Gravitational DM production, its uncertainties, and its interplay with freeze-in

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FUNDACIÓN RAMÓN ARECES

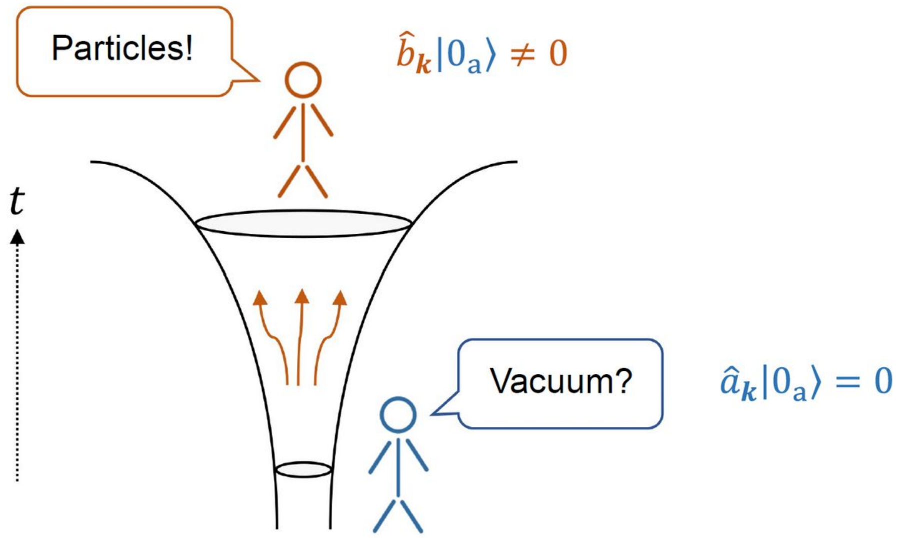
Introduction

- Spontaneous pair creation is a well-known prediction of QFT in curved spacetimes

- We denote by gravitational production the one due to a time-dependent geometry, affecting all fields on top of the expanding background (especially during inflation)

- Gravitational production is a suitable mechanism for non-thermal DM production

- Ambiguities inherent to QFTCS complicate phenomenology



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

- Non-minimally coupled spectator scalar field expanded in Fourier modes

$$\chi(\eta, \boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^{3/2}} e^{-i\boldsymbol{k}\boldsymbol{x}} \left[a_{\boldsymbol{k}} v_k(\eta) + a^*_{-\boldsymbol{k}} v^*_k(\eta)\right]$$

- Mode equation with time-dependent frequency

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

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

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

$$\chi(\eta, \boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^{3/2}} e^{i\boldsymbol{k}\boldsymbol{x}} \left[a_{\boldsymbol{k}} v_k(\eta) + a^*_{-\boldsymbol{k}} v^*_k(\eta)\right] = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^{3/2}} e^{i\boldsymbol{k}\boldsymbol{x}} \left[b_{\boldsymbol{k}} u_k(\eta) + b^*_{-\boldsymbol{k}} u^*_k(\eta)\right]$$

- Mode functions and coefficients are related by a Bogoliubov transformation

$$u_k = \alpha_k v_k + \beta_k v^*_k, \qquad b_{\boldsymbol{k}} = \alpha^*_k a_{\boldsymbol{k}} - \beta^*_k a^*_{-\boldsymbol{k}}$$

- Quantization promotes coefficients to creation and annihilation operators

- Depending on the choice of basis, we end up with different quantum theories

$$\hat{a}_{\boldsymbol{k}} |0^a\rangle = 0, \quad \forall\, \boldsymbol{k} \qquad \langle 0^a | \hat{b}^\dagger_{\boldsymbol{k}} \hat{b}_{\boldsymbol{k}} | 0^a\rangle = |\beta_k|^2 \mathcal{V}$$

Volume term

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

$$\chi(\eta, \boldsymbol{x}) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^{3/2}} e^{i\boldsymbol{k}\boldsymbol{x}} \left[a_{\boldsymbol{k}} v_k(\eta) + a^*_{-\boldsymbol{k}} v^*_k(\eta)\right] = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^{3/2}} e^{i\boldsymbol{k}\boldsymbol{x}} \left[b_{\boldsymbol{k}} u_k(\eta) + b^*_{-\boldsymbol{k}} u^*_k(\eta)\right]$$

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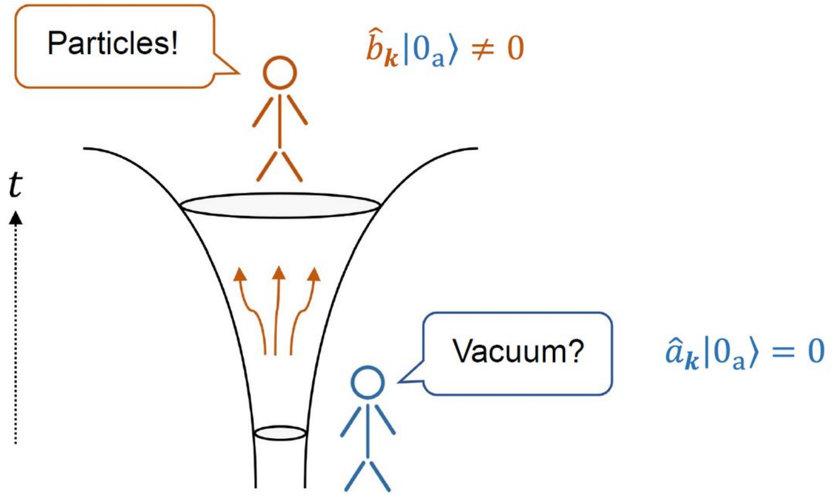


Number density of produced particles with eigenvalue k

$$\boxed{n_k = |\beta_k|^2}$$

- Geometry is approximately de Sitter during slow-roll

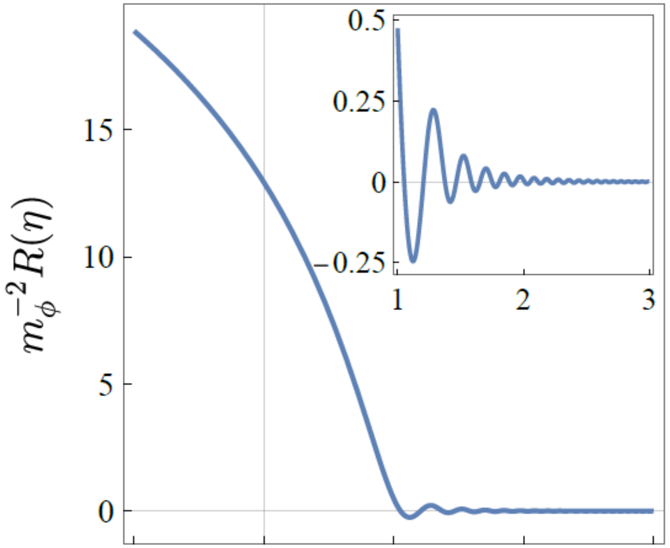
- The preferred vacuum at the beginning of inflation is Bunch-Davies Bunch & Davies, 78

But the choice of *out* vacuum is ambiguous

- The idea is to wait until the expansion of the geometry *adiabatic enough*

- η_f is the time when production is negligible

- **At this point, all notions of vacuum converge, and we can extrac the result**

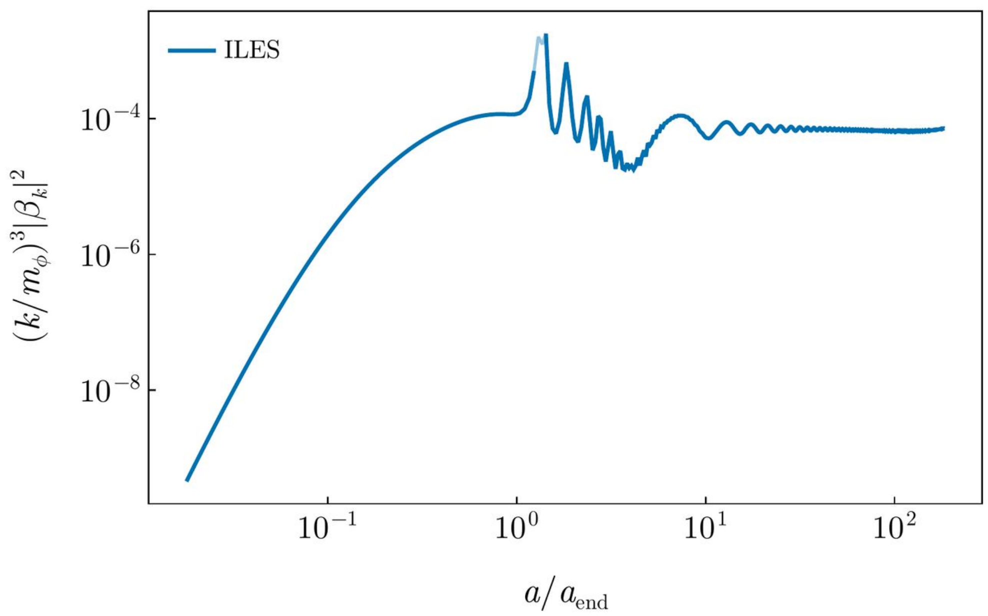


Out vacuum choices and stability

Instantaneous
Lowest Energy State

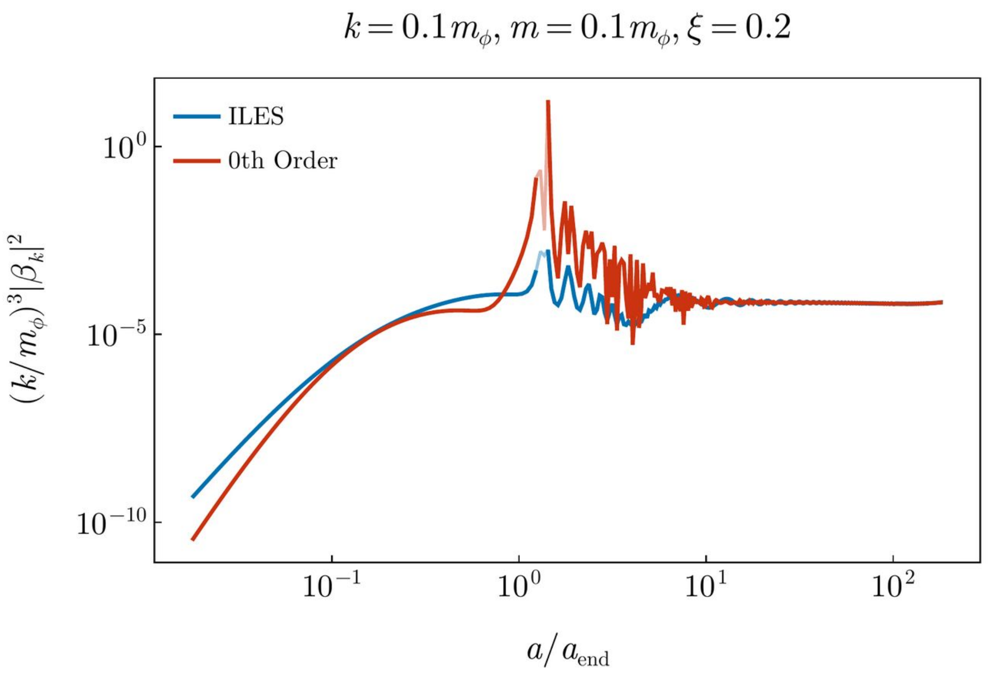
$$\Longrightarrow \quad u_k(\eta_\mathrm{f}) = \frac{1}{\sqrt{2\omega_k(\eta_\mathrm{f})}}, \qquad u_k'(\eta_\mathrm{f}) = -\frac{1}{\sqrt{2\omega_k(\eta_\mathrm{f})}}\,[i\omega_k(\eta_\mathrm{f})]$$

$k = 0.1 m_\phi, m = 0.1 m_\phi, \xi = 0.2$



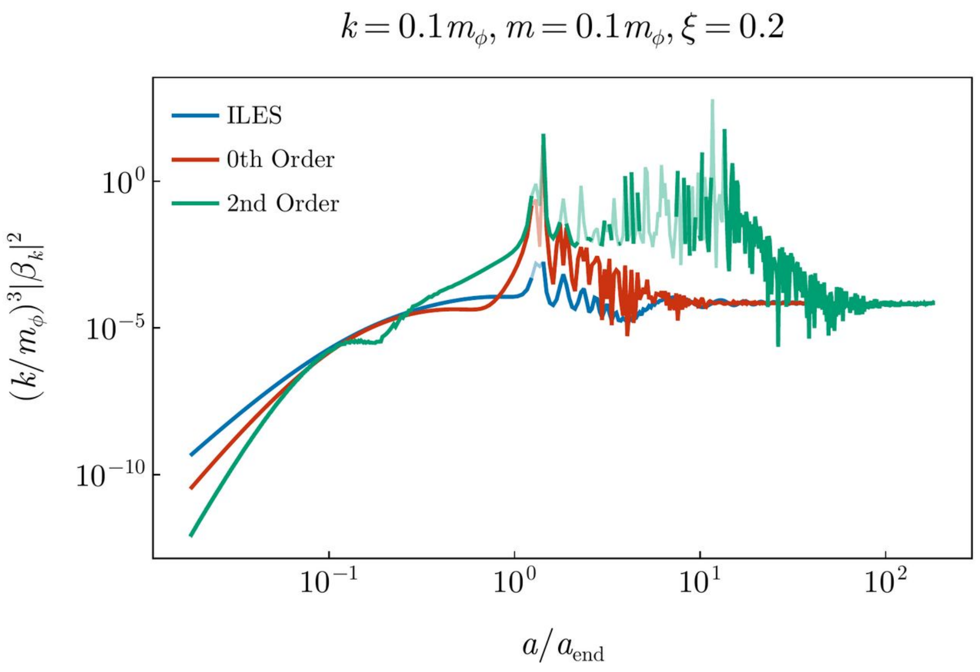
Out vacuum choices and stability

0th Order Adiabatic Vacuum $\Longrightarrow$ $$u_k(\eta_\mathrm{f}) = \frac{1}{\sqrt{2\omega_k(\eta_\mathrm{f})}}, \quad u'_k(\eta_\mathrm{f}) = -\frac{1}{\sqrt{2\omega_k(\eta_\mathrm{f})}}\left(i\omega_k(\eta_\mathrm{f}) + \frac{1}{2}\frac{\omega'_k(\eta_\mathrm{f})}{\omega_k(\eta_\mathrm{f})}\right)$$



Out vacuum choices and stability

2nd Order Adiabatic Vacuum $\Longrightarrow$ $$u_k(\eta_\mathrm{f}) = \frac{1}{\sqrt{2\omega_k(\eta_\mathrm{f})}}, \quad u_k'(\eta_\mathrm{f}) = -\frac{1}{\sqrt{2\omega_k(\eta_\mathrm{f})}}\left[i\omega_k(\eta_\mathrm{f}) + \frac{1}{2}\frac{\omega_k'(\eta_\mathrm{f})}{\omega_k(\eta_\mathrm{f})} + \mathcal{O}(\omega_k''/\omega_k^2)\right]$$



Tachyonic regime $(\xi < 1/6)$

- Frequency becomes tachyonic for IR modes during inflation

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

For low k and m, this term dominates

- These modes grow exponentially

- Production is completely dominated by the IR modes $(k \ll m_\phi)$

- The inflationary period is the most relevant stage for production

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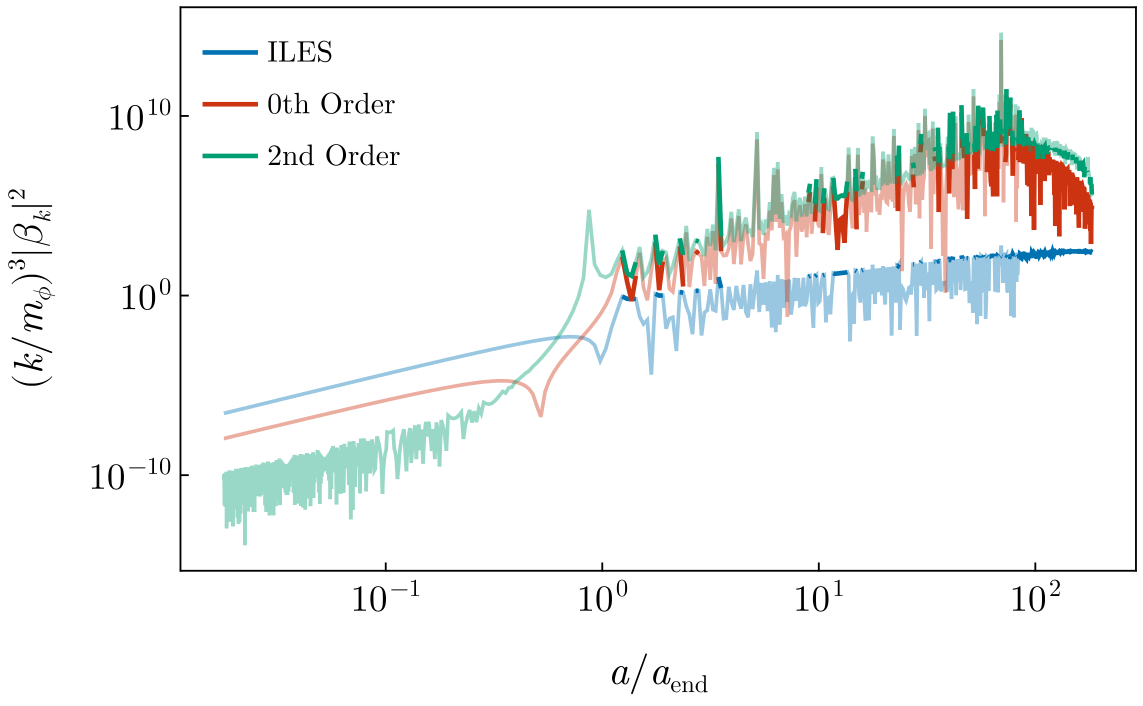
$k = 10^{-25} m_\phi,\ m = 0.001 m_\phi,\ \xi = 0.0$



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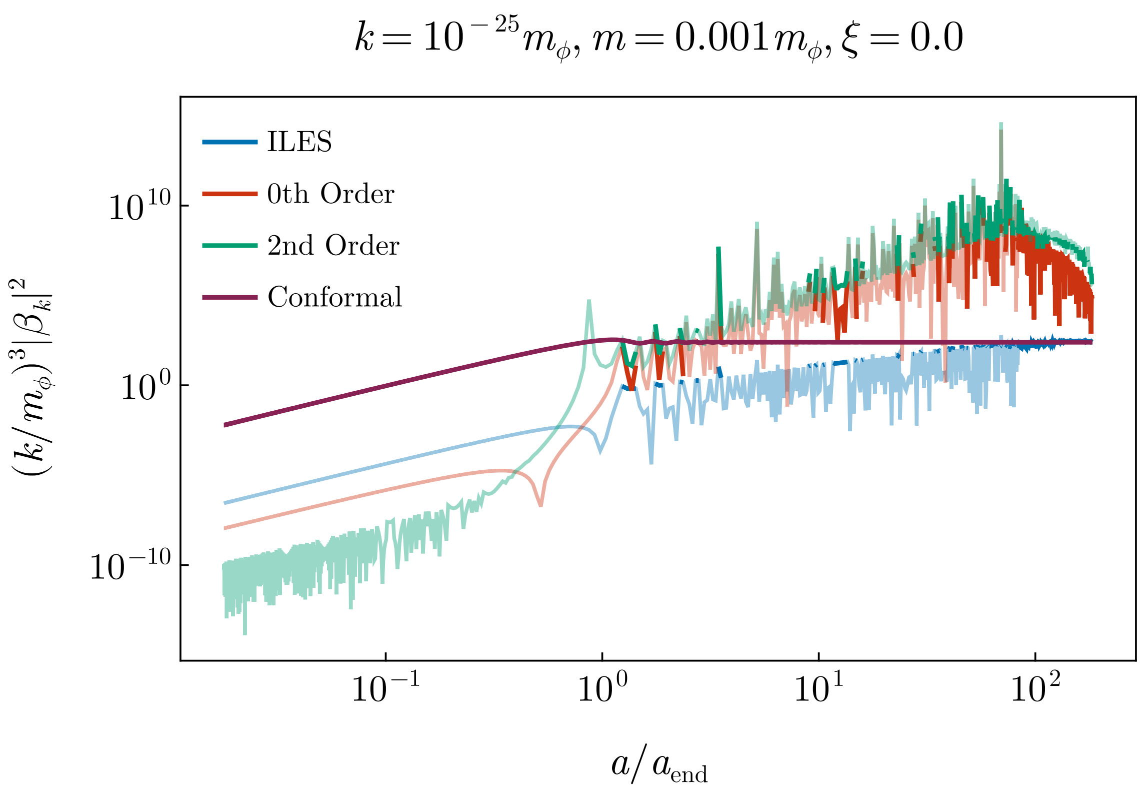
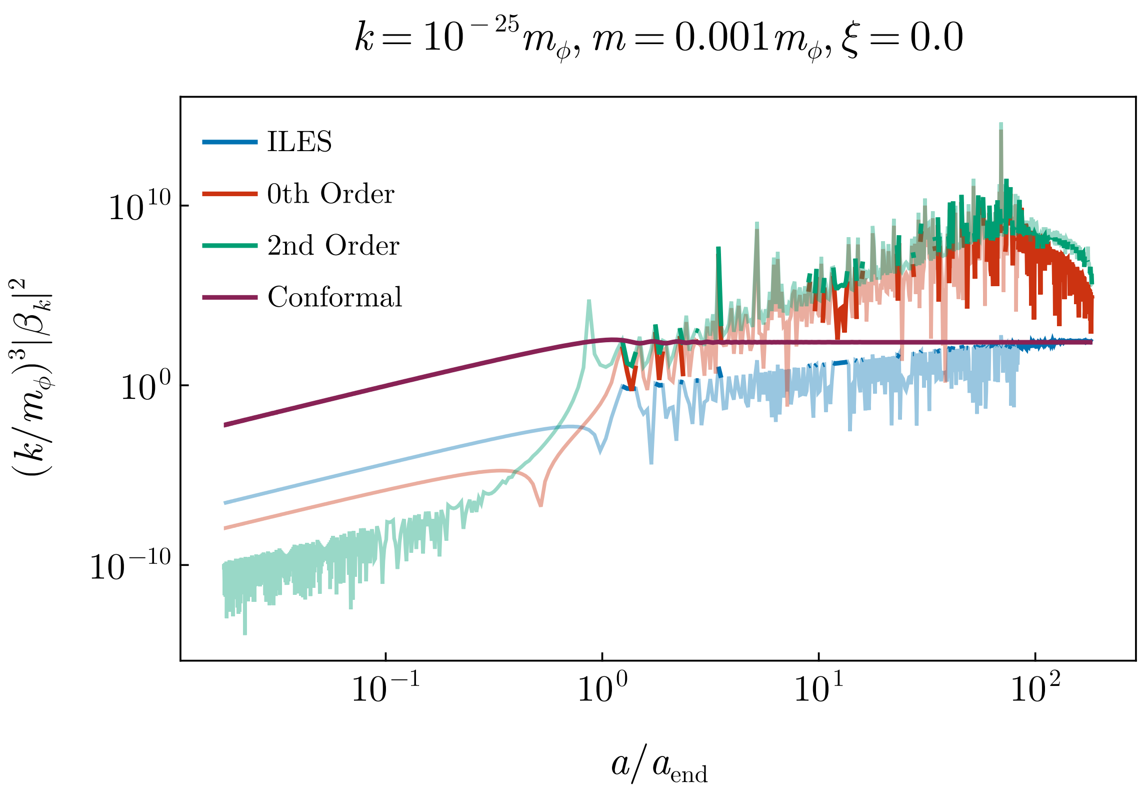


Conformal vacuum

- Define the conformal vacuum as a 0th order observer with $\xi = 1/6$
- This is the asymptotic notion of vacuum as R drecreases with time
- The *in* mode still sees the full dynamics



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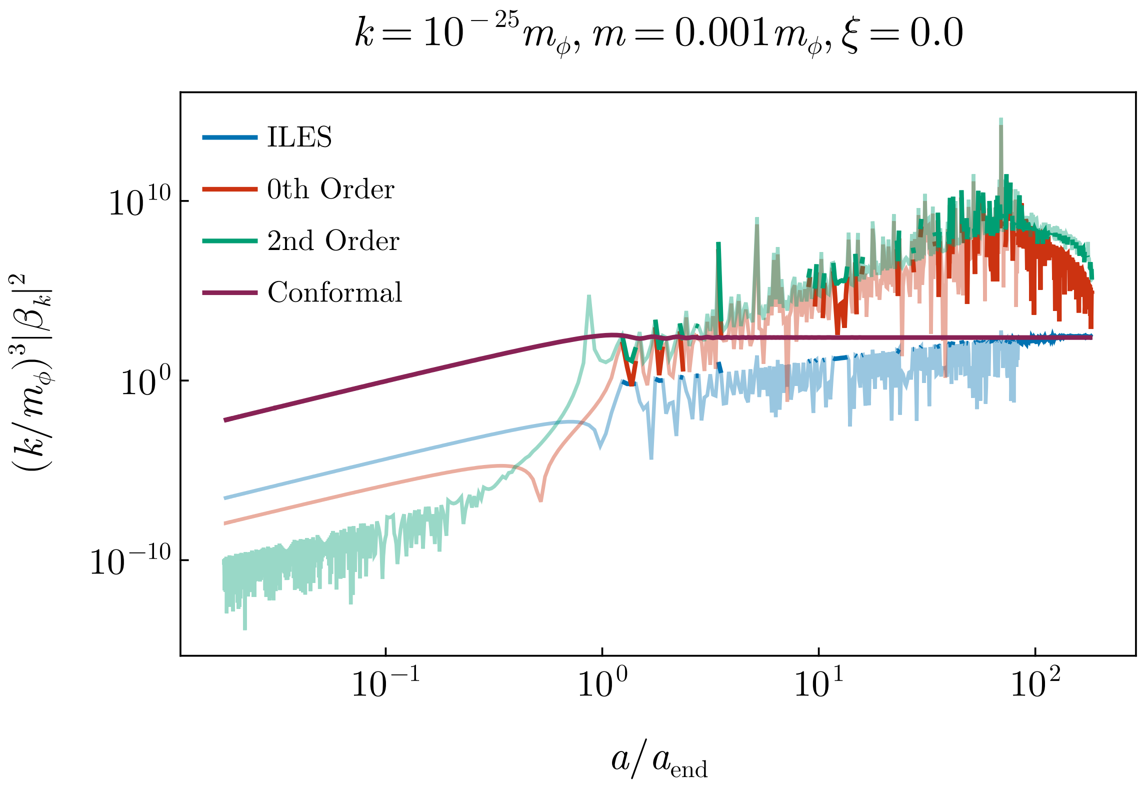
$$\omega^2_{k,\mathrm{conf}}(\eta) = k^2 + a^2(\eta) m^2$$

$$u_k(\eta_{\mathrm{f}}) = \frac{1}{\sqrt{2\omega_{k,\mathrm{conf}}(\eta_{\mathrm{f}})}}$$

$$u'_k(\eta_{\mathrm{f}}) = -\frac{1}{\sqrt{2\omega_{k,\mathrm{conf}}(\eta_{\mathrm{f}})}} \left(i\omega_{k,\mathrm{conf}}(\eta_{\mathrm{f}}) + \frac{1}{2} \frac{\omega'_{k,\mathrm{conf}}(\eta_{\mathrm{f}})}{\omega_{k,\mathrm{conf}}(\eta_{\mathrm{f}})} \right)$$



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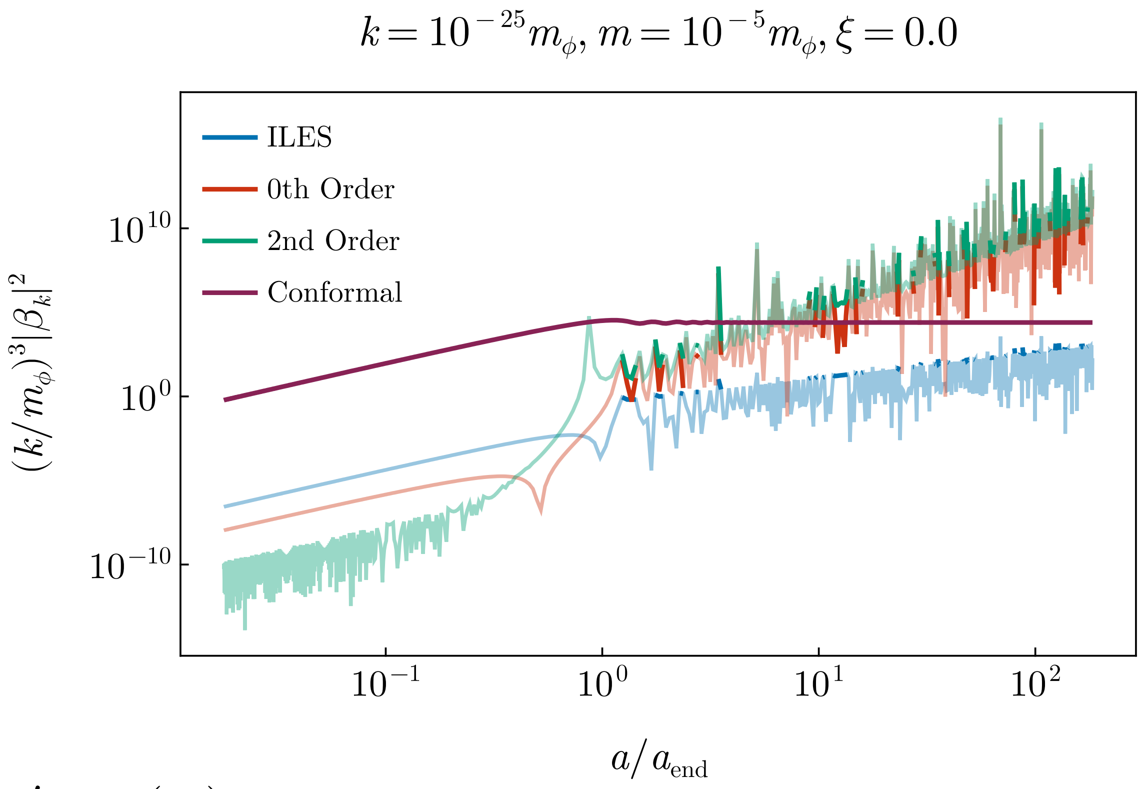
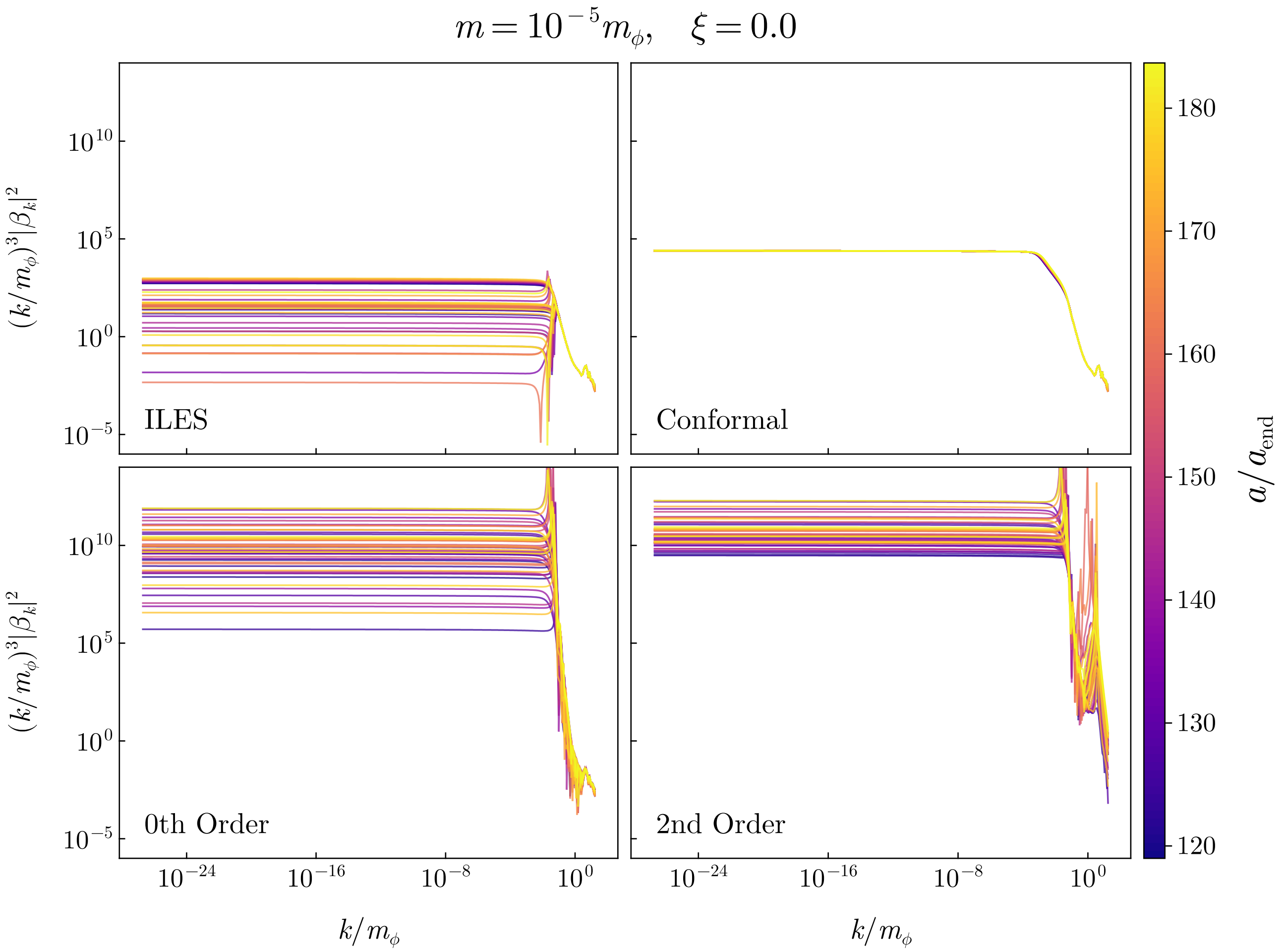
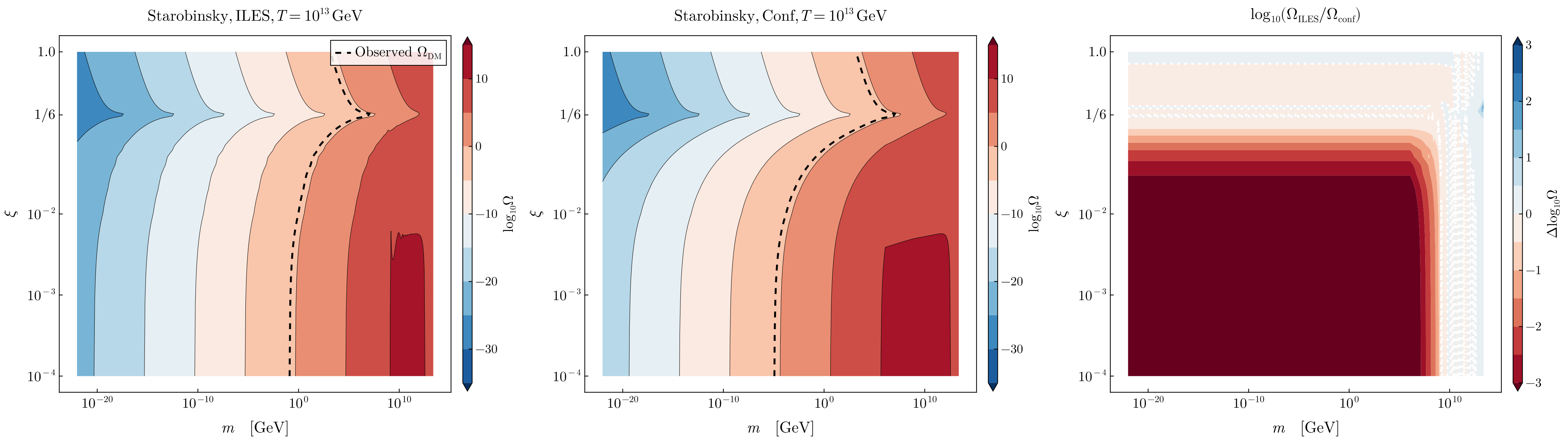


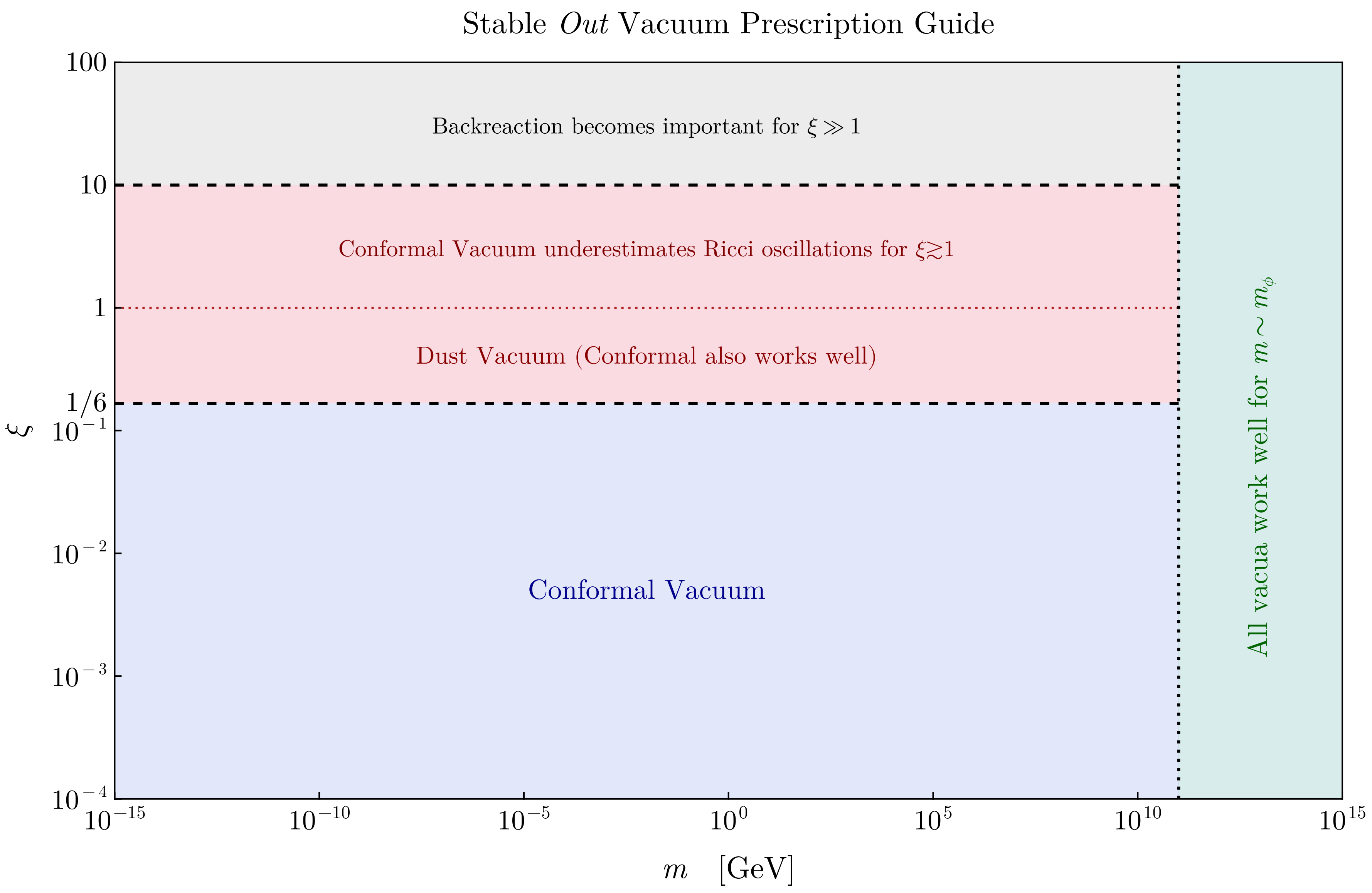
Standard prescriptions are completely unstable!



Abundance

- We assume reheating happens at some temperature T , then we dilute the density until today
- In the tachyonic regime, the difference in abundances can be of several orders of magnitude





Stable Out Vacuum Prescription Guide
Backreaction becomes important for $\xi \gg 1$
Conformal Vacuum underestimates Ricci oscillations for $\xi \gtrsim 1$
Dust Vacuum (Conformal also works well)
Conformal Vacuum
All vacua work well for $m \sim m_\phi$
100
10
1
1/6
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ξ
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
m [GeV]

Conclusions

⇒ **Gravitational particle production is a natural non-thermal mechanism for explaining the observed DM abundance**

⇒ ***Out*** **vacuum must be chosen carefully to correctly account for the relic abundance**

⇒ **Standard choices such as ILES are not justified for low masses or small couplings due to non-adiabaticity**

⇒ **We have built a *vacuum prescription guide* for accurate phenomenology**

⇒ **Abundances can change as much as ~5 orders of magnitude with the right vacuum choice**