Cosmological particle production in the lab

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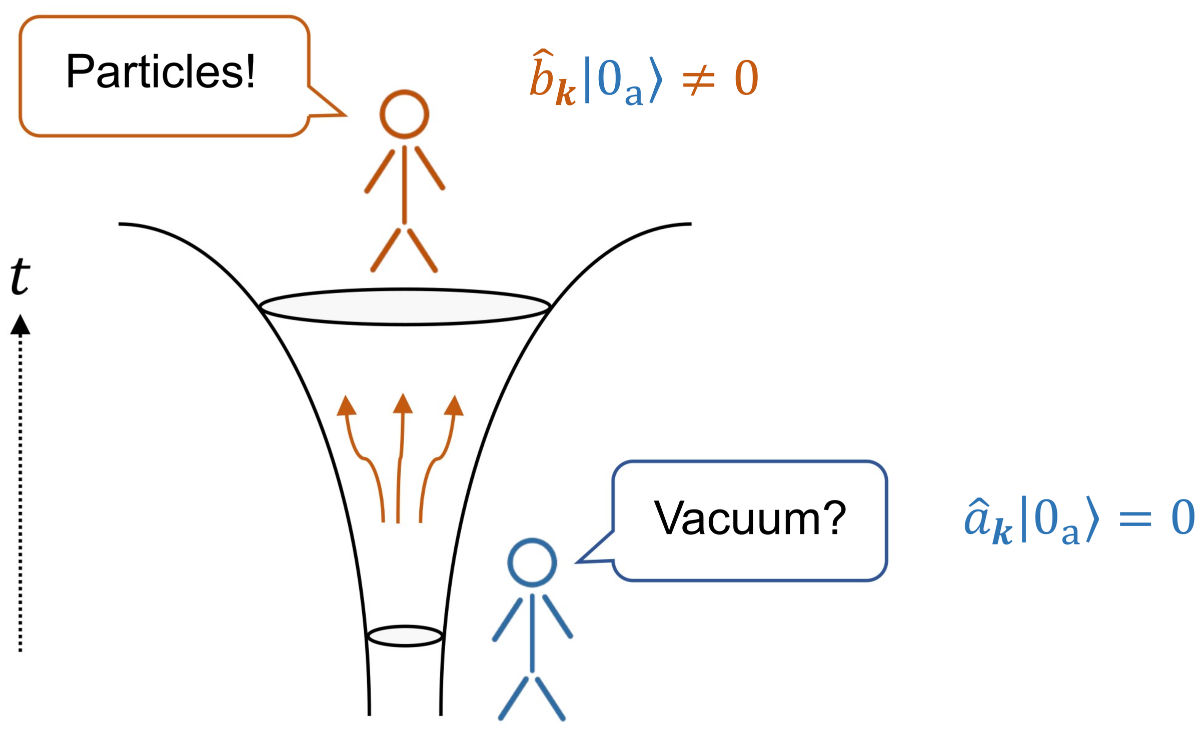
1. Introduction

Motivation

- Gravitational particle production is a phenomenon that arises when considering quantum field theory in **curved spacetime**
- It is due to the **observer-dependence of the vacuum** and can explain, for example, the abundance of dark matter



- Direct measurement in such cosmological scenarios is out of reach, so the use of **analog models of gravity** has been proposed

Objectives

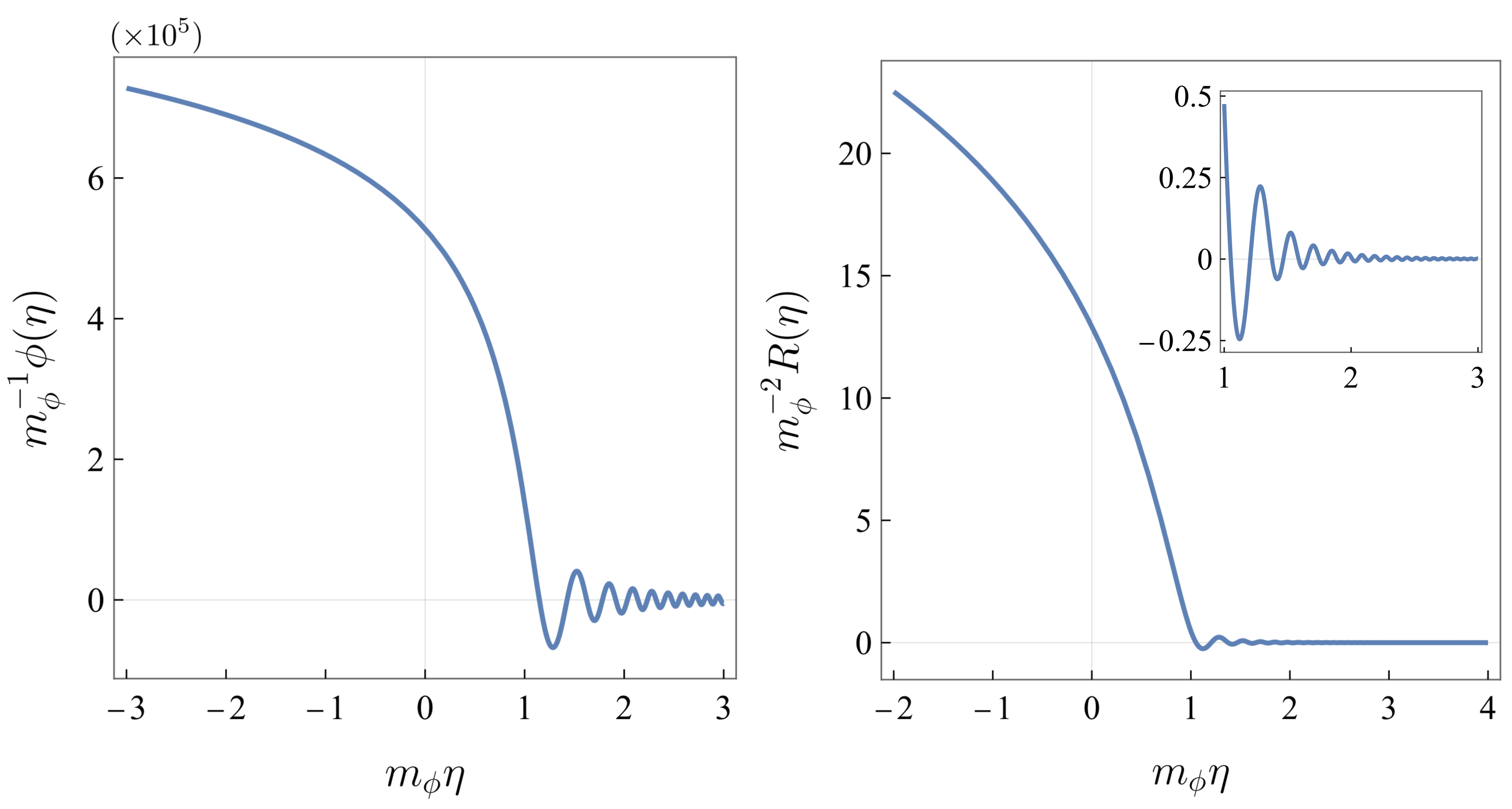
1. Study particle production during **inflation** for different fields as well as investigate the **vacuum ambiguity** in non-stationary situations.
2. Simulate cosmological production of particles for several scenarios in analog systems such as **BECs**, and measure it experimentally.

2. Particle production during inflation

- We consider a massive scalar field φ non-minimally coupled to gravity in a flat FLRW spacetime, described by the action [1]

$$\boxed{S = -\frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\left[\partial_\mu\varphi\partial^\mu\varphi + \left(m^2+\xi R\right)\varphi^2\right]}$$

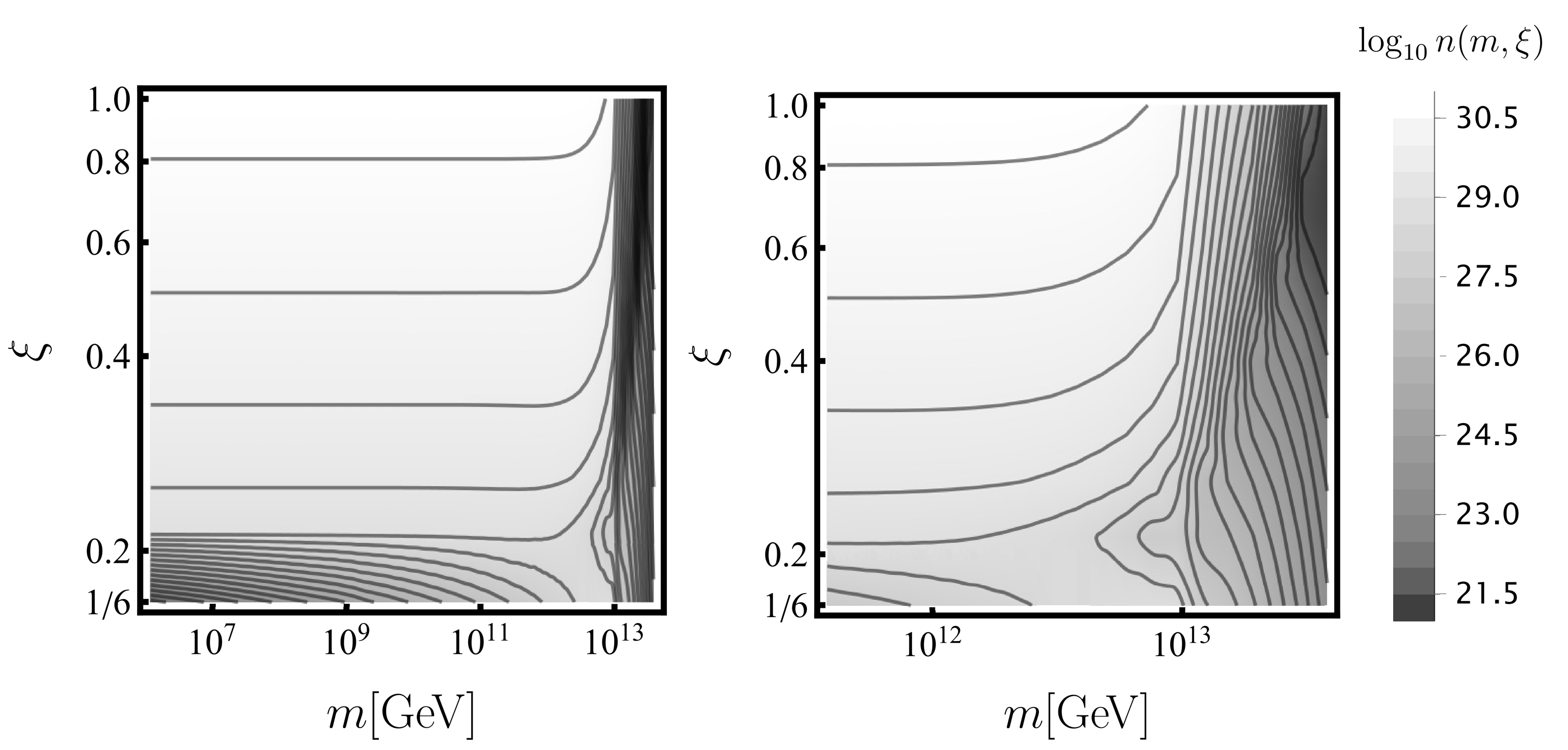
Dynamics of the inflaton $\phi(\eta)$ determines the Ricci scalar $R(\eta)$



- Our system is initially in the state $|0_a\rangle$ and we calculate the number of particles after inflation according to an observer living at this time

$$n^b = \int d^3\boldsymbol{k}\,\langle 0_a|\hat{n}_{\boldsymbol{k}}^b|0_a\rangle$$

Particles produced after inflation as function of m, ξ [1]



3. BECs as analog system

- Most extended analogy makes use of a spin-0, 2D, weakly interacting Bose-Einstein condensate, described by the complex field Φ,

$$\Phi = \text{background} + \text{fluctuations} = \phi_0 + \frac{1}{\sqrt{2}}\left(\phi_1 + i\phi\right)$$

- The system can be adjusted such that the **phononic fluctuations** behave as a massless scalar field in a FLRW universe:

Universe	BEC experiment
Spacetime	Background
FLRW metric	Acoustic metric
Massless scalar particle	Phonons

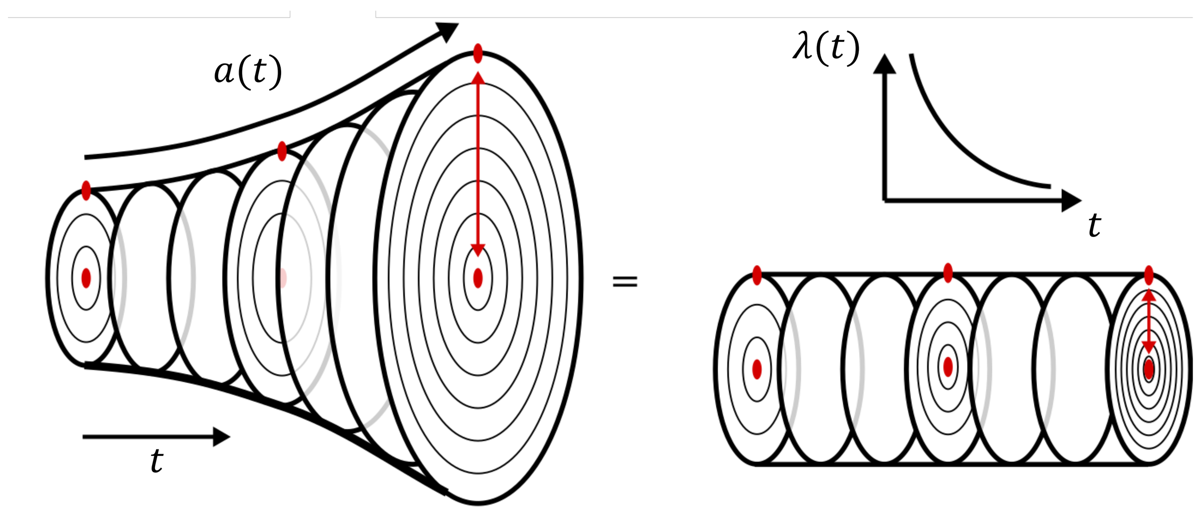
- Action for the fluctuating field ϕ in a static background and assuming **low momentum** excitations [2]:

$$\boxed{S_2[\phi] = \frac{1}{2}\int \mathrm{d}^3x\sqrt{g}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi,}$$

with $g_{\mu\nu}$ being the **acoustic metric**, corresponding to

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \frac{m}{\lambda(t)n_0(r)}\left(\mathrm{d}r^2 + r^2\mathrm{d}\varphi^2\right) \equiv -\mathrm{d}t^2 + \frac{a^2(t)}{n_0(r)}\left(\mathrm{d}r^2 + r^2\mathrm{d}\varphi^2\right)$$

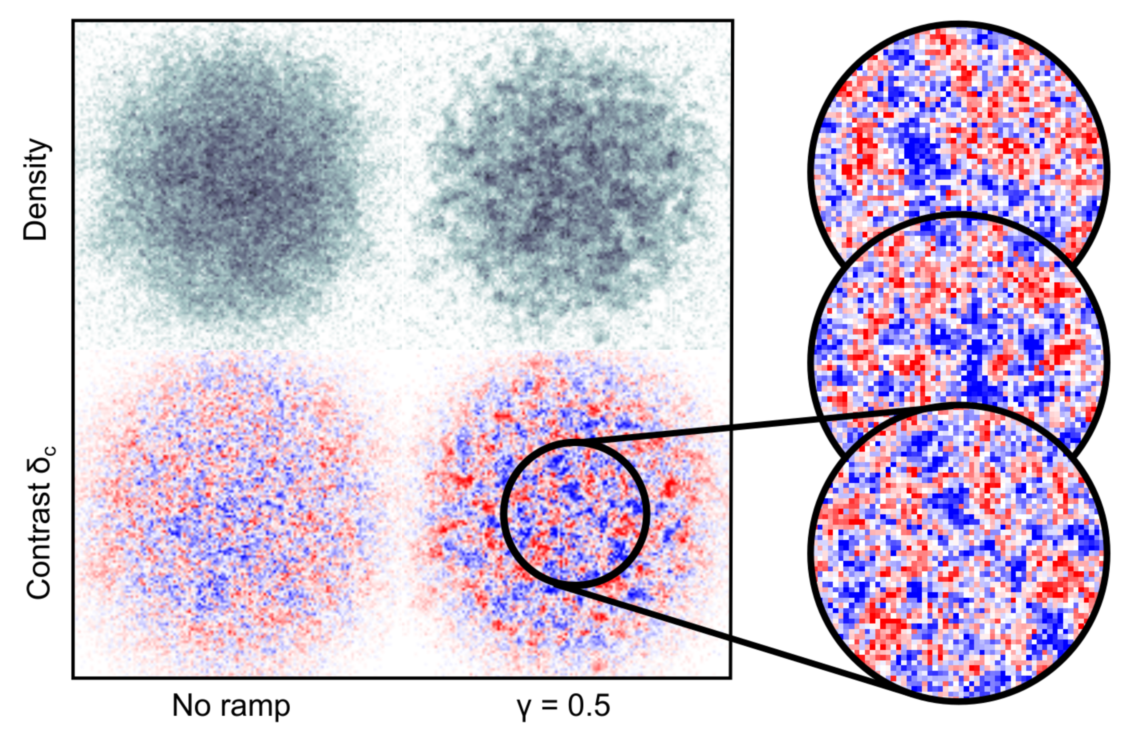
Expansion of the universe is realized through a time-dependent interaction strength $\lambda(t)$, achieved from **Feshbach resonance** [3]



- Relation between the density contrast measured δ_c and correlations of the field ϕ originated from particle production is given by [2, 4]

$$\boxed{\langle\delta_c(t,\boldsymbol{r})\delta_c(t,\boldsymbol{r}')\rangle \sim \langle\{\dot{\phi}(t,\boldsymbol{r}),\dot{\phi}(t,\boldsymbol{r}')\}\rangle_c \sim n_k^b}$$

Density fluctuations for an expansion of the form $\lambda(t) \propto t^{-2\gamma}$ [3]



4. Conclusions and outlook

- Particle production of a scalar field has been solved within a complete, slow-roll inflationary model, for FLRW universes of any curvature
- We simulated particle production in a BEC for a massless scalar field
- The aim is to investigate vector and spin-2 fields and analogs of them

References

[1] Jose A. R. Cembranos *et al*, *in preparation, (2022).*
[2] Mireia Tolosa-Simeón *et al*, *Phys. Rev. A* ***106****, 033313, (2022)*
[3] Celia Viermann *et al*, *Nature, 10.1038/s41586-022-05313-9, (2022)*
[4] Natalia Sánchez-Kuntz *et al*, *Phys. Rev. D* ***105****, 105020, (2022)*

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