# Quantum Gravity Lab Offline Viewer

Explainer for Each Chart in the Simulation Dashboard

(Notes for Internal Use)

November 24, 2025

## Overview

The *Quantum Gravity Lab — Offline Edition* viewer shows a single precomputed orbit and its associated quantum/GR diagnostics. This document explains each chart in the dashboard, in simple language but with enough math that it can sit in a paper or supplement.

Throughout we use:

- $G$ — Newton's gravitational constant.
- $M$ — central mass.
- $c$ — speed of light.
- $p$ — semi–latus rectum of the orbit.
- $e$ — eccentricity of the orbit.
- $\mathbf{r}(t) = (x(t), y(t), z(t))$ — position of the test body.
- $\mathbf{v}(t) = (v_x(t), v_y(t), v_z(t))$ — velocity.
- $r(t) = \|\mathbf{r}(t)\|$ and $v^2(t) = \|\mathbf{v}(t)\|^2$.

The classical reference dynamics is an almost–Keplerian orbit with a post–Newtonian (1PN) correction to capture relativistic perihelion precession. The quantum part is a Jaynes–Cummings (JC) sensor coupled to the orbit via a position–dependent complexity field $C_Q(r)$.

Each chart below describes one of the panels in the UI.

## 1 Left Column: GR Metrics

### 1.1 Perihelion Precession Plot

**What this shows.** This panel shows the angle of the orbit's perihelion (closest approach) from orbit to orbit. Each dot is the angle at a detected local minimum of $r(t)$; the blue curve is the measured perihelion angle, and the dashed red line is the ideal GR prediction.

**How we define the angle.** We first compute the orbital angle

$$\phi(t) = \mathrm{unwrap}\big(\arctan 2(y(t), x(t))\big),$$

so that the angle increases smoothly rather than jumping by $2\pi$.

Perihelia are detected as local minima in $r(t)$:

$$r_{i-1} > r_i < r_{i+1} \quad \Rightarrow \quad \text{perihelion at index } i.$$

The corresponding perihelion angles are $\phi_i = \phi(t_i)$.

We then look at the differences

$$\Delta\phi_i = \phi_{i+1} - \phi_i.$$

For a perfect Kepler ellipse in Newtonian gravity, you would get $\Delta\phi_i \approx 2\pi$. In GR, there is an excess per orbit:

$$\Delta\phi_{\text{excess}} = \Delta\phi_i - 2\pi.$$

**GR prediction.** For a bound orbit in a Schwarzschild spacetime, the leading 1PN perihelion advance per orbit is

$$\Delta\phi_{\text{GR}} \;=\; \frac{6\pi GM}{c^2 p}.$$

The red line in the plot is the ideal GR line:

$$\phi_{\text{GR}}(n) = \phi_0 + \big(2\pi + \Delta\phi_{\text{GR}}\big)\, n,$$

where $n$ is the perihelion index.

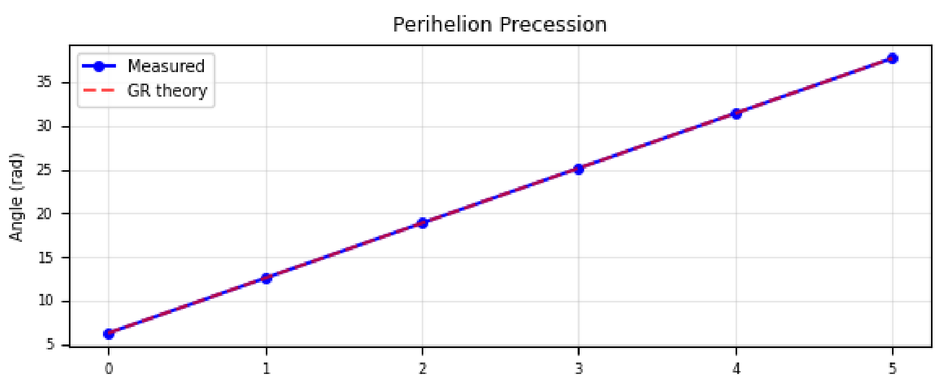


Figure 1: Perihelion precession panel. Blue: measured perihelion angle $\phi_n$. Red dashed: GR prediction with 1PN advance per orbit.

## 1.2 Time Dilation (Quantum vs Schwarzschild)

**What this shows.** This panel compares:

- the *quantum clock* rate from the unified model,
- a *classical GR clock* rate from the Schwarzschild metric.

Both are plotted as $d\tau/dt$ versus coordinate time $t$.

**Schwarzschild reference.** For a static clock at radius $r$ in a Schwarzschild spacetime,

$$\frac{d\tau_{\mathrm{GR}}}{dt} = \sqrt{1 - \frac{2GM}{c^2 r}}\ .$$

In the code we use

$$\frac{d\tau_{\mathrm{GR}}}{dt}(r(t)) = \sqrt{1 - \frac{2GM}{c^2 r(t)}}.$$

**Quantum clock.** The quantum model defines a complexity–dependent clock rate

$$\frac{d\tau_{\mathrm{Q}}}{dt} = f\big(C_Q(r(t))\big),$$

where $C_Q(r)$ is a scalar "complexity" field derived from the quantum sector, and $f$ is chosen so that in the weak field limit it behaves similarly to the GR redshift but can deviate when complexity is high.

**How to read it.**

- The red dashed curve is the Schwarzschild $d\tau_{\mathrm{GR}}/dt$.
- The blue curve is $d\tau_{\mathrm{Q}}/dt$ from the unified model.
- Agreement indicates that the complexity field is successfully reproducing GR time dilation; deviations show where the complexity–based clock disagrees.

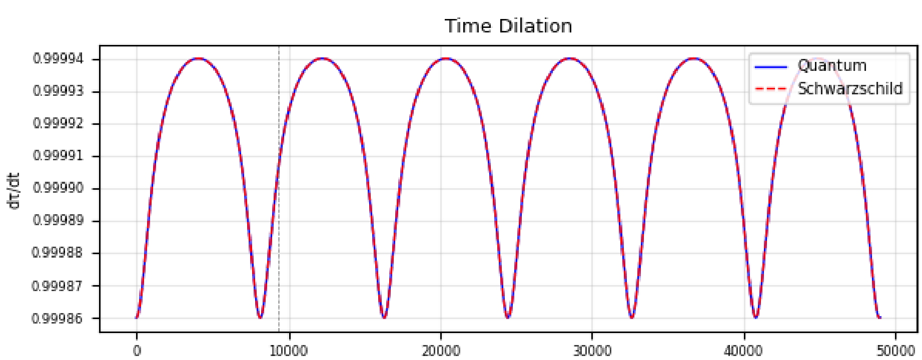


Figure 2: Time dilation panel. Blue: quantum clock $d\tau_{\mathrm{Q}}/dt$. Red dashed: Schwarzschild clock $d\tau_{\mathrm{GR}}/dt$.

## 1.3 Orbital Energy

**What this shows.** This panel shows the total orbital energy as a function of time, and a horizontal reference line at the initial energy. It is a sanity check for energy conservation in the numerical integrator.

**Definition.** In the simplest Newtonian picture,

$$E(t) = \frac{1}{2}v^2(t) - \frac{GM}{r(t)}.$$

We plot $E(t)$ and the horizontal line $E(t_0)$.

The code computes an "energy variation" as

$$\text{energy\_variation} = \frac{\sigma(E)}{|\langle E \rangle|},$$

where $\sigma(E)$ is the standard deviation and $\langle E \rangle$ is the mean energy over the run.

**How to read it.**

- A nearly flat line means excellent energy conservation.
- Slow drifts or oscillations indicate numerical error or physical coupling (if included).

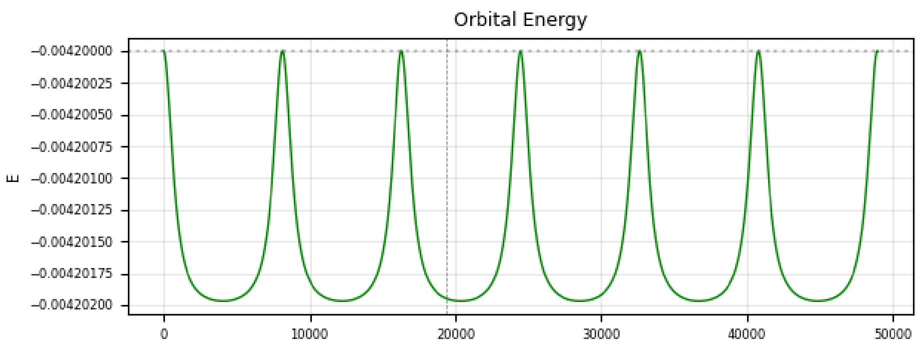


Figure 3: Orbital energy as a function of time. The dotted line marks the initial energy $E(t_0)$.

### 1.4 Angular Momentum

**What this shows.** This panel shows the magnitude of the orbital angular momentum

$$L(t) = \|\mathbf{L}(t)\|$$

as a function of time.

**Definition.** The angular momentum vector is

$$\mathbf{L}(t) = \mathbf{r}(t) \times \mathbf{v}(t).$$

We plot the scalar magnitude

$$L(t) = \|\mathbf{L}(t)\|.$$

In an ideal central potential, $L(t)$ is exactly conserved. Numerically, we expect it to be nearly constant.

**How to read it.**

- A horizontal line indicates excellent conservation of angular momentum.
- Any slow drift or noise quantifies the integrator's angular momentum error.

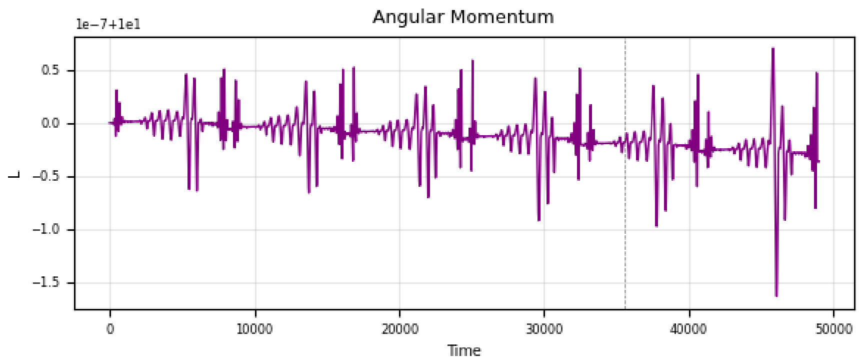


Figure 4: Angular momentum magnitude $L(t)$ over the simulation.

# 2 Center Column: Orbit and Complexity

## 2.1 Orbital Trajectory with Complexity Coloring

**What this shows.** This panel shows the orbit in the orbital plane (x–y projection), colored by the quantum complexity $C_Q$ at each point. It also draws two reference circles:

- the periapsis radius $r_{\rm peri}$,
- the apoapsis radius $r_{\rm apo}$.

**Kepler geometry.** For a bound orbit with parameters $(p, e)$:

$$r_{\rm peri} = \frac{p}{1+e}, \qquad r_{\rm apo} = \frac{p}{1-e}.$$

The code draws circles of these radii around the origin:

$$x^2 + y^2 = r_{\rm peri}^2, \qquad x^2 + y^2 = r_{\rm apo}^2.$$

**Complexity coloring.** Each point on the orbit is colored according to the scalar

$$C_Q(r(t)),$$

which is the output of the complexity field. High values (e.g. near the central mass) can show up as "hot" colors; low values as cooler colors.

**How to read it.**

- The orbit shape and orientation show precession in the plane.
- The color gradient shows where the complexity field is strongest.

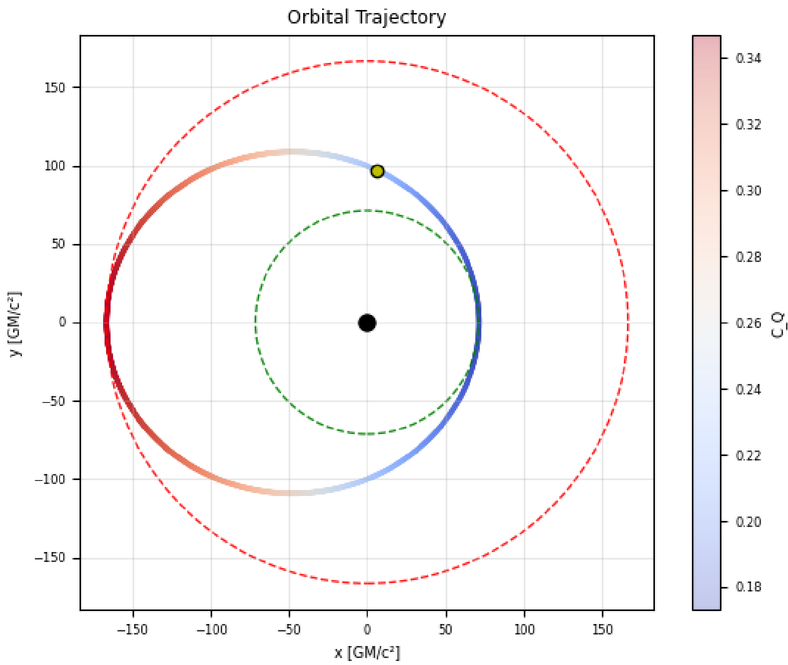


Figure 5: Orbital trajectory in the x–y plane, colored by complexity $C_Q(r)$. Green dashed circle: periapsis radius. Red dashed circle: apoapsis radius.

## 2.2 Quantum Complexity vs Time

**What this shows.** This panel plots the complexity field $C_Q$ along the orbit as a function of time:

$$t \mapsto C_Q\big(r(t)\big).$$

**Intuition.** The complexity field plays the role of a position–dependent coupling between quantum and classical sectors. In simple terms:

- Far from the mass, $C_Q$ is small, and the orbit is nearly Newtonian.
- Near the mass, $C_Q$ grows, and the orbit experiences enhanced effective GR corrections and stronger coupling to the quantum sensor.

**Example schematic form.** A generic radial profile might look like

$$C_Q(r) \sim \left(\frac{r_0}{r}\right)^{\alpha}, \qquad \alpha > 0,$$

with an exponent $\alpha$ tuned by the calibration.

**How to read it.** Spikes in $C_Q(t)$ correspond to close approaches (perihelion), where both gravity and quantum backreaction are strongest.

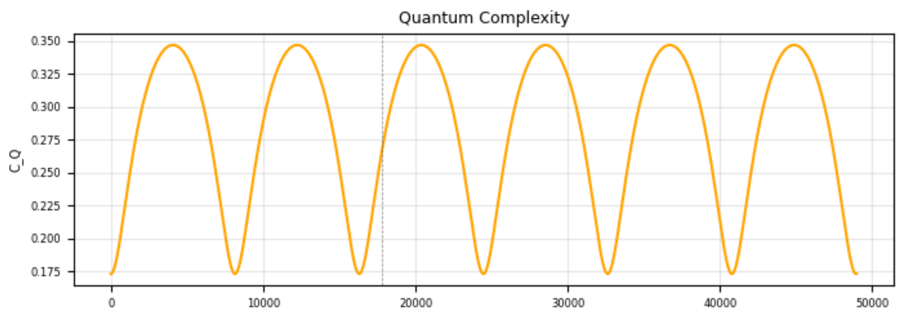


Figure 6: Complexity $C_Q(r(t))$ as a function of time along the orbit.

## 2.3 Clock Error: Quantum vs GR

**What this shows.** This panel plots the difference between the quantum clock and the Schwarzschild clock:

$$\Delta\left(\frac{d\tau}{dt}\right) = \frac{d\tau_{\mathrm{Q}}}{dt} - \frac{d\tau_{\mathrm{GR}}}{dt}.$$

The horizontal zero line means "perfect agreement."

**Interpretation.**

- Regions where the curve crosses zero show where the complexity clock exactly matches GR.
- Positive or negative excursions show where the unified model predicts more or less time dilation than GR.

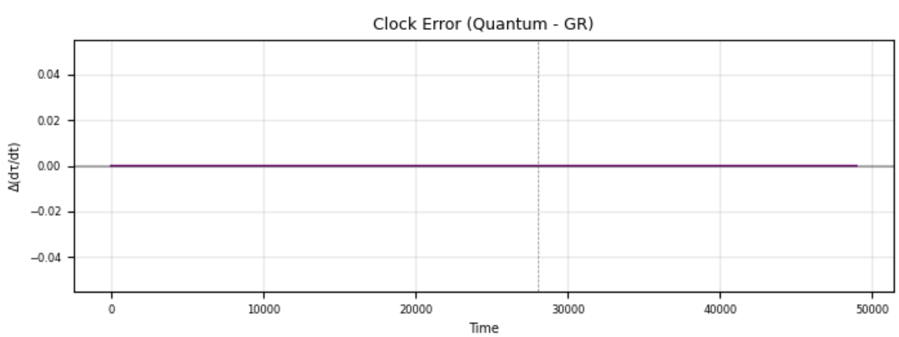


Figure 7: Clock error: difference between quantum clock and Schwarzschild clock $d\tau/dt$. The horizontal line marks zero error.

# 3 Right Column: Quantum Sensor (Jaynes–Cummings)

## 3.1 Bloch Sphere Trajectory

**What this shows.** This 3D panel shows the evolution of the effective two–level system (quantum sensor) as a trajectory on the Bloch sphere. Each point corresponds to a Bloch vector

$$\mathbf{s}(t) = (s_x(t), s_y(t), s_z(t)).$$

A short red arrow shows the current Bloch vector; a faint red curve shows the recent trail.

**From density matrix to Bloch vector.** The Jaynes–Cummings state is a density matrix $\rho(t)$ on the joint atom–cavity Hilbert space. After tracing out photons, the atomic reduced state $\rho_{\text{atom}}(t)$ can be written as

$$\rho_{\text{atom}}(t) = \frac{1}{2}\big(I + s_x\sigma_x + s_y\sigma_y + s_z\sigma_z\big),$$

where $\sigma_i$ are Pauli matrices and $(s_x, s_y, s_z)$ is the Bloch vector.

In the code we estimate $s_i$ by summing contributions from each photon number sector and normalizing.

**How to read it.**

- Points near the poles ($s_z \approx \pm 1$) are close to pure ground/excited states.
- Points near the equator show strong superposition and coherence.

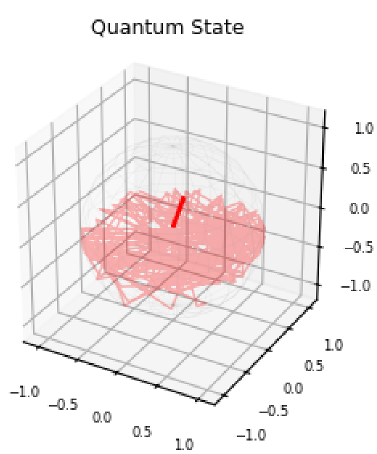


Figure 8: Bloch sphere trajectory of the atomic two–level system. The arrow shows the current Bloch vector; the faint curve shows the recent history.

## 3.2 Photon Number $\langle n \rangle$ vs Time

**What this shows.** This panel plots the expected photon number in the cavity:

$$\langle n(t) \rangle = \mathrm{Tr}\left(\rho(t)\, a^\dagger a\right).$$

**JC Hamiltonian.** The Jaynes–Cummings Hamiltonian (in units where $\hbar = 1$) is

$$H = \omega_c a^\dagger a + \frac{\omega_a}{2}\sigma_z + g(a\sigma_+ + a^\dagger\sigma_-),$$

with time–dependent parameters $\omega_c(t)$, $\omega_a(t)$, $g(t)$ that are functions of the orbital state.

**How to read it.**

- Oscillations in $\langle n(t)\rangle$ are the usual JC Rabi–like exchange between atom and field.
- Slow modulation of the envelope is induced by changes in the orbit (through $r(t)$ and $v(t)$).

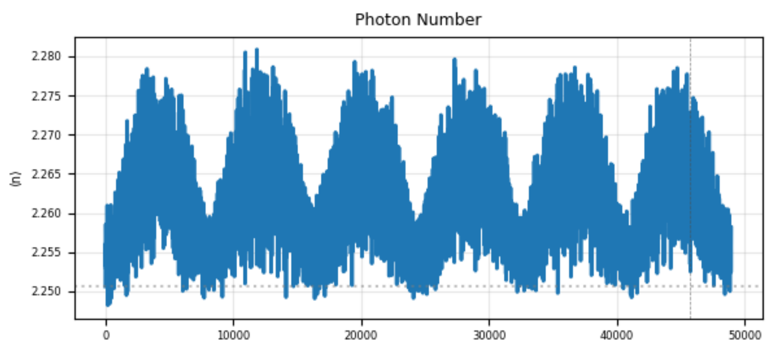


Figure 9: Expected photon number $\langle n(t)\rangle$ in the cavity as a function of time.

### 3.3 Quantum Coherence vs Time

**What this shows.** This panel plots a scalar measure of coherence, defined as a sum of off–diagonal magnitudes in the density matrix:

$$C(t) = \sum_n |\rho_{e_n,g_n}(t)|\,.$$

Here $\rho_{e_n,g_n}$ is the coherence between the excited and ground atomic states in the $n$–photon sector.

**Interpretation.**

- $C(t) \approx 0$ indicates an almost classical mixture.
- Larger $C(t)$ indicates strong quantum superposition and phase coherence.

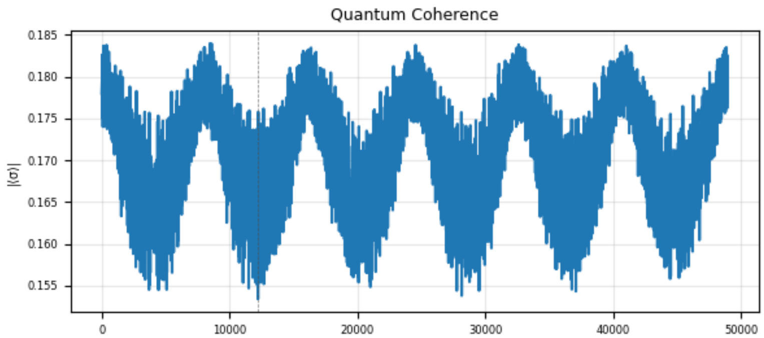


Figure 10: Quantum coherence measure $C(t)$ derived from the off–diagonal terms of the density matrix.

### 3.4 JC Parameter Modulation $\omega_c, \omega_a$

**What this shows.** This panel shows how the cavity and atomic frequencies are modulated by the orbit, in units of their nominal values:

$$\frac{\omega_c(t)}{\omega_{c,0}}, \qquad \frac{\omega_a(t)}{\omega_{a,0}}.$$

**Orbital mapping.** We map the classical orbit to JC parameters via simple dimensionless ratios. For example (schematically),

$$\rho_{\text{local}}(t) = \frac{1}{r(t)^2 + \varepsilon},$$
$$\phi_{\text{local}}(t) = -\frac{GM}{r(t)},$$
$$v_{\text{local}}(t) = \|\mathbf{v}(t)\|,$$

then define normalized versions

$$\hat{\rho} = \frac{\rho_{\text{local}}}{\rho_{\text{ref}}}, \quad \hat{\phi} = \frac{\phi_{\text{local}}}{|\phi_{\text{ref}}|}, \quad \hat{v} = \frac{v_{\text{local}}}{v_{\text{ref}}},$$

and finally

$$\omega_c(t) = \omega_{c,0}\,\big(1 + s_\rho\,\hat{\rho}(t)\big),$$
$$\omega_a(t) = \omega_{a,0}\,\big(1 + s_\phi\,\hat{\phi}(t)\big),$$
$$g(t) = g_0\,\big(1 + s_v\,\hat{v}(t)\big).$$

The sliders $s_\rho, s_\phi, s_v$ directly control the strength of this modulation.

**How to read it.**

- Deviations of $\omega_c/\omega_{c,0}$ and $\omega_a/\omega_{a,0}$ from 1 show how strongly the orbit is driving the cavity and atomic frequencies.
- Stronger modulation (larger $s_\rho, s_\phi, s_v$) leads to more dramatic JC dynamics in the other quantum panels.

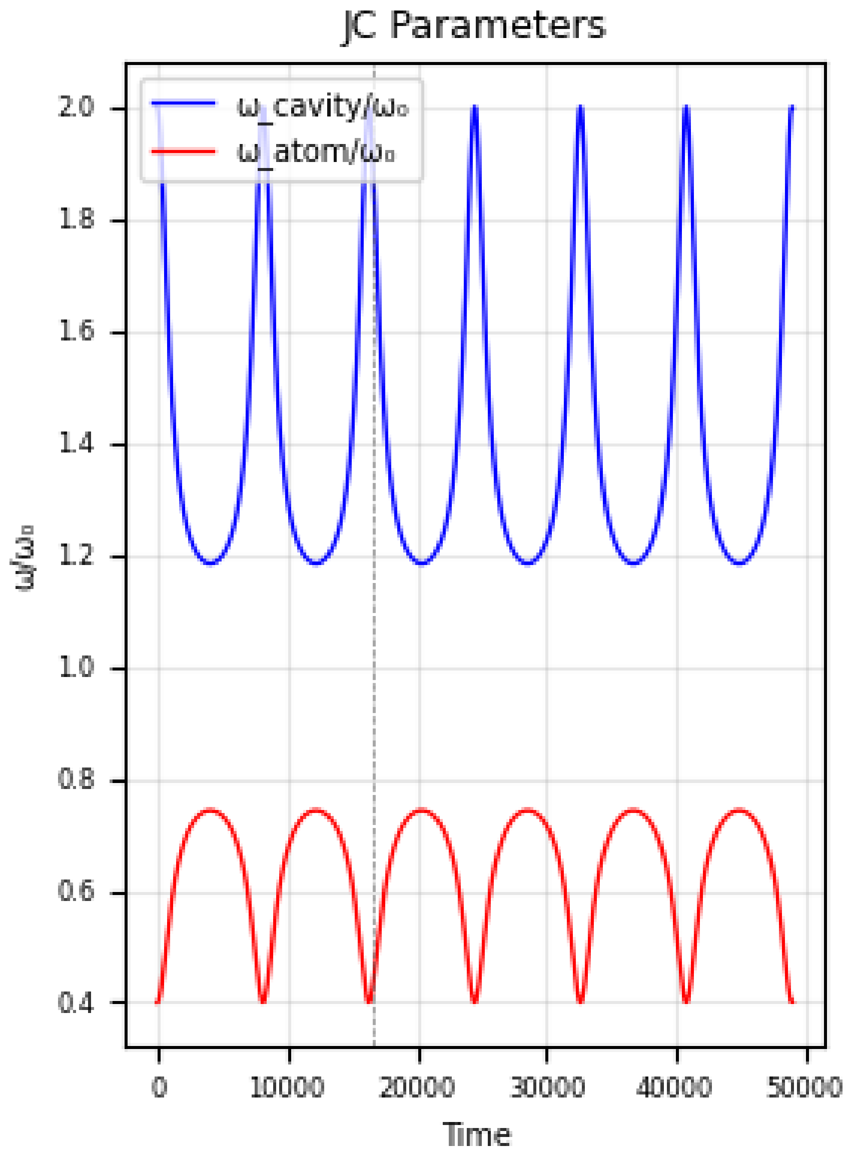


Figure 11: Orbital modulation of JC parameters: $\omega_c/\omega_{c,0}$ and $\omega_a/\omega_{a,0}$ versus time.