How Measurement Realizes Quantum Vacuum Ambiguities

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Analogue Gravity in 2023, Benasque – May 2023

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Introduction

- QFT in the presence of an external, time-dependent agent
  - Particle production (even from vacuum)
  - Vacuum/particle notion is ambiguous

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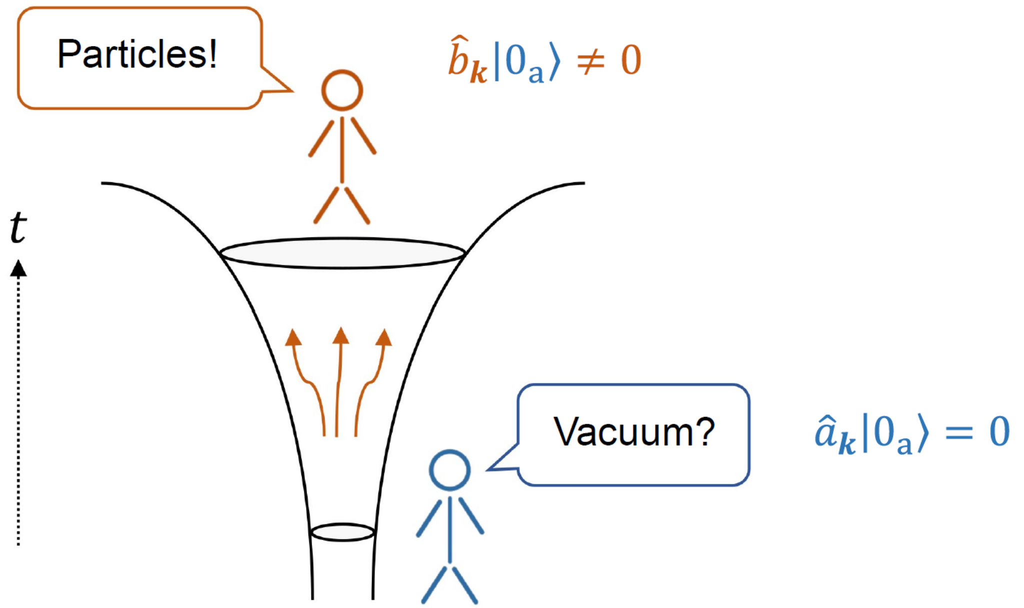
- QFT in the presence of an external, time-dependent agent
  - Particle production (even from vacuum)
  - Vacuum/particle notion is ambiguous
- Some scenarios
  - Expansion of spacetime
  - Schwinger effect



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How many ‘particles’ have been produced?

What a problematic question...

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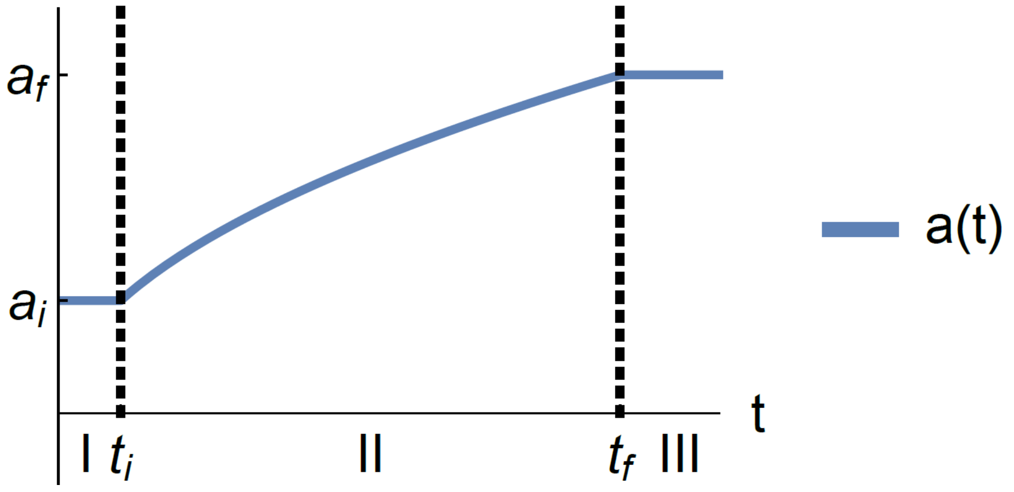
What a problematic question...

Consider the following realization

- Preferred vacuum in I, $\hat{a}_{\boldsymbol{k}}|0_{\mathrm{a}}\rangle = 0$
- There is no preferred vacuum in II
- Preferred vacuum in III, $\hat{b}_{\boldsymbol{k}}|0_b\rangle = 0$



In these processes, one often wonders...

How many ‘particles’ have been produced?

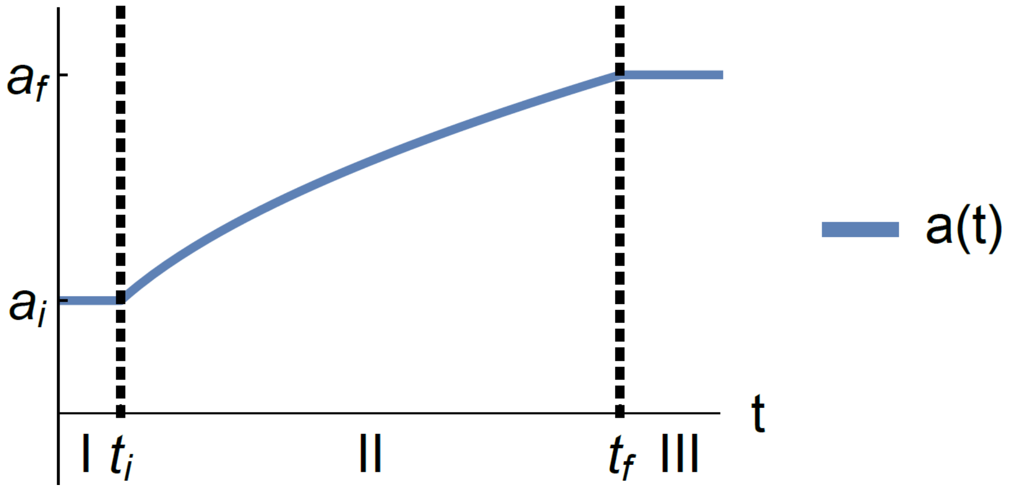
What a problematic question...

Consider the following realization

Particle production at t_f is

$$\langle 0_\mathrm{a}|\hat{b}_{\boldsymbol{k}}^{+}\hat{b}_{\boldsymbol{k}}|0_\mathrm{a}\rangle \neq 0$$

But... How many particles are at $t < t_f$?



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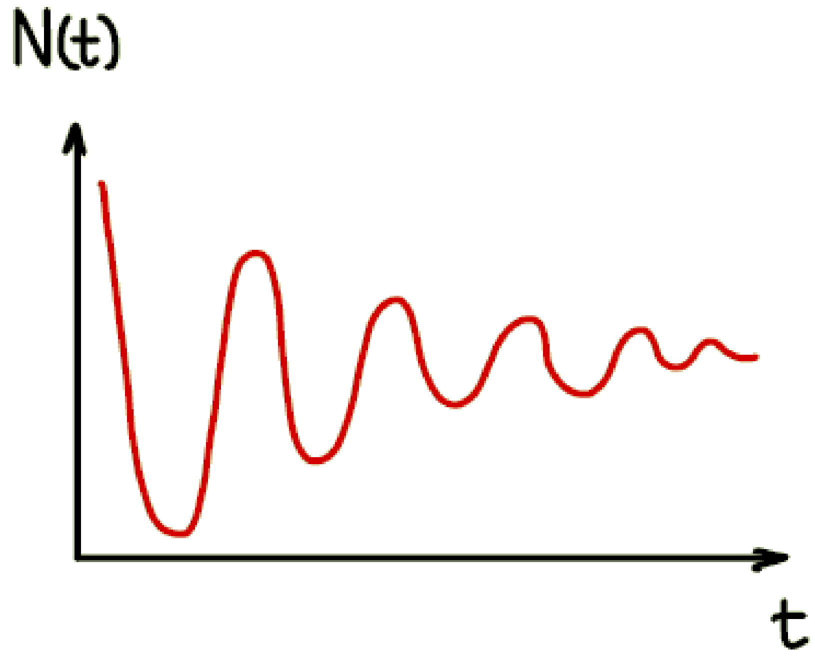
Depends on the choice of vacuum

- Vacua minimizing energy



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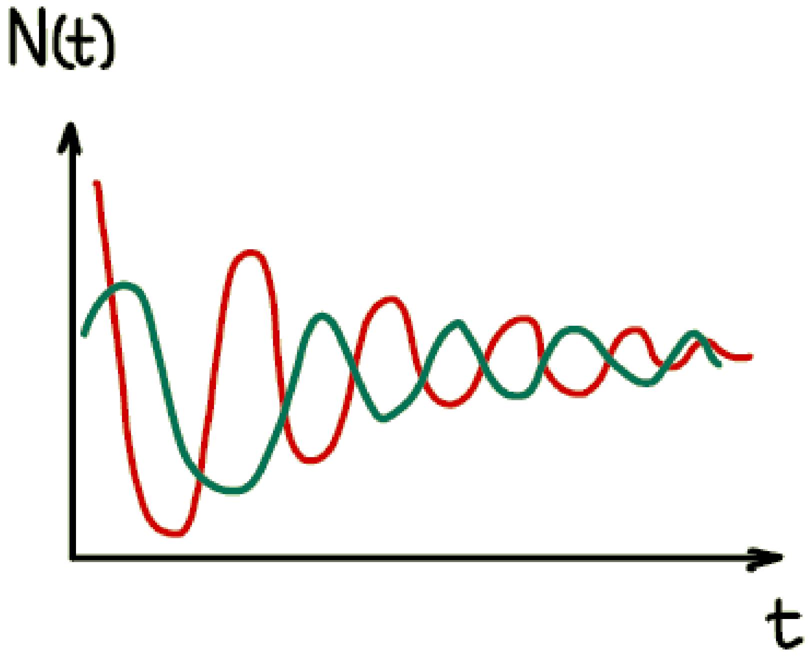
- Vacua minimizing energy
- Adiabatic vacua



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- Vacua minimizing energy
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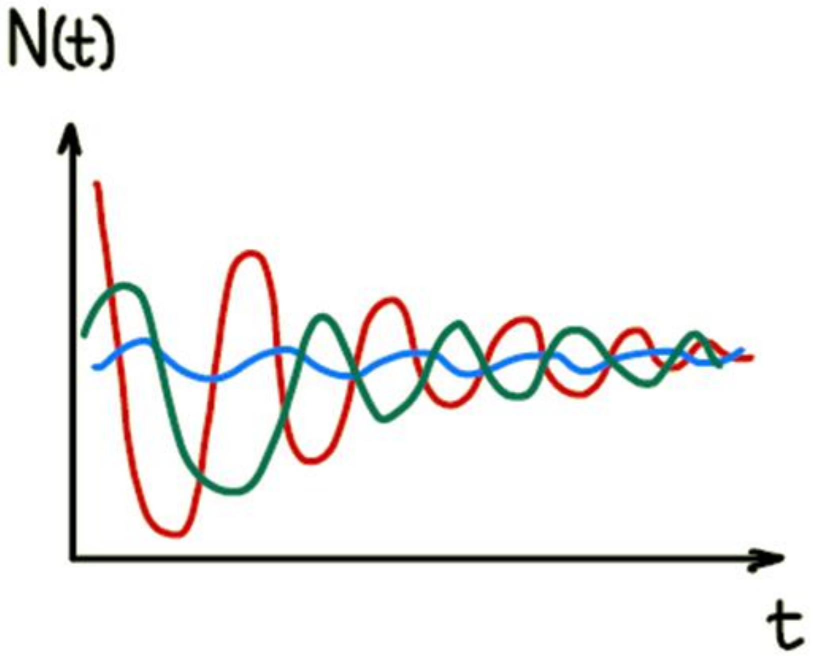
- Vacua minimizing time oscillations of particle number
- …



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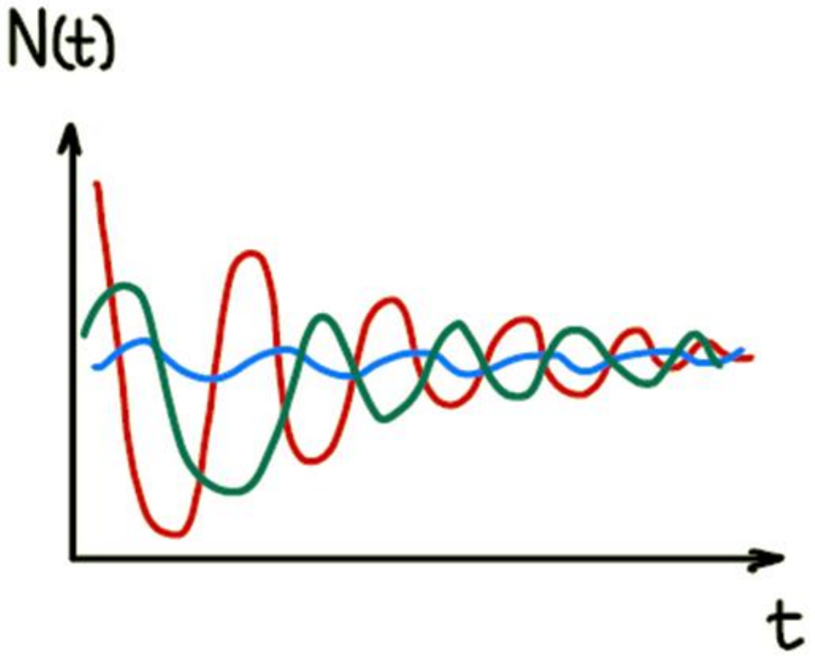
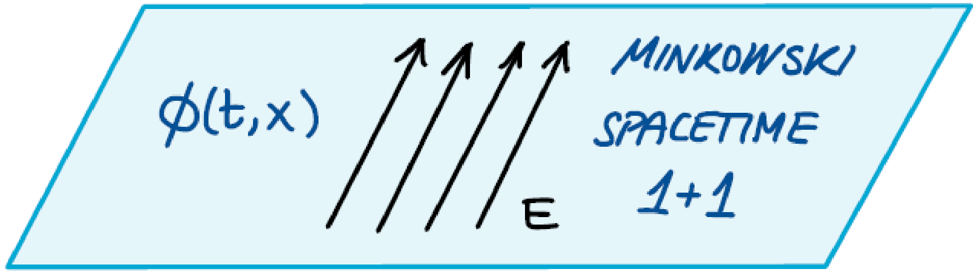


Can we use the fact that we want to measure to give an operational meaning to some of these notions of ‘particle’?

Schwinger effect in 1+1

- Scalar field $\phi(t,x)$ in the presence of a homogeneous electric field $\mathrm{E}(t)$

$$\phi(t,x) = \frac{1}{\sqrt{2\pi}} \int dk\, e^{ikx} \phi_k(t)$$



- EOM in k-space yields the mode equation

$$\ddot{\phi}_k(t) + \omega_k(t)^2 \phi_k(t) = 0$$

Time-dependent

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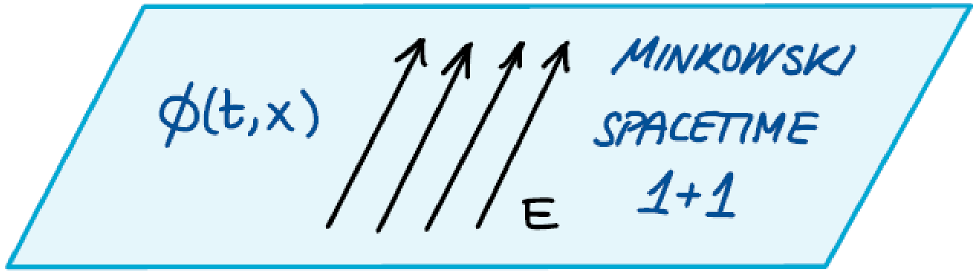

Careful: The external agent here is the **electric potential**

- We can expand the field with each particular solution of the mode equation,

$$\phi(t,x) = \frac{1}{\sqrt{2\pi}} \int dk \left[a_k e^{ikx} \varphi_k(t) + b_k^* e^{-ikx} \varphi_k^*(t)\right]$$
$$= \frac{1}{\sqrt{2\pi}} \int dk \left[c_k e^{ikx} \zeta_k(t) + d_k^* e^{-ikx} \zeta_k^*(t)\right]$$

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Creation and annihilation ops.

- Each solution leads to a different quantum theory, with different annihilation and creation operators, and therefore, different notions of particle and vacuum

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- In Minkowski, Poincarè invariance restricts the choices to plane waves,

$$\varphi_k(t) \sim e^{-i\omega_k t} \to |0_M\rangle; \quad \hat{a}_k^M, \hat{b}_k^M$$

But in the presence of the electric field...

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- Vacua minimizing time oscillations of particle number
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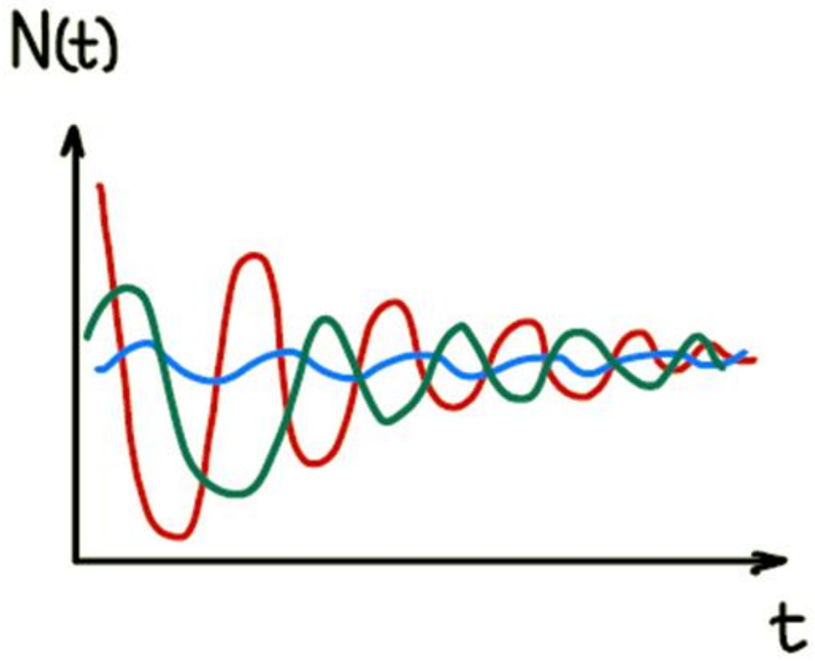
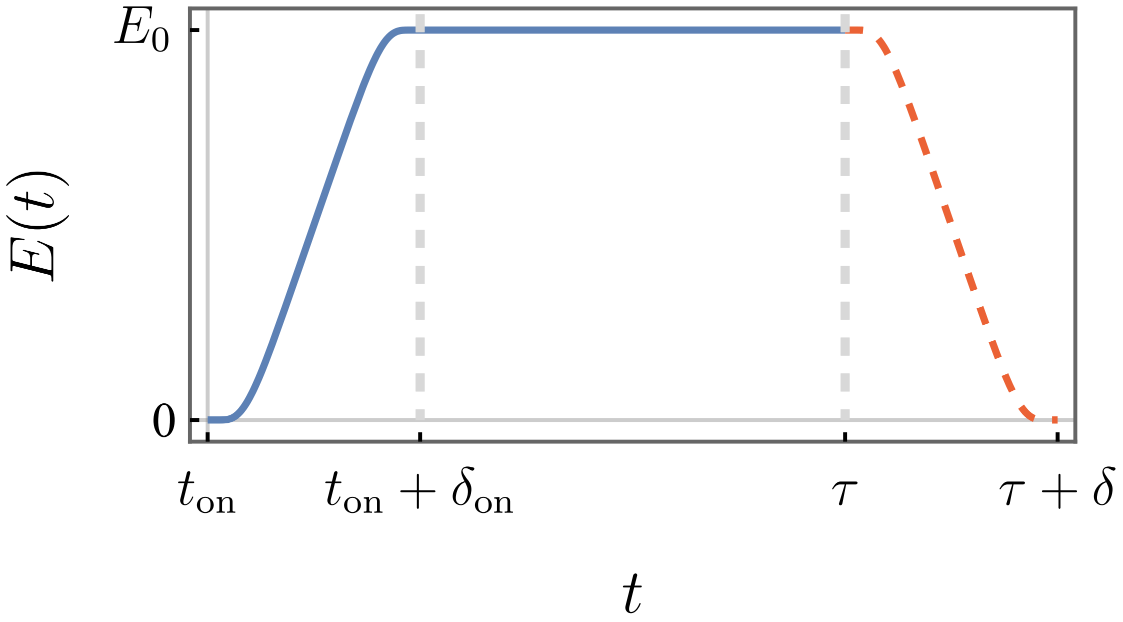


Measured particle number

IN THE 'LAB'

- Smooth switch-on and switch-off



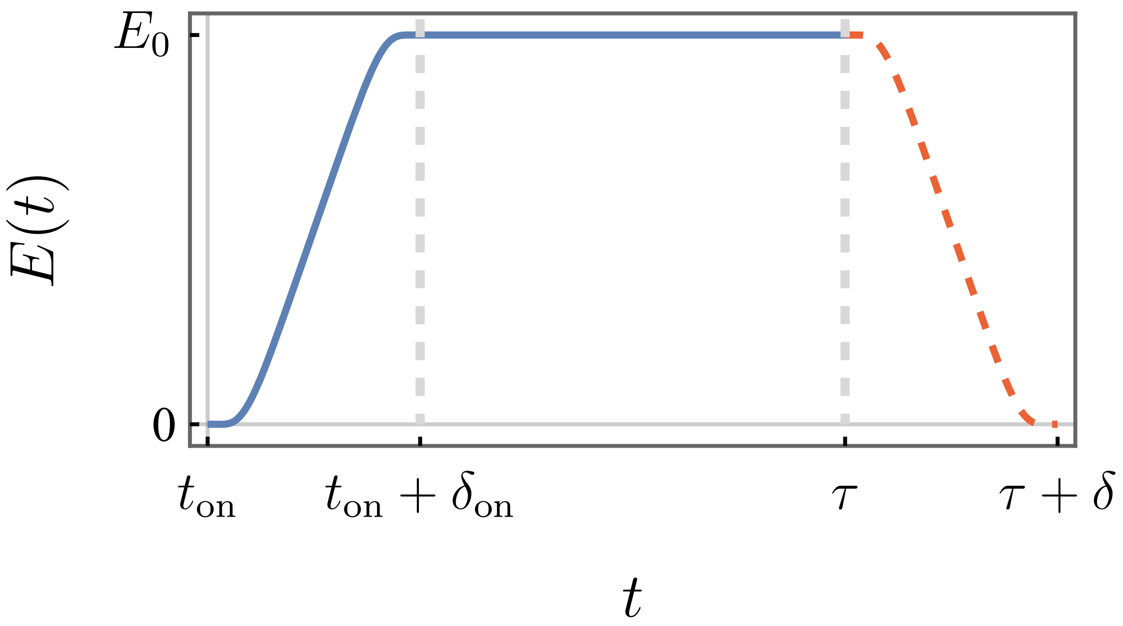
Measured particle number

IN THE 'LAB'

- Smooth switch-on and switch-off
- Preferred notions of vacua in the asymptotic past and future

$$\varphi_k^{\text{in}}(t) \sim e^{-i\omega_k^{\text{in}} t} \Rightarrow |0_{\text{in}}\rangle$$

$$\varphi_k^{\text{out}}(t) \sim e^{-i\omega_k^{\text{out}} t} \Rightarrow |0_{\text{out}}\rangle$$



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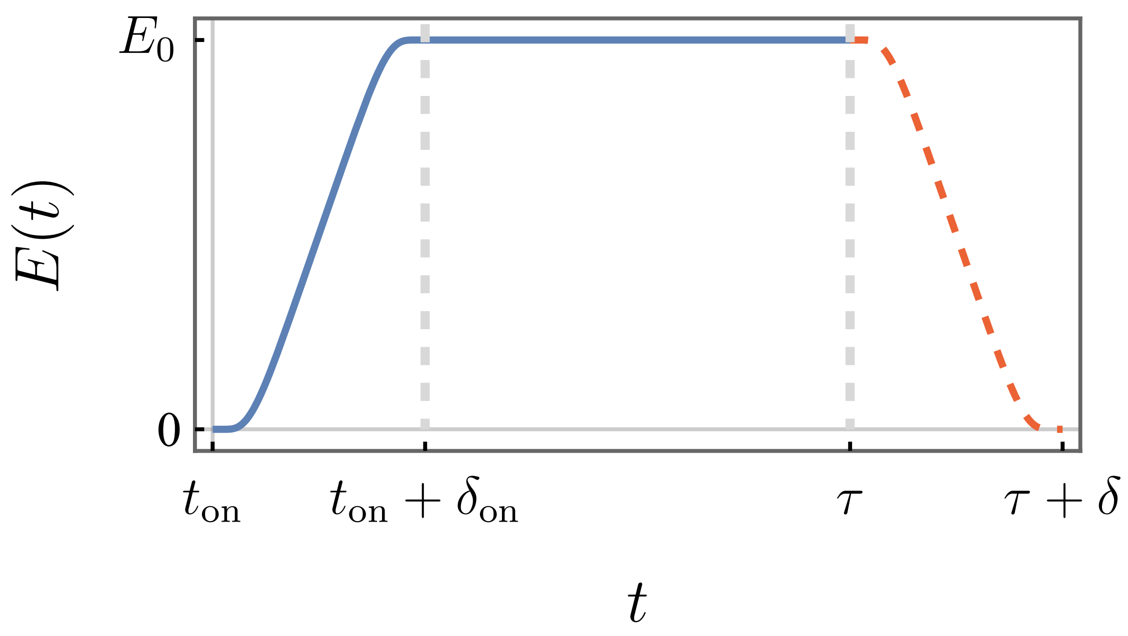

If our system is in $|0_{\text{in}}\rangle$, how many particles have been produced at $\tau + \delta$?

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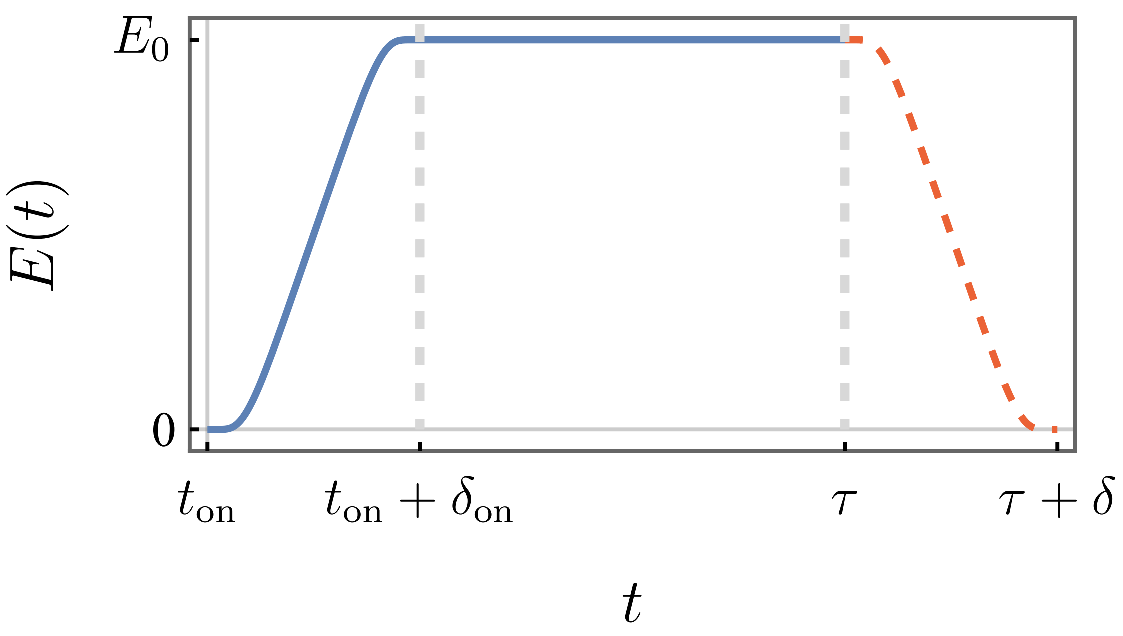

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'Measured' particle number (density)

$$N_\tau^{\text{exp}} = \langle 0_{\text{in}}|\hat{a}_k^{+,\text{out}}\hat{a}_k^{\text{out}}|0_{\text{in}}\rangle + \langle 0_{in}|\hat{b}_k^{+,\text{out}}\hat{b}_k^{\text{out}}|0_{\text{in}}\rangle$$

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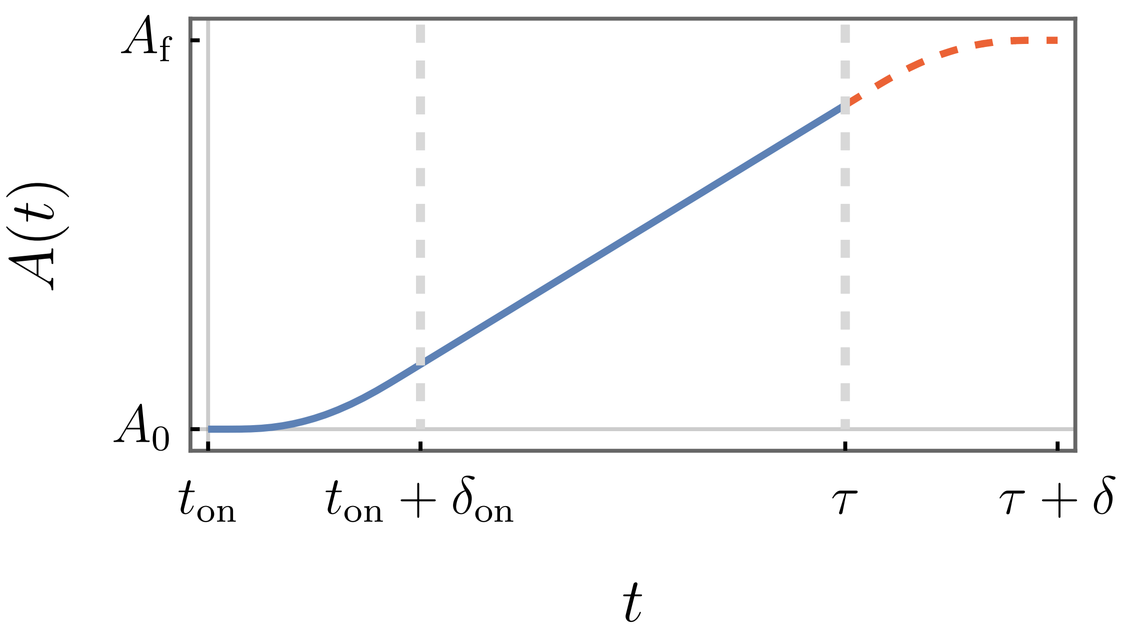

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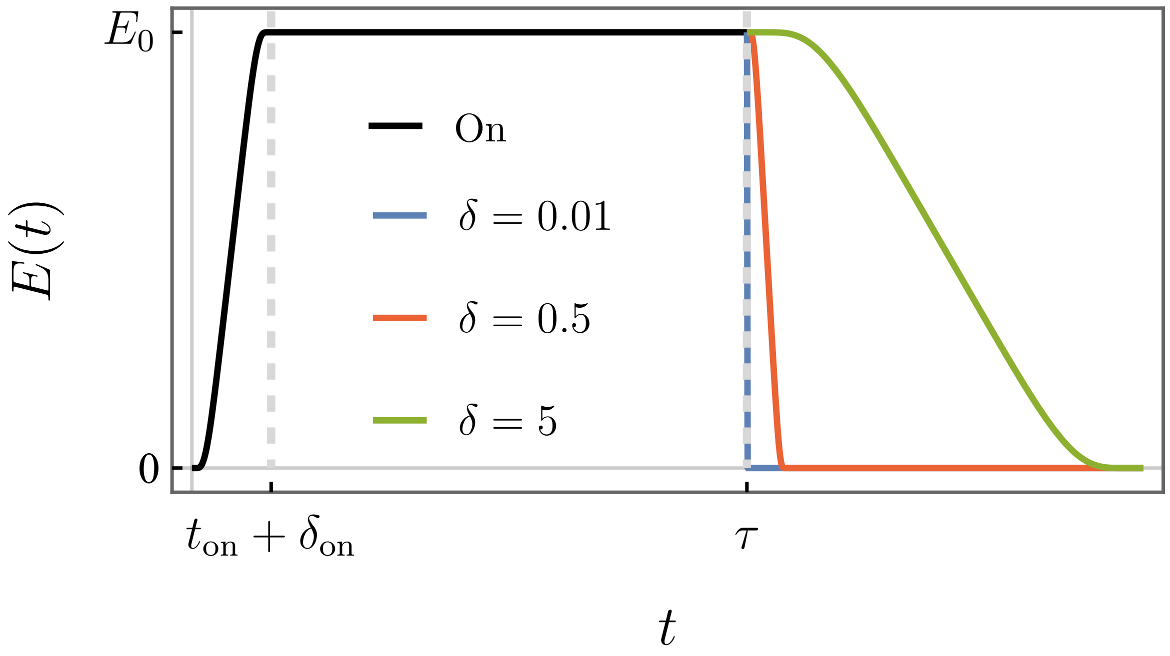
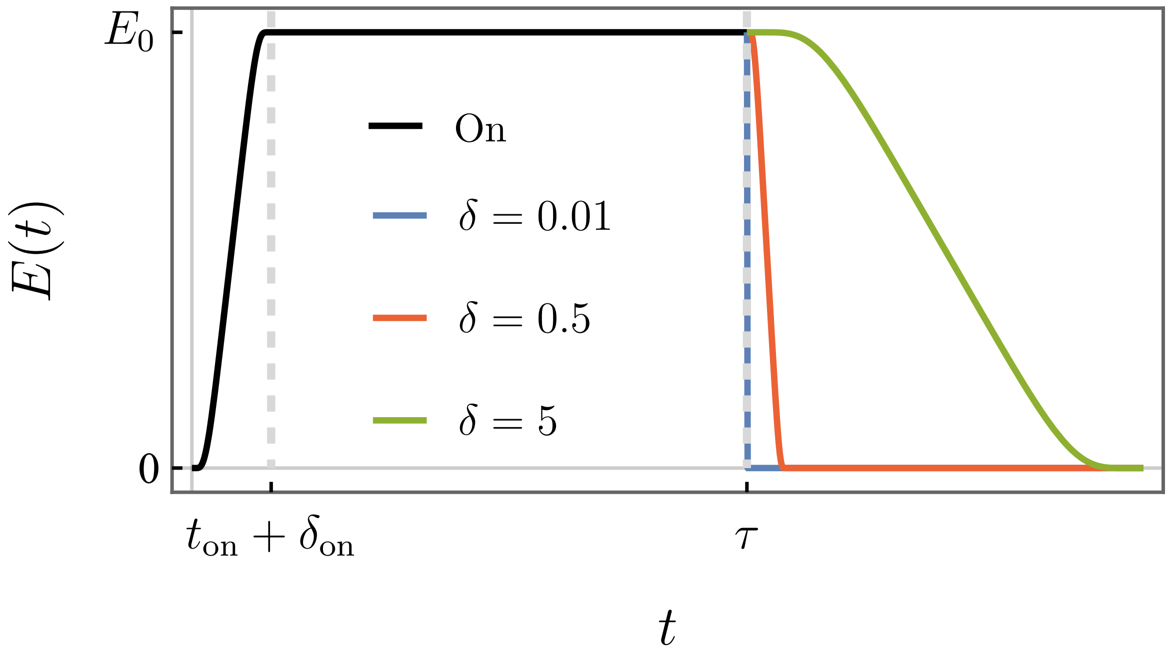


E_0
$E(t)$
On
$\delta = 0.01$
$\delta = 0.5$
$\delta = 5$
0
$t_{\text{on}} + \delta_{\text{on}}$
τ
t

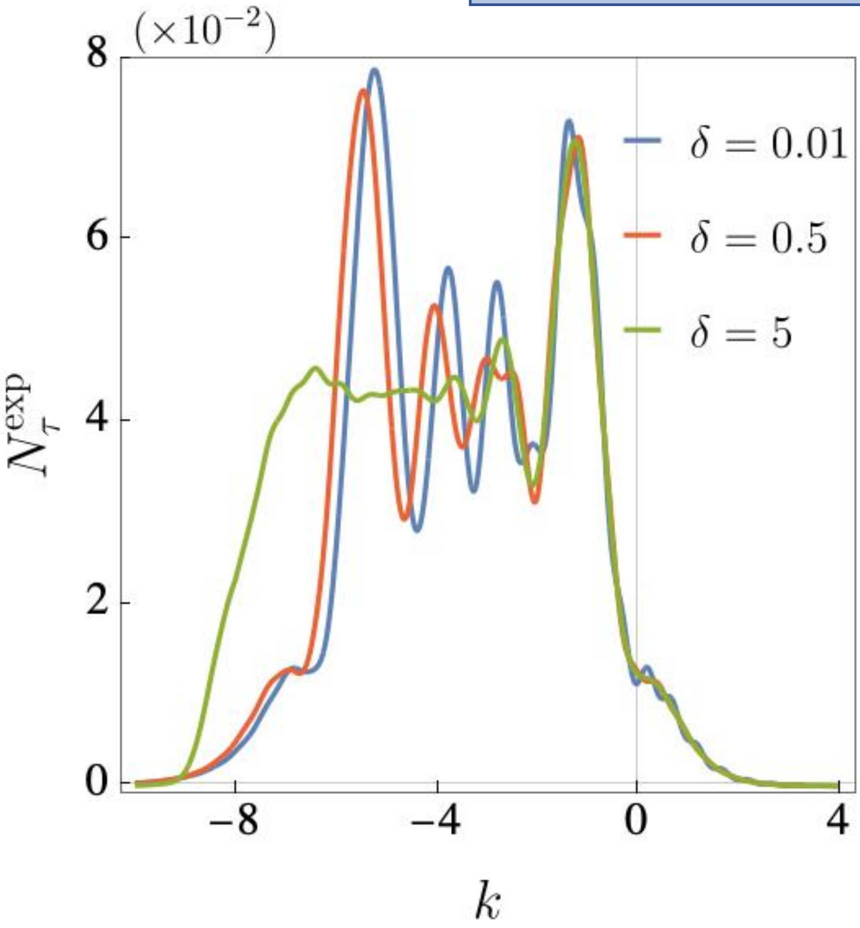


Different switch-off profiles

⬇

Different measured particle number

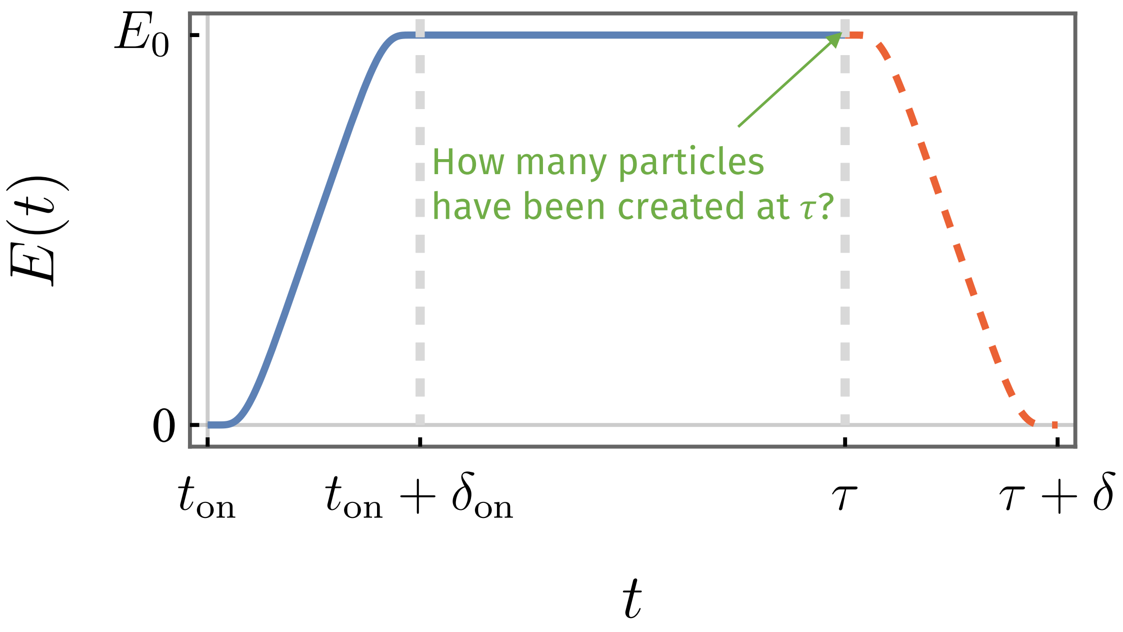
IN THE 'LAB'



(Units of $\delta_{\rm on}$, $\tau = 7, m = 1, qE_0 = 1$)

Theoretical particle number

IN THE OFFICE



Theoretical particle number

IN THE OFFICE

- Preferred notion of vacua in the asymptotic past

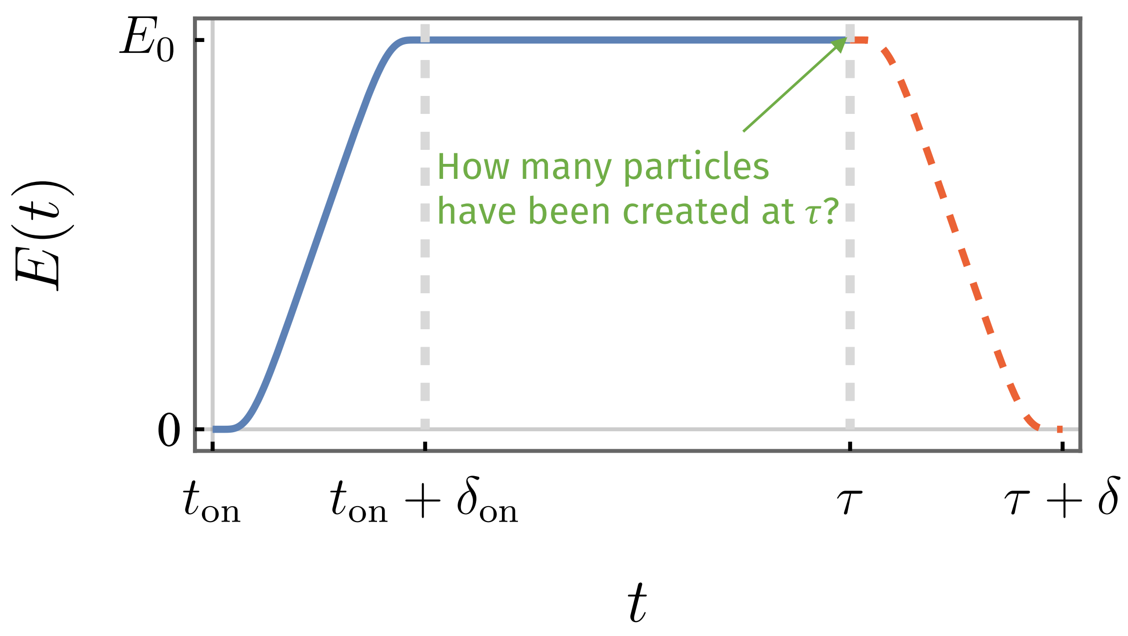
$$\varphi_k^{\text{in}}(t) \sim e^{-i\omega_k^{\text{in}} t} \Rightarrow |0_{\text{in}}\rangle$$

- We have to make a choice of φ_k^τ

$$\varphi_k^\tau(t) \;\Rightarrow |0_\tau\rangle$$

(Initial conditions at τ but defined globally)

If out system is in $|0_{\text{in}}\rangle$, how many particles have been produced at τ?



Theoretical particle number (density)

$$N(\tau) = \langle 0_{\text{in}}|\hat{a}_k^{+,\tau}\hat{a}_k^\tau|0_{\text{in}}\rangle + \langle 0_{in}|\hat{b}_k^{+,\tau}\,\hat{b}_k^\tau|0_{\text{in}}\rangle$$

IN THE 'LAB'

'Measured' particle number (density)

Different measurement procedures/switch-off profiles

IN THE OFFICE

Theoretical particle number (density)

Quantum vacuum ambiguities

IN THE 'LAB'

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We can predict or measure N_τ^{exp}

IN THE ‘LAB’

IN THE OFFICE

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Can we relate them?

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We can predict or measure N_τ^{exp}

From the infinitely many choices of vacuum at τ, there is one, $|0_\tau\rangle$, such that

$$N(\tau) = N_\tau^{\mathrm{exp}}$$

IN THE 'LAB'

IN THE OFFICE

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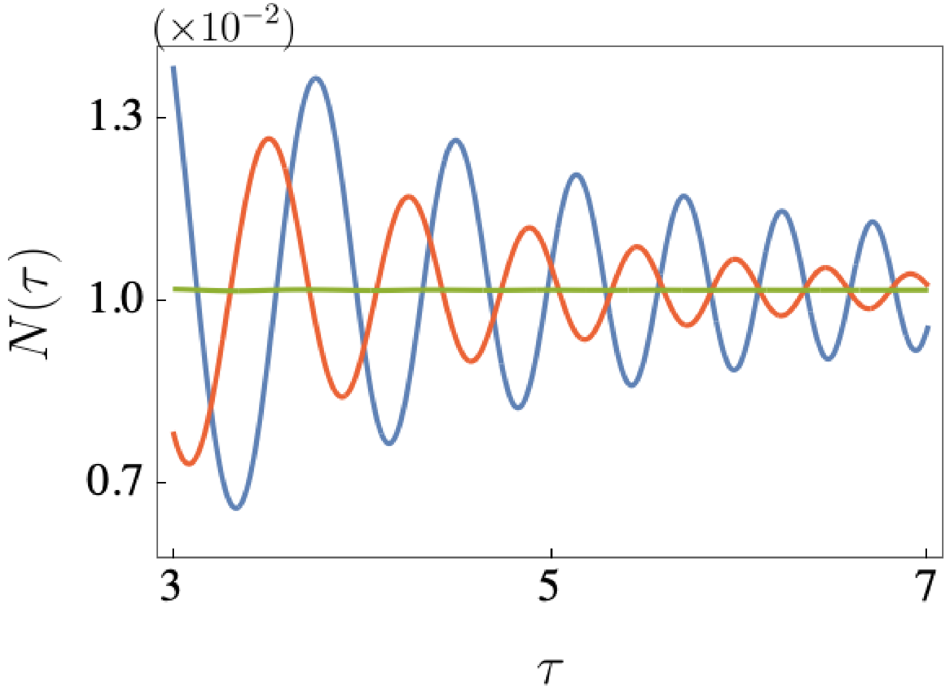
From the infinitely many choices of vacuum at τ, there is one, $|0_\tau\rangle$, such that

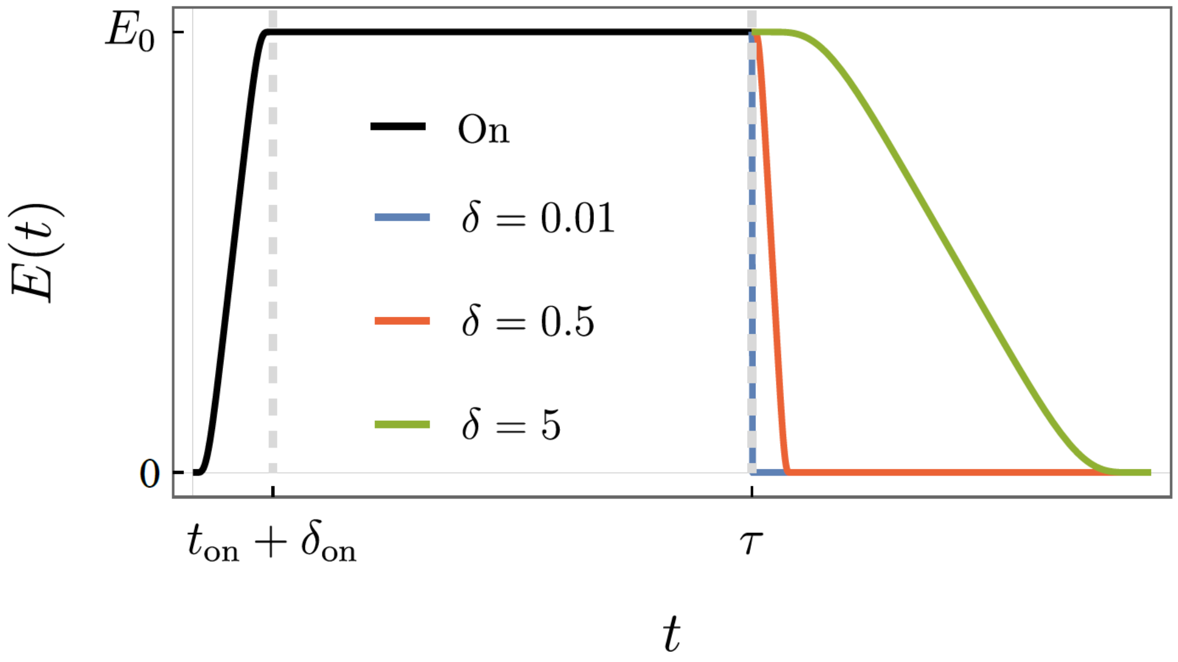
$$N(\tau) = N_\tau^{\text{exp}}$$

This vacuum has a well-defined meaning

Consider we repeat this for any other $t = \tau$. Given a switch-off profile δ, I have an rule that selects a particular vacuum $|0_{t=\tau}\rangle$ such that $N(\tau)$ has a well-defined physical meaning:

$N(\tau)$ is the number of particles that would have been measured if we had started the switch-off process at τ





(Units of δ_{on}, $\tau = 7, m = 1, qE_0 = 1, k = 0.5$)

Summary

- Quantum ambiguities arise in QFT in the presence of an external, time-dependent agent
- Particle number notion depends on the choice of vacuum
- Each measurement procedure/switching-off profile δ selects a vacuum $|0_\tau\rangle$ for which $N(\tau)$ has a well-defined physical meaning
- From the infinitely many quantizations, there is a family which accomodates information about real outcomes, i.e., they can be understood in terms of a measurement procedure
- Canonical quantum ambiguities are inherently physical: They are intimately related to the different ways of measuring

If you are still interested...

arXiv:2303.07436