Impact of other scalar fields on oscillons after hilltop inflation

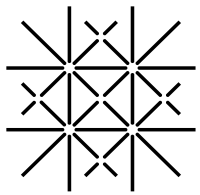
Stefano Orani

with Stefan Antusch
JCAP 1603 (2016), no.03, 026

hep-ph/1511.02336

also Francesco Cefalà and David Nolde
JCAP 1602 (2016), no.02, 044
hep-ph/1510.04856
JCAP 1506 (2015), no.06, 009

hep-ph/1503.06075



University of Basel

Outline

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

$$\boxed{\textbf{INFLATION} : \ddot{a} > 0 \Leftrightarrow \rho + 3p < 0}$$

$$ds^2 = -dt^2 + a(t)^2 d\Sigma^2$$

$\rightarrow$ allows to "explain" the initial conditions of the hot big bang

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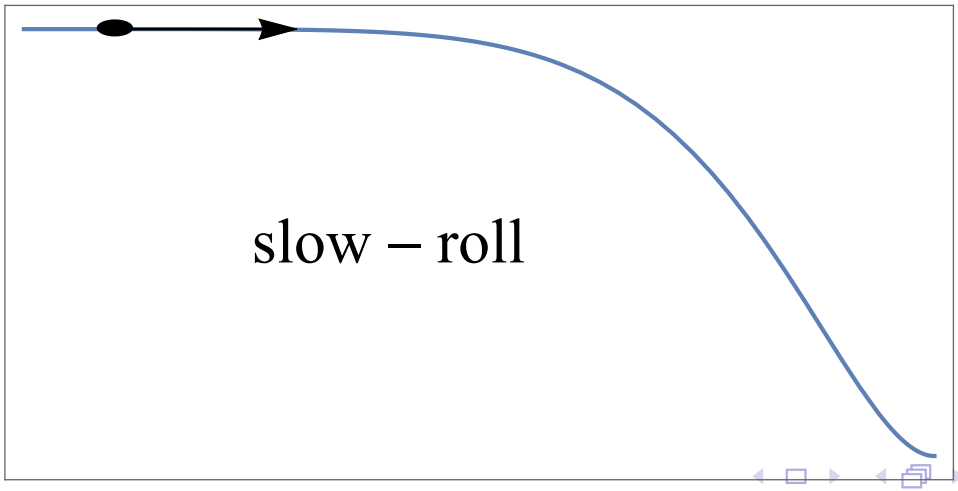
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Scalar field ϕ can source the desired equation of state:

$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$ and $\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$

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During inflation, ϕ is dominated by its potential energy: it slow-rolls along a flat potential

ϕ has quantum fluctuations $\rightarrow$ different regions undergo different expansion during inflation

$\Rightarrow$ generates a curvature perturbation

$\Rightarrow$ explains the origin of structures of the universe

$\Rightarrow$ direct link to temperature fluctuations of the CMB

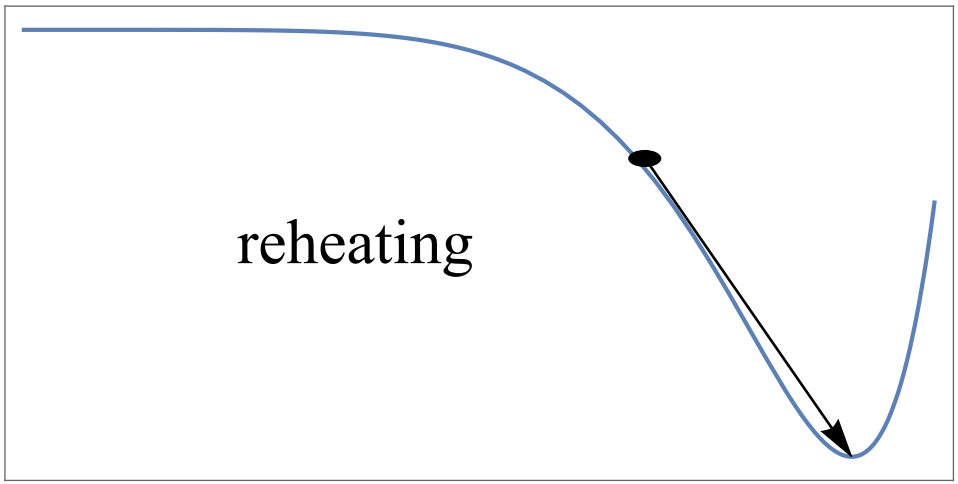
CMB properties favour inflationary potentials with a plateau shape

During inflation universe is "cold": ϕ only has potential energy, no particles

After inflation universe **reheats**: ϕ accelerates toward minimum of potential
$\rightarrow$ transfers potential energy to kinetic and gradient energy

dynamics of **reheating** depend on interaction between inflaton sector and Standard Model

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- equation of state of the universe: affects CMB fluctuations!
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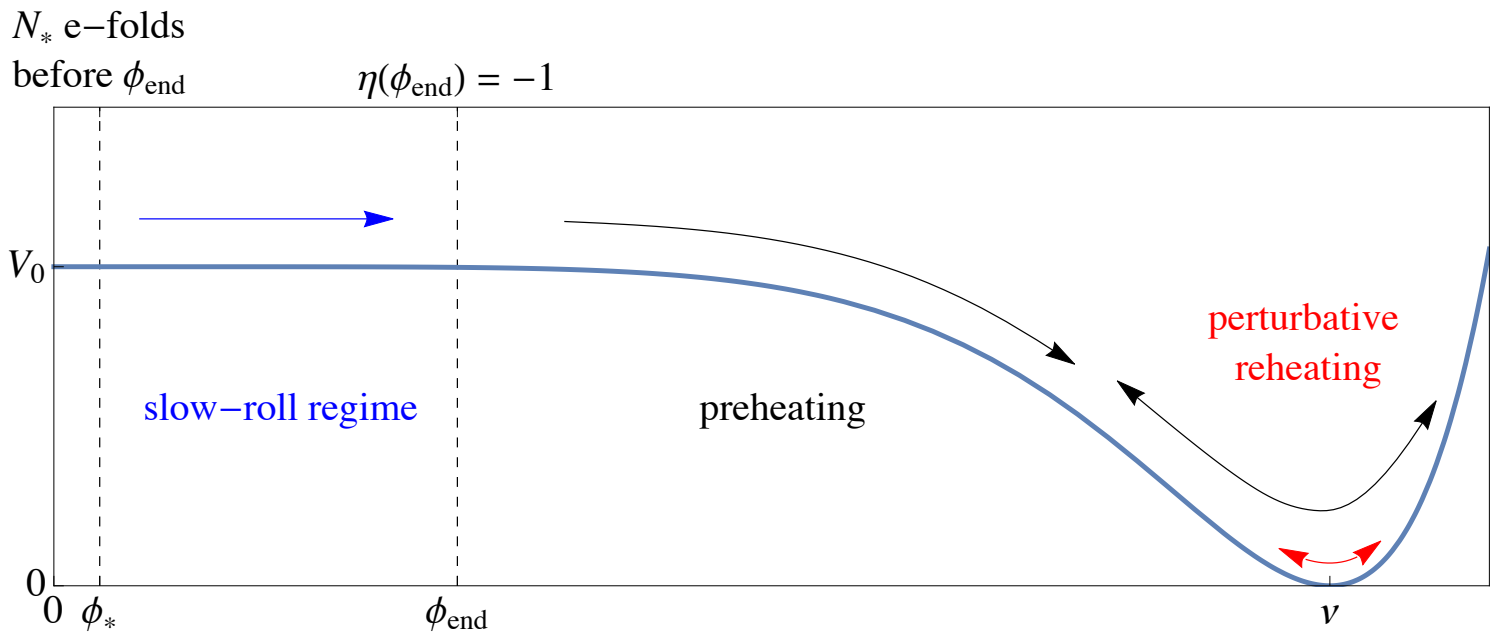
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possible embeddings of inflation in particle physics:

(i) Higgs of SM is the inflaton $\rightarrow$ non-minimal coupling between Higgs and gravity
(ii) inflaton is contained in a Grand Unified Theory
(iii) other extensions of the SM..

In what follows: reheating after inflation along a plateau motivated by supersymmetric GUT

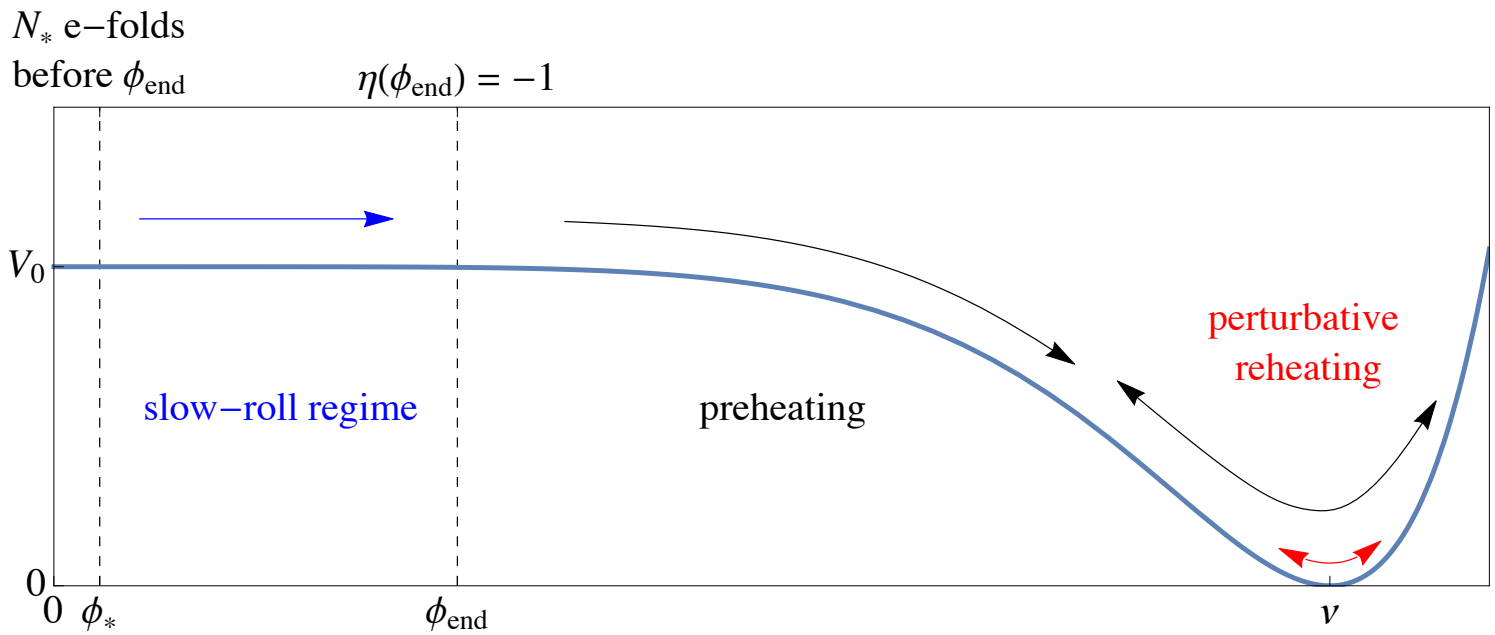
$$V(\phi) = V_0 \left(1 - \frac{\phi^6}{v^6}\right)^2, \qquad \text{with } v \ll m_{\rm Pl}$$



hilltop inflation

- potential generated from embedding in SUSY $\rightarrow$ symmetries on superpotential W
- initial conditions for inflation at $\phi \sim 0$ generated dynamically via interaction with another scalar field χ
- expansion of the universe accelerates while $\phi > 0$ slowly rolls towards v

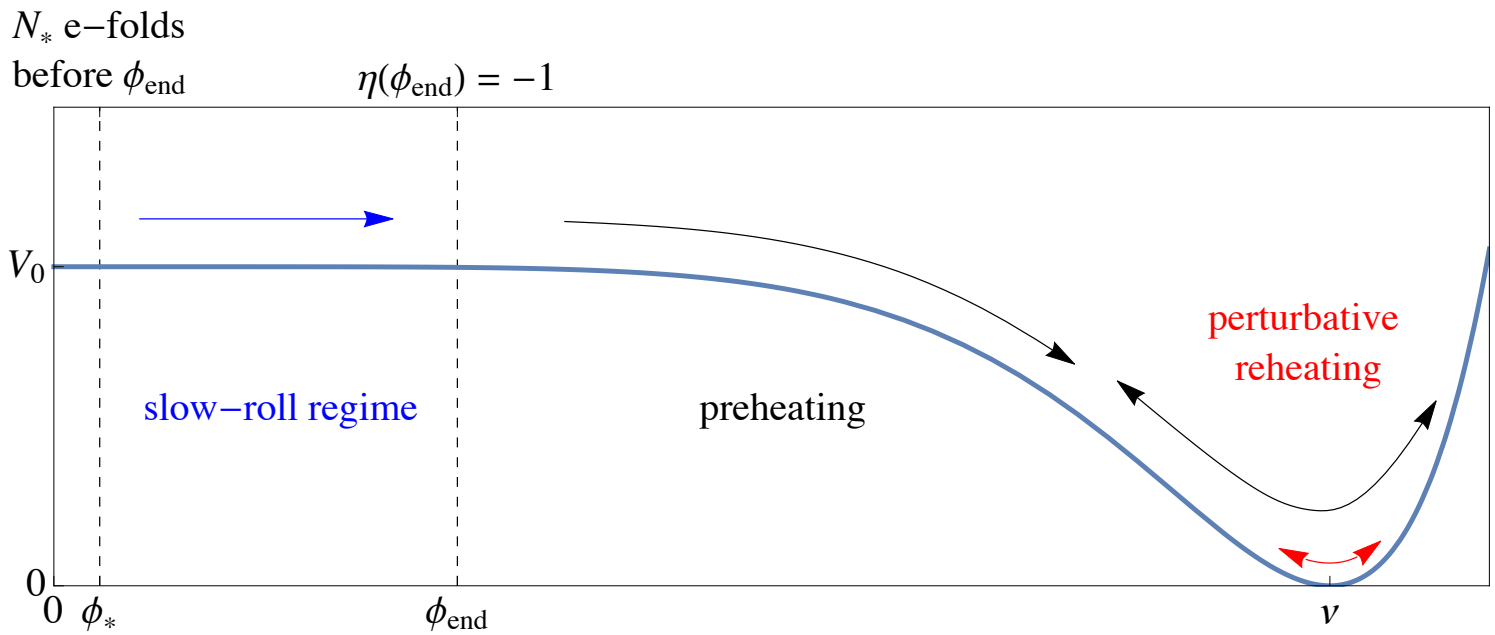
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slow-roll inflation

- as long as $|\eta| = m_{\rm Pl}^2 |V_{,\phi\phi}|/V \ll 1$
- observable scales exit horizon $N_* = 50$–60 e-folds before $\phi_{\rm end}$
- $V_0 \simeq 10^{-13}\, v^3\, m_{\rm Pl}$ with $A_{\rm s} \simeq 2.2 \times 10^{-9}$
- $n_{\rm s} \simeq 1 - \frac{10}{5+4N_*} \simeq 0.96$
- $r \simeq 4 \times 10^{-6} (v/m_{\rm Pl})^3$

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

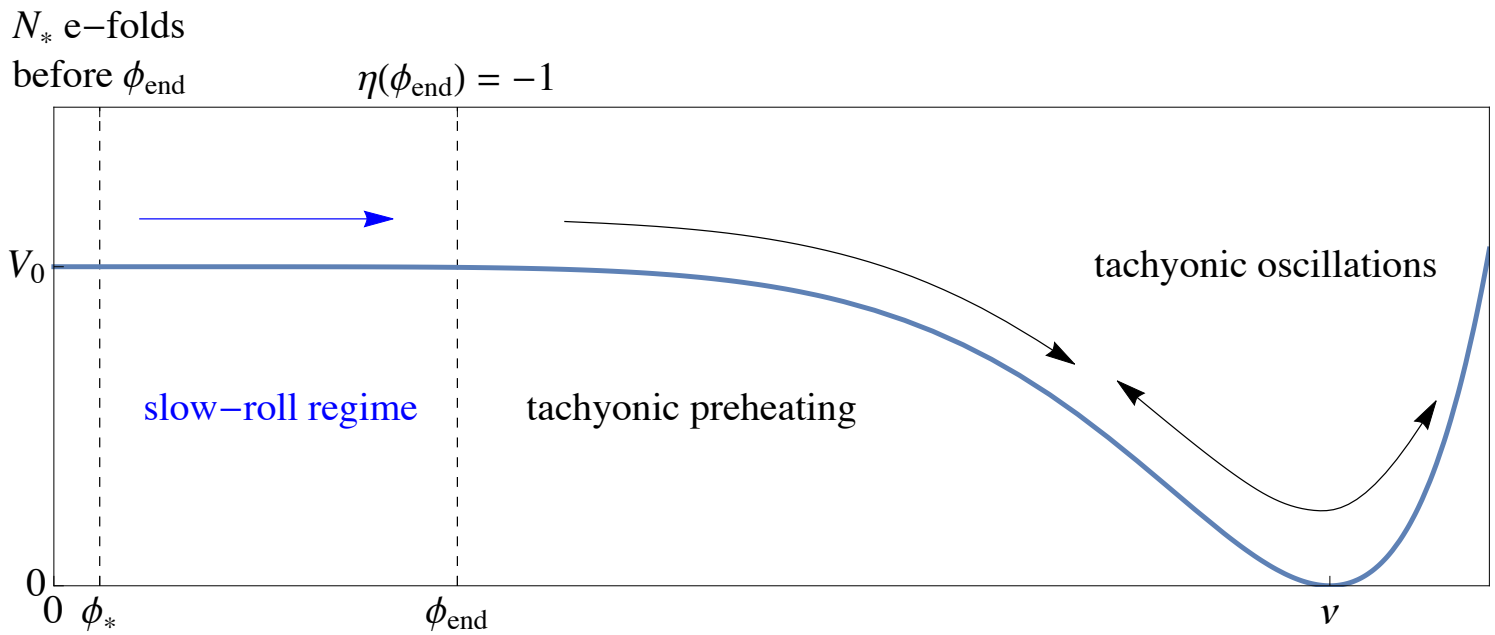


after inflation: reheating

→ transfer of energy from inflationary d.o.f. to Standard Model particles in thermal equilibrium

- initial phase of reheating characterized by non-perturbative dynamics: preheating
- preheating followed by turbulent, perturbative scattering and decays that complete transition to thermal equilibrium
- after hilltop inflation: preheating characterized by tachyonic preheating and tachyonic oscillations

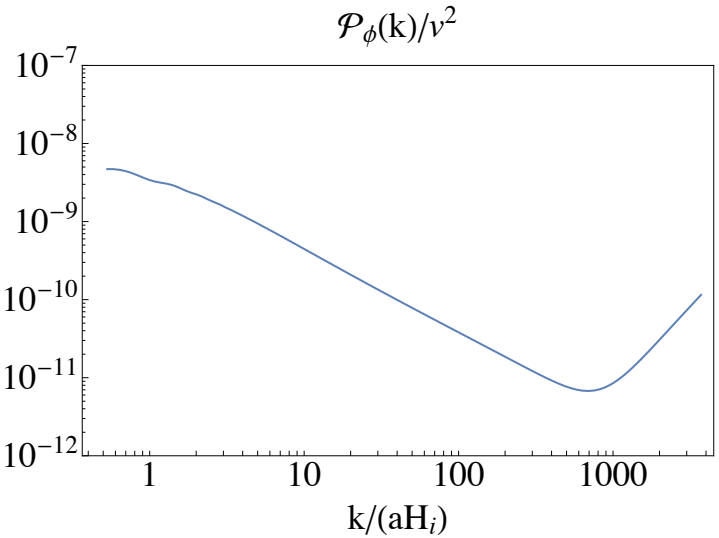
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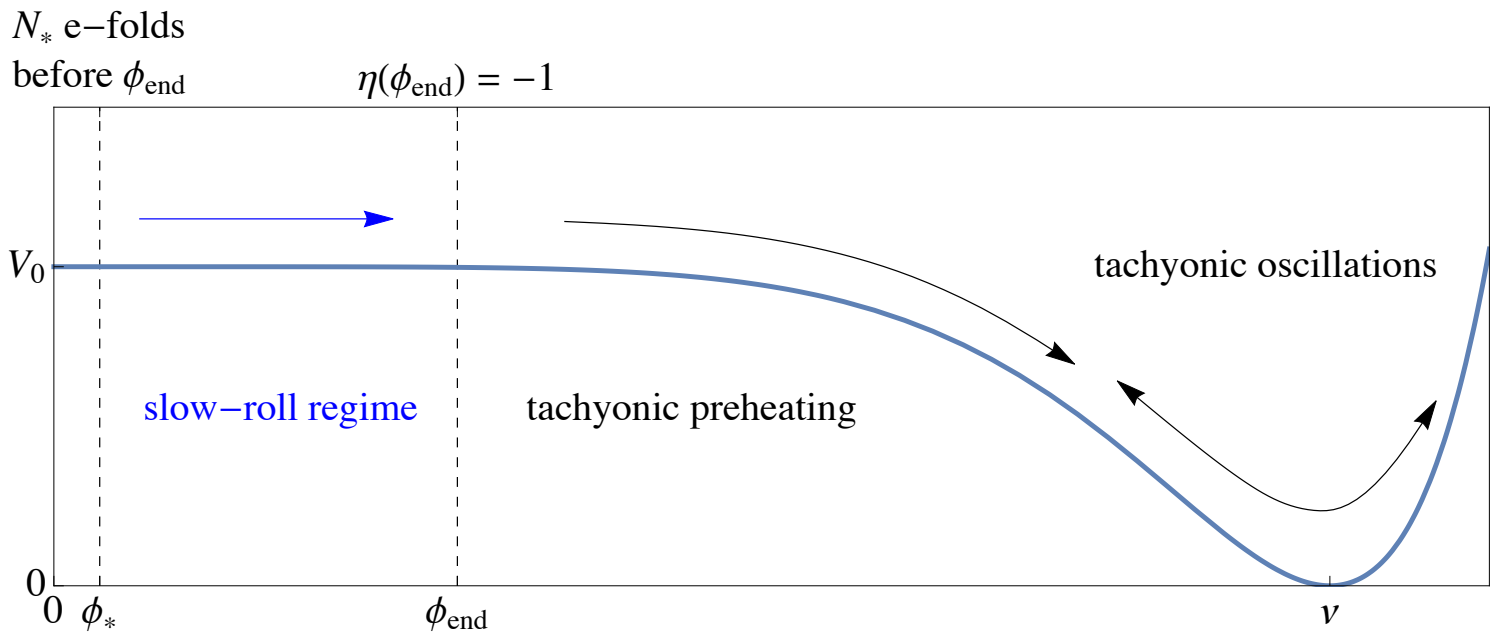
tachyonic preheating

$\Rightarrow$ 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



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



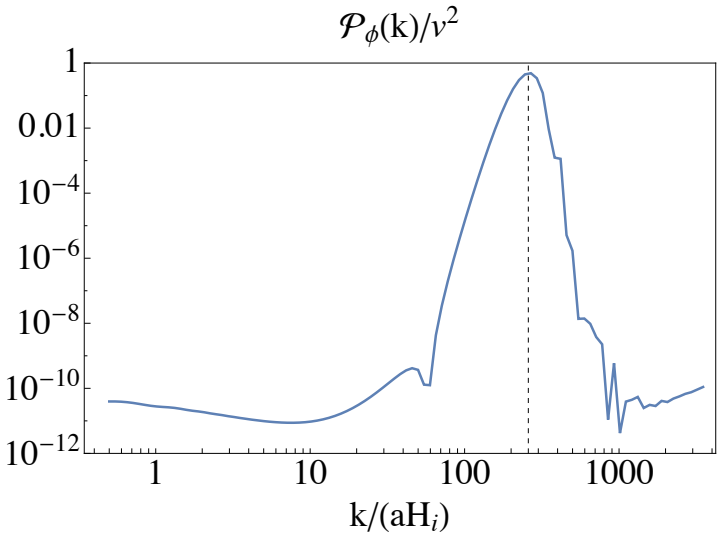
tachyonic oscillations

- periodic entering into the tachyonic region ($\partial^2 V/\partial\phi^2 < 0$)

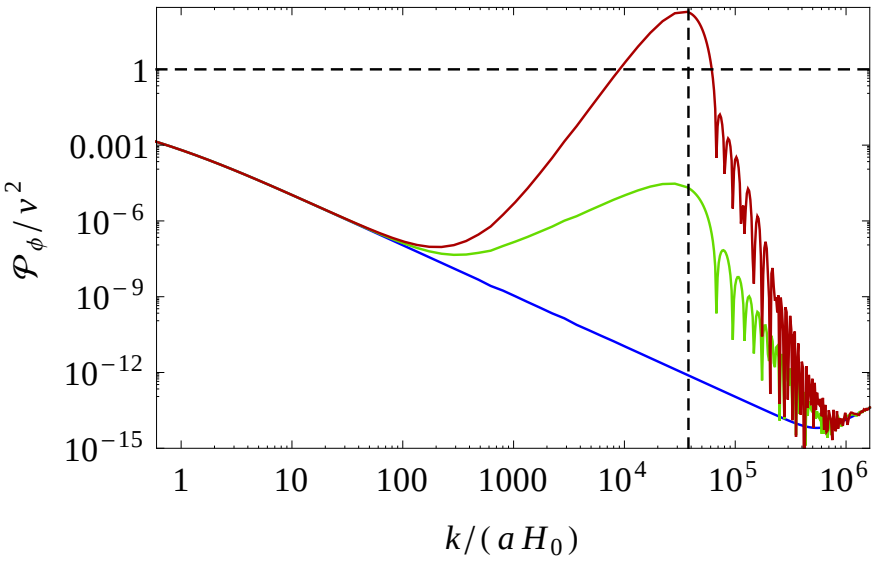
$\Rightarrow$ interplay between **growth** of ϕ fluctuations around $k_p < aH$ and **damping** due to Hubble friction, which is stronger for larger v

- for $v \lesssim 10^{-1} m_{\rm pl}$, $\langle \delta\phi^2 \rangle \sim v^2$ during this phase

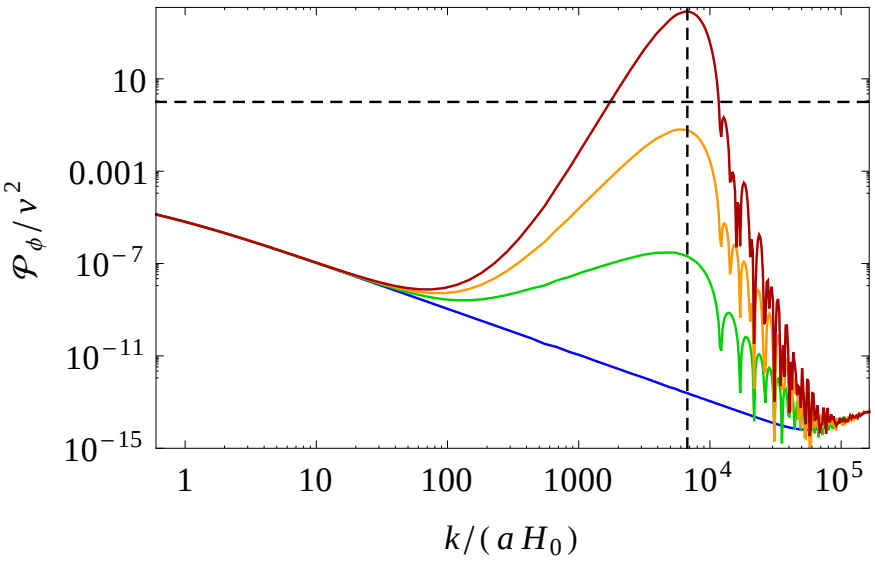
$\Rightarrow$ $10^{-5} \lesssim v/m_{\rm pl} \lesssim 10^{-1}$: growth of fluctuations at k_p forms "hill-crossing" oscillons, separated by $\xi \sim 2\pi/k_p$, which eventually settle at $\phi = v$



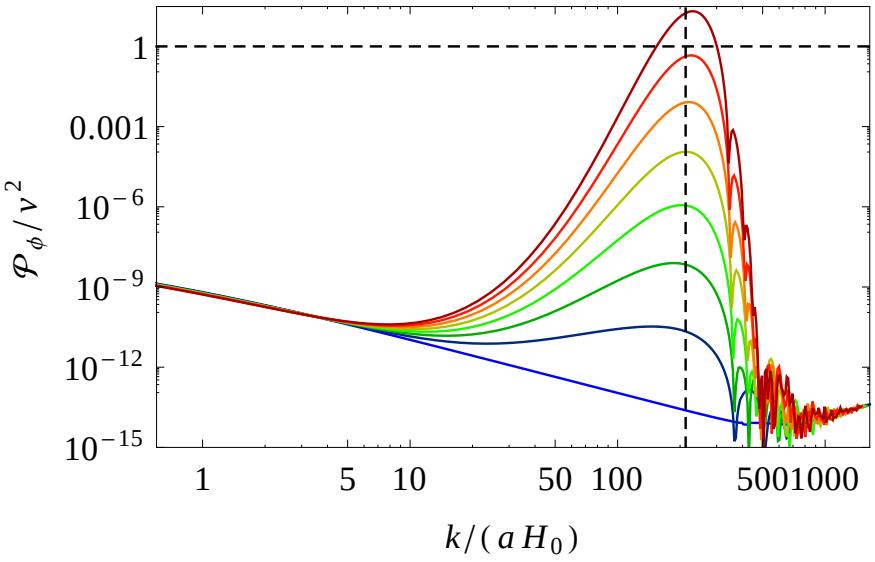
$v = 10^{-5}$, at $\phi = v$



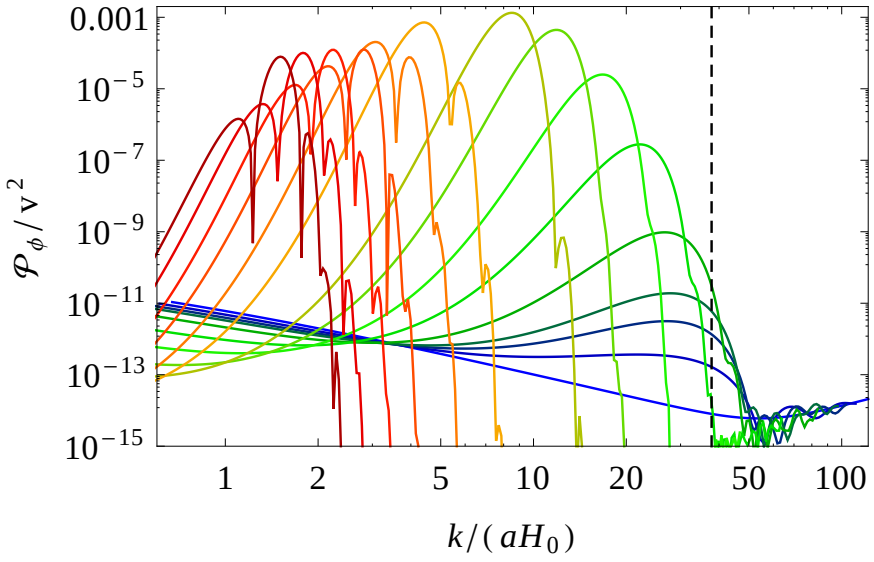
$v = 10^{-4}$, at $\phi = v$



$v = 10^{-2}$, at $\phi = v$

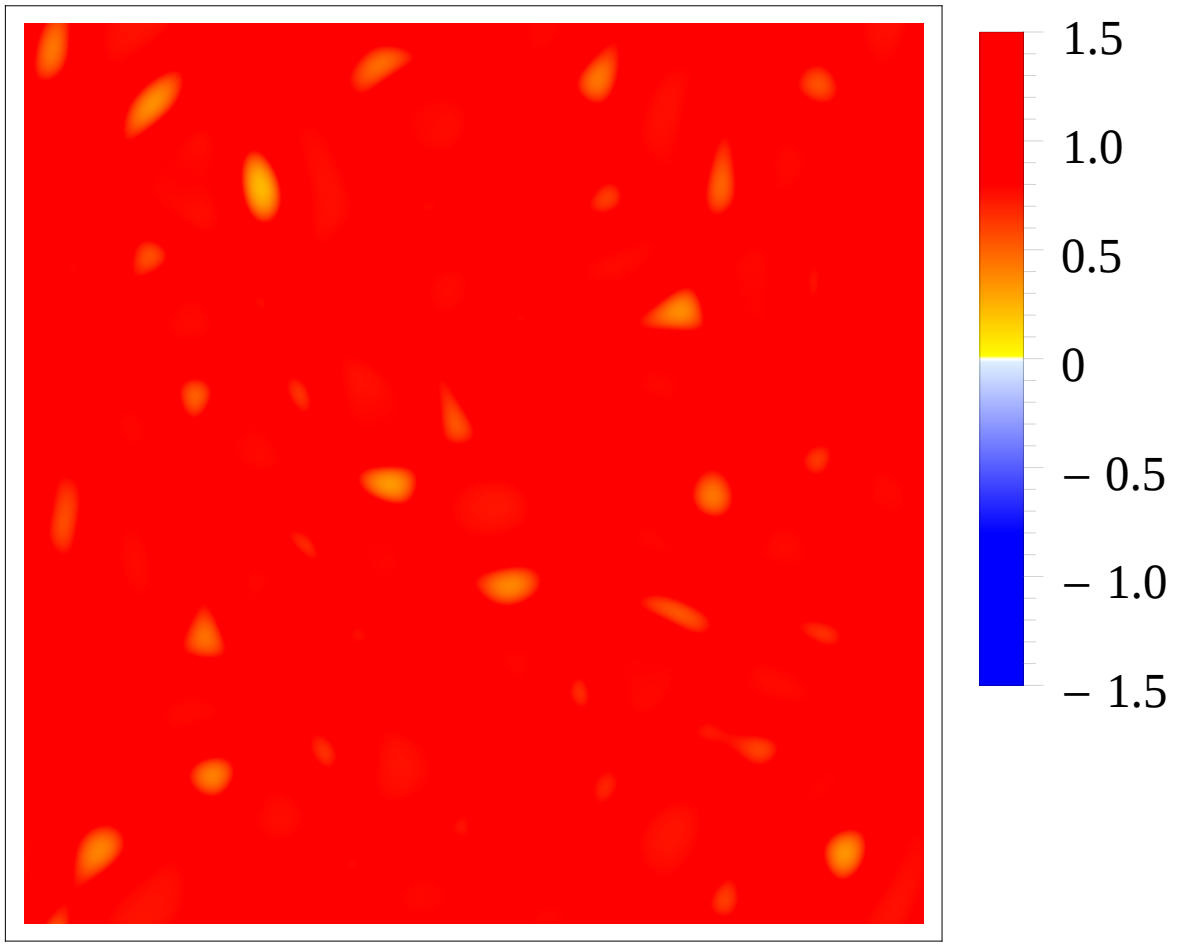


$v = 10^{-1}$, at $\phi = v$



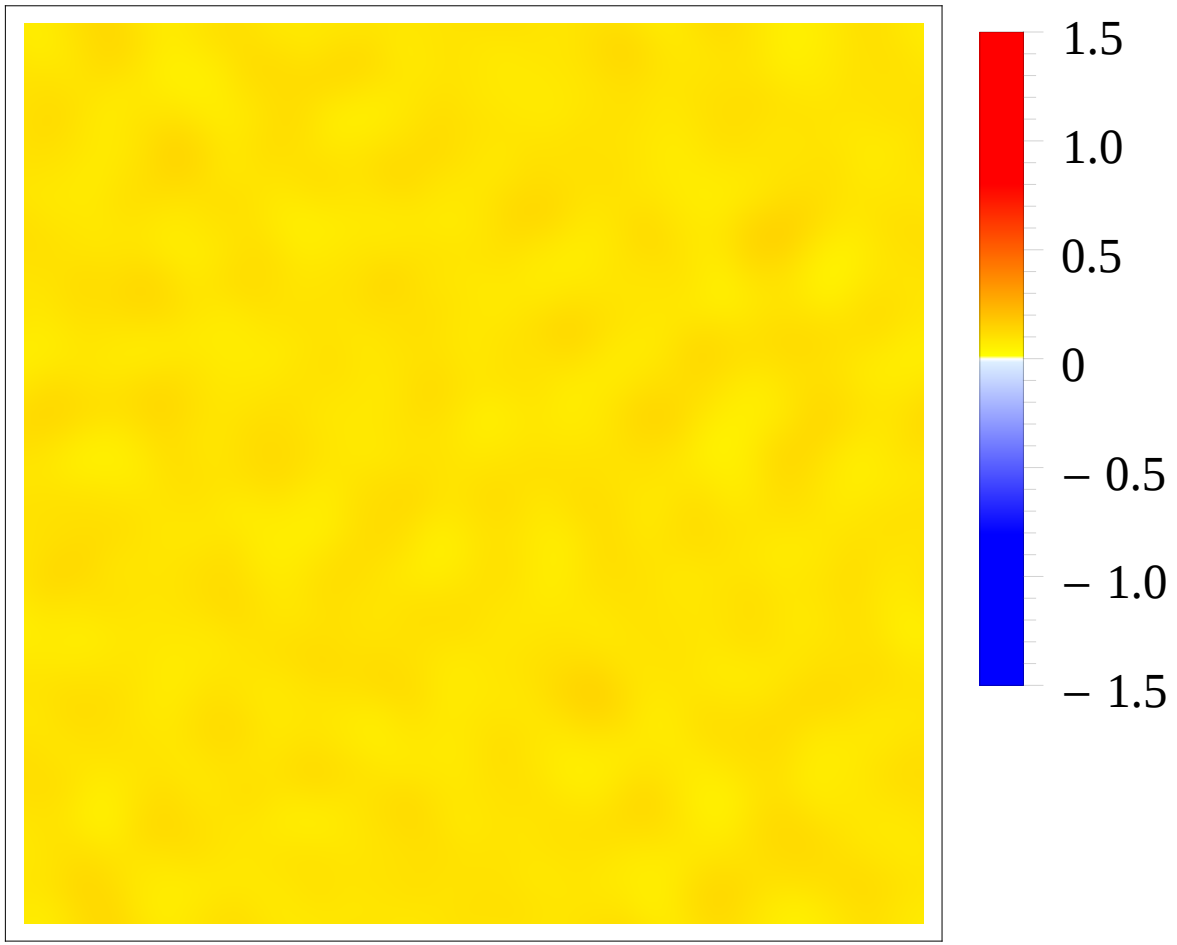
$$V(\phi) = V_0 \left(1 - \frac{\phi^6}{v^6}\right)^2, \qquad \text{with } v = 10^{-2} m_{\rm Pl}.$$

Movie of ϕ from $2D$ simulation with 1024^2 points. $L \sim 10^{-1} H$. Legend in units of ϕ/v.
In red, $\phi > 0$ and in blue, $\phi < 0$



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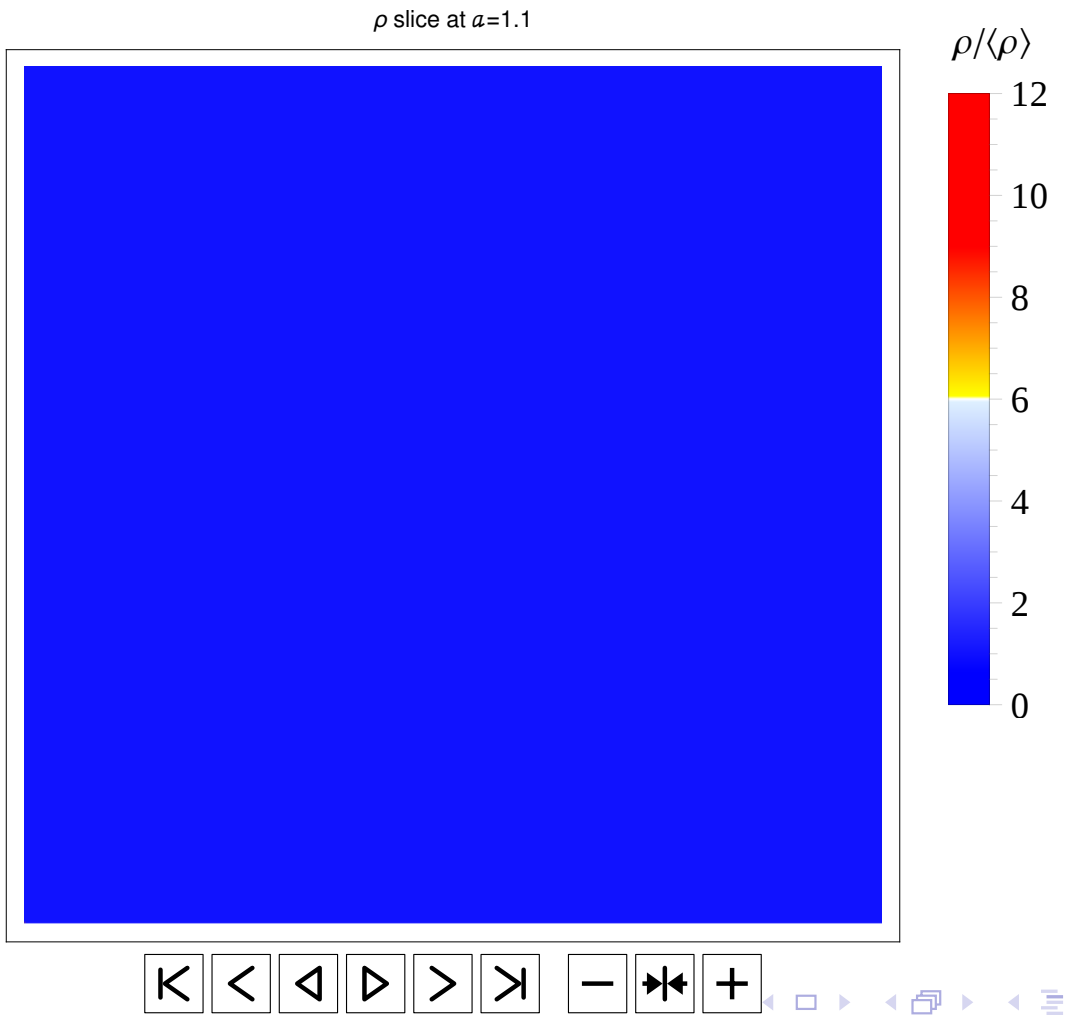
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Movie of ρ from $2D$ simulation with 1024^2 points. $L \sim 10^{-1} H$.

Note: timescale longer than previous movies: here $\mathcal{O}(100)$ oscillations



Oscillons:

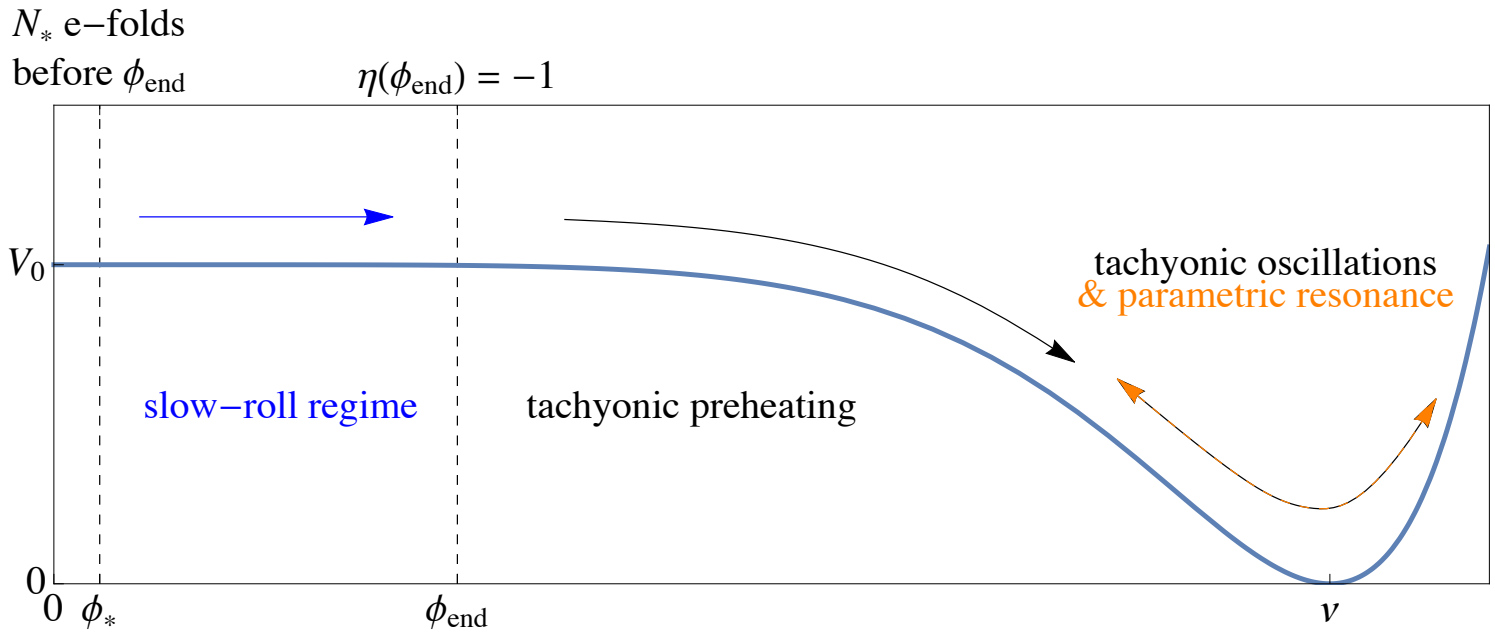
Spatially localized oscillating configurations of a real scalar field

- form when scalar field oscillates in potential that opens up 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

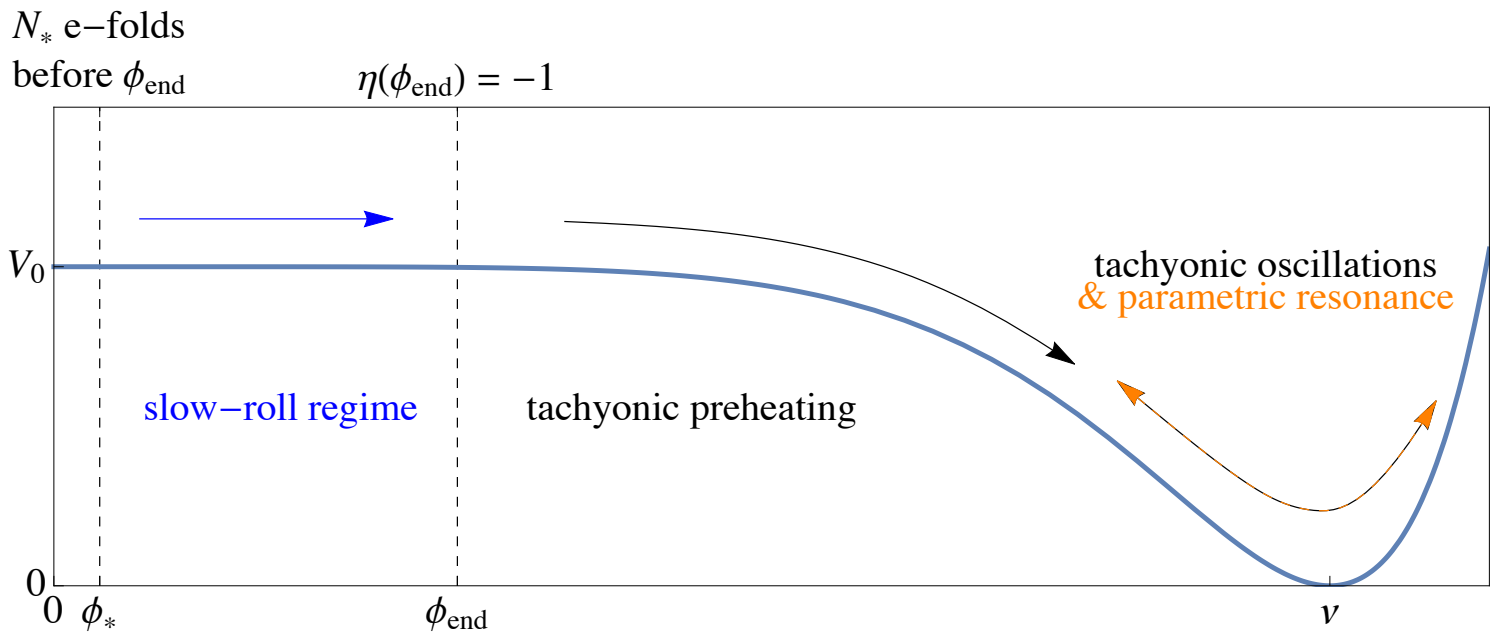
$\Rightarrow$ possible amplification of χ fluctuations which is characterised by:

- **exponential growth**
- **high sensitivity to lambda λ, or equivalently to the mass-ratio**

$$\boxed{m_\chi/m_\phi \;=\; \lambda\, v^3/\sqrt{72\, V_0} \;\propto \lambda}$$

- the resonance takes place **after** ϕ has become inhomogeneous (in contrast to a standard parametric resonance)

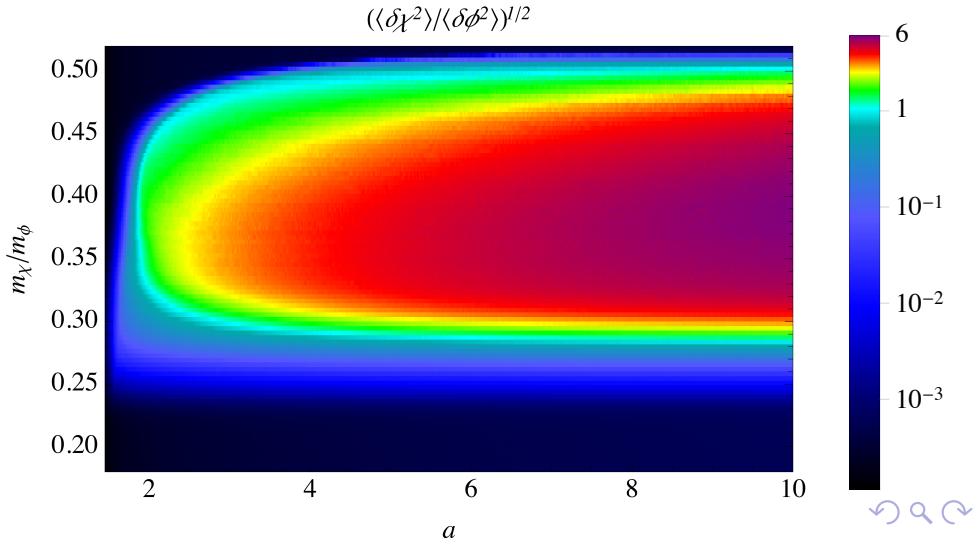
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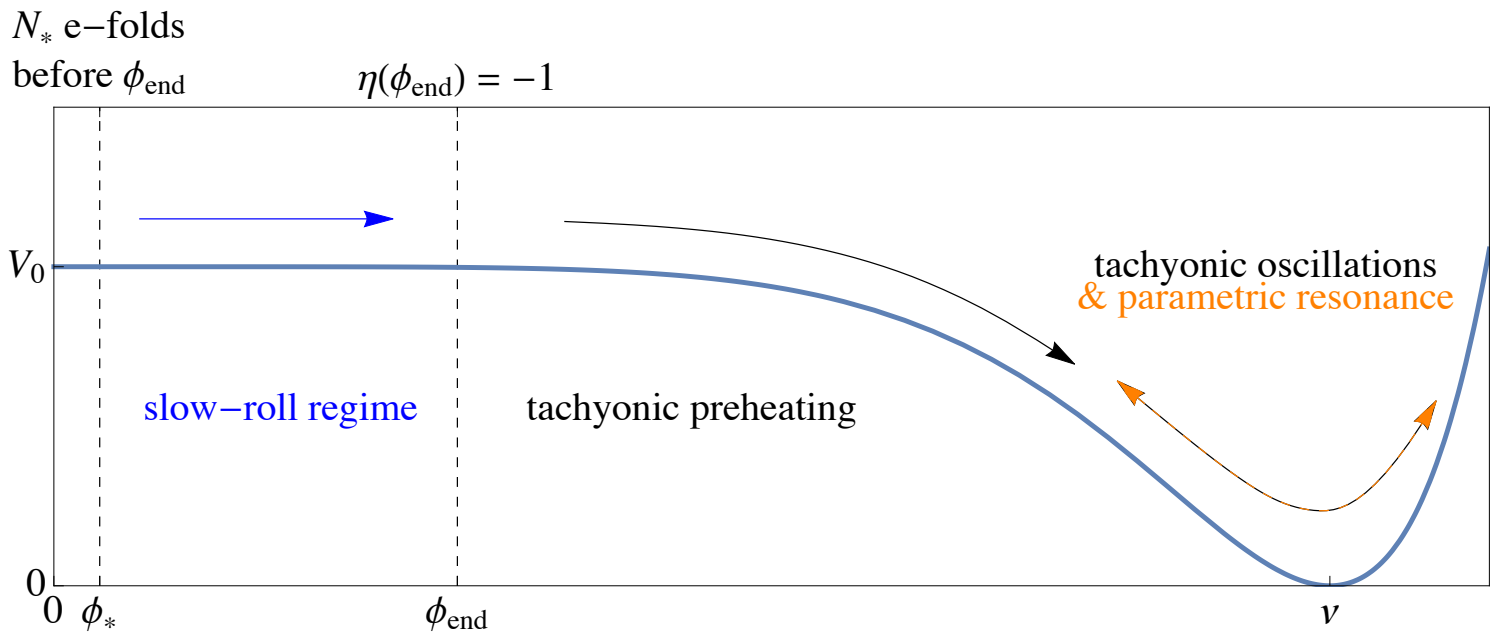
Parametric resonance of χ sourced by inhomogeneous ϕ

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

- exponential growth only if λ is inside resonance band



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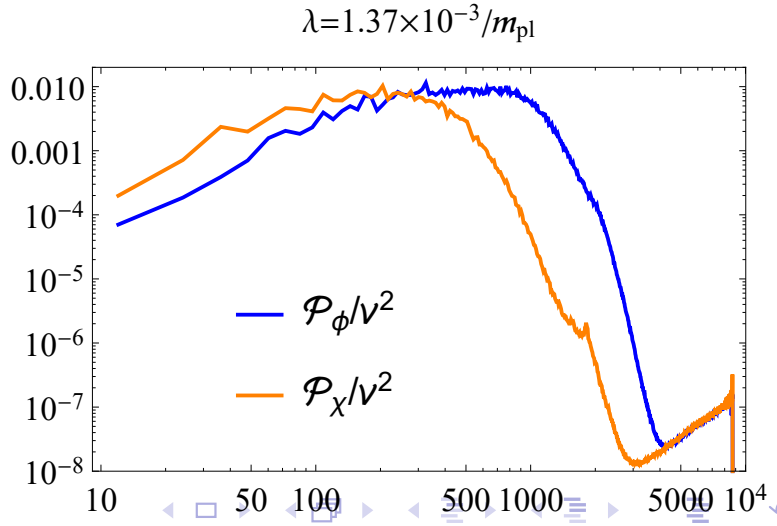


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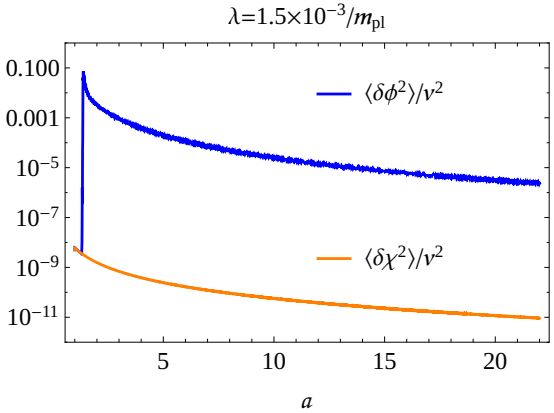
- exponential growth only if λ is inside resonance band
- χ develops spectrum peaked at $k \sim k_p$

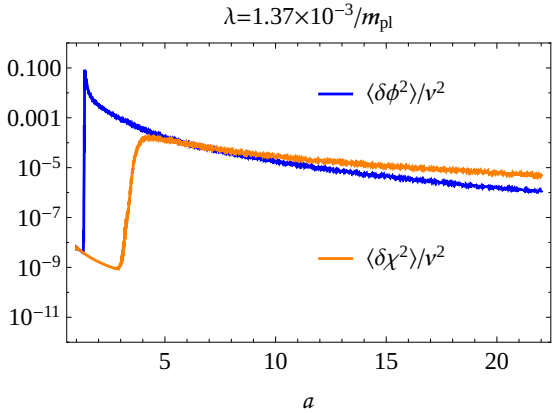
$\Rightarrow$ what is the impact of this resonance on oscillons?

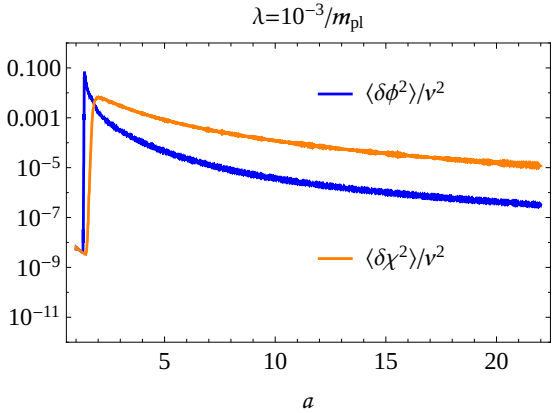


$$V(\phi,\chi) = V_0\left(1-\frac{\phi^6}{v^6}\right)^2 + \frac{\lambda^2}{2}\phi^2\chi^2(\phi^2+\chi^2), \qquad \text{with } v = 10^{-2}m_{\rm Pl}$$

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:

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

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

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

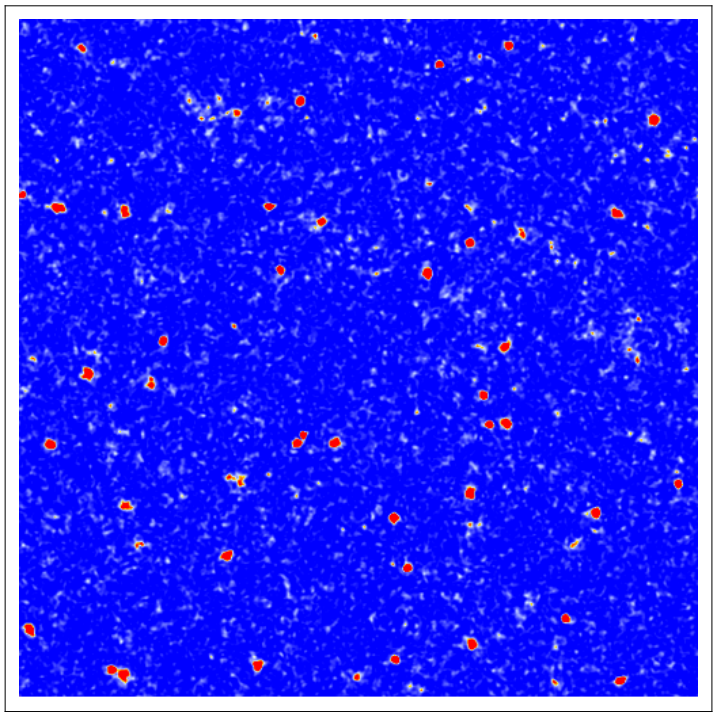
on discretized lattice with parameters:

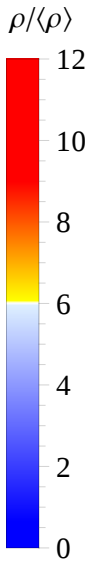
$v/m_{\rm pl}$	$\langle\phi\rangle_{\rm i}/v$	$\langle\dot{\phi}\rangle_{\rm i}/v^2$	$\langle\chi\rangle_{\rm i}/v$	$\langle\dot{\chi}\rangle_{\rm i}/v^2$	$H_{\rm i}/m_{\rm pl}$
10^{-2}	0.08	2.49×10^{-9}	0	0	1.9×10^{-10}

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

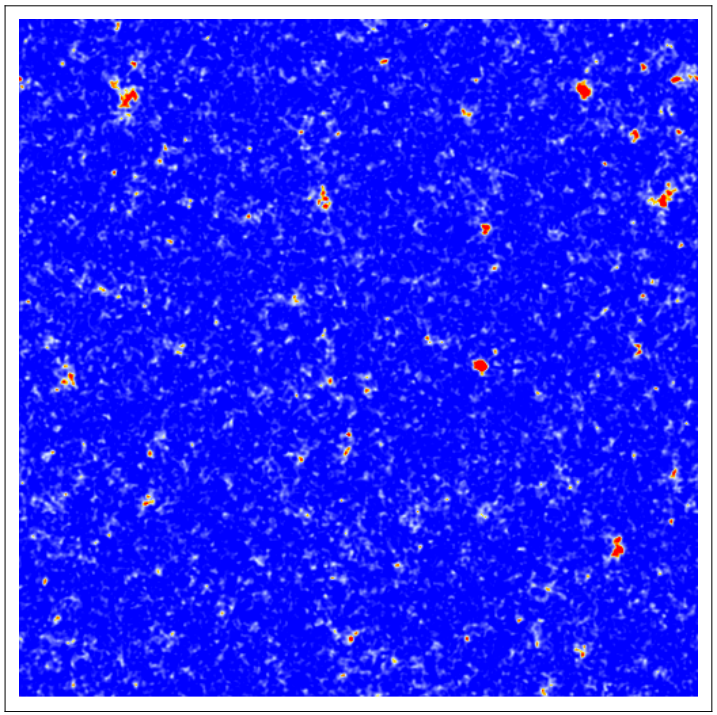
case **I**: no parametric resonance

$\lambda=1.5\times10^{-3}/m_{\rm pl}$, ρ slice at $a=10.0$





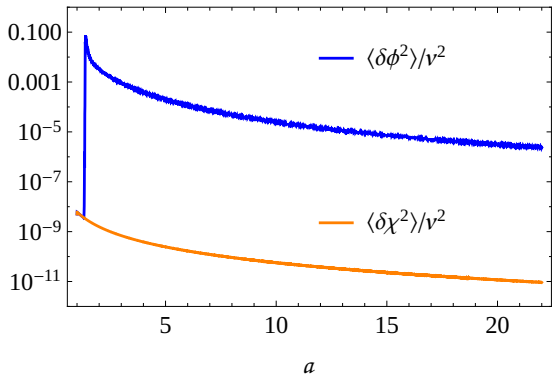
$\lambda=1.5\times10^{-3}/m_{\rm pl}$, ρ slice at $a=22.0$



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

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

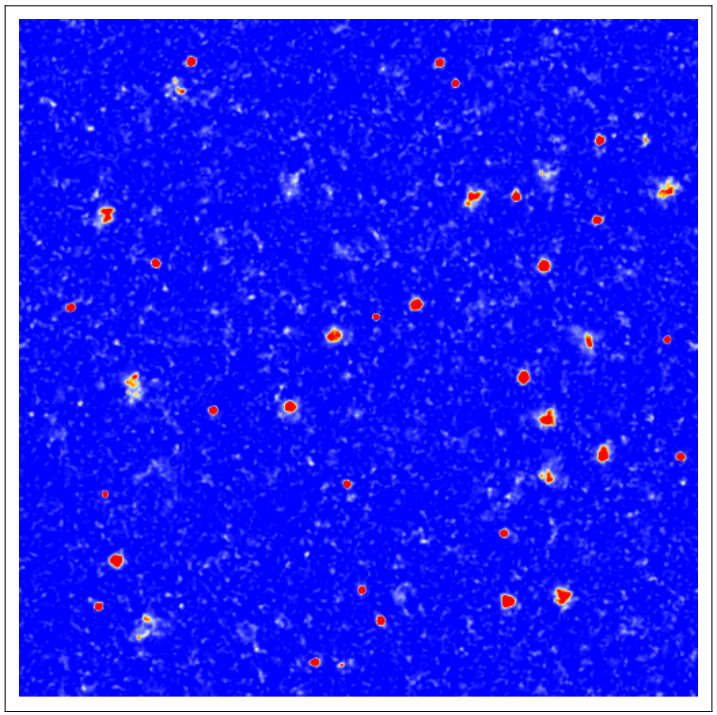
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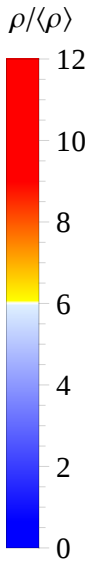


without parametric resonance of χ the evolution of oscillons is equal to single-field case

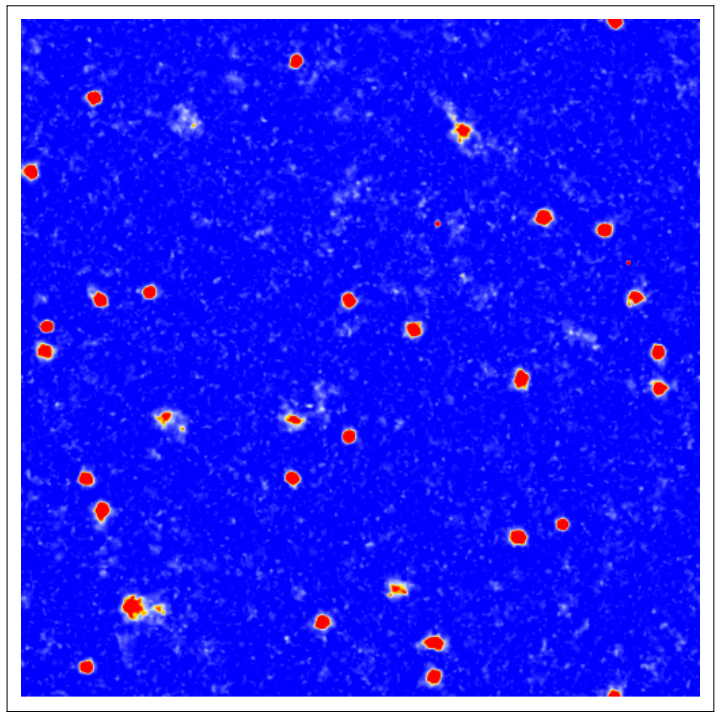
case **II**: "slow" parametric resonance

λ=1.37×10^{-3}/$m_{\rm pl}$, ρ slice at a=10.0





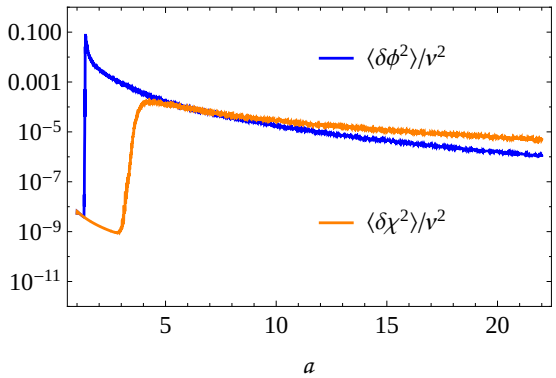
λ=1.37×10^{-3}/$m_{\rm pl}$, ρ slice at a=22.0



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

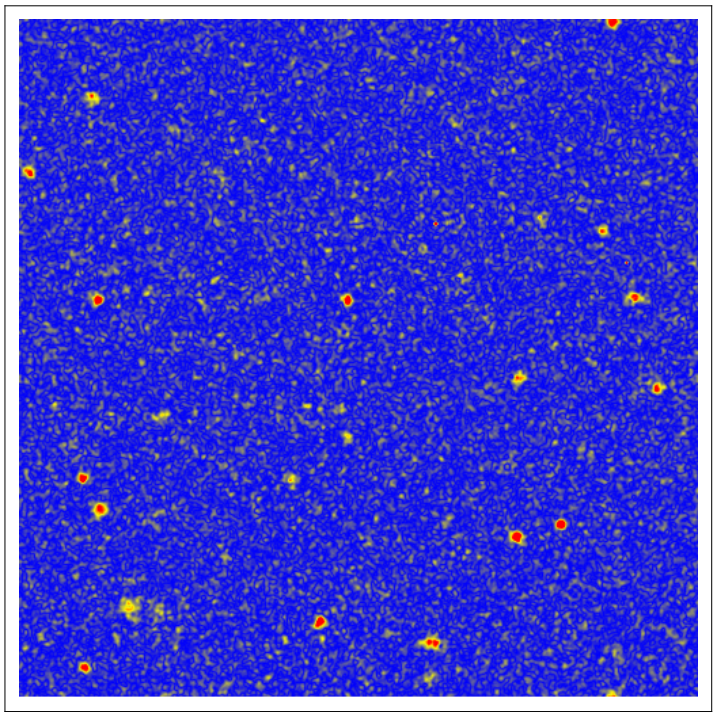
$\Rightarrow$ "slow" parametric resonance of χ enhances ϕ oscillons

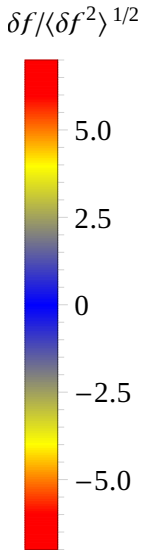
λ=1.37×10^{-3}/$m_{\rm pl}$



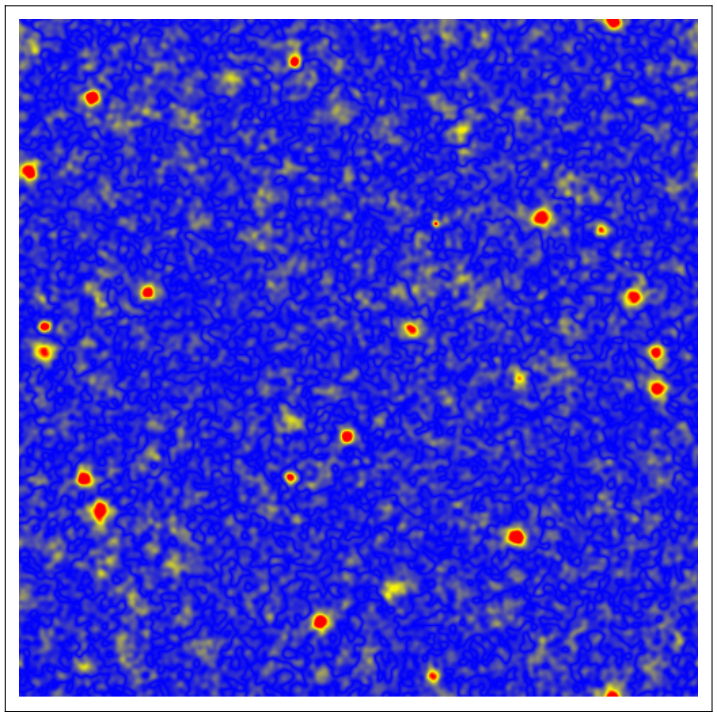
case **II**: "slow" parametric resonance

λ=1.37×10^{-3}/$m_{\rm pl}$, ϕ slice at a=22.0





λ=1.37×10^{-3}/$m_{\rm pl}$, χ slice at a=22.0

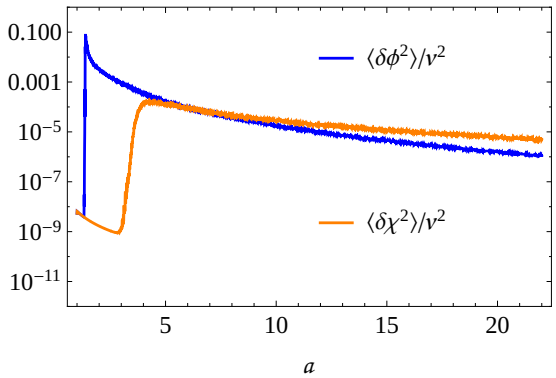


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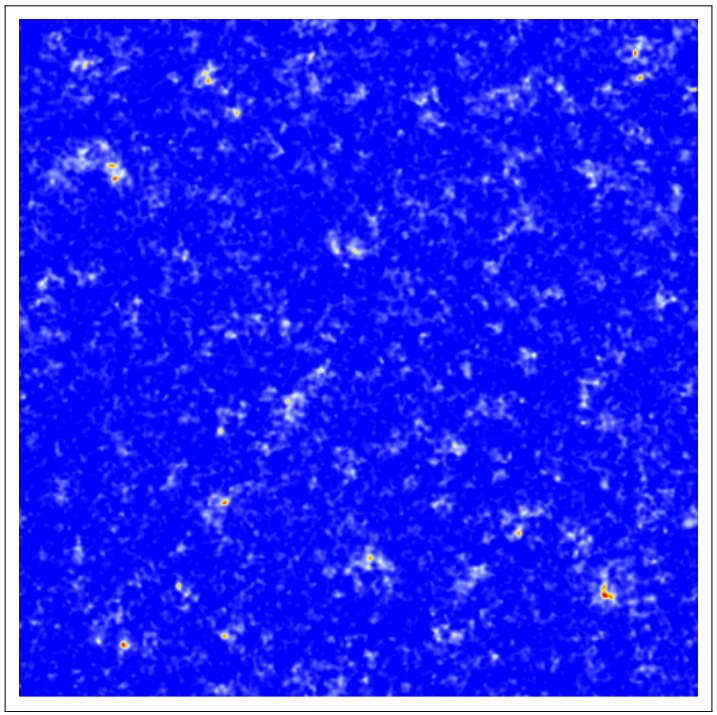
$\Rightarrow$ ϕ and χ are correlated: oscillons imprinted in χ

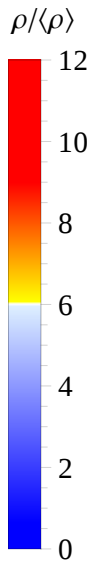
λ=1.37×10^{-3}/$m_{\rm pl}$



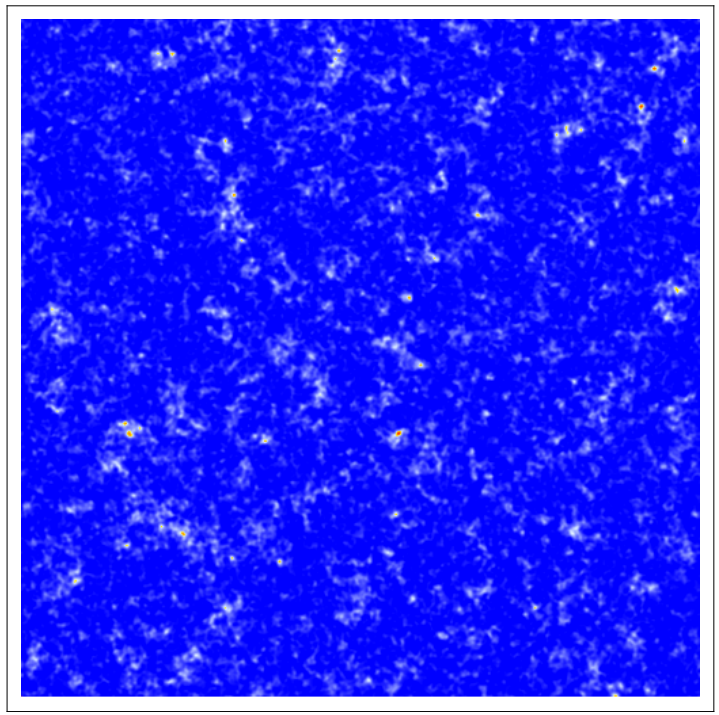
case **III**: "fast" parametric resonance

$\lambda=10^{-3}/m_{\rm pl}$, ρ slice at a=10.0



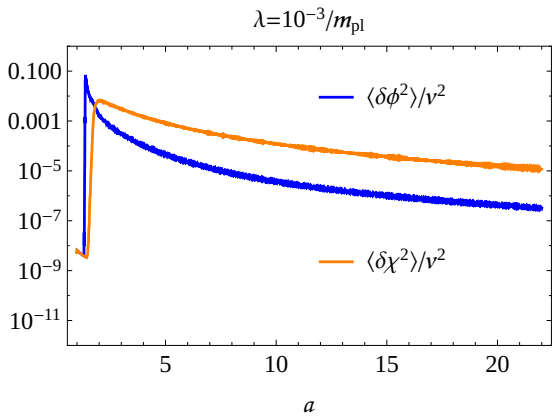


$\lambda=10^{-3}/m_{\rm pl}$, ρ slice at a=22.0

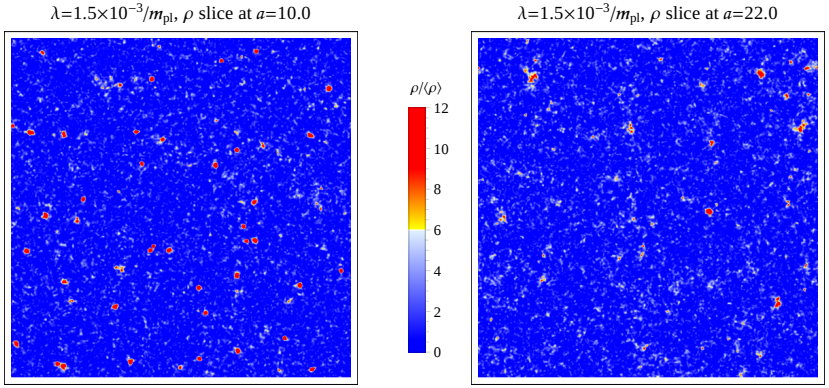


- at $a = 10$: no oscillons
- at $a = 22$: no oscillons

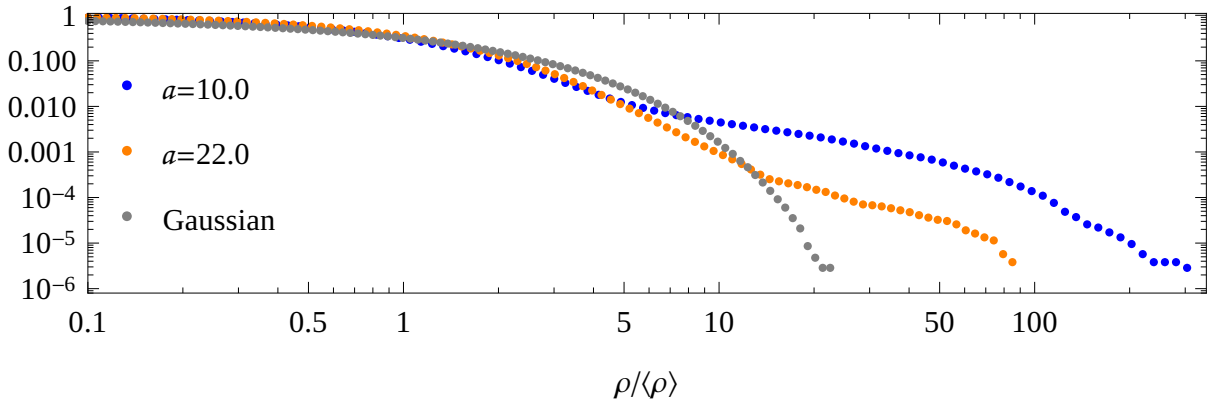
$\Rightarrow$ "fast" parametric resonance of χ suppresses ϕ oscillons



case **I**: no parametric resonance



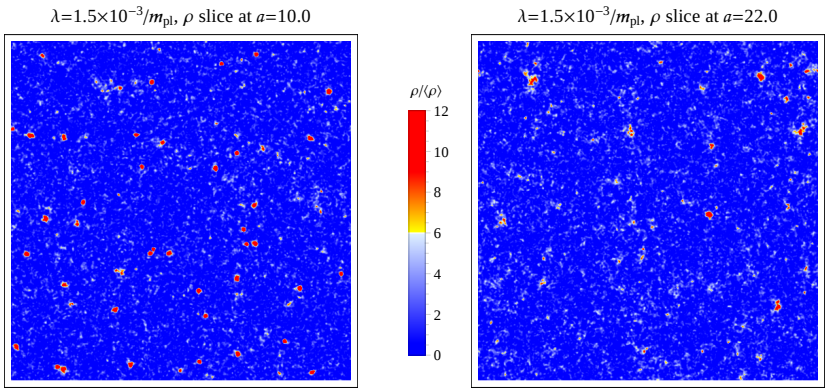
ρ tail distribution for λ=1.5×10^{-3}/$m_{\rm pl}$



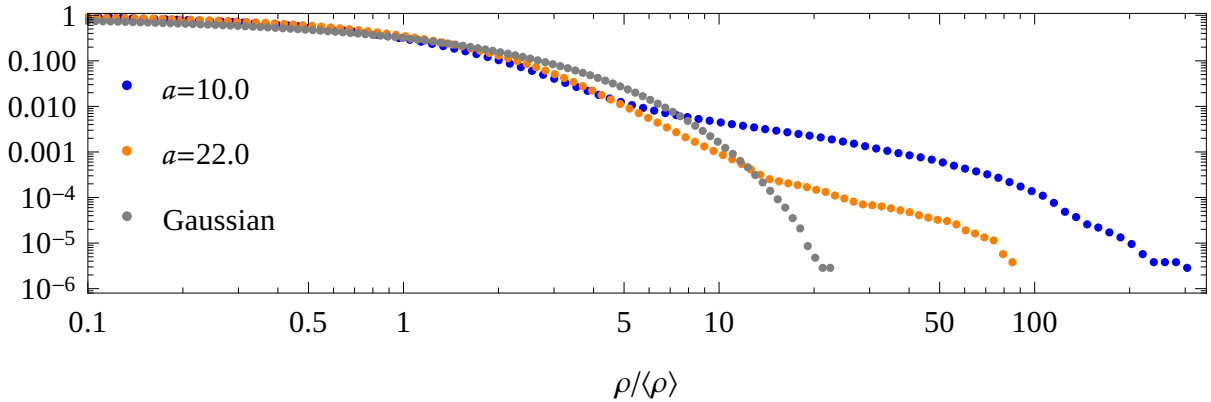
tail distribution: number of lattice points with energy density $> \rho$

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 $\langle g_2^2 \rangle = \langle \chi^2 \rangle$

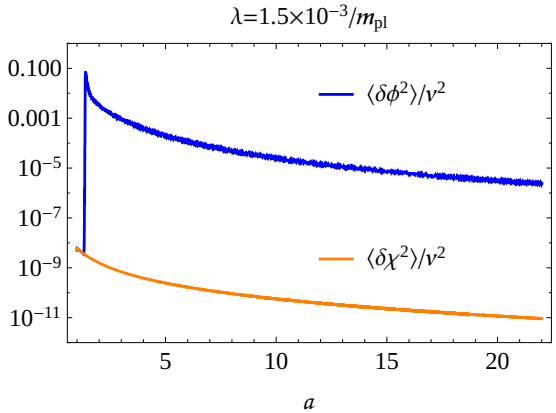
case I: no parametric resonance



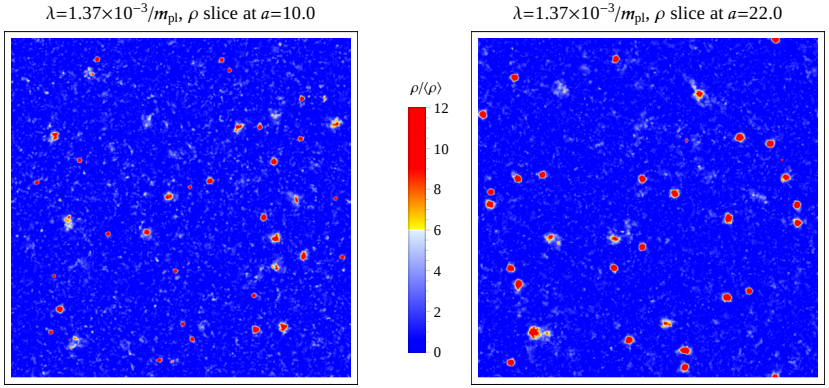
ρ tail distribution for $\lambda=1.5\times10^{-3}/m_{\rm pl}$



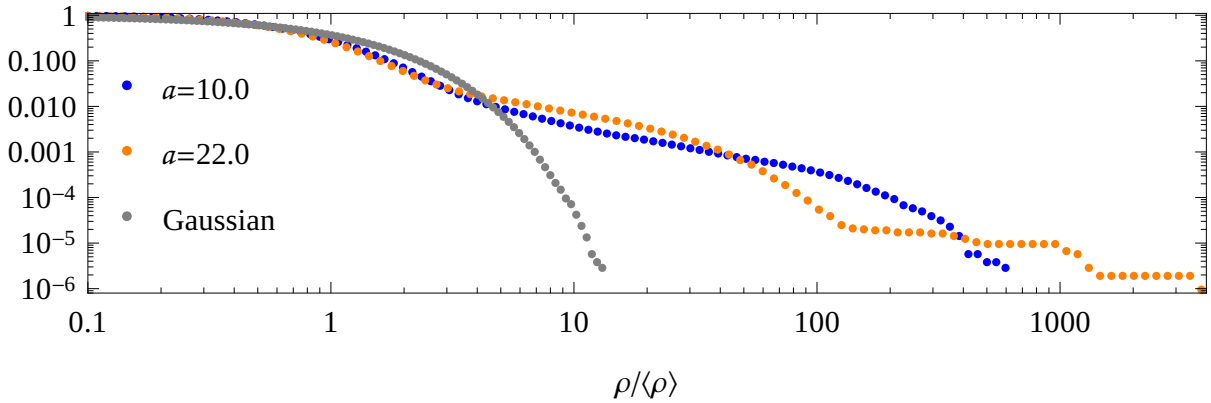
- at a = 10: tail distribution stretches to $\rho \sim 300\langle\rho\rangle$, far away from Gaussian tail
  $\Rightarrow$ expected when oscillons are present
- at a = 22: tail distribution shrunk, but still more spread than Gaussian



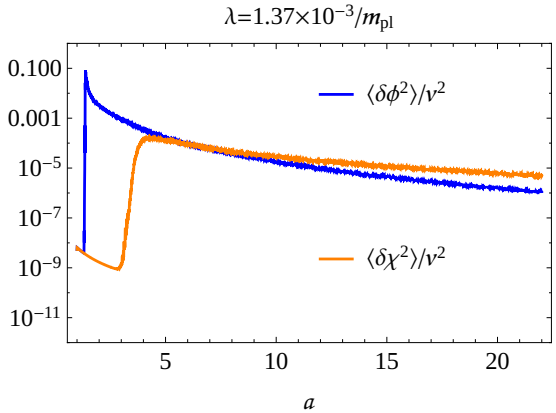
case **II**: "slow" parametric resonance



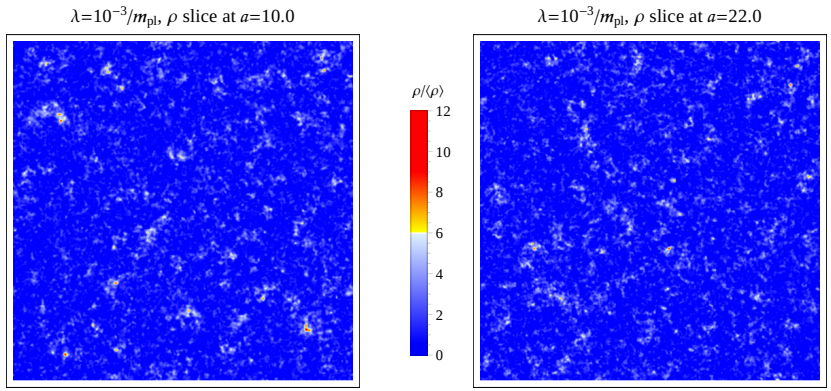
ρ tail distribution for $\lambda=1.37\times10^{-3}/m_{\rm pl}$



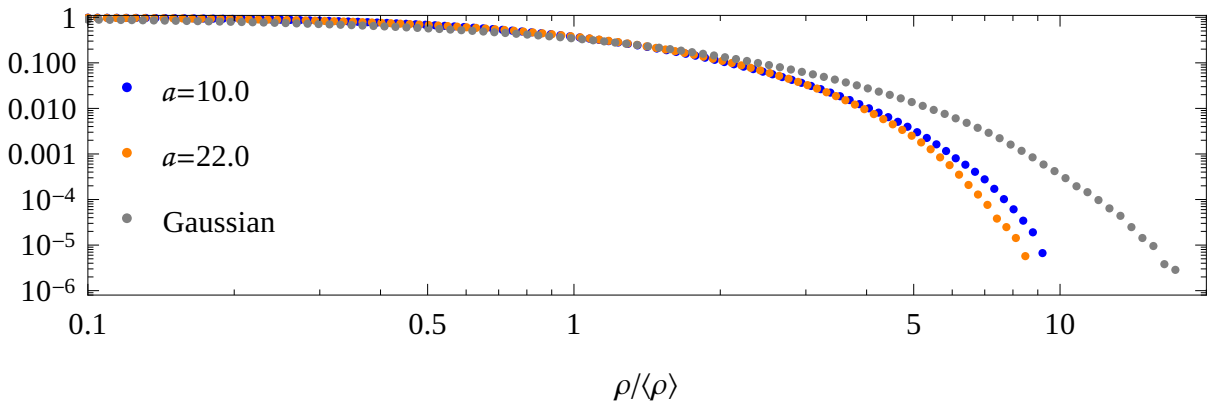
- at a = 10: tail distribution stretches to $\rho \sim 700\langle\rho\rangle$, longer than case **I** tail
  $\Rightarrow$ more energetic oscillons are present
- at a = 22: tail distribution spread to $\rho \sim 3000\langle\rho\rangle$ but lower around $\rho \sim 100\langle\rho\rangle$



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

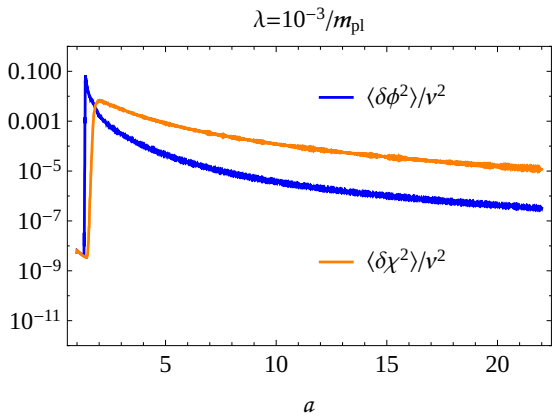


ρ tail distribution for $\lambda=10^{-3}/m_{\rm pl}$

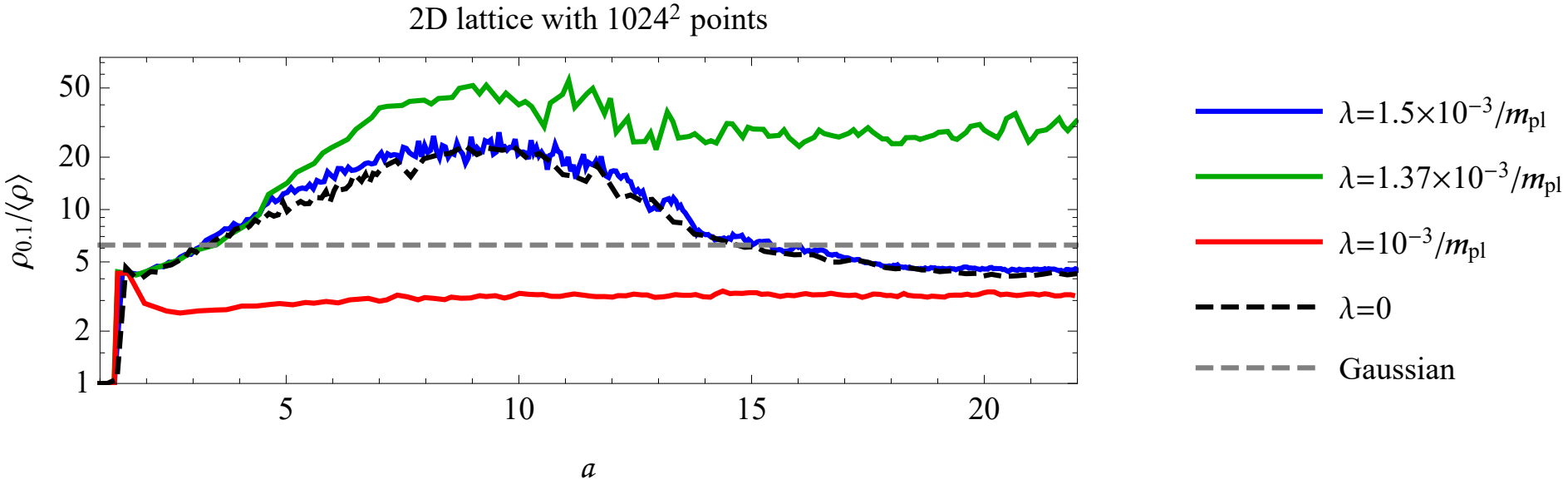


- at a = 10: tail distribution close to Gaussian tail
- at a = 22: tail distribution close to Gaussian tail

$\Rightarrow$ 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
- ...