

# Quantum Gravity Lab Offline Viewer

## Explainer for Each Chart in the Simulation Dashboard

(Notes for Internal Use)

November 23, 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

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

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

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

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

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:

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

where  $n$  is the perihelion index.

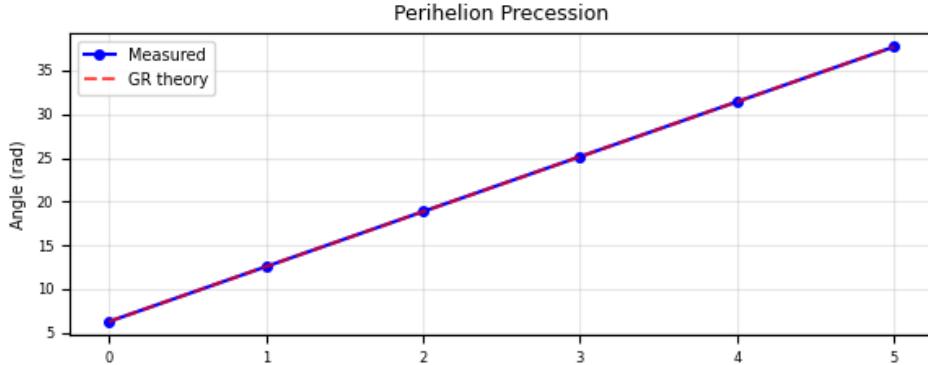


Figure 1: Perihelion precession panel. Blue: measured perihelion angle  $\phi_n$ . Red dashed: GR prediction with 1PN advance per orbit.

## 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,

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

In the code we use

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

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

$$\frac{d\tau_Q}{dt} = f(C_Q(r(t))),$$

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  $d\tau_{\text{GR}}/dt$ .
- The blue curve is  $d\tau_Q/dt$  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  $d\tau_Q/dt$ . Red dashed: Schwarzschild clock  $d\tau_{\text{GR}}/dt$ .

### 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).

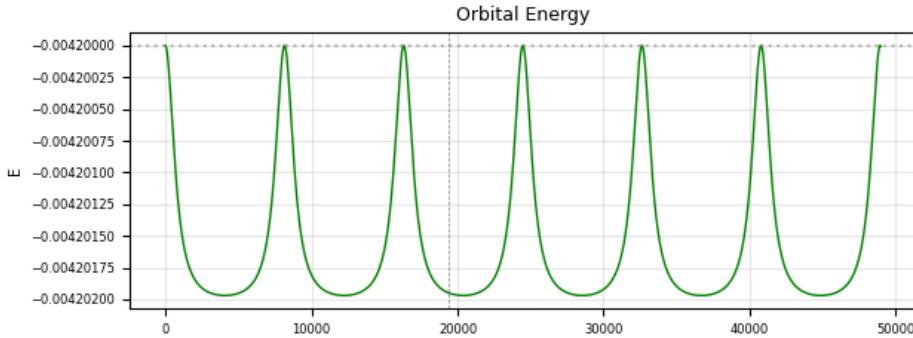


Figure 3: Orbital energy as a function of time. The dotted line marks the initial energy  $E(t_0)$ .

## 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.

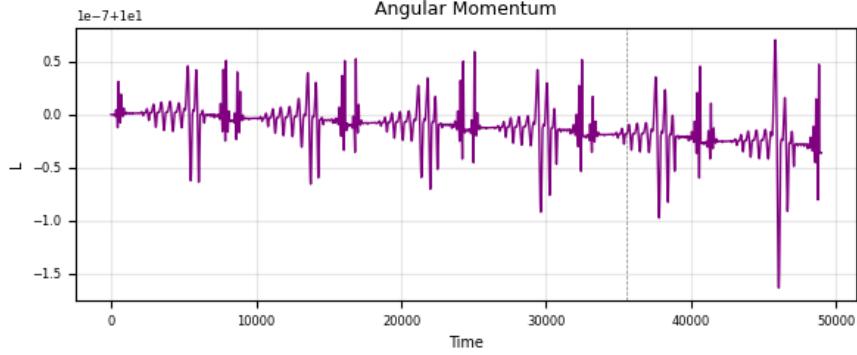


Figure 4: Angular momentum magnitude  $L(t)$  over the simulation.

## 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  $r_{\text{peri}}$ ,
- the apoapsis radius  $r_{\text{apo}}$ .

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

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

The code draws circles of these radii around the origin:

$$x^2 + y^2 = r_{\text{peri}}^2, \quad x^2 + y^2 = r_{\text{apo}}^2.$$

**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.

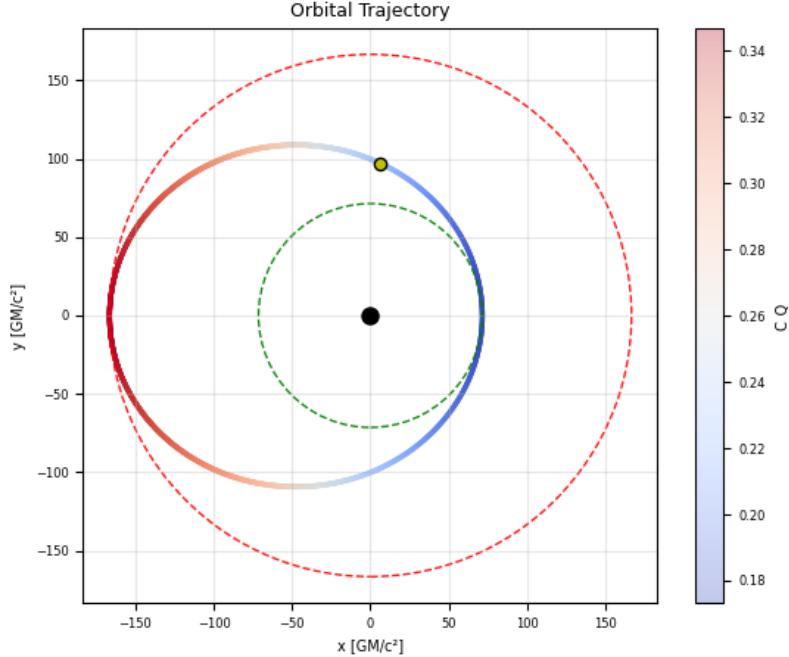


Figure 5: Orbital trajectory in the x–y plane, colored by complexity  $C_Q(r)$ . Green dashed circle: periaxis radius. Red dashed circle: apoasis radius.

## 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:

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

**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

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

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.

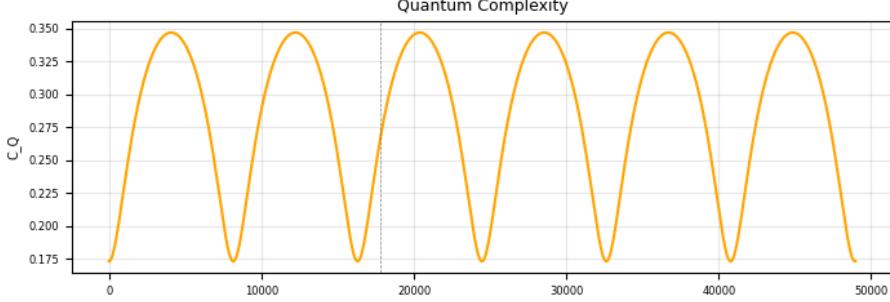


Figure 6: Complexity  $C_Q(r(t))$  as a function of time along the orbit.

### 2.3 Clock Error: Quantum vs GR

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

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

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.

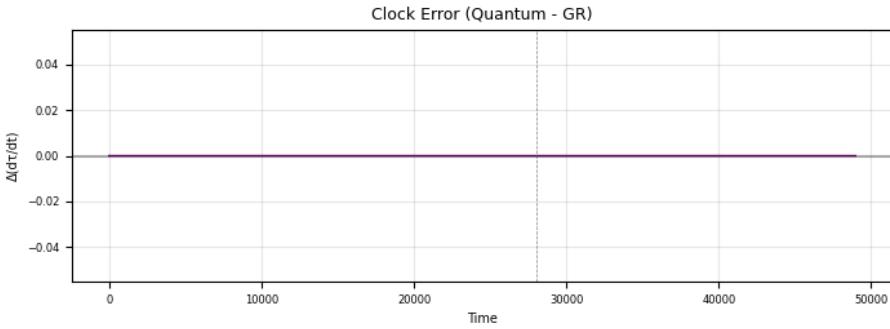


Figure 7: Clock error: difference between quantum clock and Schwarzschild clock  $d\tau/dt$ . The horizontal line marks zero error.

### 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

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

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.

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

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

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

**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  $v(t)$ ).

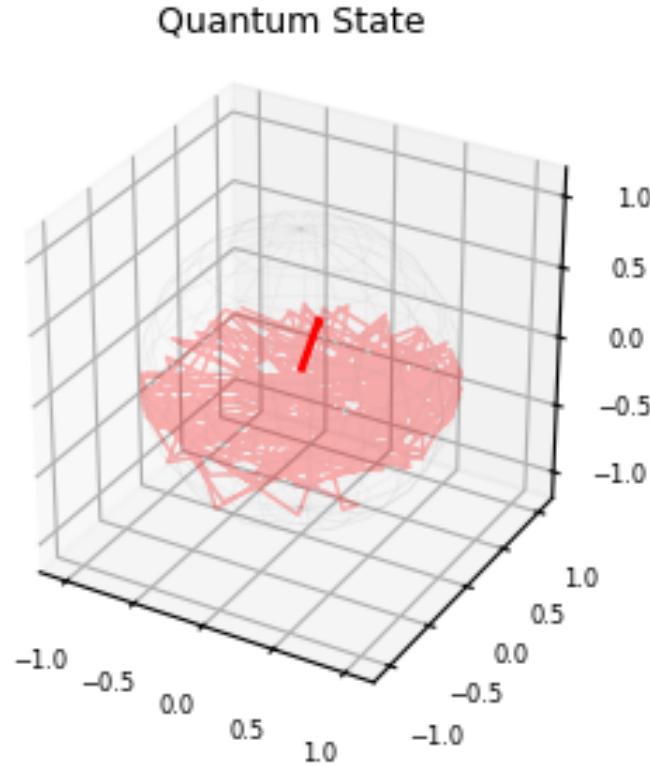


Figure 8: Bloch sphere trajectory of the atomic two-level system. The arrow shows the current Bloch vector; the faint curve shows the recent history.

### 3.3 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.

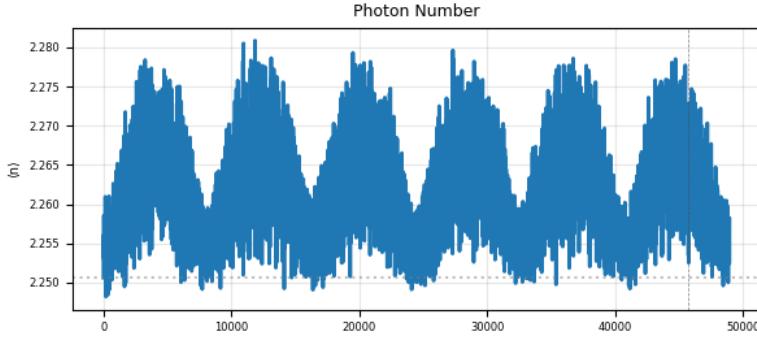


Figure 9: Expected photon number  $\langle n(t) \rangle$  in the cavity as a function of time.

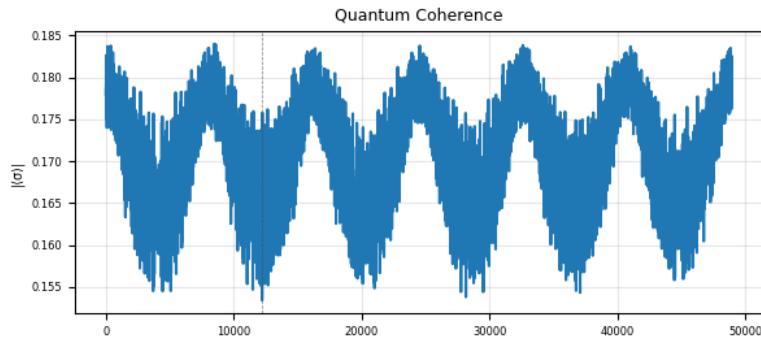


Figure 10: Quantum coherence measure  $C(t)$  derived from the off-diagonal terms of the density matrix.

### 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:

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

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

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

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

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

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.

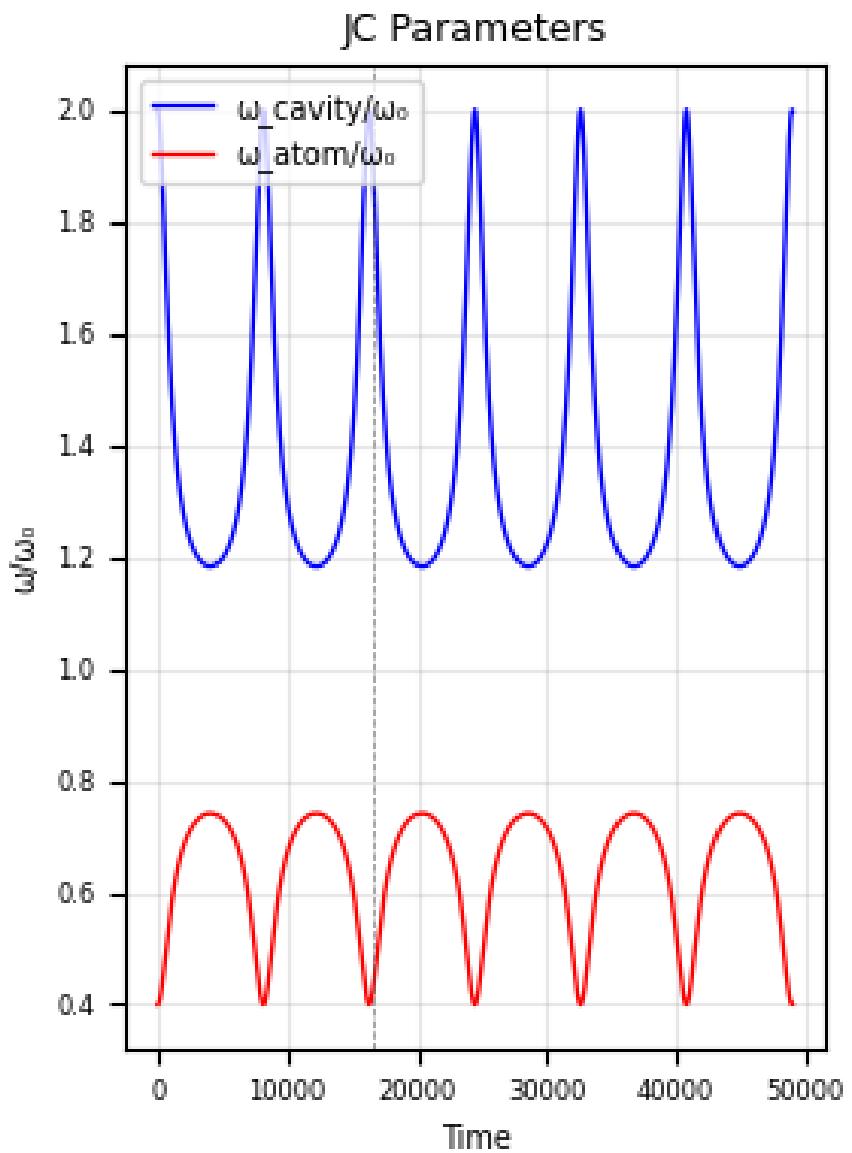


Figure 11: Orbital modulation of JC parameters:  $\omega_c/\omega_{c,0}$  and  $\omega_a/\omega_{a,0}$  versus time.