Title: Unruh-DeWitt detectors in RQI: from the basics to frontiers

Date: May 26, 2015 02:00 PM

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Abstract: <p>In relativistic quantum information (RQI) we study quantum information in relativistic systems to obtain more insights to both quantum and gravitational physics on the one hand, and to find new ideas for quantum information processing on the other. One of the popular models in RQI is the Unruh-DeWitt (UD) detector theory, in which localized objects, called detectors, are coupled to and moving in relativistc quantum fields. In this mini-course I will discuss the UD detector theory in detail, mainly on the nonperturbative methods and their applications to RQI.</p>

<p> </p>

Spatially Local Projective Measurement in Relativistic Quantum Field Theory, and Quantum Teleportation between Twins

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Department of Physics and Astronomy, University of Waterloo, and
Perimeter Institute for Theoretical Physics

May 26, 2015 @ PI

Spatially Local Measurement

- Dynamical variables of quantum fields could be essentially nonlocal in space:

$$\hat{H} = \int \frac{d^3k}{(2\pi)^3}\left[-\frac{\hbar^2}{2}(2\pi)^6 \frac{\delta}{\delta\phi_{\mathbf{k}}}\frac{\delta}{\delta\phi_{-\mathbf{k}}} + \frac{1}{2}\Omega^2_{\mathbf{k}}(\eta)\phi_{\mathbf{k}}\phi_{-\mathbf{k}}\right]$$

ϕ_k ~ plane waves

Q1: How to perform a spatially local measurement in a quantum field?

A1: One (perhaps the only one) possibility is to measure a point-like object coupled with the field, e.g. an Unruh detector or an atom. (Projective measurement in the interaction region.)

Q2: Are two post-measurement states measured in the same spatially local event but collapsed on different time-slices in different frames consistent?

A2: SYL, AOP327(2012)3102 [arXiv:1104.0772]

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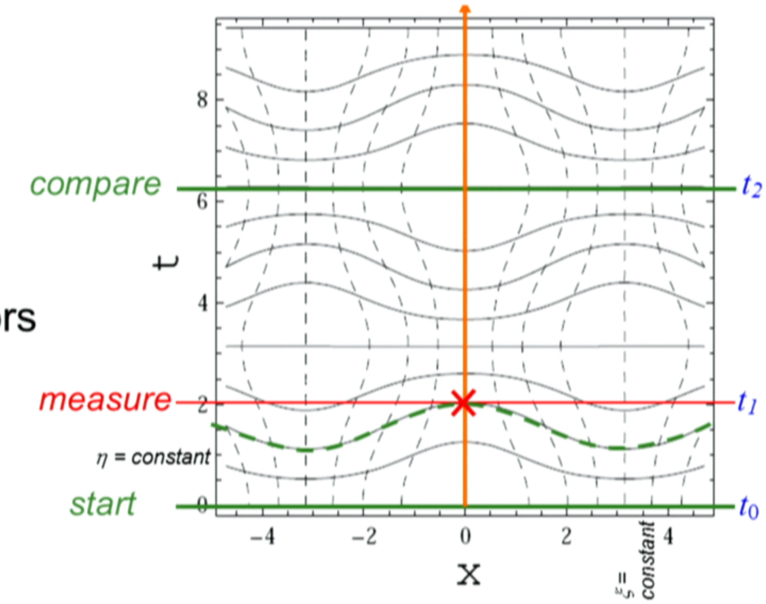
  Suffice to calculate the factors

  $\mathcal{Q}^{\mu\nu}$, $\mathcal{P}^{\mu\nu}$, $\mathcal{R}^{\mu\nu}$,

  at $t = t_2$, or equivalently, the evolution of the symmetric two-point correlators

  $\langle \phi_\mu, \phi_\nu \rangle$, $\langle \pi_\mu, \pi_\nu \rangle$, $\langle \pi_\mu, \phi_\nu \rangle$.



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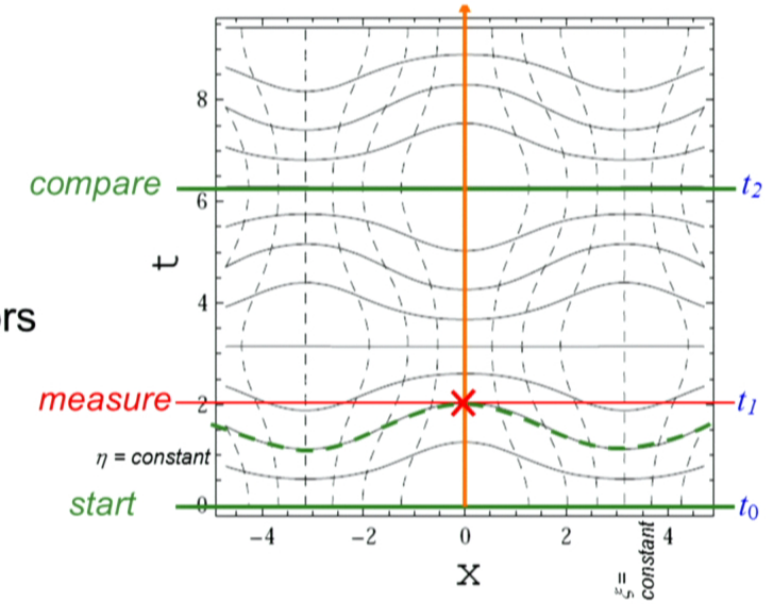

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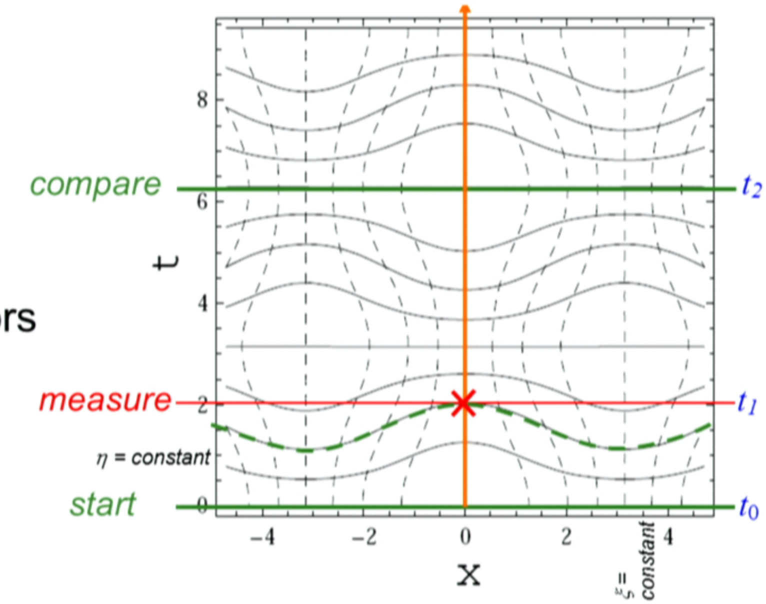

Spatially Local Measurement

- Examine the two-point correlators of the field at $t = t_2$ ($t_{mn} \equiv t_m - t_n$)

$\langle \hat{\Phi}_x, \hat{\Phi}_y \rangle_2 = \mathrm{Tr}\hat{\Phi}_x(t_{21})\hat{\Phi}_y(t_{21})\tilde{\rho}(\Phi, \Pi; t_1)$ depends only on

the mode functions corresponding to

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 localized in the point-like detector(s),
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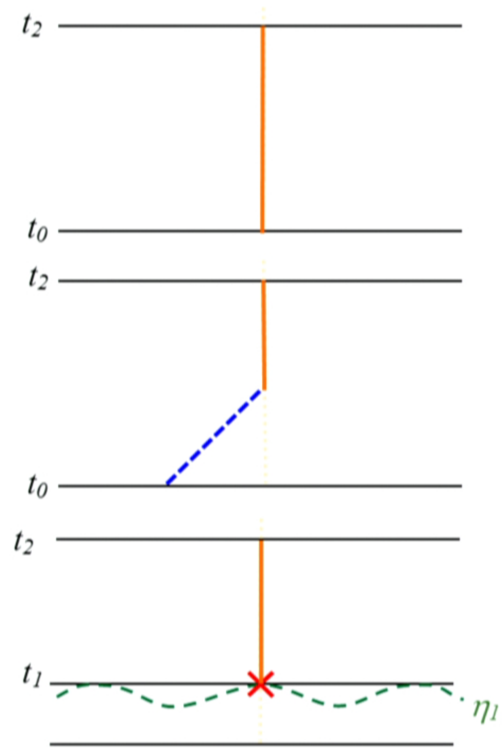

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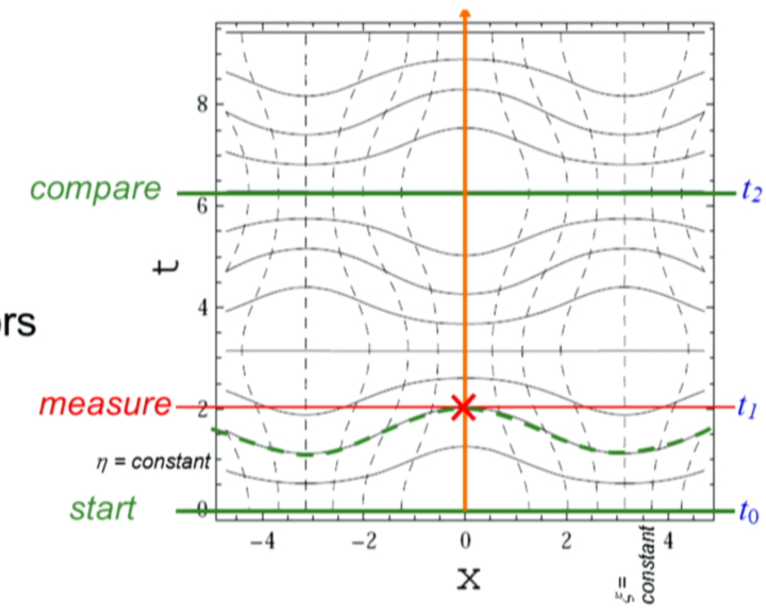

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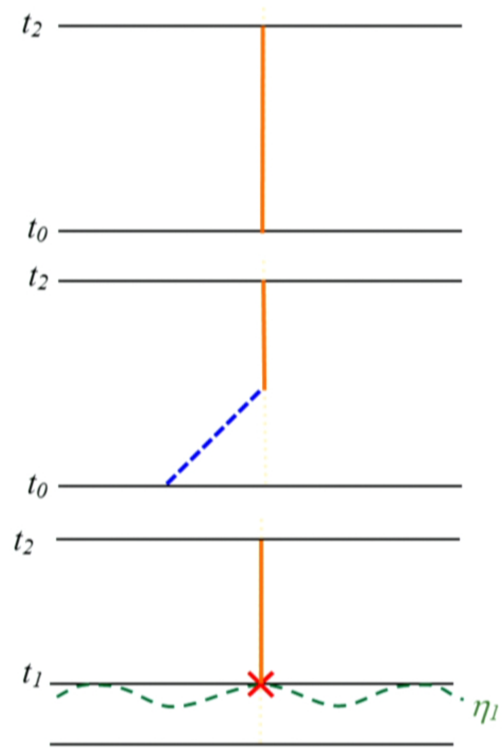

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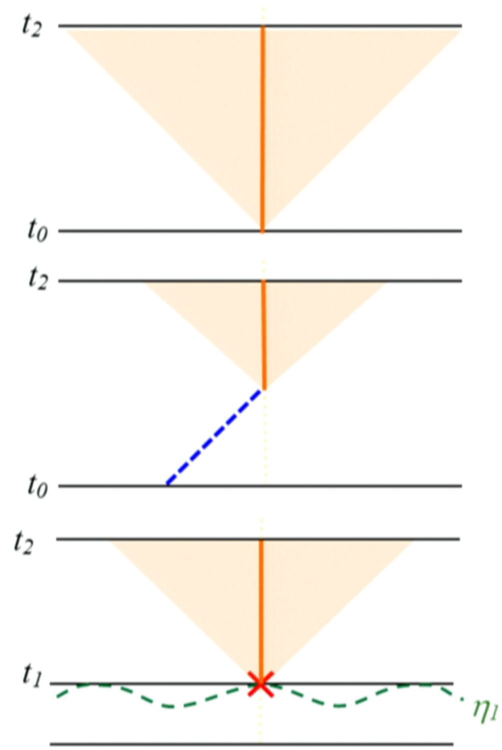
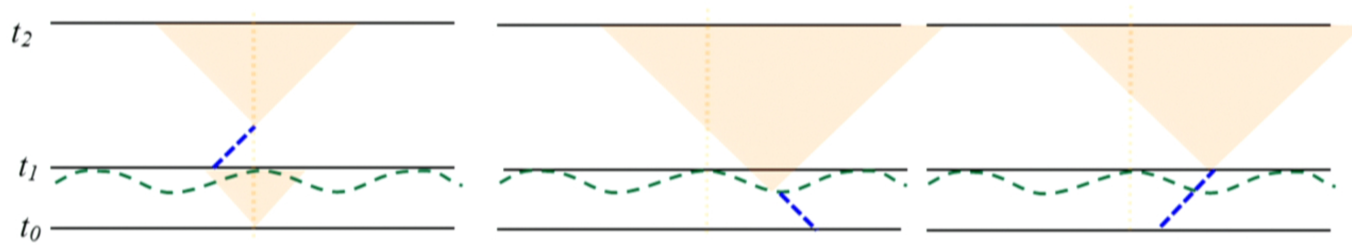


Spatially Local Measurement

No such kind of terms:



- Wave functional at t_2 is a function of explicitly *covariant* objects independent of the data on t_1 or τ_1 -slice outside the detector.
  So the wave functional in the alternative coord. at t_2 can be transformed to the conventional one under a spatial coord. transformation.

  → Each PMWF evolves to *the same* wave functional at $t = t_2$!

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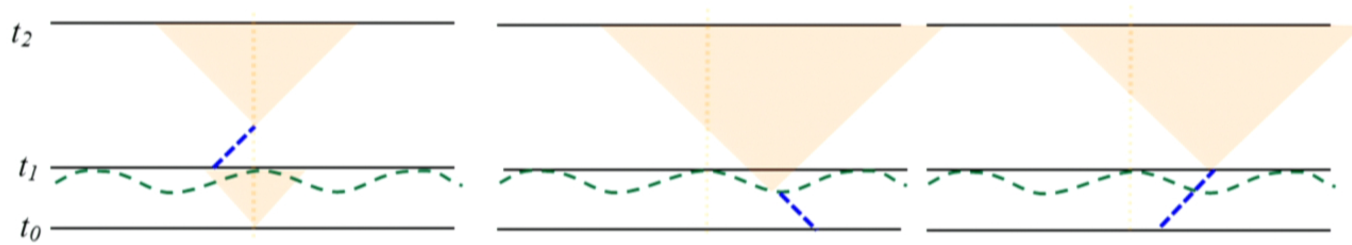

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Wave functionals collapsed by the same spatially localized measurement on different time slices in different reference frames will all evolve to the "same" field states, up to a coordinate transformation, when comparable.

(1) The spatial locality of interaction,
(2) the covariance of the mode- functions
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Quantum Teleportation: 2-Level System

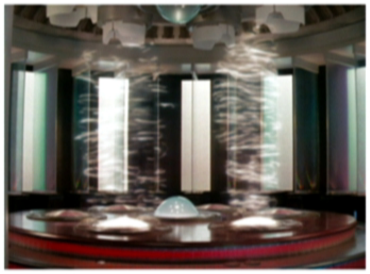
In-state

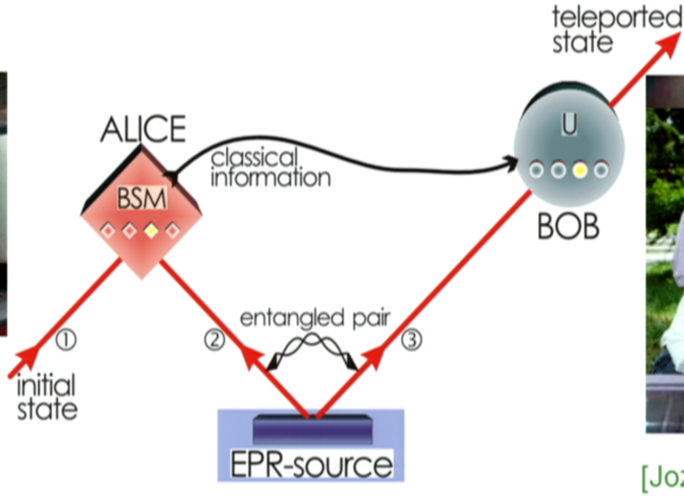
$$|\Phi\rangle_1 = \alpha|H\rangle_1 + \beta|V\rangle_1$$

Shared entangled pair

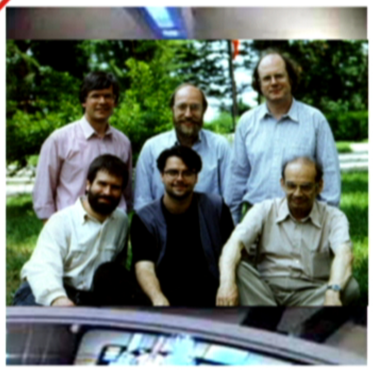
$$|\Phi^+\rangle_{23} = \frac{1}{\sqrt{2}}\left(|H\rangle_2|H\rangle_3 + |V\rangle_2|V\rangle_3\right)$$

$$\begin{aligned} |\Psi\rangle_{123} &= |\Phi\rangle_1 \otimes |\Phi^+\rangle_{23} \\ &= |\Phi^+\rangle_{12} \otimes \left(\alpha|H\rangle_3 + \beta|V\rangle_3\right) + \\ &\quad |\Phi^-\rangle_{12} \otimes \left(\alpha|H\rangle_3 - \beta|V\rangle_3\right) + \\ &\quad |\Psi^+\rangle_{12} \otimes \left(\alpha|V\rangle_3 + \beta|H\rangle_3\right) + \\ &\quad |\Psi^-\rangle_{12} \otimes \left(\alpha|V\rangle_3 - \beta|H\rangle_3\right) \end{aligned}$$





[Bouwmeeter, Pan, Mattle, Eibl, Weinfurter, Zeilinger, 1997]



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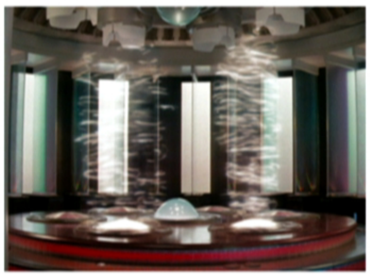

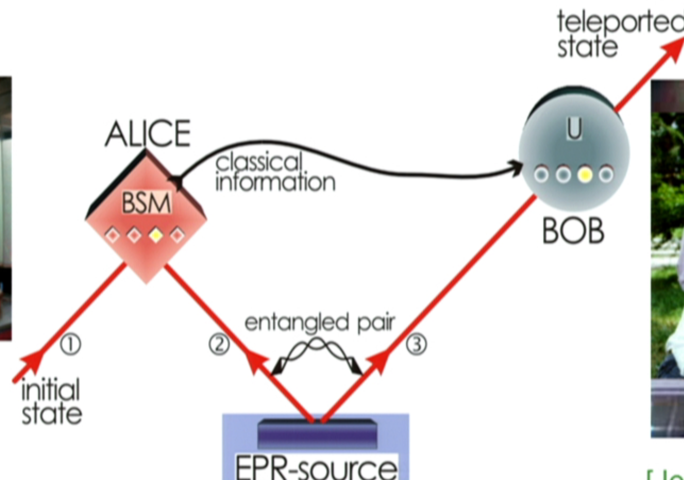

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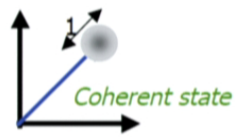
Quantum Teleportation: Continuous Variables

$$p'_3 = p_3 + b = p_1$$
$$q'_3 = q_3 + a = q_1$$

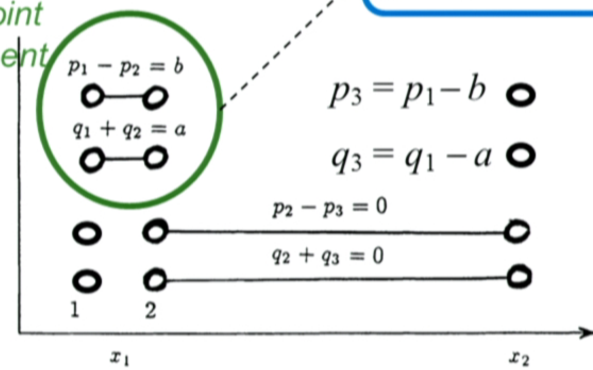
[Vaidman 1994]

In-state

$|q_1 + i\, p_1>$



Joint measurement



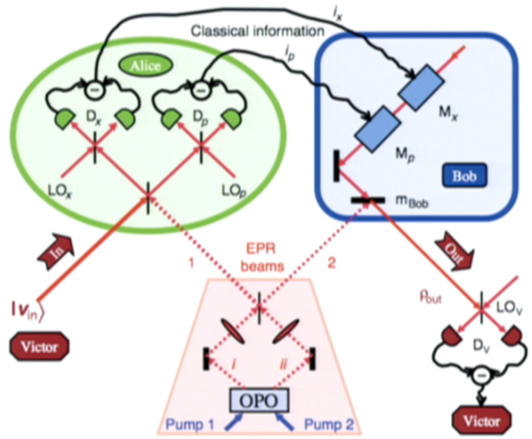
Shared entangled pair:

EPR state with

$q_2 + q_3 = 0,\ \ p_2 - p_3 = 0$

[Braunstein, Kimble 1998]

EPR state ⟶ Two-mode squeeze state



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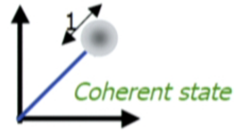

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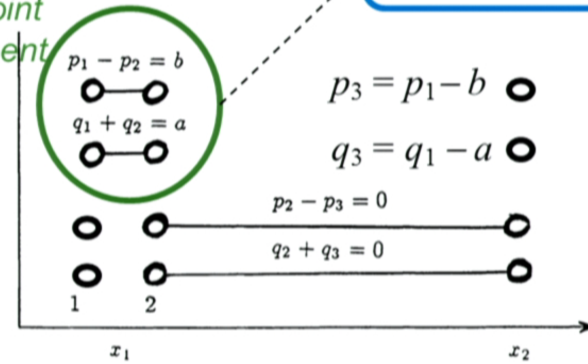

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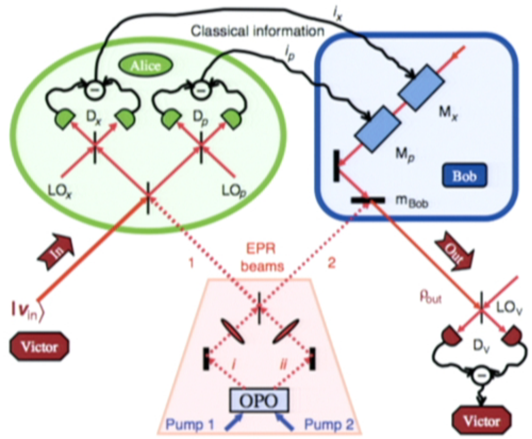

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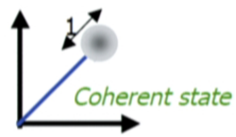

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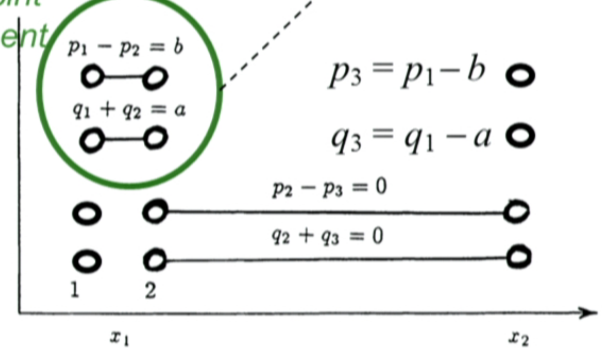

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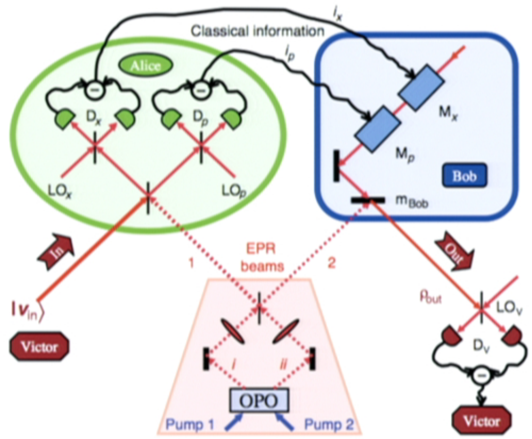

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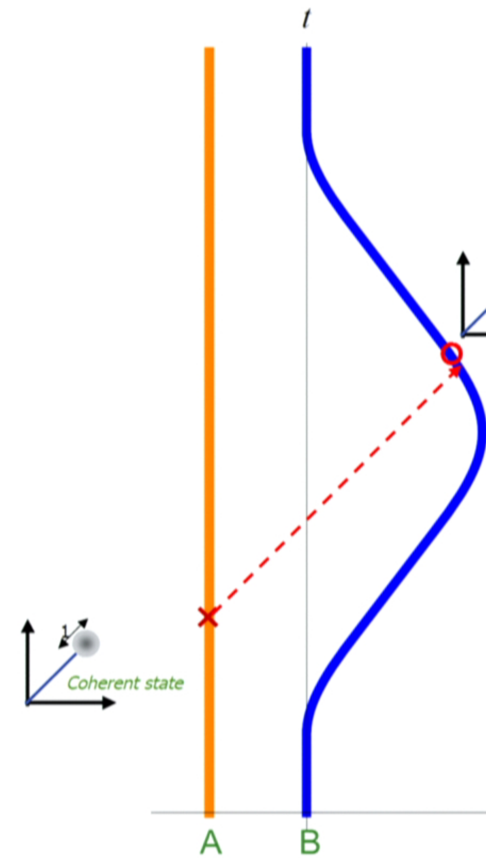
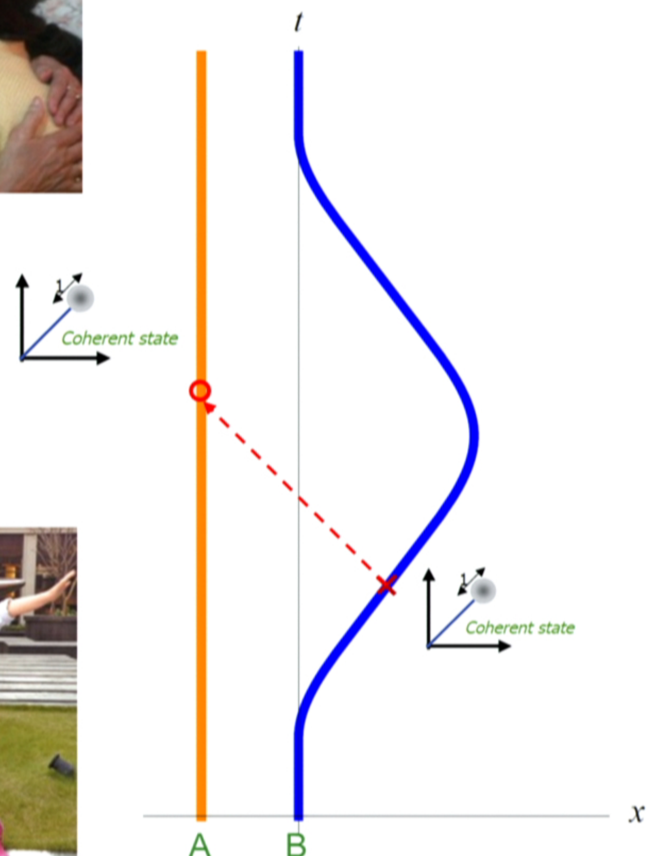
Quantum Teleportation between the Twins (Relativistic)

from Alice to Bob



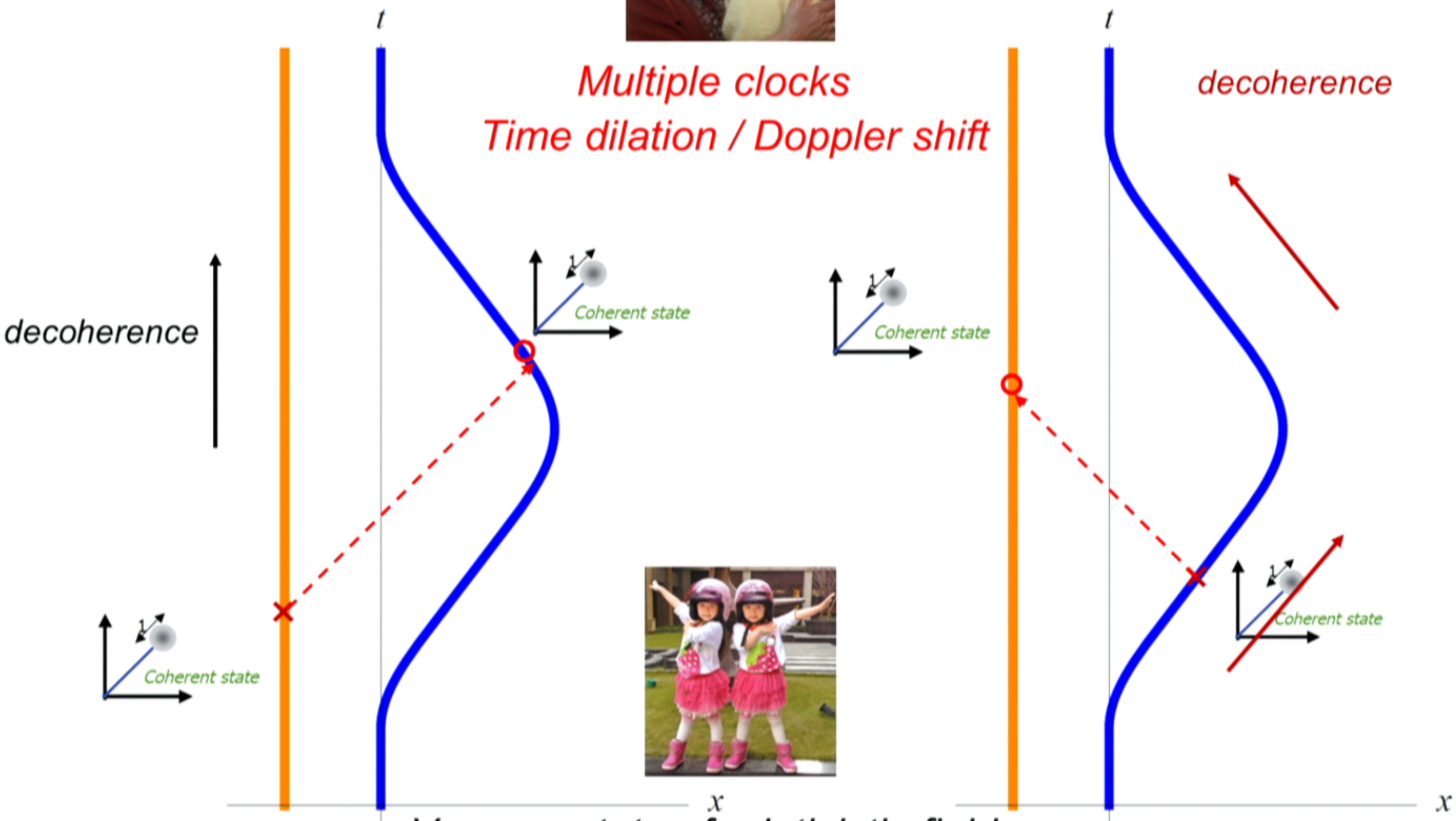
from Bob to Alice



Quantum Teleportation between the Twins in Vacuum

from Alice to Bob

from Bob to Alice



Vacuum state of relativistic fields

Quantum Teleportation between the Twins in Vacuum

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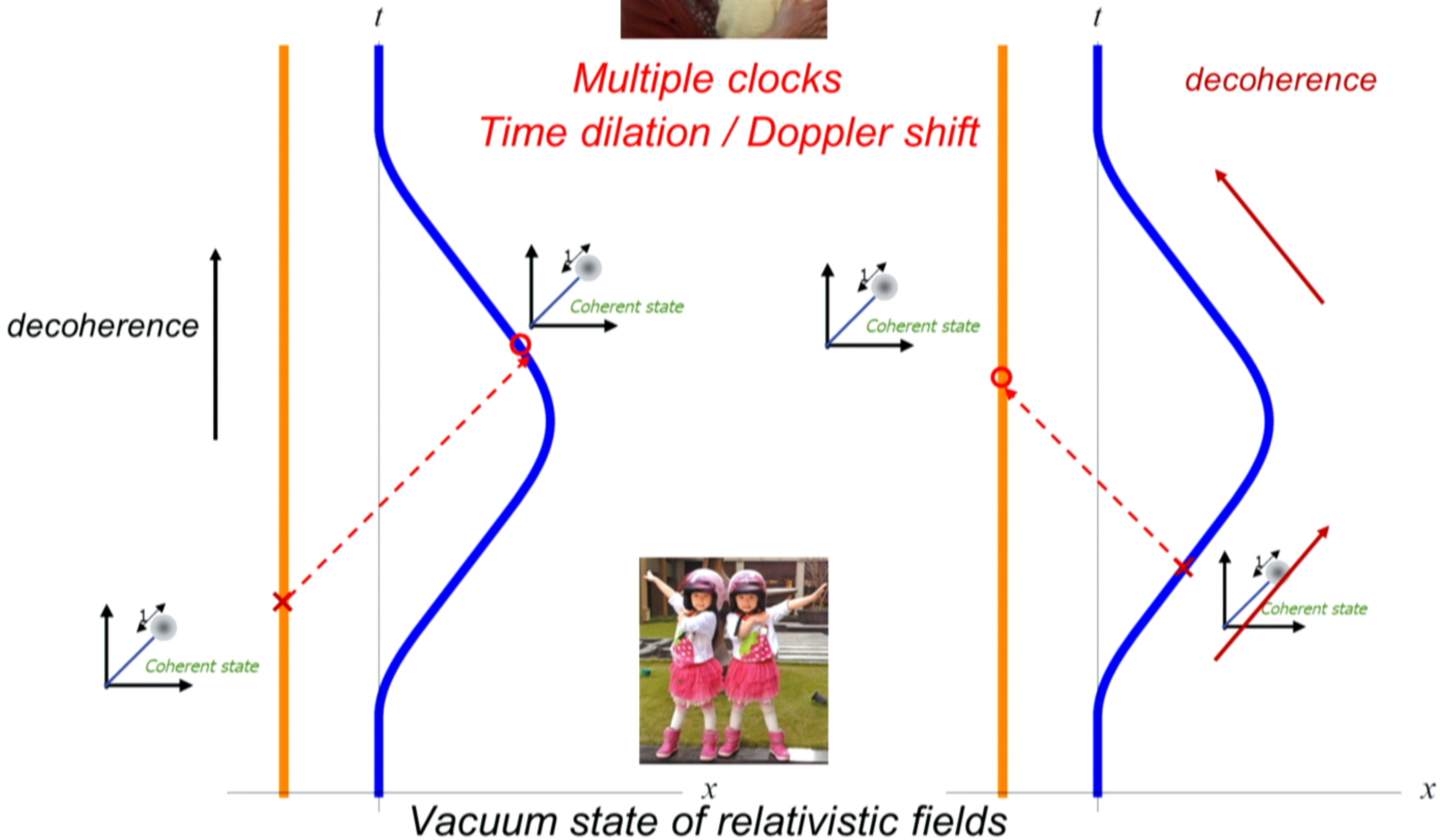
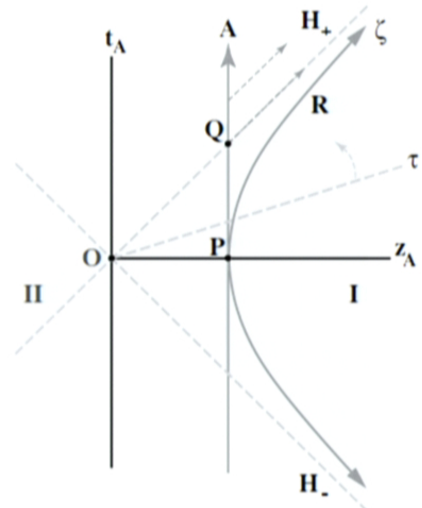


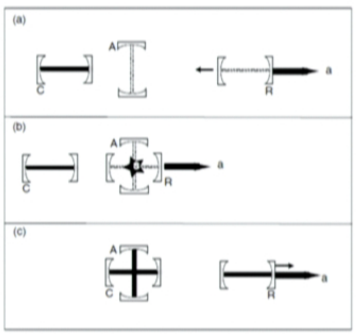
Alice-Rob problem [Alsing, Milburn PRL91(2003)180404]

"The fidelity of the teleportation is reduced due to Davies-Unruh radiation in Rob's frame"

does NOT imply

a) Fidelity of QT does not decrease in inertial motion,





(field + cavities in relativistic motion)

[Also see Schützhold, Unruh quant-ph/0506028]

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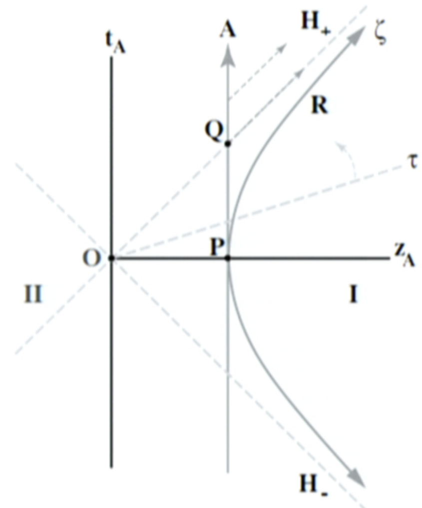
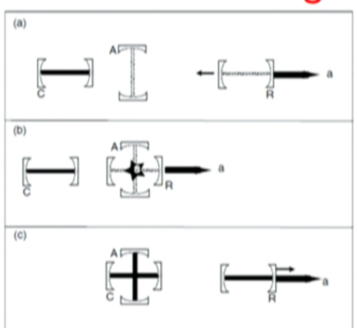
b) A larger acceleration (higher Unruh temperature) leads to a larger degradation rate in time.





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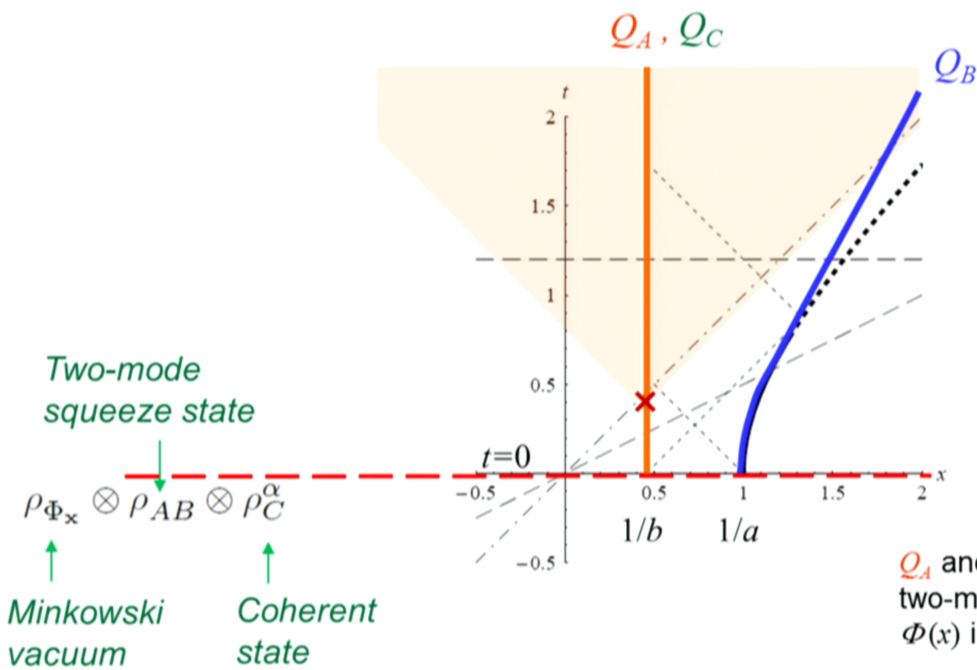
Alice-Rob Problem: Start

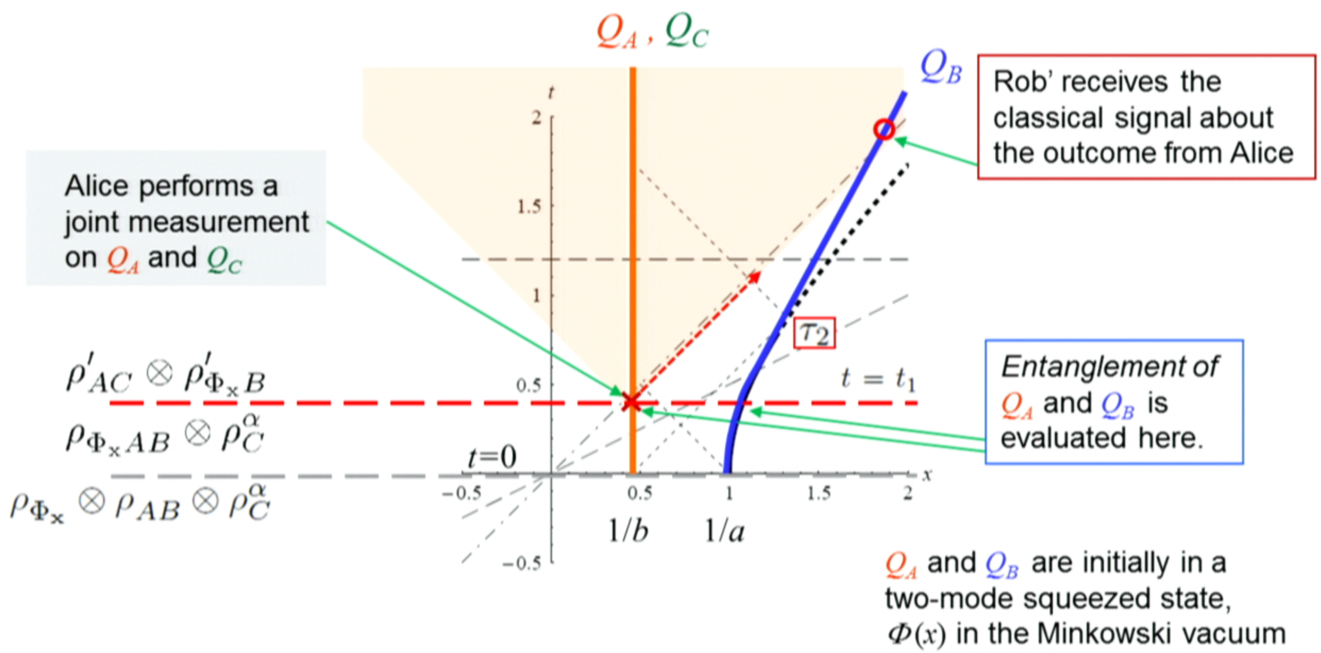
Teleport an unknown coherent state of Q_C from Alice to Rob



Q_A and Q_B are initially in a two-mode squeezed state, $\Phi(x)$ in the Minkowski vacuum

Alice-Rob Problem: Measure and Send

Teleport an unknown coherent state of Q_C from Alice to Rob



Alice-Rob Problem: Operation

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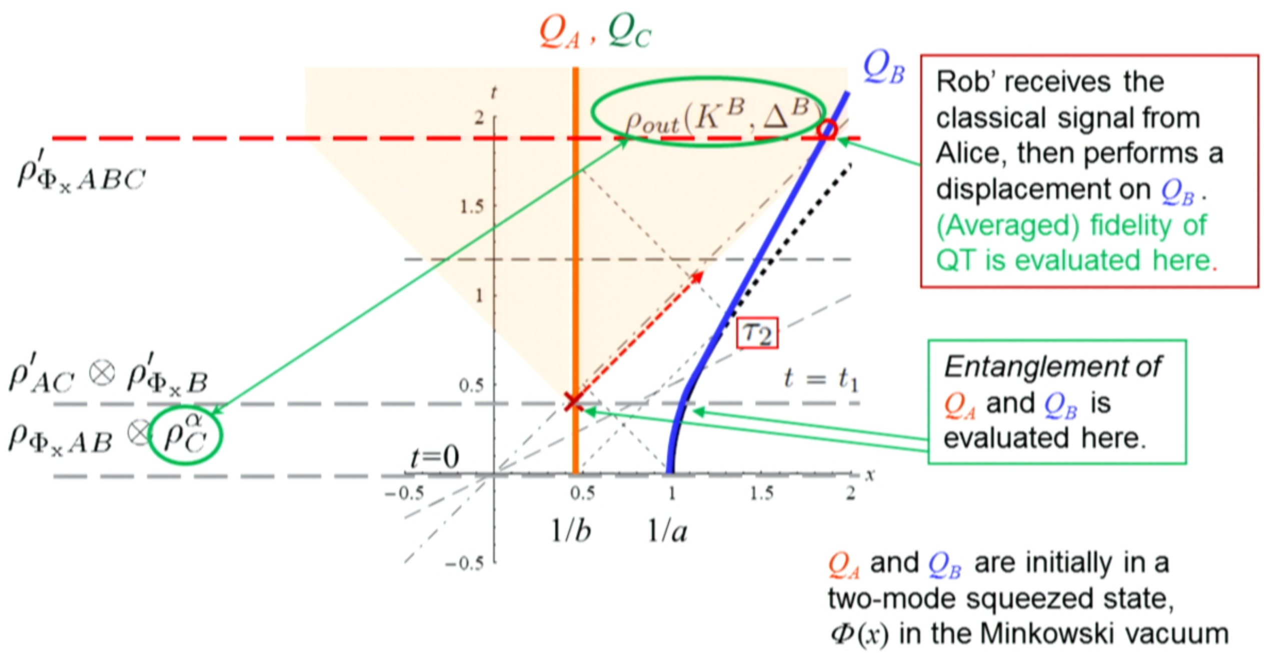


Alice-Rob Problem: Fidelity of Quantum Teleportation

Upper bound for fidelity of QTelep [Mari, Vitali PRA78('09)062340]

Theorem 1 (Upper bound). *For a given Gaussian bipartite state shared by Alice and Bob, with lowest PT symplectic eigenvalue ν, the fidelity of the teleportation of a coherent state is limited from above by*

$$\mathcal{F}_{opt} \leq \frac{1}{1+\nu}. \quad (< 1/2 \text{ if } \nu > 1)$$

$F_{cl} = 1/2$: Fidelity of classical teleportation

Entanglement : logarithmic negativity $E_{\mathcal{N}} = \max[0, -\ln \nu]$ (= 0 if $\nu > 1$)

~ correlation between two DOF on the same time-slice

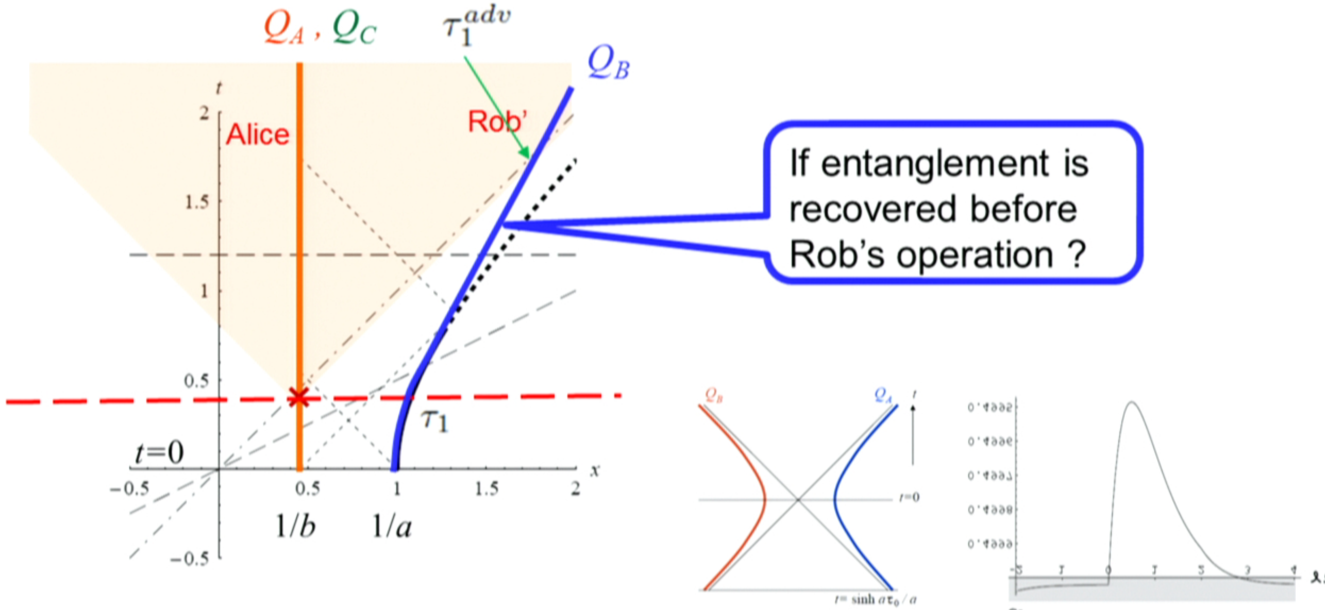
(i.e. spacelike separated DOFs)

Fidelity of QT ~ kind of auto-correlation (timelike) between

Alice's joint-measurement event and Bob's local operation.

Fidelity of Quantum Teleportation vs Entanglement

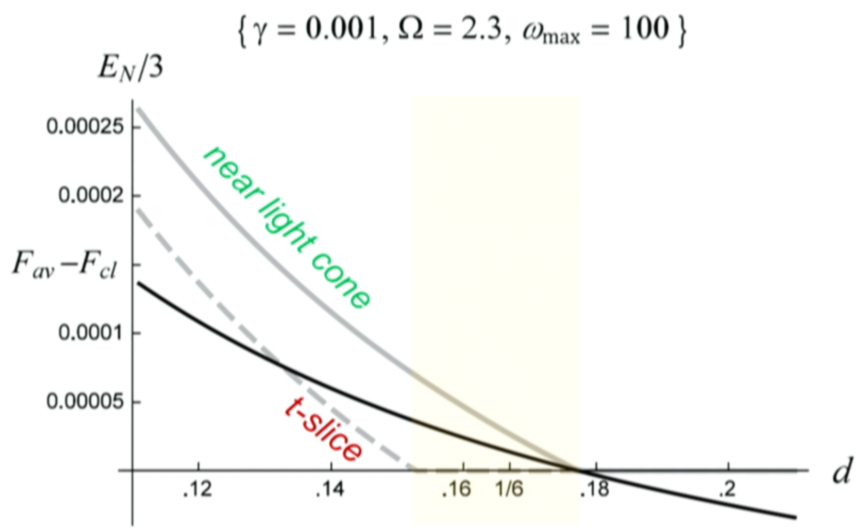
Teleport an unknown coherent state of Q_C from Alice to Rob'

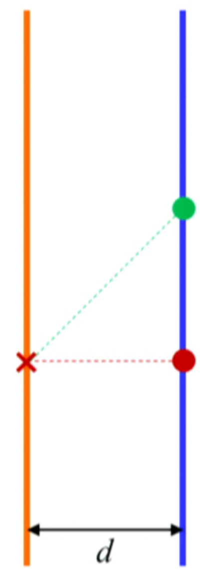


However, entanglement between two causally disconnected objects can be generated by coupling with a common quantum field.
[E.g. Reznik, Found. Phys.33(2003)167; SYL, Hu, PRD81(2010)045019]

Fidelity of Quantum Teleportation vs Entanglement

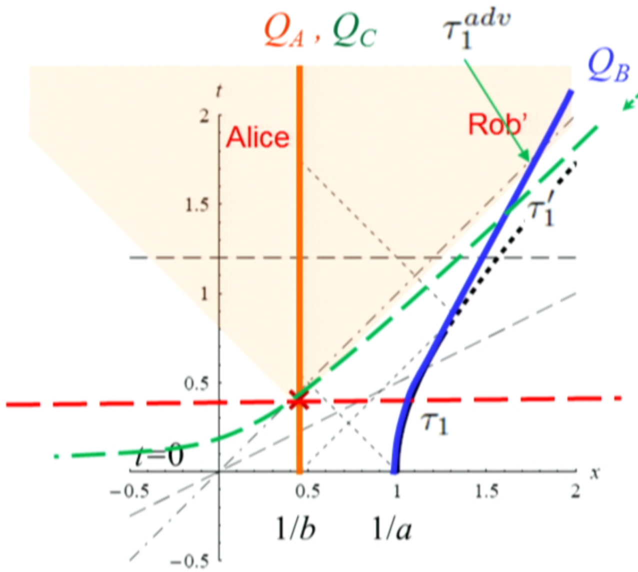
Ex: In the cases with 2 detectors are both at rest, **at late times**,
they may appear to be disentangled in the Minkowski coordinates, but entangled around the light cones of the measurement event in some parameter range.





Alice-Rob Problem: Fidelity of Quantum Teleportation

Teleport an unknown coherent state of Q_C from Alice to Rob'



The reduced state of Q_B collapsed at τ_1' then evolved to τ_1^{adv}

will be consistent with

the reduced state of Q_B collapsed at τ_1 then evolved to τ_1^{adv},

once the model respects **relativistic covariance** and the combined system starts at the same fiducial time slice.

Actually, the *reduced state of* Q_B collapsed in all frames will become consistent at τ_1^{adv} when Rob' is entering the future lightcone of the measurement event x.

Alice-Rob Problem: Fidelity of Quantum Teleportation

Upper bound for fidelity of QTelep [Mari, Vitali PRA78('09)062340]

Theorem 1 (**Upper bound**). *For a given Gaussian bipartite state shared by Alice and Bob, with lowest PT symplectic eigenvalue* ν*, the fidelity of the teleportation of a coherent state is limited from above by*

(at $\tau_I^{adv} + \varepsilon$) $$\mathcal{F}_{opt} \leq \frac{1}{1+\nu}.$$ (at $\tau_I^{adv} - \varepsilon$)

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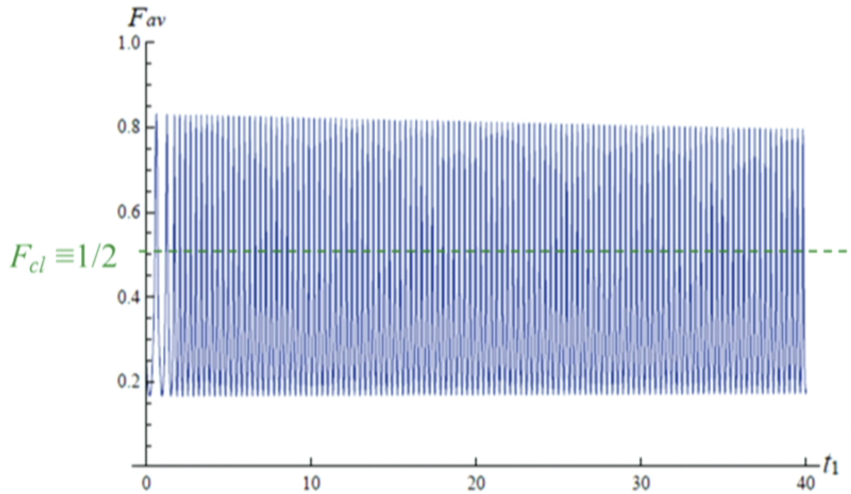
Alice-Rob Problem: Fidelity of Quantum Teleportation

Averaged physical fidelity of quantum telportation

$$F_{av} = \int d^2\beta P(\beta)_B \langle\alpha| \hat{\rho}_{out}(\tau_P) |\alpha\rangle_B$$

$$\tau_P = \tau_1^{adv} + \epsilon$$



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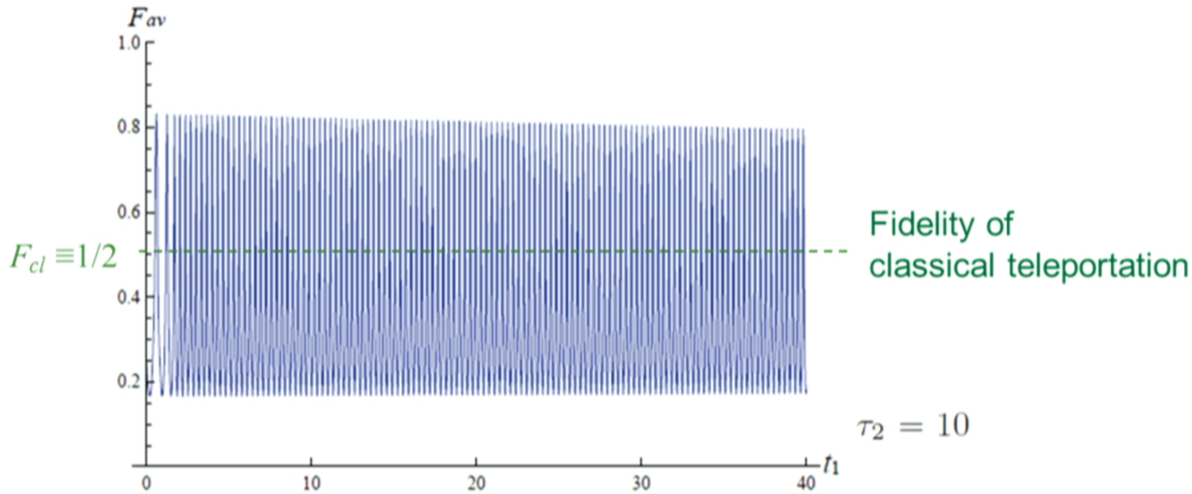
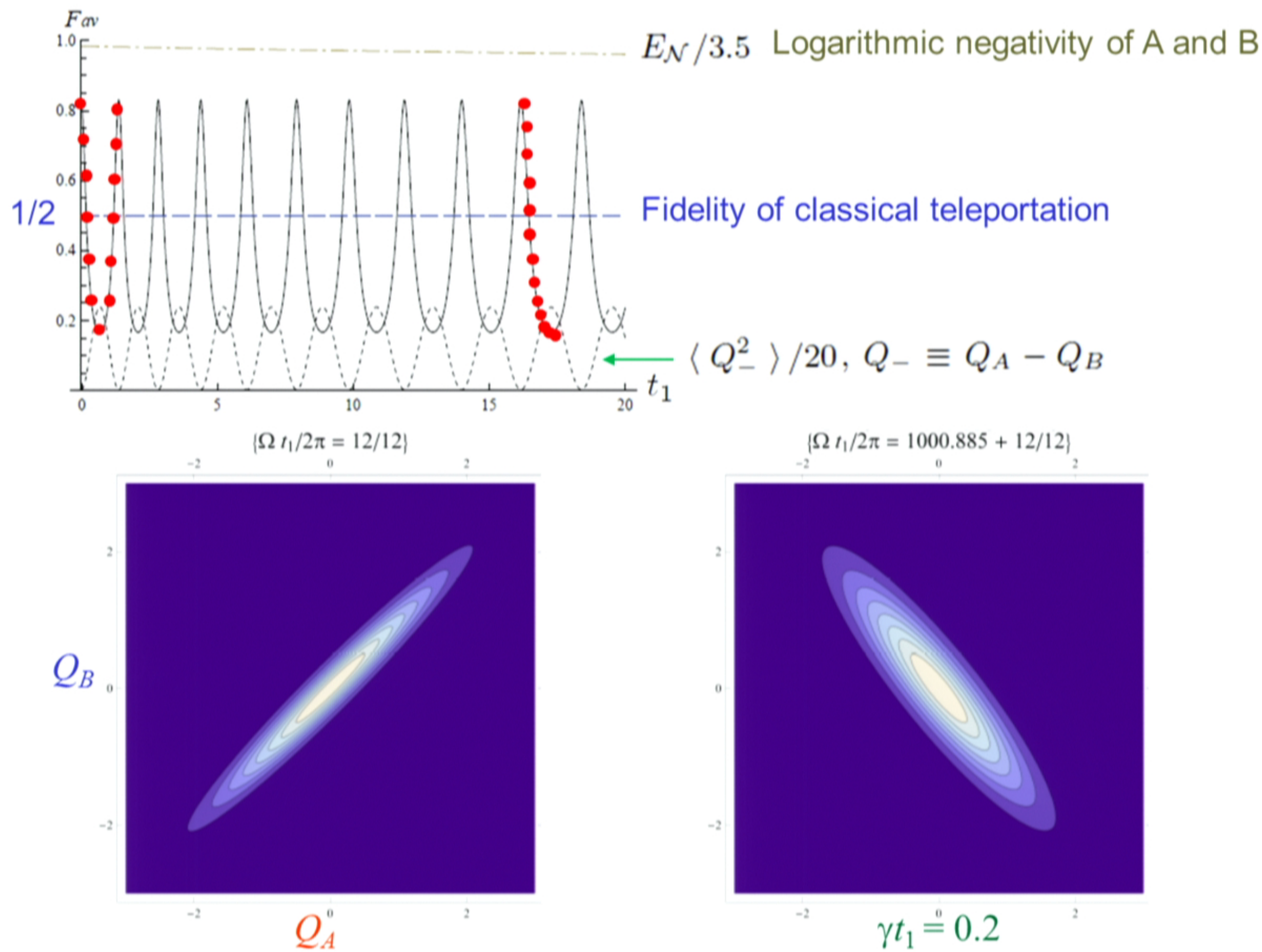


Alice-Rob Problem: Fidelity of Quantum Teleportation



Alice-Rob Problem: Fidelity of Quantum Teleportation

Averaged physical fidelity of QTelep in weak coupling limit

$$F_{av}(t_1,\tau_1) = \frac{2\mathcal{A}}{\mathcal{A}\mathcal{B}-(\mathcal{X}^2+\mathcal{Y}^2)} + O(\gamma\Lambda_1/\Omega)$$

$$\begin{aligned}
\mathcal{A}(t_1) &\equiv C_2 + e^{-2\gamma t_1}C_1 + 1 - e^{-2\gamma t_1},\\
\mathcal{B}(\tau_1) &\equiv 2 + C_2 + e^{-2\gamma\tau_1}C_1 + \left(1-e^{-2\gamma\tau_1}\right)\coth\frac{\pi\Omega}{a},\\
\mathcal{X}(t_1,\tau_1) &\equiv S_2 + e^{-\gamma(t_1+\tau_1)}\boxed{\cos\Omega(t_1+\tau_1)}S_1,\\
\mathcal{Y}(t_1,\tau_1) &\equiv e^{-\gamma(t_1+\tau_1)}\boxed{\sin\Omega(t_1+\tau_1)}S_1,
\end{aligned}$$

$$C_n \equiv \cosh 2r_n$$
$$S_n \equiv \sinh 2r_n$$

Improved protocol –
Alice continuously sends classical clock signal to Bob so that Bob can determine t_1 and perform the unitary local operation

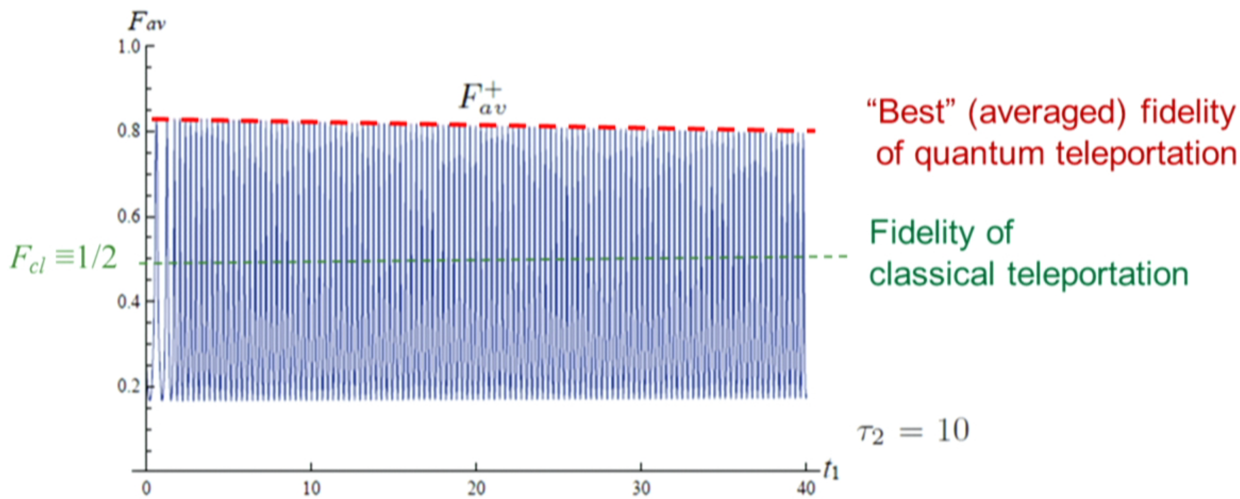
$$\hat{\rho}_{out} = \hat{D}(\beta)\hat{R}(\Omega(t_1+\tau_1))\hat{\tilde{\rho}}_B$$

where $\boldsymbol{R}(\Omega(t_1+\tau_1))$ is a (counter) rotation in phase space of detector B to undo the natural oscillation (~ local oscillators in optical QTelep expt's).

Improved Fidelity of Quantum Teleportation

Averaged physical fidelity of quantum telportation

$$F_{av} = \int d^2\beta P(\beta)_B \langle\alpha|\,\hat{\rho}_{out}(\tau_P)\,|\alpha\rangle_B \qquad \tau_P = \tau_1^{adv} + \epsilon$$



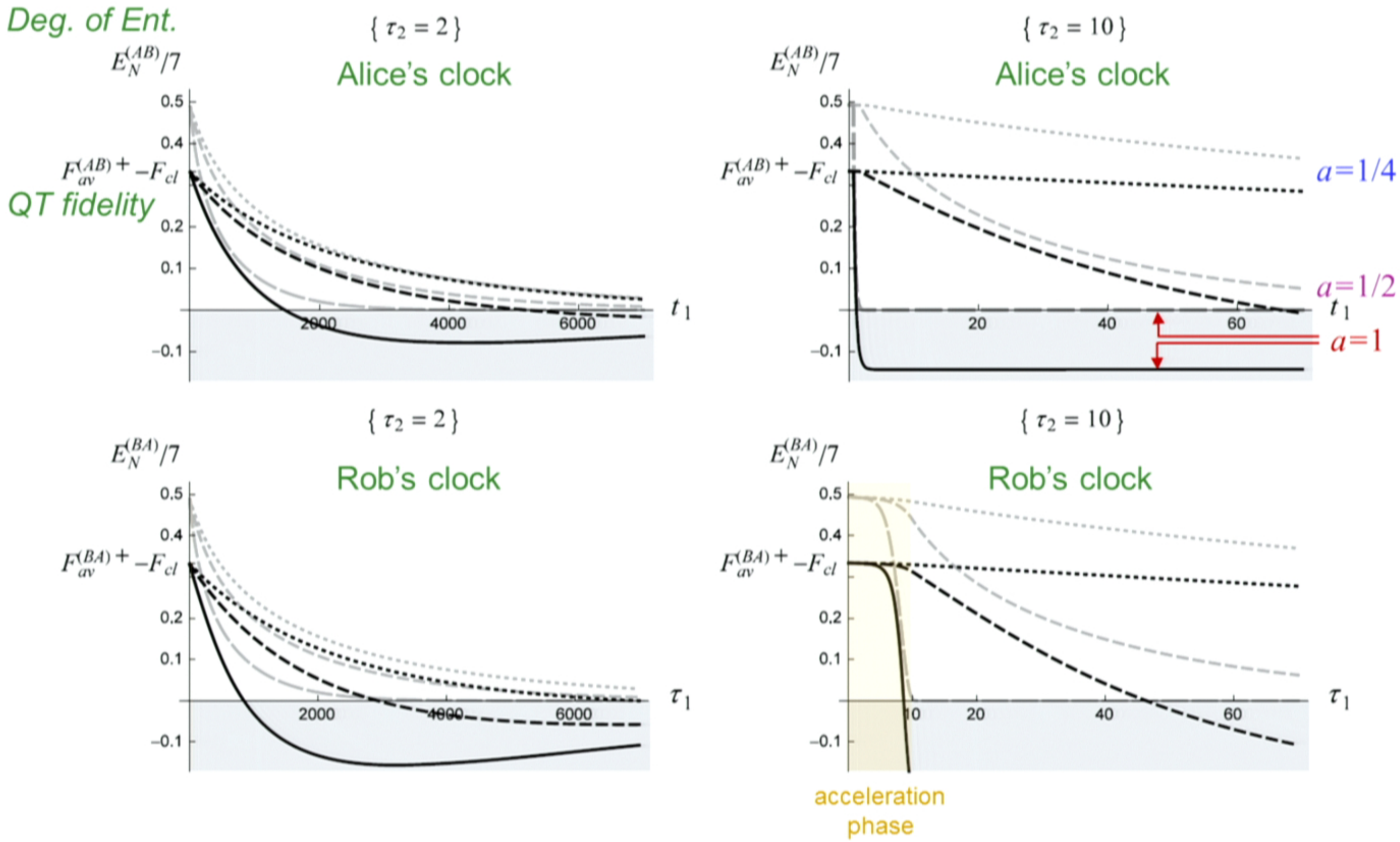
$$F_{av}^{\pm}(t_1, \tau_1) \approx \frac{2\mathcal{A}}{\mathcal{AB} - \left[S_2 \pm S_1\, e^{-\gamma(t_1+\tau_1)}\right]^2}$$ in weak coupling limit.

Almost the optimal protocol [Mari, Vitali PRA78('09)062340]

Alice-Rob Problem

Larger acceleration, larger decay rate is, but…

(τ_2 : duration of acceleration phase)



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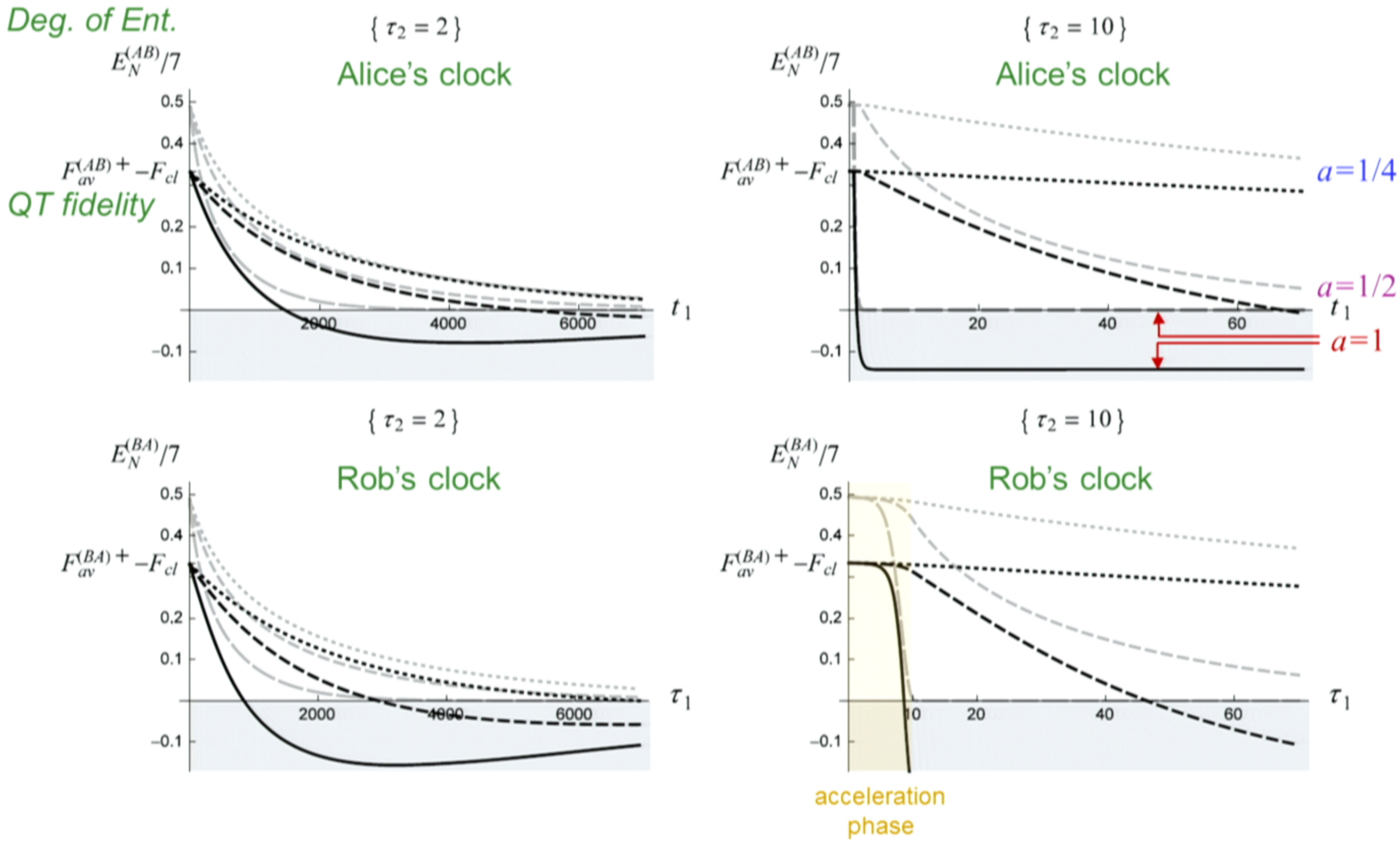
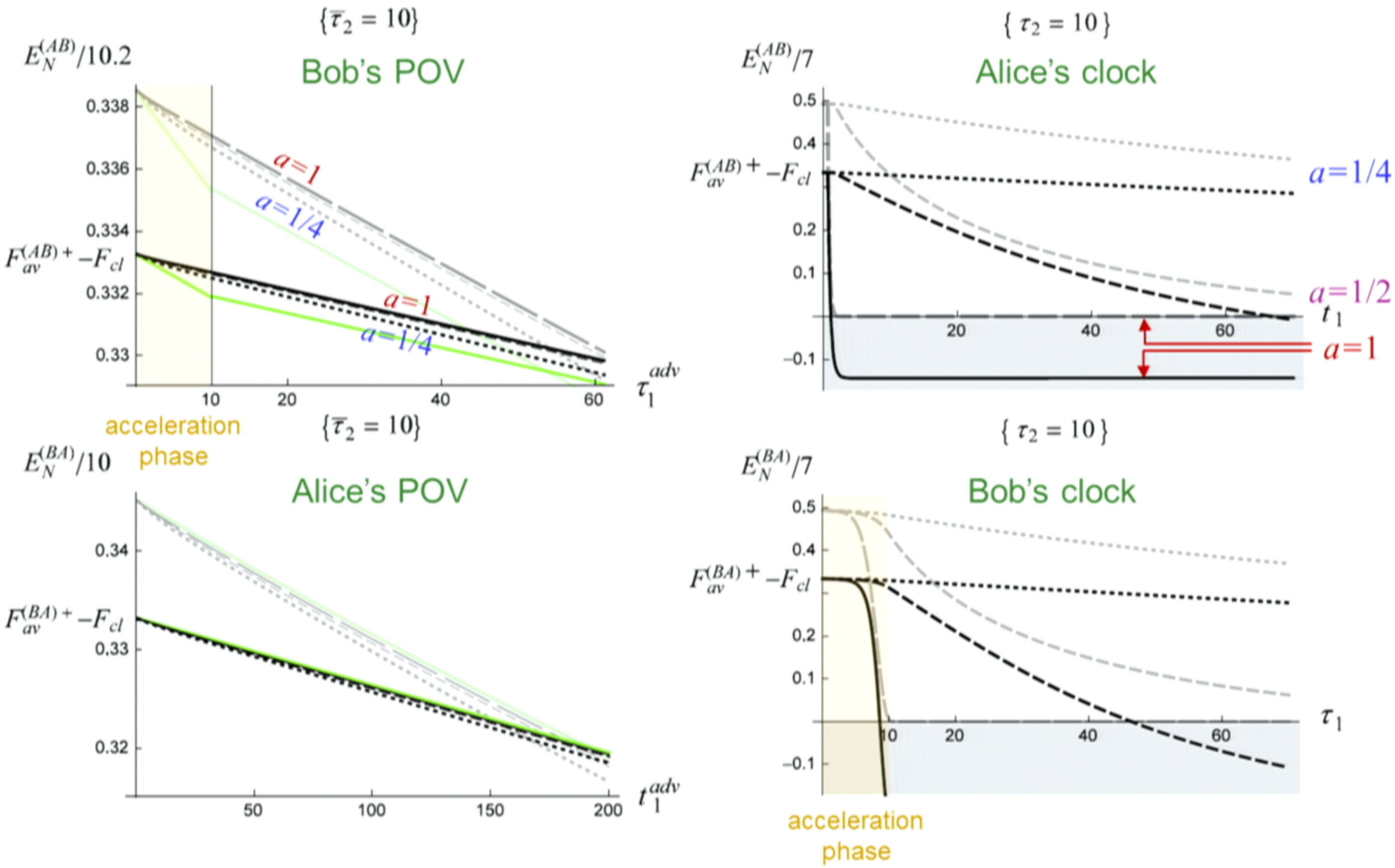


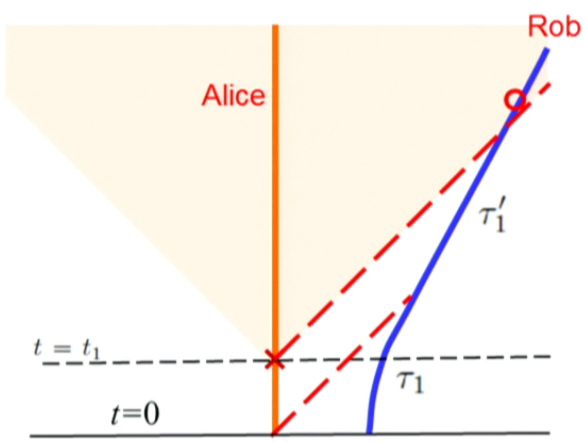
Alice-Rob Problem: Unruh effect doesn't dominate degradation for small a.

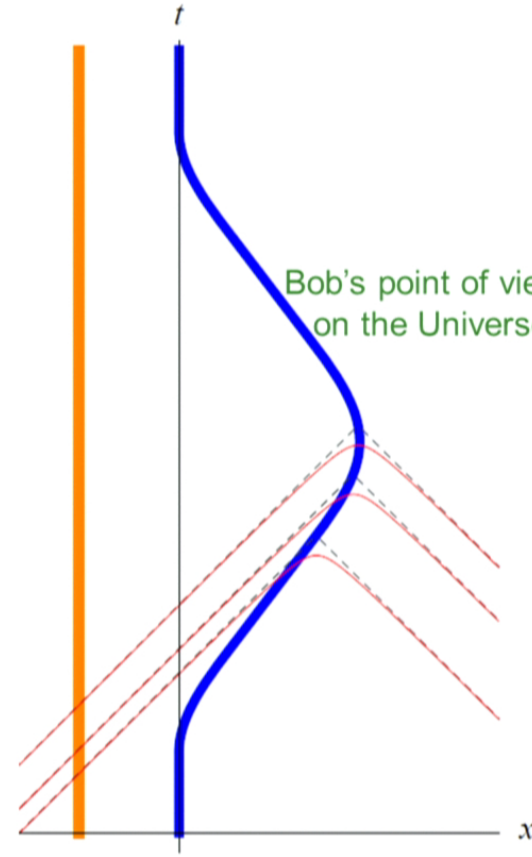
(τ_2 : duration of acceleration phase)



Point-of-View Shots

- Light cones of the detectors/observers are essential in relativistic open quantum system.





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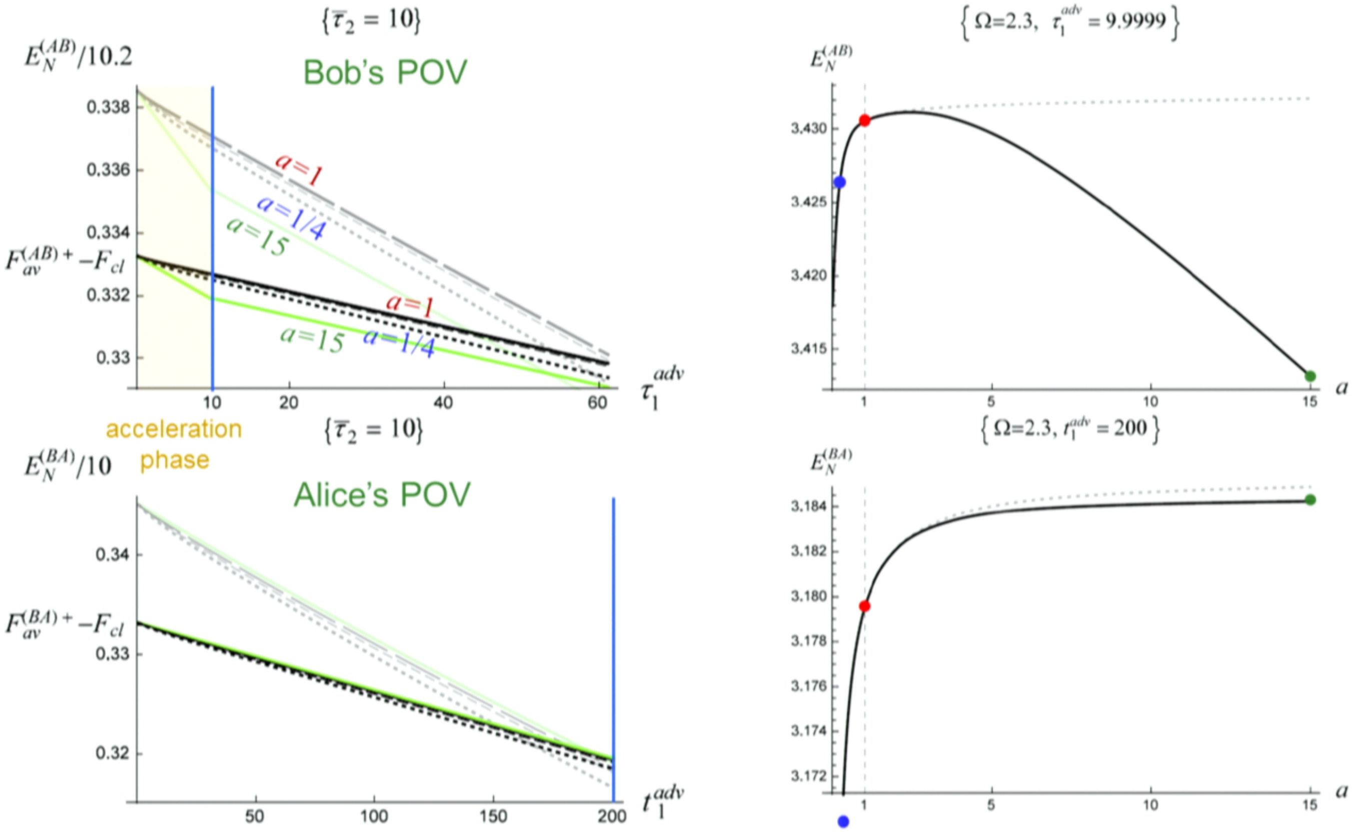
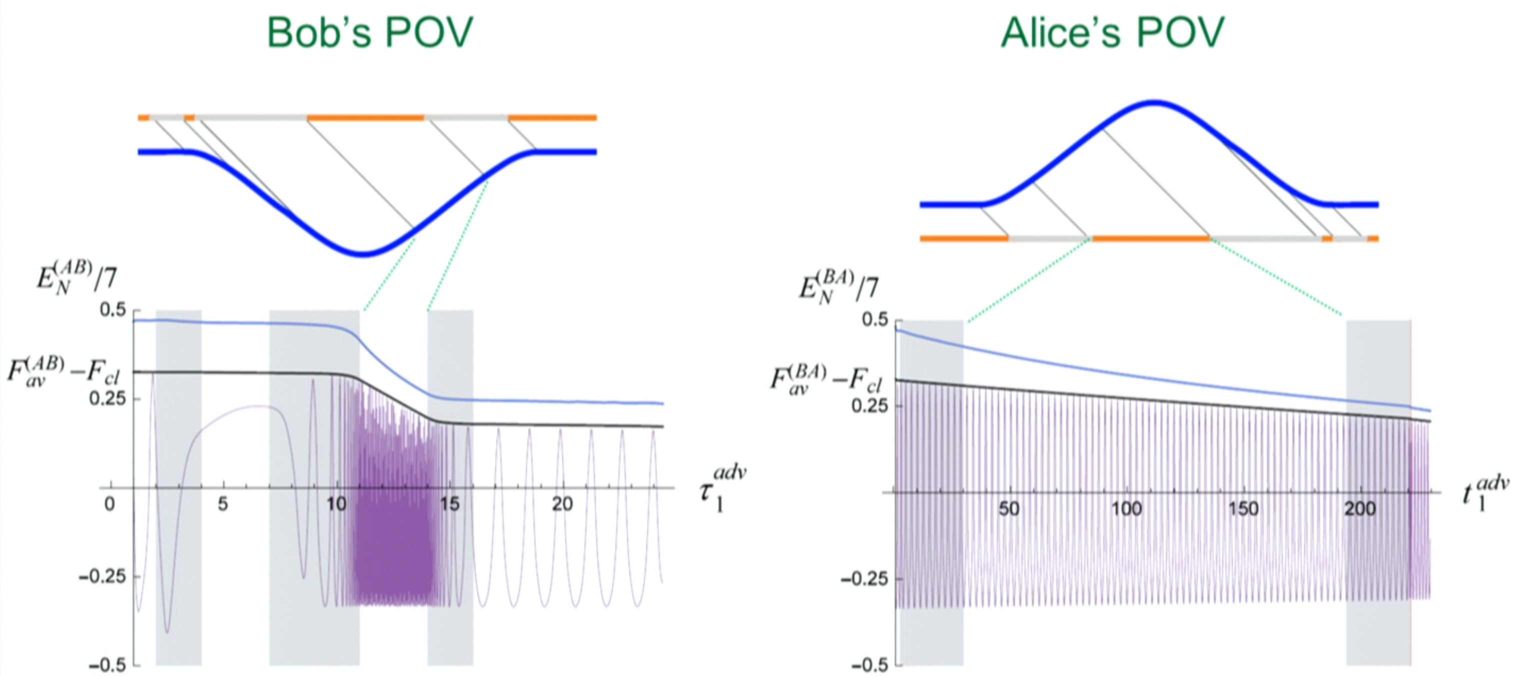


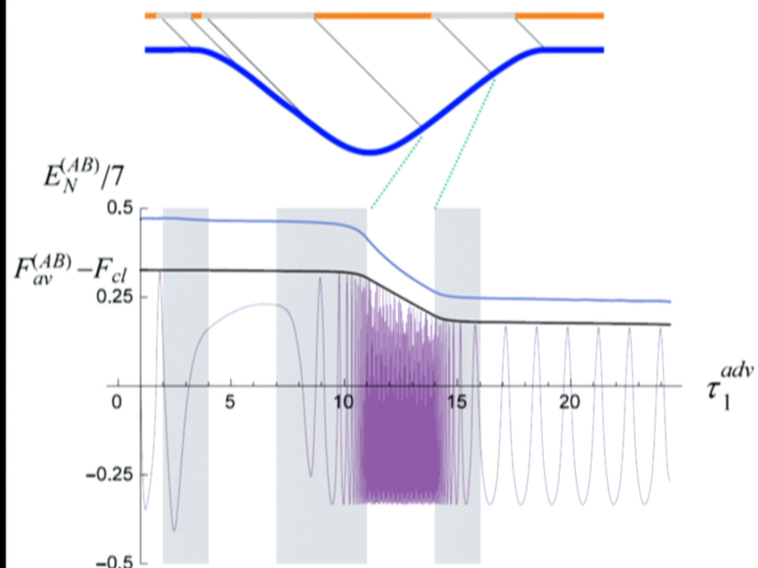
Twin Problem: Fidelity of QT vs. Entanglement around LC



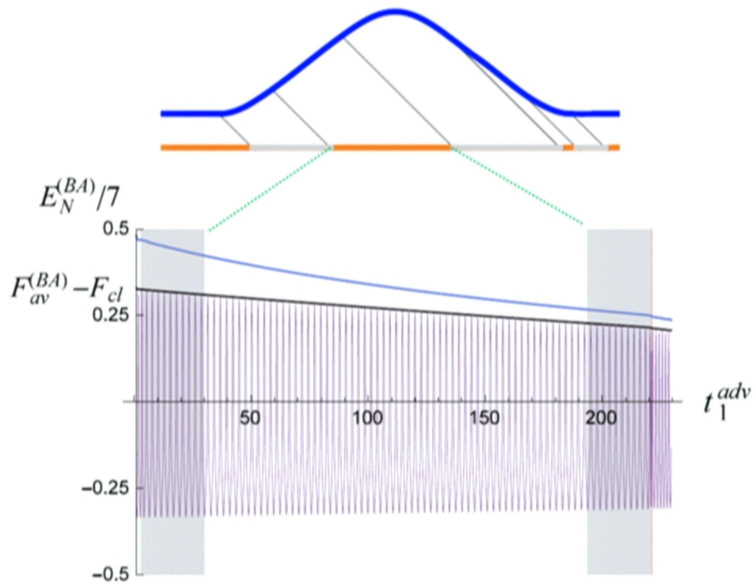
Doppler shift dominates the apparent history of degradation.

Twin Problem: Fidelity of QT vs. Entanglement around LC

Bob's POV



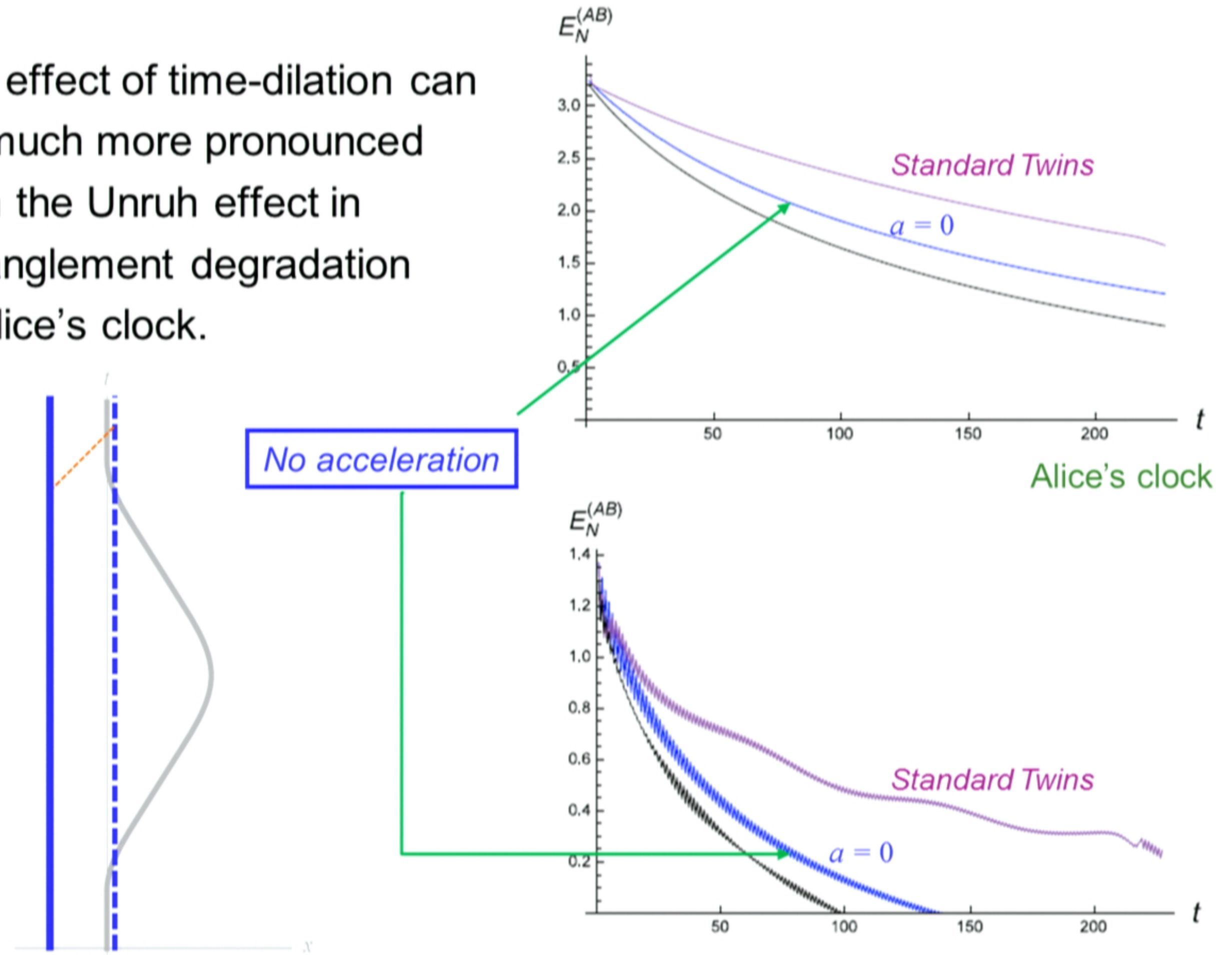
Alice's POV



Doppler shift dominates the apparent history of degradation.

Where to see Unruh Effect

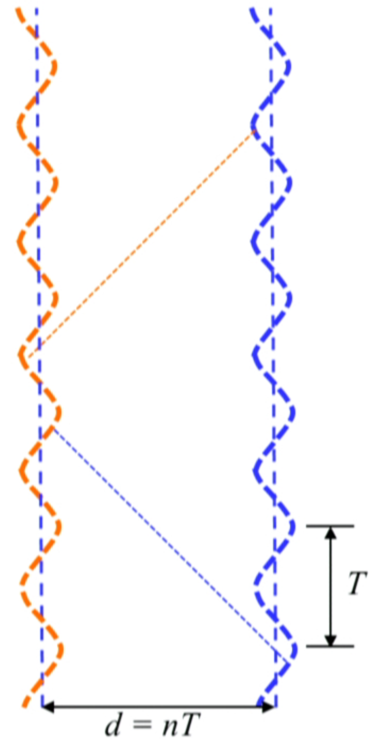
- The effect of time-dilation can be much more pronounced than the Unruh effect in entanglement degradation in Alice's clock.



Where to see Unruh Effect

- Single out the Unruh effect in quantum teleportation

Double UA/AUA detectors



Note: the effective temperature will be much lower than the Unruh temperature with the averaged proper acceleration, if T is very short.

[Doukas, SYL, Hu, Mann, JHEP11(2013)119]

Summary

- In relativistic open systems with localized objects moving in quantum fields, the optimal fidelity of quantum teleportation is relevant to the Entanglement evaluated around the future Light Cone (EnLC) of the measurement event, rather than the conventional Entanglement evaluated on the hypersurface of Simultaneity in the Minkowski coordinates (EnSM).

- When there are multiple clocks for objects localized at different places, one has to specify which clock or which point of view one would take when describing nonlocal processes.

- The effects of time-dilation and Doppler-shift (due to relative speed) can be more pronounced than the Unruh effect (due to acceleration) in the dynamics of entanglement and the fidelity of quantum teleportation.

Alice-Rob Problem: Unruh effect doesn't dominate degradation for small a.

(τ_2 : duration of acceleration phase)