HOT QUBITS ON THE HORIZON
Perturbation Theory & Late Times in Gravitational Backgrounds

Greg Kaplanek

PHENO 2021: Wednesday, May 26, 2021

[2007.05984] — Cliff Burgess & GK

McMaster University

PERIMETER INSTITUTE

Outline

1. Gravitating Quantum Systems and Secular Growth
   - Motivation: late-time breakdowns of perturbation theory
   - Late-time resummations (without solving everything)
   - Open Quantum Systems (OQSs) & Horizons

2. Application:
   - Unruh-DeWitt detector (in Schwarzschild space)
   - OQS treatment & robust late-time predictions

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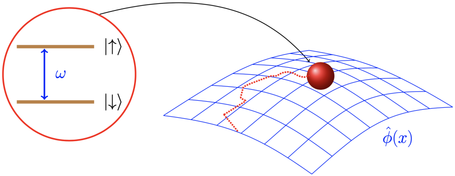

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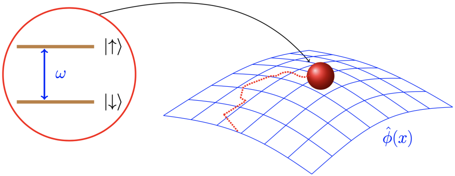

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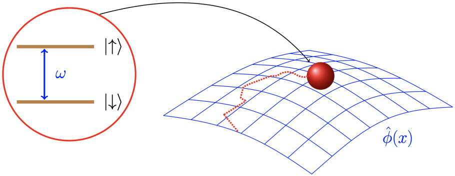
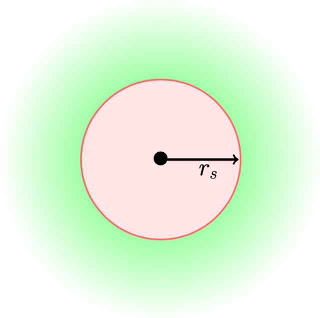


GRAVITY+QFTS AND LATE TIMES

- We care about what happens at late times
- Usually: free quantum fields in gravitational backgrounds
- Implicit Assumption: interaction with the background always dominates (neglected interactions can be treated as perturbations)



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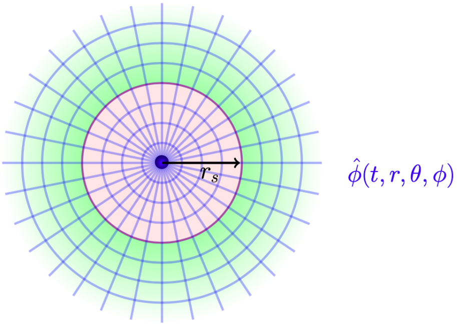

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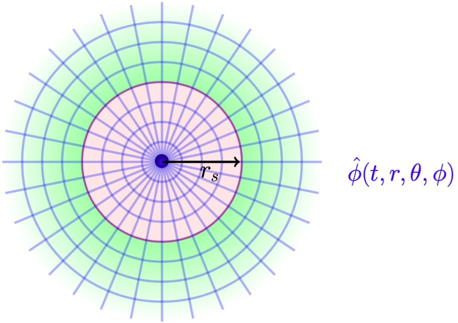

LATE-TIME BREAKDOWNS — "SECULAR GROWTH"

- Observation: Perturbation Theory $\hat{H} = \hat{H}_0 + g\hat{H}_{\text{int}}$

$$e^{-i(\hat{H}_0+g\hat{H}_{\text{int}})t} \simeq e^{-i\hat{H}_0 t}\left[1 - ig\hat{H}_{\text{int}}t + \dots\right] \tag{1}$$

For any $g \ll 1$, we eventually get $\lim_{t\to\infty}(\cdots) \simeq \infty$

- Generic issue (but usually not a problem for particle physics)

- Gravity is always there! Acts as a medium/environment where secular growth can occur[1].

[1] de Sitter: Petri [0810.3330], Schwarzschild: Akhmedov et. al. [1508.07500], Minkowski: Burgess et. al. [1806.11415]

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LATE-TIME RESUMMATIONS: PARTICLE DECAYS

- Suppose we have a species of particle with some decay rate

$$\Gamma \sim \mathcal{O}(g^2)\ . \tag{2}$$

- Why do we trust (for $\Gamma t \gg 1$)

$$N(t) \simeq N(0)\, e^{-\Gamma t} \qquad \text{vs.} \qquad N(t) \simeq N(0)(1 - \Gamma t)\ \ ? \tag{3}$$

- $\rightarrow$ because we trust $\frac{d}{dt}N = -\Gamma N$

- Does not depend *explicitly* on $t \implies$ broader domain of validity

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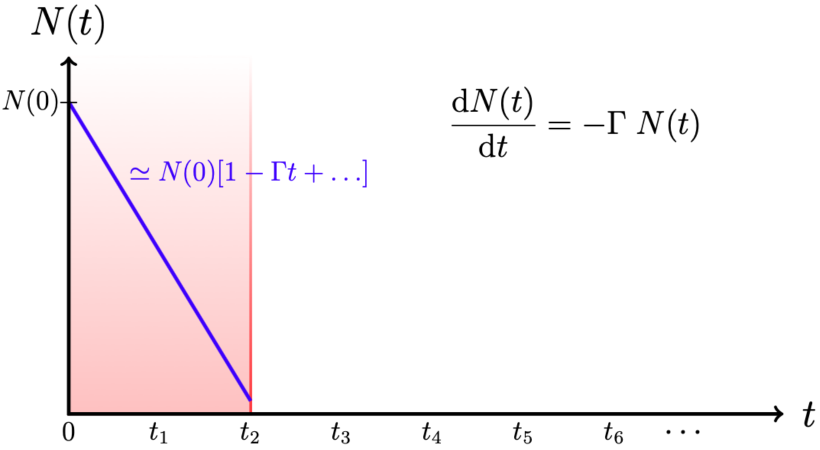

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -\Gamma\, N(t)$$

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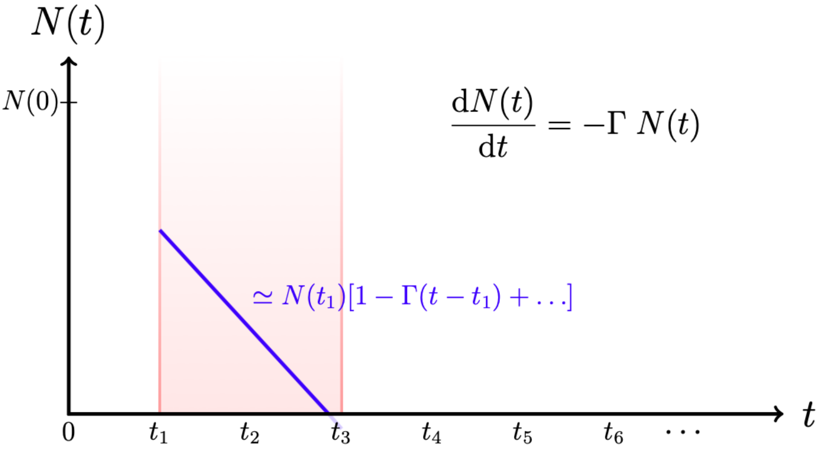

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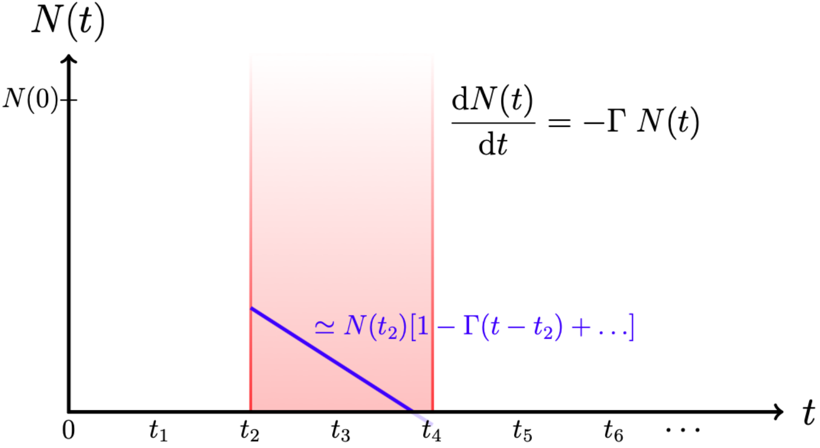

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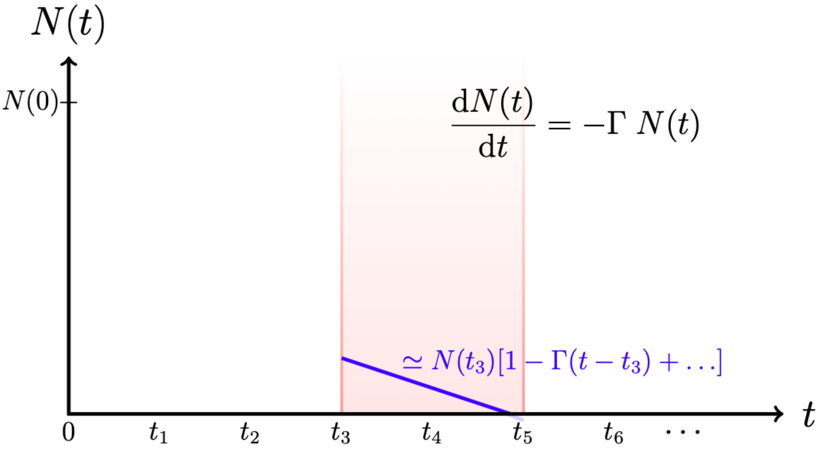

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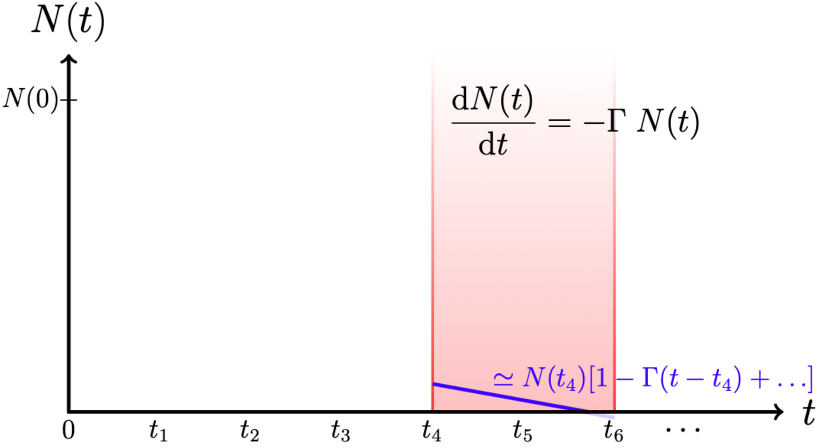

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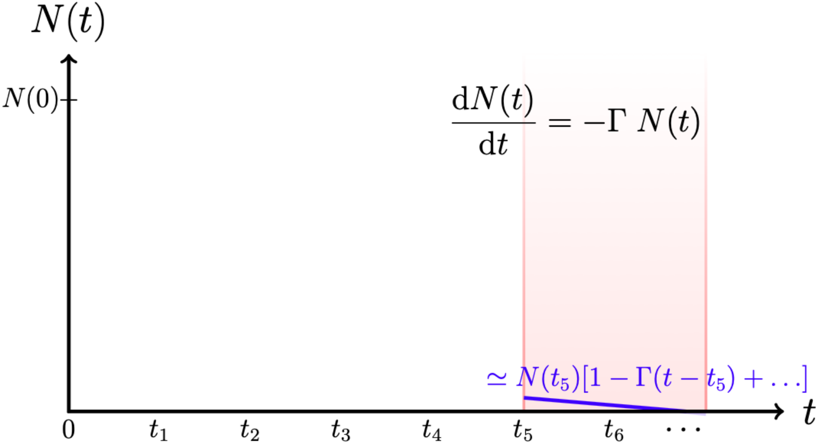

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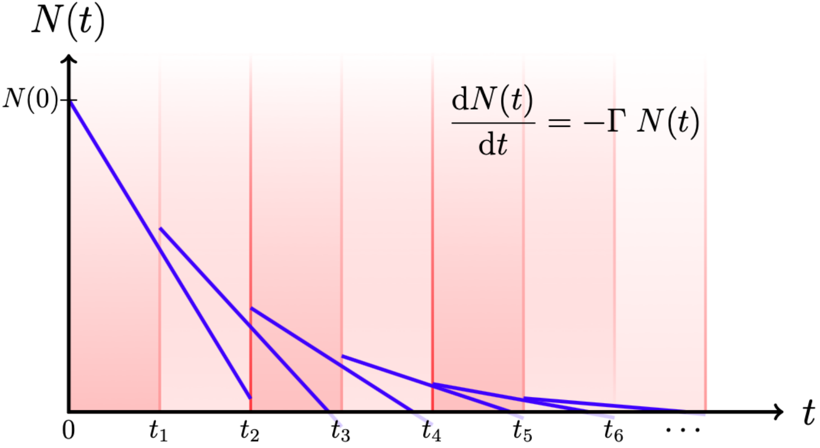

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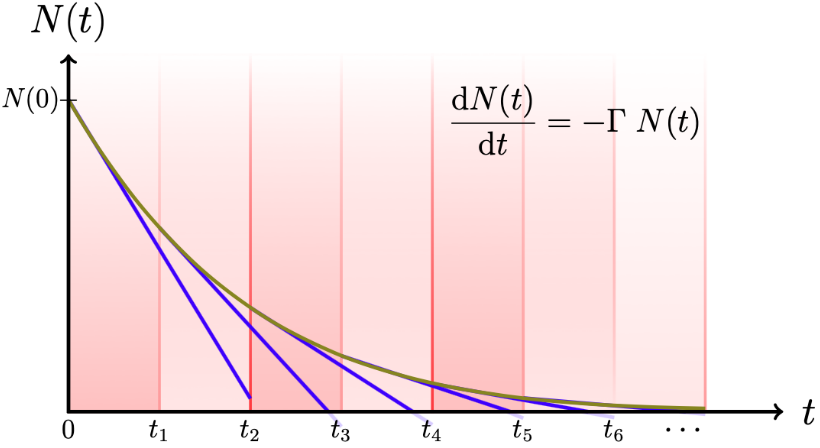

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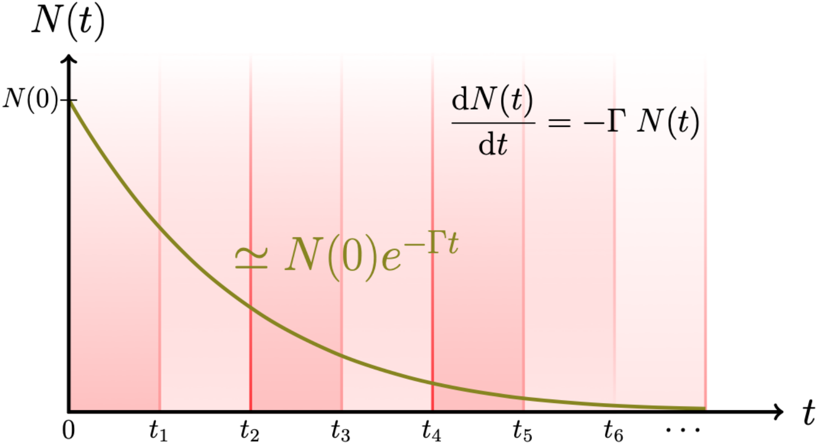
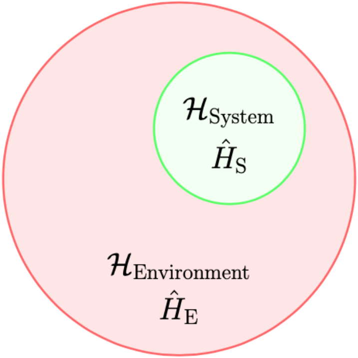


A Remedy: Open Quantum Systems



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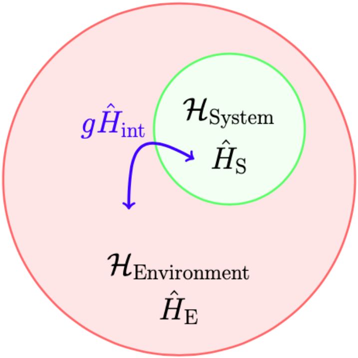

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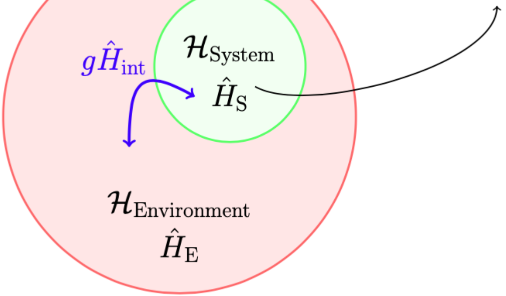

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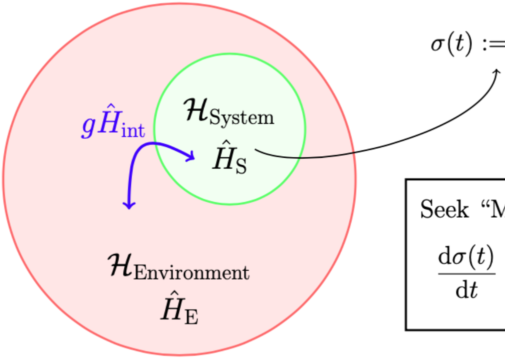

$$\sigma(t) := \operatorname*{Tr}_{\mathcal{H}_{\text{Environment}}}[\rho(t)]$$

Seek "Master Equation":

$$\frac{\mathrm{d}\sigma(t)}{\mathrm{d}t} = f(\sigma(t))$$

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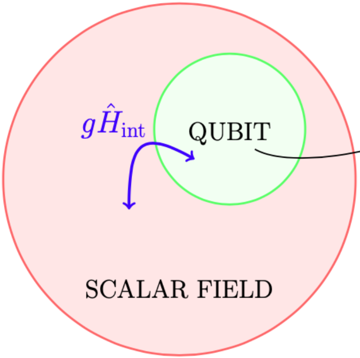

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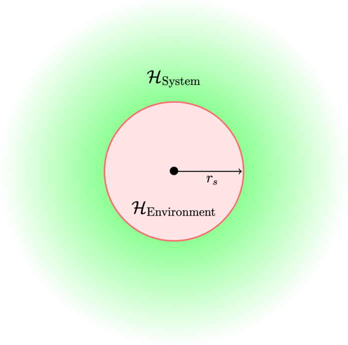
OQSs and Horizons

- Observation: spacetimes with horizons resemble OQSs
  $\rightarrow$ use OQS methods for interacting field theories!



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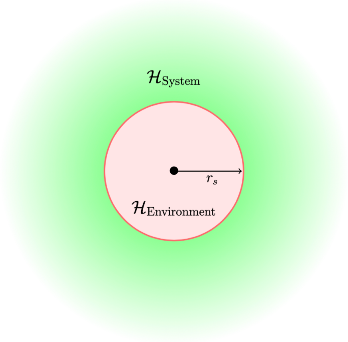

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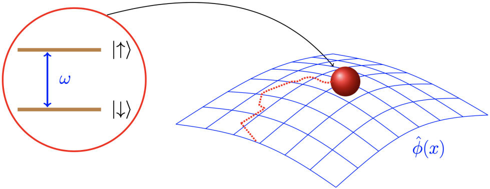
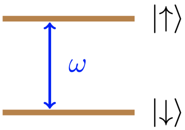
Unruh-DeWitt detector



Application of OQS Methods: Consider *Unruh-DeWitt Detector*

Unruh-DeWitt Detector

- "Open System": Qubit with free Hamiltonian



$$\hat{H}_S := \frac{\omega}{2}\,\sigma_3 \;=\; \begin{bmatrix} \omega/2 & 0 \\ 0 & -\omega/2 \end{bmatrix} \tag{4}$$

- "Environment": real scalar field $\hat{\phi}$

$$\hat{H}_E = \text{Free Hamiltonian for } \hat{\phi} \text{ in Schwarzschild space} \tag{5}$$

- Put qubit on timelike trajectory $y^\mu(\tau) = [t(\tau), r(\tau), \theta(\tau), \phi(\tau)]$

$$g\,\hat{H}_{\text{int}} \;=\; g\,\begin{bmatrix} 0 & e^{+i\omega\tau} \\ e^{-i\omega\tau} & 0 \end{bmatrix} \otimes \hat{\phi}[y(\tau)] \qquad (g \ll 1) \tag{6}$$

UNRUH-DEWITT DETECTOR

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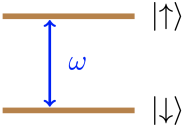

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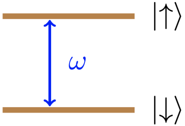

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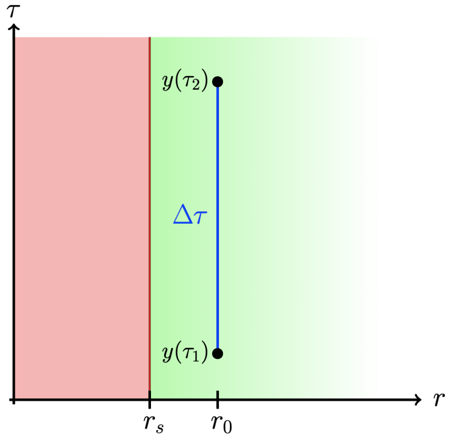
Choice of Trajectory

$y(\tau) \to$ Let the qubit hover near the event horizon at fixed $r = r_0$



with $1 - \frac{r_s}{r_0} \ll 1$

The Qubit State and ICs

- Full state $\rho(\tau)$ obeys the Liouville equation:

$$\frac{\partial \rho(t)}{\partial t} = -ig\left[H_{\text{int}}(t), \rho(t)\right] \tag{7}$$

- We focus on the state of the qubit only

$$\sigma(t) = \begin{bmatrix} \sigma_{11}(t) & \sigma_{12}(t) \\ \sigma_{21}(t) & \sigma_{22}(t) \end{bmatrix} = \underset{\text{Field}}{\text{Tr}}\left[\rho(\tau)\right] \tag{8}$$

- Assume uncorrelated initial condition

$$\rho(0) = |\downarrow\rangle\langle\downarrow| \otimes \left|\text{vac}\right\rangle\left\langle\text{vac}\right| \tag{9}$$

with $\left|\text{vac}\right\rangle$ *any* Hadamard vacuum (*eg.* $\left|\text{Unruh}\right\rangle$, $\left|\text{Hartle-Hawking}\right\rangle$)

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PERTURBATIVE BREAKDOWN

- Perturbation Theory:

$$\rho(t) \simeq \rho(0) - ig \int_0^t \mathrm{d}s \, [H_{\mathrm{int}}(t), \rho(0)] + \dots \tag{10}$$

- Partial trace both sides $\implies$ perturbative result[2] for $t \gg r_s$

$$\sigma_{11}(t) \simeq \mathcal{R} \cdot g^2 t + \mathcal{O}(g^4) \tag{11}$$

for qubit initially in ground state (with $\sigma_{11}(0) = 0$), where

$$\mathcal{R} = \frac{\omega_\infty}{2\pi[e^{4\pi r_s \omega_\infty} - 1]} \qquad \text{with} \qquad \omega_\infty := \sqrt{1 - \frac{r_s}{r_0}}\, \omega \,. \tag{12}$$

[2] P. Candelas, "Vacuum Polarization in Schwarzschild Space-Time," Phys. Rev. D **21** (1980), 2185-2202

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NAKAJIMA-ZWANZIG MASTER EQUATION

- Liouville $\partial_t \rho = -ig[H_{\text{int}}, \rho] \implies$ Nakajima-Zwanzig:

$$\frac{\partial \sigma(t)}{\partial t} = f\big(\sigma(t), g\big) \tag{13}$$

- Perturb RHS in g (and assume $\omega_\infty r_s \ll 1$) — time-local equation

$$\frac{\partial \sigma_{11}(t)}{\partial t} \simeq g^2\big[\mathcal{R} - 2\mathcal{C}\,\sigma_{11}(t)\big] + \mathcal{O}(g^4) \tag{14}$$

where $\mathcal{R} := \frac{\omega_\infty}{2\pi} \cdot \frac{1}{e^{4\pi r_s \omega_\infty} - 1}$ and $\mathcal{C} := \frac{\omega_\infty}{4\pi} \coth(2\pi r_s \omega_\infty)$.

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Late-Time State

- Late-time state is thermal

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where $\hat{H}_{\mathrm{S}} = \frac{\omega}{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$ and the local Hawking temperature is

$$\beta_{\mathrm{local}} = \sqrt{1 - \frac{r_s}{r_0}}\, 4\pi r_s \quad (17)$$

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based on [arXiv:2007.05984]

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2. Methods for resummation exist
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