Charged-vacuum-induced decoherence of quantum states of light

Agata Brańczyk, Perimeter Institute

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Olivier Simon **Allison Sachs** **Eduardo Martín-Martínez**

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS QuantumOpticsPlus.com barrio-RQI.org University of Waterloo IQC Stanford University

Decoherence is bad for quantum technologies

quantum superposition

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

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quantum superposition

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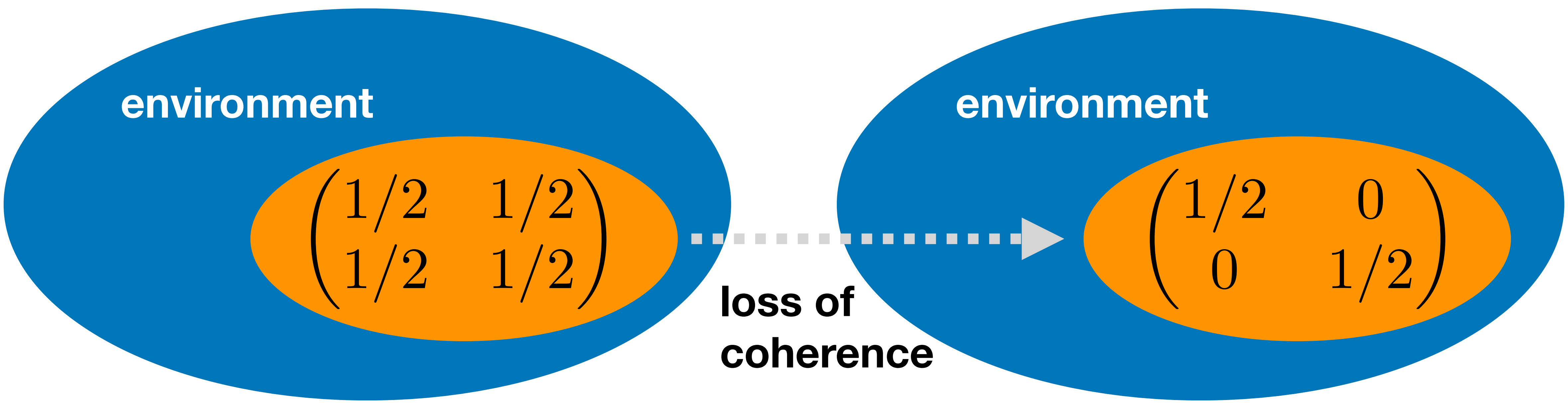
Common source of decoherence: coupling to the ENVIRONMENT



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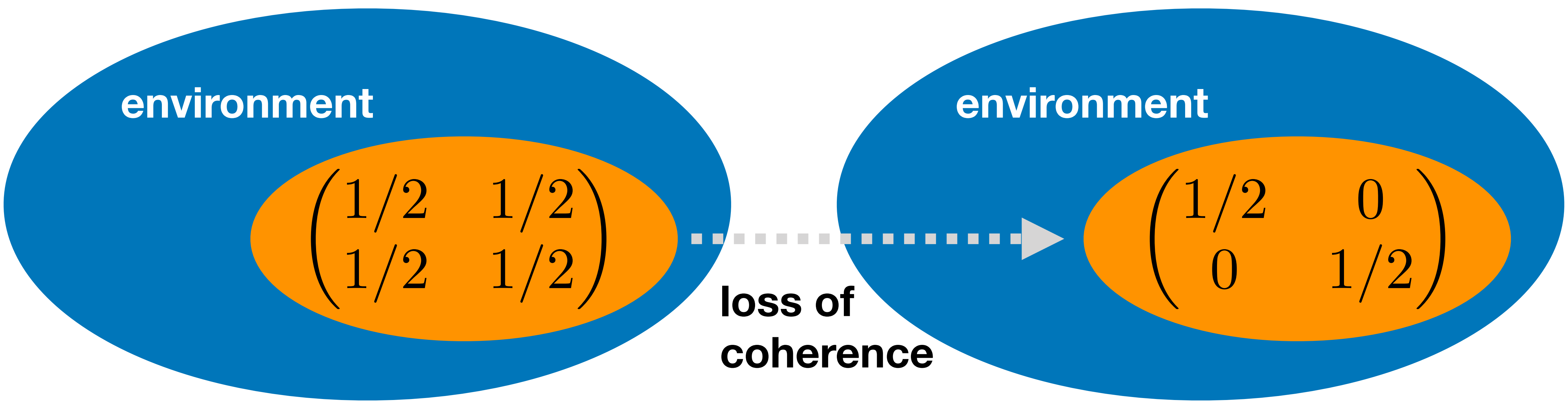


~ state-of-the-art coherence times

- photonic qubits in atomic memories: ~50 ns
- nanoelectronic devices: ~30 seconds
- room temperature nuclear spins: ~40 minutes
- nuclear spins: ~6 hours

Decoherence is bad for quantum technologies

quantum superposition

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

Common source of decoherence: coupling to the ENVIRONMENT

$$\begin{pmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{pmatrix} \longrightarrow \begin{pmatrix} 1/2 & ? \\ ? & 1/2 \end{pmatrix}$$

are we safe?

Decoherence is bad for quantum technologies

quantum superposition

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

Common source of decoherence: coupling to the ENVIRONMENT

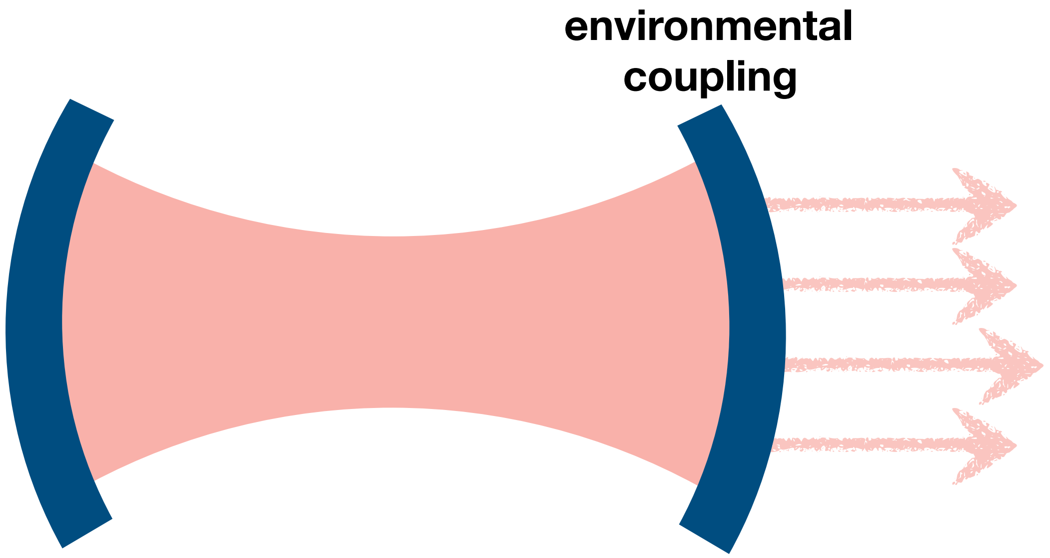
$$\begin{pmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{pmatrix} \longrightarrow \begin{pmatrix} 1/2 & ? \\ ? & 1/2 \end{pmatrix}$$

are we safe?

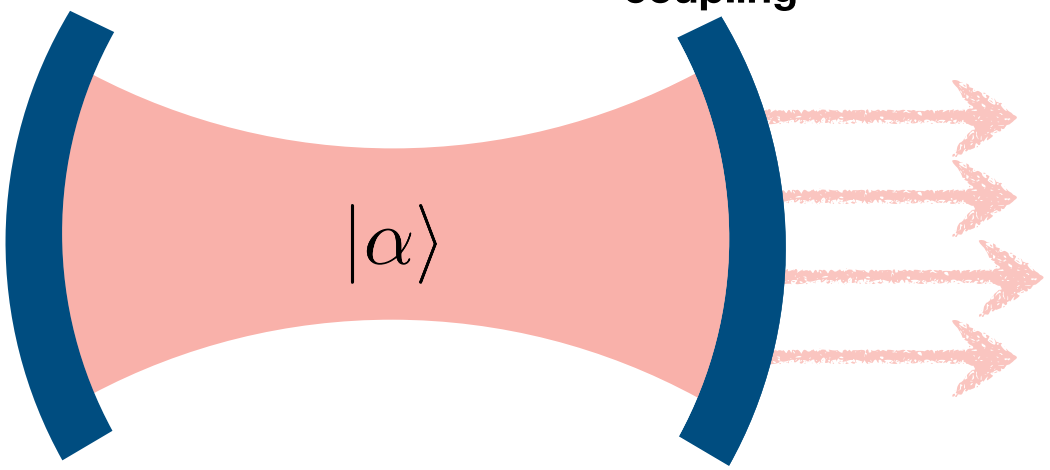
(in the absence of environmental coupling)

Are there other fundamentally unavoidable sources of decoherence?

Quantum Optics in Cavities



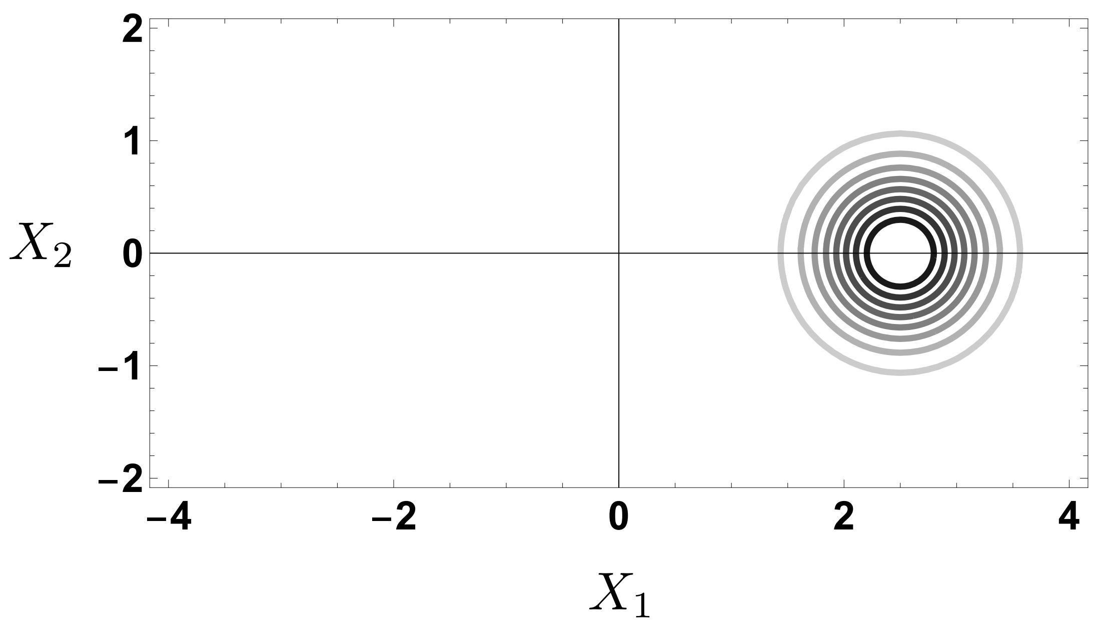
Quantum Optics in Cavities



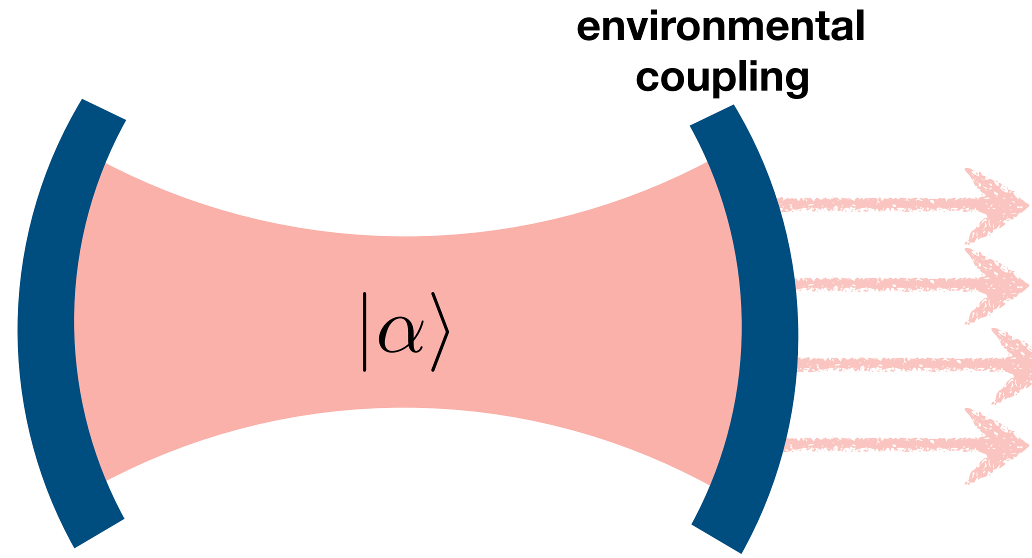
Coherent state

$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$$

Phase space (Wigner function)



Quantum Optics in Cavities



Coherent state

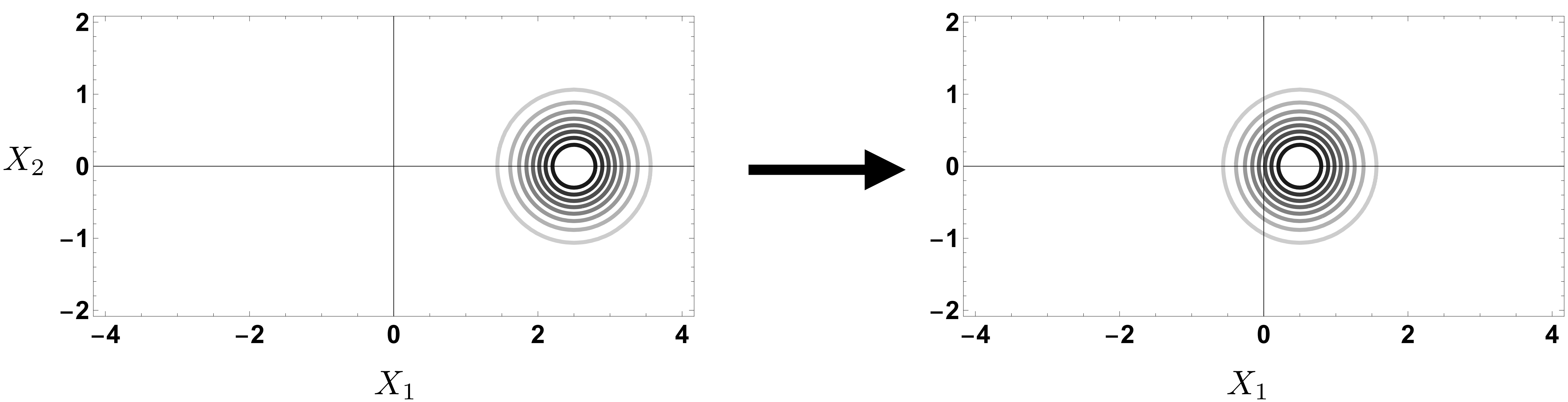
$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$$

After some time:

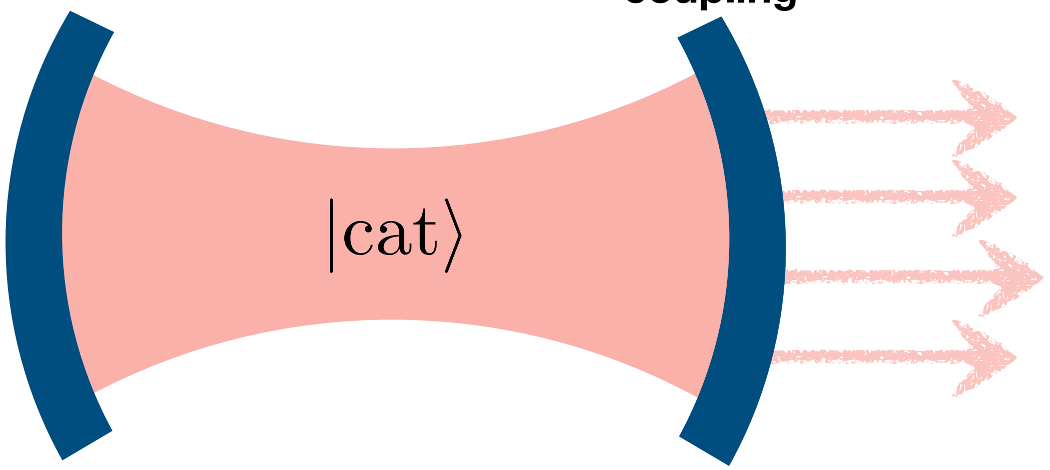
$$|\alpha\rangle \longrightarrow |\eta\alpha\rangle$$

$$\eta < 1$$

Phase space (Wigner function)



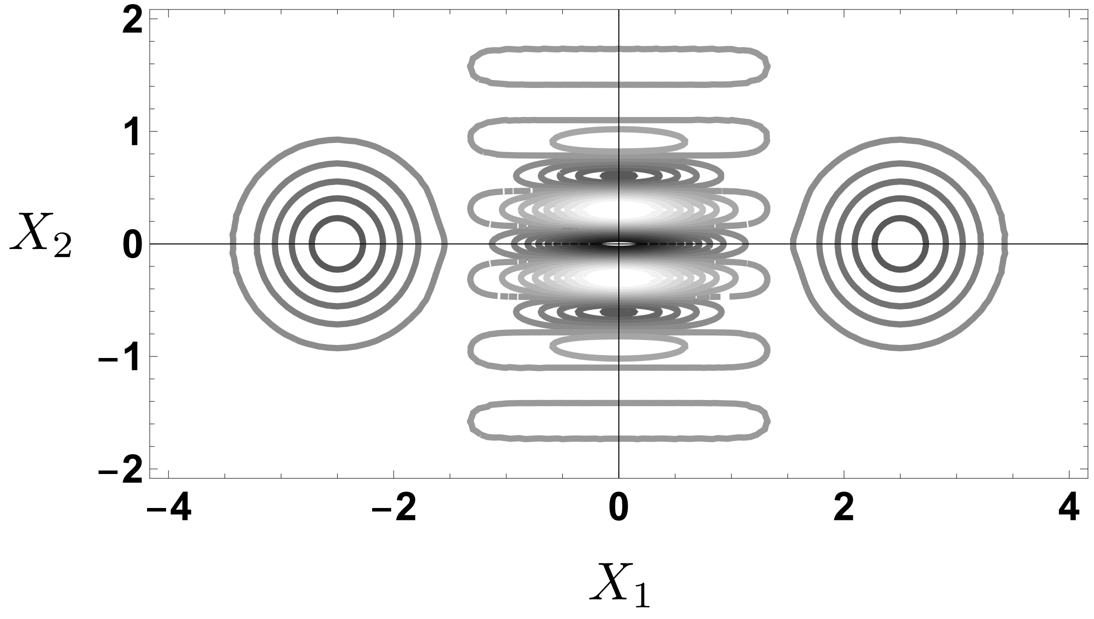
Quantum Optics in Cavities



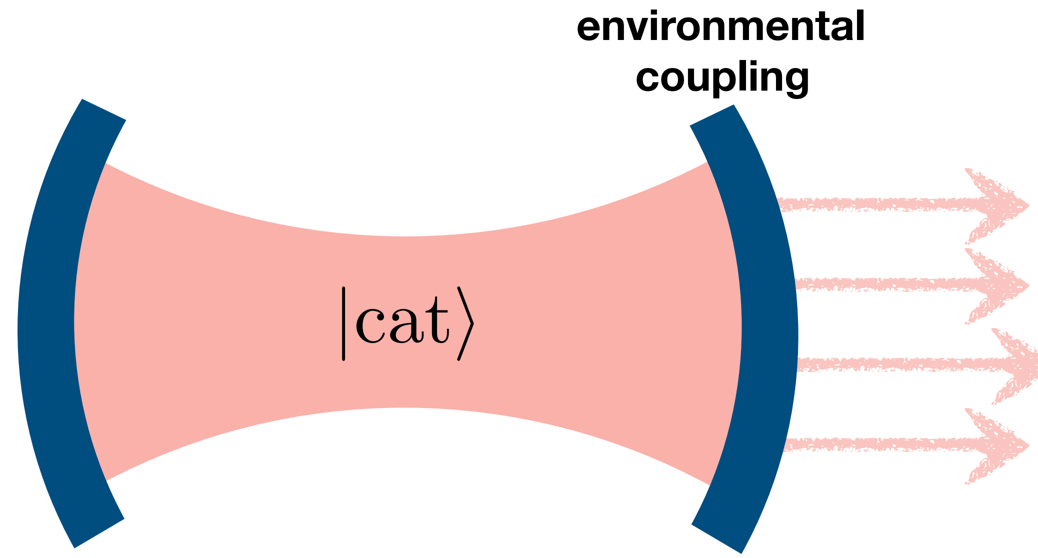
Cat state

$$|\text{cat}\rangle \propto |\alpha\rangle + |-\alpha\rangle$$

Phase space (Wigner function)



Quantum Optics in Cavities



Cat state

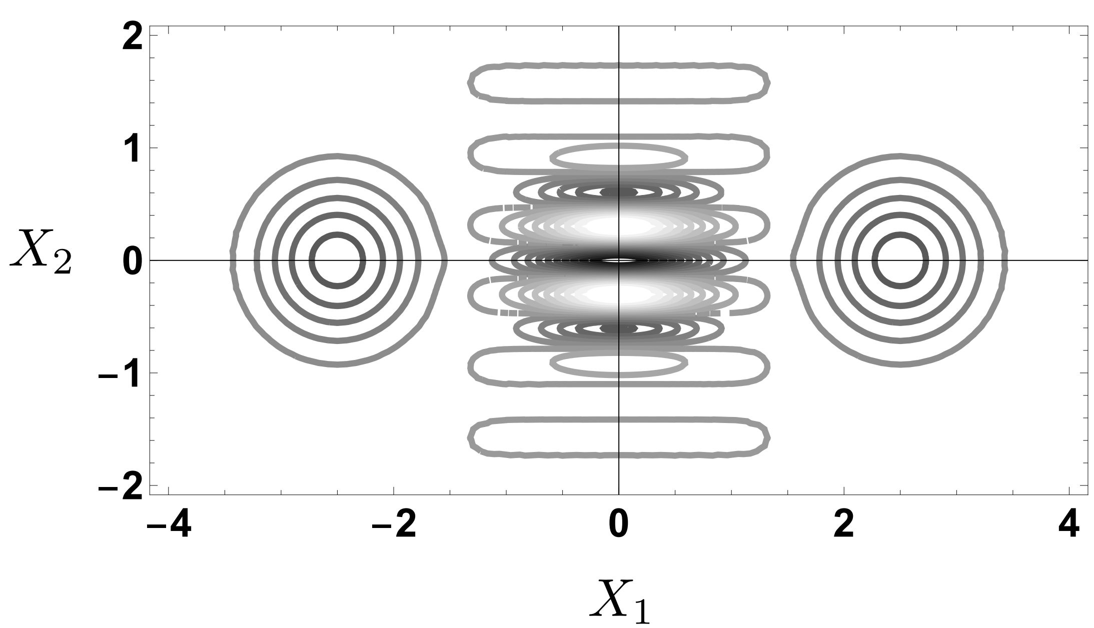
$$|\text{cat}\rangle \propto |\alpha\rangle + |-\alpha\rangle$$

$$|\text{tac}\rangle \propto |\alpha\rangle - |-\alpha\rangle$$

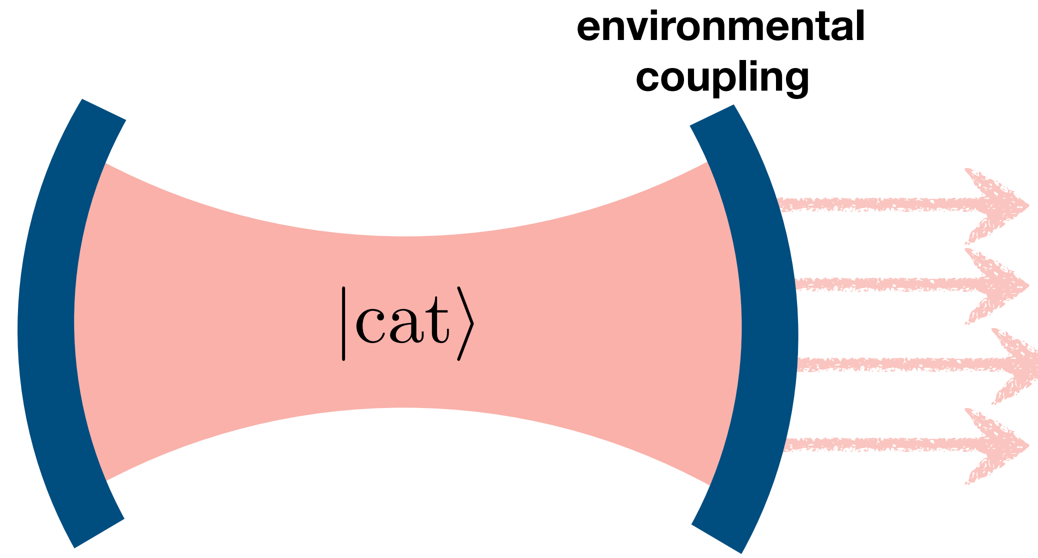
After some time:

$$|\text{cat}\rangle\langle\text{cat}| \rightarrow \approx |\text{cat}'\rangle\langle\text{cat}'| + |\text{tac}'\rangle\langle\text{tac}'|$$

Phase space (Wigner function)



Quantum Optics in Cavities



Cat state

$$|\text{cat}\rangle \propto |\alpha\rangle + |-\alpha\rangle$$

$$|\text{tac}\rangle \propto |\alpha\rangle - |-\alpha\rangle$$

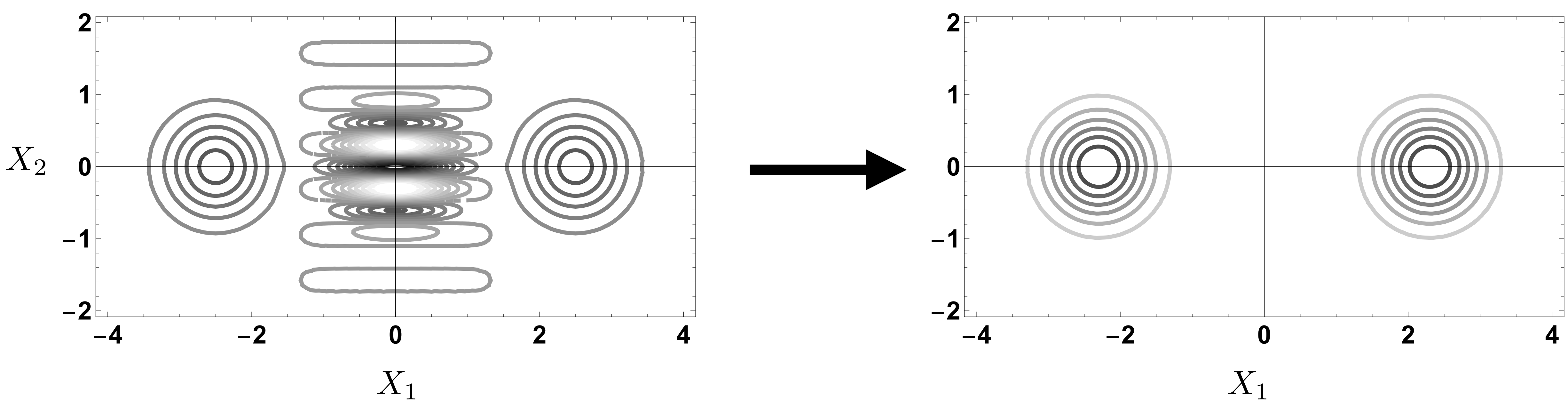
After some time:

$$|\text{cat}\rangle\langle\text{cat}| \rightarrow \approx |\text{cat}'\rangle\langle\text{cat}'| + |\text{tac}'\rangle\langle\text{tac}'|$$

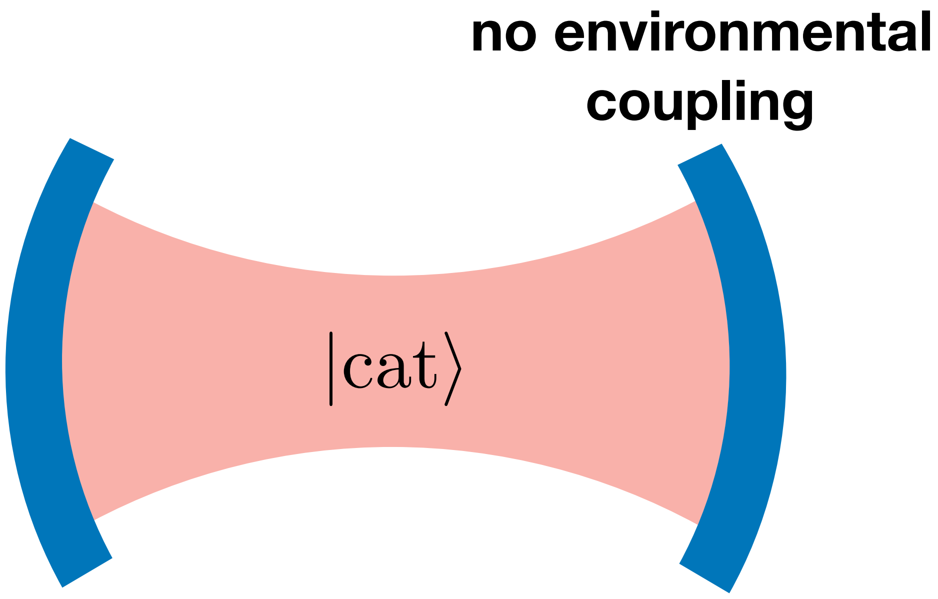
$$\approx |\eta\alpha\rangle\langle\eta\alpha| + |-\eta\alpha\rangle\langle-\eta\alpha|$$

$\eta < 1$

Phase space (Wigner function)

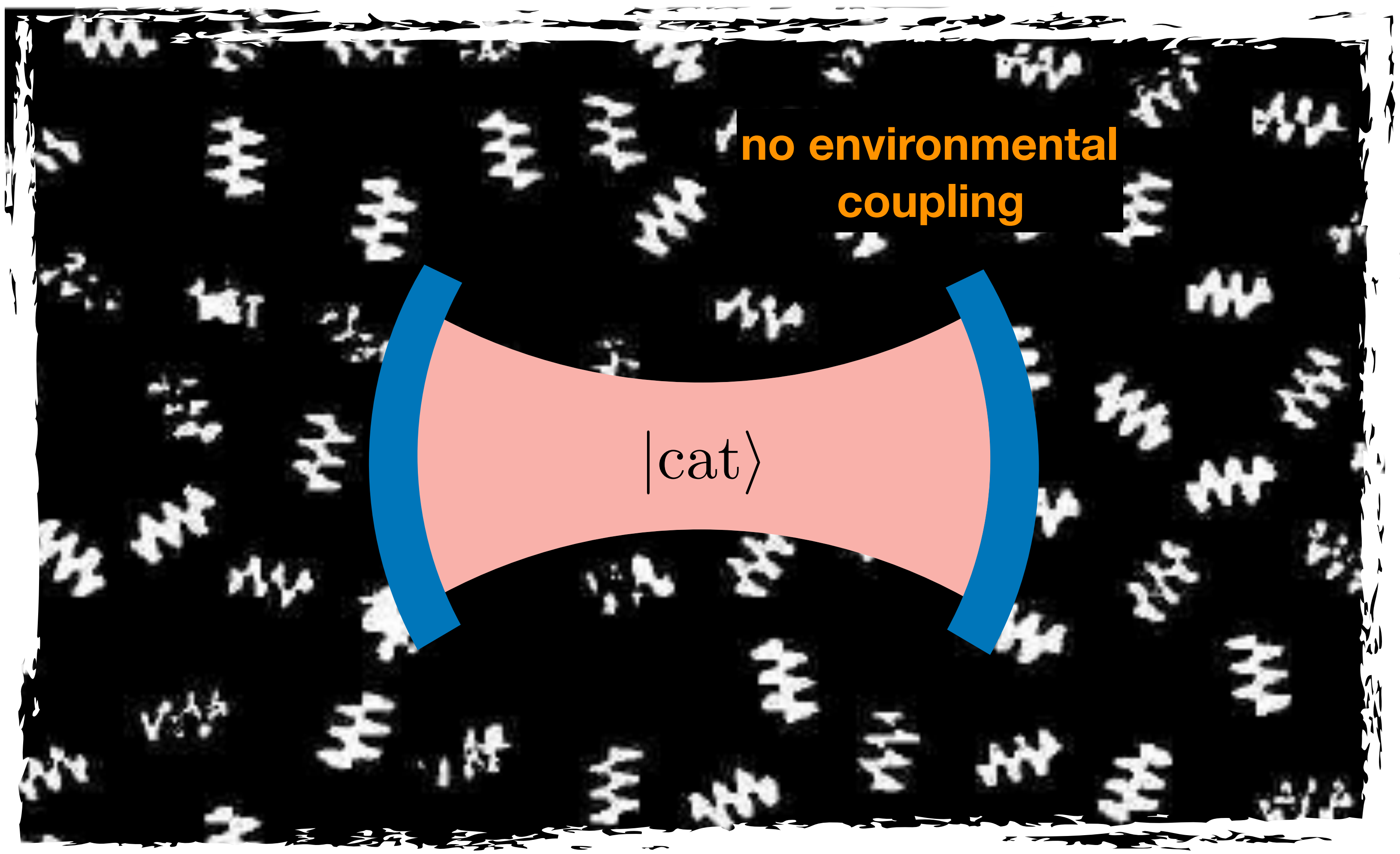


Perfect cavities



no environmental coupling = no decoherence?

Perfect cavities



coupling to the Dirac vacuum

$$|0\rangle$$

no environmental coupling = no decoherence?

Image: Caligiuri & Musha. (2014).

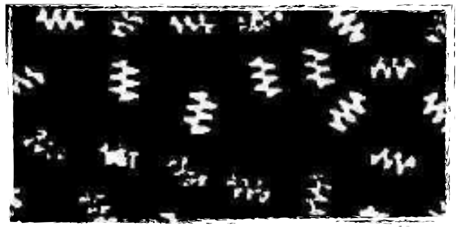
QED interaction Hamiltonian

$$\hat{H} = -e \int \mathrm{d}^3\boldsymbol{x} : \bar{\hat{\psi}}(\boldsymbol{x}) \hat{\not{A}}(\boldsymbol{x}) \hat{\psi}(\boldsymbol{x}) :$$

QED interaction Hamiltonian

$$\hat{H} = -e \int \mathrm{d}^3\boldsymbol{x} : \bar{\hat{\psi}}(\boldsymbol{x}) \hat{\not{A}}(\boldsymbol{x}) \hat{\psi}(\boldsymbol{x}) :$$

Dirac field



$$\hat{\psi}(\boldsymbol{x}) = \hat{\psi}^+(\boldsymbol{x}) + \hat{\psi}^-(\boldsymbol{x})$$

$$\hat{\psi}^+(\boldsymbol{x}) = \sum_{r=\pm} \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)^3\omega_{\boldsymbol{k}}}} \hat{c}_r^\dagger(\boldsymbol{k}) u_r(\boldsymbol{k}) e^{-\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$$

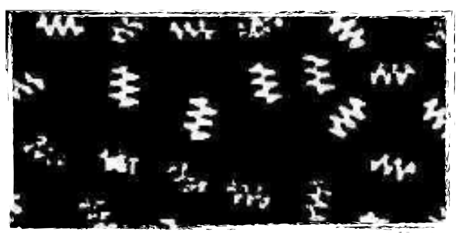
$$\hat{\psi}^-(\boldsymbol{x}) = \sum_{r=\pm} \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)^3\omega_{\boldsymbol{k}}}} \hat{d}_r(\boldsymbol{k}) v_r(\boldsymbol{k}) e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}} ,$$

$$\omega_{\boldsymbol{k}} = \sqrt{|\boldsymbol{k}|^2 + m^2}$$

QED interaction Hamiltonian

$$\hat{H} = -e \int \mathrm{d}^3\boldsymbol{x} : \bar{\hat{\psi}}(\boldsymbol{x}) \hat{\not{A}}(\boldsymbol{x}) \hat{\psi}(\boldsymbol{x}) :$$

Dirac field



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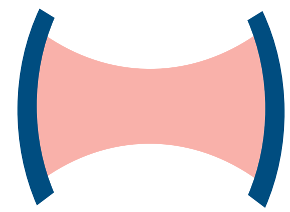
EM field



$$\hat{A}^\mu(\boldsymbol{x}) = \hat{A}^{\mu+}(\boldsymbol{x}) + \hat{A}^{\mu-}(\boldsymbol{x})$$

$$\hat{A}^{\mu+}(\boldsymbol{x}) = \sum_{r\boldsymbol{k}} \frac{1}{\sqrt{2V\Omega_{\boldsymbol{k}}}} \epsilon^\mu_{r\boldsymbol{k}} \hat{a}^\dagger_{r\boldsymbol{k}} e^{-\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$$

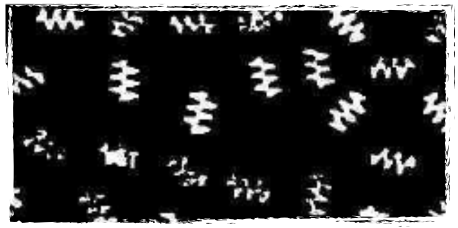
$$\hat{A}^{\mu-}(\boldsymbol{x}) = \sum_{r\boldsymbol{k}} \frac{1}{\sqrt{2V\Omega_{\boldsymbol{k}}}} \epsilon^\mu_{r\boldsymbol{k}} \hat{a}_{r\boldsymbol{k}} e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}} ,$$

$$\omega_{\boldsymbol{k}} = \sqrt{|\boldsymbol{k}|^2 + m^2}$$

Simplified Model

$$\hat{H} = -e\int \mathrm{d}^3\boldsymbol{x} : \bar{\hat{\psi}}(\boldsymbol{x})\hat{\not{A}}(\boldsymbol{x})\hat{\psi}(\boldsymbol{x}) :$$

Charged scalar field

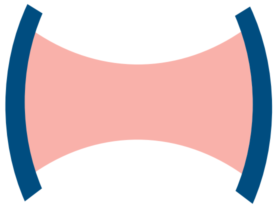


$$\hat{\phi}(\boldsymbol{x}) = \hat{\phi}^{+}(\boldsymbol{x}) + \hat{\phi}^{-}(\boldsymbol{x})$$

$$\hat{\phi}^{+}(\boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)^3\omega_{\boldsymbol{k}}}} e^{-\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}\hat{c}^{\dagger}(\boldsymbol{k})$$

$$\hat{\phi}^{-}(\boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)^3\omega_{\boldsymbol{k}}}} e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}\hat{d}(\boldsymbol{k}),$$

EM field



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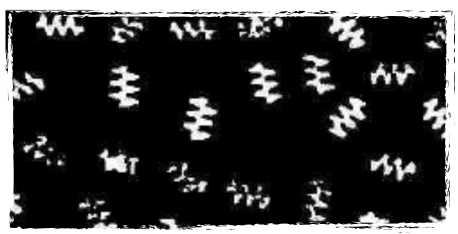
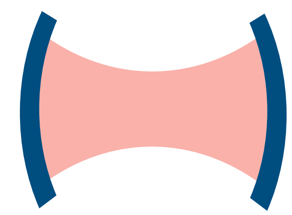
Charged scalar field



$$\hat{\phi}(\boldsymbol{x}) = \hat{\phi}^+(\boldsymbol{x}) + \hat{\phi}^-(\boldsymbol{x})$$

Single-mode EM field



$$\hat{Q} = \frac{1}{\sqrt{2V\Omega}}(\hat{a} + \hat{a}^\dagger)$$

$$\hat{\phi}^+(\boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)^3\omega_{\boldsymbol{k}}}} e^{-\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}\hat{c}^\dagger(\boldsymbol{k})$$

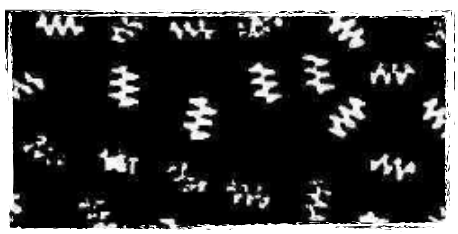
$$\hat{\phi}^-(\boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)^3\omega_{\boldsymbol{k}}}} e^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}\hat{d}(\boldsymbol{k}),$$

$$\omega_{\boldsymbol{k}} = \sqrt{|\boldsymbol{k}|^2 + m^2}$$

Simplified Model

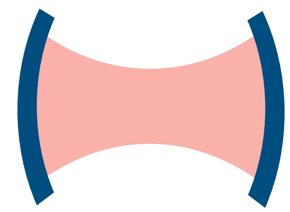
$$\hat{H}(t) = -e\chi\left(\tfrac{t}{T}\right)\int \mathrm{d}^3\boldsymbol{x}\,F(\boldsymbol{x})\hat{Q} : \hat{\phi}(\boldsymbol{x})\hat{\phi}^\dagger(\boldsymbol{x}) :$$

Charged scalar field



$$\hat{\phi}(\boldsymbol{x}) = \hat{\phi}^+(\boldsymbol{x}) + \hat{\phi}^-(\boldsymbol{x})$$

Single-mode EM field



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Switching function

$$\chi\left(\tfrac{t}{T}\right)$$

Smearing function

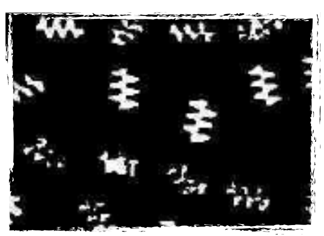
$$F(\boldsymbol{x})$$

$$\omega_{\boldsymbol{k}} = \sqrt{|\boldsymbol{k}|^2 + m^2}$$

Interaction Picture

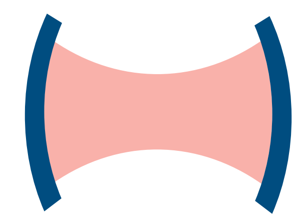
$$\hat{H}_I(t) = -e\chi\left(\tfrac{t}{T}\right)\int \mathrm{d}^3\boldsymbol{x}F(\boldsymbol{x})\hat{Q}(t) : \hat{\phi}(t,\boldsymbol{x})\hat{\phi}^\dagger(t,\boldsymbol{x}):$$

Scalar fields



$$\hat{\phi}(t,\boldsymbol{x}) = \hat{\phi}^+(t,\boldsymbol{x}) + \hat{\phi}^-(t,\boldsymbol{x})$$

Single-mode EM field



$$\hat{Q}(t) = \frac{1}{\sqrt{2V\Omega}}(\hat{a}e^{-\mathrm{i}\Omega t} + \hat{a}^\dagger e^{\mathrm{i}\Omega t})$$

$$\hat{\phi}^+(t,\boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)\omega_{\boldsymbol{k}}}} e^{-\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{x}-\omega_{\boldsymbol{k}}t)}\hat{c}^\dagger(\boldsymbol{k})$$

$$\hat{\phi}^-(t,\boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{2(2\pi)\omega_{\boldsymbol{k}}}} e^{\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{x}-\omega_{\boldsymbol{k}}t)}\hat{d}(\boldsymbol{k})\,,$$

Switching function

$$\chi\left(\tfrac{t}{T}\right)$$

Smearing function

$$F(\boldsymbol{x})$$

$$\omega_{\boldsymbol{k}} = \sqrt{|\boldsymbol{k}|^2 + m^2}$$

State after interaction

Evolution operator

$$\hat{U} = \mathcal{T}\exp\left(-\mathrm{i}\int \mathrm{d}t\,\hat{H}_I(t)\right)$$

Interaction Hamiltonian

$$\hat{H}_I(t) = -e\chi\left(\tfrac{t}{T}\right)\int \mathrm{d}^3\boldsymbol{x}\,F(\boldsymbol{x})\hat{Q}(t) :\hat{\phi}(t,\boldsymbol{x})\hat{\phi}^\dagger(t,\boldsymbol{x}):$$

State after interaction

$$\hat{\rho} = \hat{U}\hat{\rho}^{(0)}\hat{U}^\dagger$$

State after interaction

Evolution operator

$$\hat{U} = \mathcal{T} \exp\left(-\mathrm{i} \int \mathrm{d}t \hat{H}_I(t)\right)$$

Interaction Hamiltonian

$$\hat{H}_I(t) = -e\chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x} F(\boldsymbol{x}) \hat{Q}(t) : \hat{\phi}(t,\boldsymbol{x})\hat{\phi}^\dagger(t,\boldsymbol{x}) :$$

State after interaction

$$\hat{\rho} = \hat{U}\hat{\rho}^{(0)}\hat{U}^\dagger \quad = \hat{\rho}^{(0)} + \underbrace{\hat{U}_1\hat{\rho}^{(0)} + \hat{\rho}^{(0)}\hat{U}_1^\dagger}_{\text{first order}}$$

First-order term of U

$$\hat{U}_1 = \mathrm{i}e \int_{-\infty}^{\infty} \mathrm{d}t \chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x}$$
$$\times F(\boldsymbol{x})\hat{Q}(t) : \hat{\phi}(t,\boldsymbol{x})\hat{\phi}^\dagger(t,\boldsymbol{x}) :$$

State after interaction

Evolution operator

$$\hat{U} = \mathcal{T} \exp\left(-\mathrm{i} \int \mathrm{d}t \hat{H}_I(t)\right)$$

Interaction Hamiltonian

$$\hat{H}_I(t) = -e\chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x} F(\boldsymbol{x}) \hat{Q}(t) : \hat{\phi}(t,\boldsymbol{x}) \hat{\phi}^\dagger(t,\boldsymbol{x}) :$$

State after interaction

$$\hat{\rho} = \hat{U} \hat{\rho}^{(0)} \hat{U}^\dagger = \hat{\rho}^{(0)} + \underbrace{\hat{U}_1 \hat{\rho}^{(0)} + \hat{\rho}^{(0)} \hat{U}_1^\dagger}_{\text{first order}} + \underbrace{\hat{U}_1 \hat{\rho}^{(0)} \hat{U}_1^\dagger + \hat{U}_2 \hat{\rho}^{(0)} + \hat{\rho}^{(0)} \hat{U}_2^\dagger}_{\text{second order}}$$

First-order term of U

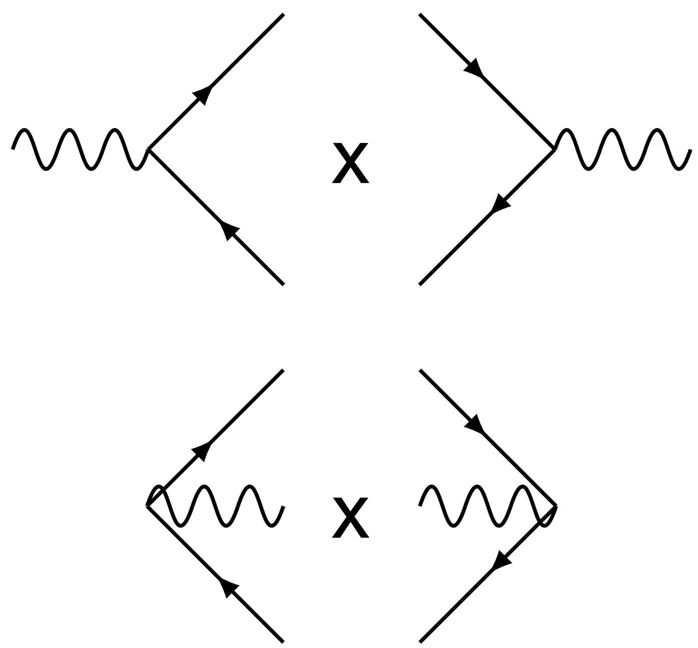
$$\hat{U}_1 = \mathrm{i}e \int_{-\infty}^{\infty} \mathrm{d}t \chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x} \times F(\boldsymbol{x}) \hat{Q}(t) : \hat{\phi}(t,\boldsymbol{x}) \hat{\phi}^\dagger(t,\boldsymbol{x}) :$$

Second-order term of U

$$\hat{U}_2 = -e^2 \int_{-\infty}^{\infty} \mathrm{d}t \int_{-\infty}^{t} \mathrm{d}t' \chi\left(\tfrac{t}{T}\right) \chi\left(\tfrac{t'}{T}\right) \times \int \mathrm{d}^3\boldsymbol{x} \int \mathrm{d}^3\boldsymbol{x}' F(\boldsymbol{x}) F(\boldsymbol{x}') \hat{Q}(t) \hat{Q}(t') \times : \hat{\phi}(t,\boldsymbol{x}) \hat{\phi}^\dagger(t,\boldsymbol{x}) :: \hat{\phi}(t',\boldsymbol{x}') \hat{\phi}^\dagger(t',\boldsymbol{x}') :$$

Feynman diagrams

$$\hat{U}_1\rho^{(0)}\hat{U}_1^\dagger$$

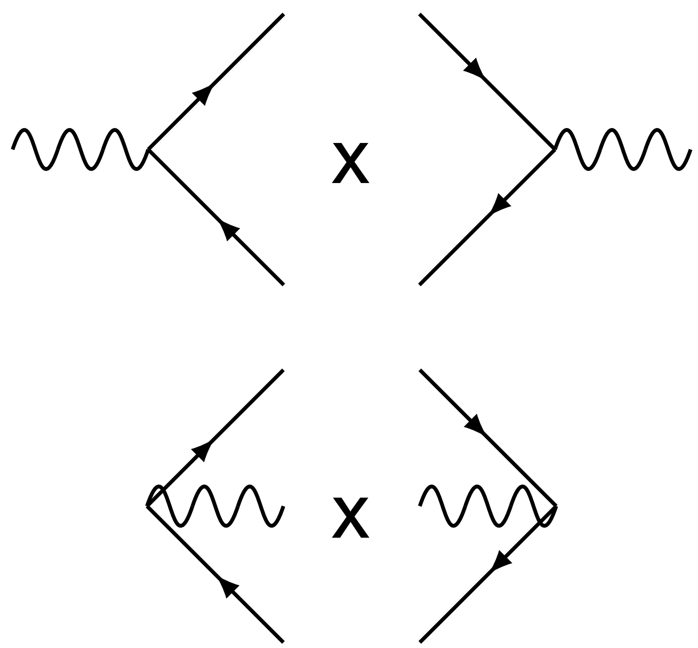


$$\hat{U}_2\rho^{(0)} + \rho^{(0)}\hat{U}_2^\dagger$$

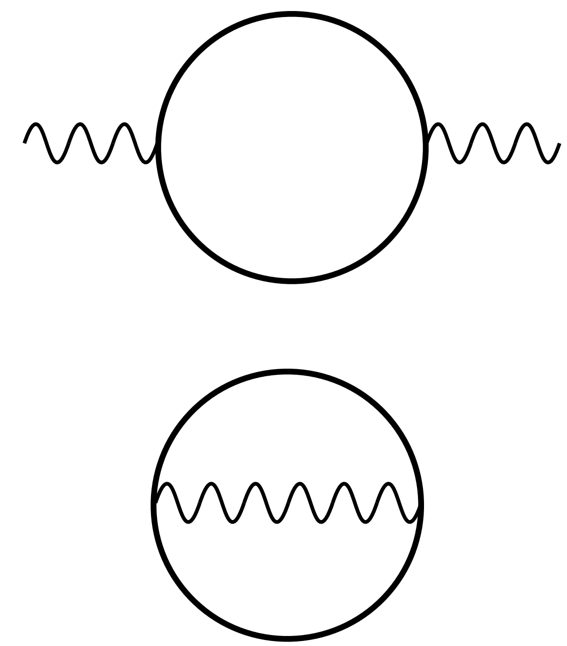
$$\underbrace{\hat{U}_1\hat{\rho}^{(0)}\hat{U}_1^\dagger + \hat{U}_2\hat{\rho}^{(0)} + \hat{\rho}^{(0)}\hat{U}_2^\dagger}_{\text{second order}}$$

Feynman diagrams

$$\hat{U}_1 \rho^{(0)} \hat{U}_1^\dagger$$



$$\hat{U}_2 \rho^{(0)} + \rho^{(0)} \hat{U}_2^\dagger$$



$$\underbrace{\hat{U}_1 \hat{\rho}^{(0)} \hat{U}_1^\dagger + \hat{U}_2 \hat{\rho}^{(0)} + \hat{\rho}^{(0)} \hat{U}_2^\dagger}_{\text{second order}}$$

State after interaction

Evolution operator

$$\hat{U} = \mathcal{T} \exp\left(-\mathrm{i} \int \mathrm{d}t \hat{H}_I(t)\right)$$

Interaction Hamiltonian

$$\hat{H}(t) = -e\chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x} F(\boldsymbol{x}) \hat{Q} : \hat{\phi}(\boldsymbol{x}) \hat{\phi}^\dagger(\boldsymbol{x}) :$$

State after interaction

$$\hat{\rho} = \hat{U}\hat{\rho}^{(0)}\hat{U}^\dagger \quad = \hat{\rho}^{(0)} + \underbrace{\hat{U}_1\hat{\rho}^{(0)} + \hat{\rho}^{(0)}\hat{U}_1^\dagger}_{\text{first order}} + \underbrace{\hat{U}_1\hat{\rho}^{(0)}\hat{U}_1^\dagger + \hat{U}_2\hat{\rho}^{(0)} + \hat{\rho}^{(0)}\hat{U}_2^\dagger}_{\text{second order}}$$

First-order term of U

$$\hat{U}_1 = \mathrm{i}e \int_{-\infty}^{\infty} \mathrm{d}t \chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x} \times F(\boldsymbol{x}) \hat{Q}(t) : \hat{\phi}(t, \boldsymbol{x}) \hat{\phi}^\dagger(t, \boldsymbol{x}) :$$

Second-order term of U

$$\hat{U}_2 = -e^2 \int_{-\infty}^{\infty} \mathrm{d}t \int_{-\infty}^{t} \mathrm{d}t' \chi\left(\tfrac{t}{T}\right) \chi\left(\tfrac{t'}{T}\right) \times \int \mathrm{d}^3\boldsymbol{x} \int \mathrm{d}^3\boldsymbol{x}' F(\boldsymbol{x}) F(\boldsymbol{x}') \hat{Q}(t) \hat{Q}(t') \times : \hat{\phi}(t, \boldsymbol{x}) \hat{\phi}^\dagger(t, \boldsymbol{x}) :: \hat{\phi}(t', \boldsymbol{x}') \hat{\phi}^\dagger(t', \boldsymbol{x}') :$$

State after interaction

Evolution operator

$$\hat{U} = \mathcal{T} \exp\left(-\mathrm{i} \int \mathrm{d}t \hat{H}_I(t)\right)$$

Interaction Hamiltonian

$$\hat{H}(t) = -e\chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x} F(\boldsymbol{x}) \hat{Q} : \hat{\phi}(\boldsymbol{x}) \hat{\phi}^\dagger(\boldsymbol{x}) :$$

State of EM field after interaction

$$\hat{\rho}_{\mathrm{EM}} = \mathrm{tr}_{\mathrm{S}}[\hat{\rho}^{(0)}] + \underbrace{\mathrm{tr}_{\mathrm{S}}[\hat{U}_1 \hat{\rho}^{(0)}] + \mathrm{tr}_{\mathrm{S}}[\hat{\rho}^{(0)} U_1^\dagger]}_{\text{first order}} + \underbrace{\mathrm{tr}_{\mathrm{S}}[\hat{U}_2 \hat{\rho}^{(0)}] + \mathrm{tr}_{\mathrm{S}}[\hat{\rho}^{(0)} \hat{U}_2^\dagger] + \mathrm{tr}_{\mathrm{S}}[\hat{U}_1 \hat{\rho}^{(0)} \hat{U}_1^\dagger]}_{\text{second order}}$$

First-order term of U

$$\hat{U}_1 = \mathrm{i}e \int_{-\infty}^{\infty} \mathrm{d}t \chi\left(\tfrac{t}{T}\right) \int \mathrm{d}^3\boldsymbol{x} \times F(\boldsymbol{x}) \hat{Q}(t) : \hat{\phi}(t,\boldsymbol{x}) \hat{\phi}^\dagger(t,\boldsymbol{x}) :$$

Second-order term of U

$$\hat{U}_2 = -e^2 \int_{-\infty}^{\infty} \mathrm{d}t \int_{-\infty}^{t} \mathrm{d}t' \chi\left(\tfrac{t}{T}\right) \chi\left(\tfrac{t'}{T}\right) \times \int \mathrm{d}^3\boldsymbol{x} \int \mathrm{d}^3\boldsymbol{x}' F(\boldsymbol{x}) F(\boldsymbol{x}') \hat{Q}(t) \hat{Q}(t') \times : \hat{\phi}(t,\boldsymbol{x}) \hat{\phi}^\dagger(t,\boldsymbol{x}) :: \hat{\phi}(t',\boldsymbol{x}') \hat{\phi}^\dagger(t',\boldsymbol{x}') :$$

State after interaction

Evolution operator

$$\hat{U} = \mathcal{T}\exp\left(-\mathrm{i}\int \mathrm{d}t\hat{H}$$

n

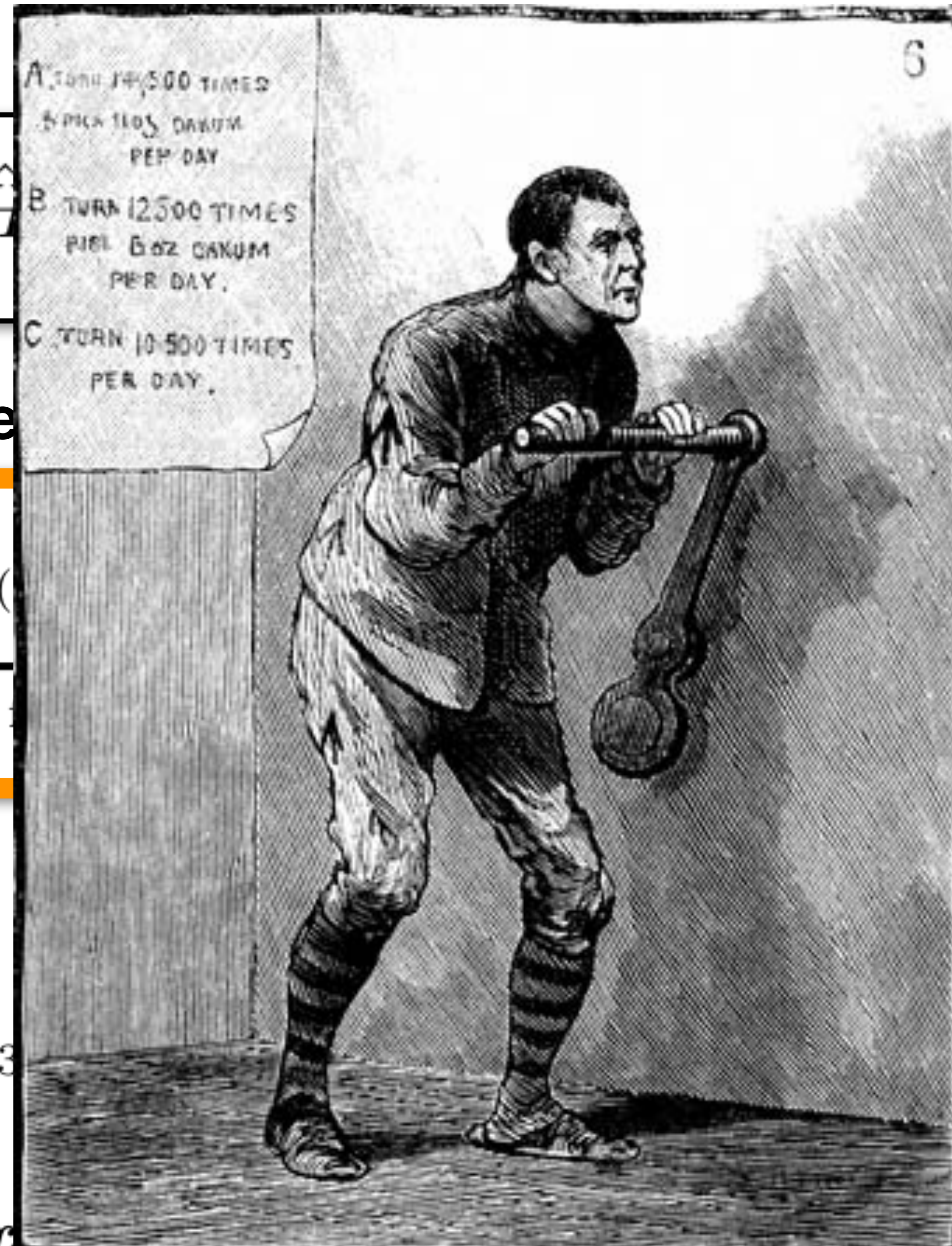
$$\mathrm{d}^3\boldsymbol{x}F(\boldsymbol{x})\hat{Q} : \hat{\phi}(\boldsymbol{x})\hat{\phi}^\dagger(\boldsymbol{x}) :$$

State of EM field after inte

$$\hat{\rho}_{\text{EM}} = \mathrm{tr}_{\text{S}}[\hat{\rho}^{(0)}] + \mathrm{tr}_{\text{S}}[\hat{U}_1\hat{\rho}^{(}$$

$$[\hat{\rho}^{(0)}\hat{U}_2^\dagger] + \mathrm{tr}_{\text{S}}[\hat{U}_1\hat{\rho}^{(0)}\hat{U}_1^\dagger]$$

econd order



First-order term of U

$$\hat{U}_1 = \mathrm{ie}\int_{-\infty}^{\infty}\mathrm{d}t\chi\left(\tfrac{t}{T}\right)\int \mathrm{d}^3$$

$$\times F(\boldsymbol{x})\hat{Q}(t) : \hat{\phi}(t, \boldsymbol{x}$$

m of U

$$t\int_{-\infty}^{t}\mathrm{d}t'\chi\left(\tfrac{t}{T}\right)\chi\left(\tfrac{t'}{T}\right)$$

$$\mathrm{d}^3\boldsymbol{x}'F(\boldsymbol{x})F(\boldsymbol{x}')\hat{Q}(t)\hat{Q}(t')$$

$$\times : \hat{\phi}(t, \boldsymbol{x})\hat{\phi}^\dagger(t, \boldsymbol{x}) :: \hat{\phi}(t', \boldsymbol{x}')\hat{\phi}^\dagger(t', \boldsymbol{x}') :$$

State after interaction

State of EM field after interaction

$$\hat{\rho}_{\mathrm{EM}} = \hat{\rho}_{\mathrm{EM}}^{(0)} - e^2 \int_{-\infty}^{\infty} \mathrm{d}t \left(\int_{-\infty}^{\infty} \mathrm{d}t' \hat{Q}(t') \hat{\rho}_{\mathrm{EM}}^{(0)} \hat{Q}(t) + \int_{-\infty}^{t} \mathrm{d}t' \{ \hat{Q}(t) \hat{Q}(t'), \hat{\rho}_{\mathrm{EM}}^{(0)} \} \right) \chi\left(\tfrac{t}{T}\right) \chi\left(\tfrac{t'}{T}\right) w(t,t')$$

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“smeared Wightman” function

$$w(t,t') = \int \mathrm{d}^3\boldsymbol{x} \int \mathrm{d}^3\boldsymbol{x}' F(\boldsymbol{x}) F(\boldsymbol{x}') \left(W^{\phi}(t,\boldsymbol{x},t',\boldsymbol{x}') \right)^2$$

State after interaction

State of EM field after interaction

$$\hat{\rho}_{\mathrm{EM}} = \hat{\rho}_{\mathrm{EM}}^{(0)} - e^2 \int_{-\infty}^{\infty} \mathrm{d}t \left(\int_{-\infty}^{\infty} \mathrm{d}t' \hat{Q}(t') \hat{\rho}_{\mathrm{EM}}^{(0)} \hat{Q}(t) + \int_{-\infty}^{t} \mathrm{d}t' \{ \hat{Q}(t) \hat{Q}(t'), \hat{\rho}_{\mathrm{EM}}^{(0)} \} \right) \chi\left(\tfrac{t}{T}\right) \chi\left(\tfrac{t'}{T}\right) w(t,t')$$

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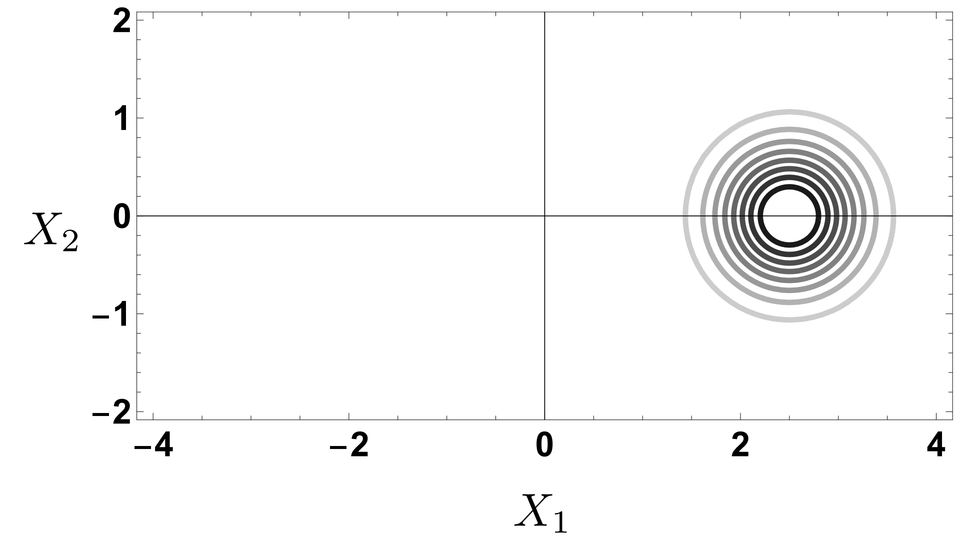
Wightman function

$$W^{\phi}(\boldsymbol{x},t,\boldsymbol{x}',t') = \langle 0|_{\mathrm{s}} \hat{\phi}(t,\boldsymbol{x}) \hat{\phi}^*(t',\boldsymbol{x}') |0\rangle_{\mathrm{s}} = \frac{m K_1 \left(m \sqrt{|\boldsymbol{x}' - \boldsymbol{x}|^2 - (t' - t + \mathrm{i}\epsilon)^2} \right)}{(2\pi)^2 \sqrt{|\boldsymbol{x}' - \boldsymbol{x}|^2 - (t' - t + \mathrm{i}\epsilon)^2}}$$

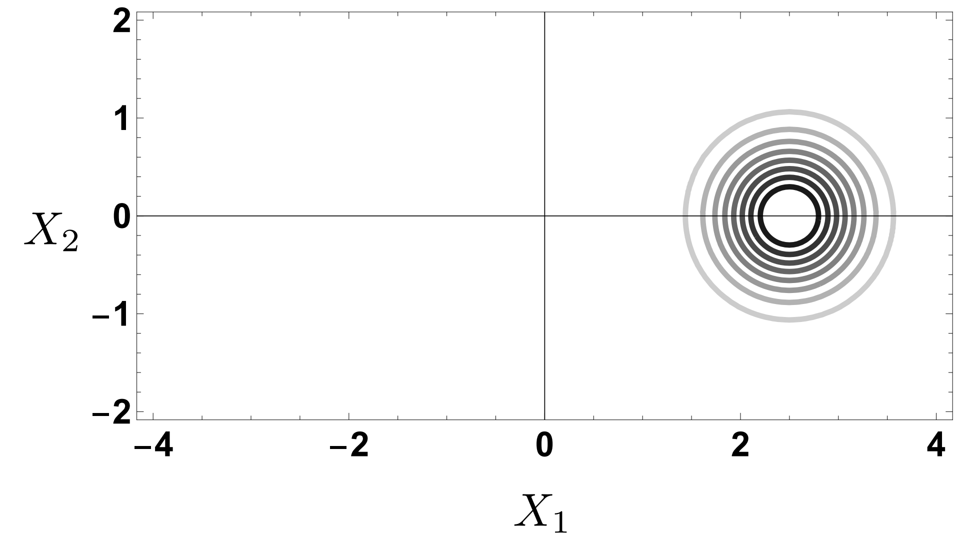
Example 1:
Coherent state



Initial state of the EM field

$$\rho_{\mathrm{EM}}^{(0)} = |\alpha\rangle\langle\alpha|$$

Example 1: Coherent state



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State of EM field after interaction

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Assuming large alpha: $\hat{a}^\dagger |\alpha\rangle \approx \alpha^* |\alpha\rangle$

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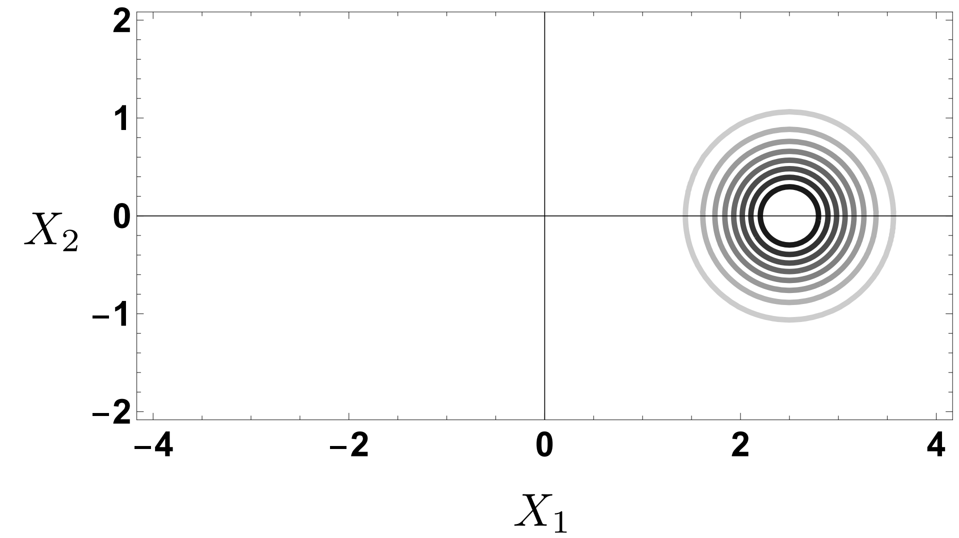

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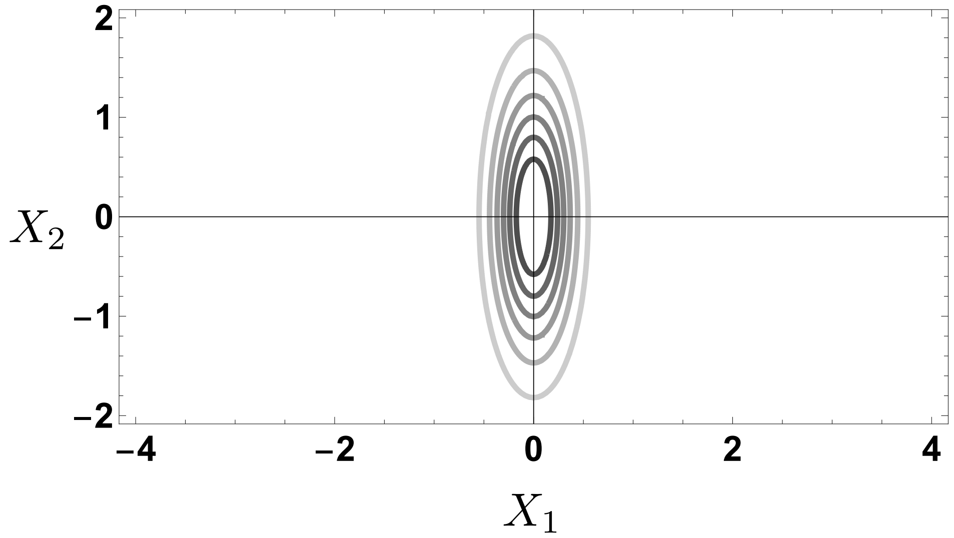
Assuming large alpha: $\hat{a}^\dagger |\alpha\rangle \approx \alpha^* |\alpha\rangle$

A coherent state is robust to interaction with a charged field in the absence of charged particles.

Example 2:
Squeezed state



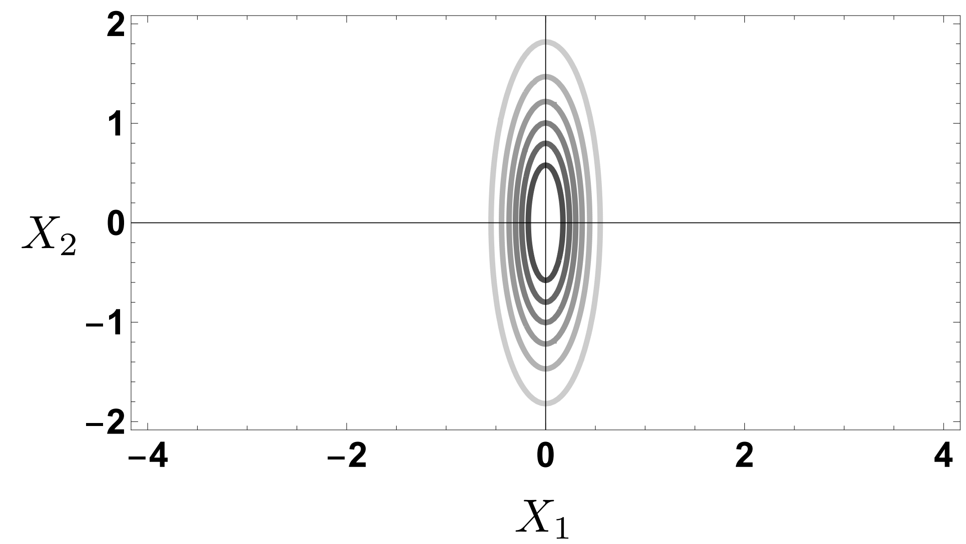
Initial state of the EM field

$$\rho_{\mathrm{EM}}^{(0)} = |S0\rangle\langle S0|$$

$$|S0\rangle = \hat{S}(\zeta)|0\rangle$$

$$\hat{S}(\zeta) = \exp(\tfrac{1}{2}(\zeta^* \hat{a}^2 - \zeta \hat{a}^{\dagger 2}))$$

Example 2:
Squeezed state



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$$|S1\rangle = \hat{S}(\zeta)\,|1\rangle$$

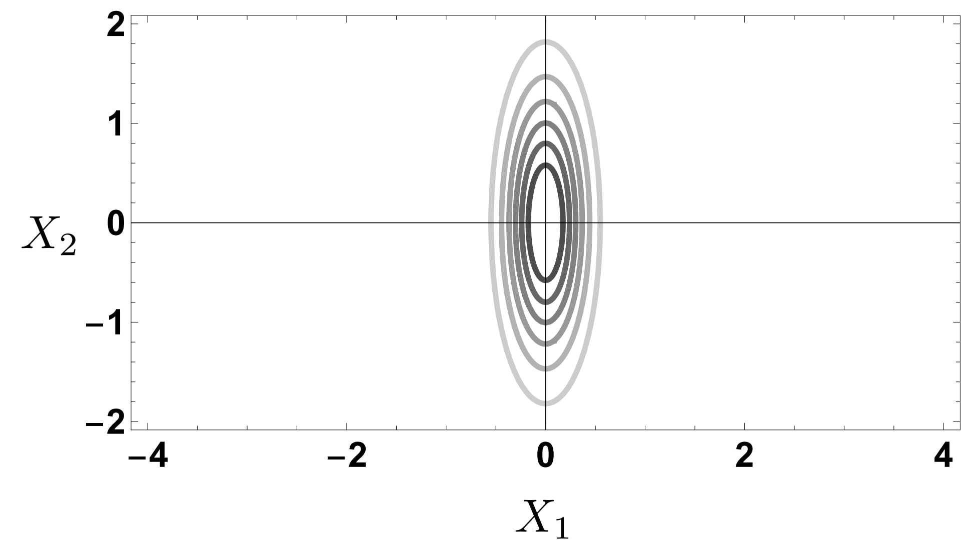
$$|S2\rangle = \hat{S}(\zeta)\,|2\rangle$$

State of EM field after interaction

$$\rho_{\mathrm{EM}} = (1-E)|S0\rangle\langle S0| + E|S1\rangle\langle S1| + d|S2\rangle\langle S0| + d^*|S0\rangle\langle S2|$$

Coefficients: $\mathcal{O}(e^2)$

Example 2: Squeezed state



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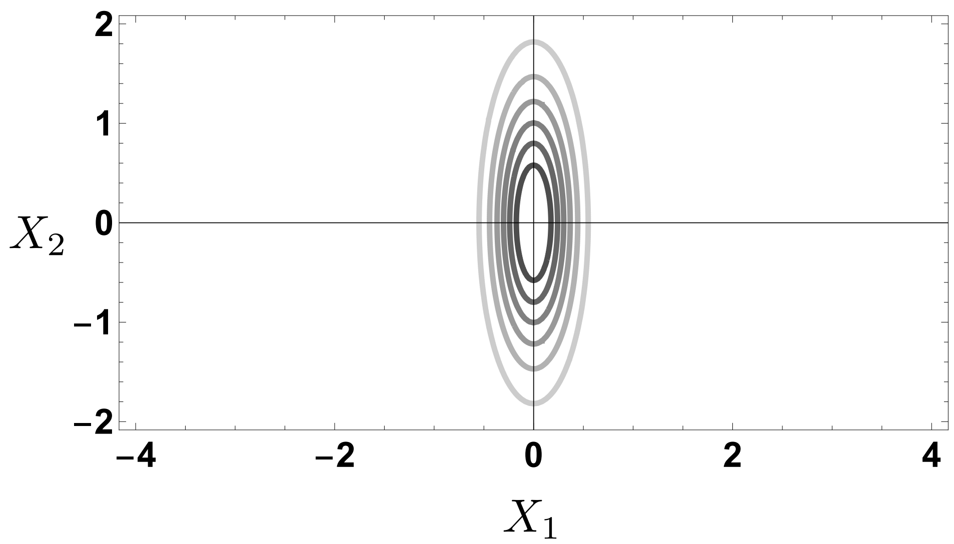
Coefficients: $\mathcal{O}(e^2)$

Purity

$$P = \mathrm{tr}[\rho_{\mathrm{EM}}^2] = 1 + \mathcal{O}(e^4)$$

Example 2: Squeezed state



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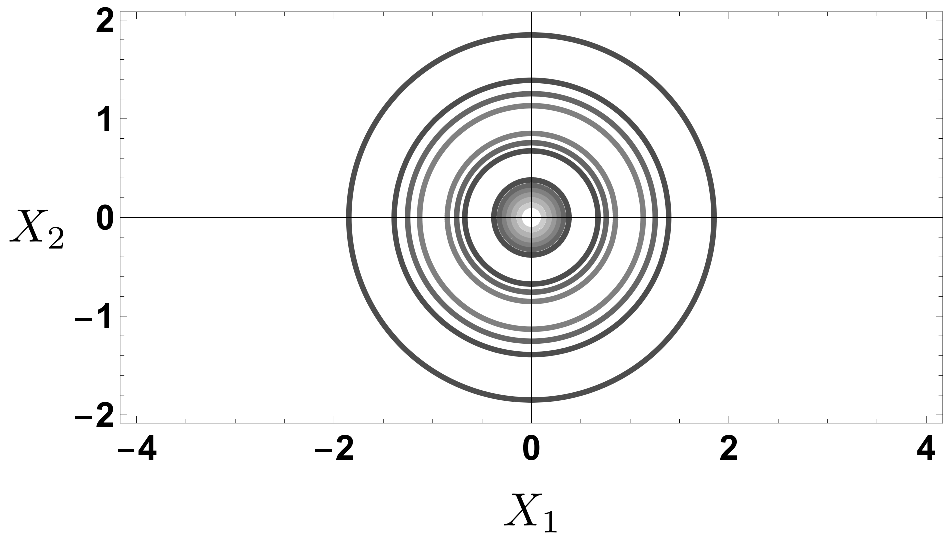
Coefficients: $\mathcal{O}(e^2)$

Purity

$$P = {\rm tr}[\rho_{\rm EM}^2] = 1 + \mathcal{O}(e^4)$$

To leading order in *e*, the squeezed state is robust to interaction with a charged field in the absence of charged particles.

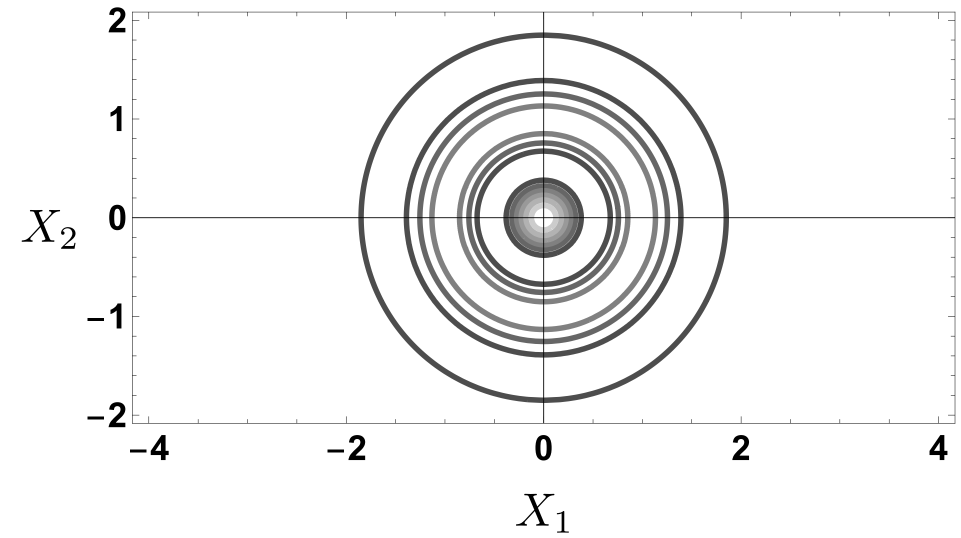
Example 3: Fock state



Initial state of the EM field

$$\rho_{\mathrm{EM}}^{(0)} = |n\rangle\langle n|$$

Example 3: Fock state



Initial state of the EM field

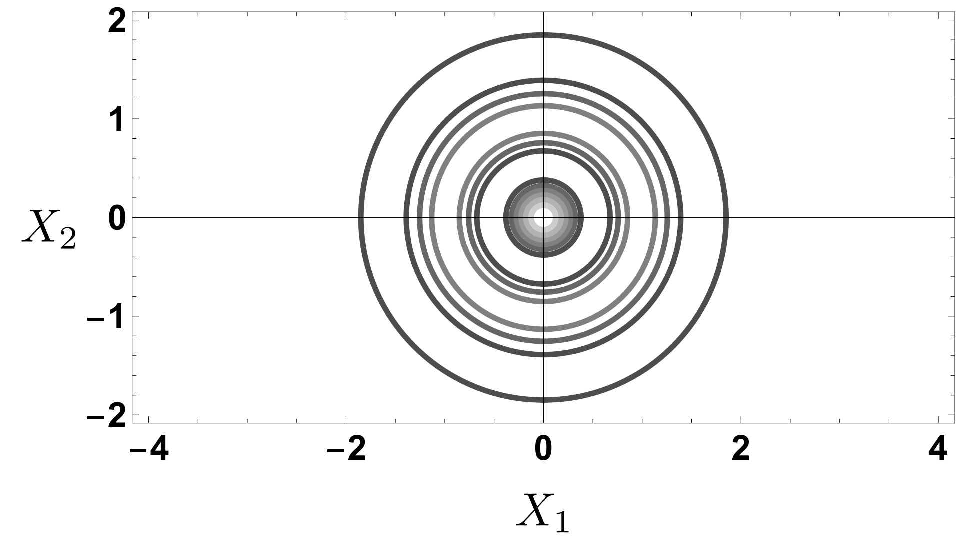
$$\rho_{\rm EM}^{(0)} = |n\rangle\langle n|$$

State of EM field after interaction

$$\begin{aligned}\rho_{\rm EM} &= (1-B-C)\,|n\rangle\,\langle n| \\ &\quad + B\,|n{-}1\rangle\,\langle n{-}1| + C\,|n{+}1\rangle\,\langle n{+}1| \\ &\quad + \big(a\,|n{-}1\rangle\,\langle n{+}1| + \text{h.c.}\big) \\ &\quad - \big(b\,|n{-}2\rangle\,\langle n| + c\,|n{+}2\rangle\,\langle n| + \text{h.c.}\big)\end{aligned}$$

Coefficients: $\mathcal{O}(e^2)$

Example 3: Fock state



Initial state of the EM field

$$\rho_{\mathrm{EM}}^{(0)} = |n\rangle\langle n|$$

Purity

$$P = \mathrm{tr}[\rho_{\mathrm{EM}}^2] = 1 - 2(B+C) + \mathcal{O}(e^4)$$

State of EM field after interaction

$$\begin{aligned}\rho_{\mathrm{EM}} &= (1-B-C)\,|n\rangle\langle n| \\ &\quad + B\,|n{-}1\rangle\langle n{-}1| + C\,|n{+}1\rangle\langle n{+}1| \\ &\quad + \left(a\,|n{-}1\rangle\langle n{+}1| + \mathrm{h.c.}\right) \\ &\quad - \left(b\,|n{-}2\rangle\langle n| + c\,|n{+}2\rangle\langle n| + \mathrm{h.c.}\right)\end{aligned}$$

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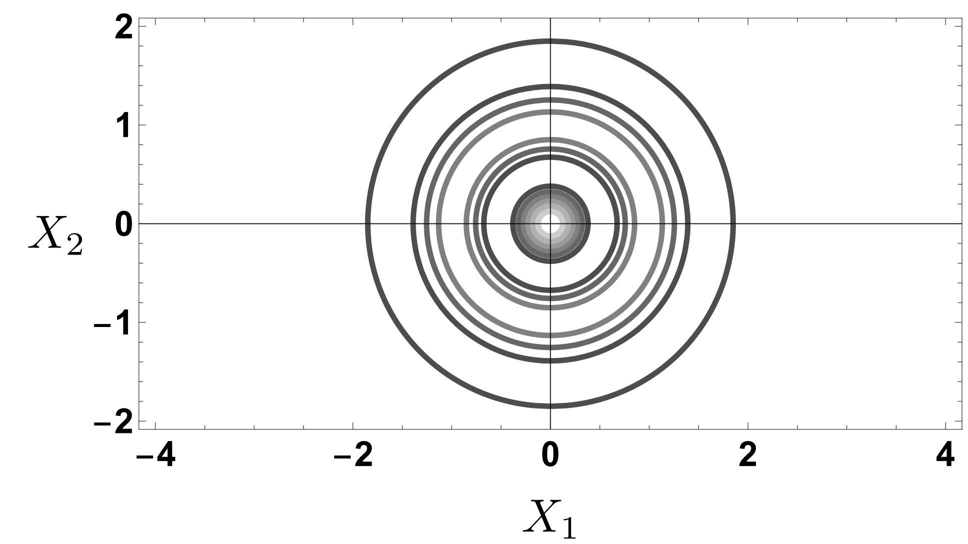

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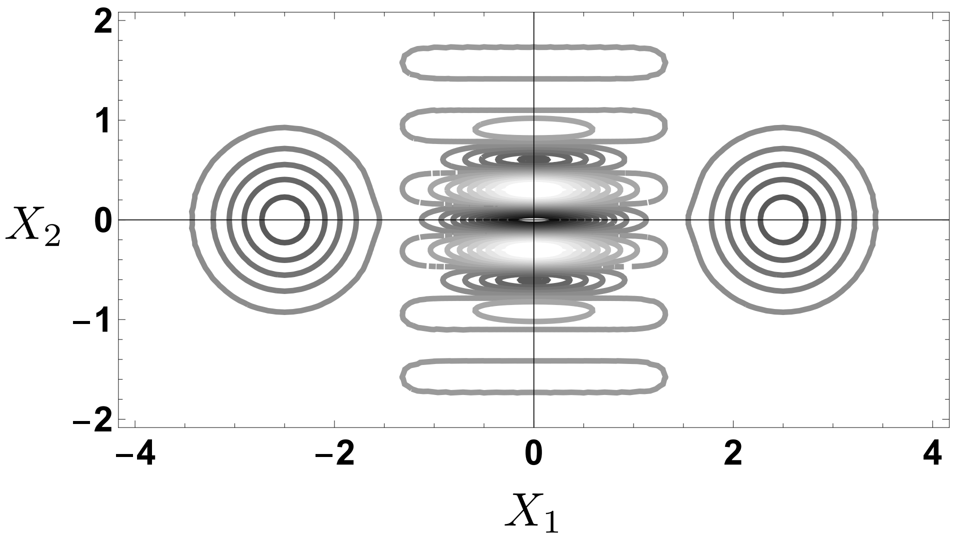
Interaction with a charged field in the absence of charged particles *does* decohere Fock states at order *e^2*

Coefficients: $\mathcal{O}(e^2)$

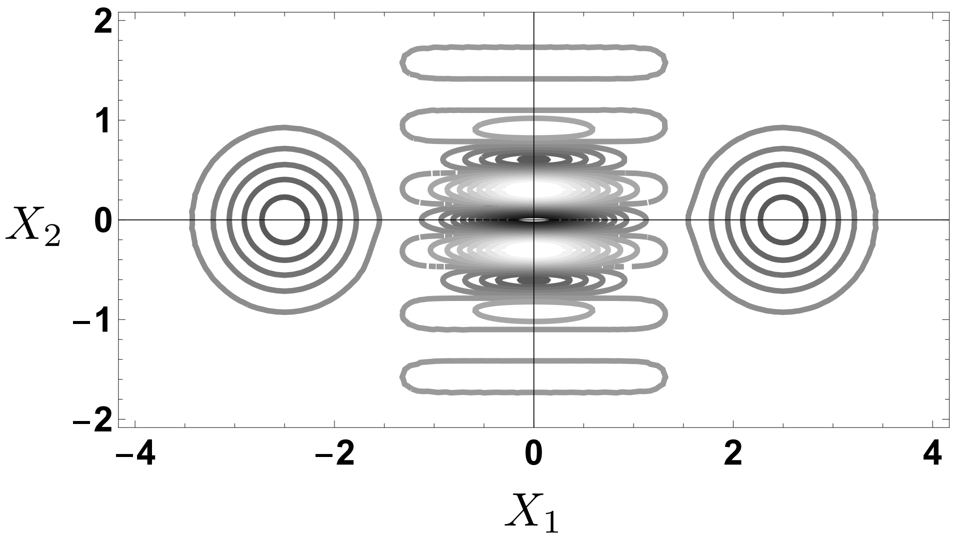
Example 4: Cat state



Initial state of the EM field

$$\rho_{\mathrm{EM}}^{(0)} = |\mathrm{cat}\rangle\langle\mathrm{cat}|$$

Example 4:
Cat state



Initial state of the EM field

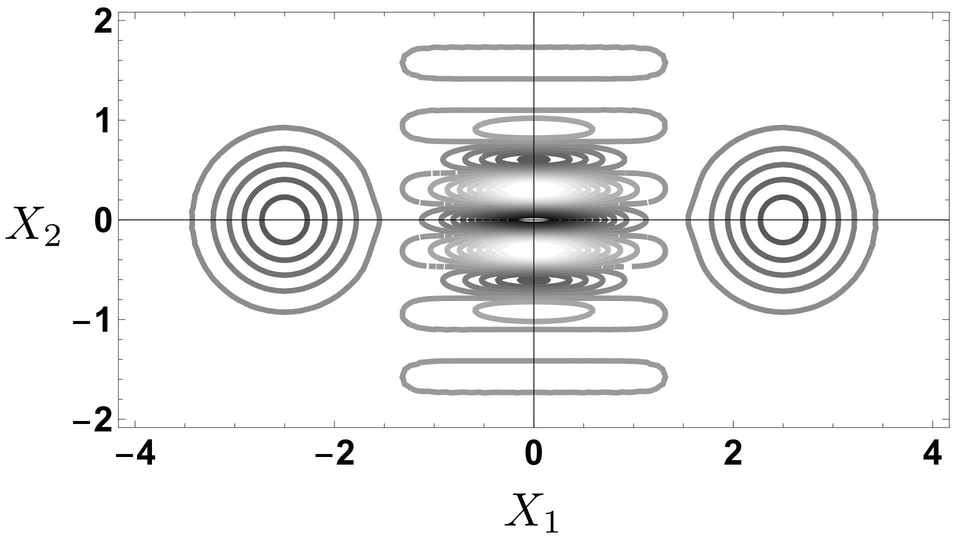
$$\rho_{\mathrm{EM}}^{(0)} = |\mathrm{cat}\rangle\langle\mathrm{cat}|$$

State of EM field after interaction

Assuming large alpha: $\hat{a}^\dagger |\alpha\rangle \approx \alpha^* |\alpha\rangle$

$$\rho_{\mathrm{EM}} = (1 - G) |\mathrm{cat}\rangle \langle\mathrm{cat}| + G |\mathrm{tac}\rangle \langle\mathrm{tac}|$$

Example 4: Cat state



Initial state of the EM field

$$\rho_{\mathrm{EM}}^{(0)} = |\mathrm{cat}\rangle\langle\mathrm{cat}|$$

Purity

$$P = \mathrm{tr}[\rho_{\mathrm{EM}}^2] = 1 - 2G + \mathcal{O}(e^4)$$

State of EM field after interaction

Assuming large alpha: $\hat{a}^\dagger |\alpha\rangle \approx \alpha^* |\alpha\rangle$

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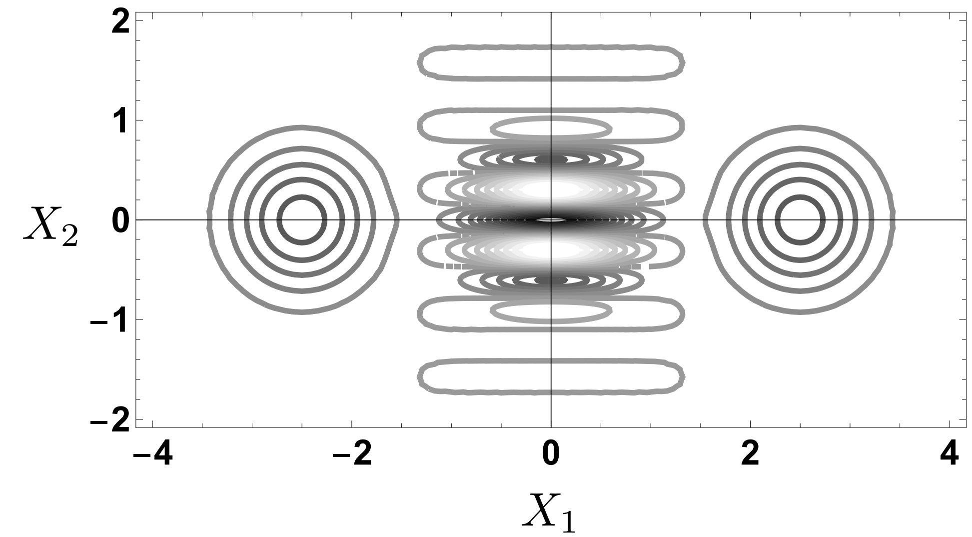

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Assuming large alpha: $\hat{a}^\dagger |\alpha\rangle \approx \alpha^* |\alpha\rangle$

Interaction with a charged field in the absence of charged particles also decoheres cat states at order e^2

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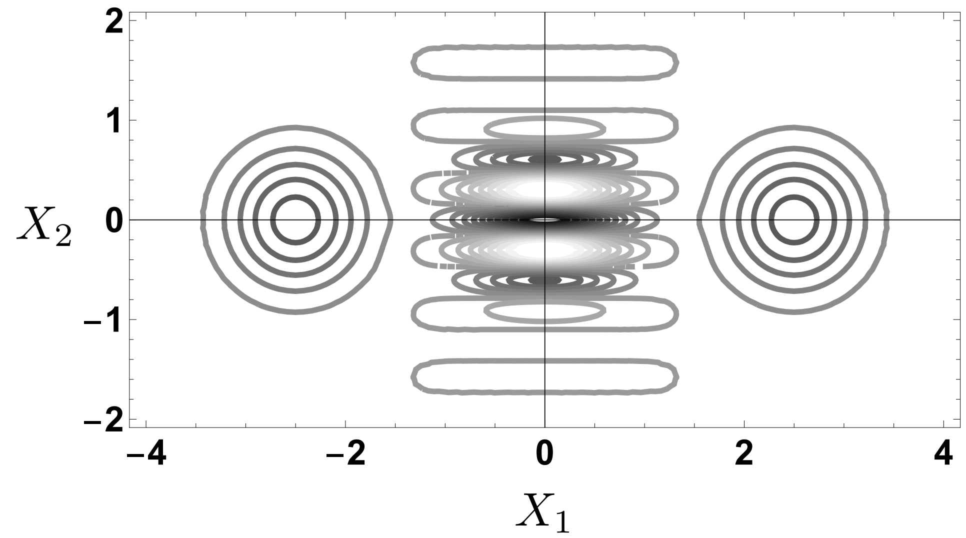

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State of EM field after interaction

$$\rho_{\mathrm{EM}} = (1 - G)\,|\mathrm{cat}\rangle\,\langle\mathrm{cat}| + G\,|\mathrm{tac}\rangle\,\langle\mathrm{tac}|$$

$$G = e^2 \int_{-\infty}^{\infty} \mathrm{d}t q(t) \int_{-\infty}^{\infty} \mathrm{d}t' q(t') \chi(\tfrac{t}{T}) \chi(\tfrac{t'}{T}) w(t, t')$$

Assuming large alpha: $\hat{a}^\dagger\,|\alpha\rangle \approx \alpha^*\,|\alpha\rangle$

Interaction with a charged field in the absence of charged particles also decoheres cat states at order e^2

$$q(t) = \frac{1}{\sqrt{2V\Omega}}(\alpha e^{-\mathrm{i}\Omega t} + \alpha^* e^{\mathrm{i}\Omega t})$$

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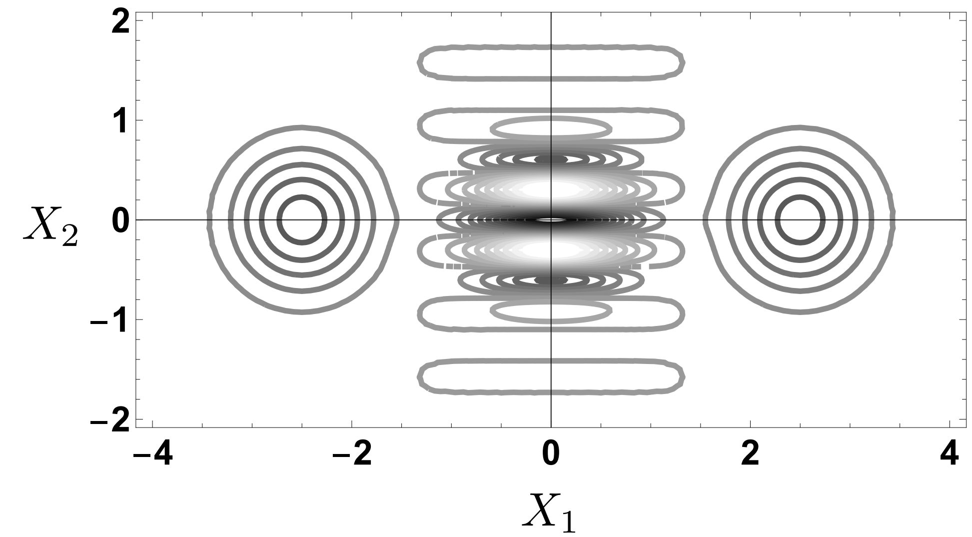

Initial state of the EM field

$$\rho_{\rm EM}^{(0)} = |{\rm cat}\rangle\langle{\rm cat}|$$

Purity

$$P = {\rm tr}[\rho_{\rm EM}^2] = 1 - 2G + \mathcal{O}(e^4)$$

State of EM field after interaction

$$\rho_{\rm EM} = (1-G)\,|{\rm cat}\rangle\,\langle{\rm cat}| + G\,|{\rm tac}\rangle\,\langle{\rm tac}|$$

$$G = e^2 \int_{-\infty}^{\infty} {\rm d}t q(t) \int_{-\infty}^{\infty} {\rm d}t' q(t') \chi\left(\tfrac{t}{T}\right)\chi\left(\tfrac{t'}{T}\right) w(t,t')$$

$$w(t,t') = \int {\rm d}^3\boldsymbol{x} \int {\rm d}^3\boldsymbol{x}' F(\boldsymbol{x}) F(\boldsymbol{x}') \left(W^{\phi}(t,\boldsymbol{x},t',\boldsymbol{x}')\right)^2$$

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Interaction with a charged field in the absence of charged particles also decoheres cat states at order e^2

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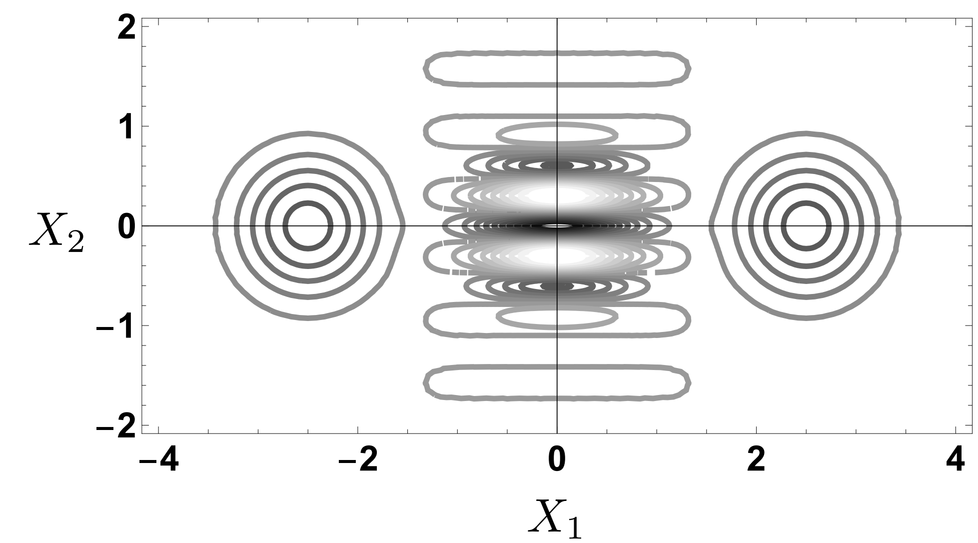
Example 4: Cat state



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State of EM field after interaction

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$$W^{\phi}(\boldsymbol{x},t,\boldsymbol{x}',t') = \frac{mK_1\left(m\sqrt{|\boldsymbol{x}'-\boldsymbol{x}|^2-(t'-t+\mathrm{i}\epsilon)^2}\right)}{(2\pi)^2\sqrt{|\boldsymbol{x}'-\boldsymbol{x}|^2-(t'-t+\mathrm{i}\epsilon)^2}}$$

Assuming large alpha: $\hat{a}^\dagger\,|\alpha\rangle \approx \alpha^*\,|\alpha\rangle$

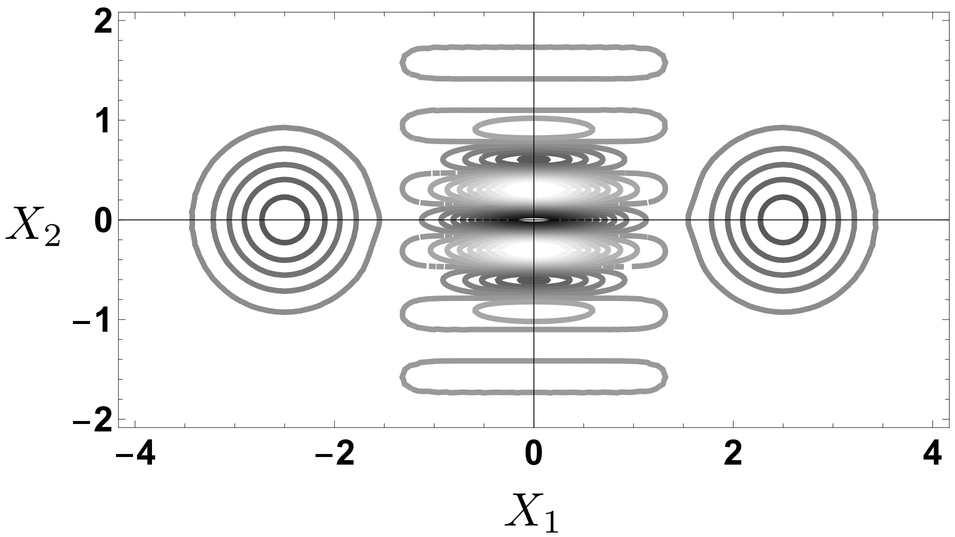
Interaction with a charged field in the absence of charged particles also decoheres cat states at order e^2

$$q(t) = \frac{1}{\sqrt{2V\Omega}}(\alpha e^{-\mathrm{i}\Omega t} + \alpha^* e^{\mathrm{i}\Omega t})$$

Example 4: Cat state

$$\chi(\tfrac{t}{T}) = \mathrm{rect}(t/T)$$

$$F(\boldsymbol{x}/\sigma) = e^{-\frac{|\boldsymbol{x}|^2}{\sigma^2}},$$



Initial state of the EM field

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State of EM field after interaction

Assuming large alpha: $\hat{a}^\dagger |\alpha\rangle \approx \alpha^* |\alpha\rangle$

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Interaction with a charged field in the absence of charged particles also decoheres cat states at order e^2

$$G = e^2 \int_{-\infty}^{\infty} \mathrm{d}t\, q(t) \int_{-\infty}^{\infty} \mathrm{d}t'\, q(t') \chi(\tfrac{t}{T}) \chi(\tfrac{t'}{T}) w(t,t')$$

$$w(t,t') = \int \mathrm{d}^3\boldsymbol{x} \int \mathrm{d}^3\boldsymbol{x}'\, F(\boldsymbol{x}) F(\boldsymbol{x}') \left(W^\phi(t,\boldsymbol{x},t',\boldsymbol{x}')\right)^2$$

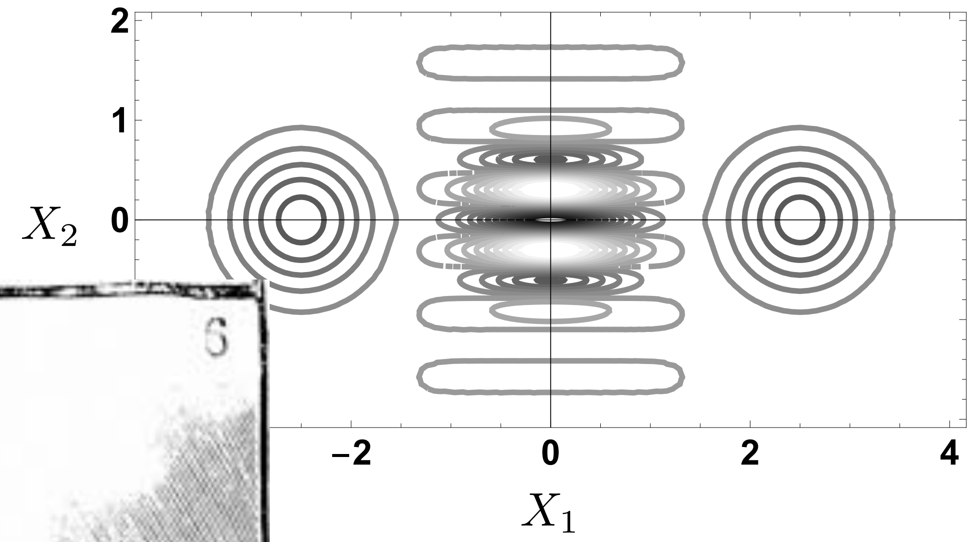
$$W^\phi(\boldsymbol{x},t,\boldsymbol{x}',t') = \frac{m K_1\left(m\sqrt{|\boldsymbol{x}'-\boldsymbol{x}|^2 - (t'-t+\mathrm{i}\epsilon)^2}\right)}{(2\pi)^2 \sqrt{|\boldsymbol{x}'-\boldsymbol{x}|^2 - (t'-t+\mathrm{i}\epsilon)^2}}$$

$$q(t) = \frac{1}{\sqrt{2V\Omega}}(\alpha e^{-\mathrm{i}\Omega t} + \alpha^* e^{\mathrm{i}\Omega t})$$

Example 4: Cat state

$$\chi\left(\tfrac{t}{T}\right) = \mathrm{rect}(t/T)$$

$$F(\boldsymbol{x}/\sigma) = e^{-\frac{|\boldsymbol{x}|^2}{\sigma^2}}\,,$$



Initial state of the EM

$$\rho^{(0)}_{\mathrm{EM}} = |\mathrm{cat}\rangle\langle\mathrm{cat}|$$

$$= \; 1 - 2G + \mathcal{O}(e^4)$$

State of EM field afte **e alpha:** $\hat{a}^\dagger\,|\alpha\rangle \approx \alpha^*\,|\alpha\rangle$

$$\rho_{\mathrm{EM}} = (1-G)\,|\mathrm{c}$$

$$G = e^2\int_{-\infty}^{\infty}\mathrm{d}t\,q(t)\int_{-\infty}$$

$$w(t,t') = \int \mathrm{d}^3\boldsymbol{x}\int \mathrm{d}^3\boldsymbol{x}'$$

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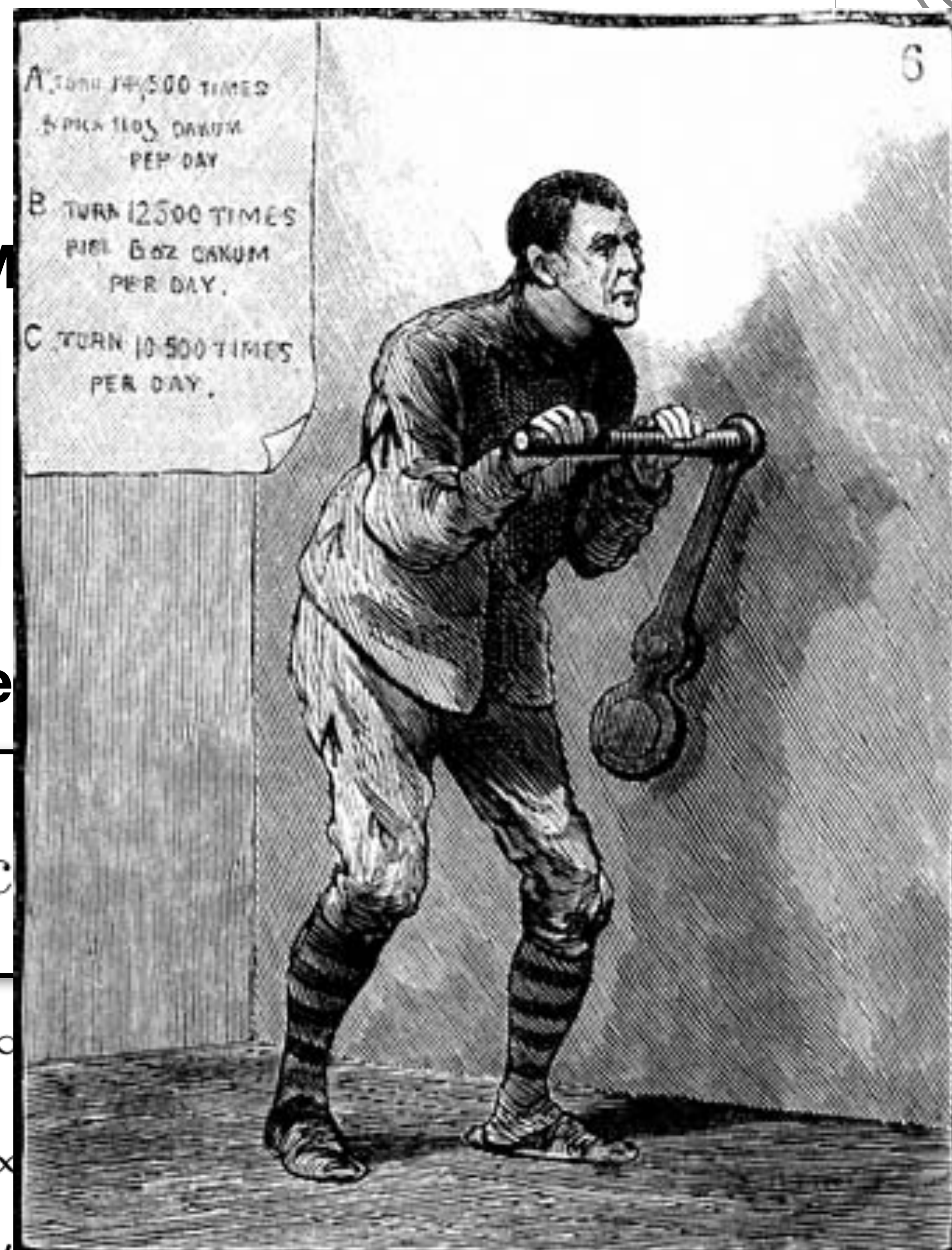
$$q(t) = \frac{1}{\sqrt{2V\Omega}}\left(\alpha e^{-\mathrm{i}\Omega t} + \alpha^* e^{\mathrm{i}\Omega t}\right)$$

Interaction with a charged field in the absence of charged particles also decoheres cat states at order e^2



Numerical results for cat state: Purity as a function cat state "size"

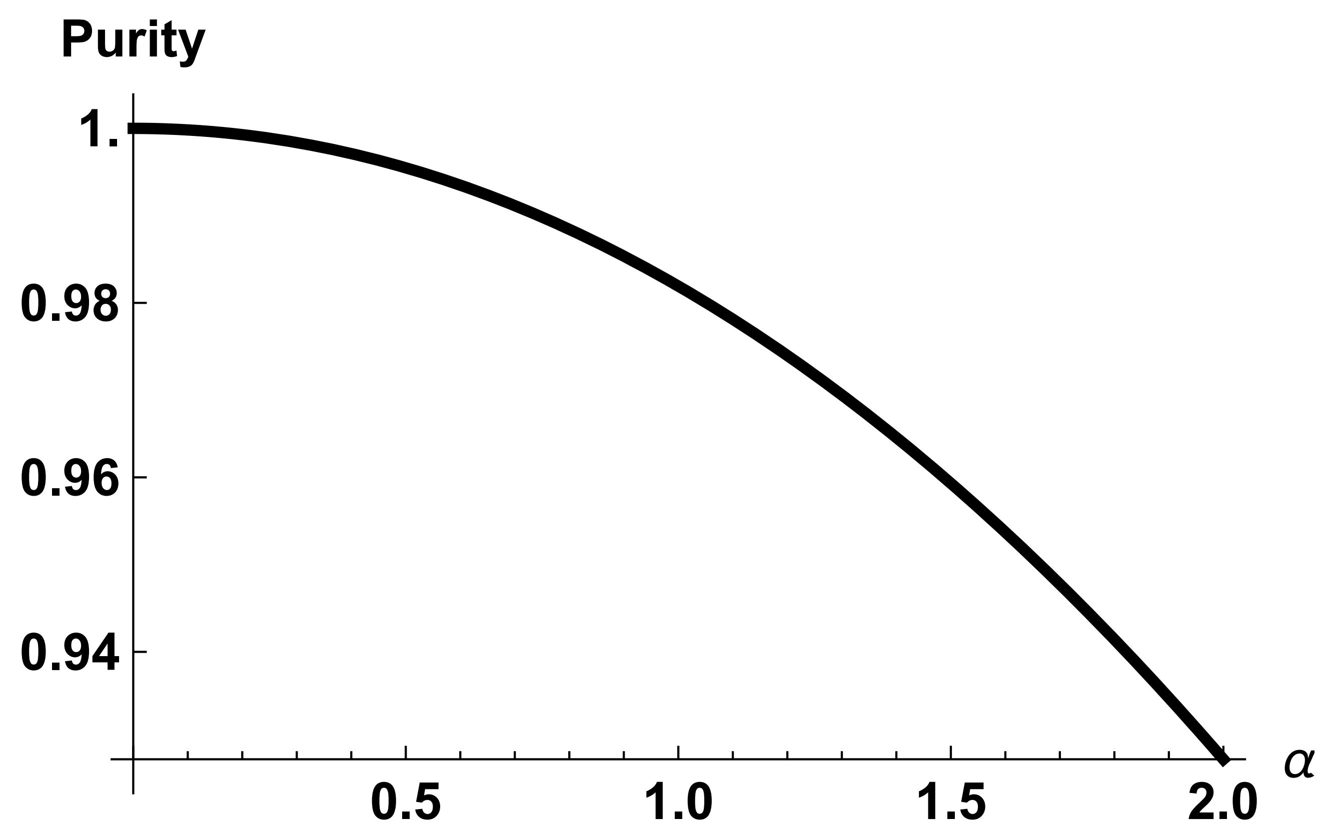
Purity

$$P = 1 - \frac{2^3\sqrt{2}}{\sqrt{\pi}}\frac{(e\alpha m)^2}{\Omega}$$

$$\times \mathrm{Re}\left[\int_0^T \mathrm{d}v(T-v)\left(\mathrm{sinc}((T-v)\Omega) + \cos(\Omega v)\right)\int_0^\infty \mathrm{d}q\; q^2 e^{-\frac{q^2}{2\sigma^2}} \frac{K_1\left(m\sqrt{q^2-(v-\mathrm{i}\epsilon)^2}\right)^2}{q^2-(v-\mathrm{i}\epsilon)^2}\right]$$

Numerical results for cat state: Purity as a function cat state "size"

e = 0.08
σ = 6
Ω = 1
m = 1
T = 1



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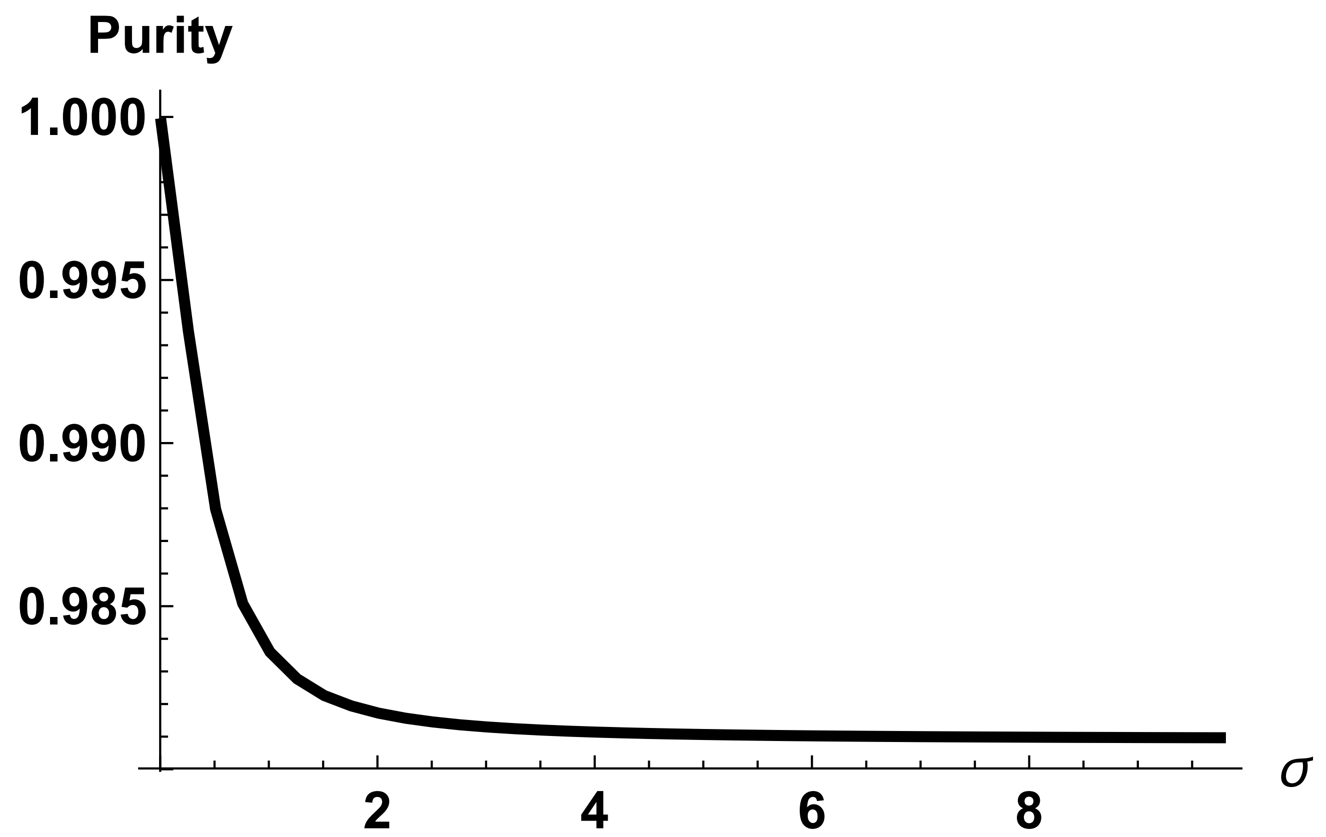
Numerical results for cat state: Purity as a function of cavity size

e = 0.08
T = 0.6
Ω = 1
m = 1
α = 1



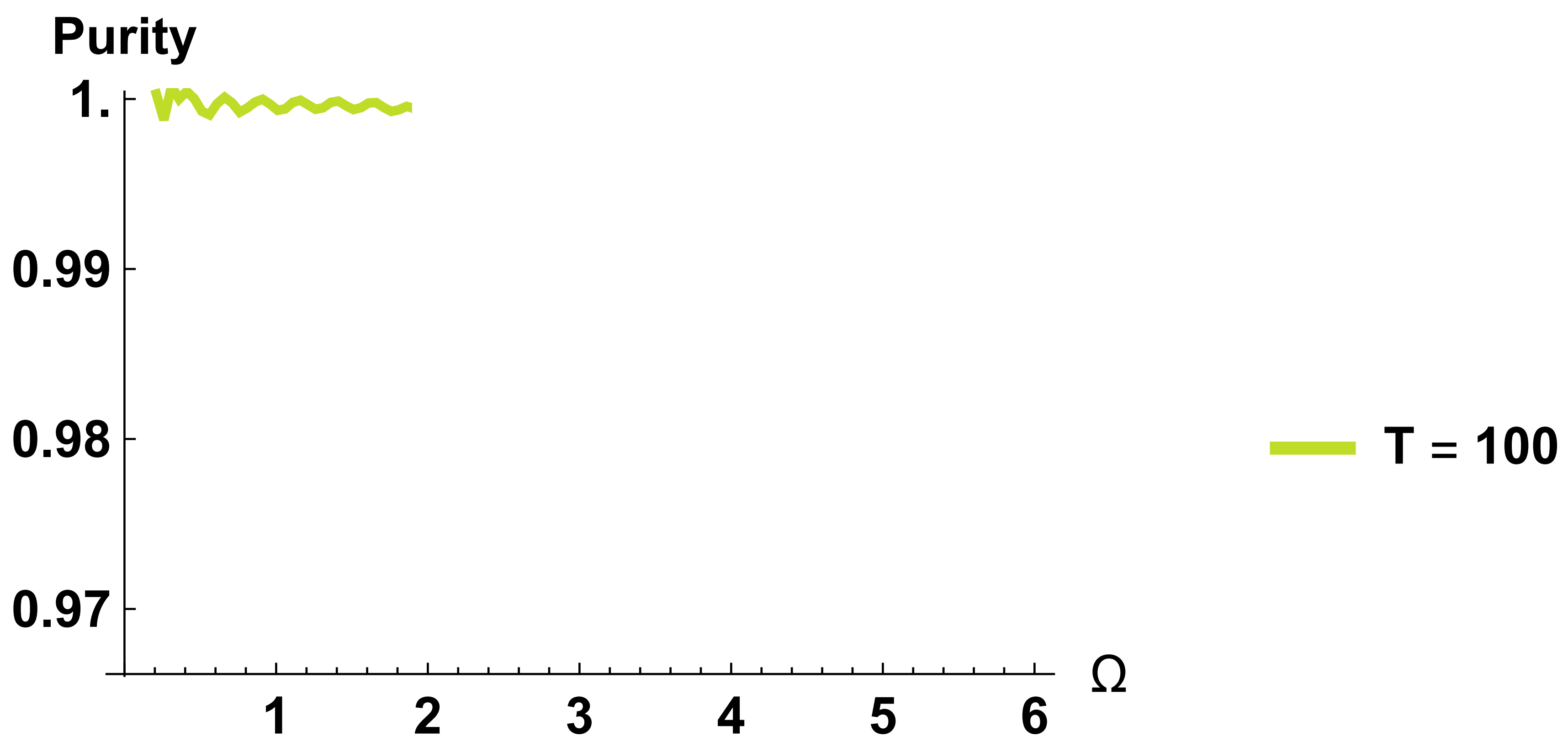
Purity

$$P = 1 - \frac{2^3\sqrt{2}}{\sqrt{\pi}}\frac{(e\alpha m)^2}{\Omega}$$

$$\times \operatorname{Re}\left[\int_0^T \mathrm{d}v (T-v)\left(\operatorname{sinc}((T-v)\Omega) + \cos(\Omega v)\right)\int_0^\infty \mathrm{d}q\; q^2 e^{-\frac{q^2}{2\sigma^2}} \frac{K_1\left(m\sqrt{q^2-(v-\mathrm{i}\epsilon)^2}\right)^2}{q^2-(v-\mathrm{i}\epsilon)^2}\right]$$

Numerical results for cat state: Purity as a function of cavity frequency

e = 0.08
σ = 6
m = 1
α = 0.2



Purity

$$P = 1 - \frac{2^3\sqrt{2}}{\sqrt{\pi}}\frac{(e\alpha m)^2}{\Omega}$$
$$\times \mathrm{Re}\left[\int_0^T \mathrm{d}v(T-v)\left(\mathrm{sinc}((T-v)\Omega) + \cos(\Omega v)\right)\int_0^\infty \mathrm{d}q\ q^2 e^{-\frac{q^2}{2\sigma^2}}\frac{K_1\left(m\sqrt{q^2-(v-\mathrm{i}\epsilon)^2}\right)^2}{q^2-(v-\mathrm{i}\epsilon)^2}\right]$$

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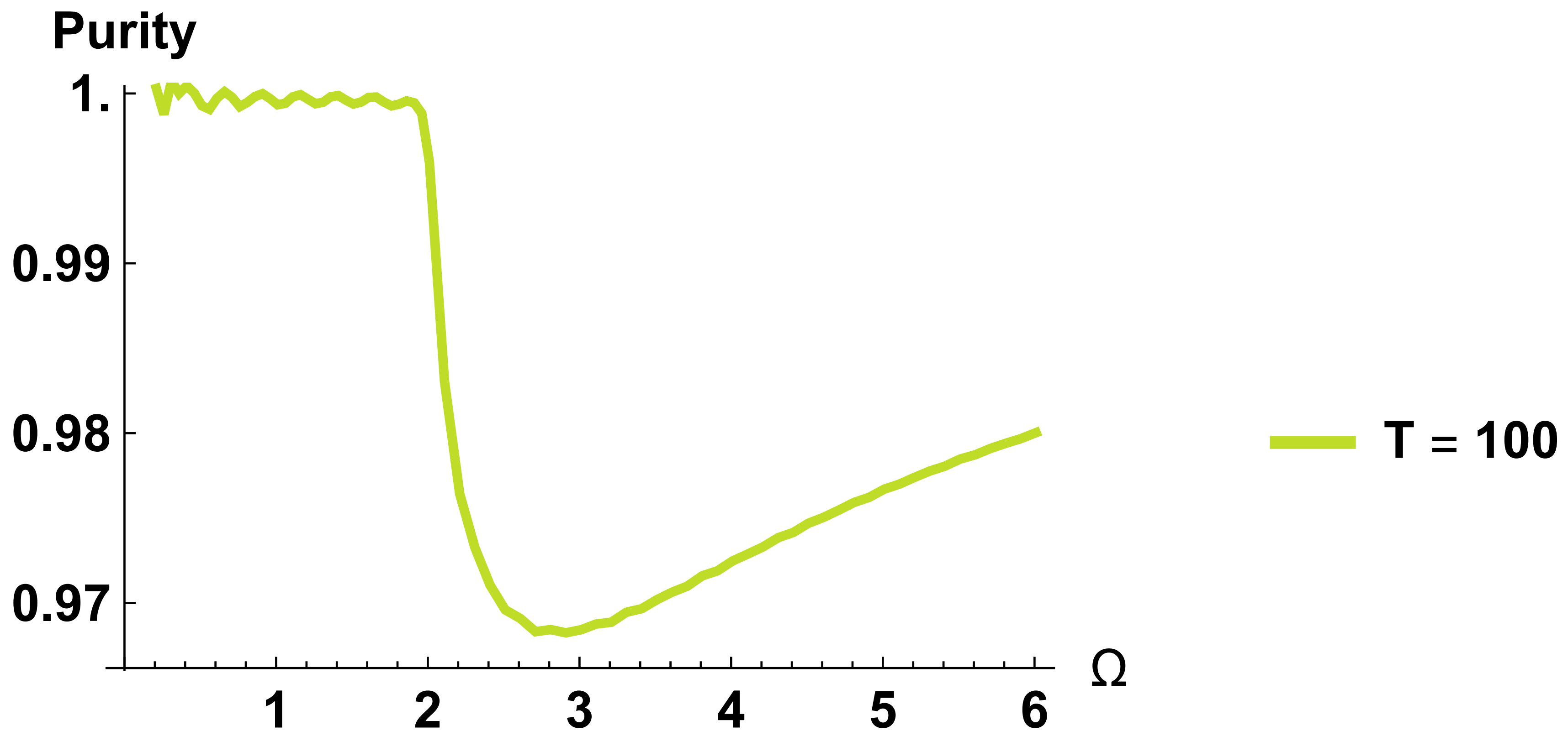

Purity

$$P = 1 - \frac{2^3\sqrt{2}}{\sqrt{\pi}}\frac{(e\alpha m)^2}{\Omega}$$
$$\times \operatorname{Re}\left[\int_0^T \mathrm{d}v(T-v)\left(\operatorname{sinc}((T-v)\Omega)+\cos(\Omega v)\right)\int_0^\infty \mathrm{d}q\; q^2 e^{-\frac{q^2}{2\sigma^2}}\frac{K_1\left(m\sqrt{q^2-(v-\mathrm{i}\epsilon)^2}\right)^2}{q^2-(v-\mathrm{i}\epsilon)^2}\right]$$

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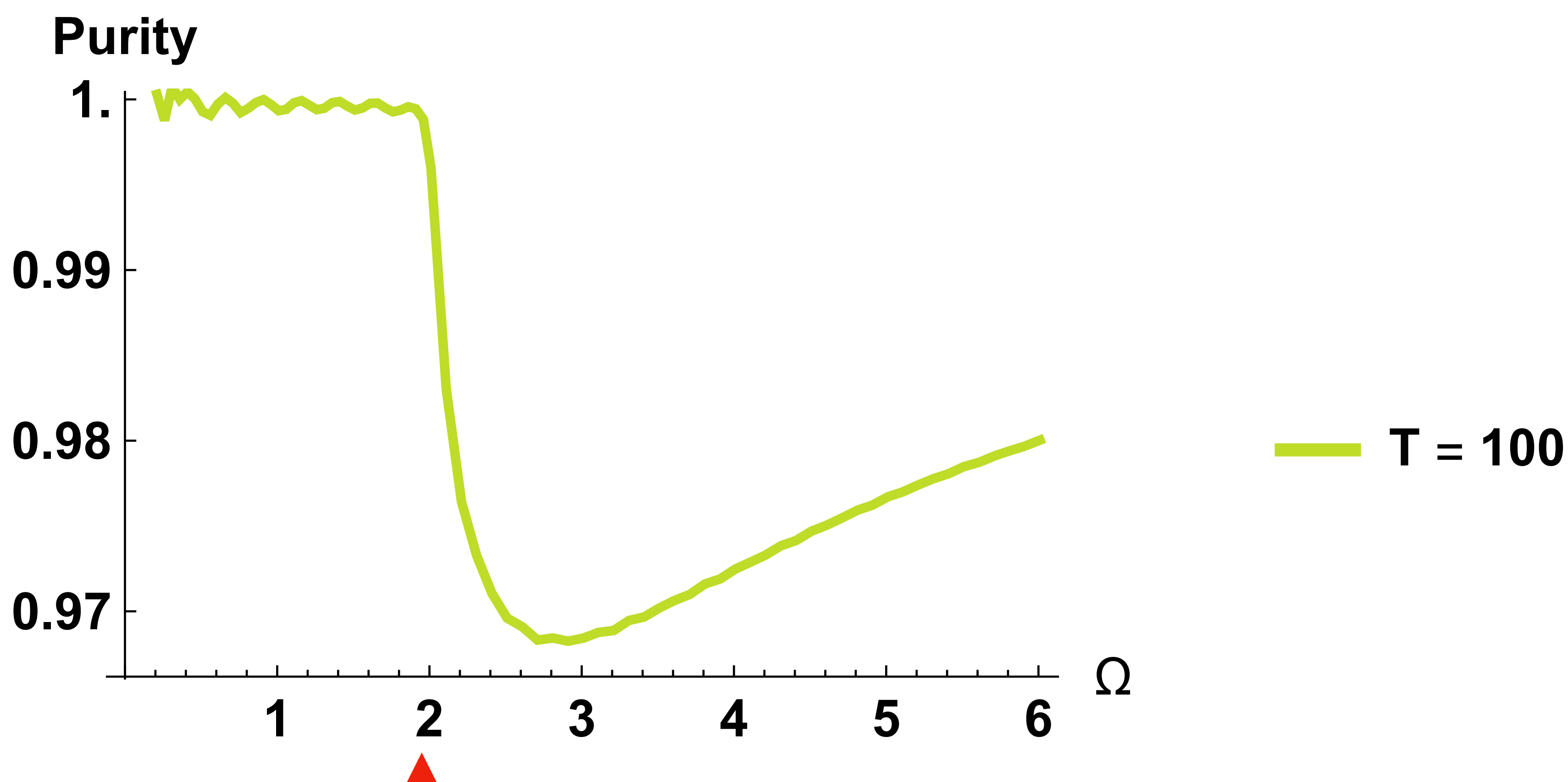

= mass of electron + positron

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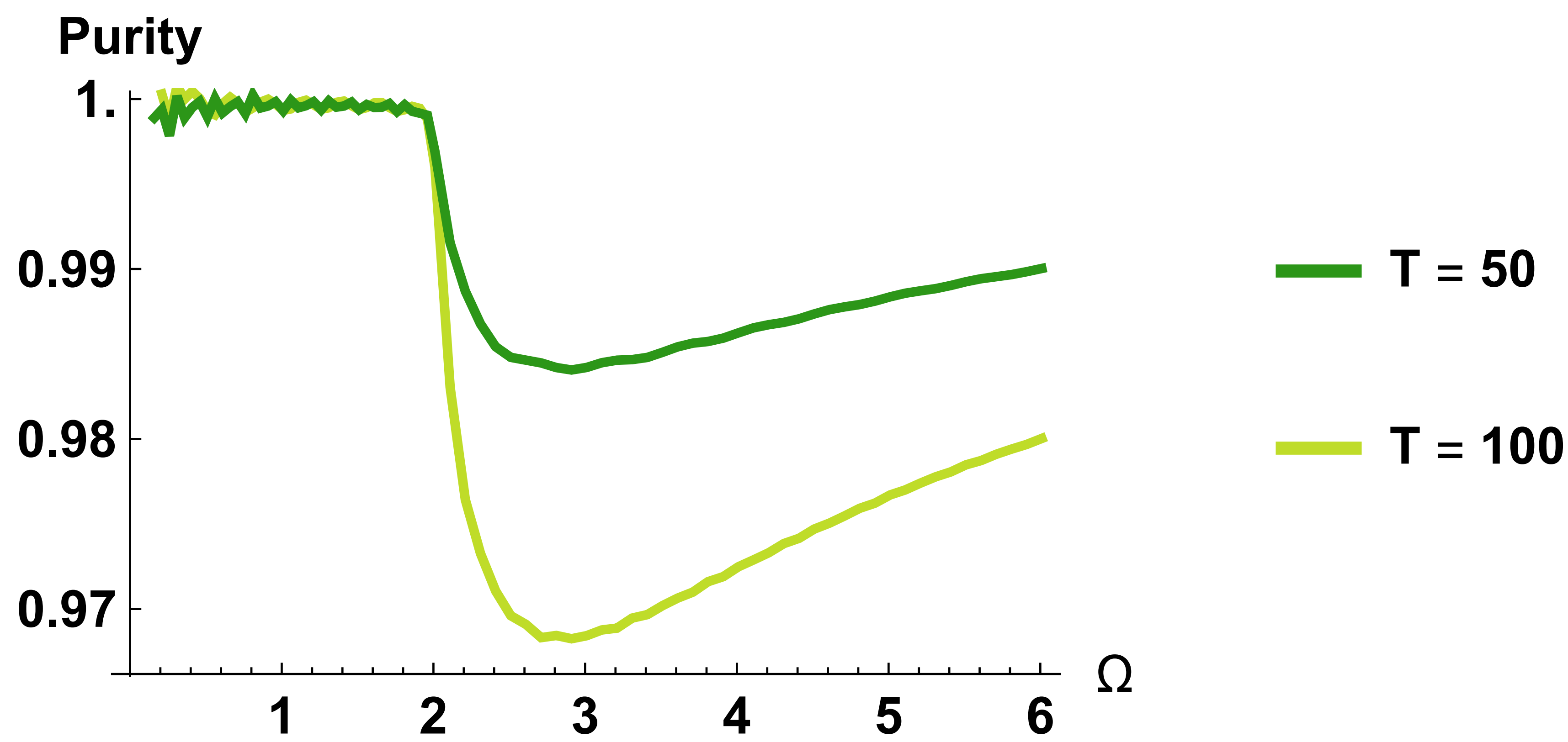

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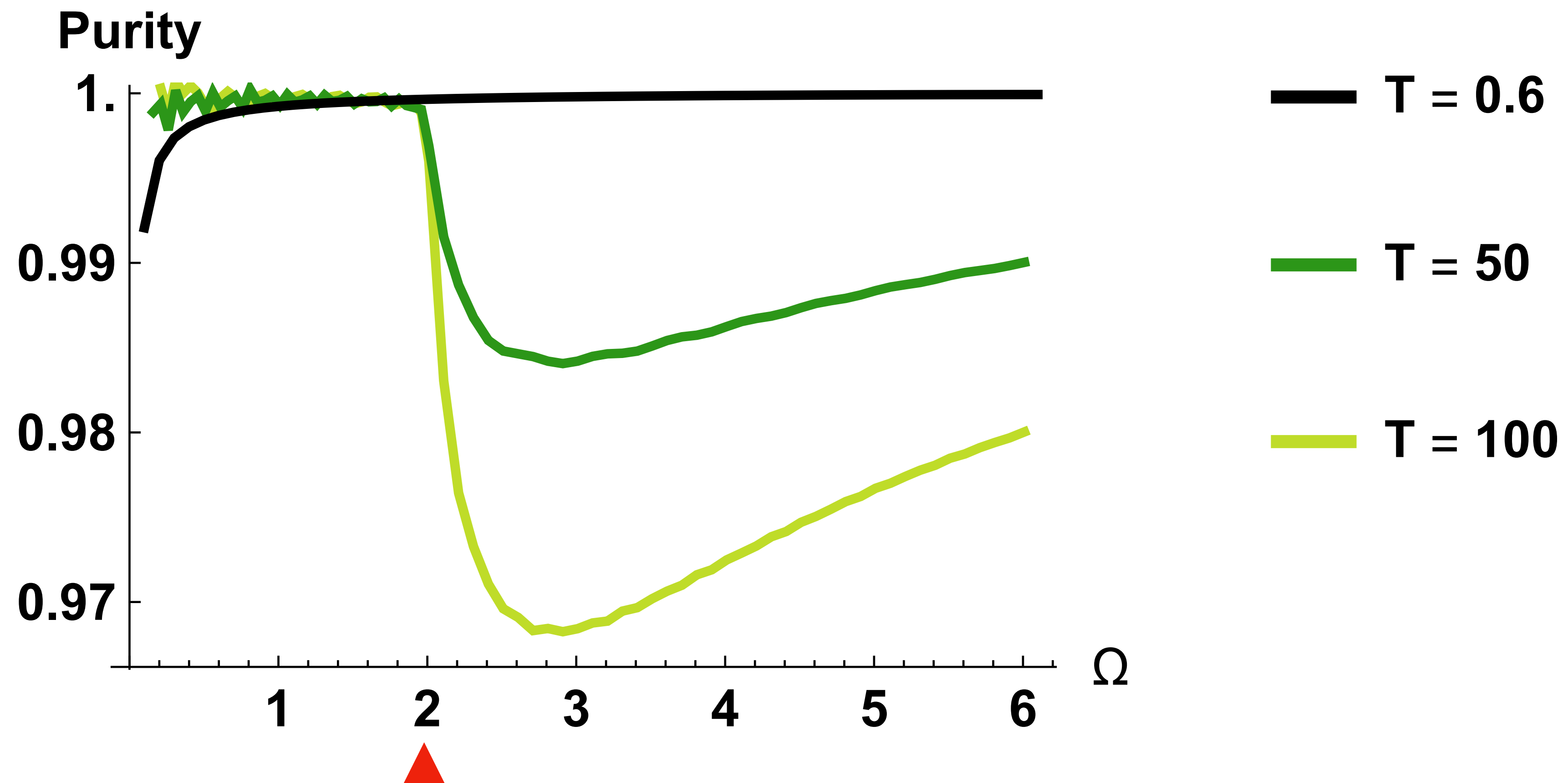

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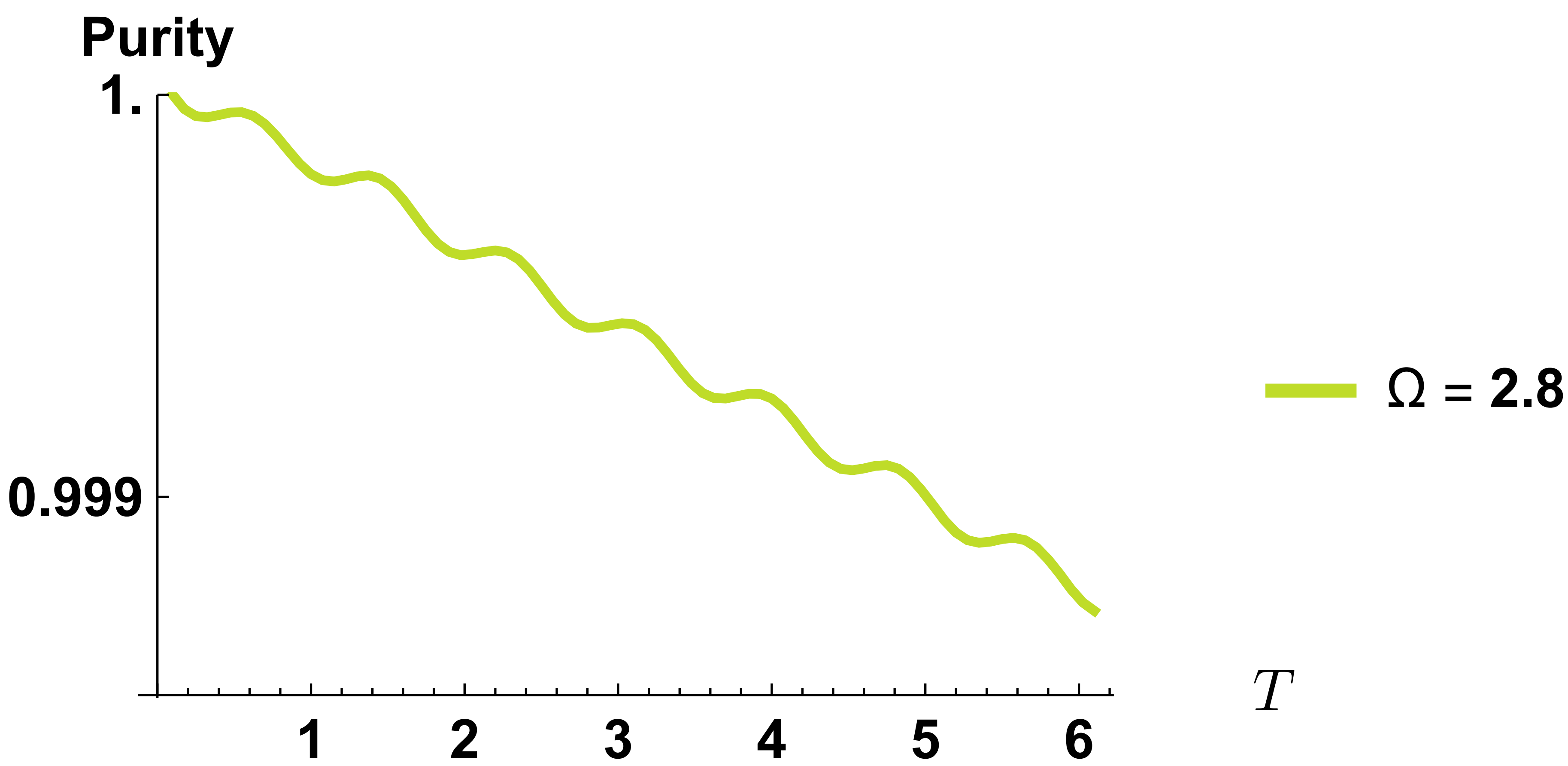
Numerical results for cat state: Purity as a function of interaction time

e = 0.08
σ = 6
m = 1
α = 0.1



Purity

$$P = 1 - \frac{2^3\sqrt{2}}{\sqrt{\pi}}\frac{(e\alpha m)^2}{\Omega}$$

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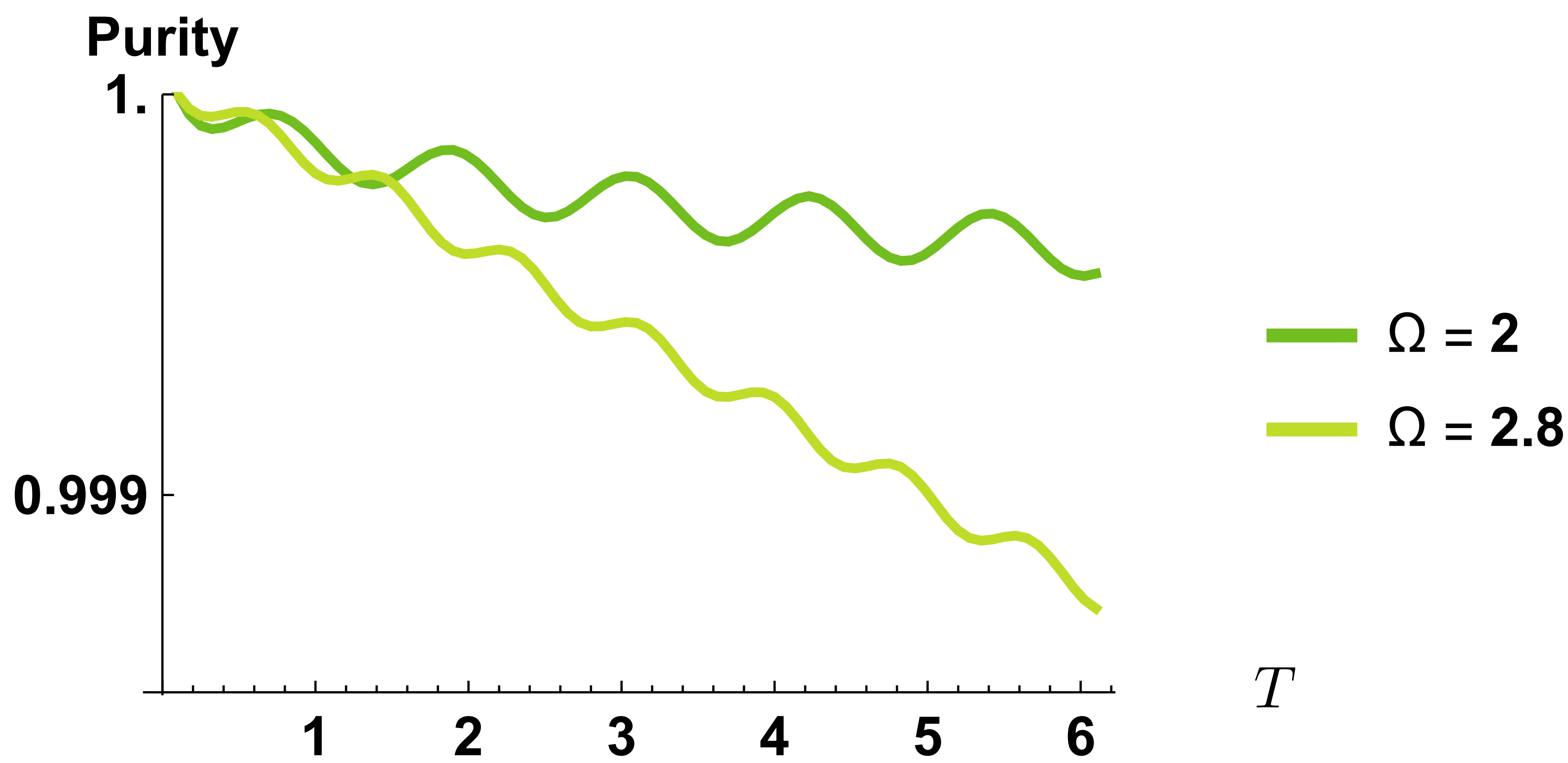

Purity

$$P = 1 - \frac{2^3\sqrt{2}}{\sqrt{\pi}}\frac{(e\alpha m)^2}{\Omega} \times \mathrm{Re}\left[\int_0^T \mathrm{d}v(T-v)\left(\mathrm{sinc}((T-v)\Omega) + \cos(\Omega v)\right)\int_0^\infty \mathrm{d}q\ q^2 e^{-\frac{q^2}{2\sigma^2}} \frac{K_1\left(m\sqrt{q^2-(v-\mathrm{i}\epsilon)^2}\right)^2}{q^2-(v-\mathrm{i}\epsilon)^2}\right]$$

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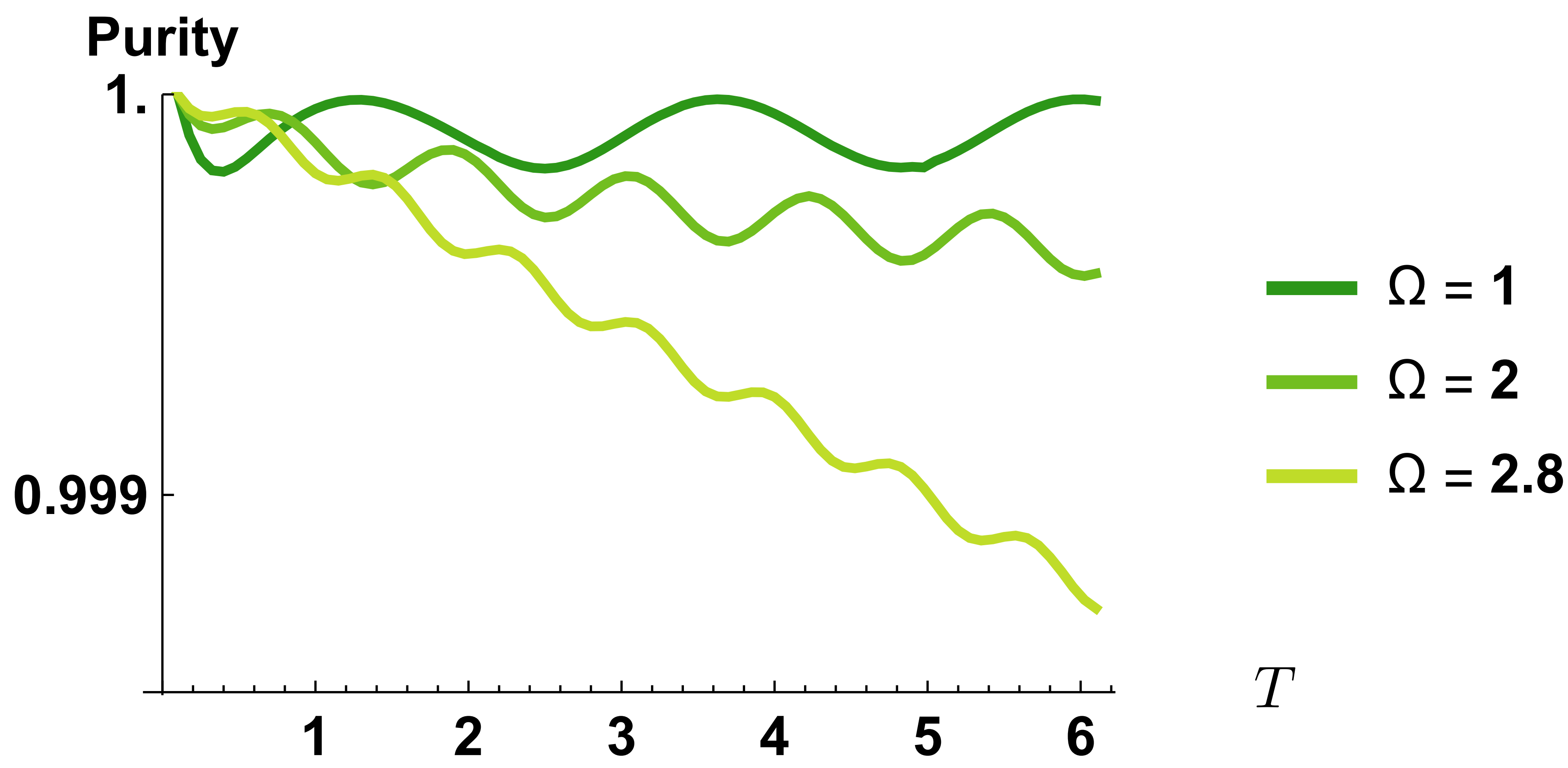

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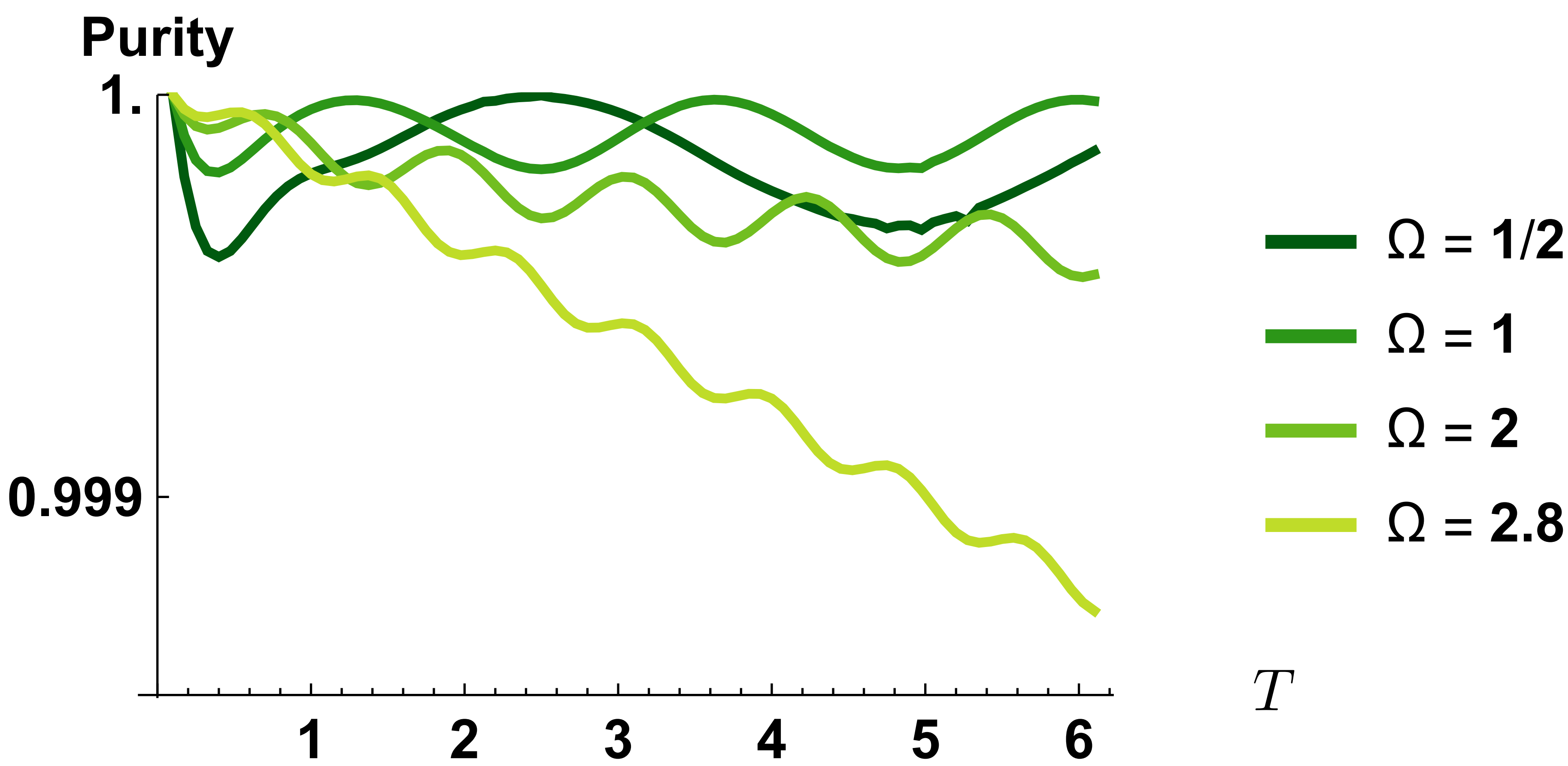

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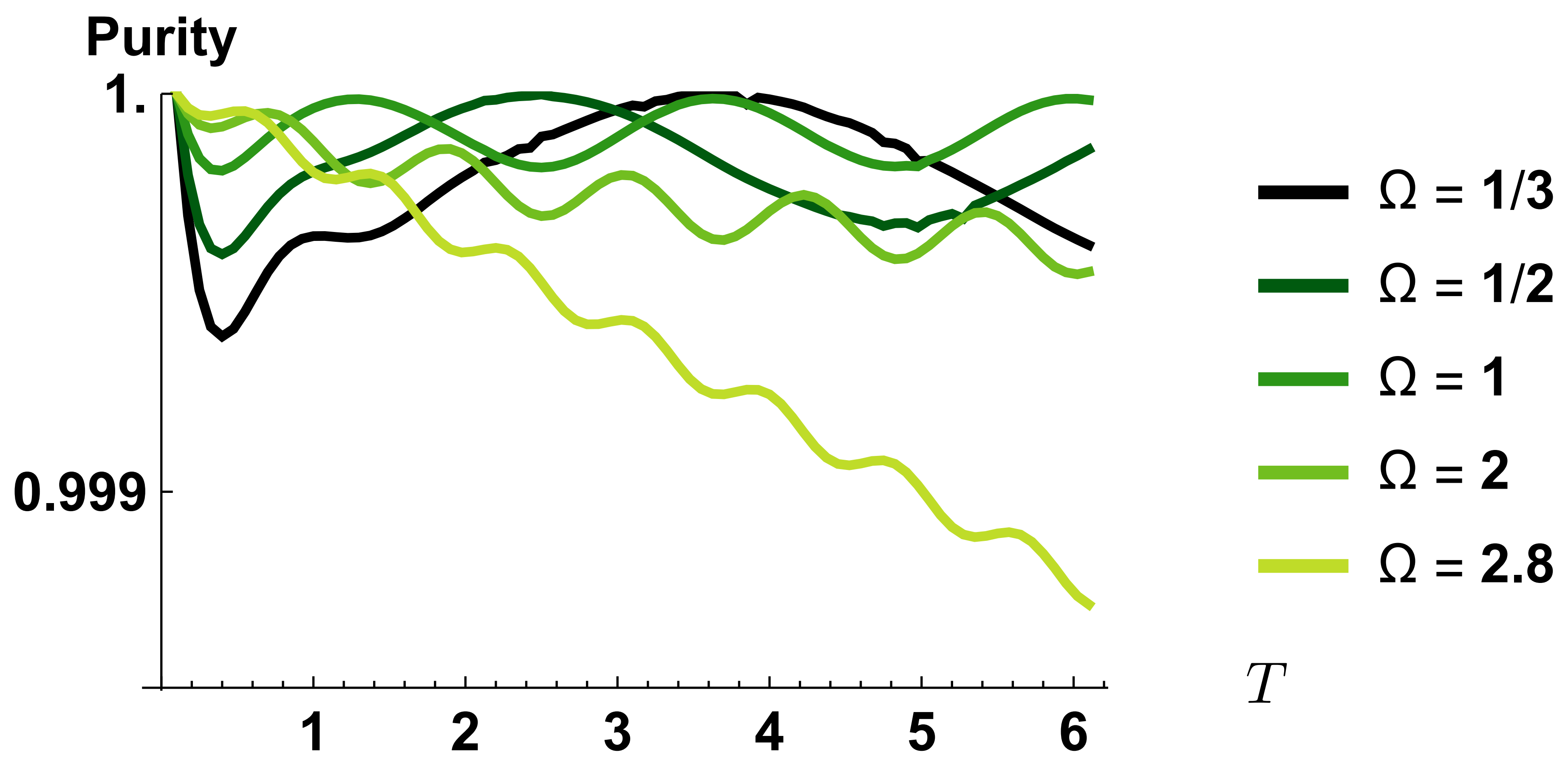

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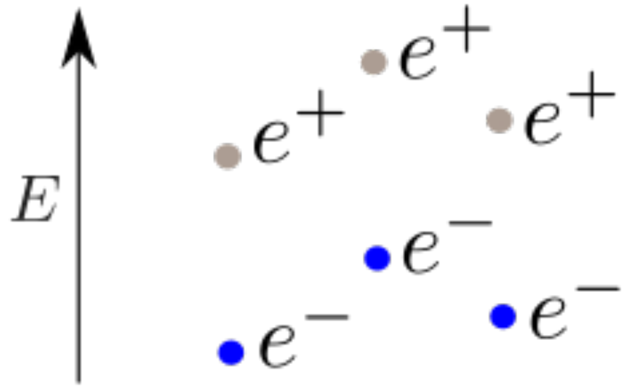
A process in which electron-positron pairs are spontaneously created in the presence of an electric field, causing the decay of the electric field.



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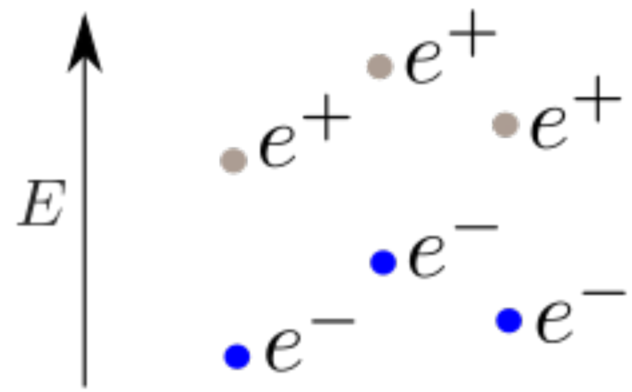

No

Schwinger effect:

- **Was originally calculated for a static electric field**
- **Is a non-perturbative effect**

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A process in which a background EM field produces virtual electron–positron pairs that change the distribution of charges and currents that generated the original EM field

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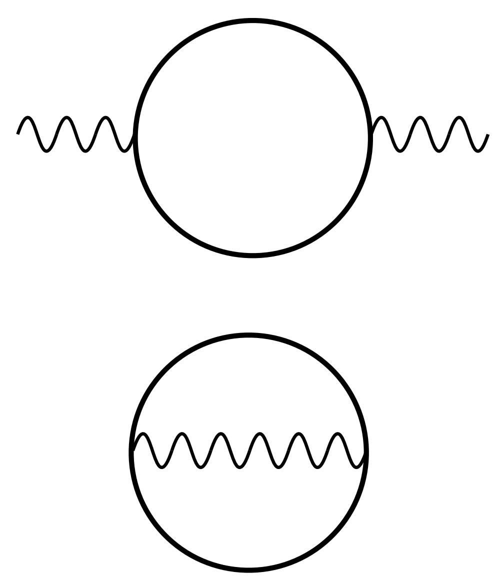

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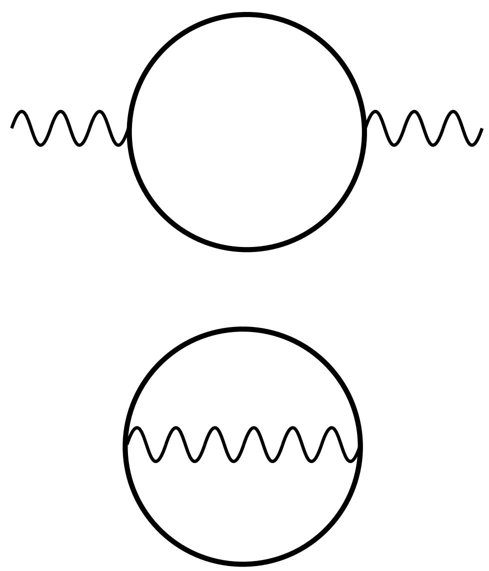
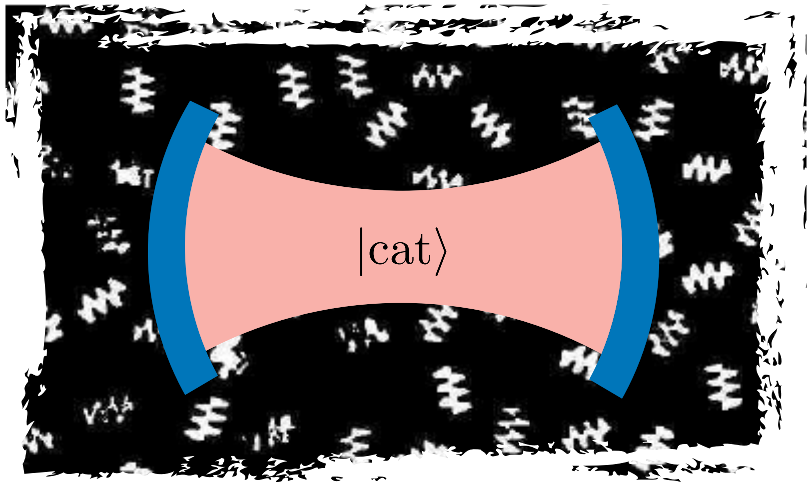


“routinely observed experimentally”

“have no measurable impact on any process”

Summary

Some QO states will decohere due to interaction with a charged field, *even in the absence of charged particles*.



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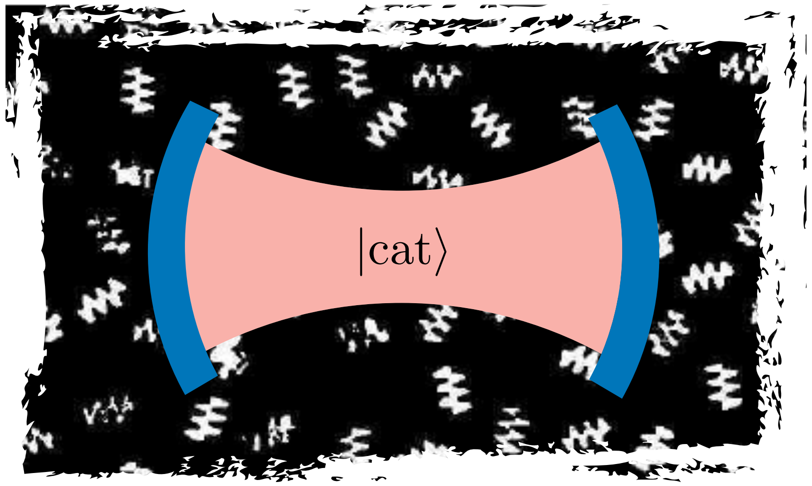

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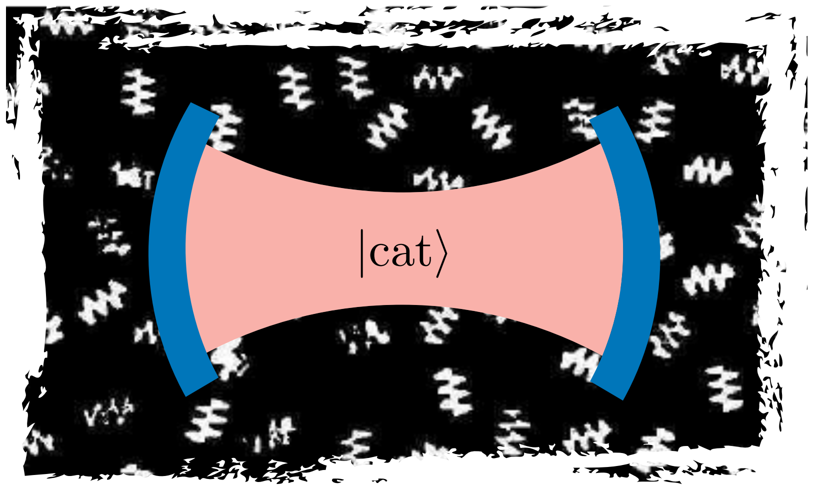

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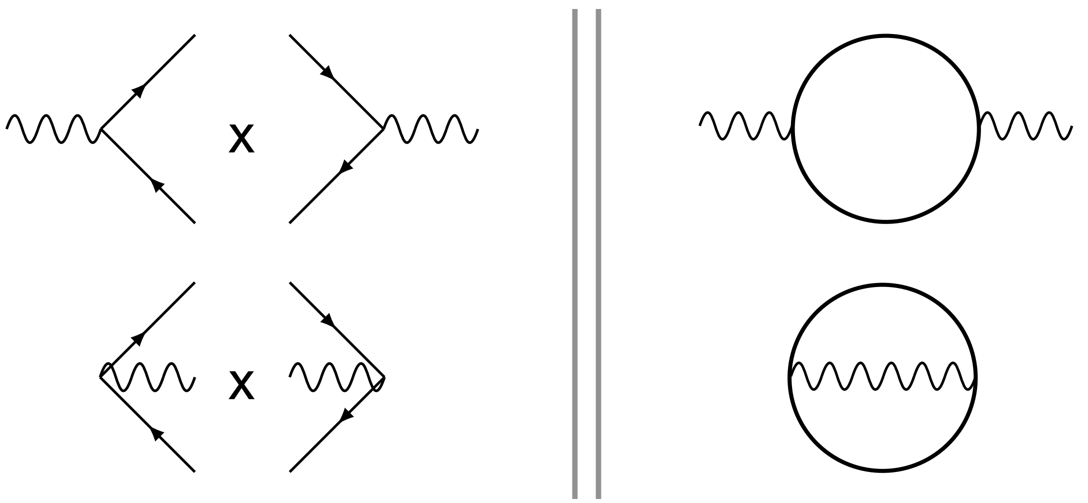
Two different decoherence mechanisms:

1. scattering
2. finite-time



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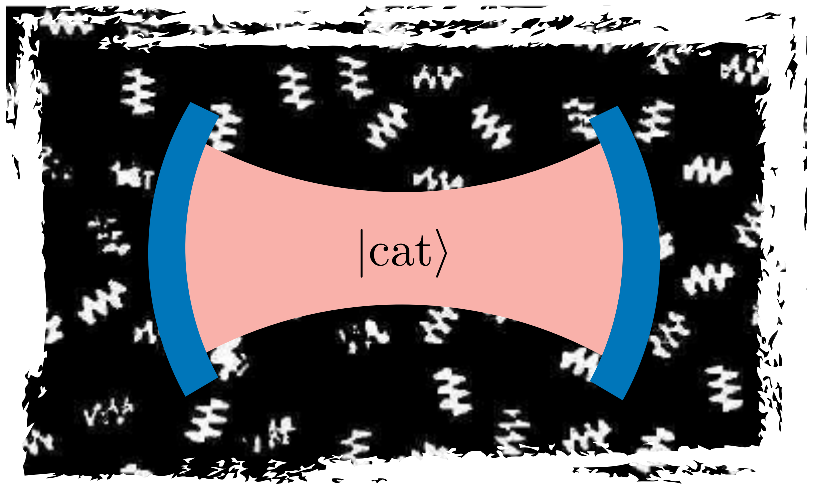

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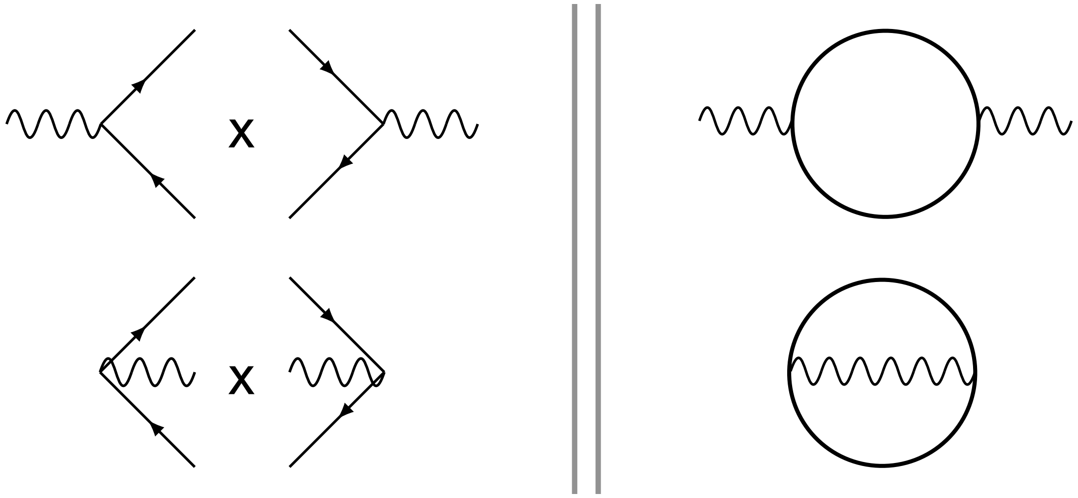

Fundamental limit on quantum technologies?

Q: Why is the cutoff soft?
A: A hard cutoff cuts the integrals sharply up to a momentum scale 1/epsilon. The epsilon we introduced is equivalent to an exponential taper in the cutoff (higher frequencies are suppressed by Exp(-\epsilon omega))

Q: Why is the cutoff soft?
A: The Wightman function dies like 1/q^2. A singularity at the origin arises because there is too much weight at the high momenta end of the Fourier transform. This can be remedied in Fourier space by using e^{-\epsilon q}/q^2 instead of 1/q^2. This kills off exponentially the large momenta (cutting off). The larger \epsilon is, the smaller the cutoff. To get the Wightman function we integrate the Fourier transform with this exponential tail. Then the \epsilon shows up in the denominator, controlling the size of the divergence at the origin t'=t, x'=x.