Spacetime dynamics as a dark matter production mechanism

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Introduction

- QFT in curved spacetimes
  - Vacuum/particle notion is ambiguous
  - Particle production (even from vacuum)

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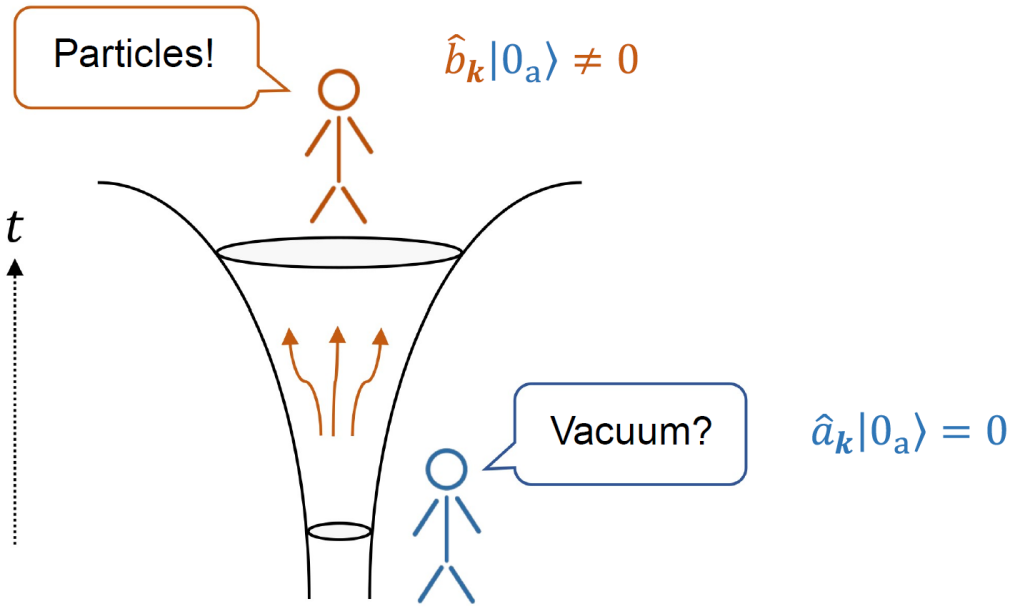
- QFT in curved spacetimes
  - Vacuum/particle notion is ambiguous
  - Particle production (even from vacuum)
- Crucial during inflation
  - Production even for spectator fields
  - Interesting DM production mechanism



Scalar field in flat FLRW

- Non-interacting real scalar field

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

- Non-minimal coupling to the curvature

- We expand the auxiliary field $\chi = a\varphi$ as

$$\chi(\eta, \boldsymbol{x}) = \int_{\boldsymbol{k}} [a_{\boldsymbol{k}} v_k(\eta) + a^*_{-\boldsymbol{k}} v^*_k(\eta)] e^{i\boldsymbol{k}\boldsymbol{x}}$$

Conformal time

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Conformal time

- The EOM of $\chi(\eta, \boldsymbol{x})$ in k-space is

$$v_k''(\eta) + \omega_k^2(\eta) v_k(\eta) = 0$$

with frequency

$$\omega_k^2(\eta) = k^2 + a^2(\eta)[m^2 + \left(\xi - \frac{1}{6}\right) R(\eta)]$$

- Background determines $a^2(\eta)$ and $R(\eta)$

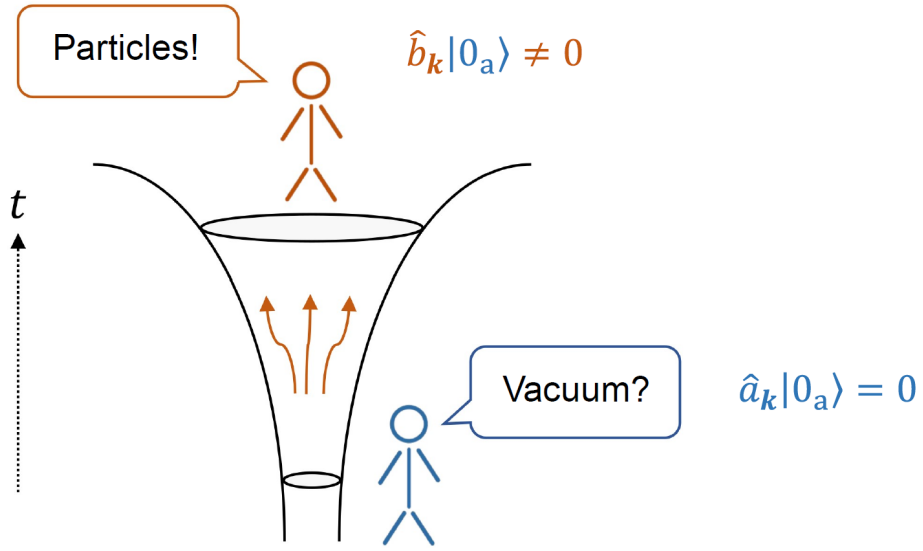
- Quantization: $a_{\boldsymbol{k}}, a^*_{\boldsymbol{k}} \rightarrow \hat{a}_{\boldsymbol{k}}, \hat{a}^+_{\boldsymbol{k}}$

Particle production

- Two particular solutions v_k and u_k expand χ with different operators (and vacua),

$$u_k = \alpha_k v_k + \beta_k v_k^*, \quad \hat{b}_k = \alpha_k^* \hat{a}_k - \beta_k^* \hat{a}_k^+$$

$$|\alpha_k|^2 - |\beta_k|^2 = 1$$



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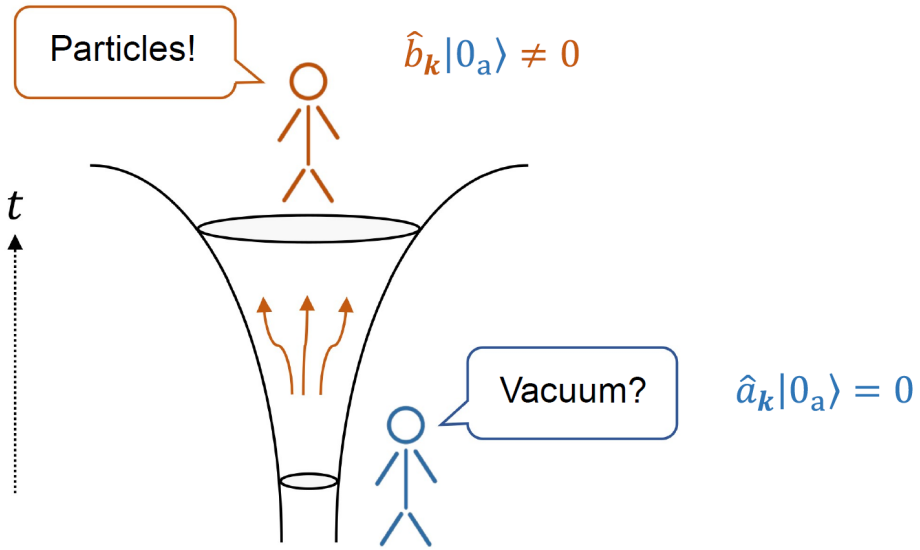

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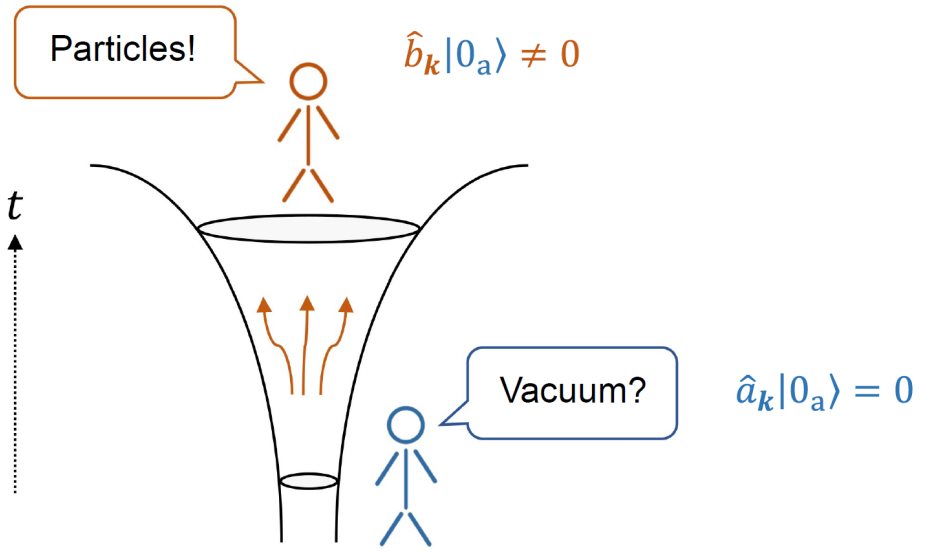
- If the systems is in the state $|0_a\rangle$ at η_i,

$$N_k(\eta_f) = \langle 0_a | \hat{b}_k^+ \hat{b}_k | 0_a \rangle = |\beta_k|^2$$

- Need to know v_k and u_k at the same time (η_f)



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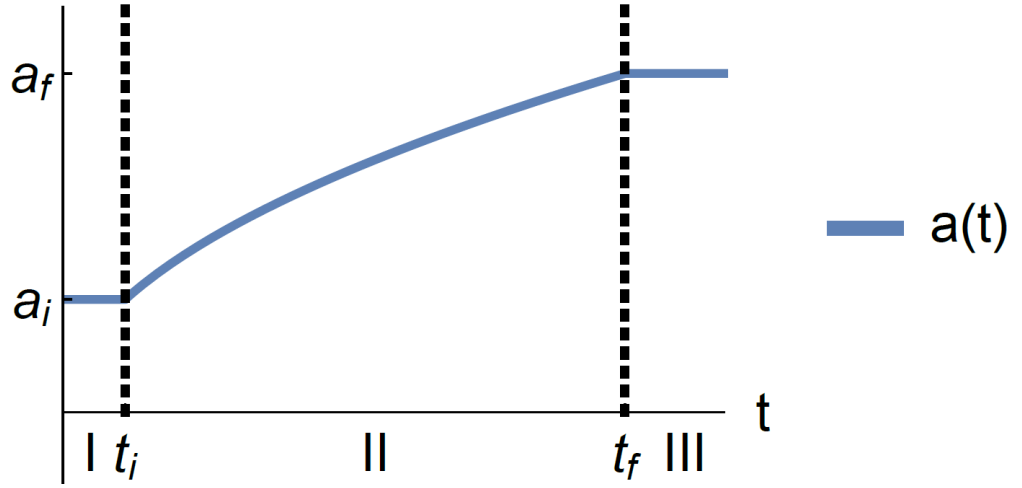
Consider the following realization

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



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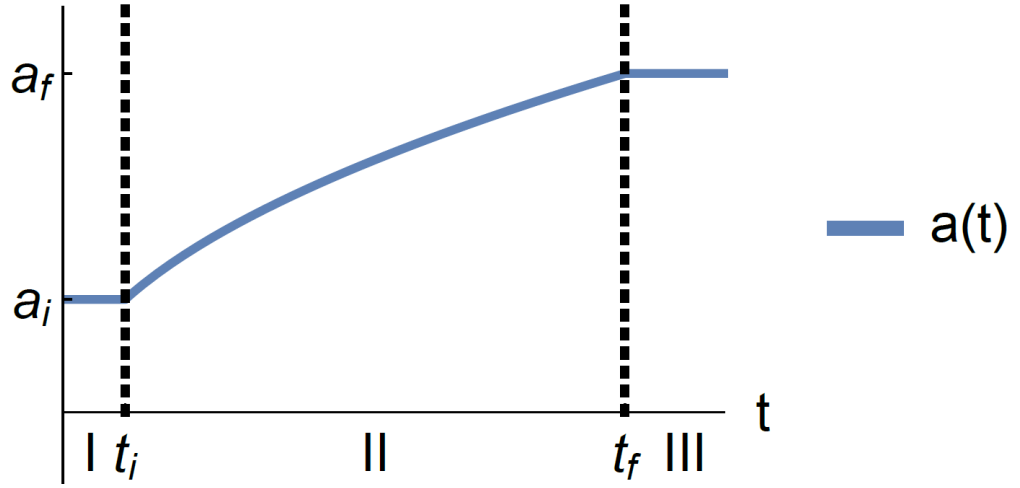
What a problematic question…

Consider the following realization

Particle production at t_f is

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

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



Abundance of produced particles

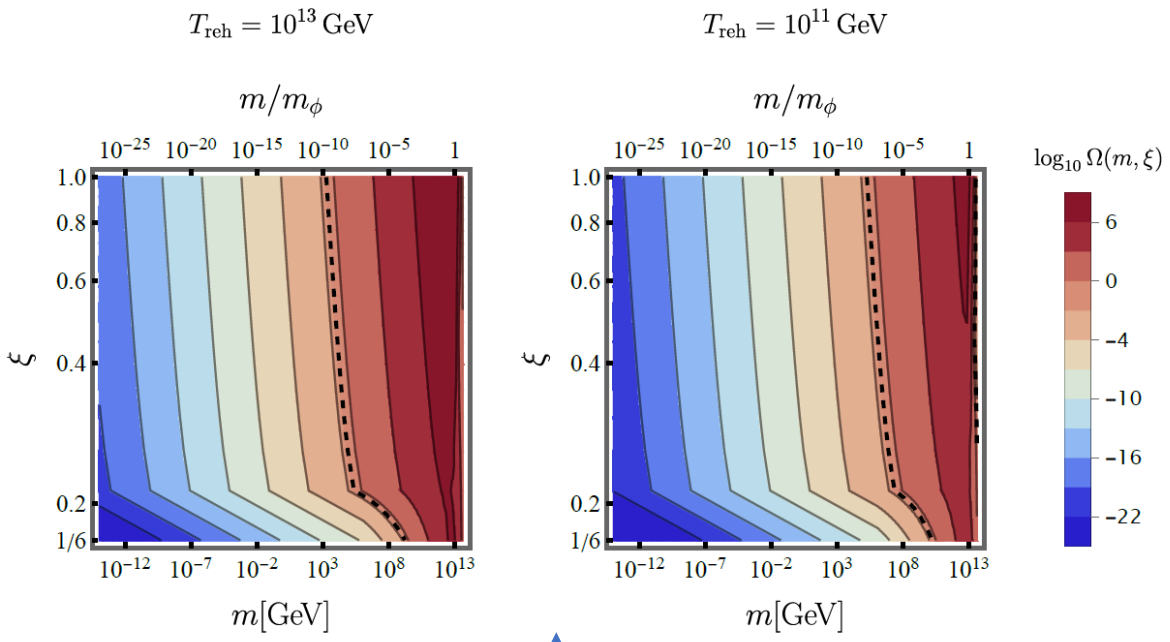
- The total comoving density of particles is $n(m,\xi) = \int dk\, k^2 |\beta_k|^2$
- The physical density at the end of reheating is $n_{rh}(m,\xi) = n(m,\xi)/a_{rh}^3$

If the field does not interact, and production is negligible afterwards, this process leads to a relic abundance that can be compared to observations

$$\Omega(m,\xi,T_{rh})$$

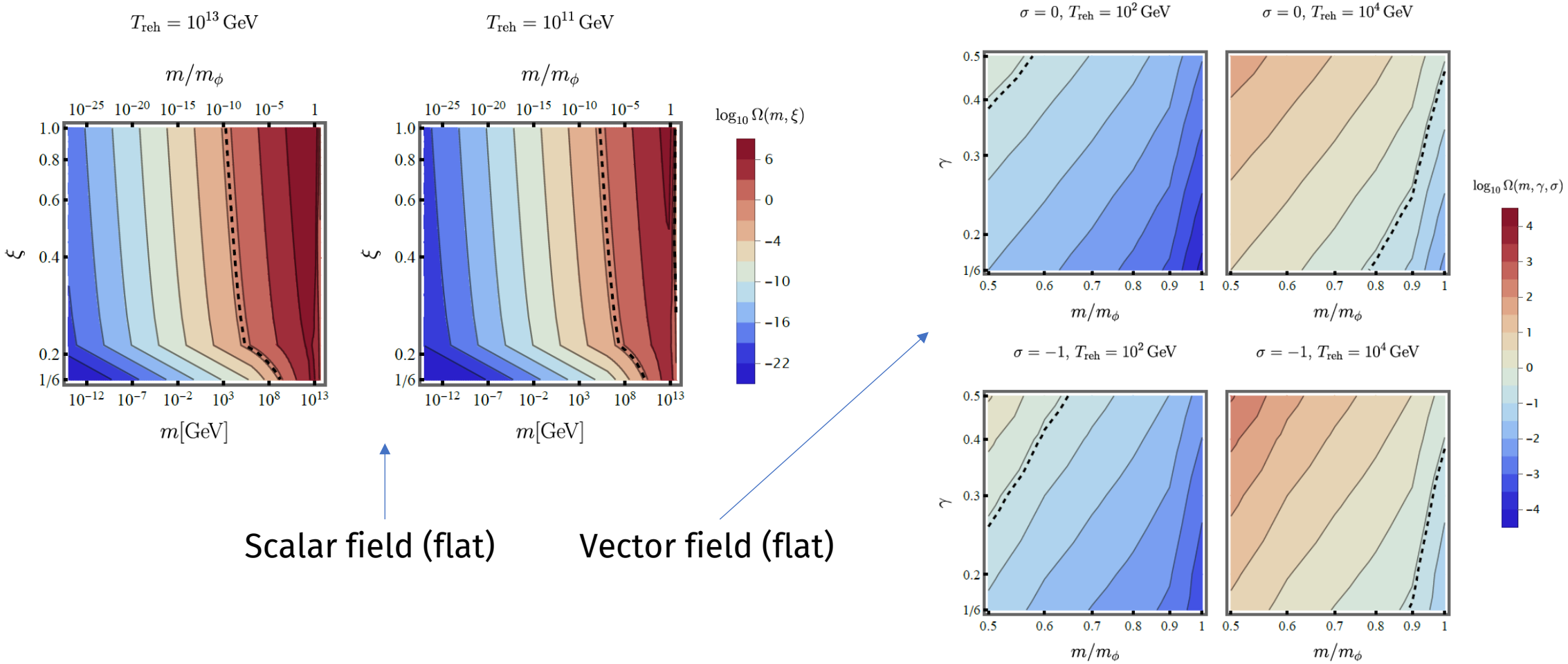
↘ Reheating temperature

Density and abundance (slow-roll)



Scalar field (flat)

Density and abundance (slow-roll)



Summary

- QFT in curved spacetimes leads to gravitational particle production
- The notion of particle depends on the choice of vacuum (quantization ambiguities)
- Gravitational production is universal, independent of couplings to other fields
- The observed abundance of dark matter can be explained solely by this mechanism