Insights from Light-Front Quantization on the Unruh Effect

A. Deur

Thomas Jefferson National Accelerator Facility

In collaboration with:

S. J. Brodsky, C. D. Roberts and B. Terzić

arXiv:2405.06002

The Unruh Effect

- **The Unruh effect**: Accelerated observers can detect particles which are unobservable to inertial observers. Occurs even if the accelerated observer is in vacuum.

S. A. Fulling, PRD 7 2850 (1973);
P. C. W. Davies, J. Phys. A 8 609 (1975);
W. G. Unruh, PRD 14 870 (1976).

The Unruh Effect

- **The Unruh effect**: Accelerated observers can detect particles which are unobservable to inertial observers. Occurs even if the accelerated observer is in vacuum.

S. A. Fulling, PRD 7 2850 (1973);
P. C. W. Davies, J. Phys. A 8 609 (1975);
W. G. Unruh, PRD 14 870 (1976).

- Formal reason: The proper time of an accelerated observer is different from the time of an inertial observer *and unrelated by Lorentz transformations*.
    - For each choice of time there is a different vacuum. (Unless time are related by Lorentz transfo.)
    - The vacuum attached to an inertial frame appears populated by real particles to an accelerated observer (whose own vacuum is empty, by definition).

The Unruh Effect

- **The Unruh effect**: Accelerated observers can detect particles which are unobservable to inertial observers. Occurs even if the accelerated observer is in vacuum.

S. A. Fulling, PRD 7 2850 (1973);
P. C. W. Davies, J. Phys. A 8 609 (1975);
W. G. Unruh, PRD 14 870 (1976).

- Formal reason: The proper time of an accelerated observer is different from the time of an inertial observer *and unrelated by Lorentz transformations*.
  - For each choice of time there is a different vacuum. (Unless time are related by Lorentz transfo.)
  - The vacuum attached to an inertial frame appears populated by real particles to an accelerated observer (whose own vacuum is empty, by definition).

- Importance: by Einstein's equivalence principle, the Unruh effect ≡ Hawking's black hole radiation. (acceleration = gravitational force ≡ spacetime curvature)
  - Doorway to quantum gravitation;

The Unruh Effect

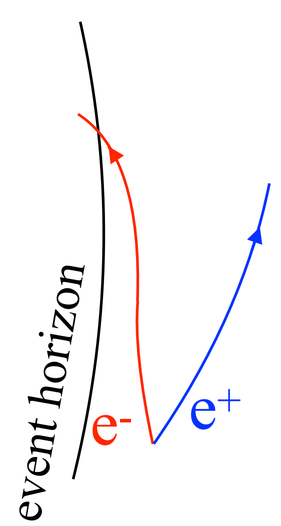
- **The Unruh effect**: Accelerated observers can detect particles which are unobservable to inertial observers. Occurs even if the accelerated observer is in vacuum.

S. A. Fulling, PRD 7 2850 (1973);
P. C. W. Davies, J. Phys. A 8 609 (1975);
W. G. Unruh, PRD 14 870 (1976).

- Formal reason: The proper time of an accelerated observer is different from the time of an inertial observer *and unrelated by Lorentz transformations*.
  - For each choice of time there is a different vacuum. (Unless time are related by Lorentz transfo.)
  - The vacuum attached to an inertial frame appears populated by real particles to an accelerated observer (whose own vacuum is empty, by definition).

- Importance: by Einstein's equivalence principle, the Unruh effect ≡ Hawking's black hole radiation. (acceleration = gravitational force ≡ spacetime curvature)
  - Doorway to quantum gravitation.

- Interpretation: If a vacuum loop's pair of virtual particles occurs near an event horizon, one of the particles may fall beyond the event horizon and the pair annihilation is prevented: one particle becomes real (taking energy from the Black Hole (Hawking radiation) or from the frame acceleration (Unruh effect)).



The Unruh Effect

LF quantization: $p^+ \geq 0 \Rightarrow$ trivial vacuum (aside from possible zero-modes).

No loops of virtual particle with non-zero momenta.

What about the Unhru effect in LF quantization?

Field decomposition

In frame x_μ (with vacuum $|0\rangle$):

Field decomposition in positive and negative frequency modes:

$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right), \text{ with } f_p \propto e^{ip^\mu x_\mu}$$

annihilation creation operators

For IF: $f_p \propto e^{-i(\omega t - pz)}$,

For LF: $f_{p^+} \propto e^{-\frac{i}{2}(p^- x^+ + p^+ x^-)}$.

Field decomposition

In frame x_μ (with vacuum $|0\rangle$):

Field decomposition in positive and negative frequency modes:

$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right), \text{ with } f_p \propto e^{ip^\mu x_\mu}$$

For IF: $f_p \propto e^{-i(\omega t - pz)}$,

For LF: $f_{p^+} \propto e^{-\frac{i}{2}(p^- x^+ + p^+ x^-)}$.

In another frame x'_μ (with vacuum $|0'\rangle$):

$$\phi = \int dp'\left(\hat{b}_{p'} f'_{p'} + \hat{b}_{p'}^\dagger f'^*_{p'}\right)$$

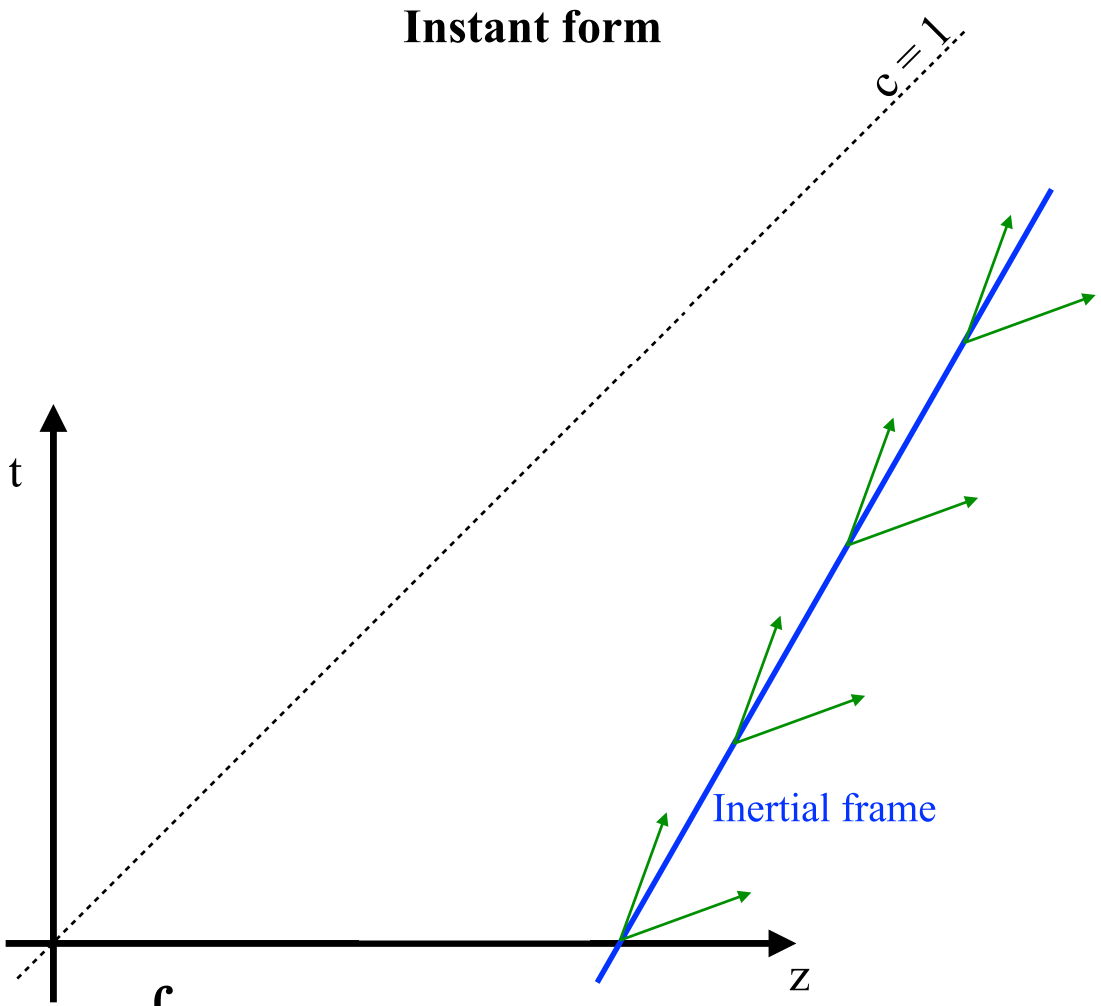
If **no un**ambiguous separation positive and negative modes in different frames, then

$$\hat{b}_{p'} = \alpha \hat{a}_p + \beta \hat{a}_p^\dagger \qquad \text{with } \beta \neq 0$$

$$\Rightarrow \hat{b}_{p'}|0'\rangle = 0 \text{ but } \hat{b}_{p'}|0\rangle = (\alpha \hat{a}_p + \beta \hat{a}_p^\dagger)|0\rangle = \hat{a}_p^\dagger |0\rangle \propto |p\rangle.$$

i.e., $\hat{b}_{p'}|0\rangle \propto |p\rangle \neq 0$ ← Unruh effect

Inertial frames

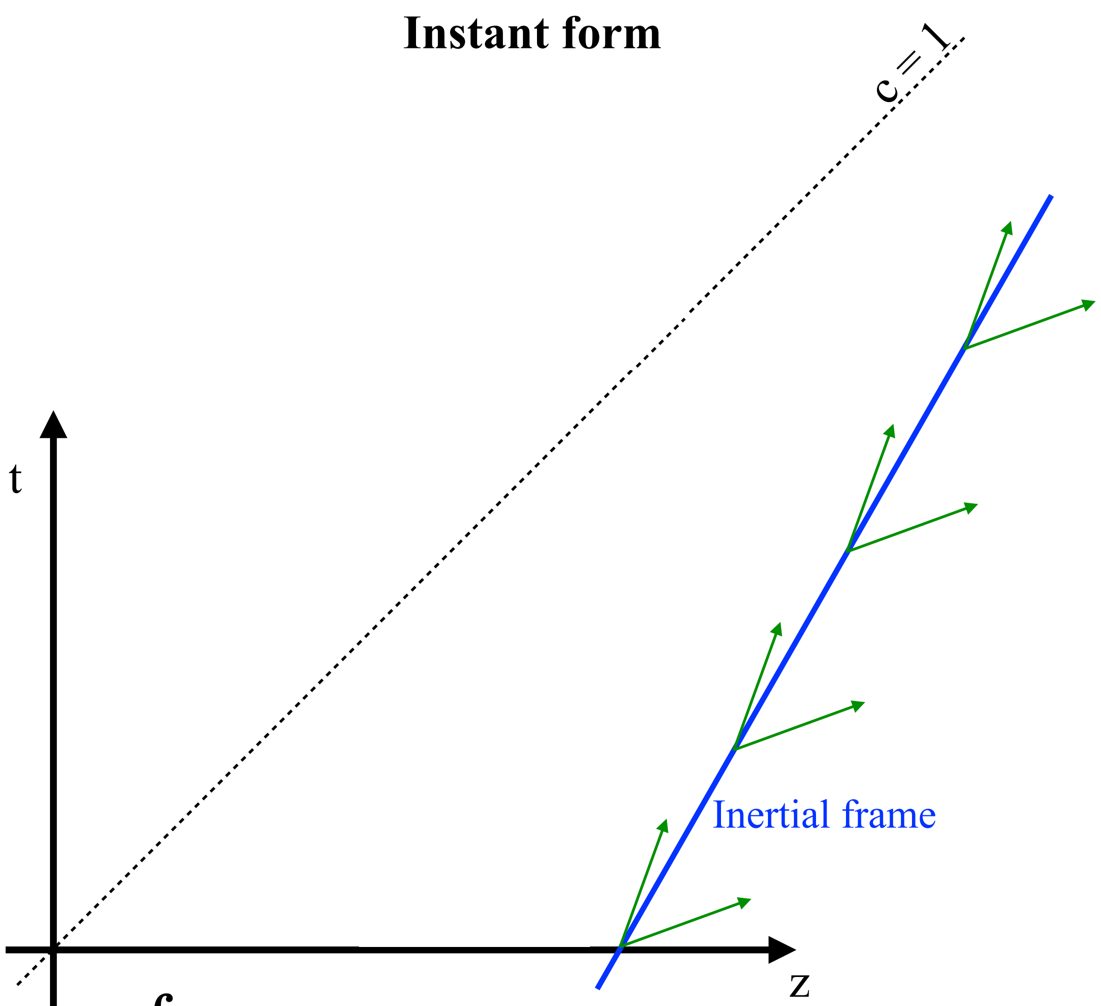


$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right), \text{ with } f_p \propto e^{ip^\mu x_\mu}$$

If the frames are related by a Lorentz boost (viz inertial frames):

$f_p \propto e^{ip^\mu x_\mu} = e^{i(\omega t - pz)} = e^{i(\omega' t' - p' z')}$ $\Rightarrow \hat{a}_p = \hat{b}_{p'}$. $\beta = 0$: No Unruh effect.

Inertial frames



$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right), \text{ with } f_p \propto e^{ip^\mu x_\mu}$$

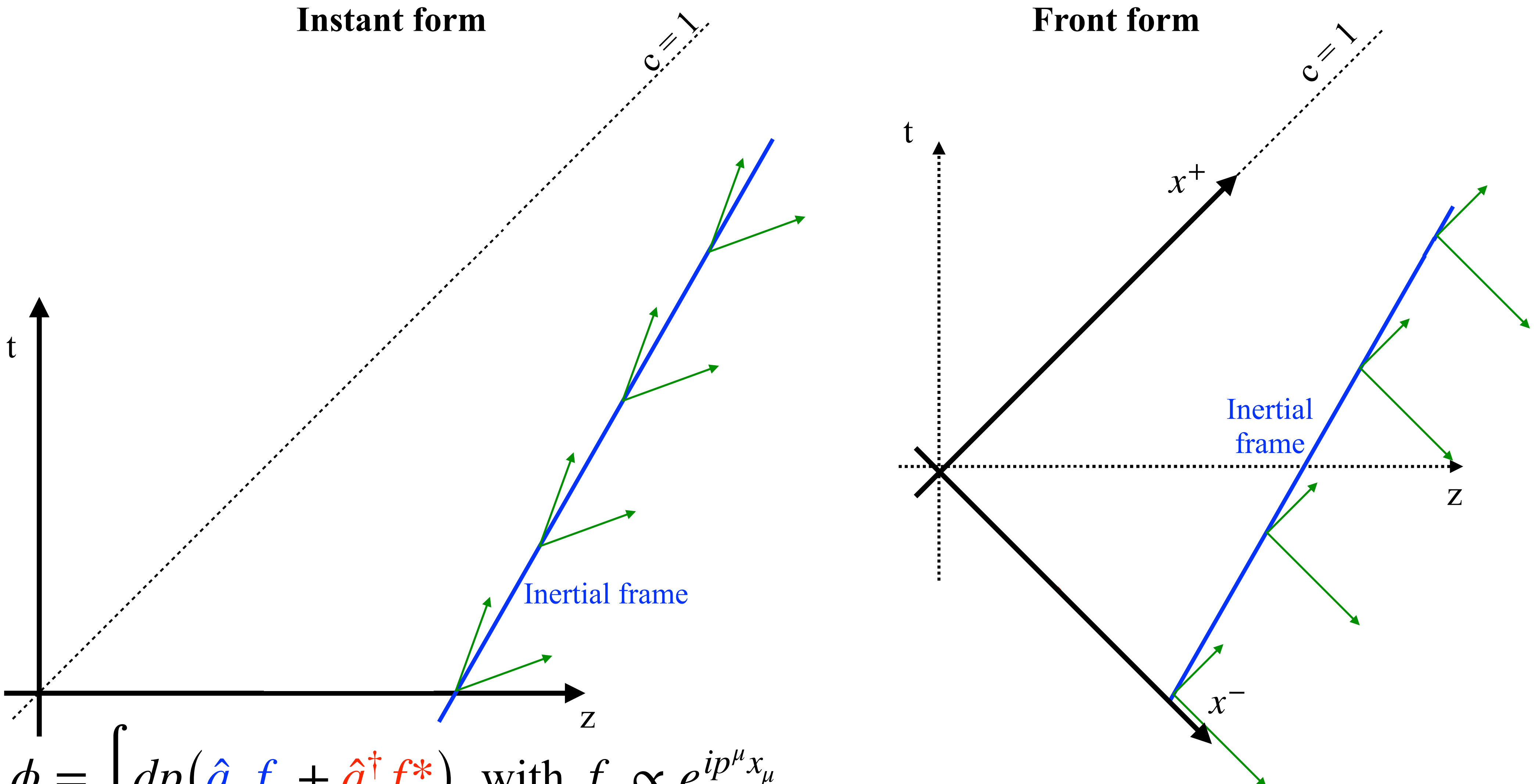
If the frames are related by a Lorentz boost (viz inertial frames):

$$f_p \propto e^{ip^\mu x_\mu} = e^{i(\omega t - pz)} = e^{i(\omega' t' - p' z')} \qquad \Rightarrow \hat{a}_p = \hat{b}_{p'}. \quad \beta = 0\text{: No Unruh effect.}$$

$$\frac{\partial f_p}{\partial t'} = \left[\frac{\partial t}{\partial t'}\partial_t + \frac{\partial z}{\partial t'}\partial_z\right] f_p = i\left[\omega \cosh\theta - p \sinh\theta\right] f_p = -i\omega' f_p$$

Frequencies in the boosted frame are boosted frequencies.
⇒ unambiguous separation of positive and negative modes.
No Unruh effect in inertial frames, as it should be.

Inertial frames



$$\phi = \int dp \left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^* \right), \text{ with } f_p \propto e^{ip^\mu x_\mu}$$

If the frames are related by a Lorentz boost (viz inertial frames):

$$f_p \propto e^{ip^\mu x_\mu} = e^{i(\omega t - pz)} = e^{i(\omega' t' - p' z')} = e^{-\frac{i}{2}(p^- x^+ + p^+ x^-)} \Rightarrow \hat{a}_p = \hat{b}_{p'}.\quad \beta = 0\text{: No Unruh effect.}$$

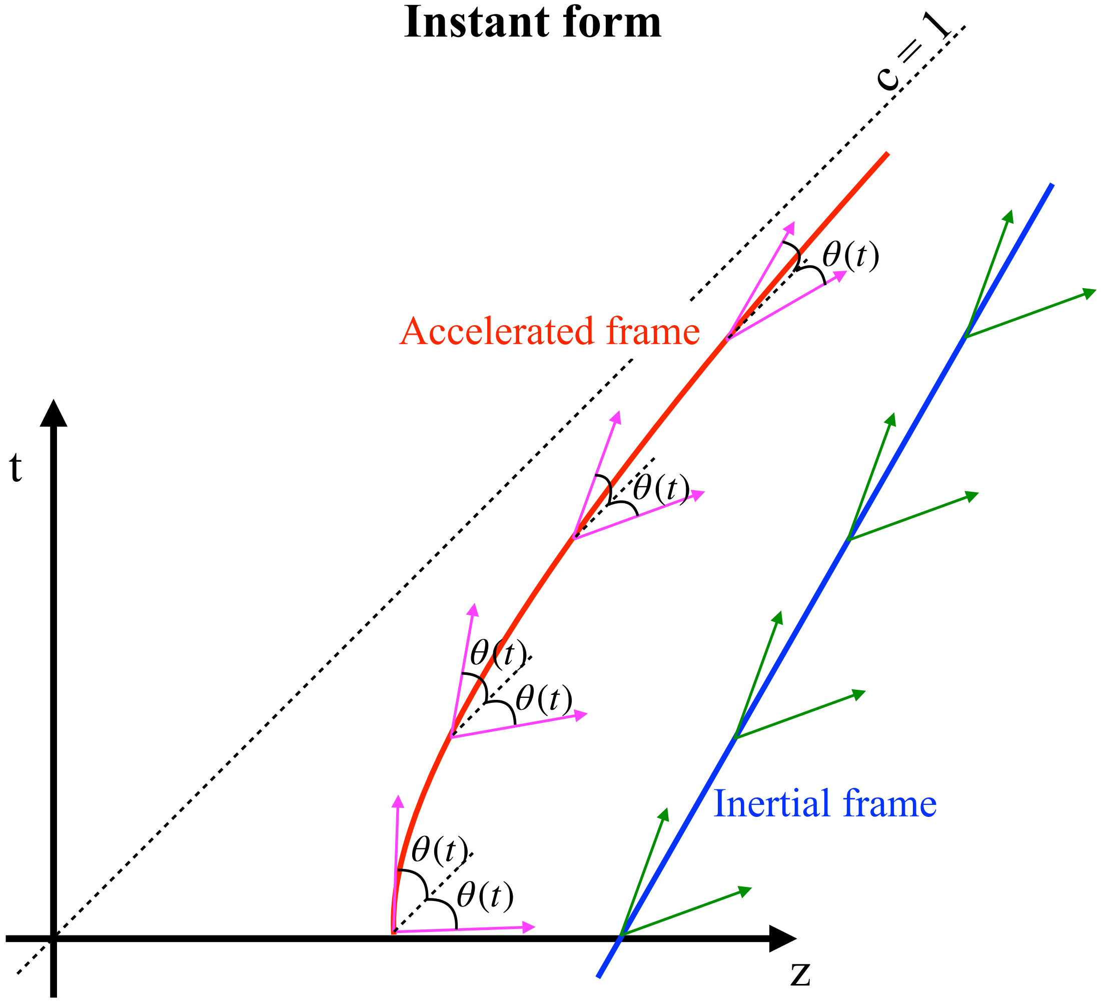
$$\left.\begin{aligned} \frac{\partial f_p}{\partial t'} &= -i\omega' f_p \text{ for IF,} \\ \frac{\partial f_{p^+}}{\partial x^{+'}} &= -\frac{i}{2} p^{-'} f_{p^+} \text{ for LF} \end{aligned}\right\}$$

Frequencies in the boosted frame are boosted frequencies.
⇒ unambiguous separation of positive and negative modes.
No Unruh effect in inertial frames, as it should be.

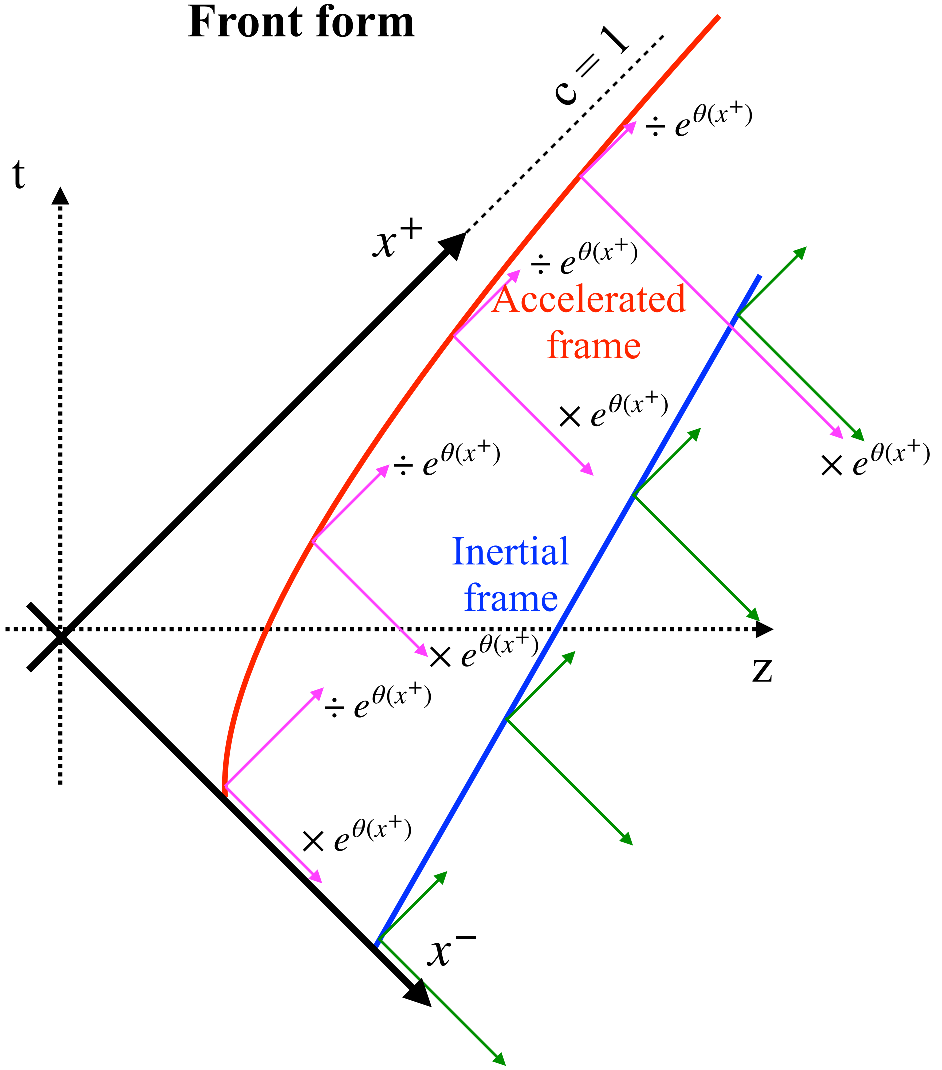
Accelerating frames

Acceleration: succession of boosts with changing rapidity, e.g., $\theta(t) = ut$ or $\theta(x^+) = ux^+$:

Instant form

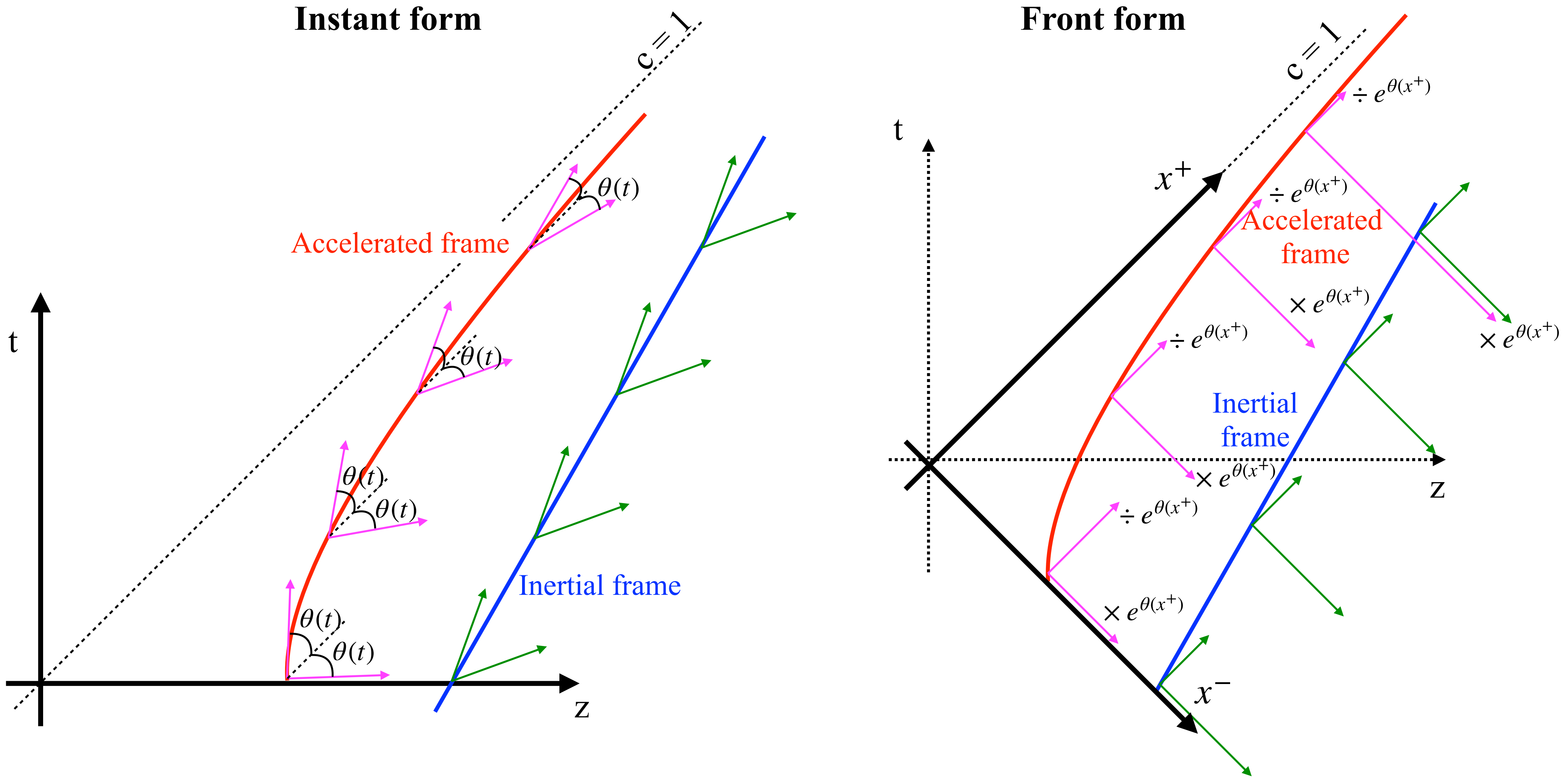


Front form



Accelerating frames

Acceleration: succession of boosts with changing rapidity, e.g., $\theta(t) = ut$ or $\theta(x^+) = ux^+$:



Time-dependent space-time mixing ⇒ ambiguous separation of + and - modes ⇒ $\beta \neq 0$ ⇒ Unruh effect

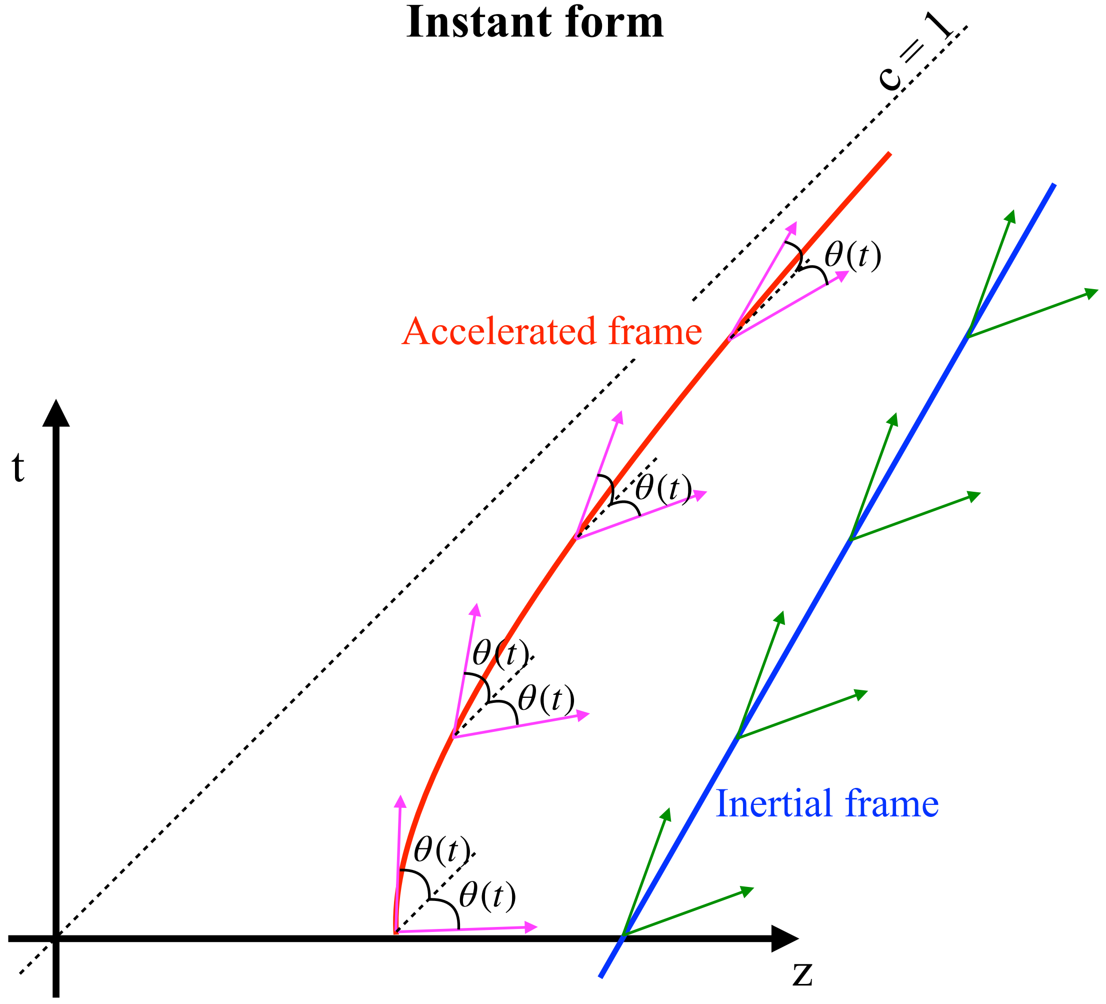
$$\frac{\partial f_p}{\partial t'} = -i\left[\omega' + \partial_{t'}\theta(\omega z - tp)\right] f_p \text{, with } \partial_{t'}\theta(t) = u\,\mathrm{sech}(ut)/[1 - uz + ut\tanh(ut)] \text{ for IF,}$$

Not Lorentz invariant.

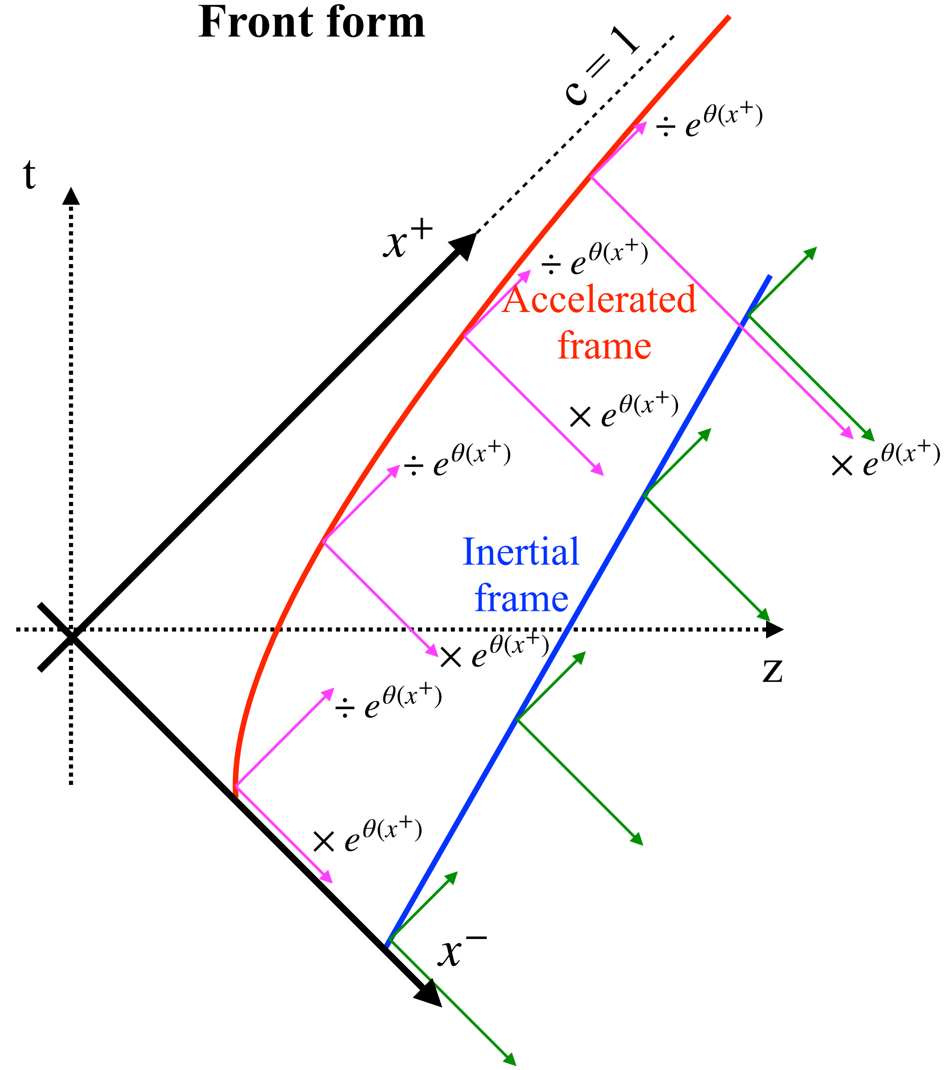
Accelerating frames

Acceleration: succession of boosts with changing rapidity, e.g., $\theta(t) = ut$ or $\theta(x^+) = ux^+$:

Instant form



Front form



Time-dependent space-time mixing ⇒ ambiguous separation of + and - modes ⇒ $\beta \neq 0$ ⇒ Unruh effect

$$\frac{\partial f_p}{\partial t'} = -i\left[\omega' + \partial_{t'}\theta(\omega z - tp)\right] f_p \text{, with } \partial_{t'}\theta(t) = u\,\mathrm{sech}(ut)/[1 - uz + ut\tanh(ut)] \text{ for IF,}$$

Not Lorentz invariant.

$$\frac{\partial f_{p^+}}{\partial x^{+\prime}} = -\frac{i}{2}\left[p^{-\prime} + \partial_{x^{+\prime}}\theta(x^-p^+ - x^+p^-)\right] f_{p^+} \text{, with } \partial_{x^{+\prime}}\theta(x^+) = \upsilon e^{-\upsilon x^+}/[1 + \upsilon x^+] \text{ for LF}$$

$\partial_{x^{+\prime}}\theta$ only time-dependent. Space ⊥ time always ⇒ unambiguous separation of + and - modes ⇒ $\beta = 0$ ⇒ No Unruh effect

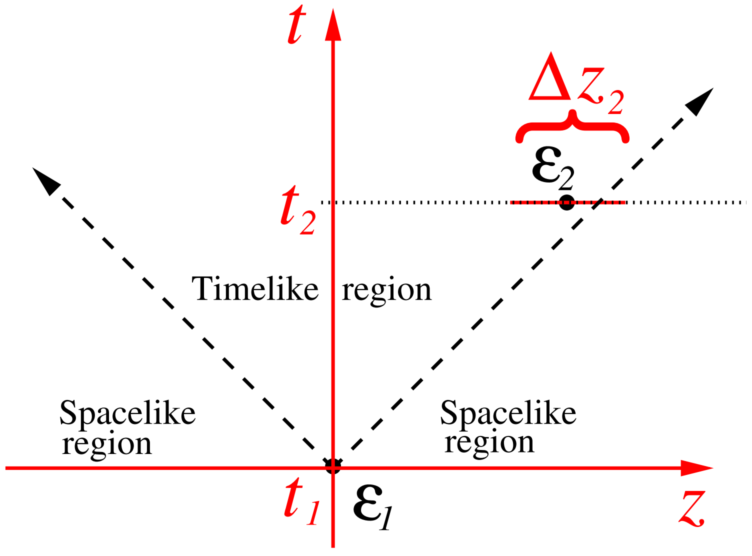
Connection to commutation relations & vacuum structure

Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.



Connection to commutation relations & vacuum structure

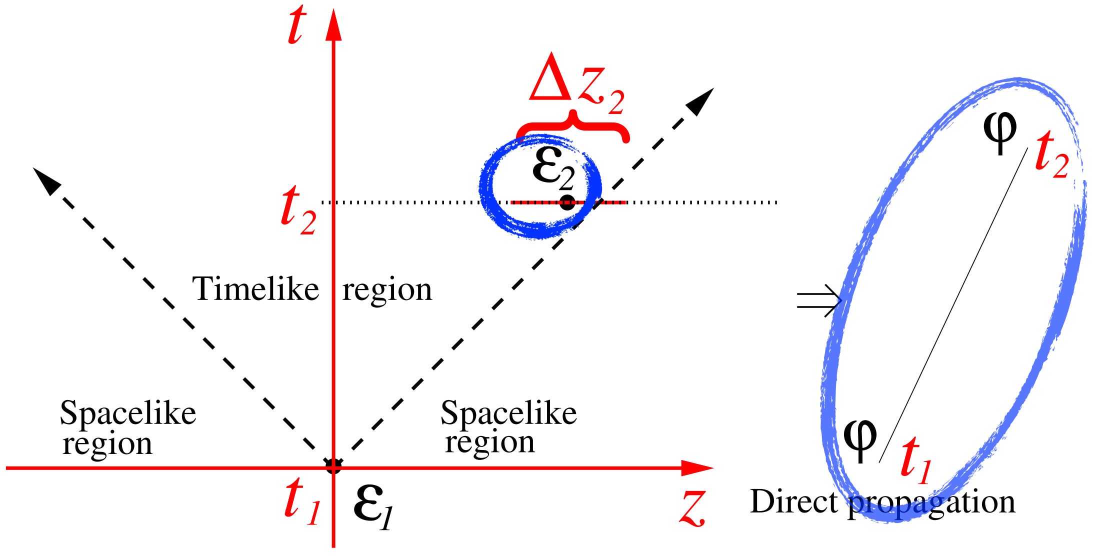
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form



Connection to commutation relations & vacuum structure

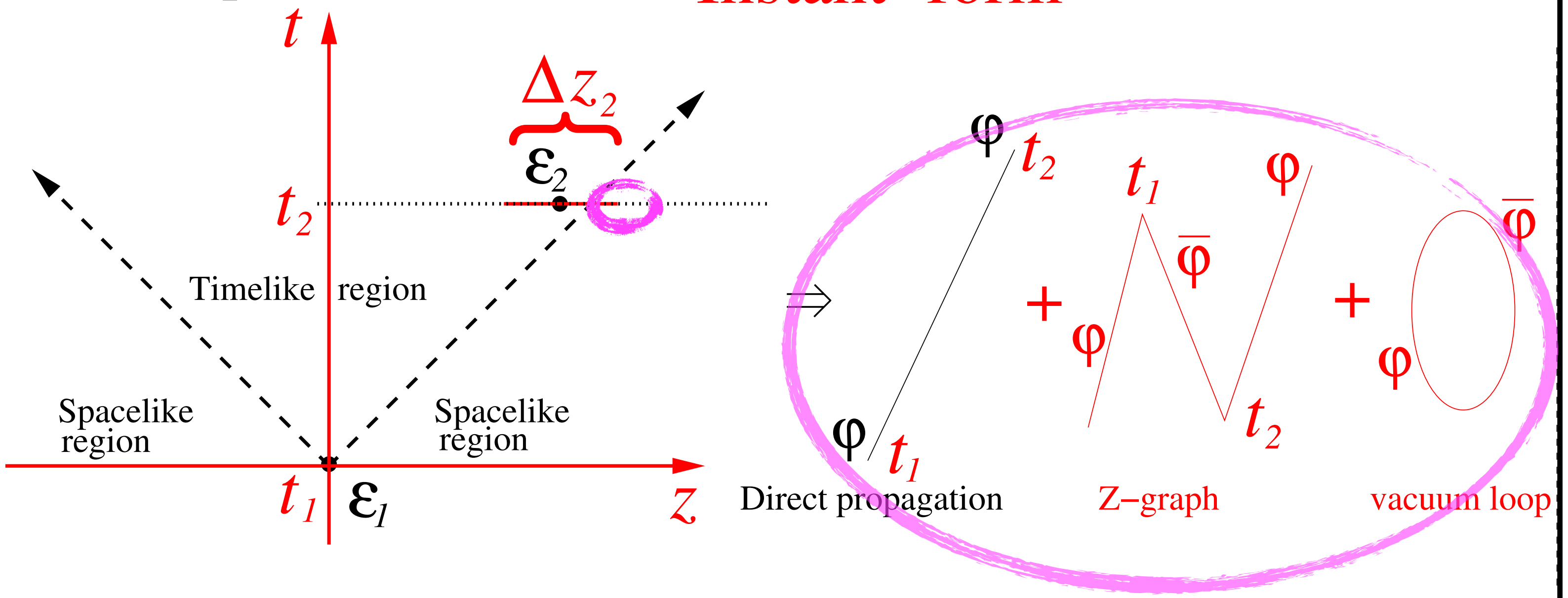
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form



If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.

In some frames, $t_1 < t_2$ and Z-graphs appear. They contribute negative probabilities.

⇒ Need disconnected vacuum loops to balance the negative probabilities.

Connection to commutation relations & vacuum structure

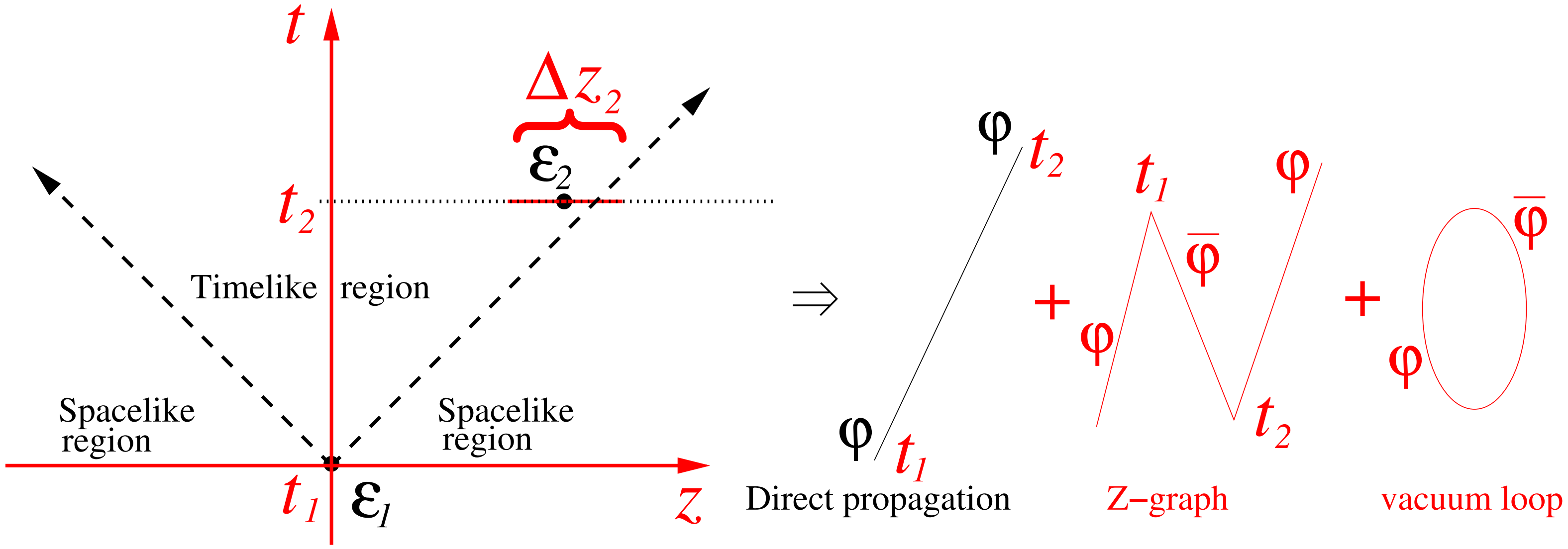
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form



If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.
In some frames, $t_1 < t_2$ and Z-graphs appear. They contribute negative probabilities.
⇒ Need disconnected vacuum loops to balance the negative probabilities.

Accelerated frames: virtual particles may borrow 4-momentum from acceleration process and become observable: Unruh effect.

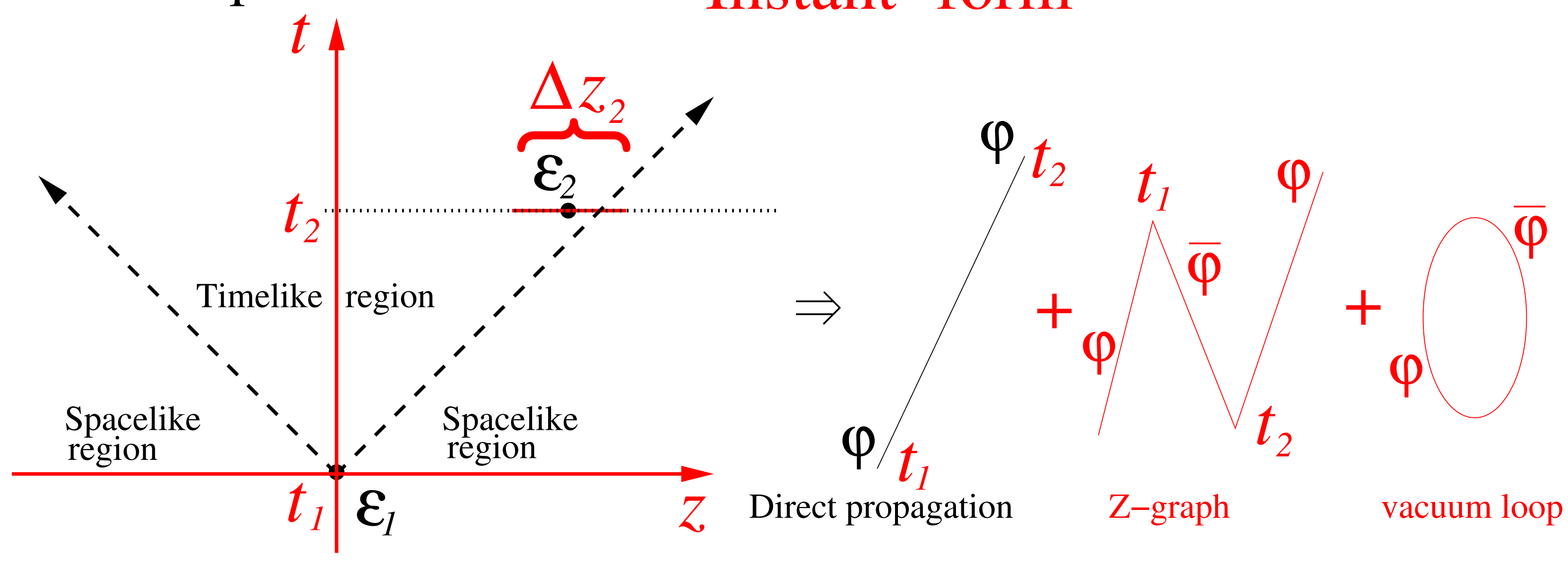
Connection to commutation relations & vacuum structure

Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

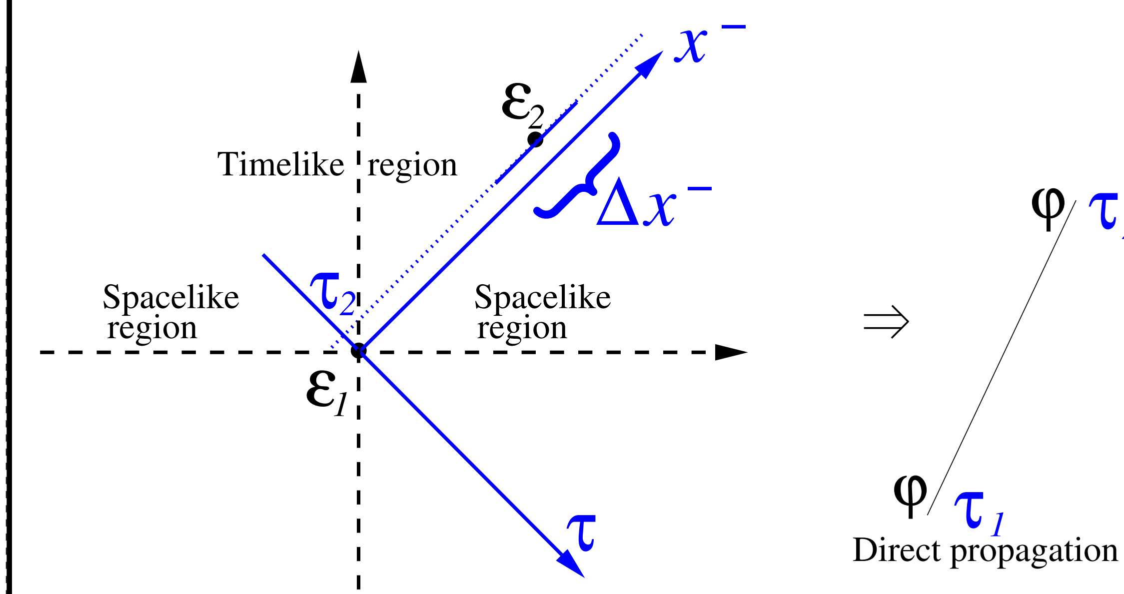


If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.
In some frames, $t_1 < t_2$ and Z-graphs appear. They contribute negative probabilities.
⇒ Need disconnected vacuum loops to balance the negative probabilities.

Accelerated frames: virtual particles may borrow 4-momentum from acceleration process and become observable: Unruh effect.

⇒ Uncertainty principle: equal time.

⇒ Trivial LF vacuum.



Boost or acceleration: rescales axes without reorienting them ⇒ uncertainty principle always operates along x^-.
$\mathscr{E}_1$ and $\mathscr{E}_2$ are always timelike-separated: No vacuum loops.

Connection to commutation relations & vacuum structure

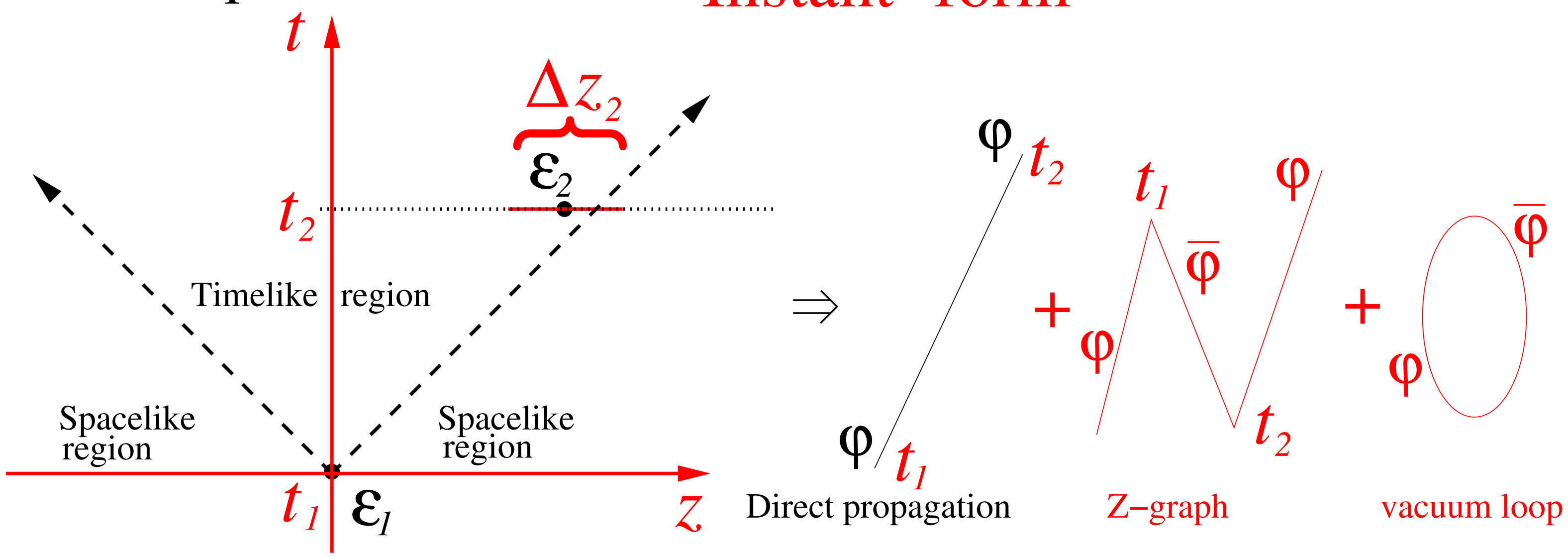
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form

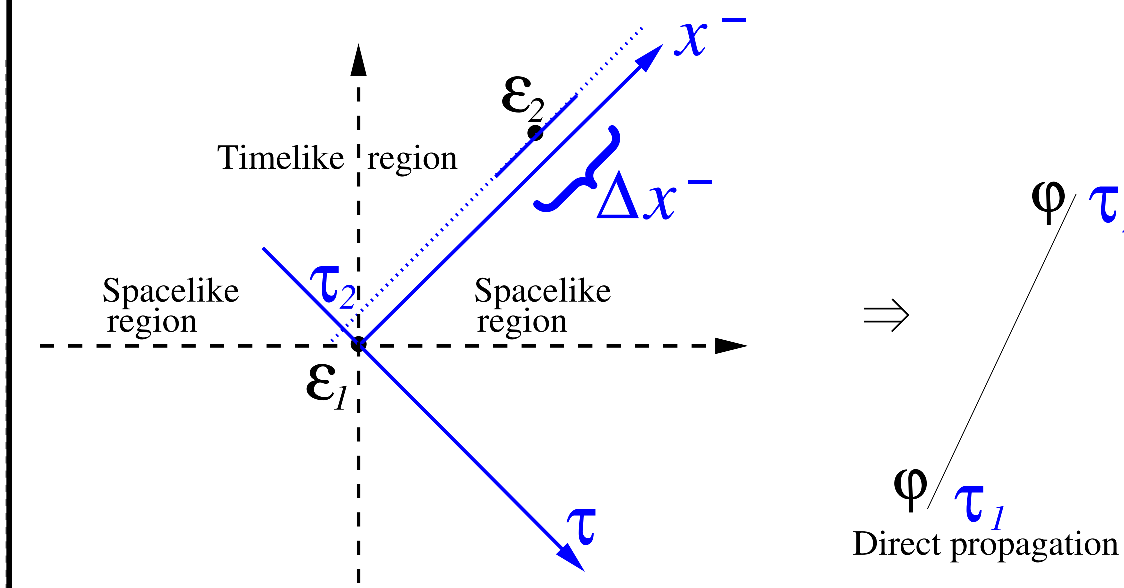


If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.
In some frames, $t_1 < t_2$ and Z-graphs appear. They contribute negative probabilities.
⇒ Need disconnected vacuum loops to balance the negative probabilities.

Accelerated frames: virtual particles may borrow 4-momentum from acceleration process and become observable: Unruh effect.

⇒ Uncertainty principle: equal time.

⇒ Trivial LF vacuum.

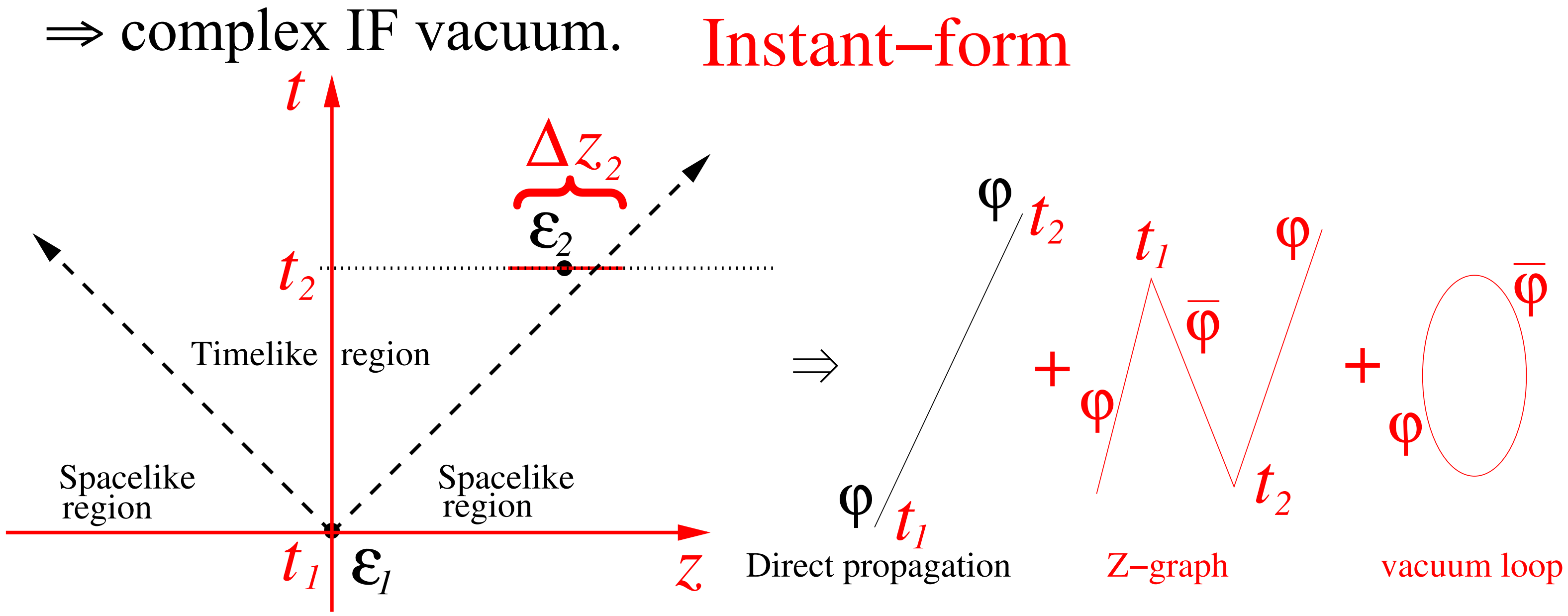


Boost or acceleration: rescales axes without reorienting them ⇒ uncertainty principle always operates along x^-.
$\mathscr{E}_1$ and $\mathscr{E}_2$ are always timelike-separated: No vacuum loops.
This persists in an accelerated LF frame: no Unruh effect.

Connection to commutation relations & vacuum structure

Canonical quantization done at constant proper time.

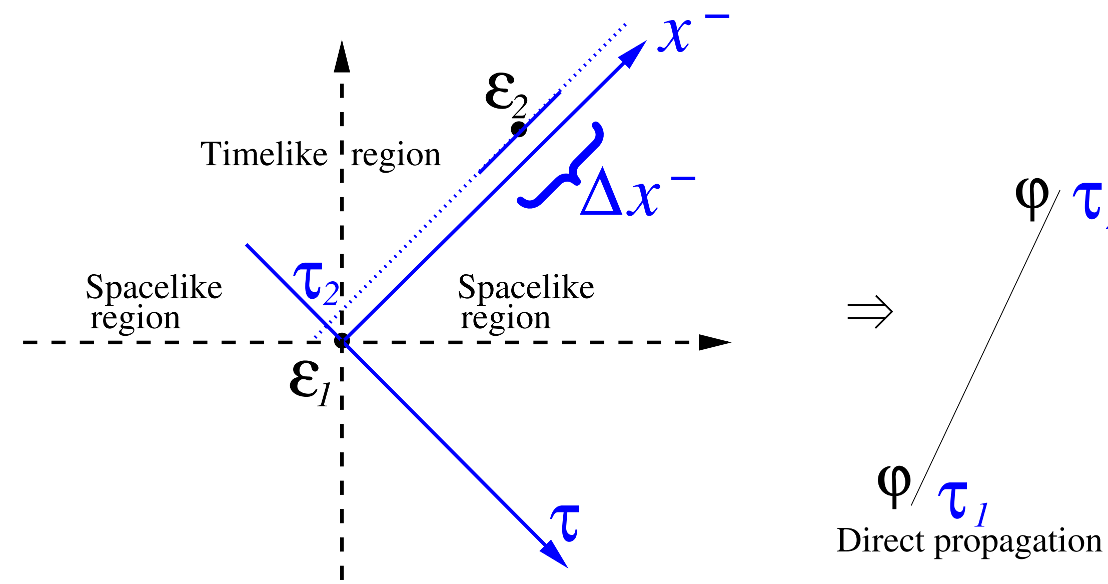
Heisenberg uncertainty principle originates from commutation relations
⇒ Uncertainty principle operates at equal time.
⇒ complex IF vacuum.



If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.
In some frames, $t_1 < t_2$ and Z-graphs appear. They contribute negative probabilities.
⇒ Need disconnected vacuum loops to balance the negative probabilities.

Accelerated frames: virtual particles may borrow 4-momentum from acceleration process and become observable: Unruh effect.

⇒ Uncertainty principle: equal time.
⇒ Trivial LF vacuum.

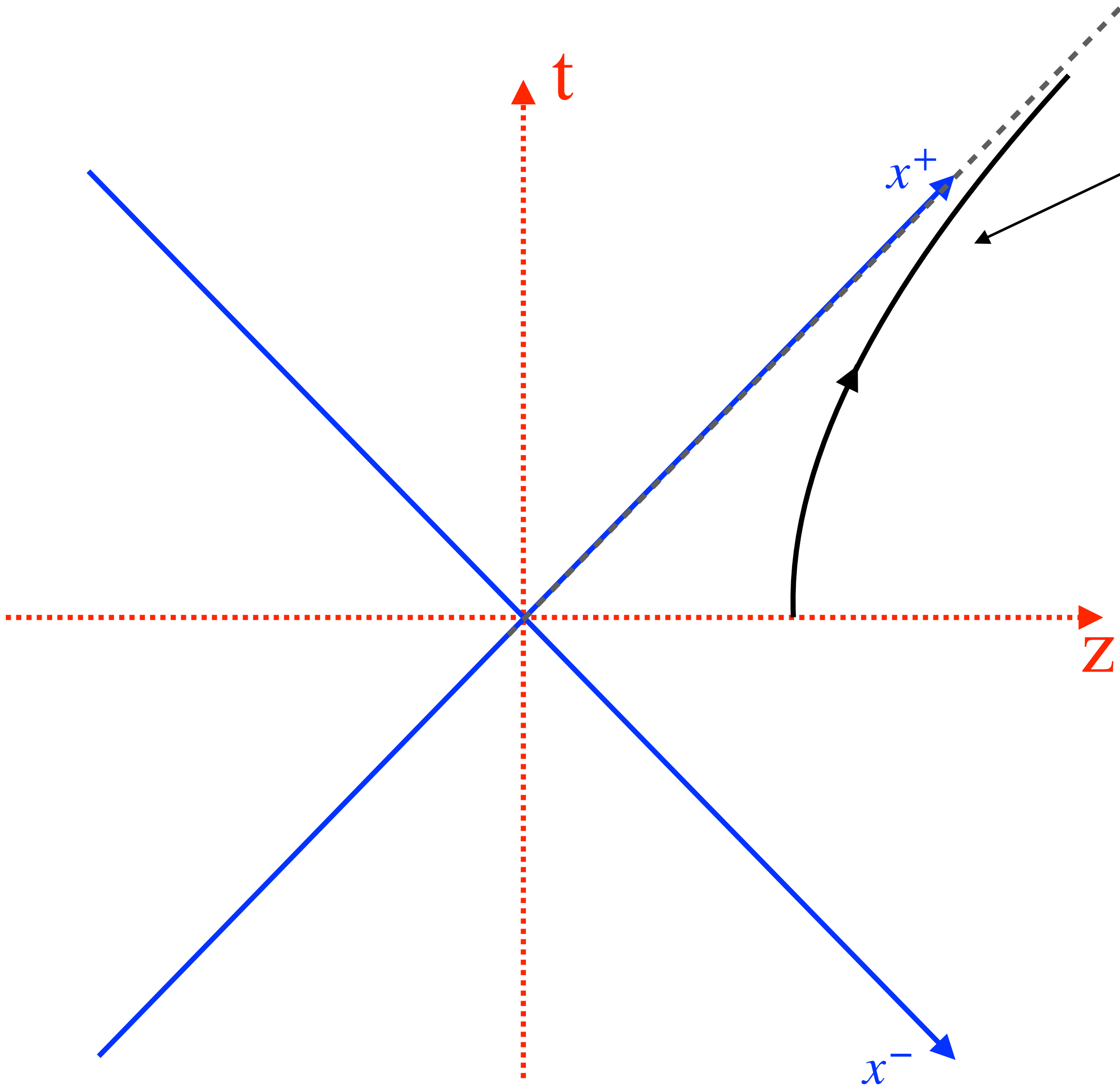


Boost or acceleration: rescales axes without reorienting them ⇒ uncertainty principle always operates along x^-.
$\mathscr{E}_1$ and $\mathscr{E}_2$ are always timelike-separated: No vacuum loops.
This persists in an accelerated LF frame: no Unruh effect.

Also: Momentum conservation ⇒ no vacuum loops: LF particles must have $p^+ \geq 0$. Vacuum $p^+ = 0$ ⇒ one of the particles of the vacuum loop would have $p^+ < 0$, which is forbidden.

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



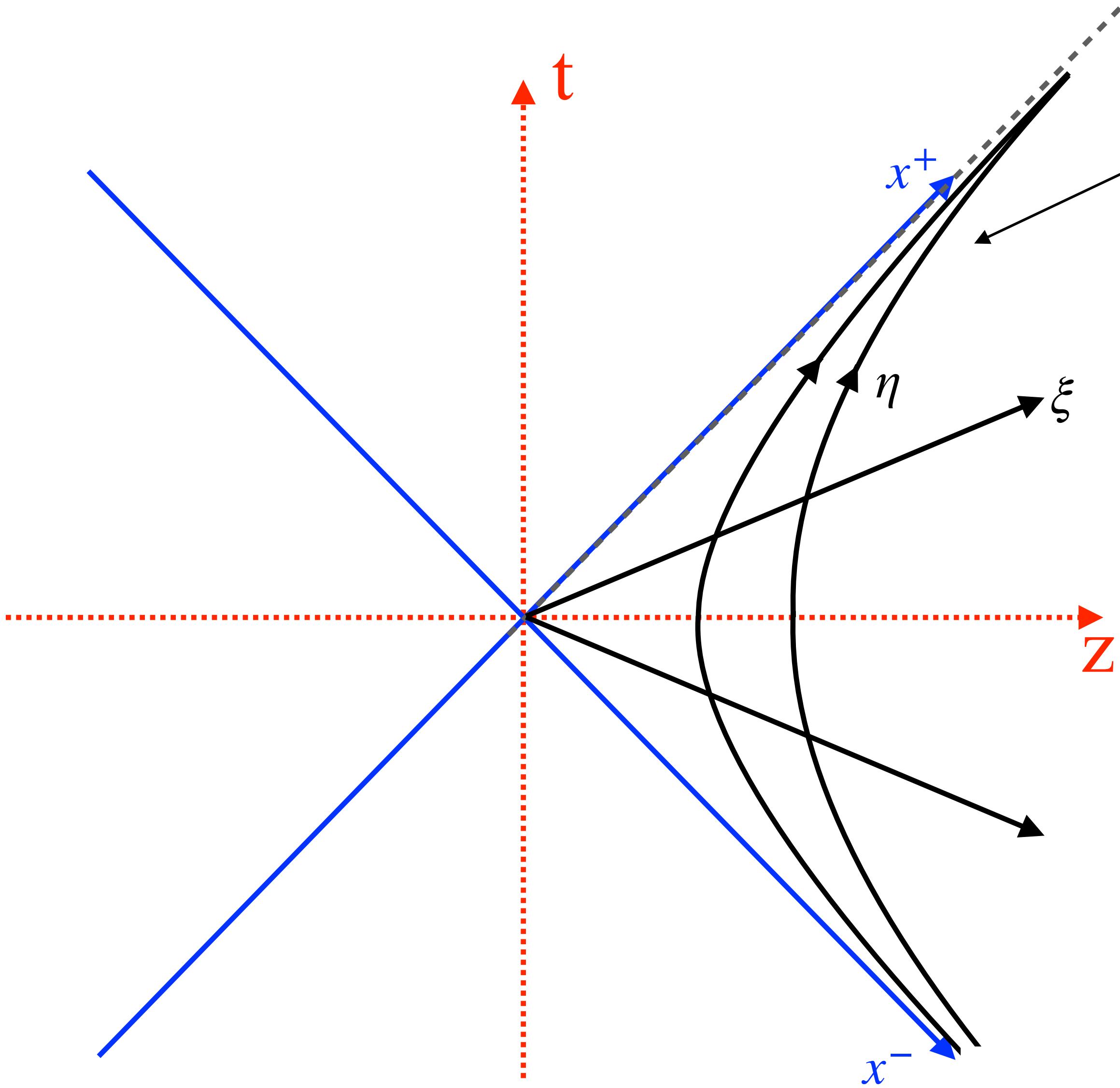
Acceleration:

- Hyperboloid in IF: $t^2(\rho) = z^2(\rho) - \alpha^2$
- Hyperbola in LF: $\tau(\rho) = \dfrac{1}{\alpha^2 x^-(\rho)}$

(ρ is a parameter)

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



Acceleration:

- Hyperboloid in IF: $t^2(\rho) = z^2(\rho) - \alpha^2$
- Hyperbola in LF: $\tau(\rho) = \dfrac{1}{\alpha^2 x^-(\rho)}$ (ρ is a parameter)

$\Rightarrow$ define new coordinate system (ξ, η):

$$z = \frac{1}{a} e^{a\xi} \cosh(a\eta), \quad t = \frac{1}{a} e^{a\xi} \sinh(a\eta) \quad \text{IF}$$

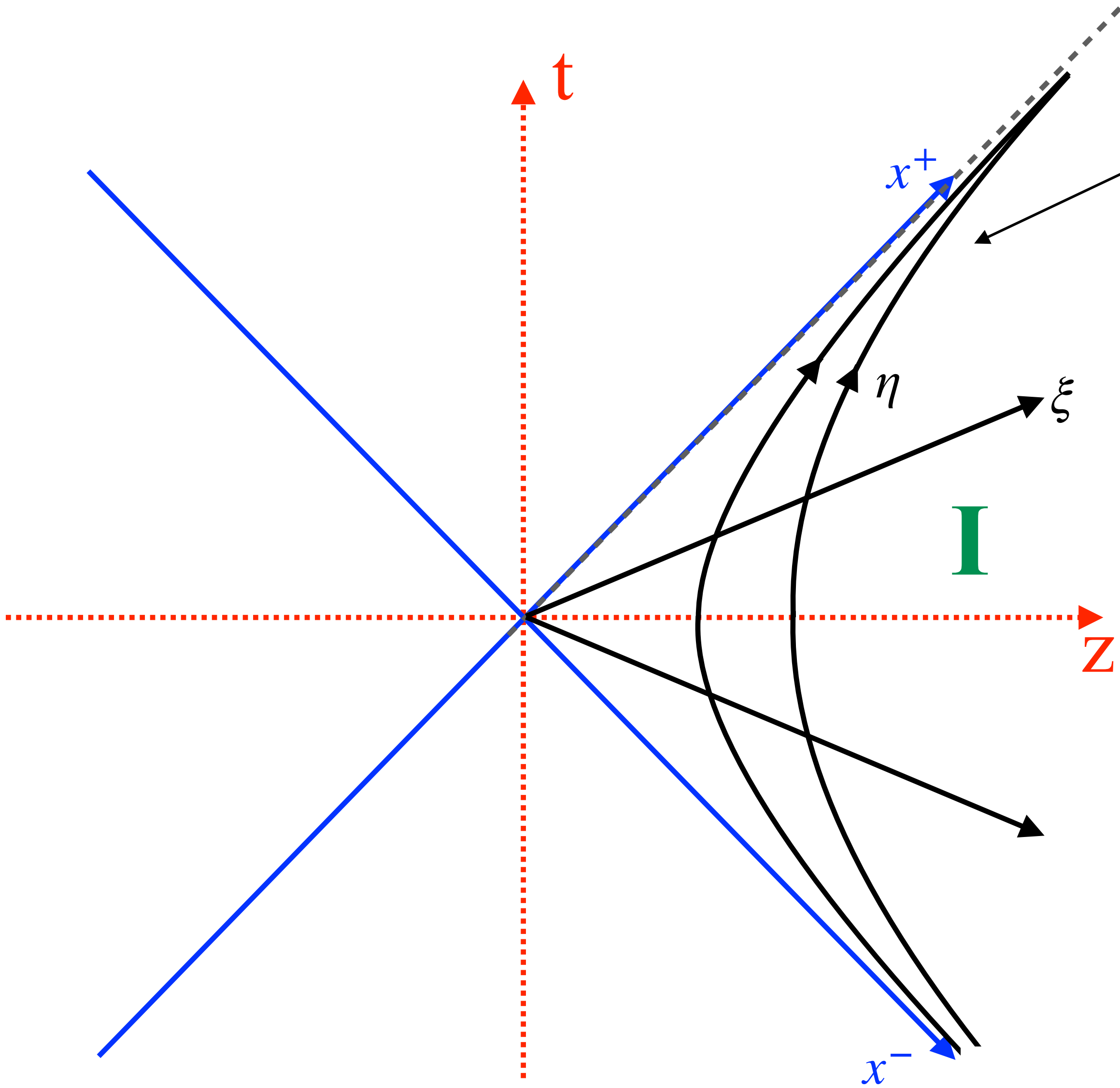
$$x^- = \frac{1}{a} e^{a(-\eta+\xi)}, \quad x^+ = \frac{1}{a} e^{a(\eta+\xi)} \quad \text{LF}$$

ξ: Rindler space; η: Rindler time

Acceleration: "Orbit" in Rindler spacetime (ξ=const., η evolves)

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



Acceleration:

- Hyperboloid in IF: $t^2(\rho) = z^2(\rho) - \alpha^2$
- Hyperbola in LF: $\tau(\rho) = \dfrac{1}{\alpha^2 x^-(\rho)}$ (ρ is a parameter)

$\Rightarrow$ define new coordinate system (ξ, η):

$$z = \frac{1}{a} e^{a\xi} \cosh(a\eta), \quad t = \frac{1}{a} e^{a\xi} \sinh(a\eta) \quad \text{IF}$$

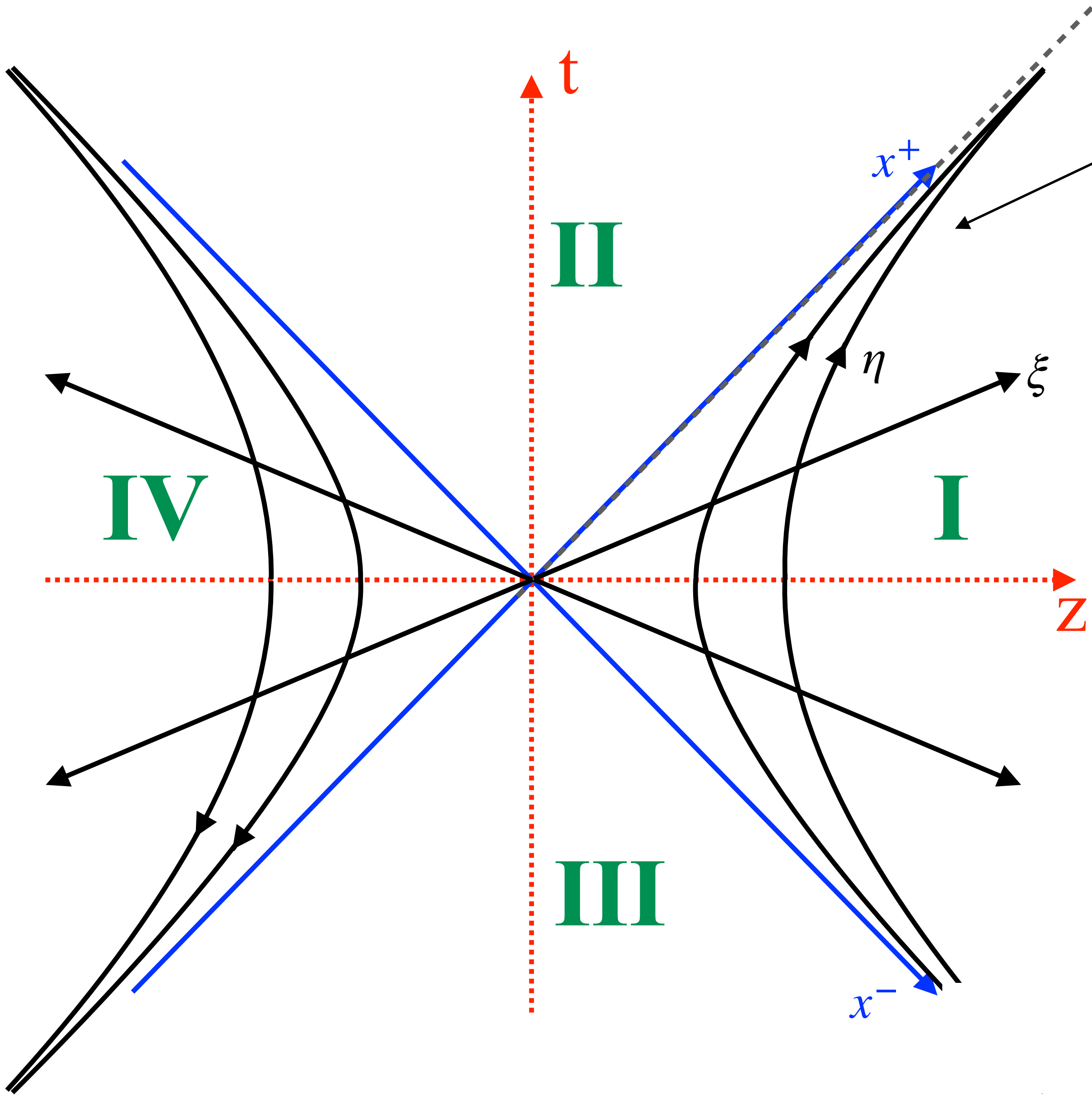
$$x^- = \frac{1}{a} e^{a(-\eta+\xi)}, \quad x^+ = \frac{1}{a} e^{a(\eta+\xi)} \quad \text{LF}$$

ξ: Rindler space; η: Rindler time
Acceleration: "Orbit" in Rindler spacetime (ξ=const., η evolves)

The coordinates above cover only Region I.

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



Acceleration:

- Hyperboloid in IF: $t^2(\rho) = z^2(\rho) - \alpha^2$
- Hyperbola in LF: $\tau(\rho) = \dfrac{1}{\alpha^2 x^-(\rho)}$ (ρ is a parameter)

$\Rightarrow$ define new coordinate system (ξ, η):

$$z = \frac{1}{a} e^{a\xi} \cosh(a\eta), \quad t = \frac{1}{a} e^{a\xi} \sinh(a\eta) \quad \text{IF}$$

$$x^- = \frac{1}{a} e^{a(-\eta+\xi)}, \quad x^+ = \frac{1}{a} e^{a(\eta+\xi)} \quad \text{LF}$$

ξ: Rindler space; η: Rindler time

Acceleration: "Orbit" in Rindler spacetime (ξ=const., η evolves)

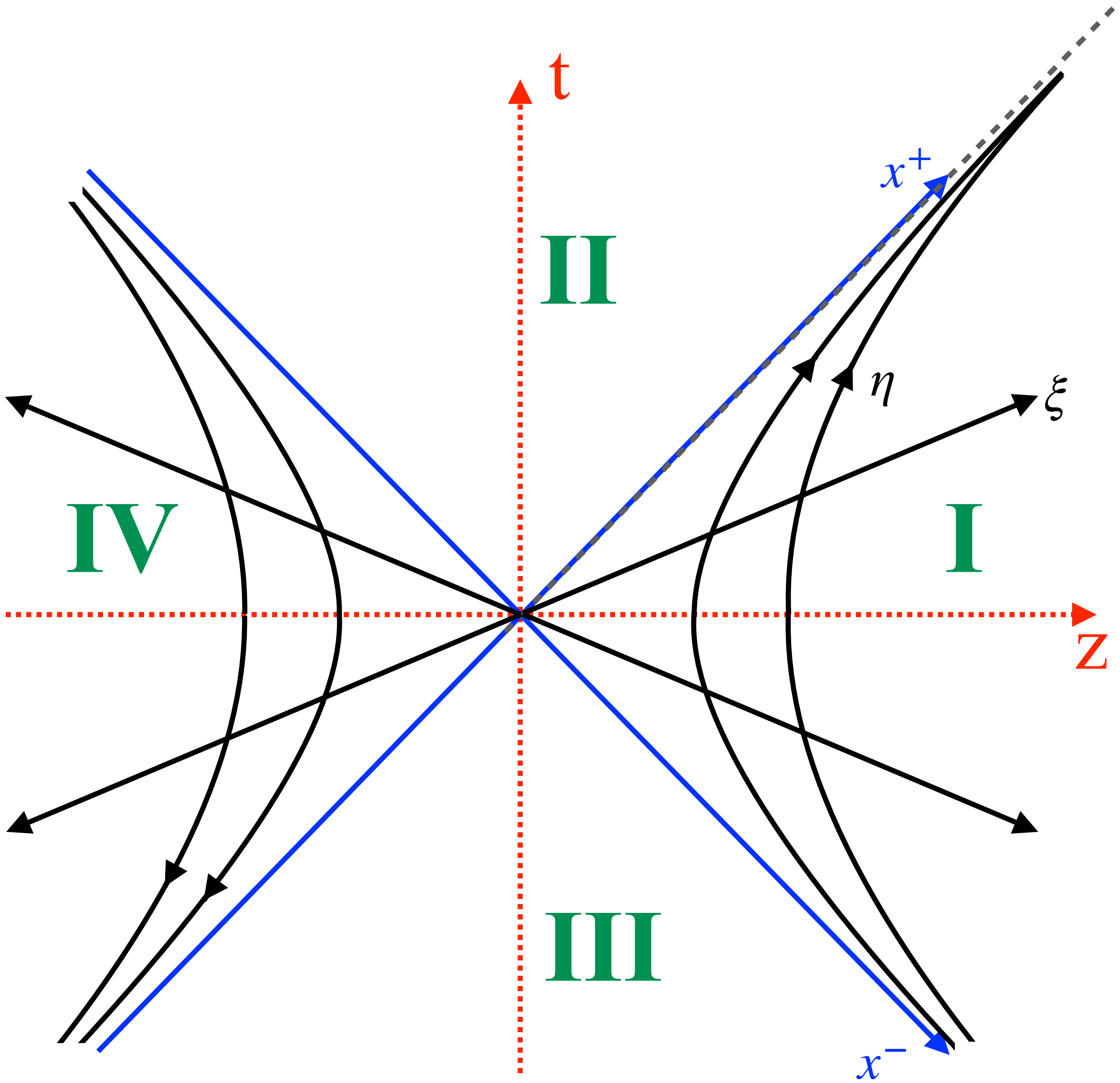
The coordinates above cover only Region I.
Other coordinates needed for region IV:

$$z = -\frac{1}{a} e^{a\xi} \cosh(a\eta); \quad t = -\frac{1}{a} e^{a\xi} \sinh(a\eta)$$

$$x^- = -\frac{1}{a} e^{a(-\eta+\xi)}; \quad x^+ = -\frac{1}{a} e^{a(\eta+\xi)}$$

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press

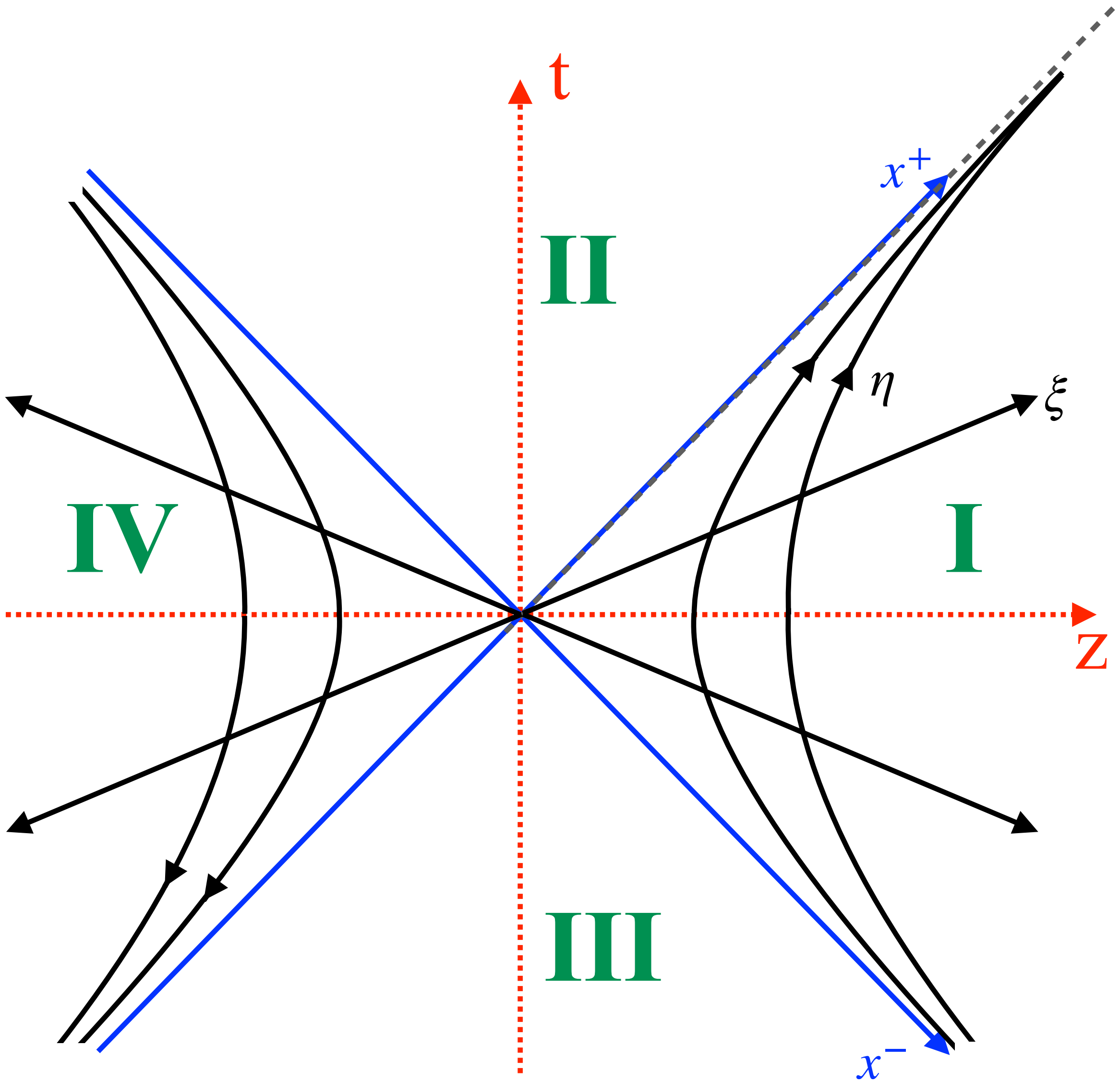


In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp \left(\hat{b}_p^{(\mathrm{I})} g_p^{(\mathrm{I})} + \hat{b}_p^{(\mathrm{I})\dagger} g_p^{(\mathrm{I})*} + \hat{b}_p^{(\mathrm{IV})} g_p^{(\mathrm{IV})} + \hat{b}_p^{(\mathrm{IV})\dagger} g_p^{(\mathrm{IV})*}\right)$$

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp\left(\hat{b}_p^{(\mathrm{I})} g_p^{(\mathrm{I})} + \hat{b}_p^{(\mathrm{I})\dagger} g_p^{(\mathrm{I})*} + \hat{b}_p^{(\mathrm{IV})} g_p^{(\mathrm{IV})} + \hat{b}_p^{(\mathrm{IV})\dagger} g_p^{(\mathrm{IV})*}\right)$$

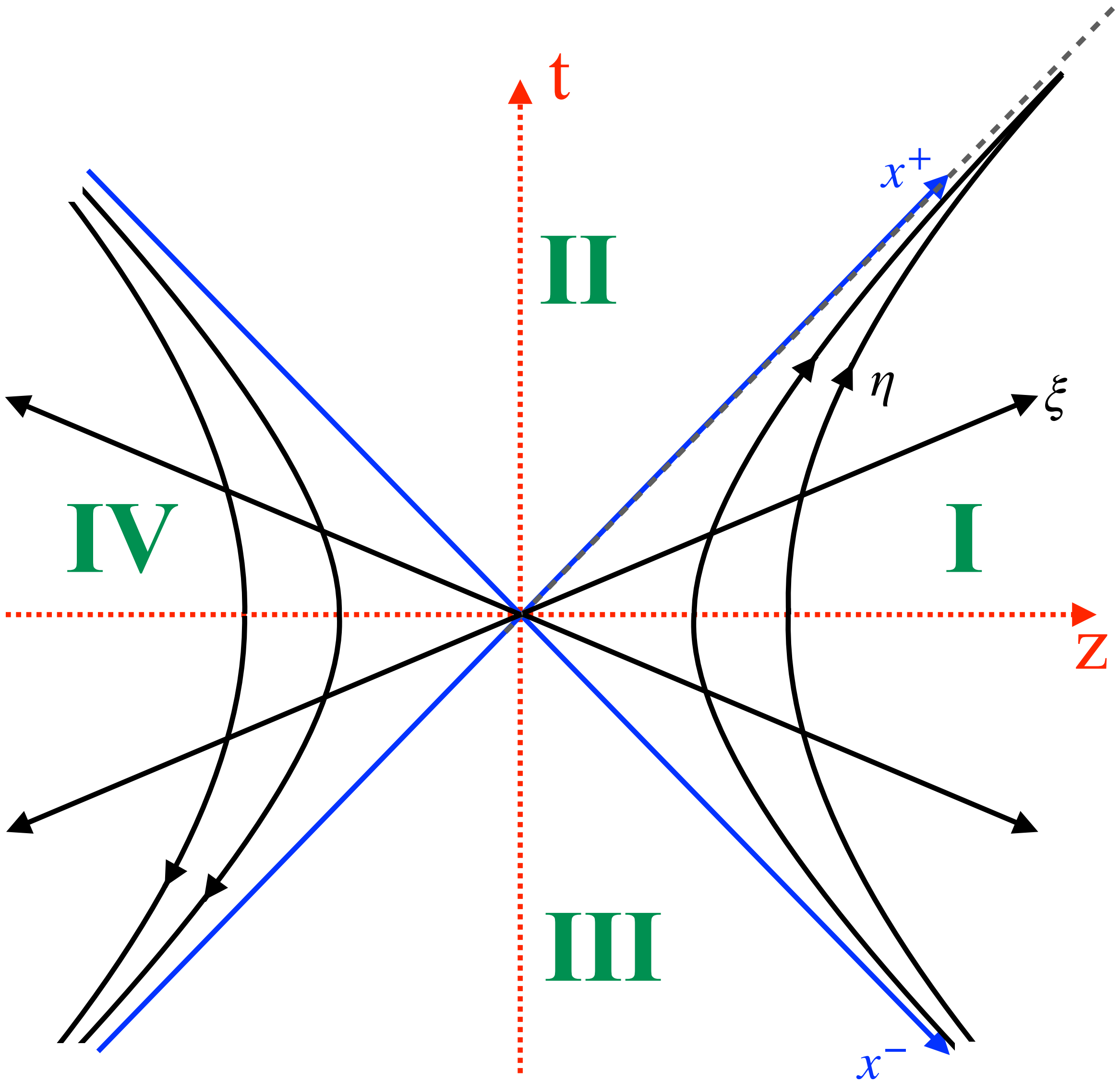
In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition ⇒ the field is decomposed as usual:

$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right) \quad \text{(IF)}$$

$$\phi = \int dp^+\left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^*\right) \quad \text{(LF)}$$

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp \left(\hat{b}_p^{(\mathrm{I})} g_p^{(\mathrm{I})} + \hat{b}_p^{(\mathrm{I})\dagger} g_p^{(\mathrm{I})*} + \hat{b}_p^{(\mathrm{IV})} g_p^{(\mathrm{IV})} + \hat{b}_p^{(\mathrm{IV})\dagger} g_p^{(\mathrm{IV})*} \right)$$

In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition ⇒ the field is decomposed as usual:

$$\phi = \int dp \left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^* \right) \quad \text{(IF)}$$

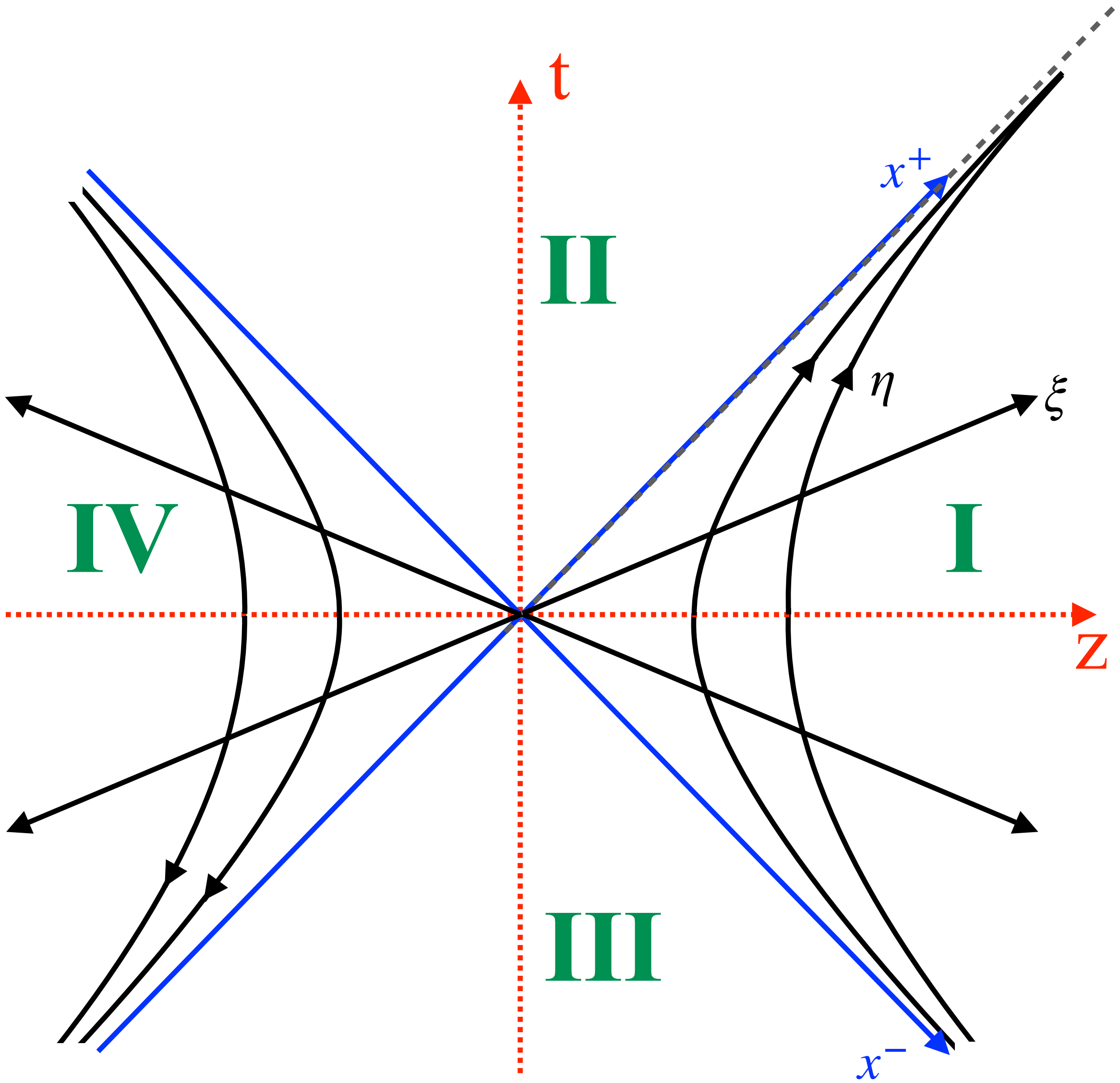
$$\phi = \int dp^+ \left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^* \right) \quad \text{(LF)}$$

Then we have the definition of the vacua:

$\hat{b}_p^{(\mathrm{I})} |0\rangle_R = 0 = \hat{b}_p^{(\mathrm{IV})} |0\rangle_R$; $\hat{a}_p |0\rangle_{M,IF} = 0$; $\hat{a}_{p^+} |0\rangle_{M,LF} = 0$

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp\left(\hat{b}_p^{(\mathrm{I})} g_p^{(\mathrm{I})} + \hat{b}_p^{(\mathrm{I})\dagger} g_p^{(\mathrm{I})*} + \hat{b}_p^{(\mathrm{IV})} g_p^{(\mathrm{IV})} + \hat{b}_p^{(\mathrm{IV})\dagger} g_p^{(\mathrm{IV})*}\right)$$

In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition $\Rightarrow$ the field is decomposed as usual:

$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right) \quad \text{(IF)}$$

$$\phi = \int dp^+\left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^*\right) \quad \text{(LF)}$$

Then we have the definition of the vacua:

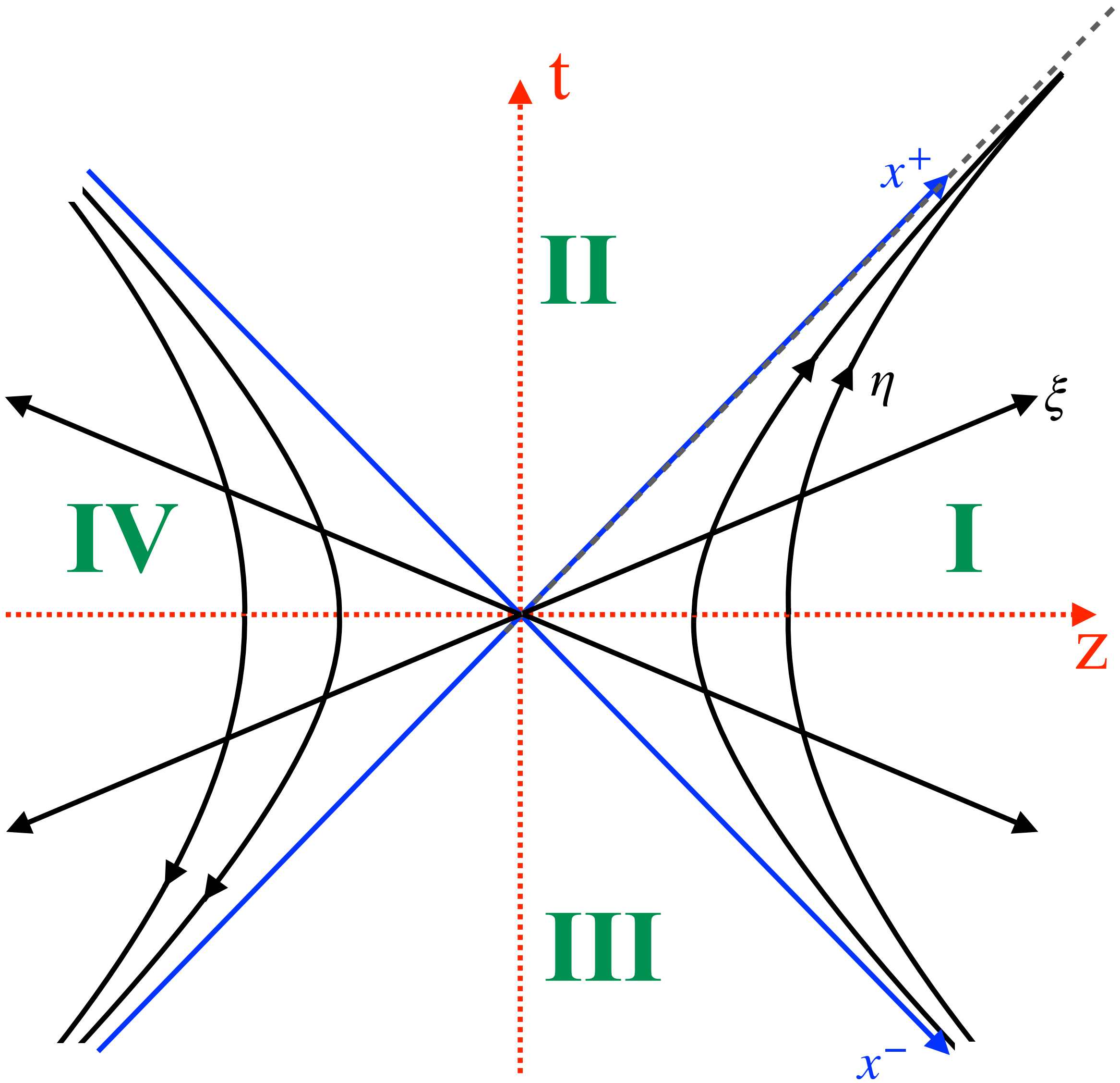
$\hat{b}_p^{(\mathrm{I})}|0\rangle_R = 0 = \hat{b}_p^{(\mathrm{IV})}|0\rangle_R$; $\hat{a}_p|0\rangle_{M,IF} = 0$; $\hat{a}_{p^+}|0\rangle_{M,LF} = 0$

To derive his effect, Unruh combined Rindler modes so that they match the spacetime dependence of Minkowski modes.

$\Rightarrow$ Rindler mode combinations $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (IF) or $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (LF) whose annihilation operators $\hat{c}_p^{(\mathrm{I,IV})}$ (or $\hat{c}_p^{(\mathrm{I,IV})}$) annihilate $|0\rangle_{M,IF}$ (or $|0\rangle_{M,LF}$).

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp\left(\hat{b}_p^{(I)} g_p^{(I)} + \hat{b}_p^{(I)\dagger} g_p^{(I)*} + \hat{b}_p^{(IV)} g_p^{(IV)} + \hat{b}_p^{(IV)\dagger} g_p^{(IV)*}\right)$$

In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition ⇒ the field is decomposed as usual:

$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right) \quad \text{(IF)}$$

$$\phi = \int dp^+\left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^*\right) \quad \text{(LF)}$$

Then we have the definition of the vacua:

$\hat{b}_p^{(I)}|0\rangle_R = 0 = \hat{b}_p^{(IV)}|0\rangle_R$; $\hat{a}_p|0\rangle_{M,IF} = 0$; $\hat{a}_{p^+}|0\rangle_{M,LF} = 0$

To derive his effect, Unruh combined Rindler modes so that they match the spacetime dependence of Minkowski modes.

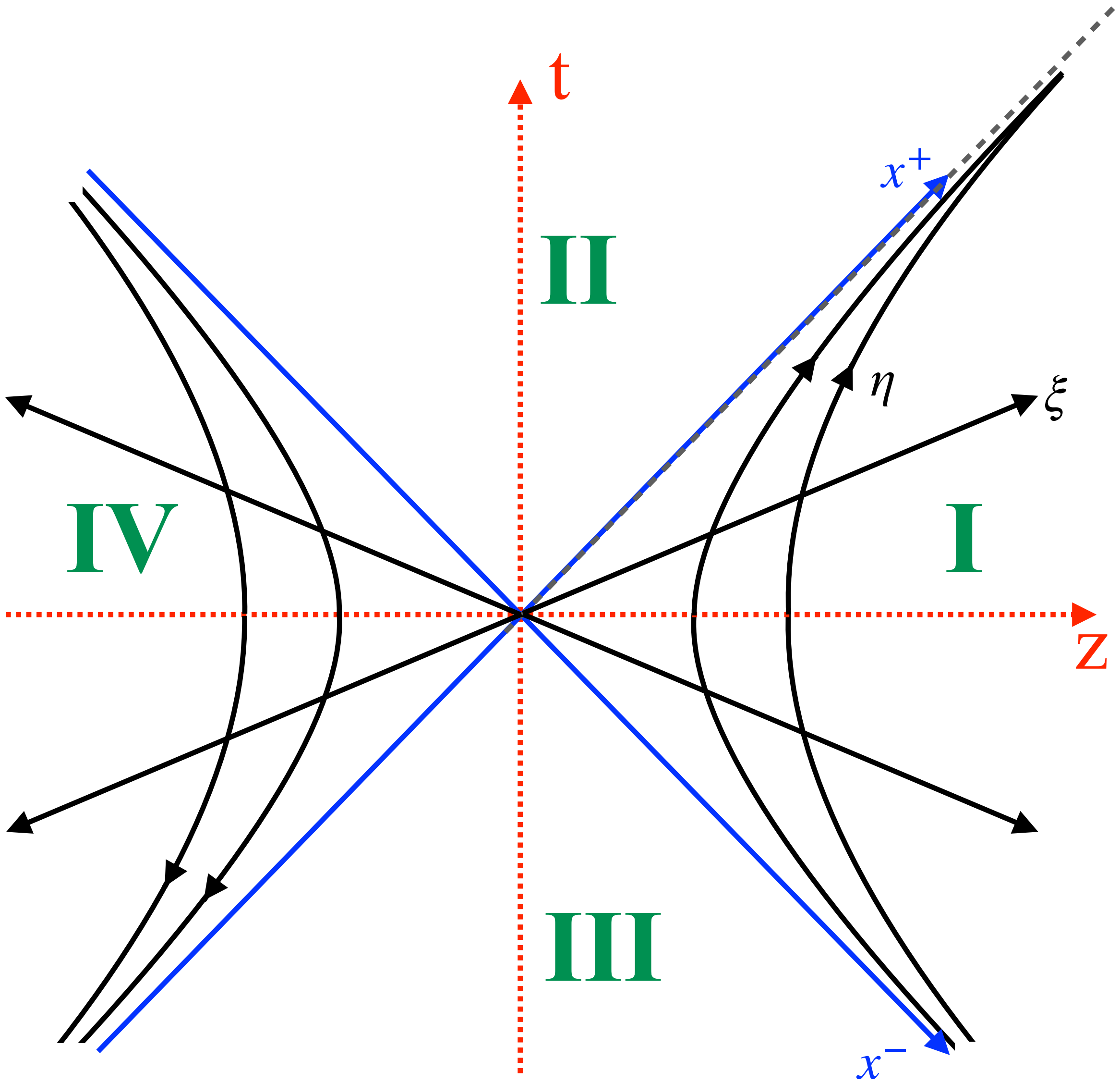
⇒ Rindler mode combinations $h_p^{(I)}$, $h_p^{(IV)}$ (IF) or $h_p^{(I)}$, $h_p^{(IV)}$ (LF) whose annihilation operators $\hat{c}_p^{(I,IV)}$ (or $\hat{c}_p^{(I,IV)}$) annihilate $|0\rangle_{M,IF}$ (or $|0\rangle_{M,LF}$).

$$h_p^{(I)} = \frac{1}{\sqrt{2\sinh(\frac{\pi\omega}{a})}}\left(e^{\pi\omega/2a} g_p^{(I)} + e^{-\pi\omega/2a} g_{-p}^{(IV)*}\right)$$

(ω is the field frequency and a the acceleration.)

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp\left(\hat{b}_p^{(\mathrm{I})} g_p^{(\mathrm{I})} + \hat{b}_p^{(\mathrm{I})\dagger} g_p^{(\mathrm{I})*} + \hat{b}_p^{(\mathrm{IV})} g_p^{(\mathrm{IV})} + \hat{b}_p^{(\mathrm{IV})\dagger} g_p^{(\mathrm{IV})*}\right)$$

In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition ⇒ the field is decomposed as usual:

$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right) \quad \text{(IF)}$$

$$\phi = \int dp^+\left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^*\right) \quad \text{(LF)}$$

Then we have the definition of the vacua:

$\hat{b}_p^{(\mathrm{I})}|0\rangle_R = 0 = \hat{b}_p^{(\mathrm{IV})}|0\rangle_R$; $\hat{a}_p|0\rangle_{M,IF} = 0$; $\hat{a}_{p^+}|0\rangle_{M,LF} = 0$

To derive his effect, Unruh combined Rindler modes so that they match the spacetime dependence of Minkowski modes.

⇒ Rindler mode combinations $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (IF) or $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (LF) whose annihilation operators $\hat{c}_p^{(\mathrm{I,IV})}$ (or $\hat{c}_p^{(\mathrm{I,IV})}$) annihilate $|0\rangle_{M,IF}$ (or $|0\rangle_{M,LF}$).

$$h_p^{(\mathrm{I})} = \frac{1}{\sqrt{2\sinh(\frac{\pi\omega}{a})}}\left(e^{\pi\omega/2a} g_p^{(\mathrm{I})} + e^{-\pi\omega/2a} g_{-p}^{(\mathrm{IV})*}\right)$$

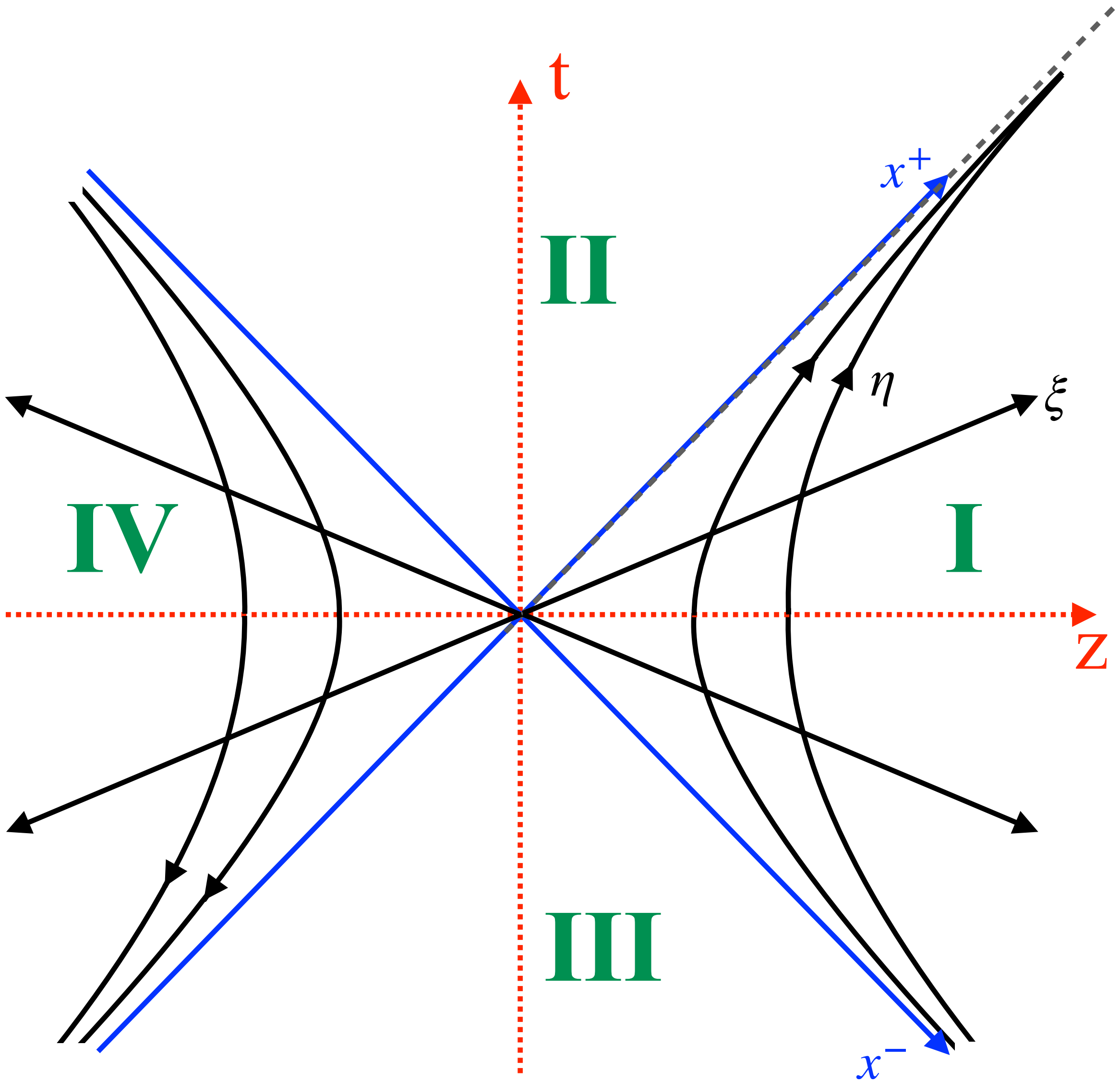
(ω is the field frequency and a the acceleration.)

$$h_p^{(\mathrm{I})} = g_p^{(\mathrm{I})}$$

← No $g_p^{(\mathrm{VI})*}$ because it would require $p^+ < 0$ (same reason why there is no LF vacuum loops).

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp\left(\hat{b}_p^{(\mathrm{I})} g_p^{(\mathrm{I})} + \hat{b}_p^{(\mathrm{I})\dagger} g_p^{(\mathrm{I})*} + \hat{b}_p^{(\mathrm{IV})} g_p^{(\mathrm{IV})} + \hat{b}_p^{(\mathrm{IV})\dagger} g_p^{(\mathrm{IV})*}\right)$$

In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition ⇒ the field is decomposed as usual:

$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right) \quad \text{(IF)}$$

$$\phi = \int dp^+\left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^*\right) \quad \text{(LF)}$$

Then we have the definition of the vacua:

$\hat{b}_p^{(\mathrm{I})}|0\rangle_R = 0 = \hat{b}_p^{(\mathrm{IV})}|0\rangle_R$; $\hat{a}_p|0\rangle_{M,IF} = 0$; $\hat{a}_{p^+}|0\rangle_{M,LF} = 0$

To derive his effect, Unruh combined Rindler modes so that they match the spacetime dependence of Minkowski modes.

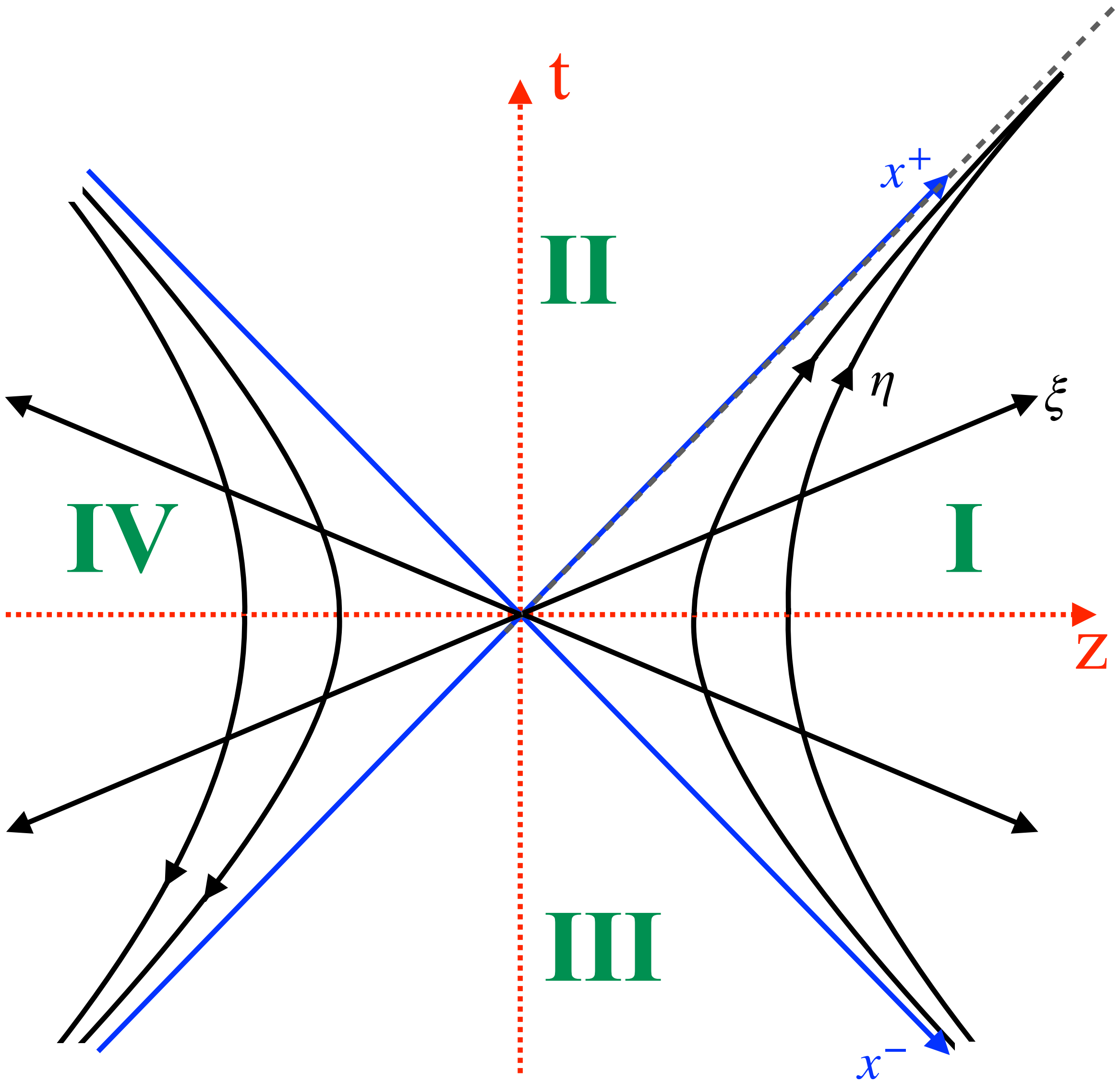
⇒ Rindler mode combinations $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (IF) or $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (LF) whose annihilation operators $\hat{c}_p^{(\mathrm{I,IV})}$ (or $\hat{c}_p^{(\mathrm{I,IV})}$) annihilate $|0\rangle_{M,IF}$ (or $|0\rangle_{M,LF}$).

$$h_p^{(\mathrm{I})} = \frac{1}{\sqrt{2\sinh(\frac{\pi\omega}{a})}}\left(e^{\pi\omega/2a} g_p^{(\mathrm{I})} + e^{-\pi\omega/2a} g_{-p}^{(\mathrm{IV})*}\right) \Rightarrow g_p^{(\mathrm{I})} \text{ annihil. op. : } \hat{b}_p^{(\mathrm{I})} = \frac{1}{\sqrt{2\sinh(\frac{\pi\omega}{a})}}\left(\mathrm{e}^{\pi\omega/2a}\hat{c}_p^{(\mathrm{I})} + \mathrm{e}^{-\pi\omega/2a}\hat{c}_{-p}^{(\mathrm{IV})\dagger}\right)$$

$$h_p^{(\mathrm{I})} = g_p^{(\mathrm{I})} \qquad \Rightarrow g_p^{(\mathrm{I})} \text{ annihil. op. : } \hat{b}_p^{(\mathrm{I})} = \hat{a}_{p^+}$$

Standard derivation (Unruh 1976)

S. M. Carroll, Spacetime and Geometry: An Introduction to General Relativity, Cambridge University Press



In Rindler space-time, the field is decomposed using regions I and IV Rindler modes:

$$\phi = \int dp \left(\hat{b}_p^{(I)} g_p^{(I)} + \hat{b}_p^{(I)\dagger} g_p^{(I)*} + \hat{b}_p^{(IV)} g_p^{(IV)} + \hat{b}_p^{(IV)\dagger} g_p^{(IV)*}\right)$$

In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition ⇒ the field is decomposed as usual:

$$\phi = \int dp \left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right) \quad \text{(IF)}$$

$$\phi = \int dp^+ \left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^*\right) \quad \text{(LF)}$$

Then we have the definition of the vacua:

$\hat{b}_p^{(I)}|0\rangle_R = 0 = \hat{b}_p^{(IV)}|0\rangle_R$; $\hat{a}_p|0\rangle_{M,IF} = 0$; $\hat{a}_{p^+}|0\rangle_{M,LF} = 0$

To derive his effect, Unruh combined Rindler modes so that they match the spacetime dependence of Minkowski modes.

⇒ Rindler mode combinations $h_p^{(I)}$, $h_p^{(IV)}$ (IF) or $h_p^{(I)}$, $h_p^{(IV)}$ (LF) whose annihilation operators $\hat{c}_p^{(I,IV)}$ (or $\hat{c}_p^{(I,IV)}$) annihilate $|0\rangle_{M,IF}$ (or $|0\rangle_{M,LF}$).

annihil. op. : $\hat{b}_p^{(I)} = \dfrac{1}{\sqrt{2\sinh(\frac{\pi\omega}{a})}}\left(e^{\pi\omega/2a}\hat{c}_p^{(I)} + e^{-\pi\omega/2a}\hat{c}_{-p}^{(IV)\dagger}\right)$ ⇒ $\hat{b}_p^{(I)}|0\rangle_{M,IF} = \dfrac{1}{\sqrt{2\sinh(\frac{\pi\omega}{a})}}\left(e^{-\pi\omega/2a}|-p\rangle\right) \neq 0$

Unruh effect

annihil. op. : $\hat{b}_p^{(I)} = \hat{a}_{p^+}$ ⇒ $\hat{b}_p^{(I)}|0\rangle_{M,LF} = \hat{a}_{p^+}|0\rangle_{M,LF} = 0$

no Unruh effect

Other standard derivation

Preliminary: Rindler time translation ⇔ Minkowski boost.

Recall the definition of Rindler coordinates:

$$z = \frac{1}{a} e^{a\xi} \cosh(a\eta); \quad t = \frac{1}{a} e^{a\xi} \sinh(a\eta)$$

$$x^- = \frac{1}{a} e^{a(-\eta+\xi)}; \quad x^+ = \frac{1}{a} e^{a(\eta+\xi)}$$

Other standard derivation

Preliminary: Rindler time translation ⇔ Minkowski boost.

Recall the definition of Rindler coordinates:

$$z = \frac{1}{a}e^{a\xi}\cosh(a\eta); \quad t = \frac{1}{a}e^{a\xi}\sinh(a\eta)$$

$$x^- = \frac{1}{a}e^{a(-\eta+\xi)}; \quad x^+ = \frac{1}{a}e^{a(\eta+\xi)}$$

Rindler time translation $\eta \to \eta + \Delta$

$$\Rightarrow \quad \left.\begin{aligned} t' &= t\cosh(a\Delta) + x\sinh(a\Delta) \\ z' &= z\cosh(a\Delta) + t\sinh(a\Delta) \end{aligned}\right\} \text{IF}$$

$$\left.\begin{aligned} x^{+'} &= \mathrm{e}^{a\Delta}x^+ \\ x^{-'} &= e^{-a\Delta}x^- \end{aligned}\right\} \text{LF}$$

Usual boost formulae with rapidity $a\Delta$ (a is the acceleration).

This is because acceleration = succession of boosts with changing rapidity.

Other standard derivation

This derivation uses the periodicity in imaginary time ($\tilde{t} \equiv it$) of a QFT at finite temperature $T \equiv /1\beta$.

Energy operator (not necessarily the time-evolution operator)

1.) Green function of $\phi(\tilde{t}, z)$: $G_\beta(\tilde{t}, z) = -\frac{1}{Z} \mathrm{Tr}\ \mathrm{e}^{-\beta H} \mathcal{T}[\phi(\tilde{t}, z)\phi(0,0)]$

Partition function

imaginary-time ordering operator

Other standard derivation

This derivation uses the periodicity in imaginary time ($\tilde{t} \equiv it$) of a QFT at finite temperature $T \equiv /1\beta$.

Energy operator (not necessarily the time-evolution operator)

1.) Green function of $\phi(\tilde{t},z)$: $G_\beta(\tilde{t},z) = -\frac{1}{Z}\mathrm{Tr}\ \mathrm{e}^{-\beta H}\mathcal{T}[\phi(\tilde{t},z)\phi(0,0)]$

Partition function

imaginary-time ordering operator

If H is also the time-evolution operator, then:

$e^{-\beta H}\phi(\tilde{t},z)\mathrm{e}^{\beta H} = \phi(\tilde{t}-\beta,z)$

This and cyclicity property of trace $\Rightarrow$ $G_\beta(\tilde{t},z) = G_\beta(\tilde{t}-\beta,z)$: QFT periodicity with period β

Other standard derivation

This derivation uses the periodicity in imaginary time ($\tilde{t} \equiv it$) of a QFT at finite temperature $T \equiv /1\beta$.

Energy operator (not necessarily the time-evolution operator)

1.) Green function of $\phi(\tilde{t}, z)$: $G_\beta(\tilde{t}, z) = -\frac{1}{Z}\text{Tr } e^{-\beta H}\mathcal{T}[\phi(\tilde{t}, z)\phi(0,0)]$

Partition function

imaginary-time ordering operator

If H is also the time-evolution operator, then:

$e^{-\beta H}\phi(\tilde{t}, z)e^{\beta H} = \phi(\tilde{t} - \beta, z)$

This and cyclicity property of trace $\Rightarrow$ $G_\beta(\tilde{t}, z) = G_\beta(\tilde{t} - \beta, z)$: QFT periodicity with period β

2.) On the other hand: Rindler line element, $ds^2 = -\xi^2 d\eta^2 + d\xi^2$. With imaginary Rindler time $\tilde{\eta} \equiv i\eta$:
$ds^2 = \xi^2 d\eta^2 + d\xi^2$: polar coordinates. For non-singular coordinates, we must have $\tilde{\eta} = \tilde{\eta} + 2\pi i$.

Other standard derivation

This derivation uses the periodicity in imaginary time ($\tilde{t} \equiv it$) of a QFT at finite temperature $T \equiv /1\beta$.

Energy operator (not necessarily the time-evolution operator)

1.) Green function of $\phi(\tilde{t}, z)$: $G_\beta(\tilde{t}, z) = -\frac{1}{Z} \mathrm{Tr}\ \mathrm{e}^{-\beta H} \mathcal{T}[\phi(\tilde{t}, z)\phi(0,0)]$

Partition function

imaginary-time ordering operator

If H is also the time-evolution operator, then:

$e^{-\beta H}\phi(\tilde{t}, z)\mathrm{e}^{\beta H} = \phi(\tilde{t} - \beta, z)$

This and cyclicity property of trace $\Rightarrow$ $G_\beta(\tilde{t}, z) = G_\beta(\tilde{t} - \beta, z)$: QFT periodicity with period β

2.) On the other hand: Rindler line element, $ds^2 = -\xi^2 d\eta^2 + d\xi^2$. With imaginary Rindler time $\tilde{\eta} \equiv i\eta$:
$ds^2 = \xi^2 d\eta^2 + d\xi^2$: polar coordinates. For non-singular coordinates, we must have $\tilde{\eta} = \tilde{\eta} + 2\pi i$.

Rindler time translation $\eta/a \to \eta/a + \Delta/a \Leftrightarrow$ boost with rapidity Δ

Rindler imaginary time periodicity: $\tilde{\eta}/a \to \tilde{\eta}/a + 2\pi i/a$ $\Rightarrow$ temperature $\beta^{-1} = T = a/2\pi$

QFT β-periodicity: $\tilde{\eta} \to \tilde{\eta} + i\beta$

$\Rightarrow$ There exist, even in the vacuum, particles thermally distributed at T: Unruh effect.

Other standard derivation

This derivation uses the periodicity in imaginary time ($\tilde{t} \equiv it$) of a QFT at finite temperature $T \equiv /1\beta$.

Energy operator (not necessarily the time-evolution operator)

1.) Green function of $\phi(\tilde{t}, z)$: $G_\beta(\tilde{t}, z) = -\frac{1}{Z}\mathrm{Tr}\ \mathrm{e}^{-\beta H}\mathcal{T}[\phi(\tilde{t}, z)\phi(0,0)]$

Partition function — imaginary-time ordering operator

If H is also the time-evolution operator, then:

$e^{-\beta H}\phi(\tilde{t}, z)\mathrm{e}^{\beta H} = \phi(\tilde{t} - \beta, z)$

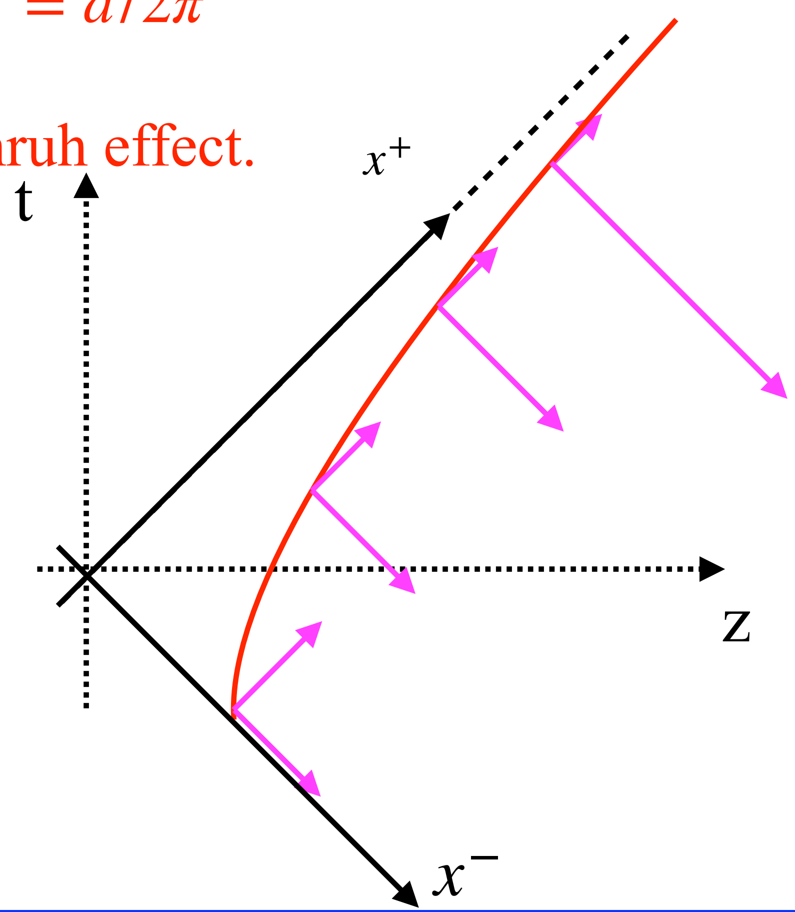
This and cyclicity property of trace ⇒ $G_\beta(\tilde{t}, z) = G_\beta(\tilde{t} - \beta, z)$: QFT periodicity with period β

2.) On the other hand: Rindler line element, $ds^2 = -\xi^2 d\eta^2 + d\xi^2$. With imaginary Rindler time $\tilde{\eta} \equiv i\eta$:
$ds^2 = \xi^2 d\eta^2 + d\xi^2$: polar coordinates. For non-singular coordinates, we must have $\tilde{\eta} = \tilde{\eta} + 2\pi i$.

Rindler time translation $\eta/a \to \eta/a + \Delta/a$ ⇔ boost with rapidity Δ
Rindler imaginary time periodicity: $\tilde{\eta}/a \to \tilde{\eta}/a + 2\pi i/a$ ⇒ temperature $\beta^{-1} = T = a/2\pi$
QFT β-periodicity: $\tilde{\eta} \to \tilde{\eta} + i\beta$

⇒ There exist, even in the vacuum, particles thermally distributed at T: Unruh effect.

But: LF boosts are kinematical ⇒ in LF dynamics, Rindler time translation operator is a kinematical operator ⇒ cannot serve as the Hamiltonian:
"~~If H is also the time-evolution operator~~"



Other standard derivation

This derivation uses the periodicity in imaginary time ($\tilde{t} \equiv it$) of a QFT at finite temperature $T \equiv /1\beta$.

Energy operator (not necessarily the time-evolution operator)

1.) Green function of $\phi(\tilde{t}, z)$: $G_\beta(\tilde{t}, z) = -\frac{1}{Z}\mathrm{Tr}\ e^{-\beta H}\mathcal{T}[\phi(\tilde{t}, z)\phi(0,0)]$

Partition function   imaginary-time ordering operator

If H is also the time-evolution operator, then:

$e^{-\beta H}\phi(\tilde{t}, z)e^{\beta H} = \phi(\tilde{t} - \beta, z)$

This and cyclicity property of trace $\Rightarrow$ $G_\beta(\tilde{t}, z) = G_\beta(\tilde{t} - \beta, z)$: QFT periodicity with period β

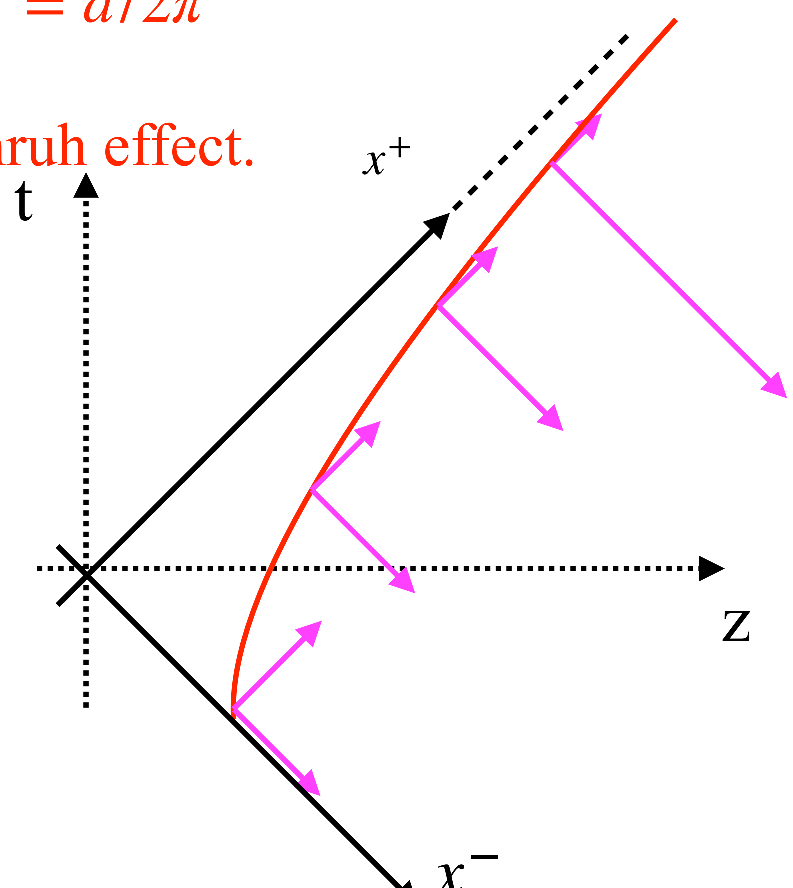
2.) On the other hand: Rindler line element, $ds^2 = -\xi^2 d\eta^2 + d\xi^2$. With imaginary Rindler time $\tilde{\eta} \equiv i\eta$:
$ds^2 = \xi^2 d\eta^2 + d\xi^2$: polar coordinates. For non-singular coordinates, we must have $\tilde{\eta} = \tilde{\eta} + 2\pi i$.

Rindler time translation $\eta/a \rightarrow \eta/a + \Delta/a \Leftrightarrow$ boost with rapidity Δ

Rindler imaginary time periodicity: $\tilde{\eta}/a \rightarrow \tilde{\eta}/a + 2\pi i/a$ $\Rightarrow$ temperature $\beta^{-1} = T = a/2\pi$

QFT β-periodicity: $\tilde{\eta} \rightarrow \tilde{\eta} + i\beta$

$\Rightarrow$ There exist, even in the vacuum, particles thermally distributed at T: Unruh effect.



But: LF boosts are kinematical $\Rightarrow$ in LF dynamics, Rindler time translation operator is a kinematical operator $\Rightarrow$ cannot serve as the Hamiltonian:
"~~If H is also the time-evolution operator~~"

In Euclidean spacetime the dilation operator serves as LF Hamiltonian.

Fubini, Hanson & Jackiw, PRD 7 1732 (1973)

~~$G_\beta(\tilde{t}, z) = G_\beta(\tilde{t} - \beta, z)$~~

No LF Unruh effect.

What gives ?

Nature is independent of any choice of frame & framework $\Rightarrow$ IF and LF must eventually agree.

What gives ?

Nature is independent of any choice of frame & framework $\Rightarrow$ IF and LF must eventually agree.

IF boost is dynamical + rapidity is time-dependent for accelerations.
$\Rightarrow$ Any detector used to measure the Unruh effect is dynamically affected by $\sum$ boost($\theta(t)$).

What gives ?

Nature is independent of any choice of frame & framework $\Rightarrow$ IF and LF must eventually agree.

IF boost is dynamical + rapidity is time-dependent for accelerations.
$\Rightarrow$ Any detector used to measure the Unruh effect is dynamically affected by $\sum$ boost($\theta(t)$).

Such detector is often described as a thermometer b/c Unruh particles are thermally distributed at T_{Unruh}.

Simple thermometer: deuterium gas. T given by Maxwell-Boltzmann law + distribution between D ground state $|S=0\rangle$ and excited state $|S=1\rangle$.

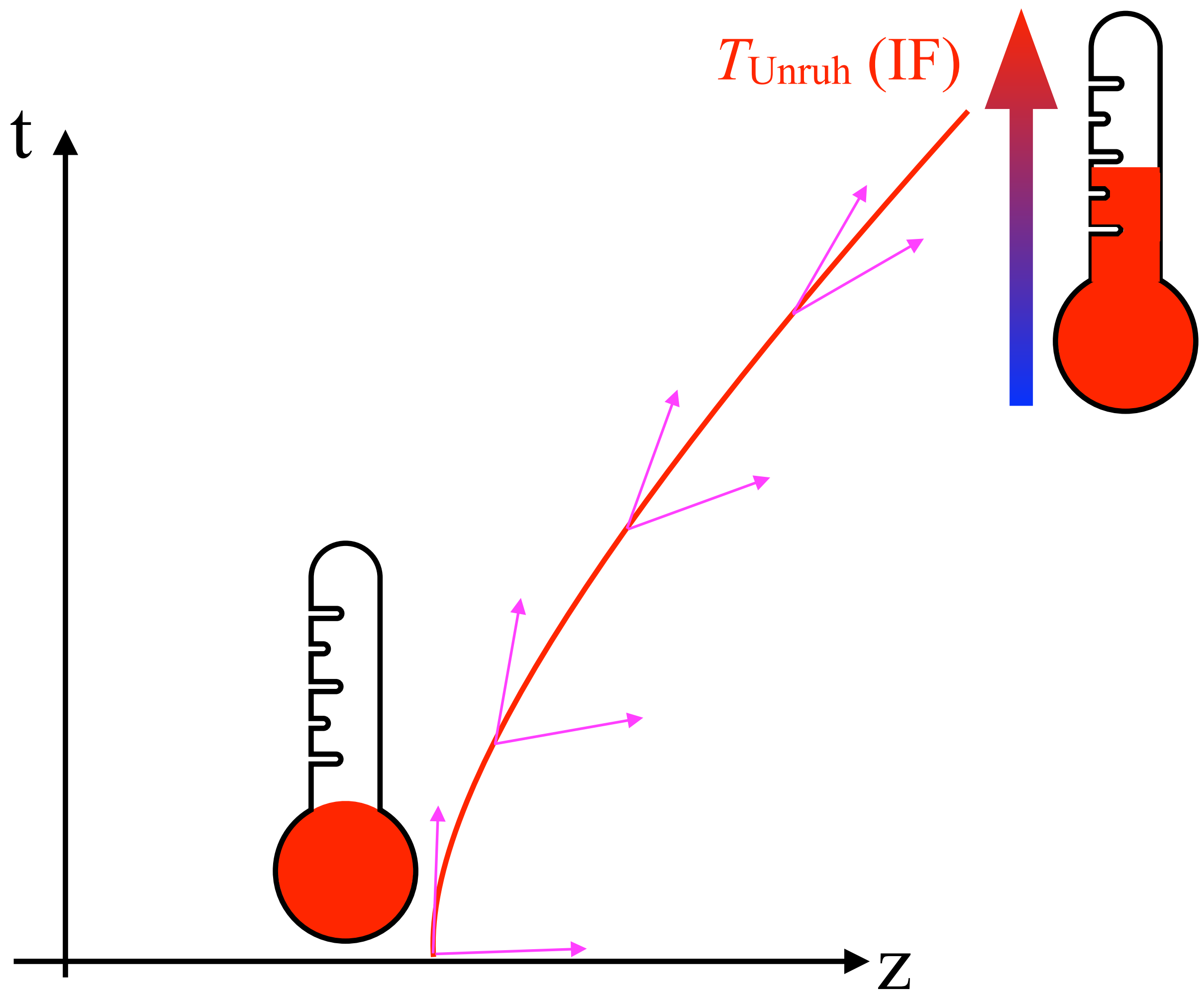
What gives ?

Nature is independent of any choice of frame & framework ⇒ IF and LF must eventually agree.

IF boost is dynamical + rapidity is time-dependent for accelerations.
⇒ Any detector used to measure the Unruh effect is dynamically affected by $\sum$ boost($\theta(t)$).

Such detector is often described as a thermometer b/c Unruh particles are thermally distributed at T_{Unruh}.

Simple thermometer: deuterium gas. T given by Maxwell-Boltzmann law + distribution between D ground state $|S=0\rangle$ and excited state $|S=1\rangle$.



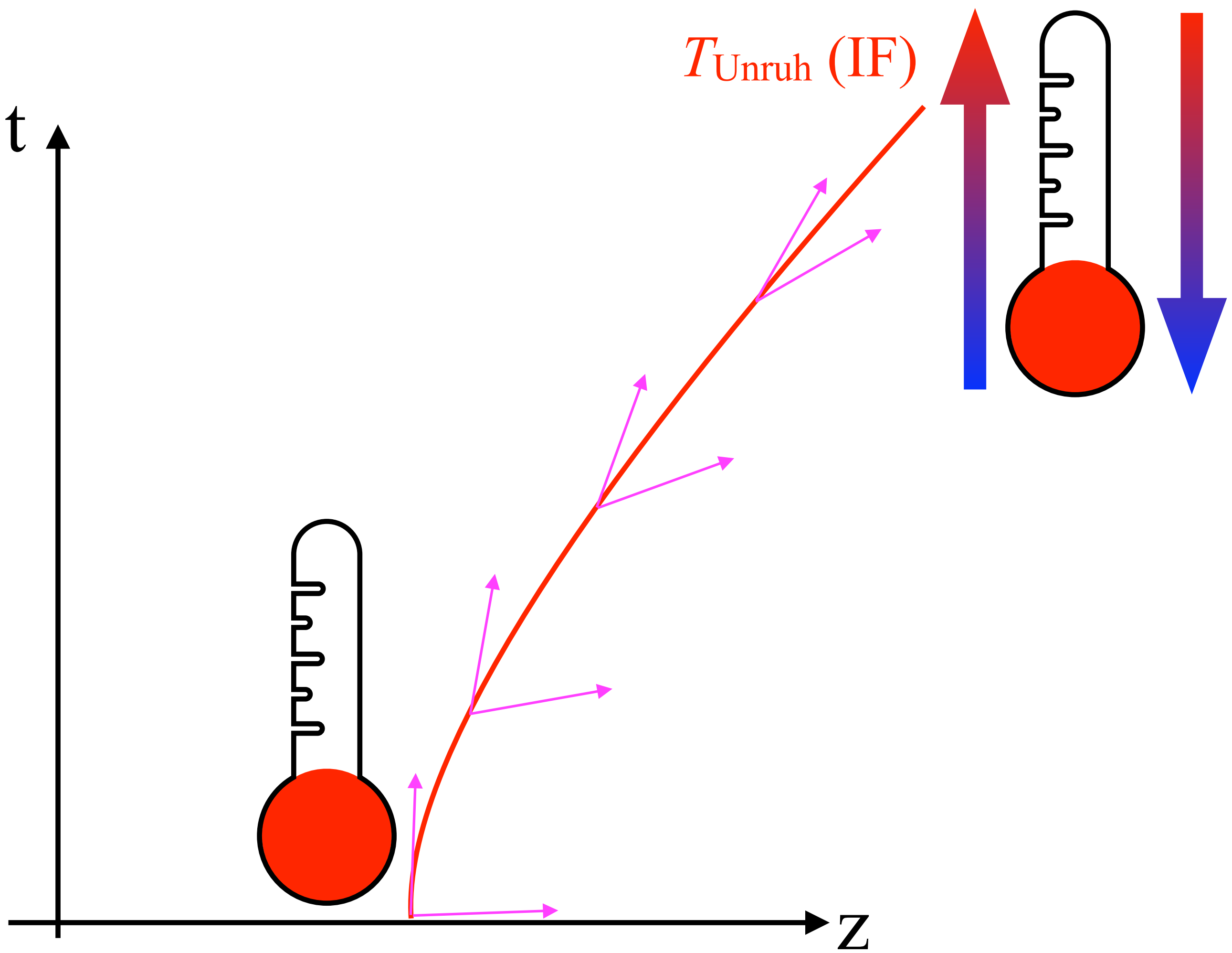
What gives ?

Nature is independent of any choice of frame & framework ⇒ IF and LF must eventually agree.

IF boost is dynamical + rapidity is time-dependent for accelerations.
⇒ Any detector used to measure the Unruh effect is dynamically affected by $\sum$ boost($\theta(t)$).

Such detector is often described as a thermometer b/c Unruh particles are thermally distributed at T_{Unruh}.

Simple thermometer: deuterium gas. T given by Maxwell-Boltzmann law + distribution between D ground state $|S=0\rangle$ and excited state $|S=1\rangle$.



Dynamical boost induces spin-orbit force.
⇒ State $|S=1\rangle$ depopulates to $|S=0\rangle$.

McGee, Phys. Rev. 158 1500 (1967);
Brodsky, Primack, Phys. Rev. 174 2071 (1968)

⇒ **The detector cools.**

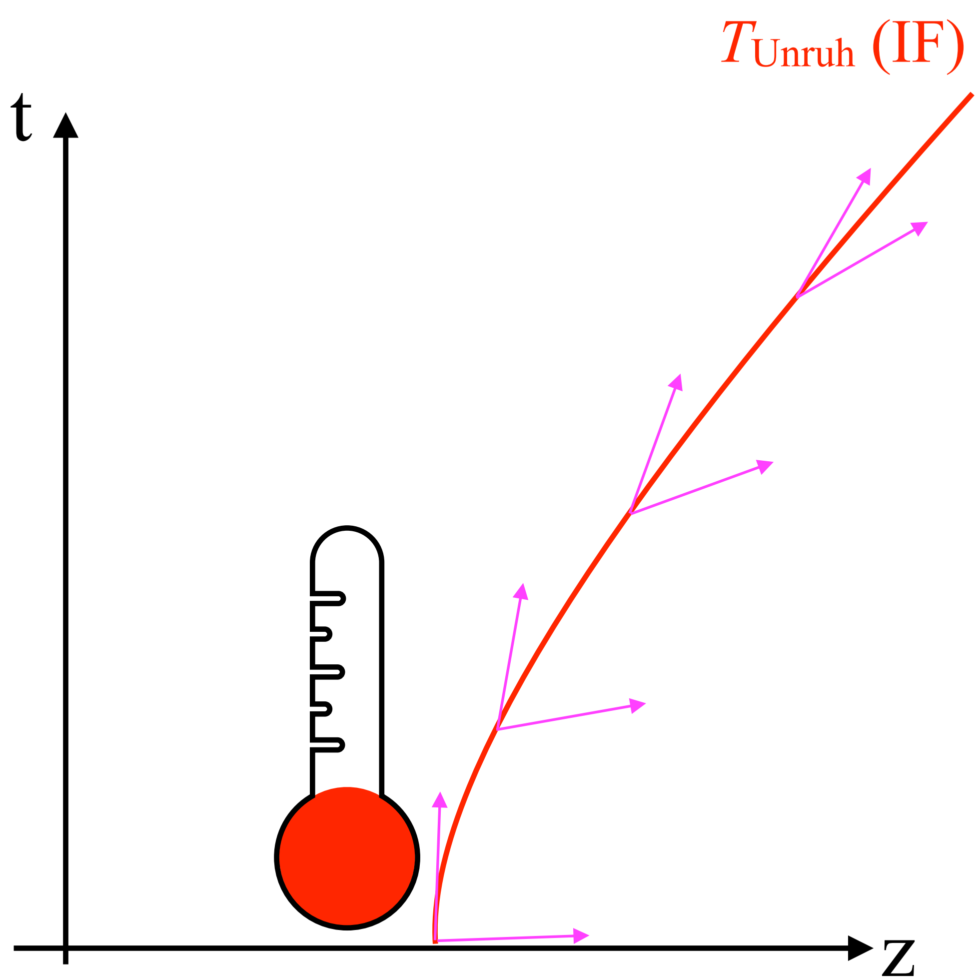
What gives ?

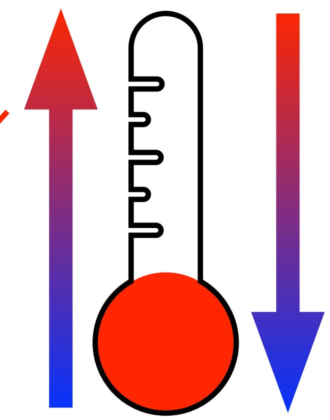
Nature is independent of any choice of frame & framework ⇒ IF and LF must eventually agree.

IF boost is dynamical + rapidity is time-dependent for accelerations.
⇒ Any detector used to measure the Unruh effect is dynamically affected by $\sum$ boost($\theta(t)$).

Such detector is often described as a thermometer b/c Unruh particles are thermally distributed at T_{Unruh}.

Simple thermometer: deuterium gas. T given by Maxwell-Boltzmann law + distribution between D ground state $|S=0\rangle$ and excited state $|S=1\rangle$.





Dynamical boost induces spin-orbit force.
⇒ State $|S=1\rangle$ depopulates to $|S=0\rangle$.

McGee, Phys. Rev. 158 1500 (1967);
Brodsky, Primack, Phys. Rev. 174 2071 (1968)

⇒ **The detector cools.**

LF: boosts are kinematical (no cooling) & vacuum is trivial (no Unruh temperature)
⇒ Suggests Unruh heating + IF-boost cooling = 0.

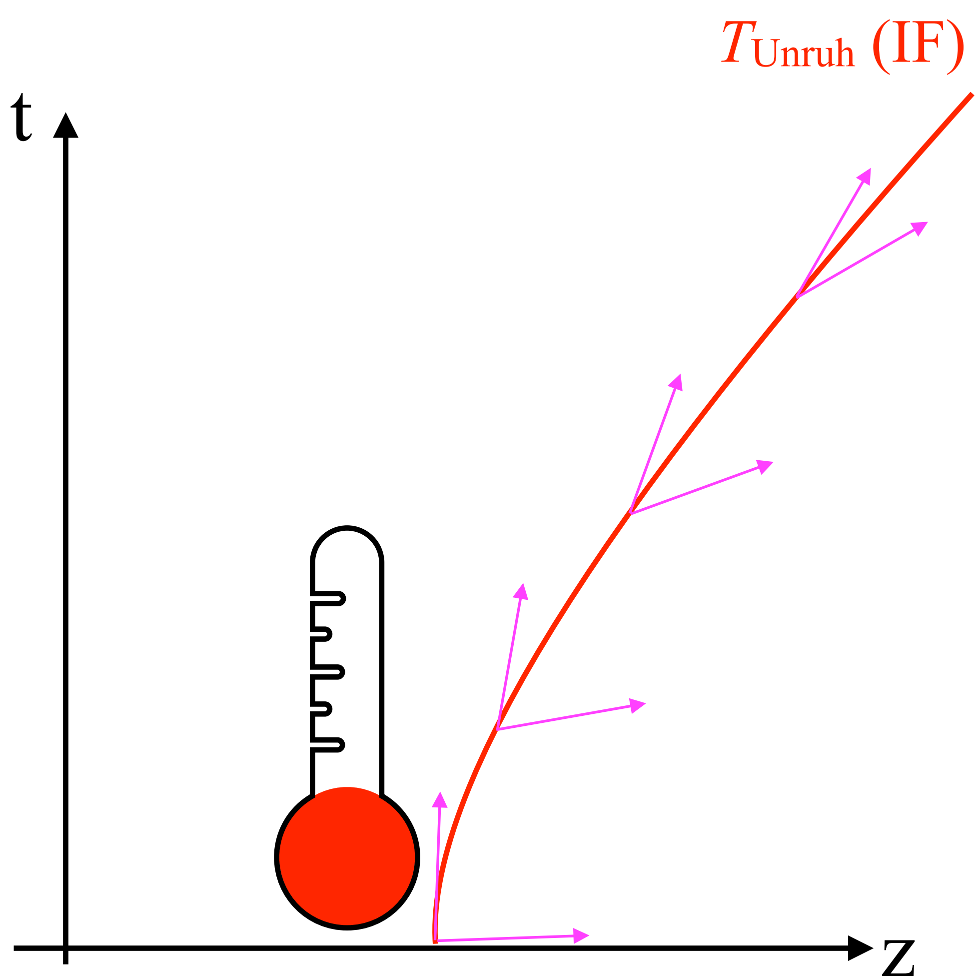
What gives ?

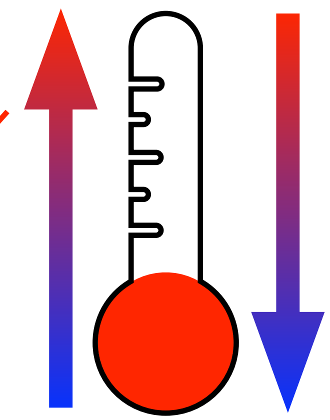
Nature is independent of any choice of frame & framework ⇒ IF and LF must eventually agree.

IF boost is dynamical + rapidity is time-dependent for accelerations.
⇒ Any detector used to measure the Unruh effect is dynamically affected by $\sum \text{boost}(\theta(t))$.

Such detector is often described as a thermometer b/c Unruh particles are thermally distributed at T_{Unruh}.

Simple thermometer: deuterium gas. T given by Maxwell-Boltzmann law + distribution between D ground state $|S=0\rangle$ and excited state $|S=1\rangle$.





Dynamical boost induces spin-orbit force.
⇒ State $|S=1\rangle$ depopulates to $|S=0\rangle$.

McGee, Phys. Rev. 158 1500 (1967);
Brodsky, Primack, Phys. Rev. 174 2071 (1968)

⇒ **The detector cools**.

LF: boosts are kinematical (no cooling) & vacuum is trivial (no Unruh temperature)
⇒ Suggests Unruh heating + IF-boost cooling = 0.

The IF cooling effect has been overlooked ⇒ No compensation mechanism for the Unruh effect, which seems objectively observable.

Implication to Black Hole Evaporation

Equivalence principle between gravity and acceleration: no Unruh effect ⇔ no Hawking effect.

⇒ No black hole evaporation

⇒No black hole information paradox. (One of the gravest problems in physics.)

Implication to Black Hole Evaporation

Equivalence principle between gravity and acceleration: no Unruh effect ⇔ no Hawking effect.

⇒ No black hole evaporation

⇒No black hole information paradox. (One of the gravest problems in physics.)

Equivalence principle + LF yields a new perspective on Unruh effect:

- Definition of positive and negative frequency modes is ambiguous in accelerated frame/curved spacetime. Since they determine the vacuum state ⇒ Unruh effect.

Implication to Black Hole Evaporation

Equivalence principle between gravity and acceleration: no Unruh effect ⇔ no Hawking effect.

⇒ No black hole evaporation

⇒No black hole information paradox. (One of the gravest problems in physics.)

Equivalence principle + LF yields a new perspective on Unruh effect:

- Definition of positive and negative frequency modes is ambiguous in accelerated frame/curved spacetime. Since they determine the vacuum state ⇒ Unruh effect.

- Apparently contradicts General Relativity's basic principle that for vanishing distances, curved spacetime → flat spacetime (=inertial frame, without Unruh effect).

Implication to Black Hole Evaporation

Equivalence principle between gravity and acceleration: no Unruh effect ⇔ no Hawking effect.

⇒ No black hole evaporation

⇒No black hole information paradox. (One of the gravest problems in physics.)

Equivalence principle + LF yields a new perspective on Unruh effect:

- Definition of positive and negative frequency modes is ambiguous in accelerated frame/curved spacetime. Since they determine the vacuum state ⇒ Unruh effect.
- Apparently contradicts General Relativity's basic principle that for vanishing distances, curved spacetime → flat spacetime (=inertial frame, without Unruh effect).
- However IF vacuum is complex, with characteristic distance scale (size of the vacuum loops). ⇒ cannot take the small distance limit ⇒ definition of positive and negative modes ambiguous: Unruh effect.

Implication to Black Hole Evaporation

Equivalence principle between gravity and acceleration: no Unruh effect ⇔ no Hawking effect.

⇒ No black hole evaporation

⇒No black hole information paradox. (One of the gravest problems in physics.)

Equivalence principle + LF yields a new perspective on Unruh effect:

- Definition of positive and negative frequency modes is ambiguous in accelerated frame/curved spacetime. Since they determine the vacuum state ⇒ Unruh effect.
- Apparently contradicts General Relativity's basic principle that for vanishing distances, curved spacetime → flat spacetime (=inertial frame, without Unruh effect).
- However IF vacuum is complex, with characteristic distance scale (size of the vacuum loops). ⇒ cannot take the small distance limit ⇒ definition of positive and negative modes ambiguous: Unruh effect.
- Classical physics (with trivial vacuum): no Unruh effect. Indeed, $T_{\text{Unruh}} \propto \hbar$: quantum effect.
- LF vacuum is trivial. No distance scale prevents reaching the flat spacetime limit, with well-defined positive and negative modes ⇒ no Unruh effect

Conclusion

Common claim: No need to test or question the Unruh effect since it is a logical consequence of QFT.

- "*the Unruh effect itself does not need experimental confirmation any more than free quantum field theory does* " (Standard review on the Unruh effect: arXiv:0710.5373)
- "*the Unruh effect does not require any verification beyond that of relativistic free field theory itself*" ("Unruh effect", Scholarpedia)

Conclusion

Common claim: No need to test or question the Unruh effect since it is a logical consequence of QFT.

- "*the Unruh effect itself does not need experimental confirmation any more than free quantum field theory does* " (Standard review on the Unruh effect: arXiv:0710.5373)
- "*the Unruh effect does not require any verification beyond that of relativistic free field theory itself*" ("Unruh effect", Scholarpedia)

Yet, despite being a legitimate approach to QFT, LF quantization does not predict an Unruh effect.

This suggests that the Unruh effect is cancelled in IF dynamics by Unruh detector cooling due to dynamical evolution from succession of IF boosts.

Conclusion

Common claim: No need to test or question the Unruh effect since it is a logical consequence of QFT.

- "*the Unruh effect itself does not need experimental confirmation any more than free quantum field theory does* " (Standard review on the Unruh effect: arXiv:0710.5373)
- "*the Unruh effect does not require any verification beyond that of relativistic free field theory itself*" ("Unruh effect", Scholarpedia)

Yet, despite being a legitimate approach to QFT, LF quantization does not predict an Unruh effect.

This suggests that the Unruh effect is cancelled in IF dynamics by Unruh detector cooling due to dynamical evolution from succession of IF boosts.

Equivalence principle: Unruh effect ⇔ Hawking radiation from black holes.

No Hawking radiation
⇒ no black hole evaporation
⇒ no black hole information paradox.

Conclusion

Common claim: No need to test or question the Unruh effect since it is a logical consequence of QFT.

- "*the Unruh effect itself does not need experimental confirmation any more than free quantum field theory does* " (Standard review on the Unruh effect: arXiv:0710.5373)
- "*the Unruh effect does not require any verification beyond that of relativistic free field theory itself*" ("Unruh effect", Scholarpedia)

Yet, despite being a legitimate approach to QFT, LF quantization does not predict an Unruh effect.

This suggests that the Unruh effect is cancelled in IF dynamics by Unruh detector cooling due to dynamical evolution from succession of IF boosts.

Equivalence principle: Unruh effect ⇔ Hawking radiation from black holes.

No Hawking radiation
⇒ no black hole evaporation
⇒ no black hole information paradox.

Then, origin of this grave problem is the same as the origin cosmological constant problem, with same resolution: trivial LF vacuum ⇒ no $\sim 10^{120}$discrepancy with observed cosmological constant.

Brodsky, Shrock, PNAS. 108, 45 (2011)
Brodsky, *et al*, PRC 82, 022201 (2010); 85, 065202 (2012).

Supplementary slides

LF vacuum

•Firmly established: no virtual particle loops in LF vacuum.

•Rôle of possible zero-momentum LF modes in the LF vacuum is less clear. But, irrelevant to the Unruh effect regardless of their possible existence:

1. $p^+ = 0$ modes do not transfer momentum/kinetic energy to the Unruh detector: zero-modes cannot heat thermometers.
2. Vacuum structure is not invoked in IF demonstration of Unruh effect. Demonstration is based on coordinate definitions of the forms of dynamics + consequent quantization conditions + generic properties of quantum field theory. Only the *interpretation* of the effect invokes the vacuum structure to provides an intuitive picture.
3. Discussions of the Unruh effect are often set for simplicity in (1+1)D. There the triviality of the LF vacuum (perturbative & non-perturbative) is established.
4. New perspective in "Implication to Black Hole Evaporation": By definition, zero-point energy occurs at a single point in space (their only possible physical contribution being from the infinite momentum loop, viz with conjugate distance $\rightarrow 0$) $\Rightarrow$ zero-modes do not provide the distance scale necessary to prevent reaching the flat spacetime limit.

Possible nontrivial nonperturbative vacuum? Also irrelevant because no field coupling nor other expansion parameter enters in the Unruh effect.