Title: Quantum energy teleportation: from theory, to experiments and spacetime engineering

Speakers: Eduardo Martin-Martinez

Series: Colloquium

Date: March 01, 2023 - 2:00 PM

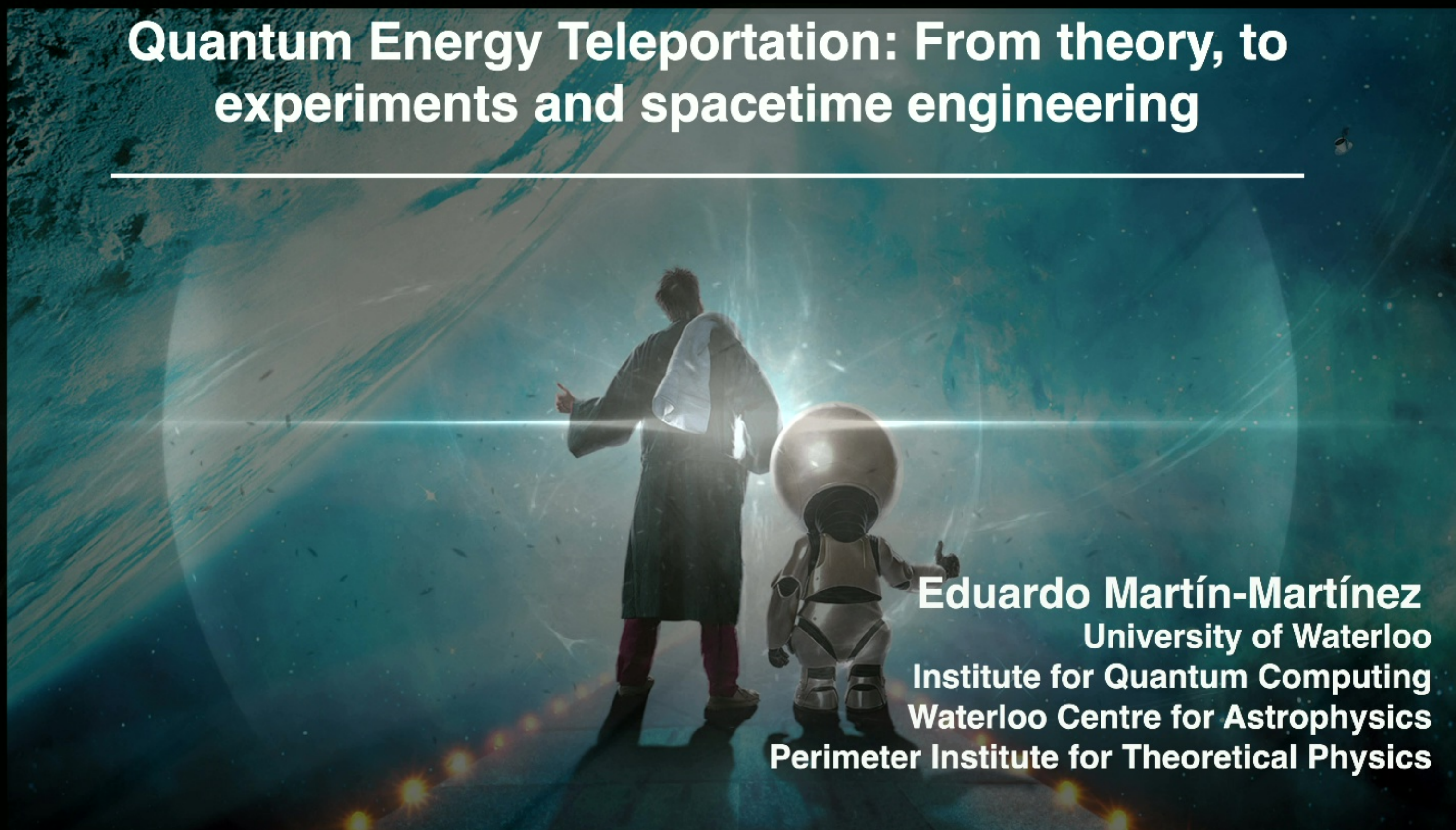
URL: https://pirsa.org/23030087

Abstract: In 2008 Masahiro Hotta proposed a protocol for transporting energy between two localized observers A and B without any energy propagating from A to B. When this protocol is applied to the vacuum state of a quantum field, the local energy density in the field achieves negative values, violating energy conditions

We will explore the protocol of quantum energy teleportation and show how quantum information techniques can be used to activate thermodynamically passive states. We will review the first experiment showcasing the local activation of ground state energy (carried out in 2022), and we will discuss the potential of this relativistic quantum information protocol to create exotic distributions of stress-energy density in a quantum field theory, and how spacetime might react to them.

Zoom link: https://pitp.zoom.us/j/98393523926?pwd=LzI4N1UyLzR4QVVGcENEbjBycjJwUT09

March 1st 2023



Quantum Energy Teleportation

Quanta magazine Physics Mathematics Biology Computer Science Topics Archive

Charlie Wood

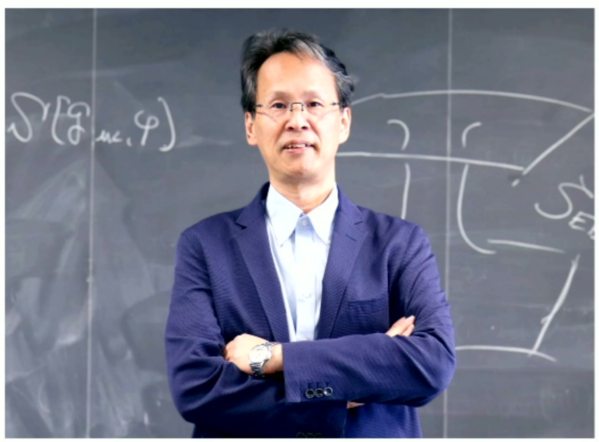
Staff Writer

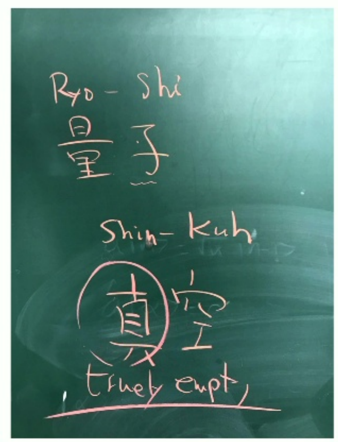
QUANTUM PHYSICS

Physicists Use Quantum Mechanics to Pull Energy out of Nothing

23

The quantum energy teleportation protocol was proposed in 2008 and largely ignored. Now two independent experiments have shown that it works.





Quantum Energy Teleportation

Outline:

Thermodynamics and QET (Strong local passivity)

Minimal Quantum Energy Teleportation Protocol

Applications to algorithmic cooling

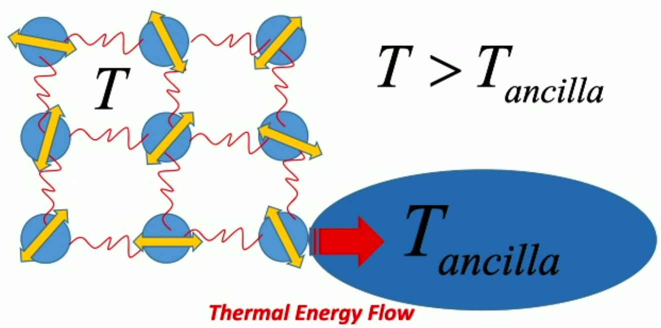
Experimental Demonstration

Application to "Spacetime Engineering"

Passivity of thermal states

How about generic operations? CPTP maps? We know how!

The map on the system resulting from coupling a colder ancilla $\rho_T \to \Gamma[\rho_T]$



$$\Delta E = \mathrm{Tr}[H\rho_T] - \mathrm{Tr}\Big(H\Gamma[\rho_T]\Big) < 0$$

Is this local?

Strong Local Passivity of thermal states

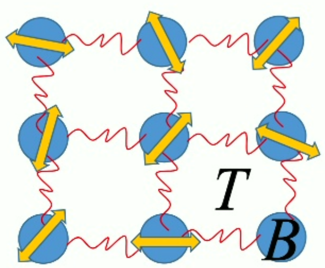
Can we extract energy purely locally by using a colder ancilla?

Will the hand get burnt?

Answer: Not in general!

In fact the hand can get cooler!

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)

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

Example: Minimal QET

Consider two qubits A and B and the following Hamiltonian

$$H = H_A + H_B + V$$

where

$$H_A = h\sigma_z^A + f(h,k)\mathbb{1}, \qquad H_B = h\sigma_z^B + f(h,k)\mathbb{1}, \qquad V = 2\left[k\sigma_x^A\sigma_x^B + \frac{k^2}{h^2}f(h,k)\mathbb{1}\right]$$

where h and k are positive constants and the function

$$f(h,k) = \frac{h^2}{\sqrt{h^2+k^2}}$$

Example: Minimal QET

Alice carries out a PVM on σ_x. She obtains the outcome α (that can take either value $+1$ or -1). The action of this measurement on the system is described by the projector

$$P_A(\alpha) = \frac{1}{2}\left(1 + \alpha\sigma_x^A\right)$$

in a single shot measurement, the resulting post-measurement state $|\psi_{\mathrm{PM}}\rangle$ is given by

$$|\psi_{\mathrm{PM}}(\alpha)\rangle = \frac{1}{\sqrt{p_A(\alpha)}} P_A(\alpha)|g\rangle \qquad p_A(\alpha) = \langle g|P_A(\alpha)|g\rangle$$

If we repeat this projection on an ensemble of identical setups, we obtain the following post-measurement average state

$$\rho_1 = \sum_{\alpha=\pm1} p_A(\alpha)|\psi_{\mathrm{PM}}(\alpha)\rangle\,\langle\psi_{\mathrm{PM}}(\alpha)| = \sum_{\alpha=\pm1} P_A(\alpha)|g\rangle\langle g|\,P_A(\alpha).$$

$$E_{P_A} = \mathrm{Tr}\,\rho_1 H - \mathrm{Tr}\left(|0\rangle\langle 0|\,H\right) = \sum_{\alpha=\pm1}\langle g|P_A(\alpha)H_A P_A(\alpha)|g\rangle = f(h,k) > 0$$

Example: Minimal QET

Steps 2,3: Classical communication and local unitary on B

$$E_{U_B} = \frac{-1}{h^2+k^2}\Big[hk\sin(2\theta) - (h^2+2k^2)(1-\cos(2\theta))\Big]$$

Now for a value of theta $0 < \theta \ll 1$ we get that

$$E_{U_B} \simeq \frac{-2hk\theta}{h^2+k^2} < 0$$

Therefore the local Unitary $U_B(\alpha)$ has a negative energy cost, thus performing it gives away energy, always smaller or equal than the energy put there by the local projective measurement on A

Example: Minimal QET

Of course, even without that protocol, after the projective measurement on A, the system is no longer in the ground state, and as such, even though we only acted on A, the energy will flow towards B. Indeed

$$\langle H_B(t)\rangle = \sum_{\alpha=\pm 1} \langle g|\, P_A(\alpha) e^{\mathrm{i}Ht} H_B e^{-\mathrm{i}Ht} P_A(\alpha)|g\rangle = \frac{1}{2} f(h,k)[1-\cos(4kt)]$$

whereas the energy expectation of the interaction term remains zero during time evolution

$$\langle V(t)\rangle = \sum_{\alpha=\pm 1} \langle g|\, P_A(\alpha) e^{\mathrm{i}Ht} V e^{-\mathrm{i}Ht} P_A(\alpha)|g\rangle = 0$$

We can interpret this as energy flowing from A to B with a characteristic time given by the inverse of the coupling strength k^{-1}. The QET protocol is not limited by that speed. Instead it can be as fast as the fastest classical channel.

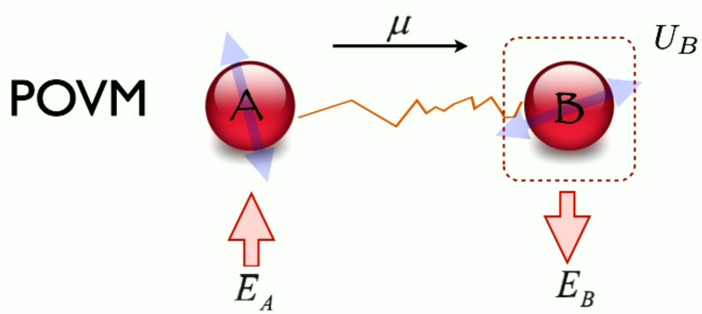
Breaking Strong Local Passivity
Quantum Energy Teleportation

Intuition:

Because of ground state entanglement, the measurement in A provides information about fluctuations in B. “Unlocking zero-point fluctuations at a cost”

extract energy with local operations assisted by the information in A.

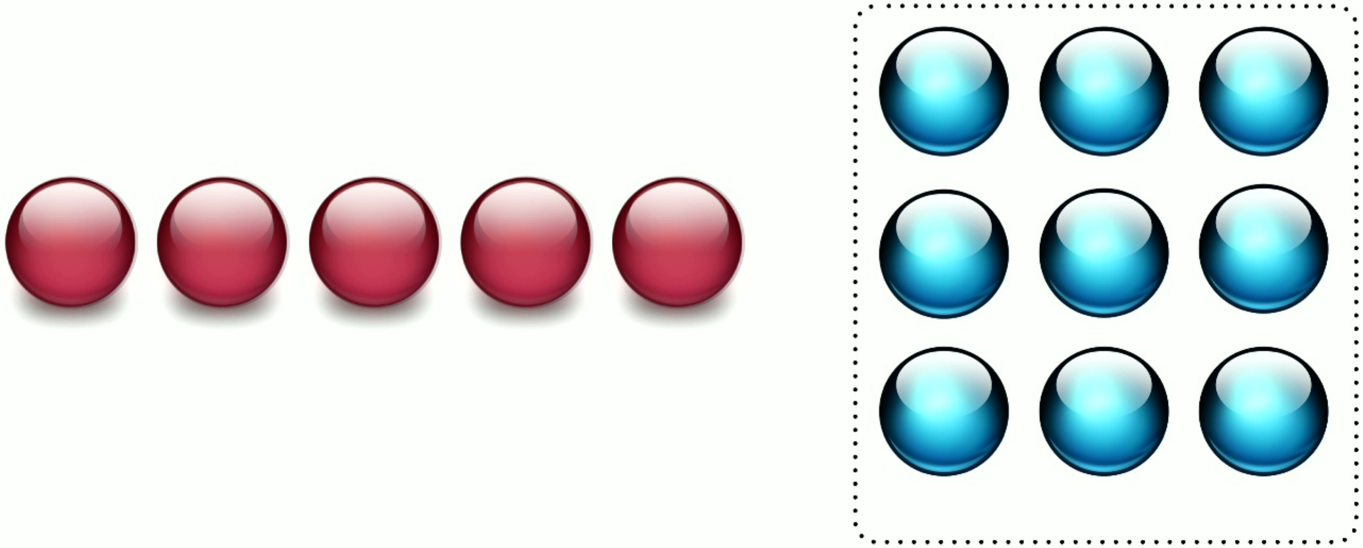
Energy does not travel from A to B. Information does.



What is heat bath algorithmic cooling?

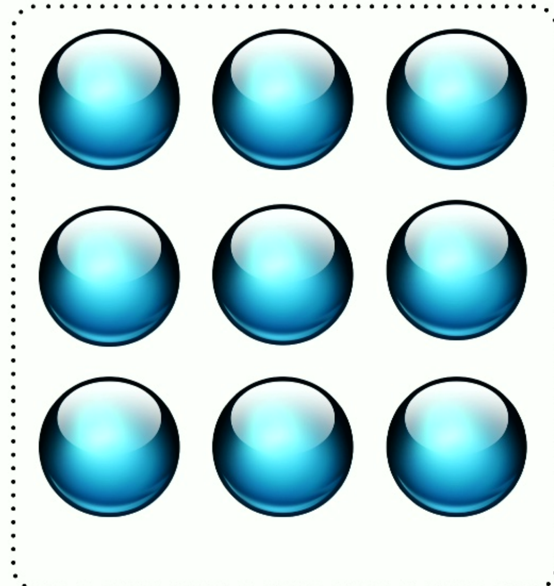
We have access to a quantum system and a thermal bath

Can we cool down the system below the temperature of the thermal bath?



P. O. Boykin, et al. Proceedings of the National Academy of Sciences 99, 3388 (2002).

Heat-Bath Algorithm Cooling



Entropy compression

$$\rho'' \rightarrow \rho''' = U' \rho'' U'^{\dagger}$$

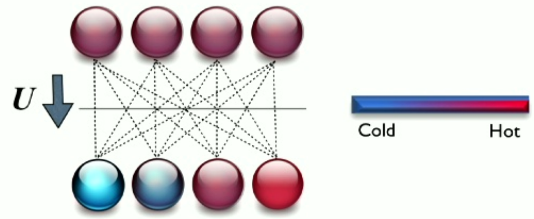
...

The Partner Pairing Algorithm (PPA-HBAC)

PPA-HBAC is the iteration of the two steps:

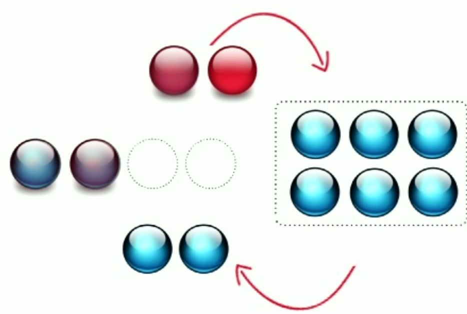
① **Entropy Compression Step.**

$$\rho \to \rho' = U \rho U^{\dagger}$$



$U \equiv$ **Descending SORT of the diagonal elements.**

② **Refresh Step.**



$$\rho' \to \rho'' = \mathrm{Tr}_m(\rho) \otimes \rho_{\epsilon_b}^{\otimes m}$$

L. J. Schulman, T. Mor, and Y. Weinstein, Phys. Rev. Lett. 94, 120501 (2005).

What about local cooling of interacting systems?

• Cool down the system:
Ground state is entangled ⟶ Subsystems are mixed

• Break entanglement through interaction with environment:
System in a Gibbs state ⟶ additional mixedness

•Apply local operations on the subsystem:
Strong local passivity ⟶ Subsystem's energy increases

How do we cool down a part of an interacting system?

What about local cooling of interacting systems?

• Cool down the system:
Ground state is entangled $\longrightarrow$ Subsystems are mixed

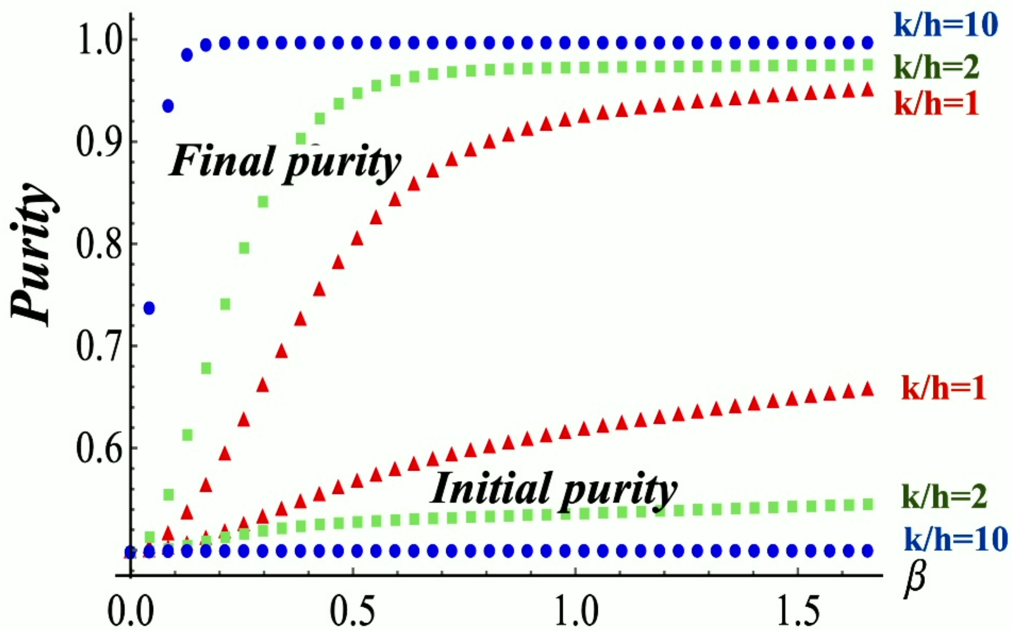
• Break entanglement through interaction with environment:
System in a Gibbs state $\longrightarrow$ additional mixedness

•Apply local operations on the subsystem:
Strong local passivity $\longrightarrow$ Subsystem's energy increases

How do we cool down a part of an interacting system?

Use of QET for algorithmic cooling

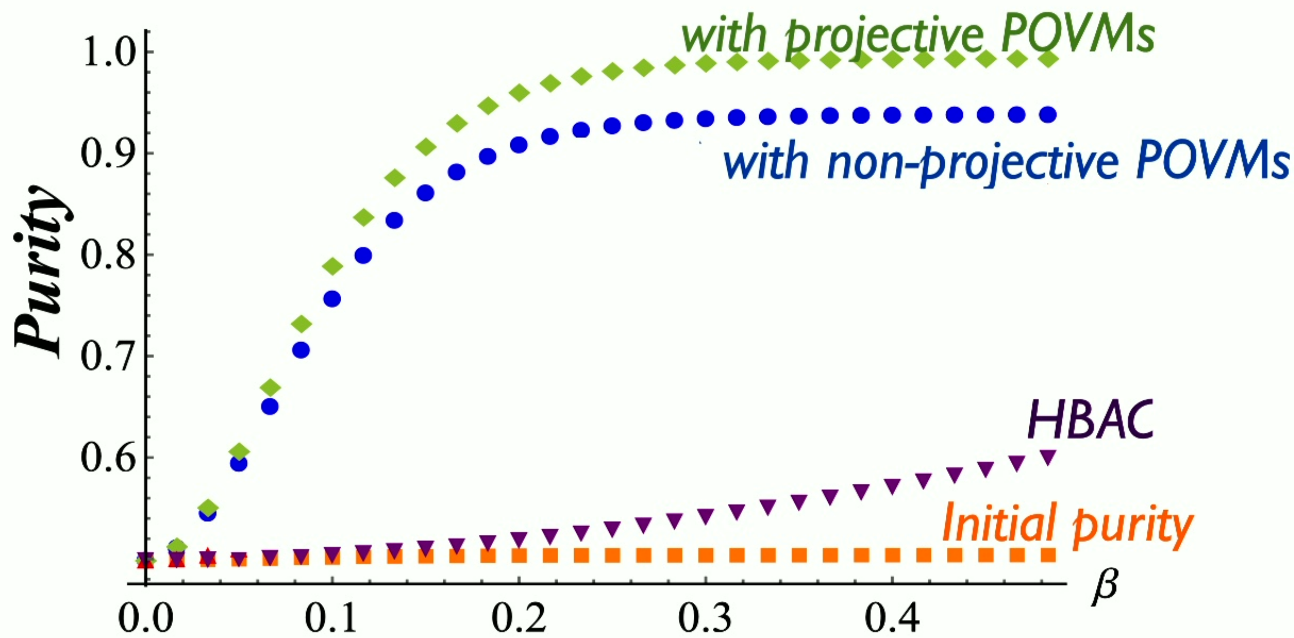
$$H = \sigma_Z^A + \sigma_Z^B + \kappa \left(\frac{1+\gamma}{2} \sigma_X^A \sigma_X^B + \frac{1-\gamma}{2} \sigma_Y^A \sigma_Y^B \right)$$



$\gamma=1$

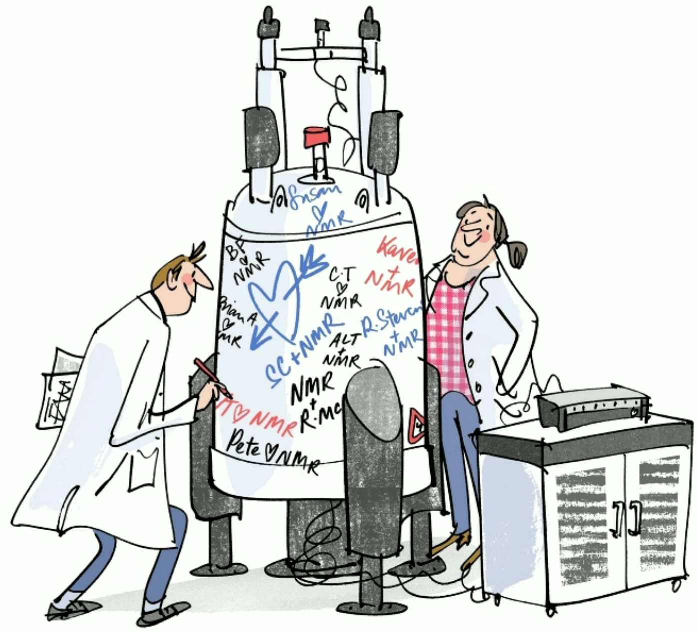
N. Rodríguez-Briones, E.Martín-Martínez, A. Kempf, R. Laflamme Phys. Rev. Lett. 119 (5), 050502

How is QET-enhanced cooling in comparison with previous methods?



44

Experimental test of QET



Experimental test of QET

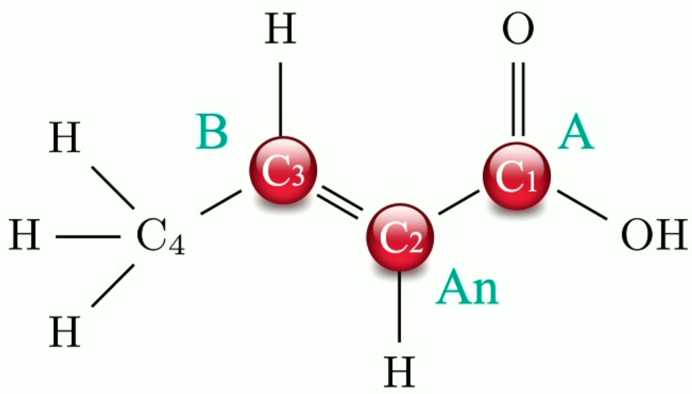
NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. In press PRL. arXiv:2203.16269

First QET experimental implementation

Transcrotonic acid

$$H = \sigma_Z^A + \sigma_Z^B + \kappa\left(\frac{1+\gamma}{2}\sigma_X^A\sigma_X^B + \frac{1-\gamma}{2}\sigma_Y^A\sigma_Y^B\right)$$

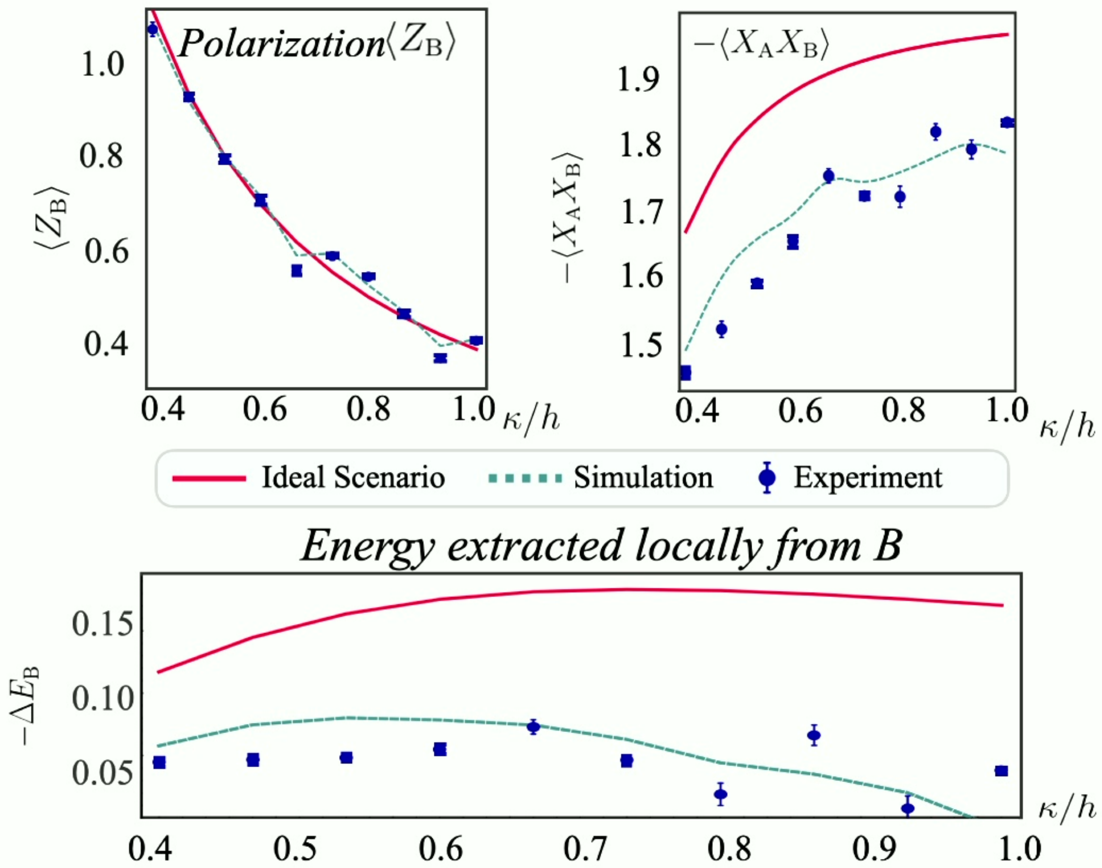
$\gamma=1$



	$\mathbf{C}_1$	$\mathbf{C}_2$	$\mathbf{C}_3$	$\mathbf{C}_1$
$\mathbf{C}_1$	-29343.19			
$\mathbf{C}_2$	72.27	-21591.54		
$\mathbf{C}_3$	1.16	69.68	-25463.29	
$\mathbf{C}_4$	7.04	1.44	41.65	-2991.62

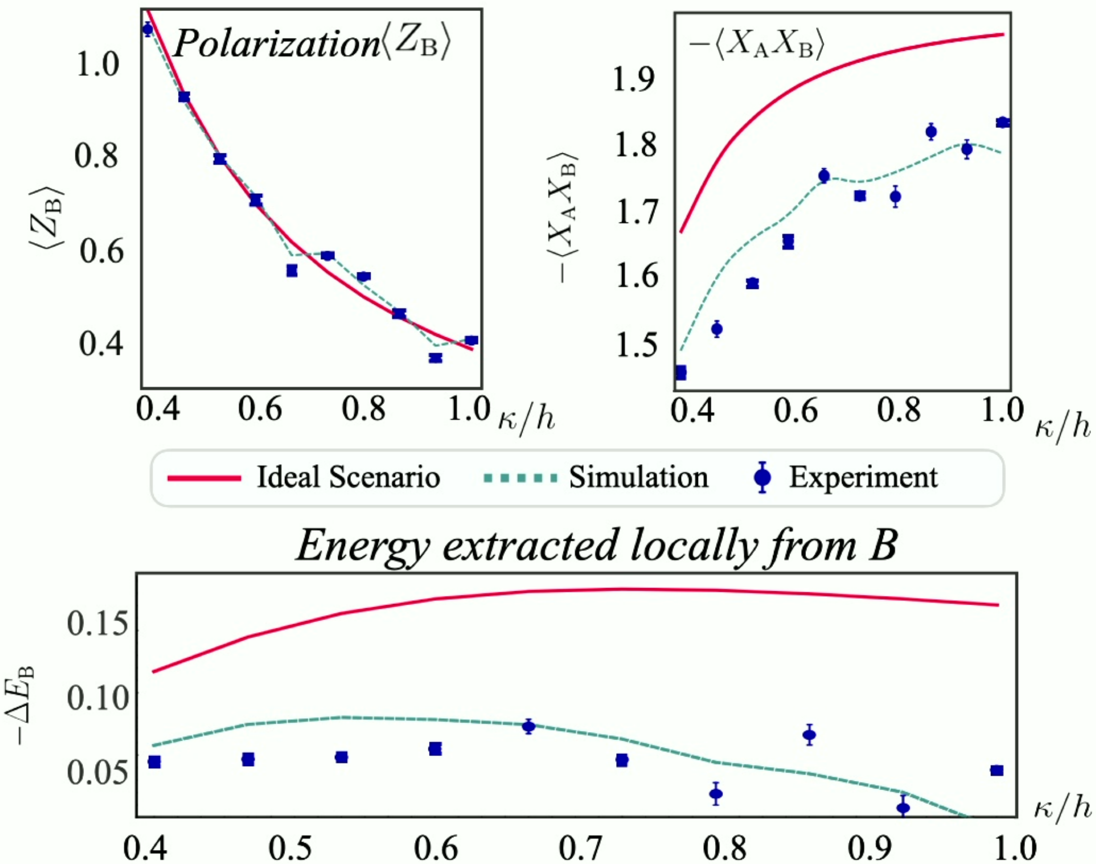
NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. arXiv preprint arXiv:2203.16269

Experimental results



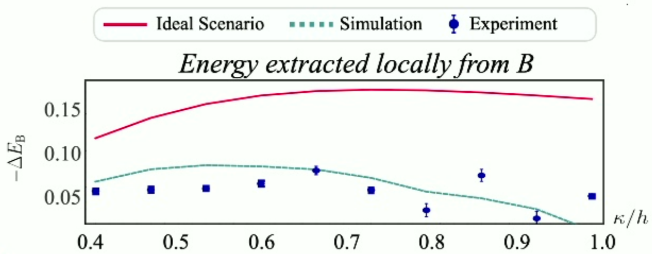
NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. arXiv preprint arXiv:2203.16269

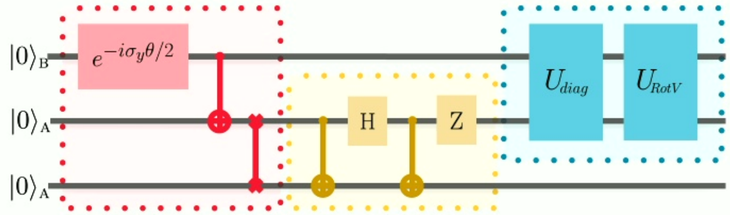
Experimental results



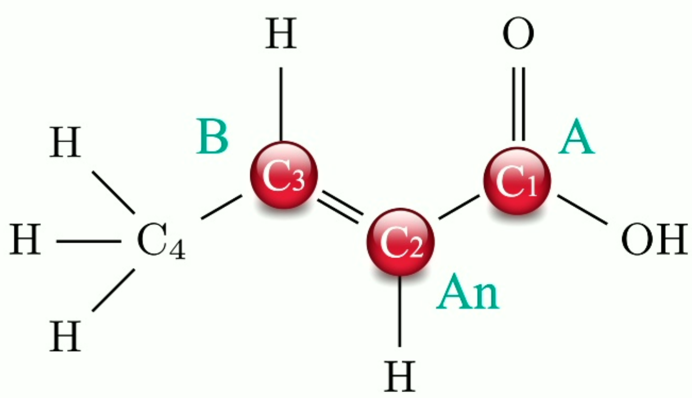
NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. arXiv preprint arXiv:2203.16269

Experimental results





13.8 ms **14.3 ms** **Pulse duration: 9.5 ms**



Energy propagation time ~1 *s*

Total experiment duration: 37.6 ms

NA Rodríguez-Briones, H Katiyar, R Laflamme, E Martín-Martínez. arXiv preprint arXiv:2203.16269

Breaking Strong Local Passivity
Quantum Energy Teleportation

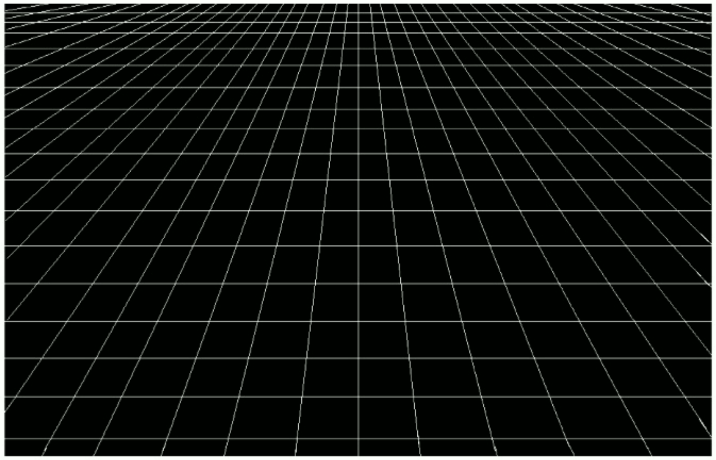
Unexpected result: Activate zero-point energy
Consuming **entanglement**

What about quantum fields?

Ground state is entangled!

Can we pull the same trick?

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)

General Relativity

Einstein Equations:

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

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:

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"
Null Energy condition: "Positive null flow of stress-energy"

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

Exotic spacetimes

Energy Conditions:

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"
Null Energy condition: "Positive null flow of stress-energy"

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

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…

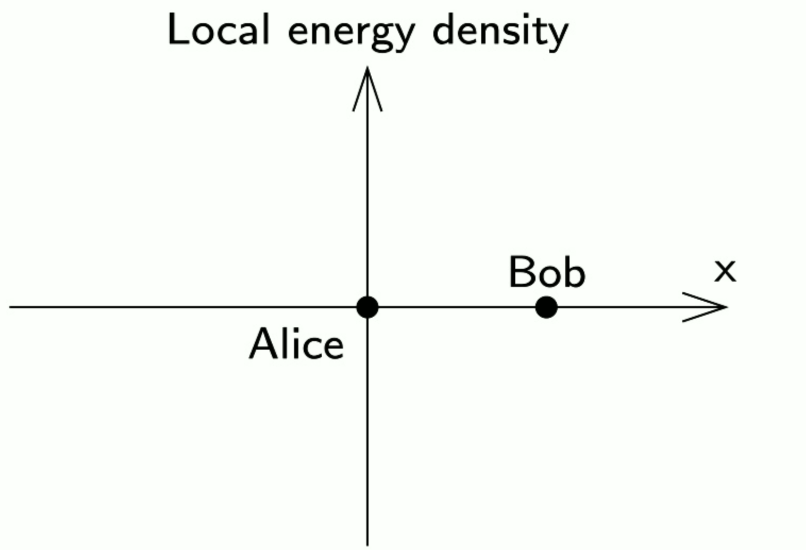
Exotic spacetimes

How can we engineer violations of AWEC?

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

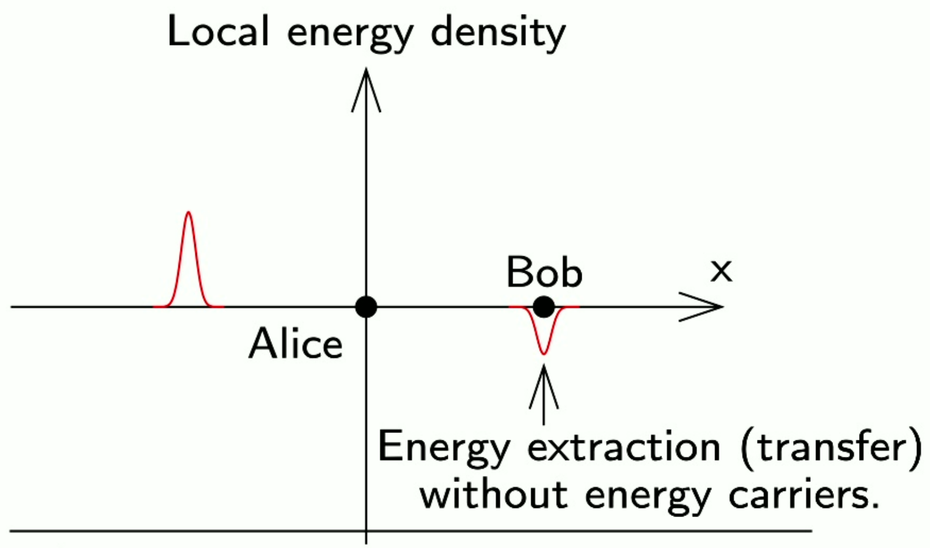
Extreme Dynamical Casimir effect

Breaking Strong Local Passivity Quantum Energy Teleportation



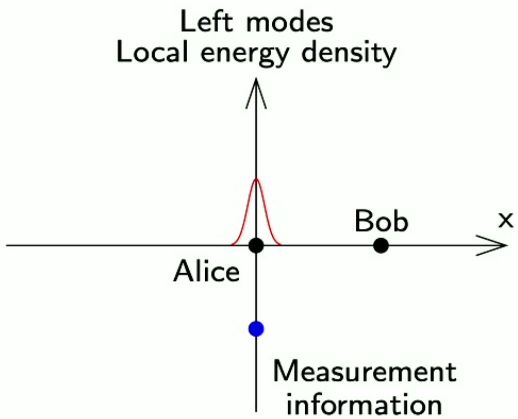
[1]Hotta, *Phys. Rev. D.*, 78.045006, Aug 2008

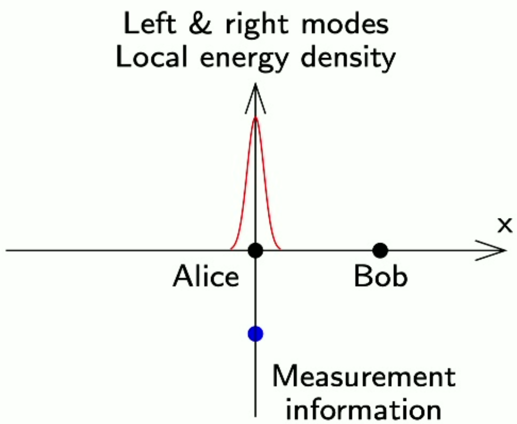
Breaking Strong Local Passivity Quantum Energy Teleportation



[1] Hotta, *Phys. Rev. D.*, 78.045006, Aug 2008
[2] Hotta, *J. Phys. A: Math. Theor.*, 43,105305 (2010)

Breaking Strong Local Passivity
Quantum Energy Teleportation





So what's the plan?

What we will do:

1-We will focus on the state of the field

Protocol

1-Alice measures the field by coupling an atom (or array of atoms) to it

2-Alice measures her non-relativistic atom

3-Alice broadcasts the result of the measurement to an agency of Bob's

A toy first: 1+1D QET stress-energy engineering

The system is initially in a separable state (qubit state $|A_0\rangle$, field vacuum state $|0\rangle$):

$$|\psi(t<0)\rangle = |A_0\rangle \otimes |0\rangle \,.$$

Alice interacts via:

$$\hat{H}_{\text{int}} = \delta(t)\hat{\sigma}_x \otimes \int \mathrm{d}^{n-1}\boldsymbol{r}\, \lambda(\boldsymbol{r})\hat{\pi}(\boldsymbol{r}).$$

Alice teleports her qubit to Bob, interacting via:

$$\hat{H}_{\text{int}} = \delta(t-T)\hat{\sigma}_z \otimes \int \mathrm{d}\boldsymbol{r}\, \mu(\boldsymbol{r})\hat{\phi}(\boldsymbol{r}).$$

LOQC variant of QET Phys. Rev. A 93, 022308 (2016)

A toy first: 1+1D QET stress-energy engineering

The system is initially in a separable state (qubit state $|A_0\rangle$, field vacuum state $|0\rangle$):

$$|\psi(t<0)\rangle = |A_0\rangle \otimes |0\rangle \,.$$

When $n = 2$ the resulting stress-energy density is given by:

$$\left\langle :\hat{T}_{00}(x,t): \right\rangle = \overbrace{\frac{(\lambda'(x-t))^2}{4} + \frac{(\lambda'(x+t))^2}{4}}^{\text{Alice's energy contribution}} + \overbrace{\frac{(\mu(x-(t-T)))^2}{4} + \frac{(\mu(x+(t-T)))^2}{4}}^{\text{Bob's energy contribution}}$$

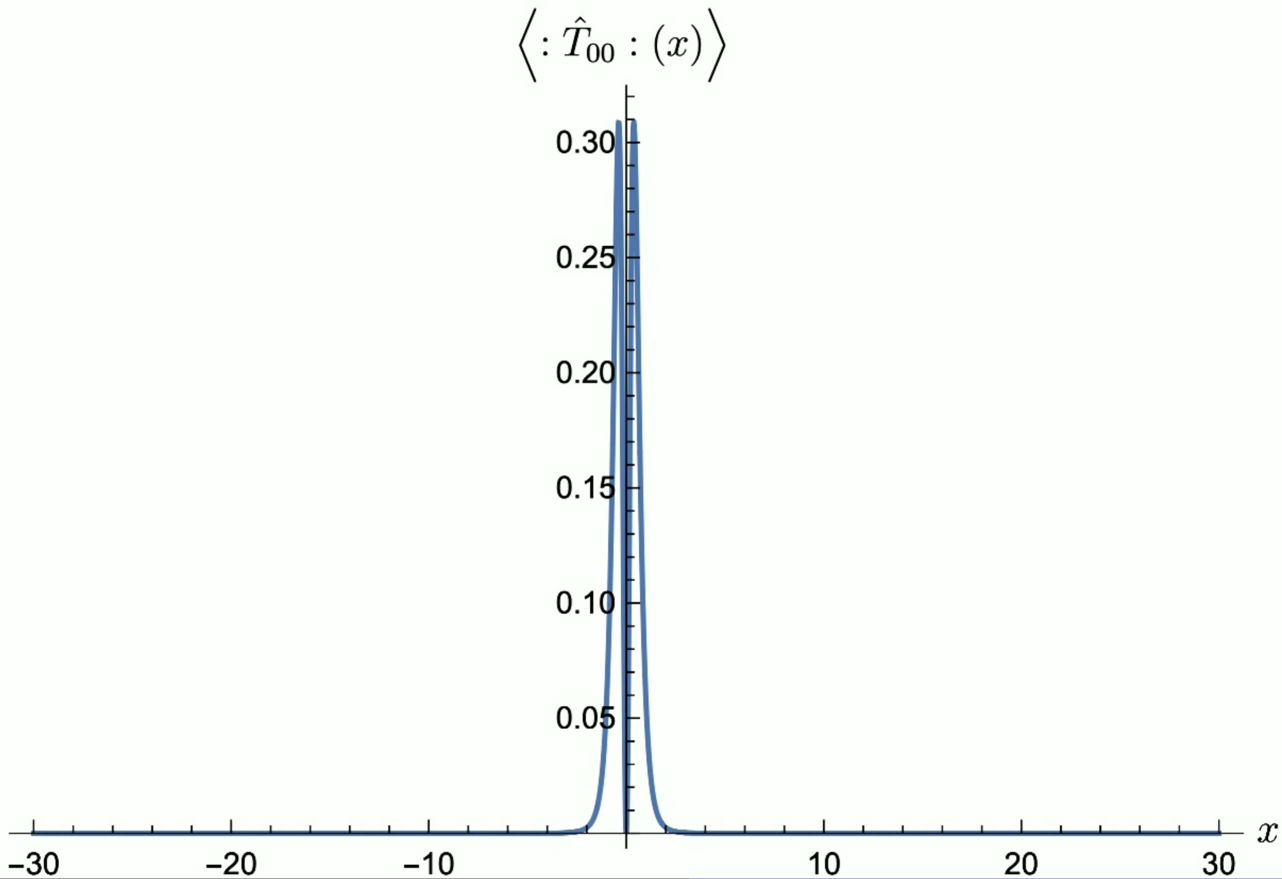
$$+ \underbrace{\frac{e^{-2\|\alpha\|}\langle A_0|\hat{\sigma}_y|A_0\rangle}{2\pi}\mu(x-(t-T))\int dy\lambda'(y)\frac{P.P}{y-x+t}}_{\text{Right moving QET term}}$$

$$+ \underbrace{\frac{e^{-2\|\alpha\|}\langle A_0|\hat{\sigma}_y|A_0\rangle}{2\pi}\mu(x+(t-T))\int dy\lambda'(y)\frac{P.P}{y-x-t}}_{\text{Left moving QET term}} \,.$$

1+1 D QET

Energy density immediately following Alice's interaction.

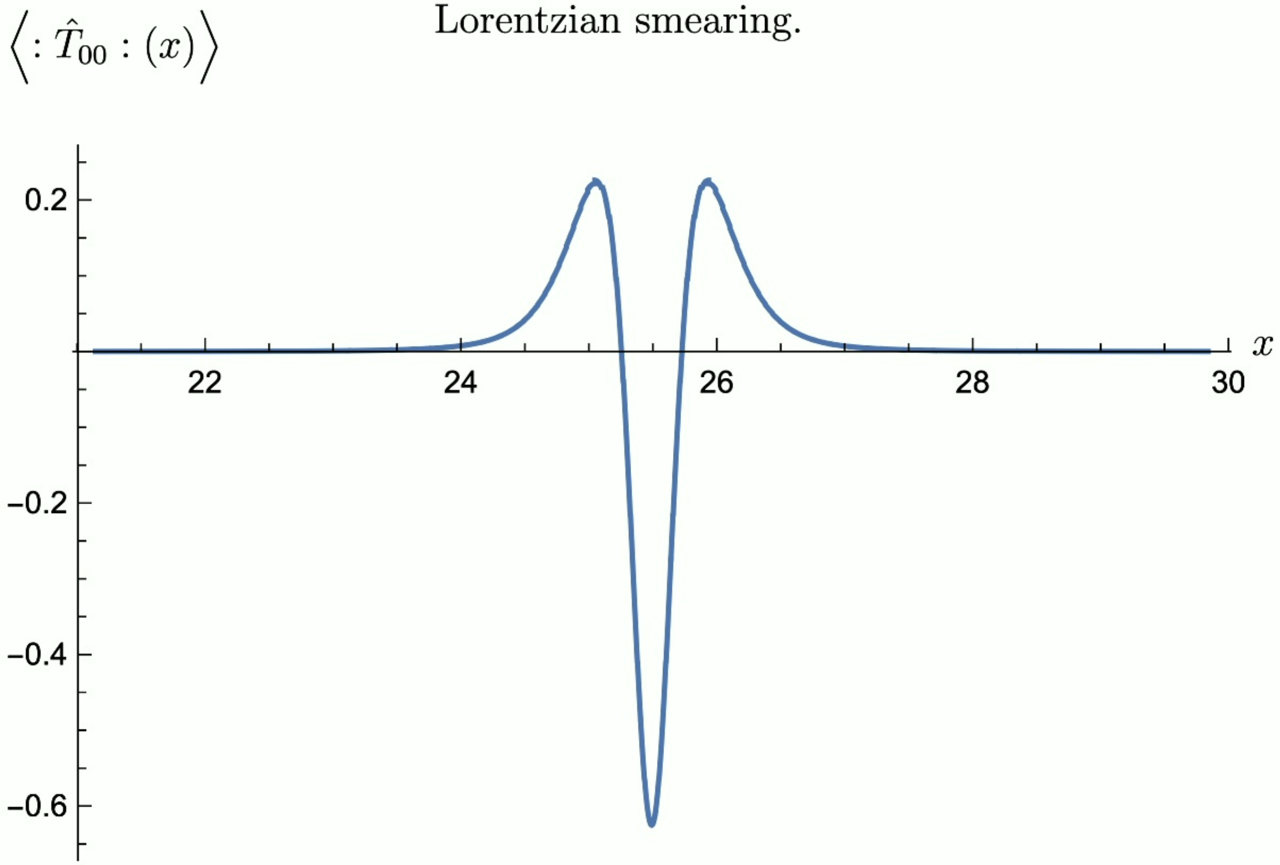
Lorentzian smearing.



1+1 D QET

Energy density ΔT after Bob's interaction.

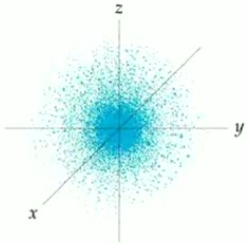
Lorentzian smearing.



3+1D Case

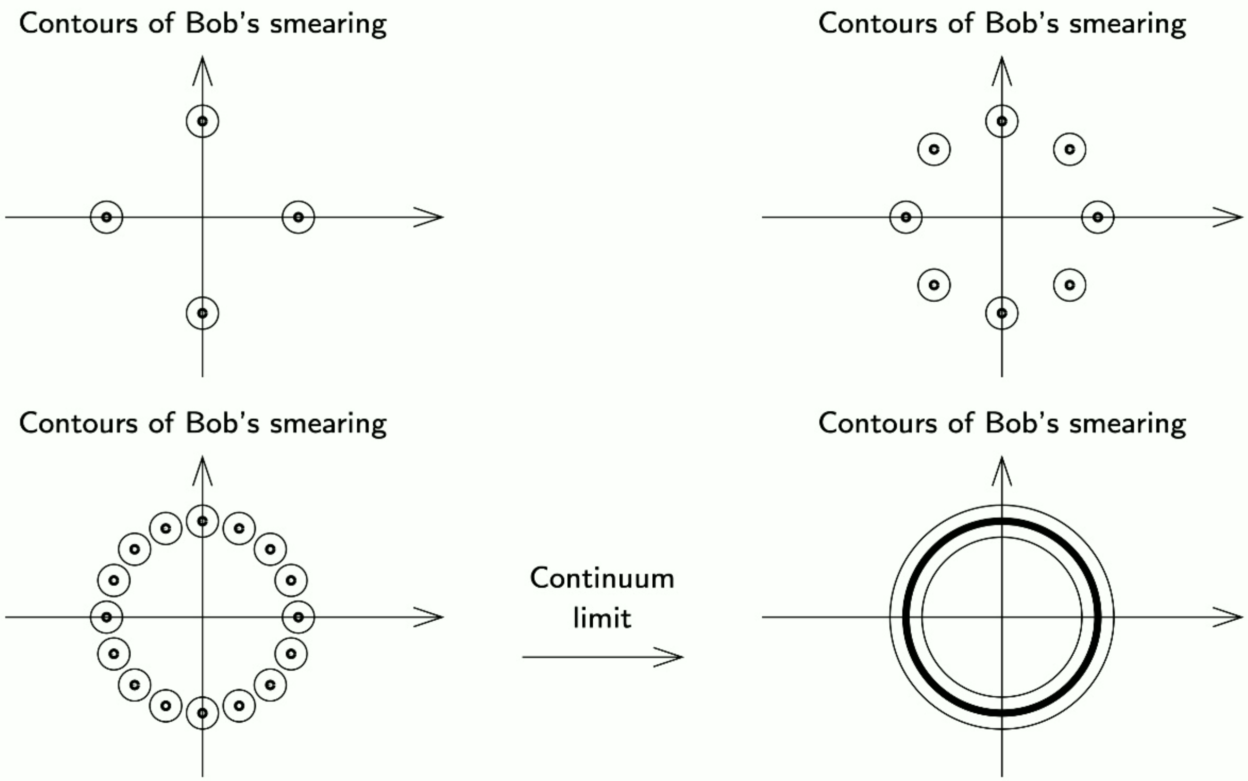
Gravity needs more dimensions….

We need a distribution of Alices and a distribution of Bobs.



We cannot teleport the state of Alice's detectors to every Bob

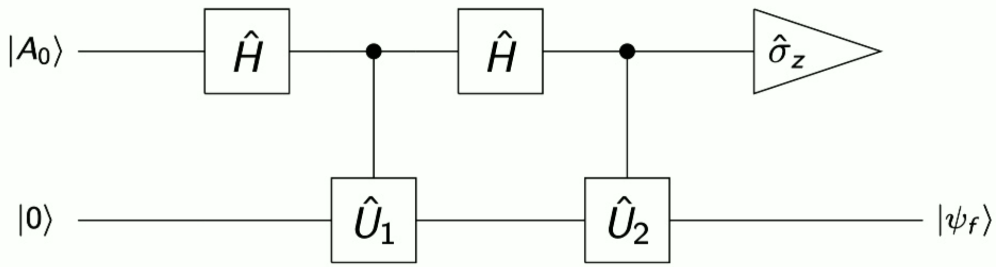
3+1D Case


Contours of Bob's smearing
Contours of Bob's smearing
Contours of Bob's smearing
Continuum
limit
Contours of Bob's smearing

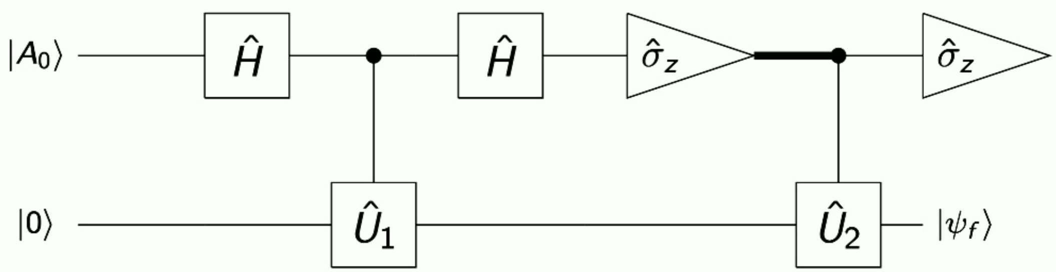
3+1D Case

If $|A_0\rangle$ is an eigenstate of $\hat{\sigma}_y$ then the LOCC protocol gives the same final state ($|\psi_f\rangle$) as LOQC, provided the final measurement $\hat{\sigma}_z$ give the same result.

LOQC



LOCC



3+1D Case

1-Alice measures the field by coupling an atom to it

2-Alice measures her non-relativistic atom

3-Alice broadcasts the result of the measurement to an agency of Bob's

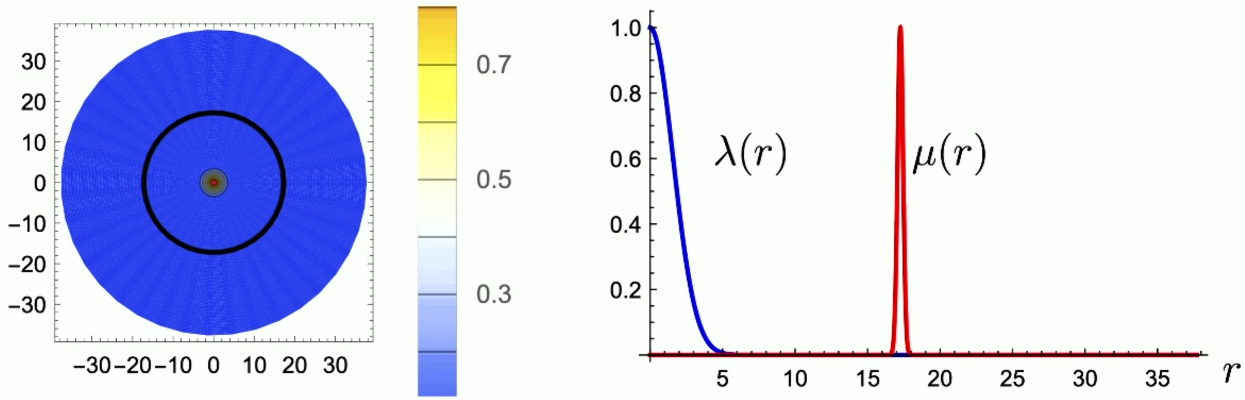
4-Bob's agents use that information to prepare atoms and couple to the field

$$
\langle\psi(t)|:\hat{T}_{\mu\nu}:(\boldsymbol{x})|\psi(t)\rangle = \Bigg\{ \overbrace{\left(I^1_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{1,\lambda}}{2}\right)}^{\text{Bob's energy contribution}} - \overbrace{\left(I^2_\mu I^2_\nu - \eta_{\mu\nu}\frac{I^2_\lambda I^{2,\lambda}}{2}\right)}^{\text{Alice's energy contribution}}
$$

$$
\underbrace{- \langle A_0|\hat{\sigma}_y|A_0\rangle e^{-2\|\alpha\|}\left(\left(I^1_\mu I^3_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right) + \left(I^3_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right)\right)}_{\text{QET term}} \Bigg\}
$$

3+1 D QET

Gaussian smearing functions used.

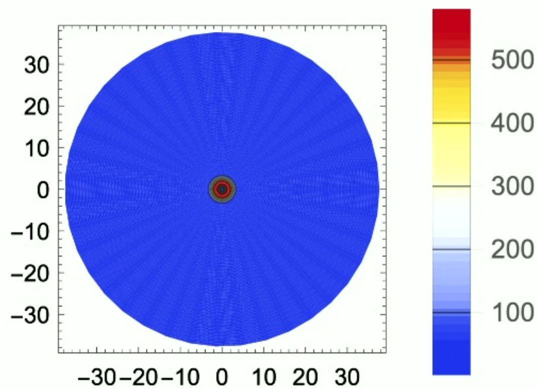


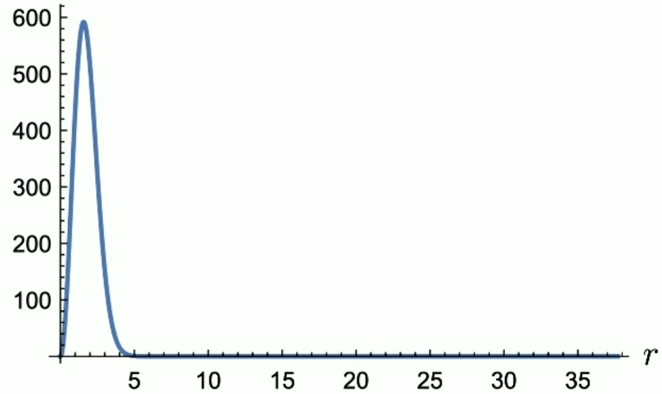
3+1 D QET

Energy density immediately following Alice's interaction.

Gaussian smearing.

$\left\langle : \hat{T}_{00} : (r) \right\rangle$



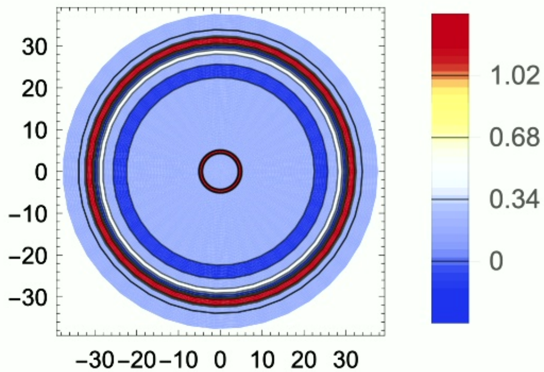


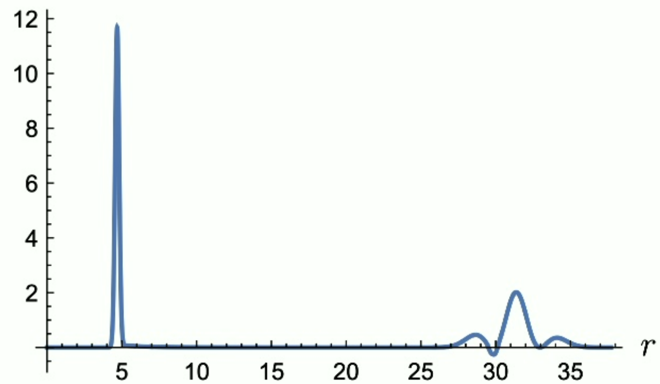
3+1 D QET

Energy density ΔT after to Bob's interaction.

Gaussian smearing.

$$\left\langle : \hat{T}_{00} : (r) \right\rangle$$





Scaling negative energy

Total amount of negative energy:

$$\Phi_E = \int\limits_{\langle : \hat{T}_{00}(\boldsymbol{x},\tau) : \rangle < 0} \langle : \hat{T}_{00} : (\boldsymbol{x}, \tau) \rangle \, d\tau$$

$$\begin{aligned}
\lambda(\boldsymbol{x}) &\to \sigma^{\frac{n-2}{2}} \lambda(\sigma \boldsymbol{x}), \\
\mu(\boldsymbol{x}) &\to \sigma^{\frac{n}{2}} \mu(\sigma \boldsymbol{x}), \\
\left\langle : \hat{T}_{\mu\nu}(\boldsymbol{x}, t) : \right\rangle &\to \sigma^{n} \left\langle : \hat{T}_{\mu\nu}(\sigma \boldsymbol{x}, \sigma t) : \right\rangle \\
\Phi_E &\to \sigma^{n-1} \Phi_E .
\end{aligned}$$

Scaling negative energy

Total amount of negative energy:

$$\Phi_E = \int_{\langle : \hat{T}_{00}(\boldsymbol{x},\tau) : \rangle < 0} \langle : \hat{T}_{00} : (\boldsymbol{x},\tau) \rangle \, d\tau$$

$$\lambda(\boldsymbol{x}) \to \sigma^{\frac{n-2}{2}} \lambda(\sigma \boldsymbol{x}),$$

$$\mu(\boldsymbol{x}) \to \sigma^{\frac{n}{2}} \mu(\sigma \boldsymbol{x}),$$

$$\left\langle : \hat{T}_{\mu\nu}(\boldsymbol{x}, t) : \right\rangle \to \sigma^{n} \left\langle : \hat{T}_{\mu\nu}(\sigma \boldsymbol{x}, \sigma t) : \right\rangle$$

$$\Phi_E \to \sigma^{n-1} \Phi_E .$$

Violates quantum inequalities optimally
and saturates QI conjecture

Summary

QET can be used to **operationally** generate **negative energy distributions**.

Does so “**consuming”** space like vacuum entanglement.

The **negative energy packets** are **accompanied by positive energy** packets.

This suggests interesting scenarios under gravitational backreaction

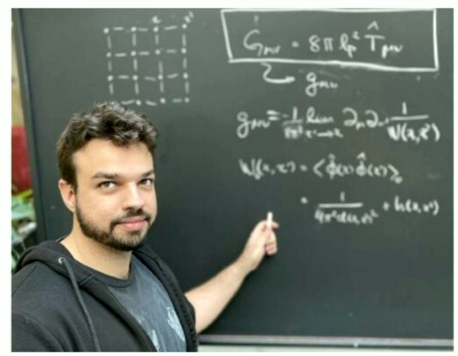
QET protocol scaling saturates the **Quantum Interest Conjecture.**

QET protocol scaling optimally violates **AWEC.**

Future work

Almost arbitrary energy density distributions with arrays of Alices and Bobs **close to the limits of the quantum energy conditions**.

Backreaction on spacetime!!



Future work

Almost arbitrary energy density distributions with arrays of Alices and Bobs **close to the limits of the quantum energy conditions**.

Backreaction on spacetime!!