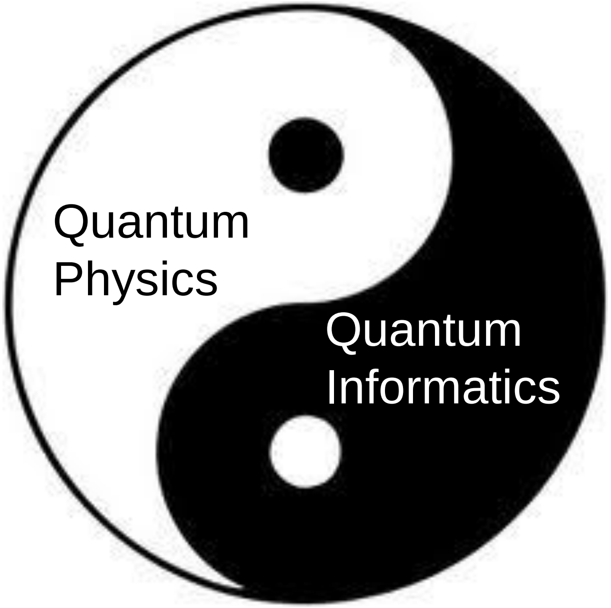
Quantum Energy Teleportation and Black Hole



Quantum Infophysics

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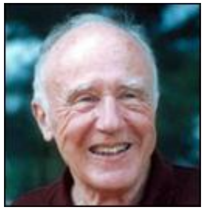
Introduction

Information-based understanding of the Universe has been attracting attention of physicists.



J. Wheeler :

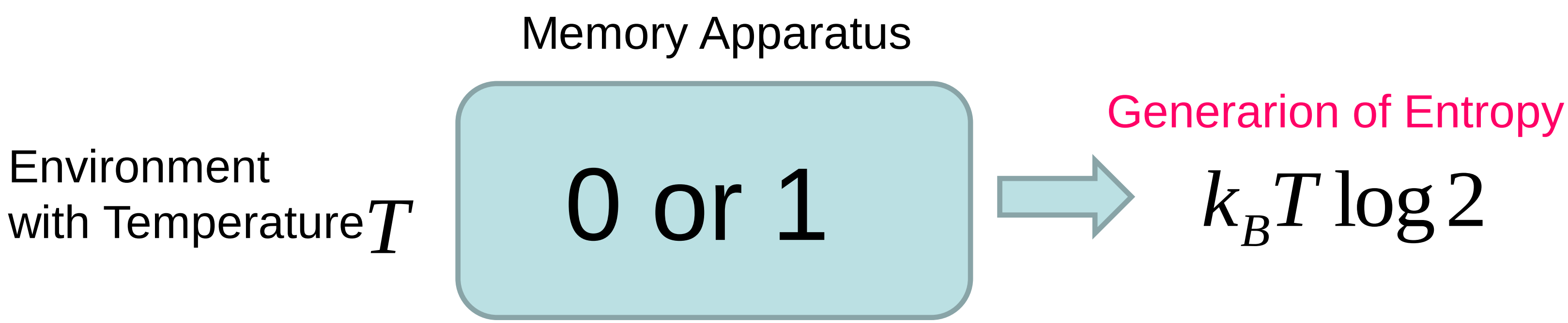
It from bit. Otherwise put, every 'it'—every particle, every field of force, even the space-time continuum itself—derives its function, its meaning, its very existence entirely—even if in some contexts indirectly— from the apparatus-elicited answers to yes-or-no questions, binary choices, bits. 'It from bit' symbolizes the idea that every item of the physical world has at bottom—a very deep bottom, in most instances—an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes–no questions and the registering of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and that this is a participatory universe. (cf. delayed choice experiment)

"Physics is Informational."

On the other hand,
physics-based understanding for computation
has been attracting attention
of information mathematicians.

R. Landauer :

erasure of a bit in a memory
⇒ entropy increase more than $k_B T \log 2$



"Information is Physical."

More recently, interplay between quantum physics and quantum information theory has attracted much attention for many physical problems.

- **Holographic Principle**
  (Origin of Black Hole Entropy, 't Hooft, …., Emergence of Gravity, Verlinde)

- **AdS/CFT Correspondence**
  (Minimal Surface Area/4G in AdS
  =Entanglement Entropy of Boundary CFT Theory, Takayanagi)

- **Information Loss Problem of Quantum Black Hole**
  (Quantum Teleportation from Singularity, Horowitz and Maldacena)

- **Quantum-Classical Transition of Field Fluctuation in Early Universe**
  (Entanglement Disappearance in Expanding Universe, Nambu)

- **Phase Transition of Condensed Matter Physics at Zero Temperature**
  (Entanglement Entropy as "Order Parameter")

Today, I would like to speak an interesting feature of quantum energy-momentum tensor. Though the operators are local, quantum energy itself is an essentially nonlocal concept from the information-theoretical viewpoint.

Performing a distant measurement of vacuum fluctuation, the zero-point energy becomes active and can be extracted by local operation dependent on the measurement result. This protocol is called quantum energy teleportation. This provides a new method of energy extraction from BLACK HOLE.

For simplicity, let us first discuss a massless scalar field in 1+1 dimensional Minkowski spacetime.

$$\left[\partial^2{}_t - \partial^2{}_x\right]\phi(t,x) = 0$$

$$x^{\pm} = t \pm x$$

$$\partial_+ \partial_- \phi = 0$$

$$\phi = \phi_R\left(x^-\right) + \phi_L\left(x^+\right)$$

right-mover component (↑ ϕ_R) **left-mover component** (↑ ϕ_L)

Chiral Momentum Operators

$$\Pi_{\pm}(x) = \Pi(x) \pm \partial_x \phi(x)$$

primary degrees of freedom for left- and right- mover modes of field

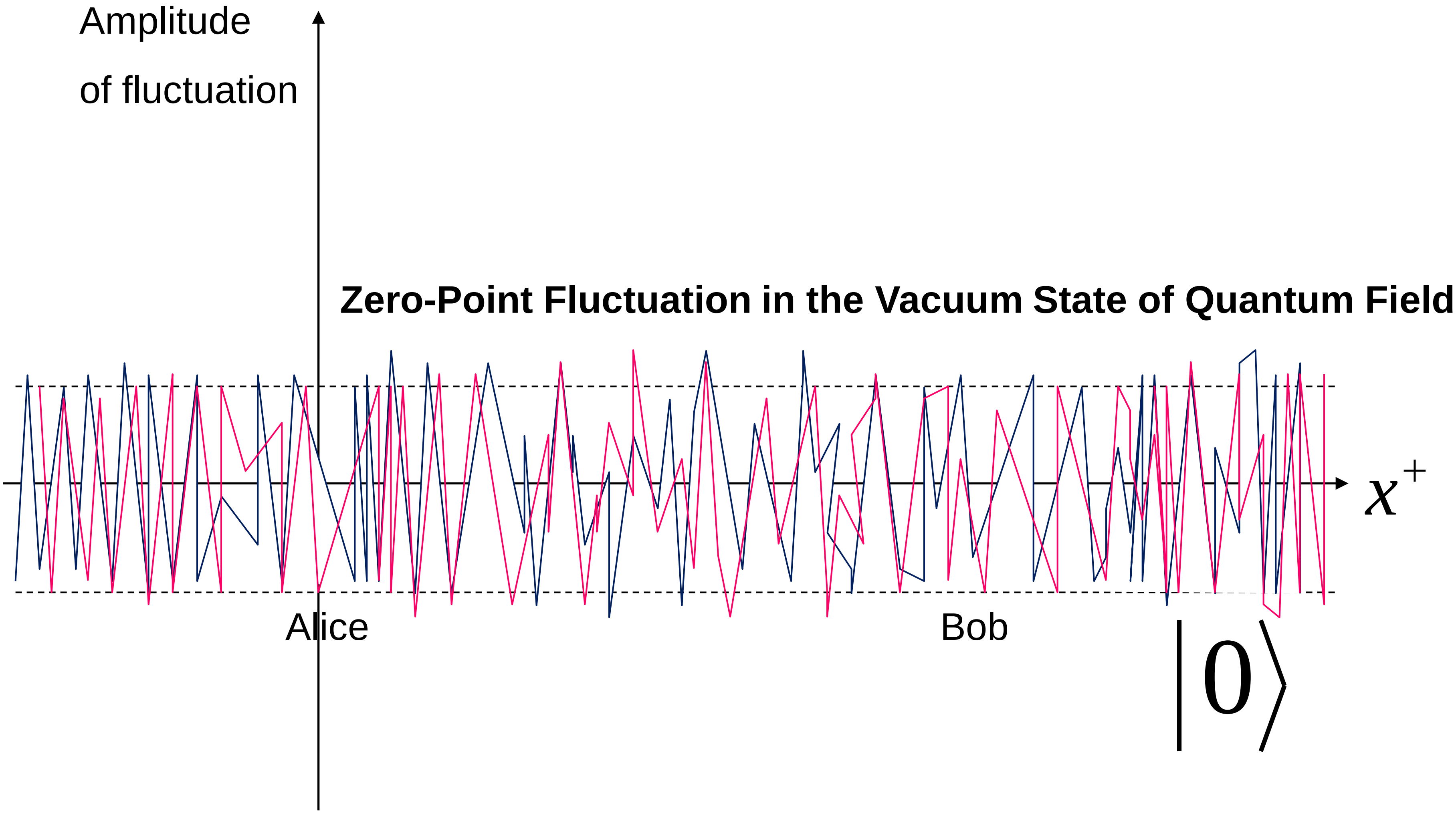
$$\exp(itH)\Pi_{\pm}(x)\exp(-itH) = \Pi_{\pm}(x \pm t) = \Pi_{\pm}(\pm x^{\pm})$$

Energy-Momentum Tensor

$$T_{\mu\nu} =: \partial_\mu \phi \partial_\nu \phi : -\frac{1}{2} g_{\mu\nu} : \left(\partial_\lambda \phi \partial^\lambda \phi\right):$$

Vacuum State

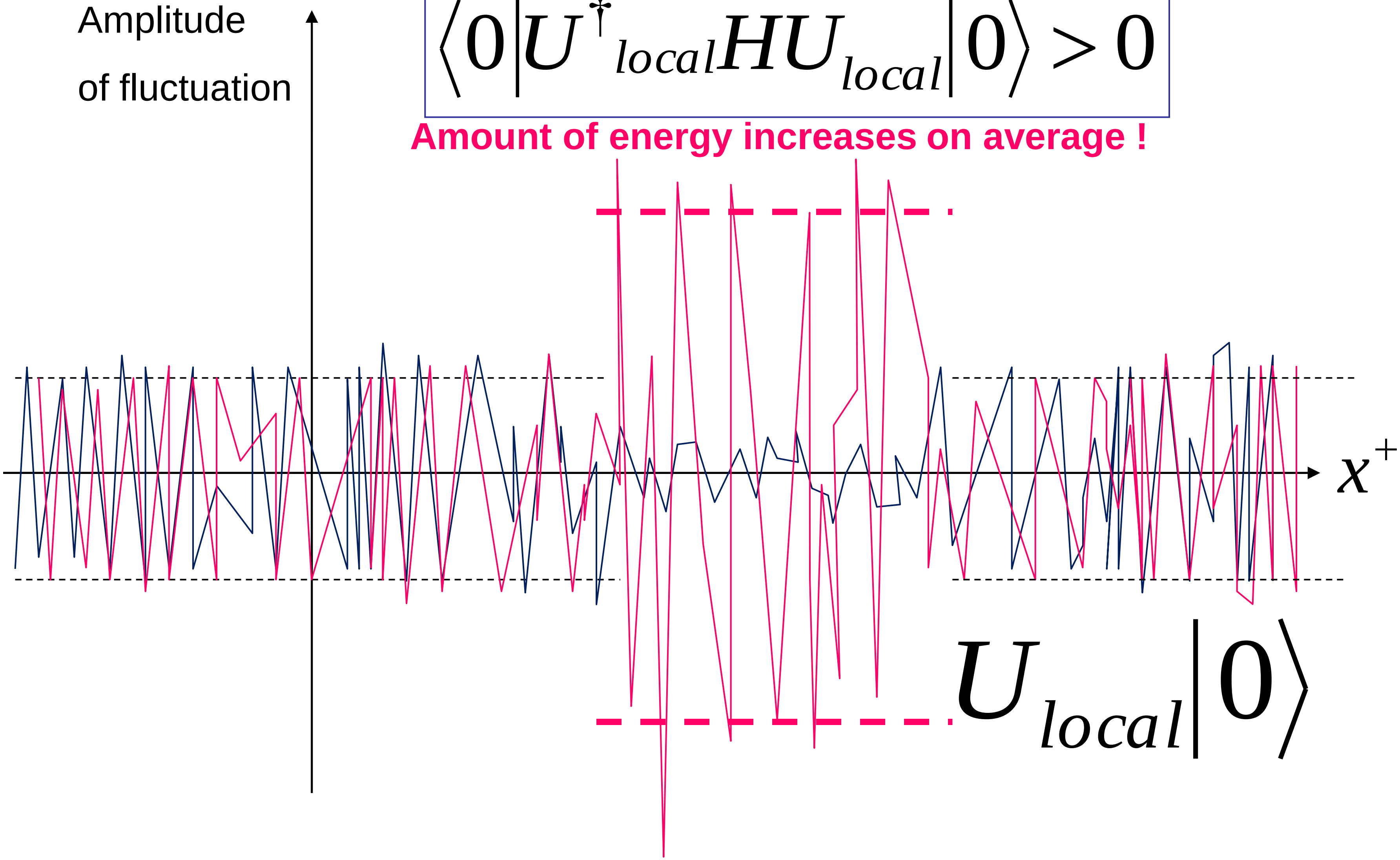
$$H\left|0\right\rangle = 0, \quad \left(H = \int T_{00} dx^3\right)$$



The vacuum state has many components of quantum fluctuation as superposition of states. In the above figure, red and blue lines simply describe those different components.

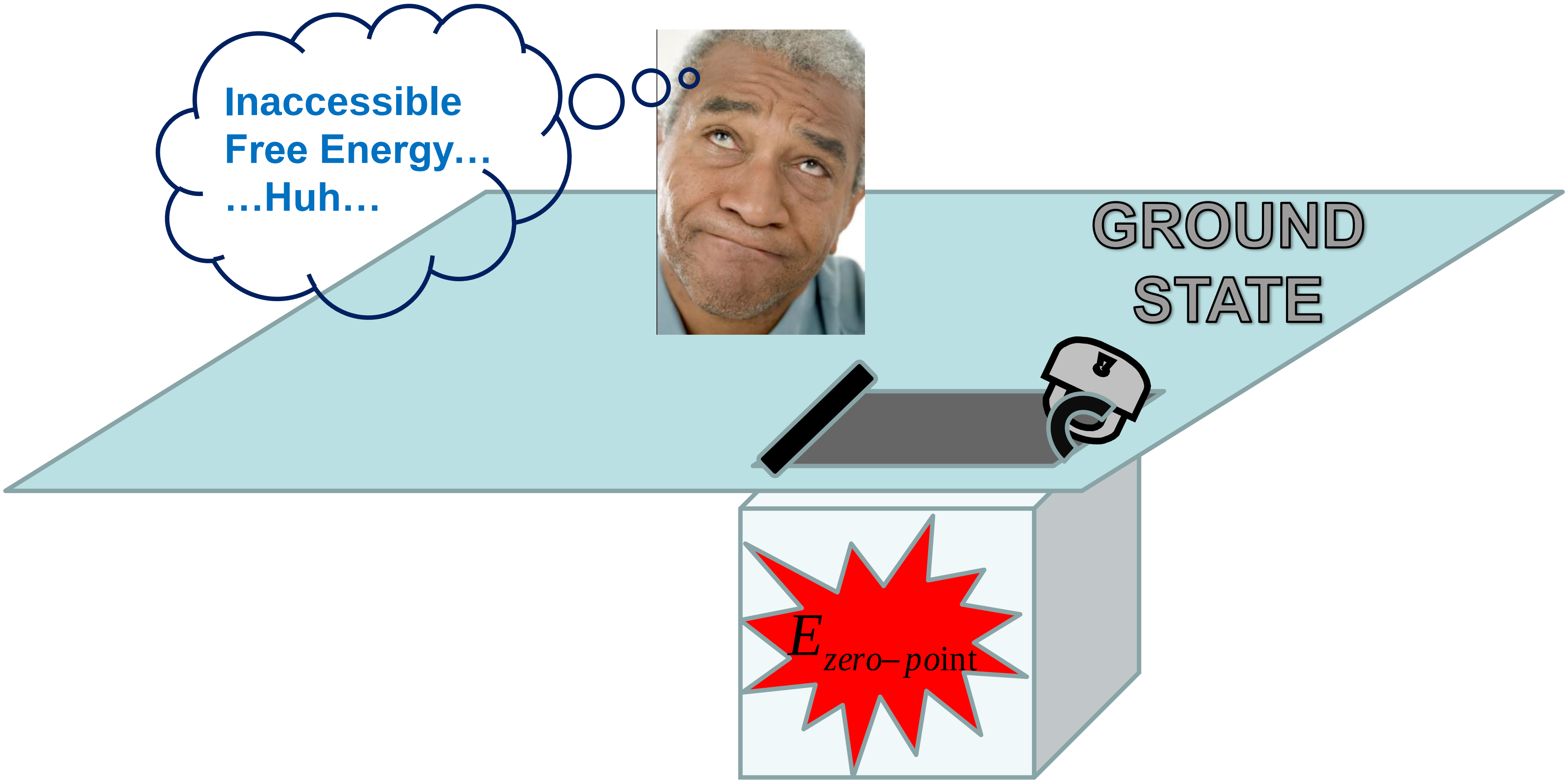
$$\langle 0 | U^{\dagger}_{local} H U_{local} | 0 \rangle > 0$$

Amount of energy increases on average !



If a local unitary acts on vacuum fluctuation, the blue-lined component may become suppressed, but the red-lined component becomes large. Thus, on average, positive amount of energy must be injected into the field. **(Passivity of Vacuum State** W. Pusz and S. L. Woronowicz, Commun. Math. Phys. 58, 273 (1978)**)**

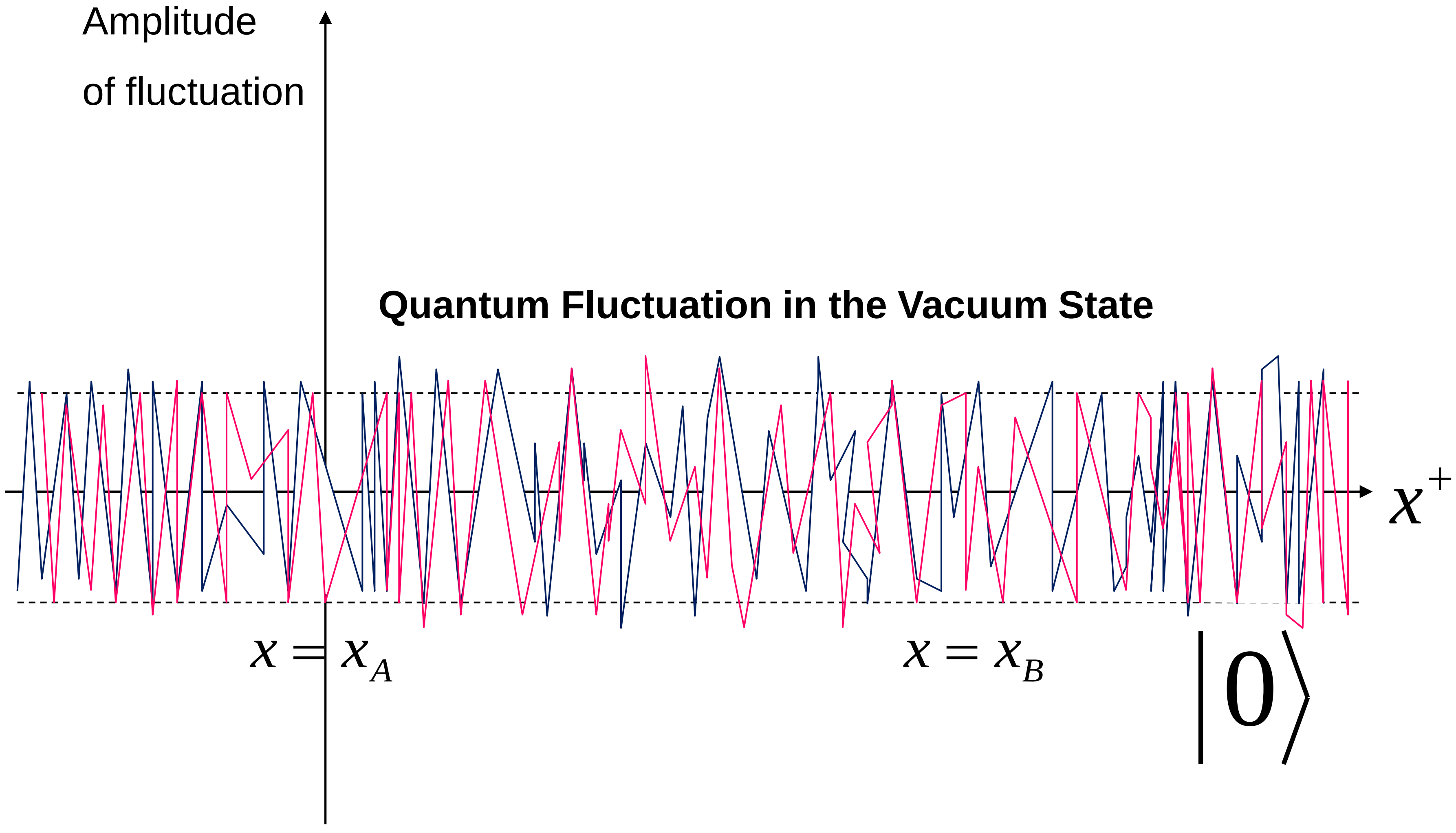
It looks like zero-point energy is saved in a locked safe under your ground...



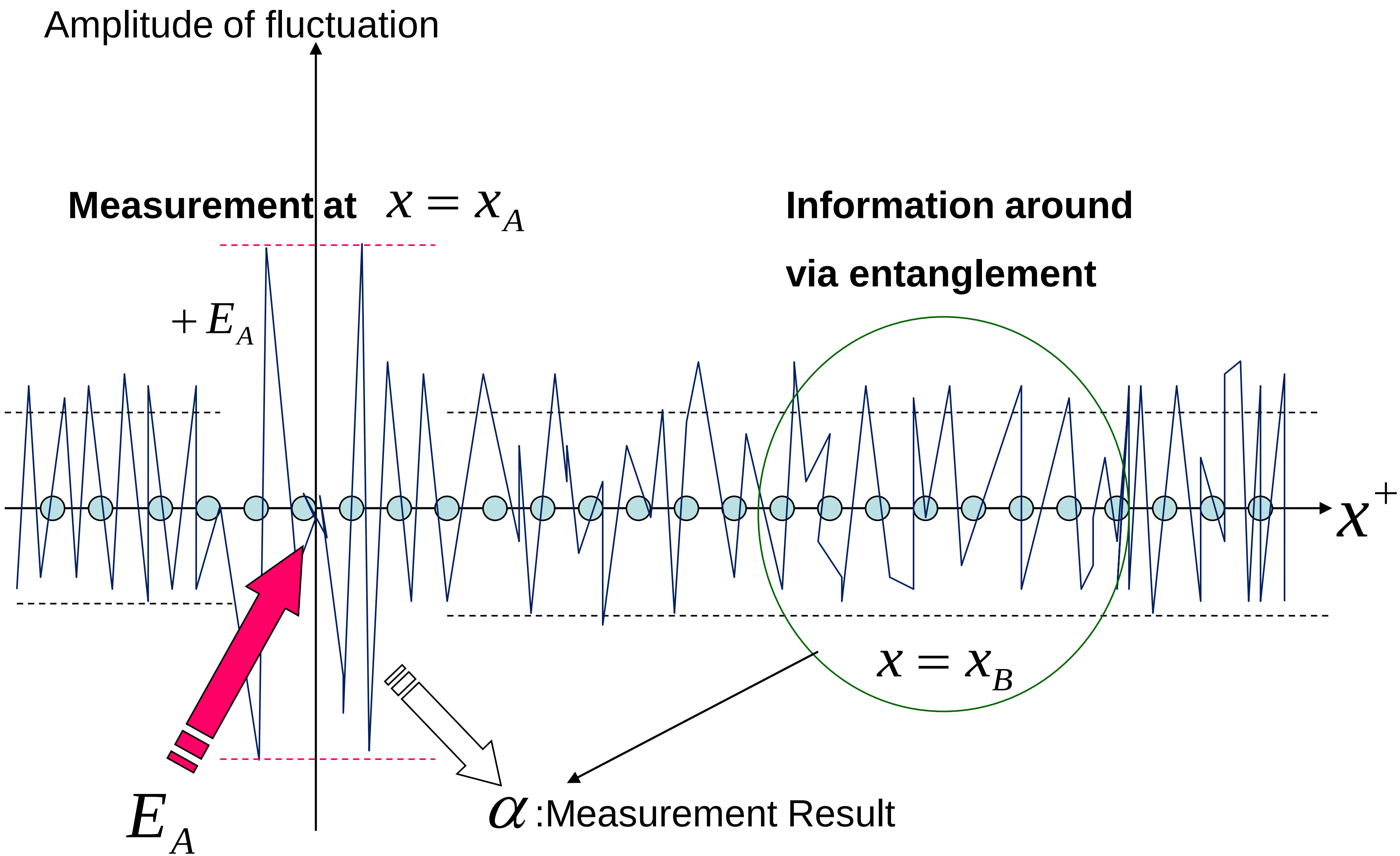
Quantum Energy Teleportation

Using One-Dimensional Massless

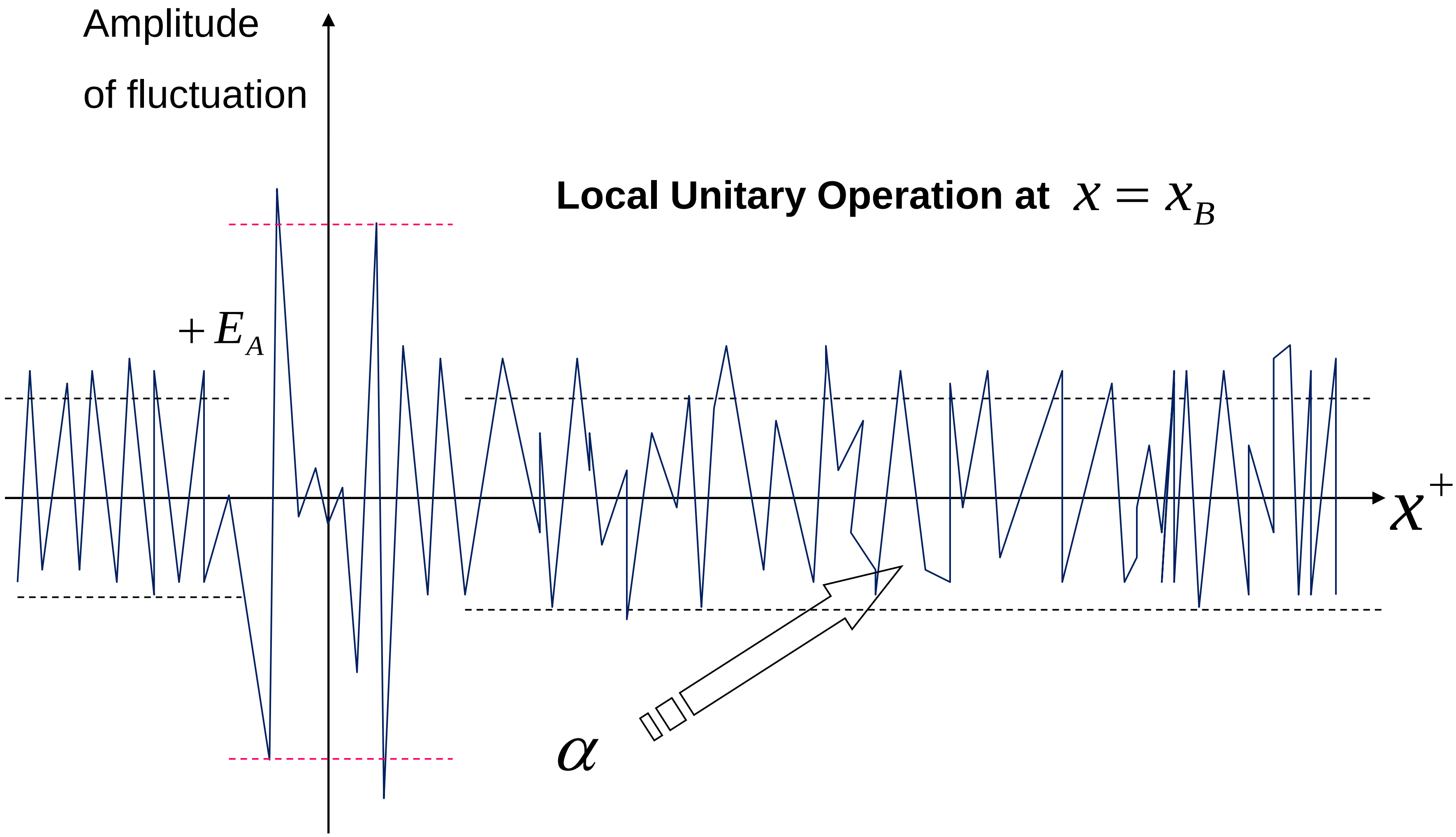
Free Scalar Field



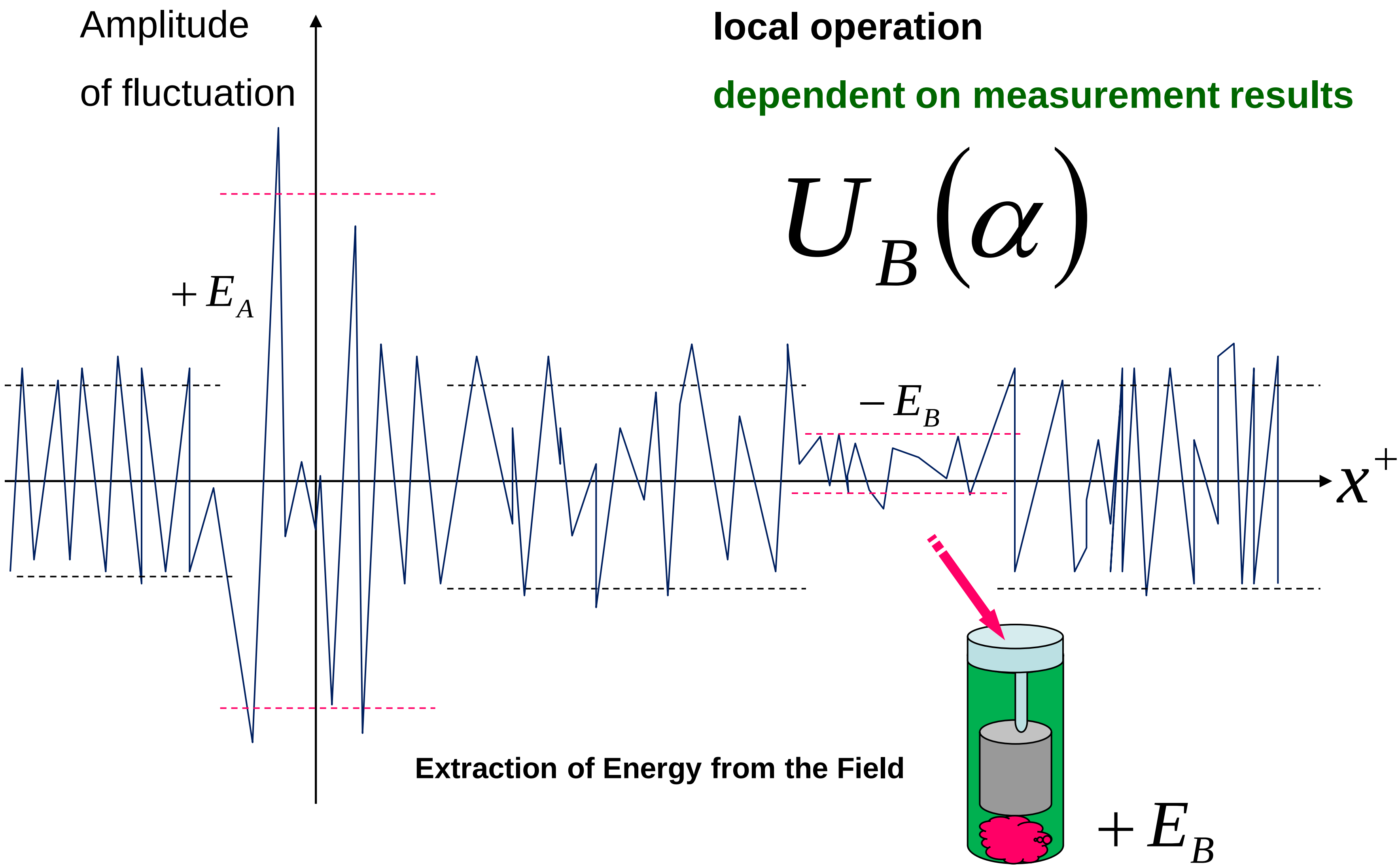
Let us perform a local measurement of zero-point fluctuation at $x = x_A$.



This measurement specifies the fluctuation-pattern component to some extent. In the figure, the blue-lined component is selected and the red-lined component vanishes due to wavefunction collapse. Because of the vacuum-state entanglement, the measurement result α includes information about fluctuation around $x = x_B$ **.**



By getting information about α at $x = x_A$, we know how the fluctuation behaves at $x = x_B$. Because the red component does not exist, we are able to choose an appropriate unitary operation corresponding to the blue-lined pattern and suppress the quantum fluctuation.



By squeezing this fluctuation locally, we can obtain energy from the field. This extracted energy was hidden in the local-vacuum region from the start ! Therefore, no energy carrier is hired in the QET protocol !!

Let us consider a two-level spin which stays at $x = x_A$ as the probe system of this QET measurement.

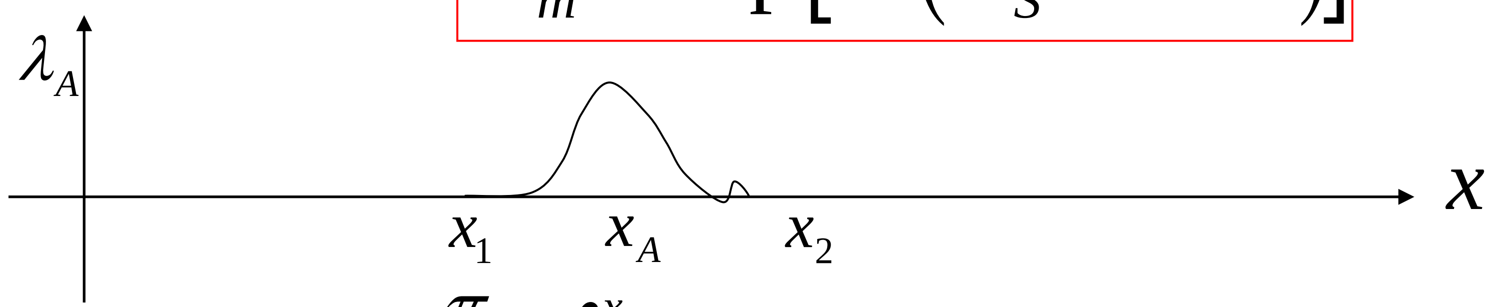
Measurement Model: Instantaneous Interaction Between Field and Spin at t=0

The initial state of the spin is the up state of the z component.

After the measurement interaction, the z component of the spin is measured.

Measurement Evolution:

$$U_m = \exp\left[-i\left(\Phi_S \otimes \sigma^y{}_P\right)\right]$$



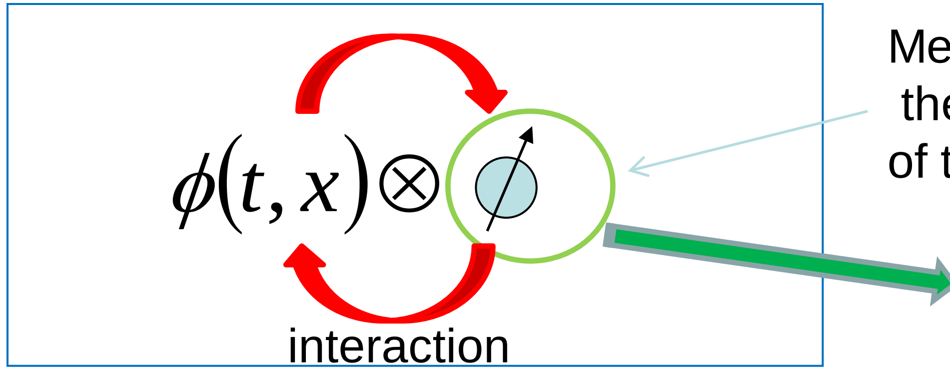
$$\Phi_S = \frac{\pi}{4} - \int_{x_1}^{x_2} \lambda_A(x)\Pi_+(x)dx$$

Measurement Operators:

$$M_A(\pm)\rho_S M^*{}_A(\pm) = Tr_P\left[\left(I \otimes |\pm\rangle\langle\pm|_P\right)U_m\left(\rho_S \otimes |+\rangle\langle+|_P\right)U_m{}^*\right]$$

$$M_A(+) = \cos\Phi_S, \quad M_A(-) = \sin\Phi_S$$

field × spin at $x = x_A$



Measure the z component of the spin

$\alpha = \pm$
measurement result

Emergence probability of $\alpha = \pm$ **for the vacuum state**

$$p_\alpha = Tr\left[|0\rangle\langle 0| M_A(\alpha)^* M_A(\alpha)\right]$$

$$M_A(+) = \cos\Phi_S, \quad M_A(-) = \sin\Phi_S$$

$$\Phi_S = \frac{\pi}{4} - \int_{-\infty}^{\infty} \lambda_A(x)\Pi_+(x)dx$$

We obtain the same probability for α **:**

$$p_\alpha = \frac{1}{2}$$

Post-Measurement States of Quantum Field

$$\alpha = + \Rightarrow |\psi_+\rangle = \frac{1}{\sqrt{2}}\left(e^{\frac{i\pi}{4}}|\lambda_A\rangle + e^{-\frac{i\pi}{4}}|-\lambda_A\rangle \right)$$

$$\alpha = - \Rightarrow |\psi_-\rangle = \frac{1}{\sqrt{2}}\left(e^{-\frac{i\pi}{4}}|\lambda_A\rangle + e^{\frac{i\pi}{4}}|-\lambda_A\rangle \right)$$

left-mover coherent state of field

$$|\pm\lambda_A\rangle \propto \exp\left[\pm i \int_{x_1}^{x_2} \lambda_A(x)\Pi_+(x)dx \right]|0\rangle$$

Time Evolution of Post-Measurement State

$$\rho_\alpha(t) = U(t)\frac{M_A(\alpha)|0\rangle\langle 0|M_A(\alpha)^*}{\langle 0|M_A(\alpha)^* M_A(\alpha)|0\rangle}U(t)^*$$

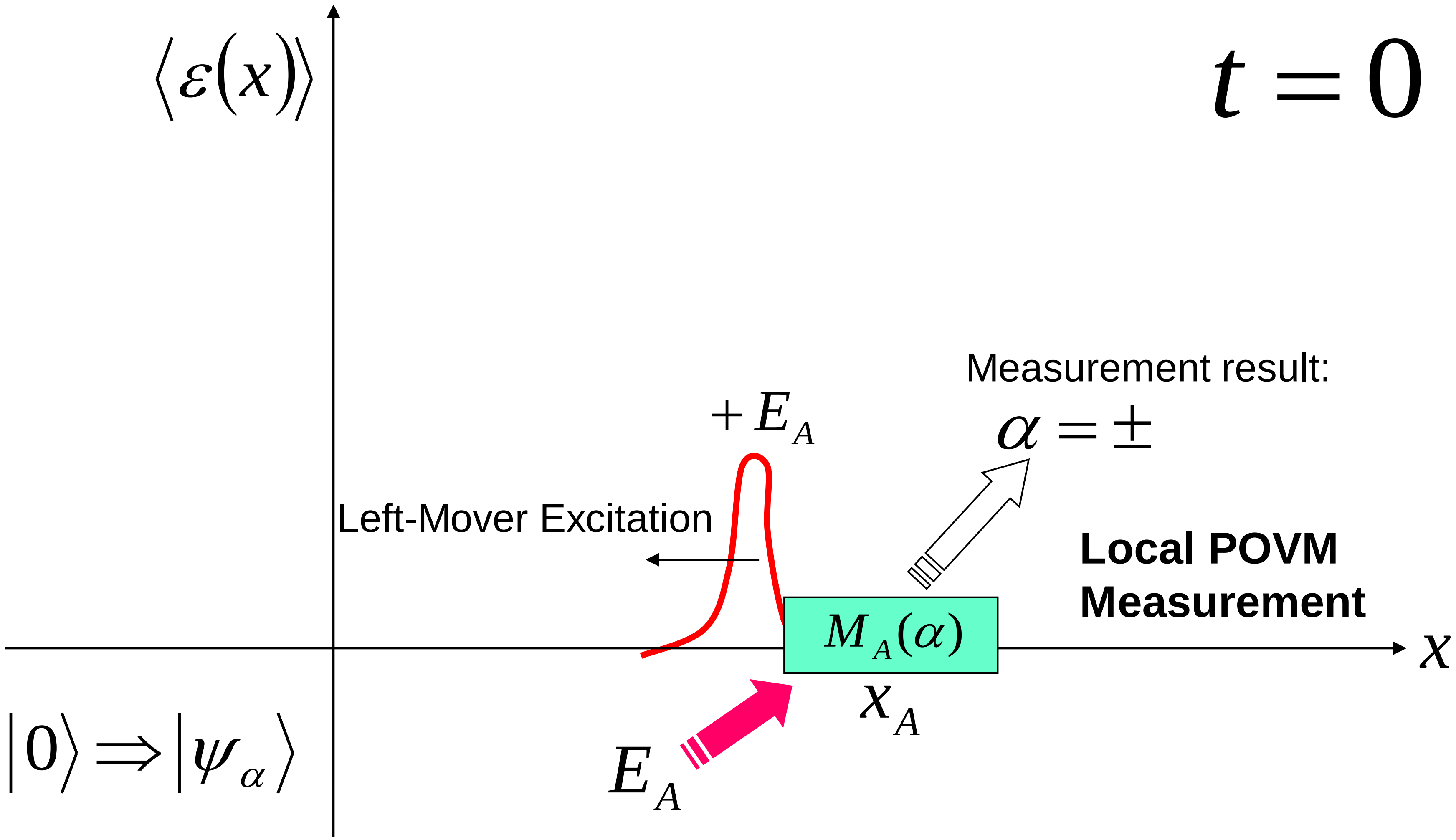
$$= U(t)|\psi_\alpha\rangle\langle\psi_\alpha|U(t)^*$$

$$\left(U(t) = \exp\left[-itH\right]\right)$$

In this model, energy density and its time evolution is independent of the measurement result:

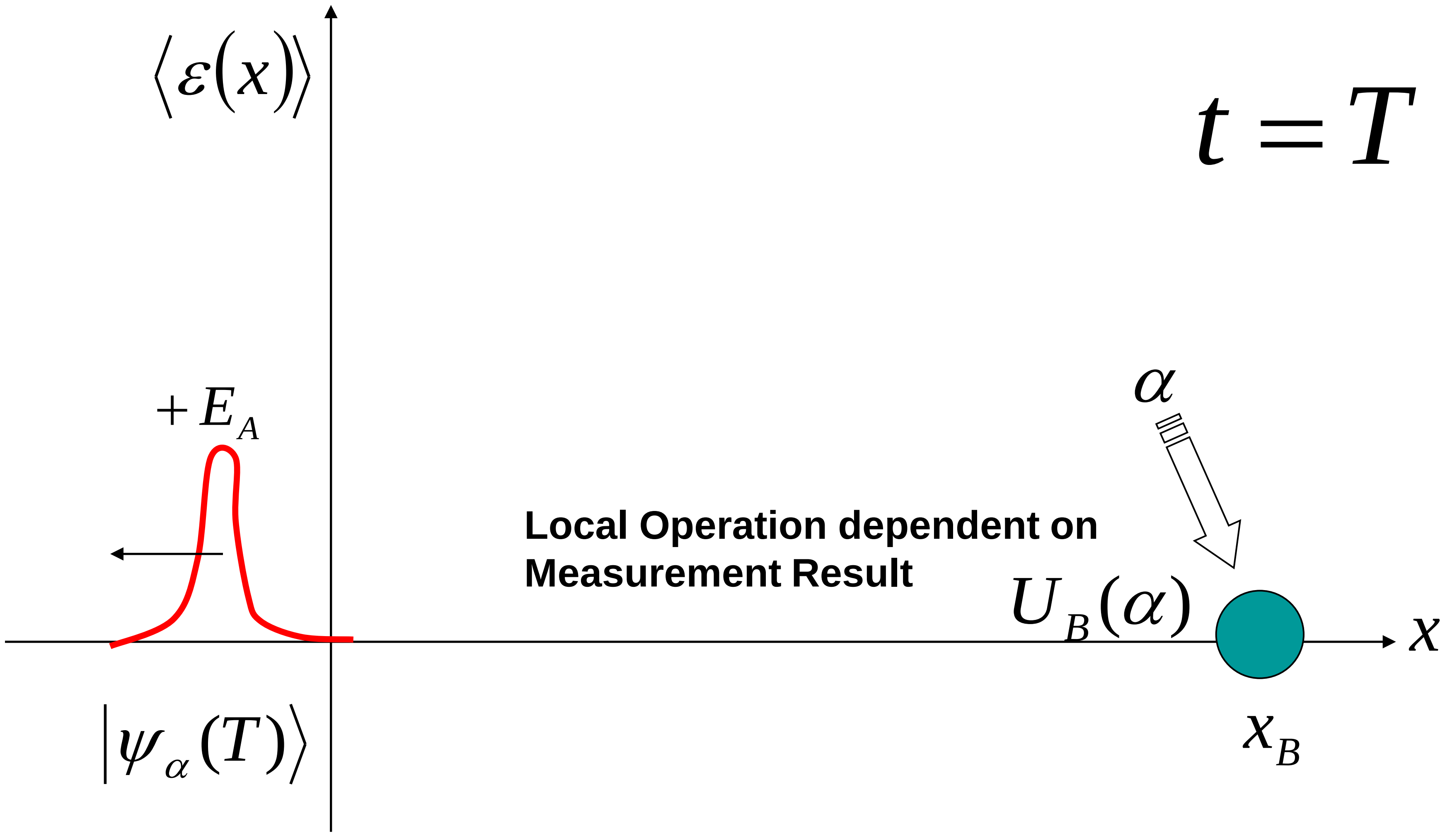
$$Tr\left[\rho_\alpha(t)\varepsilon(x)\right] = \left(\partial_x \lambda_A(x+t)\right)^2$$

At time t=0, we perform a local measurement of vacuum fluctuation. Then, the measurement device excites the left-mover mode with energy $+E_A$.



STEP 1

Next, at time t=T, the measurement result is announced to a distant point at $x = x_B$, which is a local vacuum region, and a local operation dependent on the measurement result is performed.



STEP 2

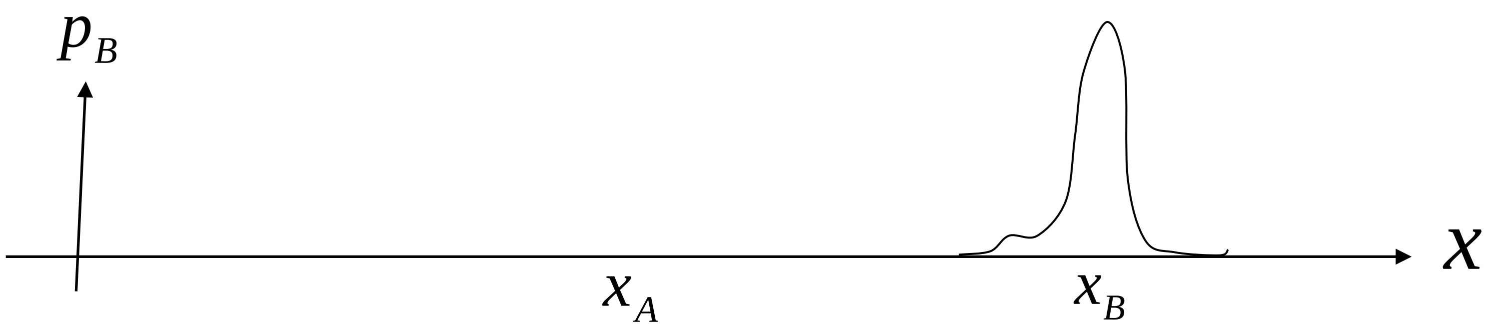
Local operation dependent on measurement result

$$U_B(\alpha) = \exp\left[i\alpha g \int_{-\infty}^{\infty} p_B(x)\Pi_+(x)dx \right]$$

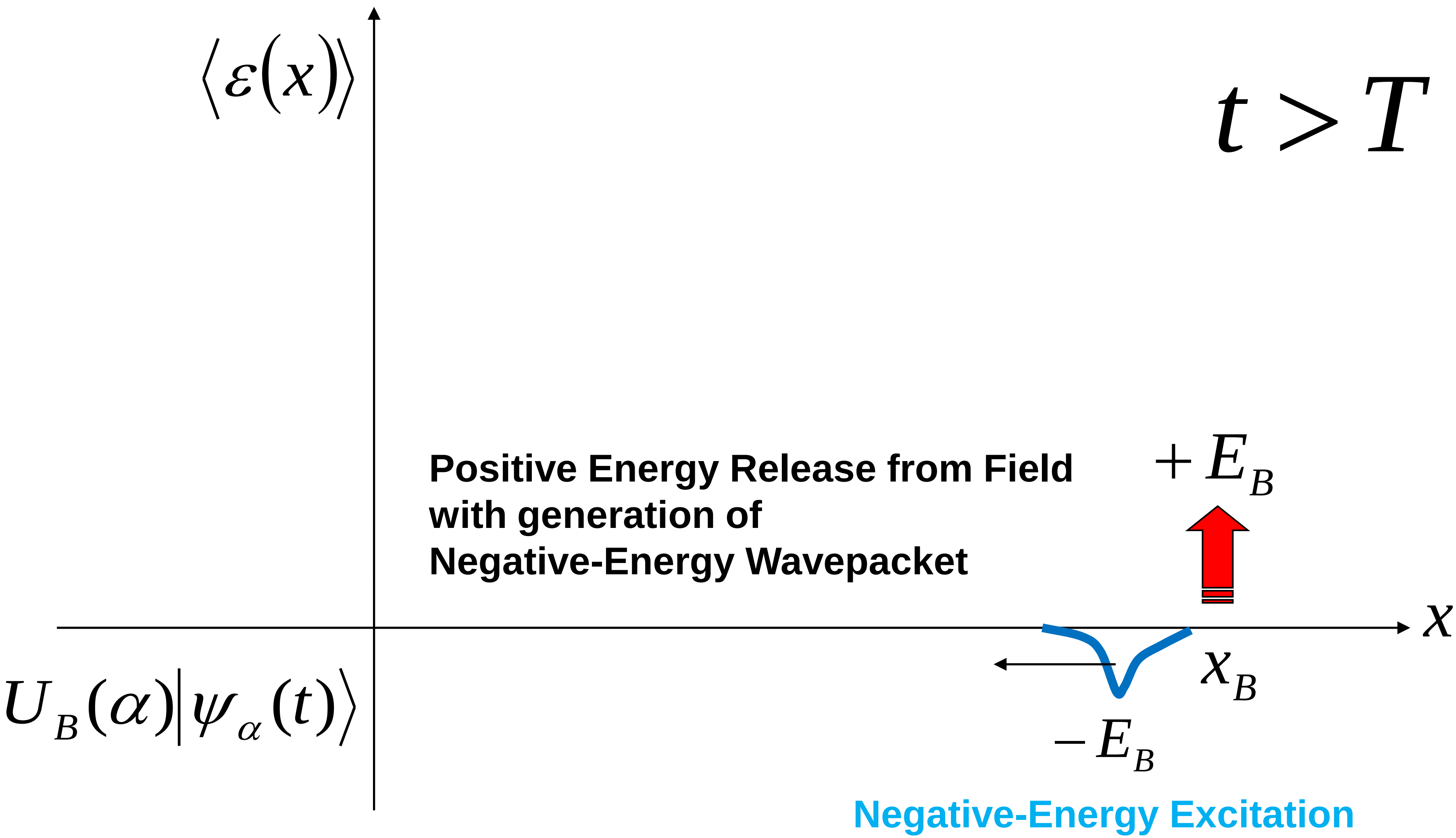
measurement result

localized function around Bob

g **is fixed so as to extract maximum energy for the field.**



Finally, positive energy is extracted by this operation accompanied by generation of negative-energy left-mover excitation of the field.

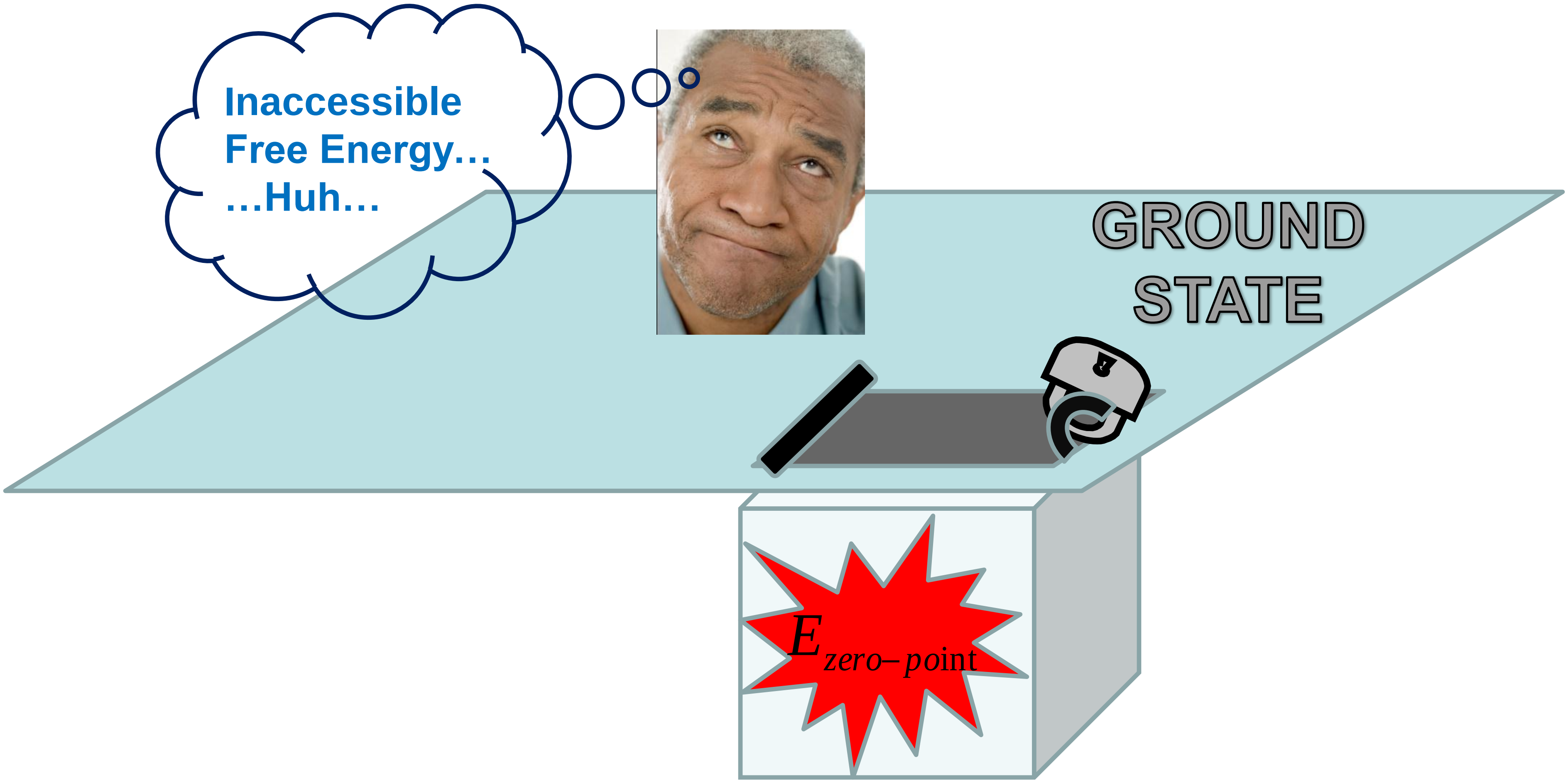


STEP 3

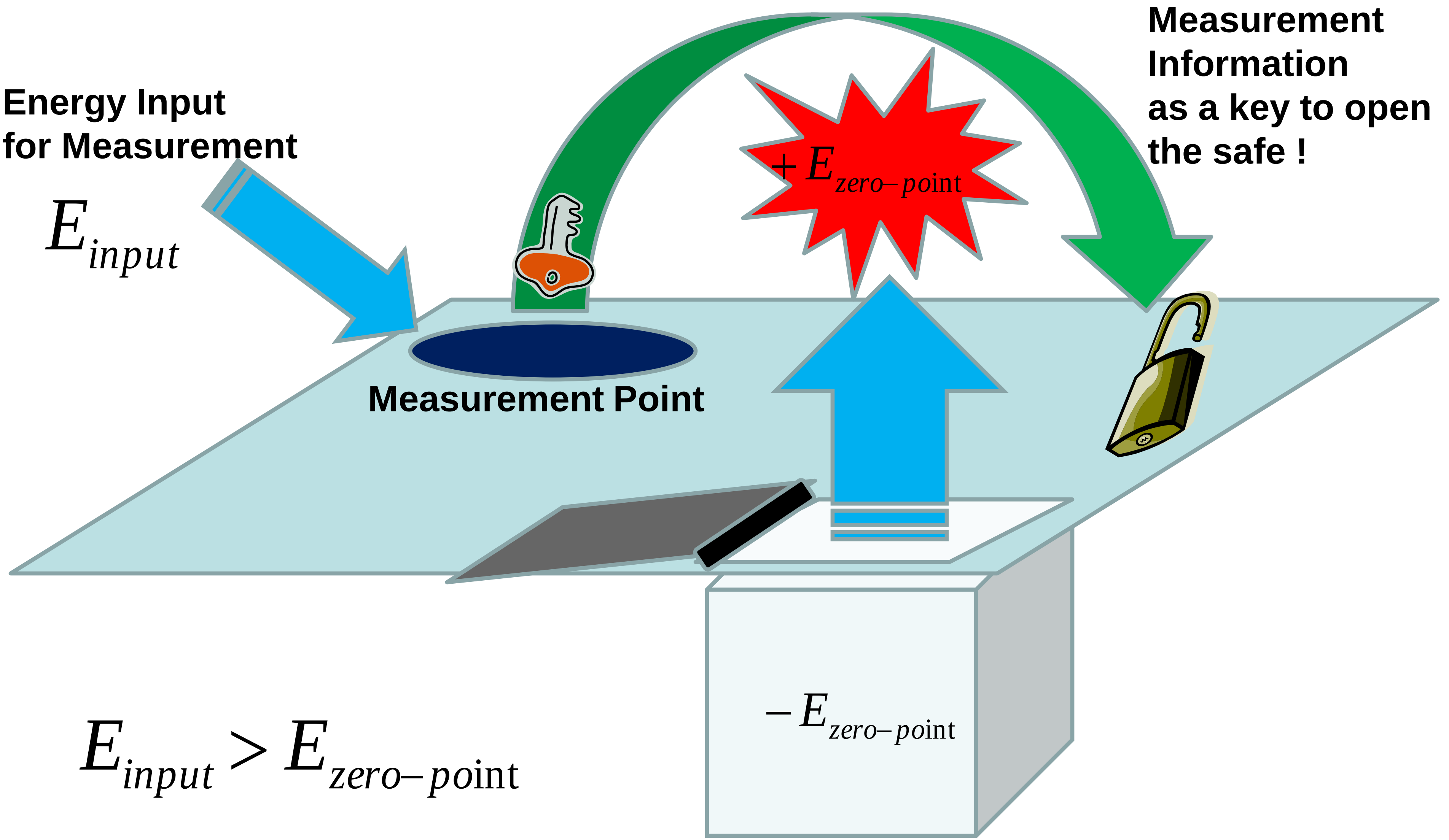
Extracted Energy by Bob

$$E_B = \frac{4\left|\langle 2\lambda_A | 0\rangle\right|^2}{\pi\int_{-\infty}^{\infty} p_B(x)^2 dx}\left[\int_{-\infty}^{\infty}dx\int_{-\infty}^{\infty}dy\, p_B(x)\frac{1}{\left(x-y+T\right)^2}\lambda_A(y)\right]^2$$

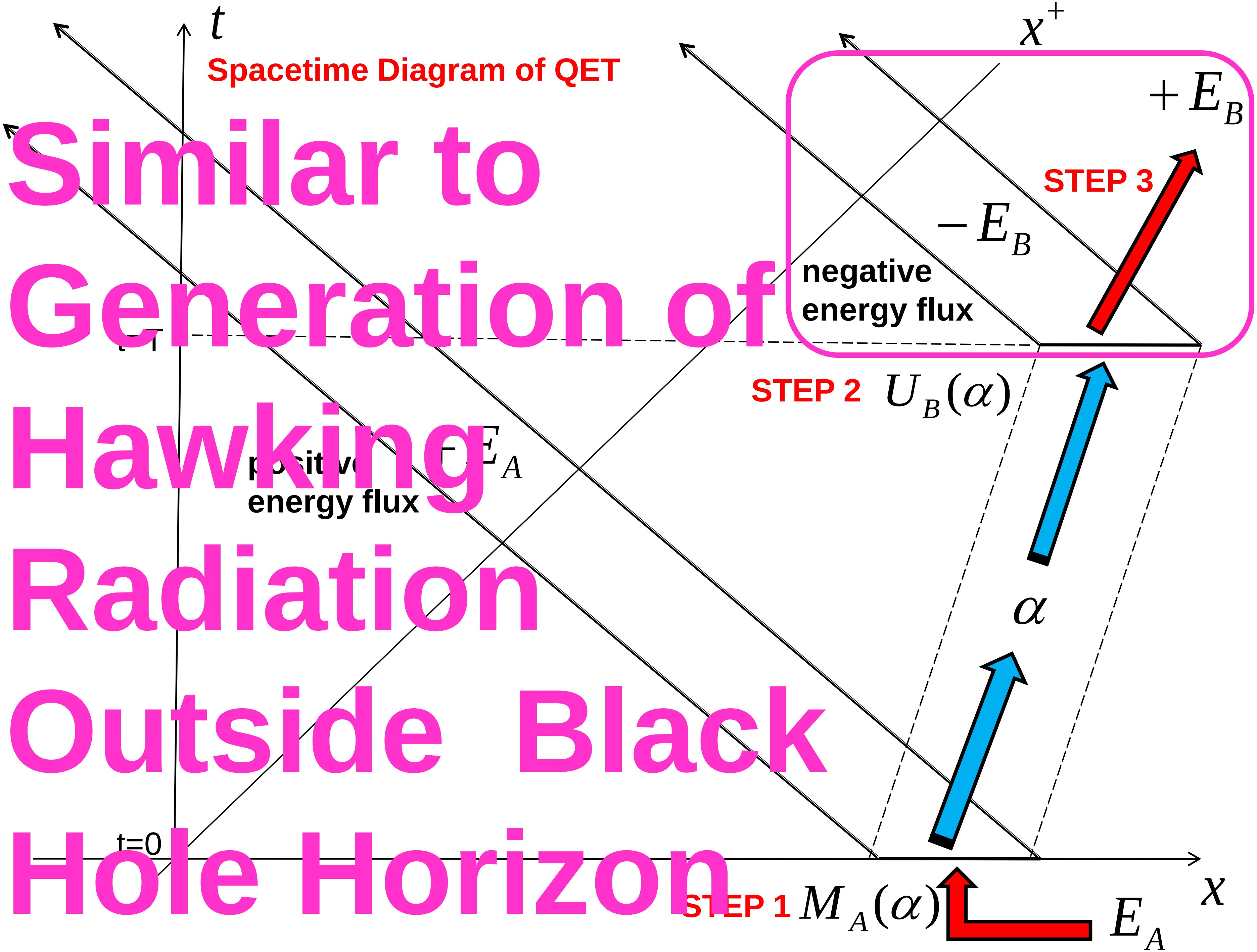
Though it looks like zero-point energy is saved in a locked safe under your ground,



In QET, we got information about a key of the safe by a remote measurement. We must pay for the information to the measurement point. The cost is energy larger than the extracted zero-point energy….

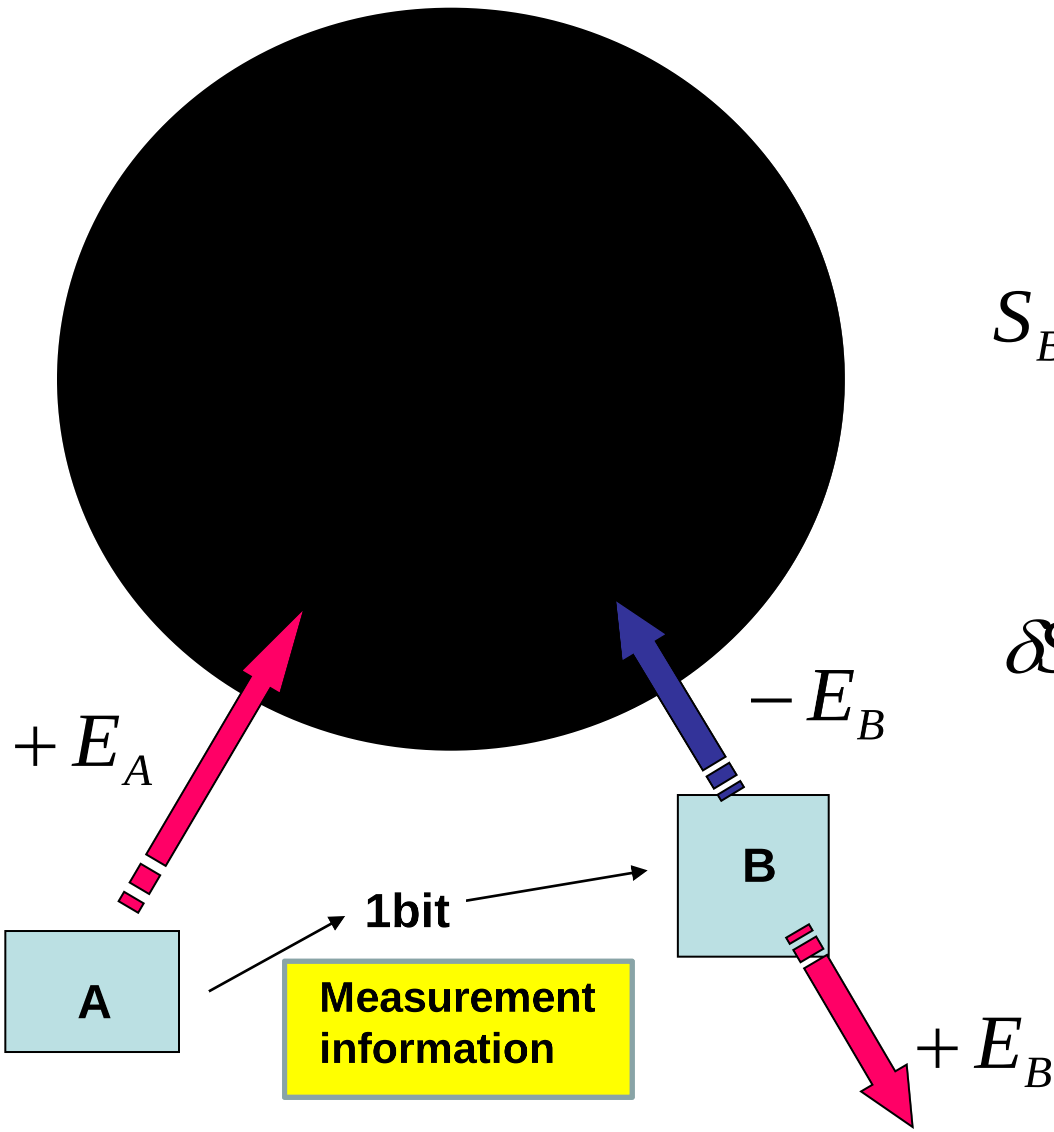


Similar to Generation of Hawking Radiation Outside Black Hole Horizon



QET provides a new method extracting energy from black holes! [M.H. Phys.Rev.D81,044025, (2010)]

Outside a black hole, we perform a measurement of quantum fields and obtain information about the quantum fluctuation. Then positive-energy wave packets of the fields are generated during the measurement and fall into the black hole. Even after absorption of the wave packets by the black hole, we can retrieve a part of the absorbed energy outside the horizon by using QET. This energy extraction yields a decrease in the horizon area, which is proportional to the entropy of the black hole. However, if we accidentally lose the measurement information, we cannot extract energy anymore. The black- hole entropy is unable to decrease. Therefore, the obtained measurement information has a very close connection with the black hole entropy.



$$S_{BH} = \frac{1}{4G} A = 4\pi G M_{BH}{}^{2}$$

$$\delta S_{BH} = 8\pi G M_{BH} \left(E_A - E_B \right)$$

The measurement information is related to the black hole entropy.

Model: Classical Gravity + Large N Matters

Ex. CGHS Model (1992)

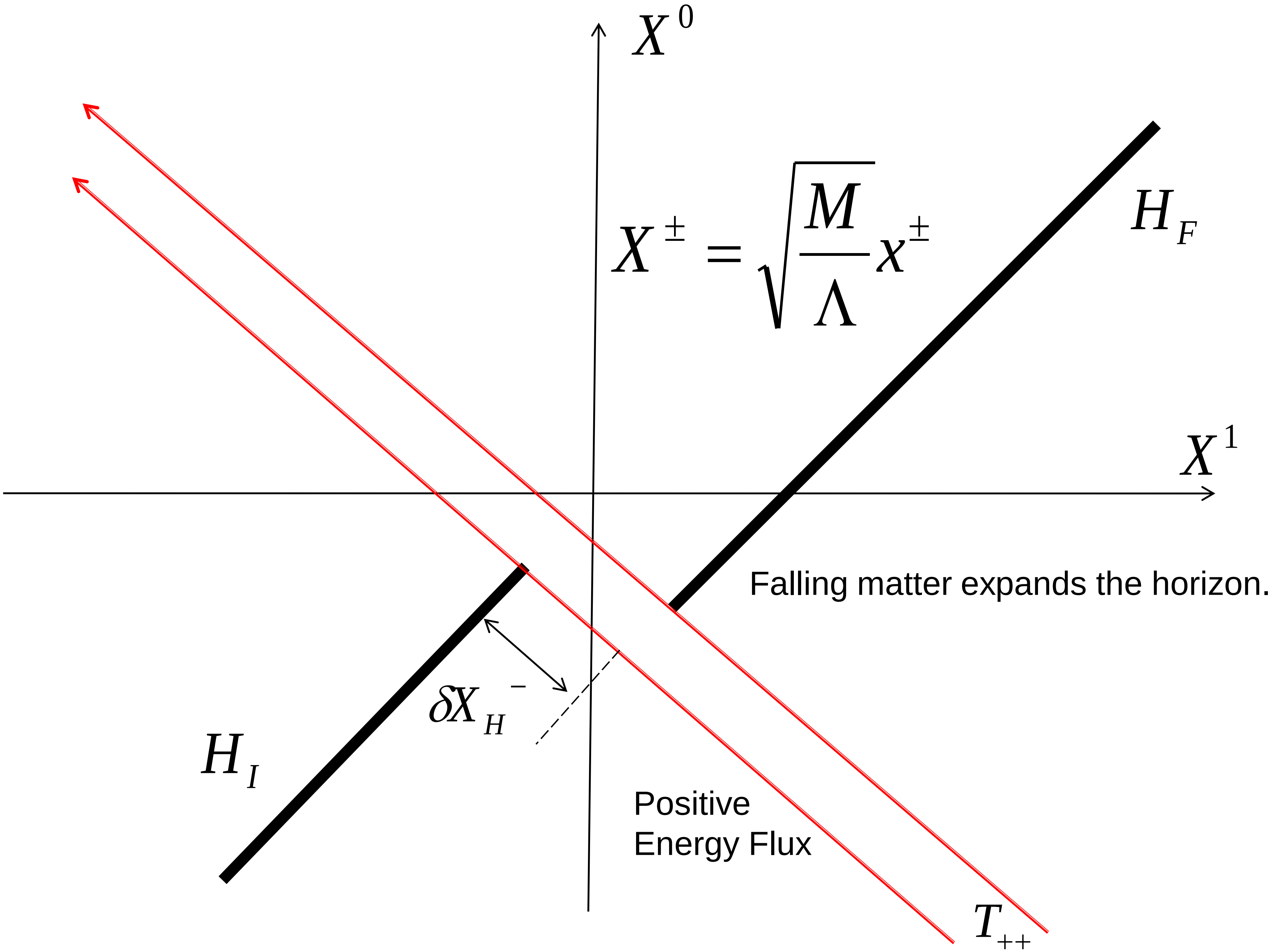
$$S = S_g + S_m$$

$$S_g = \int d^2x\sqrt{-g}\left[e^{-2\varphi}\left(R + 4(\nabla\varphi)^2 + 4\Lambda^2\right)\right]$$

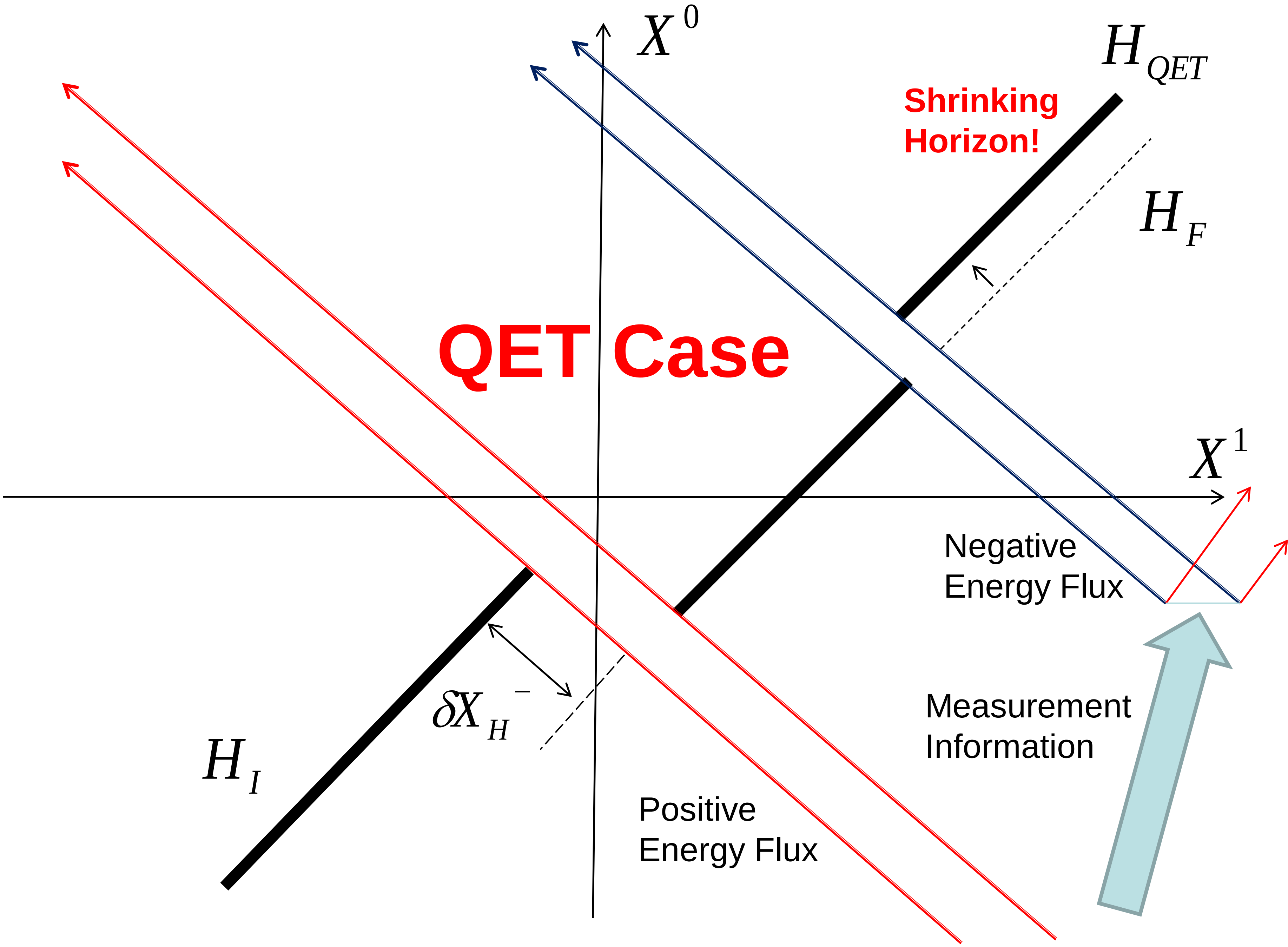
$$S_m = -\frac{1}{2}\sum_{n=1}^{N}\int d^2x\sqrt{-g}(\nabla f_n)^2$$

$$ds^2 = -\frac{dx^+dx^-}{1 - \Lambda^2 x^+ x^- - \frac{\Lambda}{2M}\int_{-\infty}^{x^+} dy^+ \int_{-\infty}^{y^+} dz^+ T_{++}(z^+)}$$

↑ Falling Matter Effect



X^0
$X^{\pm} = \sqrt{\frac{M}{\Lambda}} x^{\pm}$
H_F
X^1
Falling matter expands the horizon.
δX_H^-
H_I
Positive
Energy Flux
T_{++}



X^0
H_{QET}
Shrinking Horizon!
H_F
QET Case
X^1
Negative Energy Flux
δX_H^-
Measurement Information
H_I
Positive Energy Flux

Conclusion

Overcoming passivity of the vacuum state, we can extract zero-point energy of quantum fields using local operation and classical communication. The protocol is called Quantum Energy Teleportation (QET).

Even after absorption of a wave packet by a black hole, we can retrieve a part of the absorbed energy outside the horizon by using QET.

QET measurement information about zero-point fluctuation of quantum fields has a very close connection with black hole entropy.

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