Gravitational wave spectra from oscillon formation after inflation

"Gravitational wave spectra from oscillon formation after inflation",
TH, Sfakianakis, Yamaguchi, JHEP 03 (2021) 021

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Collaboration with Evangelos Sfakianakis (IFAE), Masahide Yamaguchi (TiTech)

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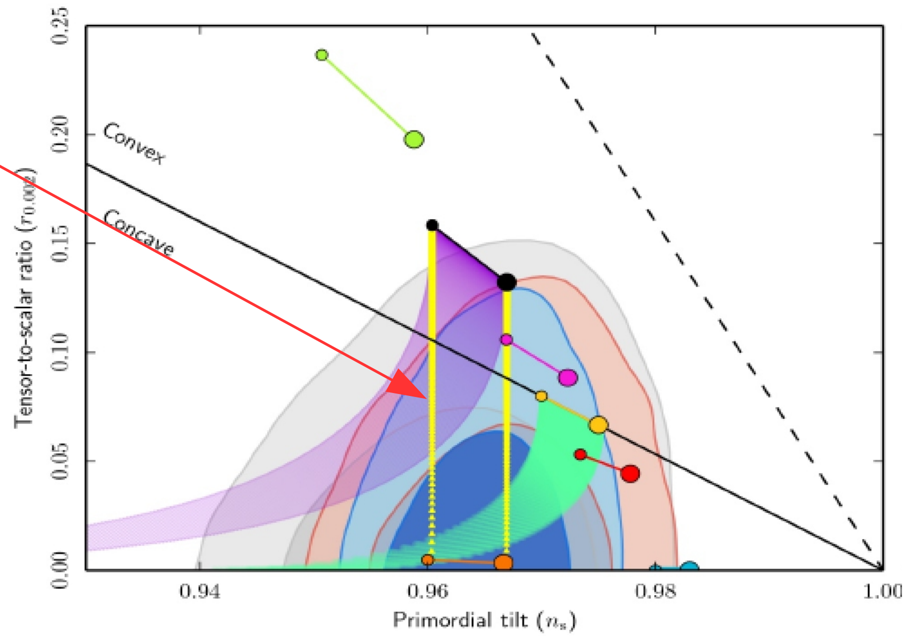
α-attractor model



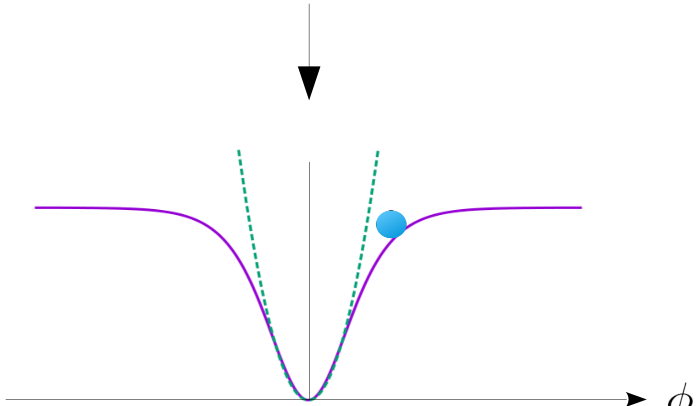
Planck Collaboration, A&A 594 (2016) A13

Looks fine.

But, what if the reheating phase is taken into account ?

Oscillon in reheating phase

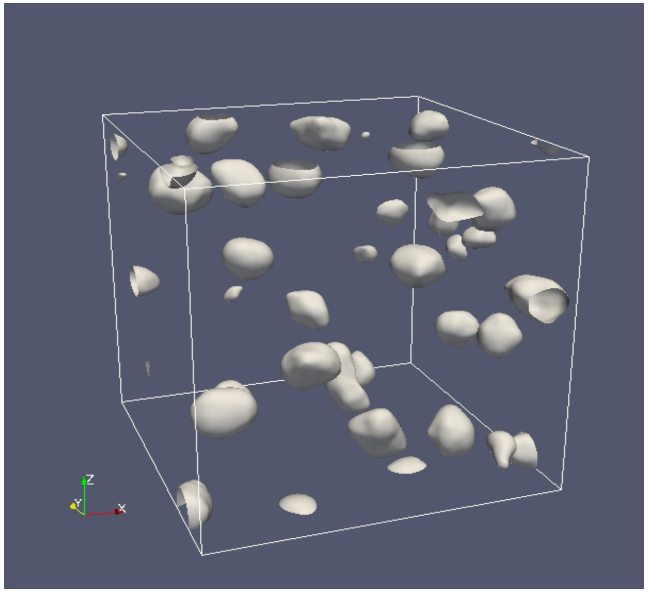
α -attractor model



flatter than $m^2\phi^2$

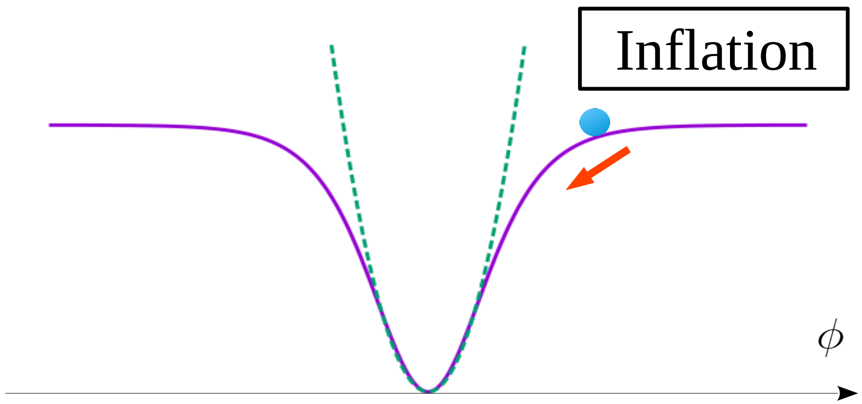
Inflaton can take large field values

Parametric resonance drives oscillon formation

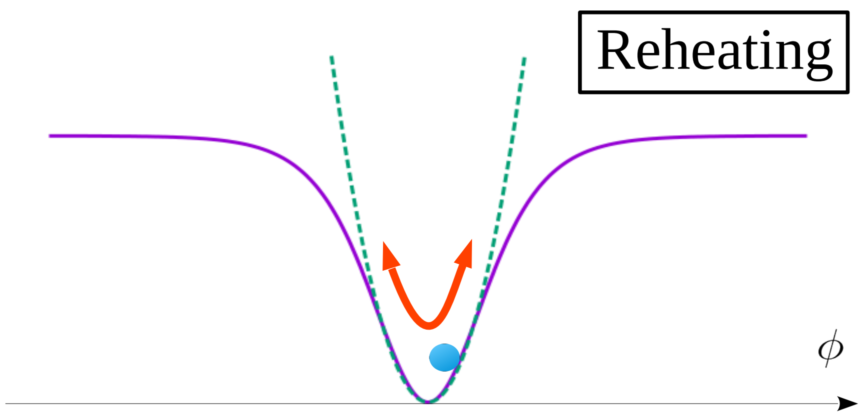


Pioneer works :

Bogolyubosky, Makhankov, PZETF 24 (1976) 15
Gleiser, PRD 49 (1994) 2978
Copeland, Gleiser, Muller, PRD 52 (1995) 1920

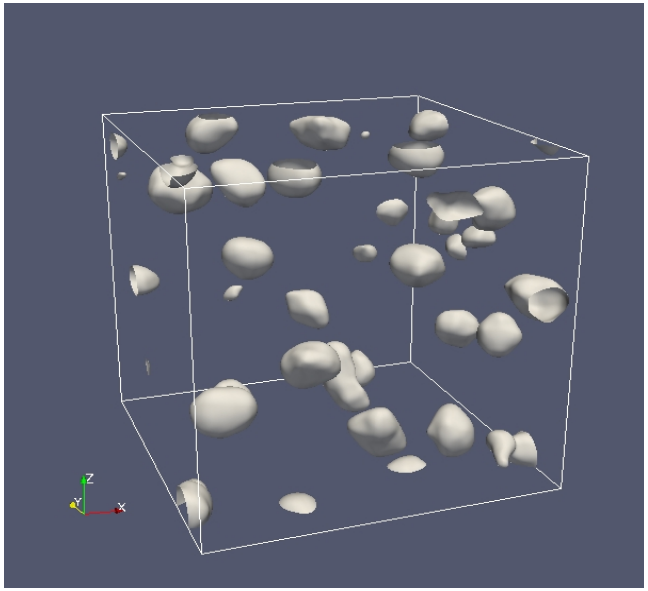


$$\ddot{\overline{\phi}} + V'(\overline{\phi}) = 0$$

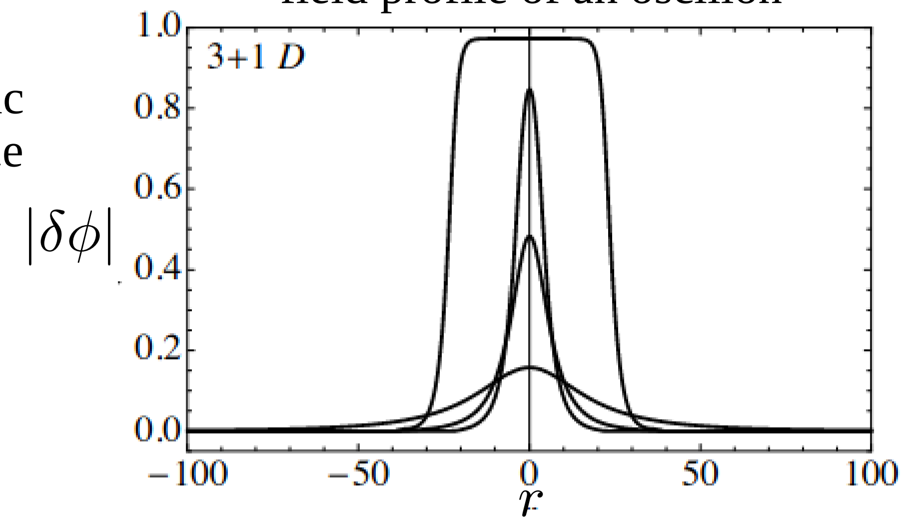


$$\phi(t, \boldsymbol{k}) = \overline{\phi}(t) + \delta\phi(t, \boldsymbol{k})$$
$$\ddot{\delta\phi}(t, \boldsymbol{k}) + (k^2 + V''(\overline{\phi}))\delta\phi = 0$$

parametric resonance



field profile of an oscillon



Amin, Shirokoff, PRD 81 (2010) 085045

Oscillon in reheating phase

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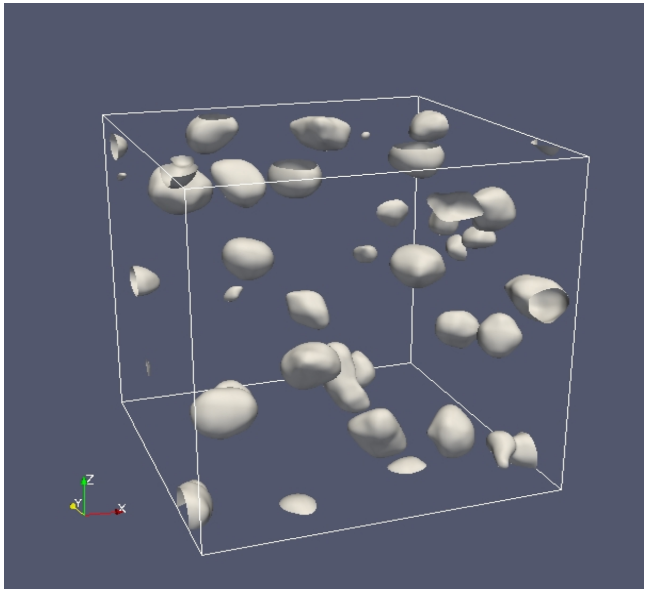
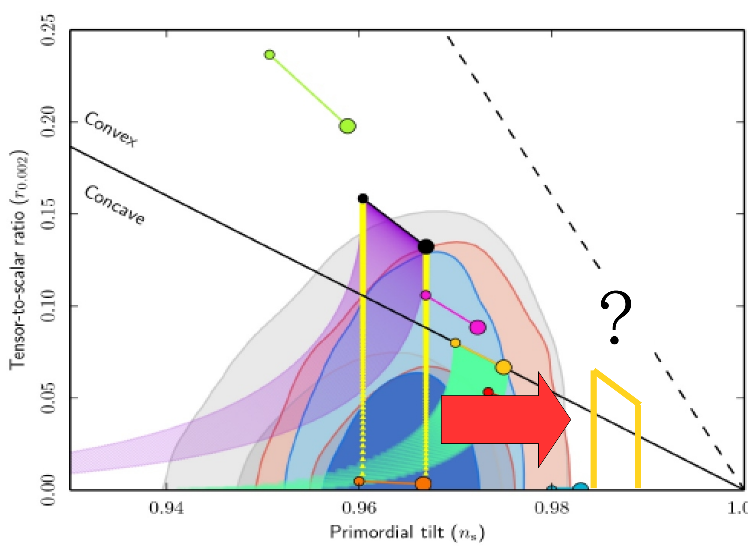


Physical properties of oscillons
- number density
- size distribution
- life-time
- decaying mechanism   etc.

depend on the shape of potential.

Long-living oscillons possibly modify cosmic expansion history after inflation

extra e-fold shifts the current prediction ?



First goal of this work

Perform 3D field-theoretic simulations of inflaton with various kinds of potentials, and clarigy the impact of potential shape on oscillons

* time-evolution of number density
* size distribution
* GW spectrum → unique signal ?

Related works :

Analytic estimation of oscillon decay

Ibe, Kawasaki, Nakano, Sonomoto, JHEP 1904 (2019) 030

GWs from oscillons with axion potential

Kitajima, Soda, Urakawa, JCAP (2018) 008

GWs & scalar perturbations from oscillons & transients

Lozanov, Amin, PRD 99 (2019) 123504

etc.

Field equations & spectrum

Field equations

$$S = -\int d^4x \sqrt{-g}\left(\frac{m_{\rm pl}^2}{2}R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + V(\phi)\right)$$

$$\longrightarrow \begin{cases} \phi'' + 2\mathcal{H}\phi' - \triangle\phi = -a^2\dfrac{dV}{d\phi} \\ h''_{ij} + 2\mathcal{H}h'_{ij} - \triangle h_{ij} = \dfrac{2}{m_{\rm pl}^2}\partial_i\phi\partial_j\phi \end{cases}$$

prime = derivative with respect to conformal time

+ (irrelevant terms for GWs)

Cosmic expansion

$$\mathcal{H}^2 = \frac{a^2}{3m_{\rm pl}^2}\langle\rho_\phi\rangle \qquad \rho_\phi = \frac{1}{2a^2}\phi'^2 + \frac{1}{2a^2}(\partial\phi)^2 + V$$

GW spectrum

$$\Omega_{\rm GW}(k,\tau) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log k} \qquad \rho_{\rm GW} = \frac{m_{\rm pl}^2}{4a^2}\langle h'_{ij}h'_{ij}\rangle$$

Numerical setup

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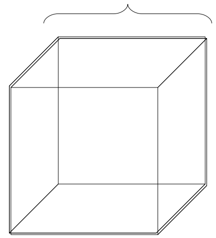
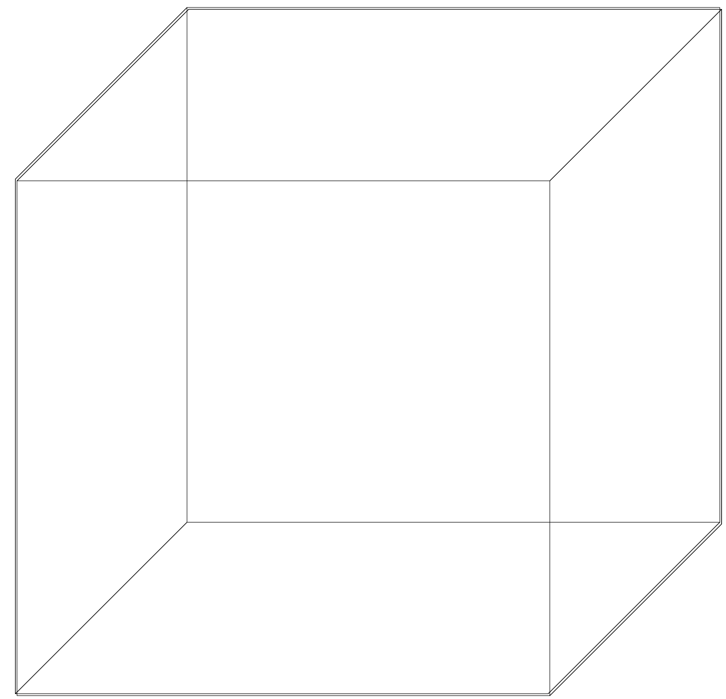
Inflaton mass

$N = 256^3$

$L = 60m^{-1}$



(periodic BC)



$a(0) = 1$

$\tau = 0$

(conformal time)

$a(\tau_f) \sim 3 \sim 4$

$\tau = 600m^{-1}$

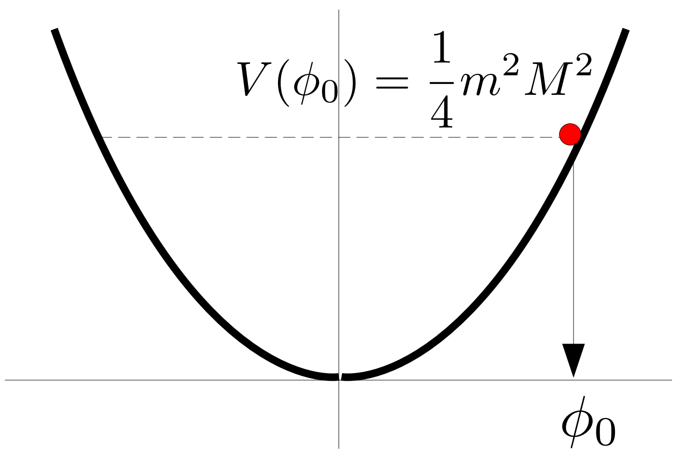
Initial condition

$$\boxed{\phi(\boldsymbol{x},0) = \phi_0 + \delta\phi(\boldsymbol{x})}$$

$$V(\phi_0) = 0.25 m^2 M^2$$
$$(\phi_0 \sim M)$$

$$P_{\delta\phi}(k) = \frac{1}{2k}$$

Vacuum fluctuations in the Minkowski space-time



Model parameters

$$\begin{cases} M = 10^{-2} m_{\rm pl} \\ m = 10^{-4} m_{\rm pl} \end{cases} \longrightarrow \begin{cases} H_{\rm in}^{-1} = \dfrac{\sqrt{12} m_{\rm pl}}{mM} \gg L \\ A_s \approx 10^{-9} \end{cases}$$

Small-field shape

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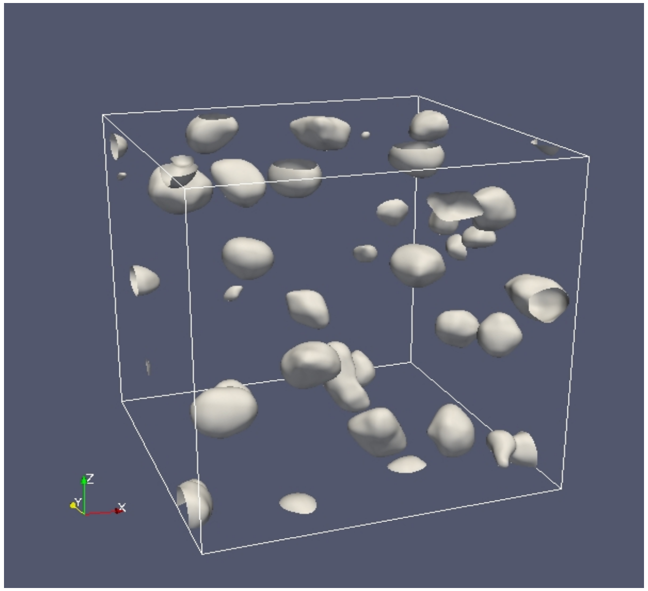
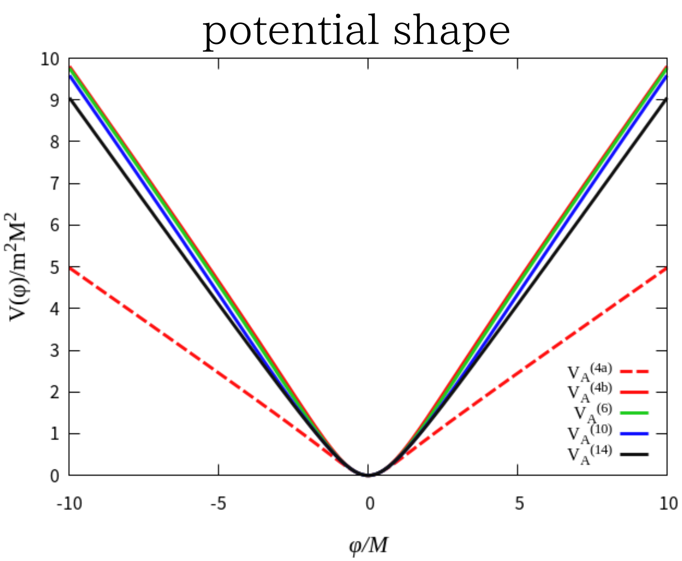
$$V_A(\phi) = m^2 M^2 \left[\left(1 + \frac{\phi^2}{M^2} \right)^{1/2} - 1 \right]$$

Zhou et al., JHEP 1310 (2013) 026
Amin et al., PRL 108 (2012) 241302



$$V_A^{(n)} \approx V_A + \mathcal{O}(x^n) \qquad x := \phi/M$$

$$\begin{cases} V_A^{(4)}(\phi) = m^2 M^2 \dfrac{x^2}{\sqrt{4+x^2}} \\ V_A^{(6)}(\phi) = m^2 M^2 \dfrac{x^2}{\sqrt{1+x^2}} \dfrac{2+x^2}{4+x^2} \\ V_A^{(10)}(\phi) = m^2 M^2 \dfrac{x^2}{\sqrt{1+x^2}} \dfrac{8+8x^2+x^4}{16+12x^2+x^4} \end{cases}$$

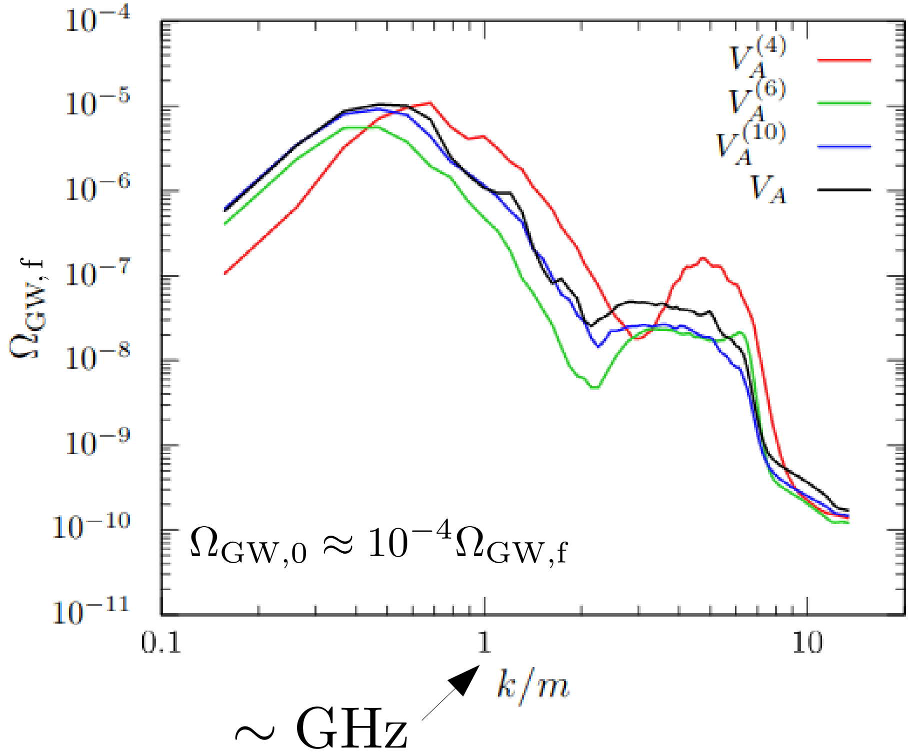


Small-field : deviates from $V_A(\phi)$

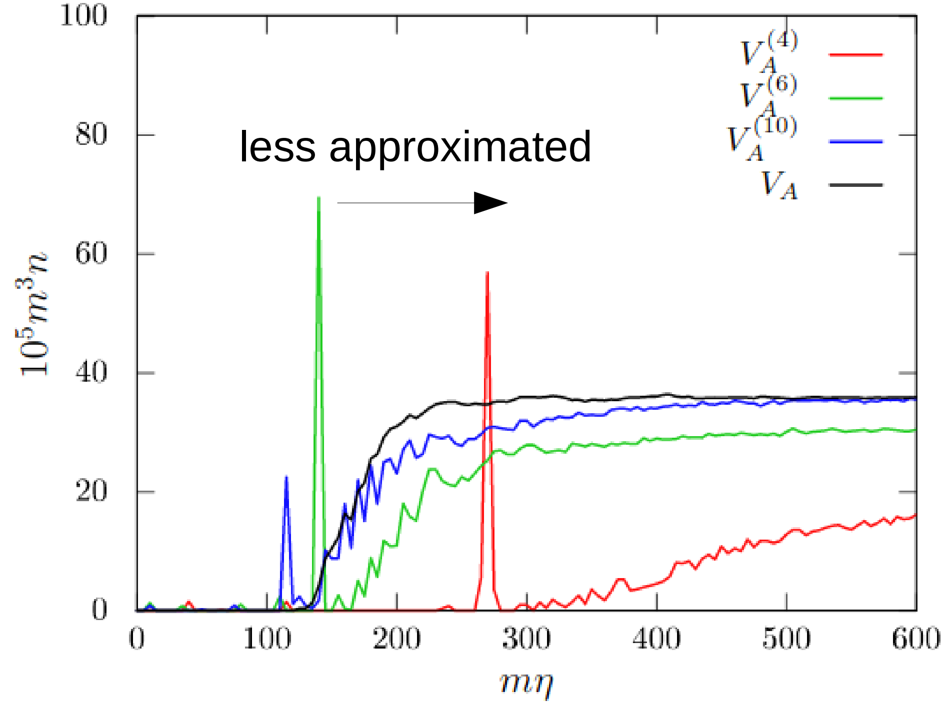
Large-field : has the same power as $V_A(\phi) \propto \phi$

Results : small-field shape

Gravitational waves
@ simulation end



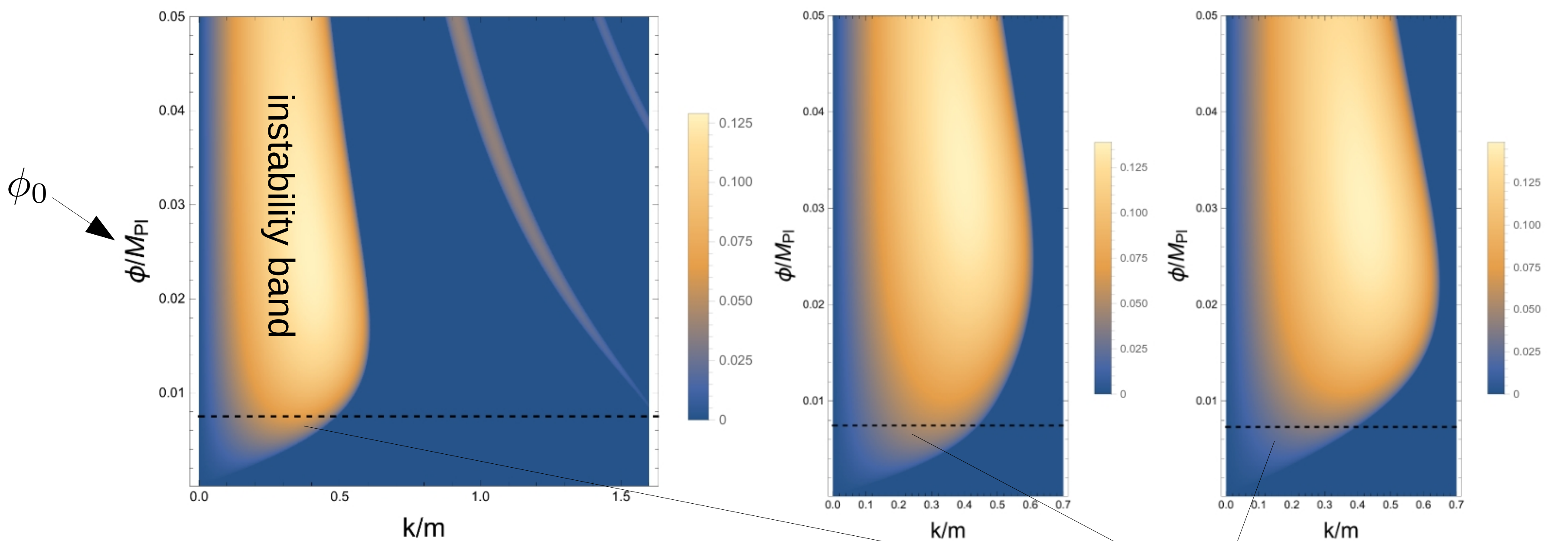
Number of oscillons
(comoving number density)



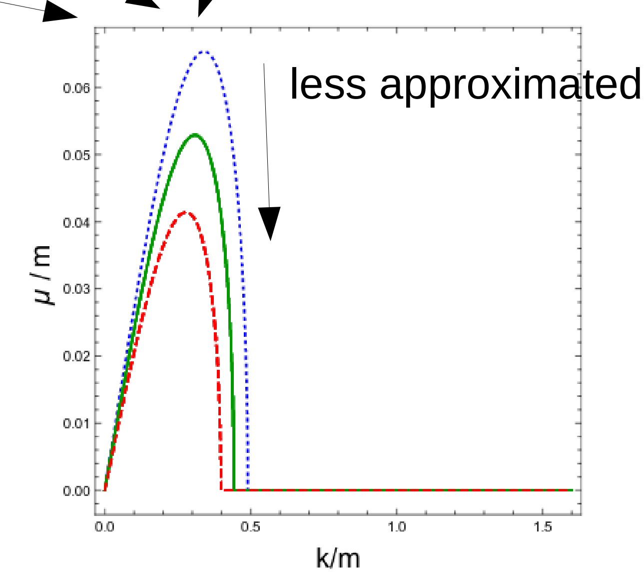
Formation time : highly sensitive

Number : highly sensitive

GW spectrum : sensitive (weak mode mixing due to delayed formation)



Significance of instability is characterised by $\delta\phi \propto e^{\mu(k)t}$



For a less approximated case,

the significance and the width are suppressed.

→ formation is delayed; number is suppressed

Large-field shape

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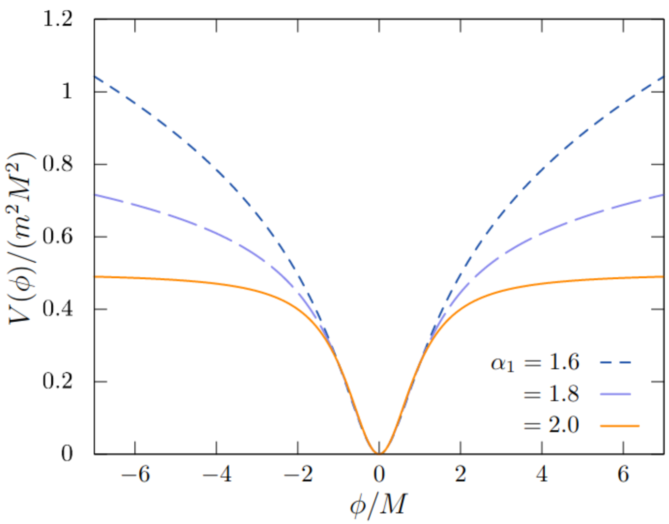
Construct model potentials varying large-field shape

Note : the fiducial potential is now $V_1(\phi;\alpha_1=2)$, not V_A.

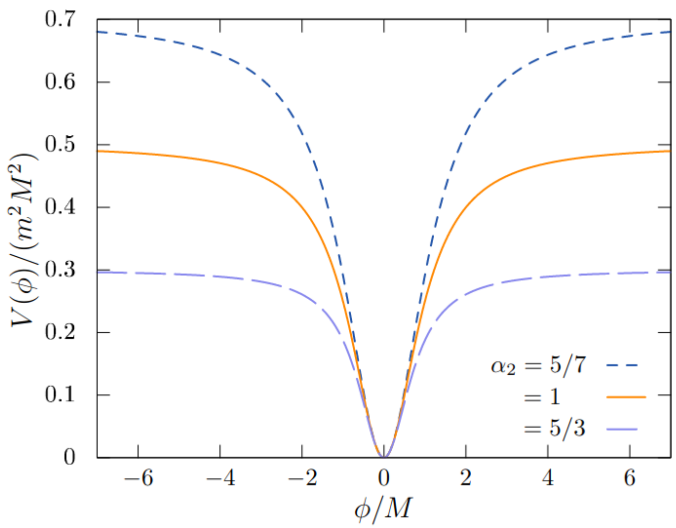
Asymptotic power

$$V_1=\frac{1}{2}m^2M^2\frac{(\phi/M)^2}{1+|\phi/M|^{\alpha_1}}$$



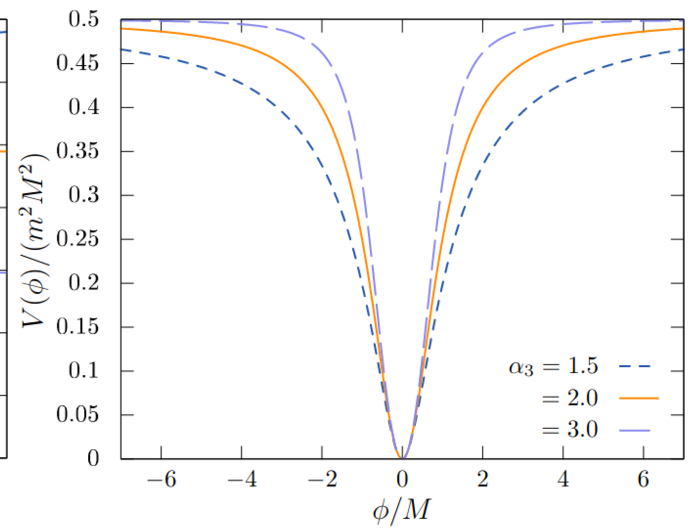
Asymptotic amplitude

$$V_2=\frac{1}{2}m^2M^2\frac{(\phi/M)^2}{1+\alpha_2(\phi/M)^2}$$



Width

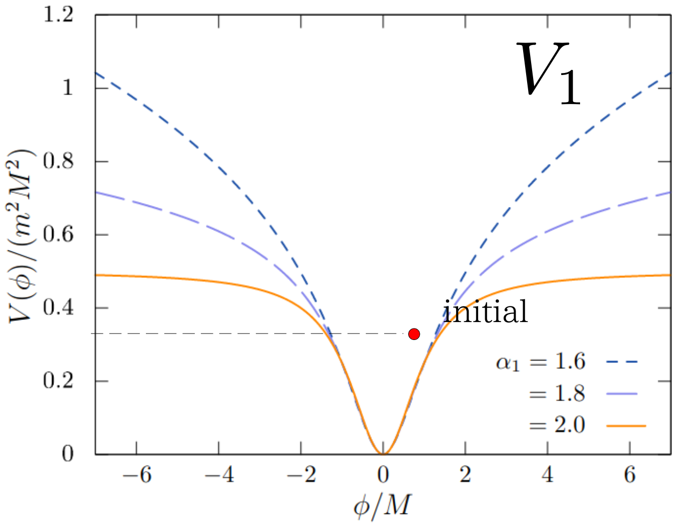
$$V_3=\frac{1}{2}m^2M^2\frac{(\phi/M)^2}{[1+|\phi/M|^{\alpha_3}]^{2/\alpha_3}}$$

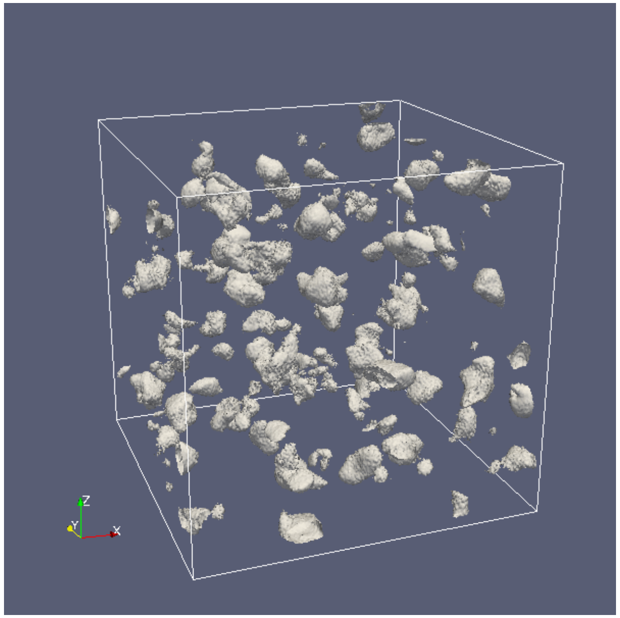


As a reference : $V_1(\phi;\alpha_1=2)$

Results : Potential 1

Inflaton potential





m97c1 (2.0) @ t=400

GW

Insensitive

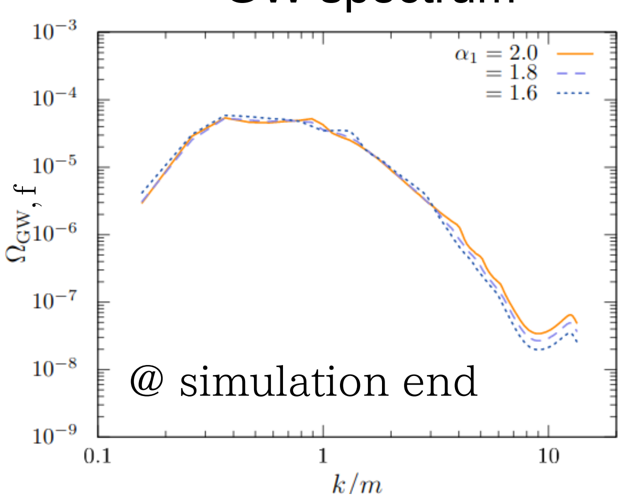
Number of oscillons

Insensitive

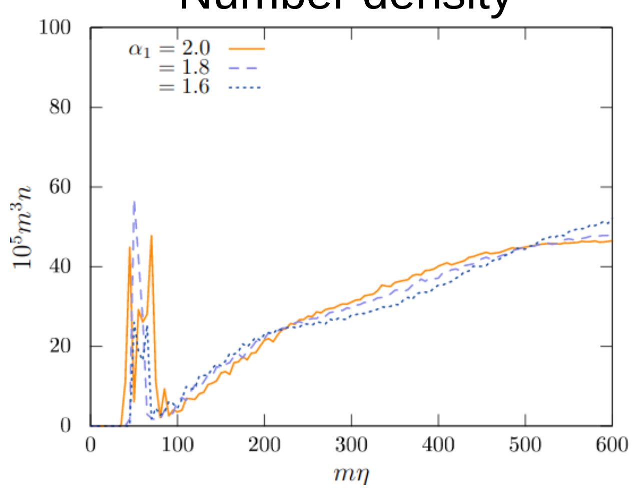
Size distribution

Not so sensitive

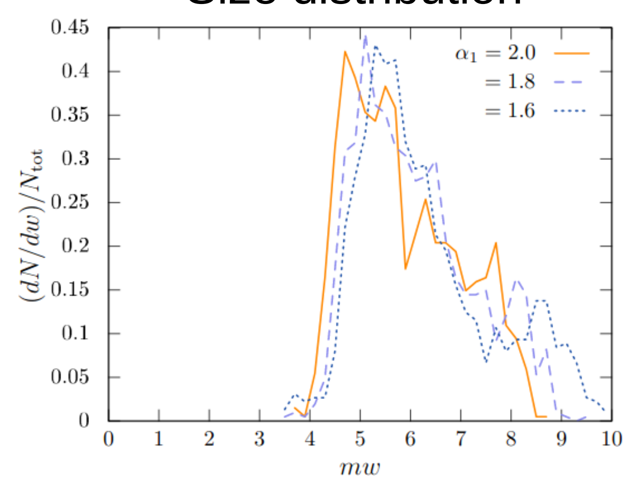
GW spectrum



Number density



Size distribution



Results : Potential 2

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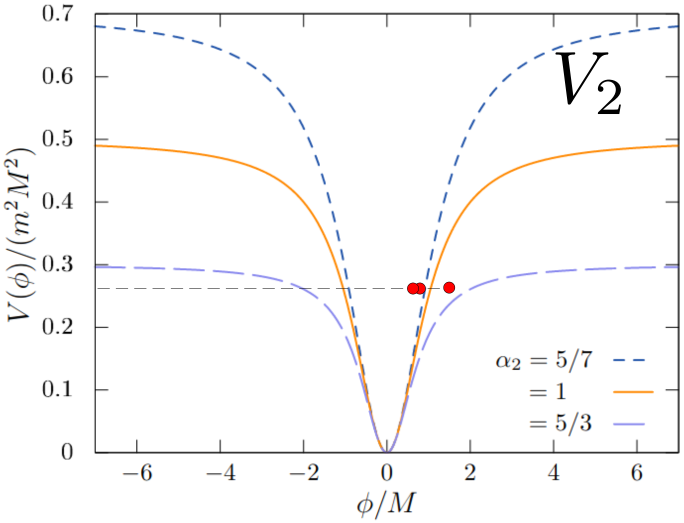
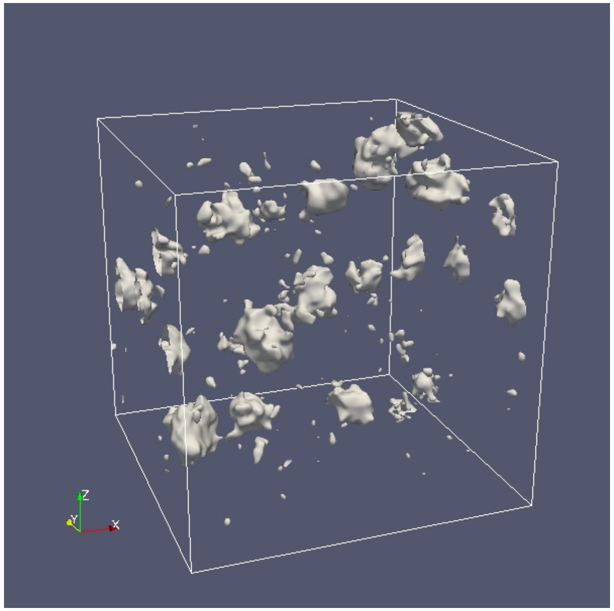
Inflaton potential





m28b1 (0.714) @ t=400

GW

Not so sensitive

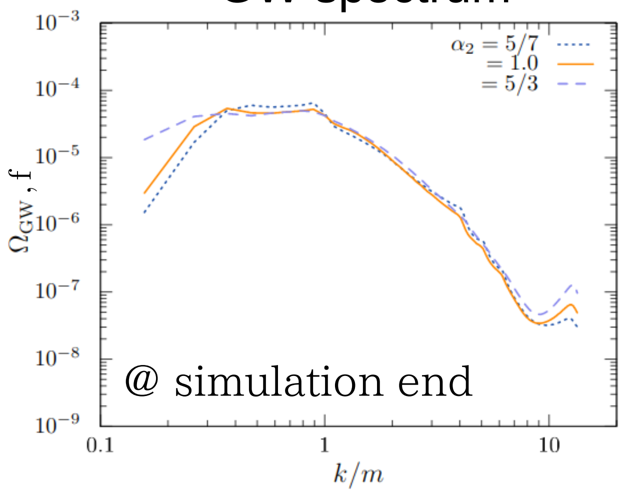
Number of oscillons

Highly sensitive

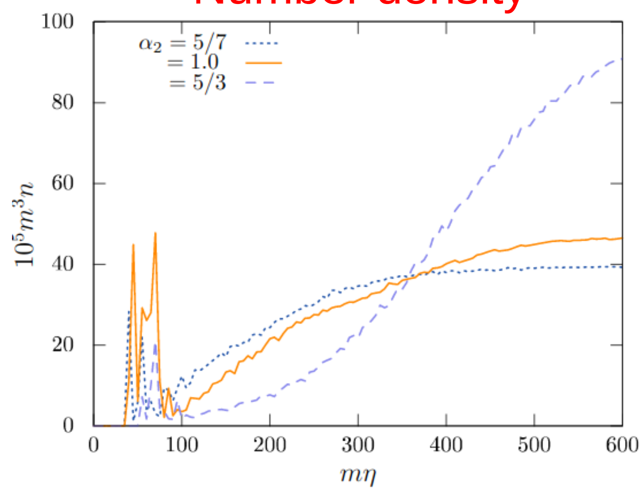
Size distribution

Not so sensitive

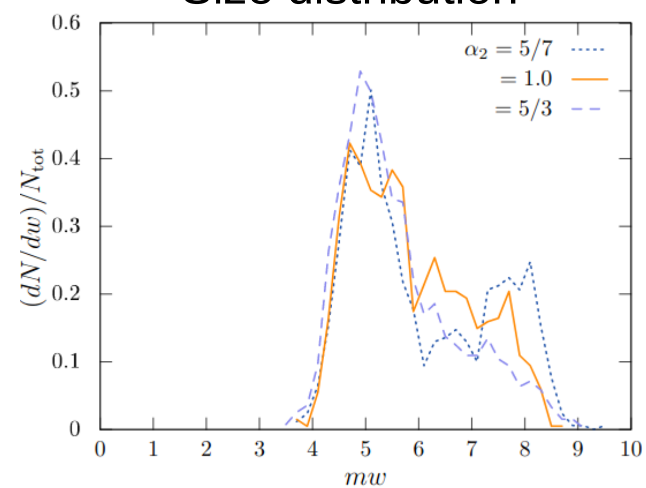
GW spectrum



Number density



Size distribution



Results : Potential 3

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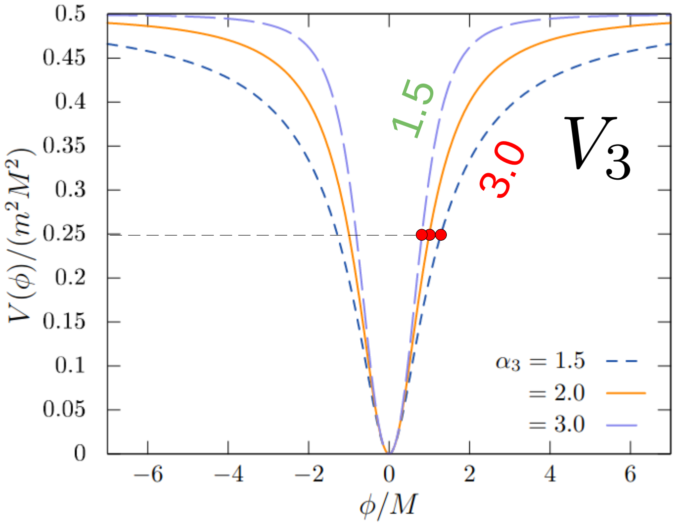
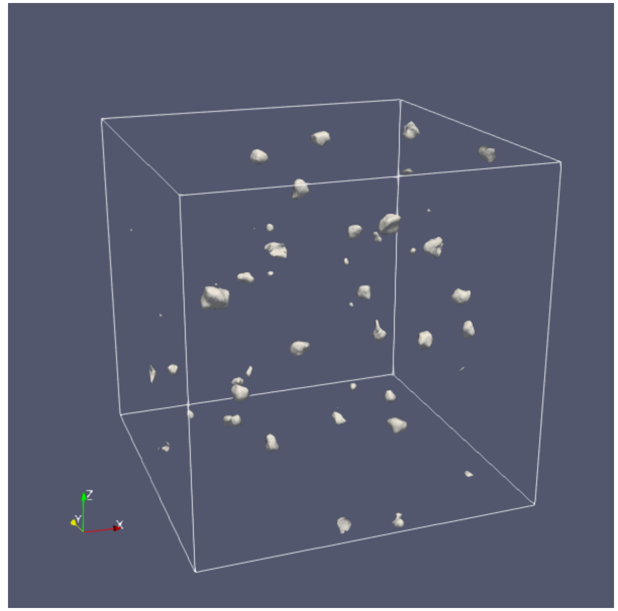
Inflaton potential





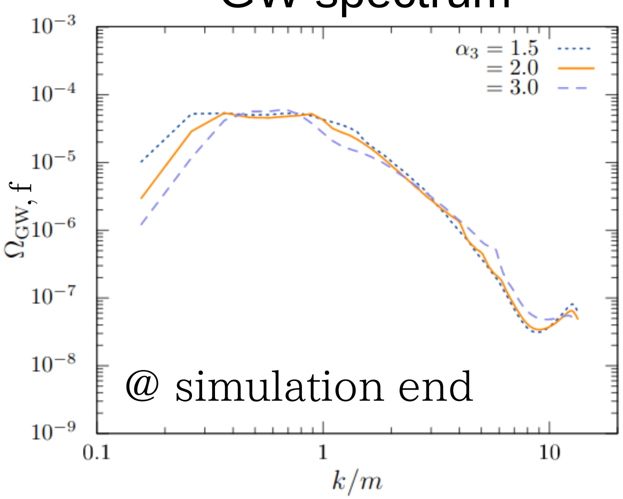
m105c1 (1.5) @ t=200

GW
Not so sensitive

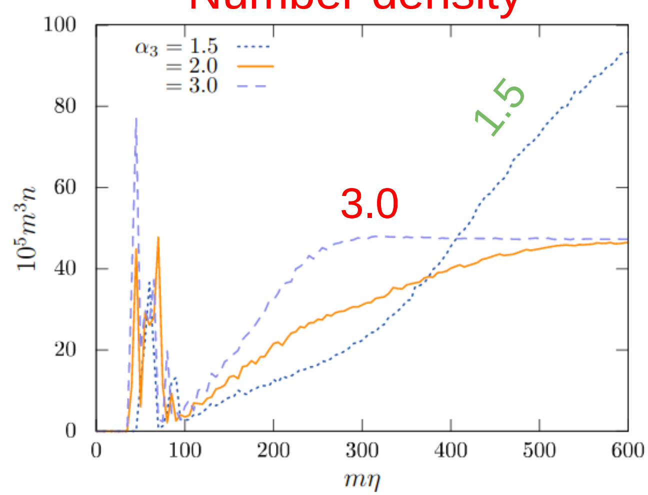
Number of oscillons
Highly sensitive

Size distribution
Not so sensitive

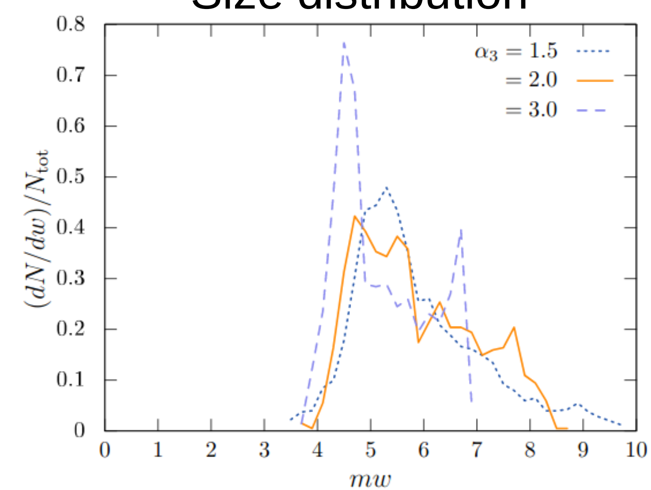
GW spectrum



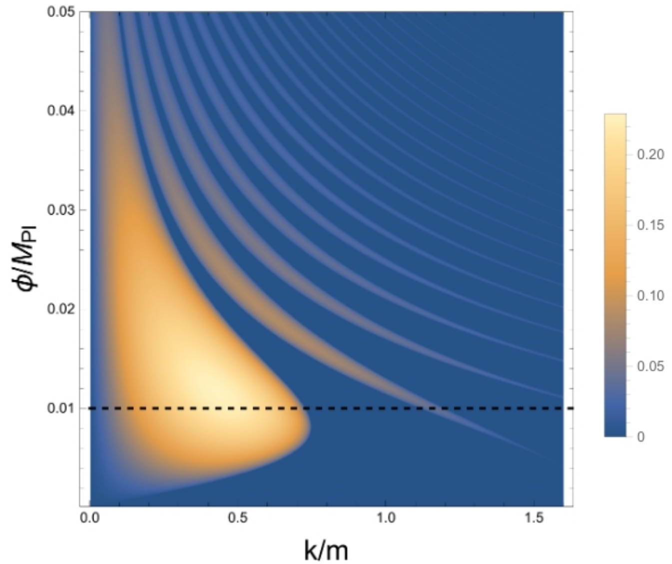
Number density



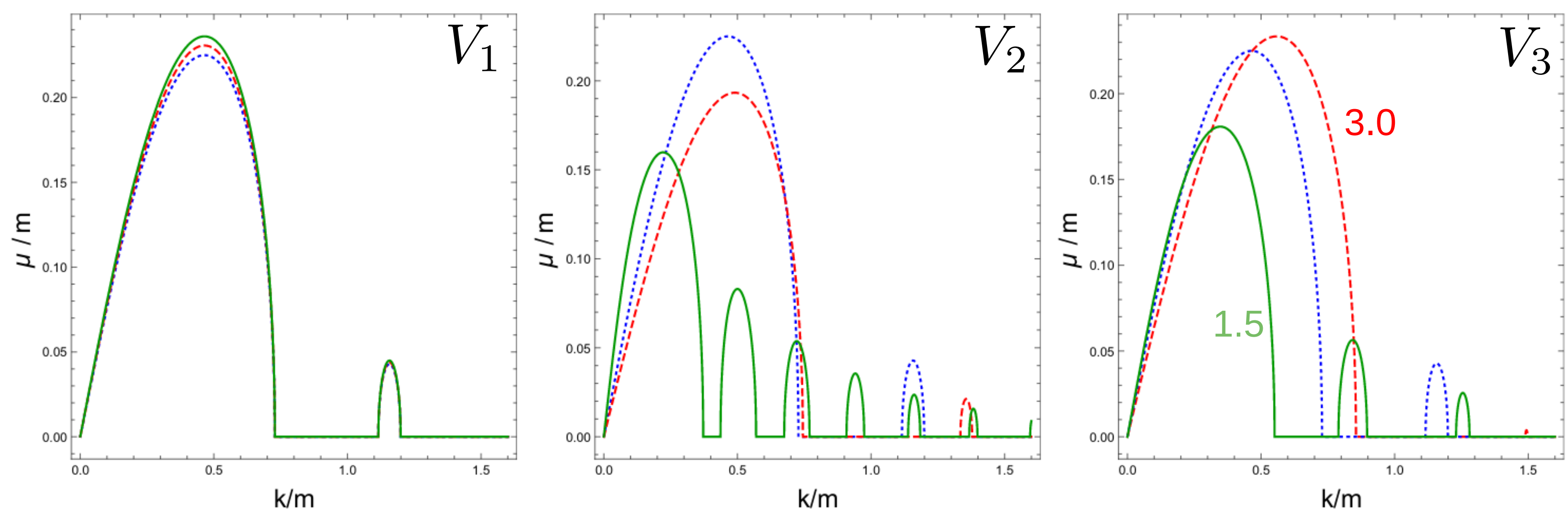
Size distribution



Results : Floquet chart



In the weird cases with $V_2(\alpha_2 = 5/3)$ and $V_3(\alpha_2 = 1.5)$, the self-resonance is weaker and there are more instability bands than the fiducial case.



$\alpha_1 = 1.6, 2.0, 1.8$ $\alpha_2 = 5/7, 1.0, 5/3$ $\alpha_3 = 3.0, 2.0, 1.5$

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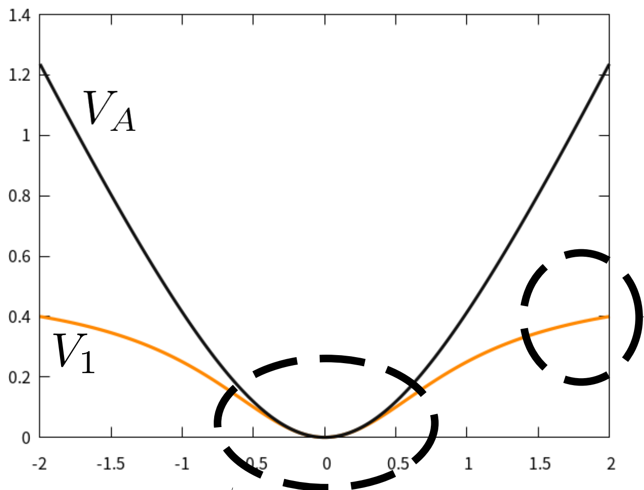
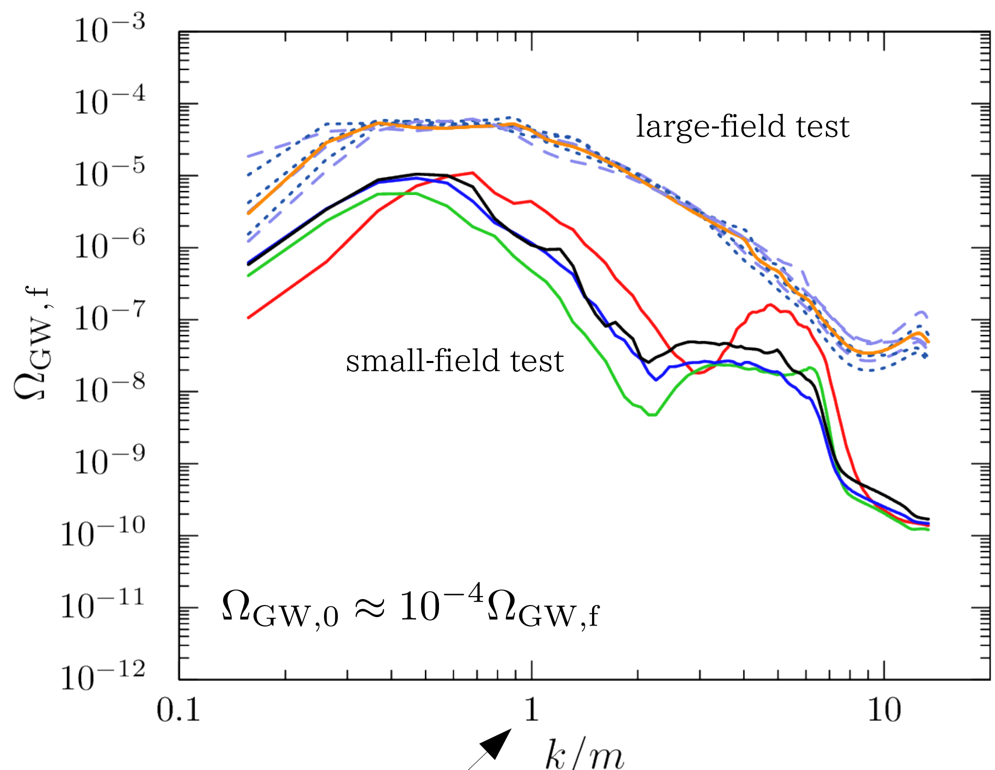


oscillon shape, number density (life-time ?)

formation efficiency
(instability driven by
parametric resonance)

GWs spectrum

(Large anisotropy is induced
only at the early time.)



typically $\sim$ GHz

Motivation

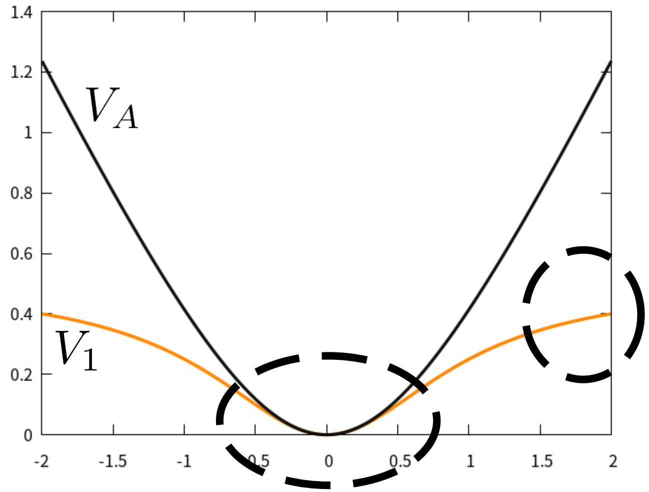
Oscillons in reheating epoch modify the current observational results for inflation ?

What we did

Study the oscillon's properties and associating GW spectra
by performing field-theoretic simulations with various potentials

Findings

- small-field shape
  * formation efficiency
  * GW spectrum (~GHz)
- large-field shape
  * oscillon shape
  * number density



"Gravitational wave spectra from oscillon formation after inflation",
TH, Sfakianakis, Yamaguchi, JHEP 03 (2021) 021 [arXiv:2011.12201]