Title: Quantum Information 2021/2022

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Measurements in Quantum Theory

What do I want from a measurement theory in QFT?

1-Capable of producing definite values

2-Provides an update rule

3-Consistent with the theory
(e.g., respect causality in a relativistic theory)

4-Reproduces experiments!!!

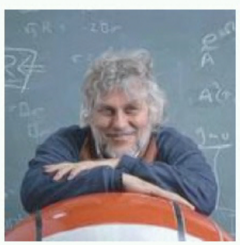
Is there an alternative to idealized measurements?

Does the particle detector approach work?

Measuring fields: Particle detectors

How do we measure quantum fields?

Particle detectors: Non-relativistic quantum systems coupling 'locally' to the field



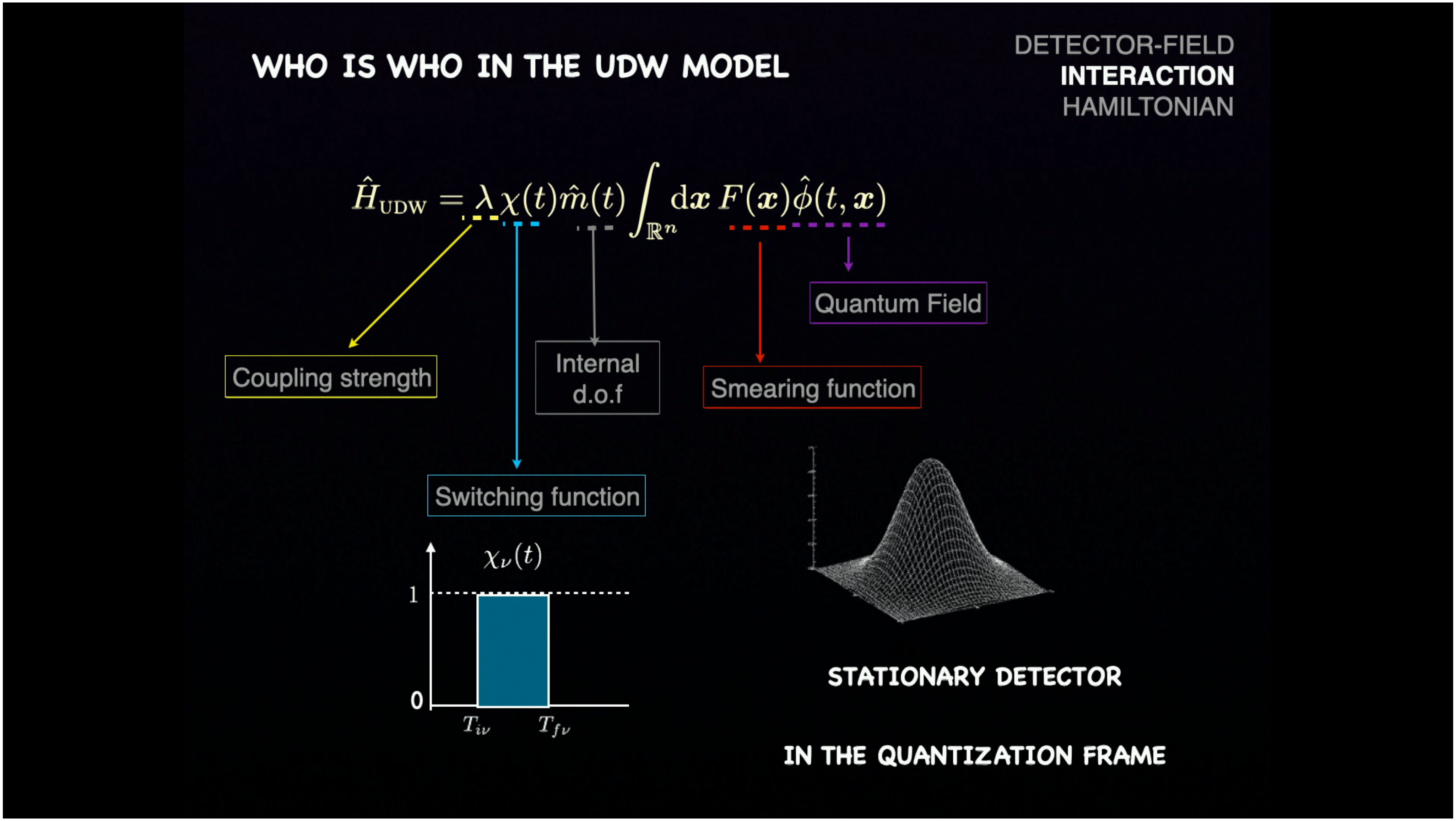
Particles are what particle detectors detect

A first particle detector Model: Unruh-DeWitt model

Two-level quantum system linearly coupling to a quantum field locally

Consider first a scalar field in flat spacetime and a quantization inertial frame $(t, \boldsymbol{x})$

$$\hat{H}_{\text{UDW}} = \lambda\,\chi(t)\hat{m}(t)\int_{\mathbb{R}^n} \mathrm{d}\boldsymbol{x}\, F(\boldsymbol{x})\hat{\phi}(t,\boldsymbol{x})$$


WHO IS WHO IN THE UDW MODEL
DETECTOR-FIELD
INTERACTION
HAMILTONIAN
$\hat{H}_{\text{UDW}} = \lambda\chi(t)\hat{m}(t)\int_{\mathbb{R}^n} \mathrm{d}\boldsymbol{x}\, F(\boldsymbol{x})\hat{\phi}(t,\boldsymbol{x})$
Coupling strength
Switching function
Internal d.o.f
Smearing function
Quantum Field
$\chi_\nu(t)$
1
0
$T_{i\nu}$
$T_{f\nu}$
STATIONARY DETECTOR
IN THE QUANTIZATION FRAME

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Mater, Light, Unruh and DeWitt

The coupling should be modelling
experimentally accessible
measurements

IS THIS MODEL JUST A TOY?

Coupling charges to the EM field: dipolar coupling

$$\hat{\boldsymbol{d}} \cdot \hat{\boldsymbol{E}} = e\,\hat{\boldsymbol{x}} \cdot \hat{\boldsymbol{E}}$$

Mater, Light, Unruh and DeWitt

Electromagnetic dipole coupling

$$H_{\text{EM}} = \chi(t) \int \mathrm{d}^3\boldsymbol{x}\, \hat{\boldsymbol{d}}(\boldsymbol{x}-\boldsymbol{x}_d, t) \cdot \hat{\boldsymbol{E}}(\boldsymbol{x}, t)$$

$$\hat{\boldsymbol{d}}(\boldsymbol{x}, t) = e\left[\boldsymbol{F}(\boldsymbol{x}) e^{\mathrm{i}\Omega t}\hat{\sigma}^+ + \boldsymbol{F}^*(\boldsymbol{x}) e^{-\mathrm{i}\Omega t}\hat{\sigma}^-\right]$$

$$\boldsymbol{F}(\boldsymbol{x}) = \boldsymbol{x}\langle e|\boldsymbol{x}\rangle\langle\boldsymbol{x}|g\rangle = \psi_e^*(\boldsymbol{x})\boldsymbol{x}\,\psi_g(\boldsymbol{x}).$$

Unruh-DeWitt coupling

$$H_{\text{UDW}} = \chi(t) \int \mathrm{d}^3\boldsymbol{x}\, \hat{\mu}(\boldsymbol{x}-\boldsymbol{x}_d, t)\, \hat{\phi}(\boldsymbol{x}, t).$$

$$\hat{\mu}(\boldsymbol{x}, t) = eF(\boldsymbol{x})\left[e^{\mathrm{i}\Omega t}\hat{\sigma}^+ + e^{-\mathrm{i}\Omega t}\hat{\sigma}^-\right]$$

UDW models capture fundamental features of the light-matter interaction (when exchange of angular momentum is not relevant)

Further Discussion: E. M-M, P. Rodriguez-Lopez Phys. Rev. D 97, 105026 (2018)
A. Pozas-Kertjens, E. M-M. Phys. Rev. D 94, 064074 (2016)
E. M-M, M. Montero, M. del Rey. Phys. Rev. D 87, 064038 (2013)
R. Lopp, E M-M. Phys. Rev. A 103, 013703 (2021)

In fact! Simplifications of this model are used in QO experiments (Jaynes Cummings, Dicke, etc)

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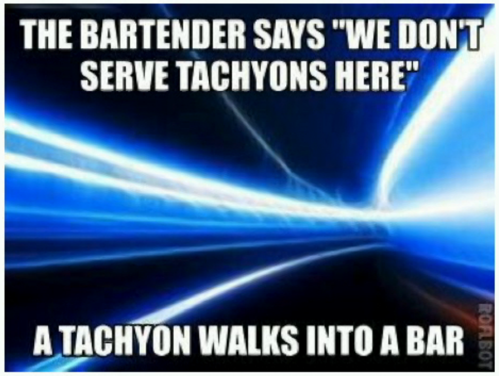
How does a detector play with Relativity

GENERAL COVARIANCE

The mathematical representations of a law of physics in different coordinate systems must be connected by the mathematics of coordinate transformations.

NO FTL SIGNALLING OR RETROCAUSALITY

The detector model should not allow for (strong) faster-than-light signalling



How does a detector play with Relativity

GENERAL COVARIANCE

General Relativistic Quantum Optics: Finite-size particle detector models in curved spacetimes
E. M-M., T. Rick Perche, Bruno, S. L. Torres. Phys. Rev. D 101, 045017 (2020)

Broken covariance of particle detector models in relativistic quantum information
E. M-M., T. Rick Perche, Bruno, S. L. Torres. Phys. Rev. D 103, 025007 (2021)

NO FTL SIGNALLING (AND NO RETROCAUSATION)

Causality issues of particle detector models in QFT and Quantum Optics
E. M-M, Phys. Rev. D 92, 104019 (2015)

Relativistic causality in particle detector models: Faster-than-light signalling and "Impossible measurements"
J. de Ramon, M. Papageorgiou, E. M-M Phys. Rev. D 103, 085002 (2021)

Measurements in Quantum Theory

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Getting that 42!

Extracting definite values:

1-Couple the detector to the field

2-Idealized measurement on the detector (remember, non-Rel)

Update rule:

3-Update the field state with the consistent POVM compatible with the outcome

A detector-based measurement theory for quantum field theory
J. Polo-Gómez, L. J. Garay, E. M-M. Phys. Rev. D 105, 065003 (2022)

A Measurement theory for QFT

A detector-based measurement theory for quantum field theory

Phys. Rev. D 105, 065003 (2022) arXiv:2108.02793

How to update the n-point function of a quantum field based on acquired knowledge

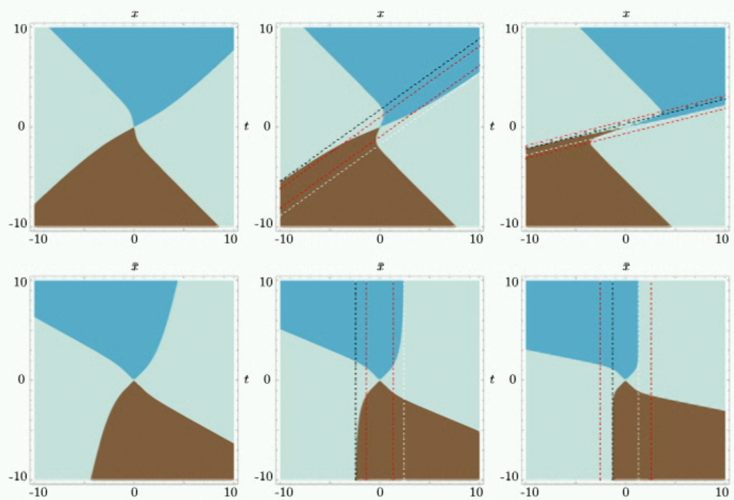
Contextual updates.

Selective vs Non-selective updates

Fundamental Topics:
"Spacetime Engineering"

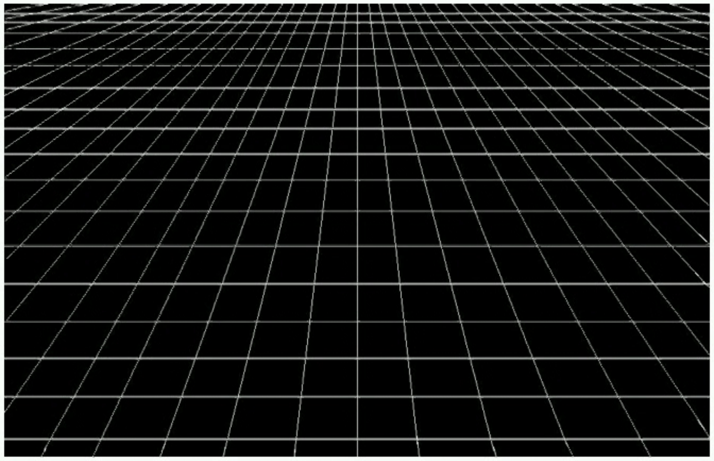
Violate energy conditions:

-Warp drives?
-Wormholes?



For more info: N.Funai, E. martin-Martinez: arXiv:1701.03805

Warping the fabric of spacetime



Preparation of states of spacetime

Engineering negative stress-energy densities with quantum energy teleportation
N. Funai, E. Martín-Martínez, Phys. Rev. D 96, 025014 (2017)

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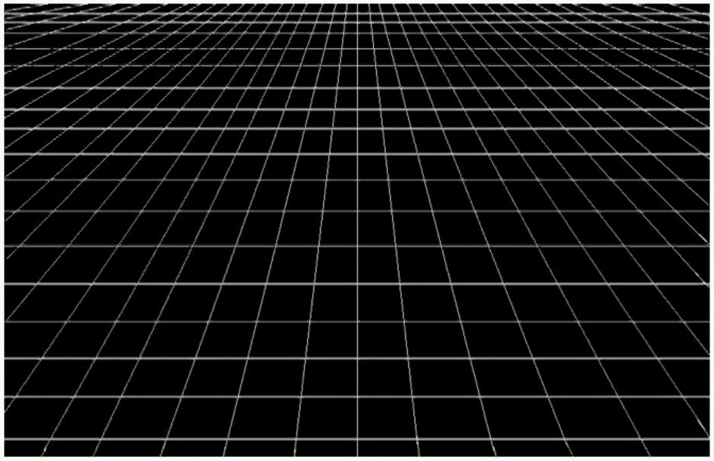

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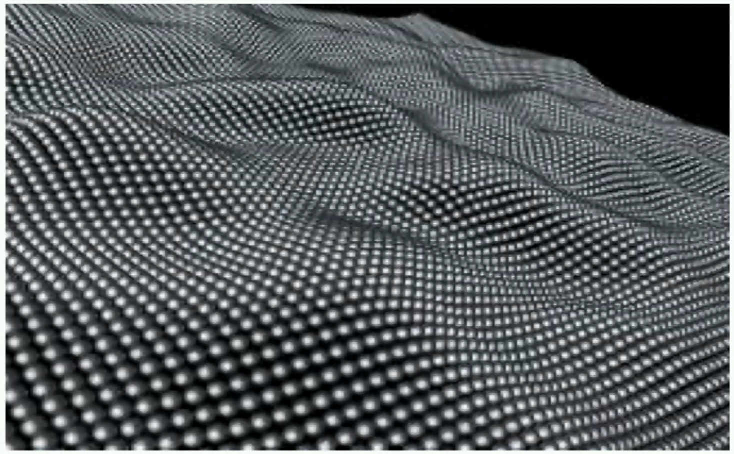

Preparation of states of spacetime

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N. Funai, E. Martín-Martínez, Phys. Rev. D 96, 025014 (2017)

General Relativity

Einstein Equations:

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{Geometry}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{Stress-energy}}$$

Geodesic Equations:

$$\frac{\mathrm{d}^2 x^\beta}{\mathrm{d}\tau^2} + \Gamma^\beta{}_{\alpha\nu} \frac{\mathrm{d}x^\alpha}{\mathrm{d}\tau} \frac{\mathrm{d}x^\nu}{\mathrm{d}\tau} = 0$$

Exotic spacetimes

Energy Conditions:

Null Energy condition: "There is no such thing as negative energy"

Weak Energy condition: "There is no such thing as negative energy"

Strong Energy condition: "Gravity is only attractive"

Dominant Energy condition: "Energy must not flow faster than light"

$$\text{Strong} \Rightarrow \text{Null} \Leftarrow \text{Weak} \Leftarrow \text{Dominant}$$

Weak Energy condition:

$$T_{\mu\nu}\xi^{\mu}\xi^{\nu} \geq 0.$$

For All future-directed ξ^{μ}

If violated, exotic solutions:

- -Wormholes
- -Warp drives
- -Anti-gravity / screening

Exotic spacetimes

Quantum Fields violate AWEC:

$$\frac{\tau_0}{\pi}\int_{-\infty}^{\infty}\frac{\langle \hat{T}_{\mu\nu}\xi^{\mu}\xi^{\nu}\rangle}{\tau^2+\tau_0^2}d\tau \geq -\frac{3}{32\pi^2\tau_0^4}.$$

Ford, Pfenning, etc...

How unphysical those solutions are?

Exotic spacetimes

How can we engineer violations of AWEC?

$$\frac{\tau_0}{\pi}\int_{-\infty}^{\infty}\frac{\langle \hat{T}_{\mu\nu}\xi^\mu\xi^\nu\rangle}{\tau^2+\tau_0^2}d\tau \geq -\frac{3}{32\pi^2\tau_0^4}.$$

Extreme Dynamical Casimir effect

Rather Unphysical...

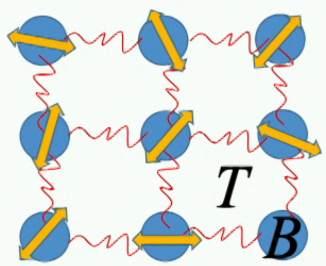
Strong Local Passivity of thermal states

Can we extract energy purely locally by using a colder ancilla?

Will the hand get burnt?

Answer: Not in general!

In fact the hand can get cooler!



Strong Local Passivity of thermal states

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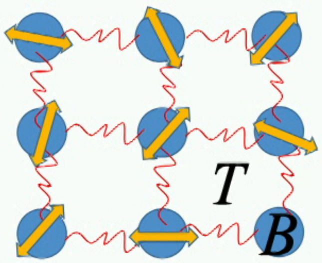
If the ground state of the system **contains** max-rank **entanglement** (not necessarily maximal entanglement):



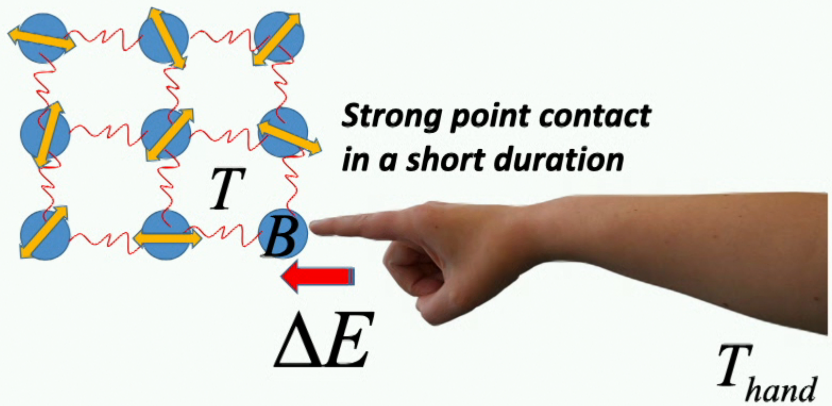
There exists a temperature $T^* > 0$

For $T < T^*$ It is **not possible** to extract work from the system through **any** local CPTP map.

Two Qubits : M. Frey, K. Gerlach, M. Hotta, J. Phys. A: Math. Theor. 46, 455304 (2013).
General Theorem: M. Frey, K. Funo, M. Hotta, Phys. Rev. E90, 012127 (2014).

A. M. Alhambra, G. Styliaris, N. A. Rodriguez-Briones, J. Sikora, E. Martín-Martinez
Phys. Rev. Lett. 123, 190601 (2019)

Strong Local Passivity of thermal states



Strong Local Passivity!

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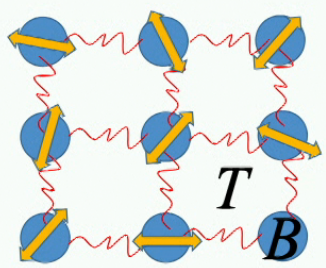

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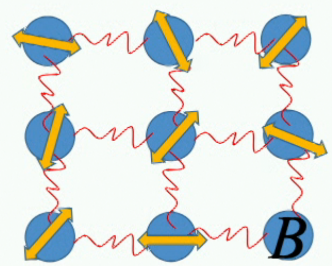
Strong Local Passivity of thermal states

Even if $T_{hand} < T$, energy is transferred from hand to B!



$$+\Delta E \geq 0 \qquad -\Delta E \leq 0$$

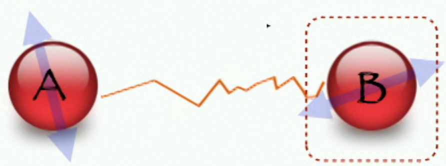
Strong Local Passivity!

Breaking Strong Local Passivity
Quantum Energy Teleportation

We can use ground state entanglement as a resource for local energy extraction!

If we assist local operations with classical communication (LOCC) it is possible to extract energy with local operations.

Even from the ground state



Breaking Strong Local Passivity Quantum Energy Teleportation

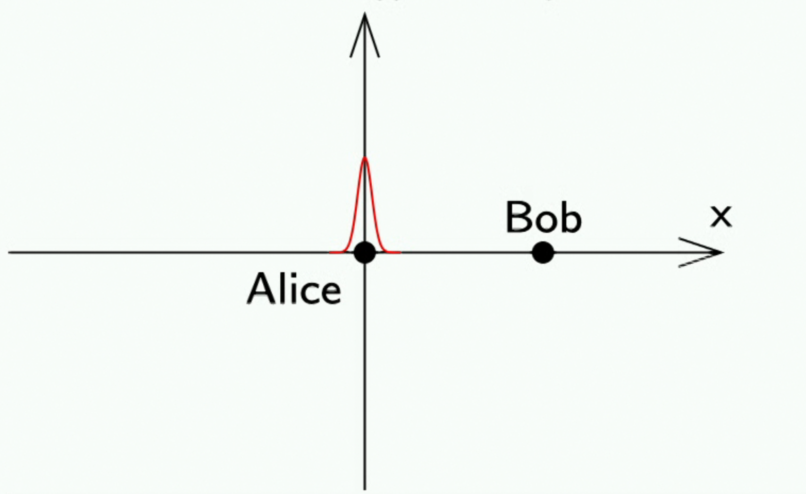
Unexpected result: Unlock zero-point energy
Consuming **entanglement**

What about quantum fields?

Ground state is entangled!

Can we pull the same trick?

Breaking Strong Local Passivity
Quantum Energy Teleportation



[1] Hotta, *Phys. Rev. D.*, 78.045006, Aug 2008