DECOHERENCE ~FROM QUANTUM THEORIES TO GRAVITY~

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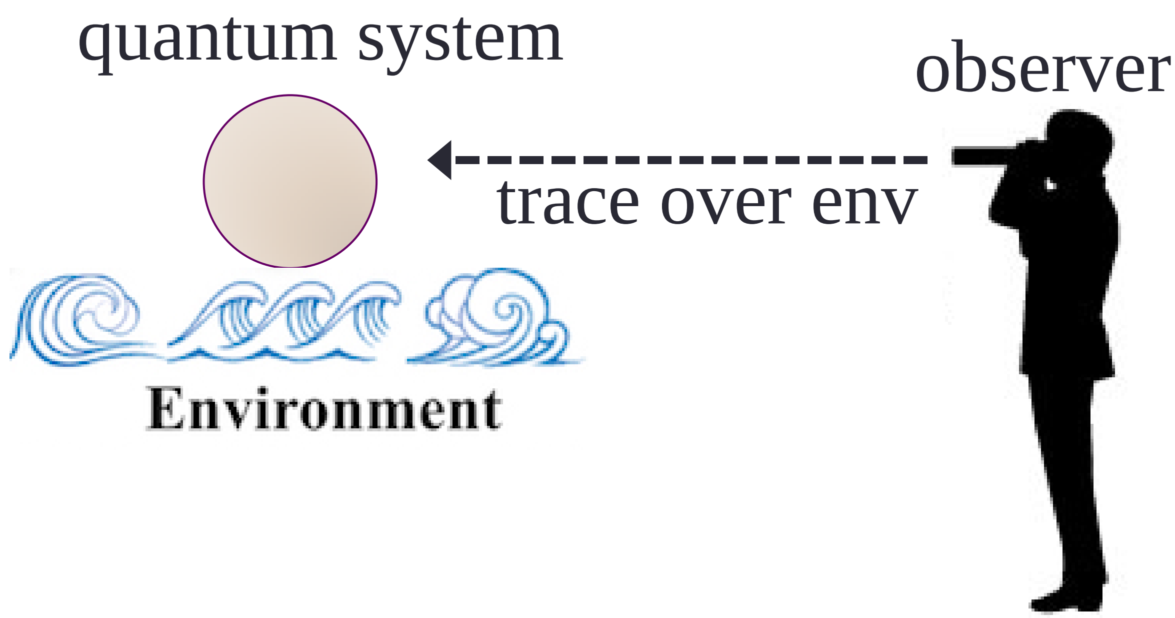
What is decoherence?



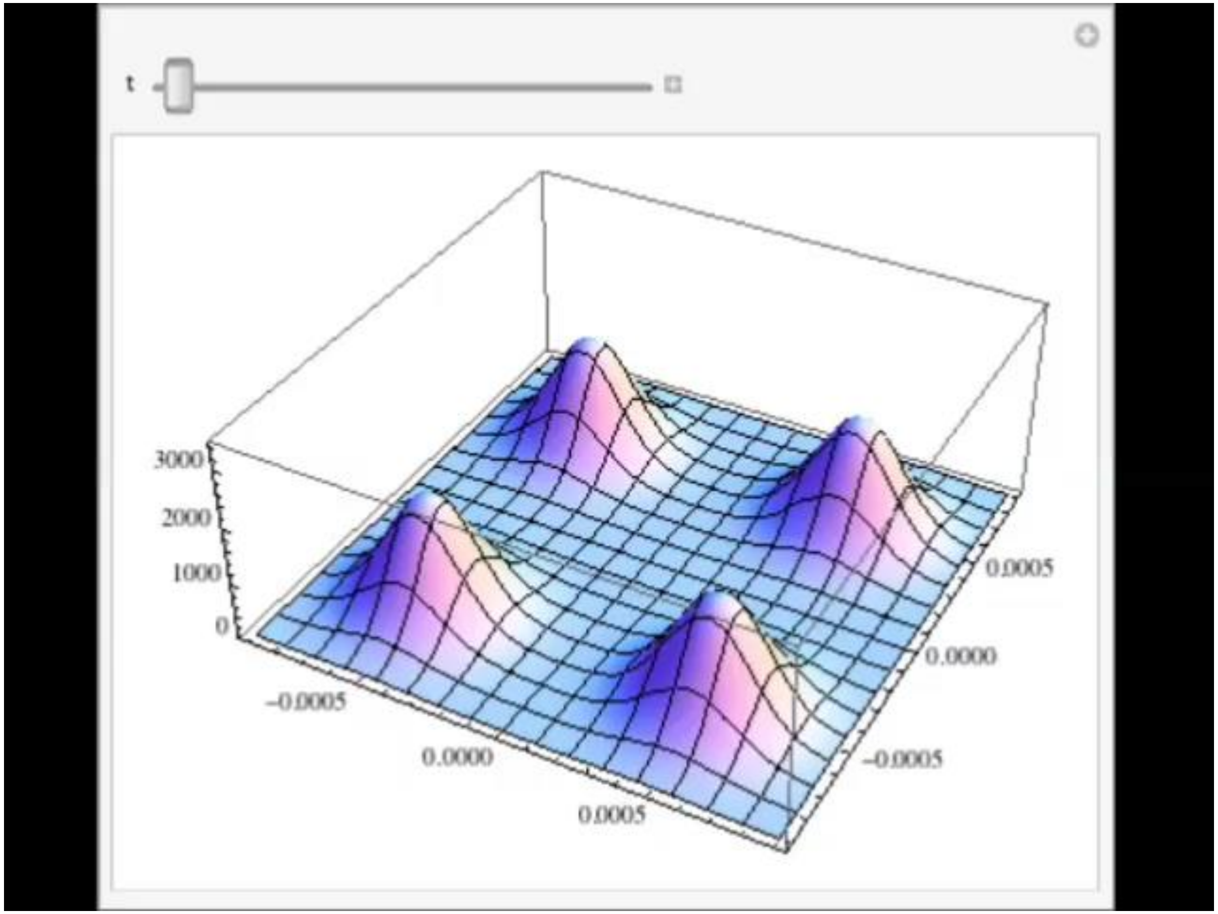
density matrix

reduced density matrix

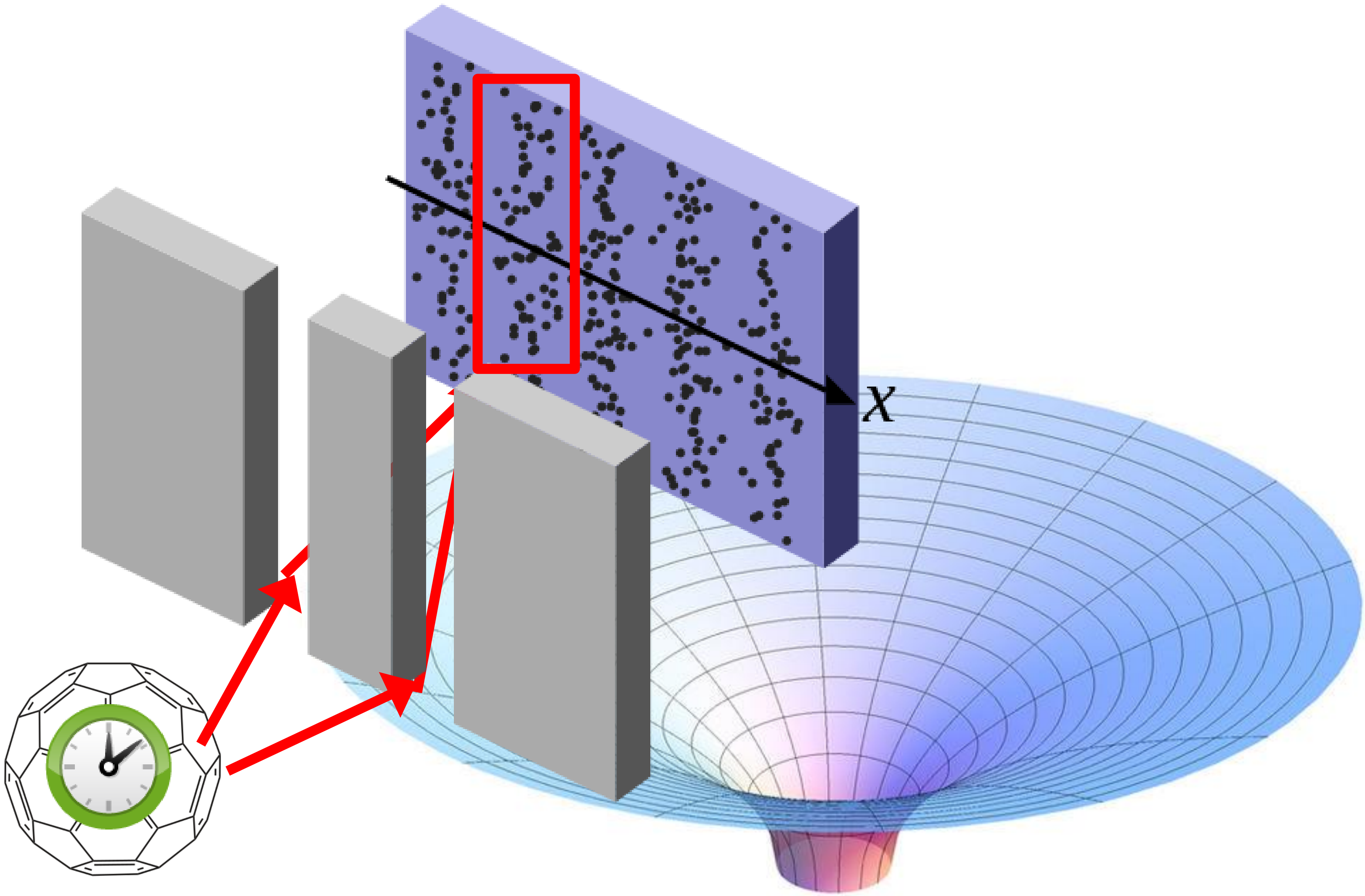
$$\rho \xrightarrow{\text{trace over env}} \rho_{red}$$

$$-\mathrm{tr}(\rho_{red} \ln \rho_{red}) \neq 0$$

Oscillator bath model

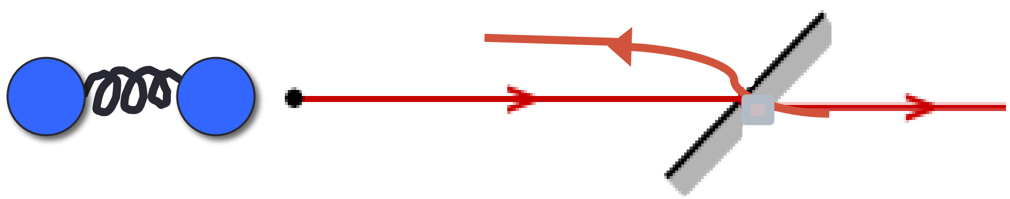


Internal degrees of freedom (internal clock)



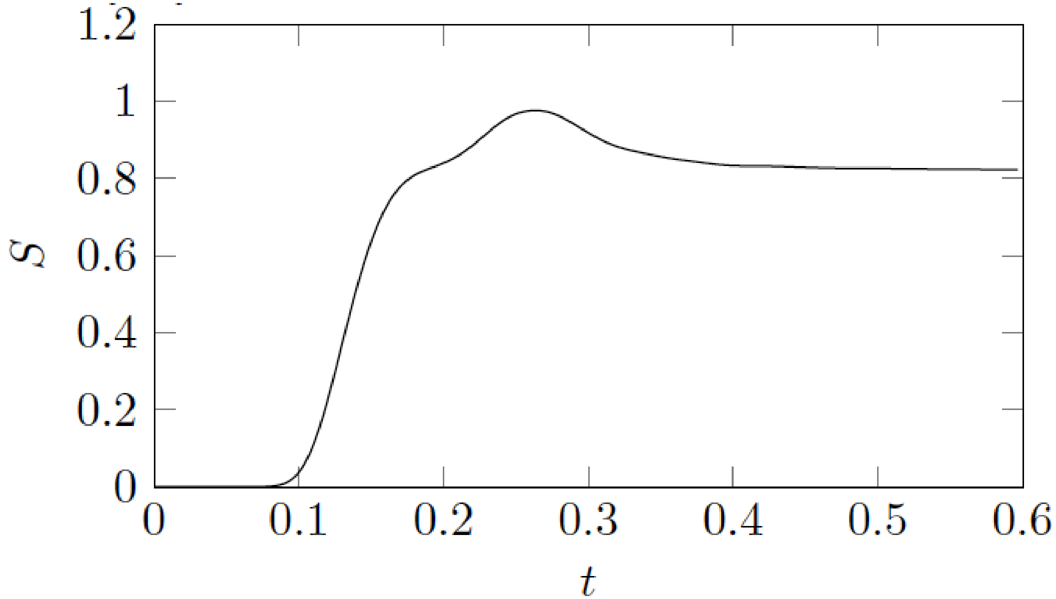
Proper time difference

Internal degrees of freedom



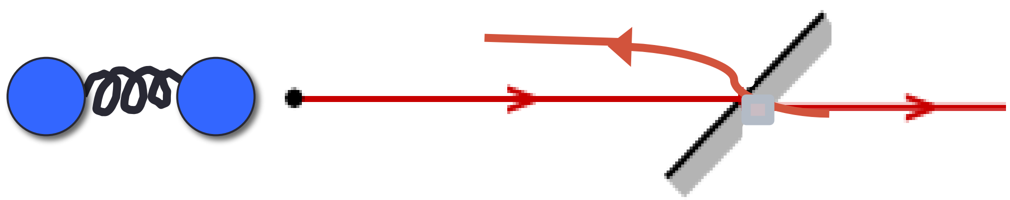
$$S = -\mathrm{tr}(\hat{\rho}_{\mathrm{cm}} \ln \hat{\rho}_{\mathrm{cm}}) = -\mathrm{tr}(\hat{\rho}_{\mathrm{rel}} \ln \hat{\rho}_{\mathrm{rel}})$$

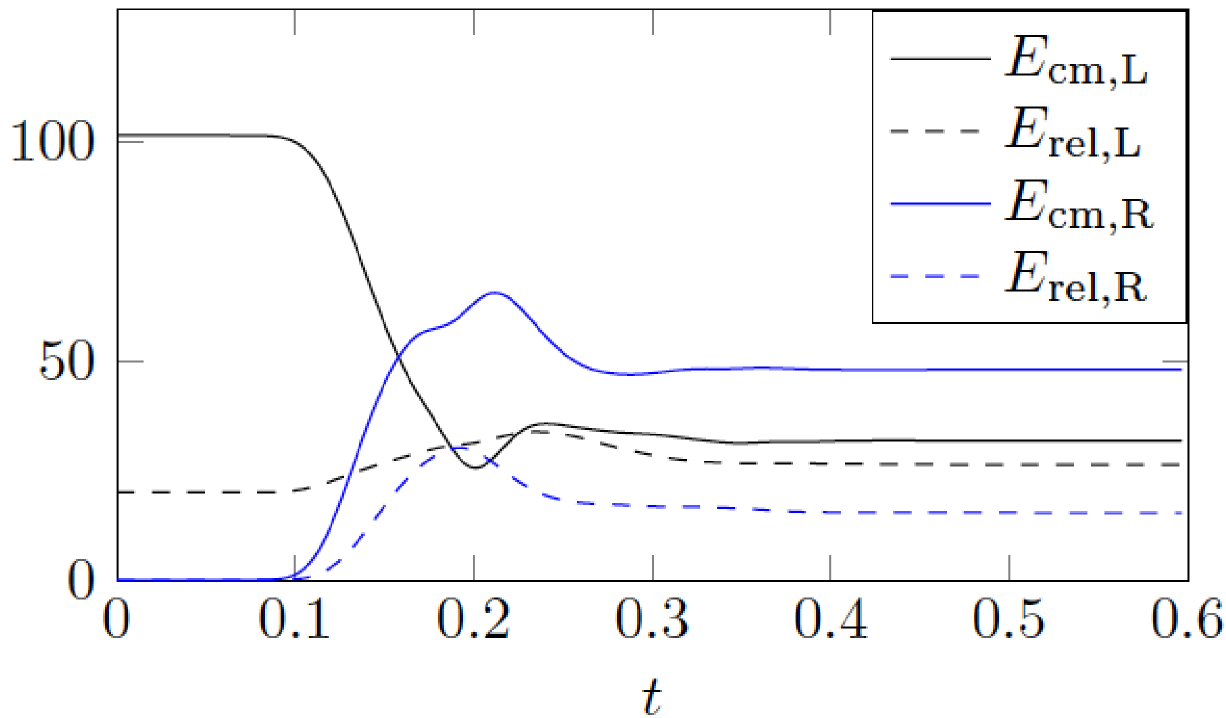
$$\rho_{\mathrm{rel}} = \int_{-\infty}^{\infty} dx_{\mathrm{cm}} \Psi^*(x_{\mathrm{cm}}, x_{\mathrm{rel}}) \Psi(x_{\mathrm{cm}}, x'_{\mathrm{rel}})$$



Friedemann Queisser and W. G. Unruh, arXiv:1503.08814 (2015)

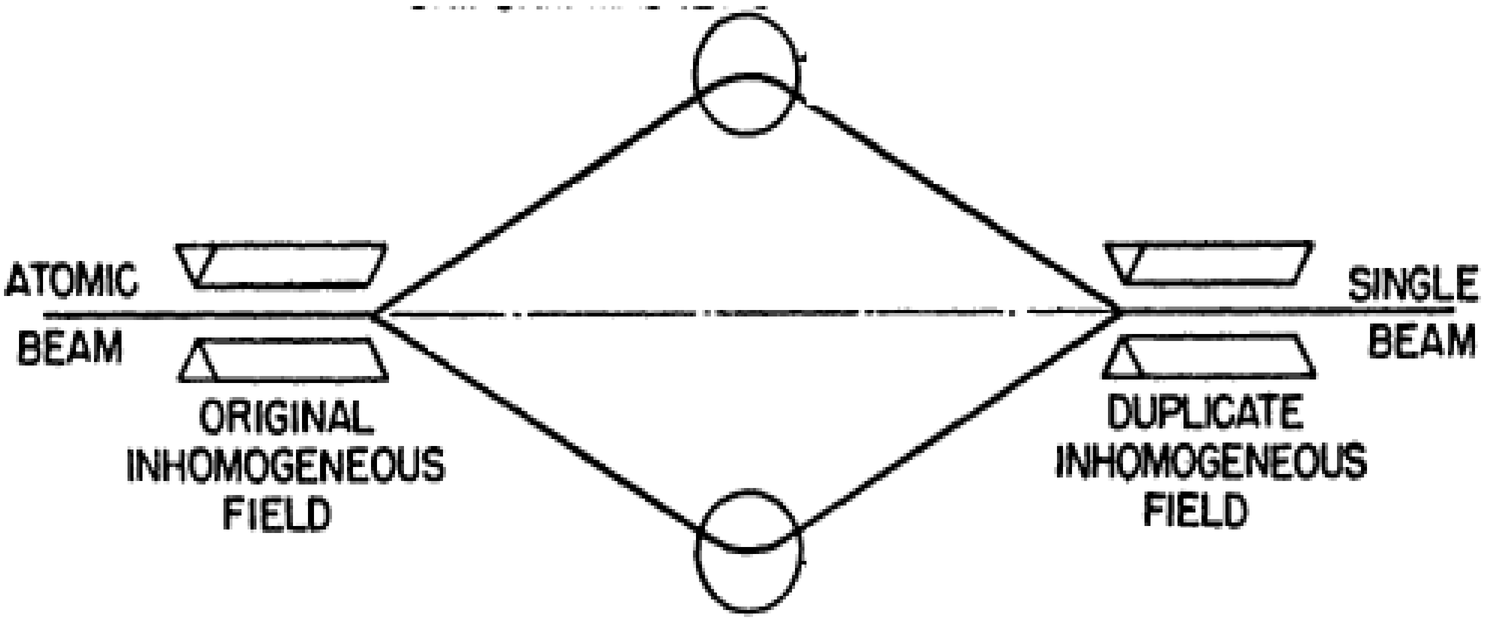
Internal degrees of freedom





Friedemann Queisser and W. G. Unruh, arXiv:1503.08814 (2015)

Reversible Stern-Gerlach apparatus



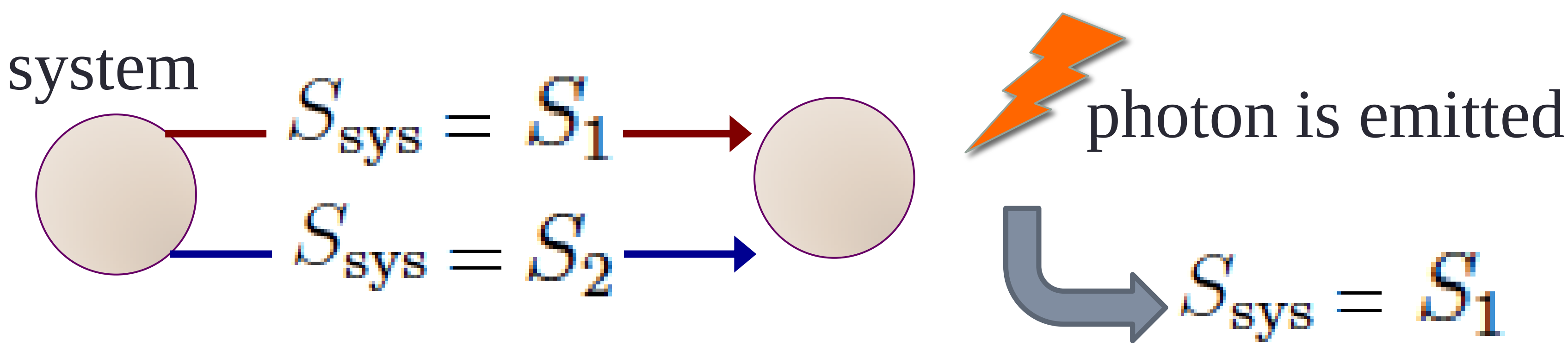
D. Bohm, Quantum Theory (Prentice-Hall, 1951)

QED (Photon bath)

$$S = S_{\text{sys}} + S_{\text{int}} + S_{\text{photon}}$$

$$S_{\text{photon}} = -\frac{1}{4}\int d^4r F^{\mu\nu}F_{\mu\nu}$$

$$S_{\text{int}} = \int d^4r J^{\mu}A_{\mu}$$



QED (Reduced density matrix propagator)

$$W(x_{\mathrm{i}}, x_{\mathrm{f}}; x'_{\mathrm{i}}, x'_{\mathrm{f}})$$
$$= \int_{x_{\mathrm{i}}}^{x_{\mathrm{f}}} \mathcal{D}x \int_{x'_{\mathrm{i}}}^{x'_{\mathrm{f}}} \mathcal{D}x' \exp(i\, S_{\mathrm{sys}}(x) - i\, S_{\mathrm{sys}}(x'))\mathcal{F}(x, x')$$

where the influence functional is

$$\mathcal{F}(\mathrm{x}, \mathrm{x}') = \exp\Bigg[-\frac{i}{2}\int_0^T d^4 r \int d^3 \mathbf{r}' \frac{\rho(\mathbf{r}, t)\rho(\mathbf{r}', t)}{4\pi|\mathbf{r}-\mathbf{r}'|} + \frac{i}{2}\int_0^T d^4 r' \int d^3 \mathbf{r}' \frac{\rho'(\mathbf{r}, t)\rho'(\mathbf{r}', t)}{4\pi|\mathbf{r}-\mathbf{r}'|}$$
$$+\frac{i}{2}\int_0^T d^4 r \int_0^t d^4 r' [J^i(r) + J'^i(r)]\gamma_{ij}(r-r')[J^j(r') - J'^j(r')]$$
$$-\frac{1}{4}\int_0^T d^4 r \int_0^t d^4 r' [J^i(r) - J'^i(r)]\eta_{ij}(r-r')[J^j(r') - J'^j(r')]\Bigg]$$

with the correlation functions $\eta_{ij}(r-r') = P_{ij} \int \frac{d^3\mathbf{k}}{(2\pi)^3|\mathbf{k}|} \cos(|\mathbf{k}|(t-t'))e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')}$

$$\gamma_{ij}(r-r') = P_{ij} \int \frac{d^3\mathbf{k}}{(2\pi)^3|\mathbf{k}|} \sin(|\mathbf{k}|(t-t'))e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')}$$

QED (Influence functional)

$$\mathcal{F}(\mathrm{x},\mathrm{x}') = \exp\Bigg[-\frac{i}{2}\int_0^T d^4r \int d^3\mathrm{r}' \frac{\rho(\mathrm{r},t)\rho(\mathrm{r}',t)}{4\pi|\mathrm{r}-\mathrm{r}'|} + \frac{i}{2}\int_0^T d^4r' \int d^3\mathrm{r}' \frac{\rho'(\mathrm{r},t)\rho'(\mathrm{r}',t)}{4\pi|\mathrm{r}-\mathrm{r}'|}$$

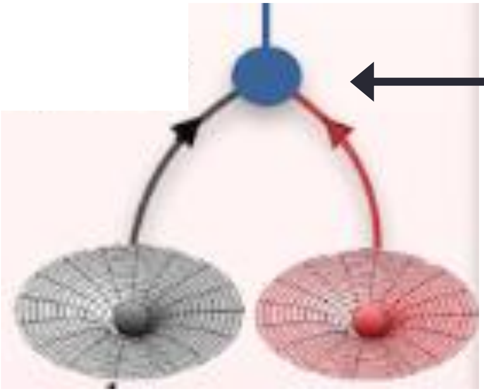
$$\boxed{+\frac{i}{2}\int_0^T d^4r \int_0^t d^4r' [J^i(r) + J'^i(r)]\gamma_{ij}(r-r')[J^j(r') - J'^j(r')]}$$

dissipation

$$\boxed{-\frac{1}{4}\int_0^T d^4r \int_0^t d^4r' [J^i(r) - J'^i(r)]\eta_{ij}(r-r')[J^j(r') - J'^j(r')]}\Bigg]$$

decoherence

False loss of coherence



Coherence is restored again

Reduced density matrix loses its coherence

W. G. Unruh, In Relativistic quantum measurement and decoherence, eds H. P. Breuer and F. Petruccione (2000)

Linearized gravity (Graviton bath)

$$S = S_{\mathrm{sys}} + S_{\mathrm{int}} + S_{\mathrm{grav}}$$

$$S_{\mathrm{grav}}(h_{\mu\nu}) = \int d^4r \Big[-\frac{1}{2}\partial_\rho h_{\mu\nu}\partial^\rho h^{\mu\nu} + \partial_\rho h_{\mu\nu}\partial^\nu h^{\mu\rho} - \partial_\nu h^{\mu\nu}\partial_\mu h + \frac{1}{2}\partial^\mu h \partial_\mu h \Big],$$

$$S_{\mathrm{int}}(h_{\mu\nu}, T_{\mu\nu}) = \frac{\kappa}{2}\int d^4r\, h_{\mu\nu}T^{\mu\nu}$$

$$\kappa = (32\pi G)^{1/2}$$

F. S. and Friedemann Queisser, J. Phys.: Conf. Ser. 626, 012039 (2015)

Linearized gravity (Influence functional)

$$\mathcal{F}(x,x')$$

$$= \exp\Big[\Phi(T_{00,\mathbf{x}};T^{00}_{\mathbf{x}}) - \Phi(T_{00,\mathbf{x}'};T^{00}_{\mathbf{x}'}) + \Phi(T^{i}{}_{i,\mathbf{x}};T^{00}_{\mathbf{x}}) - \Phi(T^{i}{}_{i,\mathbf{x}'};T^{00}_{\mathbf{x}'}) + \Phi(T_{i0,\mathbf{x}};T^{i0}_{\mathbf{x}}) - \Phi(T_{i0,\mathbf{x}'};T^{i0}_{\mathbf{x}'})$$

$$+\Phi(T_{0i,\mathbf{x}};T^{0i}_{\mathbf{x}}) - \Phi(T_{0i,\mathbf{x}'};T^{0i}_{\mathbf{x}'}) + \Phi(T_{00,\mathbf{x}};T^{i}{}_{i,\mathbf{x}}) - \Phi(T_{00,\mathbf{x}'};T^{i}{}_{i,\mathbf{x}'}) + \Phi(T^{i}{}_{i,\mathbf{x}};T^{i}{}_{i,\mathbf{x}}) - \Phi(T^{i}{}_{i,\mathbf{x}'};T^{i}{}_{i,\mathbf{x}'})$$

$$+i\int_0^{\mathrm{T}} d^4r \int_0^t d^4r' (T^{ij}_{\mathbf{x}}(r) + T^{ij}_{\mathbf{x}'}(r))\gamma_{ij,kl}(r-r')(T^{kl}_{\mathbf{x}}(r') - T^{kl}_{\mathbf{x}'}(r'))$$

$$-\int_0^{\mathrm{T}} d^4r \int_0^t d^4r' (T^{ij}_{\mathbf{x}}(r) - T^{ij}_{\mathbf{x}'}(r))\eta_{ij,kl}(r-r')(T^{kl}_{\mathbf{x}}(r') - T^{kl}_{\mathbf{x}'}(r'))\Big]$$

dissipation & dec
by grav waves

$$\Phi(T_{\mu\nu,\mathbf{x}};T^{\mu\nu}_{\mathbf{x}}) \propto -iG\int d^4r\int d^3\mathbf{r}'\,\frac{T_{\mu\nu,\mathbf{x}}(\mathbf{r}',t')T^{\mu\nu}_{\mathbf{x}}(\mathbf{r},t)}{|\mathbf{r}-\mathbf{r}'|}$$

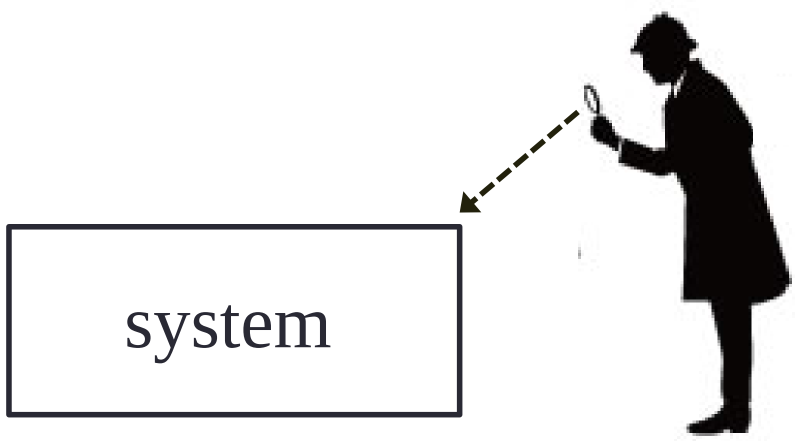
with the correlation functions

$$\gamma_{ij,kl}(r-r') = \frac{G}{4\pi^2}\int\frac{d^3k}{|\mathbf{k}|}\sin(|\mathbf{k}|(t-t'))e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')}\Pi_{ij,kl}(\mathbf{k}),$$

$$\eta_{ij,kl}(r-r') = \frac{G}{4\pi^2}\int\frac{d^3k}{|\mathbf{k}|}\cos(|\mathbf{k}|(t-t'))e^{i\mathbf{k}\cdot(\mathbf{r}-\mathbf{r}')}\Pi_{ij,kl}(\mathbf{k})$$

External observer/internal observer

QM/QFT/QED: Measurements are made from the outside

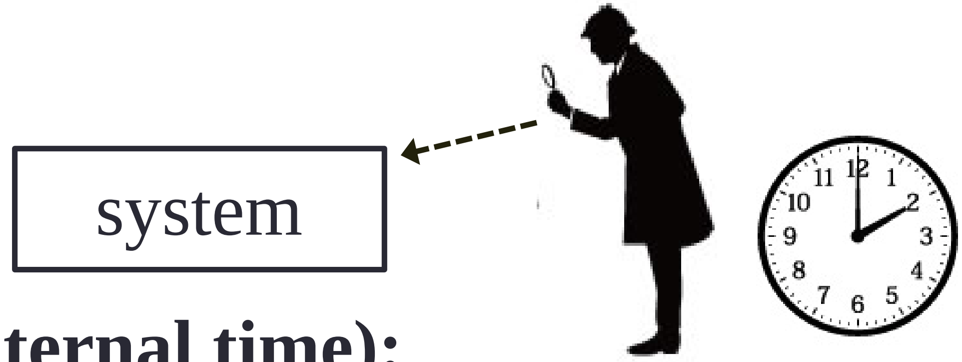


Gravity: Measurements are made from the inside

External time/internal time

QM/QFT/QED/Newtonian physics (external time):

Time flows equably from place to place

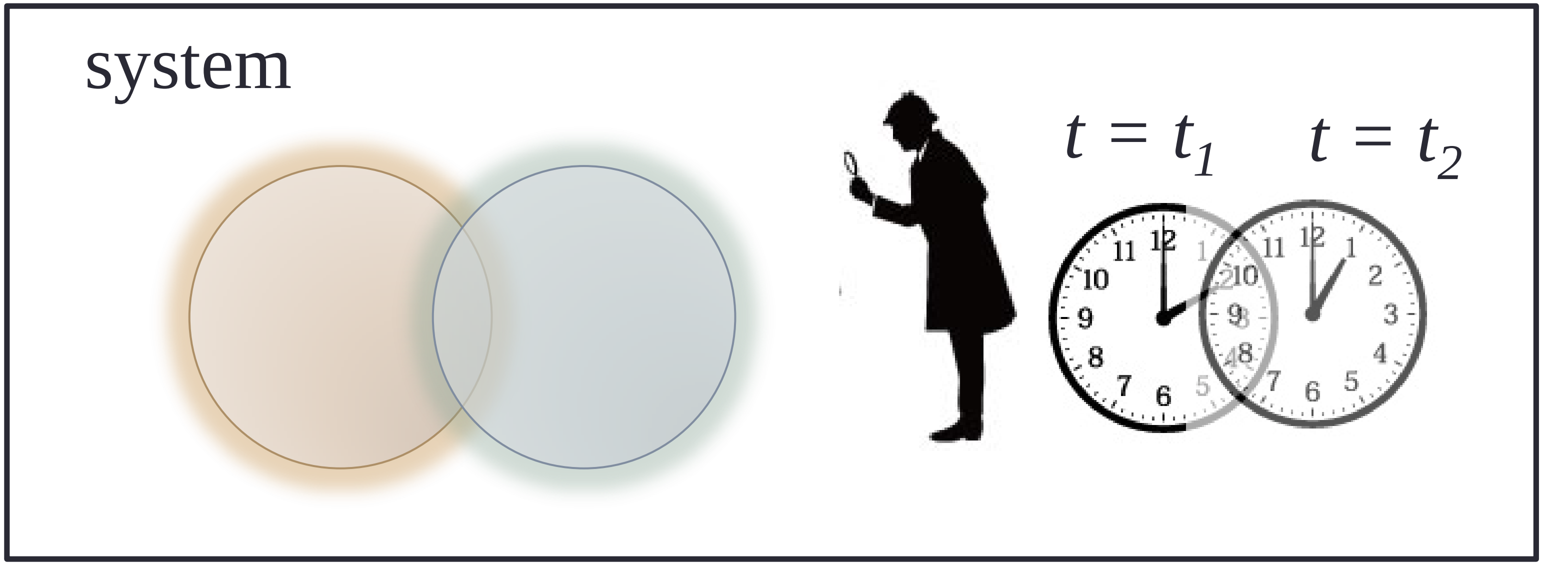


Gravity (internal time):

Inequable flow of time from place to place

Time arises from interactions of matters

Penrose problem



? Question

$$i\hbar \frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \hat{H}\Psi(\mathbf{r},t) \qquad t = t_1 \;\; or \;\; t_2 \;\; ??$$

Decoherence in QFT

$$L_j(x,\dot{x},t) = \tfrac{1}{2}(\dot{x}^2 - \omega^2 x^2) + x\, j(t)$$

Noise

$$\mathcal{L}_j(\mathbf{x},t) = \tfrac{1}{2}\partial_\mu\phi(\mathbf{x},t)\partial^\mu\phi(\mathbf{x},t) - \frac{m^2}{2}\phi^2(\mathbf{x},t) + j(\mathbf{x},t)\phi(\mathbf{x},t)$$

$$\rho_j(\phi,\phi';T) = \int \mathcal{D}\phi_0 \int \mathcal{D}\phi_0' \, W_j(\phi,T;\phi_0,0)\, W_j^*(\phi',T;\phi_0',0)\, \rho(\phi_0,\phi_0';0)$$

$$\rho(\phi_0,\phi_0';0)$$
$$= \frac{1}{N(\beta_0,m)} \exp\left[\int d\mathbf{k} \frac{-\omega_k}{2\sinh\beta_0\omega_k} \{[\phi_0(\mathbf{k})\phi_0(-\mathbf{k}) + \phi_0'(\mathbf{k})\phi_0'(-\mathbf{k})]\cosh\beta_0\omega_k - 2\phi_0(\mathbf{k})\phi_0'(-\mathbf{k})\} \right]$$

J. Cloutier and G. W. Semenoff, Phys. Rev. D 44, 3218 (1991)

Summary

❖Photon bath: dipole moment radiation➔real loss of coherence
Coulomb field ➔ false loss of coherence

❖Graviton bath: quadrupole moment radiation ➔ real
gravitational field➔ false in Newtonian limit?

? Interpretation of gravitational decoherence
with external/internal observer+time

? Decoherence in QFT?

Acknowledgements

Thank you for advices: G. W. Semenoff and W. G. Unruh
Thank you for support: Sasakawa Scientic Research Grant ,
the research foundation for opto-science and technology