

Expanding Edges of Quantum Hall Systems in a Cosmology Language

- Hawking radiation from de Sitter horizon in edge modes

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*Masahiro Hotta, Yasusada Nambu, Yuuki Sugiyama, Kazuhiro Yamamoto, and Go Yusa,
arXiv:2022.03731, Physical Review D105.105009 (2022).*

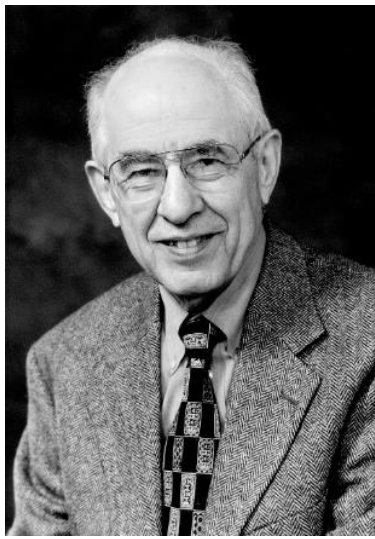


Introduction

***We only have our single Universe.
So it is difficult to collect statistics for the early era
of the Universe.***

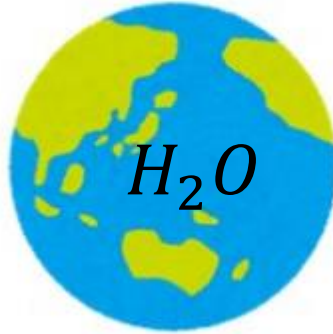
***→ A serious obstacle to answer the big question:
How did our universe develop
from its earliest moments?***



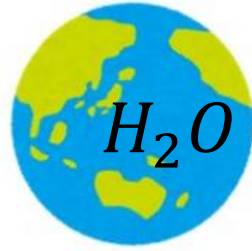


Hilary Putnam (1973)

Twin Earth Thought Experiment



“In its place there is a liquid that is superficially identical, but is chemically different, being composed not of H_2O , but rather of some more complicated formula which we abbreviate as “XYZ”... The experience of people on Earth with water and that of those on Twin Earth with XYZ would be **identical**.”



***The twin earth can be regarded as
a simulator of our earth!***

***In the similar spirit, we are going to make
a simulator of early universe
using different matters.***

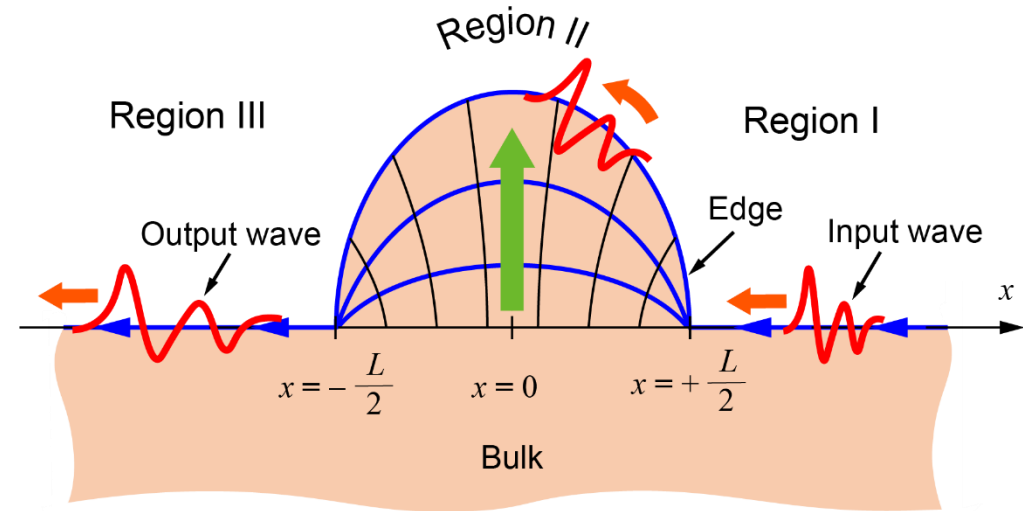
Note that the observations of Hawking radiation out of black holes are also quite difficult.

Bill Unruh first proposed a **simulator** of a black hole and its Hawking radiation using sound waves in transonic fluid flow.



W.G.Unruh, Phys.Rev.Lett.46,1351(1981).

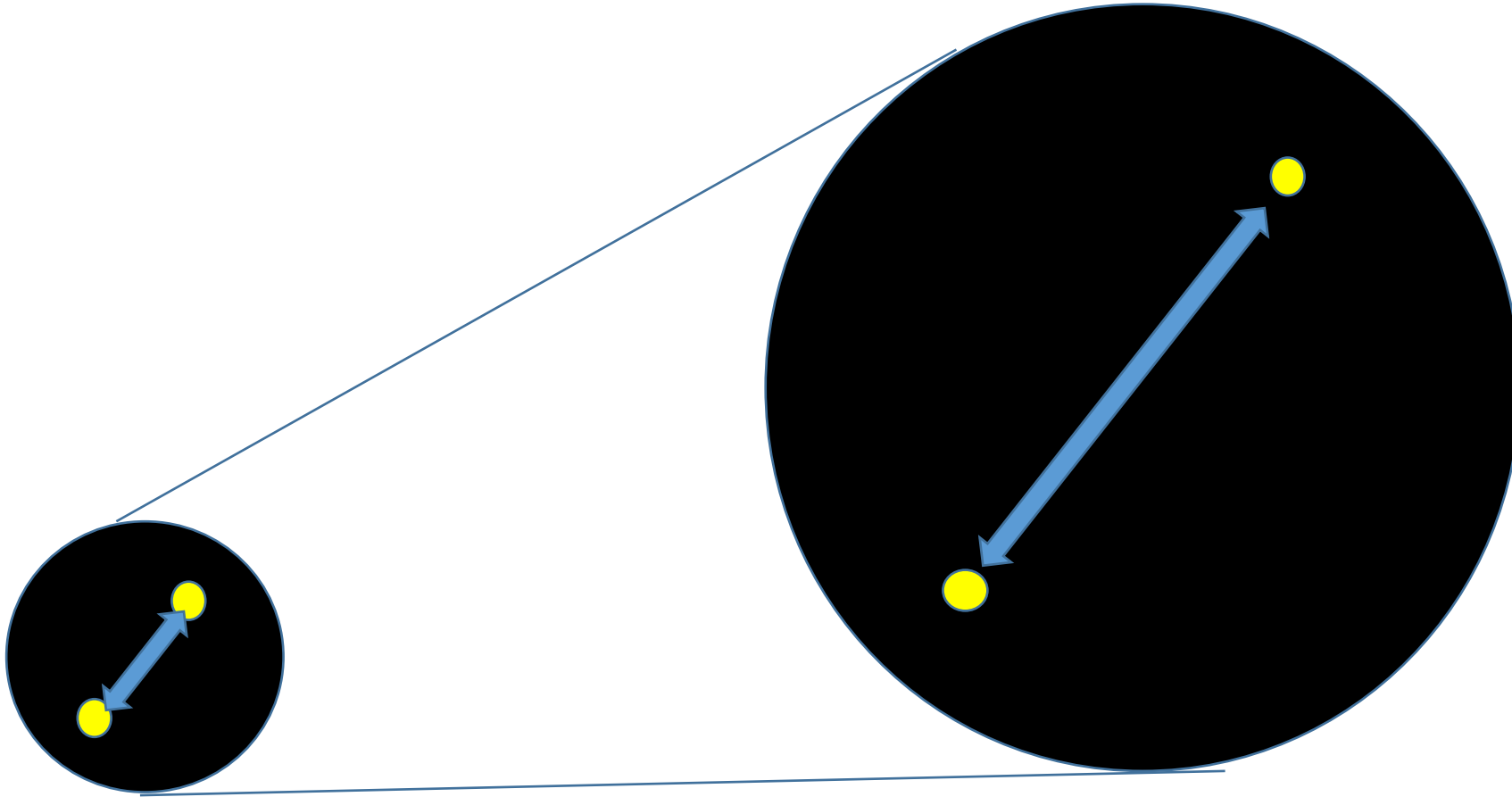
*In order to repeatedly explore the quantum features of early universe, let us make universe simulators using **quantum Hall systems!***



Tohoku University experiment group of Go Yusa just started to make the simulator!

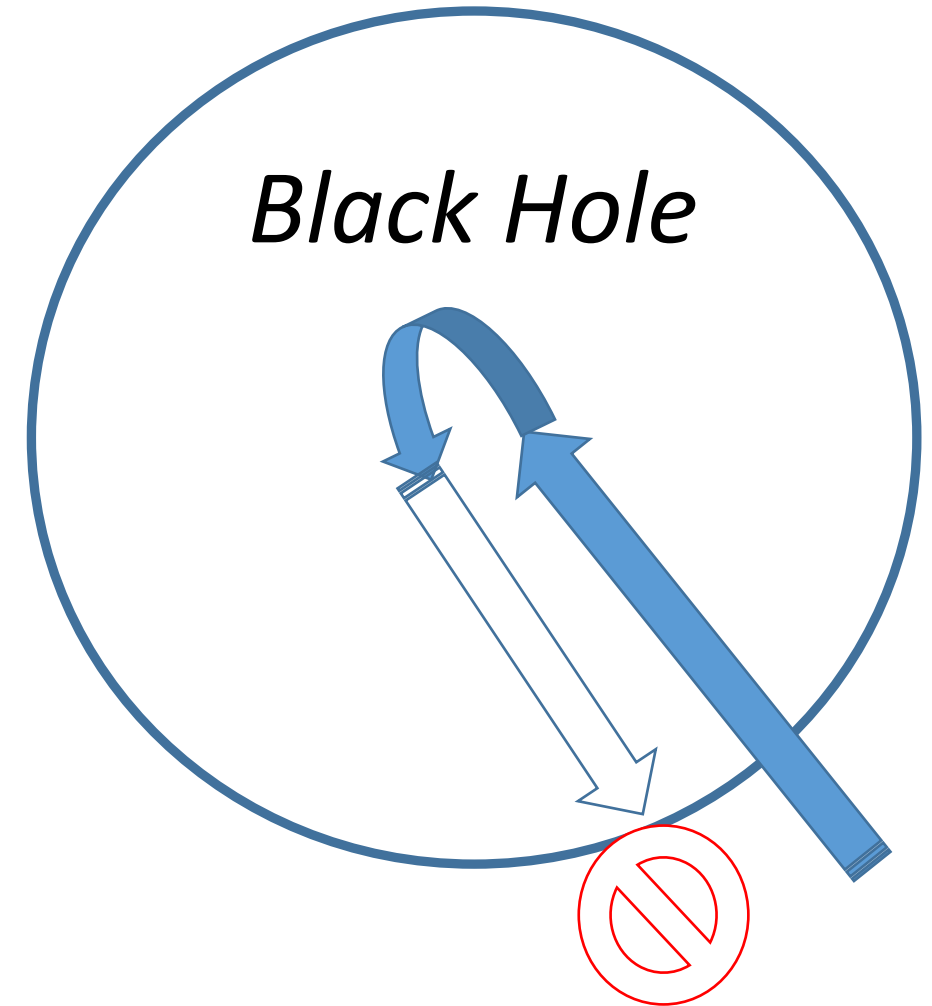
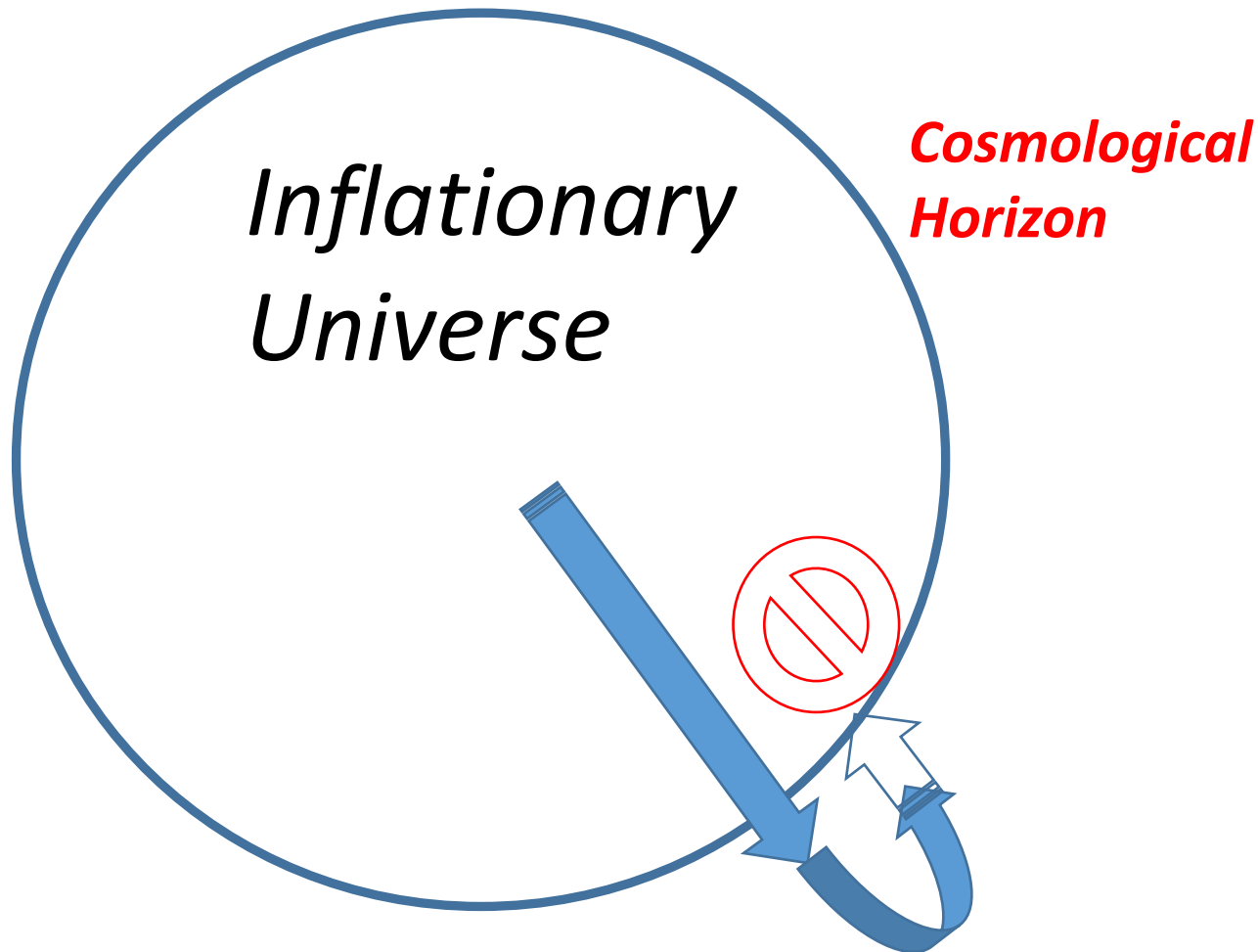
***The universe simulators can explore
spacetime-dimension-independent
conceptual cosmological issues.***

Expanding Universe makes the distance of two points larger in time.



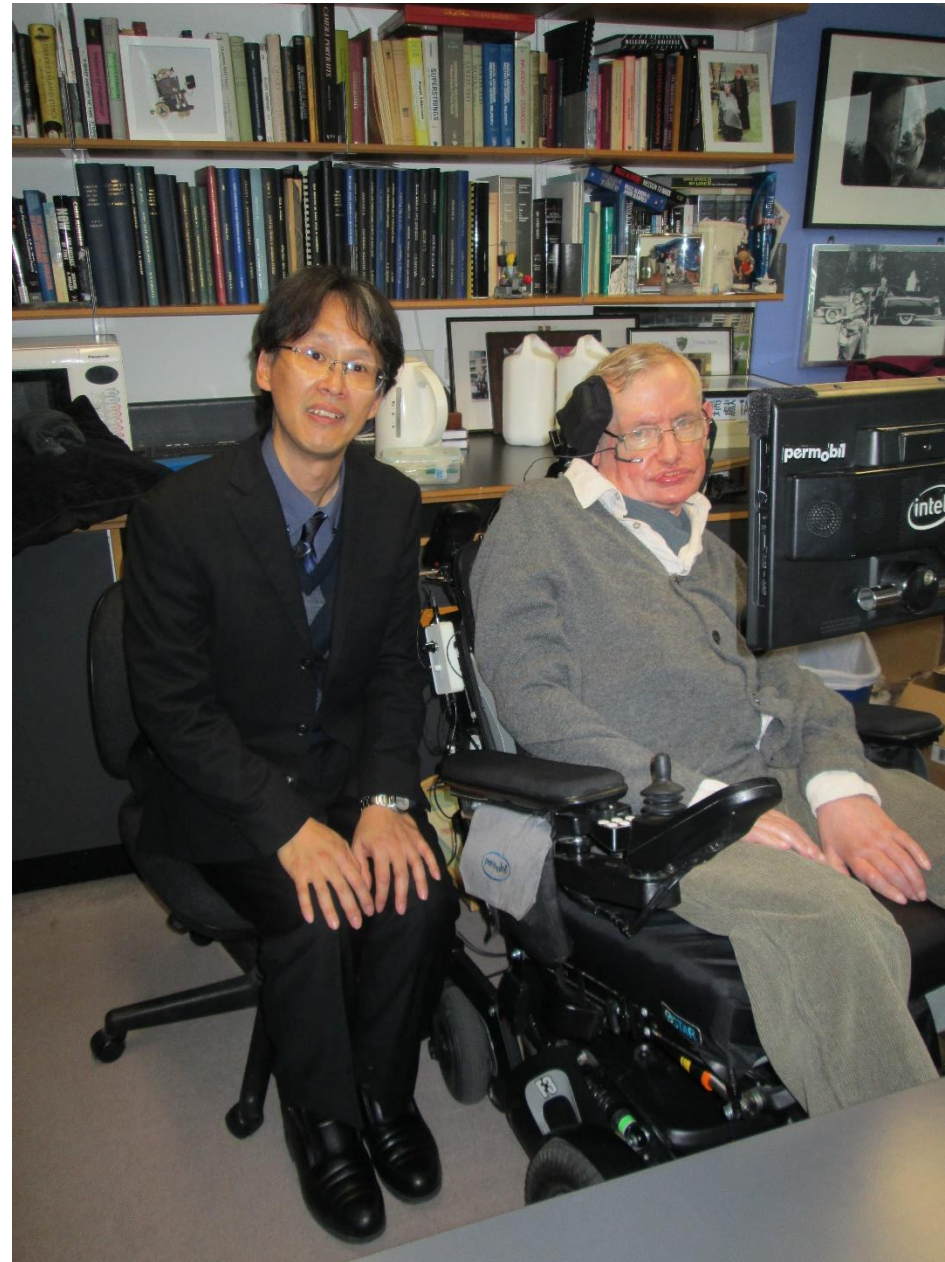
Any physical object cannot return to inside owing to rapid expansion of the inflationary universe.

Any physical object cannot return to outside owing to strong attraction of black hole gravity.



*Hawking
radiation*

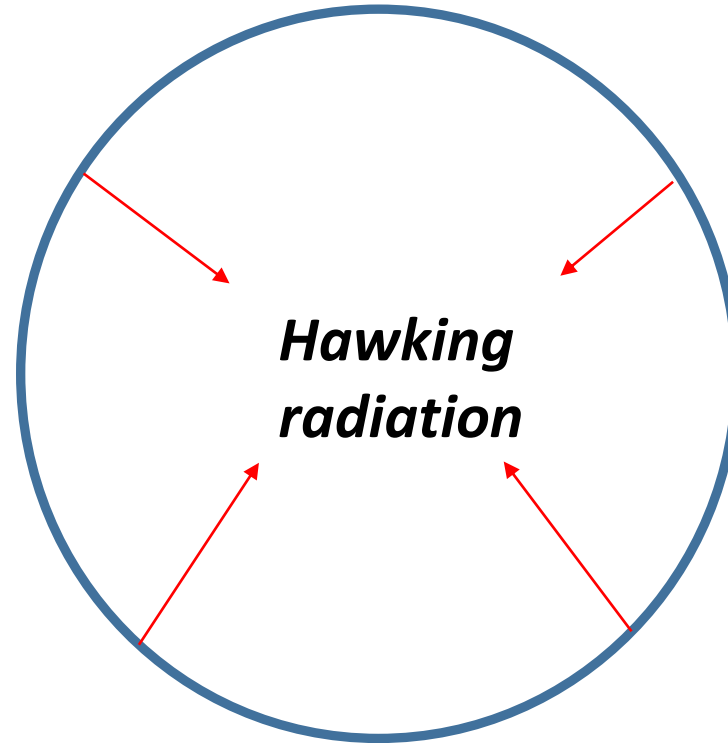
***Black
Hole***



*February,
2017
@his office,
Cambridge*

Hawking radiation out of cosmological horizon in the inflationary universe

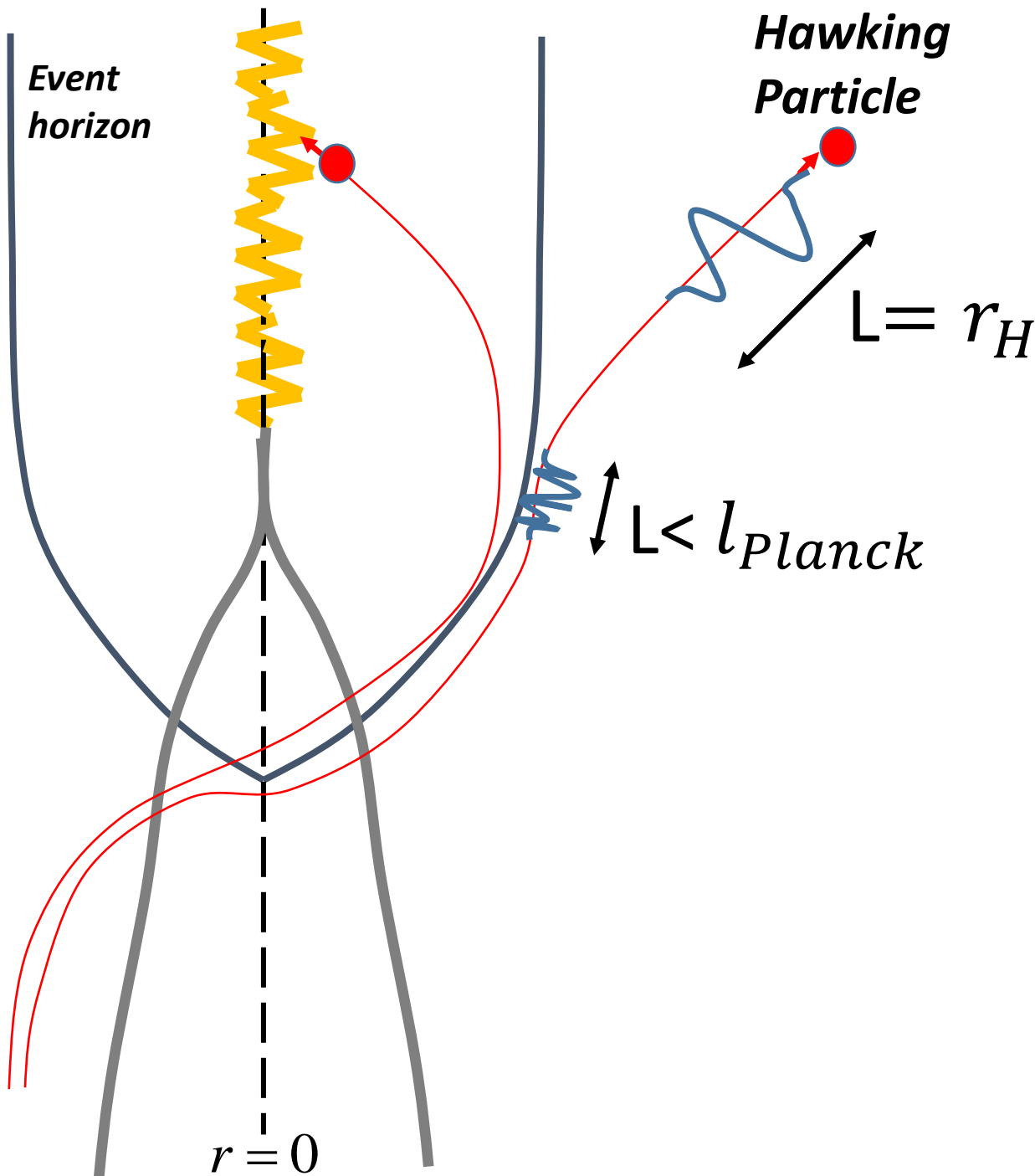
***Similar to
Black Hole!***



***Many people want to explore the Hawking radiation,
but difficult in the real universe. The universe simulators
can do that.***

Issues the simulators can address:

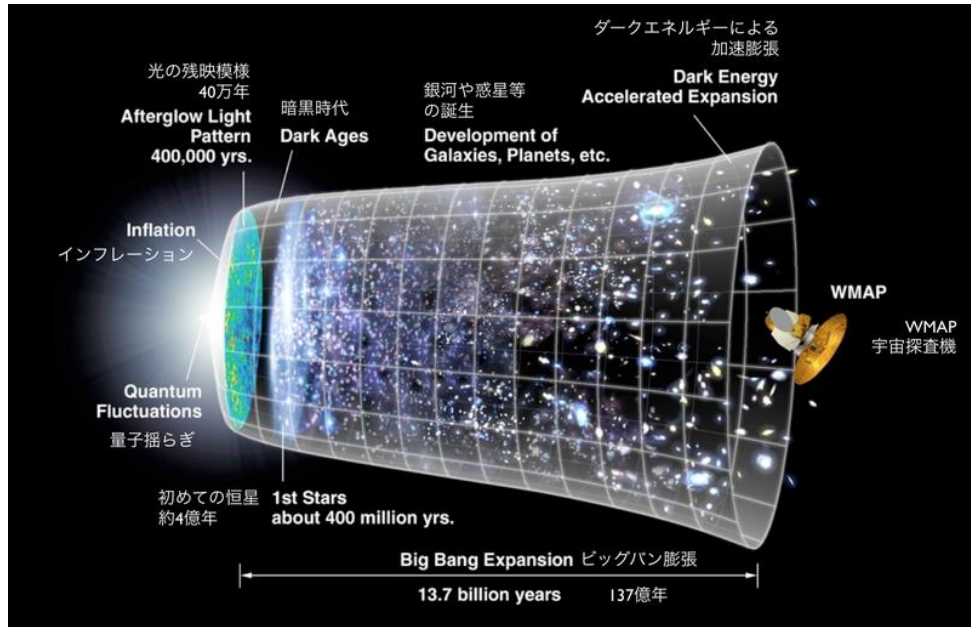
- Trans-Planckian Problems of Hawking Radiation and Inflationary Universe***
- Quantum-Classical Transition of Field Fluctuation in Inflationary Universe***
- Detection of Entanglement Structure in Early Universe***



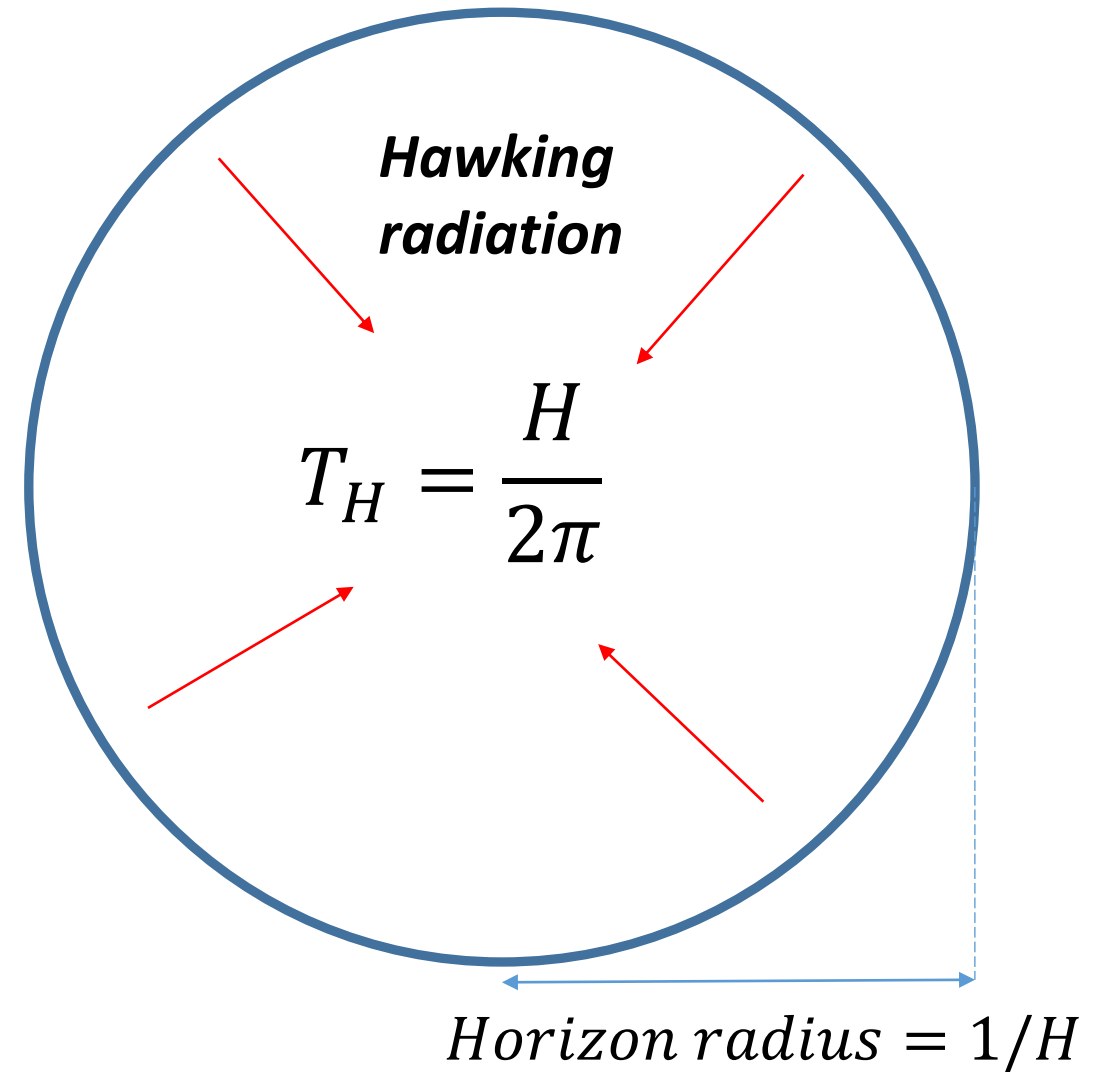
○ Trans-Planckian Problem

A precise description of the mode in the past regime is required for fundamental microscopic theories such as string theory. It is possible that Hawking's approximation is incorrect and has serious discrepancy. However, his results appear to be correct. In reality, the formula for Hawking temperature and the BH entropy with horizon area are consistent with the other theoretical results of generalized thermodynamics and statistical mechanics with state counting in string theory. Thus, why Hawking's analysis works so well despite being semi-classical is a mystery. This is called the trans-Planckian problem.

Hawking radiation out of cosmological horizon in the inflationary universe



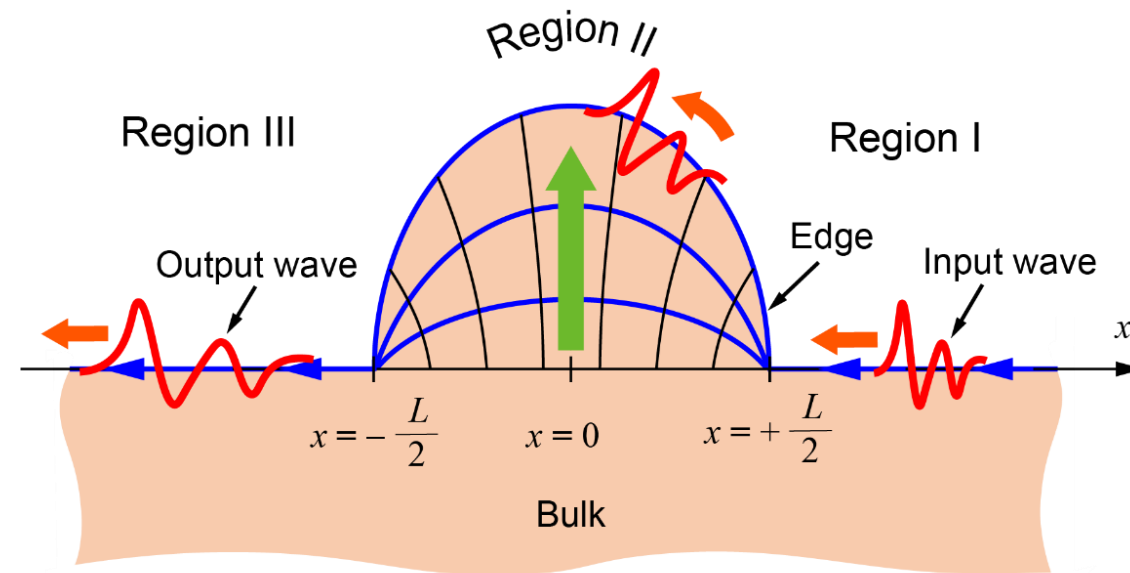
By WMAP Science team



$$ds^2 = -d\tau^2 + \exp(2H\tau)d\vec{x}^2$$

Cosmological trans-Planckian problem appears.

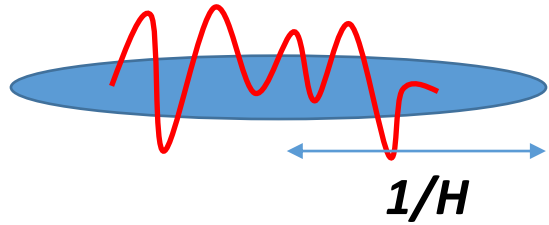
*If Hawking's prediction is correct, analog black holes also emit Hawking radiation, no matter what the analog black holes are made of. Quantum Hall analog horizons possess the magnetic length as the cutoff mimicking the Planck length. This phenomenon poses a **QH analog version** of the trans-Planckian problem.*



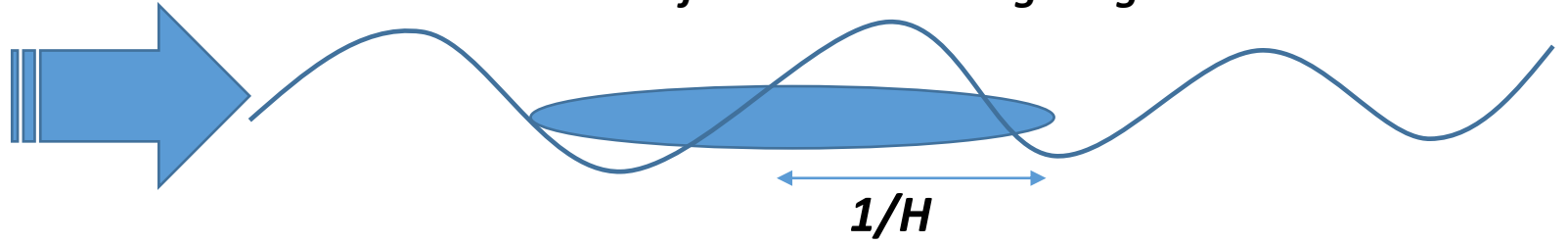
$$l_P = \sqrt{G\hbar/c^3} \quad \longrightarrow \quad l_B = \sqrt{\hbar/(eB)}$$

○ Quantum-Classical Transition of Field Fluctuation in Inflationary Universe

Quantum fluctuation in short range



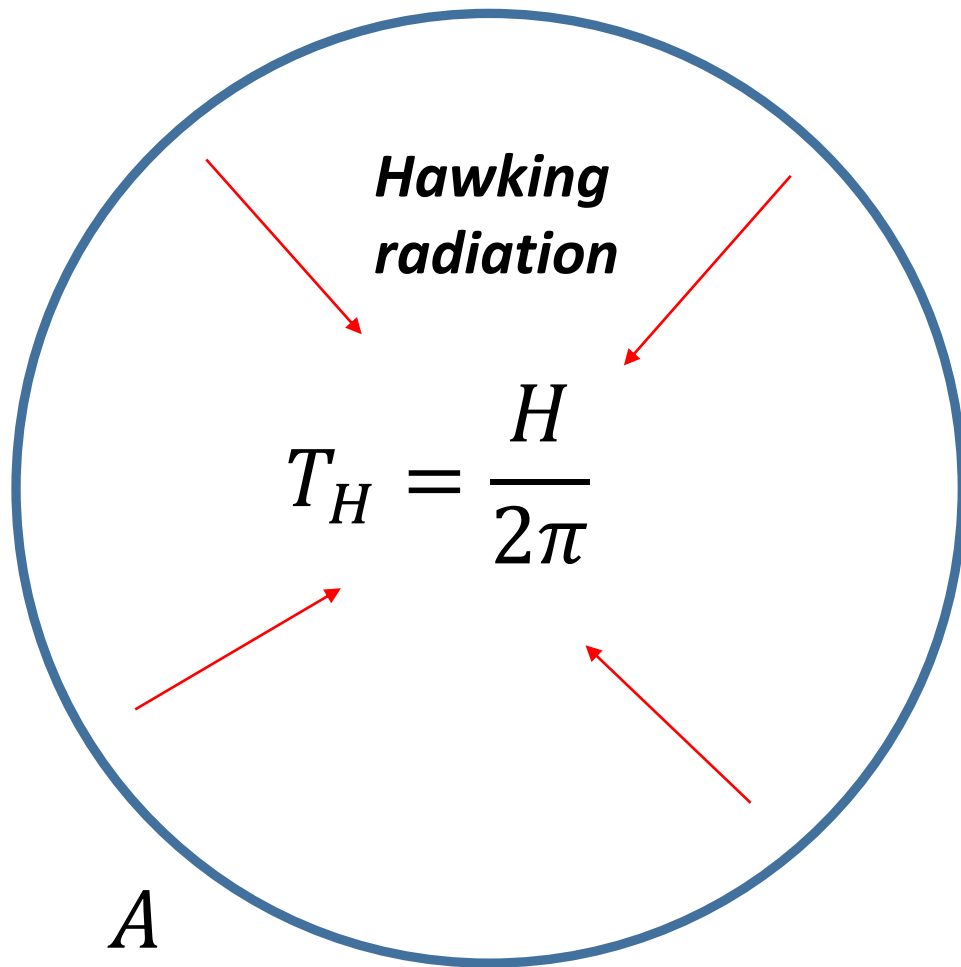
Classical fluctuation in long range



The accelerated expansion in the inflationary universe provides quantum fluctuations of the inflaton field that becomes classical fluctuation over the Hubble horizon scale. This primordial fluctuation leads to gravitational instabilities that form large-scale structures in our universe. However, it is not known how the quantum-classical transition of field fluctuation occurs. Because the details and mechanisms of the transition process are not known, it remains far from profound understanding.

○ *Detection of Entanglement Structure in Early Universe*

Bekenstein-Hawking Entropy for Cosmological Horizon



$$S_H = \frac{A}{4G}$$

= Entanglement Entropy?

[arXiv:2203.02852](https://arxiv.org/abs/2203.02852) Hikida, Nishioka, Takayanagi and Taki

Ryu-Takayanagi Formula?
Emergence of Spacetime
From Quantum Information?
It From Qbit?

Today's Talk

I. Introduction

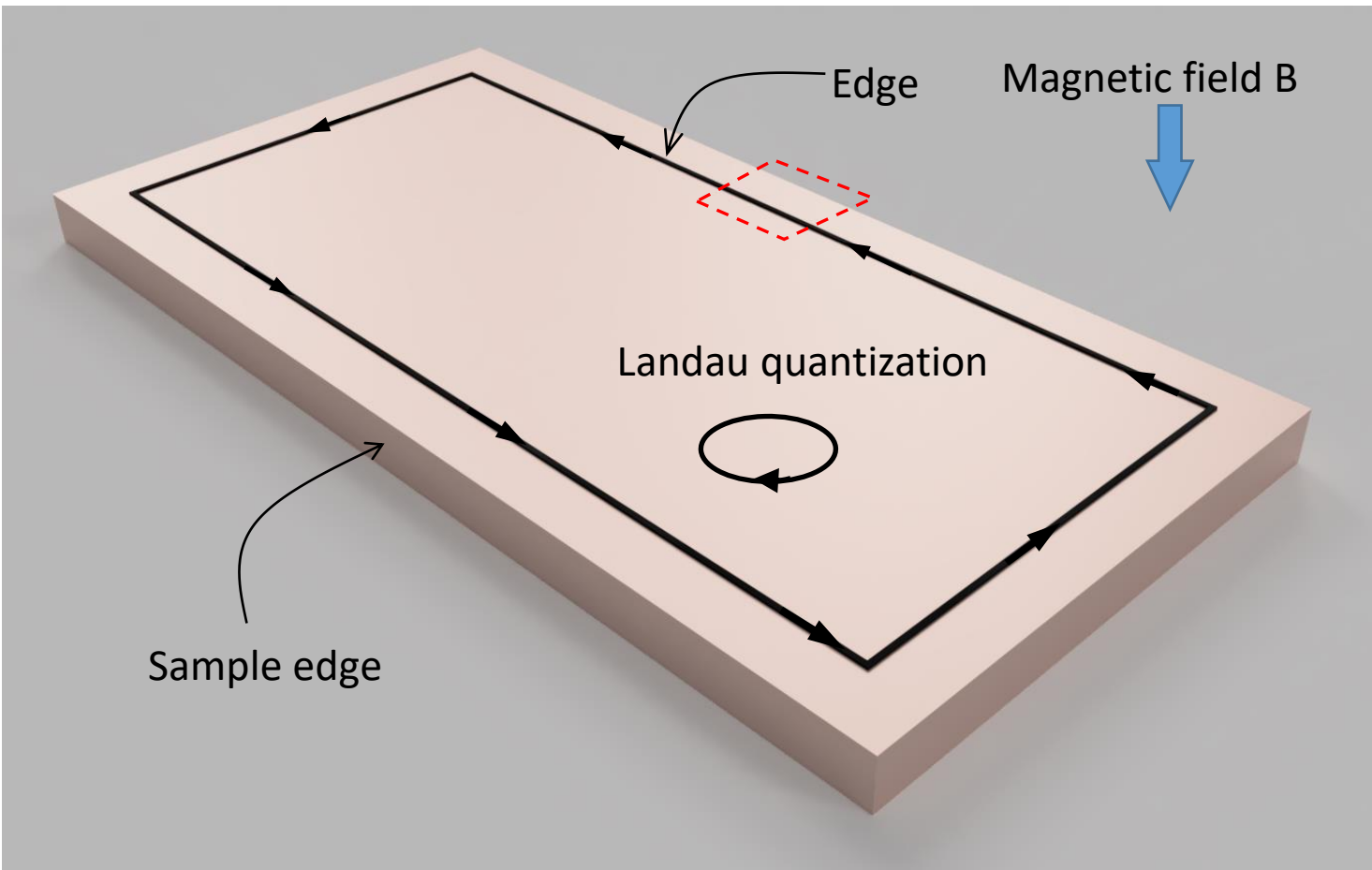
II. Quantum Hall Systems

***III. 1+1 dimensional Cosmology
for Expanding QH Edges***

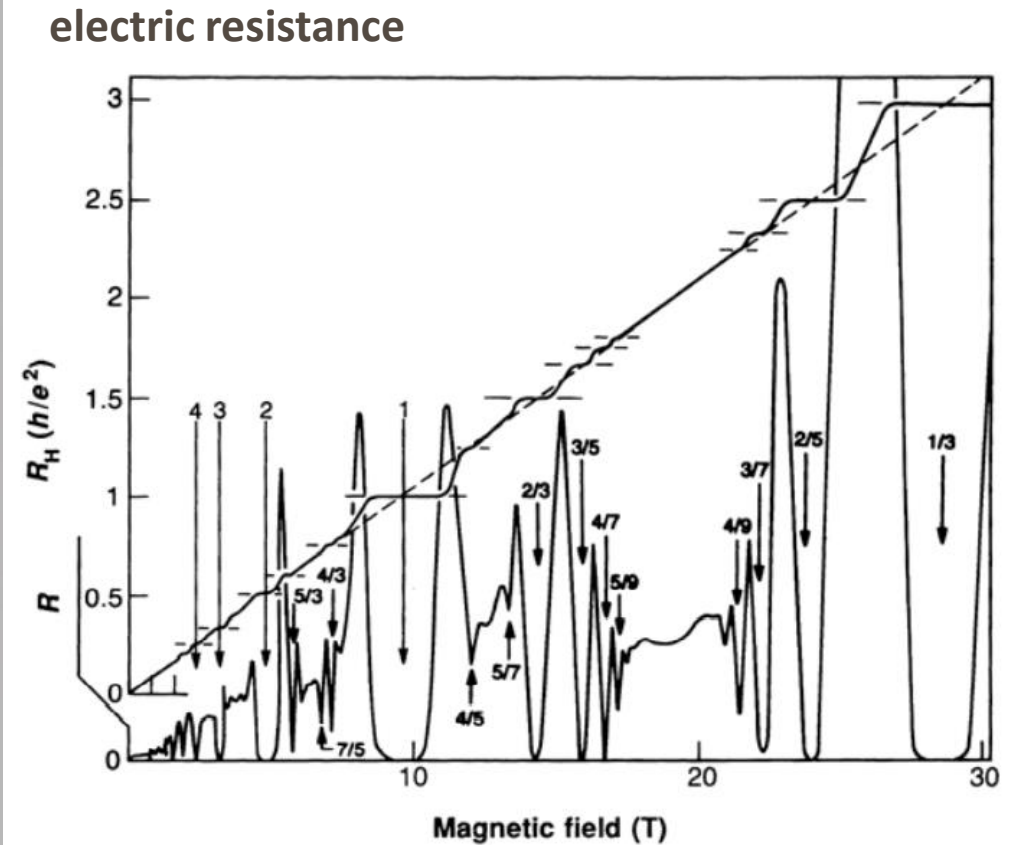
***IV. New Condensed Matter Physics
from Expanding Edge Experiments***

V. Summary

II. Quantum Hall Systems

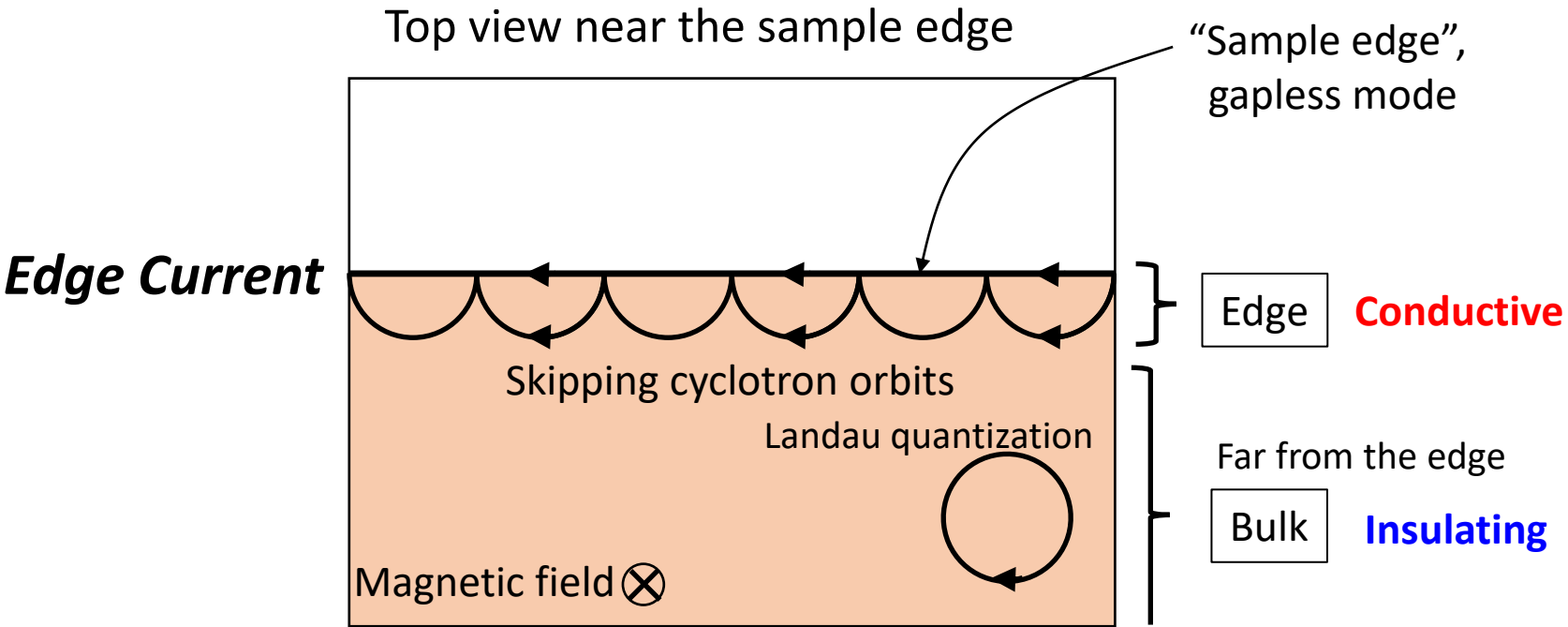


The quantum Hall effect is observed in two-dimensional electron systems subjected to **low temperatures** and **strong magnetic fields**.
(Fig. by G. Yusa)



***Quantum Hall system with edge
is a typical topological matter.***

Edge state



Skipping cyclotron orbits can be viewed as a quasi-one-dimensional channel. Such an edge channel behaves like a chiral Luttinger liquid, along which current flows unidirectionally.

=> Chiral massless field in one dimension

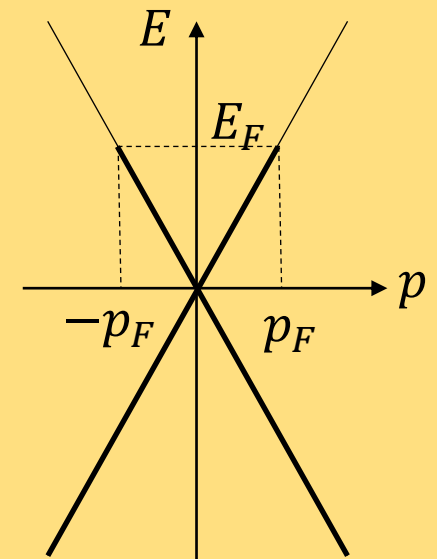
=> Described by conformal field theory (CFT)

The chiral field operator in terms of density field $\varrho(x)$

Commutation relation

$$[\varrho(x), \varrho(x')] = i \frac{\nu}{2\pi} \partial_x \delta(x - x')$$

Dispersion relation of the Luttinger model



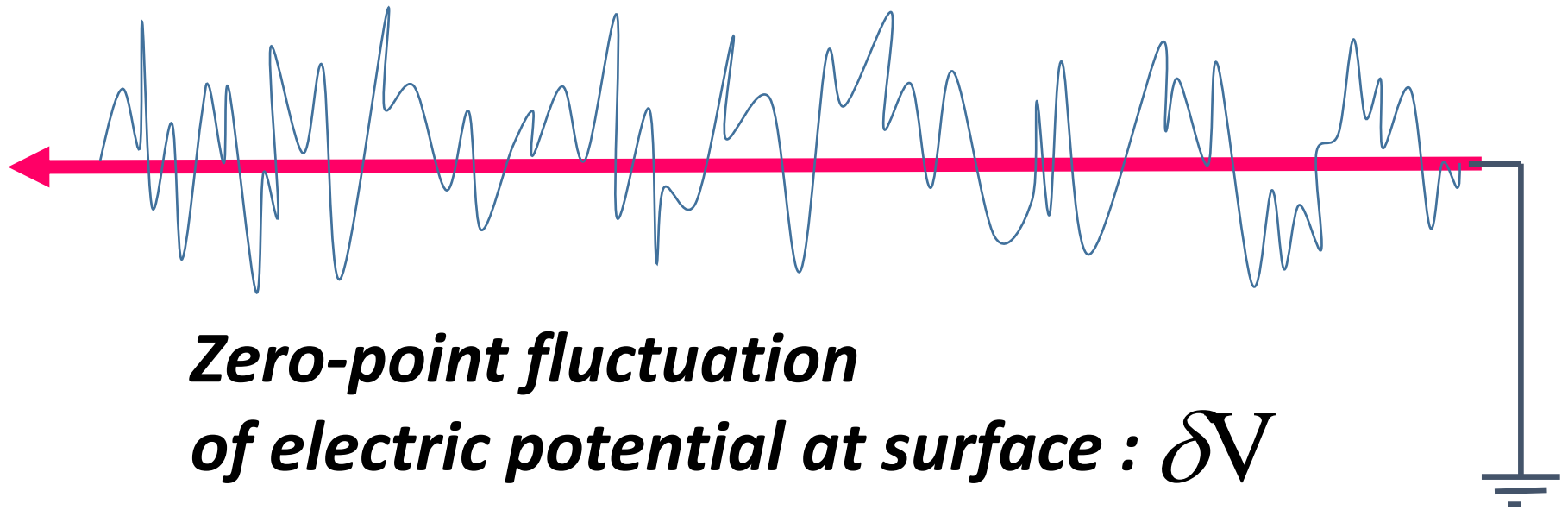
(slide by G. Yusa)

*The deviation of surface can be effectively described by **a chiral boson field**.*

(Xiao-Gang Wen 1990)

$$\varphi(x^+) = \varphi(vt + x) \propto \varrho(vt + x)$$

Edge Current



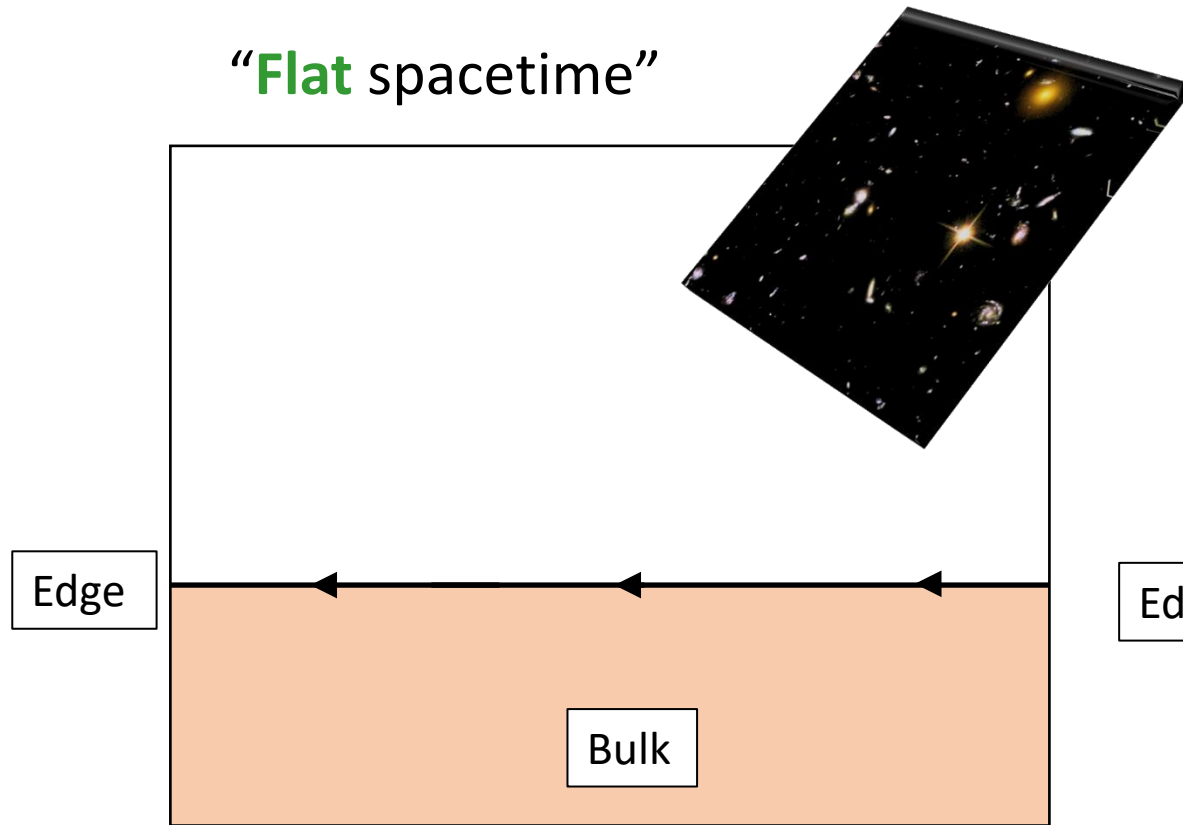
**Zero-point fluctuation
of electric potential at surface : δV**

III. 1+1 dimensional Cosmology for Expanding QH Edges

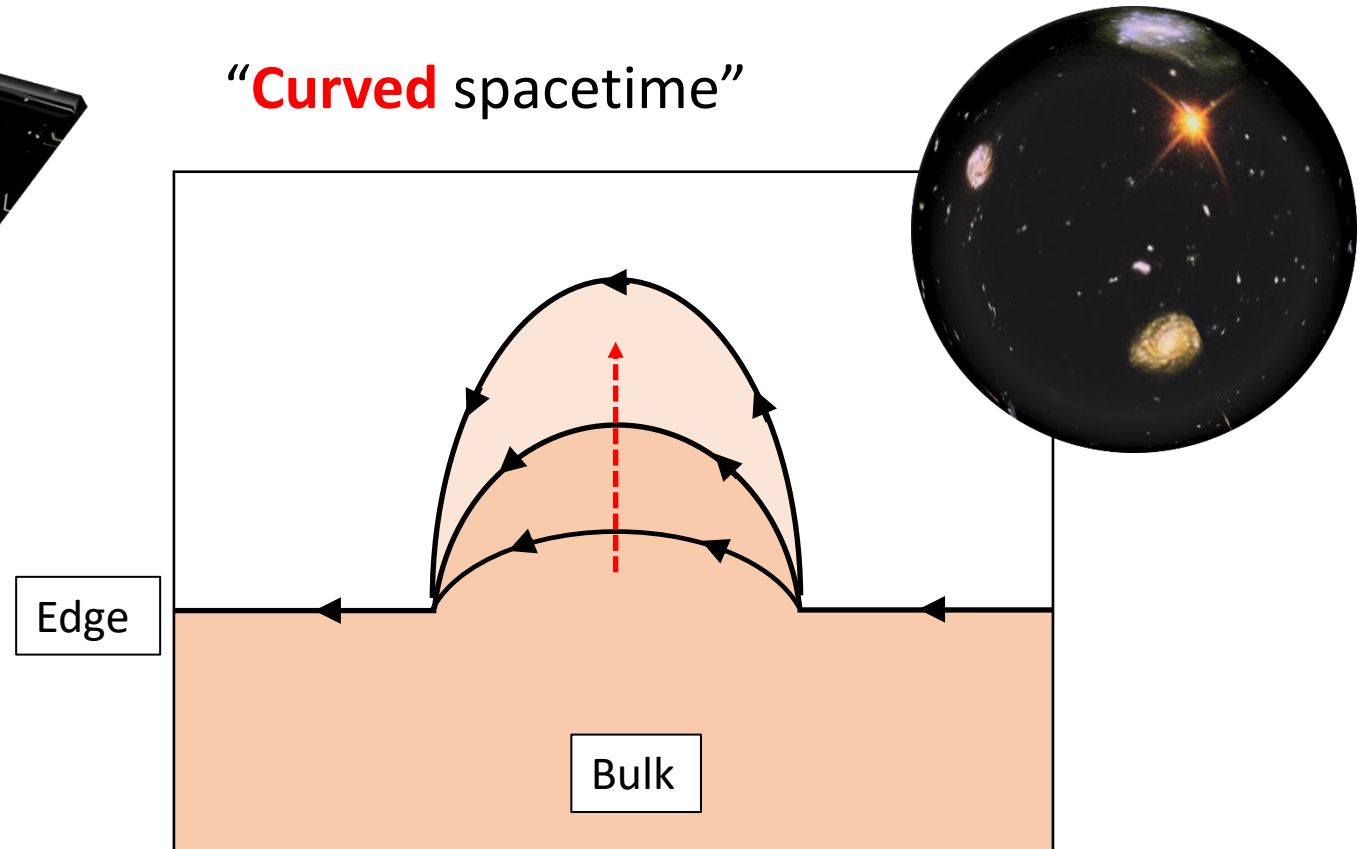
Expanding the universe in the QH edge

If this 1D edge can be controlled dynamically,
the edge may be described by (1+1)-dimensional CFT.
=> Toy model for 1+1 dim universe

“**Flat** spacetime”



“**Curved** spacetime”

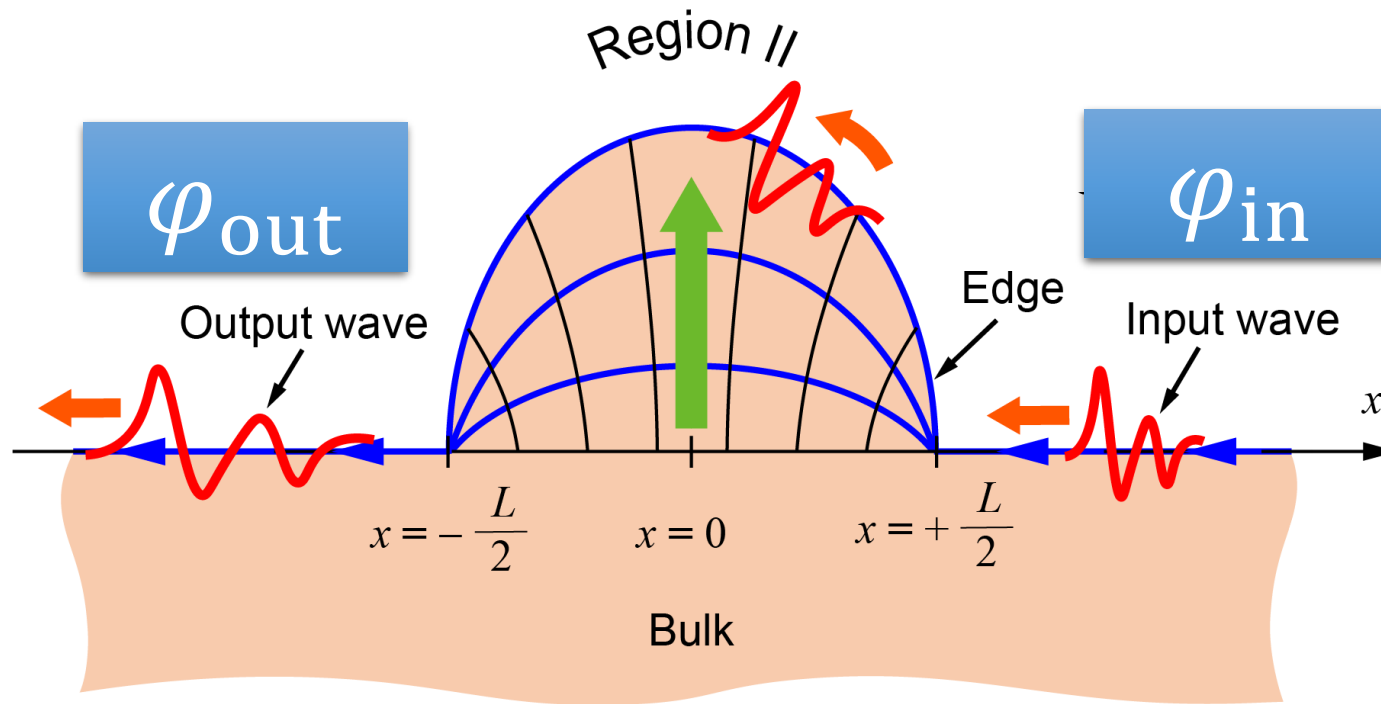


Hotta et al., arXiv:2202.03731 (2022).

Hotta et al., PRA (2014). Slide by G. Yusa

Expanding Quantum Hall Edges in a Cosmology Language

By changing the confinement potential in time with injection of additional electrons, the edge is expanded.



L: length of expanding region

Spacetime metric in expanding region

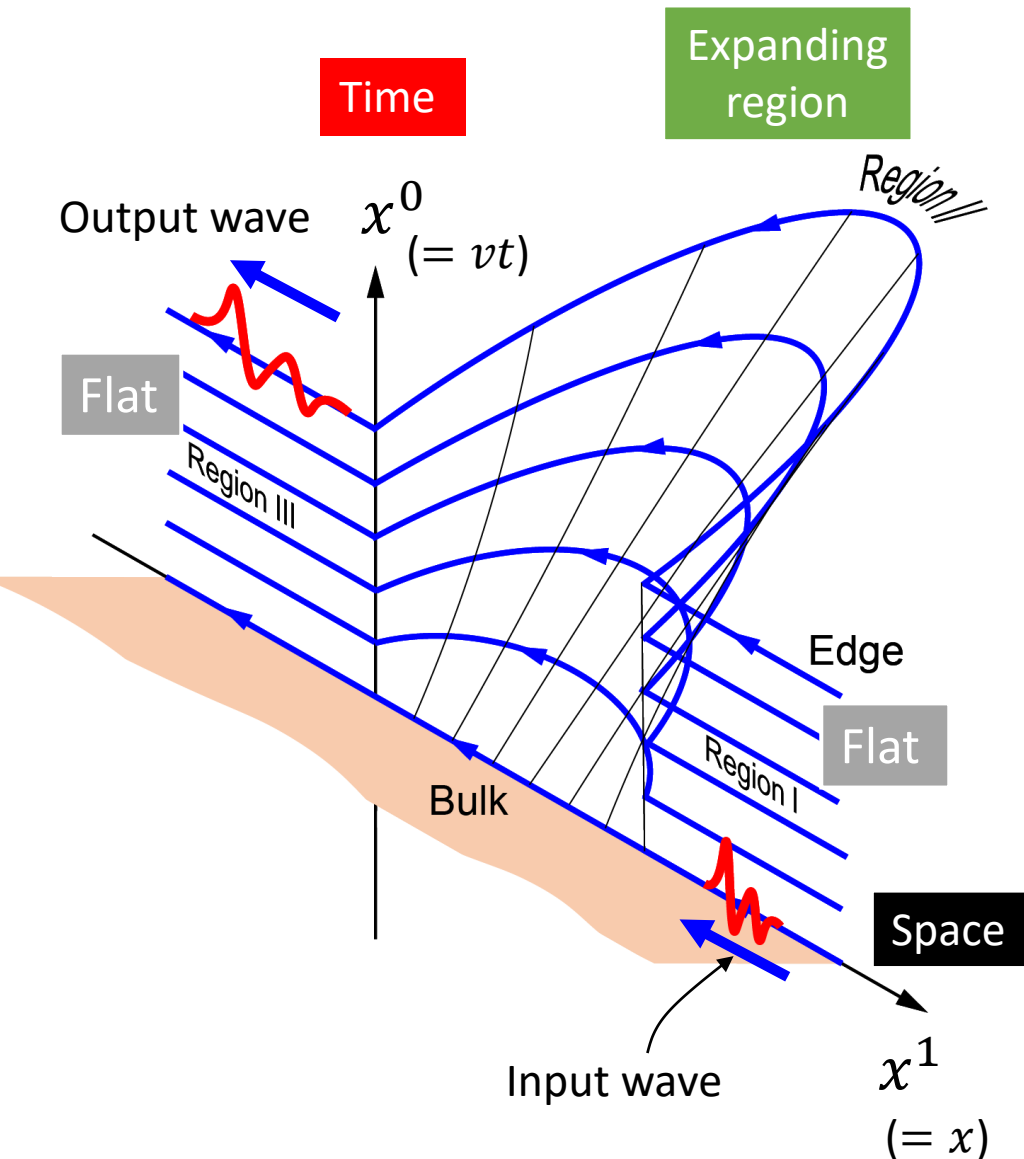
$$ds^2 = -v^2 d\tau^2 + a(\tau)^2 dx^2$$

v : Speed of "light"
(charge density wave velocity)

τ : Proper time

$a(\tau)$: Scale factor

Outline:



$$ds^2 = -v^2 d\tau^2 + a(\tau)^2 dx^2$$

↓ x^+, x^- : Light cone coordinates

Conformally flat spacetime metric

$$ds^2 = -\exp(2\Theta(x^+, x^-)) dx^+ dx^-$$



$\exp(2\Theta(x^+, x^-))$: Conformal factor

Smoothly connect Regions I and II for x_{in}^+
and Regions II and III for x_{out}^+



The expanding edge can be regarded as
FLRW (Friedmann–Lemaître–Robertson–Walker) metric
Simulator in 2D dilaton gravity model including
JT (Jackiw–Teitelboim) model

FLRW metric

$$\text{AdS } ds^2 = -v^2 d\tau^2 + \cos^2(\sqrt{2}\lambda vt) dx^2$$

$$\text{de Sitter } ds^2 = -v^2 d\tau^2 + \cosh^2(\sqrt{2}\lambda vt) dx^2$$

R : Curvature

$$R = -4\lambda^2 \text{ (AdS)} \\ \text{or } +4\lambda^2 \text{ (dS)}$$

Region II

$$ds^2 = -v^2 d\tau^2 + a^2(\tau) dx^2$$

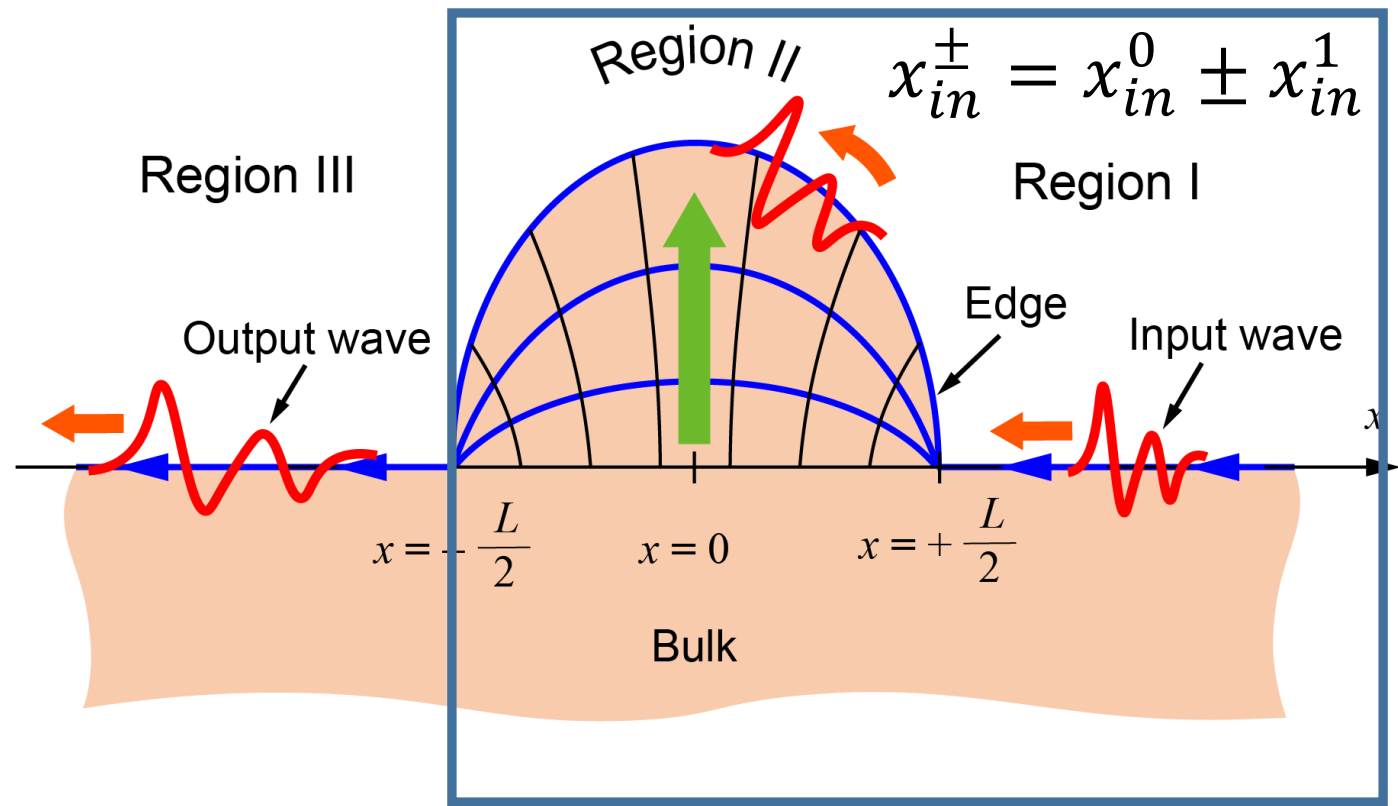
$$ds^2 = a^2(\tau) \left[-v^2 \left(\frac{d\tau}{a(\tau)} \right)^2 + dx^2 \right]$$

$$x^0 = v t = v \int_0^\tau \frac{d\tau'}{a(\tau')}, \quad x^1 = x, \quad \Theta(x^0) = \ln a(\tau)$$

$$x^\pm = x^0 \pm x^1$$

$$ds^2 = -\exp \left[2\Theta \left(\frac{x^+ + x^-}{2} \right) \right] dx^+ dx^-$$

Region I + Region II



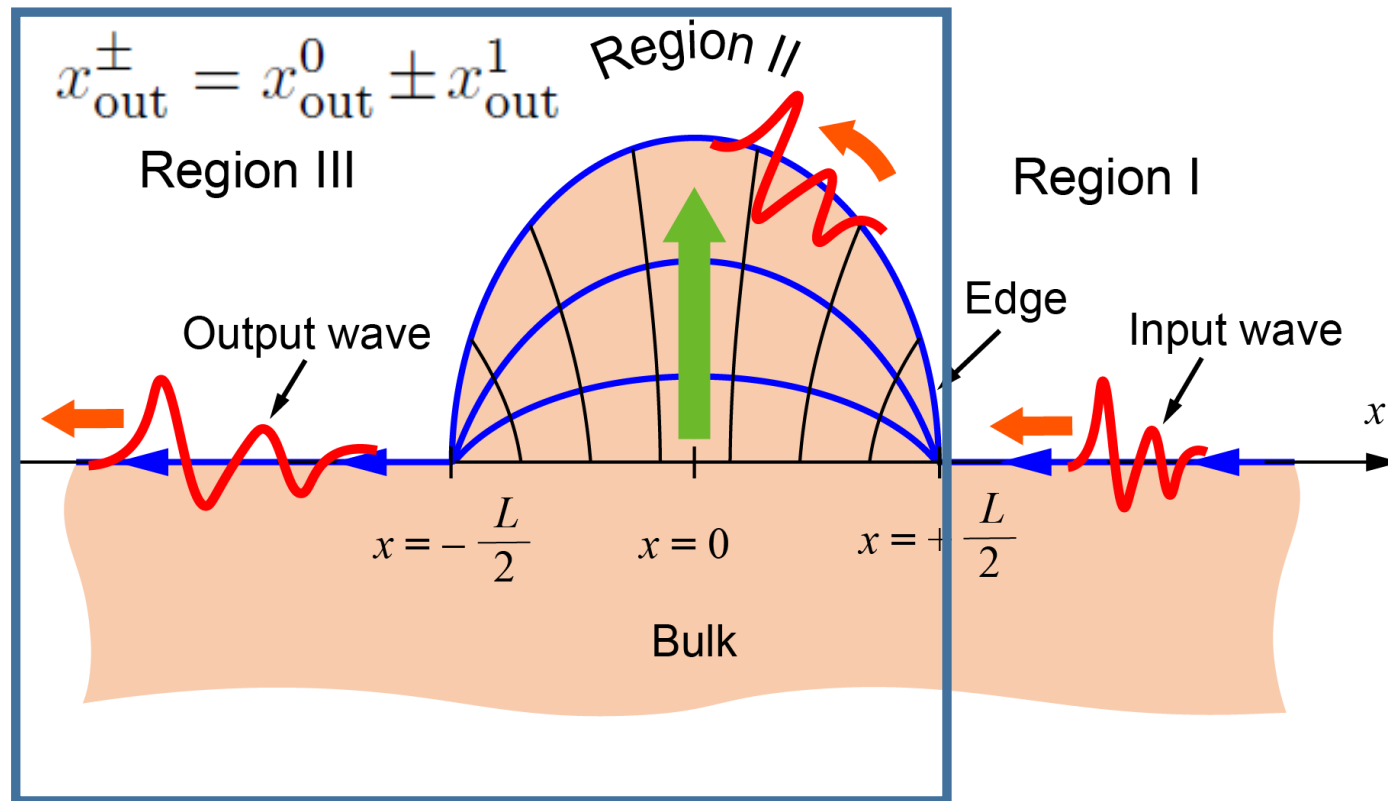
Region I: $ds^2 = -dx_{in}^+ dx_{in}^-$

Region II: $ds^2 = -\exp\left[2\Theta\left(\frac{x^+ + x^-}{2}\right)\right] dx^+ dx^-$

$x^{\pm} = x^{\pm}(x_{in}^{\pm})$

$ds^2 = -\exp\left(2\Theta\left(\frac{x^+(x_{in}^+) + x^-(x_{in}^-)}{2}\right) - \ln\left(\frac{dx_{in}^+}{dx^+} \frac{dx_{in}^-}{dx^-}\right)\right) dx^+ dx^-$

Region II + Region III



Region III:

$$ds^2 = -dx_{\text{out}}^+ dx_{\text{out}}^-$$

Region II:

$$ds^2 = -\exp \left[2\Theta \left(\frac{x^+ + x^-}{2} \right) \right] dx^+ dx^-$$

$$x^{\pm} = x^{\pm}(x_{\text{out}}^{\pm})$$

$$ds^2 = -\exp \left[2\Theta \left(\frac{x^+(x_{\text{out}}^+) + x^-(x_{\text{out}}^-)}{2} \right) - \ln \left(\frac{dx_{\text{out}}^+}{dx^+} \frac{dx_{\text{out}}^-}{dx^-} \right) \right] dx_{\text{out}}^+ dx_{\text{out}}^-.$$

$$x_{\text{in}}^+ = F(x_{\text{out}}^+)$$

We can fix this transformation using the two coordinates in Region II.

Our Result:

$$X = \int_{L/2}^{F_{\text{out}}(X)+L/2} dy \exp(\Theta(y))$$

$F_{\text{out}}(X)$




$$F(X) = X - \int_{F_{\text{out}}(X)-L/2}^{F_{\text{out}}(X)+L/2} dy \exp(\Theta(y)) + \int_{-L/2}^{L/2} dy \exp(\Theta(y))$$

***Any expanding edge corresponds to
an expanding universe
in one of 1+1 dilaton gravity models.***

1+1 dimensional dilaton gravity model as effective theory of expanding edges:

$$S = \int d^2x \sqrt{-g} \left(\Phi R - 4\lambda^2 \underline{V(\Phi)} \right)$$


Dilaton Field

potential term

By controlling the potential term, any expanding QH edge can be described.

$$\delta S / \delta g^{\alpha\beta}(x) = 0 \qquad (g_{\alpha\beta} \nabla^2 - \nabla_\alpha \nabla_\beta) \Phi + 2\lambda^2 V(\Phi) g_{\alpha\beta} = 0$$

$$\delta S / \delta \Phi(x) = 0 : \qquad R = 4\lambda^2 V'(\Phi)$$

$$ds^2 = - \exp \left(2\Theta \left(x^+, x^- \right) \right) dx^+ dx^-$$

$$\partial_+ \partial_- \Phi - \lambda^2 V(\Phi) e^{2\Theta} = 0,$$

$$\partial_+^2 \Phi - 2\partial_+ \Theta \partial_+ \Phi = 0,$$

$$\partial_-^2 \Phi - 2\partial_- \Theta \partial_- \Phi = 0.$$

$$2\partial_+ \partial_- \Theta - \lambda^2 V'(\Phi) e^{2\Theta} = 0.$$

To describe FLRW universes, let us consider metric forms such that Θ does not have any x dependence

$$ds^2 = -e^{2\Theta((x^+ + x^-)/2)} dx^+ dx^- = e^{2\Theta(vt)} \left(-v^2 dt^2 + dx^2 \right) .$$

$$\frac{d^2\Phi}{dt^2} - 4v^2\lambda^2 V(\Phi(t)) e^{2\Theta(vt)} = 0, \tag{1}$$

$$\frac{d^2\Theta}{dt^2} - 2v^2\lambda^2 V'(\Phi(t)) e^{2\Theta(vt)} = 0. \tag{2}$$

$$\frac{d^2\Phi}{dt^2} - 2\frac{d\Theta}{dt} \frac{d\Phi}{dt} = 0. \tag{3}$$

Integration of Eq(3) →

$$\Phi(t) = \lambda v \int_0^t dt' \underbrace{e^{2\Theta(vt')}}_{\text{Expanding edge information}} + \Phi_0 \quad (4)$$

Subtraction of Eq(3) from Eq(1) →

$$2 \frac{d\Theta}{dt} \frac{d\Phi}{dt} = 4v^2 \lambda^2 V(\Phi(t)) e^{2\Theta(vt)} \quad (5)$$

Substitution of Eq(4) into Eq(5) →

$$V(\Phi(t)) = \frac{1}{2v\lambda} \frac{d\Theta}{dt} (vt)$$

Reversed relation of Eq(4) →

$$V(\Phi) = \frac{1}{2v\lambda} \frac{d\Theta}{dt} (vt(\Phi))$$

The potential term yields the desired edge expansion!

$$\exp(2\Theta(vt))$$

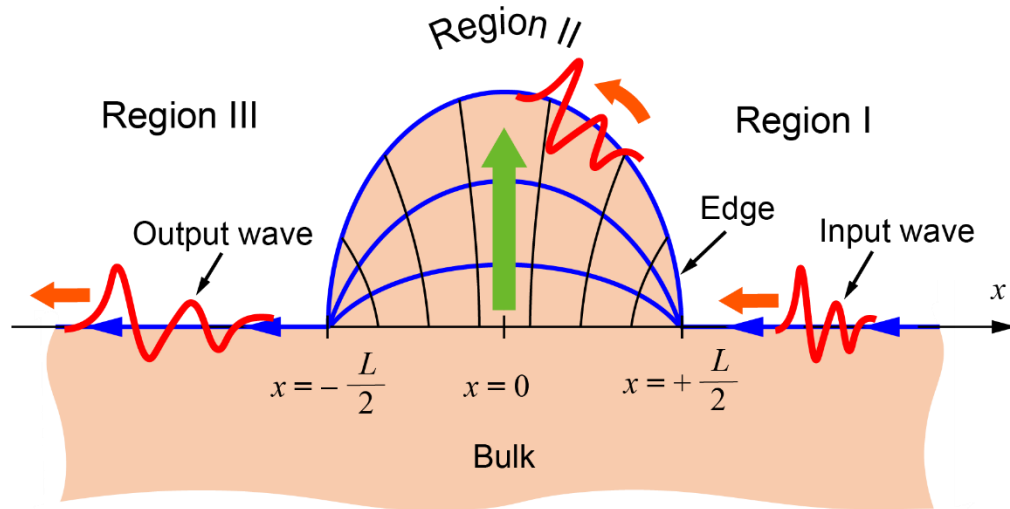

Quantum Hall Edge Expansion

$$\exp(2\Theta(vt))$$



1+1 Dimensional Dilaton Gravity

$$S = \int d^2x \sqrt{-g} (\Phi R - 4\lambda^2 V(\Phi))$$



Early Universe Simulator!

When we consider $V(\Phi) = -\Phi$, the model becomes the Jackiw–Teitelboim (JT) model

AdS spacetime emerges.

$$ds^2 = -v^2 d\tau^2 + \cos^2 (Hv\tau) dx^2$$

$$H = \sqrt{2} \lambda$$

$$e^{\Theta(vt)} = \frac{1}{\cosh (Hvt)}$$

$$\Phi(t) = \frac{Hv}{\sqrt{2}} \int_0^t \frac{dt'}{\cosh^2 (Hvt')} + \Phi_0 = \frac{1}{\sqrt{2}} \tanh (Hvt) + \Phi_0$$

$H \rightarrow iH$ in the JT model

dSJT model

$$V(\Phi) = \Phi$$

de Sitter spacetime (inflationary universe)

$$ds^2 = -v^2 d\tau^2 + \cosh^2 (Hv\tau) dx^2$$

$$\dot{R} = 4\lambda^2$$

$$\Phi(t) = \frac{1}{\sqrt{2}} \tan (Hvt) + \Phi_0$$

“Einstein-Rosen Bridge” in de Sitter Spacetime + Two Flat Spacetimes

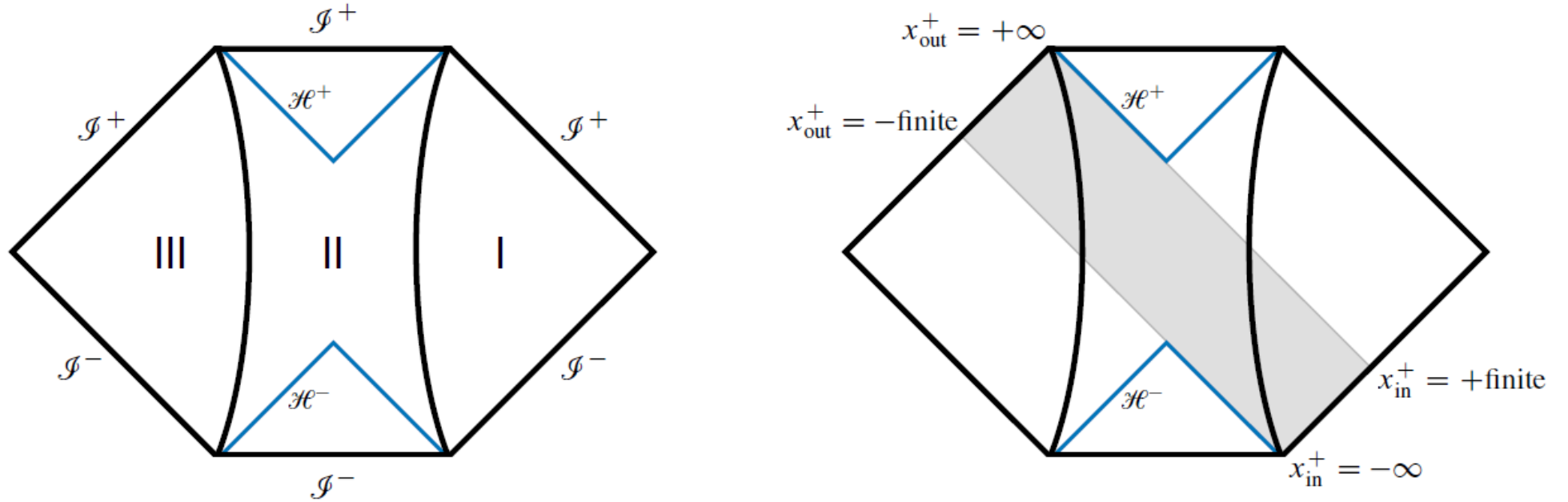
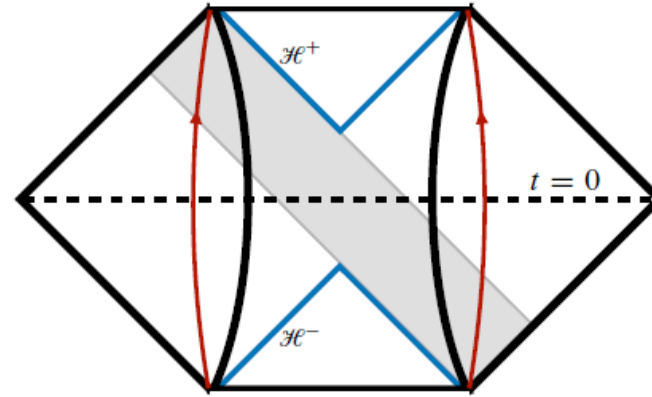
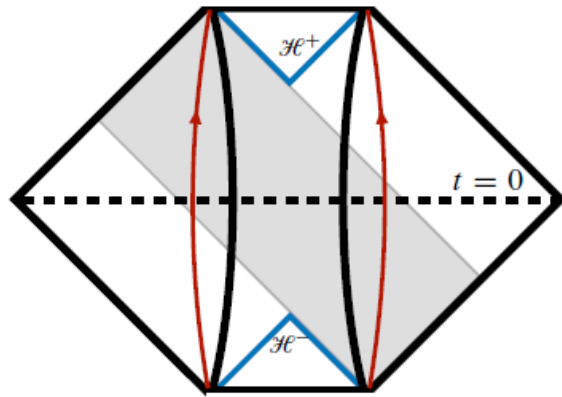


FIG. 4. Penrose diagram for the QH system with an expanding ($t > 0$) and a contracting ($t < 0$) edge Region II, which is assumed to be a part of the de Sitter spacetime with the global chart. Owing to its global structure, this spacetime possesses a future horizon \mathcal{H}^+ and a past horizon \mathcal{H}^- . The shaded region of the right panel shows the region that the edge modes in \mathcal{J}^- in Region I move to reach \mathcal{J}^+ in Region III.

“Einstein-Rosen Bridge” in de Sitter Spacetime + Two Flat Spacetimes

Small L
Traversable



Large L
Untraversable

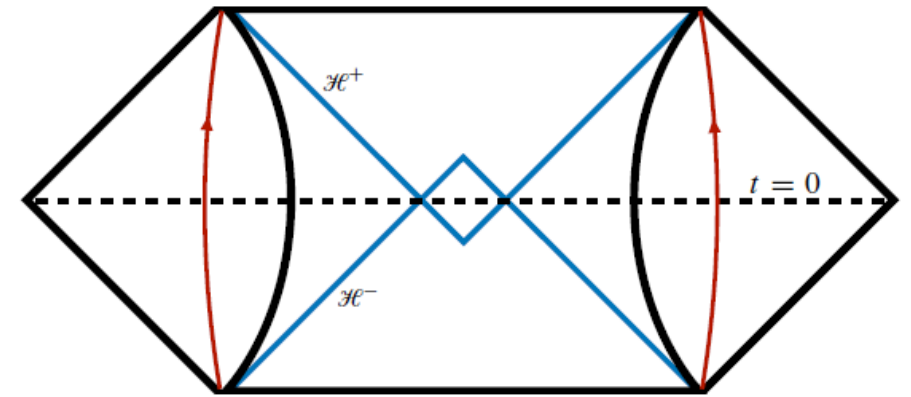
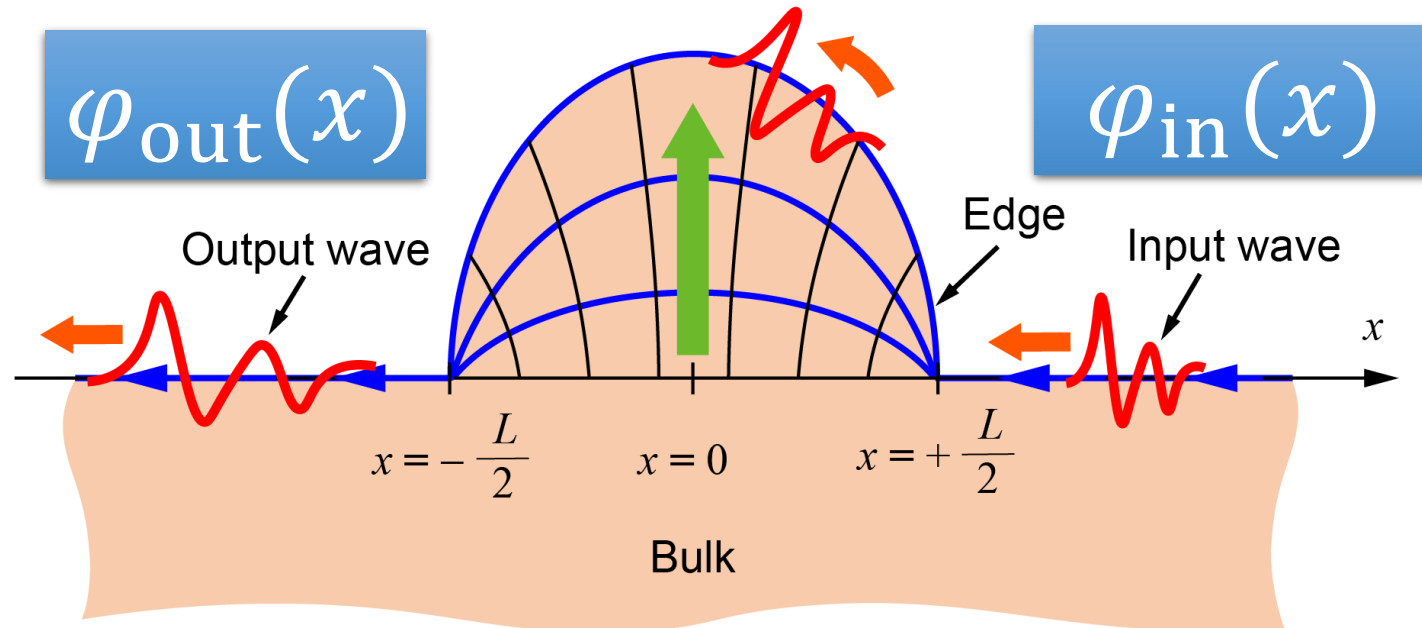


FIG. 5. L dependence of the global structure of spacetime. Red lines represent world lines for fixed spatial points in Region I and Region III. From left panel to right panel, $0 < LH < \pi/4$, $\pi/4 < LH < \pi/2$, $\pi/2 < LH$. For $\pi/2 < LH$, signals emitted from the in-region I cannot reach the out-region III.

$$\nabla^2 \varphi = 0$$

$$\varphi_{\text{out}}(x_{\text{out}}^+) = \varphi_{\text{in}}(F(x_{\text{out}}^+))$$



dSJT model

$$X = \frac{1}{2H} \ln \left[\frac{1 + \sin (H (F_{\text{out}} (X) + L/2))}{1 - \sin (H (F_{\text{out}} (X) + L/2))} \times \frac{1 - \sin (H L/2)}{1 + \sin (H L/2)} \right]$$

$$F_{\text{out}} (X) = -\frac{L}{2} + \frac{1}{H} \arcsin \left[\frac{(1 + \sin (H L/2)) e^{2H X} - (1 - \sin (H L/2))}{(1 + \sin (H L/2)) e^{2H X} + (1 - \sin (H L/2))} \right],$$

$$F(X) = \frac{1}{2H} \ln \left[\frac{1 + \sin (H (F_{\text{out}} (X) - L/2))}{1 - \sin (H (F_{\text{out}} (X) - L/2))} \times \frac{1 + \sin (H L/2)}{1 - \sin (H L/2)} \right].$$

de Sitter/anti de Sitter universe

$$\varphi_{\text{out}}(x_{\text{out}}^+) = \varphi_{\text{in}}(F(x_{\text{out}}^+))$$

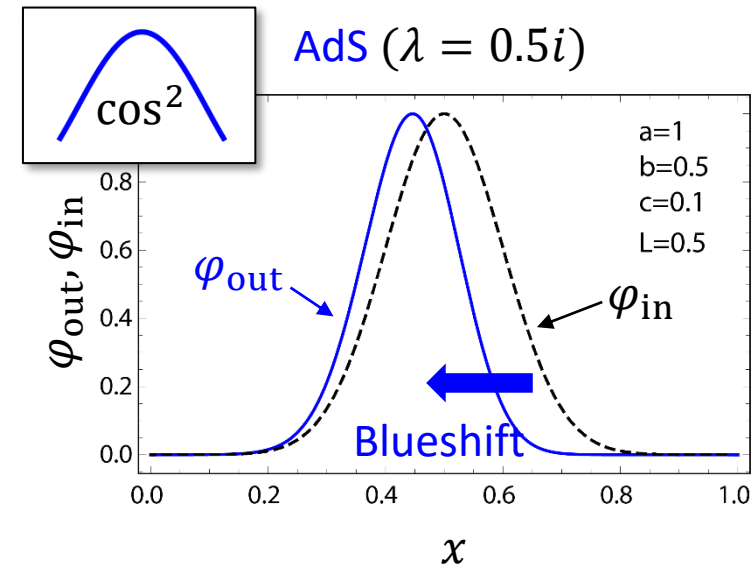
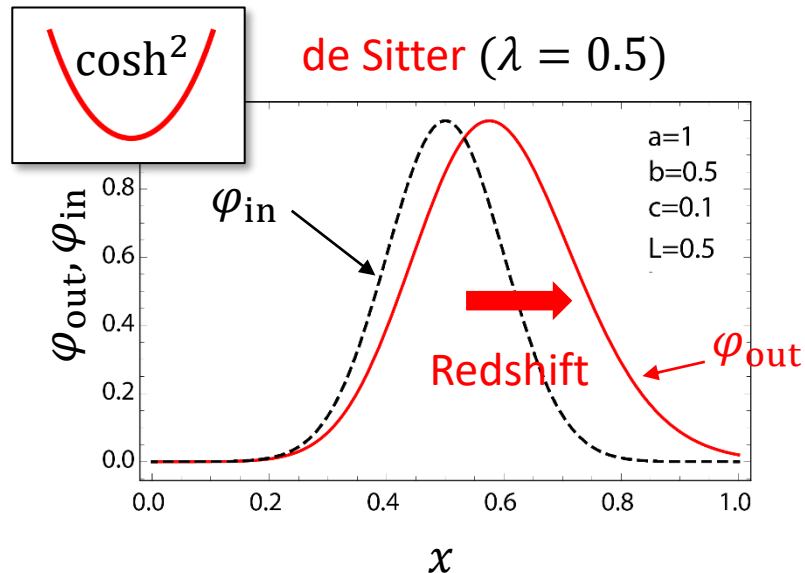
$$F_{\text{in}}^{-1}(x) = \frac{1}{4\sqrt{2}\lambda} \ln \left(\frac{1 + \sin \left(\sqrt{2}\lambda \left(2x - \frac{L}{2} \right) \right)}{1 - \sin \left(\sqrt{2}\lambda \left(2x - \frac{L}{2} \right) \right)} \times \frac{1 + \sin \left(\frac{\lambda L}{\sqrt{2}} \right)}{1 - \sin \left(\frac{\lambda L}{\sqrt{2}} \right)} \right)$$

$$F(x) = F_{\text{in}}^{-1}(F_{\text{out}}(x))$$

$$F_{\text{out}}(X) = -\frac{L}{4} + \frac{1}{2\sqrt{2}\lambda} \arcsin \frac{\left(1 + \sin \left(\frac{\lambda L}{\sqrt{2}} \right) \right) e^{4\sqrt{2}\lambda X} - \left(1 - \sin \left(\frac{\lambda L}{\sqrt{2}} \right) \right)}{\left(1 + \sin \left(\frac{\lambda L}{\sqrt{2}} \right) \right) e^{4\sqrt{2}\lambda X} + \left(1 - \sin \left(\frac{\lambda L}{\sqrt{2}} \right) \right)}$$

Input wave: Gaussian

$$\varphi_{\text{in}}(x) := a \exp \left(-\frac{(x-b)^2}{2c^2} \right)$$



x denotes x_{in}^+ and x_{out}^+ for φ_{in} and φ_{out} , respectively.

Cosmological horizon features in de Sitter case:

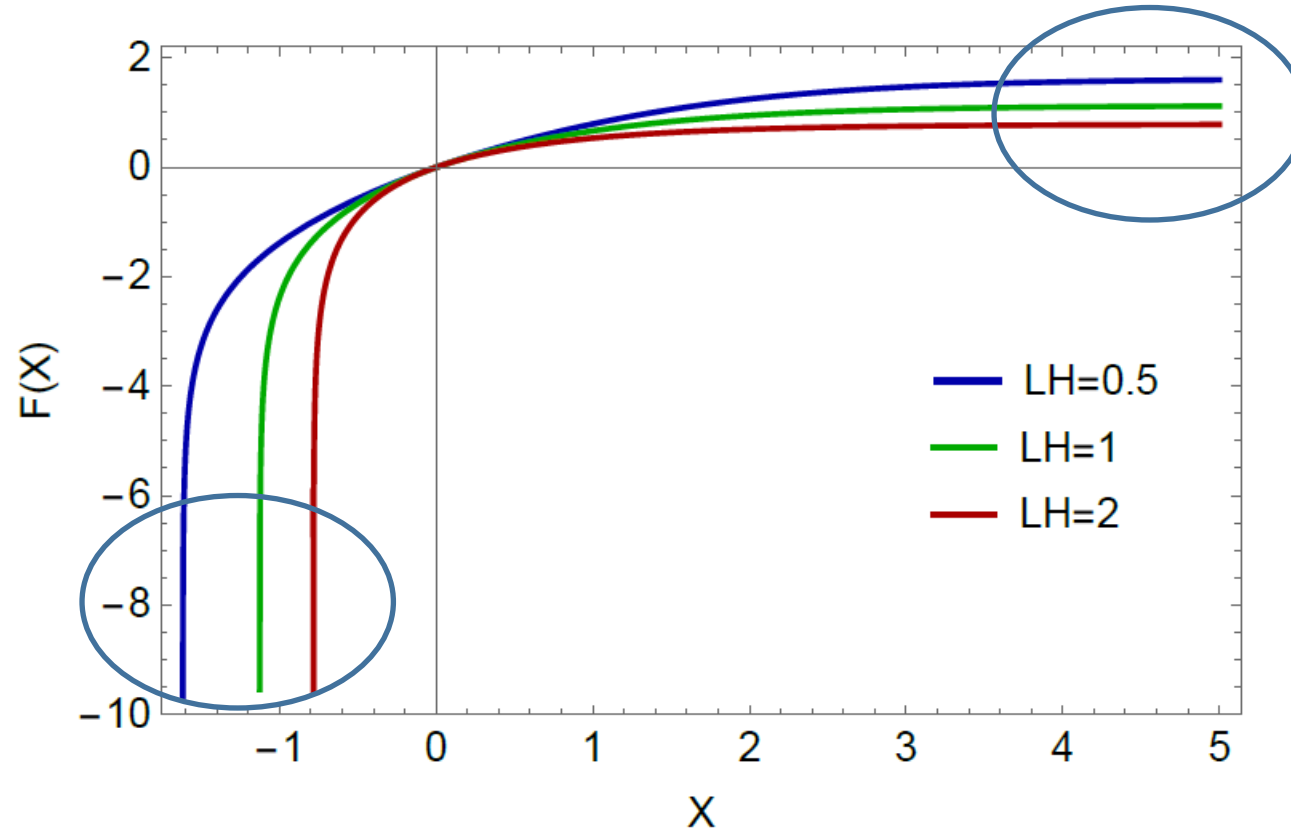


FIG. 3. Behavior of the function $F(X)$ which relates x_{in}^+ and x_{out}^+ as $x_{\text{in}}^+ = F(x_{\text{out}}^+)$. The domain and the range of $F(X)$ become semi-indefinite, which indicates existence of horizons in the present spacetime.

Output wave form in de Sitter case

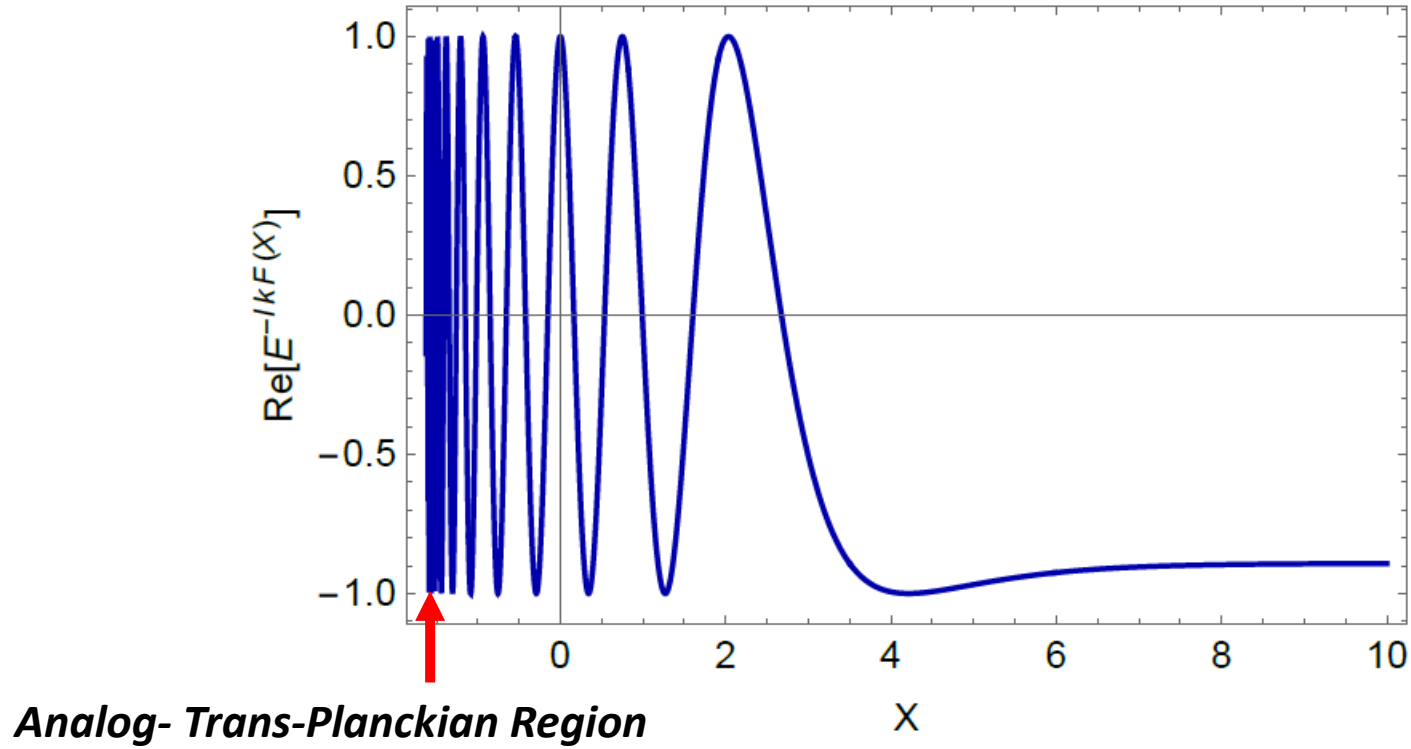


FIG. 6. The wave form received at a detection point in Region III ($LH = 0.5$). X corresponds to x_{out}^+ . The input signal is a plane wave $\varphi_{\text{in}} = e^{-ikX}$ with $k = 10$. For $X \rightarrow X_* \approx -1.6$, the input wave is infinitely blue-shifted owing to the past de Sitter horizon \mathcal{H}^- in Region II, and for $X \rightarrow +\infty$, the input wave is infinitely red-shifted owing to the future de Sitter horizon \mathcal{H}^+ in Region II.

Hawking radiation emission out of the cosmological horizon in QH edge system

$$\varphi_{\text{in}}(x_{\text{in}}^+) = \int_0^\infty dk \left(a_k^{(\text{in})} u_k(x_{\text{in}}^+) + a_k^{(\text{in})*} u_k^*(x_{\text{in}}^+) \right) \quad u_k(x) = \frac{e^{-ikx}}{\sqrt{4\pi k}}$$

$$\varphi_{\text{out}}(x_{\text{out}}^+) = \int_0^\infty dk' \left(a_{k'}^{(\text{in})} u_{k'}(F(x_{\text{out}}^+)) + a_{k'}^{(\text{in})*} u_{k'}^*(F(x_{\text{out}}^+)) \right)$$

$$u_{k'}(F(x_{\text{out}}^+)) = \int_0^\infty dk \left(\alpha(k, k') u_k(x_{\text{out}}^+) + \beta(k, k') u_k^*(x_{\text{out}}^+) \right)$$

$$\int_0^\infty dq \left(\alpha(k, q) \alpha^*(k', q) - \beta(k, q) \beta^*(k', q) \right) = \delta(k - k'),$$

$$\int_0^\infty dq \left(\alpha(k, q) \beta(k', q) - \beta(k, q) \alpha(k', q) \right) = 0.$$

$$\varphi_{\text{out}}(x_{\text{out}}^+) = \int_0^\infty dk \left(b_k^{(\text{out})} u_k(x_{\text{out}}^+) + b_k^{(\text{out}) *} u_k^*(x_{\text{out}}^+) \right) .$$

$$u_k(x) = \frac{e^{-ikx}}{\sqrt{4\pi k}} .$$

$$\left[\hat{a}_k^{(\text{in})}, \hat{a}_{k'}^{(\text{in})\dagger} \right] = \hbar \delta(k - k'), \quad \left[\hat{b}_k^{(\text{out})}, \hat{b}_{k'}^{(\text{out})\dagger} \right] = \hbar \delta(k - k')$$

$$\hat{b}_k^{(\text{out})} = \int_0^\infty dk' \left(\alpha(k, k') \hat{a}_{k'}^{(\text{in})} + \beta^*(k, k') \hat{a}_{k'}^{(\text{in})\dagger} \right),$$

$$\hat{b}_k^{(\text{out})\dagger} = \int_0^\infty dk' \left(\alpha^*(k, k') \hat{a}_{k'}^{(\text{in})\dagger} + \beta(k, k') \hat{a}_{k'}^{(\text{in})} \right).$$

$$\hat{a}_k^{(\text{in})} |0_{\text{in}}\rangle = 0$$

$$\left\langle \hat{n}_k^{(\text{out})} \right\rangle = \frac{1}{\hbar} \langle 0_{\text{in}} | \hat{b}_k^{(\text{out})\dagger} \hat{b}_k^{(\text{out})} | 0_{\text{in}} \rangle = \int_0^\infty dk' |\beta(k, k')|^2$$

$$\left\langle \hat{N}^{(\text{out})} \right\rangle = \int_0^\infty dk \left\langle \hat{n}_k^{(\text{out})} \right\rangle$$

$$\alpha(k, k') = \sqrt{\frac{k}{k'}} \int_{-\infty}^{\infty} dX e^{-ik' F(X)} e^{ikX}, \quad \beta(k, k') = \sqrt{\frac{k}{k'}} \int_{-\infty}^{\infty} dX e^{-ik' F(X)} e^{-ikX}.$$

To extract information of late time particle creations in Region II, we consider the asymptotic behavior of the function $F(X)$ for $HX \gg 1$:

$$F(X) \approx -c_0 - c_1 e^{-HX}$$

$$c_0 = \frac{2}{H} \ln(\tan(HL/2)), \quad c_1 = \frac{4}{H} \sqrt{\frac{1 - \sin(HL/2)}{1 + \sin(HL/2)}}.$$

$$\begin{aligned}\beta(k, k') &\approx \sqrt{\frac{k}{k'}} \frac{e^{ik'c_0}}{H} \int_0^\infty dy y^{-ik/H-1} e^{ik'c_1 y} \\ &= \sqrt{\frac{k}{k'}} \frac{e^{ik'c_0}}{H} (-ik'c_1)^{-ik/H} \Gamma\left(\frac{ik}{H}\right).\end{aligned}$$

Hawking radiation out of Region II

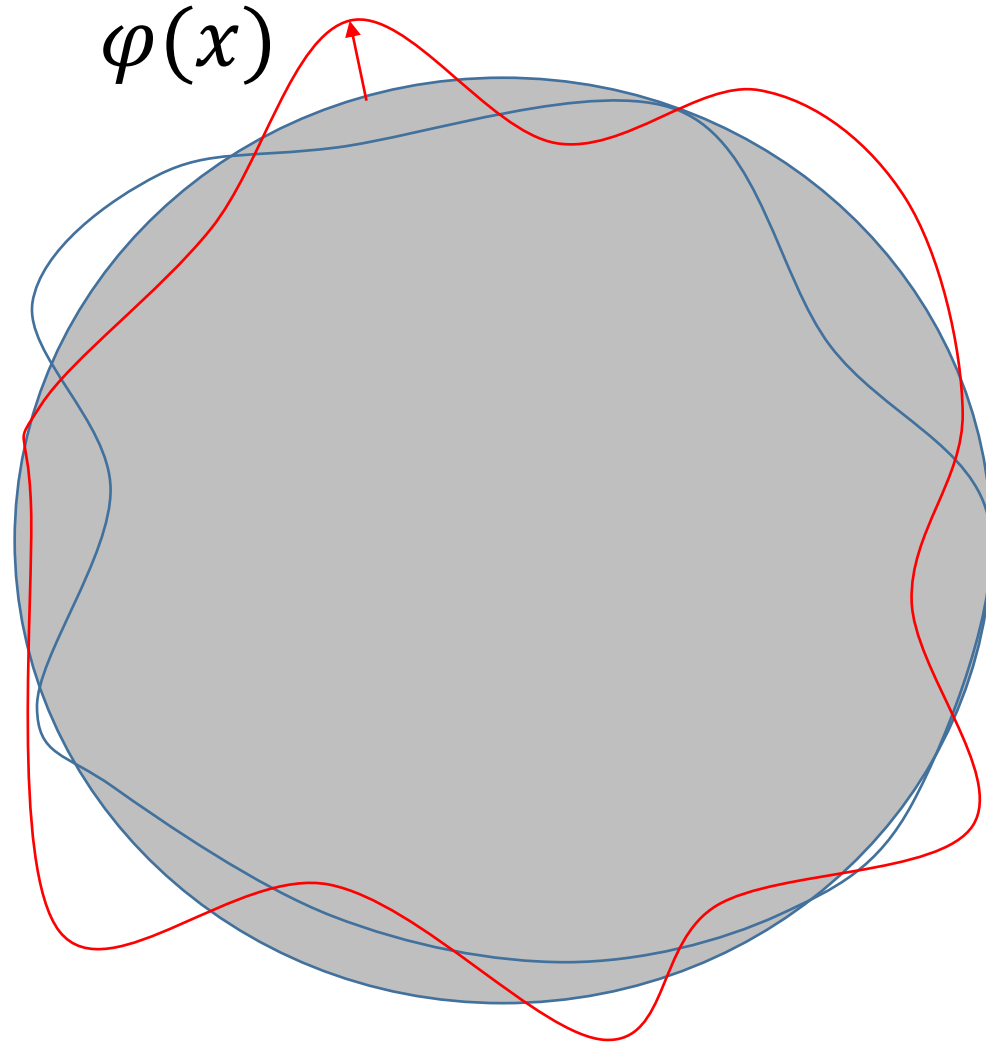
$$|\beta(k, k')|^2 \approx \frac{2\pi}{Hk'} \frac{1}{\exp(2\pi k/H) - 1}$$

$$T_{\text{H}} = \frac{H}{2\pi}$$

***QH edge mimics a quantum field
in a curved spacetime.***

***Interestingly, there is a possibility that
the QH edge is also described by
a quantum gravity model.***

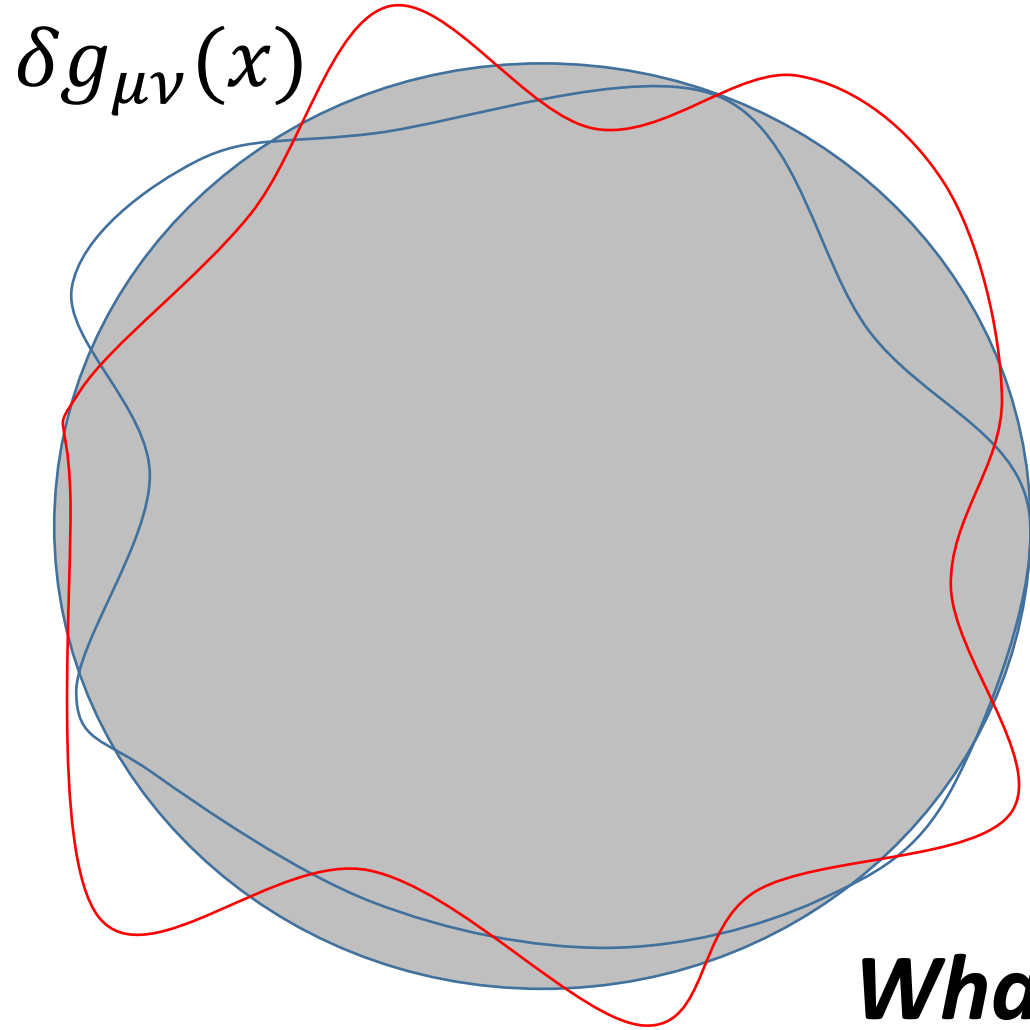
Edge fluctuation as quantum matter in 1+1 dim classical spacetime



***Quantum superposition
of field configurations
in a fixed background spacetime***

$$\int D\varphi \exp(iS_g [\varphi])$$

Can the same edge be regarded as a 1+1 dim quantum gravity system?



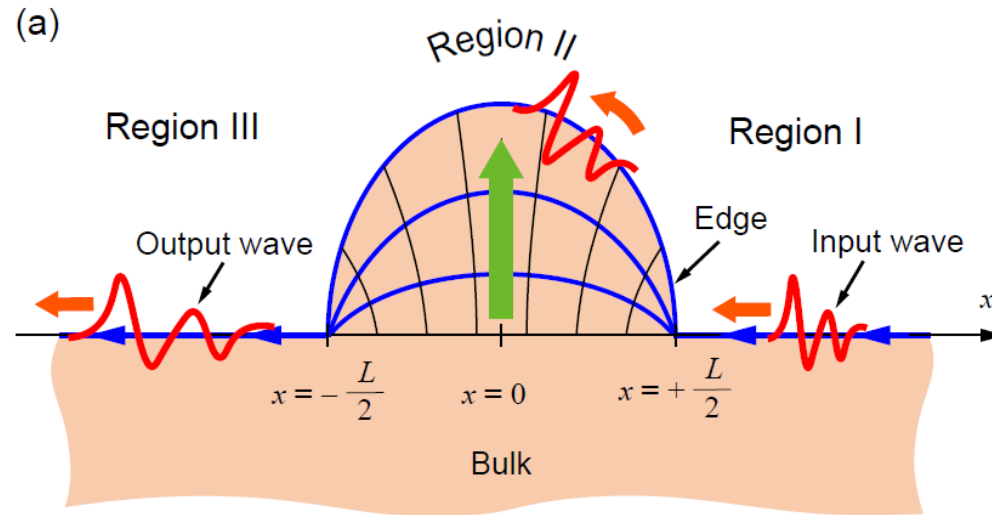
***Superposition of quantum spacetimes
in 1+1 dimensions***

$$\int Dg \exp(iS[g]) ?$$

***What kind of quantum gravity theory?
(In progress.)***

***IV. New Condensed Matter Physics
from Expanding Edge Experiments***

Study of expanding edges open a new physics of quantum Hall systems.



Accessible issues:

- (1) This experiment can determine whether conformal symmetry of edge currents survives or not. (Chern-Simon + edge effective theory?)***
- (2) This experiment can determine whether interaction of edge excitations appears or not. (Free field theory?)***
- (3) This experiment can determine whether bulk-edge interaction appears or not. (Do gapped bulk excitations interact edge excitations?)***

Quantum Energy Teleportation (QET) Experiments using Quantum Hall Edges

arXiv.org > quant-ph > arXiv:1109.2203

Quantum Physics

[Submitted on 10 Sep 2011]

Quantum energy teleportation in a quantum Hall system

[Go Yusa](#), [Wataru Izumida](#), [Masahiro Hotta](#)

arXiv.org > quant-ph > arXiv:1305.3955

Quantum Physics

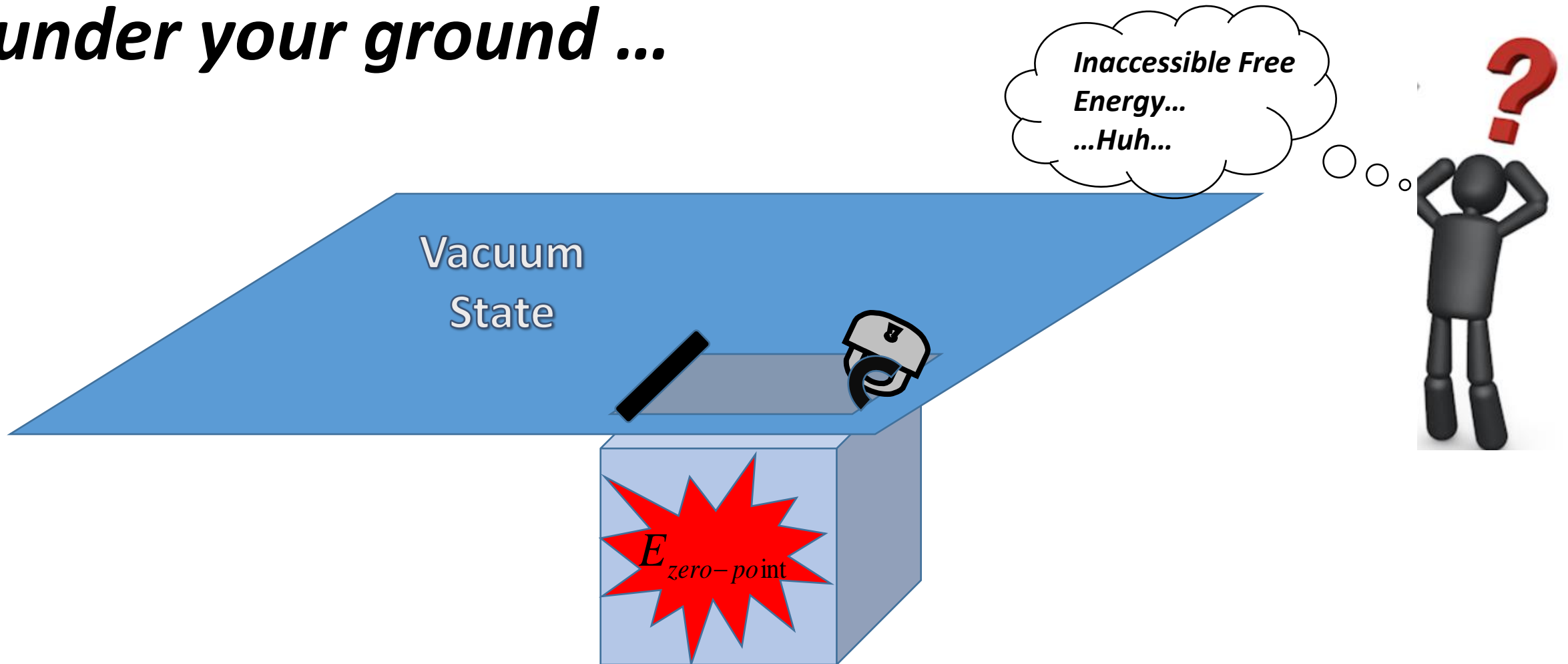
[Submitted on 17 May 2013 ([v1](#)), last revised 6 Jan 2014 (this version, v2)]

Quantum Energy Teleportation without Limit of Distance

[Masahiro Hotta](#), [Jiro Matsumoto](#), [Go Yusa](#)

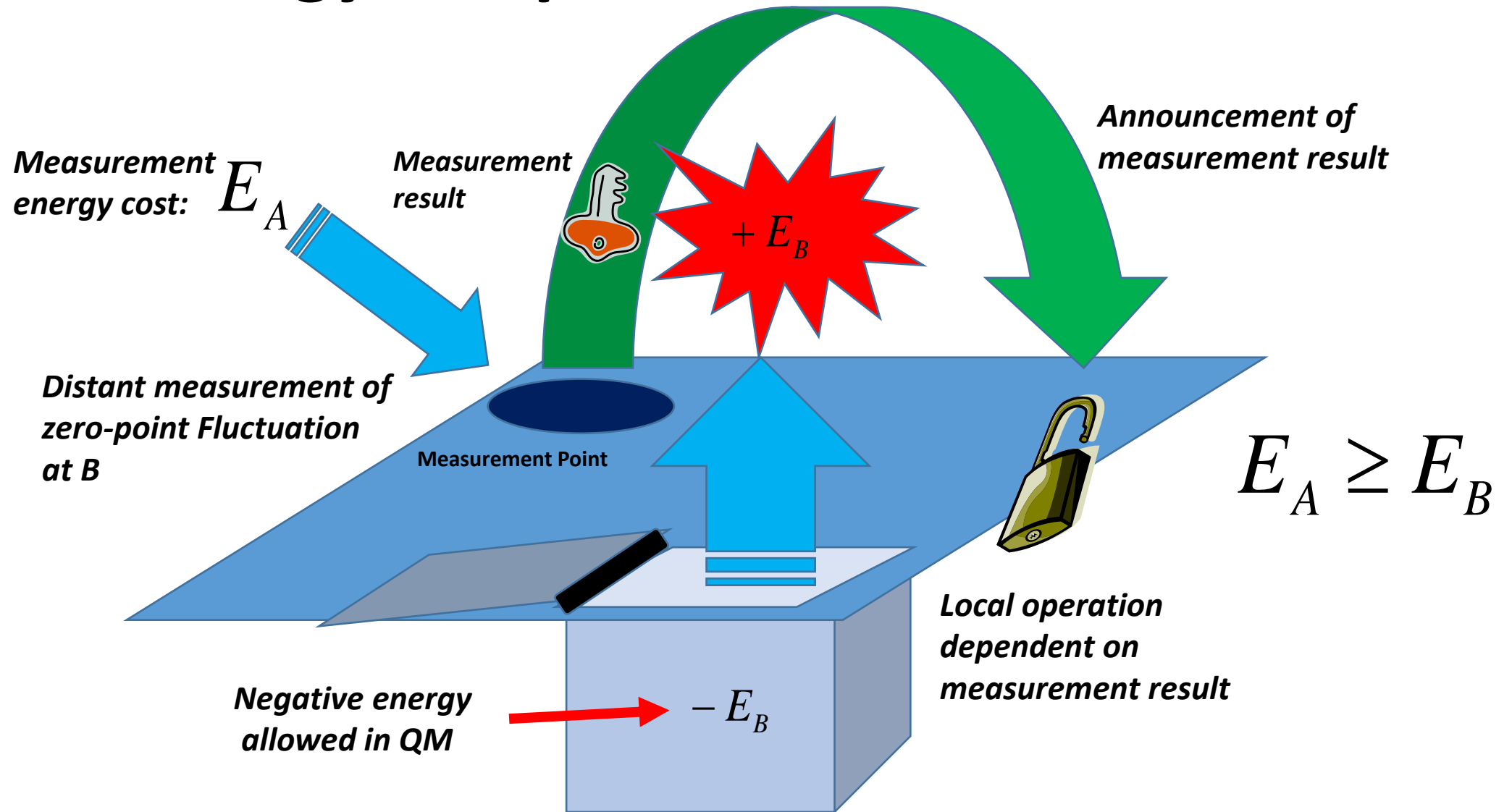
Zero-Point Energy Physics of Quantum Hall Systems

You may feel that zero-point energy of quantum fields is saved in a locked safe under your ground ...



Unable to use by **local** operations

Quantum Energy Teleportation (Hotta, 2008)



Local operation and classical communication allow extraction of zero-point energy in the entangled vacuum state!

Recently, an experiment result of *finite-temperature* version of QET has been reported using nuclear magnetic resonance.

arXiv > quant-ph > arXiv:1002.0200

Search... Help | Advanced Search

Quantum Physics

[Submitted on 1 Feb 2010 (v1), last revised 25 Jun 2010 (this version, v2)]

Energy-Entanglement Relation for Quantum Energy Teleportation

Masahiro Hotta

Protocols of quantum energy teleportation (QET), while retaining causality and local energy conservation, enable the transportation of energy from a subsystem of a many-body quantum system to a distant subsystem by local operations and classical communication through ground-state entanglement. We prove two energy-entanglement inequalities for a minimal QET model. These relations help us to gain a profound understanding of entanglement itself as a physical resource by relating entanglement to energy as an evident physical resource.

arXiv > quant-ph > arXiv:1404.5081

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Quantum Physics

[Submitted on 20 Apr 2014 (v1), last revised 1 Aug 2014 (this version, v2)]

Strong Local Passivity in Finite Quantum Systems

Michael Frey, Ken Funo, Masahiro Hotta

Passive states of quantum systems are states from which no system energy can be extracted by any cyclic (unitary) process. Gibbs states of all temperatures are passive. Strong local (SL) passive states are defined to allow any general quantum operation, but the operation is required to be local, being applied only to a specific subsystem. Any mixture of eigenstates in a system-dependent neighborhood of a nondegenerate, entangled ground state is found to be SL passive. In particular, Gibbs states are SL passive with respect to a subsystem only at or below a critical, system-dependent temperature. SL passivity is associated in many-body systems with the presence of ground state entanglement in a way suggestive of collective quantum phenomena such as quantum phase transitions, superconductivity, and the quantum Hall effect. The presence of SL passivity is detailed for some simple spin systems where it is found that SL passivity is neither confined to systems of just a few particles nor limited to the near vicinity of the ground state.

Cornell University

arXiv > quant-ph > arXiv:2203.16269

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Quantum Physics

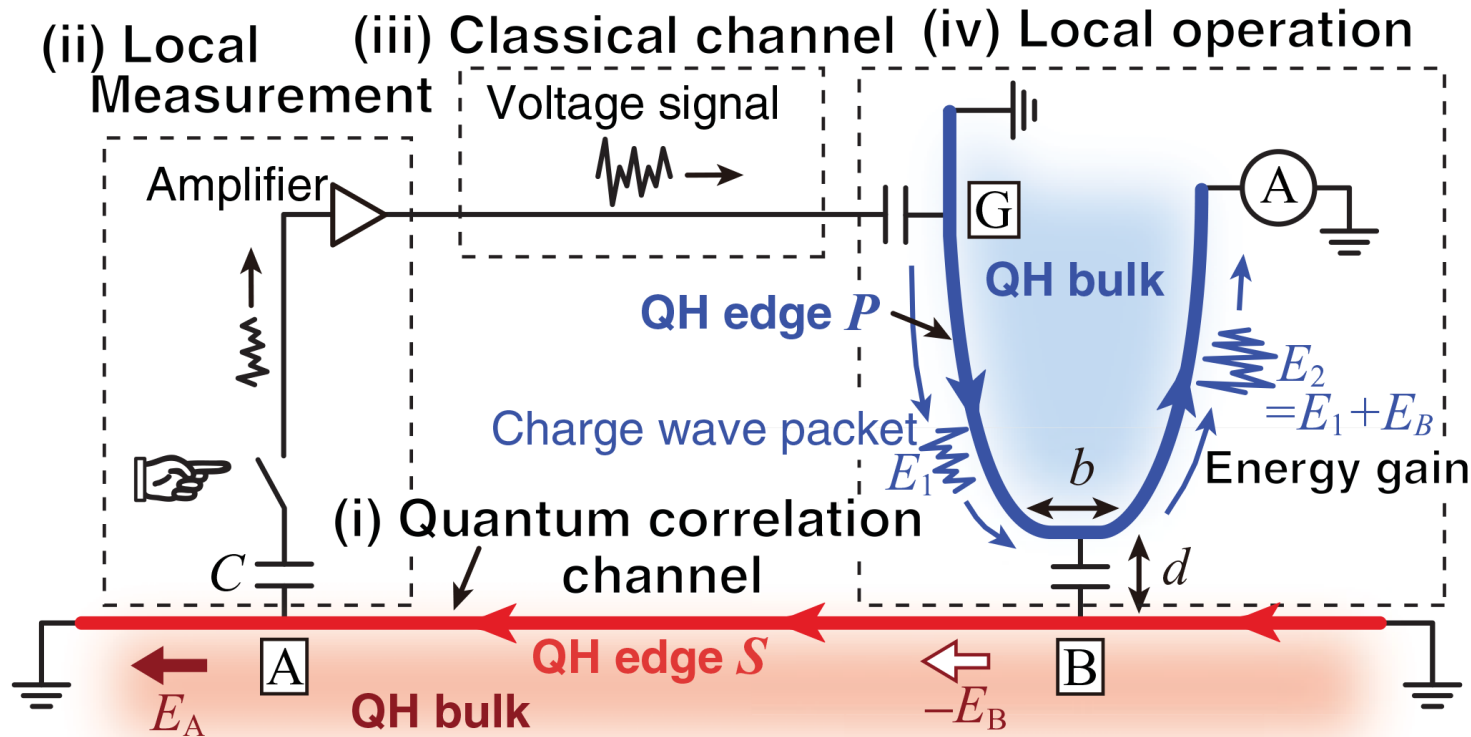
[Submitted on 30 Mar 2022]

Experimental activation of strong local passive states with quantum information

Nayeli A. Rodríguez-Briones, Hemant Katiyar, Raymond Laflamme, Eduardo Martín-Martínez

Strong local passivity is a property of multipartite quantum systems from which it is impossible to locally extract energy. A popular example is the vacuum state of a quantum field theory from which it is impossible to extract zero-point energy. However, adding classical communication between different partitions of the system through so-called 'quantum energy teleportation' protocols makes it possible to activate local energy of strong local passive states, including the ground state of quantum systems if this state displays entanglement. Here we report the first experimental realization of both the activation of a strong local passive state and the demonstration of a quantum energy teleportation protocol by using nuclear magnetic resonance on a bipartite quantum system.

We are able to perform direct observation of teleported energy for the *vacuum state* using the QH edge!
Long-distance QET is possible using expanding edges.



arXiv.org > quant-ph > arXiv:1109.2203

Quantum Physics

[Submitted on 10 Sep 2011]

Quantum energy teleportation in a quantum Hall system

Go Yusa, Wataru Izumida, Masahiro Hotta

arXiv.org > quant-ph > arXiv:1305.3955

Quantum Physics

[Submitted on 17 May 2013 (v1), last revised 6 Jan 2014 (this version, v2)]

Quantum Energy Teleportation without Limit of Distance

Masahiro Hotta, Jiro Matsumoto, Go Yusa

Summary

We have started creating quantum universe simulators made of QH edges. Conceptual cosmological issues including Hawking radiation, trans-Planckian problem, and quantum-classical transition of field fluctuation can be studied in the experiments. The expanding edge currents will be explored to open a window of new QH physics.