Gravitational wave forest from string axiverse

Yuko Urakawa (Nagoya university, IAR)

J.Soda & Y.U.(1710.00305)

Kitajima, Soda & Y.U. (1807.07037)

w/ Naoya Kitajima (Nagoya U.), Jiro Soda (Kobe U.)

Axions (or ALPs) from string theory

Superstring theory in compact 6D

↓

4D low energy EFT + Axions + Moduli ….

Wide mass ranges → Probe of exDim

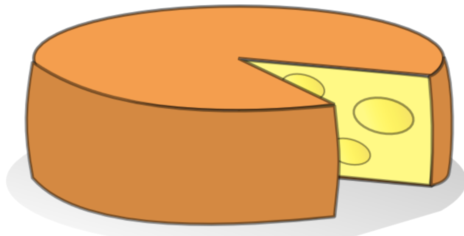
↓

Inflaton, DM candidate (Fuzzy DM)

Wu et al.(00), ⋯

ex. Large Volume Scenario *Conlon et al. (05)*

Predicts light mass axions



Scalar potential of axion

continuous shift sym. $\xrightarrow[\text{e.g. instanton effects}]{\text{NP effects}}$ $\phi \to \phi + 2\pi n/f$

$\phi \to \phi + c$

$n \in \boldsymbol{Z}$

$V(\phi) \sim \Lambda^4 \cos\phi/f$

Are you sure with $\cos\phi/f$?

- ~~Dilute instanton gas approximation~~

for $\phi/f << 1$ $\quad V(\phi) \propto \phi^2$

for $\phi/f \geqq 1$ $\quad \cos\phi/f$? $\quad$ *Witten(79, 80)*

SU(N) in large N $\quad f_{\rm eff} \propto N \longrightarrow$ Plateau structure

Dubovski et al. (11), Yamazaki & Yonekura(17), ⋯

$$V(\phi) = M^4 \left[1 - \frac{1}{(1+(\phi/F)^2)^p}\right]$$

Scalar potential of axion

continuous shift sym.

$\phi \to \phi + c$

$\xrightarrow[\text{e.g. instanton effects}]{\text{NP effects}}$

$\phi \to \phi + 2\pi n/f$

$n \in \mathbf{Z}$

$V(\phi) \sim \Lambda^4 \cos\phi/f$

$\boxed{\text{Potential can be more flatten than } \cos\phi/f}$

i) Dilute instanton gas approximation

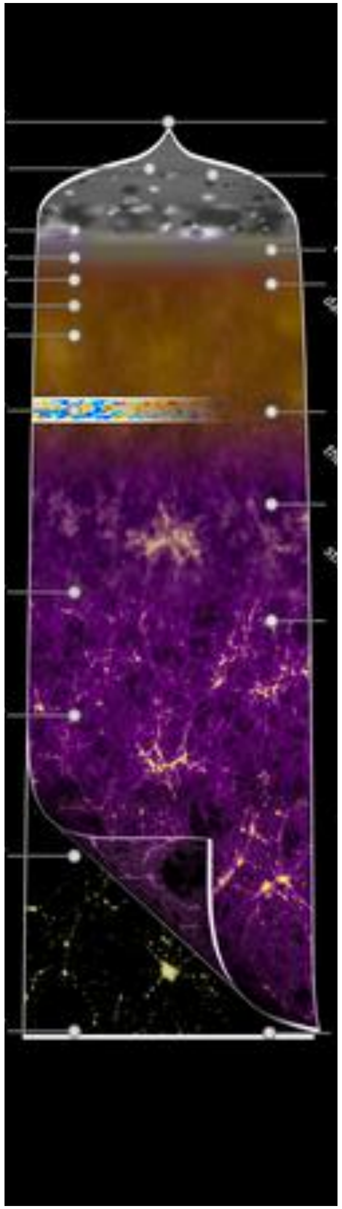
see. implications for axion=inflaton, *Nomura + (17, 18)*

ii) Non-min. coupling w/gravity, Non-canonical kinetic term

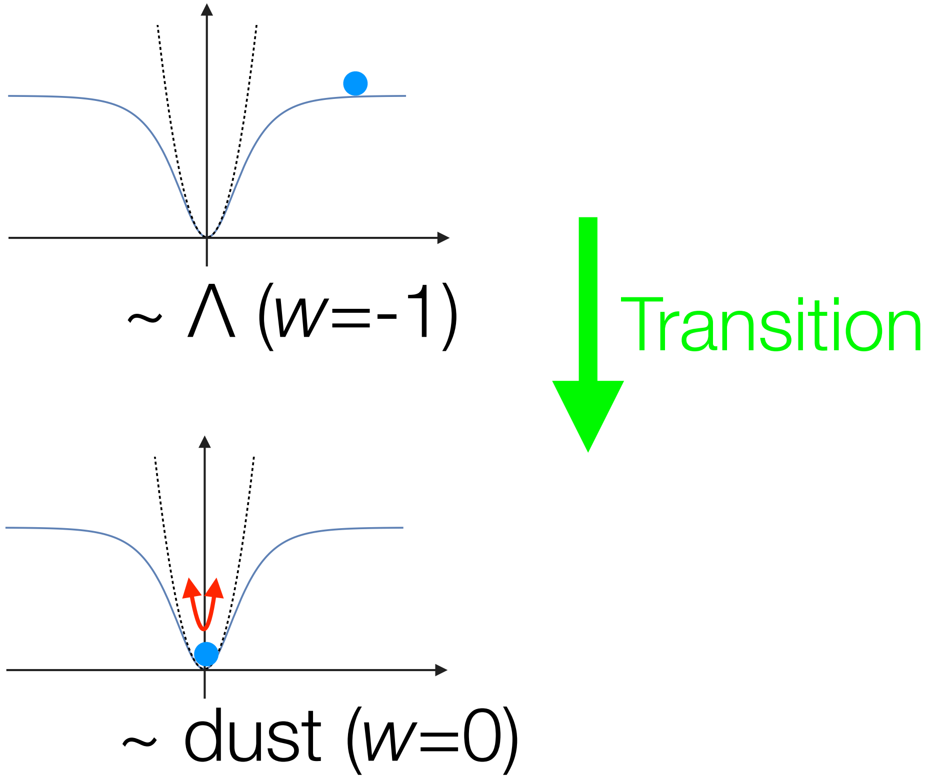
Recall α attractor model for Re[T] *Kallosh & Linde + (13, 14, ···)*

iii) Superposition of multiple cosine terms

Plateau phenomenology



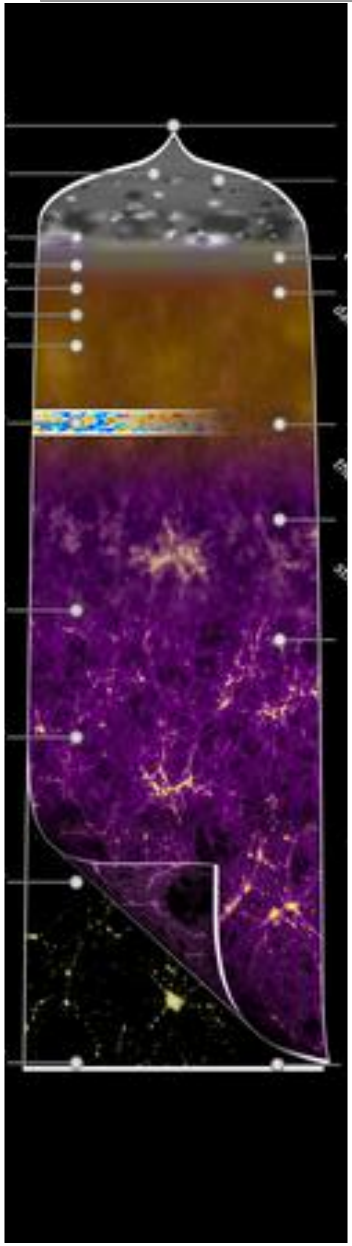
← Onset of oscillation



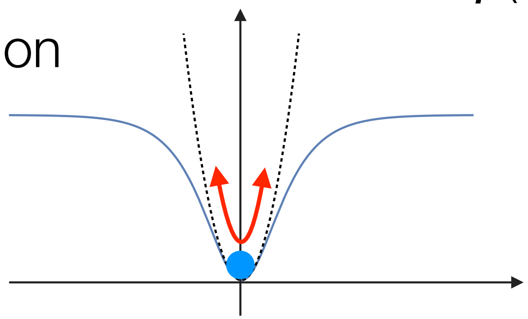
Search for string axiverse

Soda & Y.U.(17)

Kitajima, Soda & Y.U.(18)



Onset of oscillation



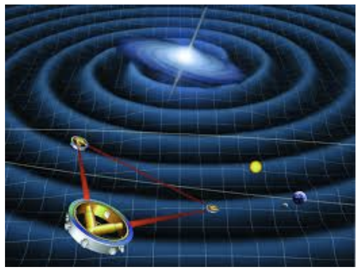
Delay $\boxed{H_{osi} << m}$

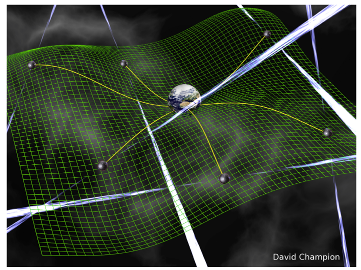
$\phi(t) \xrightarrow[\text{inst.}]{} \delta\phi(t, x)$ turbulence

(b)GW

axion

~~bio~~-marker





Contents

1. Evolution of k=0 mode

2. Evolution of $k \neq 0$ mode
   - Linear
   - Non-linear

3. Pheno. Prediction: GW forests

Normalization

Neglect back-reaction on geometry

$\longrightarrow$ Axion's dynamics is independent of (*m*, *f*)

$$\partial_t^2 \phi + 3H\partial_t \phi - \frac{\partial^2}{a^2}\phi + V_{,\phi} = 0 \qquad a \propto t^p, \;\; H = \frac{p}{t}$$

$$\tilde{x}^\mu \equiv m x^\mu \qquad \tilde{\phi} \equiv \frac{\phi}{f} \qquad V(\phi) = (mf)^2\,\tilde{V}(\tilde{\phi})\,, \qquad \tilde{\phi} \equiv \frac{\phi}{f}$$

$$\downarrow$$

$$\partial_{\tilde{t}}^2 \tilde{\phi} + \frac{3p}{\tilde{t}}\partial_{\tilde{t}}\tilde{\phi} - \frac{\partial_{\tilde{\mathbf{x}}}^2}{a^2}\,\tilde{\phi} + \tilde{V}_{,\tilde{\phi}} = 0$$

Evolution of k=0 mode

$\psi \equiv a^{3/2}\tilde{\phi}$ $\qquad \frac{m}{H} = \frac{mt}{p} \sim \tilde{t}$

$$\frac{d^2}{d\tilde{t}^2}\psi + \left[\frac{(**)}{\tilde{t}^2} + \frac{\tilde{V}_{,\tilde{\phi}}}{\tilde{\phi}}\right]\psi = 0$$

(**) : O(1) number

>> slow-roll

~ onset of oscillation

<< oscillation

e.g. $V \propto \phi^2 \rightarrow \psi \sim \cos mt$

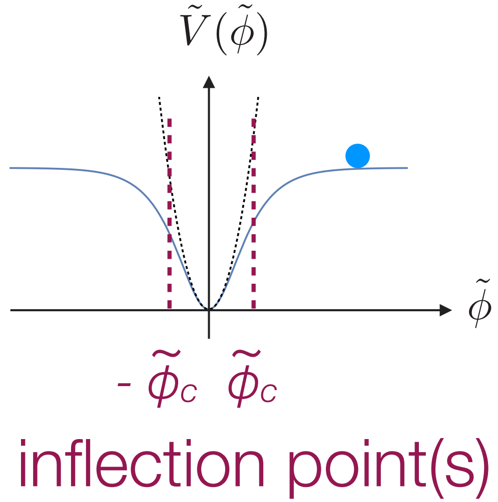
if initially $\left|\frac{\tilde{V}_{,\tilde{\phi}}}{\tilde{\phi}}\right|$ <<1, $\tilde{t}_{osc} \sim \frac{m}{H_{osc}} \gg 1$ delayed oscillation

Plateau condition, $\tilde{V}$ shallower than $\tilde{\phi}^2$

Scalar potential

$$V(\phi) = (mf)^2\,\tilde{V}(\tilde{\phi})\,, \qquad \tilde{\phi} \equiv \frac{\phi}{f}$$

where $\tilde{V}(\tilde{\phi})$ satisfies



(0) Z_2 symmetry

(1) $\tilde{V}(\tilde{\phi}) \to \tilde{\phi}^2/2$ in the limit $\tilde{\phi} \to 0$

(2) Plateau $\left|\frac{\tilde{V}_{,\tilde{\phi}}}{\tilde{\phi}}\right|$ <<1 for $|\tilde{\phi}|$ >1

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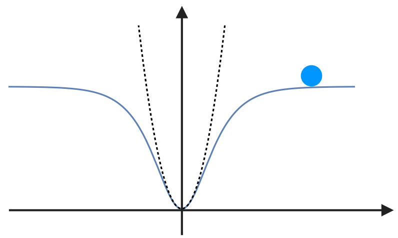
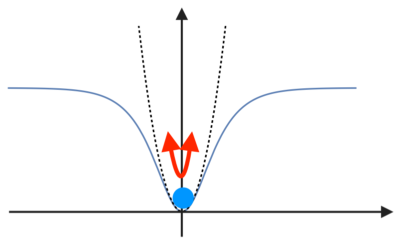


~ Λ (w=-1)

Transition

for $m/H_{osc} \gg 1$



~ dust (w=0)

3. Pheno. Prediction: GW forests

Linear analysis

Linearized KG eq. in FRW universe (w/ *k/aH* << 1)

$$\frac{d^2}{d\tilde{t}^2}\chi_k + \omega_k^2\ \chi_k = 0 \qquad\qquad \chi_k \equiv a^{3/2}\,\frac{\delta\phi_k}{f}$$

$$\omega_k^2 \equiv \left(\frac{k}{ma}\right)^2 + \tilde{V}_{\tilde{\phi}\tilde{\phi}}$$

see e.g. Johnson & Kamionkowski (08) for analyses w/metric perturbations

3 phases for axions in plateau

for $m/H_{osc} \gg 1$

$$mt \sim \frac{m}{H}$$

$$mt_{osc}$$

(1) Slowly rolling down in $\tilde{V}_{\tilde\phi\tilde\phi} < 0$

Tachyonic inst. $\quad \dfrac{k}{am} \leq \sqrt{|\tilde{V}_{\tilde\phi\tilde\phi}|}$

(2) Oscillation between

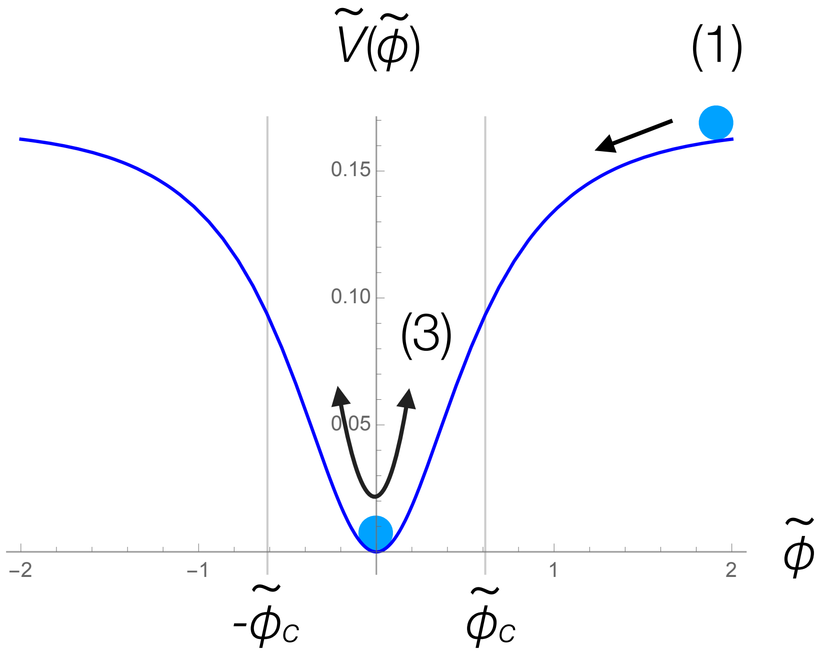
$$\tilde{V}_{\tilde\phi\tilde\phi} < 0 \longleftrightarrow \tilde{V}_{\tilde\phi\tilde\phi} > 0$$

continues long

(3) Oscillation in $\tilde{V}_{\tilde\phi\tilde\phi} > 0$

$$\tilde{V} = \frac{\tilde\phi^2}{2} + \underbrace{\frac{\lambda}{4!}\tilde\phi^4 + O(\tilde\phi^4)}_{\text{corrections}}$$

Narrow res. $\quad$ sustainable

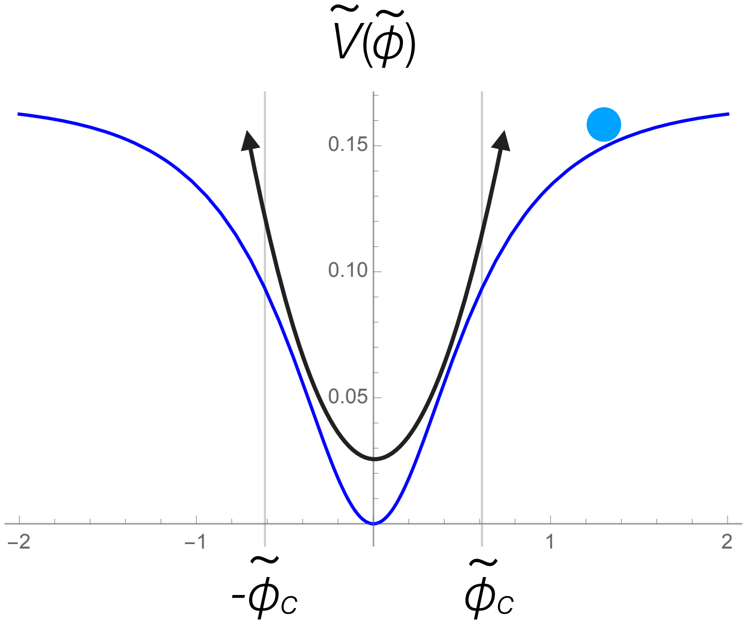


$\tilde{V}_{\tilde\phi\tilde\phi} < 0 \qquad \tilde{V}_{\tilde\phi\tilde\phi} > 0 \qquad \tilde{V}_{\tilde\phi\tilde\phi} < 0$

Soda & Y.U.(17)

Instability in phase 2

$\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0 \longleftrightarrow \tilde{V}_{\tilde{\phi}\tilde{\phi}} > 0$



$\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$	$\tilde{V}_{\tilde{\phi}\tilde{\phi}} > 0$	$\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$
$\omega_k^2 < 0$	$\omega_k^2 > 0$	$\omega_k^2 < 0$

$$\frac{d^2}{d\tilde{t}^2}\chi_k + \omega_k^2\,\chi_k = 0$$

$$\omega_k^2 \equiv \left(\frac{k}{ma}\right)^2 + \tilde{V}_{\tilde{\phi}\tilde{\phi}}$$

Adiabatic condition

Broad res.? Tachyonic inst. like phase 1?

- Tachyonic instability $\quad \frac{k}{am} \le \sqrt{|\tilde{V}_{\tilde{\phi}\tilde{\phi}}|}$
- "some advantage" for larger k

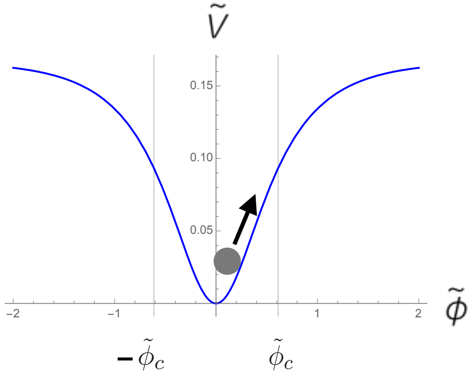
$\Big\} \rightarrow$ peak at k ≠0

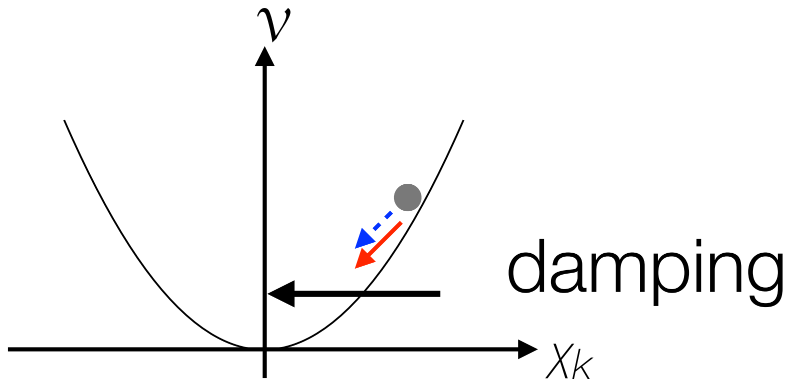
$$\mathcal{V} \equiv \omega_k^2 \chi_k^2/2$$

Kinematics

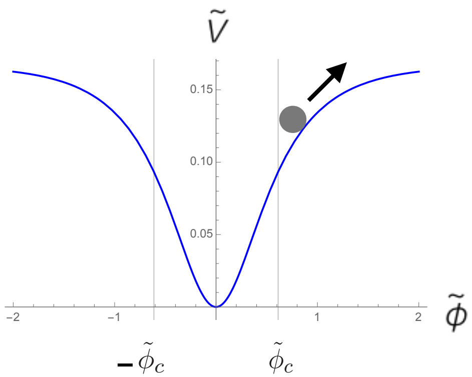
$$\omega_k^2 \equiv \left(\frac{k}{ma}\right)^2 + \tilde{V}_{\tilde{\phi}\tilde{\phi}}$$

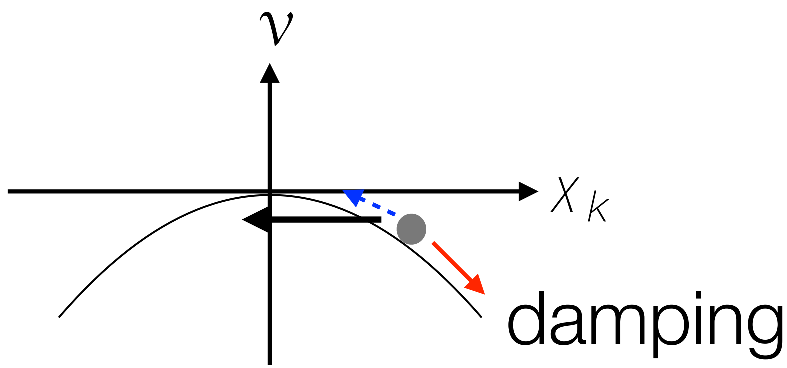
① $\tilde{V}_{\tilde{\phi}\tilde{\phi}} > 0$



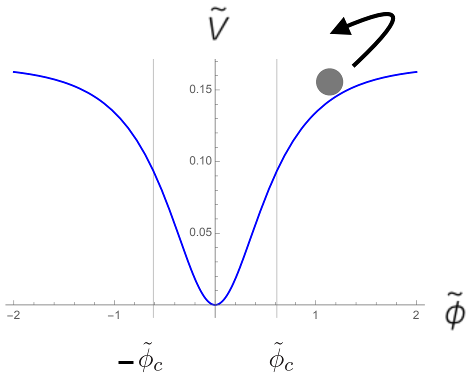


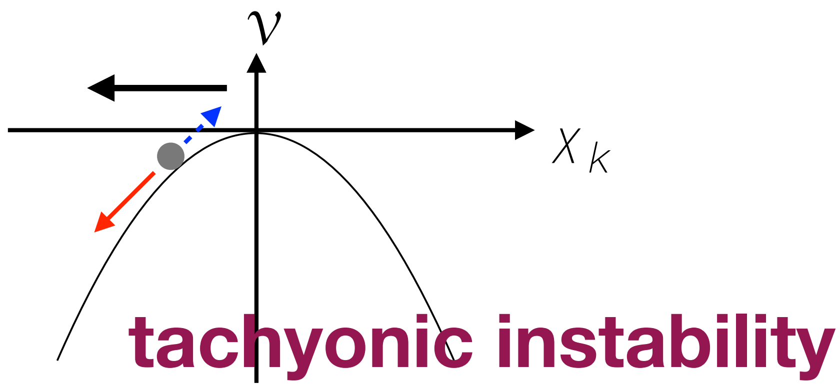
② $\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$





③ $\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$



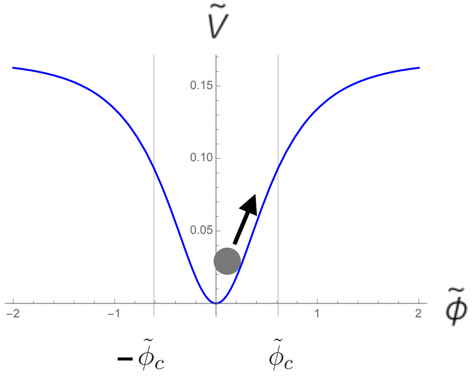


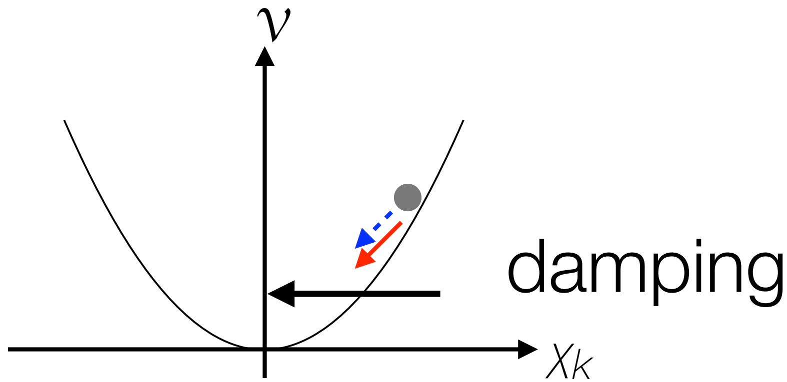
$$\mathcal{V} \equiv \omega_k^2\, \chi_k^2/2$$

Kinematics

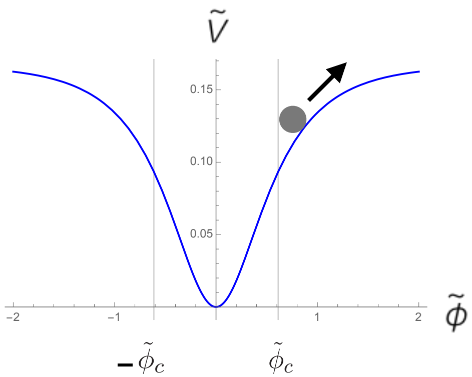
$$\omega_k^2 \equiv \left(\frac{k}{ma}\right)^2 + \tilde{V}_{\tilde{\phi}\tilde{\phi}}$$

① $\tilde{V}_{\tilde{\phi}\tilde{\phi}} > 0$

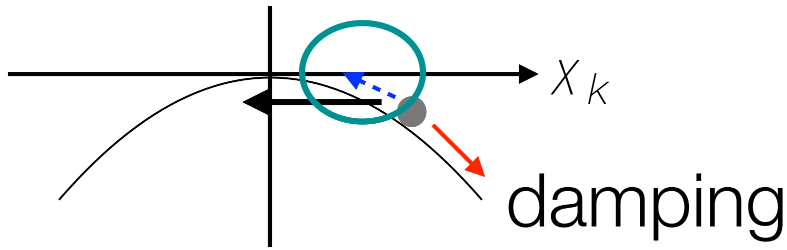




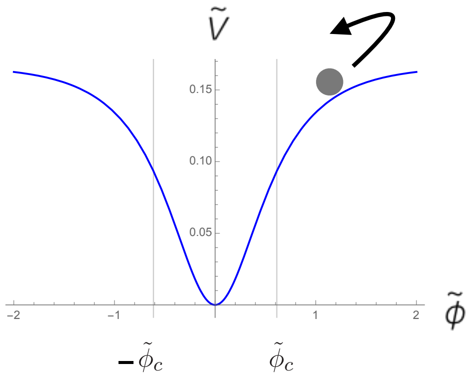
② $\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$

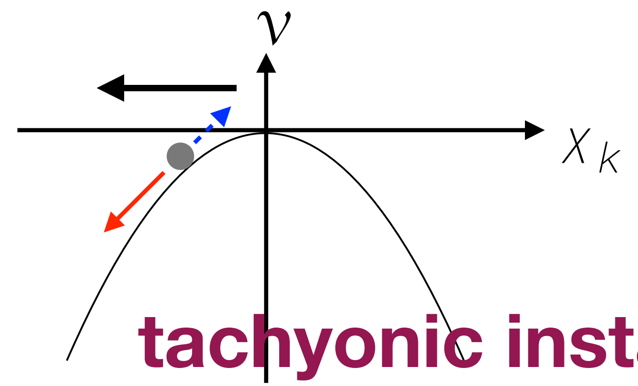


② finishes soon for k ≠ 0



③ $\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$

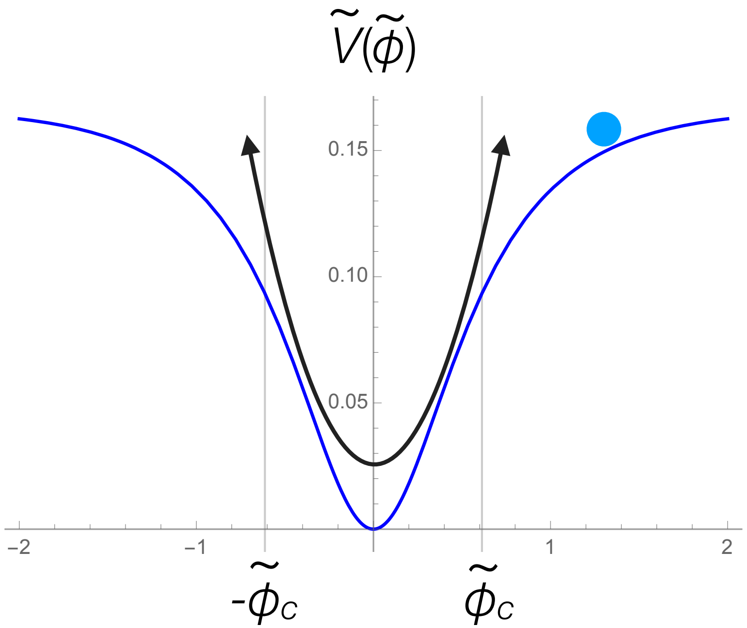




tachyonic instability

Instability in phase 2

$\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0 \longleftrightarrow \tilde{V}_{\tilde{\phi}\tilde{\phi}} > 0$



$$\frac{d^2}{d\tilde{t}^2}\chi_k + \omega_k^2\,\chi_k = 0$$

$$\omega_k^2 \equiv \left(\frac{k}{ma}\right)^2 + \tilde{V}_{\tilde{\phi}\tilde{\phi}}$$

$\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$	$\tilde{V}_{\tilde{\phi}\tilde{\phi}} > 0$	$\tilde{V}_{\tilde{\phi}\tilde{\phi}} < 0$
$\omega_k^2 < 0$	$\omega_k^2 > 0$	$\omega_k^2 < 0$

~~Adiabatic condition~~

Broad res.? Tachyonic inst. like phase 1?

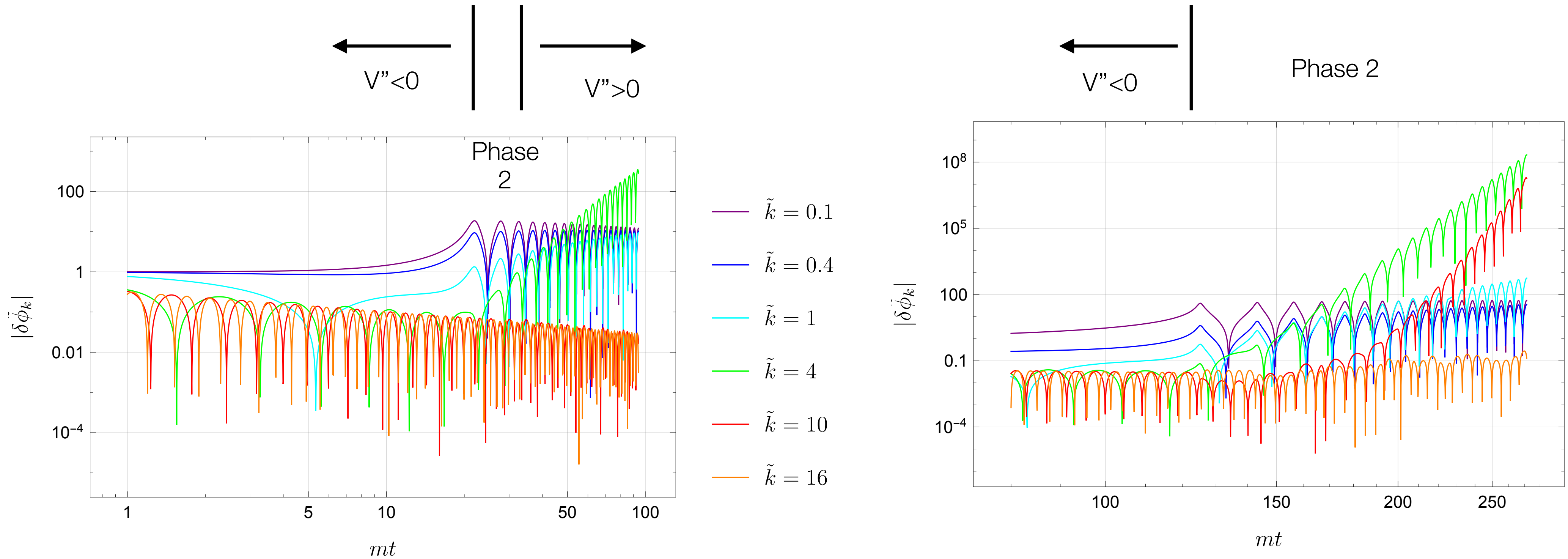
- Tachyonic instability

- To shorten ②, larger k

$$\left.\frac{k}{am} \leq \sqrt{|\tilde{V}_{\tilde{\phi}\tilde{\phi}}|}\right\} \longrightarrow \frac{k_{\rm peak}}{a_{\rm res} m} \simeq \sqrt{|\tilde{V}^{(\rm plat)}_{\tilde{\phi}\tilde{\phi}}|}$$

Two instabilities for plateau axion

Kitajima, Soda & Y.U. (18)



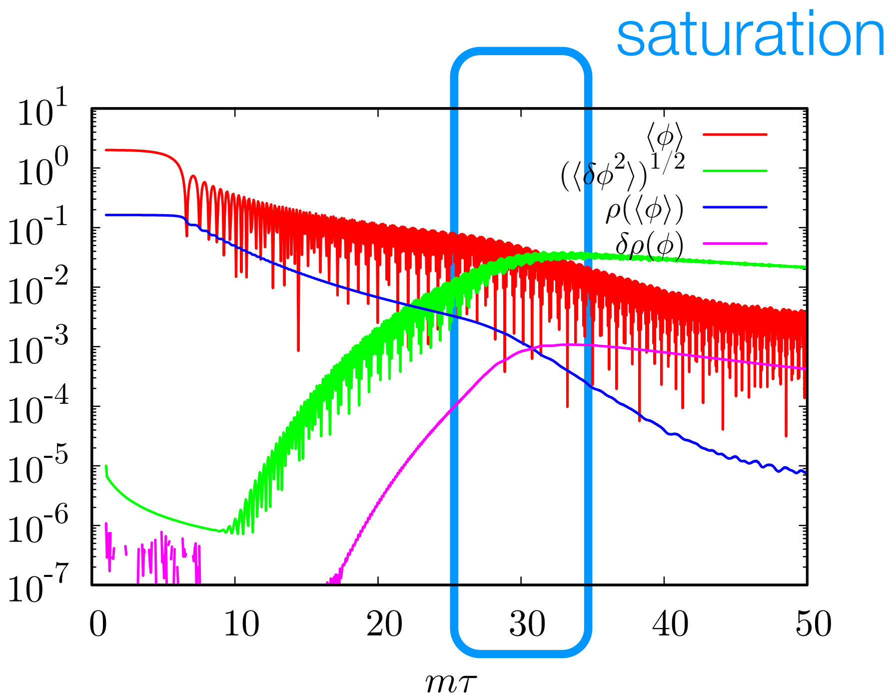
Narrow res. dominant

Flapping res. dominant

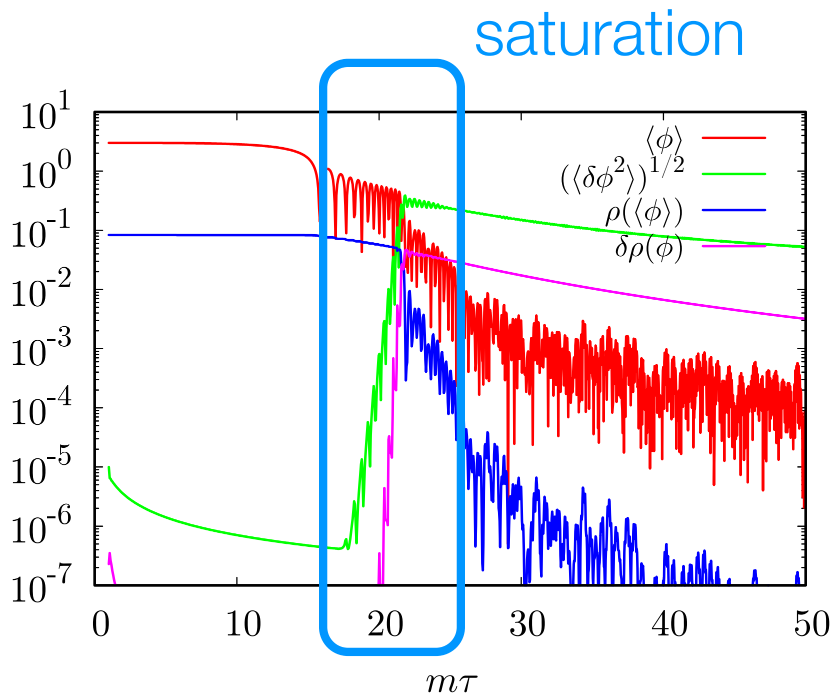
- broader peak
- Much more efficient

Lattice simulation

Kitajima, Soda & Y.U. (18)



(b) $c = 2, \phi_i = 2f$



(a) $c = 5, \phi_i = 3f$

Narrow res. dominant

Phase 2: Short

Flapping res. dominant

Phase 2: Long

Lattice simulation $N_{grid}=(256)^3$

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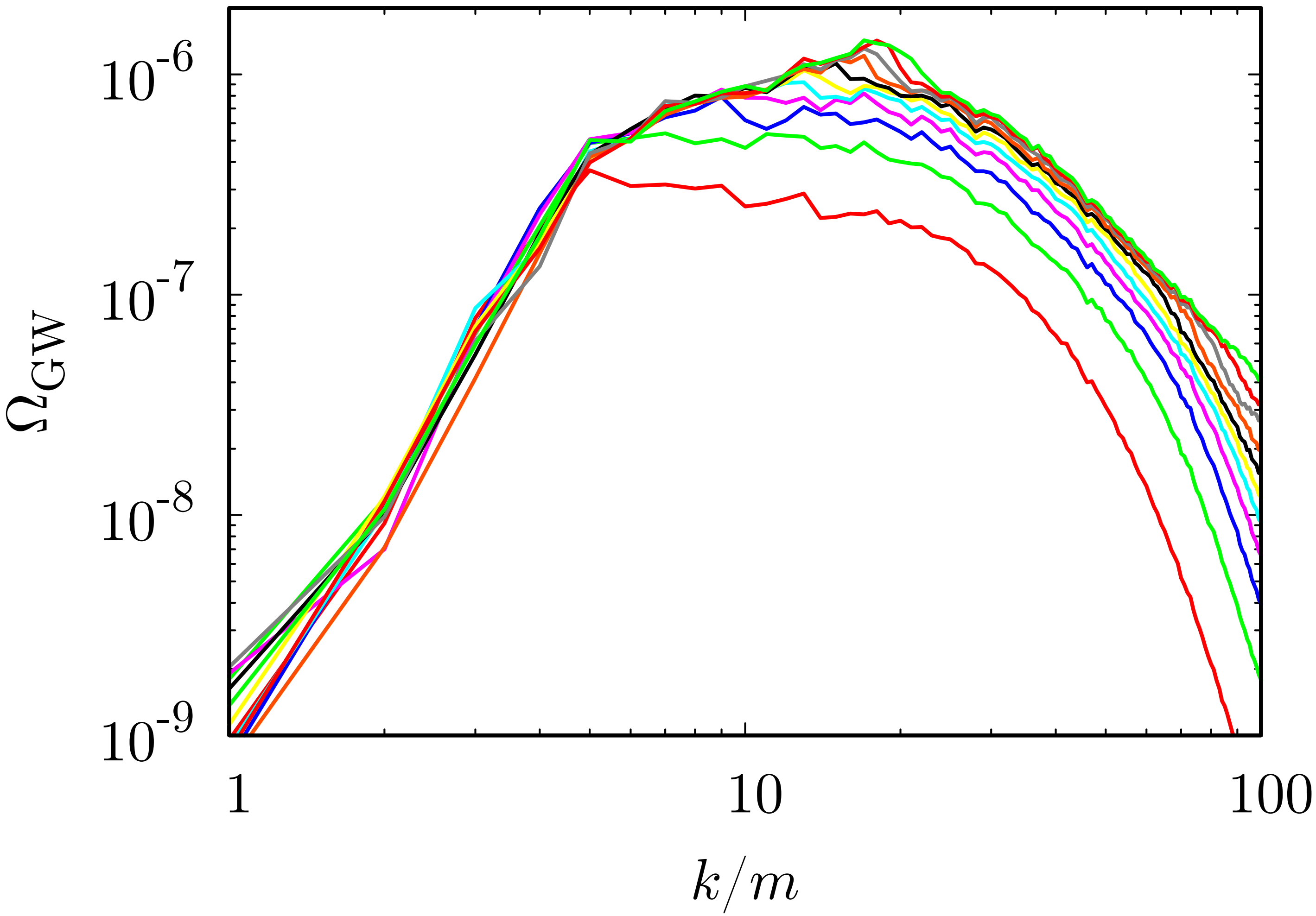
GW spectrum



$f = 10^{16}$ GeV, $c = 5$ and $\phi_i = 3f$

to evaluate the present value, x Ω_r

GW's frequency

Kitajima, Soda & Y.U. (18)

<u>Redshifted frequency</u>

$$\nu_0 = \frac{\kappa m}{2\pi}\left(\frac{a_{\rm em}}{a_0}\right)$$

$$\kappa \equiv \frac{\omega_{\rm phys}}{m} = \frac{k^{\rm em}_{\rm peak}}{m\, a_{\rm em}} = \frac{k^{(res)}_{\rm peak}}{m\, a_{\rm res}} \times \underline{\frac{k^{(em)}_{\rm peak}/a_{\rm em}}{k^{(res)}_{\rm peak}/a_{\rm res}}}$$

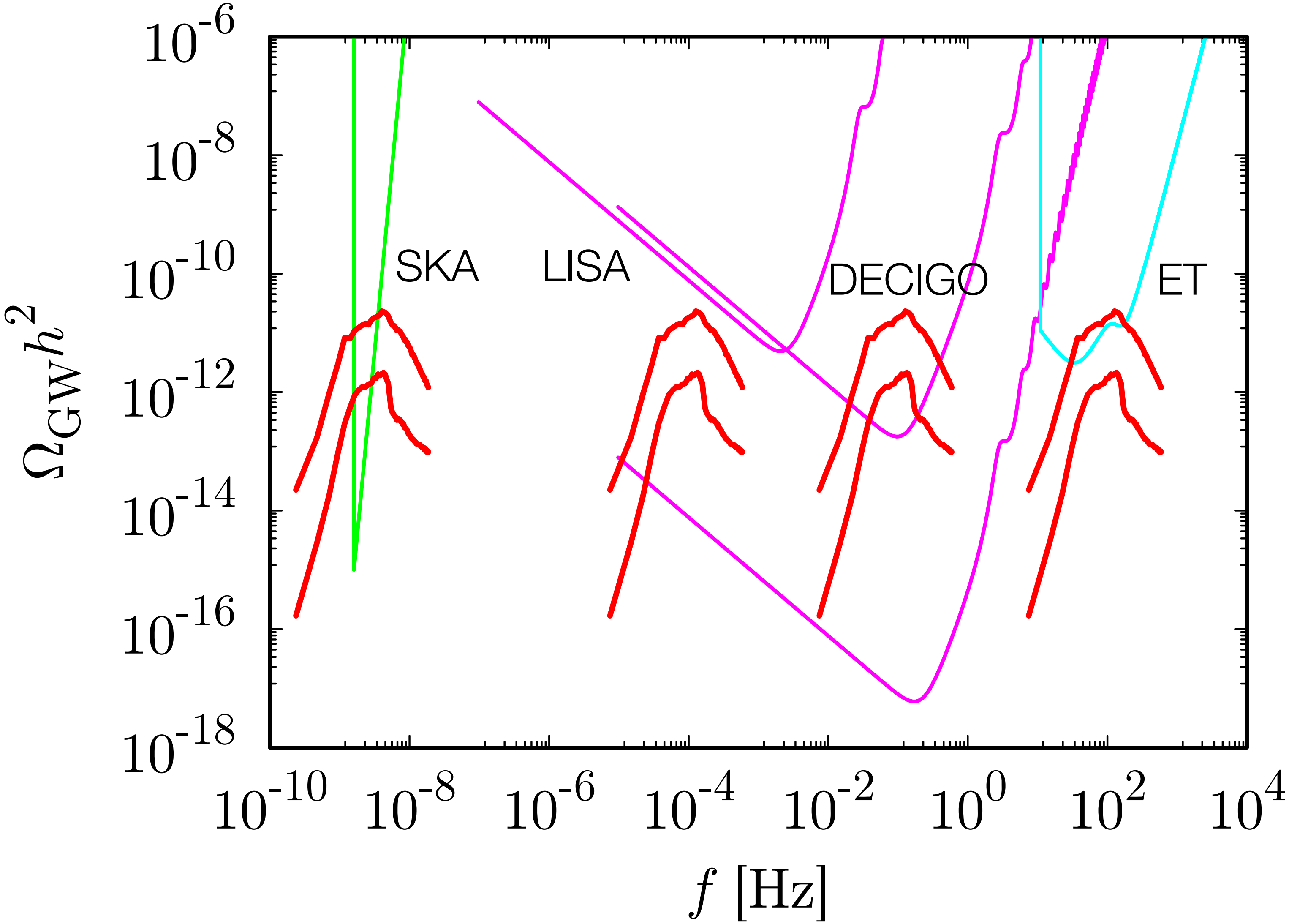
momentum flow due to turbulence

e.g. GWs emitted during radiation domination

$$\nu_0 = \frac{\kappa m}{2\pi} \times \left(\frac{\rho_{\rm r,0}}{\rho_{\rm r,\,em}}\right)^{1/4} \simeq 0.78 {\rm nHz}\, \kappa \left(\frac{m}{H_{\rm em}}\right)^{1/2} \left(\frac{m}{10^{-12}{\rm eV}}\right)^{1/2}$$

GW forest

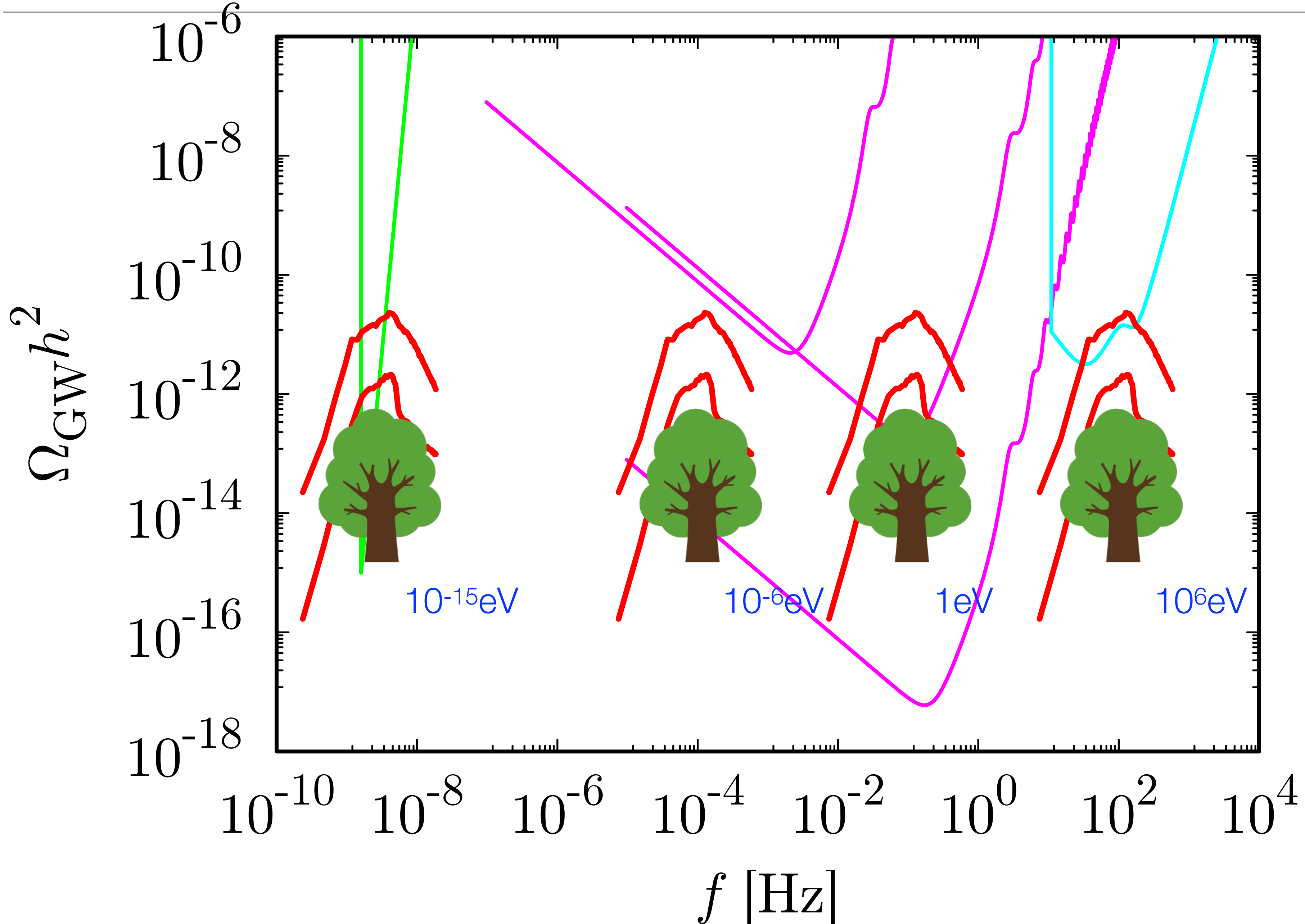
Kitajima, Soda & Y.U. (18)



Axions from string theory $\quad$ $f \sim 10^{16}$ GeV $\quad$ *e.g.,Svrcek & Witten (06)*

GW forest

Kitajima, Soda & Y.U. (18)



GWs from axion DM

Kitajima, Soda, Y.U. (18)

freq. of GW ***f₀*** ⟶ mass ***m***

+

abundance of axion ⟶ decay const. ***f*** x mass ***m***

<u>Crude Order estimation</u>

using $\varphi(t, x) \sim f\,(a_{\rm osc}/a)^{3/2}$

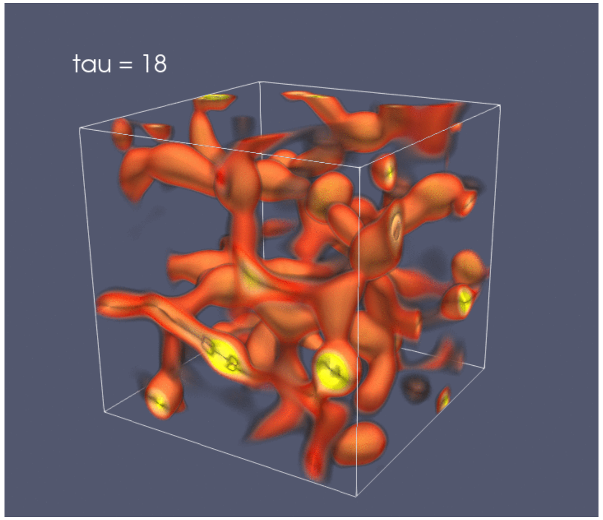
Δ : Sym. suppression (< 1)

$$\Omega_{\rm GW}h^2 \simeq 0.8 \times 10^{-18}\kappa^4\Delta^2\left(\frac{\rm nHz}{\nu_0}\right)^2(\Omega_\phi h^2)^2$$

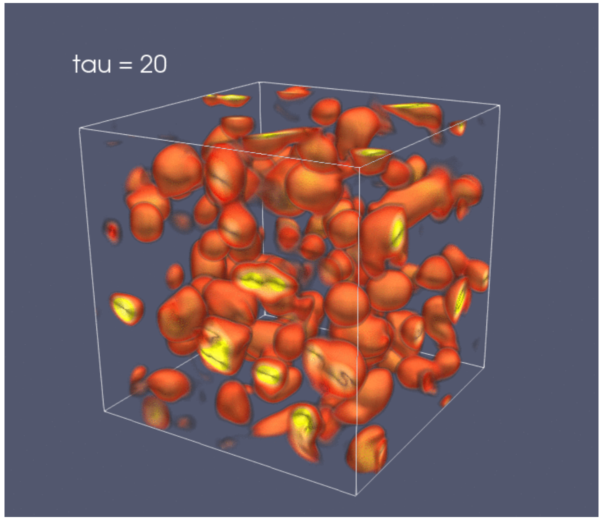
for κ=10 $\Omega_{\rm GW}h^2 \simeq 10^{-16}$ at $\nu_0 =$nHz

or lower frequency btwn CMB & PTAs?

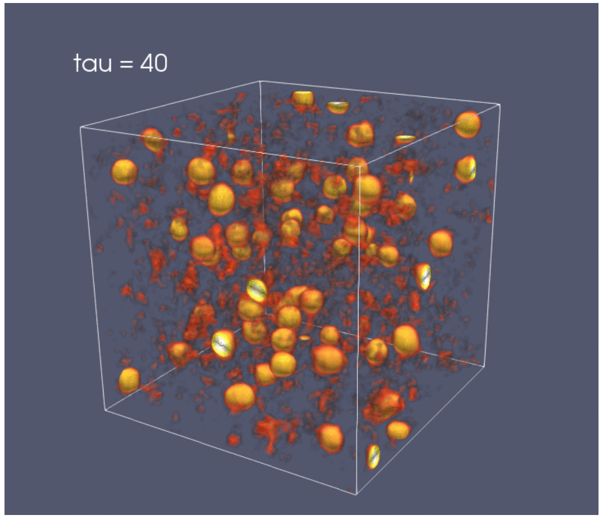
Oscillon formation



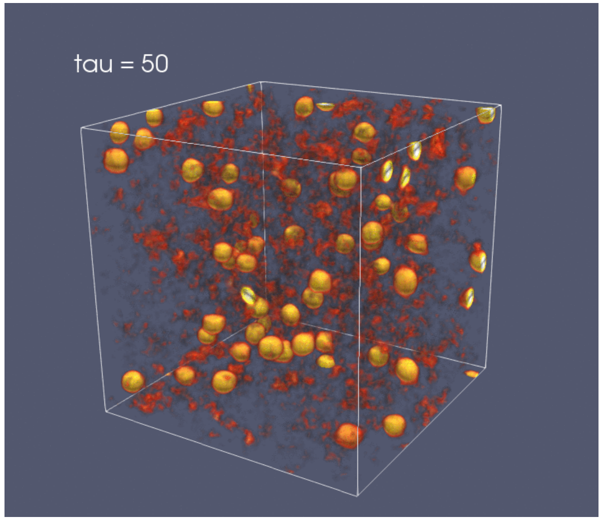
(a)



(b)



(c)



(d)

$N_{grid}=(256)^3$

$c = 5$ and $\phi_i = 2f$.

The red, yellow and white region correspond to $\rho/\bar{\rho} > 2$, 4 and 10

Summery

New window of axions in plateau

Theory side

Various instabilities for scalar fields who are initially located at plateau region.

Keys: Delayed oscillation, Flapping term (Phase 2)

Phenomenology side

Predicts bGWs at various frequencies, multi-band obs.?

GWs from axion DM: sweet spot is btwn CMB & PTAs.