# Oscillons: gravitational wave factories in the early universe

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based on arXiv:1607.01314 [PRL118 (2017) 011303]
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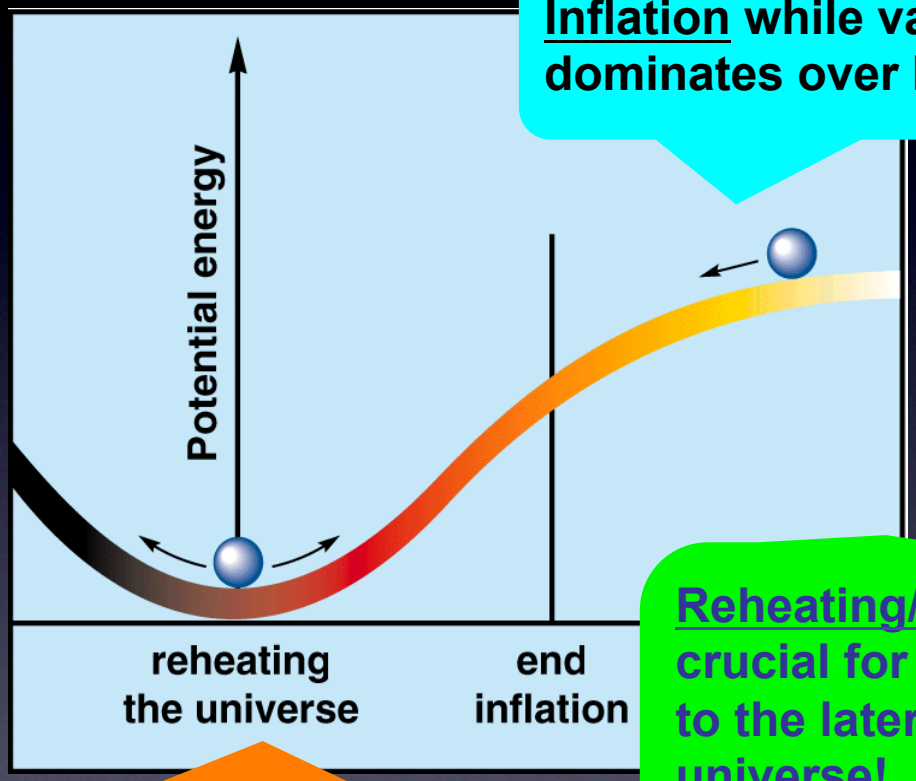
# Framework: Dynamics during and after inflation



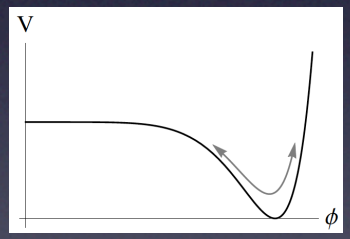

**Inflation while vacuum energy dominates over kinetic energy**

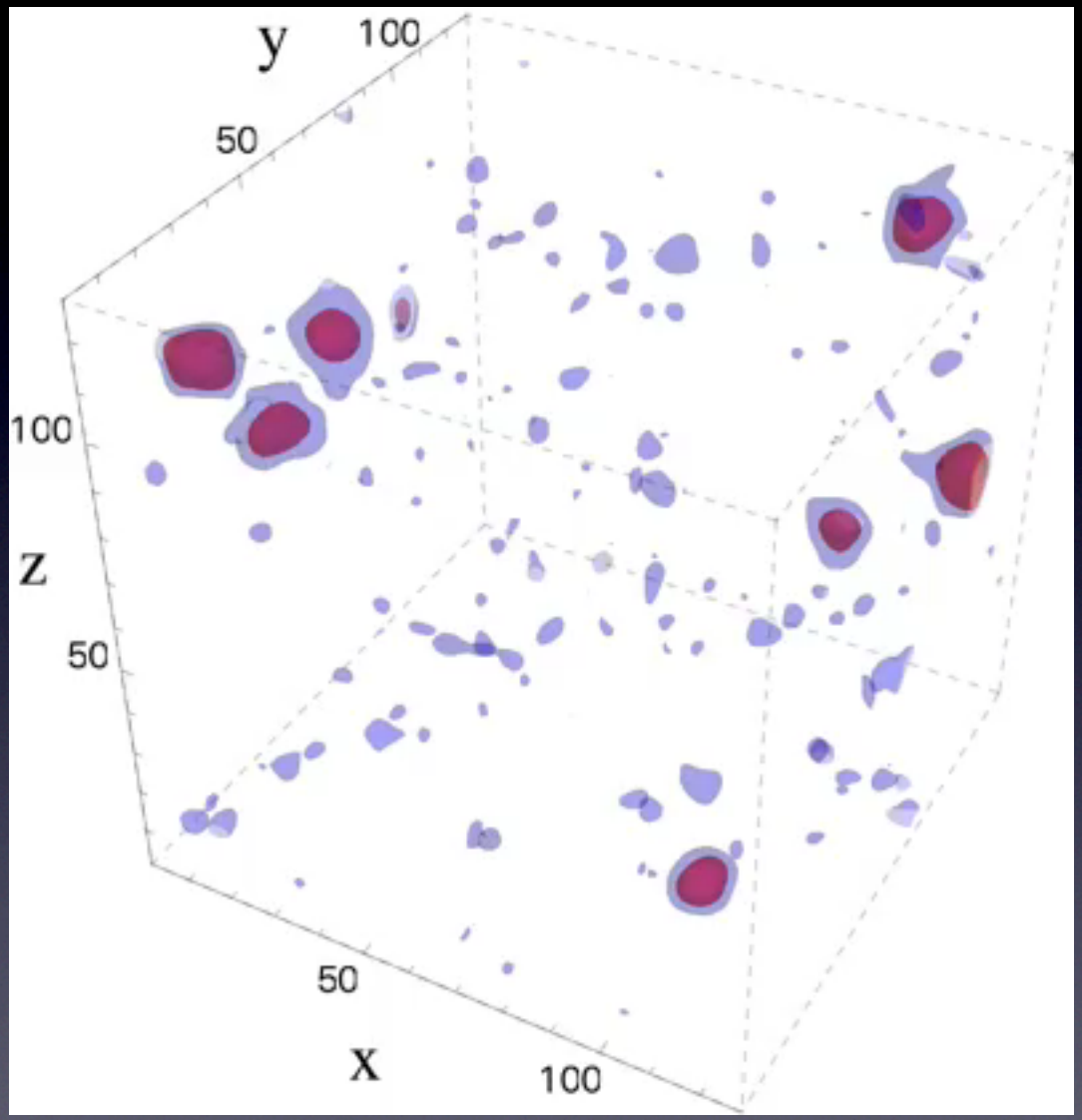
**Reheating/preheating is crucial for linking inflation to the later evolution of the universe!**
**This talk: Role of oscillons during this phase**

**After inflation: Vacuum energy is transferred into particles → matter & antimatter, and also their asymmetry get produced!**

# Teaser – Oscillons after inflation ...

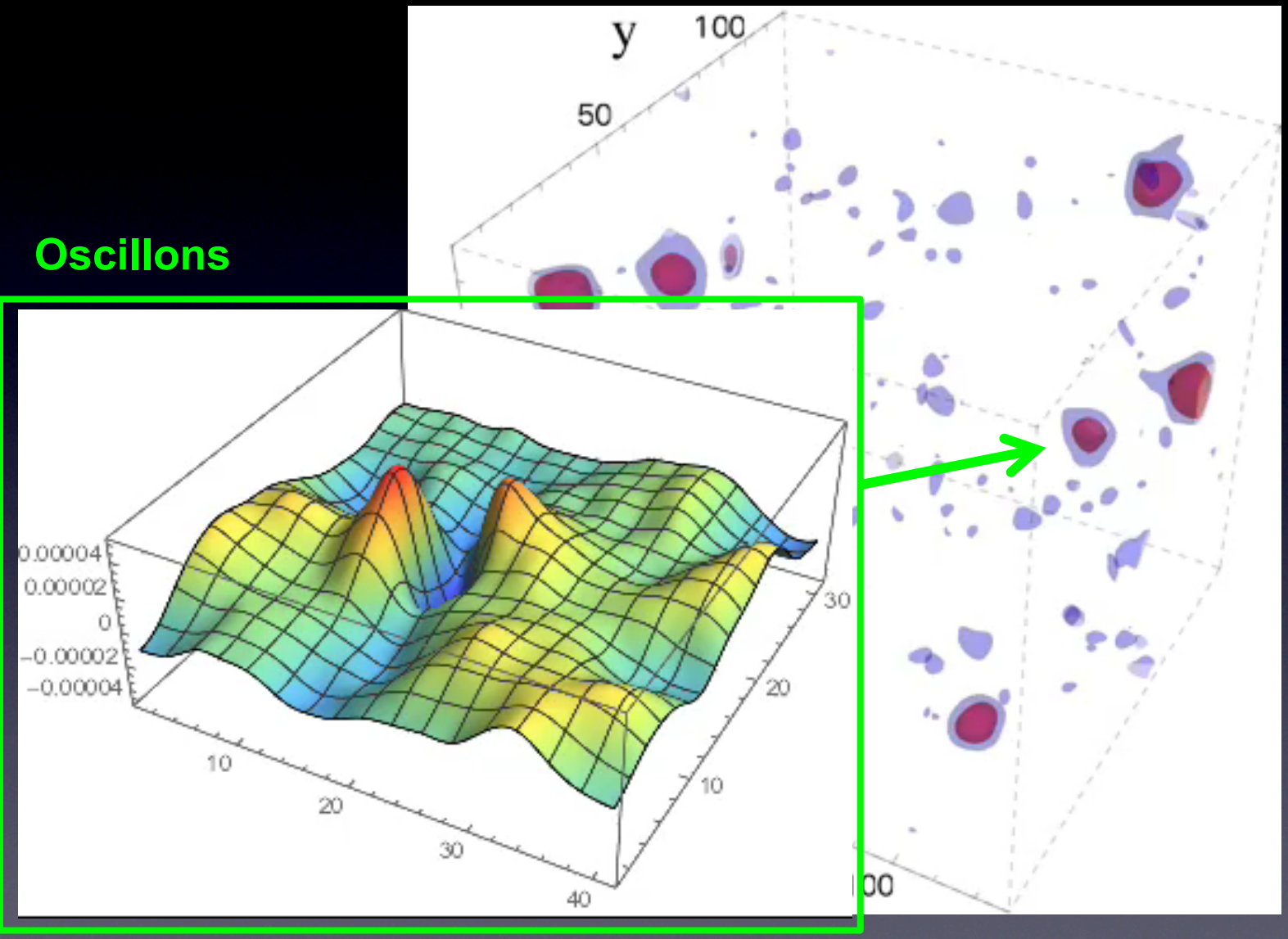
**Energy overdensities of the inflaton field after hilltop inflation:**
- blue: small overdensities
- red: large overdensities (oscillons)




**Movie from lattice simulations after hilltop inflation ...**

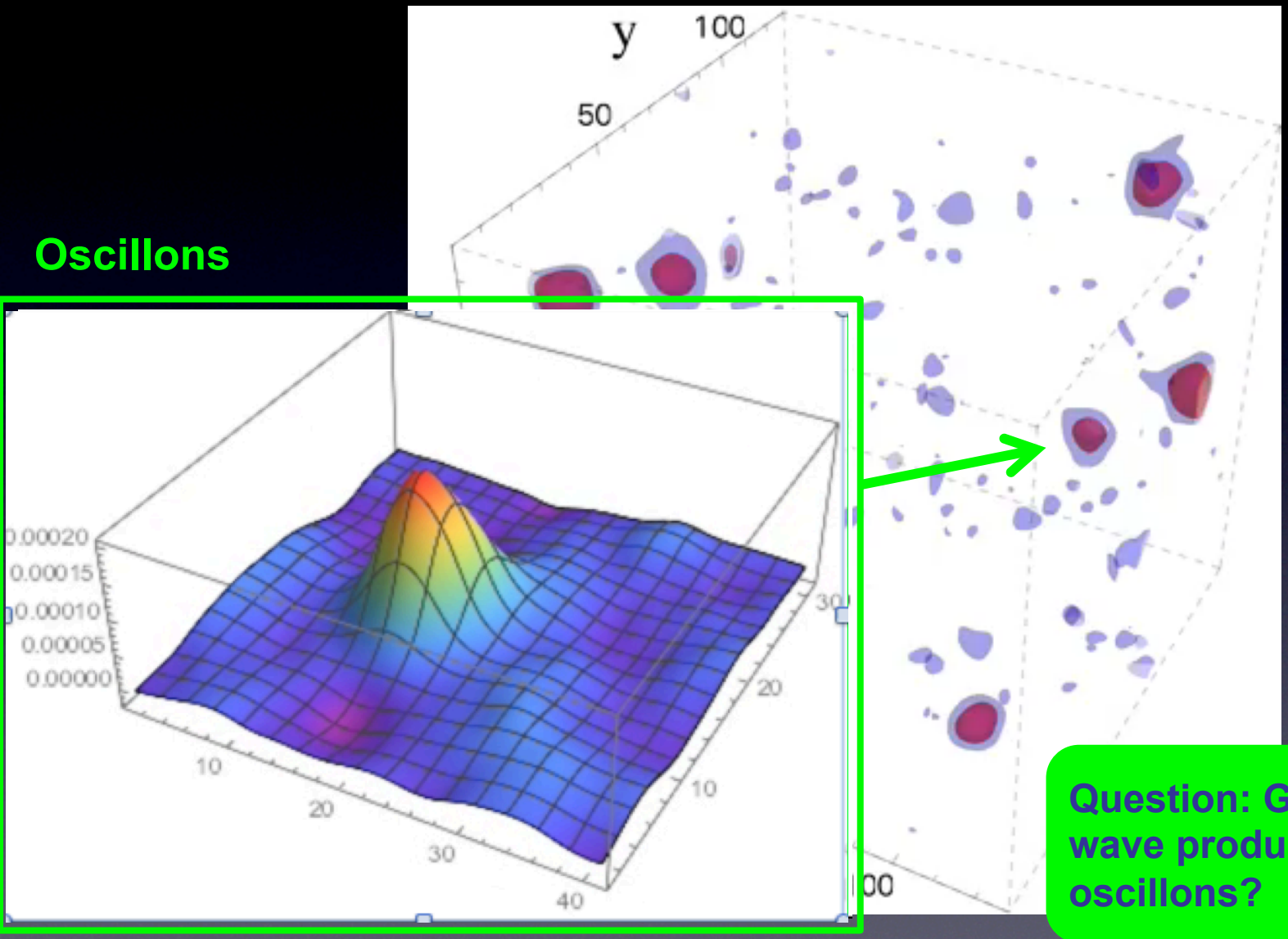
# Teaser – Oscillons after inflation ...




**Movie: Single oscillon (in an asymmetric potential)**

# Teaser – Oscillons after inflation ...

Oscillons




**Question: Gravitation wave production by the oscillons?**

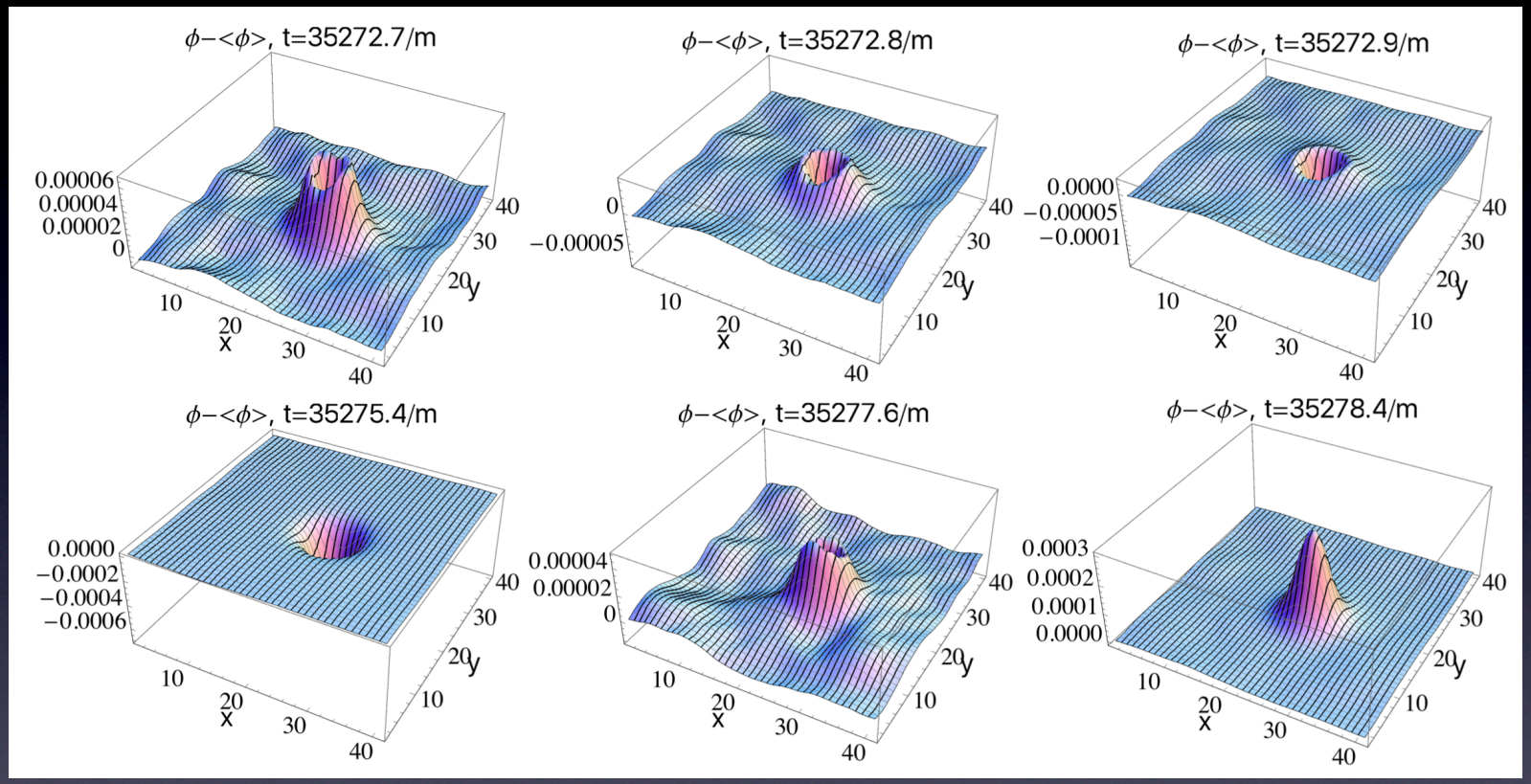
**Movie: Single oscillon (in an asymmetric potential)**

# *Outline*

- What are oscillons?
- How do they form? Example: Preheating after “hilltop inflation”
- Gravitational wave production from oscillons: Results from lattice simulations ➔ oscillons can act as efficient GW factories

# What are oscillons?

- Spatially localized, oscillatory field configurations with large amplitude

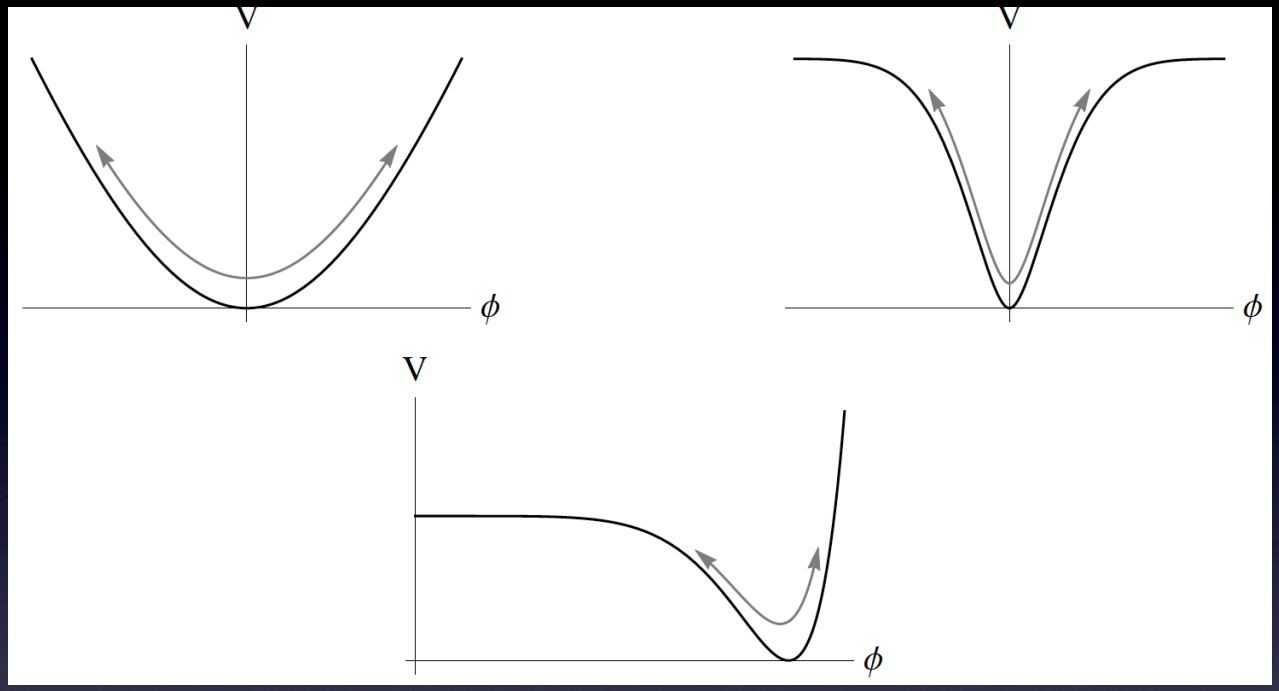



**Characteristics:**

- Can be quite long-lived ➔ can survive many thousands of oscillations!
- Radiate energy ➔ live long but not forever!
- Often tend to be spherical (with some deformations) ➔ depends on potential!

See e.g.: Copeland, Gleiser, Muller ('95), Amin et al. ('11), Gleiser, Graham('14), Kawasaki, Takahashi, Takeda, ('15), ⋯

# When do oscillons form?




**Oscillon formation:**

- Oscillons are a generic feature of scalar field theories where the potential opens up away from the minimum (e.g. plateau-like (hilltop) inflation models with a minimum, axion monodromy inflation, hybrid-like inflation models, ...)

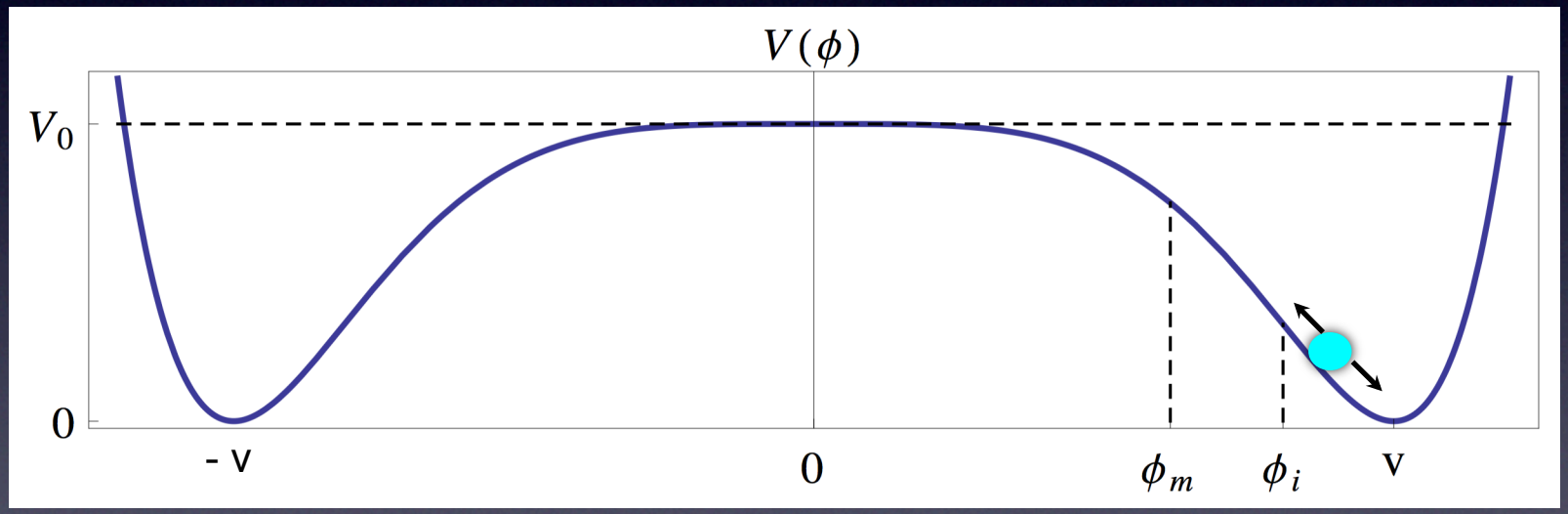
  See e.g.: Copeland, Gleiser, Muller ('95), Amin et al. ('11), ⋯
- Necessary condition ➔ potential must be shallower than quadratic around the minimum for some ΔΦ!
- They form efficiently during the non-linear oscillatory phase (i.e. during preheating) after inflation!

# *Preheating and oscillon formation after small-field hilltop inflation*

For a more detailed overview, see:
S. A., D. Nolde, S. Orani (arXiv:1503.06075)

**Preheating:**

- Phase I: Tachyonic preheating (growth of IR modes; strongest for very small v)
- Phase II: Tachyonic oscillations (growth of modes around a certain scale
  ➔ oscillon formation!)



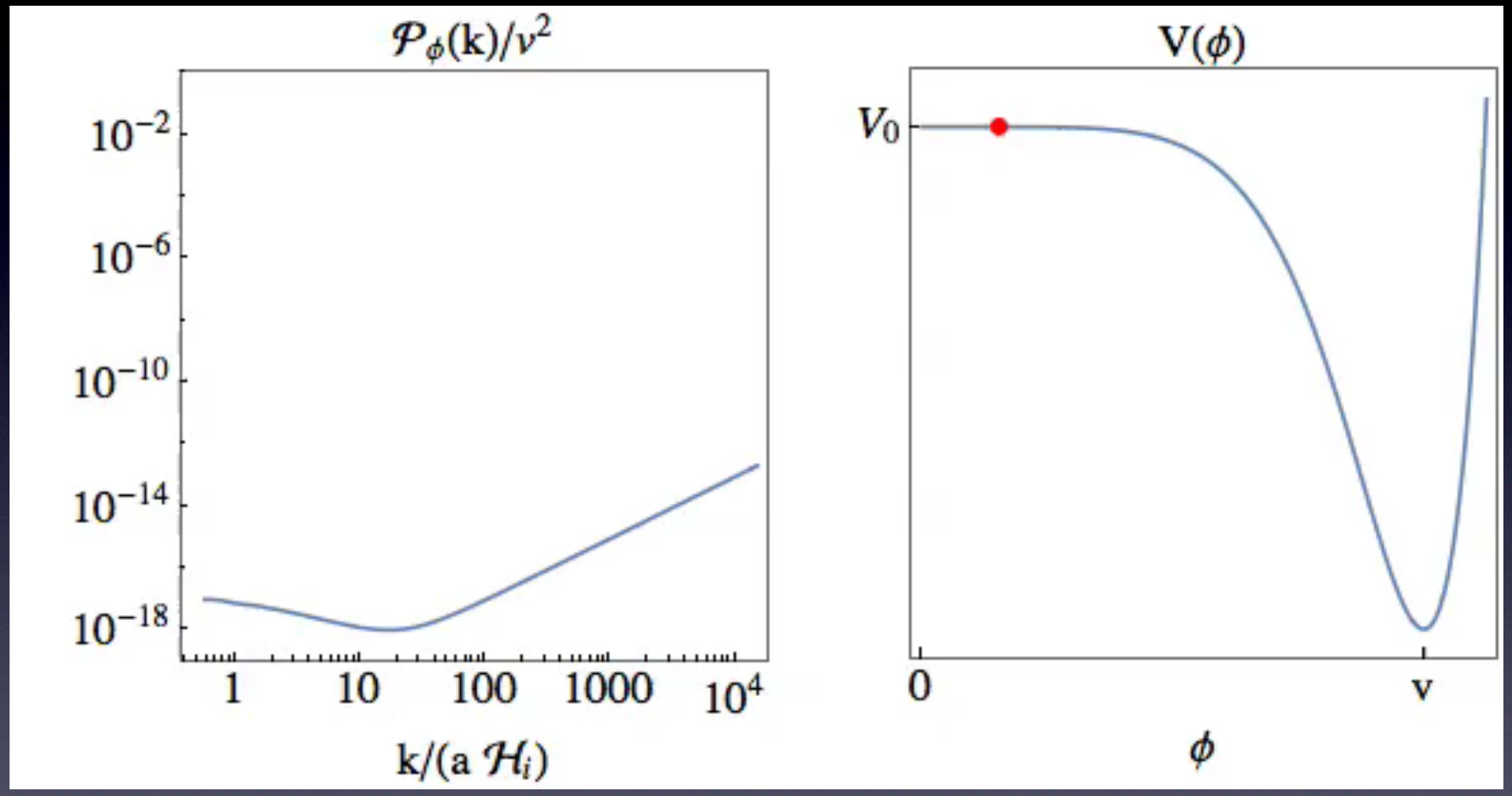

Simple Model:

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

Note: For given p ≥ 4 and v, $V_0$ is fixed by CMB observations

# Phases I and II: linear analysis

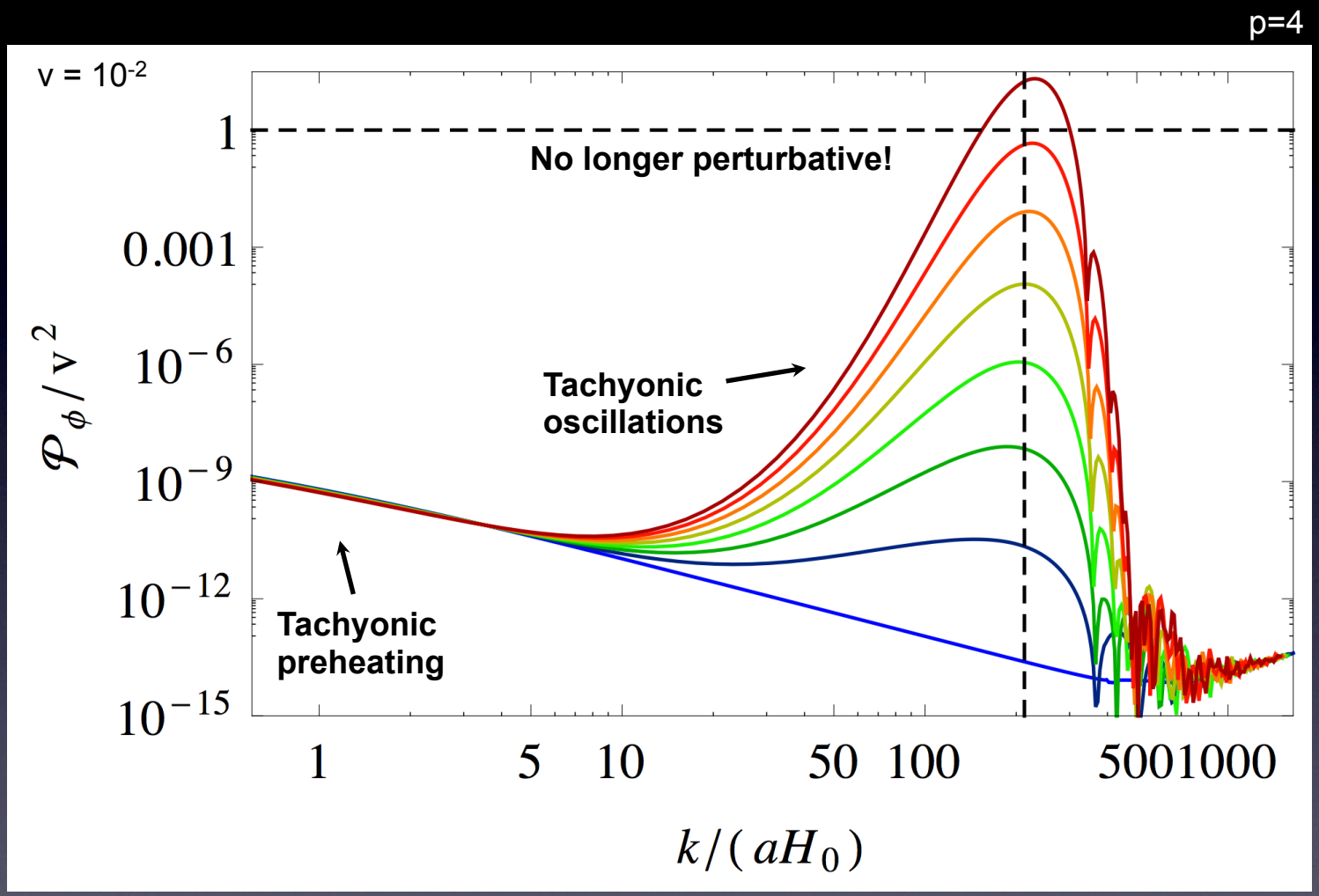
p=6




Movie: Early (linear) phase of preheating after hilltop inflation

$$\mathcal{P}_\phi(t,k) = \frac{k^3}{2\pi^2}\,|\phi_k(t)|^2$$

# Phases I and II: linear analysis




$$\mathcal{P}_\phi(t,k) = \frac{k^3}{2\pi^2}|\phi_k(t)|^2$$

from: S. A., D. Nolde, S. Orani (arXiv:1503.06075)

# Analysis of preheating: inhomogeneous field equations on the lattice

Lattice: (Non-linear) field equations for $\phi(t,x)$ using LATTICEEASY

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

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

In addition we calculate the produced gravitational waves, using the TT part $\Pi^{TT}_{ij}$ of the anisotropic stress tensor on the lattice as source:

$$\Pi_{ij}^{\rm TT} = [\partial_i\phi\partial_j\phi]^{\rm TT}$$

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

and then:

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

with:

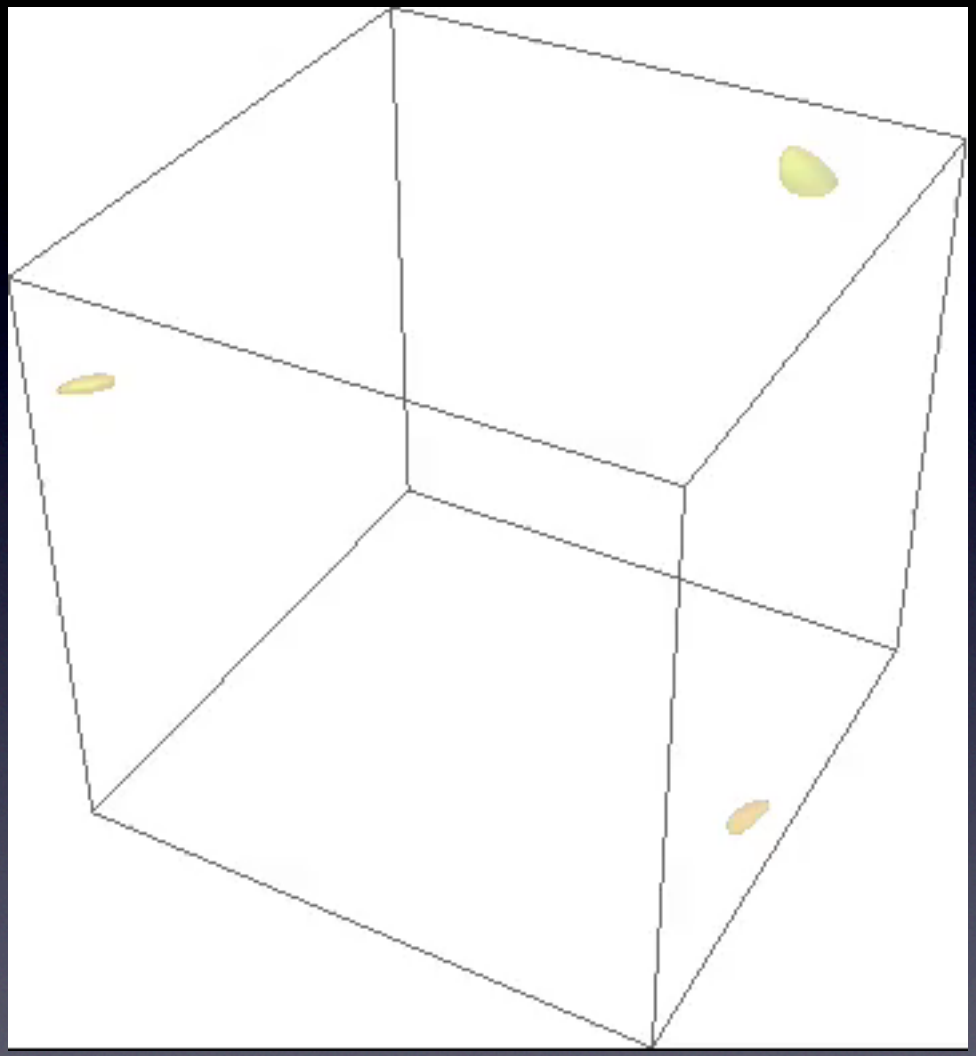
$$\rho_{\rm GW}(t) = \frac{m_{\rm Pl}^2}{4}\left\langle \dot{h}_{ij}(\mathbf{x},t)\dot{h}_{ij}(\mathbf{x},t)\right\rangle_{\mathcal{V}}$$

For more details, see e.g.: Figueroa, Garcia-Bellido, Rajantie (2011)

https://particlesandcosmology.unibas.ch/files/hilltop_preheating.html

# *Early stage: “hill-crossing” oscillons*

**... Periodically appearing and collapsing bubbles of wrong vacuum**



3D lattice simulation

$v = 10^{-2}$

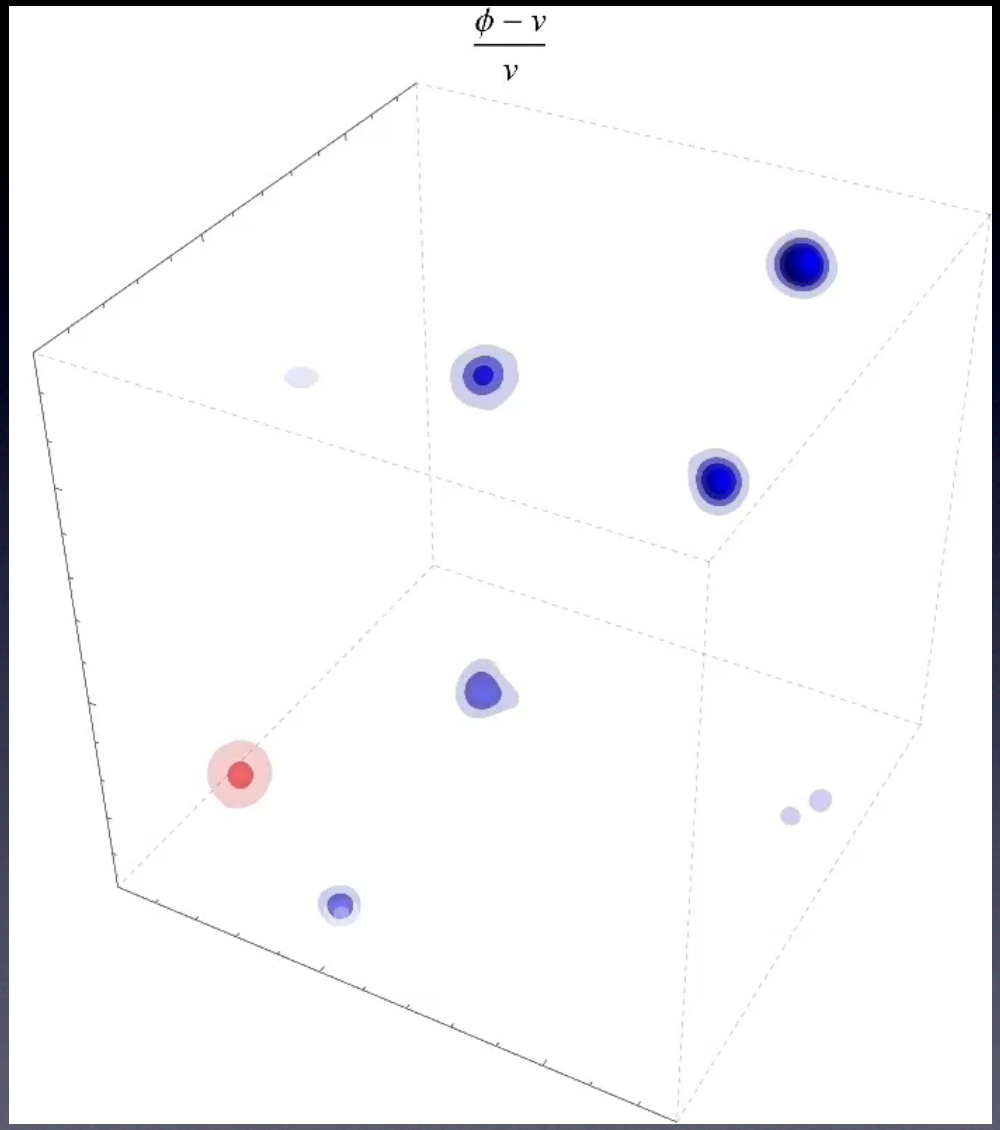
Colored regions: Overshooting to “wrong” vacuum;
yellow: $\Phi <\approx 0$
blue: $\Phi << 0$

**Movie from lattice simulations after hilltop inflation ...**

S. A., D. Nolde, S. Orani
arXiv:1503.06075

# Later stage: “quasi-stable” oscillons

**... Long-lived, for many thousands of oscillations**

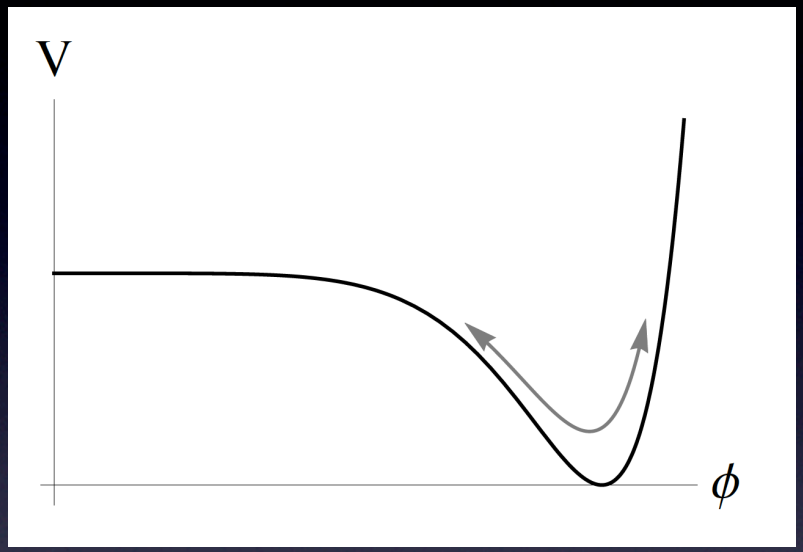



3D lattice simulation

$v = 10^{-1}$

Colors:
field values larger or smaller than v:
red: $\Phi > v$
blue: $\Phi < v$

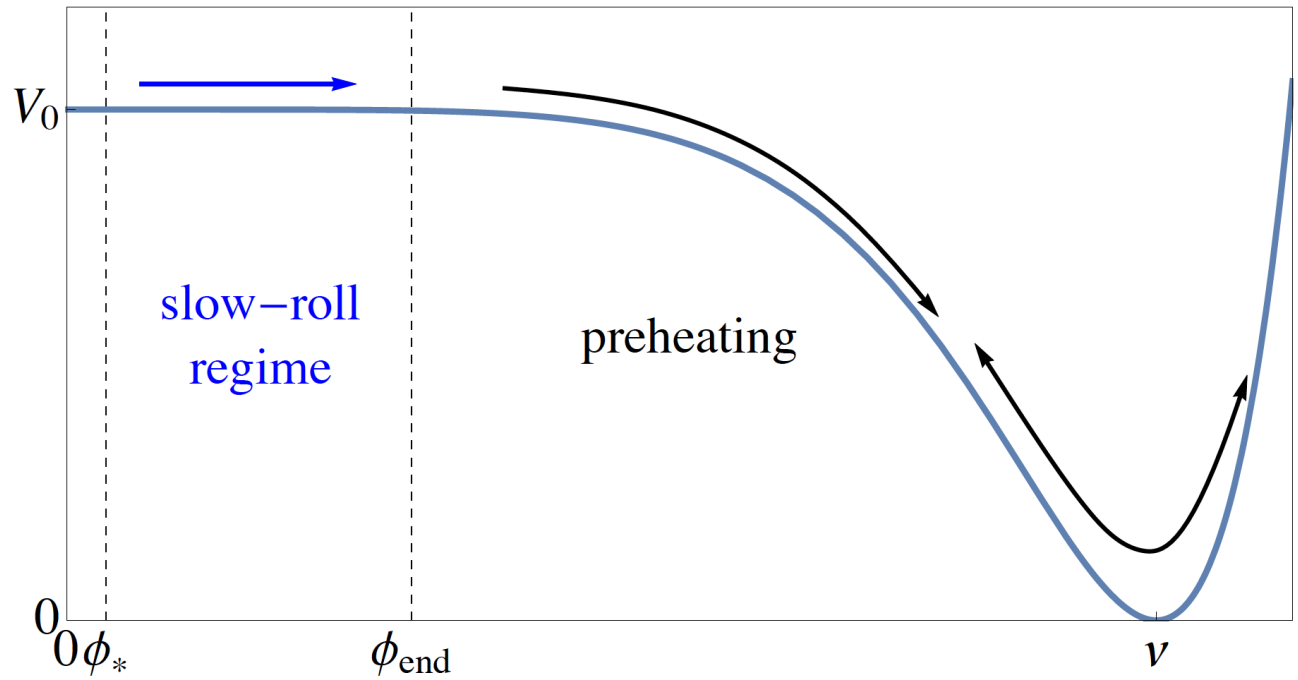
# *Possible observable effects from oscillons*




- Affect dynamics of preheating and expansion history ➔ delay of reheating!
- **Production of gravitational waves**

# GW from oscillons after single field hilltop inflation

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



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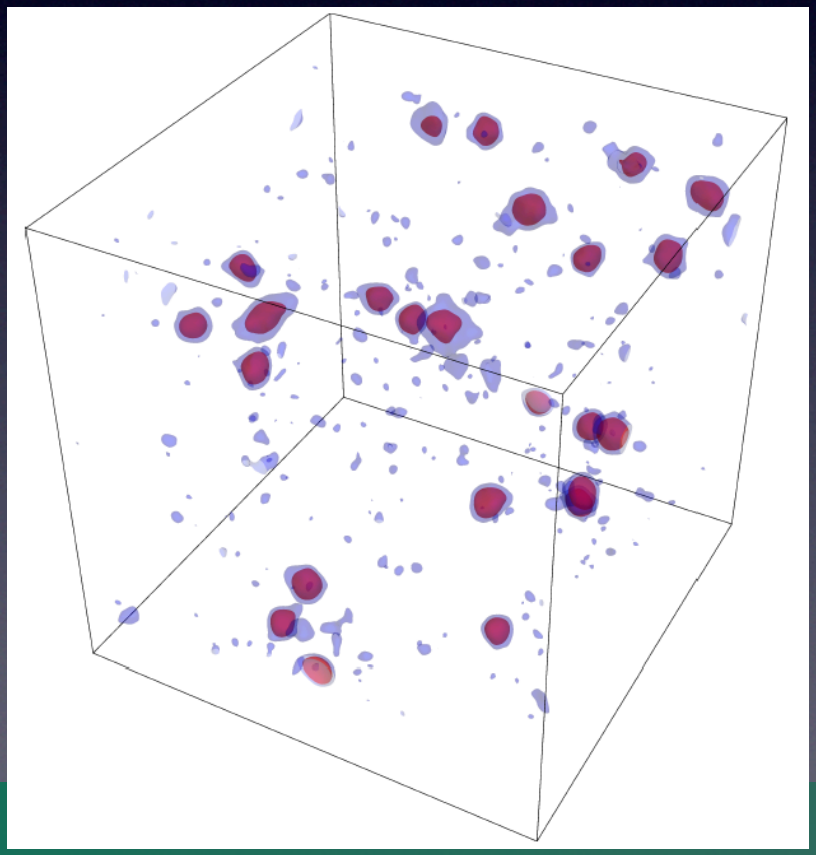
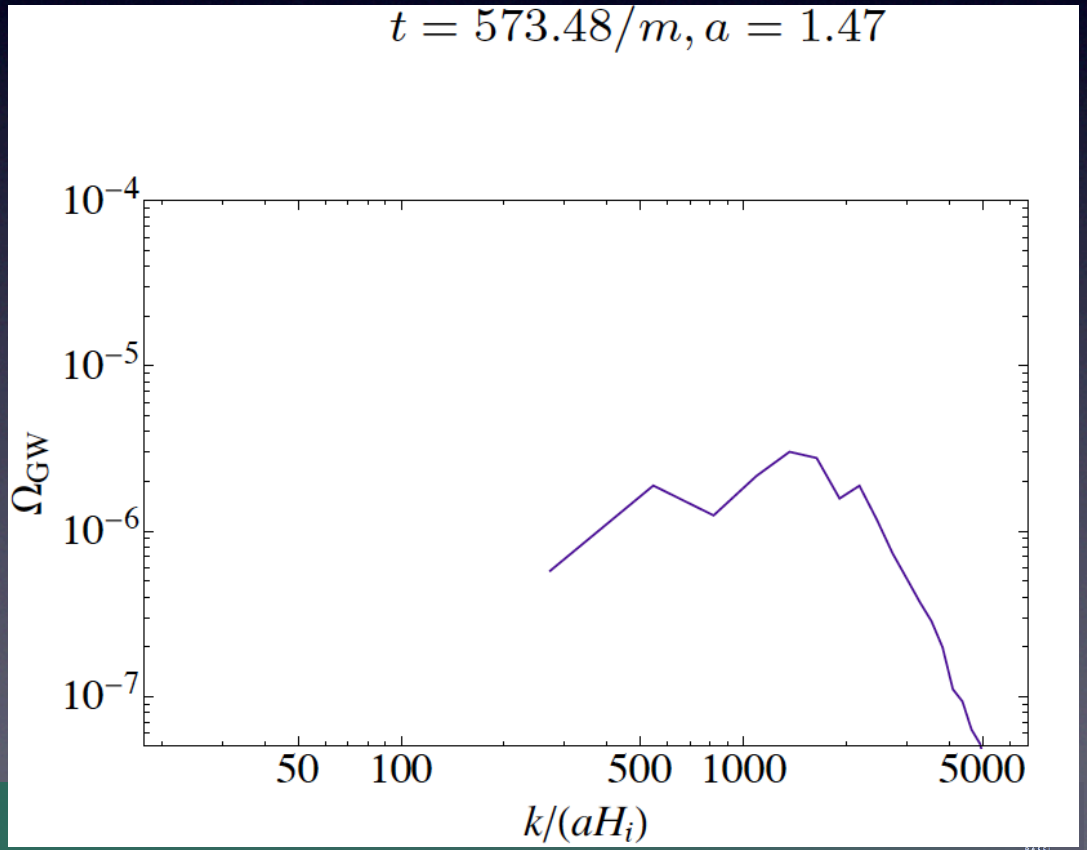
With p = 6, v = $10^{-2}$, $V_0$ = fixed from CMB





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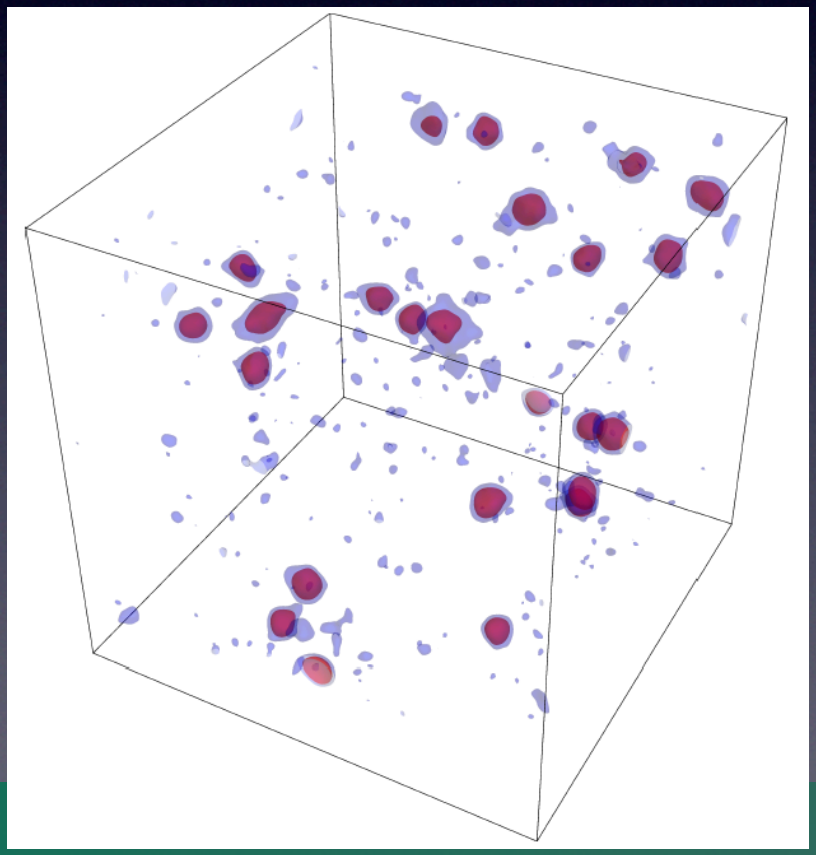

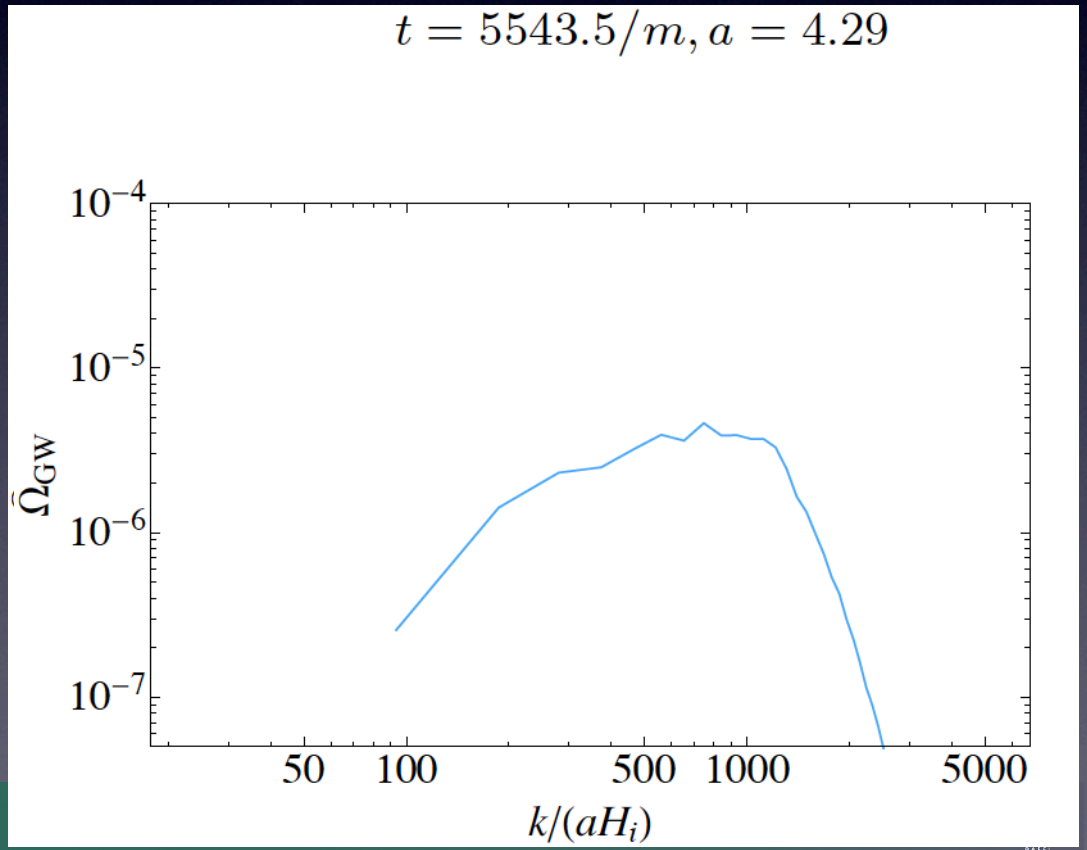

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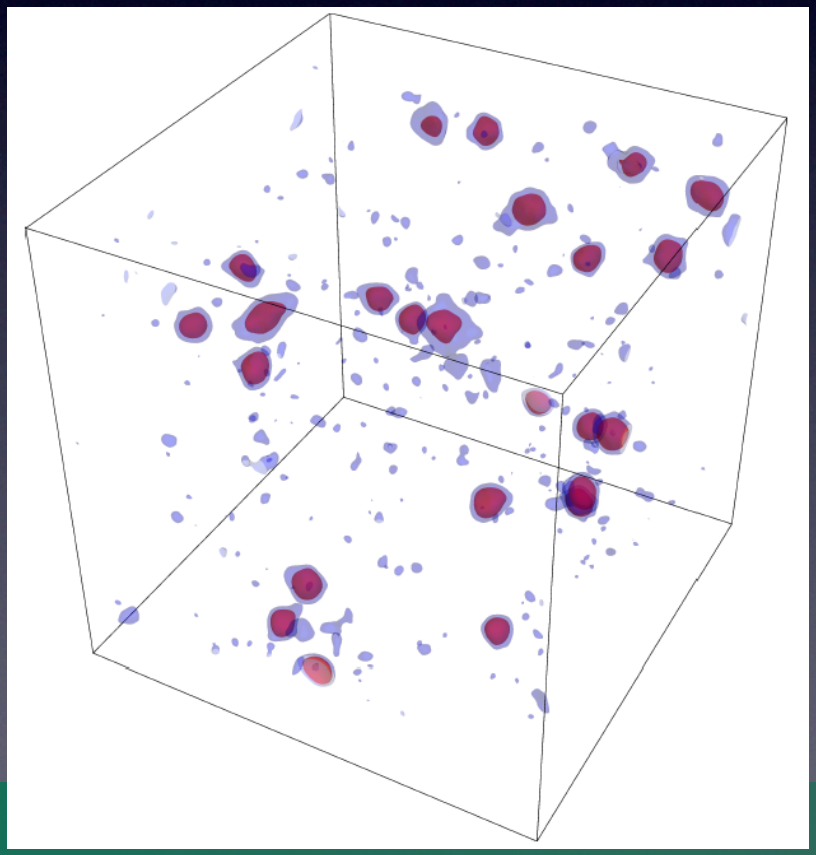

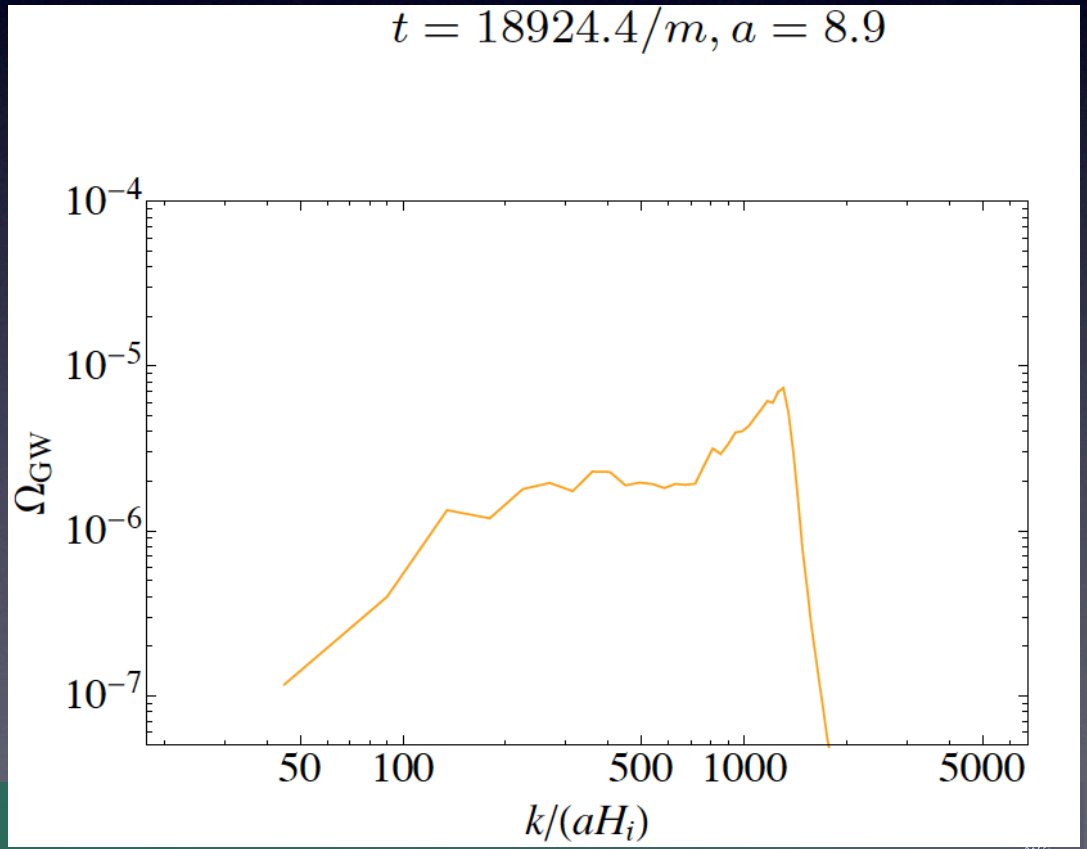

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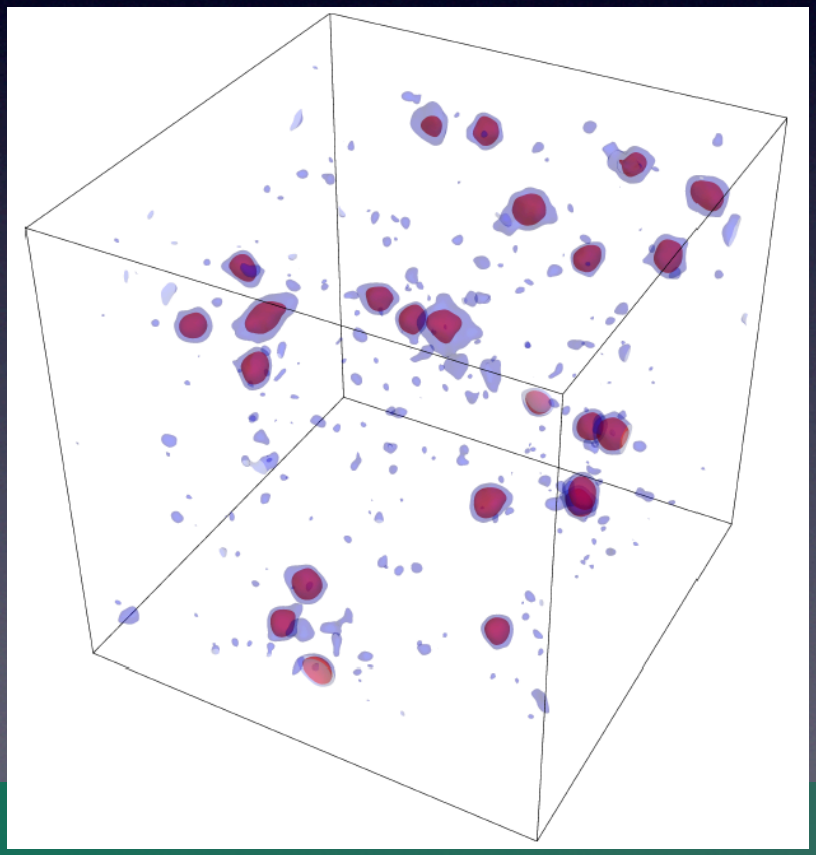

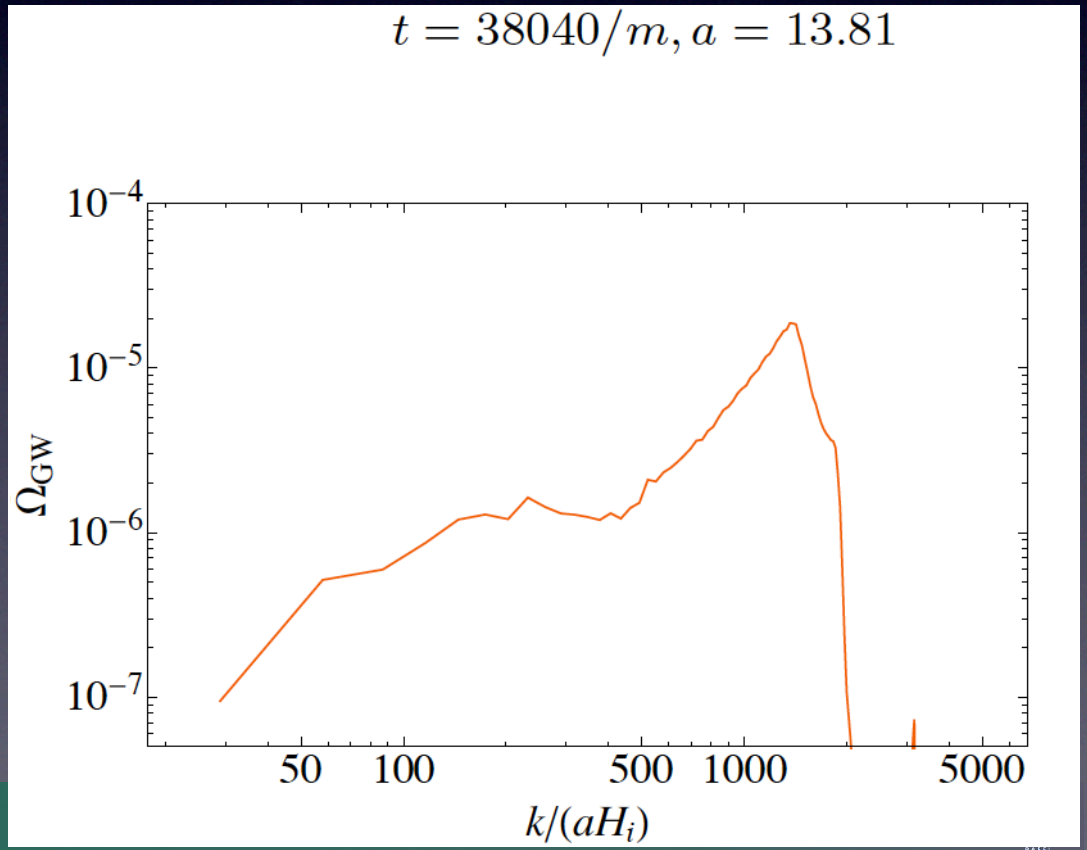

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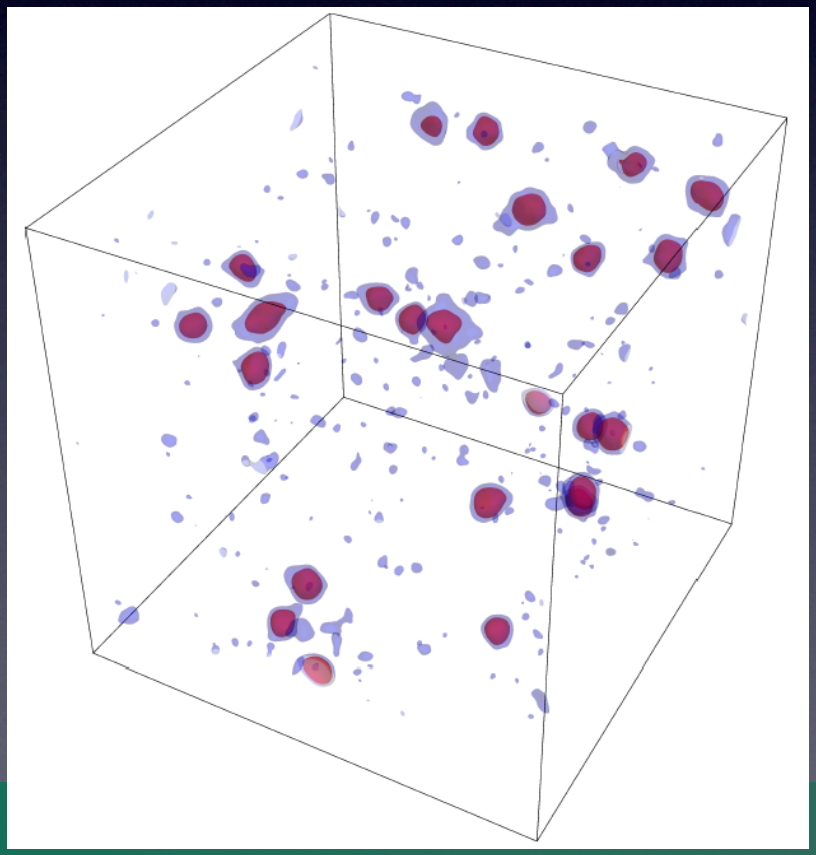

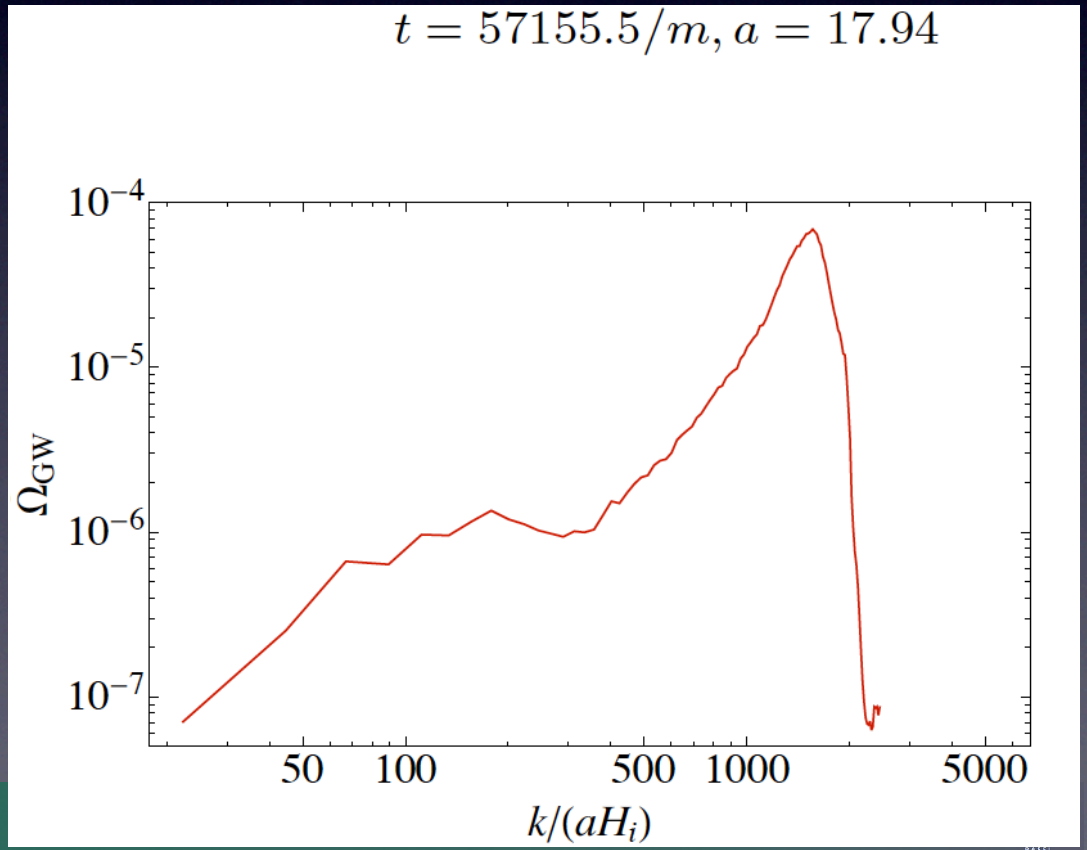

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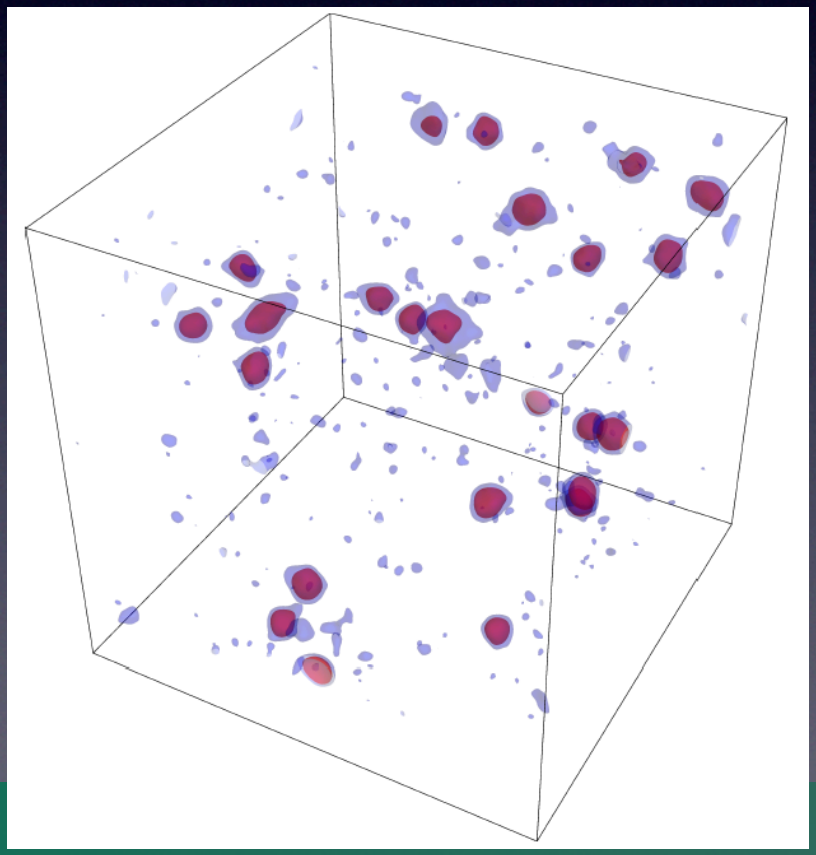
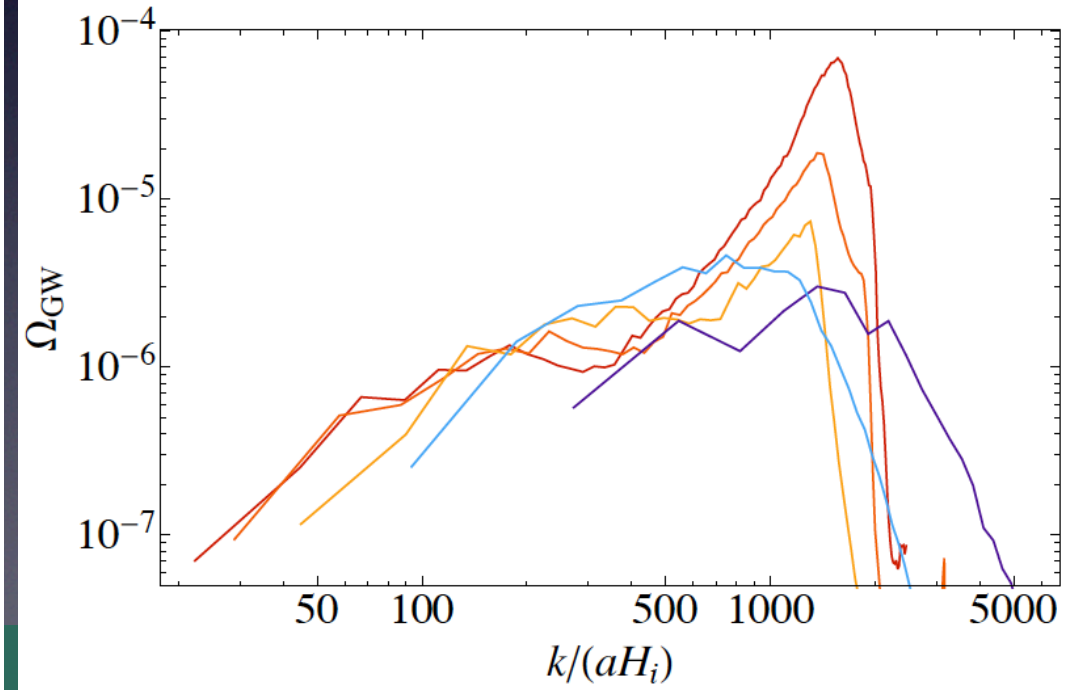


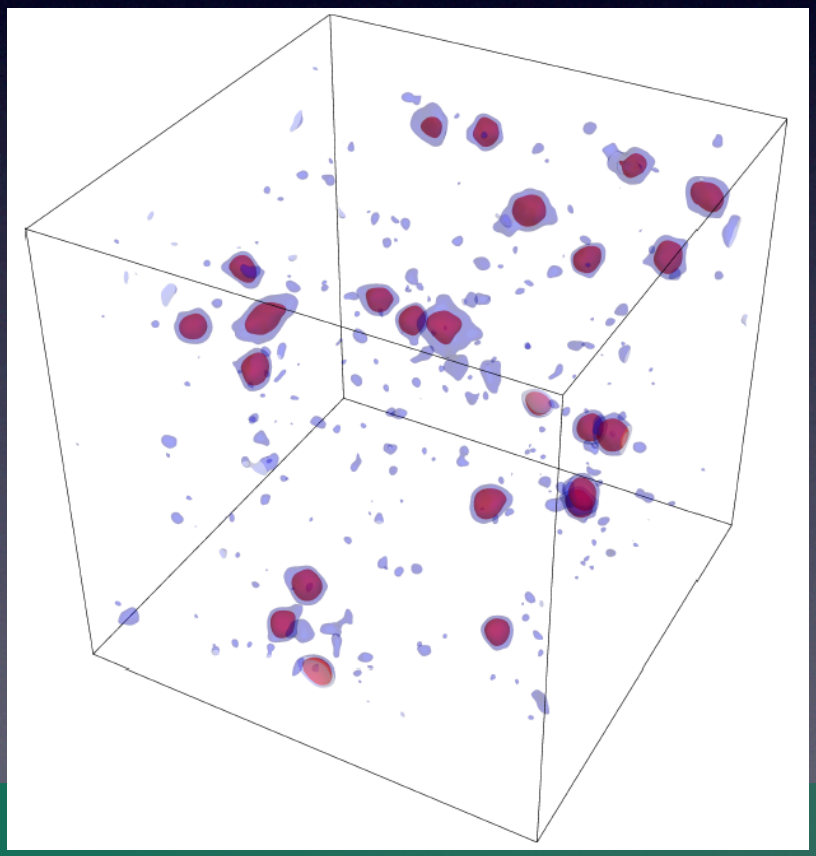
S.A., F. Cefala, S. Orani (arXiv:1607.01314)

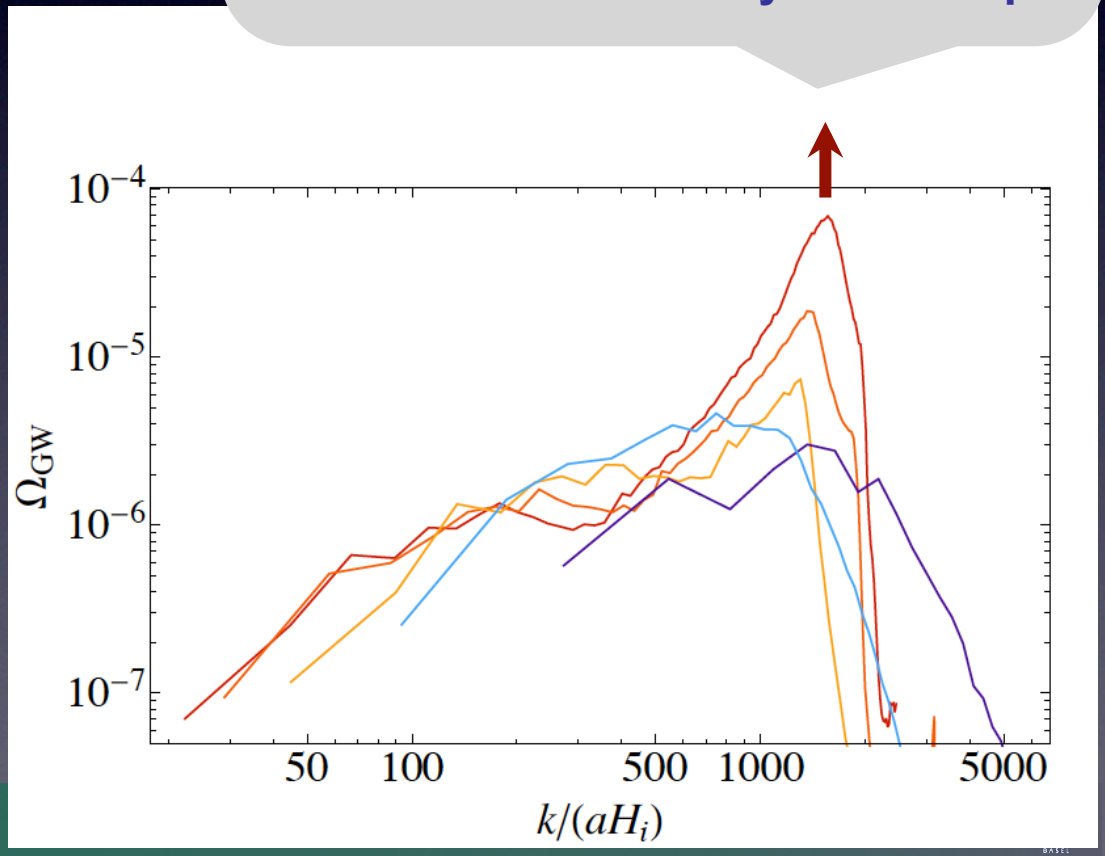


# GW from oscillons after single field hilltop inflation

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

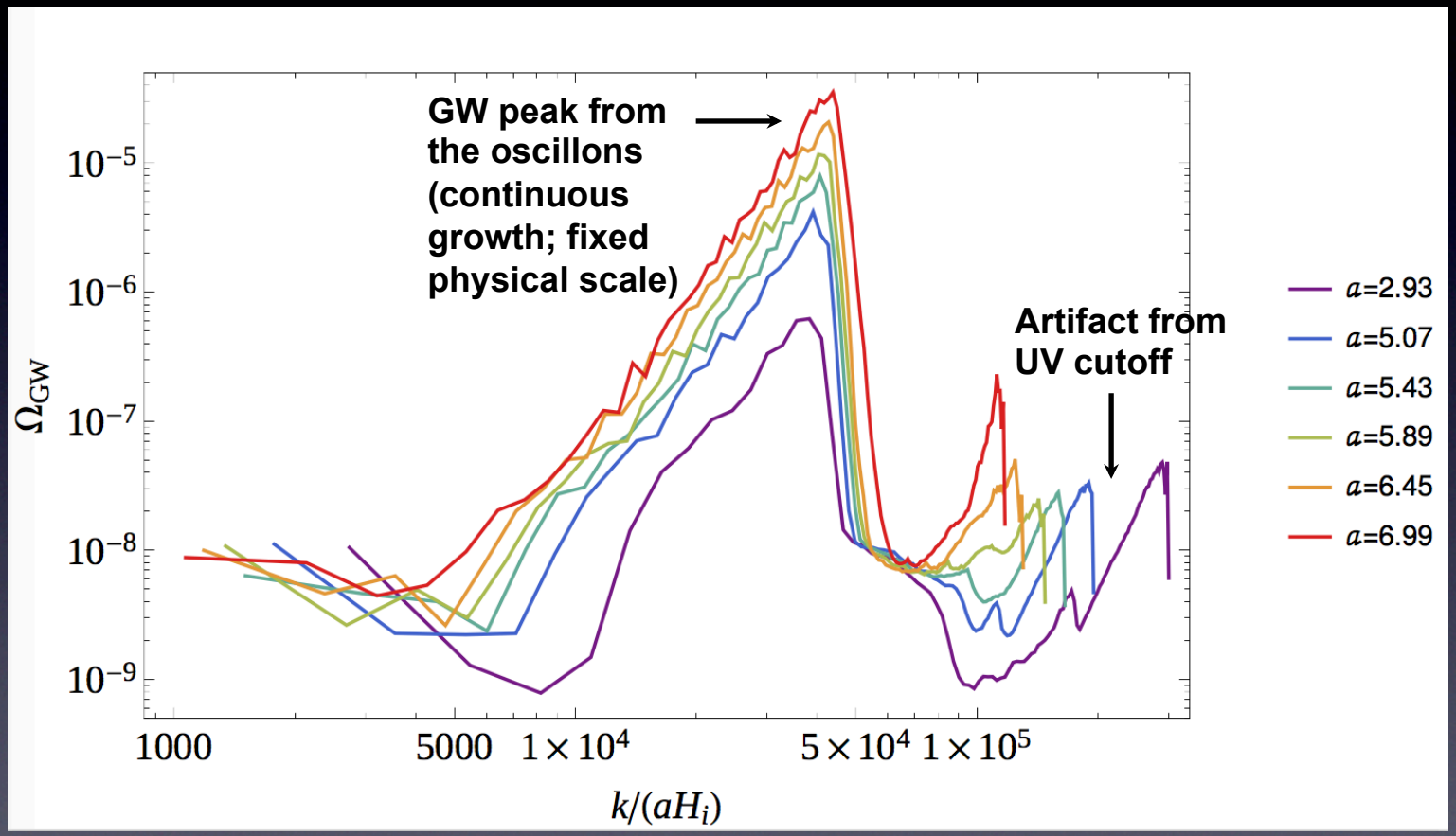
**Remark 1: We stopped our simulations here because we were reaching the limit of our lattice resolution. But we expect the growth of the GW peak to continue. Unknown when exactly it will stop!**





# Remark 2: Effect is physical – not an artifact of UV lattice cutoff!

- Higher resolution (more UV) possible when oscillons are initialized by hand:




- Note: GW peak from oscillons at fixed physical scale! (In comparison, there is also a numerical artifact from the UV cutoff, which is redshifting as it should ⋯ cleanly separated from the GW peak)

# Remark 3: Effects of a secondary field X?

**Assume ϕ couples to SM via field X:**

$$W = \Lambda^2 \hat{S} \left( \frac{4\hat{\Phi}^4}{\mu^4} - 1 \right) + \lambda_i \hat{\Phi}^2 \hat{X}_i^2$$

X may be a right-handed sneutrino and can explain the initial position of ϕ and do non-th. leptogenesis ... (cf. S.A., Orani, Nolde, arXiv:1402.5328)

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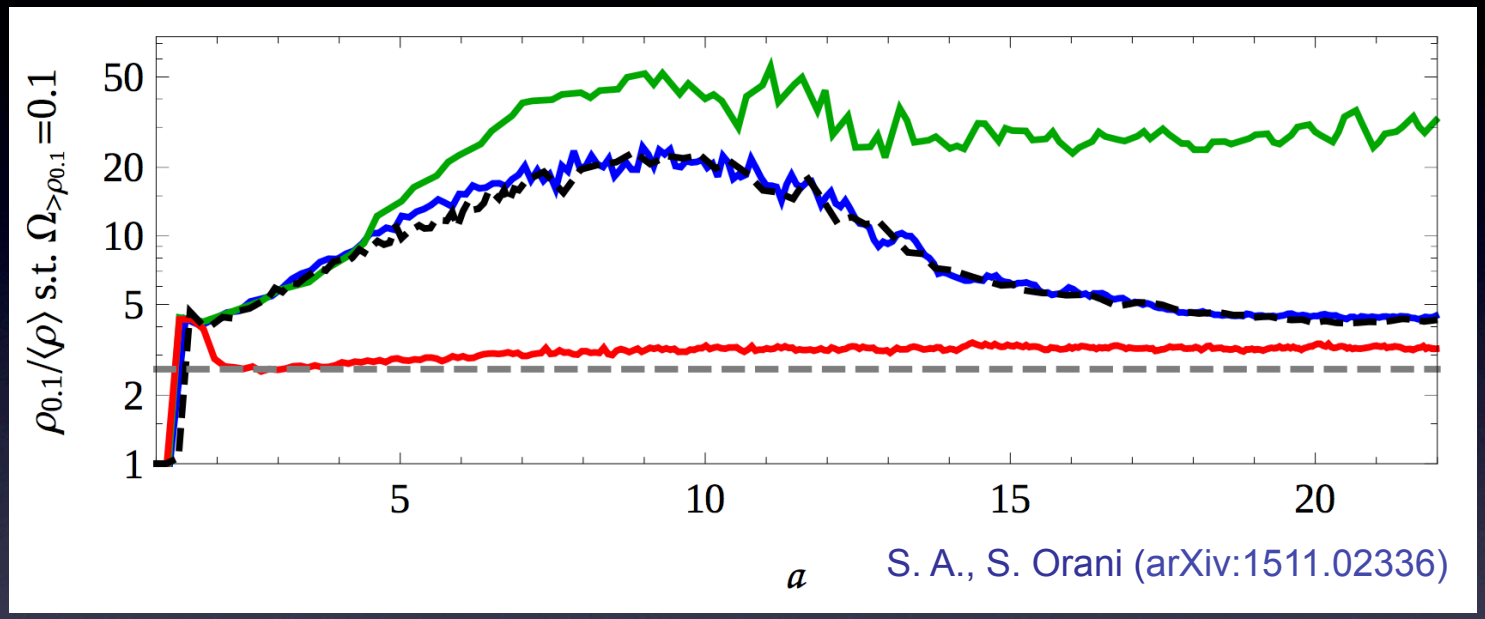


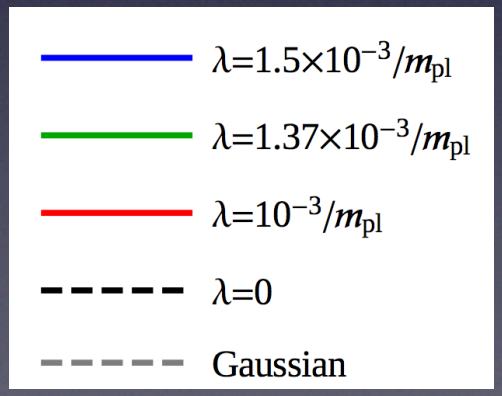

S. A., S. Orani (arXiv:1511.02336)

From 2D lattice simulations

v = $10^{-2}$

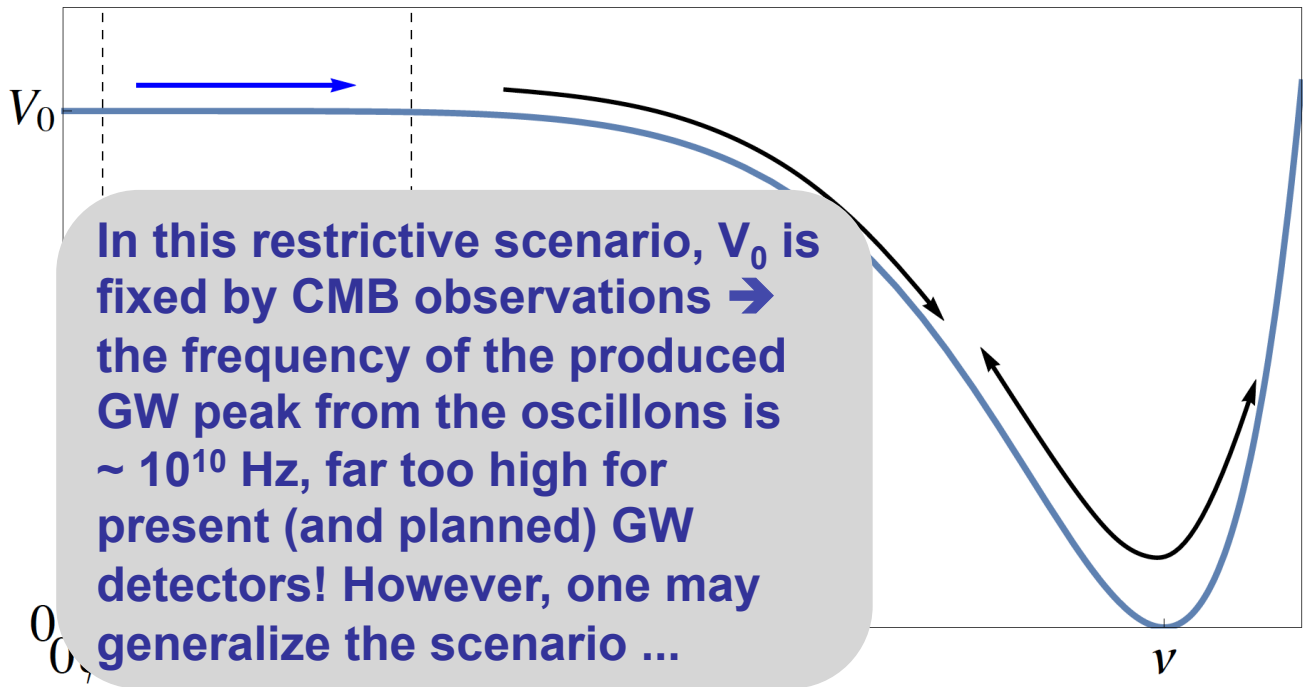
**<u>Three cases:</u> depending on whether X gets enhanced by a (strong) parametric resonance:**

- No effect on oscillons when X stays subdominant
- Strong and fast enhancement of X: oscillons suppressed
- Weaker and delayed enhancement: Oscillons imprinted on X field; further "stabilisation" of the oscillon system!



# Remark 4: Frequency of the GW peak?

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



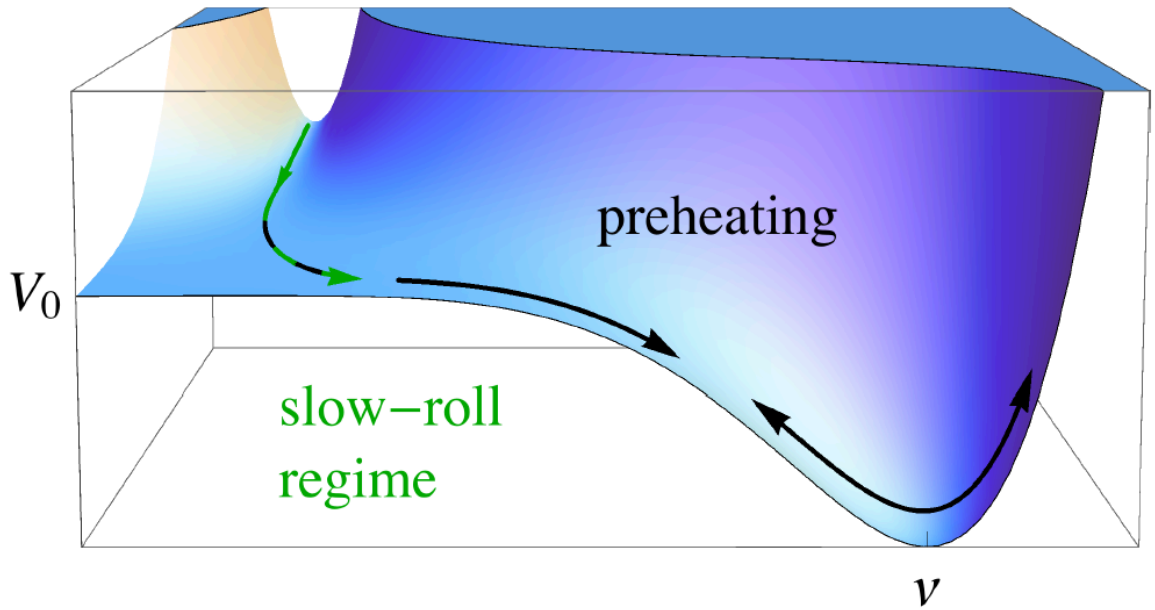

**In this restrictive scenario, $V_0$ is fixed by CMB observations ➔ the frequency of the produced GW peak from the oscillons is ~ $10^{10}$ Hz, far too high for present (and planned) GW detectors! However, one may generalize the scenario ...**

Note: Very restrictive; for given p ≥ 4 and v, $V_0$ is fixed by CMB observations

# Generalized scenario: GW from oscillons after a 2nd order phase transition

- Example: inflation orthogonal to the hill: “hybrid-like” inflation models

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




**Slow roll inflation:**

- Universe inflates as $\chi$ rolls along the valley
- Inflation ends by a tachyonic instability in $\phi$
- Here: $v$ and $V_0$ are free!
- CMB observables from $V_{inf}$

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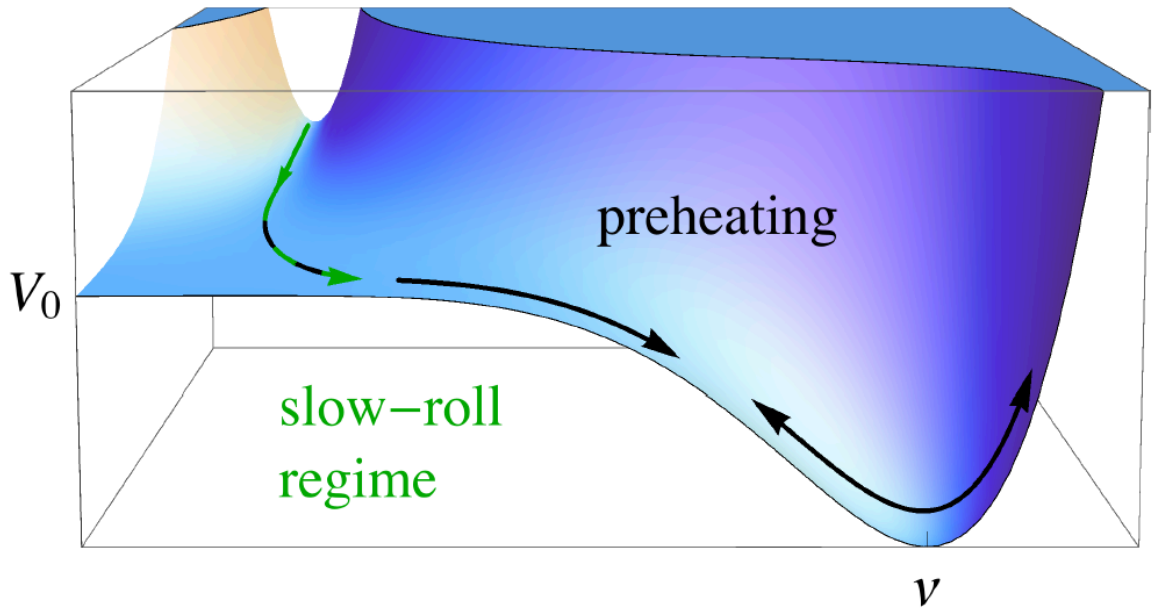


**Preheating (as before!):**

- Typically non-linear, two phases
  - Phase I: Tachyonic preheating (growth of IR modes, most efficient for very small v)
  - Phase II: Tachyonic oscillations: Growth of modes around a certain scale ➔ oscillon formation!

# Generalized scenario: GW from oscillons after a 2nd order phase transition

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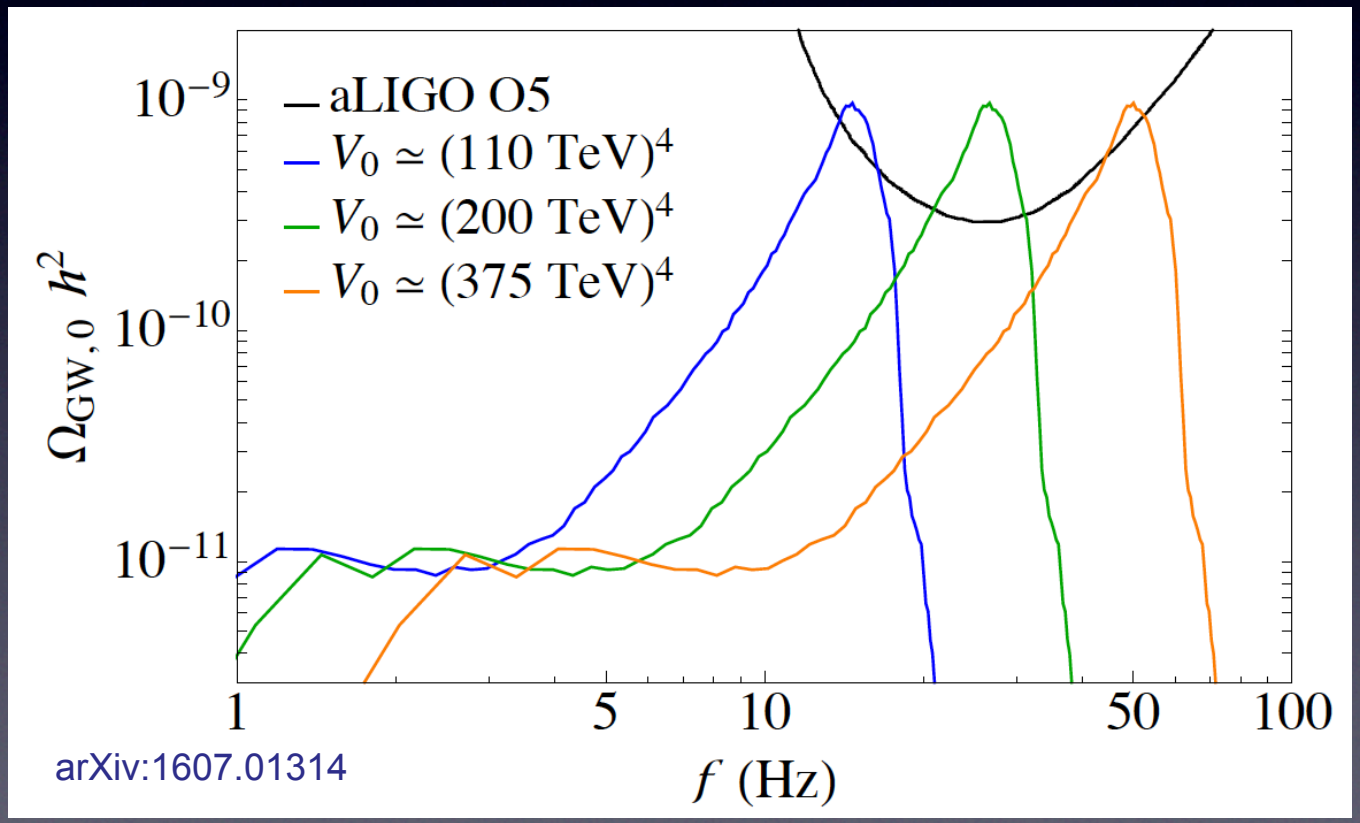


arXiv:1607.01314

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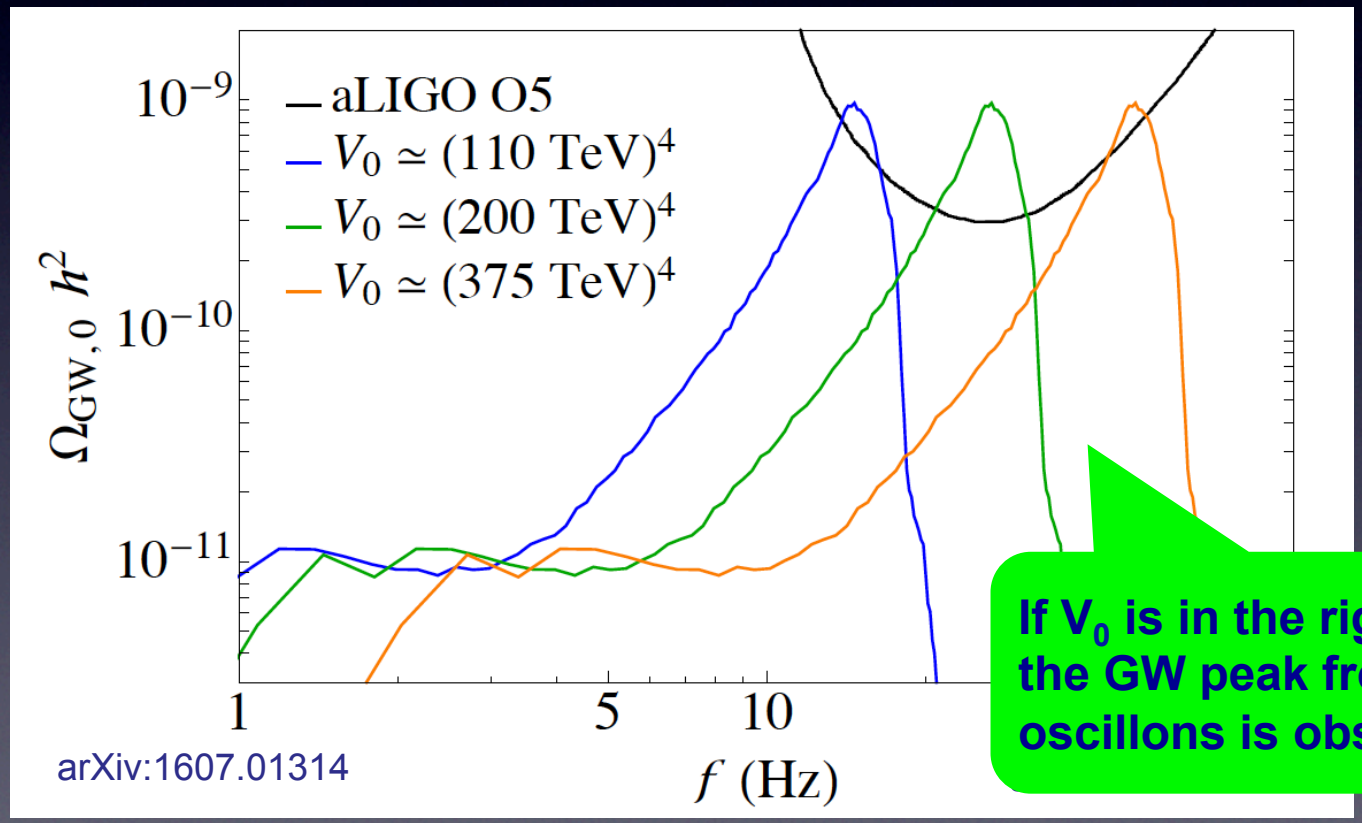


arXiv:1607.01314

**If $V_0$ is in the right range, the GW peak from the oscillons is observable!**

# *Summary*

- Oscillons are localized and strong scalar field fluctuations which are remarkably long-lived.
- They are quite common in the early universe (e.g. they can be produced efficiently during preheating after “hilltop-type” inflation models).
- We recently found that the oscillons can act as “GW factories” (continuous GW production) and generate a pronounced peak in the GW spectrum!
- Much stronger signal compared to previous study (which assumed a different, symmetric potential). Zhou, Copeland, Easther, Finkel, Mou and Saffin (’13)
- If the GW peak is in the right frequency range (generalized scenarios with lower $V_0$) the effects from the oscillons can be observed (e.g. at future runs of the aLIGO-AdVirgo detector network, ⋯).

For details and further references: S.A., F. Cefala, S. Orani, arXiv:1607.01314 [PRL118 (2017) 011303]

# Thanks for your attention!