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

Particles 9 42 (2026)

The Unruh Effect

- **The Unruh effect**: Accelerated observers can detect particles which are unobservable to inertial observers. This 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. This 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 times 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. This 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 times 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)

The Unruh Effect

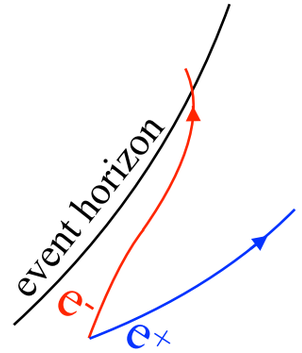
- **The Unruh effect**: Accelerated observers can detect particles which are unobservable to inertial observers. This occurs even if the accelerated observer is in vacuum.

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 times 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)

- Heuristic interpretations:
  - Hawking radiation: 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 their annihilation is prevented.



  - Unruh effect: In vacuum, an inertial detector is quiet since a vacuum fluctuation causing a transition $E_i \to E_j$ must be followed after $\Delta t \approx 1/|E_i - E_j|$ by an opposite fluctuation $E_j \to E_i$. Due to its time resolution, the detector appears quiet. If the detector accelerates, after Δt, $\Delta E \equiv |E_i - E_j|$ becomes $\Delta E' = |E_i - E'_f| \neq \Delta E$, and the opposite fluctuation cannot compensate for the initial one: a signal is perceived.

⇒ one particle becomes real, taking energy from the Black Hole (Hawking radiation) or from the detector's acceleration (Unruh effect).
Interpretations relies on the complexity of quantum vacuum

The Unruh Effect

LF quantization: $p^+ \geq 0 \Rightarrow$ trivial vacuum.

No loops of virtual particles 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: (we will use massless scalar field case in 2D throughout)

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

We impose $\omega \geq 0$ always ("negative frequency" modes is just a label).

Definitions of:

Positive frequency modes: $\frac{\partial f_p}{\partial t} = -i\omega f_p$ (i.e., particles)

Negative frequency modes: $\frac{\partial f_p^*}{\partial t} = i\omega f_p^*$ (antiparticles)

Field decomposition

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

Field decomposition in positive and negative frequency modes: (we will use massless scalar field case in 2D throughout)

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

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: (we will use massless scalar field case in 2D throughout)

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

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 $|0'\rangle$):

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

Unless the classification between positive and negative modes is consistent for the two frames,

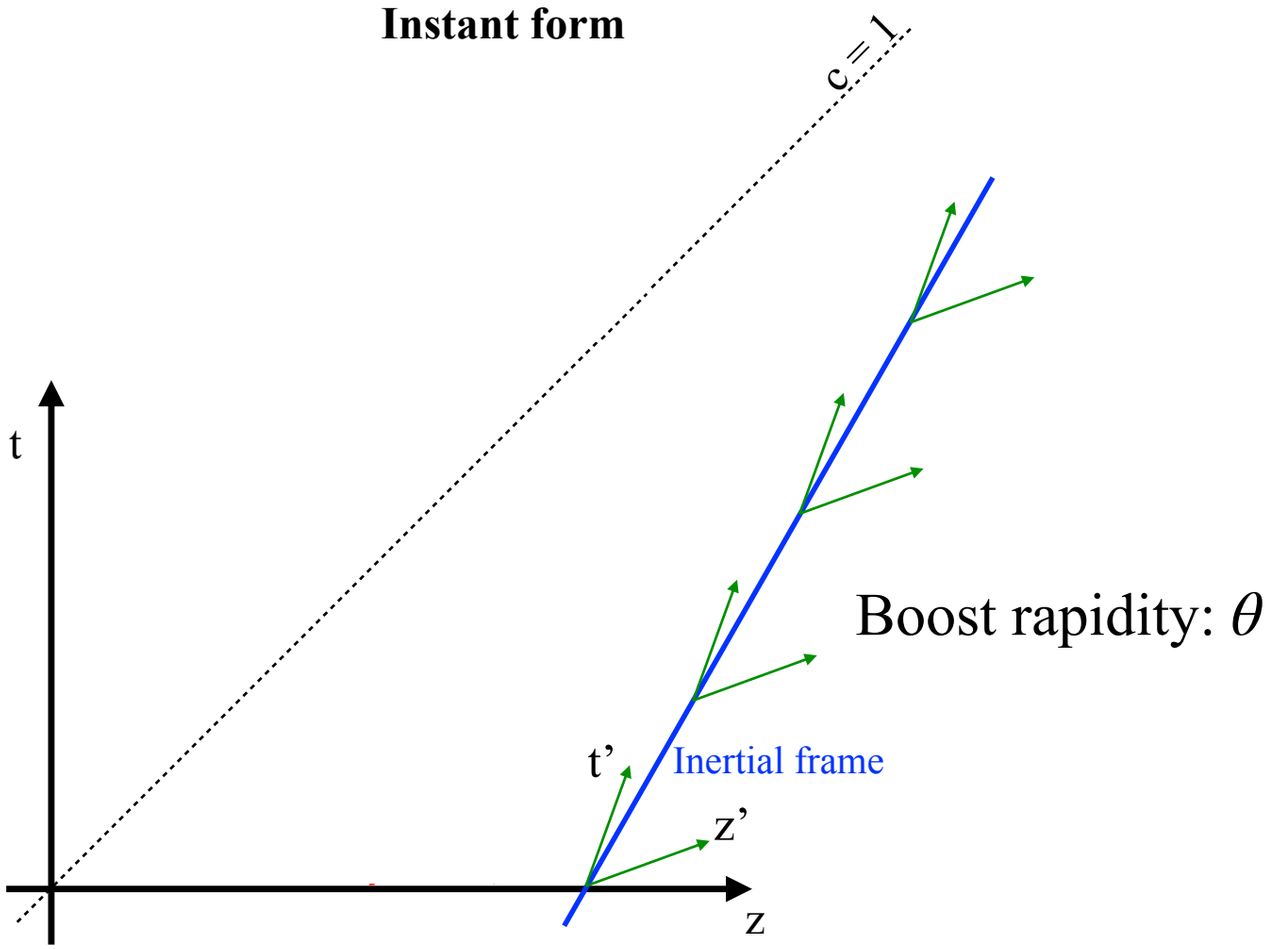
$\hat{b}_{p'} = \alpha \hat{a}_p + \beta \hat{a}_p^\dagger$ with $\beta \neq 0$ if x_μ or/and x'_μ are not an inertial frame.

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

$\hat{b}_{p'} |0\rangle \propto |p\rangle \neq 0$

Unruh effect

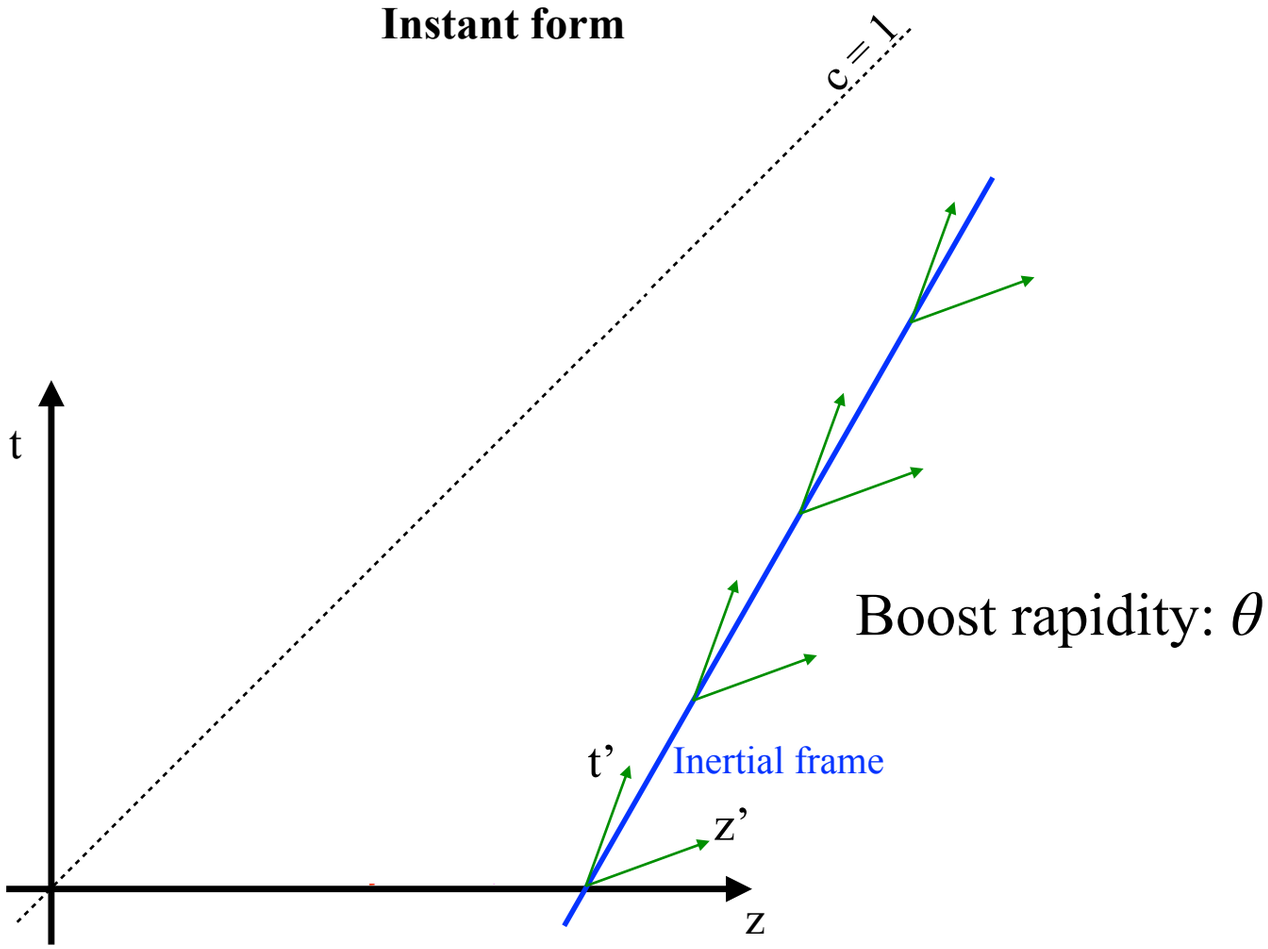
Inertial frames



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

$$f_p \propto e^{ip^\mu x_\mu} = e^{-i(\omega t - pz)} = e^{-i(\omega' t' - p' z')}$$

Inertial frames



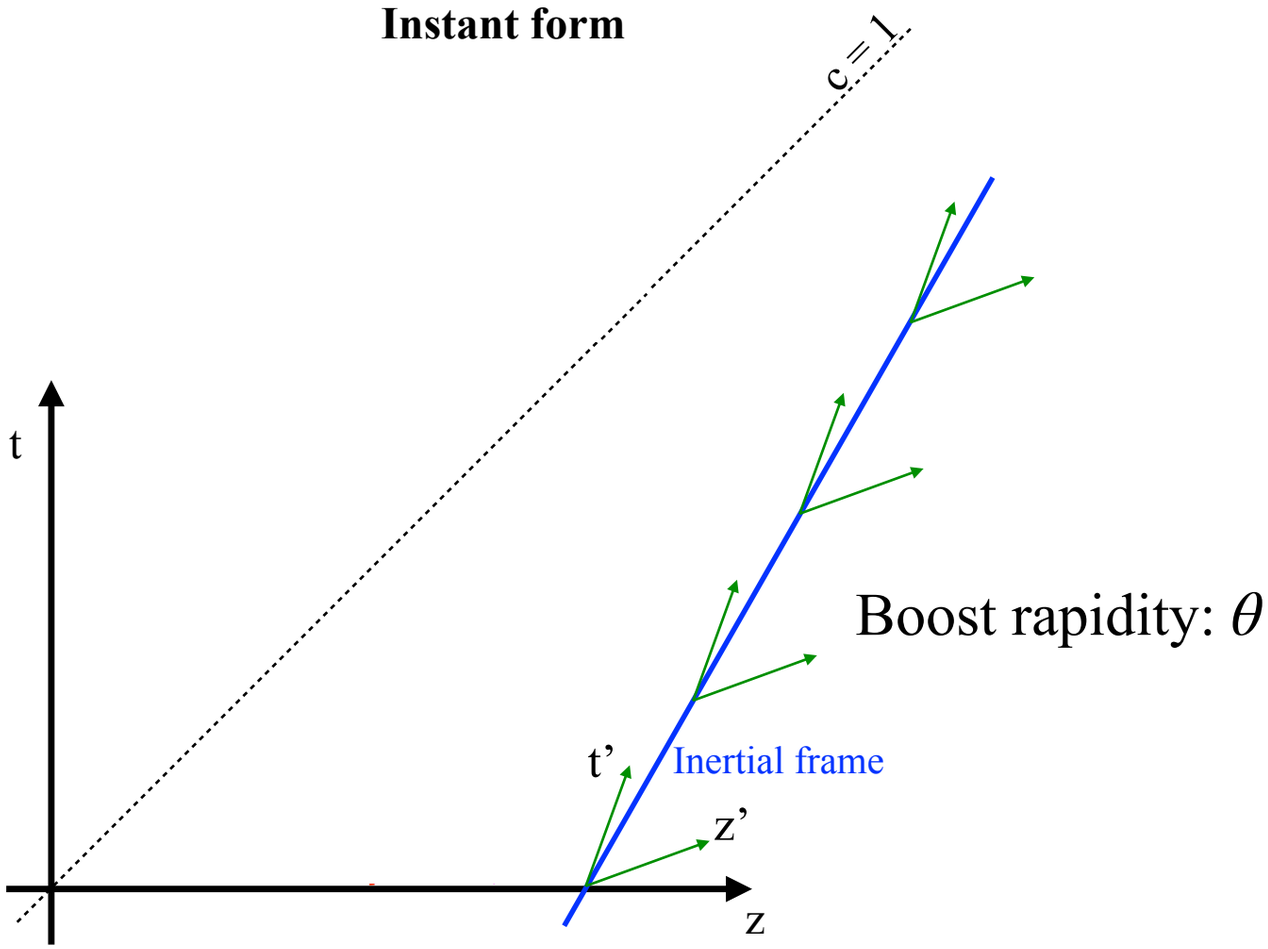
$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right), \text{ with } f_p \propto e^{ip^\mu x_\mu}$$

$$f_p \propto e^{ip^\mu x_\mu} = e^{-i(\omega t - pz)} = e^{-i(\omega' t' - p' z')}$$

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

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

Inertial frames



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

$$f_p \propto e^{ip^\mu x_\mu} = e^{-i(\omega t - pz)} = e^{-i(\omega' t' - p' z')}$$

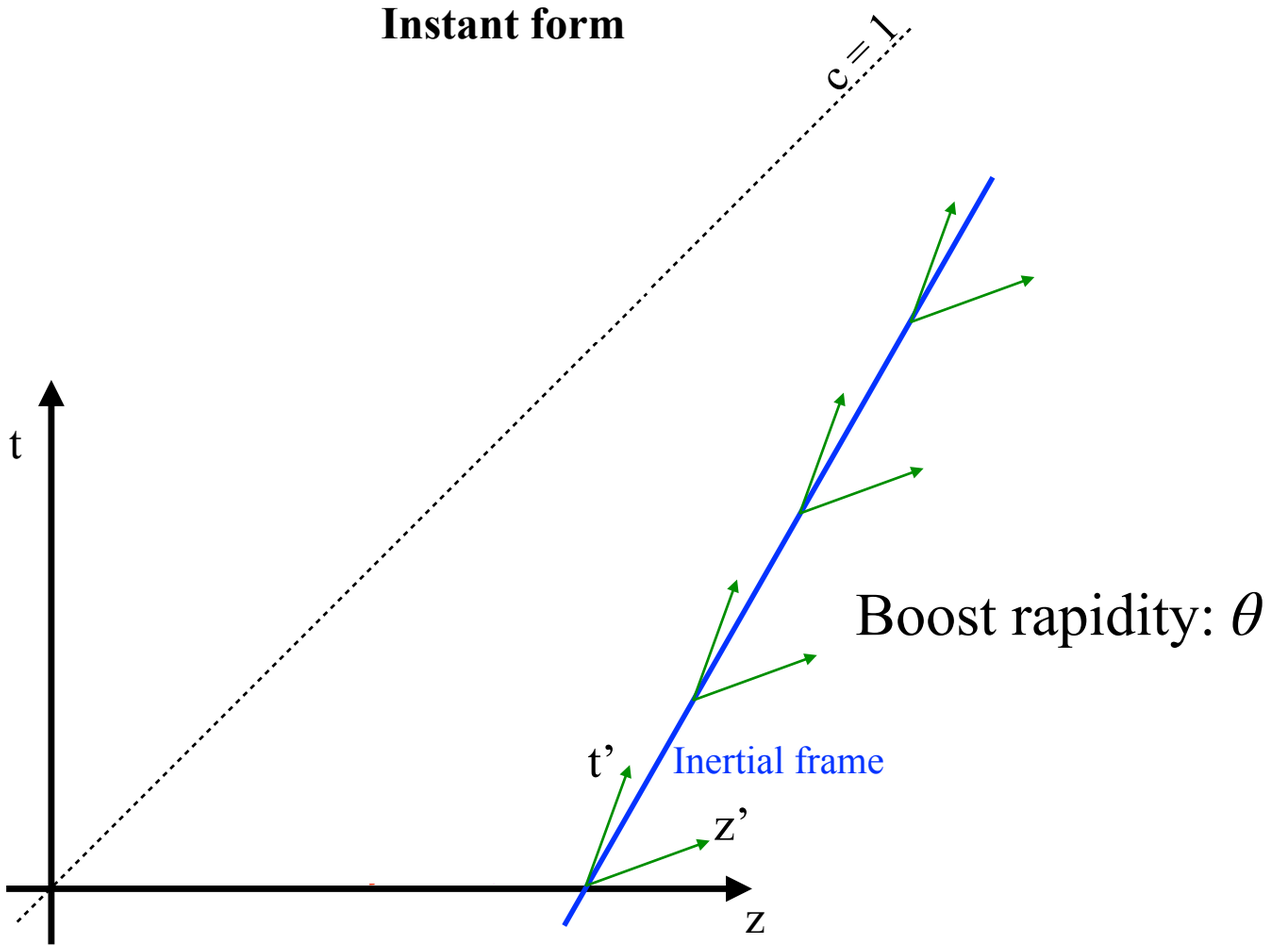
If the frames are related by a Lorentz boost (viz inertial frames):

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

Frequencies in the boosted frame are boosted frequencies.

Dispersion relation: $\omega = |p| \Rightarrow \omega' = \omega(\cosh\theta \pm \sinh\theta) = \omega e^{\pm\theta}$: same sign as ω.

Inertial frames



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

$$f_p \propto e^{ip^\mu x_\mu} = e^{-i(\omega t - pz)} = e^{-i(\omega' t' - p' z')}$$

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

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

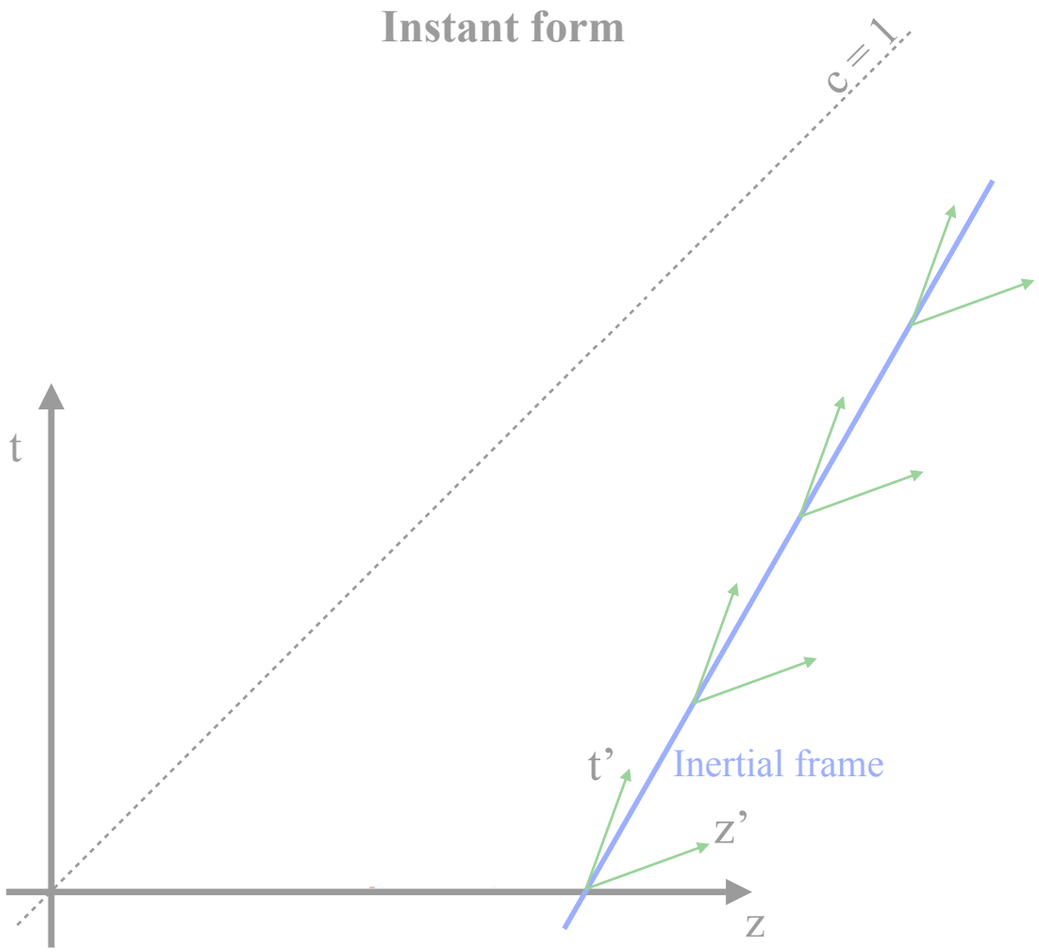
Frequencies in the boosted frame are boosted frequencies.

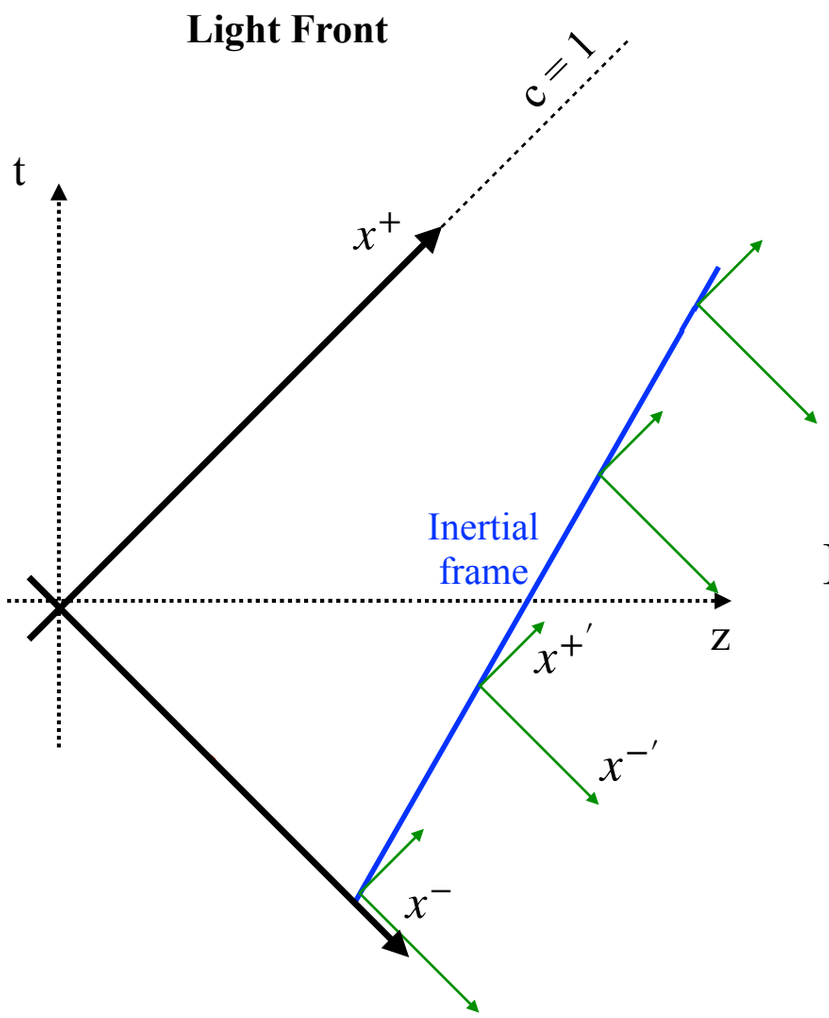
Dispersion relation: $\omega = |p| \Rightarrow \omega' = \omega(\cosh\theta \pm \sinh\theta) = \omega e^{\pm\theta}$: same sign as ω.

$\Rightarrow$ consistent separation of positive and negative modes in the two frames.

$\hat{b}_{p'} = \hat{a}_p$: no Unruh effect in inertial frames, as it should be.

Inertial frames





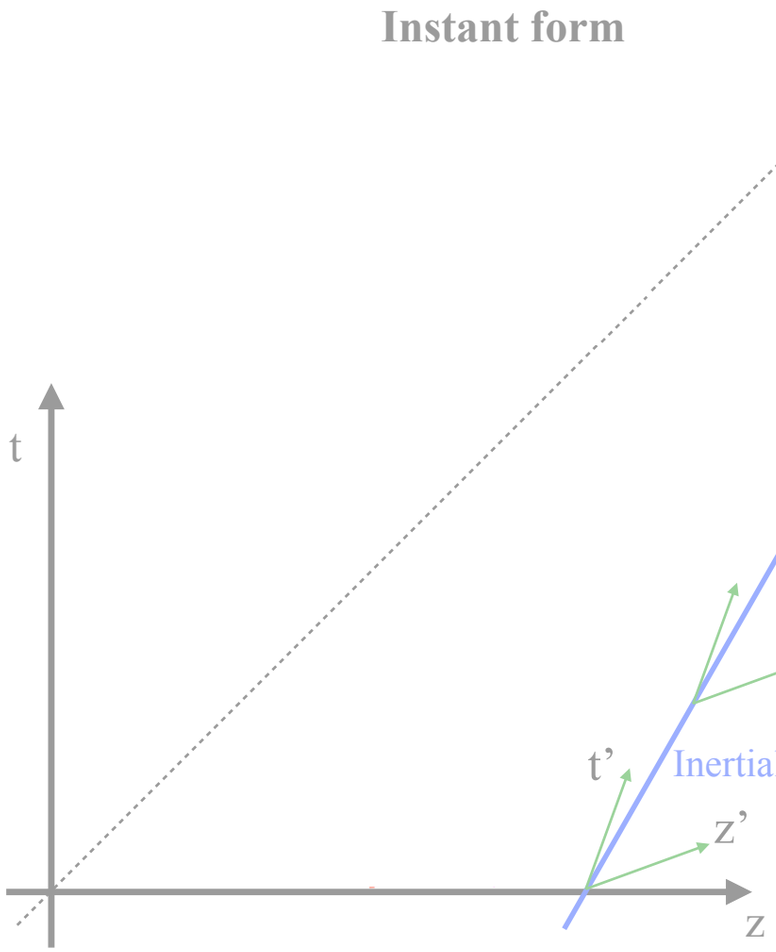
Boost rapidity: θ

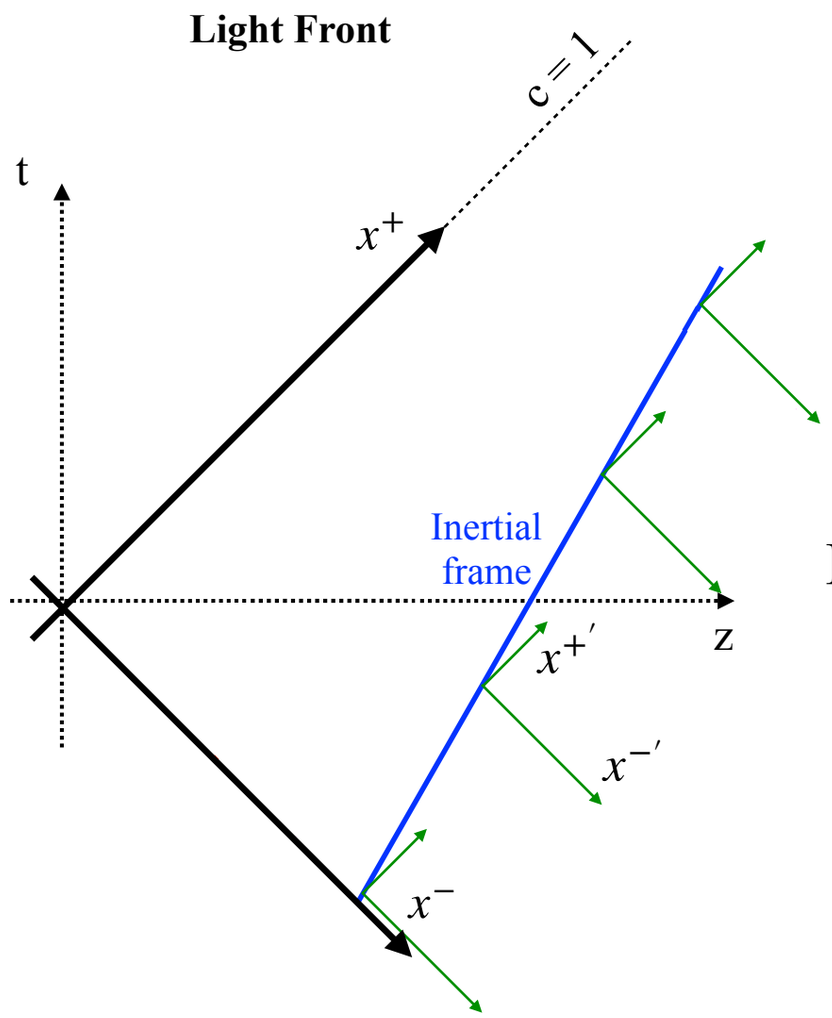
$$\phi = \int dp\left(\hat{a}_p f_p + \hat{a}_p^\dagger f_p^*\right), \text{ with } f_p \propto e^{ip^\mu x_\mu}$$

$$f_p \propto e^{ip^\mu x_\mu} = e^{-i(\omega t - pz)} = e^{-i(\omega' t' - p' z')}$$

$$\frac{\partial f_p}{\partial t'} = -\, i\omega' f_p \text{ for IF,}$$

Inertial frames





Boost rapidity: θ

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

$$f_p \propto e^{ip^\mu x_\mu} = e^{-i(\omega t - pz)} = e^{-i(\omega' t' - p' z')} = e^{-\frac{i}{2}(p^- x^+ + p^+ x^-)} = e^{-\frac{i}{2}(p^{-'} x^{+'} + p^{+'} x^{-'})}$$

$$\frac{\partial f_p}{\partial t'} = -\, i\omega' f_p \text{ for IF,}$$

$$\frac{\partial f_{p^+}}{\partial x^{+'}} = -\frac{i}{2} p^{-'} f_{p^+} \text{ for LF}$$

Frequencies in the boosted frame are boosted frequencies.

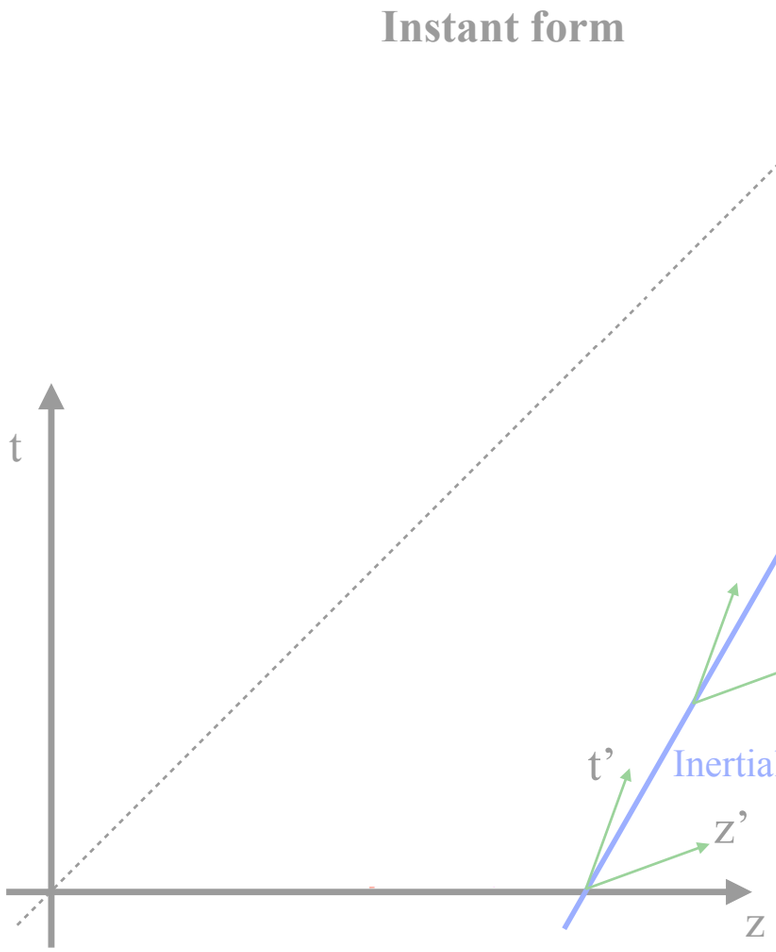
Dispersion relation: $\omega = |p| \Rightarrow \omega' = \omega e^{\pm\theta}$: same sign as ω.

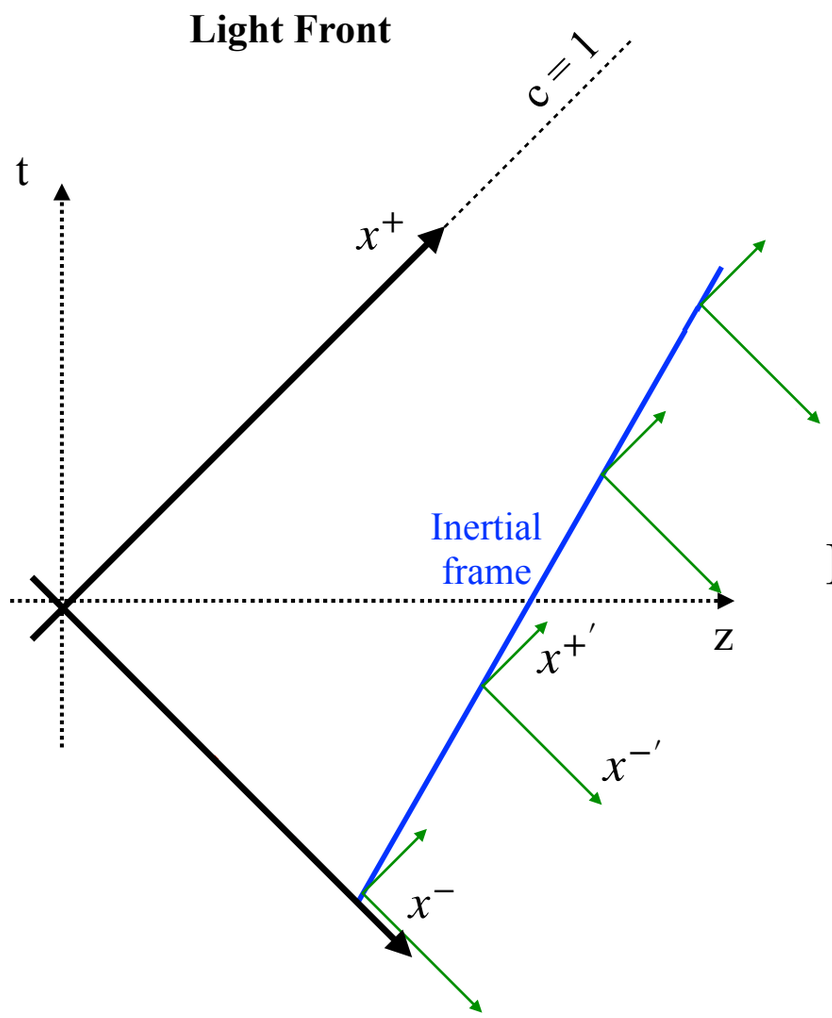
$p^{-'} = p^- e^{-\theta}$: same sign as p^-.

$\Rightarrow$ consistent separation of positive and negative modes in the two frames.

$\hat{b}_{p'} = \hat{a}_p$: no Unruh effect in inertial frames, as it should be.

Inertial frames





Boost rapidity: θ

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

$$f_p \propto e^{ip^\mu x_\mu} = e^{-i(\omega t - pz)} = e^{-i(\omega' t' - p' z')} = e^{-\frac{i}{2}(p^- x^+ + p^+ x^-)} = e^{-\frac{i}{2}(p^{-'} x^{+'} + p^{+'} x^{-'})}$$

$$\frac{\partial f_p}{\partial t'} = -\, i\omega' f_p \text{ for IF,}$$

$$\frac{\partial f_{p^+}}{\partial x^{+'}} = -\frac{i}{2} p^{-'} f_{p^+} \text{ for LF}$$

Frequencies in the boosted frame are boosted frequencies.

Dispersion relation: $\omega = |p| \Rightarrow \omega' = \omega e^{\pm\theta}$: same sign as ω.

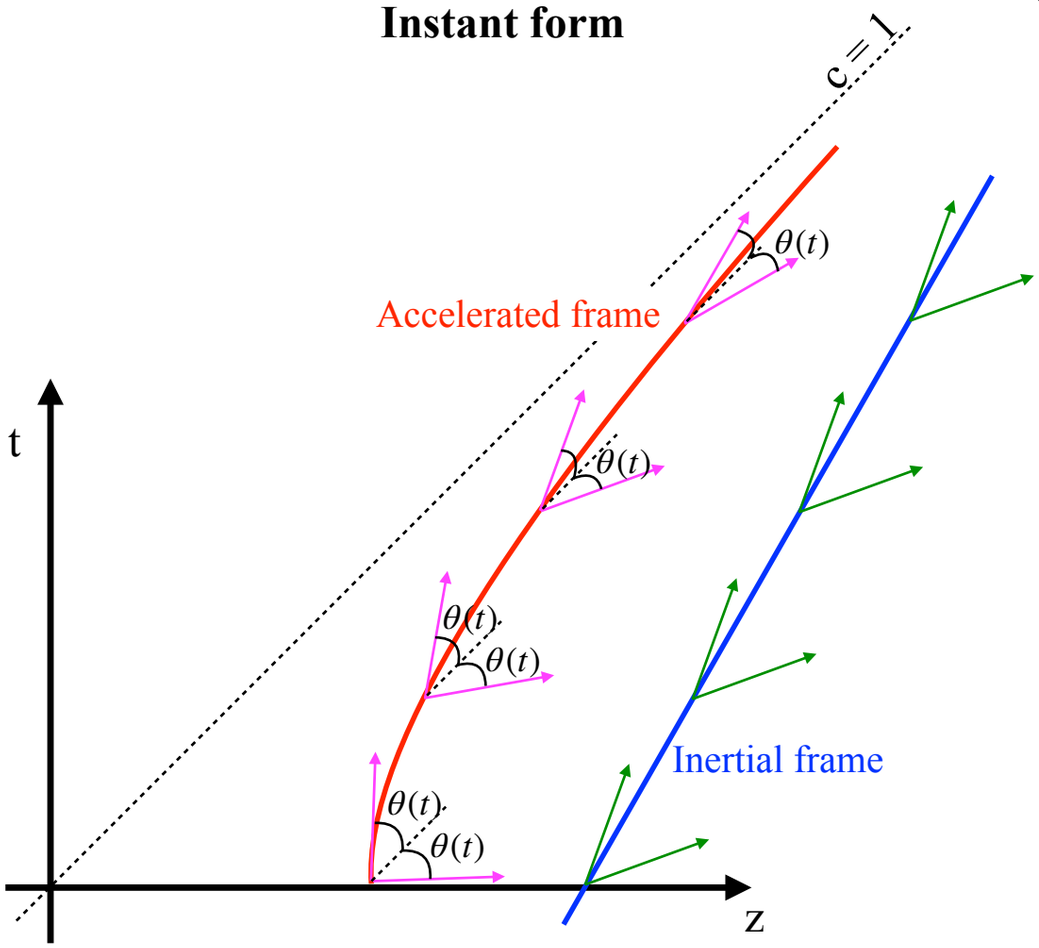
$p^{-'} = p^- e^{-\theta}$: same sign as p^-.

$\Rightarrow$ consistent separation of positive and negative modes in the two frames.

$\hat{b}_{p'} = \hat{a}_p$: no Unruh effect in inertial frames, as it should be.

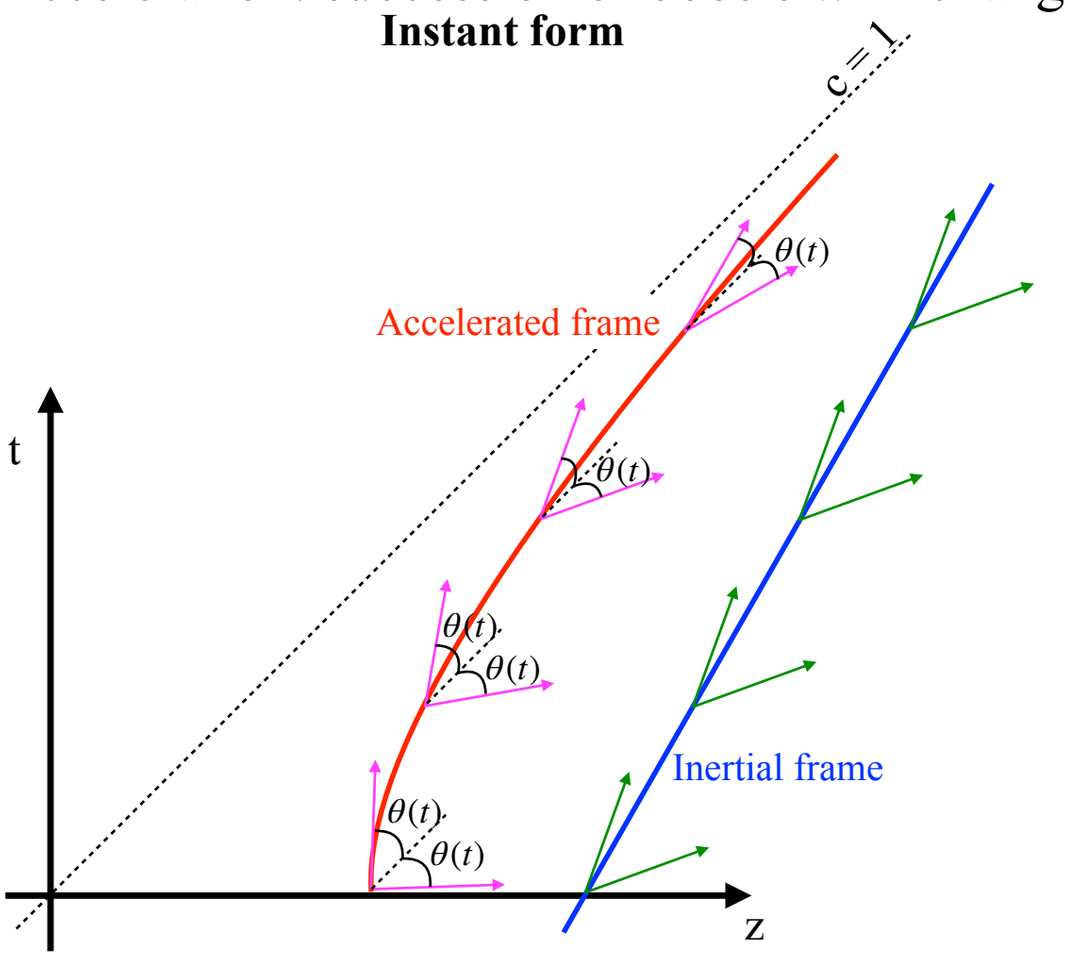
Accelerating frames

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



Accelerating frames

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



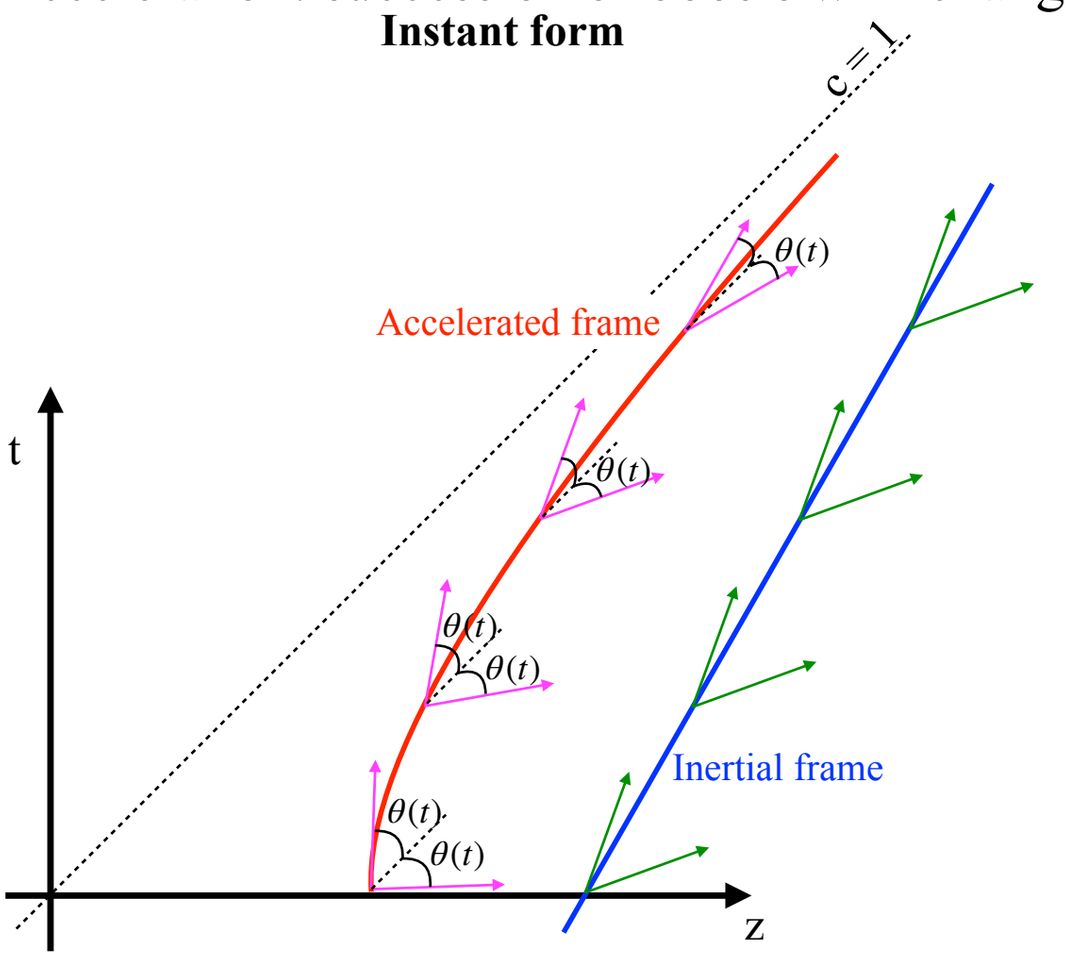
Not Lorentz invariant.

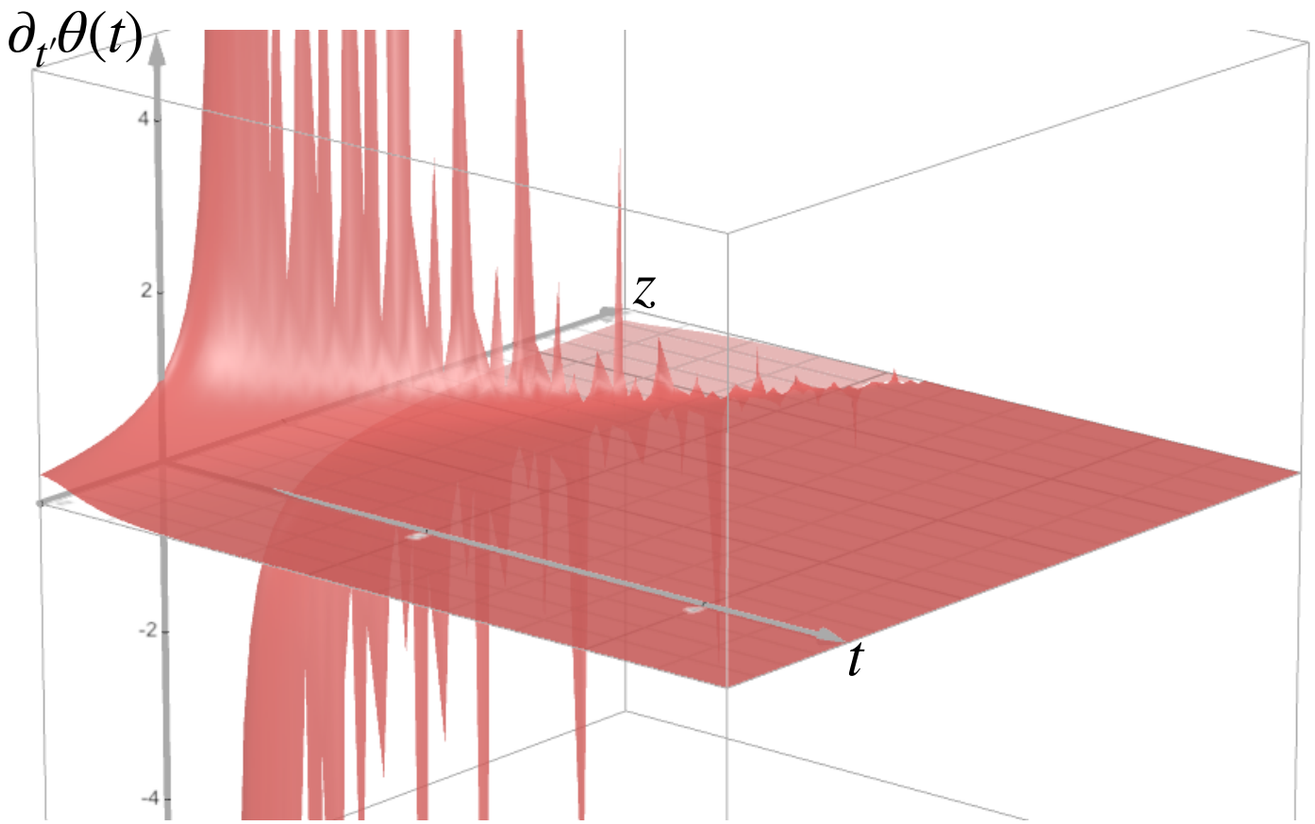
$$\frac{\partial f_p}{\partial t'} = -\,i\left[\omega' + \partial_{t'}\theta(\omega z - tp)\right] f_p \,, \text{ with } \partial_{t'}\theta(t) = u\,\mathrm{sech}(ut)/[1 - uz + ut\,\tanh(ut)] \text{ for IF,}$$

$$\boxed{(\omega z - tp) = \omega(z \pm t) > 0}$$

Accelerating frames

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





$\partial_{t'}\theta(t) > 0$ or < 0 depending on z and t.

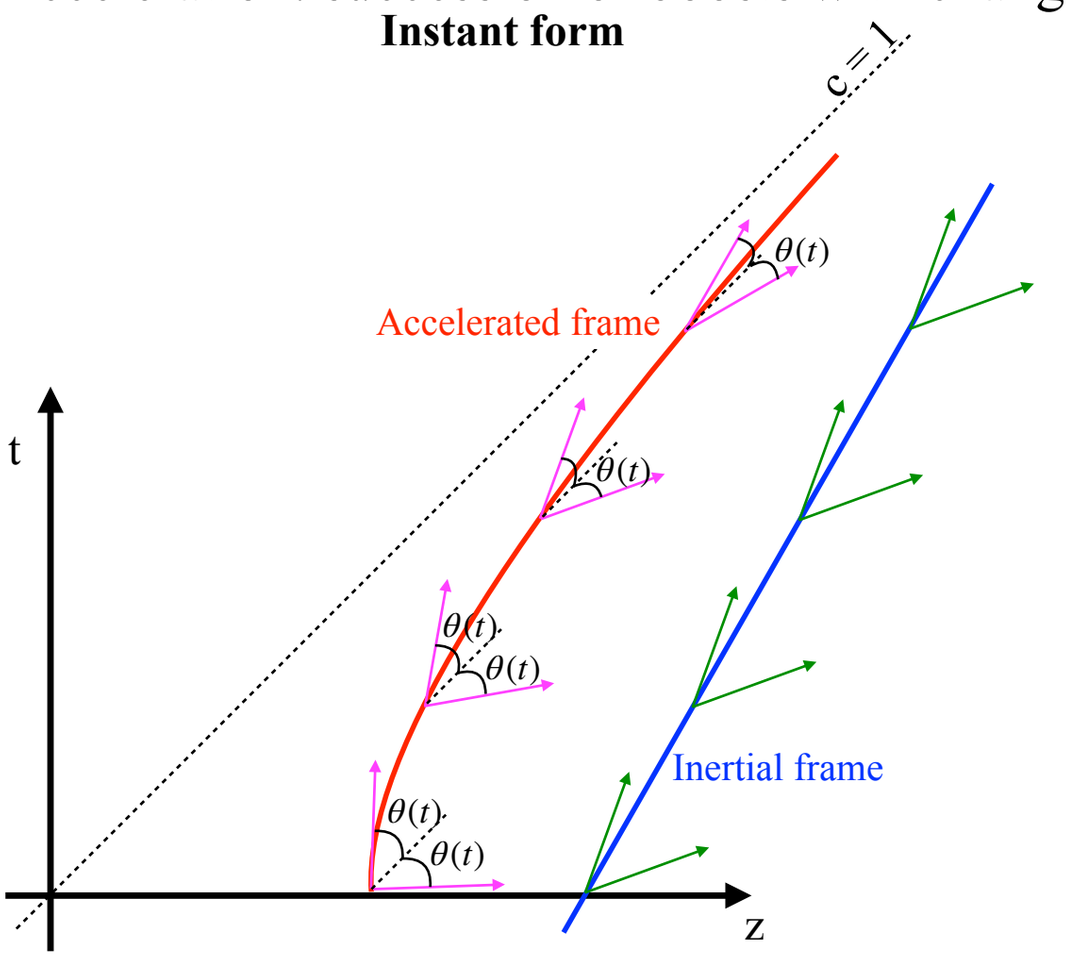
Not Lorentz invariant.

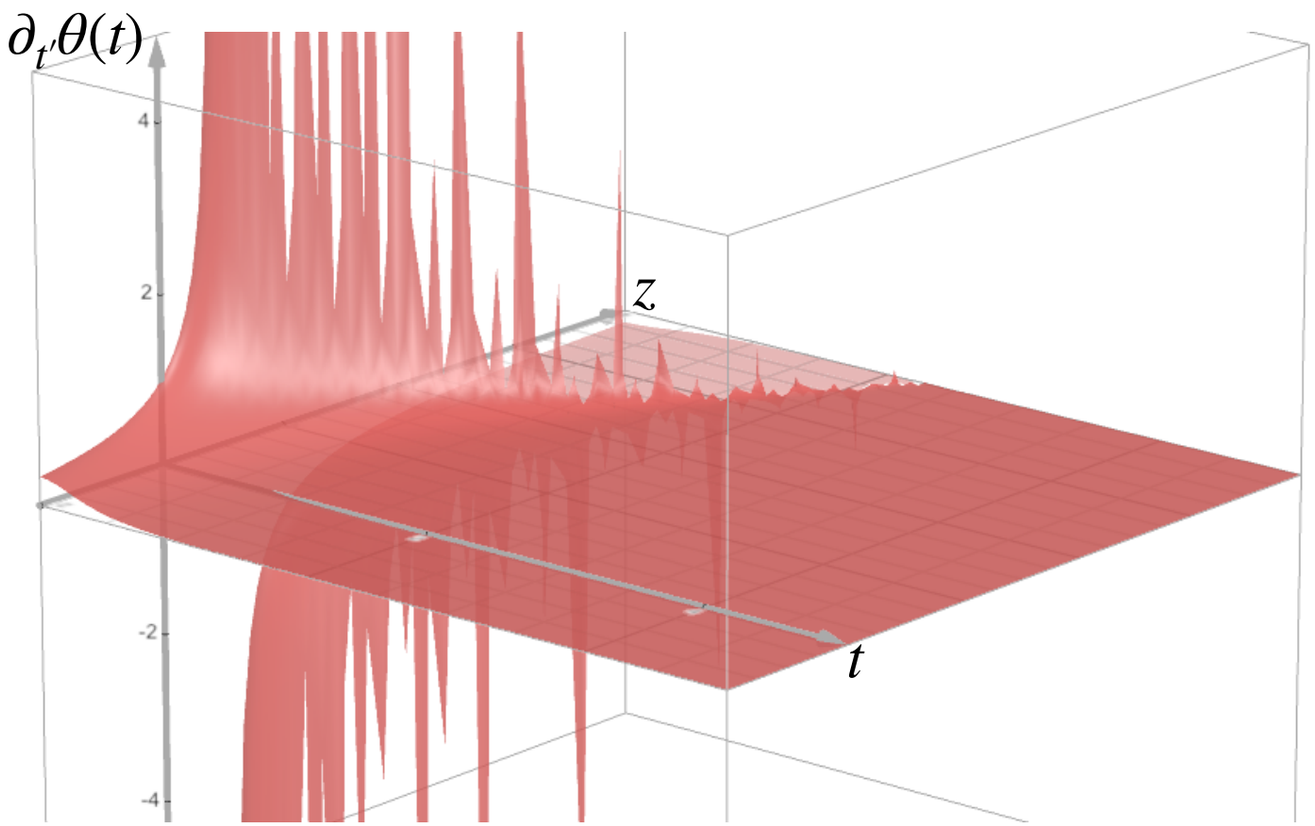
$$\frac{\partial f_p}{\partial t'} = -\,i\left[\omega' + \partial_{t'}\theta(\omega z - tp)\right] f_p \text{ , with } \partial_{t'}\theta(t) = u\,\mathrm{sech}(ut)/[1 - uz + ut\,\tanh(ut)] \text{ for IF,}$$

$$(\omega z - tp) = \omega(z \pm t) > 0$$

Accelerating frames

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





$\partial_{t'}\theta(t) > 0$ or < 0 depending on z and t.
$\Rightarrow$ inconsistent separation of + and - modes in the 2 frames $\Rightarrow$ Unruh effect

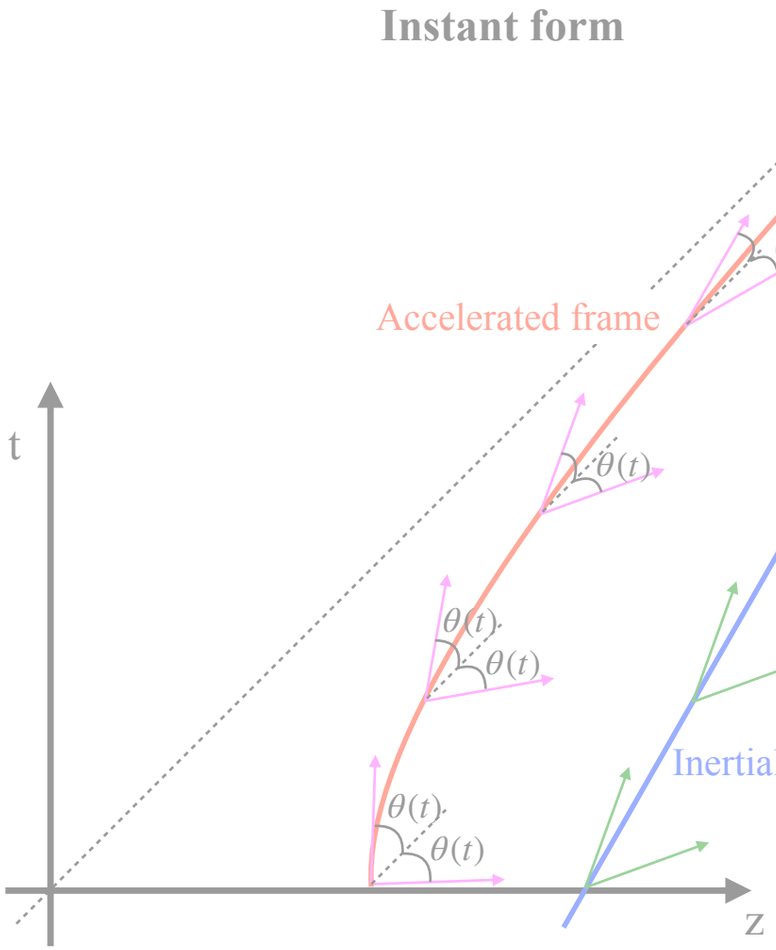
Not Lorentz invariant.

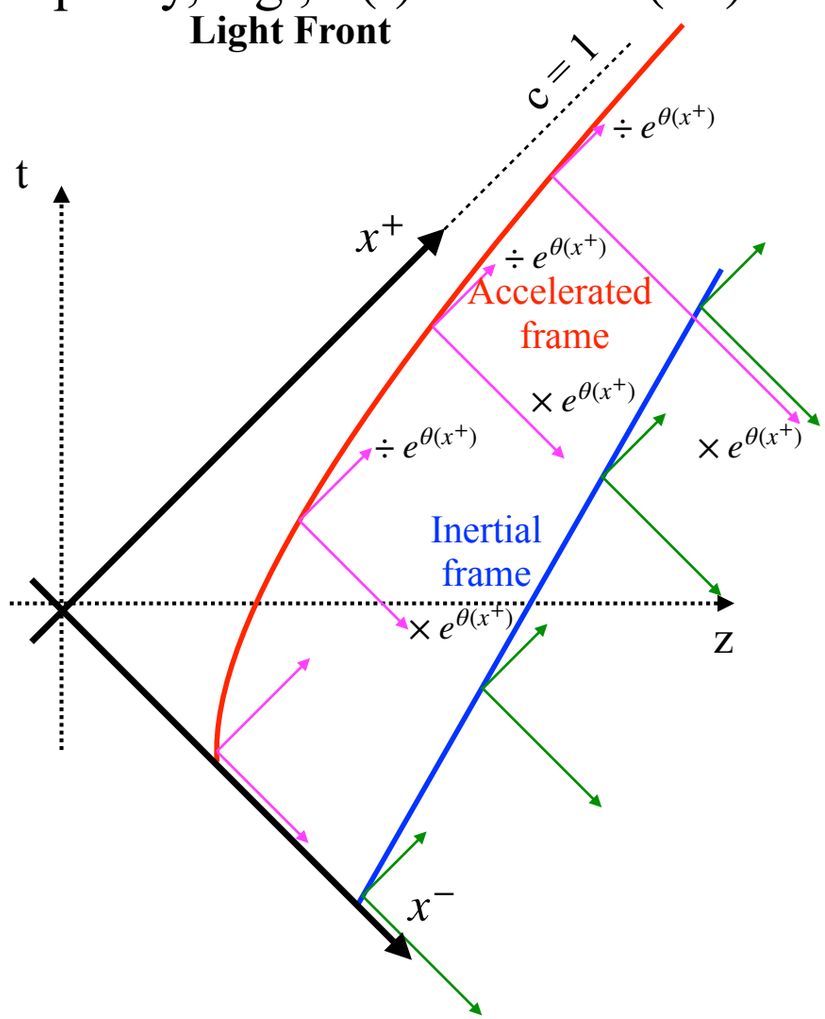
$$\frac{\partial f_p}{\partial t'} = -\,i\left[\omega' + \partial_{t'}\theta(\omega z - tp)\right] f_p \text{ , with } \partial_{t'}\theta(t) = u\,\mathrm{sech}(ut)/[1 - uz + ut\,\tanh(ut)] \text{ for IF,}$$

$(\omega z - tp) = \omega(z \pm t) > 0$

Accelerating frames

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

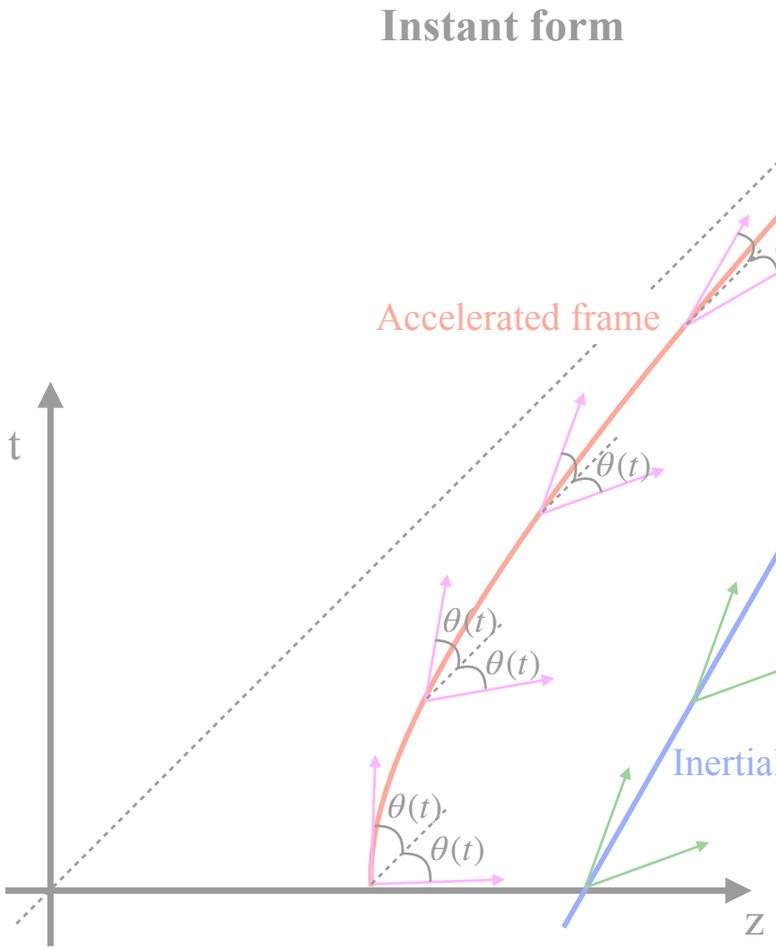


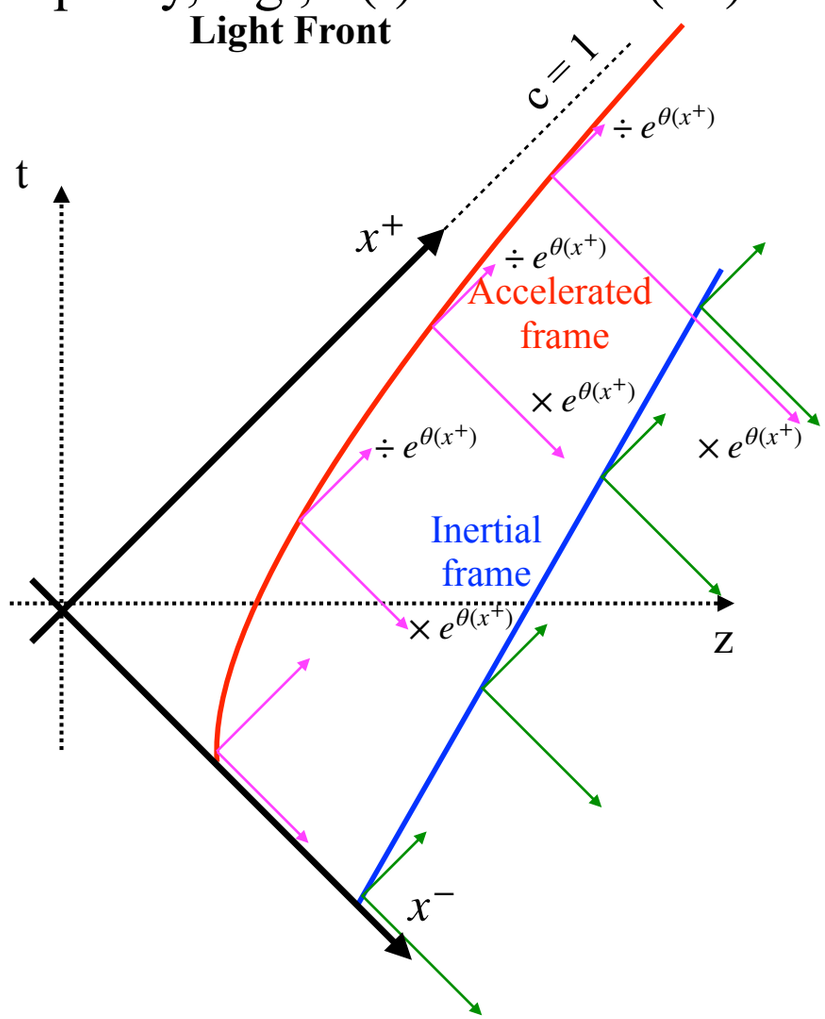


$$\frac{\partial f_p}{\partial t'} = -\,i\left[\omega' + \partial_{t'}\theta(\omega z - tp)\right] f_p \text{ , with } \partial_{t'}\theta(t) = u\,\mathrm{sech}(ut)/[1 - uz + ut\,\tanh(ut)] \text{ for IF,}$$

Accelerating frames

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





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

Not Lorentz invariant.

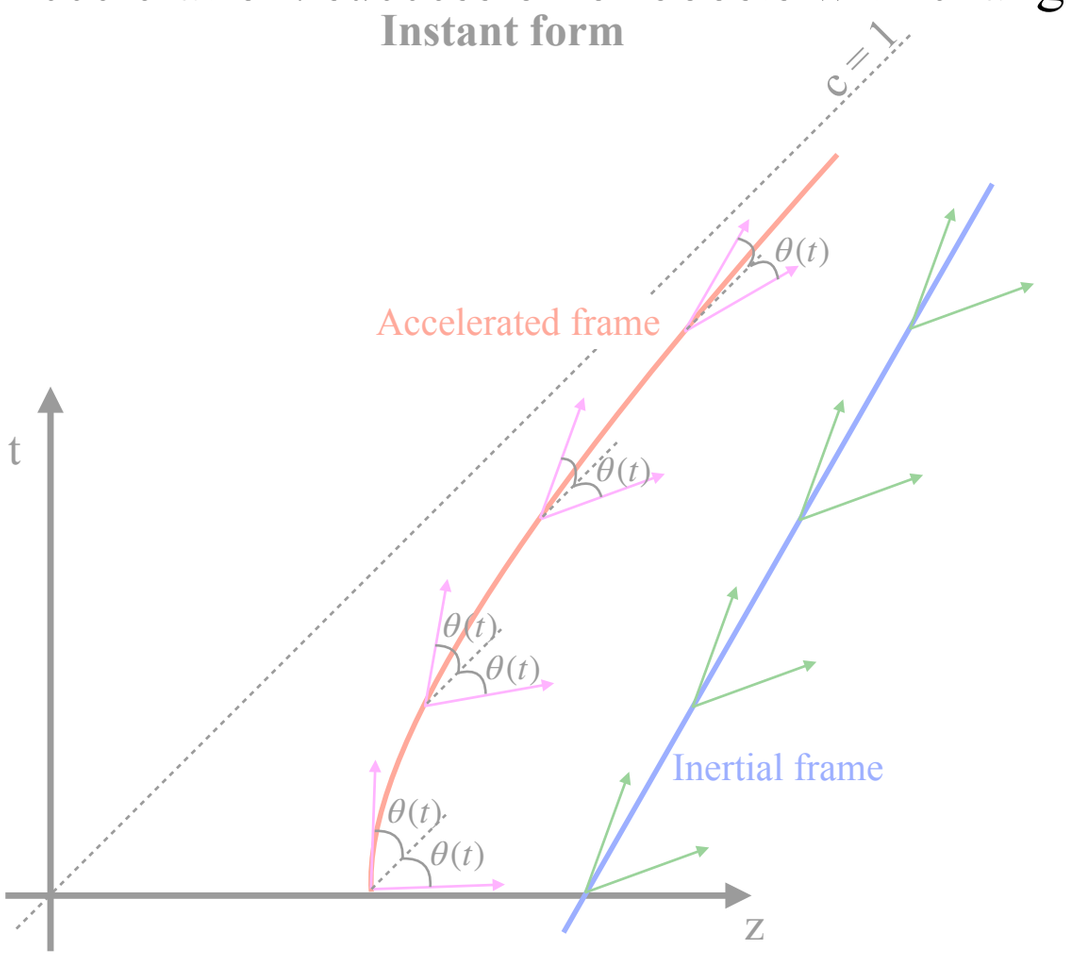
$$\frac{\partial f_{p^+}}{\partial x^{+\prime}} = -\frac{i}{2}\left[p^{-\prime} + \partial_{x^{+\prime}}\theta(x^- p^+ - x^+ p^-)\right] f_{p^+} \text{ , with } \partial_{x^{+\prime}}\theta(x^+) = u e^{-ux^+}/[1 + ux^+] \text{ for LF}$$

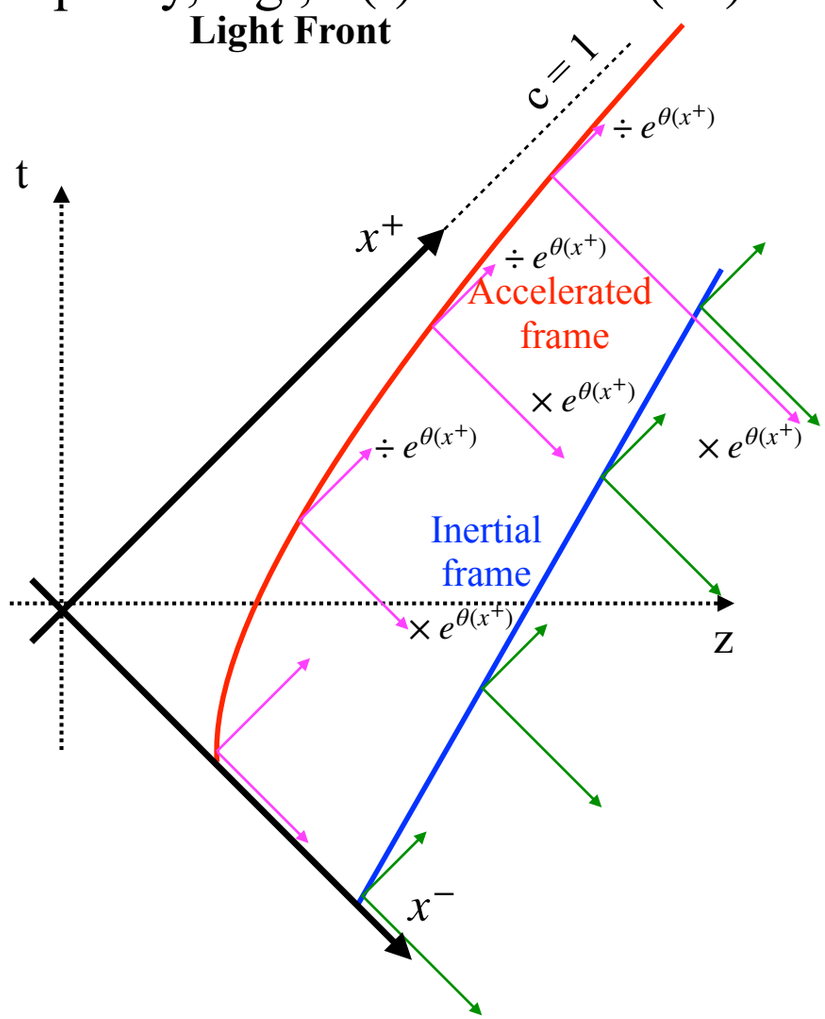
(disp. relat.: $p^- p^+ = 0$)

$(x^- p^+ - x^+ p^-) > 0$ because $p^+ > 0$ and $p^+(x^- p^+ - x^+ p^-) = x^-(p^+)^2 - x^+ p^- p^+ = x^-(p^+)^2 > 0$

Accelerating frames

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





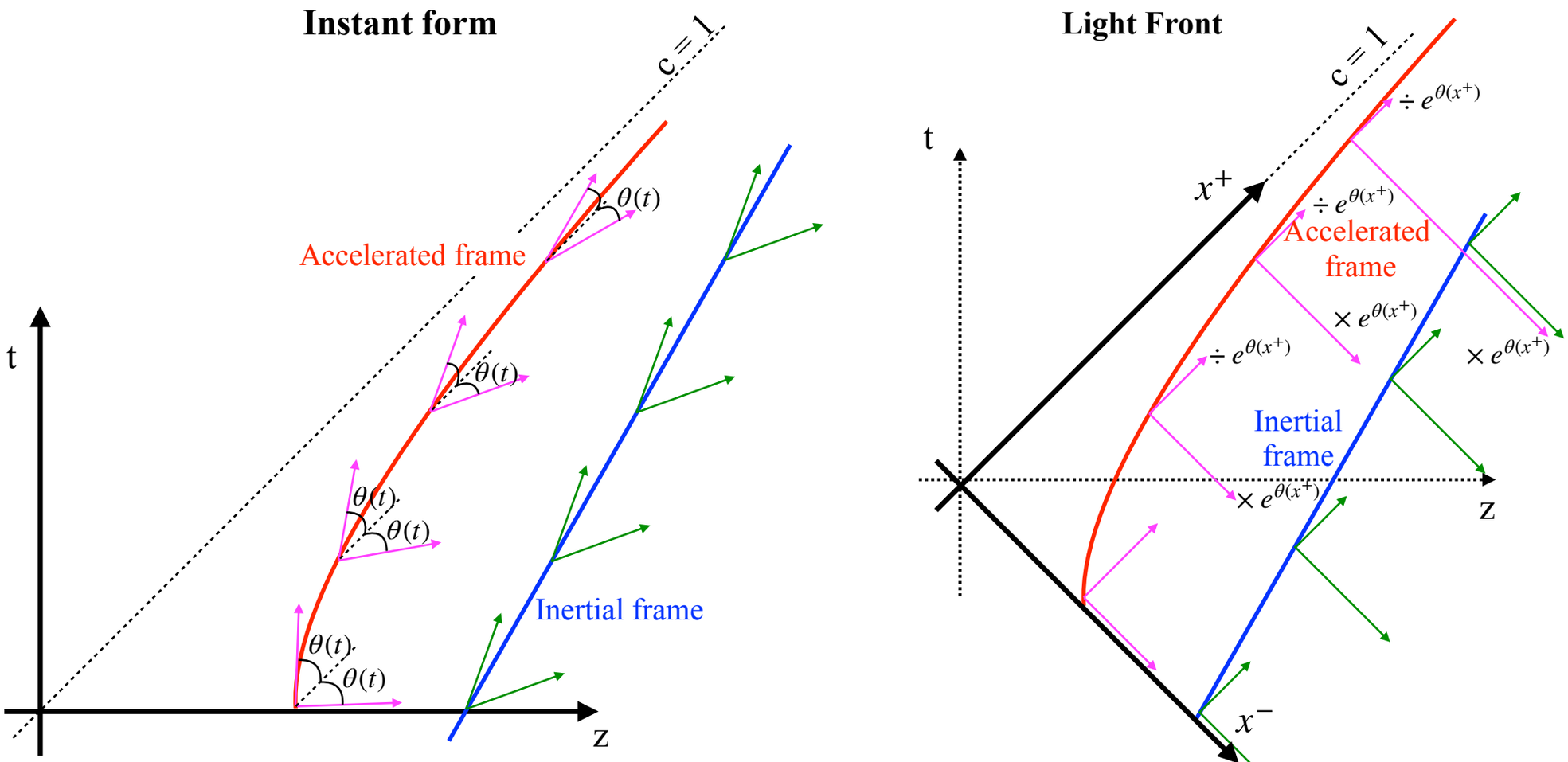
$$\frac{\partial f_p}{\partial t'} = -\,i\left[\omega' + \partial_{t'}\theta(\omega z - tp)\right] f_p \text{ , with } \partial_{t'}\theta(t) = u\,\mathrm{sech}(ut)/[1 - uz + ut\,\tanh(ut)] \text{ for IF,}$$

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

$(x^- p^+ - x^+ p^-) > 0$

$x^+ > 0 \Rightarrow \partial_{x^{+\prime}}\theta > 0 \Rightarrow$ consistent separation of + and - modes
$\Rightarrow$ No Unruh effect (as intuited because LF vacuum is trivial)

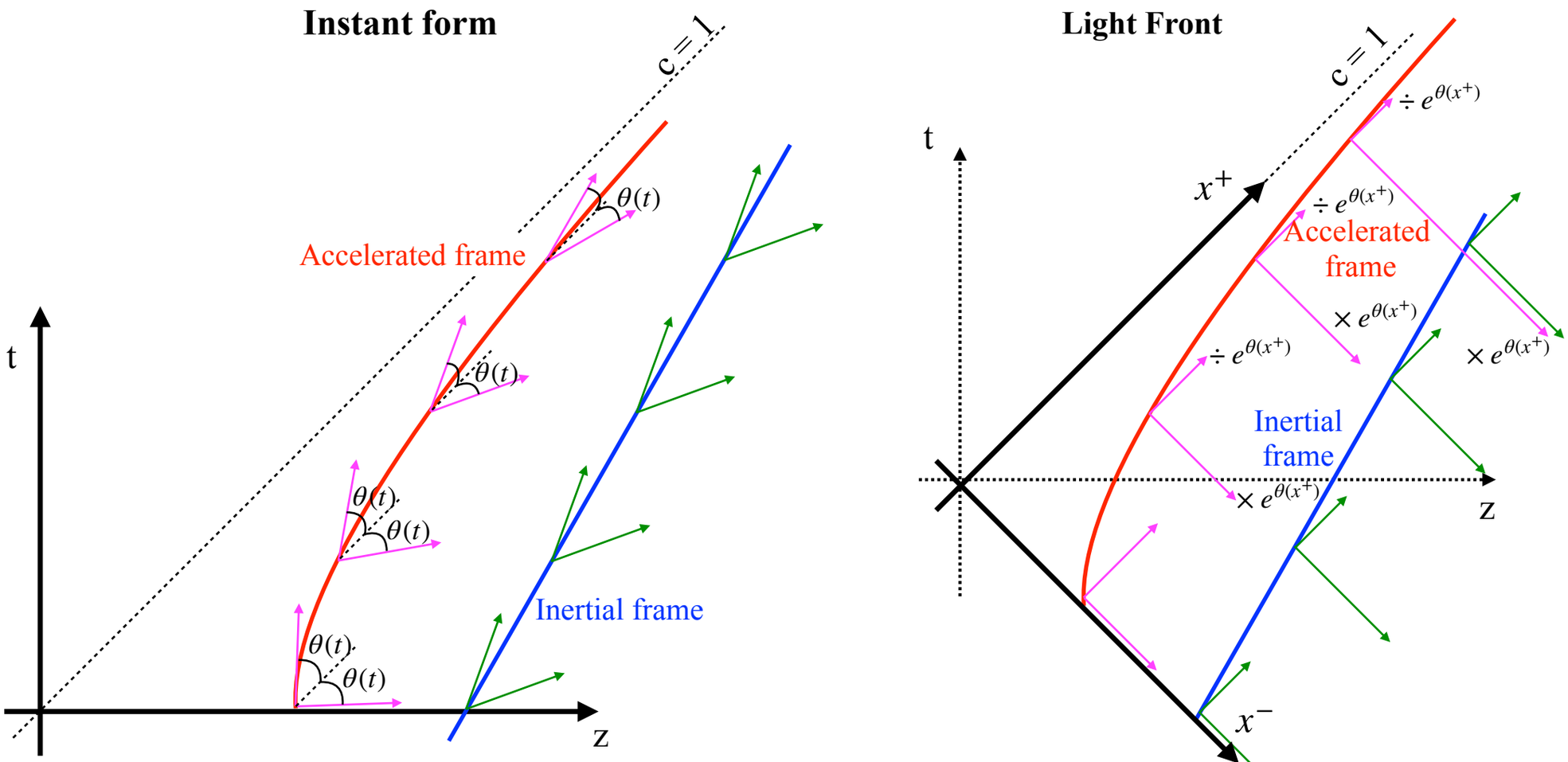
Accelerating frames



Origin of the Unruh effect:

- IF: boosts are dynamical operators. Time and space mix.

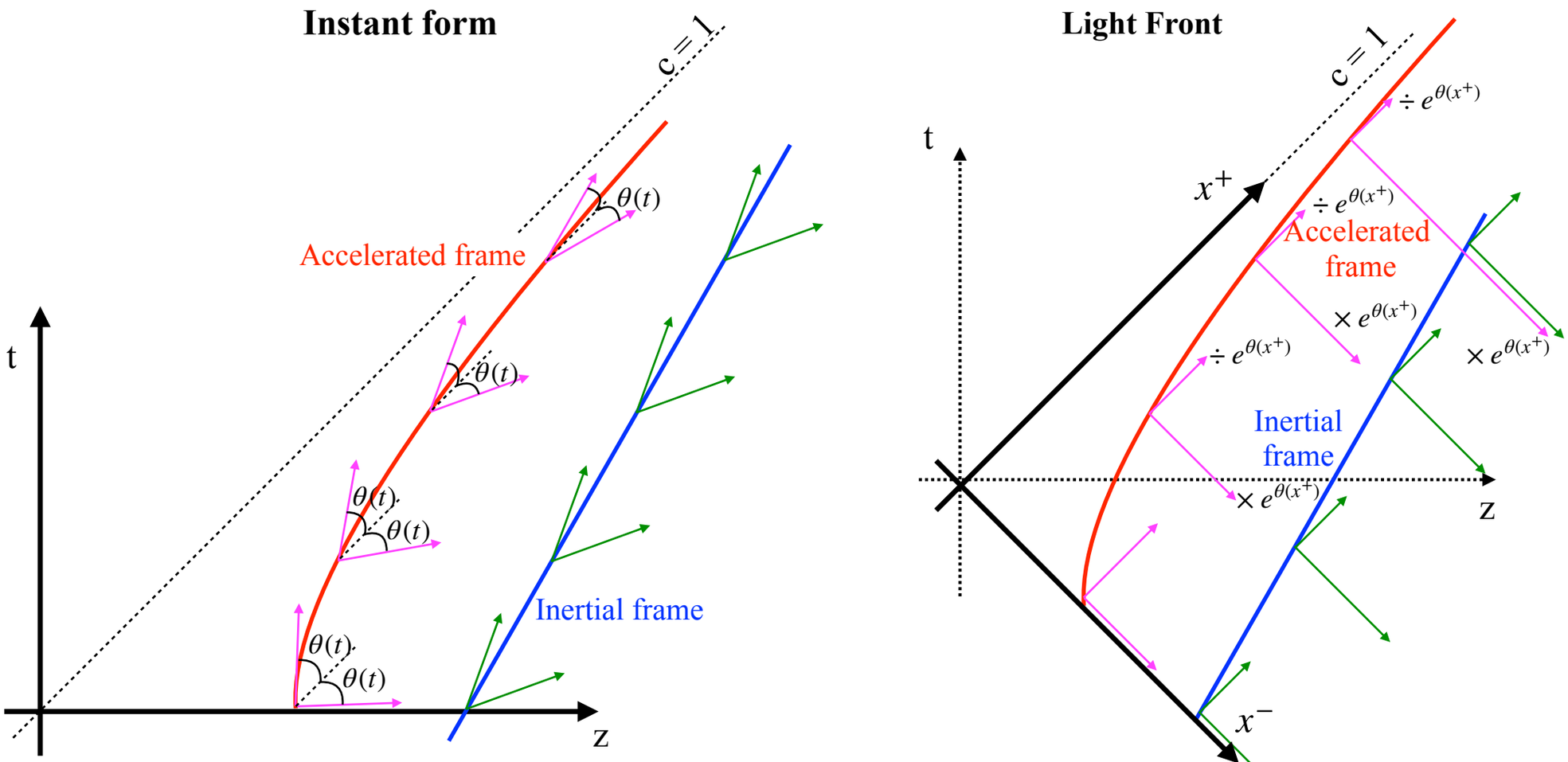
Accelerating frames



Origin of the Unruh effect:

- IF: boosts are dynamical operators. Time and space mix.
- LF: boosts are kinematical operators. Time and space never mix.

Accelerating frames



Origin of the Unruh effect:

- IF: boosts are dynamical operators. Time and space mix.
- LF: boosts are kinematical operators. Time and space never mix.

⇒Unruh effect: Inertial effect, similar to Coriolis, centrifugal or Euler pseudo-forces.

Non-relativistic system symmetry: Galilean invariance. Violation (non-galilean frames) ⇒ pseudo-forces.

Relativistic system symmetry: Poincaré invariance. Violation (dynamical operators beside Hamiltonian) ⇒ Unruh effect.

Rotational Unruh effect

How about centripetal acceleration generating a "Rotational Unruh effect"?
Important question because large centripetal accelerations can be achieved in collider rings.

- Linear Unruh effect: boost operator, dynamical in IF.
- Rotational Unruh effect: rotation operator, kinematical in IF.
  ⇒ From previous slide, no rotational Unruh effect is expected, even in IF.

Indeed, direct IF studies (Denardo & Percacci, N. Cim. B **48** 81 (1978); Letaw & Pfautsch, PRD **22**, 1345 (1980)) yielded no rotational Unruh effect.

This has been puzzling for the Unruh effect community, but it is easily understood using Dirac forms of relativistic dynamics.

A "rotational" Unruh effect can still be summoned by
- adding boosts in the derivation (Bell & Leinaas: Nucl. Phys. B **284**, 488 (1987)), or
- redefining IF time so that it mixes with space, (De Lorenci, De Paola & Svaiter, CQG **17** 4241 (2000))

but it really amounts to a linear Unruh effect.

What gives ?

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

What gives ?

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

IF boost is dynamical + rapidity is time-dependent for accelerations. ⇒ Pseudo-dynamical evolution.
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 ⇒ IF and LF analyses must eventually agree.

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

An objective analysis must account for all pseudo-effects. Others exist: composite system (as a Unruh detector must be) will experience e.g. a spin-orbit pseudoforce since dynamical boost induces spin-orbit force in composite systems.

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

What gives ?

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

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

An objective analysis must account for all pseudo-effects. Others exist: composite system (as a Unruh detector must be) will experience e.g. a spin-orbit pseudoforce since dynamical boost induces spin-orbit force in composite systems.

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

LF: boosts are kinematical (no spin-orbit pseudoforce) & vacuum is trivial (no Unruh effect)
⇒ Suggests that in IF, Unruh + spin-orbit force (?+ …?) = 0.

What gives ?

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

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

An objective analysis must account for all pseudo-effects. Others exist: composite system (as a Unruh detector must be) will experience e.g. a spin-orbit pseudoforce since dynamical boost induces spin-orbit force in composite systems.

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

LF: boosts are kinematical (no spin-orbit pseudoforce) & vacuum is trivial (no Unruh effect)
⇒ Suggests that in IF, Unruh + spin-orbit force (?+ …?) = 0.

Such other IF pseudoeffects affecting composite systems have been overlooked ⇒ No compensation mechanism for the Unruh effect, which then seems objectively observable.

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 a pseudoeffect cancelled in IF dynamics by other artificial effects, e.g., spin-orbit pseudoforce in an Unruh detector 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 a pseudoeffect cancelled in IF dynamics by other artificial effects, e.g., spin-orbit pseudoforce in an Unruh detector 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 a pseudoeffect cancelled in IF dynamics by other artificial effects, e.g., spin-orbit pseudoforce in an Unruh detector 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.

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

Supplementary slides

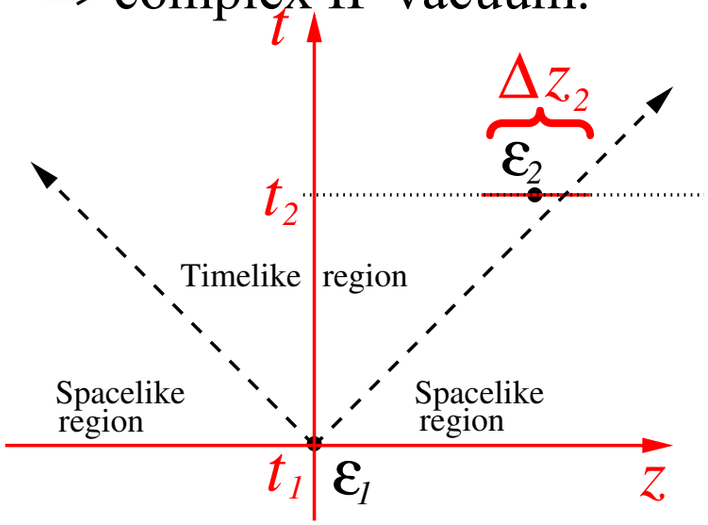
Connection to commutation relations & vacuum structure

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

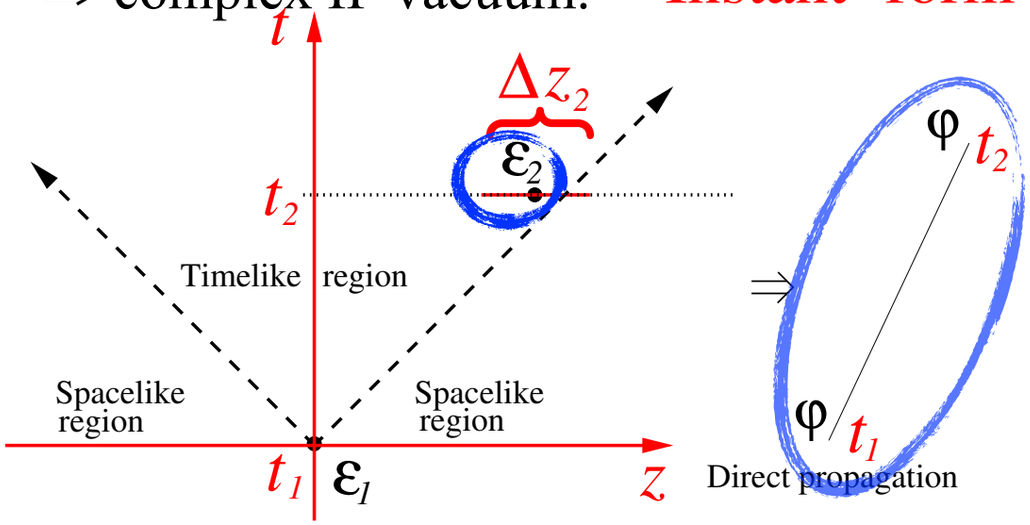
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form



Connection to commutation relations & vacuum structure

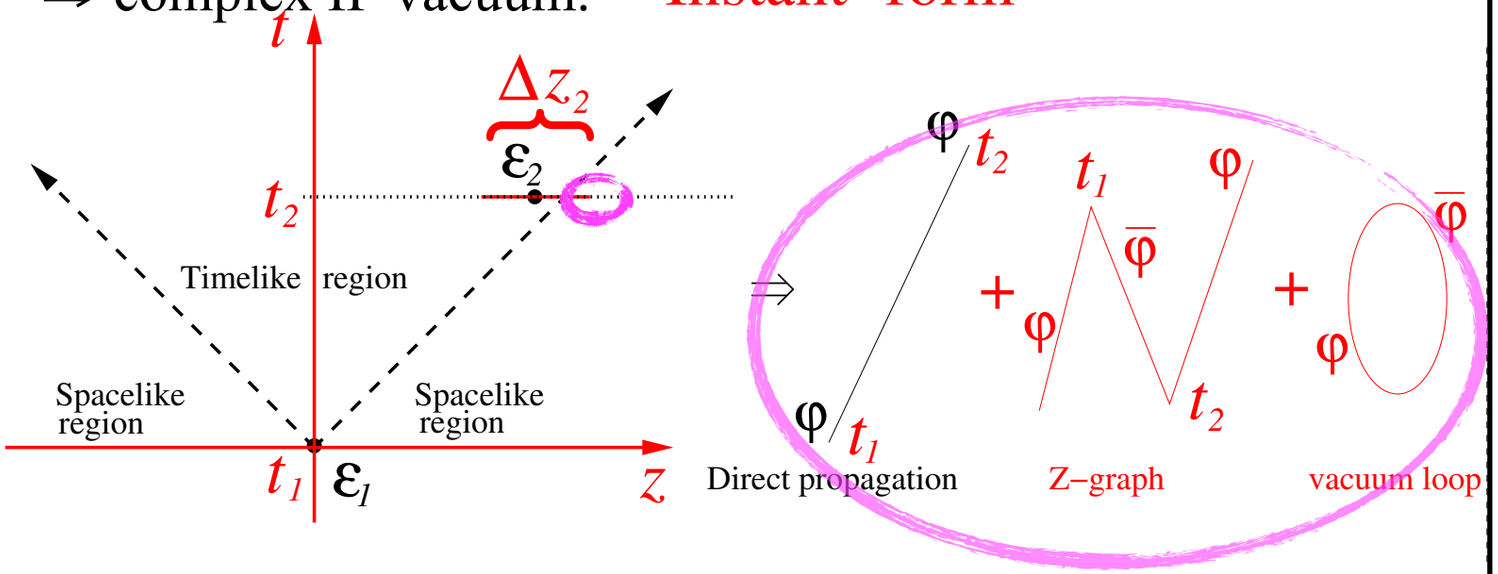
Canonical quantization done at constant proper time.

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

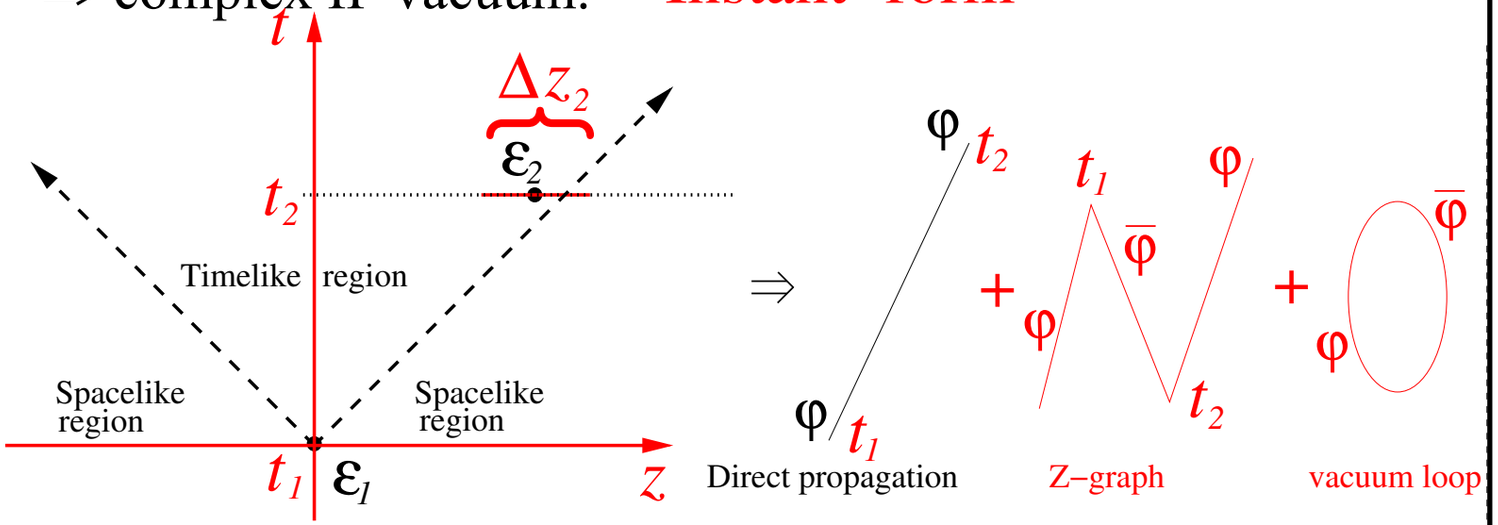
Canonical quantization done at constant proper time.

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

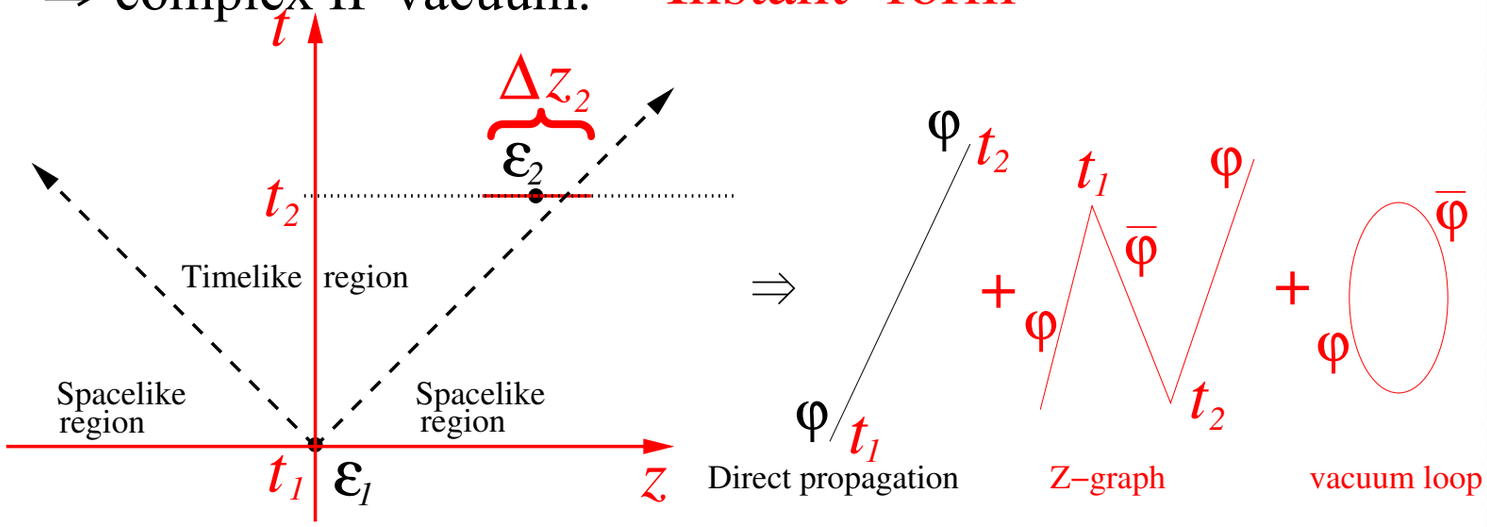
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form

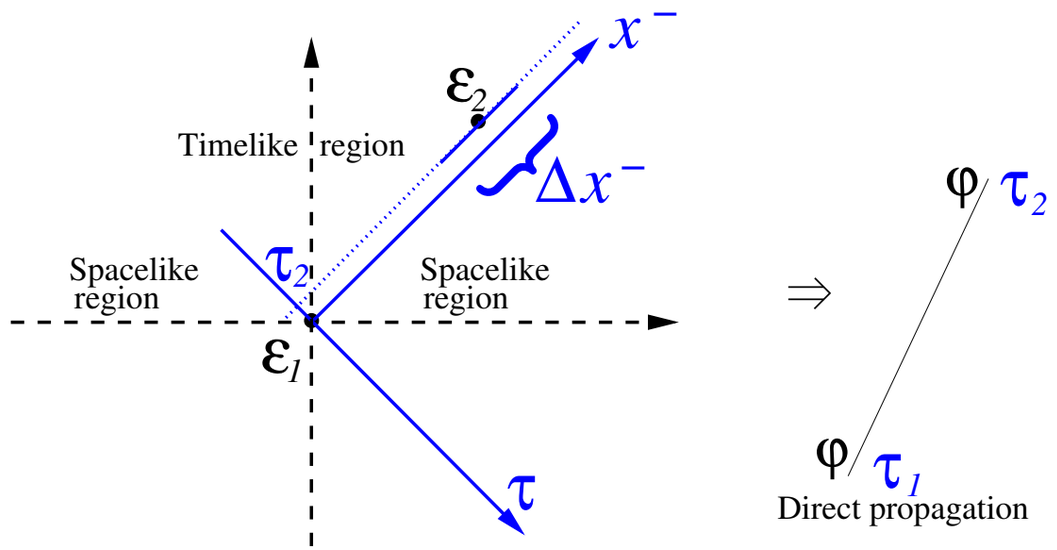


If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.
In some frames, $t_1 > t_2$ and Z-graphs appear. They contribute negative probabilities.
⇒ Need disconnected vacuum loops to balance the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

Connection to commutation relations & vacuum structure

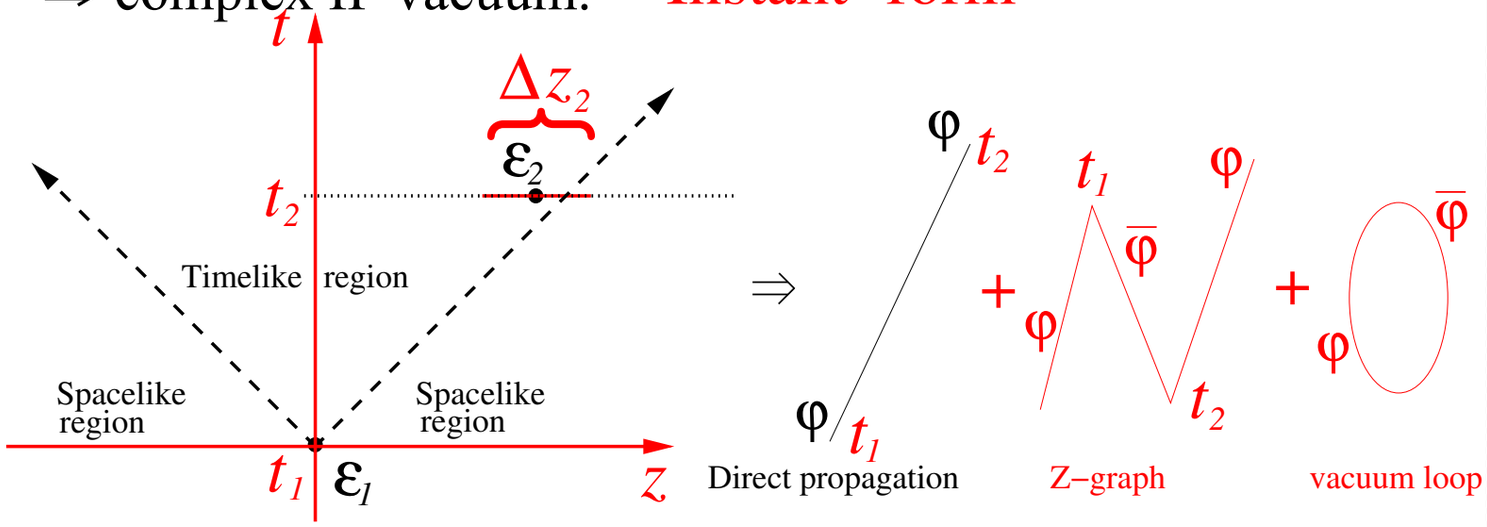
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form

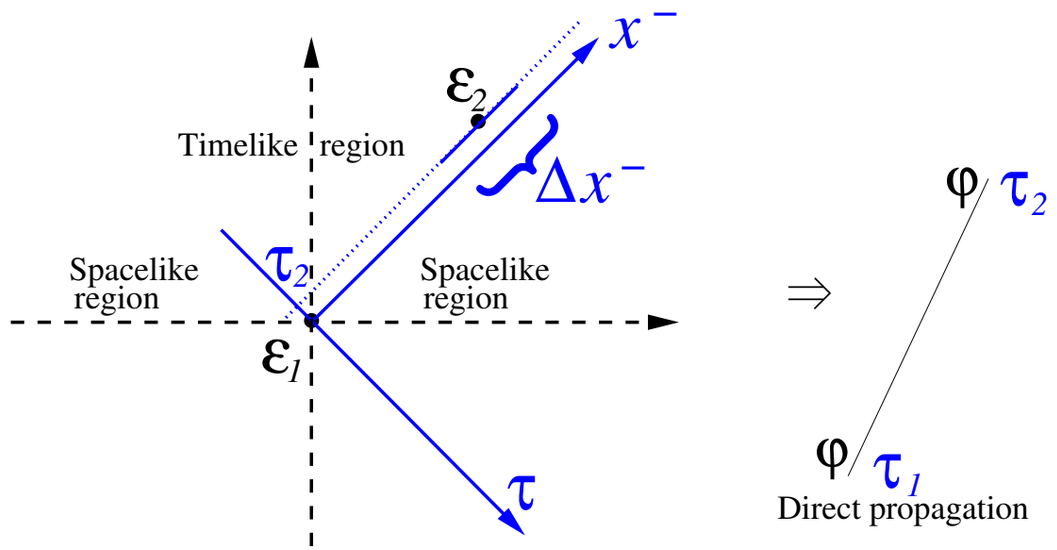


If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.
In some frames, $t_1 > t_2$ and Z-graphs appear. They contribute negative probabilities.
⇒ Need disconnected vacuum loops to balance the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

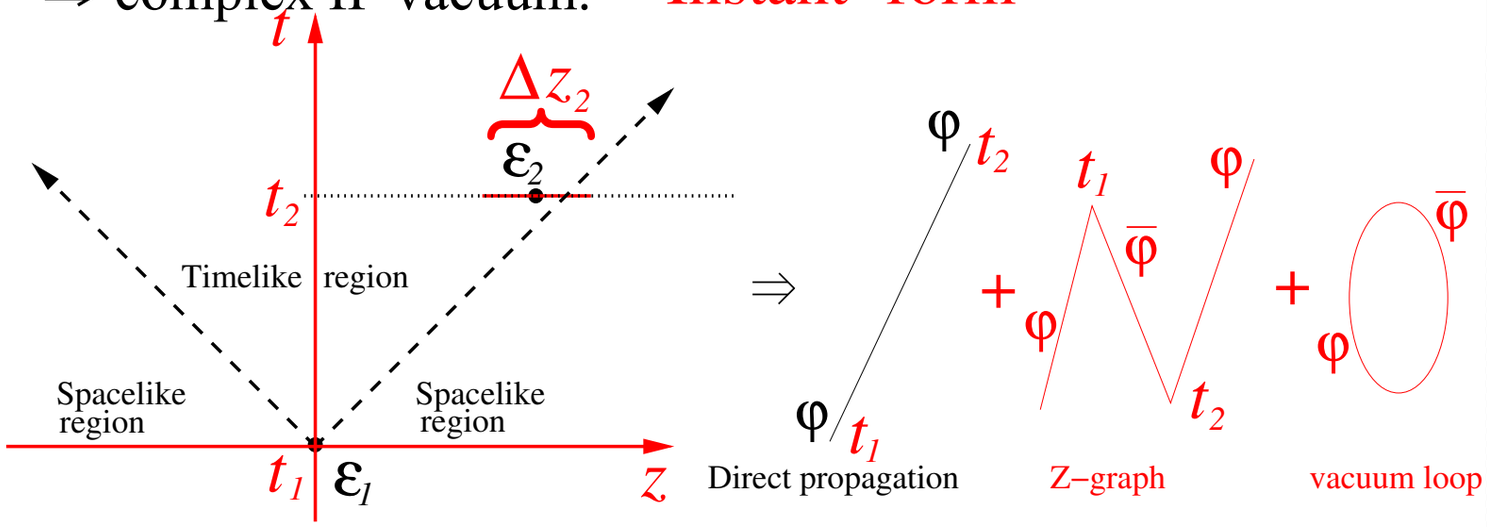
Canonical quantization done at constant proper time.

Heisenberg uncertainty principle originates from commutation relations

⇒ Uncertainty principle operates at equal time.

⇒ complex IF vacuum.

Instant–form

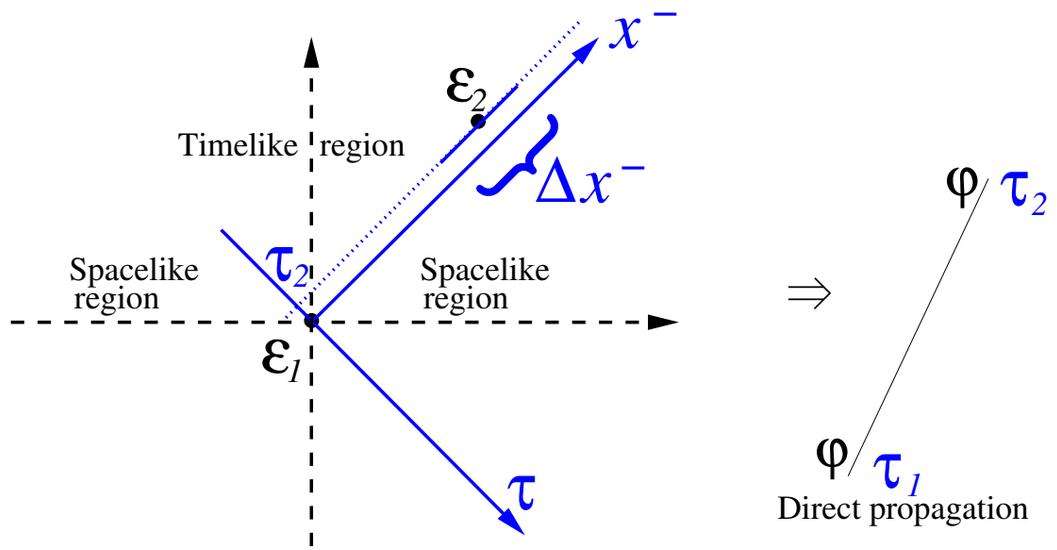


If events $\mathscr{E}_1$ and $\mathscr{E}_2$ at times t_1 and t_2 are spacelike-separated, time-ordering of $\mathscr{E}_1$ and $\mathscr{E}_2$ is frame-dependent.
In some frames, $t_1 > t_2$ and Z-graphs appear. They contribute negative probabilities.
⇒ Need disconnected vacuum loops to balance the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

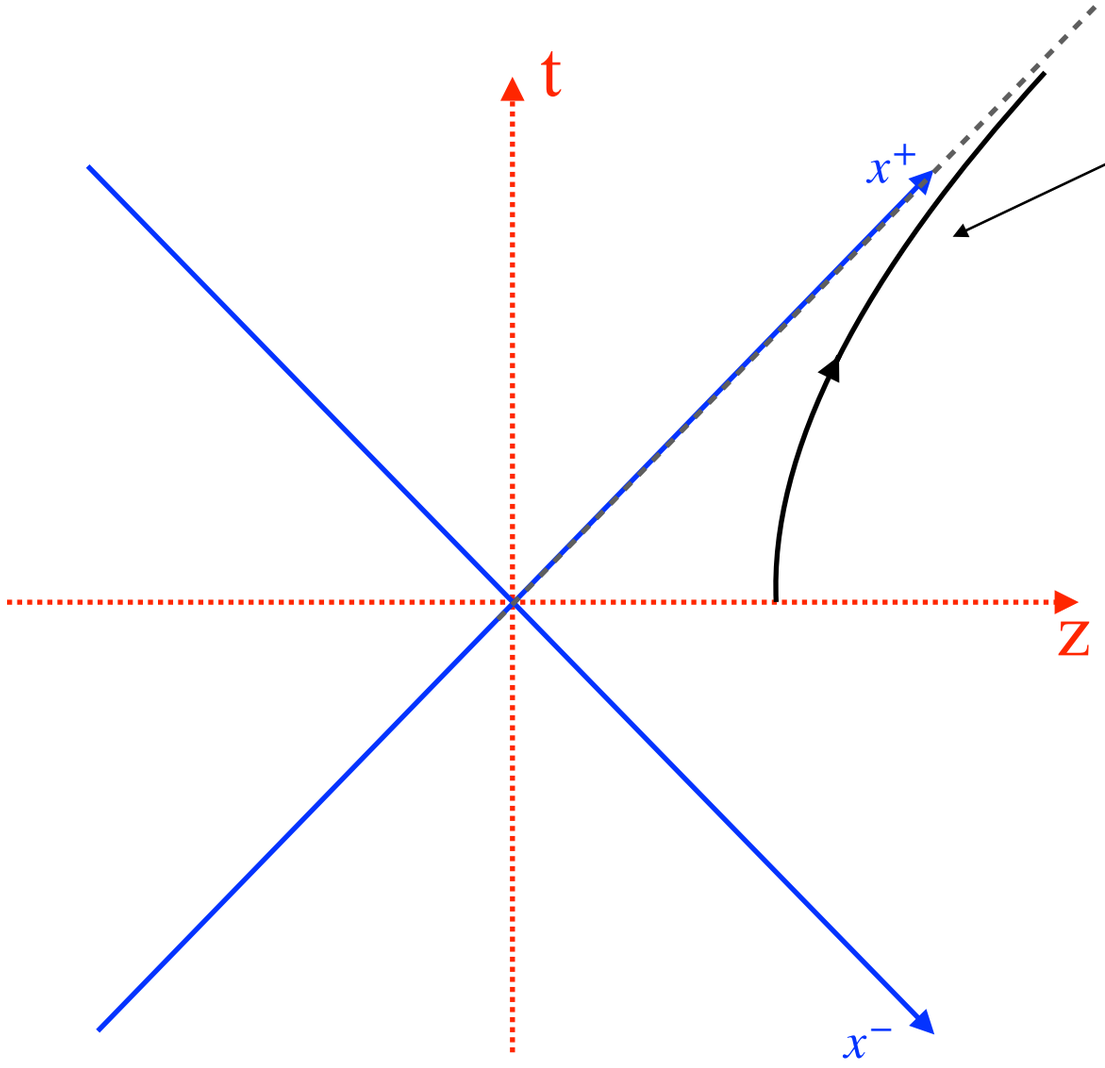


Boost or acceleration: rescales axes without reorienting them ⇒ uncertainty principle always operates along x^-.
$\mathscr{E}_1$ and $\mathscr{E}_2$ are always timelike-separated: No vacuum loops.
This persists in an accelerated LF frame: no Unruh effect.

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



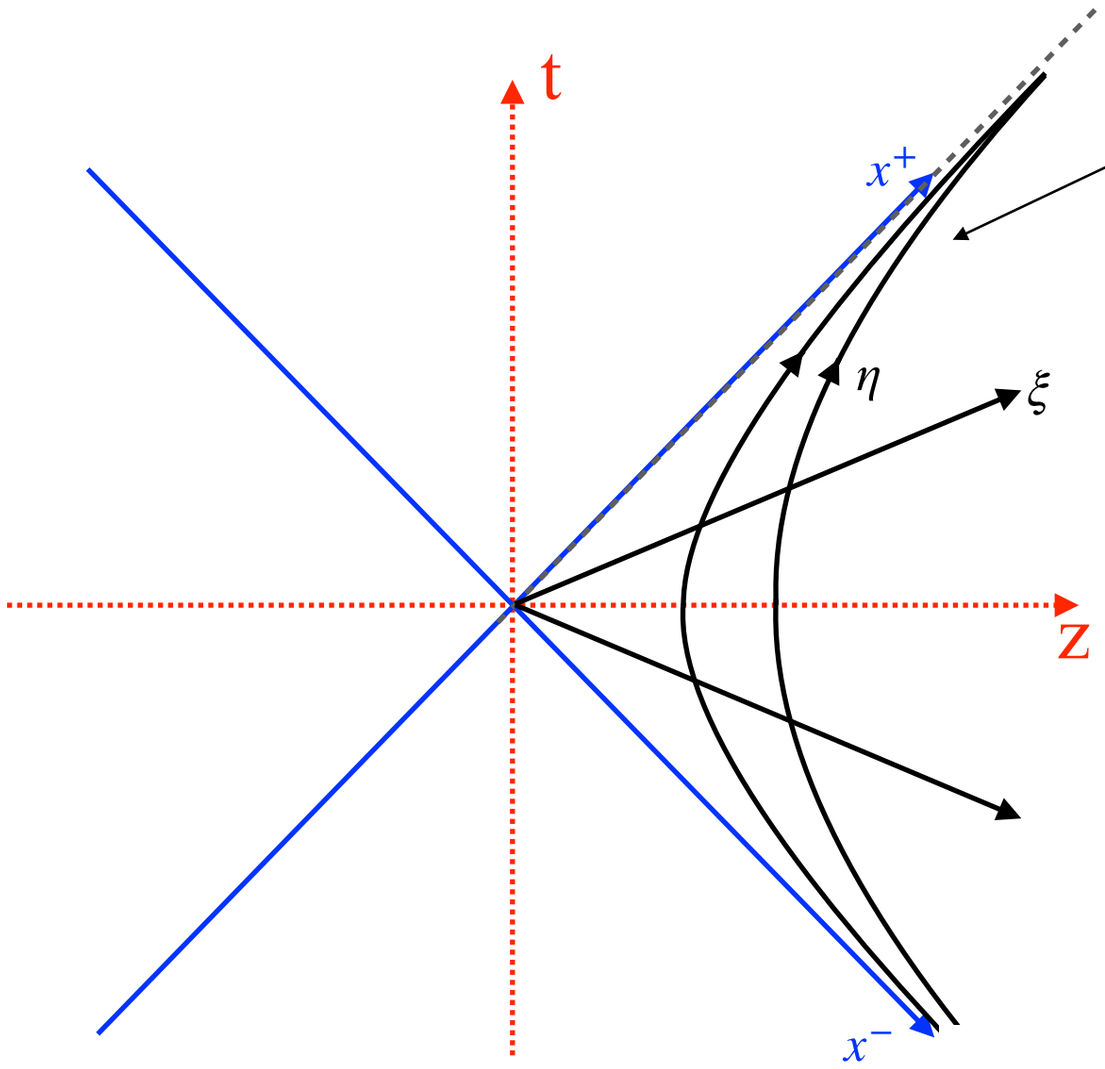
Acceleration:

- 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):

$$\left.\begin{aligned} z &= \frac{1}{a} e^{a\xi} \cosh(a\eta) \\ t &= \frac{1}{a} e^{a\xi} \sinh(a\eta) \end{aligned}\right\} \text{IF}$$

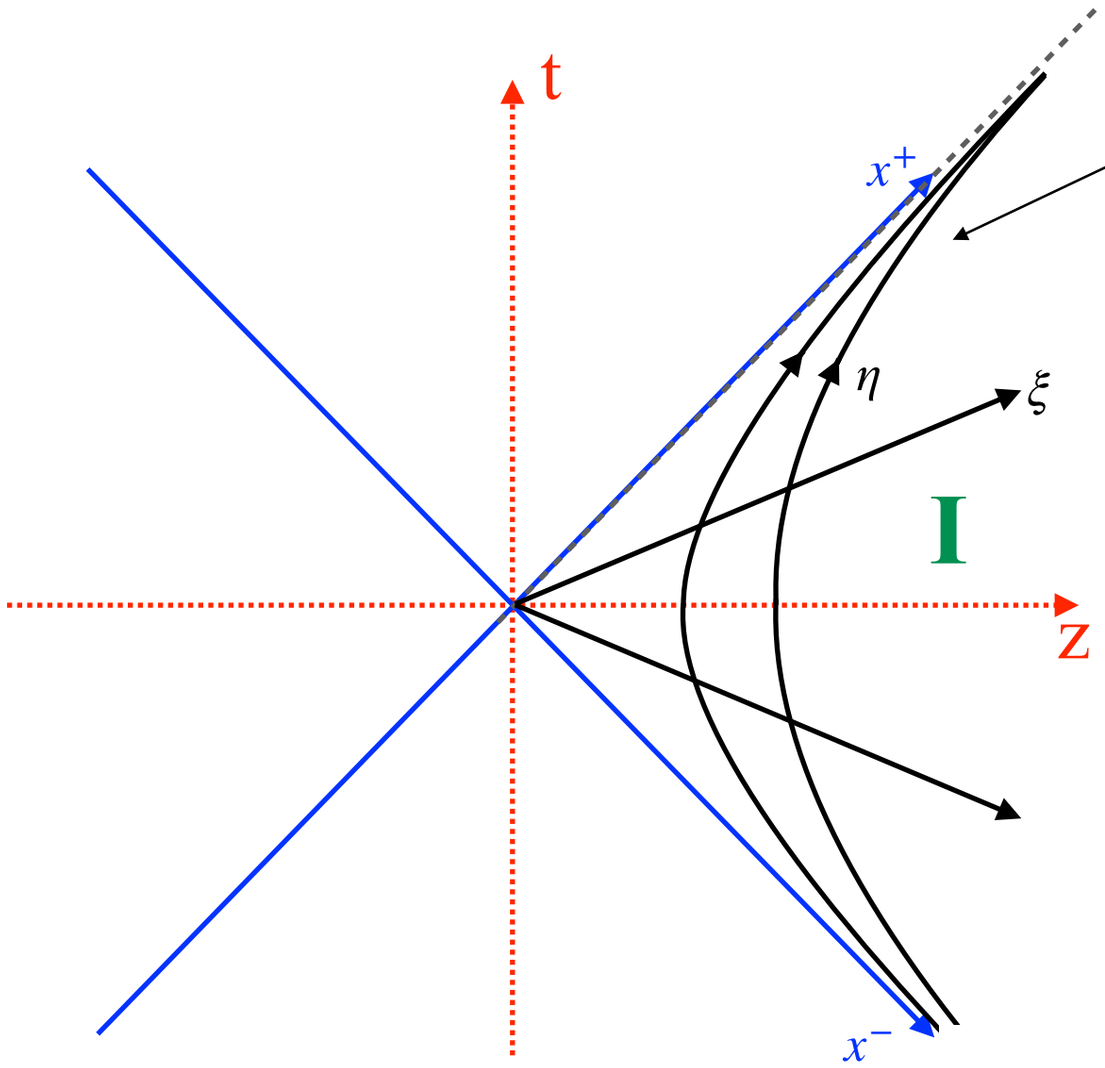
$$\left.\begin{aligned} x^- &= \frac{1}{a} e^{a(-\eta+\xi)} \\ x^+ &= \frac{1}{a} e^{a(\eta+\xi)} \end{aligned}\right\} \text{LF}$$

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):

$$\left.\begin{aligned} z &= \frac{1}{a} e^{a\xi} \cosh(a\eta) \\ t &= \frac{1}{a} e^{a\xi} \sinh(a\eta) \end{aligned}\right\} \text{IF}$$

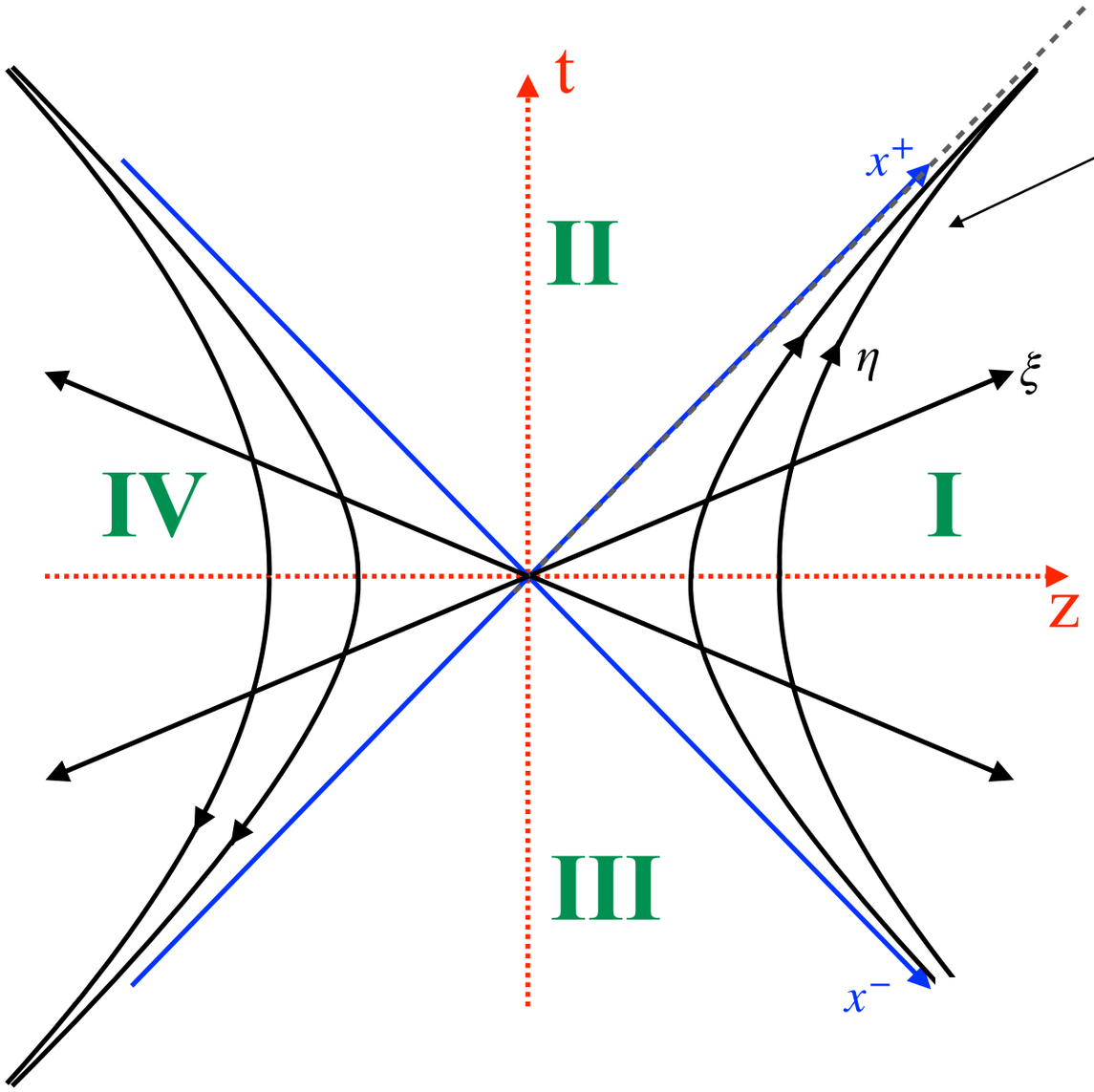
$$\left.\begin{aligned} x^- &= \frac{1}{a} e^{a(-\eta+\xi)} \\ x^+ &= \frac{1}{a} e^{a(\eta+\xi)} \end{aligned}\right\} \text{LF}$$

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):

$$\left.\begin{aligned} z &= \frac{1}{a} e^{a\xi} \cosh(a\eta) \\ t &= \frac{1}{a} e^{a\xi} \sinh(a\eta) \end{aligned}\right\} \text{IF}$$

$$\left.\begin{aligned} x^- &= \frac{1}{a} e^{a(-\eta+\xi)} \\ x^+ &= \frac{1}{a} e^{a(\eta+\xi)} \end{aligned}\right\} \text{LF}$$

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

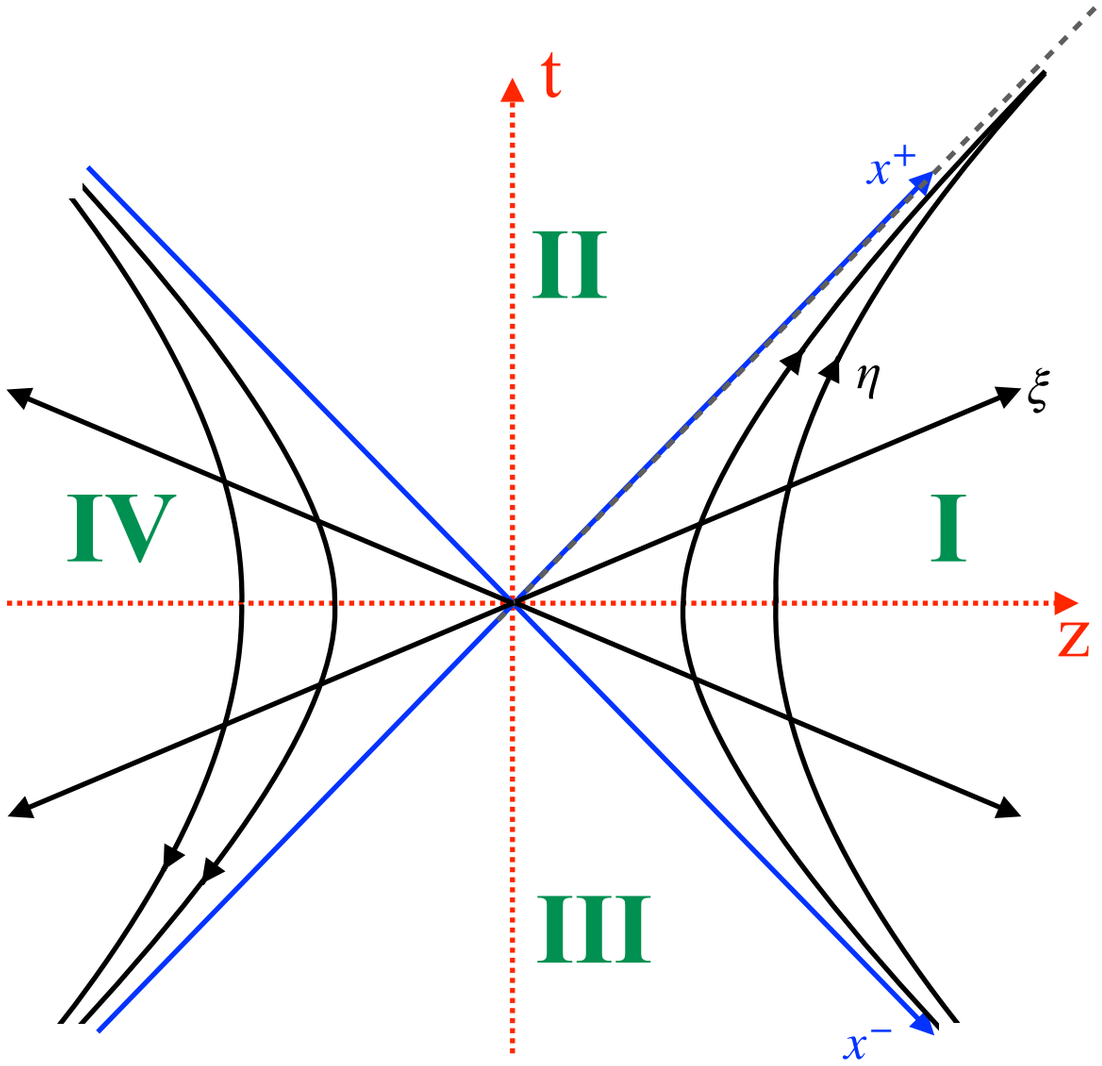
The coordinates above cover only Region I.
Other coordinates needed for region IV:

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

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

Standard derivation (Unruh 1976)

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

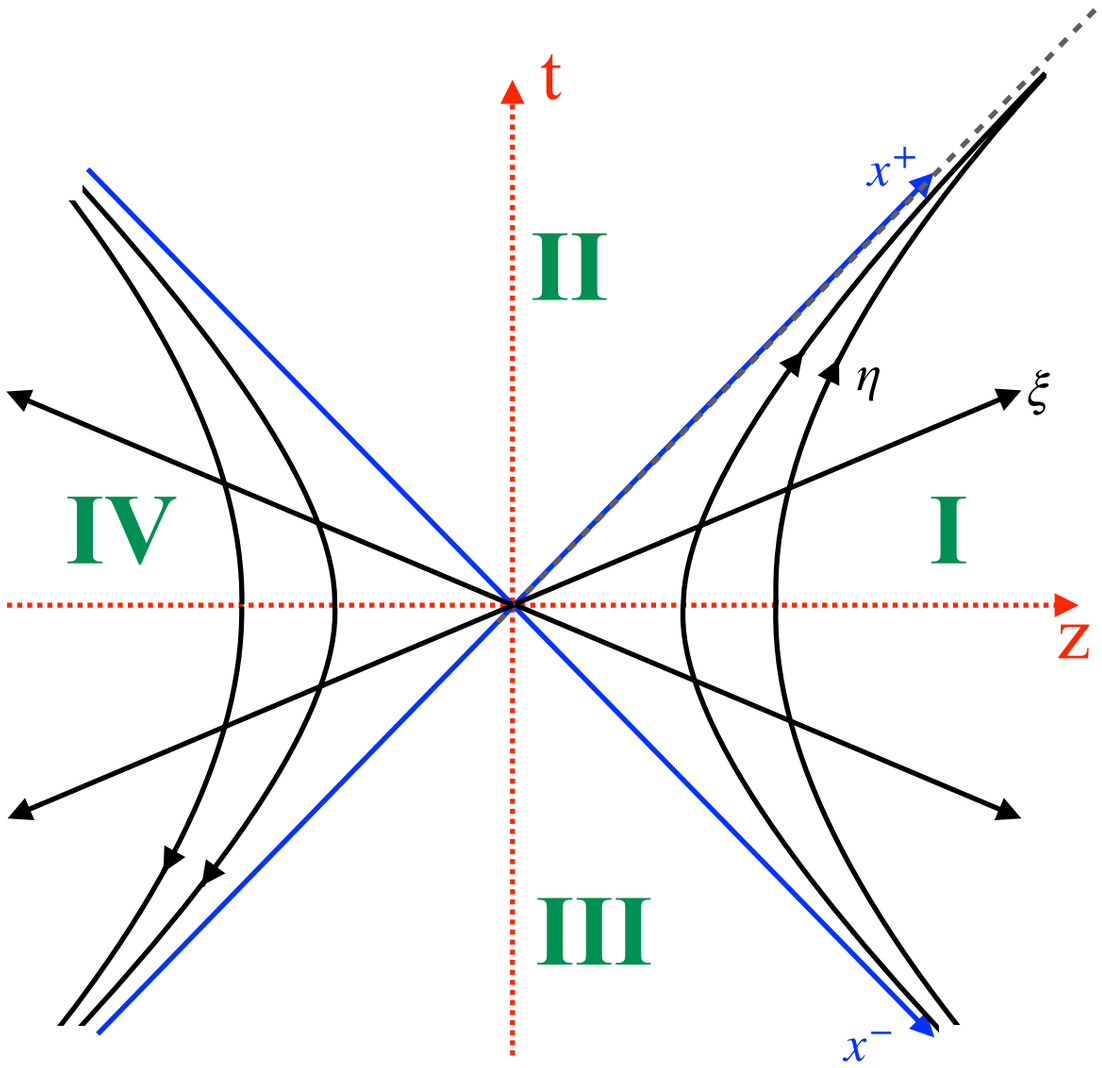


In Rindler spacetime, the field is decomposed using regions I and IV Rindler modes:

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

Standard derivation (Unruh 1976)

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



In Rindler spacetime, the field is decomposed using regions I and IV Rindler modes:

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

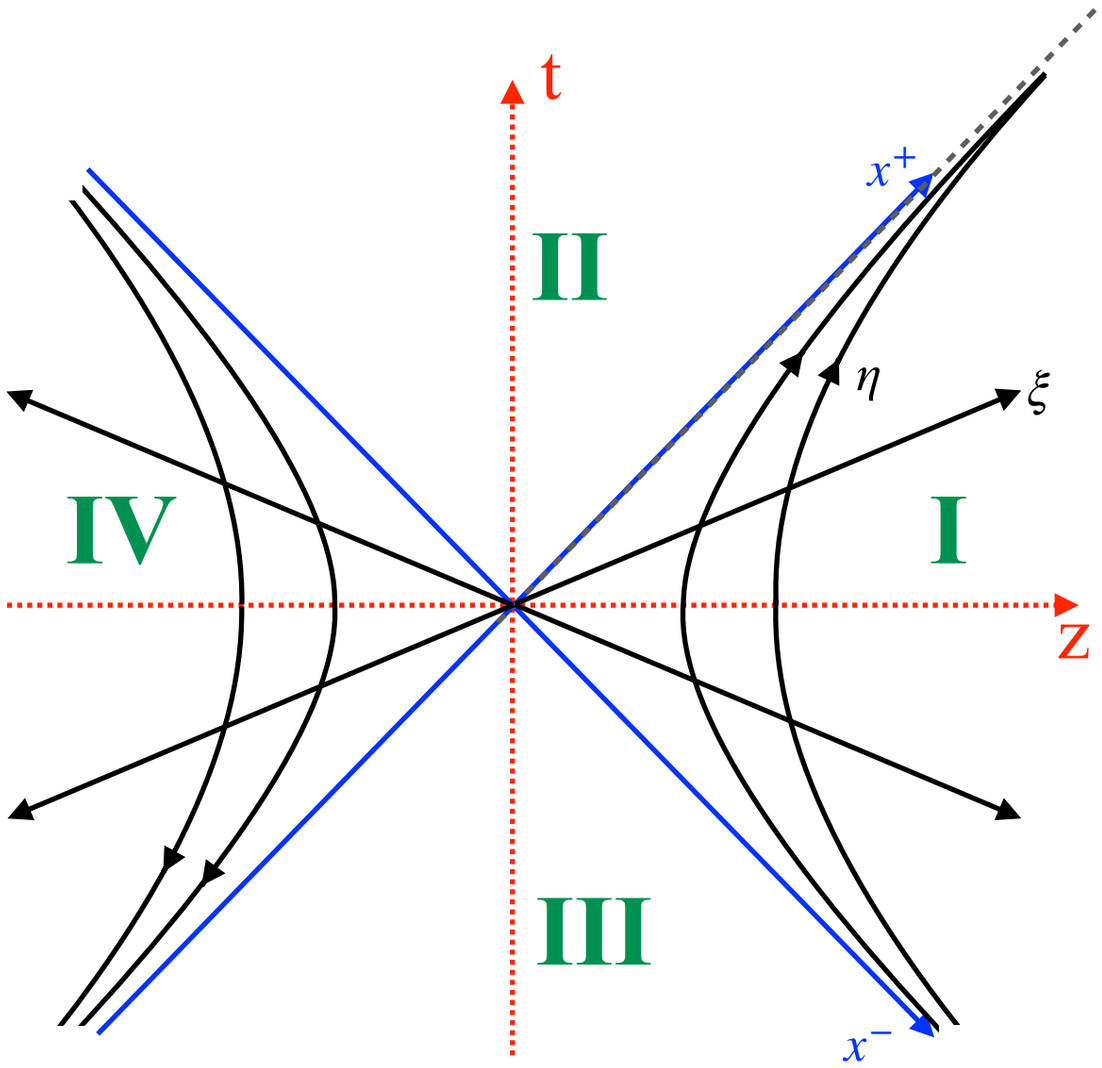
In Minkowski (=inertial) frame (t, z) (IF) or (x^+, x^-) (LF), no spacetime partition ⇒ the field is decomposed as usual:

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

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

Standard derivation (Unruh 1976)

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



In Rindler spacetime, 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:

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

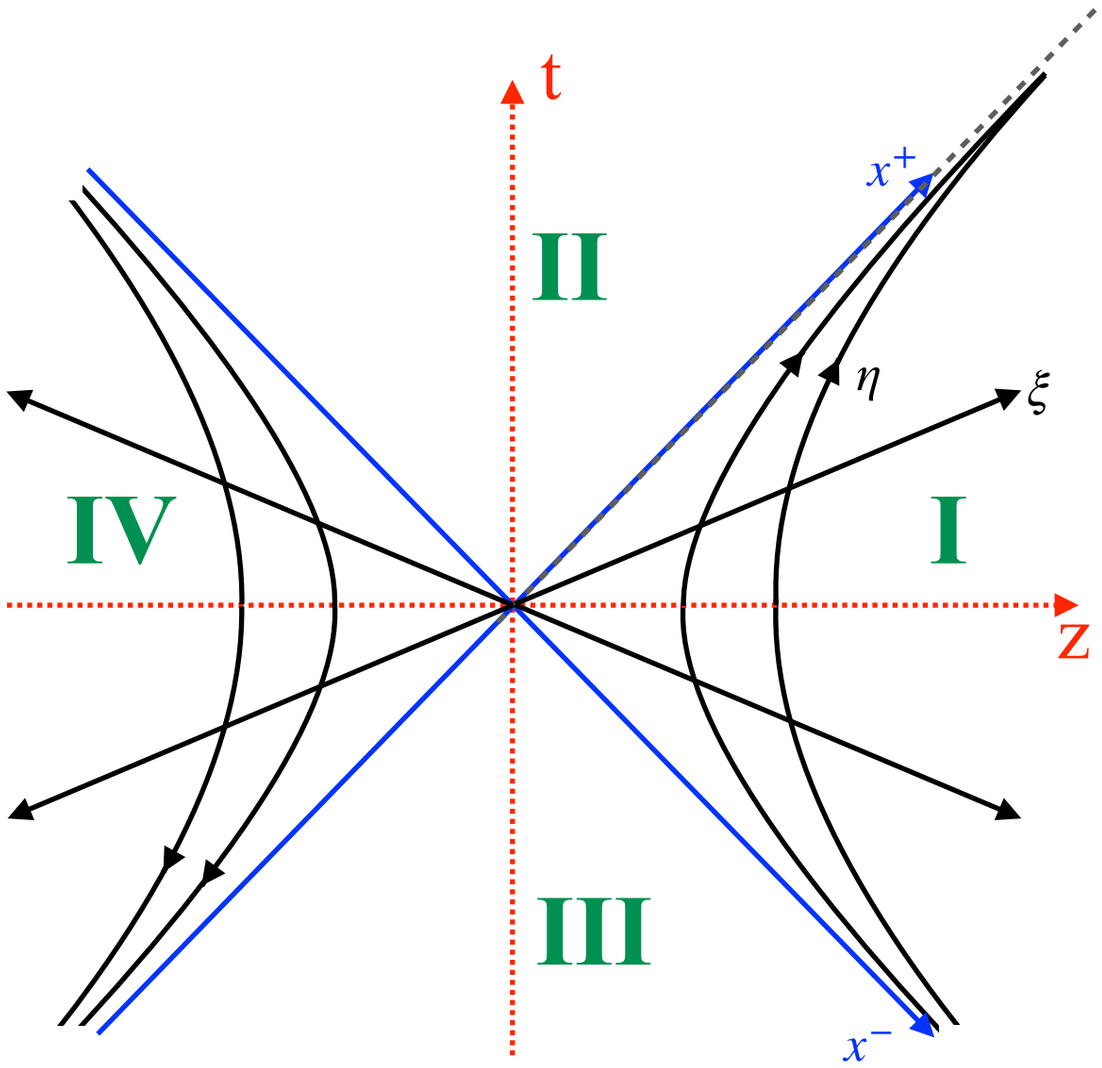
$$\phi = \int dp^+ \left(\hat{a}_{p^+} f_{p^+} + \hat{a}_{p^+}^\dagger f_{p^+}^* \right) \quad \text{(LF)}$$

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 spacetime, 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:

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

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

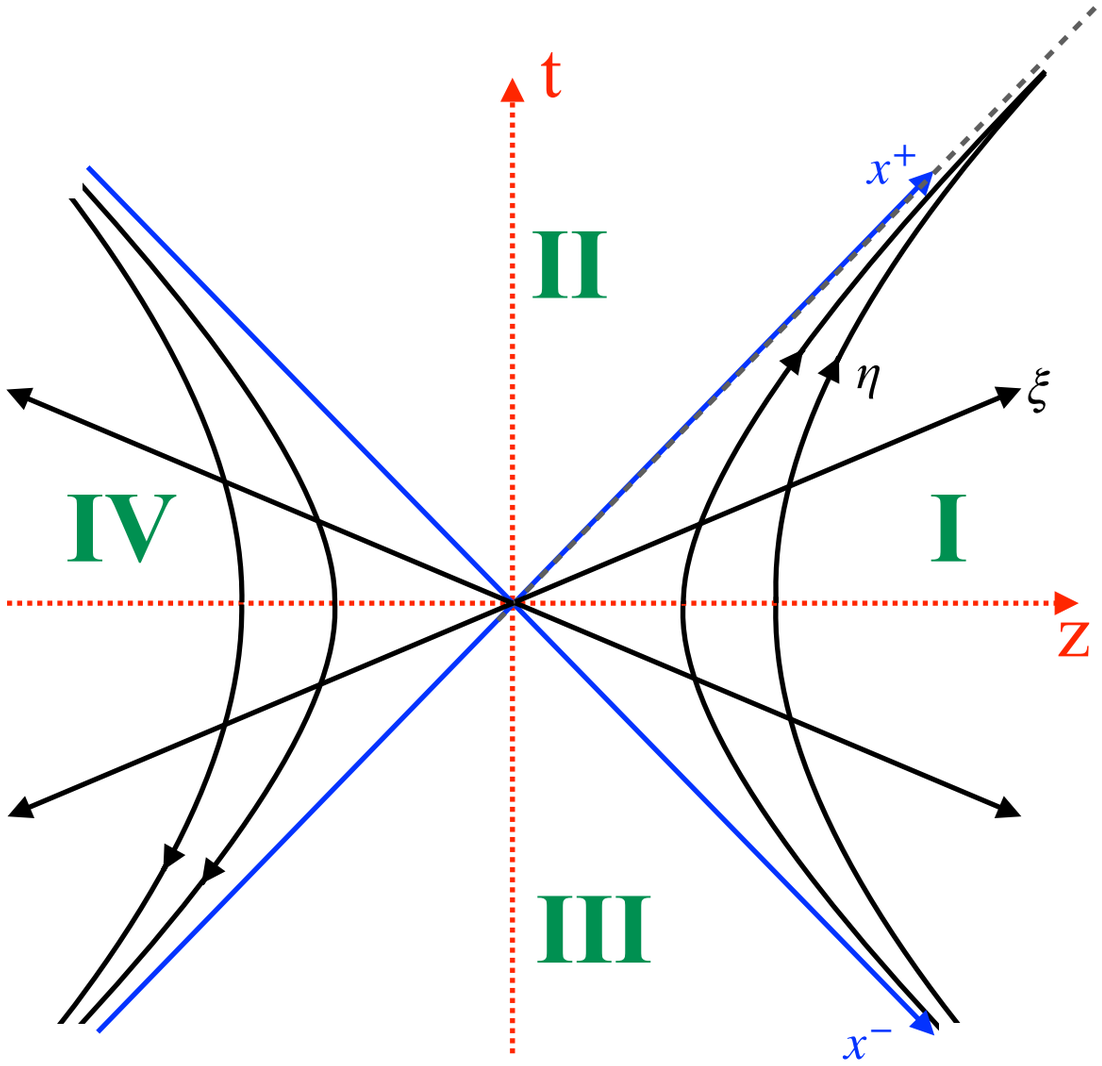
Then we have the definition of the vacua:

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

To derive his effect, Unruh combined Rindler modes so that the combination matches the spacetime dependence of Minkowski modes (i.e. the same separation of + and - 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 $|0\rangle_{M,LF}$).

Standard derivation (Unruh 1976)

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



In Rindler spacetime, 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:

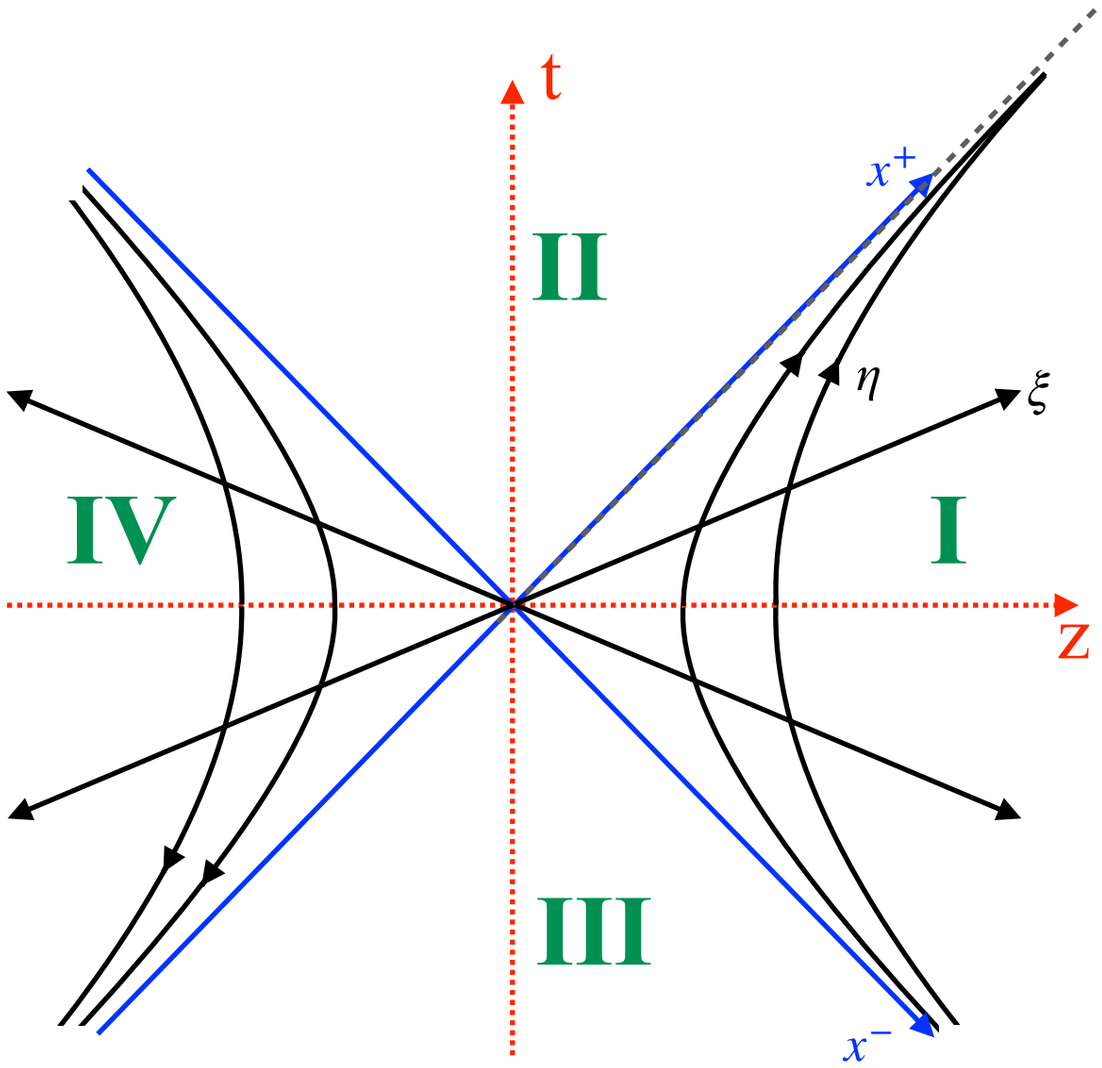
$$\hat{b}_p^{(\mathrm{I})} |0\rangle_R = 0 = \hat{b}_p^{(\mathrm{IV})} |0\rangle_R \; ; \; \hat{a}_p |0\rangle_{M,IF} = 0 \; ; \; \hat{a}_{p^+} |0\rangle_{M,LF} = 0$$

To derive his effect, Unruh combined Rindler modes so that the combination matches the spacetime dependence of Minkowski modes (i.e. the same separation of + and - 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.)

Standard derivation (Unruh 1976)

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



In Rindler spacetime, 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 the combination matches the spacetime dependence of Minkowski modes (i.e. the same separation of + and - modes).

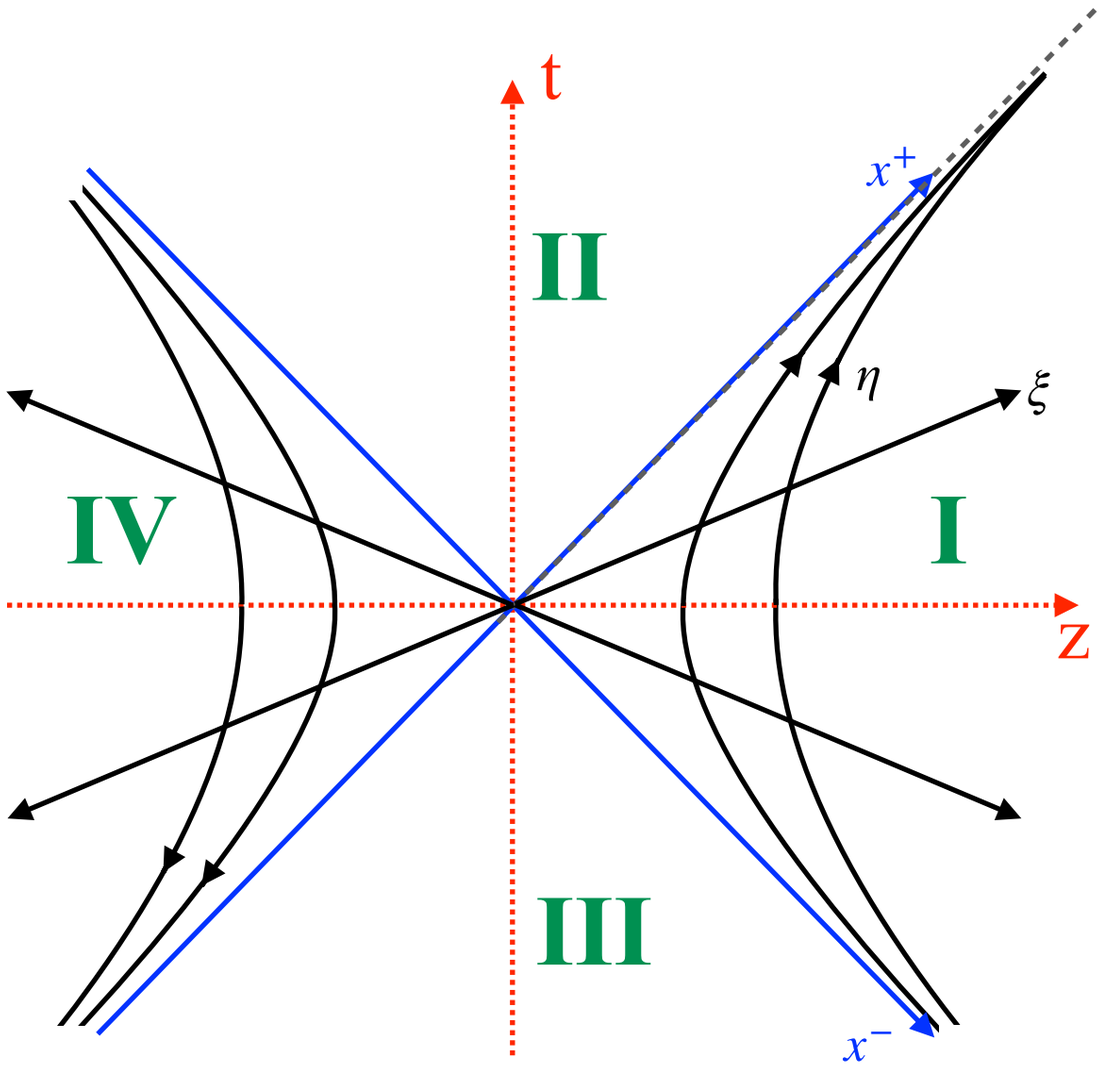
⇒ Rindler mode combinations $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (IF) or $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (LF) whose annihilation operators $\hat{c}_p^{(\mathrm{I,IV})}$ (or $\hat{c}_p^{(\mathrm{I,IV})}$) annihilate $|0\rangle_{M,IF}$ (or $|0\rangle_{M,LF}$).

$$h_p^{(\mathrm{I})} = \frac{1}{\sqrt{2 \sinh\left(\frac{\pi\omega}{a}\right)}} \left(e^{\pi\omega/2a} g_p^{(\mathrm{I})} + e^{-\pi\omega/2a} g_{-p}^{(\mathrm{IV})*} \right)$$ (ω is the field frequency and a the acceleration.)

$$h_p^{(\mathrm{I})} = g_p^{(\mathrm{I})}$$ ← No $g_p^{(\mathrm{IV})*}$ 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 spacetime, 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 the combination matches the spacetime dependence of Minkowski modes (i.e. the same separation of + and - modes).

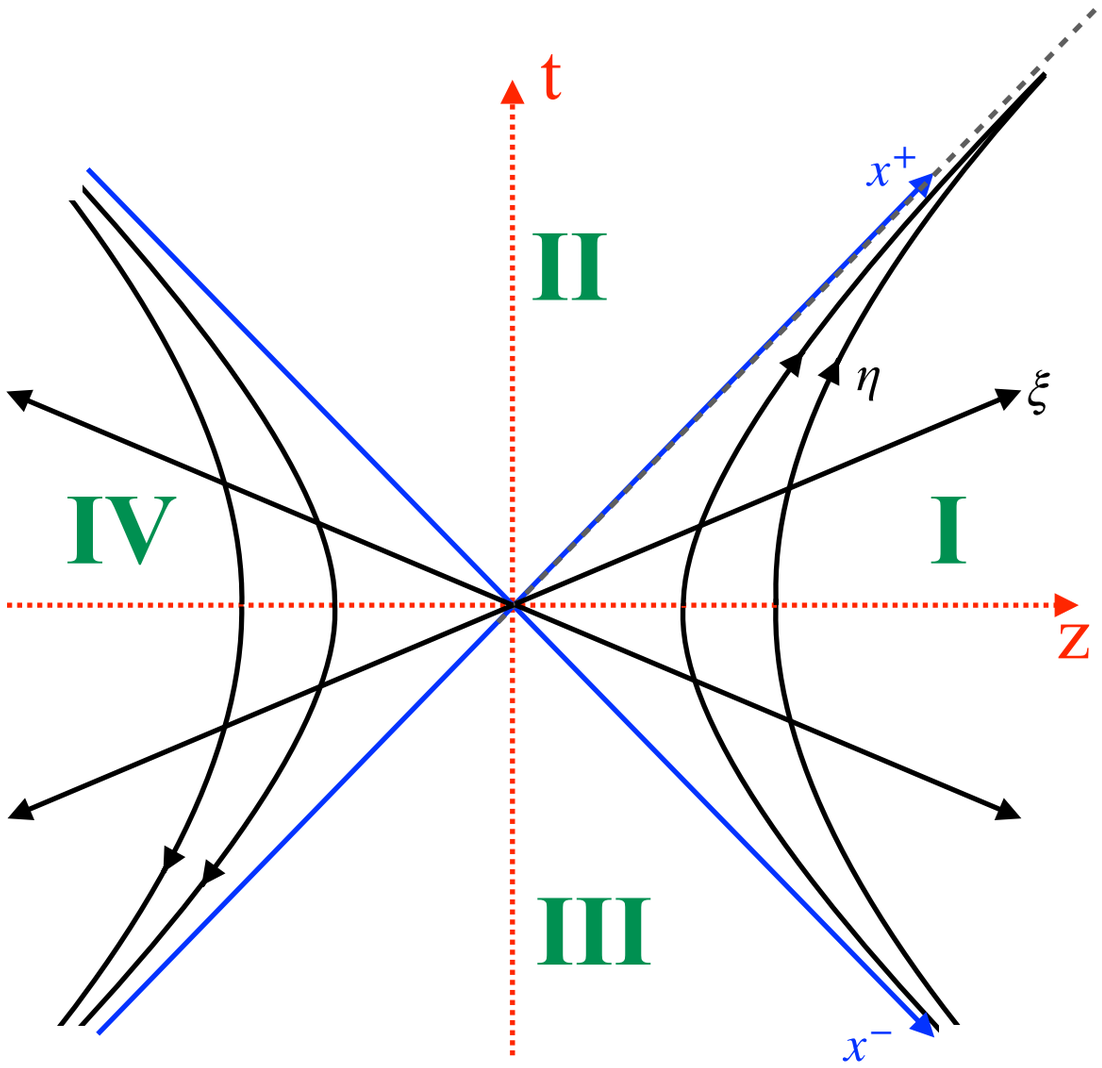
⇒ Rindler mode combinations $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (IF) or $h_p^{(\mathrm{I})}$, $h_p^{(\mathrm{IV})}$ (LF) whose annihilation operators $\hat{c}_p^{(\mathrm{I,IV})}$ (or $\hat{c}_p^{(\mathrm{I,IV})}$) annihilate $|0\rangle_{M,IF}$ (or $|0\rangle_{M,LF}$).

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

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

Standard derivation (Unruh 1976)

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



In Rindler spacetime, 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 the combination matches the spacetime dependence of Minkowski modes (i.e. the same separation of + and - 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 $|0\rangle_{M,LF}$).

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

$$\hat{b}_p^{(\mathrm{I})} |0\rangle_{M,IF} = \frac{1}{\sqrt{2\sinh(\frac{\pi\omega}{a})}} \left(e^{-\pi\omega/2a} |-p\rangle \right) \neq 0$$

Unruh effect

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

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

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 $\eta \to \eta + \Delta$

$\Rightarrow$

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

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

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 $T \equiv 1/\beta$.

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

Energy operator (not necessarily the time-evolution operator)

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 $T \equiv 1/\beta$.

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

Energy operator (not necessarily the time-evolution operator)

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 $T \equiv 1/\beta$.

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

Energy operator (not necessarily the time-evolution operator)

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 $\tilde{\eta} = \tilde{\eta} + 2\pi i$.

Other standard derivation

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

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

Energy operator (not necessarily the time-evolution operator)

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 $T \equiv 1/\beta$.

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

Energy operator (not necessarily the time-evolution operator)

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

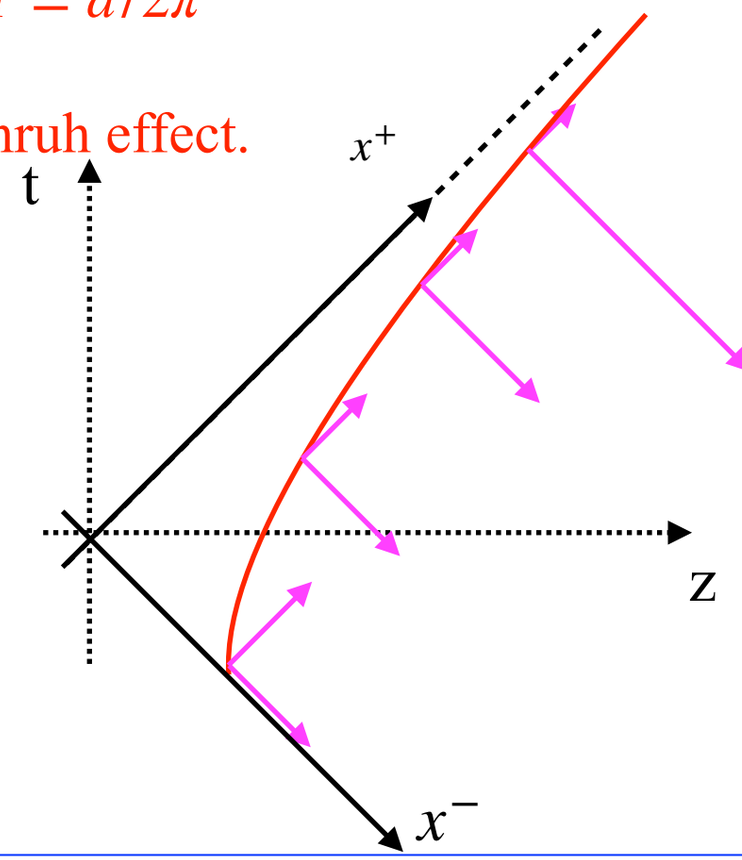
2.) On the other hand: Rindler line element, $ds^2 = -\xi^2 d\eta^2 + d\xi^2$. With imaginary Rindler time $\tilde{\eta} \equiv i\eta$:
$ds^2 = \xi^2 d\eta^2 + d\xi^2$: polar coordinates. For non-singular coordinates, we must have $\tilde{\eta} = \tilde{\eta} + 2\pi i$.

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.

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~~"



Other standard derivation

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

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

Energy operator (not necessarily the time-evolution operator)

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: $\tilde{\eta} \to \tilde{\eta} + i\beta$

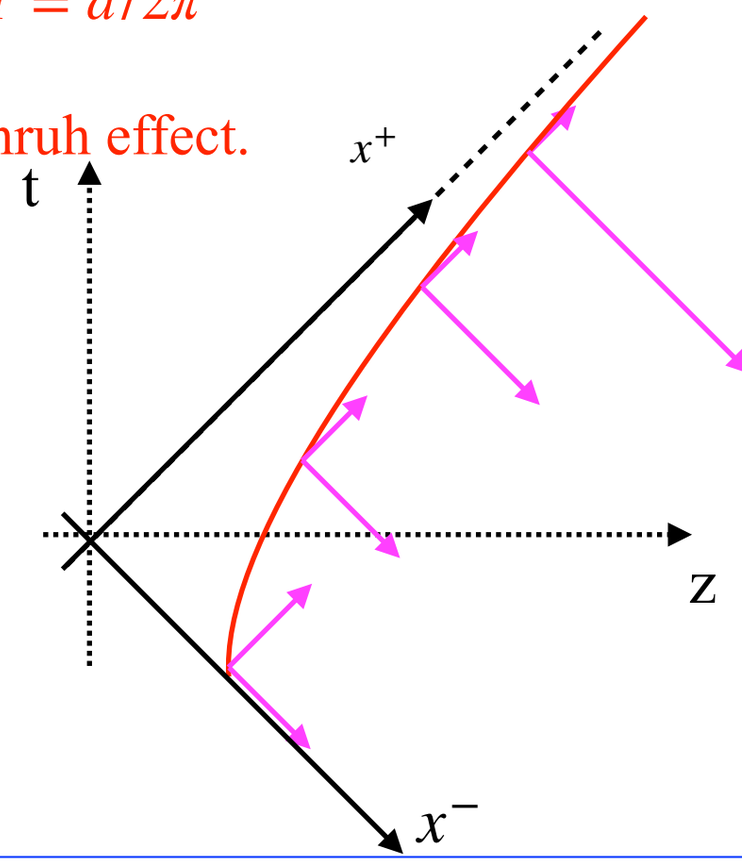
$\Rightarrow$ There exist, even in the vacuum, particles thermally distributed at T: Unruh effect.

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.



Implication of the Equivalence Principle

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

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

Implication of the Equivalence Principle

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

- Definition of positive and negative frequency modes is inconsistent 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 of the Equivalence Principle

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

- Definition of positive and negative frequency modes is inconsistent 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 inconsistent: Unruh effect.

Implication of the Equivalence Principle

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

- Definition of positive and negative frequency modes is inconsistent 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 inconsistent: Unruh effect.

- Classical physics (with trivial vacuum): no Unruh effect. Indeed, $T_{\text{Unruh}} \propto \hbar$: quantum effect.

Implication of the Equivalence Principle

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

- Definition of positive and negative frequency modes is inconsistent 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 inconsistent: 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

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 of the Equivalence Principle": 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 $\to 0$) $\Rightarrow$ 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.

Rise of the Unruh effect

One may follow how the Unruh effect arises, from absent in LF to present in IF by using LF↔IF interpolating coordinates.

Using C.R. Ji *et al.* generalized coordinates $(x^{\hat{+}}, x^{\hat{-}})$ (Monday talk, PRD **64** 085013, 2001), we get

$$\frac{\partial f_p}{\partial x^{\hat{+}'}} = -i\left[\mp e^{\mp\theta} p^{\hat{-}} + \frac{\partial\theta}{\partial x^{\hat{+}'}} \left(x^{\hat{-}} p^{\hat{+}} - x^{\hat{+}} p^{\hat{-}} \right) \right] f_p$$

with

$$\boxed{\frac{\partial\theta}{\partial x^{\hat{+}'}} = \frac{u \operatorname{sech}\theta}{1 + \sin(2\delta)\,\tanh\theta + \theta\big(\tanh\theta + \sin(2\delta)\big) - u\, x^{\hat{-}} \cos(2\delta)}}$$

and δ the interpolating parameter ($\delta = 0$: IF, $\delta = \frac{\pi}{4}$: LF)

Rise of the Unruh effect

One may follow how the Unruh effect arises, from absent in LF to present in IF by using LF↔IF interpolating coordinates.

Using C.R. Ji *et al.* generalized coordinates $(x^{\hat{+}}, x^{\hat{-}})$ (Monday talk, PRD **64** 085013, 2001), we get

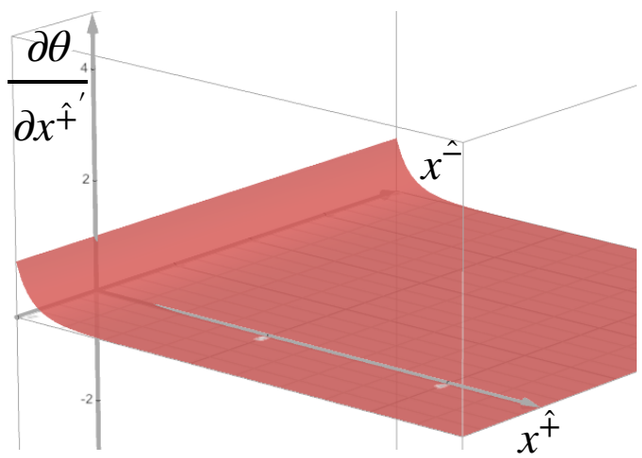
$$\frac{\partial f_p}{\partial x^{\hat{+}'}} = -i\left[\mp e^{\mp\theta} p^{\hat{-}} + \frac{\partial\theta}{\partial x^{\hat{+}'}} \left(x^{\hat{-}} p^{\hat{+}} - x^{\hat{+}} p^{\hat{-}} \right) \right] f_p$$

with

$$\boxed{\frac{\partial\theta}{\partial x^{\hat{+}'}} = \frac{u\,\mathrm{sech}\,\theta}{1 + \sin(2\delta)\,\tanh\theta + \theta\left(\tanh\theta + \sin(2\delta)\right) - u\,x^{\hat{-}}\cos(2\delta)}}$$

and δ the interpolating parameter ($\delta = 0$: IF, $\delta = \frac{\pi}{4}$: LF)

$$\delta = \frac{\pi}{4}$$



Rise of the Unruh effect

One may follow how the Unruh effect arises, from absent in LF to present in IF by using LF↔IF interpolating coordinates.

Using C.R. Ji *et al.* generalized coordinates $(x^{\hat{+}}, x^{\hat{-}})$ (Monday talk, PRD **64** 085013, 2001), we get

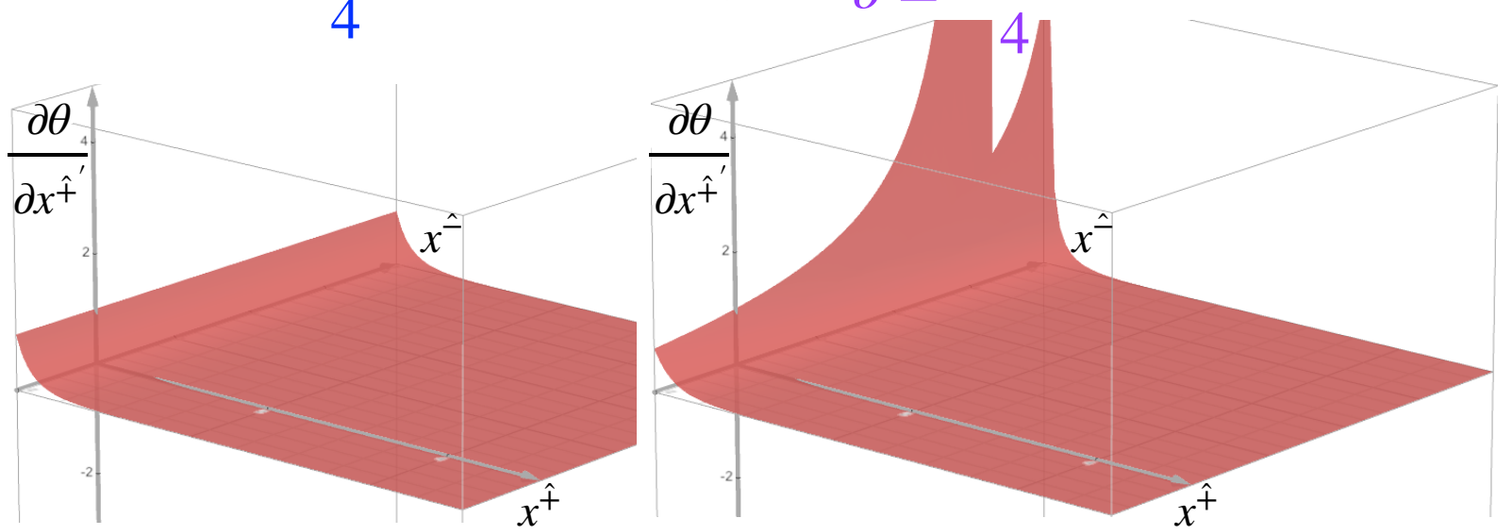
$$\frac{\partial f_p}{\partial x^{\hat{+}'}} = -i\left[\mp\, e^{\mp\theta} p^{\hat{-}} + \frac{\partial\theta}{\partial x^{\hat{+}'}} \left(x^{\hat{-}} p^{\hat{+}} - x^{\hat{+}} p^{\hat{-}} \right) \right] f_p$$

with

$$\boxed{\frac{\partial\theta}{\partial x^{\hat{+}'}} = \frac{u\,\mathrm{sech}\,\theta}{1 + \sin(2\delta)\,\tanh\theta + \theta\big(\tanh\theta + \sin(2\delta)\big) - u\,x^{\hat{-}}\cos(2\delta)}}$$

and δ the interpolating parameter ($\delta = 0$: IF, $\delta = \frac{\pi}{4}$: LF)

$\delta = \frac{\pi}{4}$ → $\delta = \frac{0.9\pi}{4}$



Rise of the Unruh effect

One may follow how the Unruh effect arises, from absent in LF to present in IF by using LF↔IF interpolating coordinates.

Using C.R. Ji *et al.* generalized coordinates $(x^{\hat{+}}, x^{\hat{-}})$ (Monday talk, PRD **64** 085013, 2001), we get

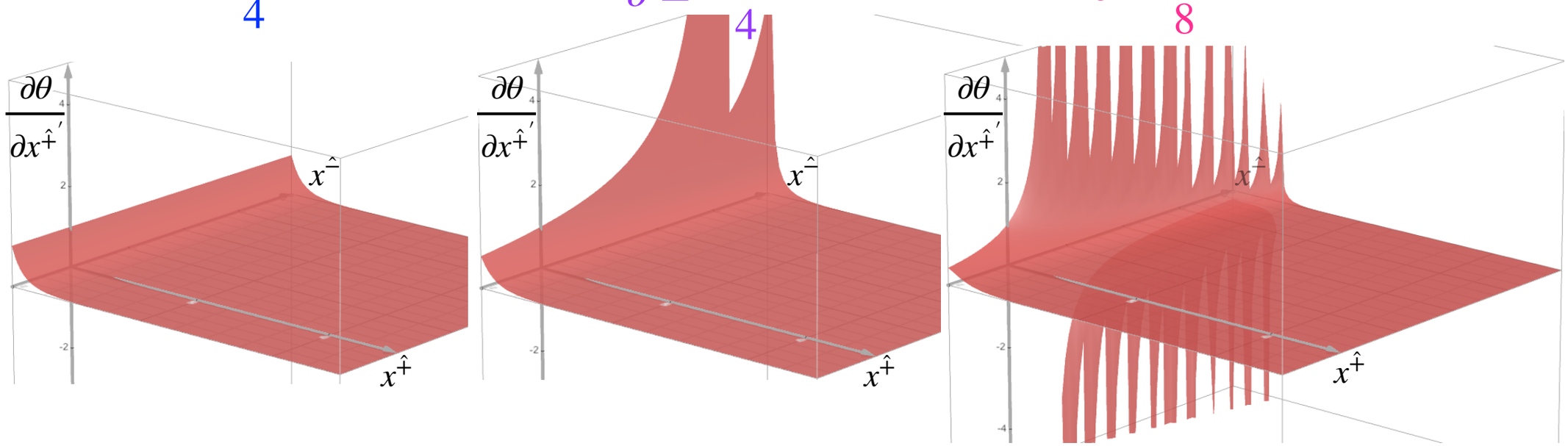
$$\frac{\partial f_p}{\partial x^{\hat{+}'}} = -i\left[\mp\, e^{\mp\theta} p^{\hat{-}} + \frac{\partial\theta}{\partial x^{\hat{+}'}} \left(x^{\hat{-}} p^{\hat{+}} - x^{\hat{+}} p^{\hat{-}} \right) \right] f_p$$

with

$$\boxed{\frac{\partial\theta}{\partial x^{\hat{+}'}} = \frac{u\,\mathrm{sech}\,\theta}{1 + \sin(2\delta)\,\tanh\theta + \theta\big(\tanh\theta + \sin(2\delta)\big) - u\,x^{\hat{-}}\cos(2\delta)}}$$

and δ the interpolating parameter ($\delta = 0$: IF, $\delta = \frac{\pi}{4}$: LF)

$\delta = \frac{\pi}{4}$ → $\delta = \frac{0.9\pi}{4}$ → $\delta = \frac{\pi}{8}$



Rise of the Unruh effect

One may follow how the Unruh effect arises, from absent in LF to present in IF by using LF↔IF interpolating coordinates.

Using C.R. Ji *et al.* generalized coordinates $(x^{\hat{+}}, x^{\hat{-}})$ (Monday talk, PRD **64** 085013, 2001), we get

$$\frac{\partial f_p}{\partial x^{\hat{+}'}} = -i\left[\mp\, e^{\mp\theta} p^{\hat{-}} + \frac{\partial\theta}{\partial x^{\hat{+}'}} \left(x^{\hat{-}} p^{\hat{+}} - x^{\hat{+}} p^{\hat{-}} \right) \right] f_p$$

with

$$\boxed{\frac{\partial\theta}{\partial x^{\hat{+}'}} = \frac{u\,\mathrm{sech}\,\theta}{1 + \sin(2\delta)\,\tanh\theta + \theta\big(\tanh\theta + \sin(2\delta)\big) - u\,x^{\hat{-}}\cos(2\delta)}}$$

and δ the interpolating parameter ($\delta = 0$: IF, $\delta = \frac{\pi}{4}$: LF)

$\delta = \frac{\pi}{4}$ → $\delta = \frac{0.9\pi}{4}$ → $\delta = \frac{\pi}{8}$ → $\delta = 0$