Impact of other scalar fields on oscillons after hilltop inflation

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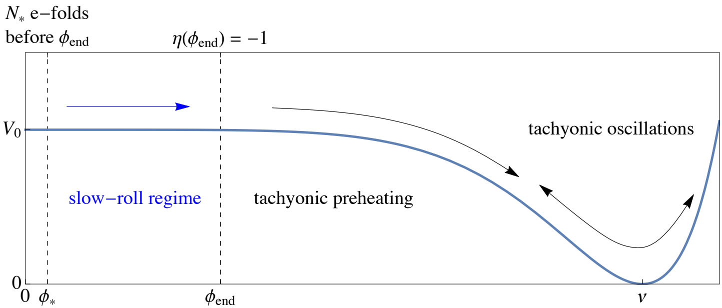
Outline

1. Preheating in single-field hilltop inflation
2. Oscillon formation
3. Parametric resonance of χ sourced by inhomogeneous ϕ
4. Impact of χ on oscillons
5. Conclusions

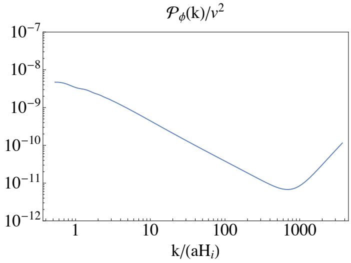
$$V(\phi) = V_0 \left(1 - \frac{\phi^6}{v^6}\right)^2, \qquad \text{with } v \ll m_{\rm Pl}$$



tachyonic preheating

⇒ ϕ fluctuations grow for $k^2 + V_{\phi\phi} < 0$

- leads to formation of IR dominated spectrum
- ends when $\phi = v$ for the first time
- for $v \lesssim 10^{-5} m_{\rm pl}$, $\langle \delta\phi^2 \rangle \sim v^2$ during this phase
- for $v \gtrsim 10^{-5} m_{\rm pl}$, tachyonic preheating is followed by coherent oscillations of the inflaton



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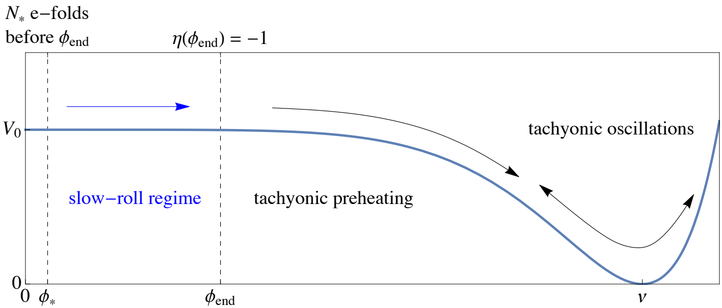

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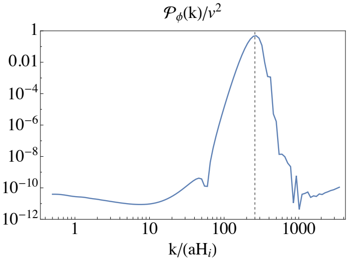
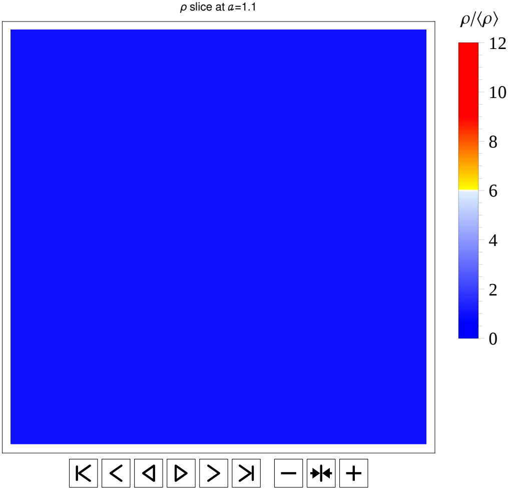
tachyonic oscillations

- $\Rightarrow$ ϕ fluctuations grow around $k_p/a \sim 200\sqrt{V0/3}$
  - leads to spectrum peaked at k_p
  - for $v \lesssim 10^{-1} m_{\rm pl}$, $\langle \delta\phi^2 \rangle \sim v^2$ during this phase
- $\Rightarrow$ for $10^{-5} \lesssim v/m_{\rm pl} \lesssim 10^{-1}$, growth of fluctuations at k_p leads to formation of "hill-crossing" oscillons, separated by $\xi \sim 2\pi/k_p$
  - oscillons eventually settle around $\phi = v$



$$V(\phi) = V_0 \left(1 - \frac{\phi^6}{v^6}\right)^2, \qquad \text{with } v = 10^{-2} m_{\rm Pl}.$$

Movie of ρ from $2D$ simulation with 1024^2 points.



Oscillons:

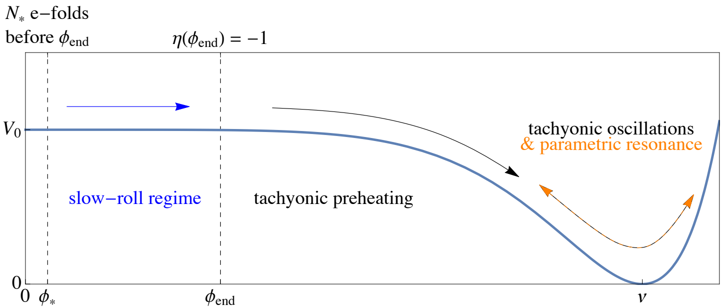
Spatially localized oscillating configurations of a real scalar field

- form when scalar field oscillates in potential that is shallower than quadratic away from the minimum
- they have a surprisingly long lifetime:
  stable for large number of oscillations, can survive for many e-folds
- arise in many inflationary models favoured by observations

Interesting and potentially observable consequences:

- generate gravitational waves when they form and when they decay
- affect the expansion history of the universe possibly leading to signatures in the CMB
- ...

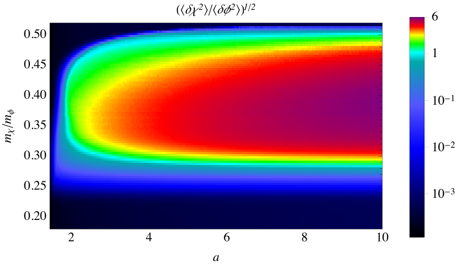
$$V(\phi,\chi) = V_0\left(1-\frac{\phi^6}{v^6}\right)^2 + \frac{\lambda^2}{2}\phi^2\chi^2(\phi^2+\chi^2), \qquad \text{with } v = 10^{-2} m_{\rm Pl}$$



parametric resonance of χ sourced by inhomogeneous ϕ

$\Rightarrow$ χ fluctuations grow after $\delta\phi \ll \sqrt{\langle\delta\phi^2\rangle}$

- exponential growth only if λ is inside resonance band



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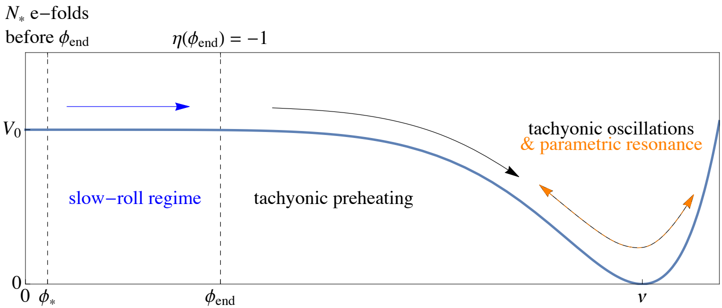
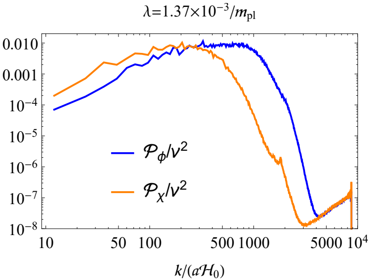


parametric resonance of χ sourced by inhomogeneous ϕ

- $\Rightarrow$ χ fluctuations grow after $\delta\phi \ll \sqrt{\langle\delta\phi^2\rangle}$
  - exponential growth only if λ is inside resonance band
  - χ develops spectrum peaked at $k \sim k_p$
- $\Rightarrow$ what is the impact of this resonance on oscillons?



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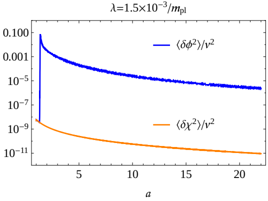
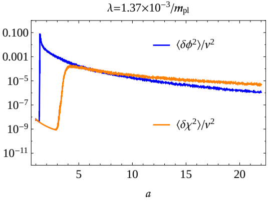
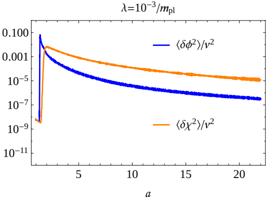
Consider three cases:







I no resonance

$\Rightarrow$ λ outside resonance band

$\langle\delta\chi^2\rangle$ not amplified and its vacuum fluctuations redshift

II "slow" resonance

$\Rightarrow$ λ inside resonance band

$\langle\delta\chi^2\rangle$ amplified ~ 1 e-fold after ϕ has formed oscillons

III "fast" resonance

$\Rightarrow$ λ inside resonance band

$\langle\delta\chi^2\rangle$ amplified during initial phase of oscillons formation

$$V(\phi,\chi) = V_0\left(1-\frac{\phi^6}{v^6}\right)^2 + \frac{\lambda^2}{2}\phi^2\chi^2(\phi^2+\chi^2), \qquad \text{with } v = 10^{-2} m_{\rm Pl}$$

In what follows: results of lattice simulations of cases **I**, **II** and **II**
$\Rightarrow$ solve system of equations:

$$\ddot{\phi}(t,\bar{x}) + 3H\dot{\phi}(t,\bar{x}) - \frac{1}{a^2}\bar{\nabla}^2\phi(t,\bar{x}) + \frac{\partial V}{\partial \phi} = 0$$

$$\ddot{\chi}(t,\bar{x}) + 3H\dot{\chi}(t,\bar{x}) - \frac{1}{a^2}\bar{\nabla}^2\chi(t,\bar{x}) + \frac{\partial V}{\partial \chi} = 0$$

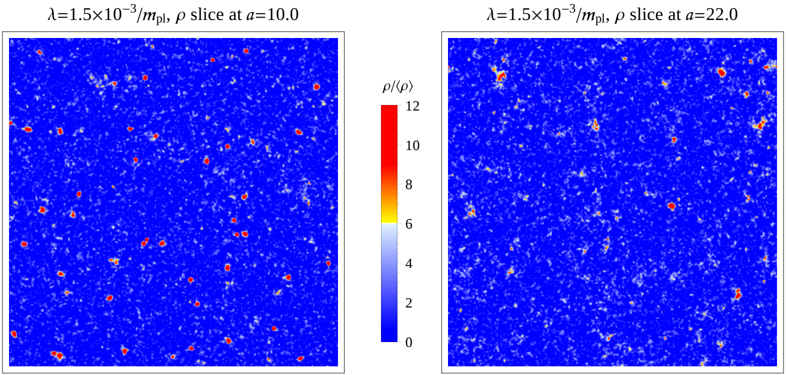
$$H^2 \equiv \frac{\langle\rho\rangle}{3m_{\rm pl}^2} = \frac{1}{3m_{\rm pl}^2}\left\langle V + \sum_f\left(\frac{1}{2}\dot{f}^2 + \frac{1}{2a^2}\left|\bar{\nabla} f\right|^2\right)\right\rangle$$

on discretized lattice with parameters:

$v/m_{\rm pl}$	$\langle\phi\rangle_{\rm i}/v$	$\langle\dot{\phi}\rangle_{\rm i}/v^2$	$\langle\chi\rangle_{\rm i}/v$	$\langle\dot{\chi}\rangle_{\rm i}/v^2$	$H_{\rm i}/m_{\rm pl}$
10^{-2}	0.08	2.49×10^{-9}	0	0	1.9×10^{-10}

D	N	$k_{\rm uv}$	$k_{\rm ir}$	δx	L
2	1024	$6.2\times10^4 H_{\rm i}$	$60.5 H_{\rm i}$	$10^{-4}/H_{\rm i}$	$0.1/H_{\rm i}$

case **I**: no parametric resonance

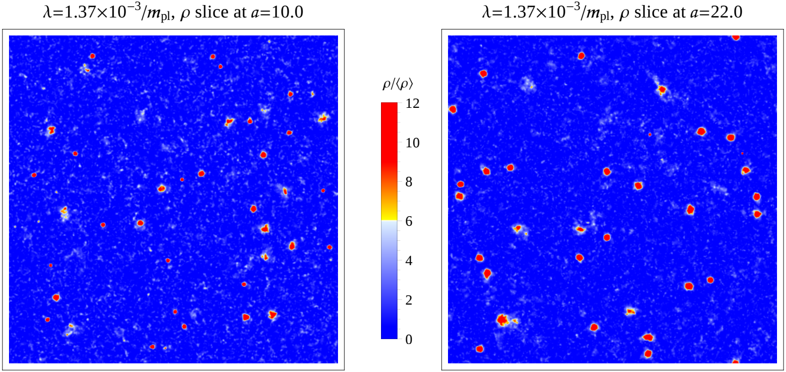


- at $a = 10$: many oscillons still present
- at $a = 22$: less oscillons

$\Rightarrow$ they start decaying before the end of the simulation

without parametric resonance of χ the evolution of oscillons is equal to single-field case

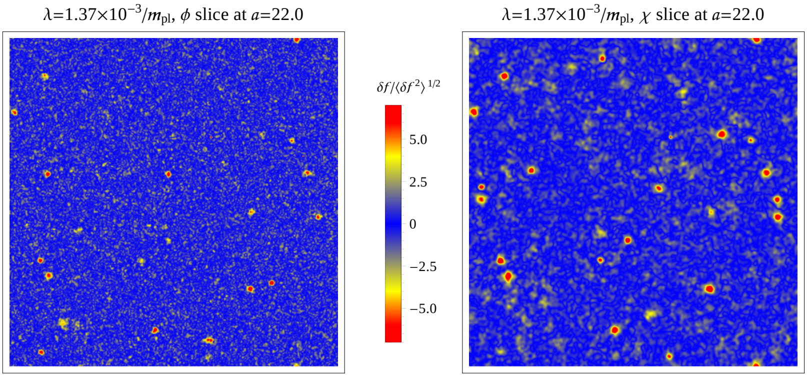
case **II**: ”slow” parametric resonance



- at $a = 10$: many oscillons still present, as in case **I**
- at $a = 22$: more oscillons, more pronounced

$\Rightarrow$ ”slow” parametric resonance of χ enhances the oscillons formed by ϕ

case **II**: "slow" parametric resonance



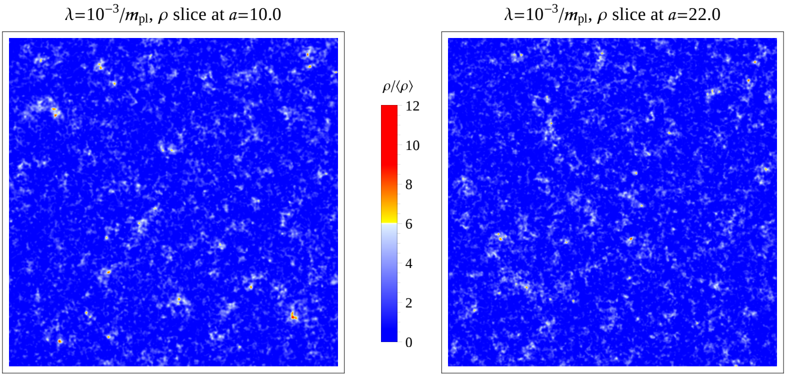
- at $a = 10$: many oscillons still present, as in case **I**
- at $a = 22$: more oscillons, more pronounced

$\Rightarrow$ ϕ and χ are correlated: the oscillons get imprinted in the χ field

$\Rightarrow$ "slow" parametric resonance of χ enhances the oscillons formed by ϕ

$\Rightarrow$ ϕ and χ are correlated: the oscillons get imprinted in the χ field

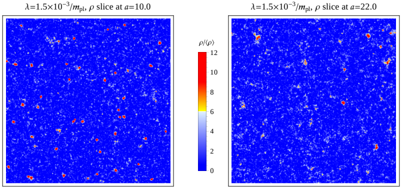
case **III**: "fast" parametric resonance



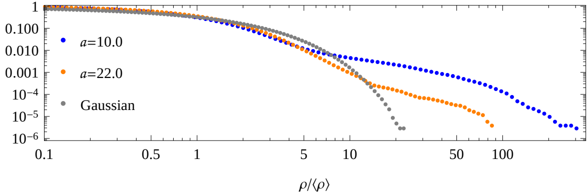
- at $a = 10$: no oscillons
- at $a = 22$: no oscillons

$\Rightarrow$ "fast" parametric resonance of χ suppresses the oscillons formed by ϕ

case **I**: no parametric resonance



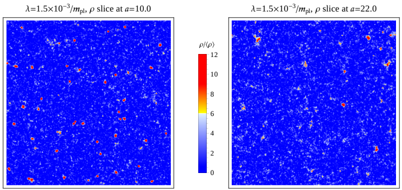
ρ tail distribution for $\lambda=1.5\times10^{-3}/m_{\rm pl}$

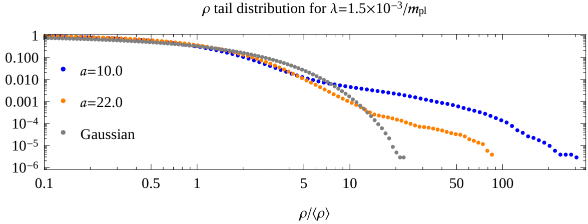


tail distribution: number of lattice points with energy density $> \rho$

in grey: tail distribution of energy $\rho_g = m_\phi^2 g_1^2/2 + m_\chi^2 g_2^2/2$,
where g_1 and g_2 are discrete Gaussian fields with variances $\langle g_1^2\rangle = \langle\phi^2\rangle$ and $\langle g_2^2\rangle = \langle\chi^2\rangle$

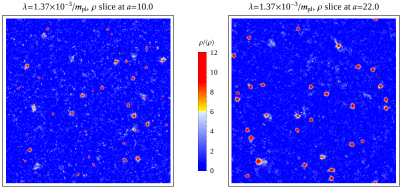
case **I**: no parametric resonance

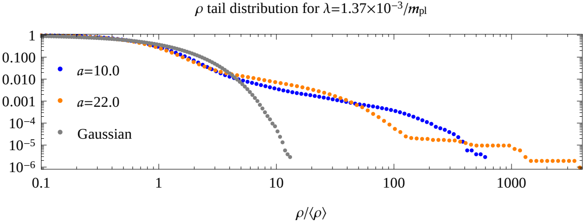




- at $a = 10$: tail distribution stretches to $\rho \sim 300\langle\rho\rangle$, far away from Gaussian tail $\Rightarrow$ expected when oscillons are present
- at $a = 22$: tail distribution shrunk, but still more spread than Gaussian

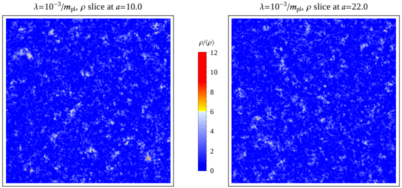
case **II**: "slow" parametric resonance

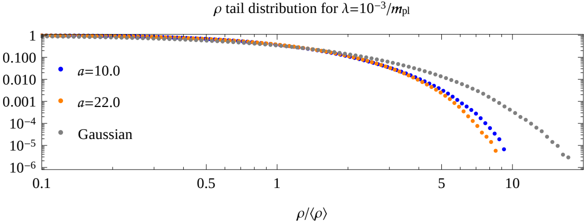




- at a $= 10$: tail distribution stretches to $\rho \sim 700\langle\rho\rangle$, longer than case **I** tail $\Rightarrow$ more energetic oscillons are present
- at a $= 22$: tail distribution spread to $\rho \sim 3000\langle\rho\rangle$ but lower around $\rho \sim 100\langle\rho\rangle$

case **III**: "fast" parametric resonance

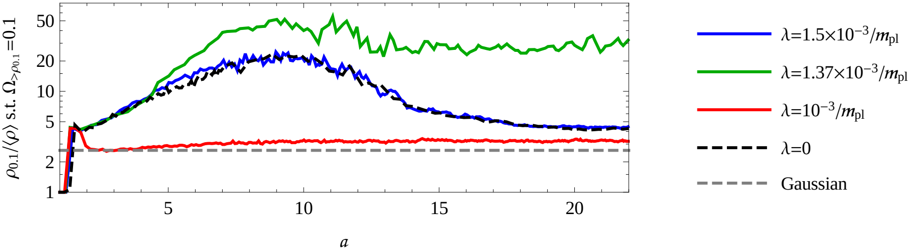




- at $a = 10$: tail distribution close to Gaussian tail
- at $a = 22$: tail distribution close to Gaussian tail

$\Rightarrow$ no oscillons are formed and field fluctuations close to Gaussian

evolution of ρ in cases I, II and III



$\rho_{0.1}$ for which 10% of the energy is stored in regions with $\rho > \rho_{0.1}$
$\Rightarrow$ larger $\rho_{0.1}$ indicates that more energy is in regions with larger ρ
$\Rightarrow$ more oscillons

- **I** no resonance case as single field case (dashed black): $\rho_{0.1}$ grows until $a = 10$, then decreases
- **II** "slow" resonance leads to more energy stored in oscillons
- **III** "fast" resonance suppresses the formation of oscillons, statistics close to Gaussian

$\Rightarrow$ the timing of the resonance of χ determines whether the oscillons are enhanced or suppressed

Summary:

- ϕ oscillons form after hilltop inflation, during the phase of tachyonic oscillations
- when another scalar field χ is present, a parametric resonance of χ sourced by the inhomogeneous ϕ can happen
- depending on the occurrence and timing of the resonance, χ can have different impacts on the oscillons:

I if no resonance, χ has no effect on oscillons $\Rightarrow$ as single field case

II "slow" resonance: χ amplified ~ 1 e-fold after ϕ oscillons have formed
$\Rightarrow$ oscillons are enhanced, their lifetime extended

III "fast" resonance: χ amplified during formation of oscillons
$\Rightarrow$ oscillons are suppressed, and the fields have statistics close to Gaussian

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Outlook:

- oscillons affect the expansion history of the universe: effect on equation of state, delay thermalization
- their evolution depends on χ, light degree of freedom during inflation
  $\Rightarrow$ possible effect on CMB scales via dependence on (ϕ_*, χ_*)
- production of gravitational waves during formation and decay of oscillons
- ...