Oscillons in Higgs Inflation

Based on JCAP 12 (2023) 002
with Javier Rubio

Planck 2024 - Lisbon

The choice of gravity: beyond Eisntein's theory

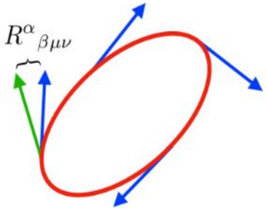
In Einstein's theory the only fundamental geometric variable is the metric

$$\Gamma^{\sigma}{}_{\mu\nu} = \frac{1}{2} g^{\sigma\rho} \left(\partial_\mu g_{\nu\rho} + \partial_\nu g_{\rho\mu} - \partial_\rho g_{\mu\nu} \right)$$

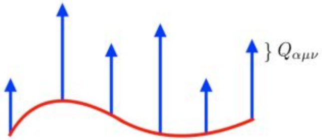
A generic connection contains different contributions

$$\Gamma^{\sigma}{}_{\mu\nu} = \left\{ {\rho \atop \mu\nu} \right\} + S^{\rho}_{\mu\nu} + T^{\rho}_{\mu\nu}$$

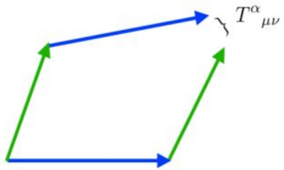
Levi-Civita — Disformation tensor — Contortion tensor



Curvature

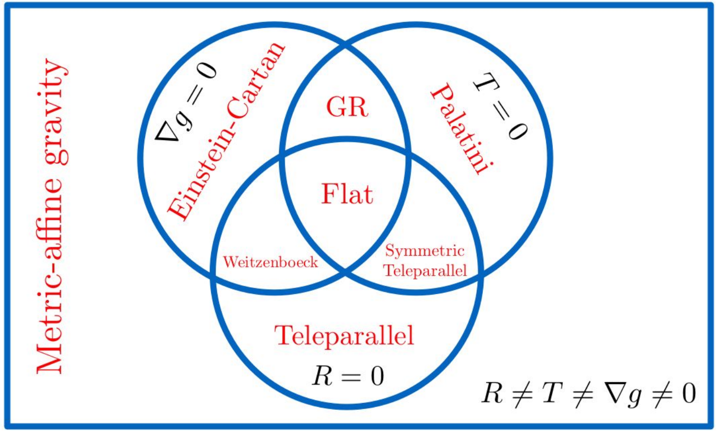


Non-metricity



Torsion

The choice of gravity: an ambiguity in GR



$$\mathcal{L}_{\text{affine}} \sim \mathring{R} + c_{TT}T^2 + c_{QQ}Q^2 + c_{TQ}TQ$$

Formulation of gravity	$R_{\alpha\beta\gamma\delta}$	$T_{\alpha\beta\gamma}$	$Q_{\alpha\beta\gamma}$	Equivalent to metric GR for arbitrary coefficients of T^2, QT, Q^2
Metric-affine				Yes
Einstein-Cartan			$= 0$	Yes
Weyl		$= 0$		Yes
Metric		$= 0$	$= 0$	(not applicable)
Generic teleparallel	$= 0$			No
Metric teleparallel	$= 0$		$= 0$	No
Symmetric teleparallel	$= 0$	$= 0$		No

Adapted from 2204.03003

For pure gravity, all theories are equivalent to GR
Only 2 degrees of freedom of the massless graviton

The choice of gravity: breaking the equivalence

No reason to exclude any possible gravity-matter coupling

$$\mathcal{L} \sim \frac{M_P^2 + \xi h^2}{2} R + C_{TT}(h) T^2 + C_{QQ}(h) Q^2 + C_{QT}(h) TQ + \ldots$$

Solve for Q and T
(they do not propagate)

Move to a minimally-coupled frame
(Einstein-frame)

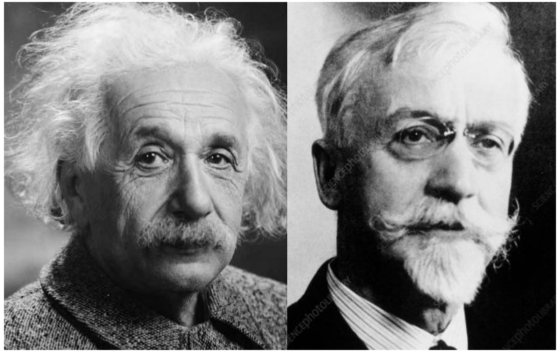
$$\mathcal{L} \sim \frac{R}{2} - \frac{1}{2} \boxed{K(h)} (\partial h)^2 - \frac{U(h)}{\Omega^4(h)}$$

From a gravity formulation to an EFT

The choice of gravity: Einstein-Cartan gravity

$$g_{\alpha\beta} = e_\alpha^A e_\beta^B \eta_{AB} \ , \qquad \eta_{AB} = e_A^\alpha e_B^\beta g_{\alpha\beta}$$

$$\Gamma^\kappa_{\nu\mu} = e^\kappa_A \left(\partial_\mu e^A_\nu + \omega_{\mu B}^A e^B_\nu\right)$$



- Tetrads and spin-connection are the fundamental variables
- Obtained by gauging the Poincaré group
- Non-vanishing torsion
- Fermions are naturally introduced in the theory

The connection is not assumed to be symmetric *a priori* $\qquad T^\mu{}_{\nu\rho} = \Gamma^\mu{}_{\nu\rho} - \Gamma^\mu{}_{\rho\nu}$

Einstein-Cartan gravity: the Nieh-Yan term

Many free parameters

Not predictive

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{2} - \frac{1}{2}\frac{1+c\,h^2}{(1+\xi h^2)^2}(\partial h)^2 - \frac{\lambda}{4}\frac{h^4}{(1+\xi h^2)^2}\right]$$

$$c(h) = \xi + 6\xi^2 + 4(1+\xi h^2)\frac{G_{aa}(\zeta_h^v)^2 + G_{vv}(\zeta_h^a)^2 - G_{va}\zeta_h^v\zeta_h^a}{G_{vv}G_{aa} - G_{va}^2}$$

A study case: the Nieh-Yan term

$$c_{va} = \xi_{va} = 0\,, \qquad c_{vv} = -16c_{aa} = -\frac{2}{3}\,, \qquad \xi_{vv} = \xi_{aa} = -\zeta_h^v = \xi\,, \qquad \zeta_h^a = \frac{1}{4}\xi_\eta$$

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{4}\int d^4x\,\xi_\eta h^2\partial_\mu\left(\sqrt{-g}\epsilon^{\mu\nu\rho\sigma}T_{\nu\rho\sigma}\right) \qquad c = \xi + 6\xi_\eta^2$$

Nieh-Yan Higgs Inflation: predictions

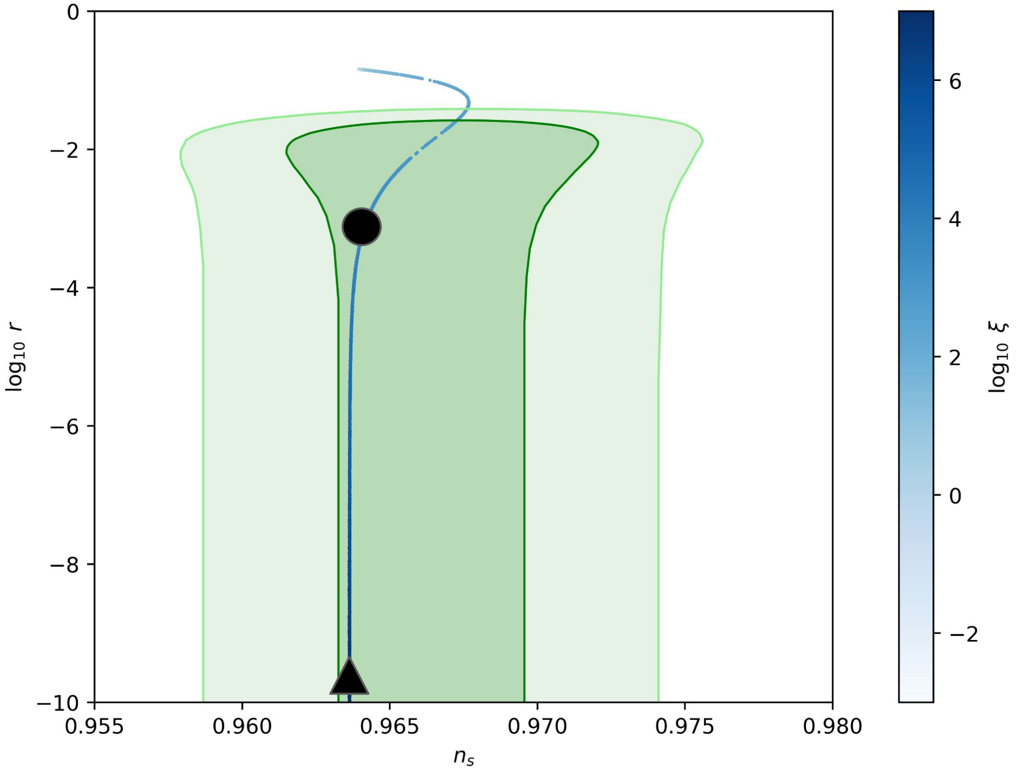
$$n_s = 1 - \frac{2}{N}$$

$$r = \frac{2c}{\xi N^2}$$

$$c = \frac{2}{5}\lambda N^2 \cdot 10^7$$

Metric ● Palatini ▲

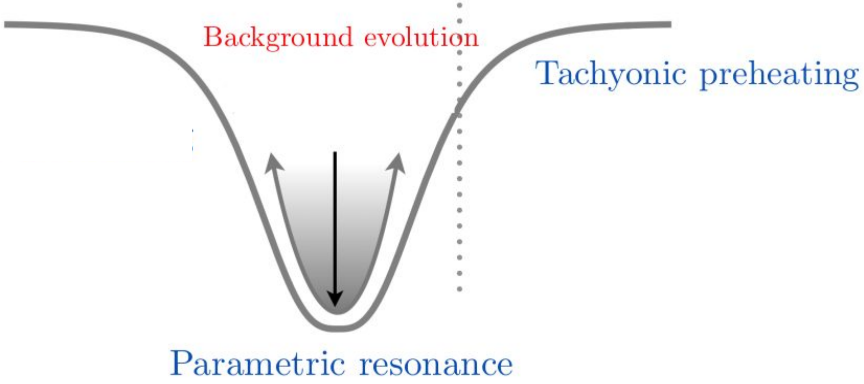
$\xi \to \sqrt{c/6}$ $\xi \to c$



Particle production in an oscillating background

$$\ddot{\chi} - a^{-2}(t)\nabla^2\chi + 3\dot{\chi}H + \frac{\mathrm{d}V(\chi)}{\mathrm{d}\chi} = 0$$

$$\delta\ddot{\chi}_{\mathbf{k}} + 3H\delta\dot{\chi}_{\mathbf{k}} + \left(\frac{\mathbf{k}^2}{a^2(t)} + \frac{\mathrm{d}^2V(\chi)}{\mathrm{d}\chi^2}\bigg|_{\chi=\bar{\chi}(t)}\right)\delta\chi_{\mathbf{k}} = 0$$



Oscillations beyond the inflection point induce a tachyonic instability

$$\chi_i = \frac{\sqrt{c}\ln(2)}{2\xi}$$

Rapid growth of low momenta perturbation ⟶ **Backreaction** ⟶ **Fragmentation**

Linear analysis

Background

$$\ddot{\chi} - a^{-2}(t)\nabla^2\chi + 3\dot{\chi}H + \frac{\mathrm{d}V(\chi)}{\mathrm{d}\chi} = 0$$

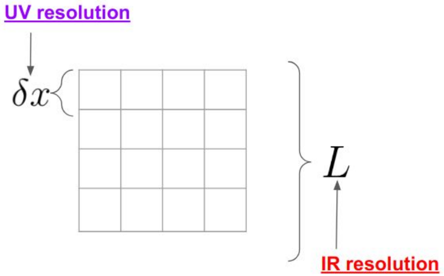
Perturbations

$$\delta\ddot{\chi}_{\mathbf{k}} + 3H\delta\dot{\chi}_{\mathbf{k}} + \left(\frac{\mathbf{k}^2}{a^2(t)} + \frac{\mathrm{d}^2V(\chi)}{\mathrm{d}\chi^2}\bigg|_{\chi=\overline{\chi}(t)}\right)\delta\chi_{\mathbf{k}} = 0$$

Exponential growth due to tachyonic instability when the term in the parenthesis is negative

Growth of perturbations in the IR → **Backreaction** → **Fragmentation**

Lattice simulations



- Can handle the non linearity of the problem
- You can follow the system even after backreaction
- You can compute the expected background of GWs

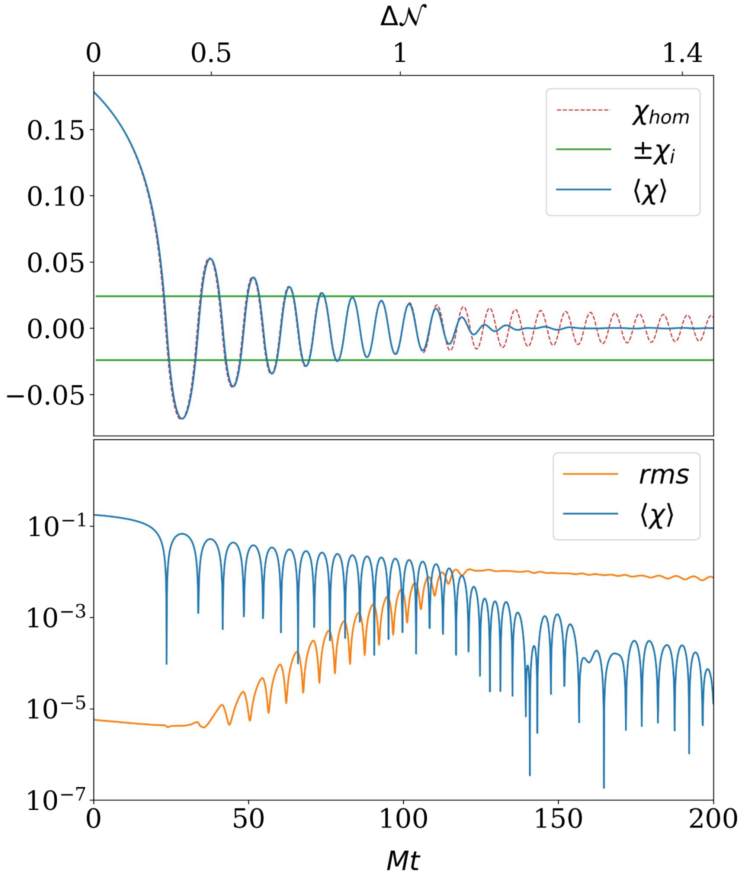
Results from the lattice: fragmentation

$$L = 50M^{-1} \quad N = 256 \quad \xi = 50000$$

$$M^2 = V_{,\chi\chi} = \frac{2\lambda}{c}$$

$$\mathrm{rms} = \sqrt{\langle \chi^2 \rangle - \langle \chi \rangle^2}$$

The condensate fragments within the first 10 oscillations

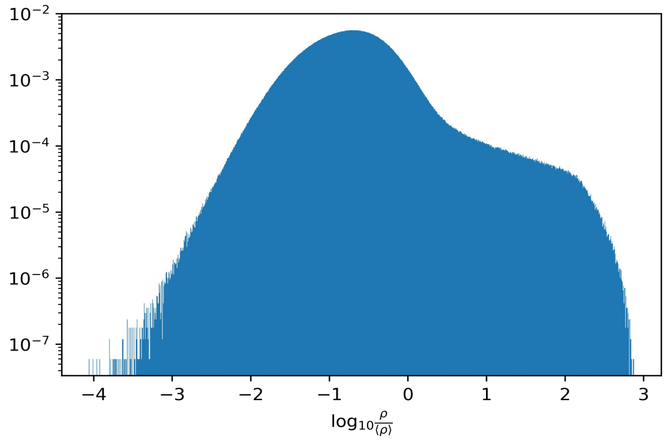


Oscillons in Higgs inflation

Formation of non-linear structures of fixed physical size called **oscillons**.

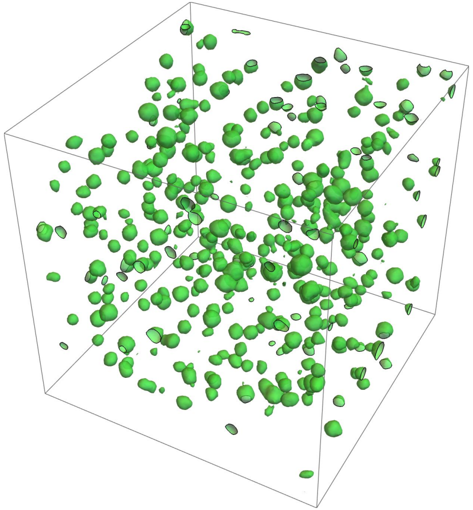
Oscillons

- Pseudo-solitonic objects
- Quasi-spherical shape
- Similar to boson stars (and Q-balls)



Related phenomena

- Production of sizeable amount of gravitational waves
- Non-standard expansion history
- Change of the inflationary observables



New features compared to the metric and Palatini scenarios

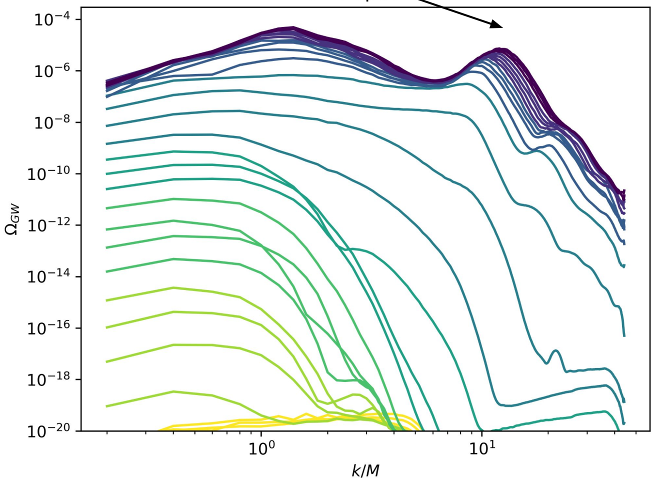
Gravitational waves signal

The fragmentation of the condensate can lead to the generation of a stochastic gravitational wave background

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - a^{-2}\nabla^2 h_{ij} = 2a^{-2}\Pi_{ij}^{TT}$$

$$\Pi_{ij}^{TT} = (\partial_i\chi\partial_j\chi)^{TT}$$

Oscillons themselves can source a secondary peak at larger frequencies



Strong signal

High frequency

What about the other SM particles?

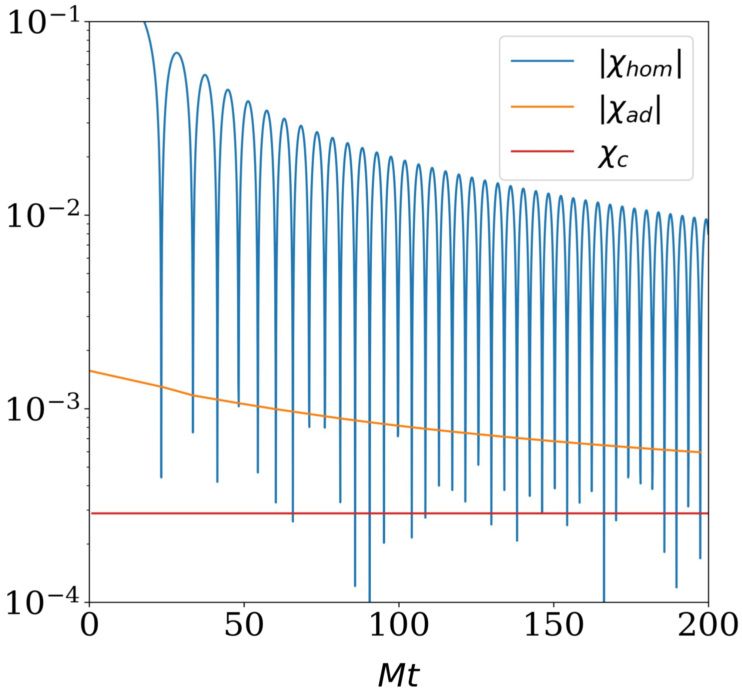
- Higgs inflation provides a framework in which all the couplings to SM particles are known and understood
- Fermions are produced perturbatively from the decay of gauge bosons
- Do the other SM particles spoil oscillons formation?

Gauge bosons

Gauge bosons are produced at higher momenta

$$k_{osc} \sim M \qquad\qquad k_{gb} \sim 30M$$

$$m^2 = \frac{g^2}{4\xi}\left(1 - e^{-2\frac{\xi}{\sqrt{c}}|\chi|}\right) \qquad\qquad g^2 = 0.29$$



- They are produced at each 0-crossing through parametric resonance
- In absence of fermions their production requires “few” oscillations to be efficient
- If they don’t decay the effect might be competitive with oscillons formation

Fermions

Introducing fermions on the lattice pose a serious challenge due to the “fermion doubling” doubling.

We can introduce the gauge bosons decay at the perturbative level

$$\langle \Gamma \rangle \propto \langle m \rangle$$

$$\begin{cases} \dot{\rho}_T + 3H\left(\rho_T + p_T\right) = 0 \\ \rho_T = \rho_\chi + \rho_F + \rho_B \\ P_T = P_\chi + P_F + P_B \end{cases}$$

The decay of gauge bosons into fermions significantly affects the efficiency of parametric resonance

Condition for efficient decay

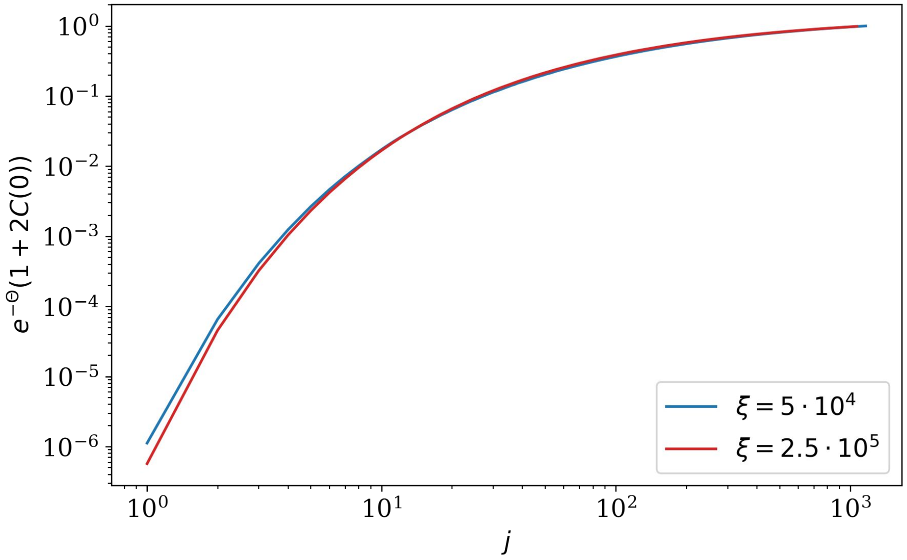
$$\langle \Gamma \rangle > H$$

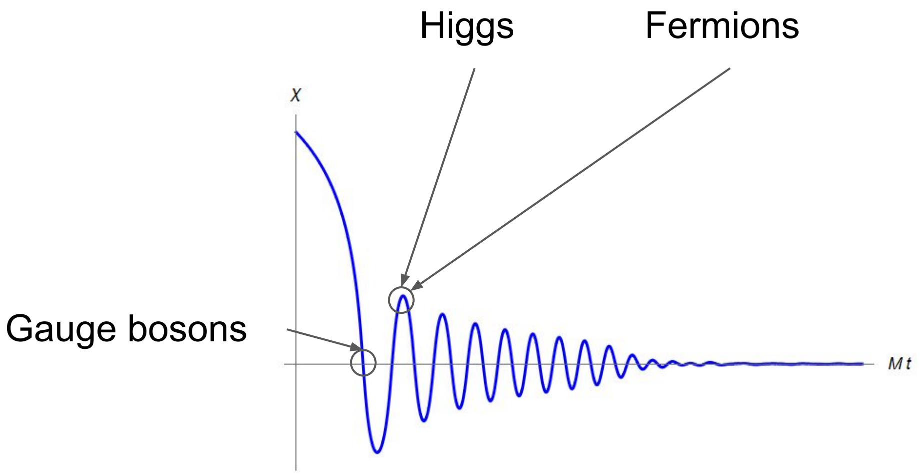
Combined preheating

Gauge bosons occupation number

$$\left[\frac{1}{2}+n_k((j+1)^+)\right]=(1+2C_k(j))\left[\frac{1}{2}+n_k(j^+)\,e^{-\Theta(j)}\right]$$

$$\Theta(j)=\int_{t_j}^{t_j+1}\Gamma(t)dt$$





Conclusions and outlook

- For the first time we have observed the presence of oscillons in the context of Higgs-Inflation

- Their presence can source a sizeable amount of GWs, providing an extra observational channel besides inflation

- Fermions and gauge bosons are not expected to spoil oscillons formation, but can play a role once they have formed

- Long lived oscillons can strongly affect the inflationary predictions, and help distinguish between different formulation of gravity

Thank you