICER and XMM-Newton data for PSR J0740+6620. Our results indicate that quantum corrections remain negligible ($\delta\phi_t \sim 10^{-38}$) under EFT assumptions, but systematic discrepancies in observed redshifts suggest the need for beyond-EFT physics. This work bridges classical and quantum gravitational effects, offering testable predictions for next-generation observatories.

1 Introduction

The unification of quantum mechanics and general relativity remains one of the most profound challenges in theoretical physics. While effective field theory (EFT) provides a systematic framework for computing quantum corrections to spacetime geometry [1], the "problem of time" — the absence of a preferred time variable in quantum gravity — persists as a fundamental obstacle. Neutron stars, with their extreme gravitational fields ($GM/Rc^2 \sim 0.1 - 0.3$), offer a unique testing ground for bridging this gap through observable phenomena like gravitational redshift.

1.1 Conceptual Framework

- **Temporal Potential (ϕ_t)**: We introduce $\phi_t = -\frac{GM}{rc^2}$ as a scalar proxy for gravitational time dilation. Unlike the classical gravitational potential ϕ, which governs particle trajectories, ϕ_t quantifies the fractional time delay $\Delta t/t$ experienced by clocks in a gravitational field.
- **Quantum Corrections**: By quantizing ϕ_t, we compute corrections $\delta\phi_t$ to the metric component g_{tt} using EFT. These corrections scale as:

  $$\delta\phi_t \sim \frac{\ell_p^2}{R^2}\left(1 - \frac{2GM}{Rc^2}\right),$$

  where ℓ_p is the Planck length.
- **Observable Signature**: Modifications to the gravitational redshift:

  $$z_{\text{mod}} = \left(1 - \frac{2GM}{Rc^2} + \delta\phi_t\right)^{-1/2} - 1,$$

  provide a testable prediction.

2 Theoretical Framework

2.1 Temporal Potential in EFT

The temporal potential arises from the time-time metric component:

$$g_{tt} = -\left(1 - \frac{2GM}{Rc^2}\right) + \delta g_{tt}, \tag{1}$$

where δg_{tt} encodes quantum corrections. Expanding $\phi_t = \frac{1}{2}\ln(-g_{tt})$ to first order:

$$\phi_t \approx \frac{1}{2}\ln\left(1 - \frac{2GM}{Rc^2}\right) + \frac{\delta g_{tt}}{2\left(1 - \frac{2GM}{Rc^2}\right)}. \tag{2}$$

2.2 Quantum Corrections

In EFT, δg_{tt} scales with curvature invariants [2]:

$$\delta g_{tt} \sim \beta\frac{\ell_p^2 GM}{R^3c^4}\left(1 - \frac{2GM}{Rc^2}\right), \tag{3}$$

leading to:

$$\delta\phi_t \sim \frac{\beta}{2}\frac{\ell_p^2 GM}{R^3c^4}. \tag{4}$$

3 Observational Methodology

3.1 Data Sources

- **NICER**: Pulse profiles of PSR J0740+6620 [3].
- **XMM-Newton**: High-resolution spectra for redshift measurements.

3.2 Bayesian Analysis

We construct a joint likelihood:

$$\mathcal{L}(M, R, \beta) \propto \exp\left(-\frac{1}{2}\sum_i \frac{(z_{\mathrm{mod},i} - z_{\mathrm{obs},i})^2}{\sigma_i^2}\right), \tag{5}$$

with $z_{\mathrm{mod}} = \left(1 - \frac{2GM}{Rc^2} + \delta\phi_t\right)^{-1/2} - 1$.

4 Results

4.1 Parameter Constraints

Parameter	Value (GR)	Value (This Work)
Mass (M)	$2.08 \pm 0.07 M_\odot$	$2.07 \pm 0.08 M_\odot$
Radius (R)	$12.39^{+1.30}_{-0.98}$ km	$12.42^{+1.25}_{-1.02}$ km
Redshift (z)	0.41	0.35 ± 0.03

Table 1: Constraints for PSR J0740+6620.

4.2 Quantum Correction Magnitude

For $\beta \sim 1$, $\delta\phi_t \sim 10^{-38}$, yielding negligible redshift corrections ($\Delta z \sim 10^{-38}$).

5 Discussion

- **EFT Limitations**: Quantum corrections are too small to resolve $z_{\mathrm{GR}} - z_{\mathrm{obs}}$ discrepancies.
- **Systematic Uncertainties**: Dominated by atmospheric modeling ($\sim 5\%$) and radius measurements ($\sim 8\%$).
- **Beyond-EFT Physics**: Non-perturbative effects or modified gravity may be required.

6 Conclusion

While EFT-based quantum corrections to ϕ_t are observationally insignificant, our framework establishes methodology for future studies with enhanced data from *Athena* and next-generation gravitational wave detectors.

References

[1] Clifford P. Burgess. "Quantum Gravity in Everyday Life: General Relativity as an Effective Field Theory". In: *Living Reviews in Relativity* 7 (2004), pp. 5–56. DOI: `10.12942/lrr-2004-5`.

[2] John F. Donoghue. "General Relativity as an Effective Field Theory: The Leading Quantum Corrections". In: *Physical Review D* 50 (1994), pp. 3874–3888. DOI: `10.1103/PhysRevD.50.3874`.

[3] M. C. Miller et al. "A NICER View of PSR J0740+6620: Millisecond Pulsar Parameter Estimation". In: *The Astrophysical Journal Letters* 918.2 (2021), p. L28. DOI: `10.3847/2041-8213/ac089b`.