Gravitational waves from oscillons after inflation

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slides by Francesco Cefalà

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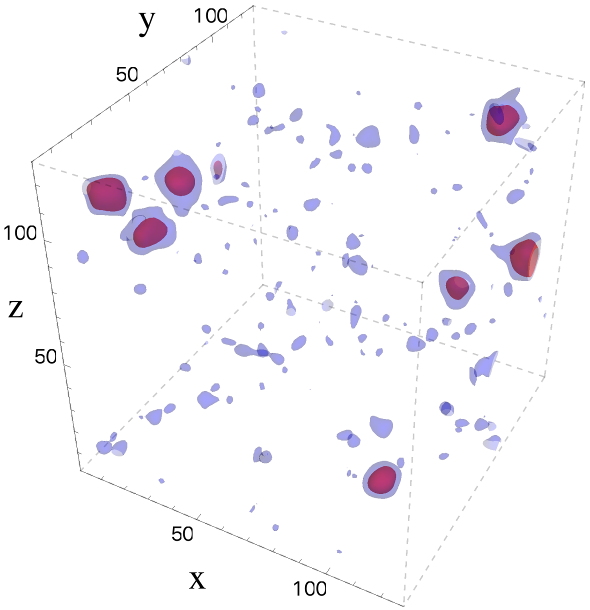
Based on
S. Antusch, F. Cefala and S. Orani, arXiv:1607.01314 [astro-ph.CO]
and references therein.



y
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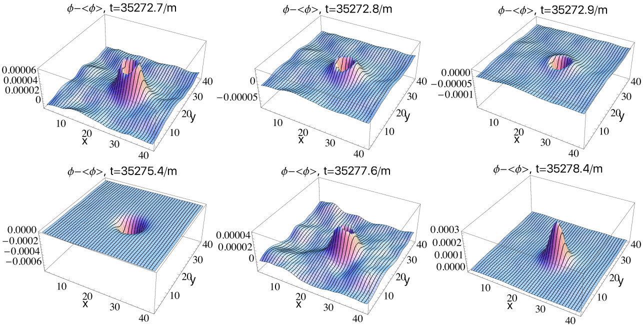
Oscillons

spatially localized, oscillatory scalar field configurations with large amplitude



characteristics

- can be extremely long-lived → can survive many thousands of oscillations!
  [Graham, Stamatopoulos 2006, Antusch, SO 2015 ...]
- radiate energy → live long but not forever!
  [Gleiser, Sicilia 2009, Salmi, Hindmarsh 2012, Saffin, Tognarelli, Tranberg 2014 ...]
- often tend to be spherical (depends on potential!)

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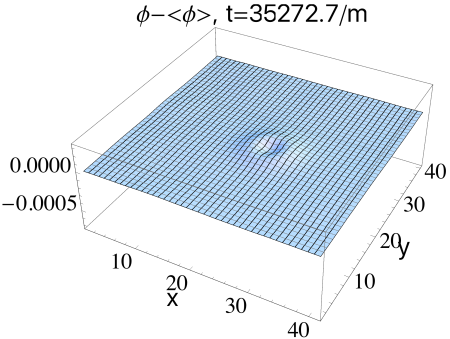

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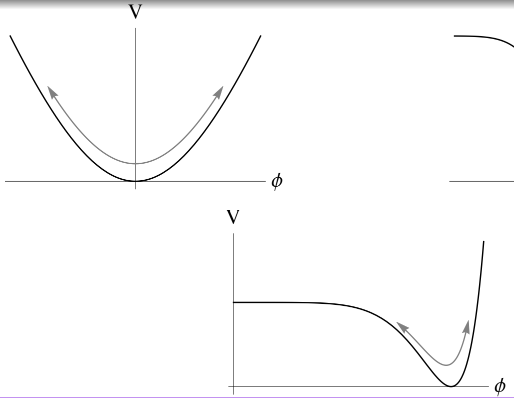
Oscillons



When do they form?

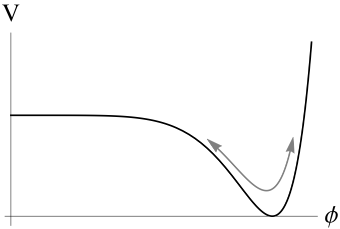
- generic feature of scalar field theories where the potential opens up away from the minimum
  (e.g. plateau-like inflation models with a minimum, axion monodromy inflation, hybrid-like models...)
- necessary condition: potential must be shallower than quadratic around the minimum for some $\Delta\phi$ [Amin 2013]
- form during non-linear, oscillatory phase e.g. during preheating after inflation
  [Amin, Easther, Finkel, Flauger, Hertzberg 2011...]

Oscillons

possible (observable) consequences

- affect expansion history → delay of reheating
- production of gravitational waves

Oscillons



possible (observable) consequences

- affect expansion history → delay of reheating
- **production of gravitational waves**

Using the program LATTICEEASY:

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

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

$$H^2 = \frac{1}{3m_{\rm Pl}^2}\left\langle V + \frac{\dot{\phi}^2}{2} + \frac{1}{2a^2}\left|\vec{\nabla}\phi\right|^2 \right\rangle$$

+Vacuum fluctuations

Using the program LATTICEEASY:

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

Simultaneously with $ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$:

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\vec{\nabla}^2 h_{ij} = \frac{2}{m_{\rm Pl}^2 a^2}\Pi_{ij}^{\rm TT},$$

[Garcia-Bellido, Figueroa 2007]

where $\Pi_{ij}^{\rm TT} = [\partial_i\phi\partial_j\phi]^{\rm TT}$ satisfies $\partial_i\Pi_{ij}^{\rm TT} = \Pi_{ii}^{\rm TT} = 0$

The spectrum of gravitational wave energy per logarithmic momentum interval is

$$\Omega_{\rm GW}h^2 \equiv \frac{h^2}{\rho_c}\frac{d\,\rho_{\rm GW}}{d\ln k}$$

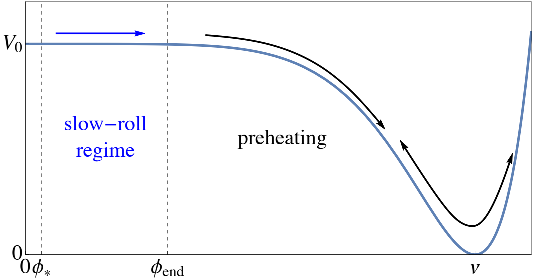
with

$$\rho_{\rm GW} = \frac{m_{\rm pl}^2}{4}\left\langle \dot{h}_{ij}(\mathbf{x})\dot{h}_{ij}(\mathbf{x})\right\rangle_{\mathcal{V}} .$$

Gravitational waves from oscillons after single-field hilltop inflation

Inflation along the hill

$$V(\phi) = V_0 \left(1 - \frac{\phi^p}{v^p}\right)^2 , \qquad v \ll m_{\rm Pl} \text{ “small-field hilltop”}$$



slow-roll inflation

- universe inflates while ϕ rolls away from the hilltop towards $\phi = v$
- end of inflation: $\eta(\phi) = m_{\rm Pl}^2 V_{,\phi\phi}/V \simeq -1$
- once $p \geq 4$ and v are chosen, V_0 is determined by CMB observations

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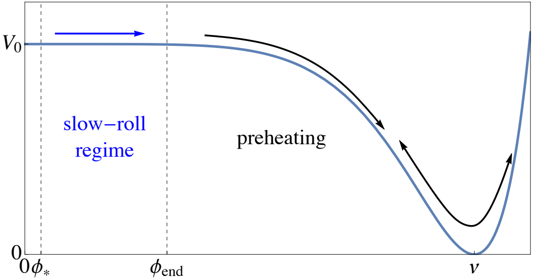


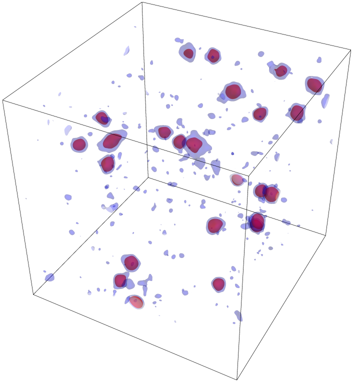
preheating

- typically non-linear
- two phases (strong dependence in v, weaker on p):
  tachyonic preheating: growth of IR modes; most efficient for very small v
  [Desroche, Kratochvil, Linde 2005, Brax, Dufaux, Mariadassou 2010]
  tachyonic oscillations: growth of modes around a certain scale → oscillon formation
  [Antusch, Cefala, Nolde, SO 2014]

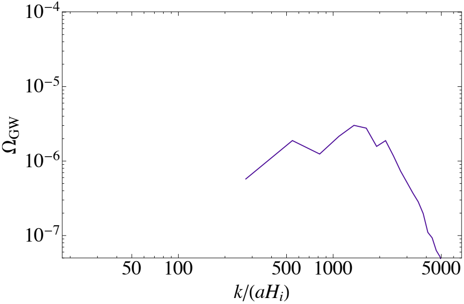
Gravitational waves from oscillons after single-field hilltop inflation

Lattice & model setup:

Model	$L\,H_i$	$v/m_{\rm Pl}$	$V_0/m_{\rm Pl}^4$	p	$\langle\phi_i\rangle/v$	$\langle\dot{\phi}_i\rangle/v^2$
hilltop inflation	0.01	10^{-2}	10^{-19}	6	0.08	2.49×10^{-9}



$t = 573.48/m, a = 1.47$



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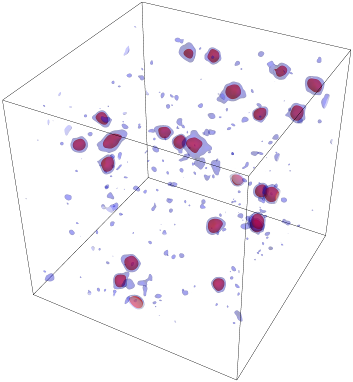
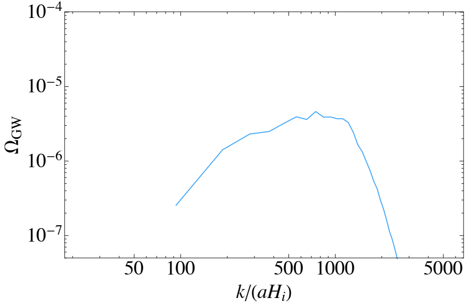


$t = 5543.5/m, a = 4.29$



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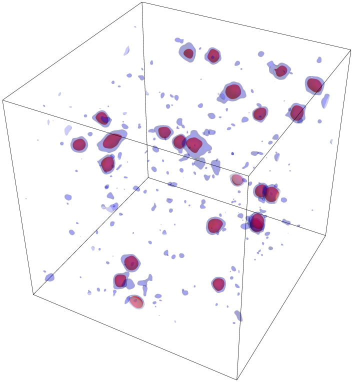
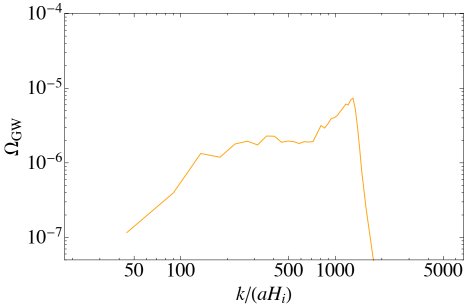


$t = 18924.4/m, a = 8.9$



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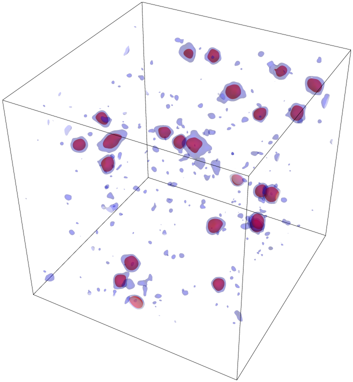
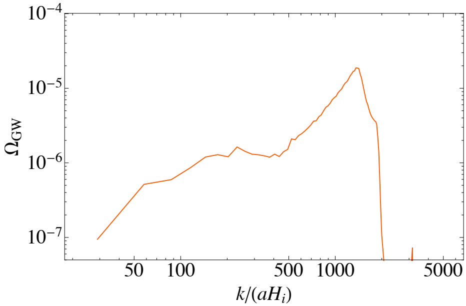


$t = 38040/m, a = 13.81$



Gravitational waves from oscillons after single-field hilltop inflation

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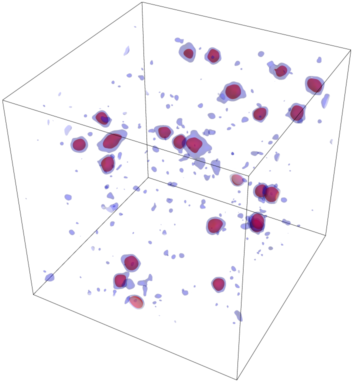
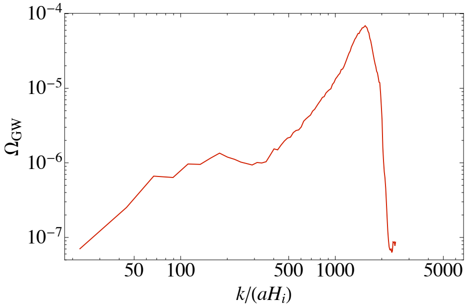


$t = 57155.5/m, a = 17.94$



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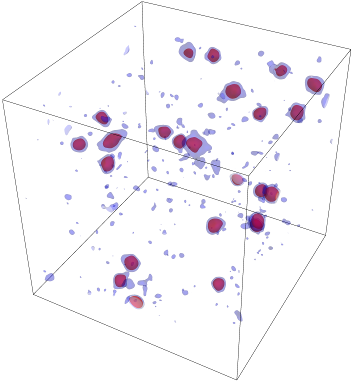
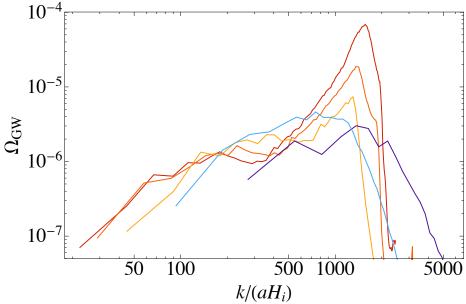
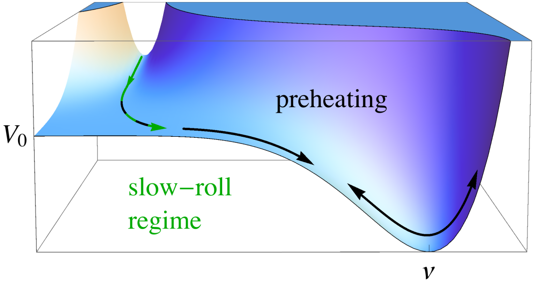




Gravitational waves from oscillons after a 2^{nd} order phase transition

Inflation orthogonal to the hill ("hybrid-like" inflation)

$$V(\phi,\chi) = V_0\left(1-\frac{\phi^p}{v^p}\right)^2 + V_{\rm inf}(\phi,\chi)\,, \qquad v \ll m_{\rm Pl}$$



slow-roll inflation

- universe inflates as χ rolls along the valley
- inflation is ended by a tachyonic instability in ϕ
- $p \geq 2$, v and V_0 are free!
- CMB observables are determined by $V_{\rm inf}$!

Gravitational waves from oscillons after a 2^{nd} order phase transition

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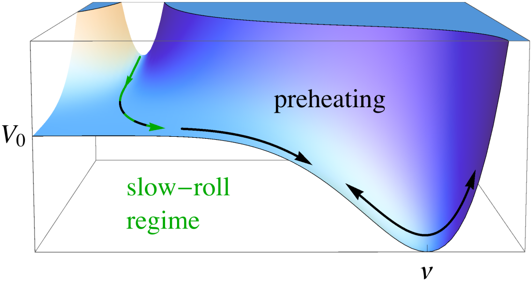

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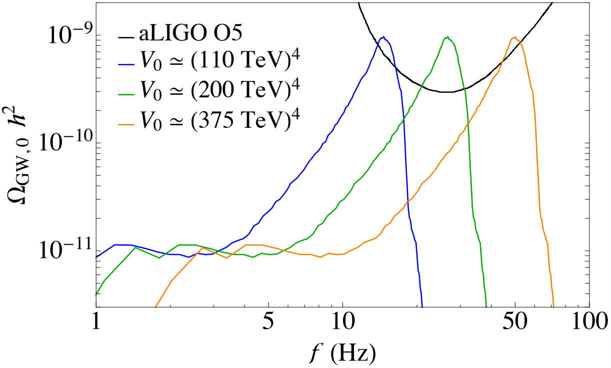
inflation $\perp$ hill	0.01	10^{-2}	free	6	0	0



We have investigated the gravitational wave production from oscillons in a potential

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

If ϕ is the inflaton (V_0 constrained):

- production of a pronounced GW peak at frequencies $f \sim 10^{10}$ Hz
- continuous growth of the peak until the end of the simulations
- stronger signal compared to previous studies (which assumed a symmetric potential)

If ϕ is a waterfall field (V_0 unconstrained):

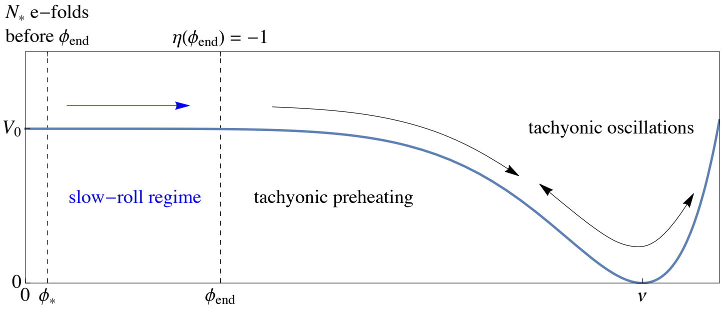
- observable prediction for current and future experiments
- e.g. if $(100\,\text{TeV})^4 \lesssim V_0 \lesssim (400\,\text{TeV})^4 \rightarrow$ peak at $10\,\text{Hz} \lesssim f \lesssim 70\,\text{Hz} \rightarrow$ potentially observable by aLIGO O5
- $\Omega_{\rm GW,0}\, h^2$ and f depend on the expansion history $\rightarrow$ might also be pushed into sensitivity region of BBO and DECIGO

ToDo:

- impact of p, v?
- multiple fields?

Backup

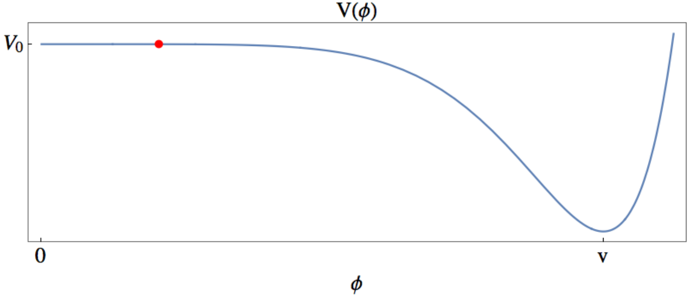
$$V(\phi) = V_0 \left(1 - \frac{\phi^6}{v^6}\right)^2 , \qquad \text{with } v \ll m_{\rm Pl}$$

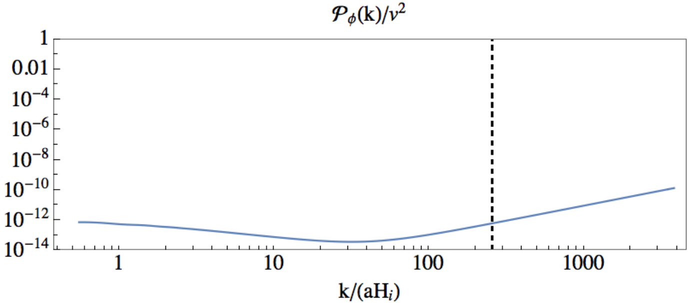


Tachyonic oscillations:

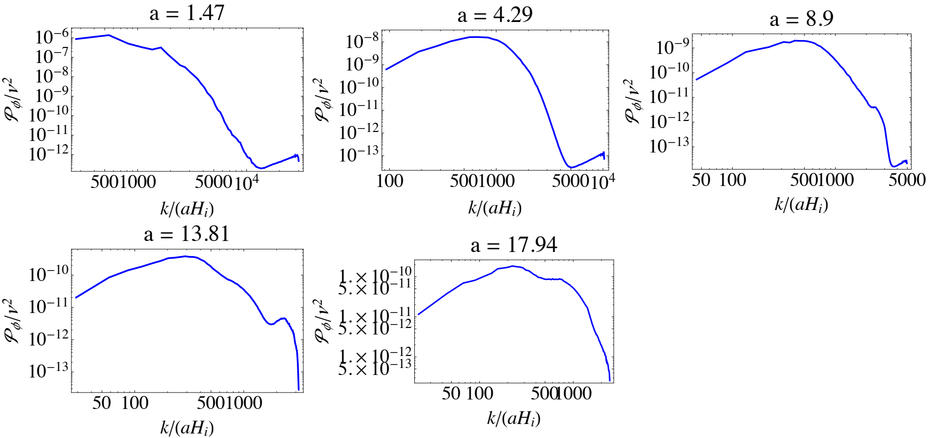
- periodic entering into the tachyonic region ($\partial^2 V/\partial\phi^2 < 0$)
  $\rightarrow$ interplay between **growth** of the $\phi_{\vec{k}}$ around $|\vec{k}_{\rm peak}|$ and **damping** due to Hubble friction
- For $v \gtrsim 10^{-1} m_{\rm Pl}$ $\rightarrow$ strong damping
- For $10^{-5}\, m_{\rm Pl} < v < 10^{-1}\, m_{\rm Pl}$ $\rightarrow$ fluctuations eventually grow non-linear $\rightarrow$ system eventually develops localized bubbles which oscillate between the two minima $\phi = \pm v$, typically separated by a distance $\lambda_{\rm peak} \sim 2\pi/k_{\rm peak}$

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





Field spectra



128^3, initially $\sim 30^3$ points per oscillon