Oscillons and gravitational waves from preheating after inflation

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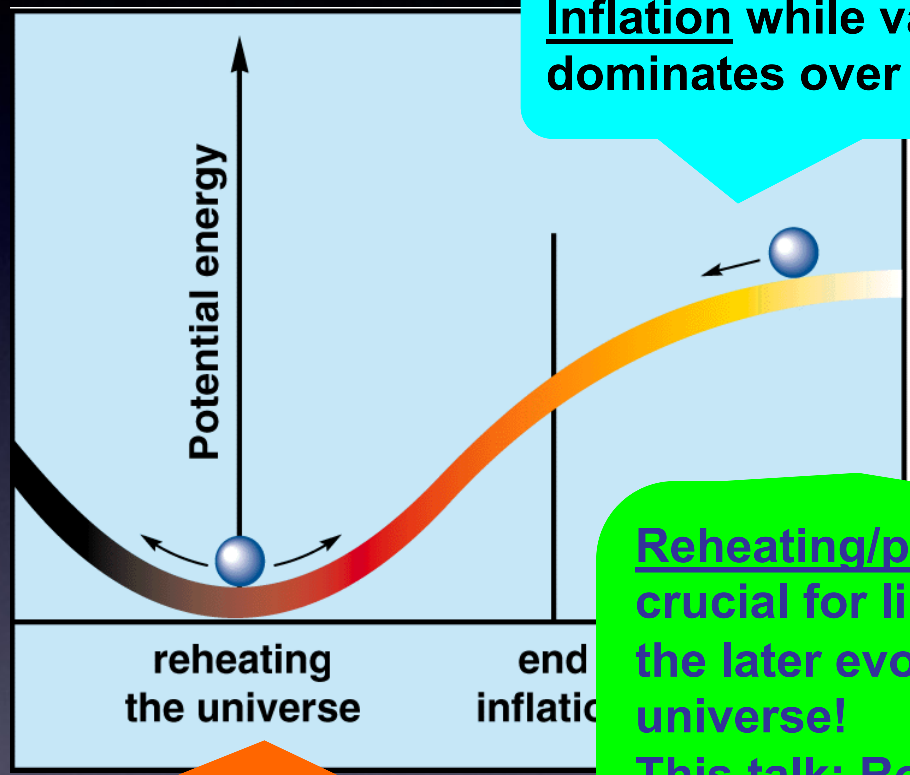
UNI BASEL

Seminar talk at the MPIK Heidelberg

November 14, 2022

Framework: Dynamics after inflation



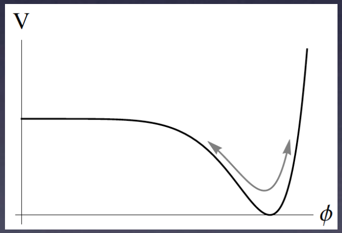
<u>Inflation</u> while vacuum energy dominates over kinetic energy

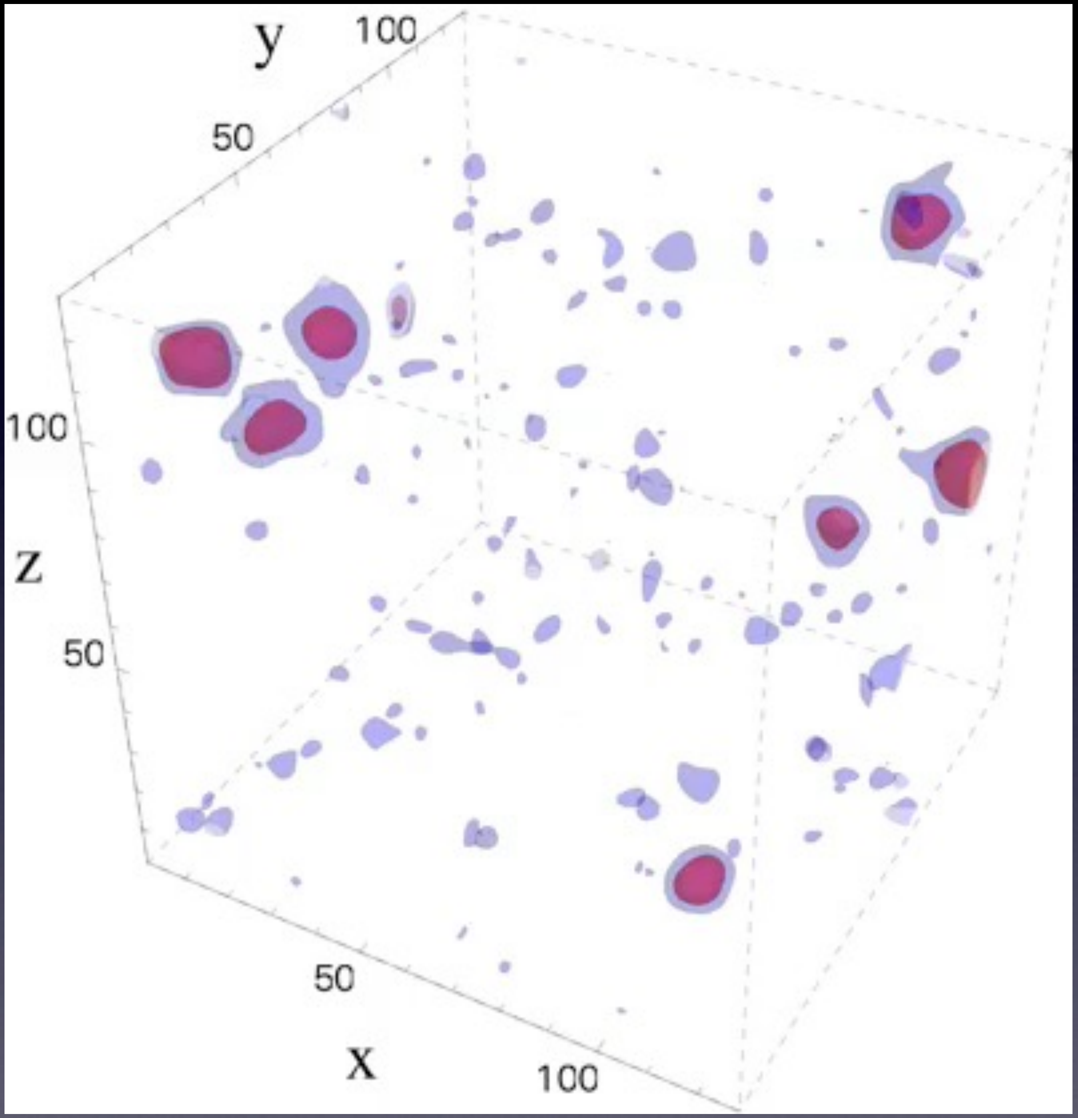
<u>Reheating/preheating</u> is crucial for linking inflation to the later evolution of the universe!
This talk: <u>Role of oscillons</u> during this phase and <u>GW production during preheating</u>

<u>After inflation</u>: 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)

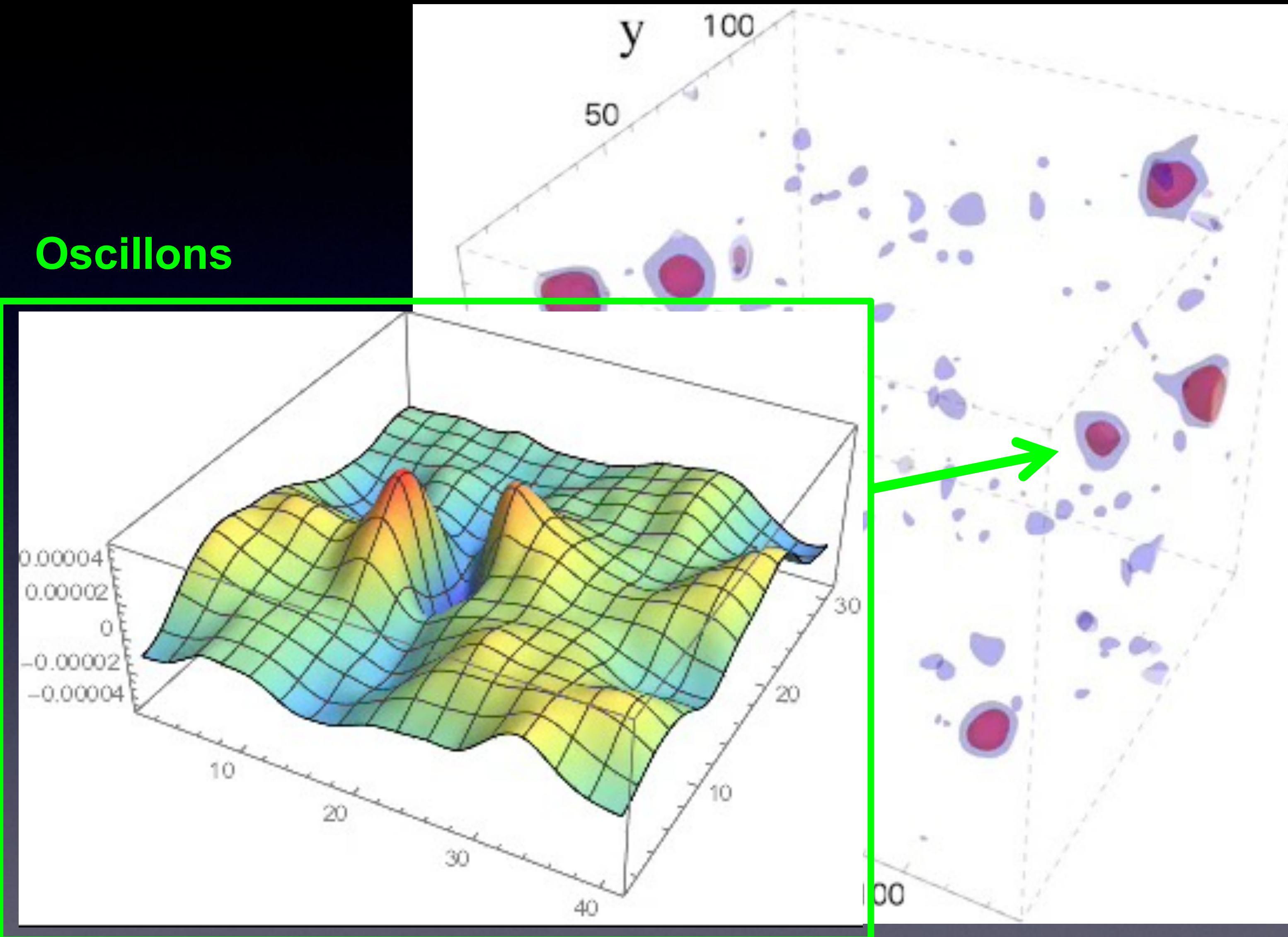




Movie from lattice simulations after hilltop inflation ...

Teaser – Oscillons after inflation ...

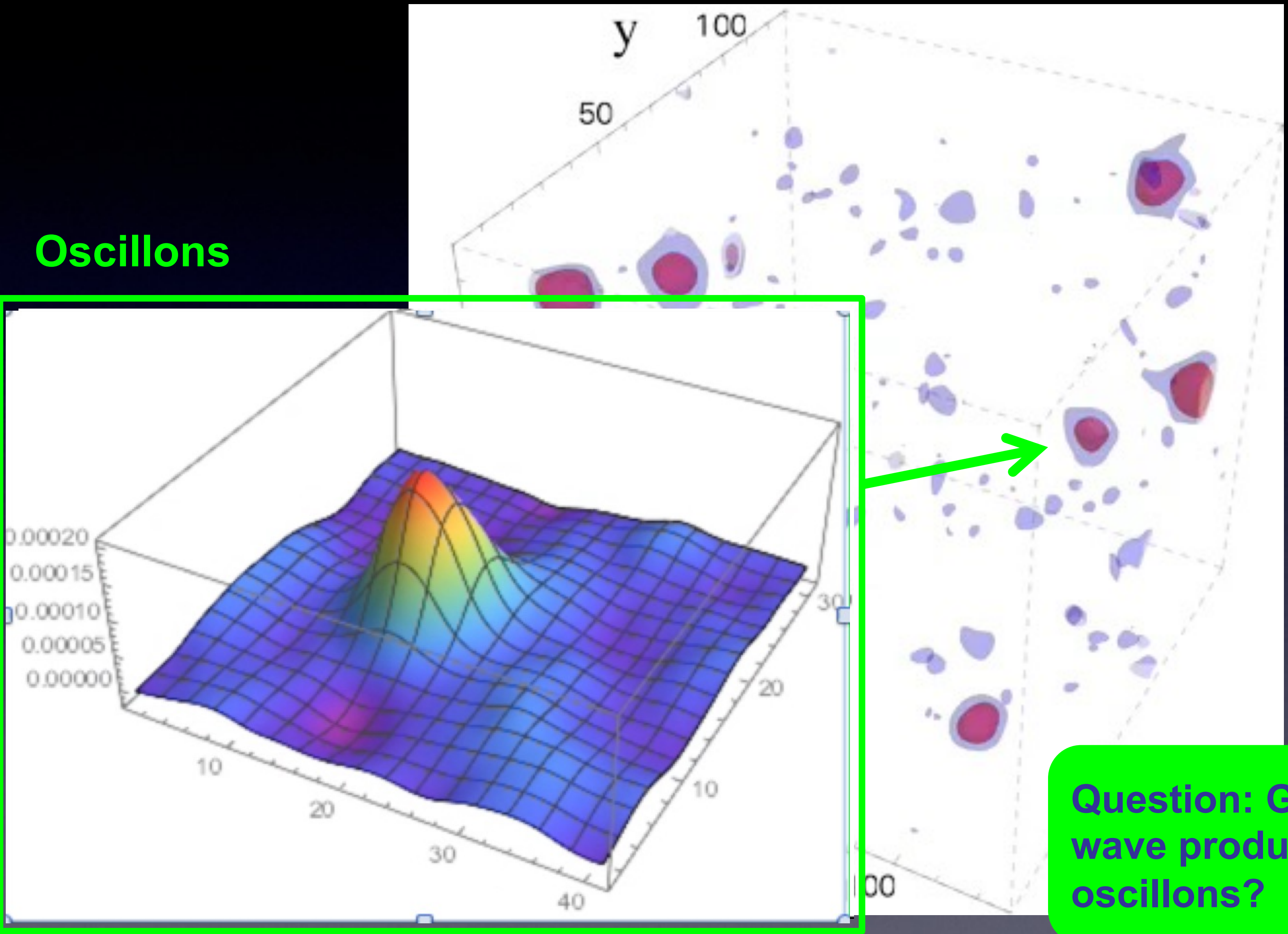
Oscillons



Movie: Single oscillon

Teaser – Oscillons after inflation ...

Oscillons



Question: Gravitation wave production by the oscillons?

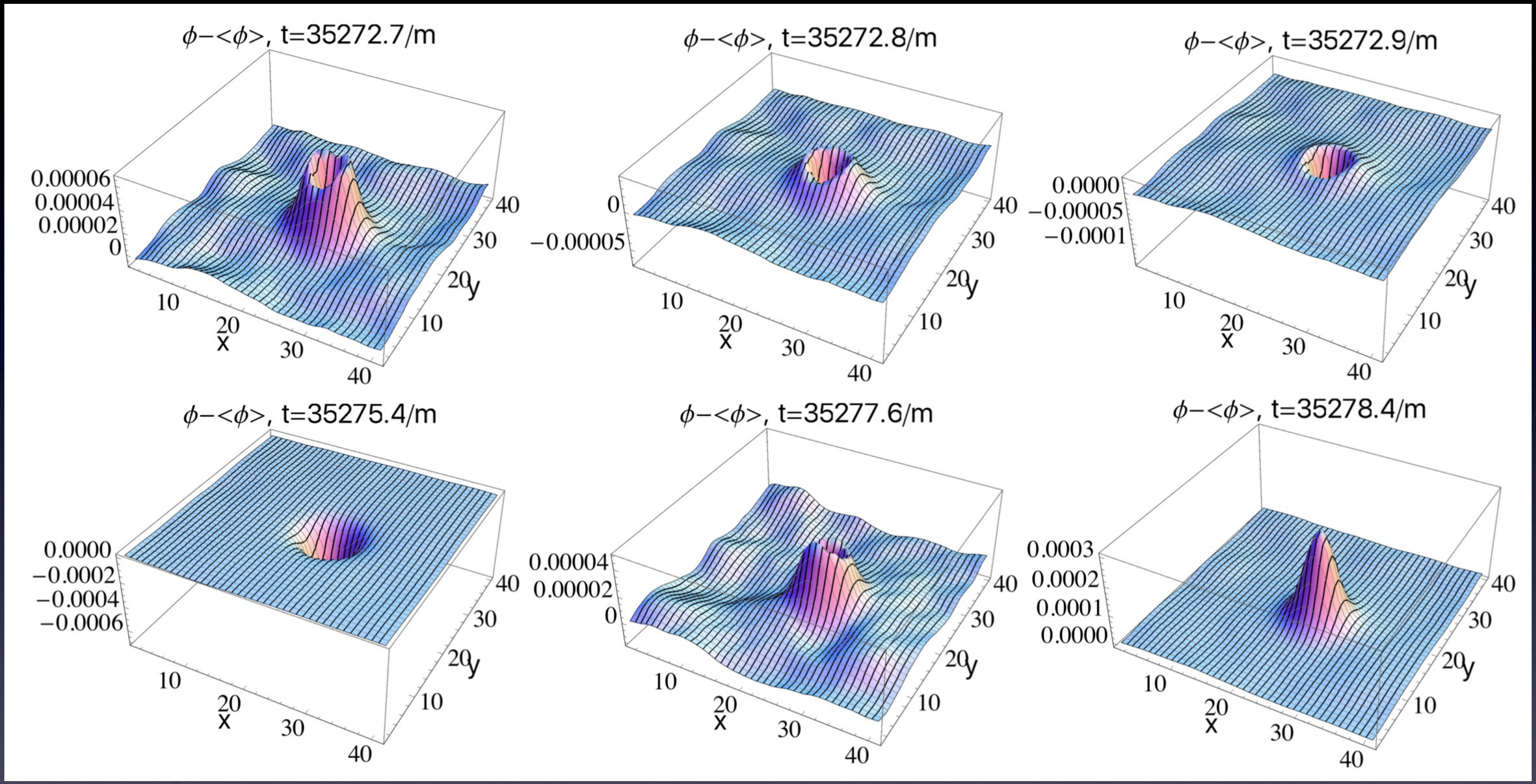
Movie: Single oscillon

Outline

- What are oscillons?
- How do they form? Example: Preheating after “hilltop inflation” (later also other examples, e.g. in KKLT scenario, …)
- Gravitational wave production from asymmetric oscillons (→ part of the stochastic GW background from preheating)
- Results of simulations and open questions …

What are oscillons?

- Spatially localized, oscillatory field configurations with large amplitude



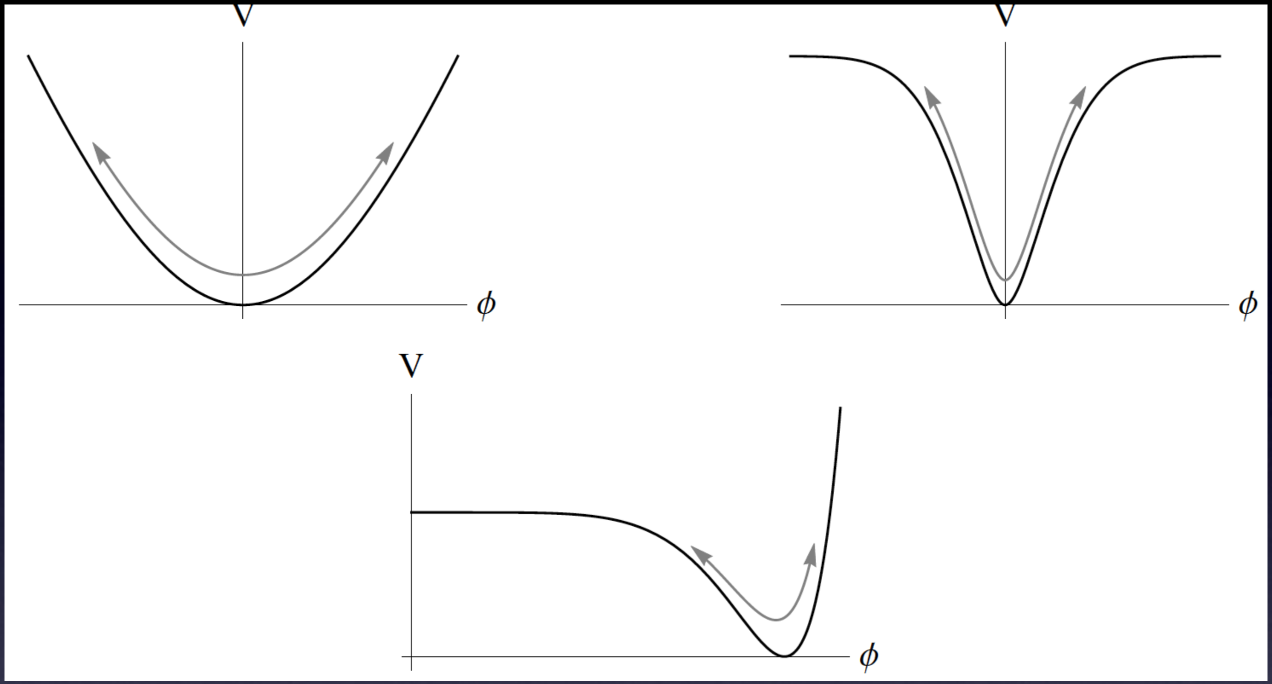
Characteristics:

- Can be quite long-lived ➔ can survive many thousands of oscillations!
- Radiate energy ➔ live long but not forever!

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

- Often tend to be spherical (with some deformations) ➔ depends on potential!

When do oscillons form?



Oscillon formation:

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

See e.g.: Copeland, Gleiser, Muller (‘95), Amin et al. (’11), …

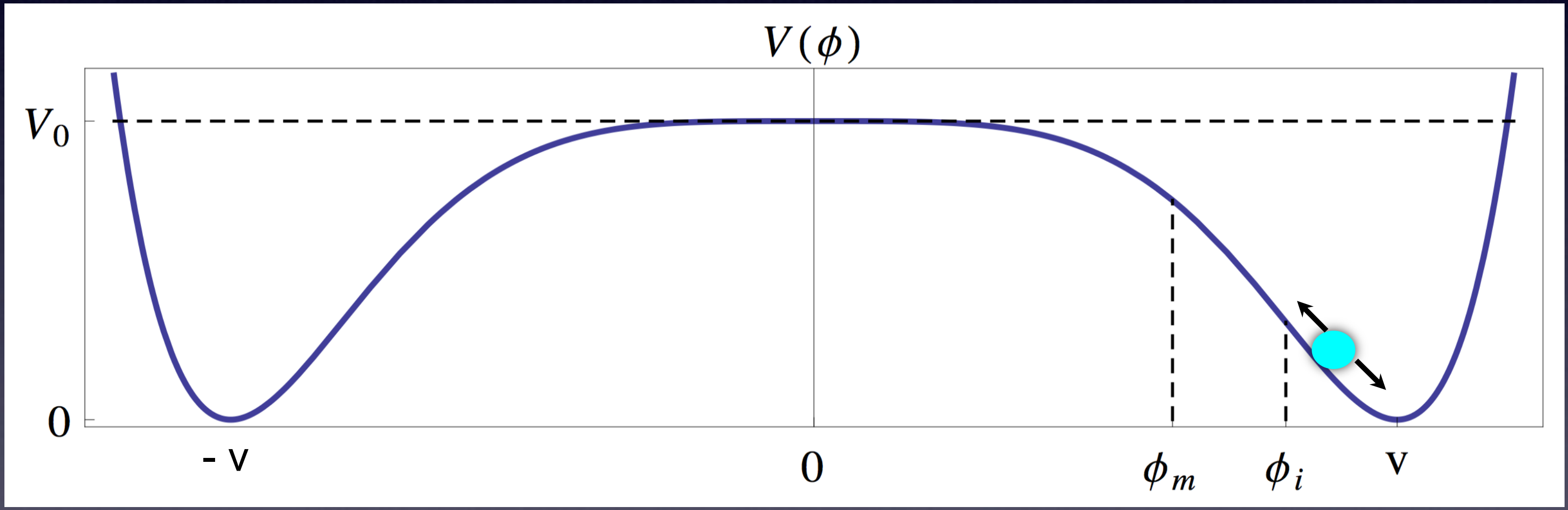
- Necessary condition ➔ potential must be shallower than quadratic around the minimum for some ΔΦ!
- They can form efficiently during the non-linear oscillatory phase (i.e. during preheating) after inflation!

Preheating and oscillon formation after small-field hilltop inflation

Preheating:

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

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



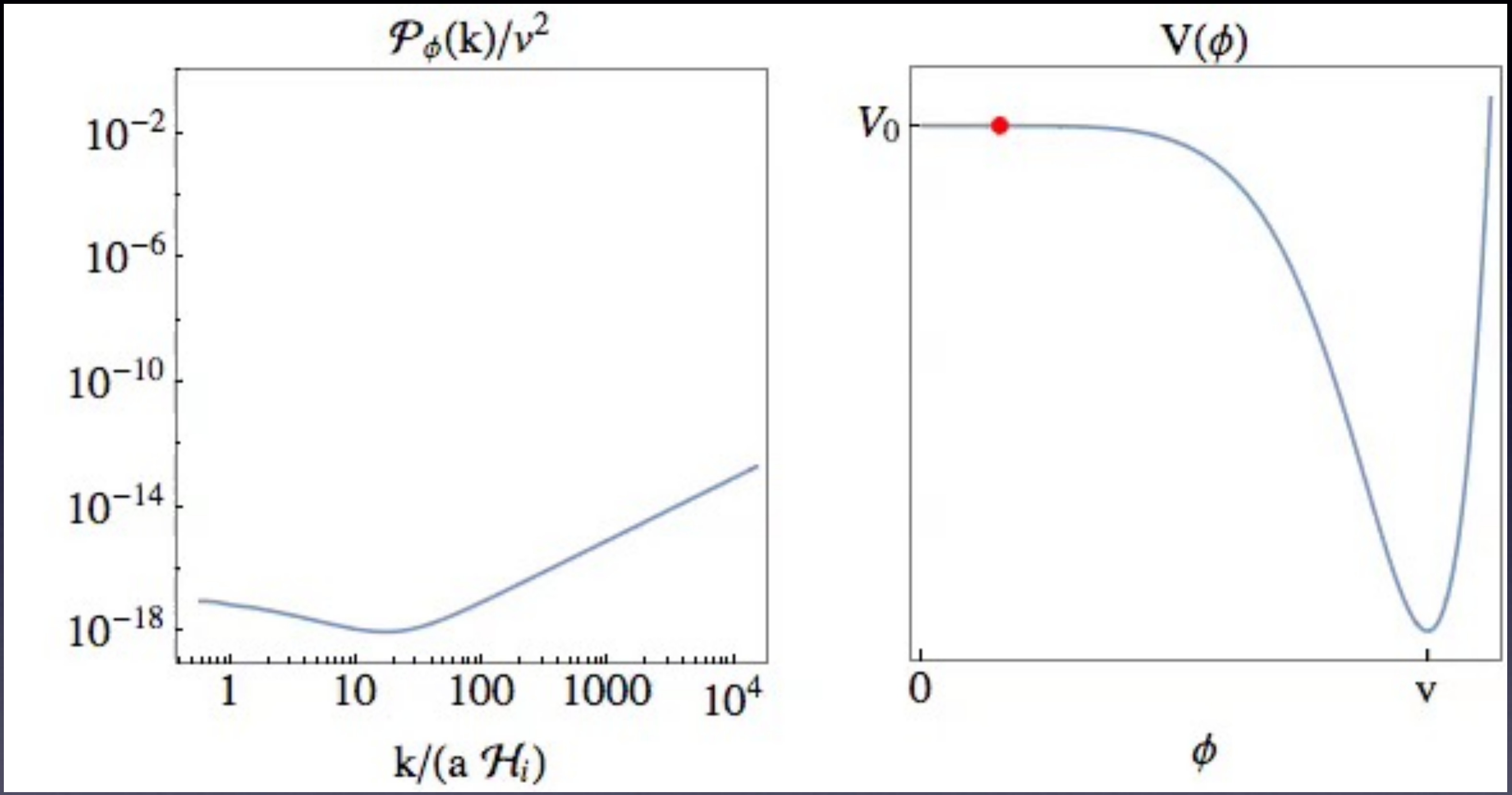
Simple Model:

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

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

Phases I and II: linear analysis

Linearized equations ... p=6



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

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

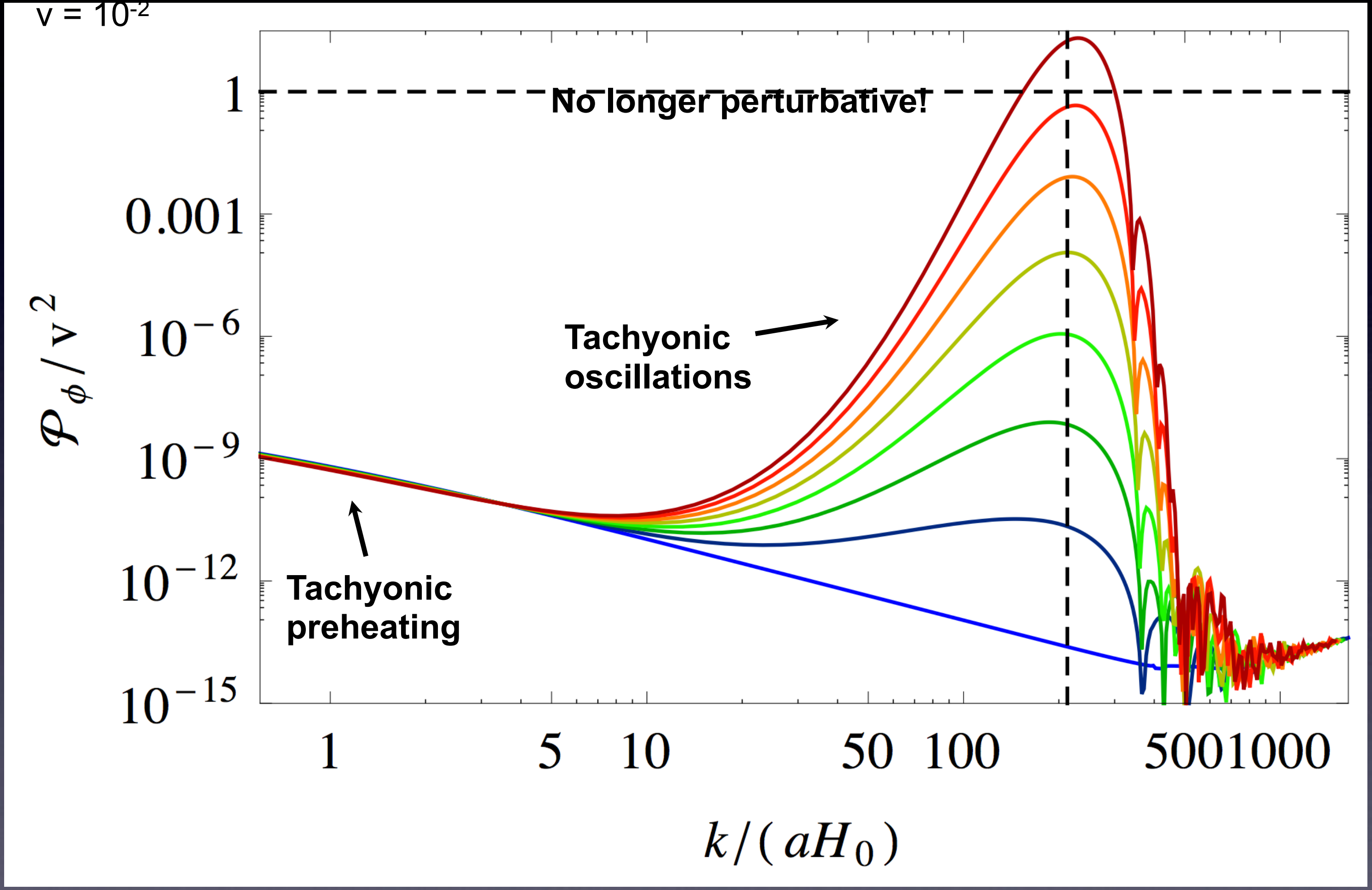
from solving the mode equation

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left(V''(\bar{\phi}) + \frac{k^2}{a^2}\right)\phi_k = 0$$

with Bunch-Davis vacuum at very early times

Phases I and II: linear analysis

Linearized equations ... p=4



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

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

Analysis of preheating: inhomogeneous field equations on the lattice

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

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

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

In addition we calculate the produced gravitational waves, using the TT part Π^{TT}_{ij} of the anisotropic stress tensor on the lattice as source: $\Pi_{ij}^{\rm TT} = [\partial_i\phi\partial_j\phi]^{\rm TT}$

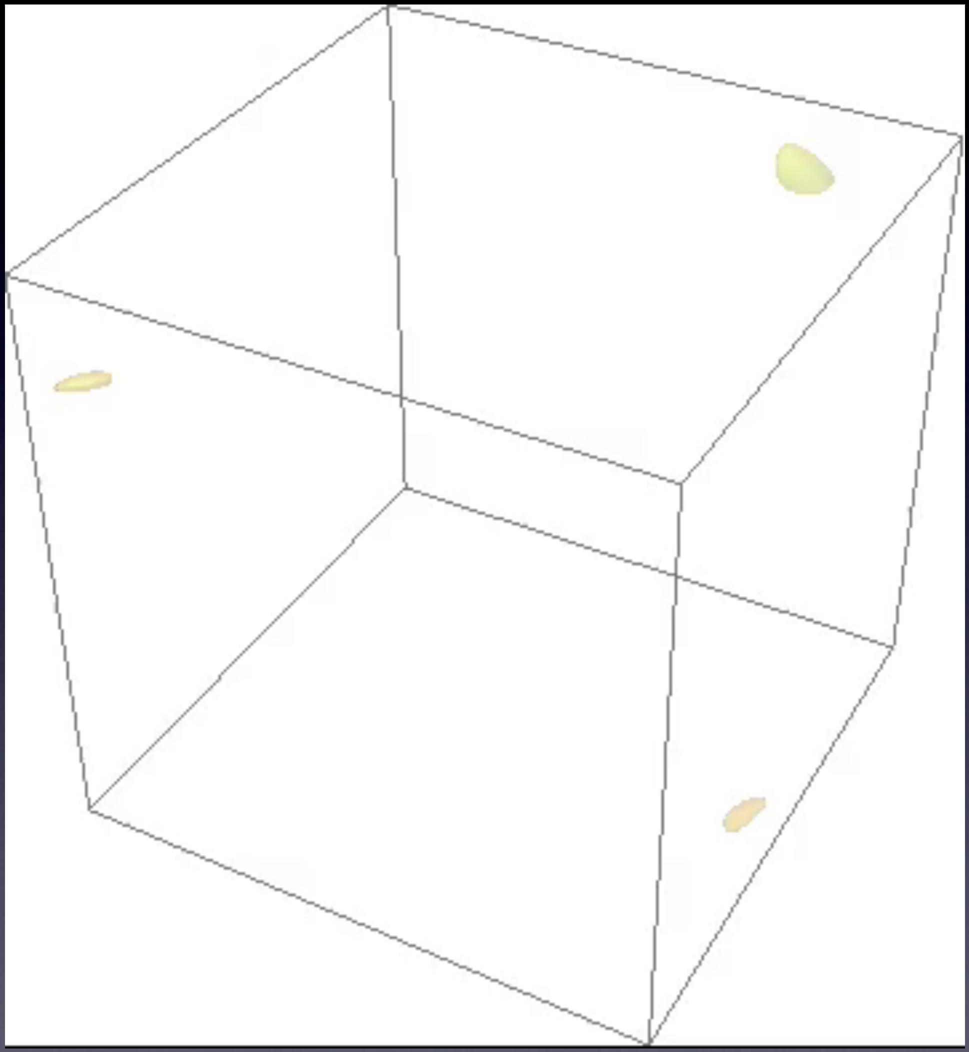
$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = \frac{2}{m_{\rm Pl}^2 a^2}\Pi_{ij}^{\rm TT}$$

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

$v = 10^{-2}$

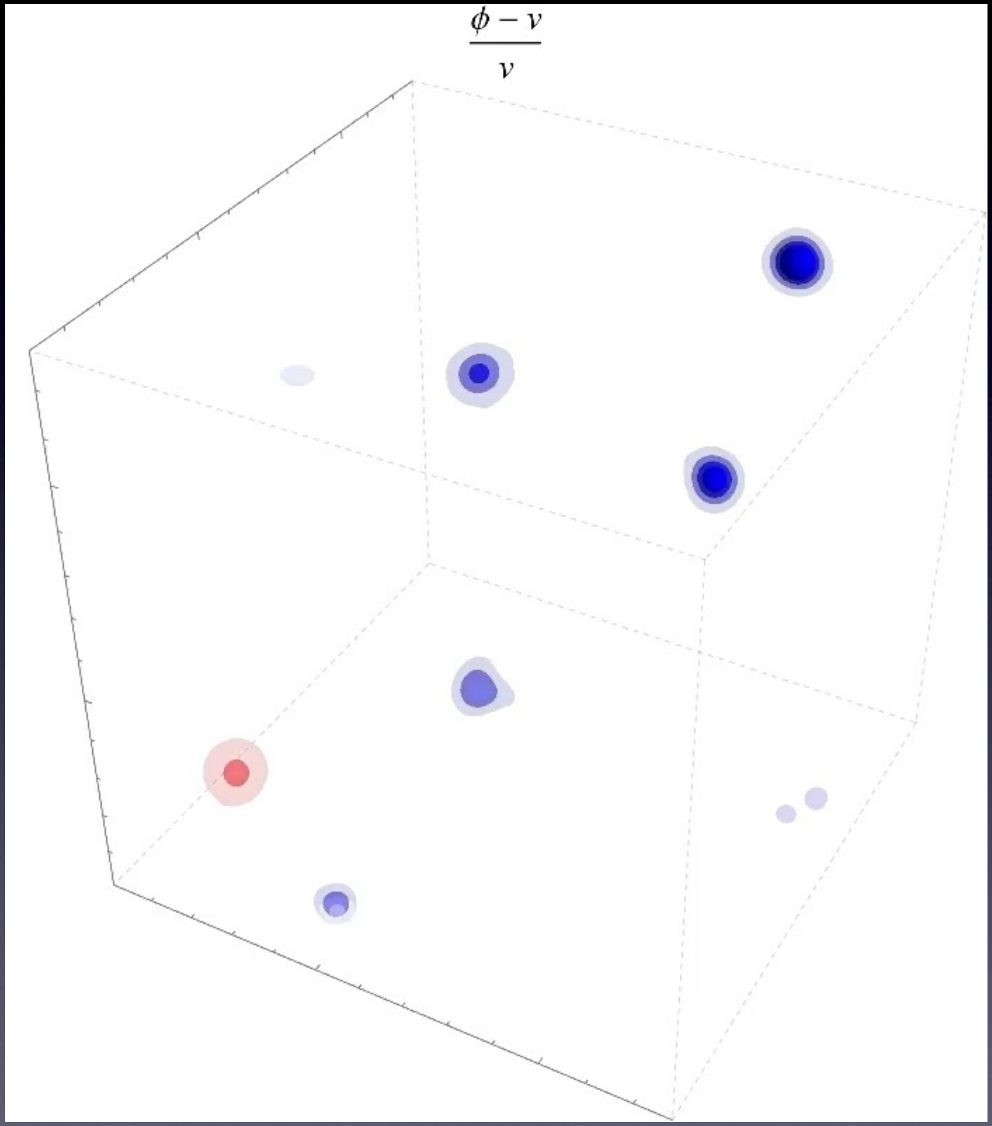
Colored regions: Overshooting to "wrong" vacuum;
yellow: $\Phi <\approx 0$
blue: $\Phi << 0$

Movie from lattice simulations after hilltop inflation ...

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

Later stage: "quasi-stable" oscillons

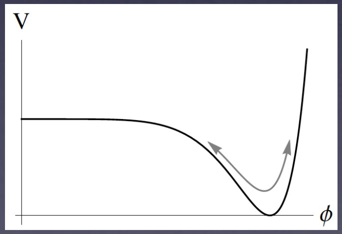
... Long-lived, for many thousands of oscillations



3D lattice simulation

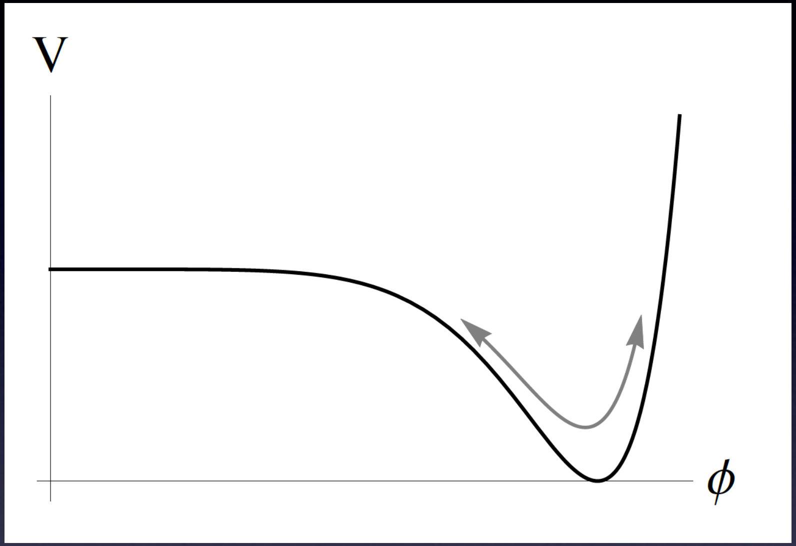
v = 10^{-1}

Colors:
field values larger or smaller than v:
red: Φ > v
blue: Φ < v



↑
v

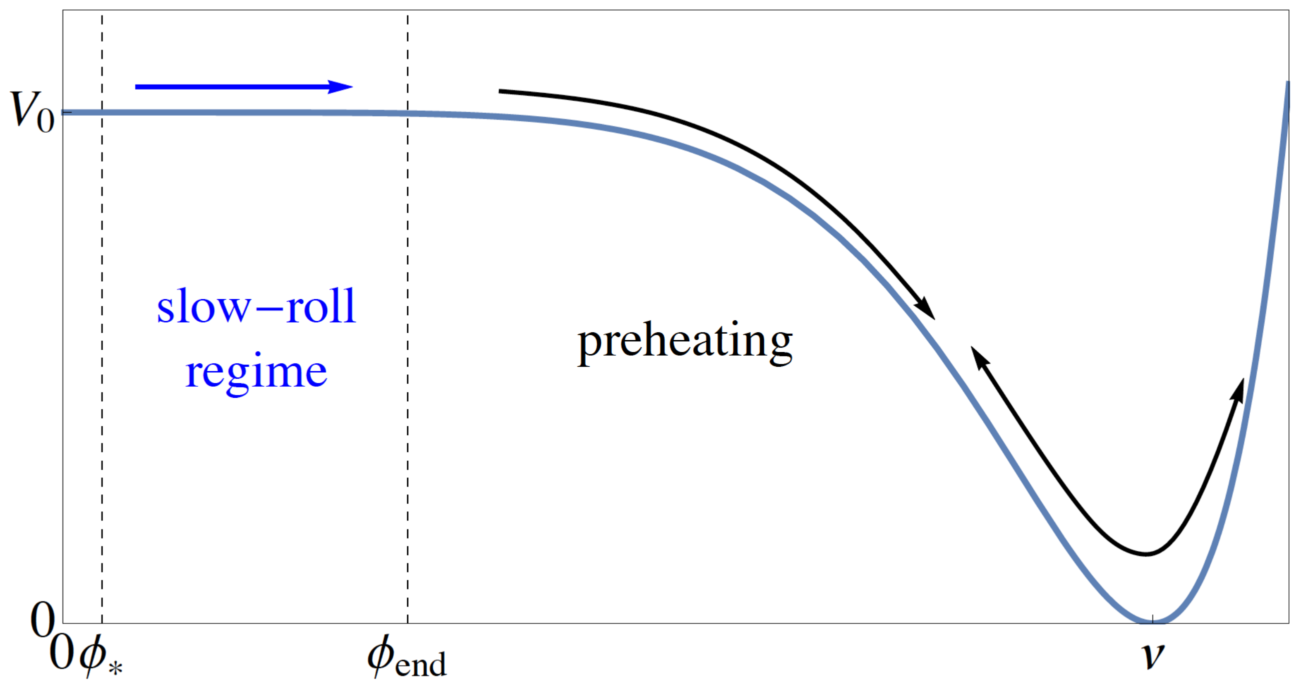
Potentially observable effects from oscillons



- Modify dynamics of preheating and expansion history ➔ affect equation of state (and thus the inflationary predictions), ...
- **Production of stochastic gravitational wave background (from oscillon production, oscillations of asymmetric oscillons, oscillon decay)**

Example: GW from oscillons after single field hilltop inflation

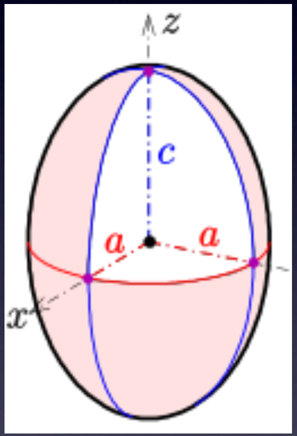
$$V(\phi) = V_0 \left(1 - \frac{\phi^p}{v^p}\right)^2 , \qquad v \ll m_{\rm Pl} \text{ “small-field hilltop”}$$



<u>Challenge for lattice simulations</u>: High resolution and accuracy needed in oder to resolve oscillons properly.
Numerical limits: Only rather early times can be simulated ...

First look: GW from oscillations of asymmetric oscillons in a semi-analytical treatment

Simulation: We assume **a single ellipsoidal (spheroidal) oscillon with Gaussian shape as GW (fixed) source in an expanding universe** ...



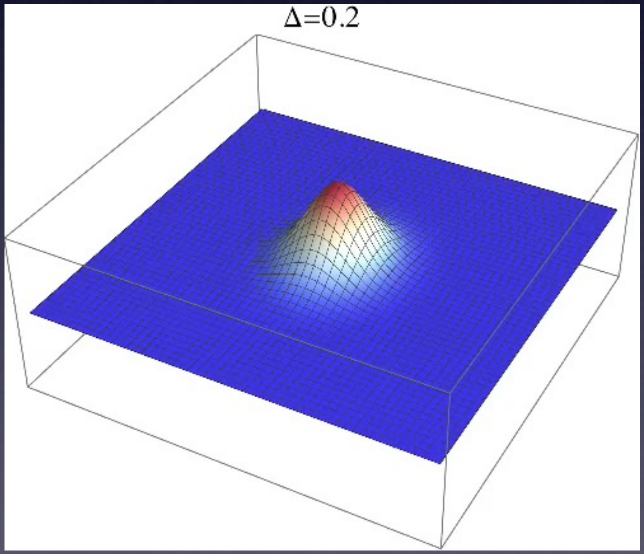
Oscillon parameters from lattice simulations (at some early time):

- **Size, Amplitude** (with approximation: **Gaussian profile**)
- **Oscillation dynamics** from homogeneous solution in exp. background → ϕ**(t)**
- **Number** (per comoving volume): **N**/V (assumed constant) from lattice simulation
- **Asymmetry:** Δ (assumed constant for first look, defined: **c = a (1 +** Δ**)**)

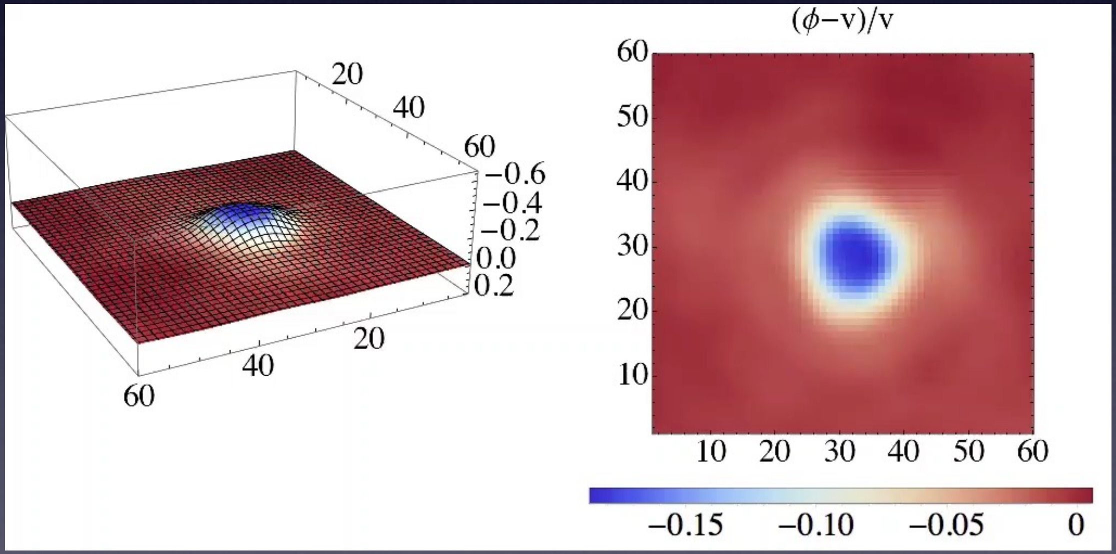
First look: GW from oscillons in a semi-analytical treatment

Simulation: We assume a single ellipsoidal (spheroidal) oscillon with Gaussian shape as GW (fixed) source in an expanding universe ...

Approximation (in our semi-analytical treatment)



" Real Oscillon": Oscillon from lattice simulations



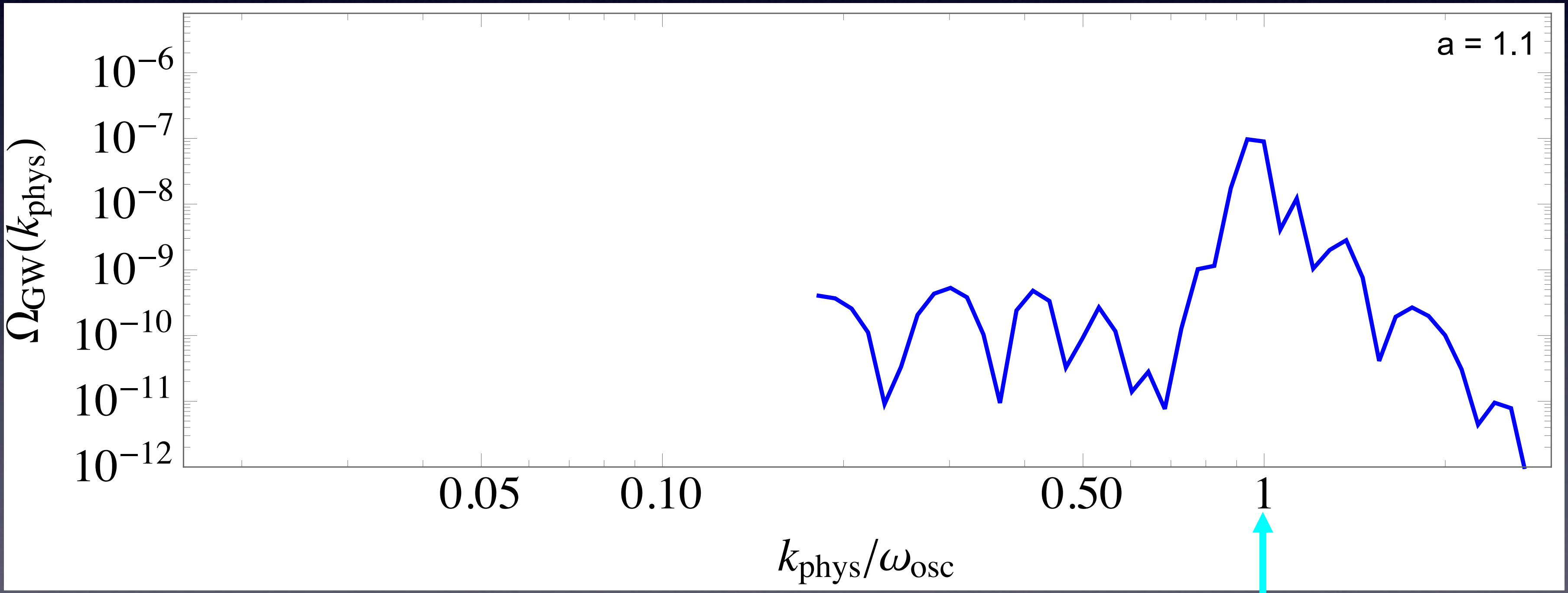
GW from oscillons after single field hilltop inflation

Semi-analytical first look ... parameters similar to hilltop inflation

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

With p = 6, v = 10^{-2},
V_0 = fixed from CMB,
Δ = 0.1

cf. S.A., F. Cefala, S. Orani, arXiv:1712.03231



Peak at $k_{phys} = \omega_{osc}$ (oscillation frequency of the oscillon)

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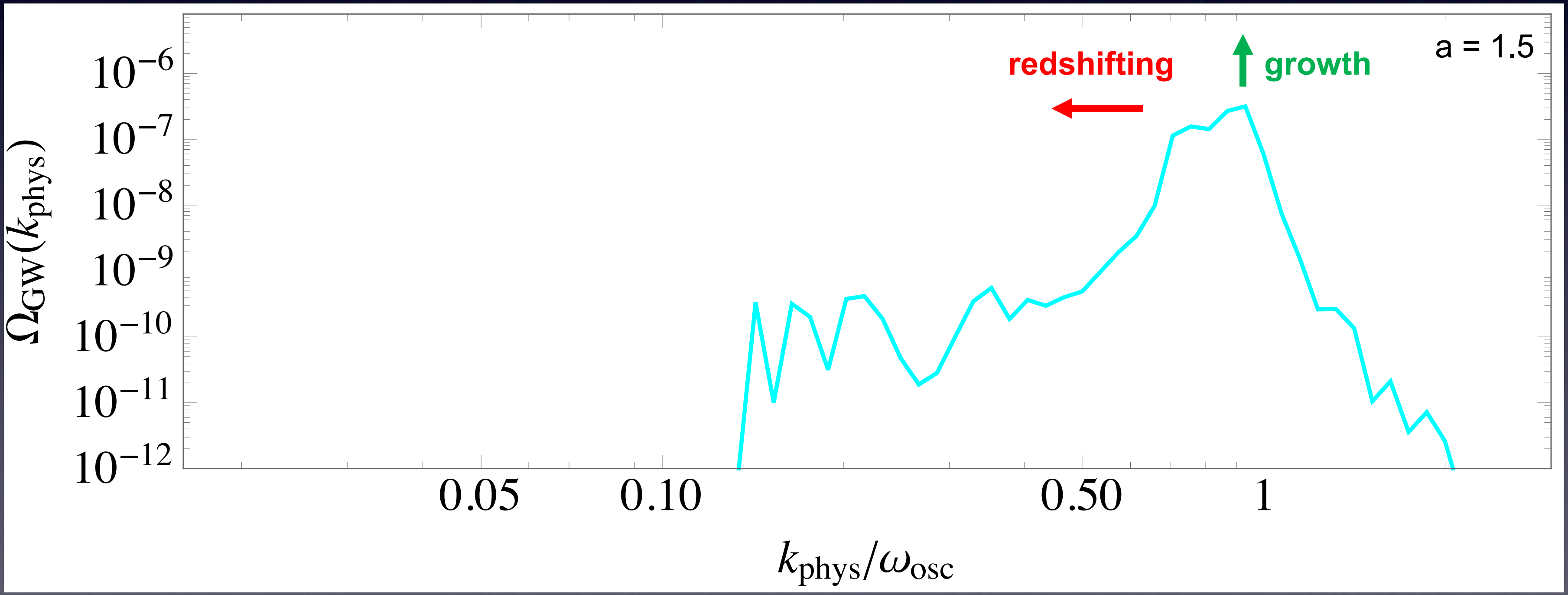
Background: expanding matter-dominated universe ...



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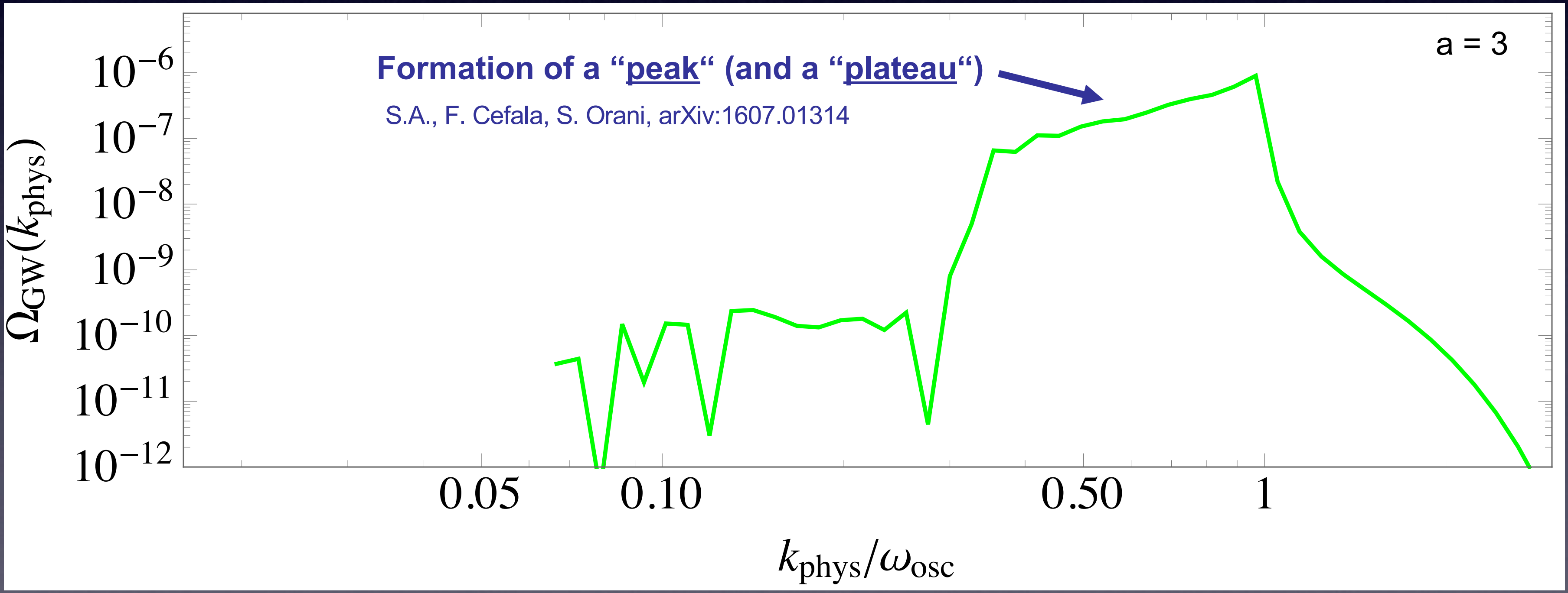

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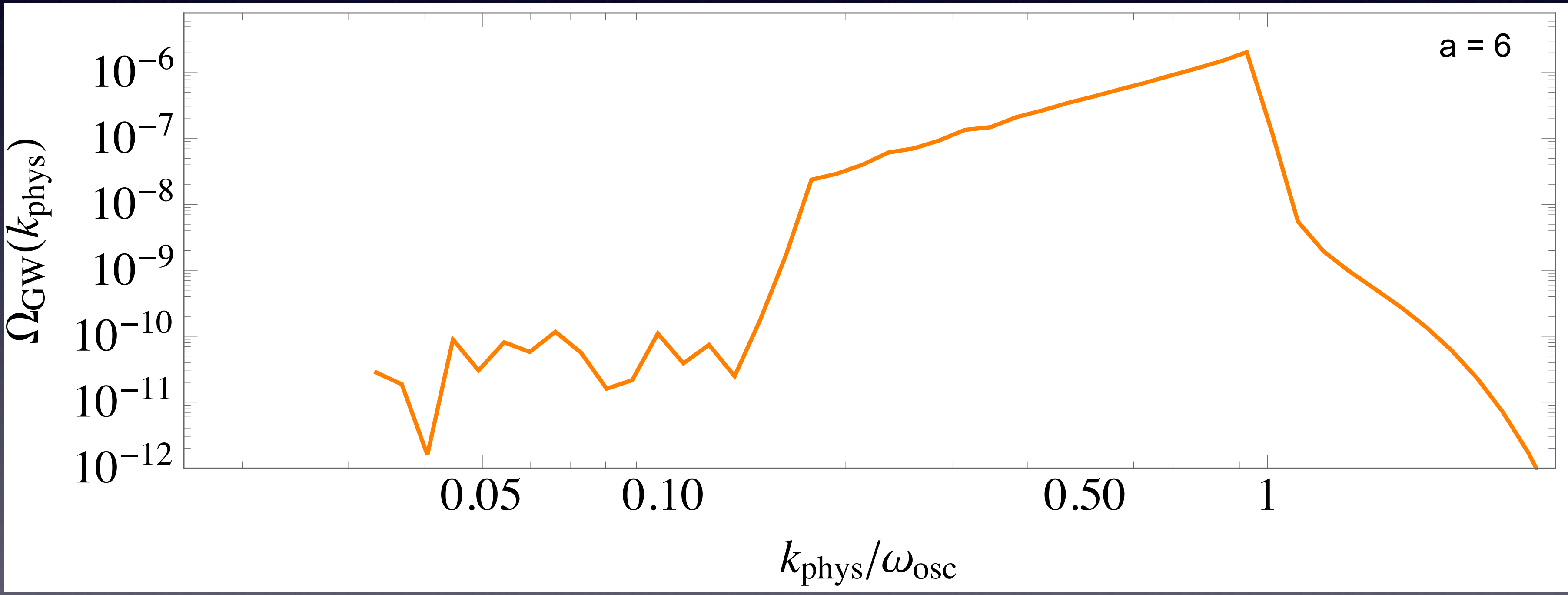

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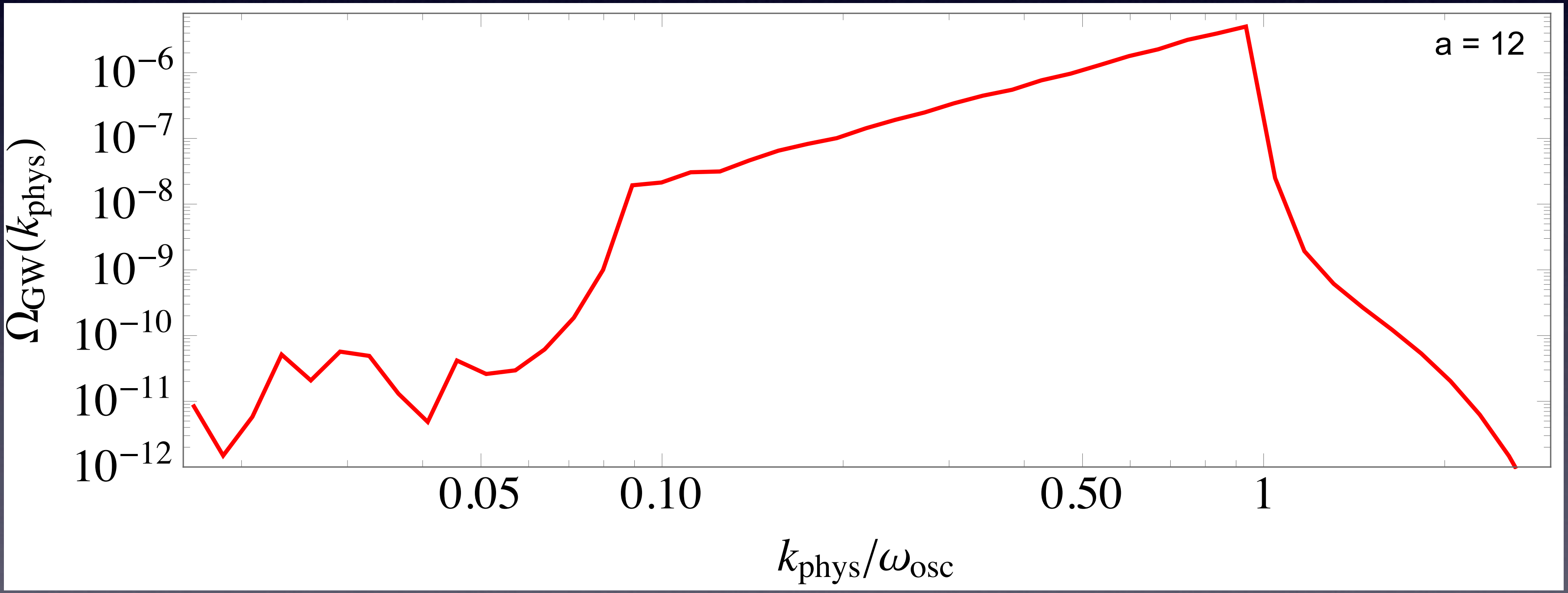

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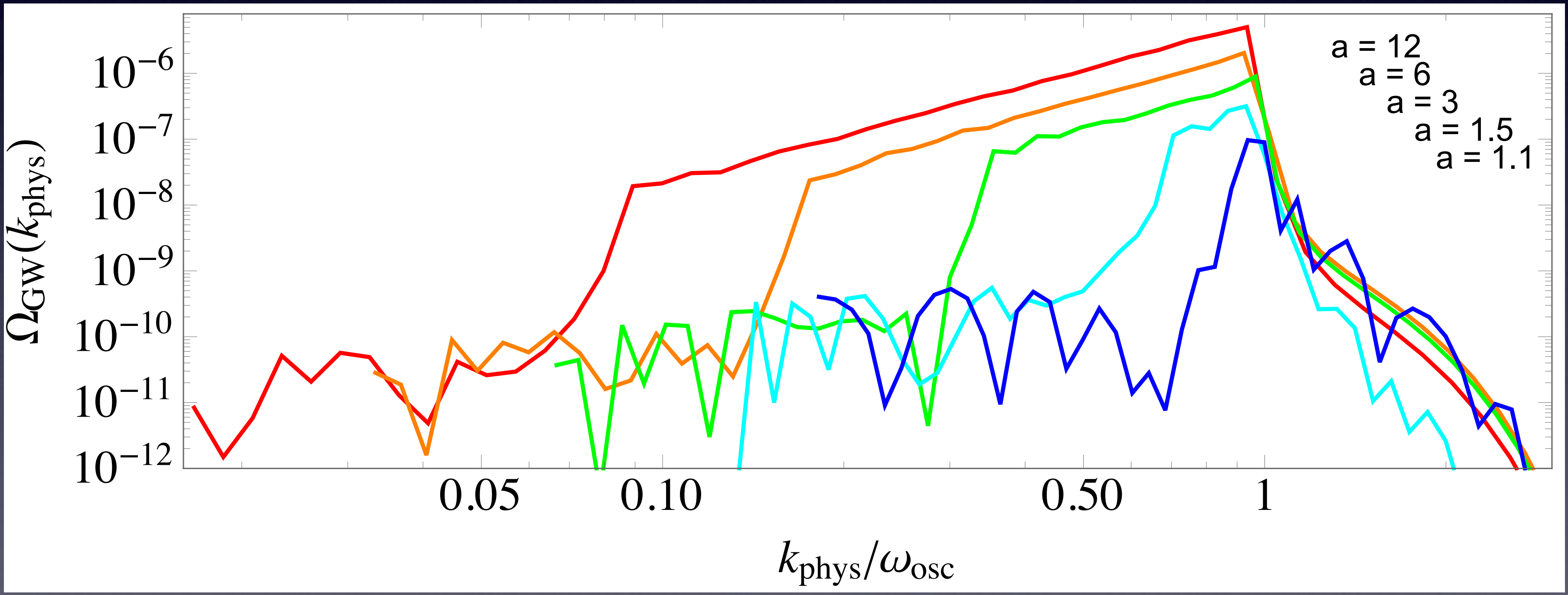

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GW from oscillons after single field hilltop

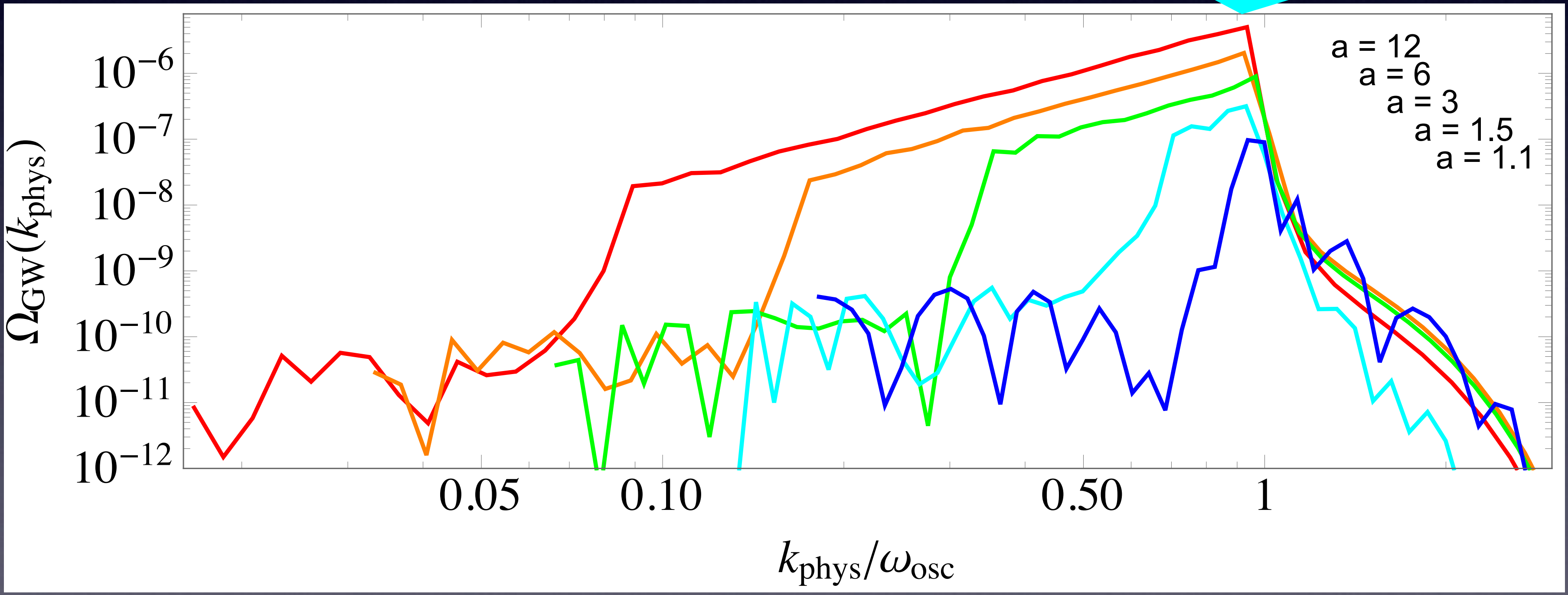
Semi-analytical first look ...

3231

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

Various questions arise e.g.:

Question 1: What is the frequency of the GWs produced during preheating ... ?



Question 1: Frequency of the GWs from preheating?

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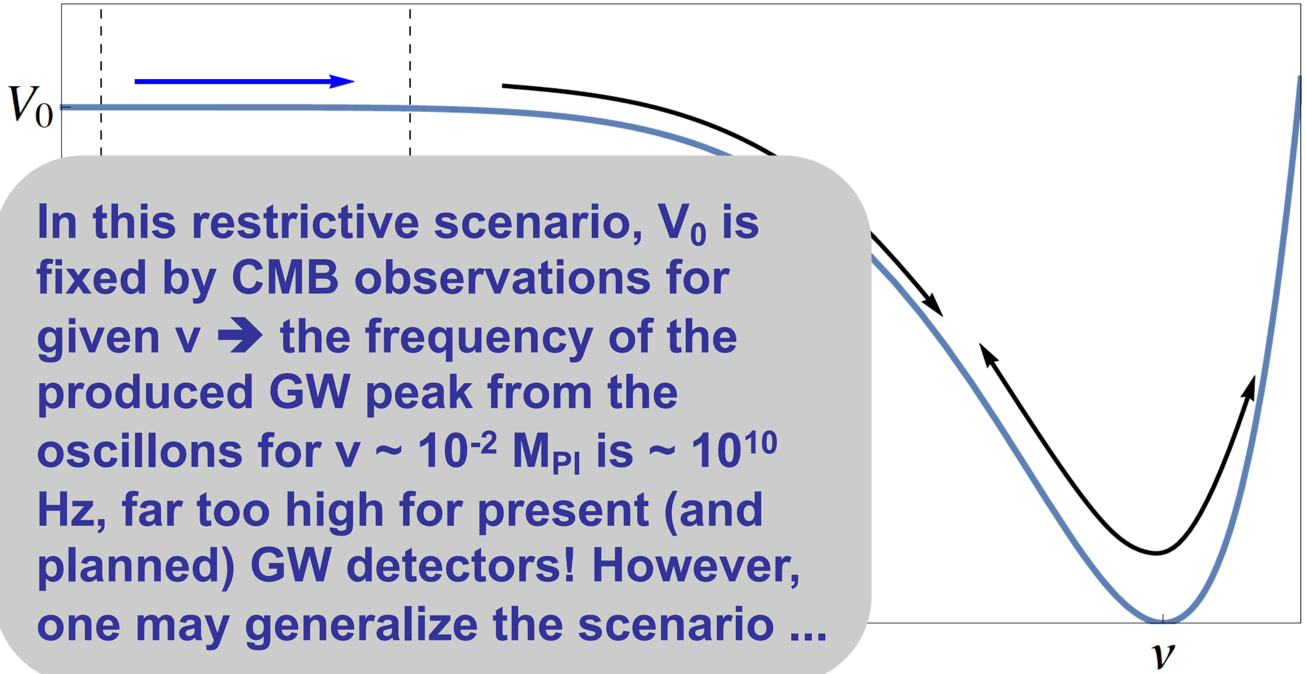


In this restrictive scenario, V_0 is fixed by CMB observations for given v ➔ the frequency of the produced GW peak from the oscillons for v ~ 10^{-2} M_{Pl} is ~ 10^{10} Hz, far too high for present (and planned) GW detectors! However, one may generalize the scenario ...

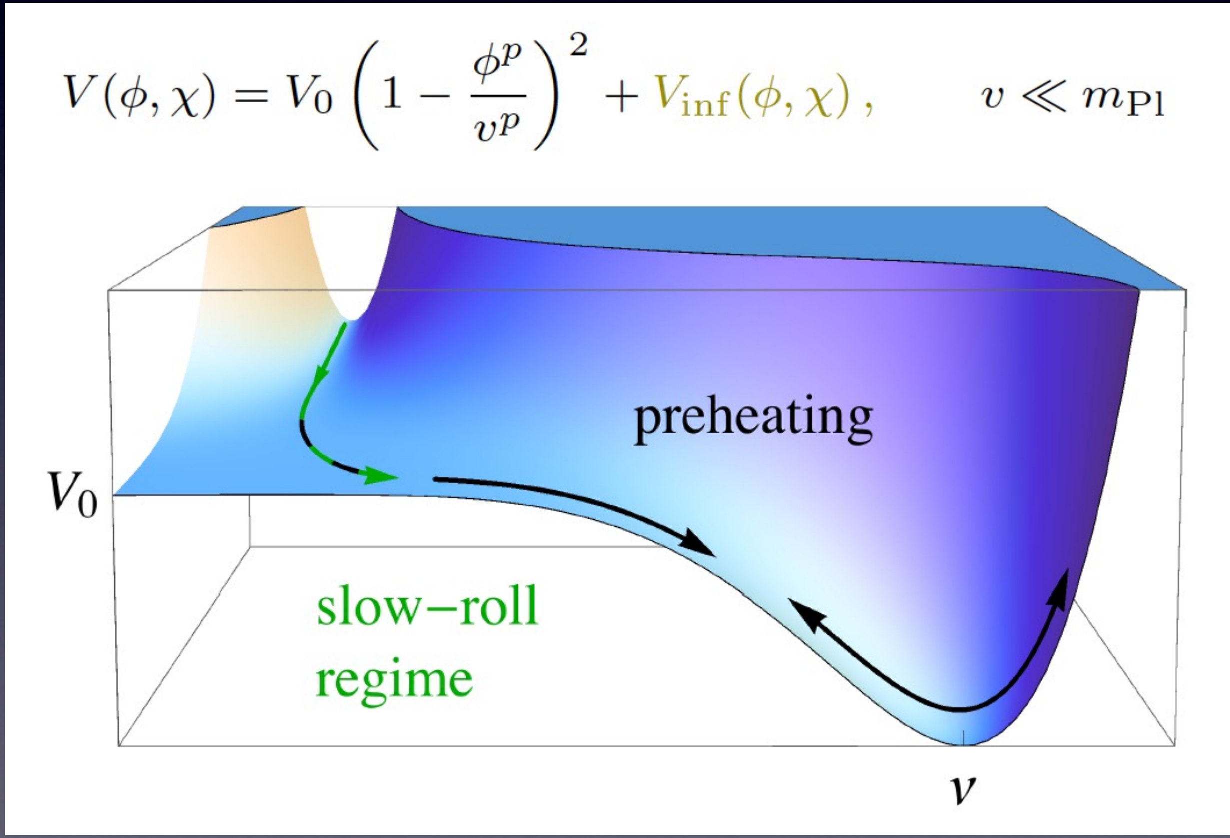
Note: Very restrictive; for given p ≥ 4 and v, V_0 is fixed by CMB observations

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

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

... at the end of inflation
... or even independent of inflation!

- Example: inflation orthogonal to the hill: Low scale "hybrid-like” inflation models

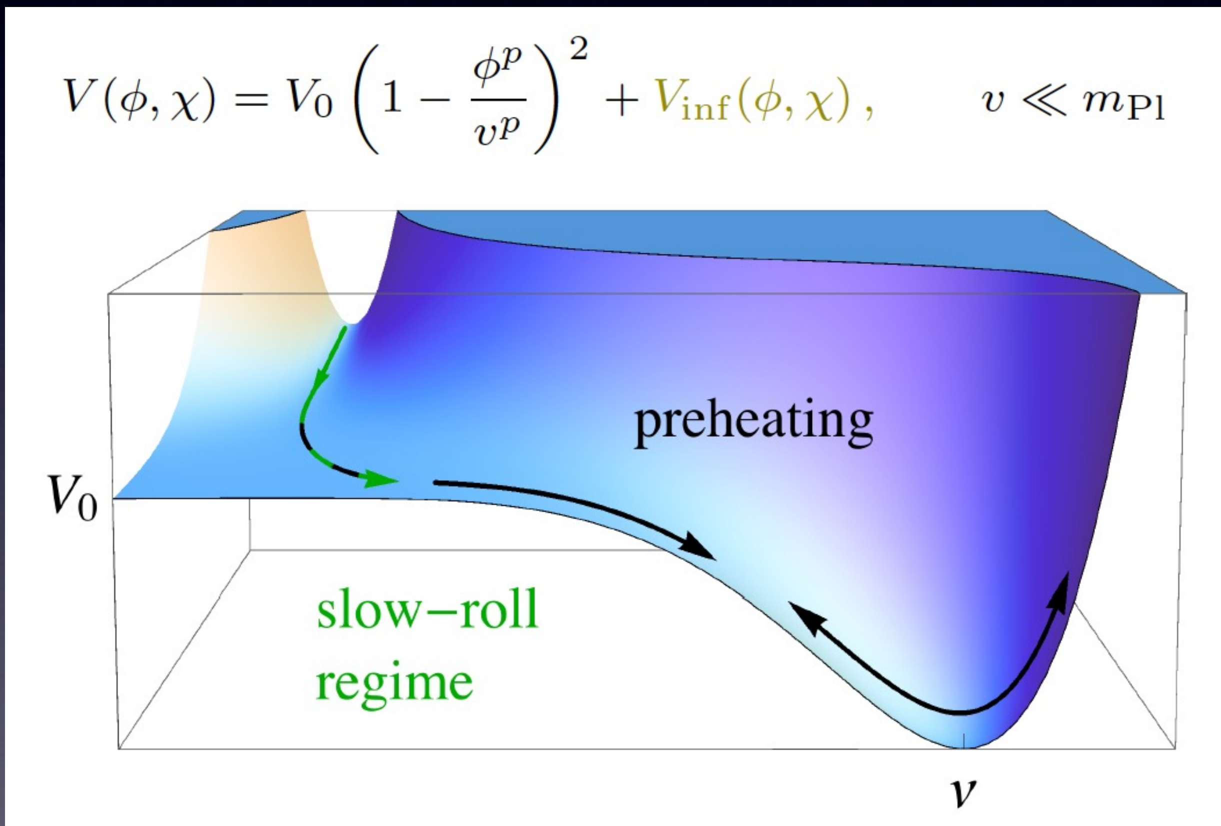


Slow roll inflation:

- Universe inflates as χ rolls along the valley
- Inflation ends by a tachyonic instability in ϕ
- Here: v and V_0 are in principle free parameters … !
- CMB observables from V_{inf}

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

- Example: inflation orthogonal to the hill: Low scale "hybrid-like" inflation models



Preheating (as before!):

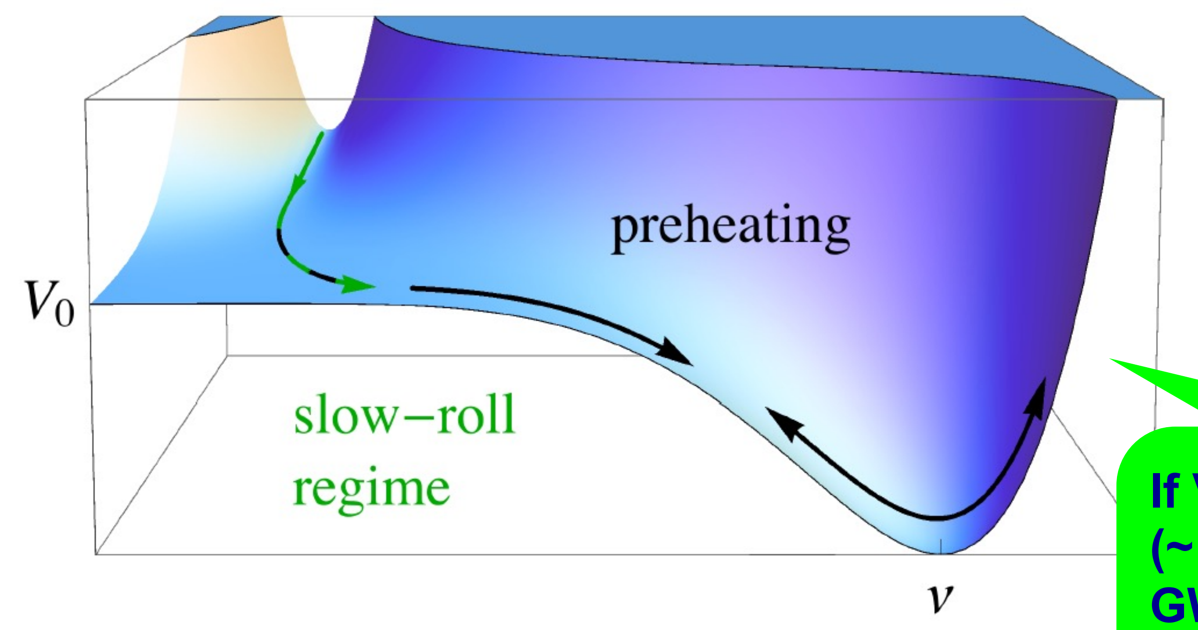
- Typically non-linear, two phases
  - Phase I: Tachyonic preheating (growth of IR modes, most efficient for very small v)
  - Phase II: Tachyonic oscillations: Growth of modes around a certain scale ➔ oscillon formation!

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

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

- Example: inflation orthogonal to the hill: Low scale "hybrid-like" inflation models

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



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

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

If V_0 is in the right range (~ few 100 TeV), then the GW from preheating can be in the observable 1 Hz ... 100 Hz range!

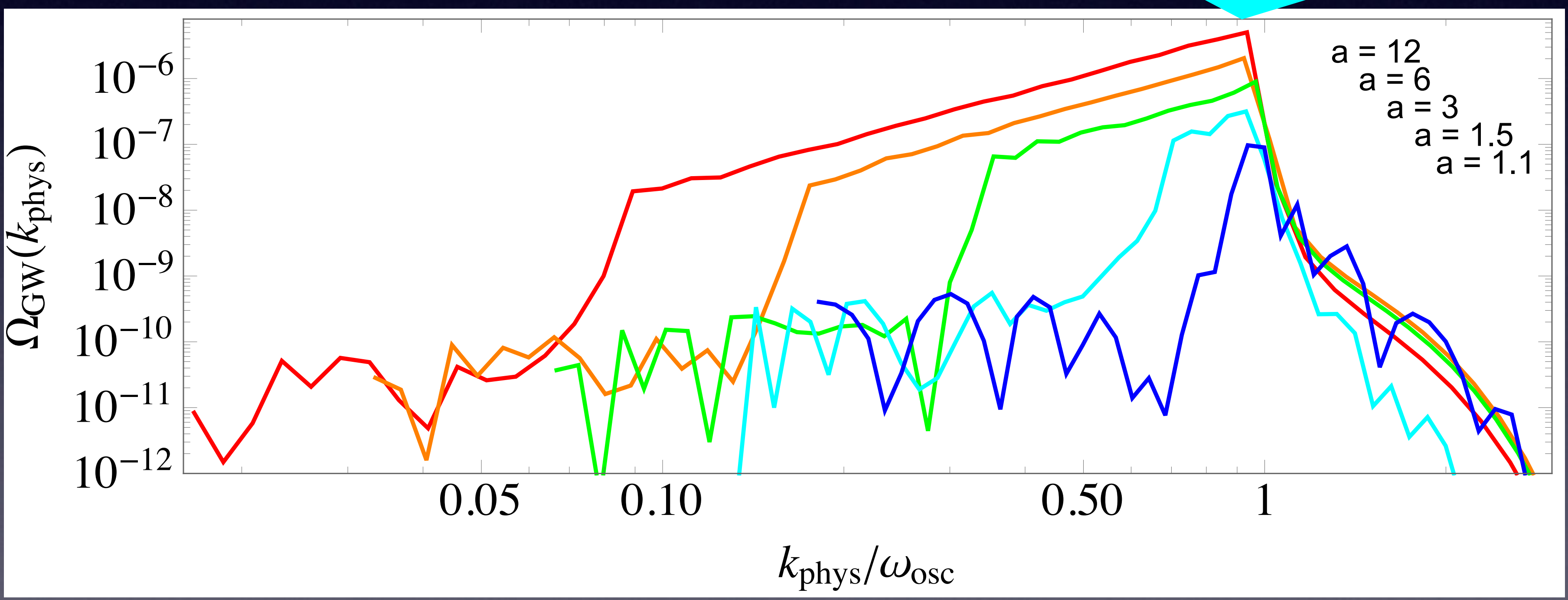
GW from oscillons after single field hilltop

Semi-analytical first look ... 3231

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

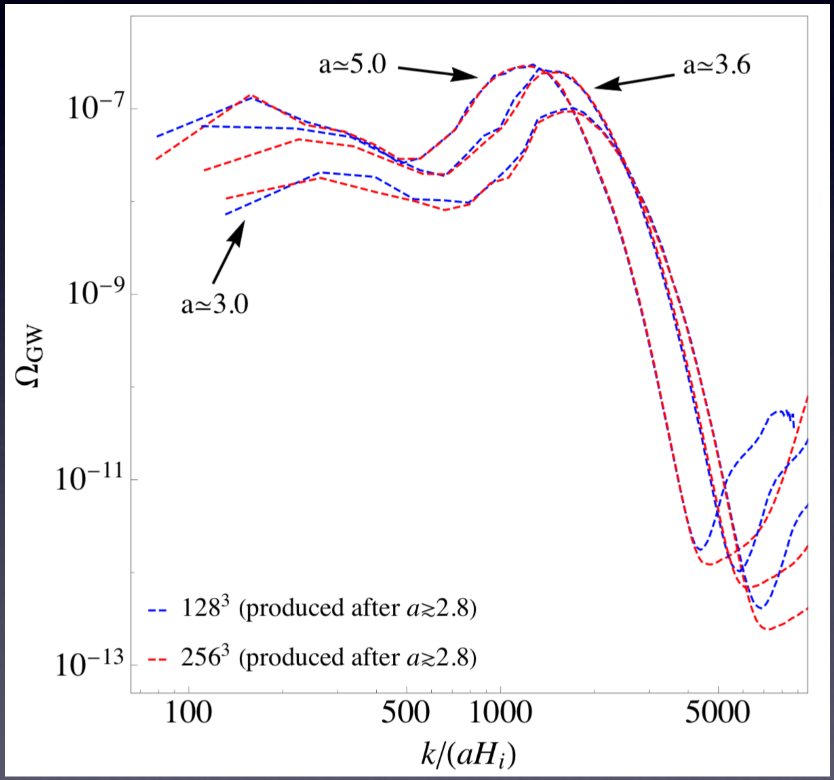
Various questions arise e.g.:

<u>Question 2</u>: Is this GW peak from the oscillons visible under realistic conditions (in this model)?



GW spectrum from lattice simulations after "hilltop inflation" model ...

Only GW from oscillon oscillations (i.e. GW produced after tachyonic oscillation phase)



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

... oscillon GW peak "burried" under large broad peak from tachyonic oscillations

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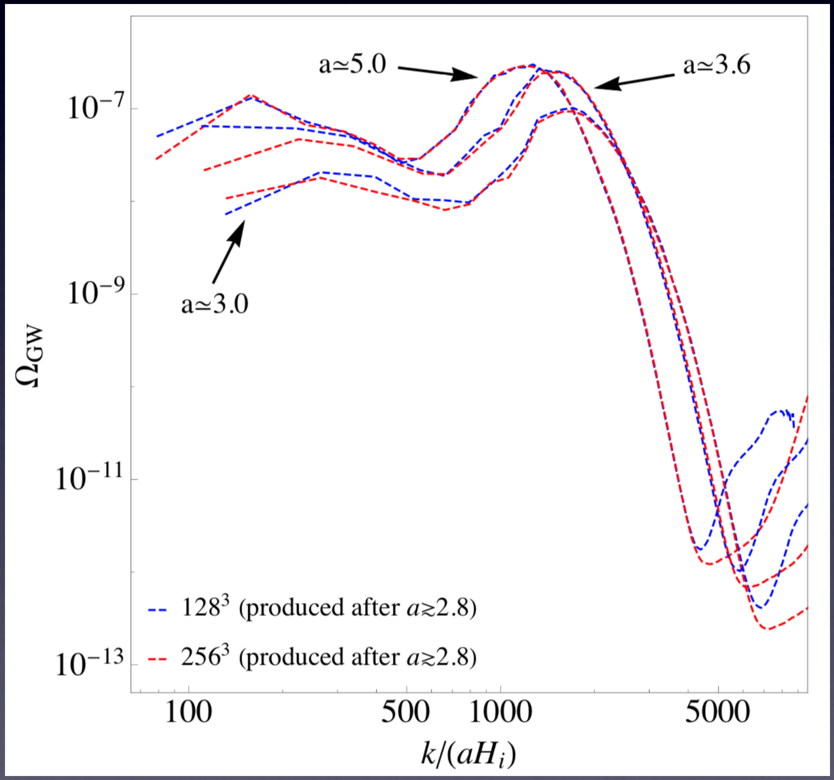
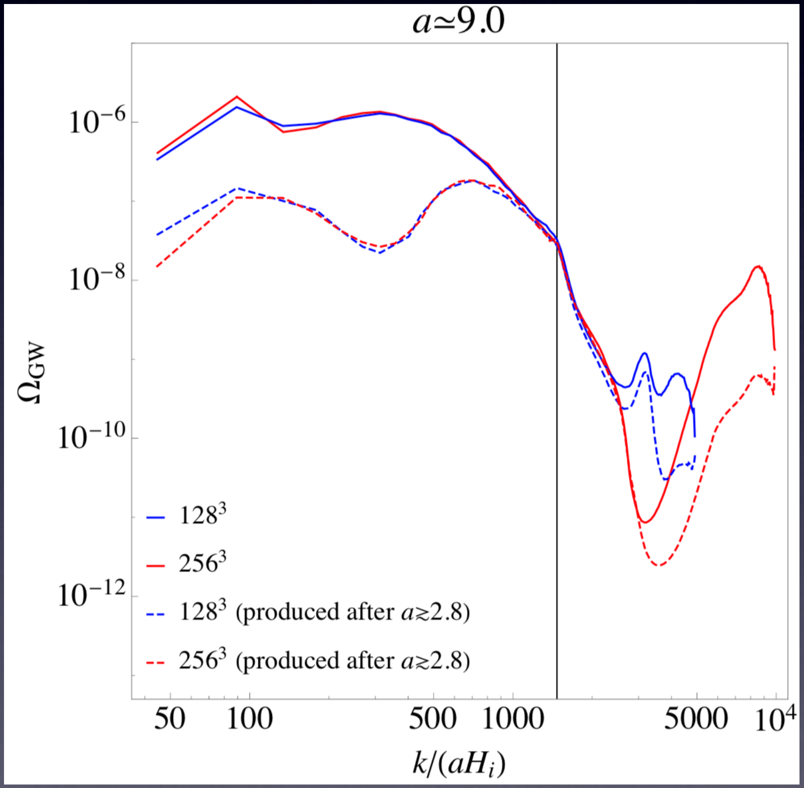


Solid lines: **GW including earlier produced gravitational waves** (from tachyonic preheaing & tachyonic oscillation phase)



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

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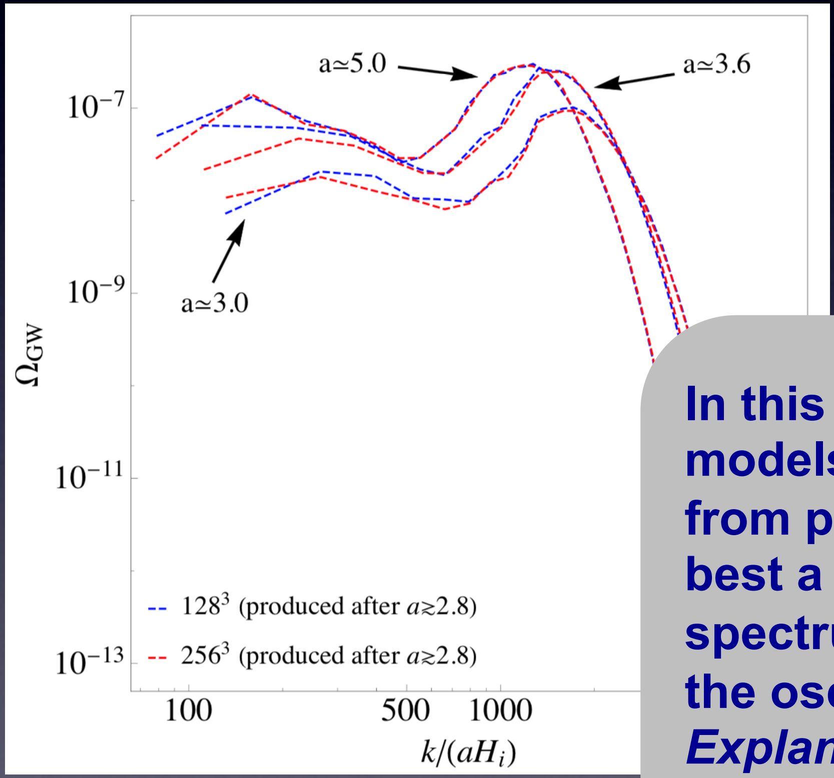

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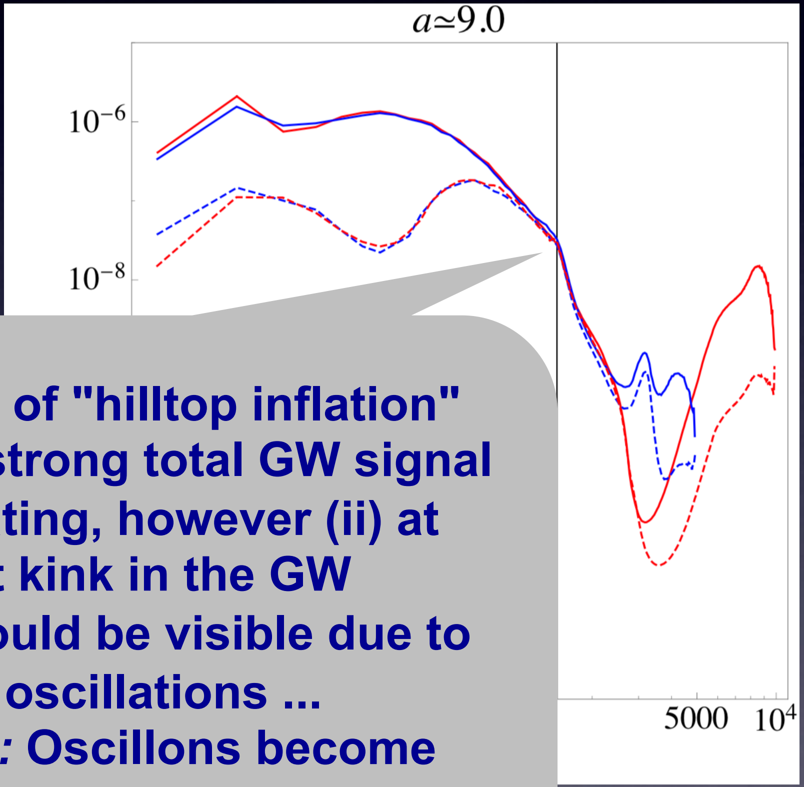
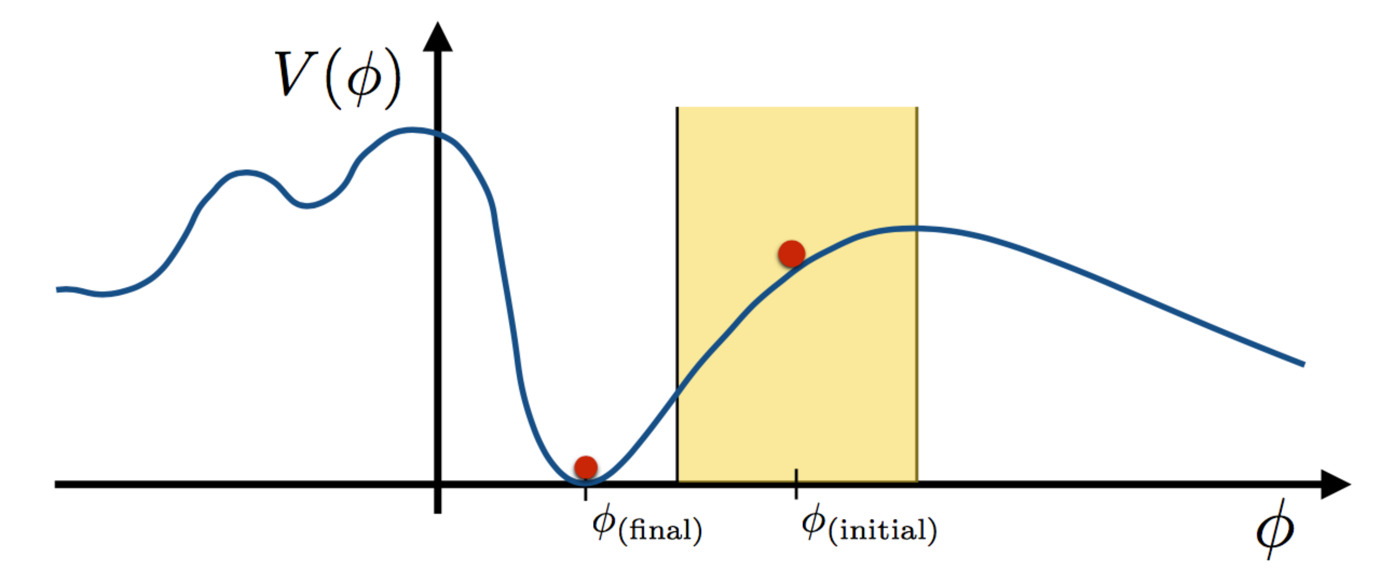


In this class of "hilltop inflation" models: (i) strong total GW signal from preheating, however (ii) at best a slight kink in the GW spectrum could be visible due to the oscillon oscillations ...
Explanation: **Oscillons become quite spherical rather quickly ...**

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

Other scenarios with oscillons (and potentially lower frequency of GWs): Oscillons from string moduli ...

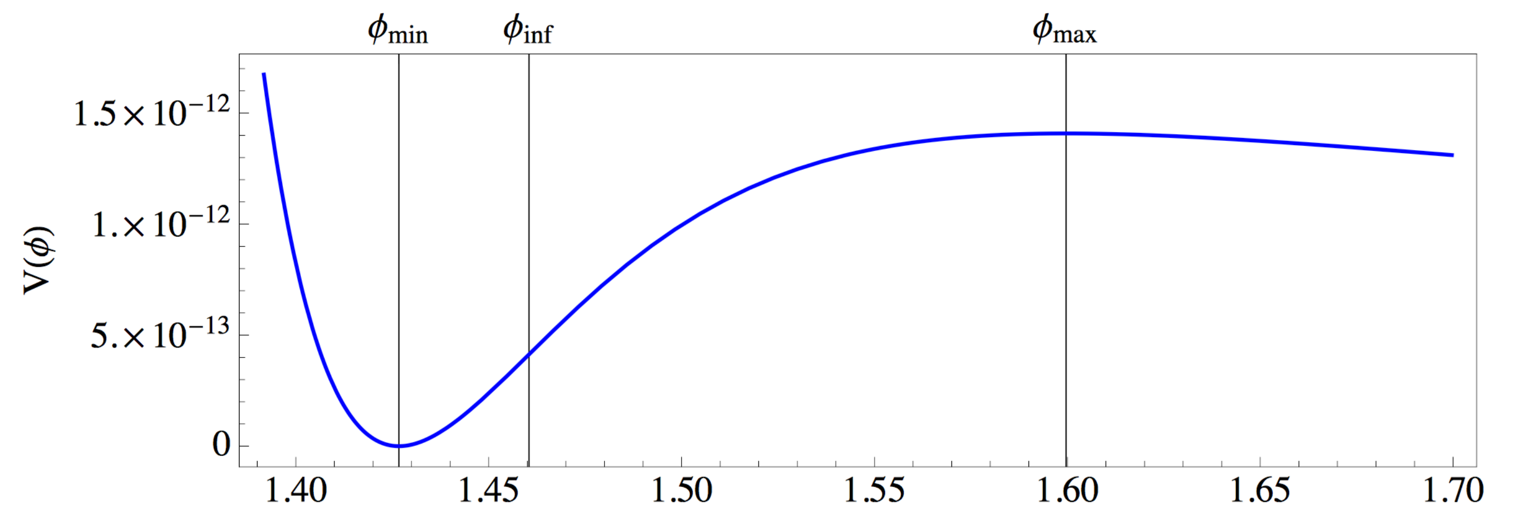
- In string theory models, there are typically many moduli. Their field values determine, for example, the size of the extra dimensions, ...
- Typically, they are displaced from their true minima during inflation, and their dynamics dominates the early universe at some time after inflation ...



S.A., F. Cefala, S. Krippendort, F. Muia, S. Orani, F. Quevedo [arXiv:1708.08922]

Example: *Kähler modulus in the KKLT scenario*

- Example 1: (overall) *Kähler modulus in KKLT for* $W_0 = 10^{-5}$ $A = 10$ *and* $a = 2\pi$

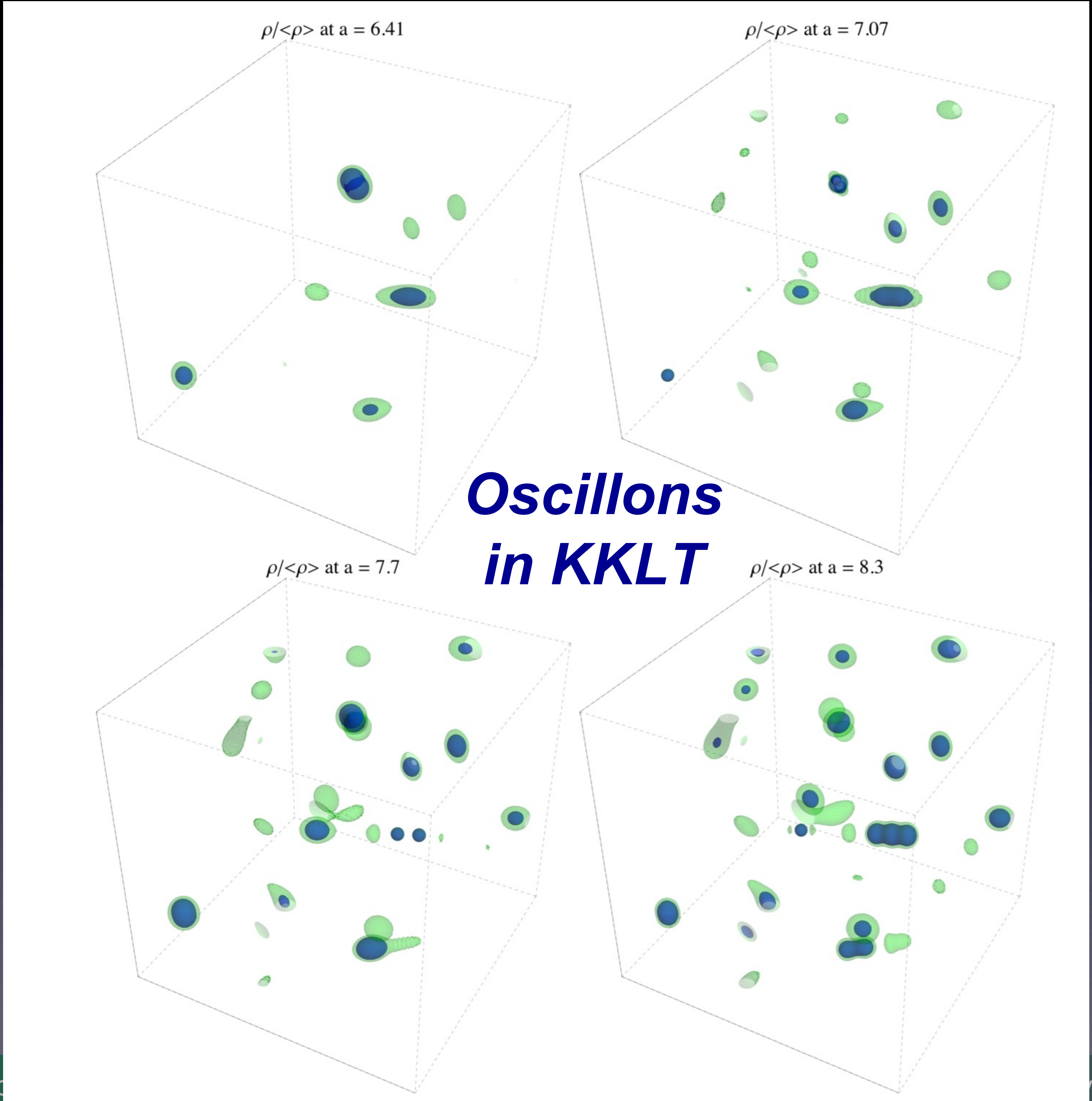


where: $\phi/m_{\rm Pl} = \sqrt{3}\log\tau/2$

$$V/M_{\rm Pl}^4 = \frac{e^{K_{\rm cs}}}{6\tau^2}\left(aA^2(3+a\tau)e^{-2a\tau} - 3aAe^{-a\tau}W_0\right)$$

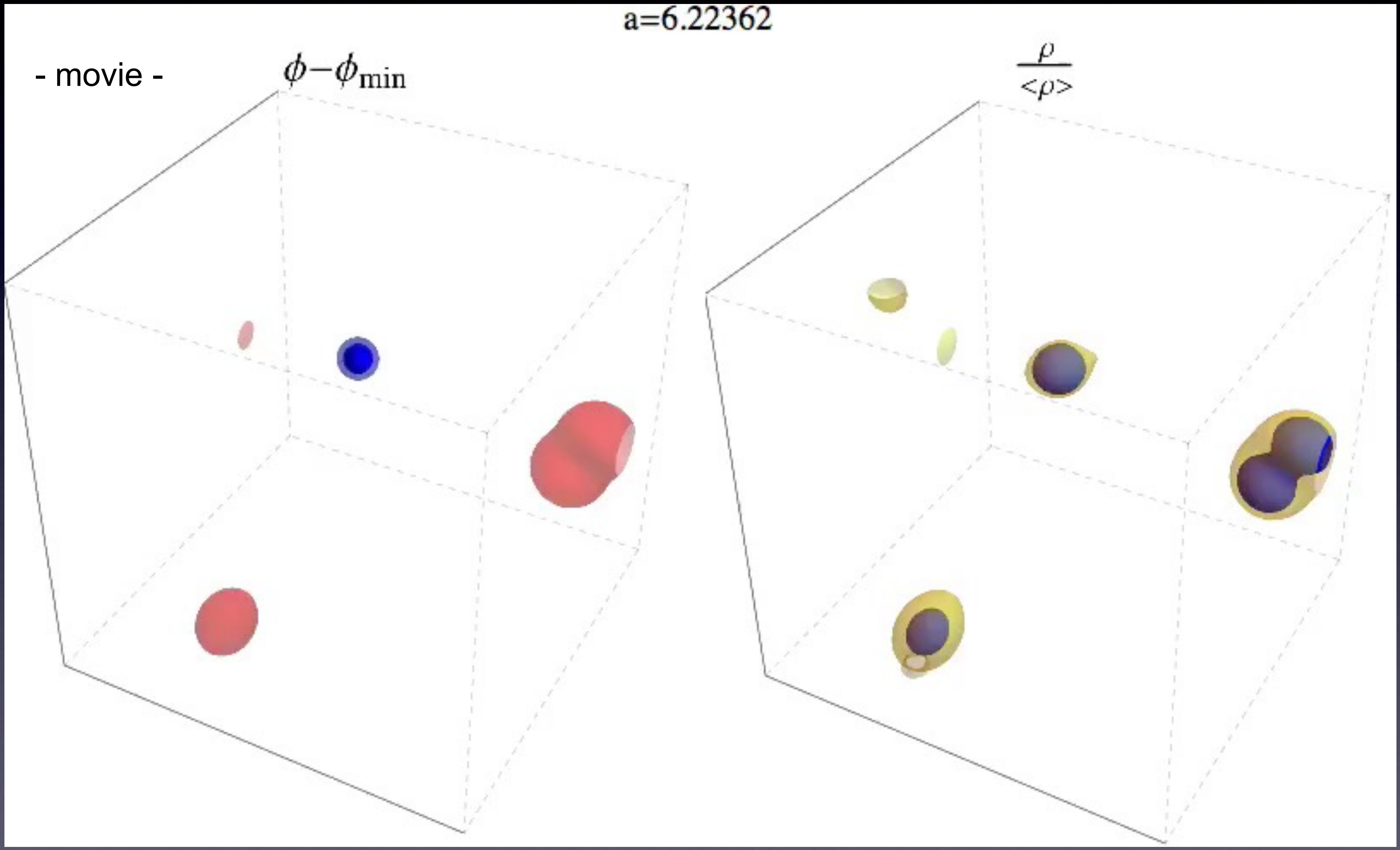
Kachru, Kallosh, Linde, Trivedi ('03)

Oscillons in KKLT



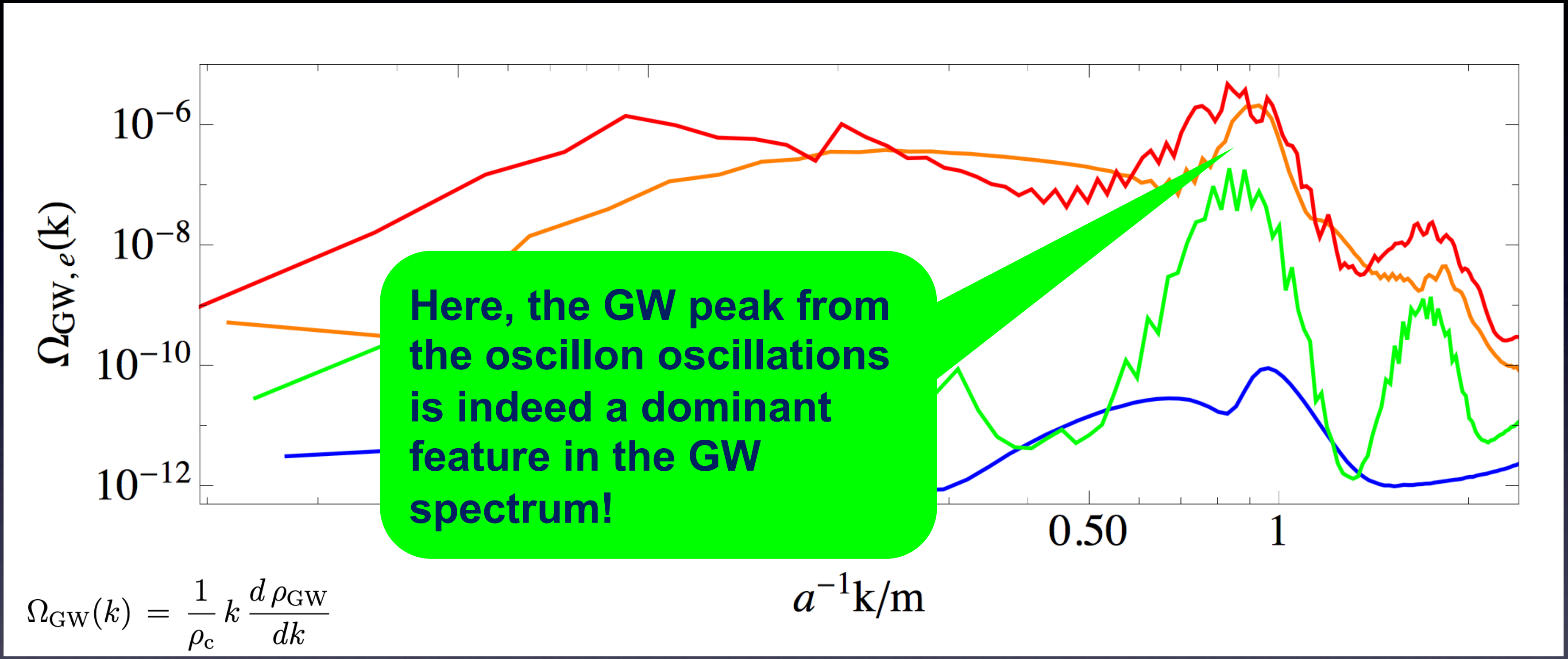
Oscillons in KKLT

Note: In contrast to hilltop-inflation potentials, the main production mechanism for oscillons is via parameteric (self-)resonance of the modulus.



S.A., F. Cefala, S. Krippendort, F. Muia, S. Orani, F. Quevedo [arXiv:1708.08922]
https://particlesandcosmology.unibas.ch/en/downloads/oscillons-from-string-moduli-movies.html

GW from oscillons in KKLT



S.A., F. Cefala, S. Krippendort, F. Muia, S. Orani, F. Quevedo [arXiv:1708.08922]

On the other hand, with parameters preferred from string theory, the GW frequency is still very high ... Search for scenario with testable GW spectrum from moduli-oscillons ongoing ...

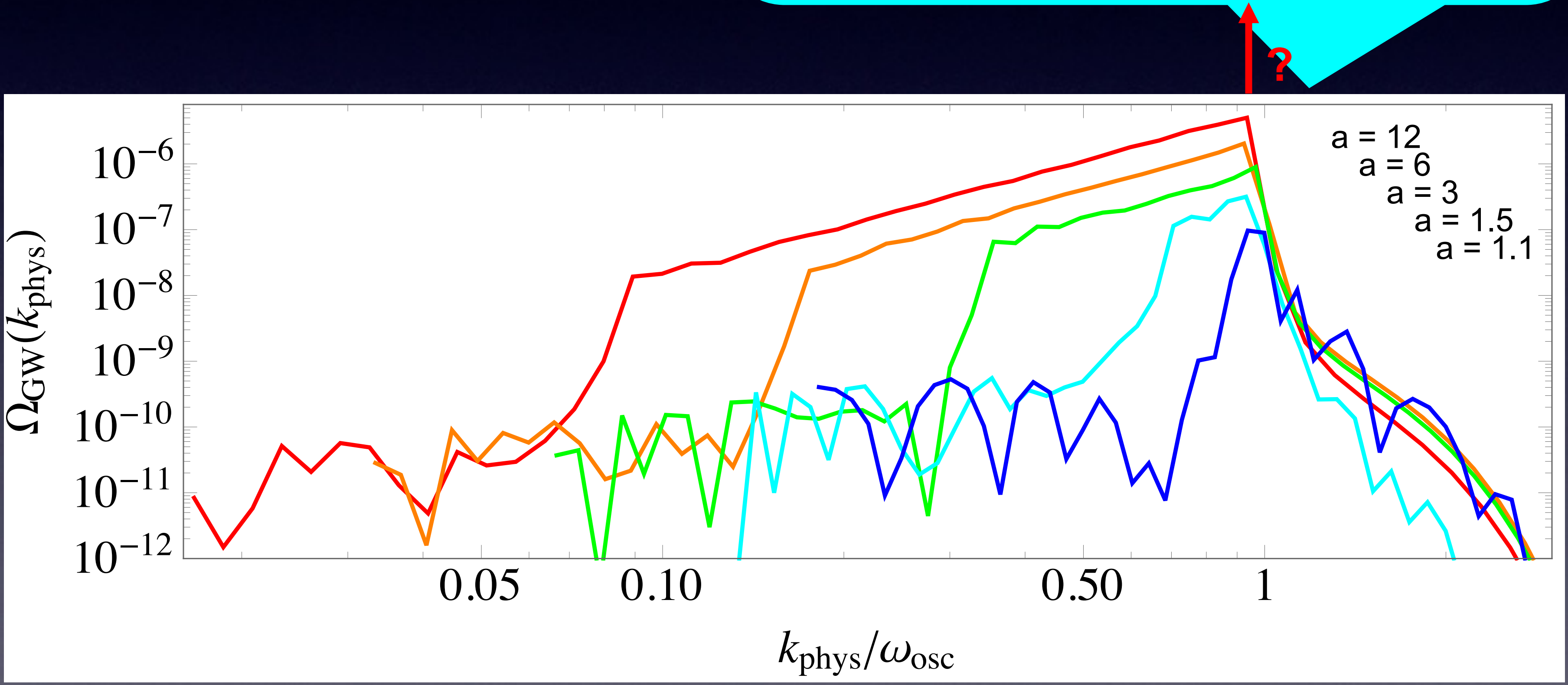
GW from oscillo... hilltop...

Semi-analytical first look ...

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

Question 3: When does the GW peak from oscillons stop growing?
... Lifetime of the oscillons?
... Time dependence of the asymmetry of the oscillons, $\Delta(t)$?
... Time dependent N(t)/V?

e.g.: $\Omega_{\mathrm{GW}} \propto \Delta^2$

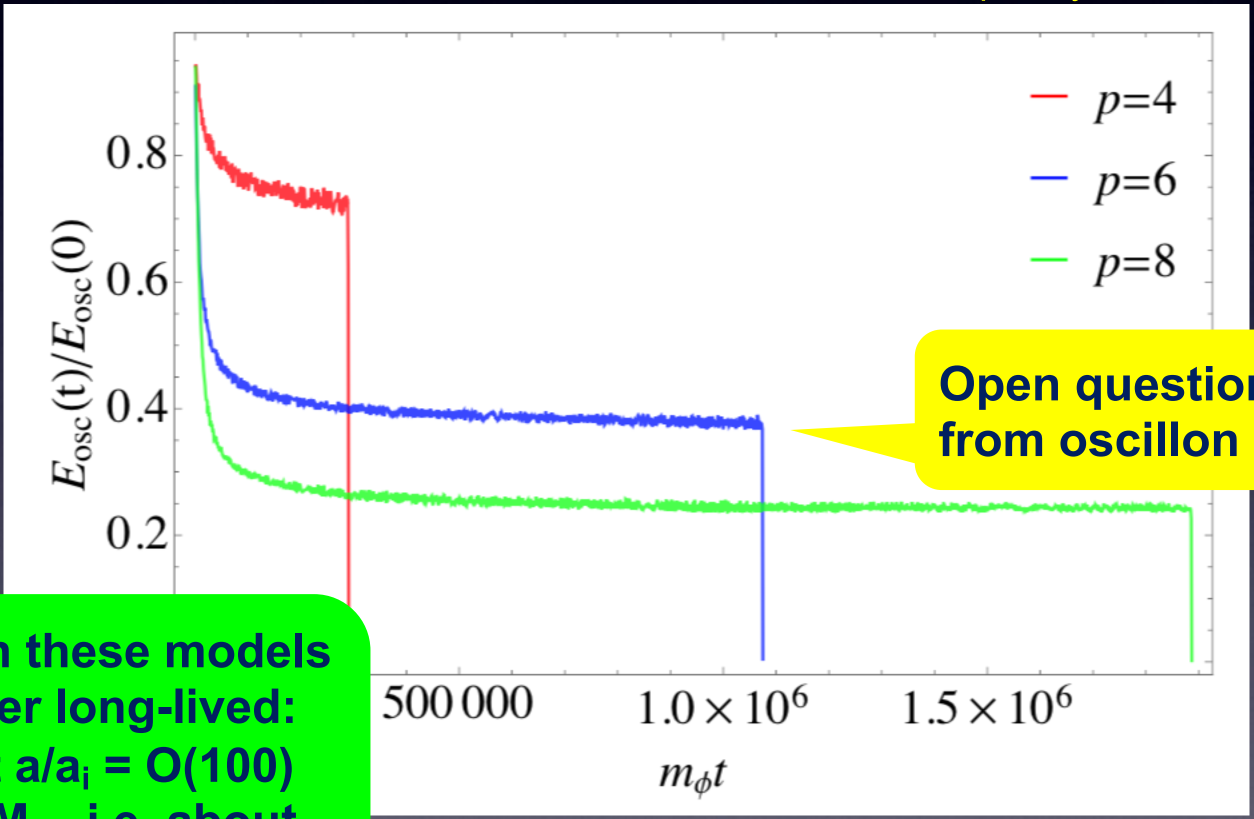


Oscillon lifetime in hilltop models

S.A., F. Cefala, F. Torrenti [arXiv:1907.00611]

- Treatment: spherically symmetric oscillons (long-time, high accuracy simulations possible!)

plot by F. Cefala



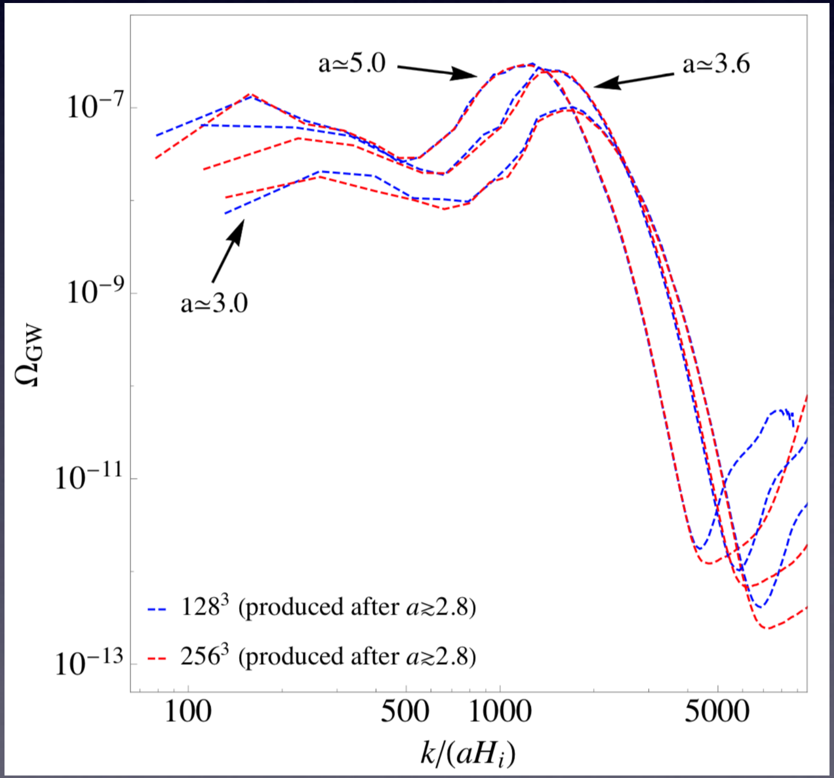
Open question: GWs from oscillon decays!

Oscillons in these models can be rather long-lived: up to about $a/a_i = O(100)$ for $v = 10^{-2} M_{Pl}$, i.e. about 4-5 e-foldings

Time dependence of asymmetry: ... model dependent and hard to estimate!

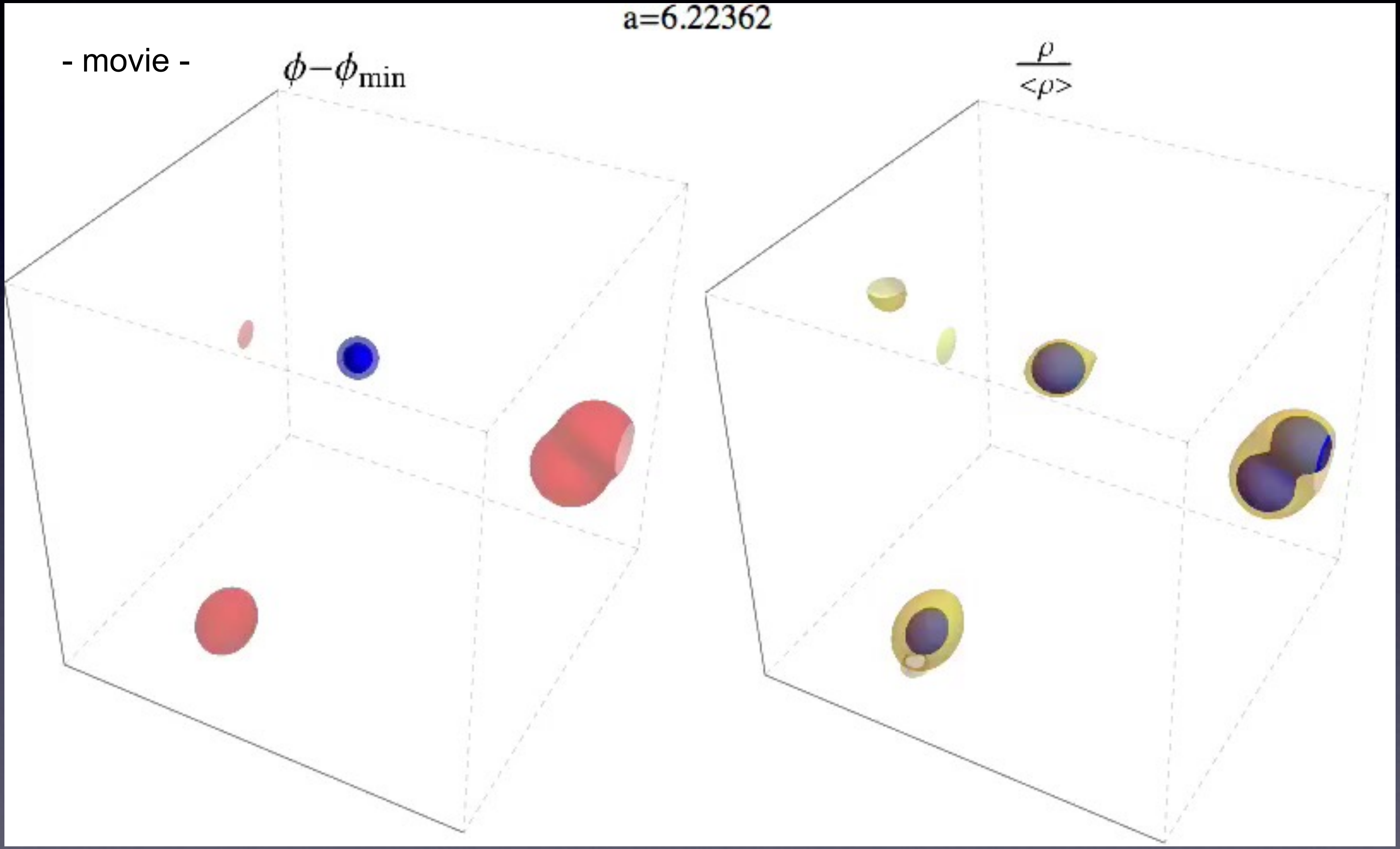
In hilltop models, the asymmetry Δ of the oscillons decreases with time and the growth of the oscillon GW peak slows down ...

Only GW from oscillons (i.e. GW produced after tachyonic oscillation phase)



On the other hand, in the KKLT scenario, new oscillons from (oscillons split up into multiple oscillons!) and the new oscillons are again very asymmetric ...

S.A., F. Cefala, S. Krippendort, F. Muia, S. Orani, F. Quevedo [arXiv:1708.08922]

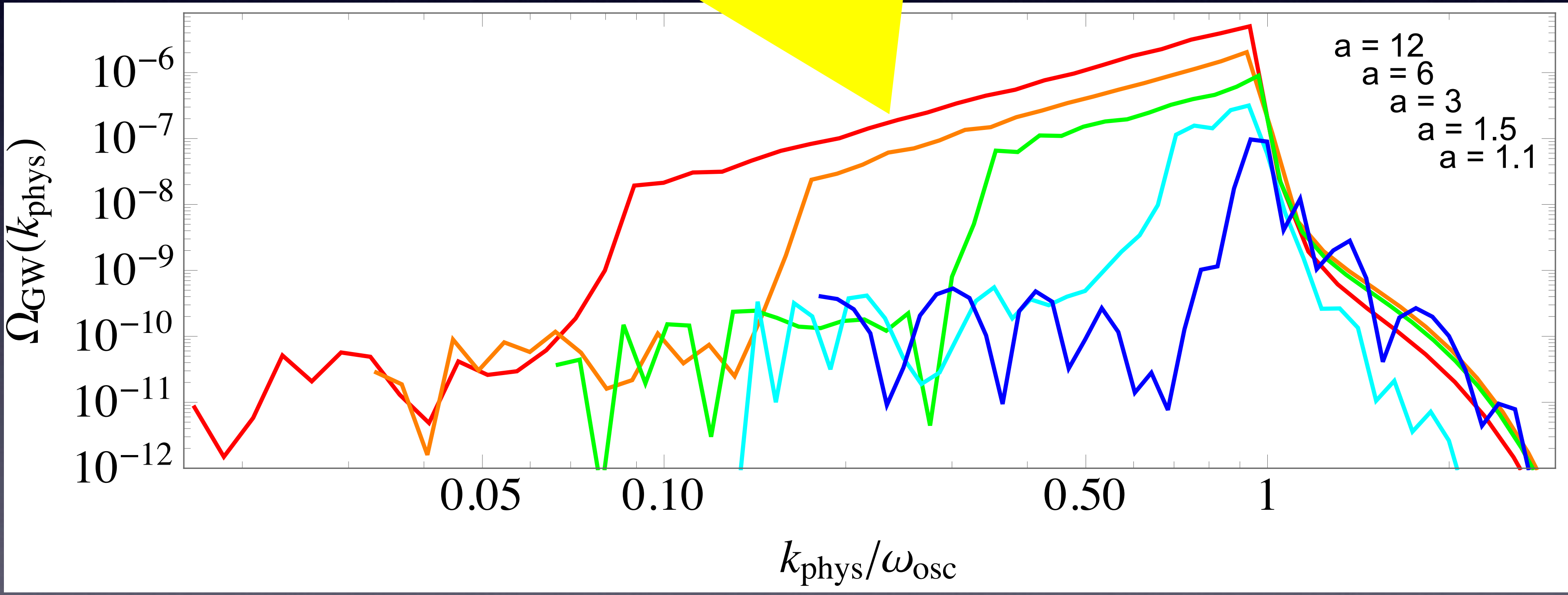


GW from oscillons after single field hilltop inflation

Semi-analytical first look ...

Model: $V(\phi) = V_0 \left(1 - \frac{\phi}{v}\right.$

The effects of time-dependent N(t) and $\Delta(t)$, etc., are imprinted in the shape of the "peak/plateu" …
cf. S.A., F. Cefala, S. Orani, arXiv:1712.03231



GW from oscillons after single field hilltop

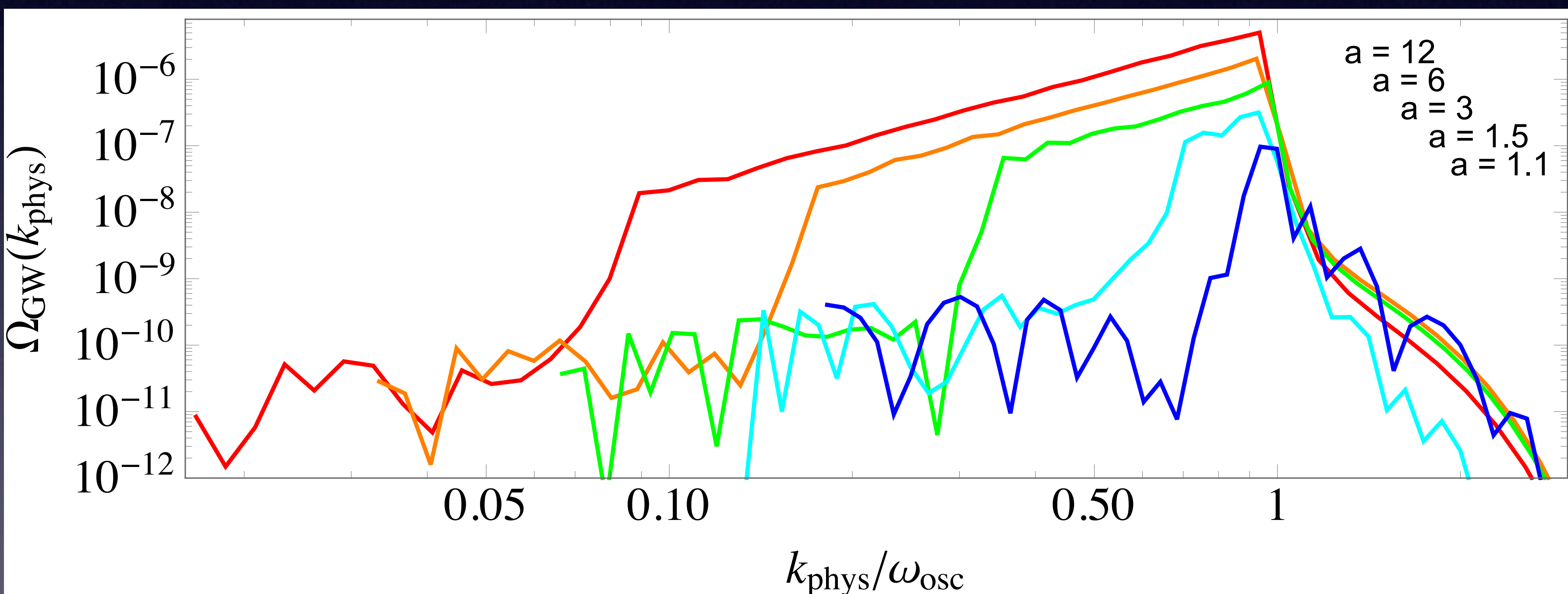
Semi-analytical first look ...

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

1

Question 4: What happens if other fields are around?

... Impact of secondary fields?!



Question 4: 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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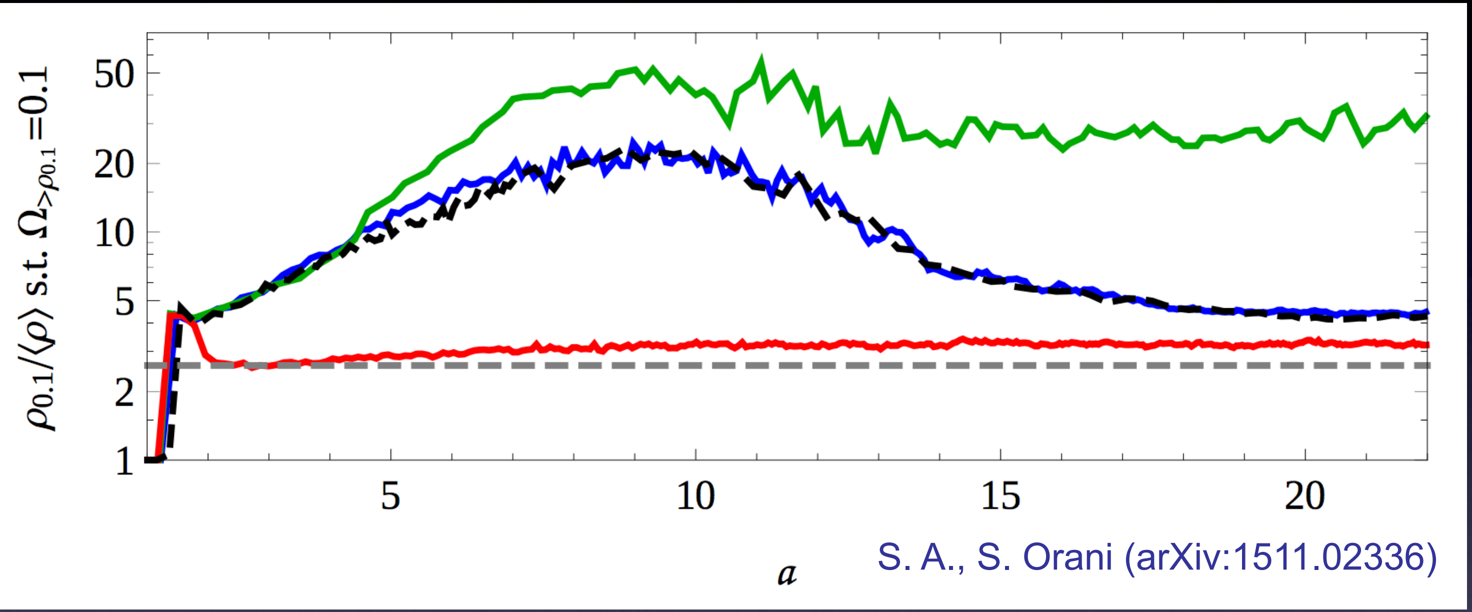
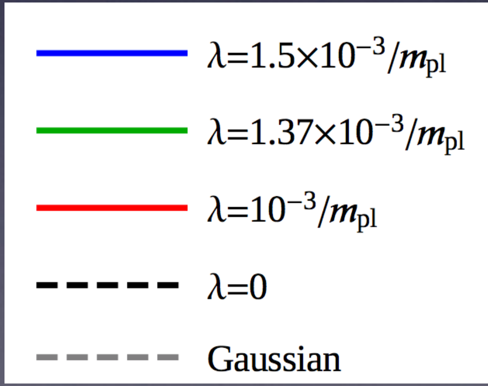


From 2D lattice simulations

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!

GW from oscillons after single field hilltop

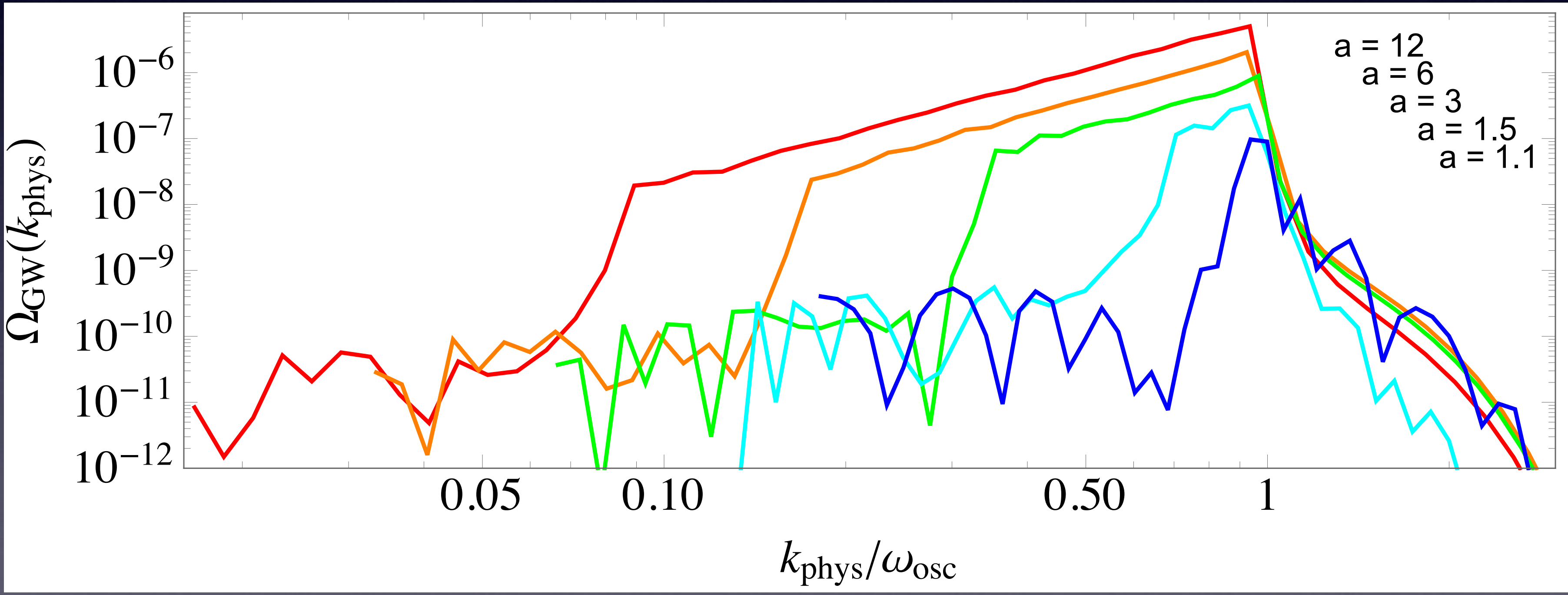
Semi-analytical first look ...

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

1

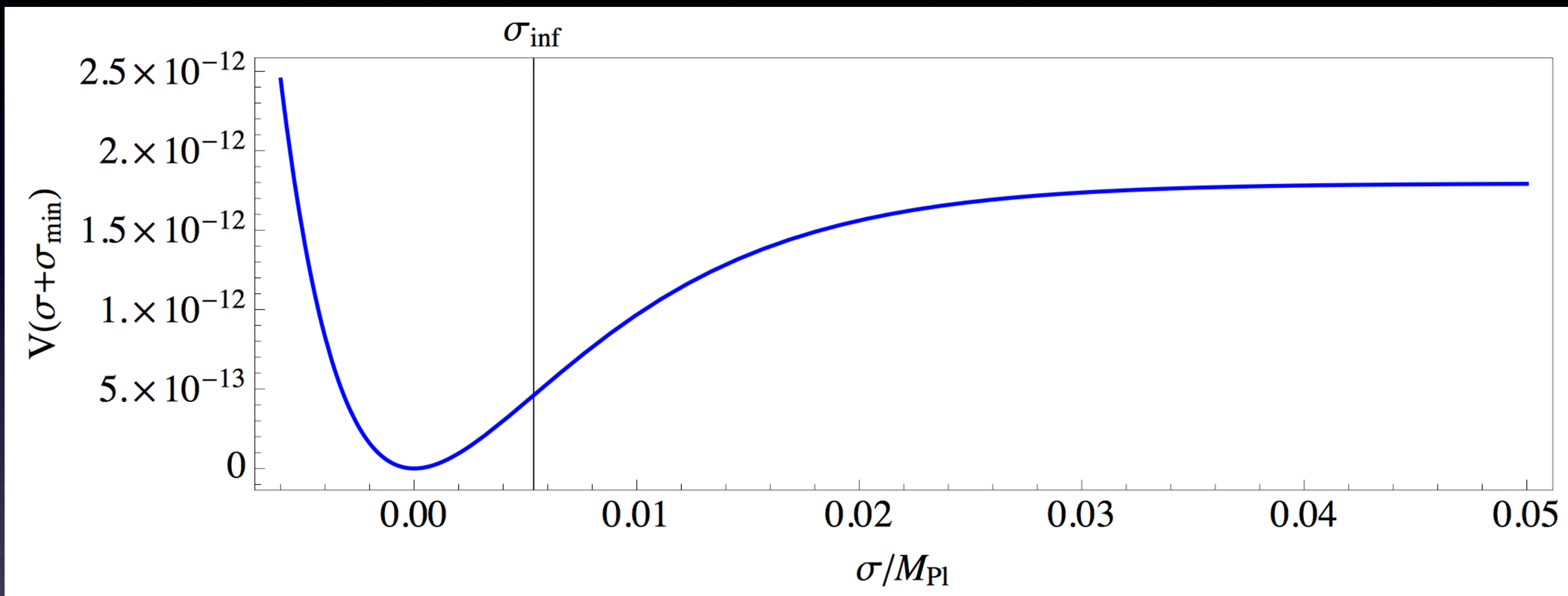
Question 4:

What happens in other models ...?



Oscillons from string moduli - Example 2: ***Blow-up Kähler modulus in the Large Volume Scenario***

Also used for Kähler inflation ...

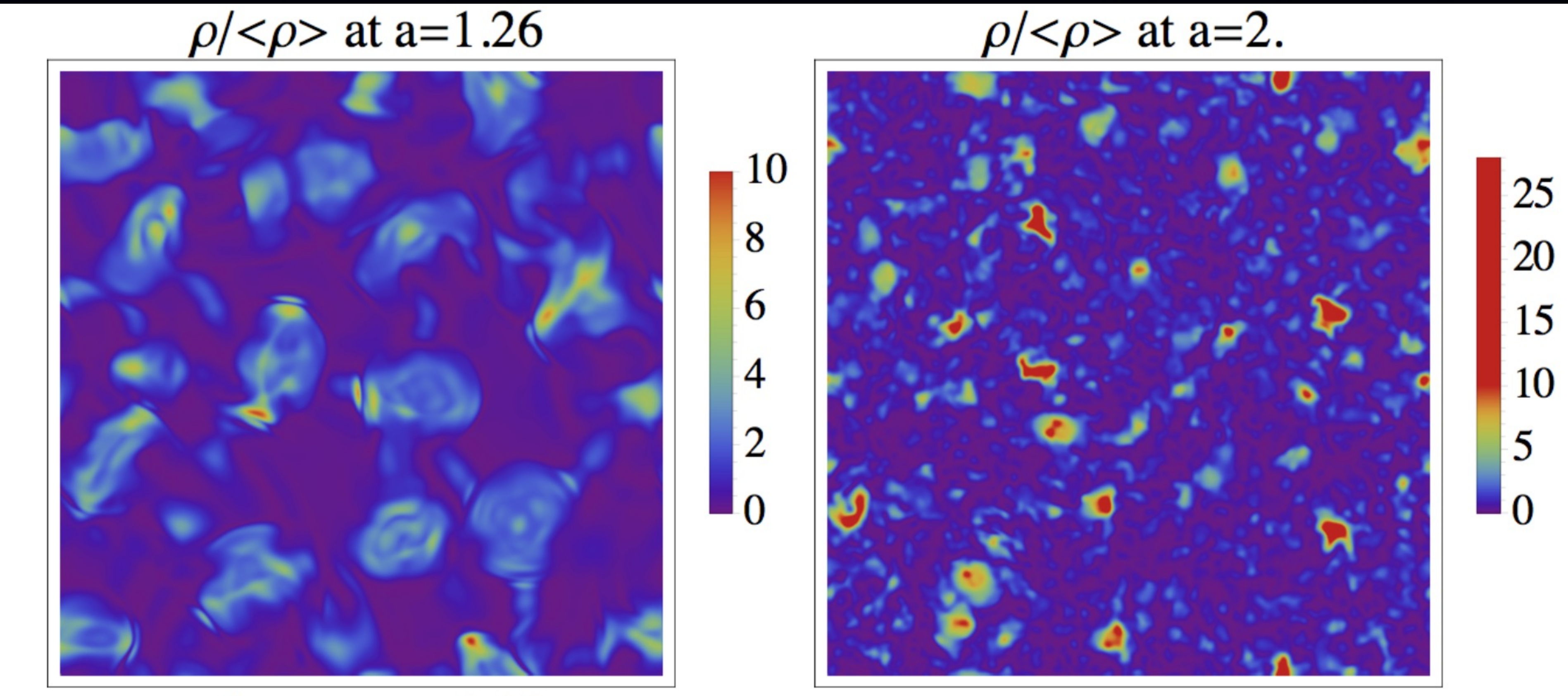


$$
\begin{aligned}
K/M_{\rm Pl}^2 &= -2\log\left(\mathcal{V}+\frac{\xi s^{3/2}}{2}\right) \\
W/M_{\rm Pl}^3 &= W_0+\sum_{i=2}^{N} A_i e^{-a_i T_{s,i}} ,
\end{aligned}
$$

V. Balasubramanian, P. Berglund, J. P. Conlon, and F. Quevedo (2005),
J. P. Conlon, F. Quevedo, and K. Suruliz (2005)

Oscillons in the LVS

Note: Now, similar to hilltop-inflation potentials, the main production mechanism for oscillons is tachyonic oscillations.



S.A., F. Cefala, S. Krippendort, F. Muia, S. Orani, F. Quevedo [arXiv:1708.08922]

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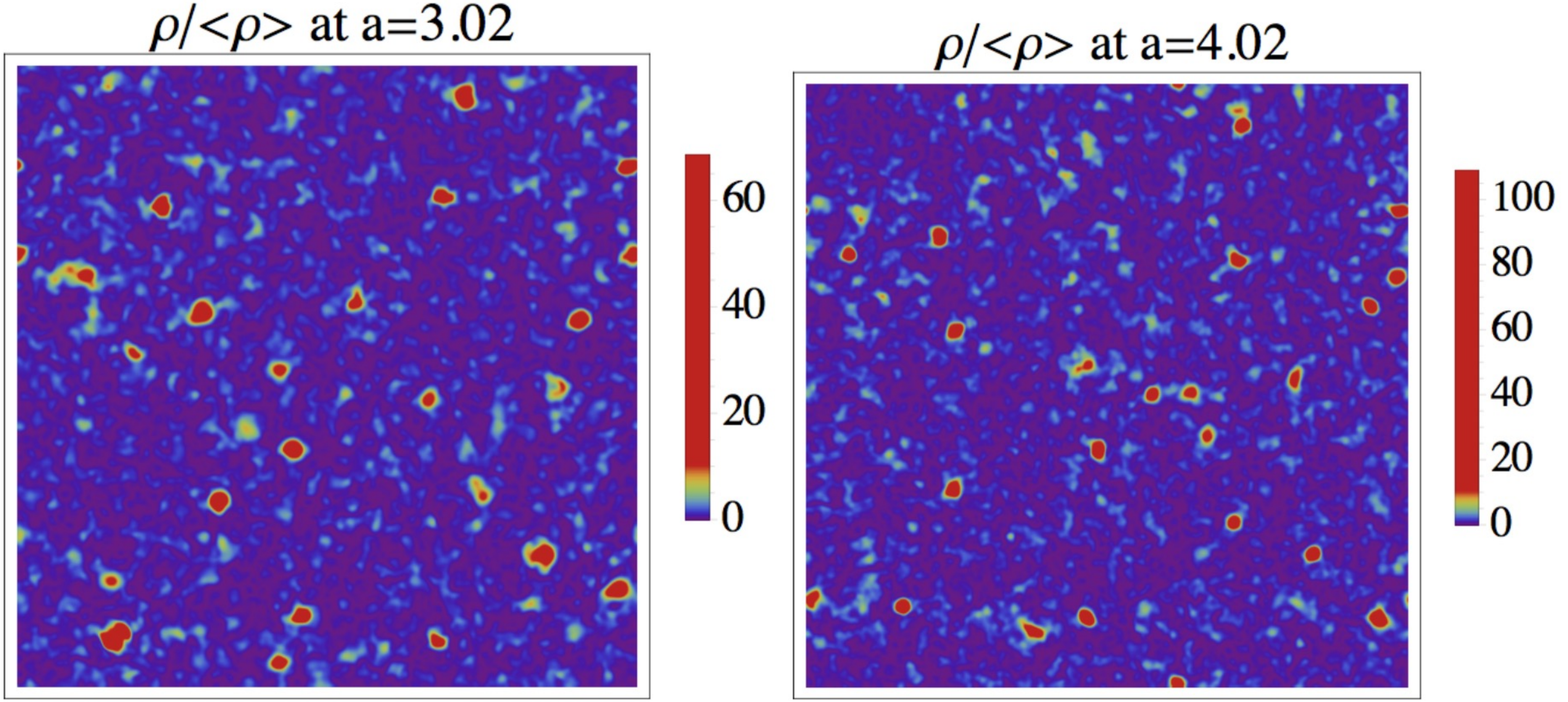

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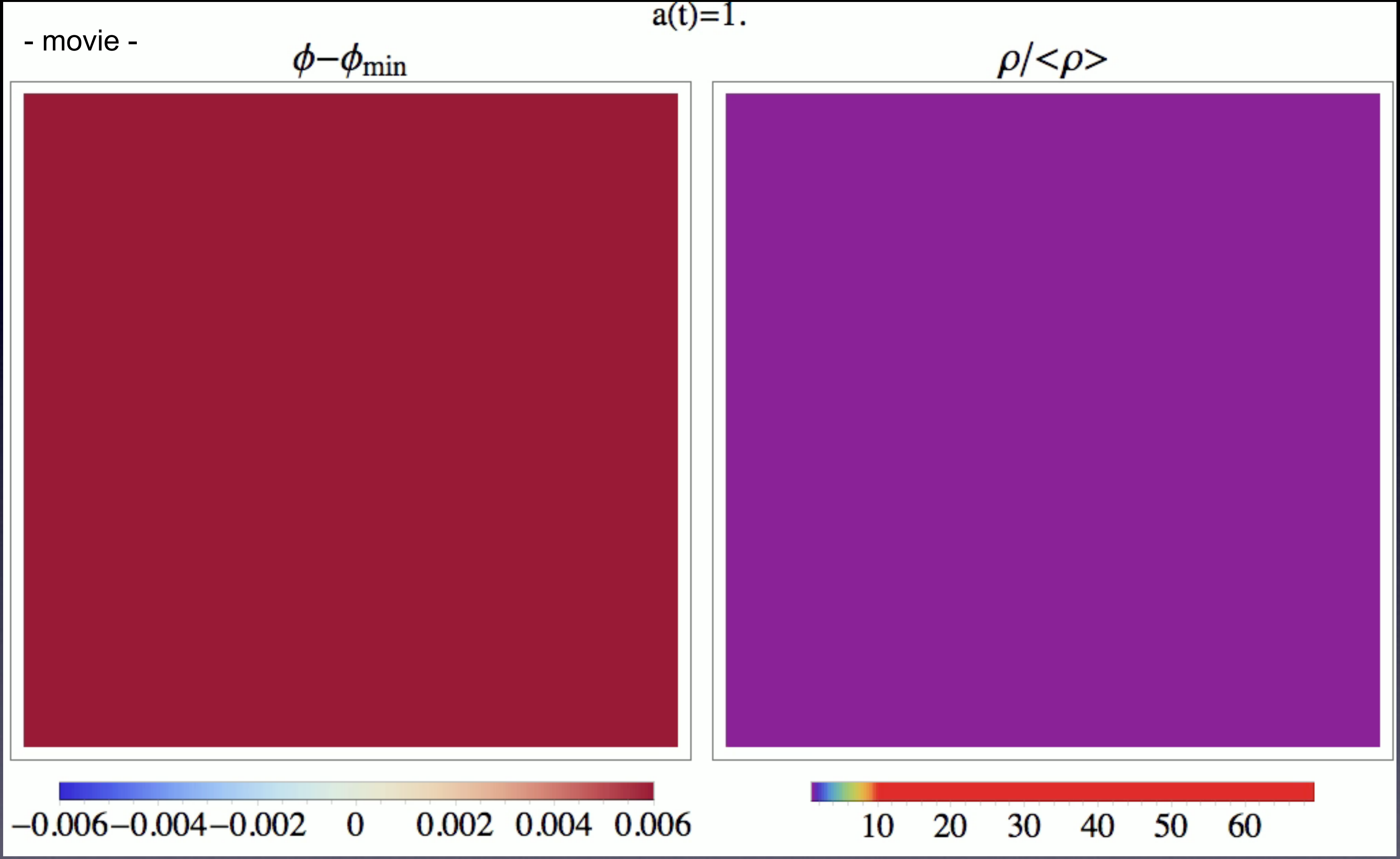
Oscillons in the LVS



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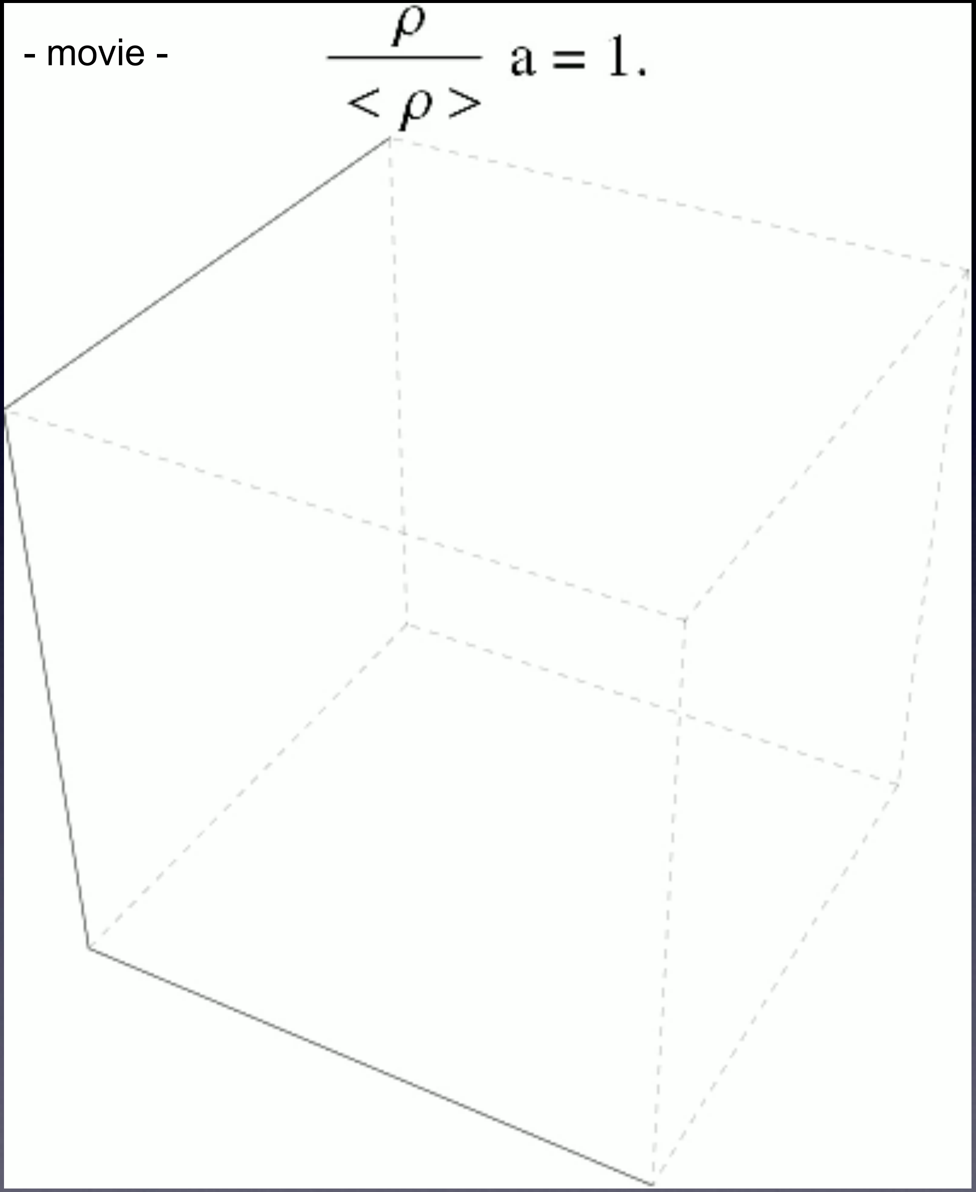
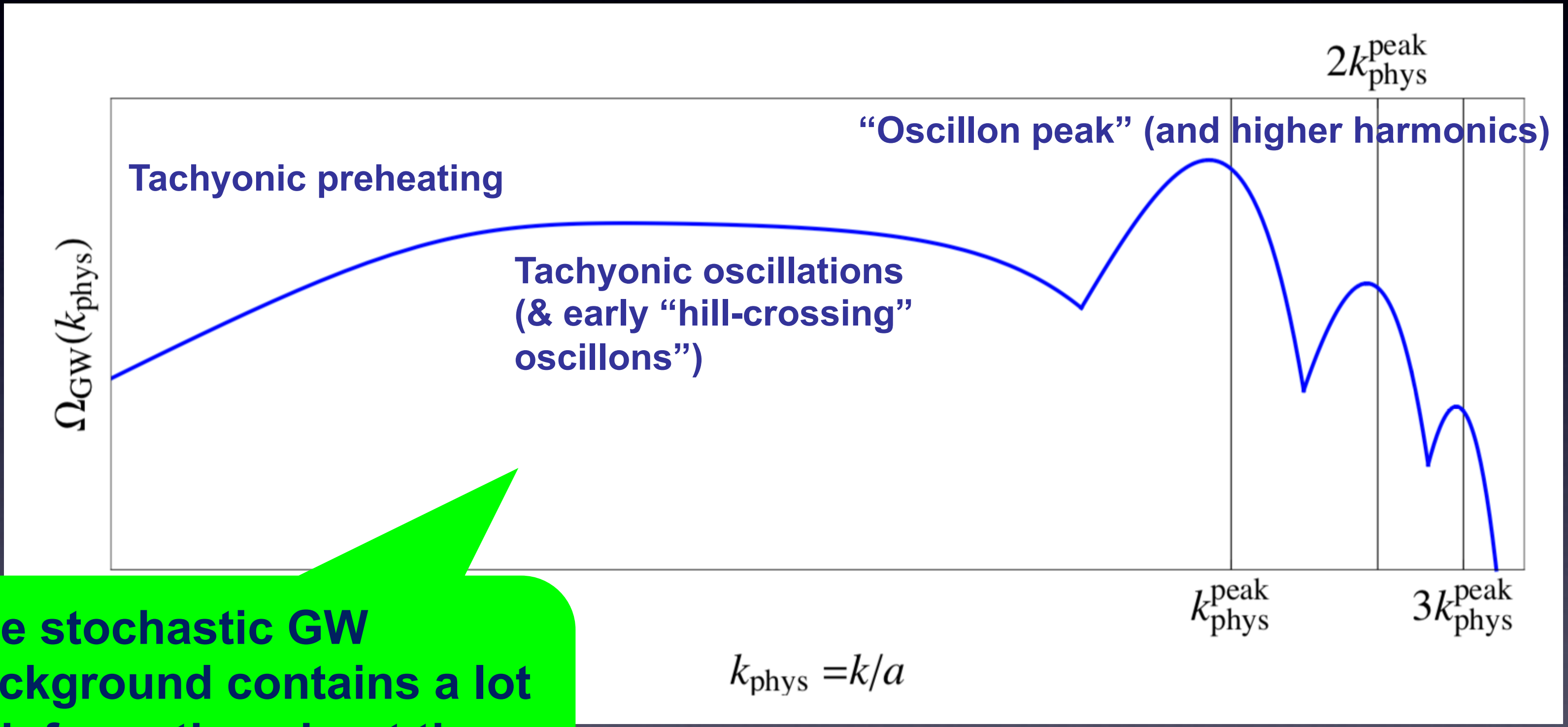


What could we learn from a measurement of the GW spectrum from preheating ...

Schematically ...



The stochastic GW background contains a lot of information about the field dynamics of the very early universe!

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 or from string moduli).
- Asymmetric oscillons can generate a characteristic signature, i.e. a "peak" (and a "plateau") in the GW spectrum!
- While in some models the growth of the oscillons GW peak stops due to the oscillons becoming symmetric Zhou, Copeland, Easther, Finkel, Mou and Saffin ('13) rather quickly, in other models it can become a dominant feature!

  For details and further references: S.A., F. Cefala, S. Orani [arXiv:1607.01314]
  S.A., F. Cefala, S. Krippendort, F. Muia, S. Orani, F. Quevedo [arXiv:1708.08922]

- If the GW spectrum from preheating is in the right frequency range (scenarios with lower V_0) it could be probed with planned/ongoing GW detectors ... could be a fascinating window to early universe dynamics!

Thanks for your attention!