Once again:
Do accelerated detectors click more often? (Anti-Unruh Phenomena)

RQI-N Kyoto, July 4th 2017

W.G. Brenna, R. B. Mann, E. Martin-Martinez, Phys. Lett. B 757, 307 (2016)

L. J. Garay, E. Martin-Martinez, J. de Ramon Phys. Rev. D 94, 104048 (2016)

And Work in progress with L. J. Garay and J. de Ramon

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Perimeter Institute for Theoretical Physics

Catastrophic fail

Detecting temperature

We need a thermometer!

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To measure the temperature of a field: Stick a thermometer into the field!

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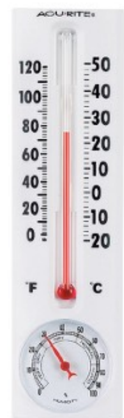

We need a thermometer!

To measure the temperature of a field: Stick a thermometer into the field!

Unruh-DeWitt detector:

$$H_I = \lambda \chi(\tau) \mu(\tau) \phi[\boldsymbol{x}(\tau), t(\tau)]$$

Captures the core features of the L-M interaction

Detecting temperature

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$$\mathcal{R}(\Omega,\sigma)=\frac{P^{+}(\Omega)}{P^{-}(\Omega)}\propto e^{-\beta\Omega}$$

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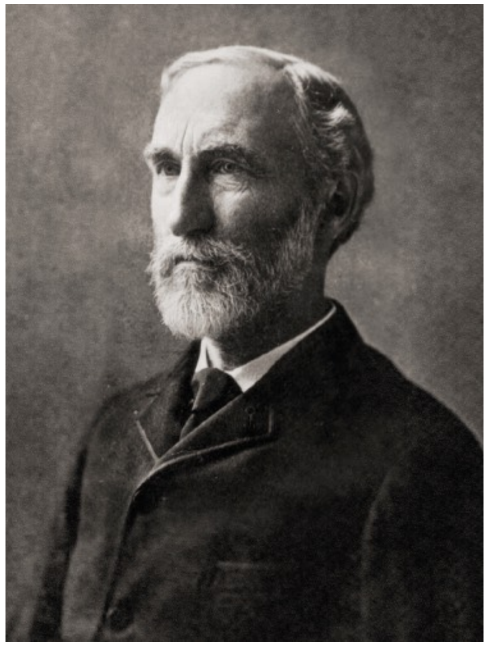
$$\mathcal{R}(\Omega,\sigma)=\frac{P^{+}(\Omega)}{P^{-}(\Omega)}\propto e^{-\beta\Omega} \qquad \beta_{\text{EDR}}(\Omega,\sigma,\beta)=-\frac{\log\left(\mathcal{R}(\Omega,\sigma,\beta)\right)}{\Omega}$$

To what extent is this a good estimator?

The KMS condition and equilibrium states

Thermality: Maximization of entropy at constant energy



Well defined for systems with finite (or countably infinite) degrees of freedom.

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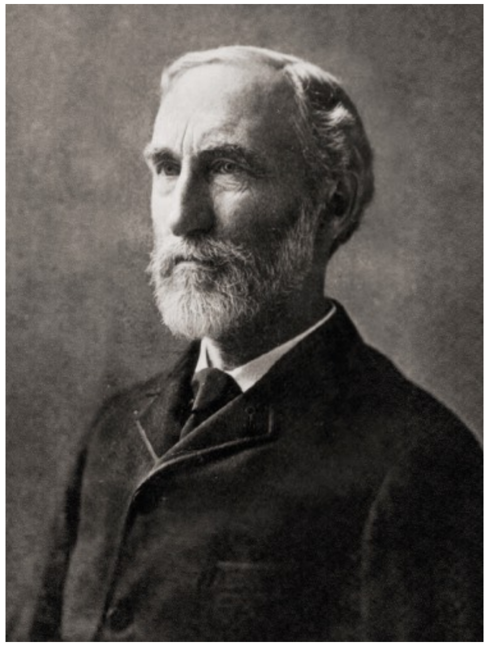

Well defined for systems with finite (or countably infinite) degrees of freedom.

Warning:

The Gibbs distribution is not well defined, in general, for systems of continuous variables, (e.g., quantum fields in free space)

The KMS condition and equilibrium states

Ingredients:

- -(Scalar) field $\hat{\phi}(\mathrm{x})$
- -Time evolution ∂_τ
- -Field state $\hat{\rho}$

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Pull-back of the Wightman function on the curve:

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A stationary Wightman function satisfies the KMS condition
With KMS parameter β if and only if

$$W(\Delta\tau - \mathrm{i}\beta) = W(-\Delta\tau)$$

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A state of the field $\hat{\rho}$ is KMS with respect to the time evolution generated by ∂_τ (with KMS parameter β) if (1) is satisfied

The KMS condition and equilibrium states

Connection between equilibrium and correlations

Gibbs states are KMS

KMS states are passive

KMS is a necessary condition for thermodynamic equilibrium

The parameter $\beta = 1/T_{\rm KMS}$ is called the KMS (inverse) temperature

To all effects, KMS states are thermal states

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Detailed balance condition: $\tilde{W}(-\omega) = e^{\beta\omega}\tilde{W}(\omega)$ (2)

The field commutator is prop. to the imaginary part of the Wightman:

$$[\hat{\phi}(x(\tau)), \hat{\phi}(x(\tau'))] = C(\Delta\tau)\mathbb{1} \qquad C(\Delta\tau) = 2\mathrm{i}\,\mathrm{Im}\big(W(\Delta\tau)\big)$$

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In terms of Fourier transforms:

$$\tilde{C}(\omega) = \tilde{W}(\omega) - \tilde{W}(-\omega) \quad (3)$$

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For a KMS state we can combine (2) and (3)

$$\tilde{W}(\omega, \beta) = -\tilde{C}(\omega, \beta)\mathcal{P}(\omega, \beta)$$

Where $\mathcal{P}(\omega, \beta)$ is a Planckian distribution of inverse temperature equal to the KMS parameter.

$$\mathcal{P}(\omega, \beta) = \frac{1}{e^{\beta\omega} - 1}$$

Probing a KMS state: Particle detectors

We couple an Unruh-DeWitt detector to the field:

$$H_I = \lambda\chi(\tau/\sigma)\mu(\tau)\hat{\phi}(\mathsf{x}(\tau))$$

Quick aside: UDW detectors are physical

$$H_{\mathrm{EM}} = \hat{\boldsymbol{d}} \cdot \hat{\boldsymbol{E}} = e\hat{\boldsymbol{x}} \cdot \hat{\boldsymbol{E}},$$

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$$\hat{\boldsymbol{x}}\cdot\hat{\boldsymbol{E}}(\boldsymbol{x},t) = \int \mathrm{d}^3\boldsymbol{x}\left[\boldsymbol{F}(\boldsymbol{x})\cdot\hat{\boldsymbol{E}}(\boldsymbol{x},t)e^{\mathrm{i}\Omega t}|e\rangle\langle g| + \boldsymbol{F}^*(\boldsymbol{x})\cdot\hat{\boldsymbol{E}}(\boldsymbol{x},t)e^{-\mathrm{i}\Omega t}|g\rangle\langle e|\right],$$

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$$\boldsymbol{F}(\boldsymbol{x}) = \psi_e^*(\boldsymbol{x})\boldsymbol{x}\,\psi_g(\boldsymbol{x}). \qquad \psi_g(\boldsymbol{x}) = \langle \boldsymbol{x}|\,g\rangle$$

$$\hat{\boldsymbol{d}}(\boldsymbol{x}, t) = e\left[\boldsymbol{F}(\boldsymbol{x})e^{\mathrm{i}\Omega t}\hat{\sigma}^+ + \boldsymbol{F}^*(\boldsymbol{x})e^{-\mathrm{i}\Omega t}\hat{\sigma}^-\right]$$

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$$H_{\text{EM}} = \chi(t)\int \mathrm{d}^3\boldsymbol{x}\,\hat{\boldsymbol{d}}(\boldsymbol{x}-\boldsymbol{x}_d,t)\cdot\hat{\boldsymbol{E}}(\boldsymbol{x},t).$$

$$H_{\text{UDW}} = e\chi(t)\int \mathrm{d}^3\boldsymbol{x}\,F(\boldsymbol{x}-\boldsymbol{x}_d)\hat{\mu}(t)\,\hat{\phi}(\boldsymbol{x},t).$$

Almost same phenomenology (except for angular momentum exchange)

More details in A. Pozas and E. Martín-Martínez, Phys. Rev. D 94, 064074 (2016)

And also in Richard Lopp’s talk

Probing a KMS state: Particle detectors

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For an arbitrary field state, the excitation and de-excitation probabilities are:

$$P^+ = \lambda^2|\langle e|\mu(0)|g\rangle|^2\sigma\mathcal{F}(\Omega,\sigma)$$

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$$\mathcal{F}(\Omega,\sigma)=\frac{1}{\sigma}\int_{-\infty}^{\infty}\mathrm{d}\tau'\int_{-\infty}^{\infty}\mathrm{d}\tau\,\chi(\tau/\sigma)\chi(\tau'/\sigma)W(\tau,\tau')e^{-\mathrm{i}\Omega(\tau-\tau')}$$

Probing a KMS state: Particle detectors

In terms of Fourier transforms

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Assuming that $\tilde{\chi}(\bar{\omega})$ decays fast enough:

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The response function when the interaction is on for long times is the Fourier transform of the Wightman function.

Probing a KMS state: Particle detectors

Excitation-Deexcitation ratio:

$$\mathcal{R}(\Omega,\sigma) = \frac{P^{+}(\Omega)}{P^{-}(\Omega)} = \frac{\mathcal{F}(\Omega,\sigma)}{\mathcal{F}(-\Omega,\sigma)} \xrightarrow[\sigma\to\infty]{} \frac{\tilde{W}(\Omega)}{\tilde{W}(-\Omega)}$$

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For a KMS state $\tilde{W}(-\Omega,\beta) = e^{\beta\Omega}\tilde{W}(\Omega,\beta)$

$$\mathcal{R}(\Omega,\sigma) \underset{\sigma\to\infty}{\longrightarrow} e^{-\beta\Omega}$$

We can define the (inverse) EDR temperature as

$$\beta_{\text{EDR}}(\Omega,\sigma,\beta) = -\frac{\log\big(\mathcal{R}(\Omega,\sigma,\beta)\big)}{\Omega}$$

Which coincides with the KMS temperature for long interaction times

Probing a KMS state: Particle detectors

Examples of KMS states:

Free field thermal state of temperature T with respect to inertial observer time:

$$T_{\mathrm{KMS}} = \beta^{-1} = T$$

Vacuum state of a free field with respect to proper time of constantly accelerated observer:

$$T_{\mathrm{KMS}} = \beta^{-1} = \frac{a}{2\pi}$$

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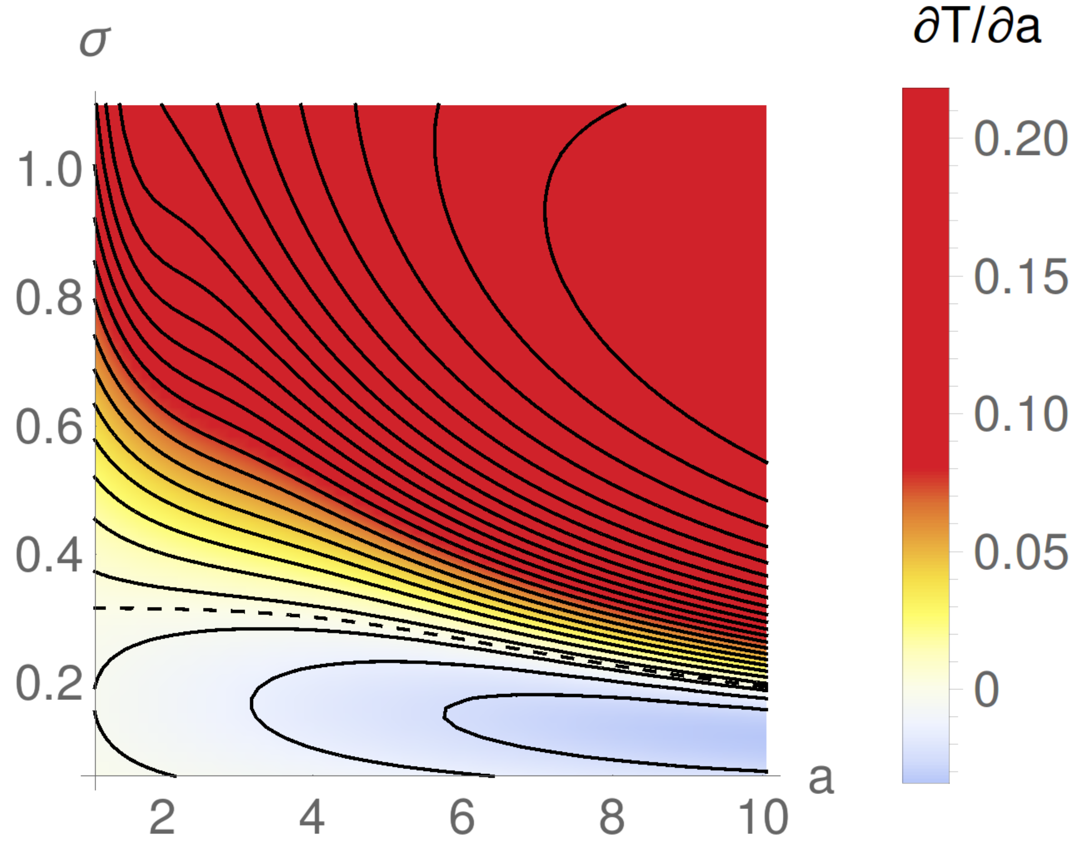
Unruh effect!

The 'Anti-Unruh' effect

The transition probability of an accelerated detector can actually decrease with acceleration [1]



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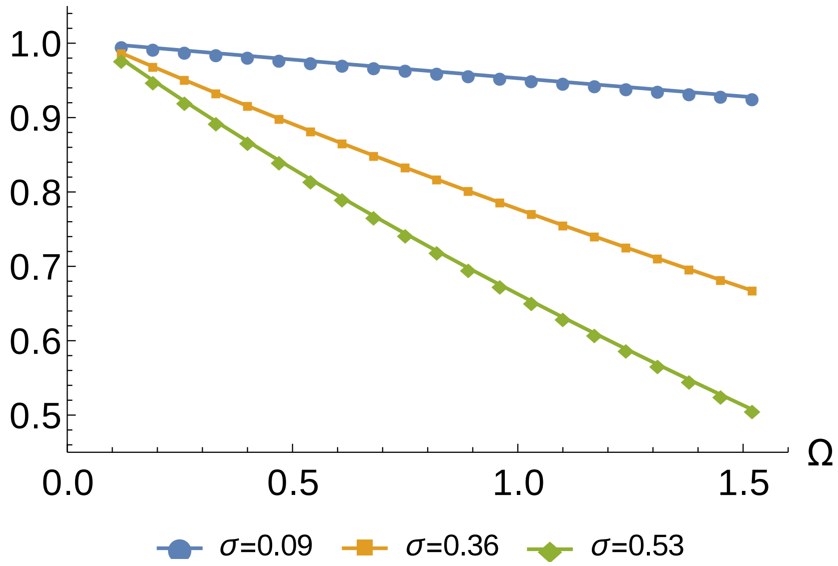

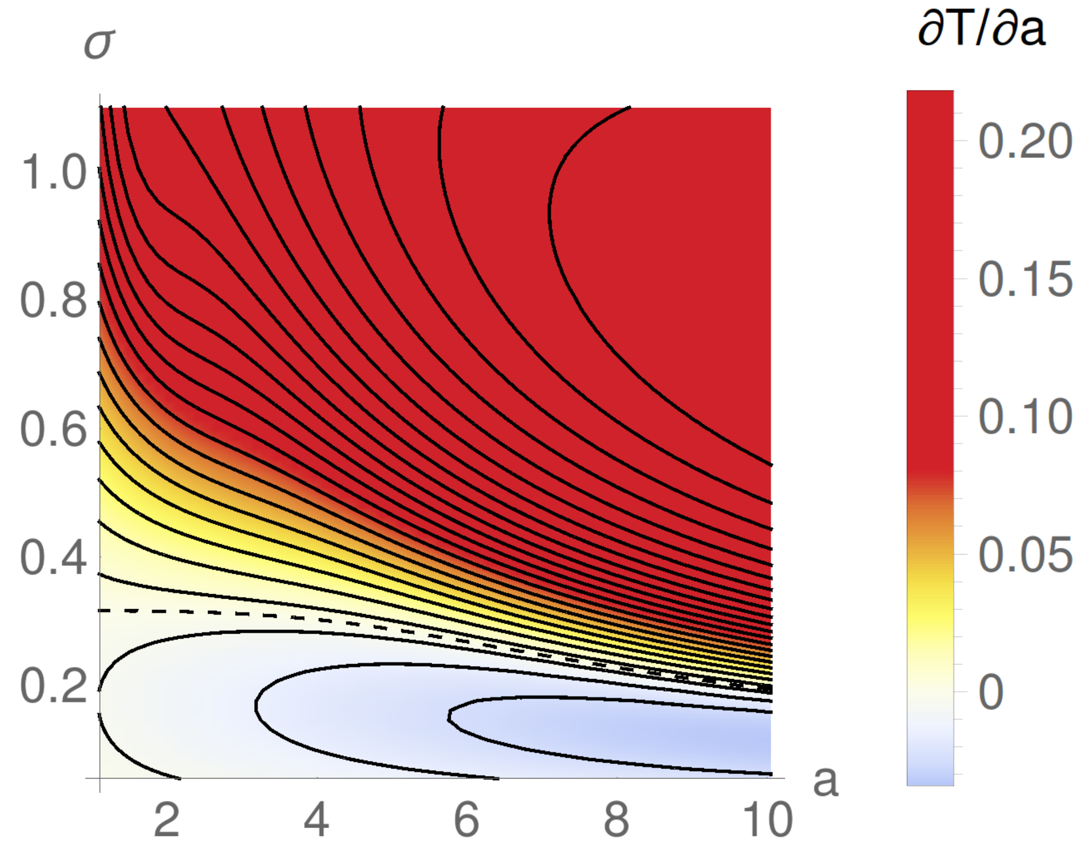

Is it a transient effect?

This is a cavity effect (or IR cutofff) that breaks KMS. Is that it?

Is the EDR independence of a good estimator for thermally?

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The "Anti-Unruh" effect

Weak Anti-Unruh: The transition probability decreases when the KMS temperature increases

$$\partial_\beta \mathcal{F}(\Omega, \sigma, \beta) > 0$$

Strong Anti-Unruh: effective EDR temperature decreases as the KMS temperature increases (while still being largely independent of Ω):

$$\partial_\beta \beta_{\mathrm{EDR}} < 0$$

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The "Anti-Unruh" effect

-Pullback of Commutator does not depend on the KMS parameter

E.g., Thermal states for inertial observers
Accelerated detectors coupled to massless fields in free space

-Pullback of Commutator depends on the KMS parameter

E.g., Accelerated detectors coupled to massive fields,
Accelerated detectors coupled to massless fields in cavities

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Commutator does not depend on β

If the pull-back of the commutator does not depend on the KMS parameter:

No Weak Anti-Unruh $\Rightarrow$ No Strong Anti-Unruh

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Necessary condition for weak Anti-Unruh:

$$-\partial_\beta \tilde{W}(\omega) = \partial_\beta \big(\tilde{C}(\omega, \beta)\mathcal{P}(\omega, \beta)\big) = \tilde{C}(\omega)\partial_\beta \mathcal{P}(\omega, \beta) < 0$$

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Can be simplified to $\omega \tilde{C}(\omega) > 0$

But $\mathrm{sgn}[\tilde{C}(\omega)] = -\mathrm{sgn}(\omega)$ The condition cannot be satisfied!

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Commutator does not depend on β

E.g., The trajectory does not depend on the KMS parameter

E.g., accelerated detector coupled to massless field vacuum

There is no Anti-Unruh phenomena (neither weak nor strong)

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E.g., accelerated detector coupled to massless field vacuum

There is no Anti-Unruh phenomena (neither weak nor strong)

An inertial detector in a thermal bath will always click more often when Exposed to higher temperatures.

An accelerated detector coupled to a massless field in free space will click more often the larger its acceleration

Commutator depends on β

If the trajectory depends on the KMS parameter, there is a chance the pull-back of the commutator does too.

Accelerated detector in free space coupled to a massive field:

$$\tilde{W}_d(\omega,\beta) = \frac{\beta e^{-\frac{\beta\omega}{2}}}{2\pi^2}\int \frac{\mathrm{d}^{d-1}\boldsymbol{k}}{(2\pi)^{d-1}}\left|K_{\mathrm{i}\frac{\beta\omega}{2\pi}}\left(\frac{\beta}{2\pi}\sqrt{m^2+\boldsymbol{k}^2}\right)\right|^2$$

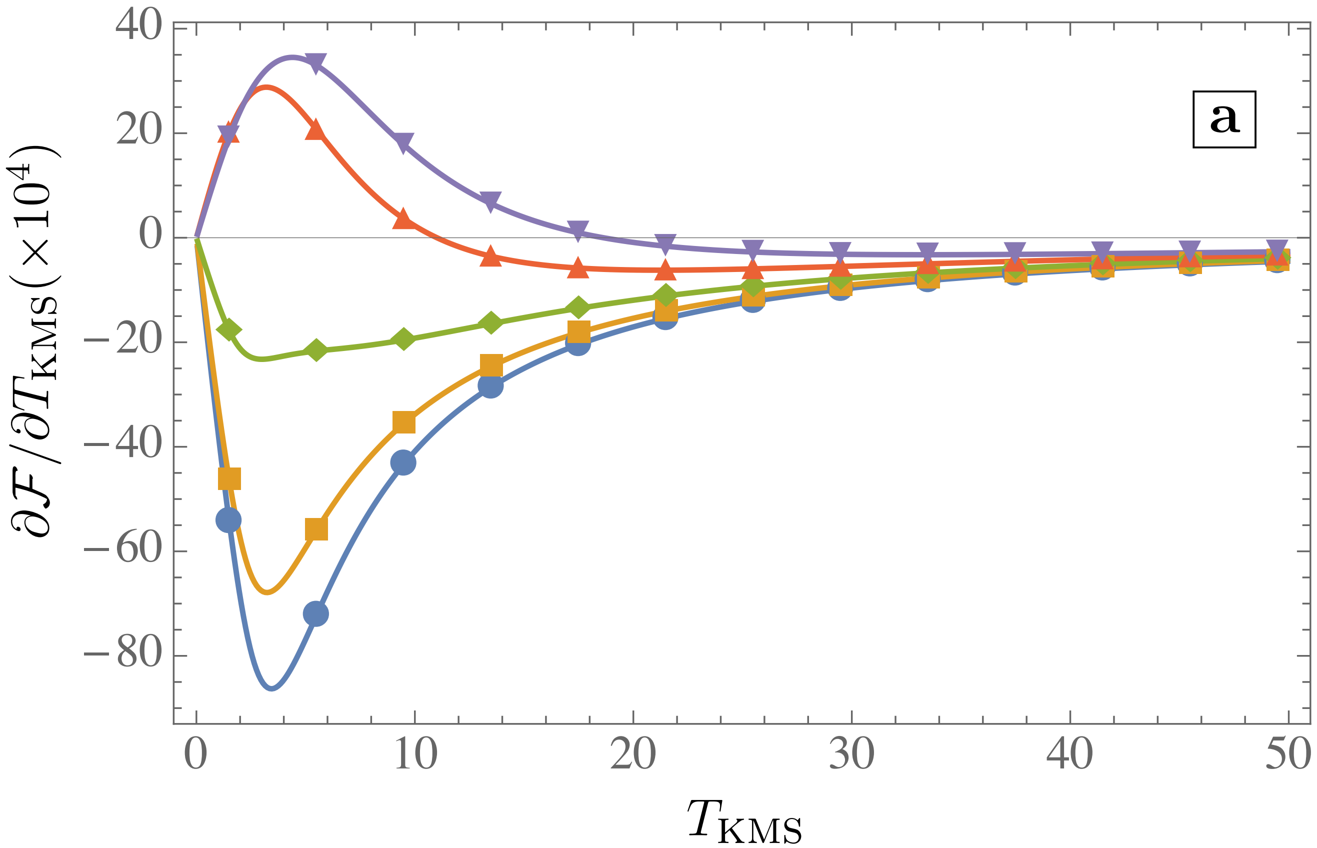
Where the KMS parameter $\beta = \frac{2\pi}{a}$

Necessary conditions for Anti-Unruh are satisfied.

Weak Anti-Unruh

Accelerated detector in free space coupled to a massive field (1+1D):

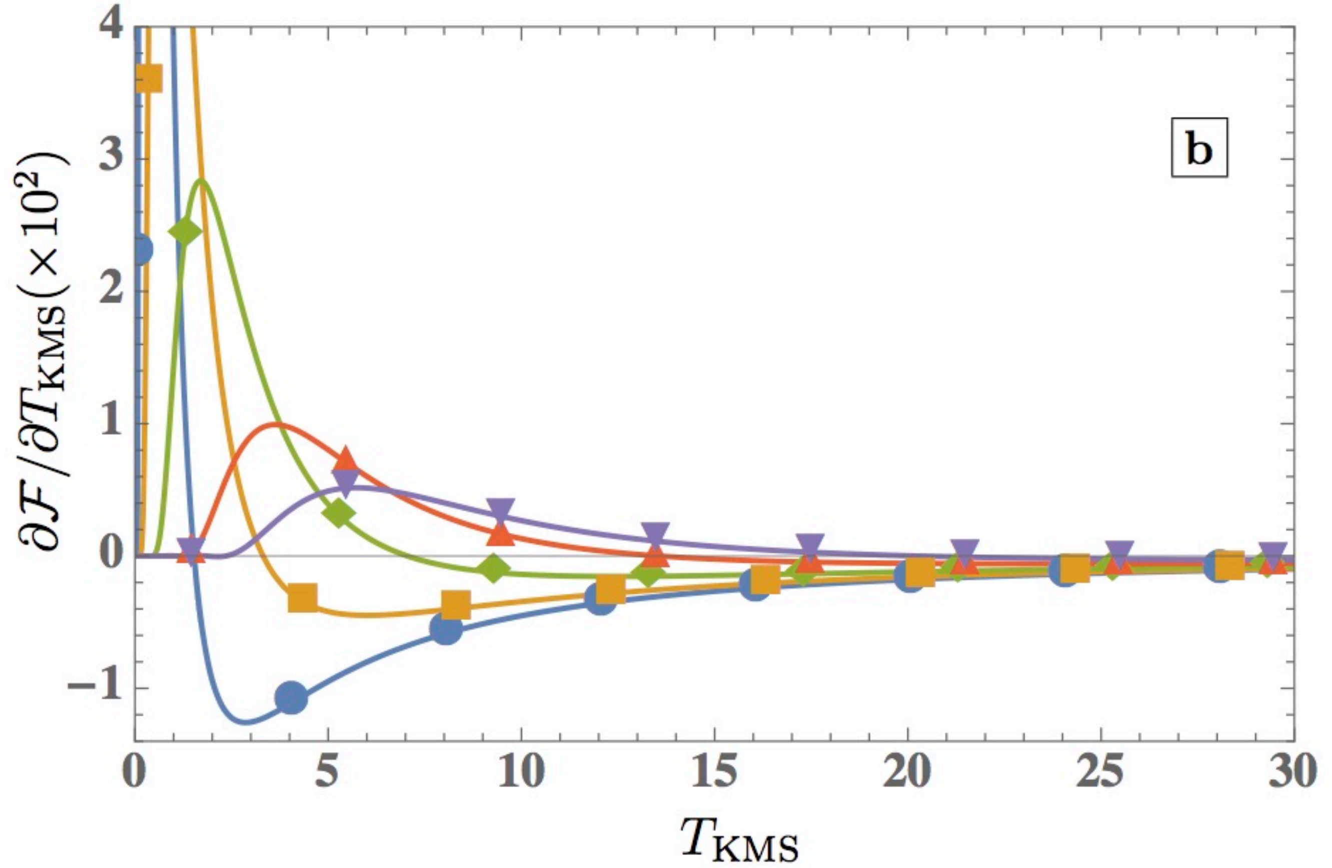
$$\chi(\tau/\sigma) = \pi^{-1/4} e^{-\tau^2/(2\sigma^2)}$$



Short time regimes $0.1\Omega^{-1} \lesssim \sigma \lesssim 10\Omega^{-1}$

Weak Anti-Unruh

Accelerated detector in free space coupled to a massive field (1+1D):



Long time regimes $\sigma \to \infty$ for ANY switching function shape

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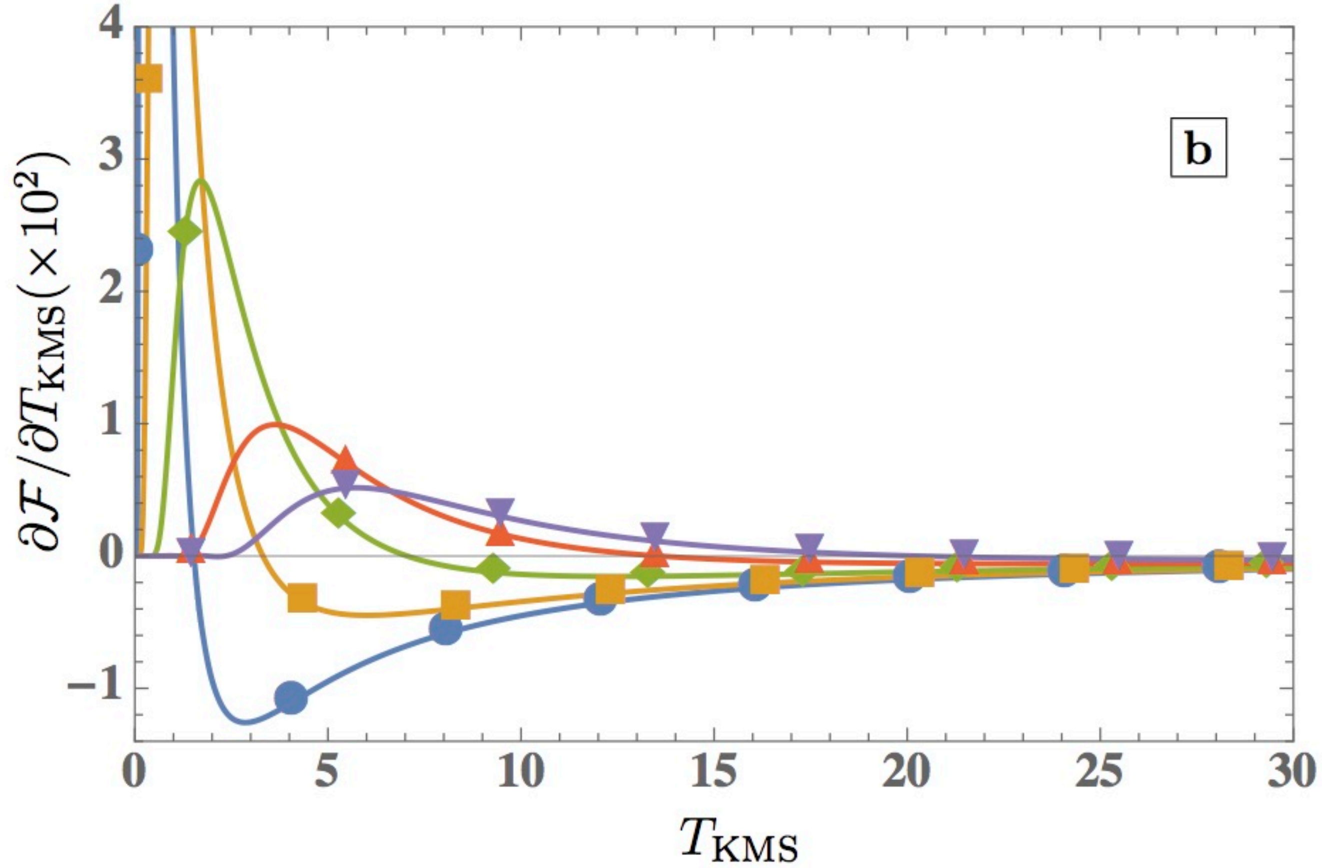


Long time regimes $\sigma \to \infty$ for ANY switching function shape

Dominant scale for Anti-Unruh $\beta m \lesssim 1$

Weak Anti-Unruh

Long time regimes $\sigma \to \infty$ for ANY switching function shape

Presence of Anti-Unruh when $\beta m \lesssim 1$

The response function in the limit of small βm, where $\beta\Omega$, is kept constant is not a monotonically increasing function of β.

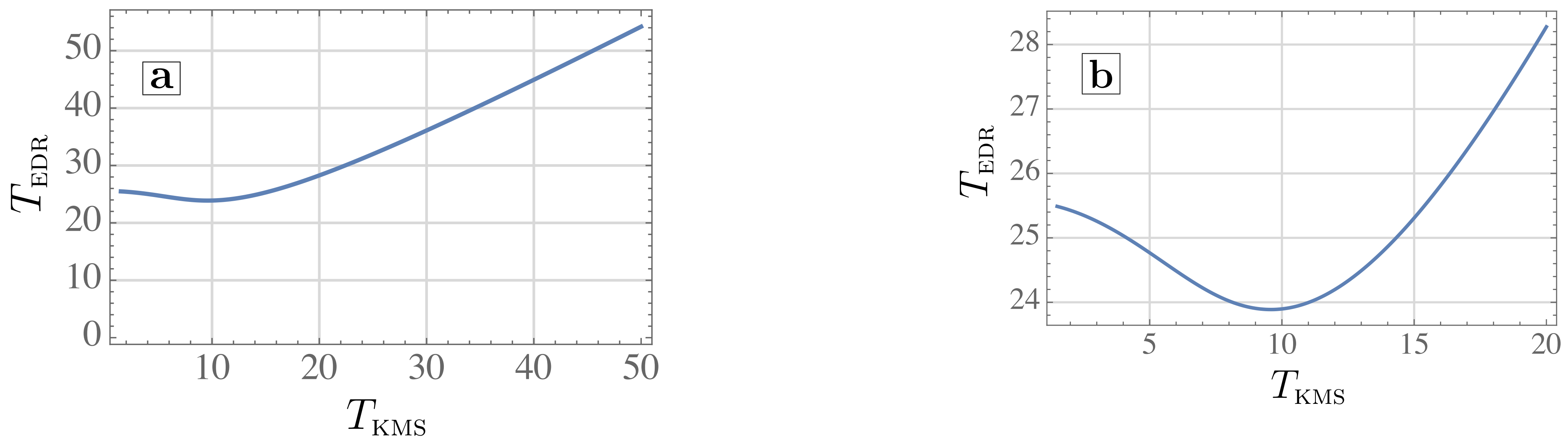
In fact, it becomes highly oscillatory as $\beta m \to 0$

Thus, its derivative with respect to the KMS temperature will take negative values.

The Anti-Unruh phenomena will appear therefore for sufficiently small βm regardless of the constant value of β and Ω .

Strong Anti-Unruh

$$\beta_{\text{EDR}}(\Omega, \sigma, \beta) = -\frac{\log\left(\mathcal{R}(\Omega, \sigma, \beta)\right)}{\Omega}$$



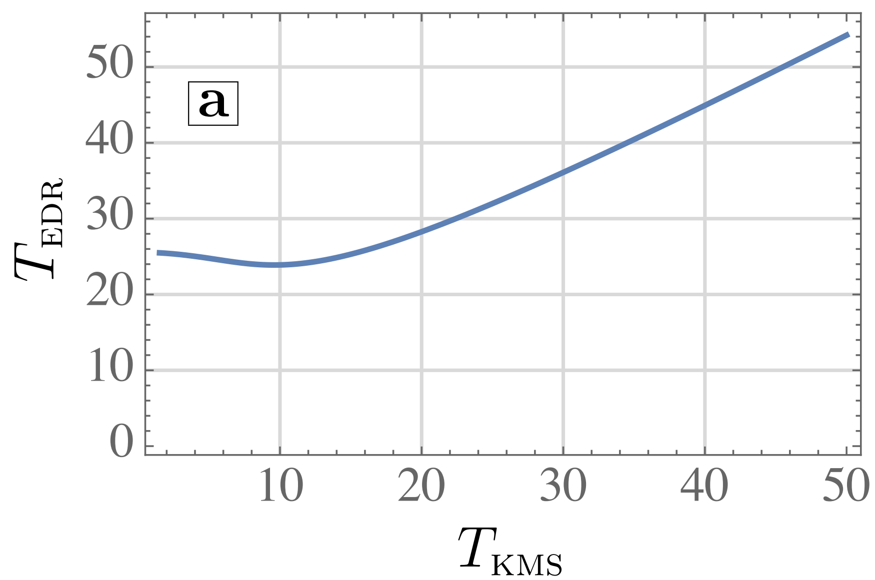
Short time regime (interaction time below Heisenberg time)

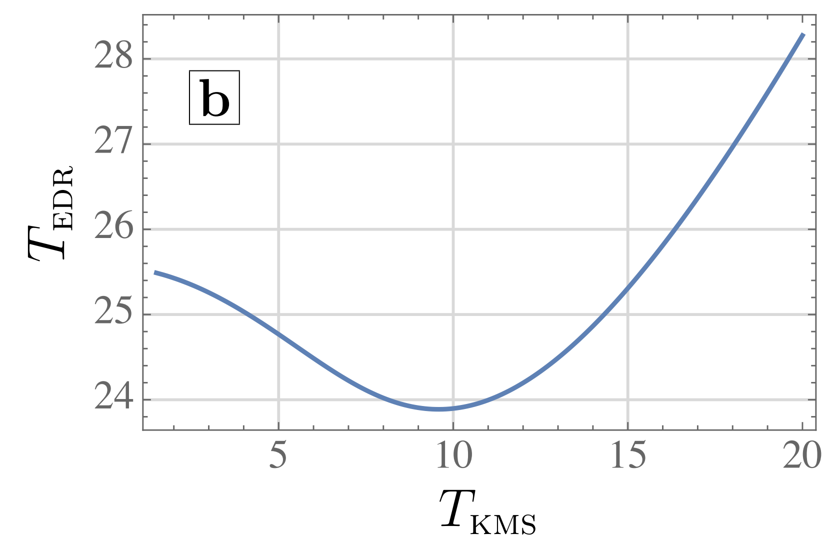
$$\sigma \approx 10^{-1}\Omega^{-1}$$

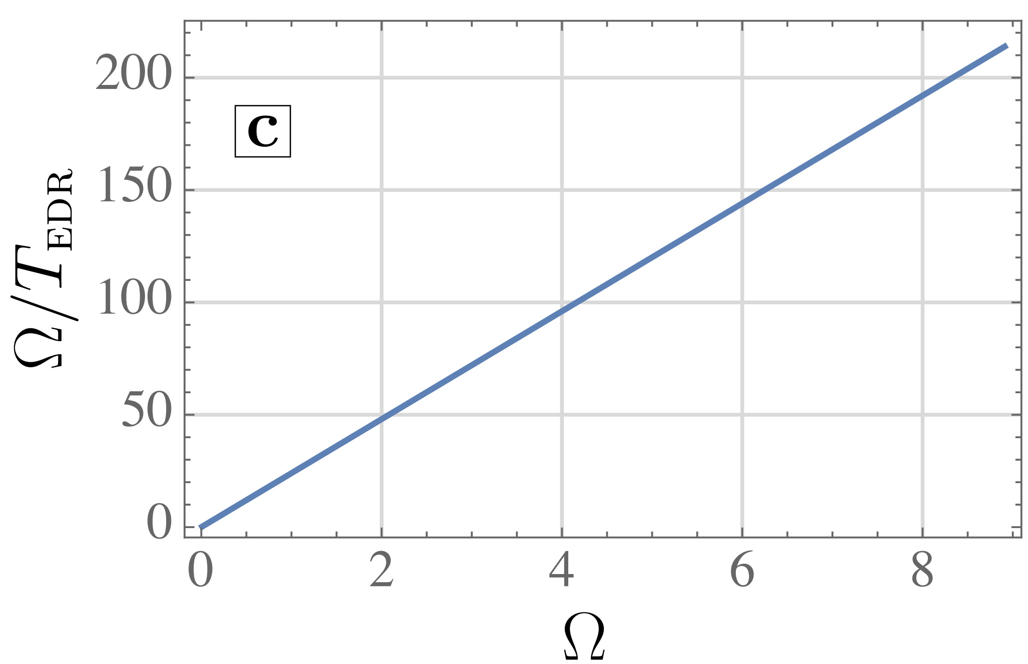
$$m = \Omega$$

Strong Anti-Unruh

$$\beta_{\text{EDR}}(\Omega, \sigma, \beta) = -\frac{\log\left(\mathcal{R}(\Omega, \sigma, \beta)\right)}{\Omega}$$







Seems to satisfy “Detailed Balance”

Conclusions

Particle detectors can click less often when they accelerate!

- Characteristic of accelerated trajectories
- Related to the existence of an IR cutoff (covariant or not)
- Does not come from transient behaviour!
- Does not come from break down of Lorentz Invariance

- It appears in cavities for massless fields (non-KMS).

A difference between Thermal vs Unruh response

Lessons from strong Anti-Unruh:

- The EDR temperature may depend very weekly on Ω , yet not be a good temperature estimator for finite times