

Cosmological Particle Production

- From dark matter creation in the early universe to quantum field simulation in the laboratory-

Álvaro Parra-López · alvarop@uio.no

Theory Section, University of Oslo

Before: *Institute of Theoretical Physics (IFT) UAM-CSIC*

(Even before: *Complutense University of Madrid & IPARCOS*)



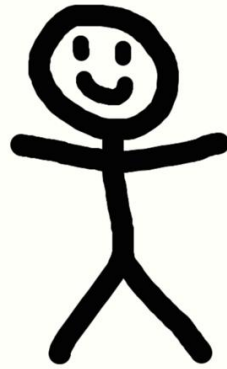
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Theory seminars, UiO, November 2025

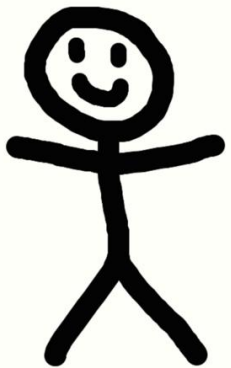


FUNDACIÓN
RAMÓN ARECES

Who am I?



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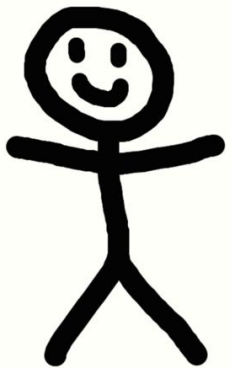
I work in cosmological settings (early Universe), but I am not a pure **cosmologist**

I work with QFT, but I am not a **particle physicist** (yet!)

I work with Bose-Einstein condensates, but I don't come from **Condensed Matter**

I study entanglement, but I am not a **(Relativistic) Quantum Information** guy...

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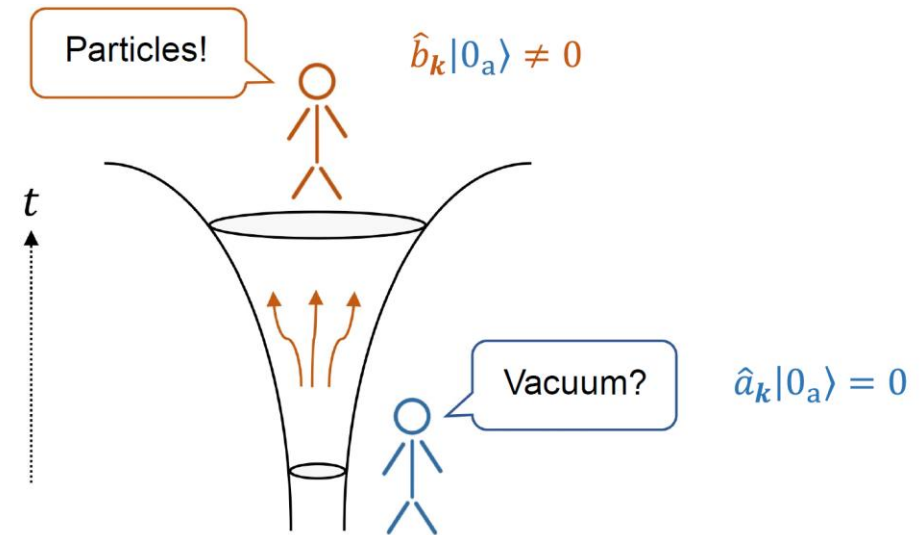
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I have focused on **particle production (and entanglement) in the context of QFT in curved spacetimes**, in both cosmological scenarios and analog gravity experiments in BECs

So maybe I am a bit of everything... Or none of that ;)

Introduction

- Spontaneous pair creation is a well-known prediction of QFT in curved spacetimes
- We denote by **cosmological production** the one due to a time-dependent geometry, affecting all fields on top of the expanding background
- The more *violent* the expansion, the more important the production (early Universe)
- Cosmological production seems a suitable mechanism for **dark matter** production
- These scenarios can be reproduced in **analog gravity** experiments



Contents

- I. Basics of (analog) cosmological particle production
- II. Cosmological production of (dark matter) particles in the early Universe
- III. Experimental realization of analog cosmological production
- IV. A bridge between the Universe and the laboratory
- V. Conclusions

I. Basics of (analog) cosmological particle production

Scalar field in a **flat** (1+**3**) FLRW background

- Non-minimally coupled spectator scalar field

$$S = -\frac{1}{2} \int dt d^3x \sqrt{-g} [g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + (m^2 + \xi R) \varphi^2]$$

- Rescaled field expanded in Laplace-Beltrami operators $-\Delta e^{-i\mathbf{k}\mathbf{x}} = k^2 e^{-i\mathbf{k}\mathbf{x}}$

$$\chi(\eta, \mathbf{x}) = a(\eta) \varphi(\eta, \mathbf{x})$$

$$\chi(\eta, \mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}} e^{-i\mathbf{k}\mathbf{x}} [a_{\mathbf{k}} v_k(\eta) + a_{-\mathbf{k}}^* v_k^*(\eta)]$$

Only depends on the eigenvalue

- Mode equation with time-dependent frequency $v_k''(\eta) + \omega_k^2(\eta) v_k(\eta) = 0$,

$$\omega_k^2(\eta) = k^2 + m^2 a^2(\eta) + \frac{1 + (4\xi - 1)3}{2} \frac{a''(\eta)}{a(\eta)}$$

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$$\omega_k^2(\eta) = k^2 + a^2(\eta) [m^2 + (\xi - 1/6) R(\eta)], \quad 1/6 \leq \xi \leq 1$$

- We can expand χ with **any basis** of solutions of the mode equation

$$\chi(\eta, \mathbf{x}) = \int \frac{d^3 \mathbf{k}}{(2\pi)^{3/2}} e^{i\mathbf{k}\mathbf{x}} [a_{\mathbf{k}} v_{\mathbf{k}}(\eta) + a_{-\mathbf{k}}^* v_{\mathbf{k}}^*(\eta)] = \int \frac{d^3 \mathbf{k}}{(2\pi)^{3/2}} e^{i\mathbf{k}\mathbf{x}} [b_{\mathbf{k}} u_{\mathbf{k}}(\eta) + b_{-\mathbf{k}}^* u_{\mathbf{k}}^*(\eta)]$$

- Mode functions and coefficients are related by a **Bogoliubov** transformation

$$u_{\mathbf{k}} = \alpha_k v_{\mathbf{k}} + \beta_k v_{\mathbf{k}}^*, \quad b_{\mathbf{k}} = \alpha_k^* a_{\mathbf{k}} - \beta_k^* a_{-\mathbf{k}}^*$$

- Quantization promotes coefficients to creation and annihilation operators
- Depending on the choice of basis, we end up with different quantum theories

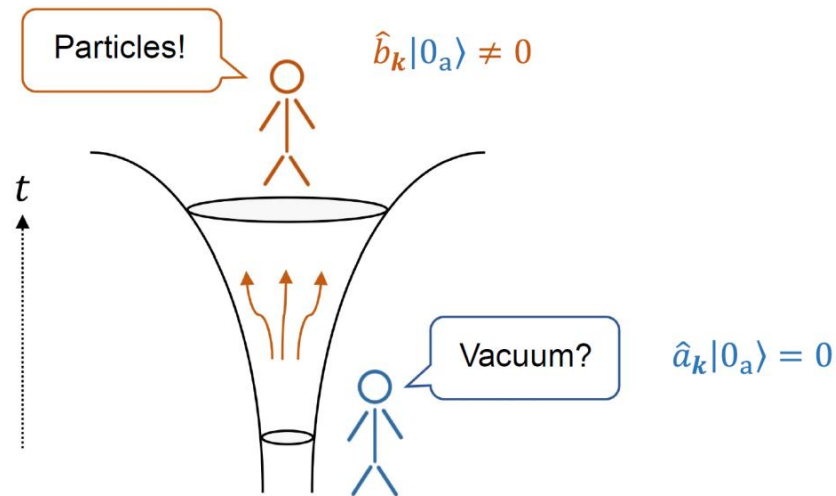
$$\hat{a}_{\mathbf{k}} |0^a\rangle = 0, \quad \forall \mathbf{k} \quad \langle 0^a | \hat{b}_{\mathbf{k}}^\dagger \hat{b}_{\mathbf{k}} | 0^a \rangle = |\beta_k|^2 \mathcal{V} \quad \text{Volume term}$$

- We can expand χ with **any basis** of solutions of the mode equation

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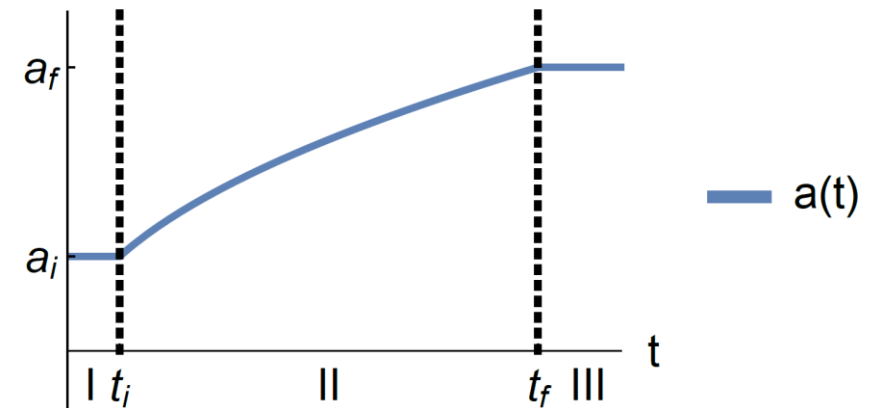
Number density of produced particles with eigenvalue k

$$n_k = |\beta_k|^2$$

Particle production as an *in-out* process

- A priori, no preferred quantization, but **symmetries** can restrict this choice
- Consider locally static **in** and **out** regions
- Observers in these regions (I and III) have preferred notions of vacuum (Minkowski-like)

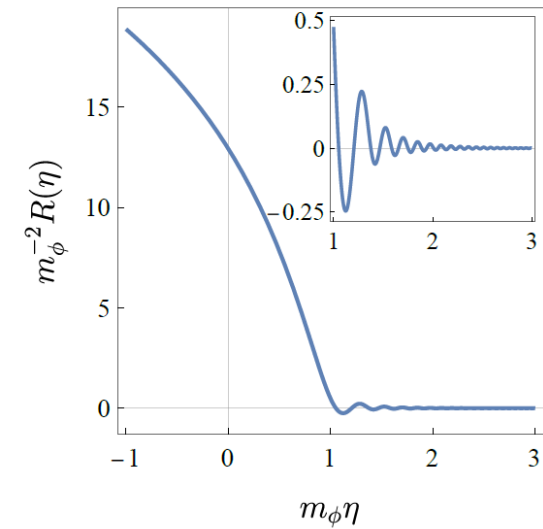
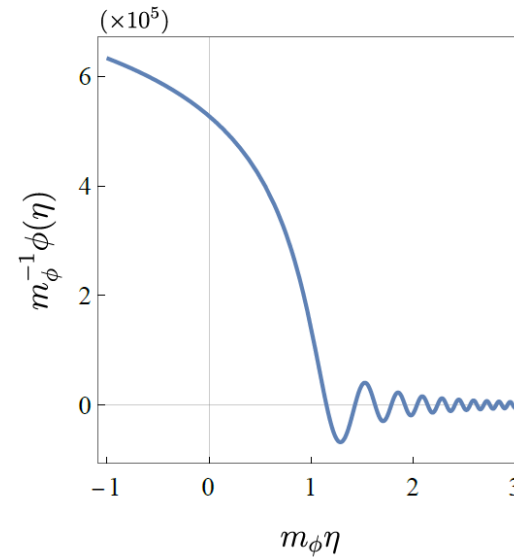
$$v_k = \frac{1}{\sqrt{2\omega_{k,i}}} e^{-i\omega_{k,i}\eta}, \quad \text{for } \eta \leq \eta_i$$
$$u_k = \frac{1}{\sqrt{2\omega_{k,f}}} e^{-i\omega_{k,f}\eta}, \quad \text{for } \eta \geq \eta_f,$$



II. Cosmological production of (dark matter) particles in the early Universe

Single field slow-roll inflation

- **Slow-roll** at the beginning of inflation
- Transition to reheating at $t = \eta = 0$
- Ricci **oscillations relevant** for production
- Scale factor is quasi-exponential at the beginning, matter-dominated at the end



Scalar field in a **flat** (1+3) FLRW background

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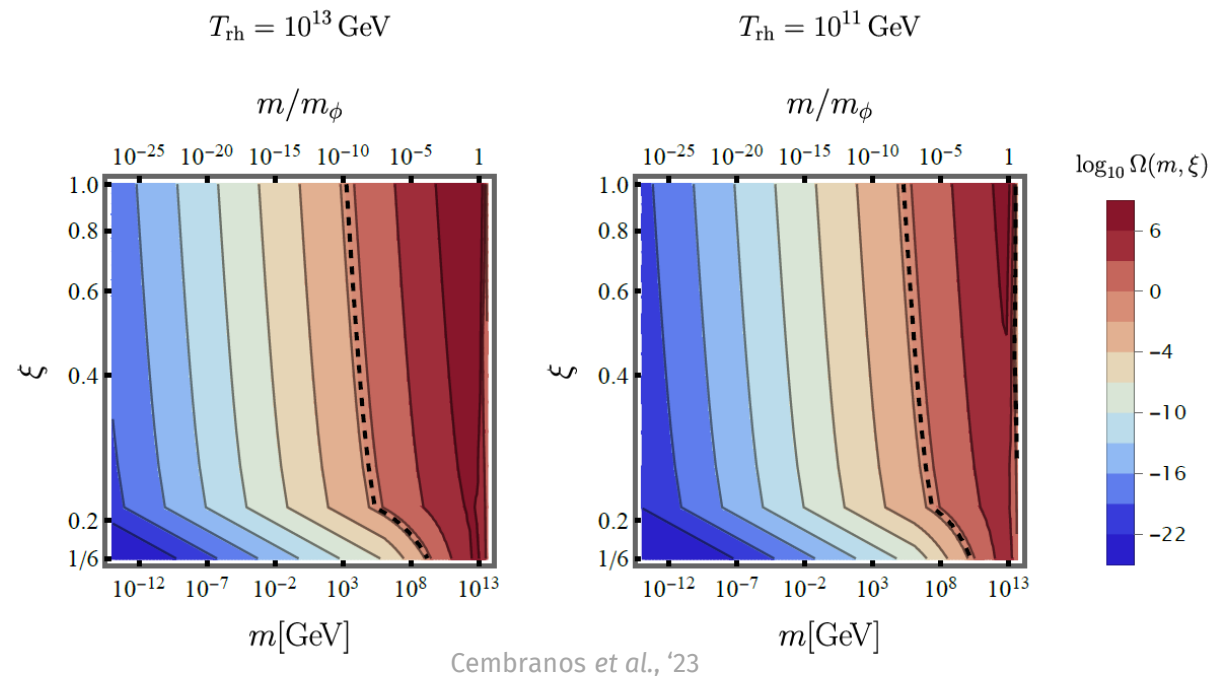
Choice of *in* and *out* modes

- Geometry is approximately **de Sitter** during slow-roll
- The natural vacuum at the beginning of inflation is **Bunch-Davies** Bunch & Davies, 78
- η_f is the time when production is **negligible** $\mathcal{C}_k(\eta_f) = \left| \frac{\omega'_k(\eta_f)}{\omega_k^2(\eta_f)} \right| \ll 1$
- **Adiabatic vacuum** is a good prescription

$$u_k(\eta_f) = \frac{1}{\sqrt{2\omega_k(\eta_f)}}, u'_k(\eta_f) = -\frac{1}{\sqrt{2\omega_k(\eta_f)}} \left(i\omega_k(\eta_f) + \frac{1}{2} \frac{\omega'_k(\eta_f)}{\omega_k(\eta_f)} \right)$$

Produced abundance

- If the spectator field does not interact, the produced density leads to a relic **abundance**
- For a given **temperature** at the end of reheating, the abundance can be extrapolated to today

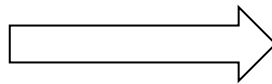


III. Experimental realization of analog cosmological production

Quantum fluids simulate quantum fields in curved spacetimes

- Fields propagate on top of a non-trivial background as **perturbations on a fluid** Unruh, '81
- The **dynamics** of quantum fields can be simulated with quantum fluids
- Polariton fluids, superfluid helium or **Bose-Einstein condensates** Garay et al., '00

Can simulate quantum fields
in **cosmological** backgrounds



Real world	BEC experiment
Spacetime geometry	Background parameters
FLRW metric	Acoustic metric
Massless scalar particles	Phonons

Phononic fluctuations = Scalar field in curved spacetime

Specific scenario: 1+2 dimensions

- Assume low energy excitations (**acoustic regime**) and **stationary** background density

EoM for φ : $-\partial_t(c_s^{-1}\partial_t\varphi) + \partial_i(c_s\partial_i\varphi) = \partial_\mu(\sqrt{-g}g^{\mu\nu}\partial_\nu\varphi)$

Phononic fluctuations

- Rewrite as a Klein-Gordon equation in curved spacetime with **acoustic metric** $g_{\mu\nu}$

Interaction strength $\leftarrow$ Speed of phonons $\leftarrow c_s^2(t, \mathbf{r}) = \frac{\lambda(t) n_0(\mathbf{r})}{m},$
Background density profile $\rightarrow$ Mass of the atoms

$$g_{\mu\nu} = \begin{bmatrix} -1 & 0 \\ 0 & c_s^{-2} \mathbb{1}_2 \end{bmatrix}$$

- Phononic fluctuations behave as a massless scalar field in an effective geometry

- The acoustic line element is determined by the background

$$ds^2 = -dt^2 + \frac{m}{\lambda(t)\bar{n}_0} \frac{\bar{n}_0}{n_0(r)} (dr^2 + r^2 d\phi^2)$$

↓ Density at the center

- The acoustic line element is determined by the background

$$ds^2 = -dt^2 + a^2(t) \frac{\bar{n}_0}{n_0(r)} (dr^2 + r^2 d\phi^2)$$

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 Density at the center

- Consider the following density profiles

$$n_0(r) = \bar{n}_0 \quad \longrightarrow \quad \text{Flat FLRW geometry}$$

$$n_0(r) = \bar{n}_0 \left[1 \mp \frac{r^2}{R^2} \right]^2 \quad \longrightarrow \quad \text{Need to do something about the spatial dependence}$$

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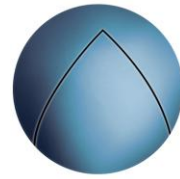
Flat FLRW geometry

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Curved FLRW geometry

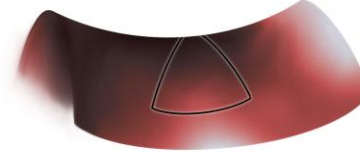
- Spatial curvature depends on the **density profile**, engineered through the trapping potential



$$\kappa > 0$$

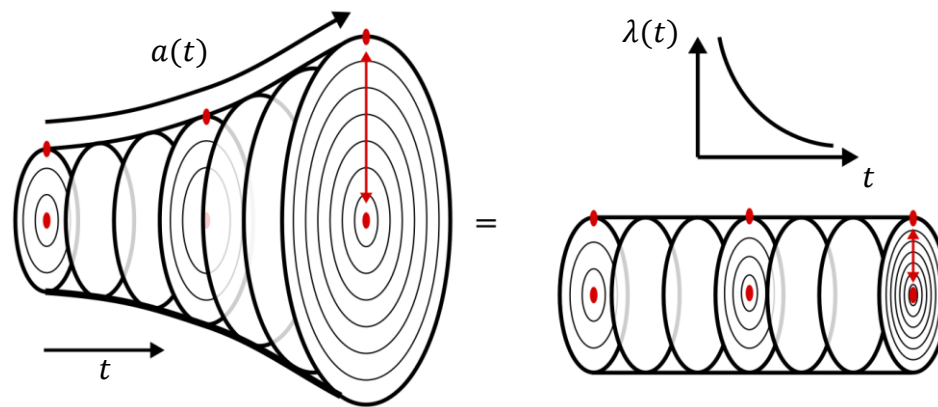


$$\kappa = 0$$



$$\kappa < 0$$

- Scale factor is realized by changing the **interaction strength**



$$a^2(t) = \frac{m}{\lambda(t)\bar{n}_0} \propto \frac{1}{c_s^2}$$

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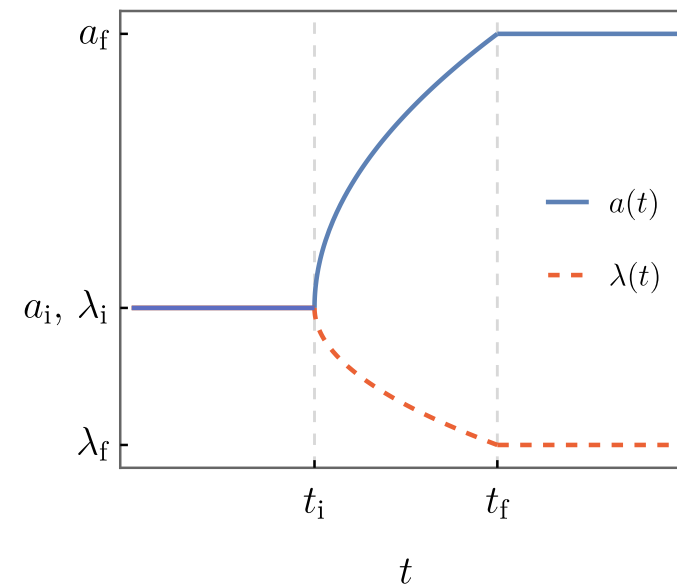
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Particle production as an *in-out* process

- Initial **thermal** occupation $n_k^{\text{in}}(T) = \frac{1}{e^{\hbar\omega_{k,i}/(k_B T)} - 1}$
- In experiments, we **do** have *in* and *out* regions
- Observers in these regions have preferred notions of vacuum (Minkowski-like)

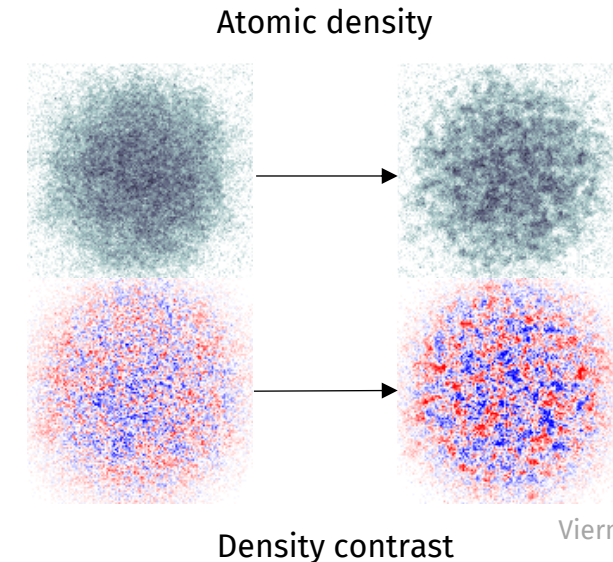
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Viermann et al., '22

Rescaled density contrast and two-point functions

- Define the density contrast

$$\delta_c(t, \mathbf{x}) = (\text{total density}) - (\text{background density})$$

- Compute correlations at $t \geq t_f$

$$\langle \delta_c(t, \mathbf{x}) \delta_c(t, \mathbf{x}') \rangle \propto \langle \{ \hat{\chi}'(t, \mathbf{x}), \hat{\chi}'(t, \mathbf{x}') \} \rangle$$

- The momentum transform of the two-point function is the the spectrum of fluctuations S_k

$$\frac{1}{2} \langle \{ \hat{\chi}'(t, \mathbf{x}), \hat{\chi}'(t, \mathbf{x}') \} \rangle = \int \frac{d^2 \mathbf{k}}{(2\pi)^2} e^{-i\mathbf{k}\mathbf{x}} e^{-i\mathbf{k}\mathbf{x}'} \omega_k(t) S_k(t)$$

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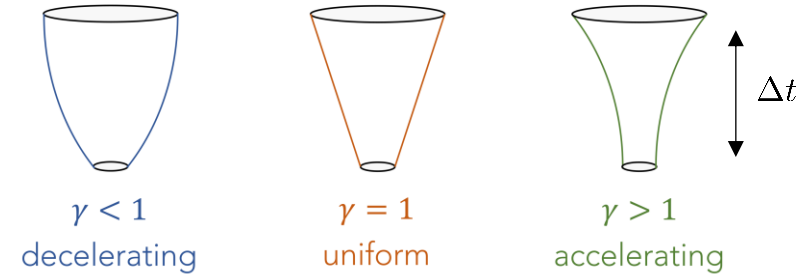
- Write the spectrum in terms of **offset**, **amplitude** and **phase**

$$S_k(t) = S_{k,0} + A_k \cos [2\omega_{k,f} (t - t_f) / a_f + \vartheta_k],$$

$$S_{k,0} = (1 + 2n_k^{\text{in}}) \left[\frac{1}{2} + |\beta_k|^2 \right], \quad A_k = (1 + 2n_k^{\text{in}}) |\alpha_k \beta_k|, \quad \vartheta_k = \arg(\alpha_k \beta_k) + 2\omega_{k,f} t_f / a_f$$

Measurement of cosmological production

- Power-law scale factors $a(t) \propto t^\gamma$

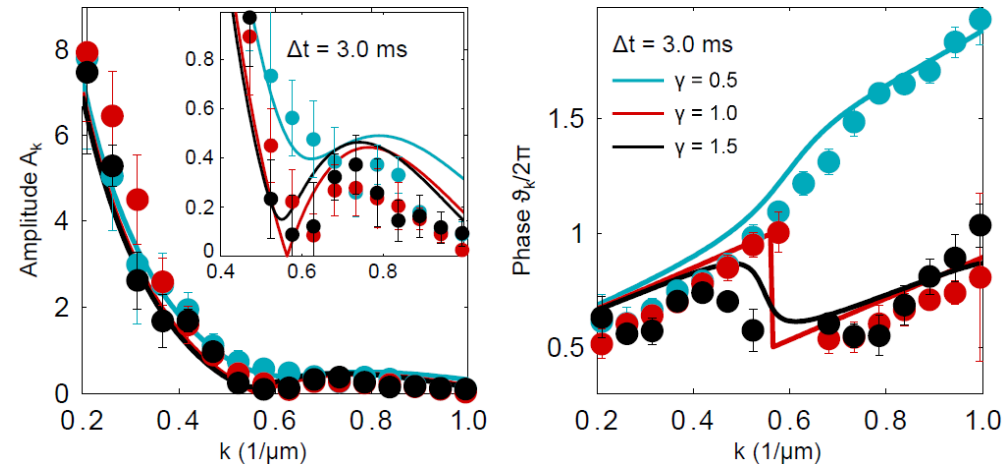


- Amplitude and phase of $S_k(t) = S_{k,0} + A_k \cos [2\omega_{k,f} (t - t_f) / a_f + \vartheta_k]$,

$$A_k = (1 + 2n_k^{\text{in}}) |\alpha_k \beta_k|,$$

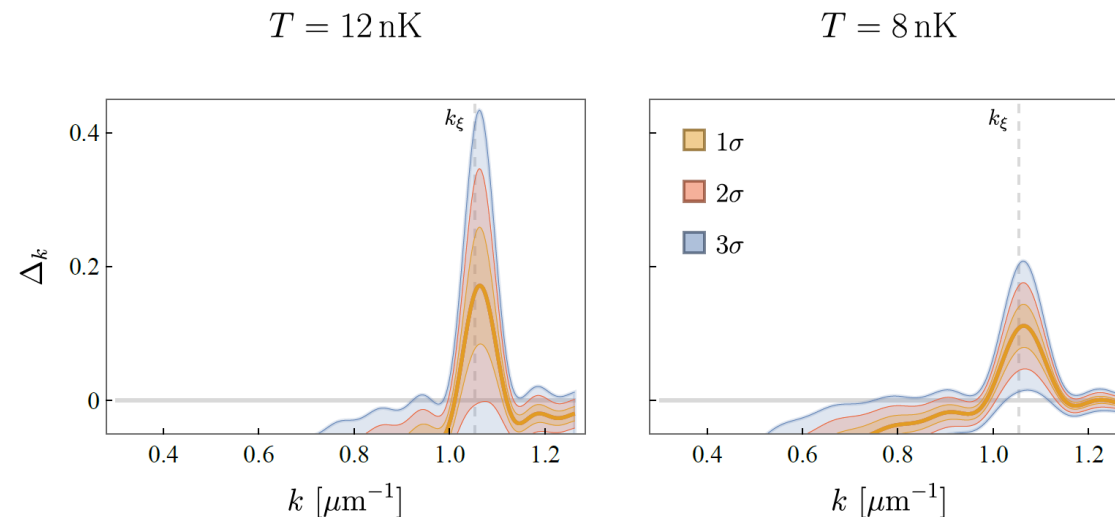
$$\vartheta_k = \arg(\alpha_k \beta_k) + 2\omega_{k,f} t_f / a_f$$

Viermann et al., '22



Entanglement between produced pairs

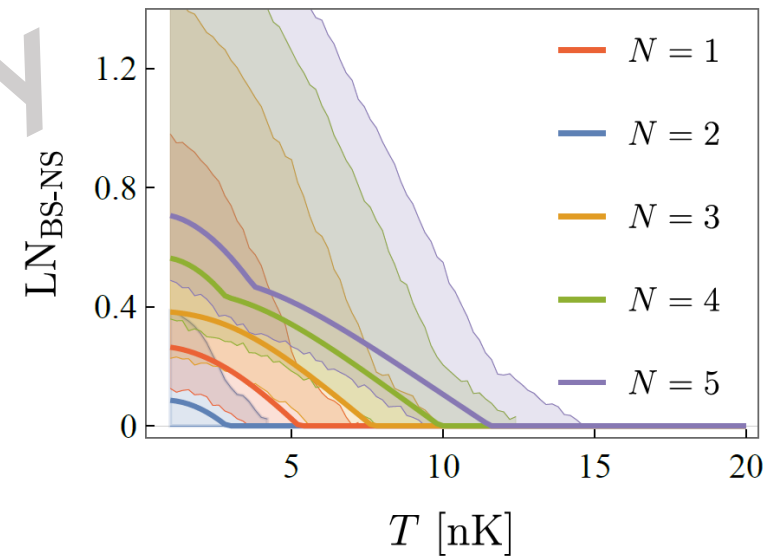
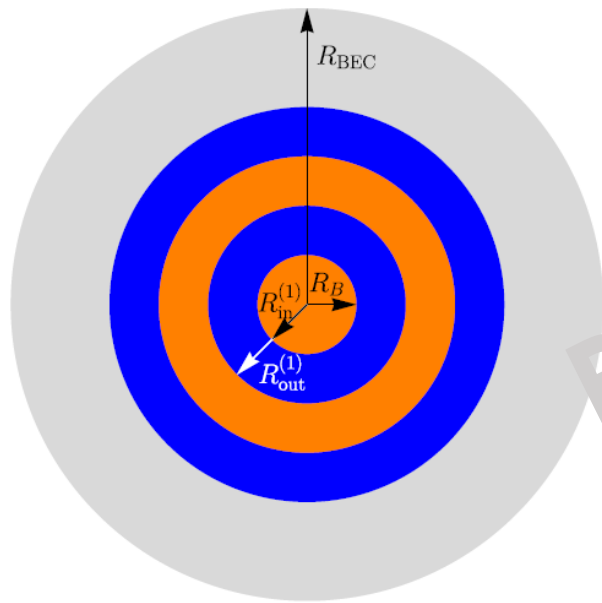
- Density contrast correlations characterize all two-point functions (**covariance matrix**)
- If the state is Gaussian, we have full **state reconstruction** from these measurements
- Build a **Cauchy-Schwarz inequality** $\Delta_k = |\langle \hat{a}_{\mathbf{k}} \hat{a}_{-\mathbf{k}} \rangle|^2 - \langle \hat{a}_{\mathbf{k}}^\dagger \hat{a}_{\mathbf{k}} \rangle \langle \hat{a}_{-\mathbf{k}}^\dagger \hat{a}_{-\mathbf{k}} \rangle > 0 \Rightarrow \text{Entanglement!}$



Agullo et al., '24

Entanglement between modes supported in different spatial regions

- Several configurations can be explored with these kind of setups
- For example, the entanglement between modes in a ball-shell configuration (in Minkowski)

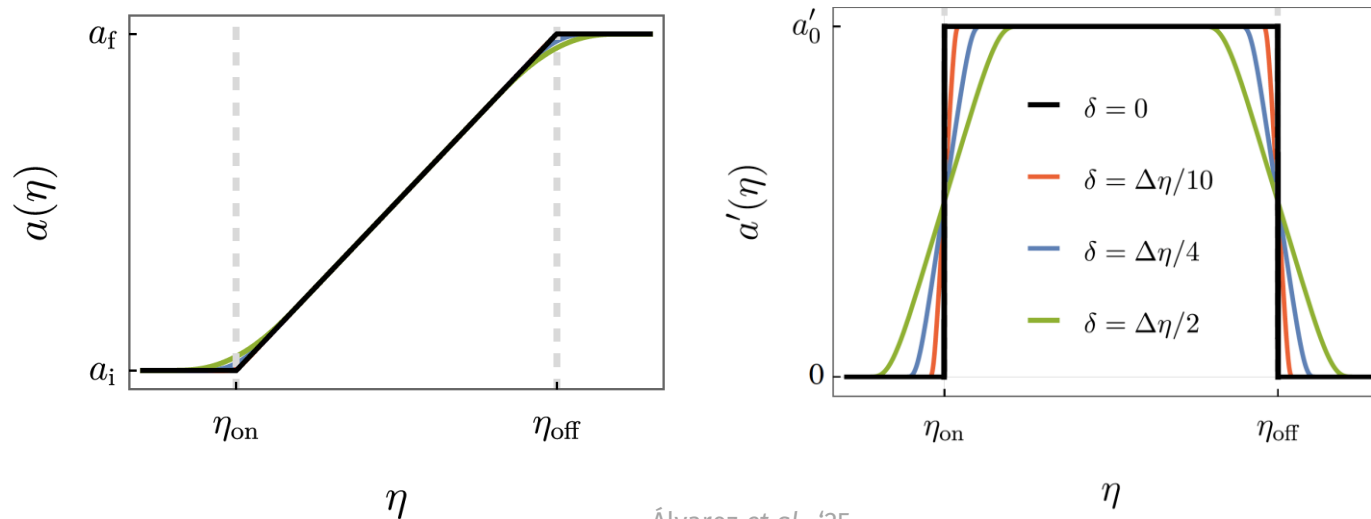


Agullo et al., In preparation

IV. A bridge between the Universe and the laboratory

'On' and 'off' transitions

- Slow-roll and transition to reheating after inflation can be understood as 'on' and 'off' transitions, as the ones we have in analog experiments
- What is their importance relative to the region in between?

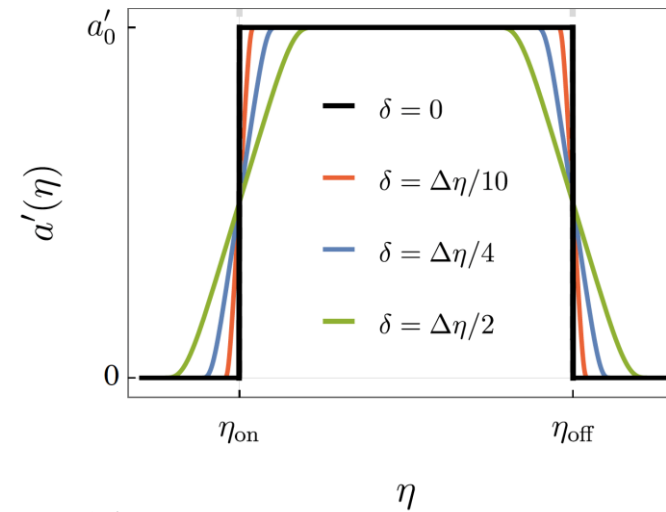
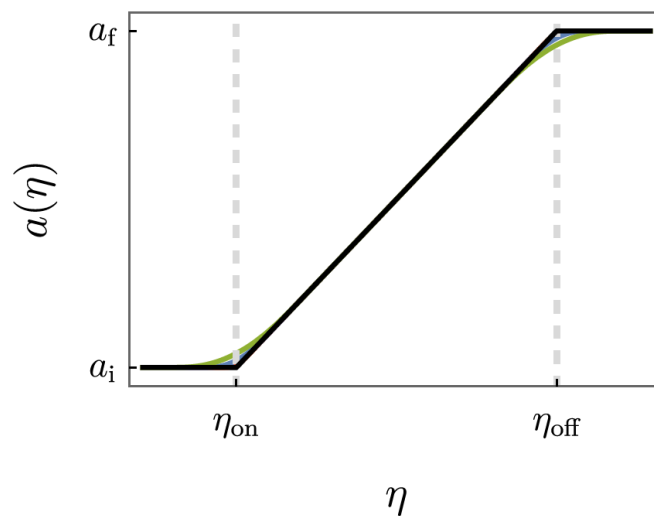


Álvarez et al., '25

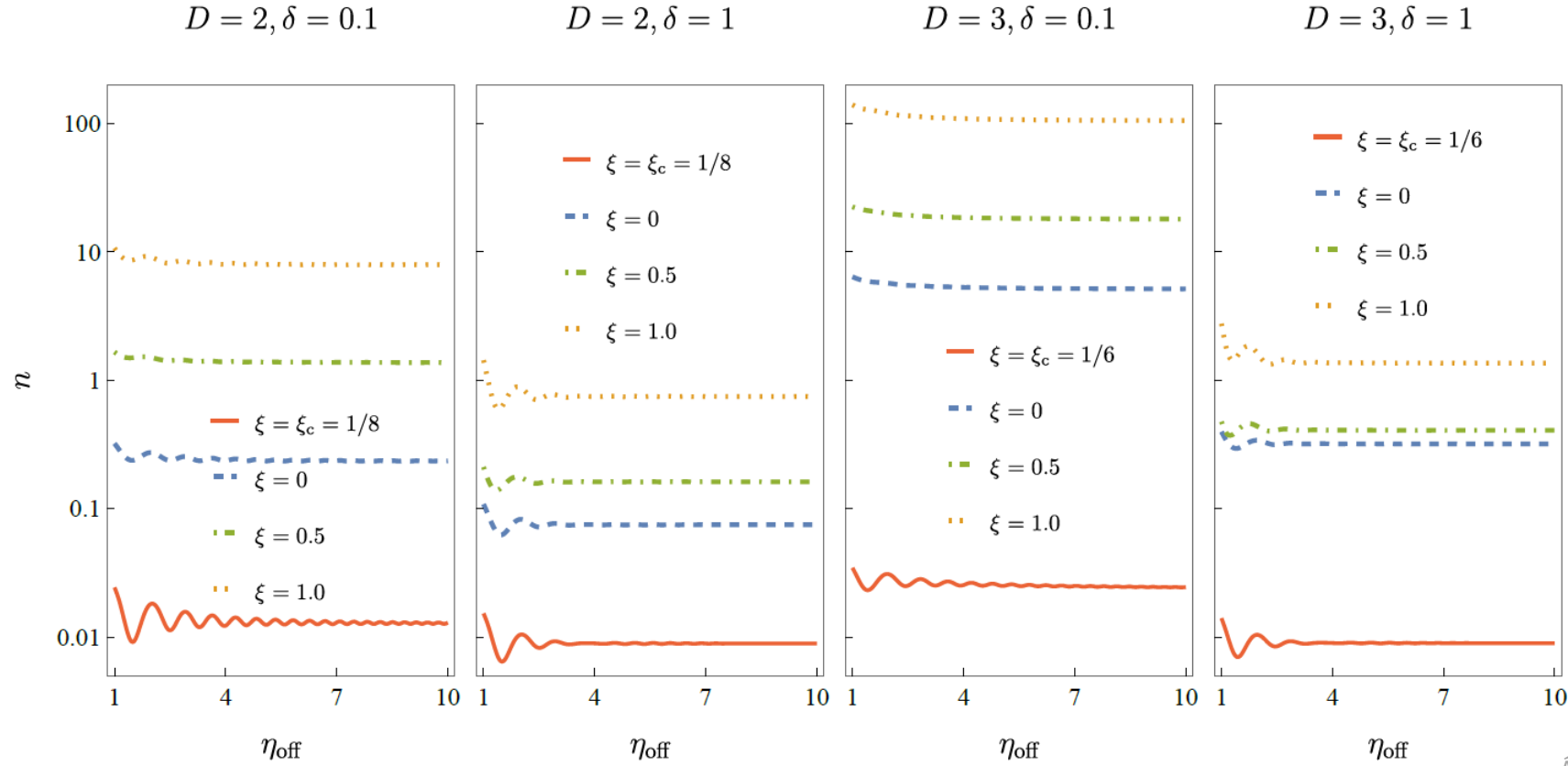
'On' and 'off' transitions

- Consider **symmetric** 'on' and 'off' transitions of different duration and a **linear** scale factor in between

$$a'(\eta) = a'_0 [\Theta_\delta(\eta - \eta_{\text{on}} - \delta/2) - \Theta_\delta(\eta - \eta_{\text{off}} + \delta/2)]$$

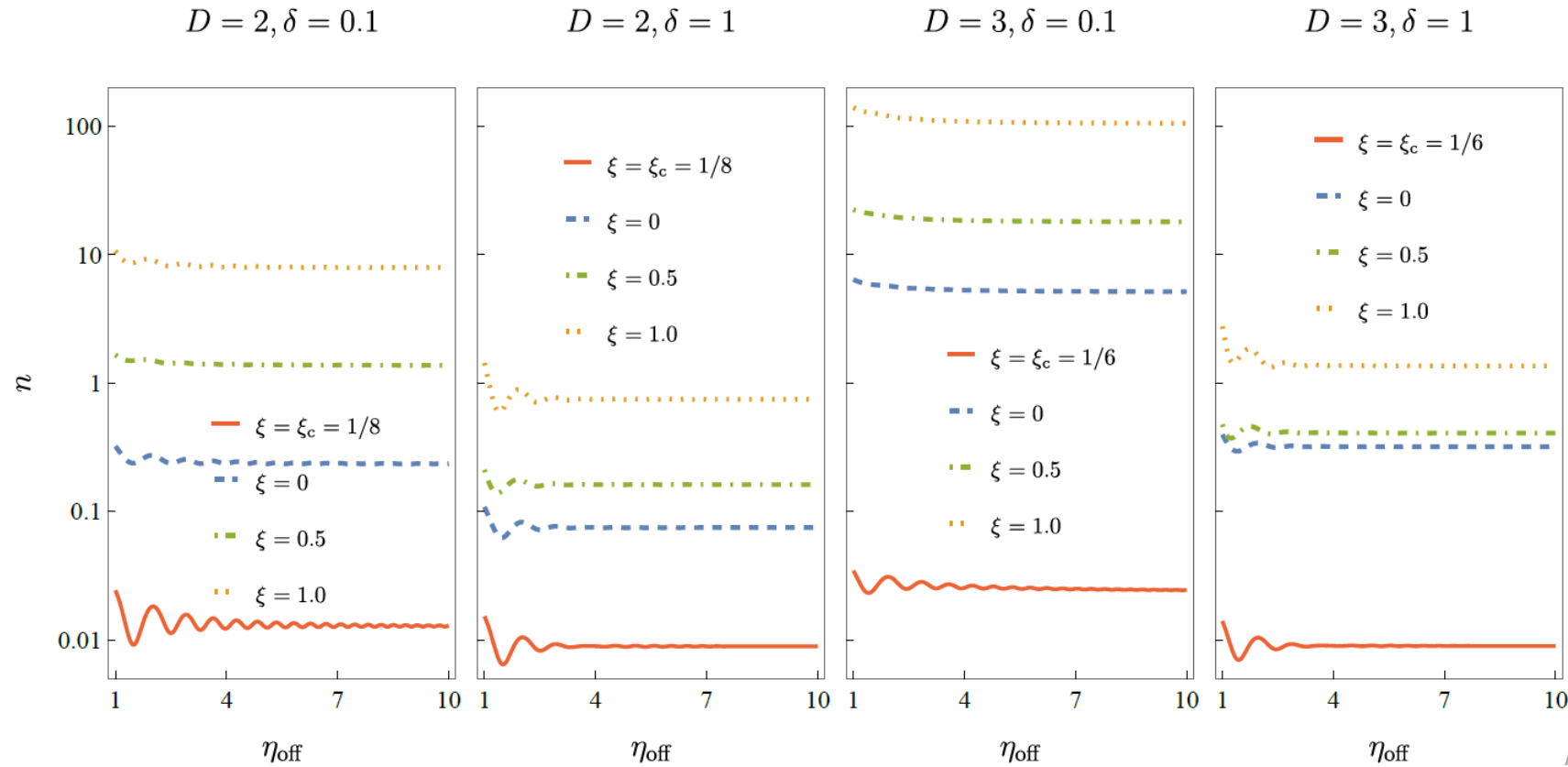


Álvarez et al., '25



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$$\omega_k^2(\eta) = k^2 + m^2 a^2(\eta) + \frac{1 + (4\xi - 1)D}{4} \left[(D - 3) \left(\frac{a'(\eta)}{a(\eta)} \right)^2 + 2 \frac{a''(\eta)}{a(\eta)} \right]$$



Álvarez et al., '25

- Production in the conformal case is **suppressed** with respect to that of the non-conformal case, and **stabilizes** for sufficiently long intermediate expansions
- For **non-conformal couplings**, fast transitions yield a **much larger** asymptotic number density than slower transitions

- The “adiabatic” function gives an idea of how important is particle production

$$\mathcal{C}_k(\eta) \equiv |\omega'_k(\eta)/\omega_k^2(\eta)|$$

- For a scalar field in a flat cosmology the frequency reads

$$\omega_k^2(\eta) = k^2 + m^2 a^2(\eta) + \frac{1 + (4\xi - 1)D}{4} \left[(D - 3) \left(\frac{a'(\eta)}{a(\eta)} \right)^2 + 2 \frac{a''(\eta)}{a(\eta)} \right]$$

We distinguish two cases regarding scale factor derivatives appearing in the frequency

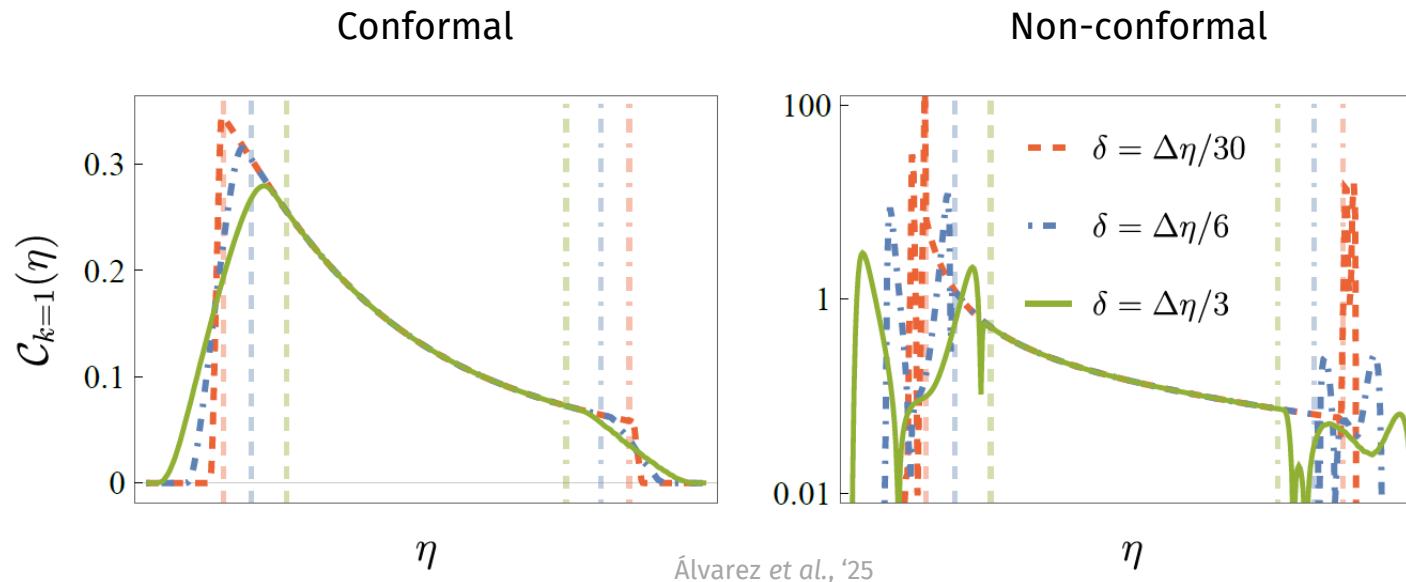
- 1) **Conformal** coupling, $\xi = (D - 1)/(4D)$: **no** scale factor **derivatives**
- 2) **Non-conformal** coupling: scale factor **derivatives** up to 2nd order appear

Importance of the switch-on and -off

- Conformal case

$$\mathcal{C}_k(\eta) = \frac{m^2 a^2(\eta) a'(\eta)}{[k^2 + m^2 a^2(\eta)]^{3/2}}$$

Less particle production, 'on' and 'off' relevance is of the **same order** as intermediate expansion

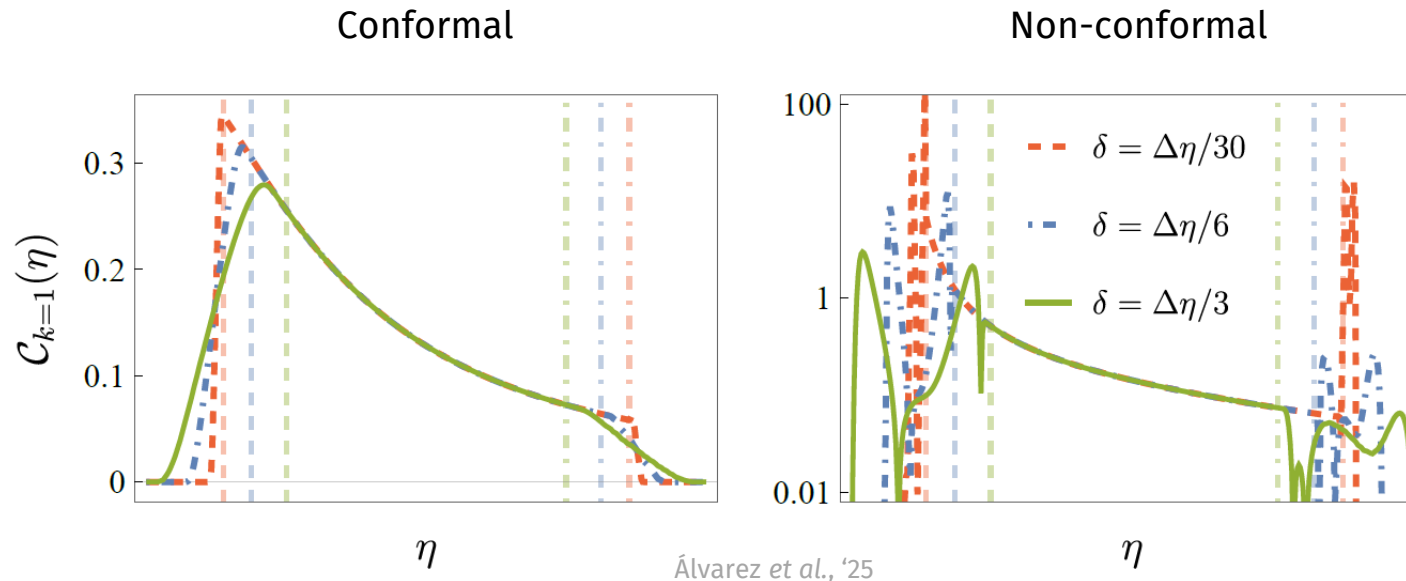


Importance of the switch-on and -off

- Non-conformal case

$$\mathcal{C}_k(\eta) = \omega_k(\eta)^{-3} \left| m^2 a(\eta) a'(\eta) + \frac{1 + (4\xi - 1)D}{4} \left[\frac{a'''(\eta)}{a(\eta)} + (D-4) \frac{a'(\eta) a''(\eta)}{a(\eta)^2} - (D-3) \left(\frac{a'(\eta)}{a(\eta)} \right)^3 \right] \right|$$

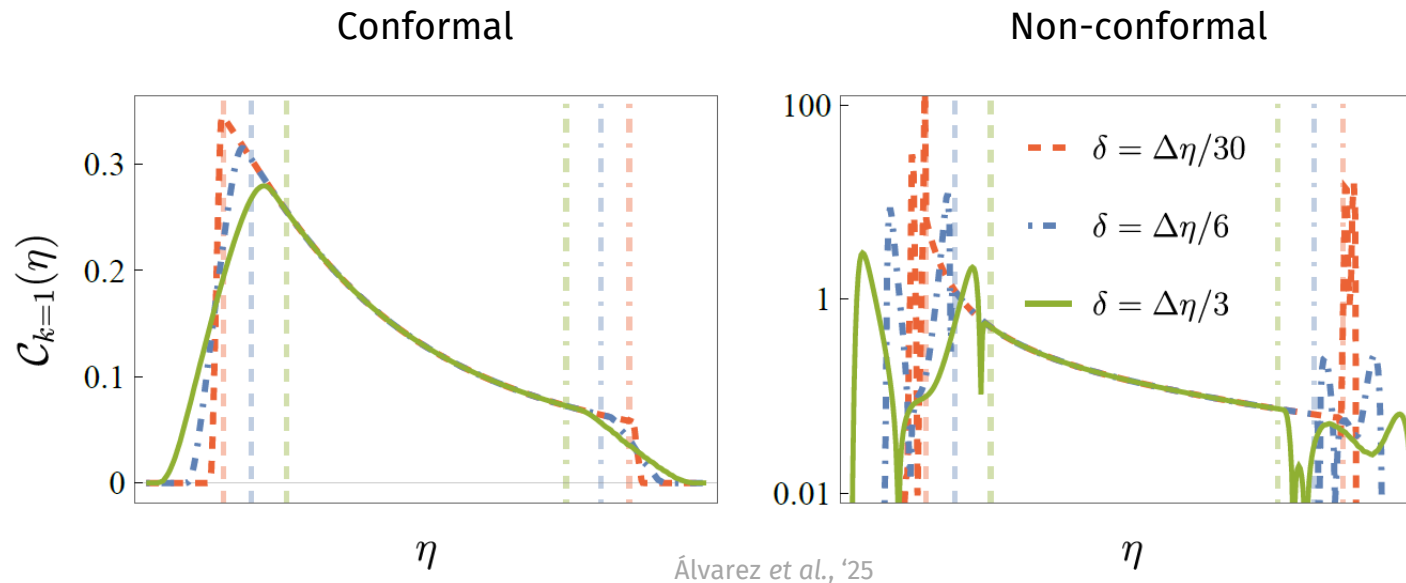
This term dominates!



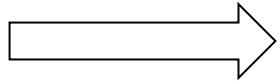
Importance of the switch-on and -off

- Non-conformal case

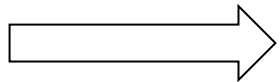
Expect **enhanced particle production during the transitions**,
intermediate region is less relevant



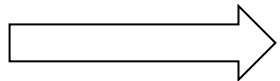
V. Conclusions



Cosmological particle production should be taken into account in the context of DM



BECs are a powerful tool for simulating quantum fields (also in curved spacetimes)



Now is the time to explore Relativistic Quantum Information with these kind of setups