Non-minimal coupling to gravity in the early universe

based on “Dark matter production via a non-minimal coupling to gravity” (2211.11773),
and “On unitarity in singlet inflation with a non-minimal coupling to gravity” (2305.05682)

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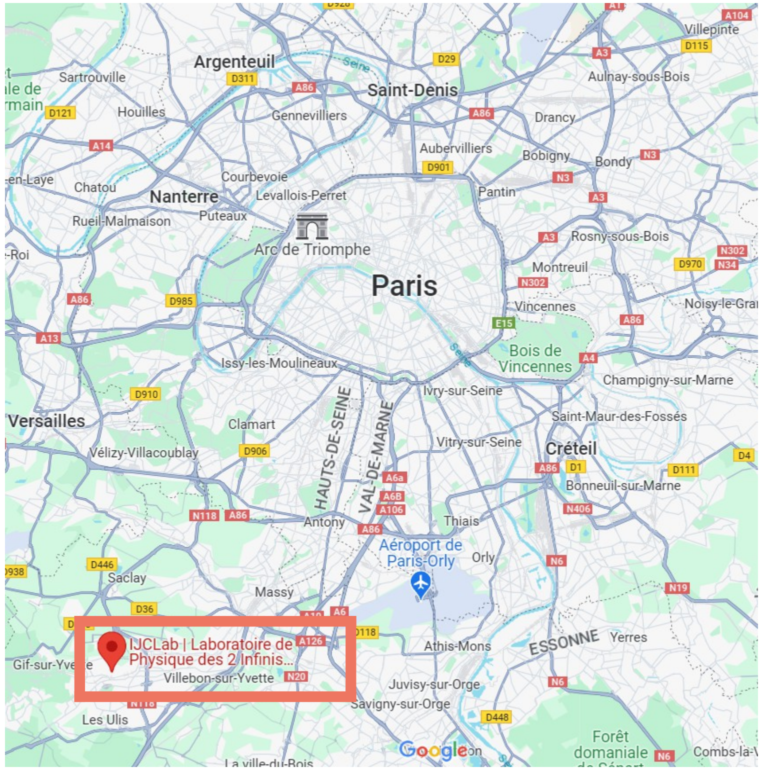
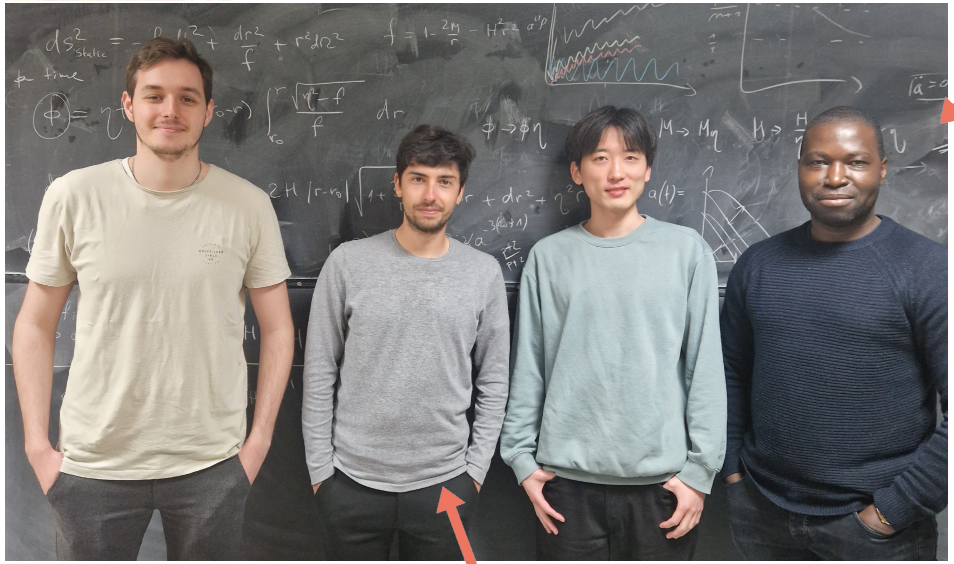
IJCLab @ University Paris-Saclay



Yann Mambrini

Essodjolo Kpatcha (Donald)



Mathieu Gross, “Effects of Fragmentation on Post-Inflationary Reheating” (after Simon)

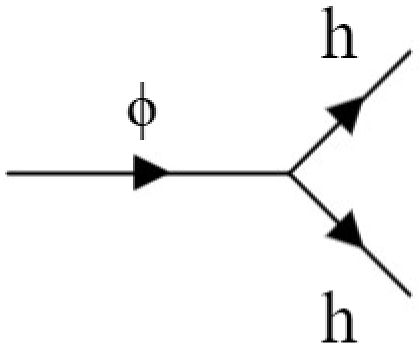
Simon Cléry, “Probing Reheating with Graviton Bremsstrahlung” (right after this talk)

Contents

- Reheating and Preheating
- DM production via a Non-Minimal Coupling to gravity
- Singlet inflation with a NMC

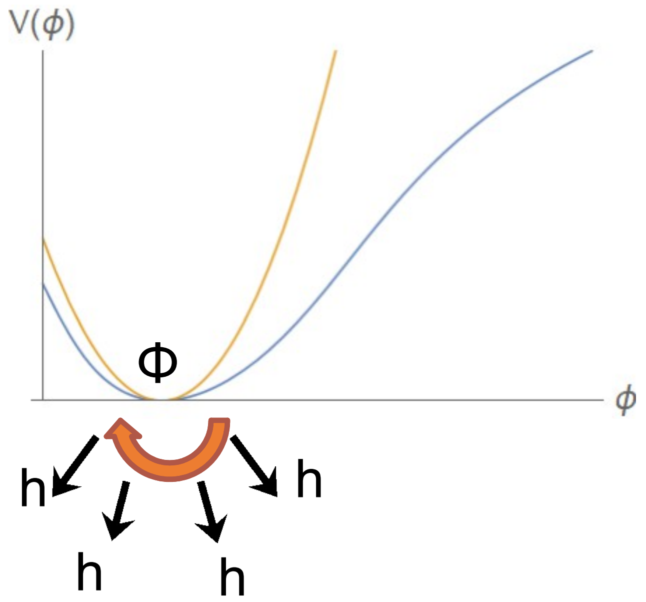
Reheating (Inflaton → SM bath)

- From Inflaton quanta



- From Inflaton oscillations

\- B.E. enhancement ('preheating')



Minimal Scalar DM models

- While Inflaton → SM (reheating the universe),

DM is produced during preheating:

Inflaton=DM

Inflaton-DM scattering

Inflaton F.O., decay to DM

Inflaton-DM non-renormalizable couplings

Inflaton-DM via gravity

Minimal Scalar DM models

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Inflaton-DM via gravity

Inflaton-DM via gravity

- Non-minimal coupling to gravity

ξ: coefficient
R: Ricci scalar
Φ: Inflaton field
s: scalar DM

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{2}M_{\rm Pl}^2 R - \frac{1}{2}\xi R\, s^2 - \frac{1}{2}g^{\mu\nu}\partial_\mu s\,\partial_\nu s - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - V\right)$$

- R is a function of energy and dominated by Φ, so DM can interact with Φ via

$$R = -\frac{1}{M_{\rm Pl}^2}T^\mu_\mu$$

For $\xi \gg 1$

- Previous studies based on perturbative methods (for small ξ)

- Resonant particle production followed by backreaction and rescattering

- Non-analytic behavior of curvature

→ Numerical approach needed

Lattice simulations

- EOMs + Friedmann Eqs.

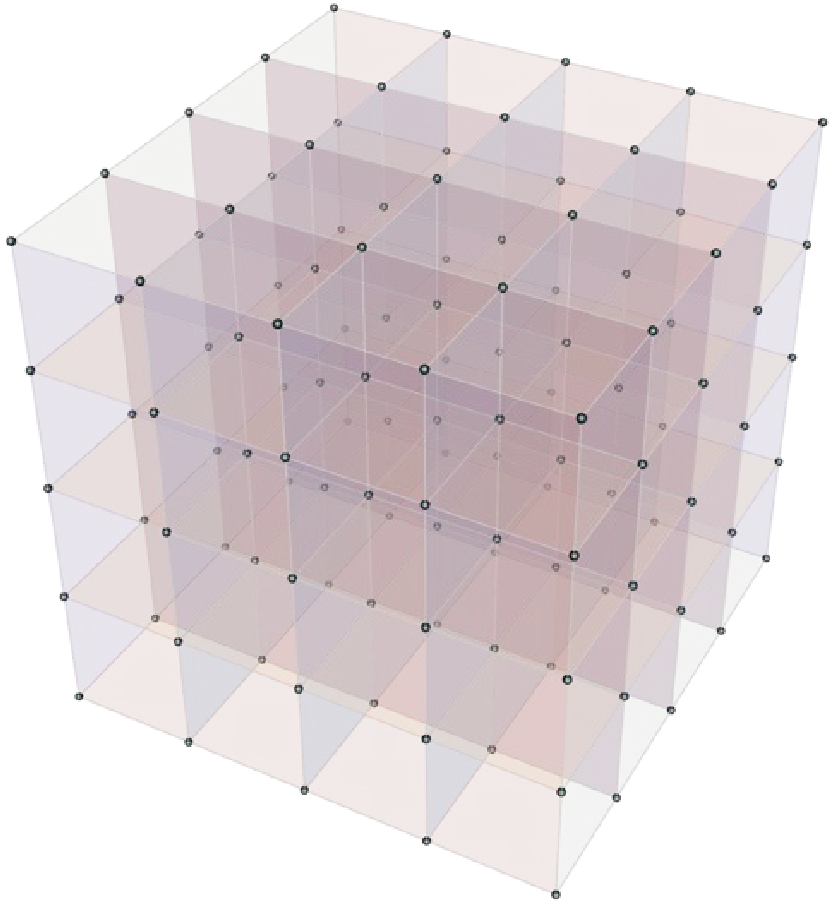
$$\ddot{f} + 3\frac{\dot{a}}{a}\dot{f} - \frac{1}{a^2}\nabla^2 f + \frac{\partial V}{\partial f} = 0$$

$$\ddot{a} = -\frac{4\pi a}{3}(\rho + 3p)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}\rho$$

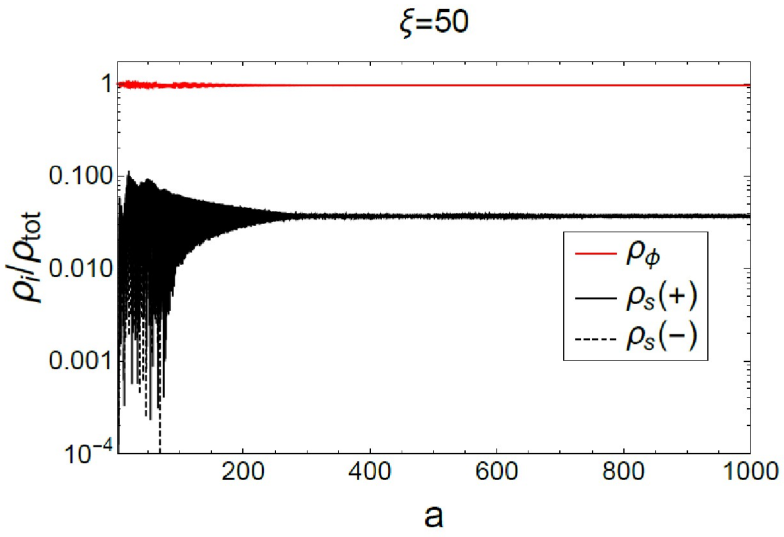
$$\rho = T + G + V \; ; \; p = T - \frac{1}{3}G - V$$

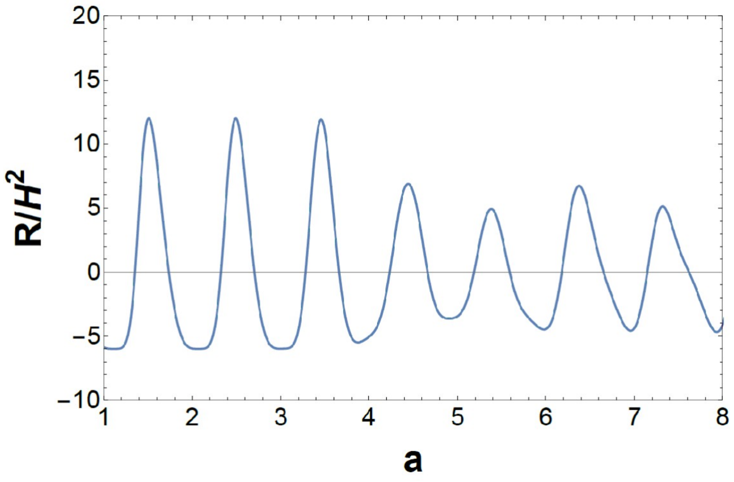
$$T = \frac{1}{2}\dot{f}^2 \; ; \; G = \frac{1}{2a^2}|\nabla f|^2 \; .$$

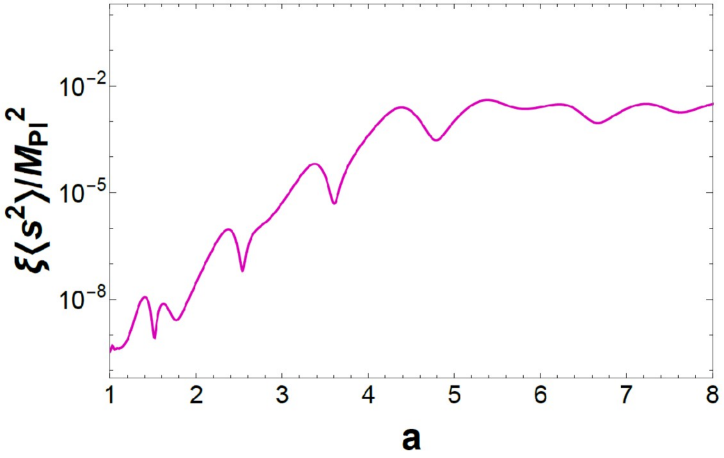


Simulation outcome

- CosmoLattice customized for NMC
- Energy distribution, R breakdown, resonant production, etc.







Simulations provide intuitive insights into events in the early universe

Exp. constraints on DM

- DM relic abundance (conserved since reheating)

$$Y = \frac{n}{s_{\rm SM}} \quad , \quad s_{\rm SM} = \frac{2\pi^2}{45}\, g_{*s}\, T^3$$

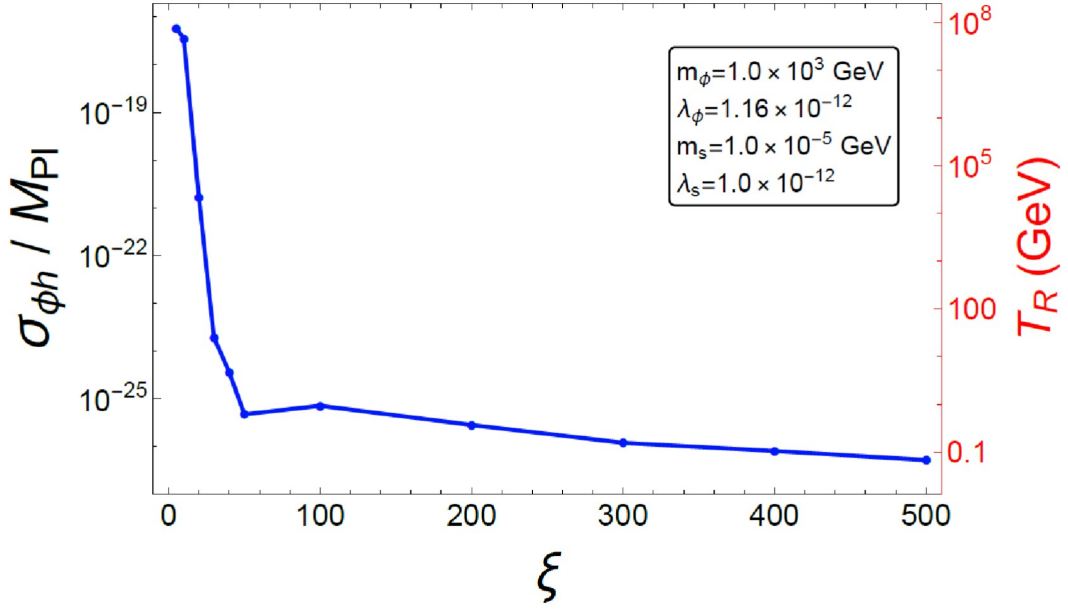
$$Y_\infty = 4.4 \times 10^{-10} \left(\frac{\rm GeV}{m_s}\right)$$

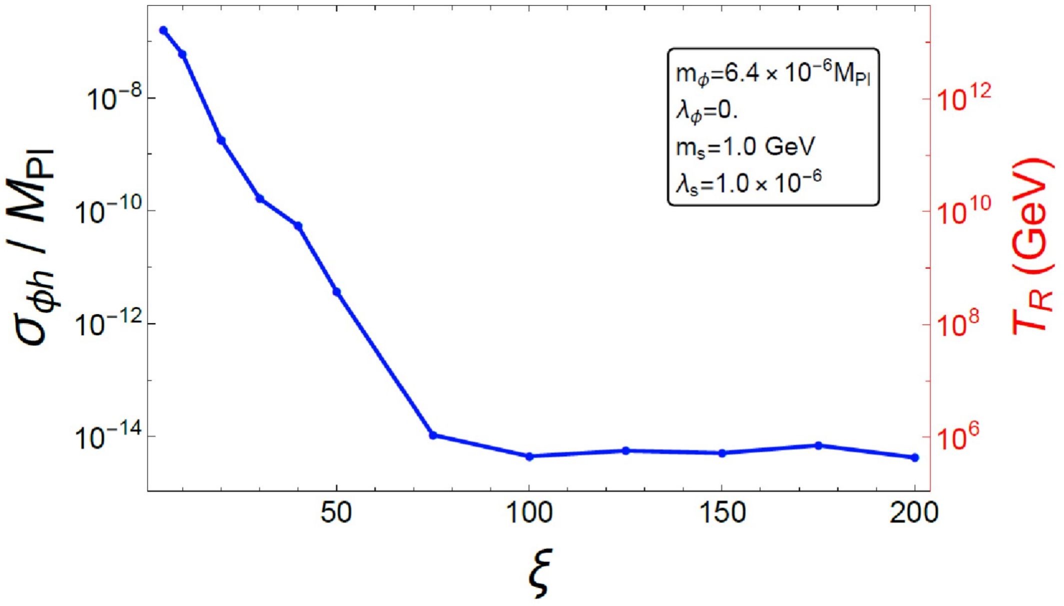
- Reheating via inflaton decay into Higgs $V_{\phi h} = \sigma_{\phi h} \phi H^\dagger H$

$$H_R \simeq \Gamma_{\phi \to hh} \ , \quad \Gamma_{\phi\to hh} = \frac{\sigma_{\phi h}^2}{8\pi m_\phi} \qquad H_R = \sqrt{\frac{\pi^2 g_*}{90}}\, \frac{T_R^2}{M_{\rm Pl}}$$

Parameter space (ξ, T_R)

- (locally) quartic and quadratic inflaton potential





- BBN, Cold DM $\quad T_R > 4\ \mathrm{MeV} \quad \dfrac{T_{\rm SM}}{\langle E(s)\rangle} \sim \left(\dfrac{1}{\lambda_\phi}\,\dfrac{a_R}{a_*}\right)^{1/4} \gg 1$

Singlet inflation w/ NMC

- Singlet scalar Φ with a quartic potential + a non-minimal coupling to gravity

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{2}M_{\rm Pl}^2 R + \frac{1}{2}\xi R\,\phi^2 - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - V\right) \qquad V = \frac{1}{4}\lambda_\phi\phi^4$$

- Well justified from a phenomenological perspective

- Higgs inflation? Unitarity problem (E << Λ ?)

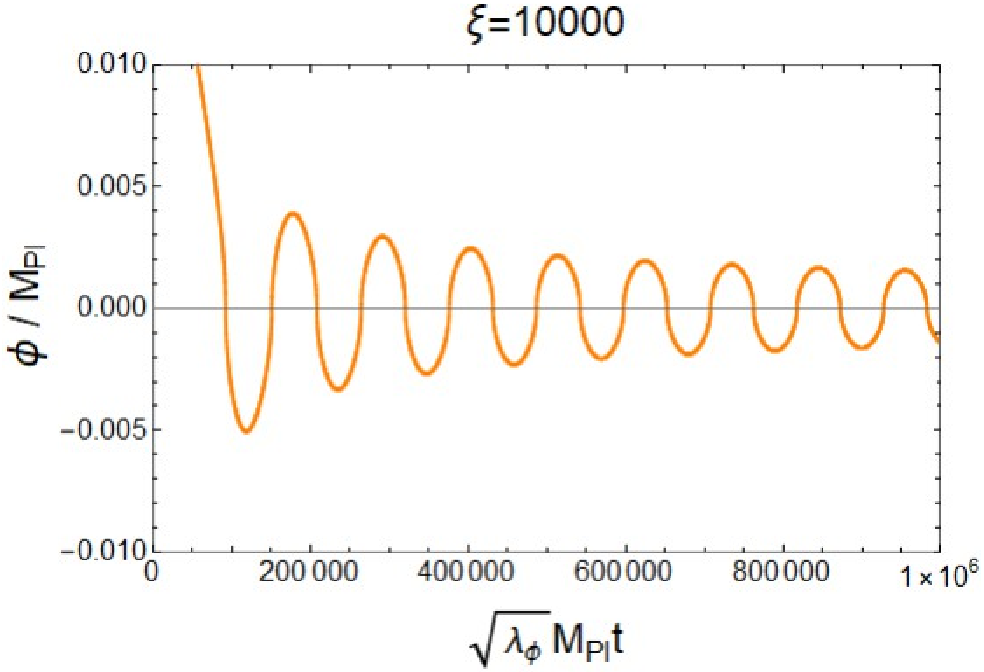
Oleg Lebedev, Yann Mambrini, Jong-Hyun Yoon, "On unitarity in singlet inflation with a non-minimal coupling to gravity" (2305.05682)

Inflaton dynamics with ξ (=10000)

- Solve EOM (linear analysis)

$$\ddot{\phi} + 3H\,\dot{\phi} - \frac{1}{a^2}\nabla^2\phi - \xi R\phi + \frac{\partial V}{\partial\phi} = 0\,,$$
$$3H^2 = \rho(\phi)\,.$$

$$R = \frac{1}{1+(6\xi+1)\xi\,\phi^2}\left[(1+6\xi)\,\partial^\mu\phi\partial_\mu\phi + 4V + 6\xi\,\phi V'_\phi\right]$$
$$\rho(\phi) = \frac{1}{2}\dot{\phi}^2 + V(\phi) - 3\xi H^2\phi^2 - 6\xi H\phi\dot{\phi}\,,$$

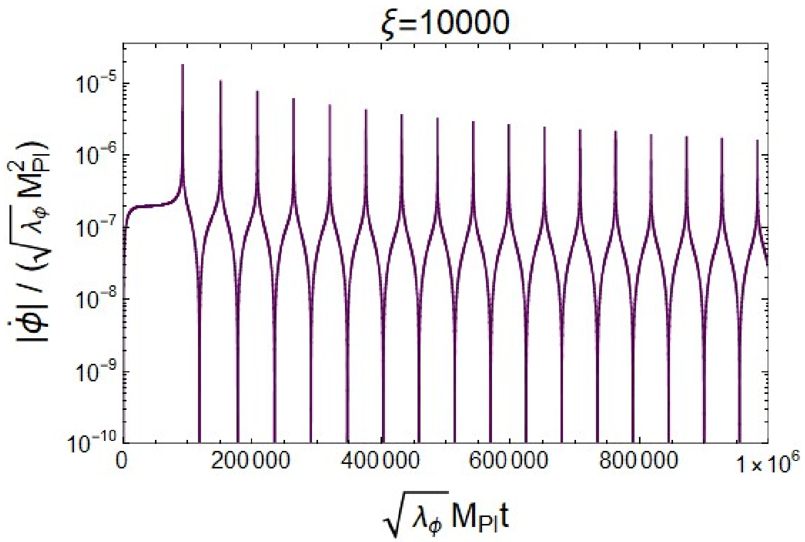


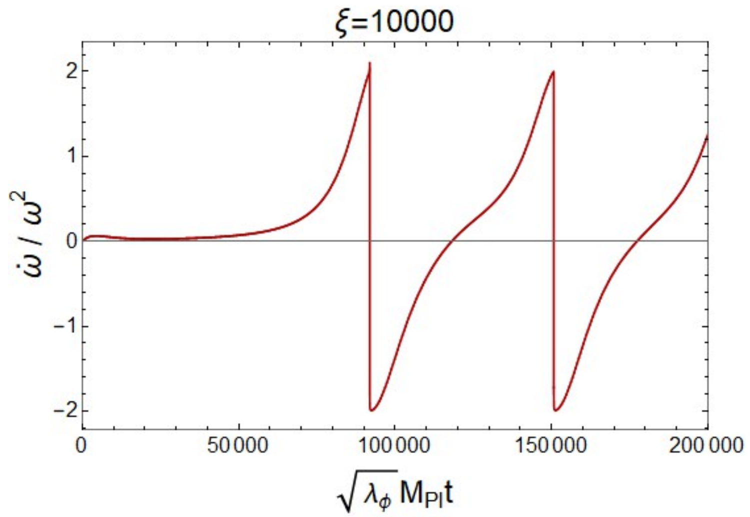
NMC makes ‘steep’ zero-crossings

Y. Ema, R. Jinno, K. Mukaida and K. Nakayama, Violent preheating in inflation with nonminimal coupling, JCAP 02 (2017) 045 [arXiv:1609.05209]

Inflaton dynamics with ξ (=10000)

- Non-adiabaticity (~ dw/dt >> w^2) → Particle production

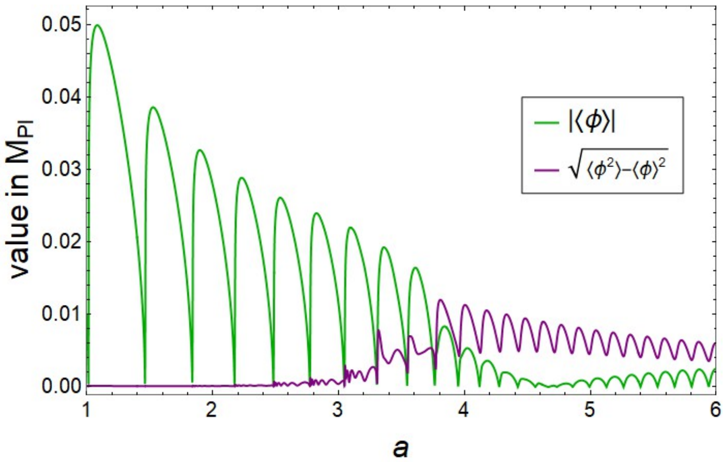


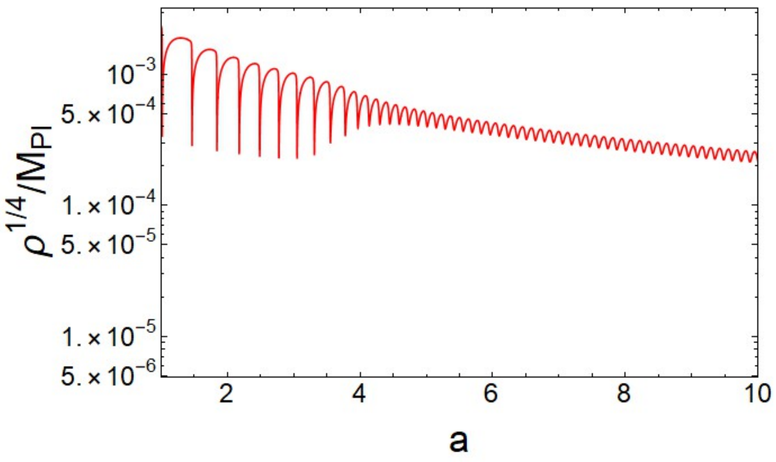


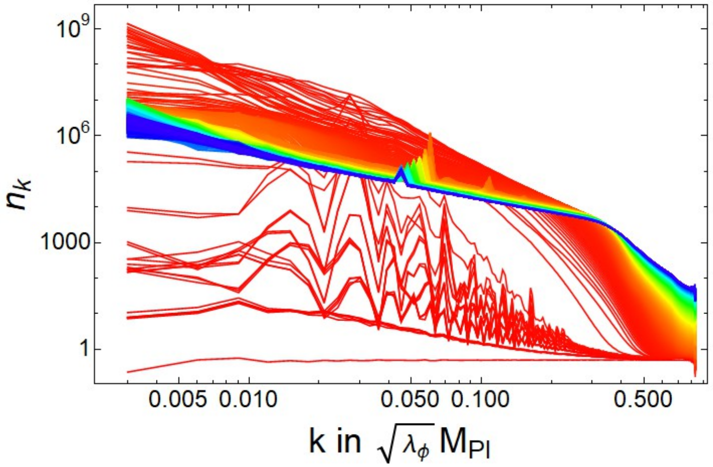
- Efficient particle production can spoil the linear analysis

Simulation outcome for ξ=100

- Non-instantaneous but very-early fragmentation
- Non-trivial scaling law in energy (0<w<1/3)
- Non-pertrubative effects (resonance, backreaction, and rescattering)







Collective effects

- Possible Higgs couplings $\Delta V = \sigma_{\phi h}\, \phi\, H^\dagger H$

In Einstein frame $\longrightarrow$ $\Delta V / \left[4(1+\xi\phi^2)^2\right]$

χ: canonical normalized inflaton $\quad \sigma_{\phi h}\, H^\dagger H\, \frac{\chi^n}{\Lambda^{n-1}}$

- Unitarity in n-particles states (transition prob. < 1)

$$\rho(n \to 2) \propto \left(c_n \frac{p_{\max}\sqrt{f}}{\Lambda} \right)^{2n} \qquad \Lambda \equiv \frac{1}{\xi}$$

$$\kappa \sim \frac{p_{\max}\sqrt{f}}{\Lambda} \lesssim 1 \quad \longrightarrow \quad \xi_{\max} \sim \text{few} \times 100$$

Conclusion

- Studied DM production during preheating via a NMC (for $\xi \gg 1$)

→ Obtained viable parameter space in terms of ξ and T_R

- Implemented singlet inflation model (w/ NMC) on the lattice and learned about its nontrivial dynamics (for $\xi \gg 1$)

→ Considering unitarity with collective effects within EFT, ξ can be extended to a few 100