Oscillons after inflation and gravitational waves

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Collaboration with

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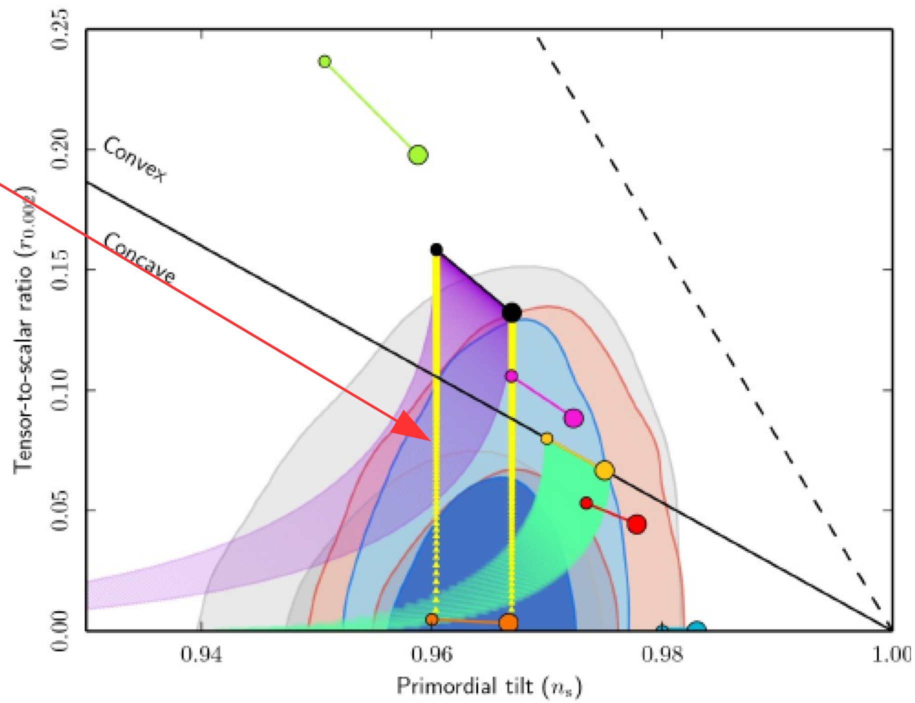
α-attractor model

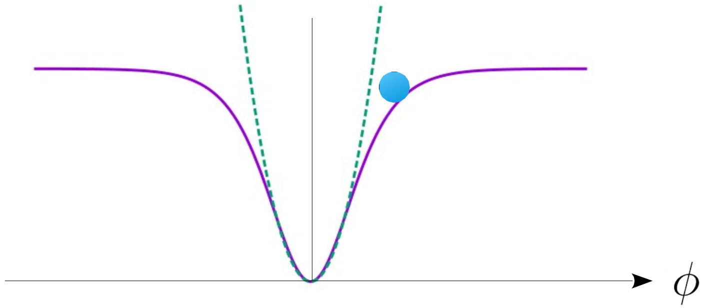


Planck Collaboration, A&A 594 (2016) A13

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

Oscillon

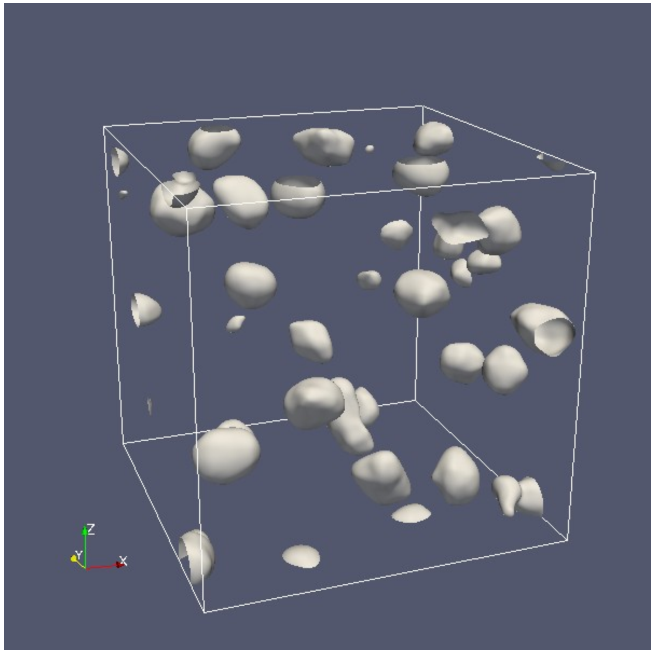
α -attractor model



More gentle potential than harmonics $m^2\phi^2$

Inflaton tends to have large field values

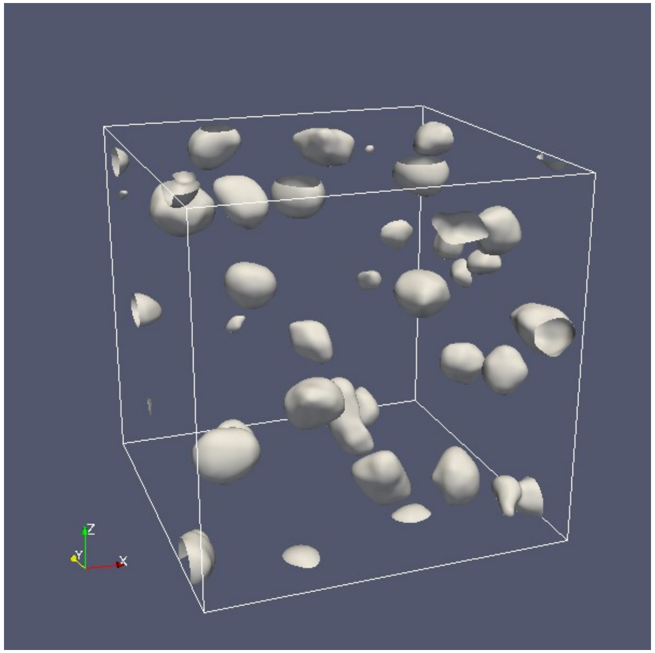
Oscillons
(= soliton of inflaton)
form due to instability



Pioneer works :

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

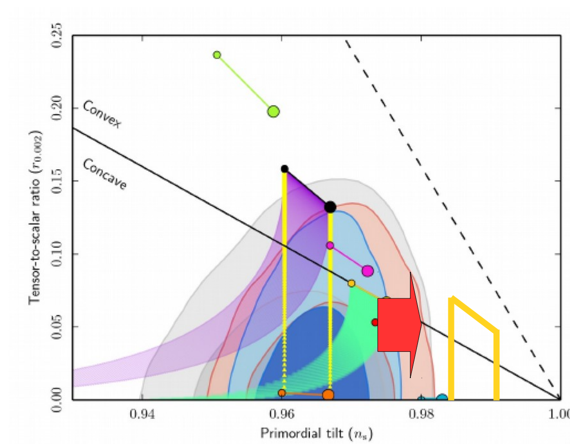
Oscillon



Once oscillons form, they modify cosmic expansion history after inflation ?

Physical properties, e.g. life-time, decaying mechanism, depend on the shape of inflaton potential.

Modify the predictions ?



Goal

As the first step,

- Inflaton potential shape

⟺ oscillon formation efficiency

- GWs reveal the existence of oscillons,

(is it possible to reconstruct the inflaton potential ?)

Related works :

Analytic estimation of oscillon decay

Ibe, Kawasaki, Nakano, Sonomoto, arXiv:1901.06130

GWs from oscillons with axion potential

Kitajima, Soda, Urakawa, JCAP (2018) 008

Field equations

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

$\longrightarrow$

$$\phi'' + 2\mathcal{H}\phi' - \triangle\phi = -a^2 \frac{dV}{d\phi}$$

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \triangle h_{ij} = \frac{2}{m_{\rm pl}^2} \partial_i \phi \partial_j \phi$$ + trace parts

Backreaction to cosmic expansion

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

slow-roll inflation $\rightarrow$ early matter-dominant Universe

(we start the simulations at $\epsilon \sim \mathcal{O}(1)$, though)

Numerical setup

Box size : $L = 50m^{-1}$ (comoving)

Grid size : $N = 128^3 \sim 256^3$

Typical scale of scalar field : $\frac{M}{m_{\rm pl}} = 10^{-3}$

Background amplitude : $\phi_0 = \mathcal{O}(M)$

Initial fluctuation : $\delta\phi_0 = 10^{-4}M$

Simulation time : $\tau_f = 800m^{-1}$

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Energy spectrum

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

$$\Omega_{\rm GW}(k,\tau_0) = \Omega_{r,0}\left(\frac{g_{*,0}}{g_{*,f}}\right)^{1/3}\Omega_{\rm GW}(k,\tau_f)$$

Observed frequency

$$f_0 = \mathcal{O}(1)\times 10^7\ {\rm Hz}\left(\frac{m}{10^{-10}M_{\rm pl}}\right)\left(\frac{\overline{L}}{100}\right)^{-1}\left(\frac{T_R}{10^{12}\ {\rm GeV}}\right)^{-1}$$

Past studies

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$$V_A(\phi) = \frac{m^2 M^2}{2\alpha_1}\left[\left(1+\frac{\phi^2}{M^2}\right)^{\alpha_1} - 1\right]$$

Zhou et al., JHEP 1310 (2013) 026

$$V_B(\phi) = m^2 M^2 \left(1 - \frac{\phi^{\alpha_2}}{M^{\alpha_2}}\right)^2$$

Antusch, Cefala, Orani, PRL 118 (2017) 011303

$$V_C(\phi) = m^2 M^2 \left|\frac{\phi}{M}\right|^{\alpha_3}$$

Liu et al., PRL 120 (2018) 031301

$$V_D(\phi) = \frac{1}{2} m^2 M^2 \left[1 - \alpha_4 \log\left(\frac{\phi^2}{2M^2}\right)\right]\frac{\phi^2}{M^2}$$

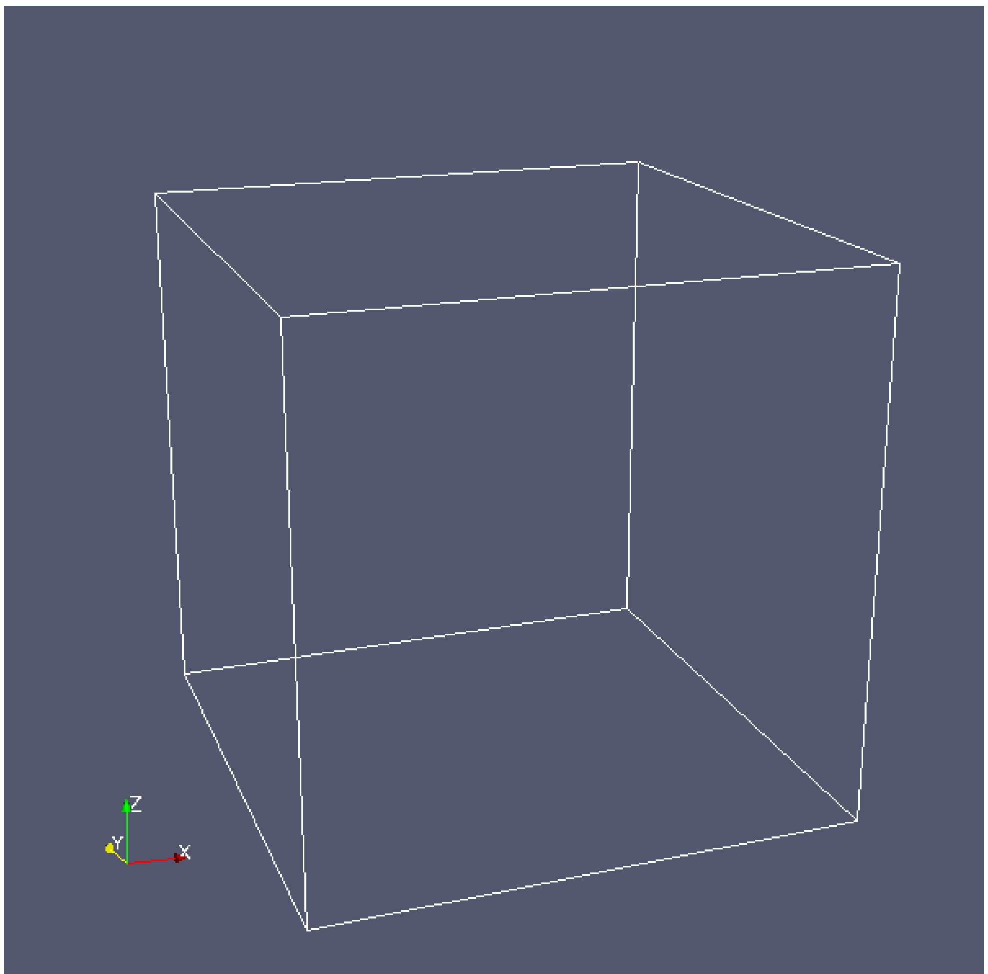
Kawasaki, Takahashi, Takeda, PRD 92 (2015) 105024

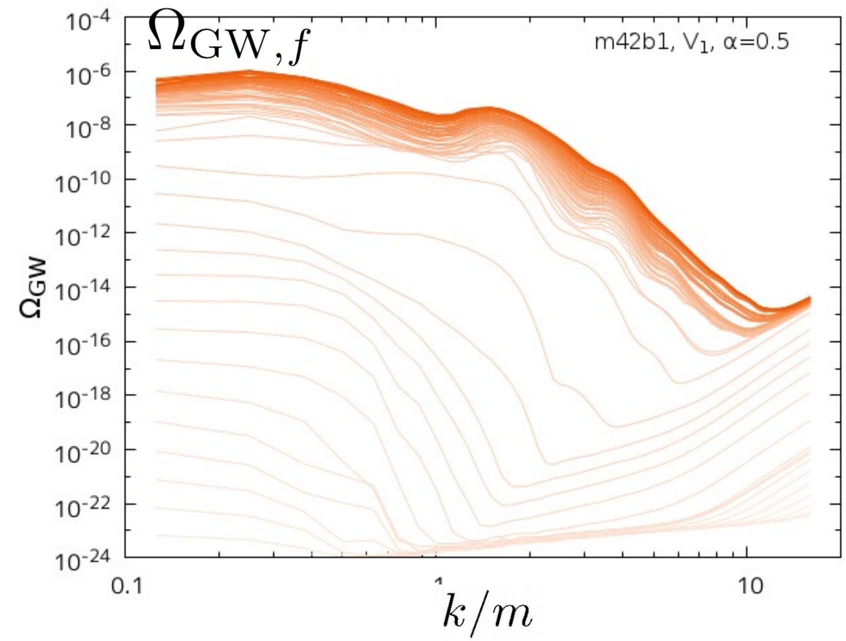
Potential V_A

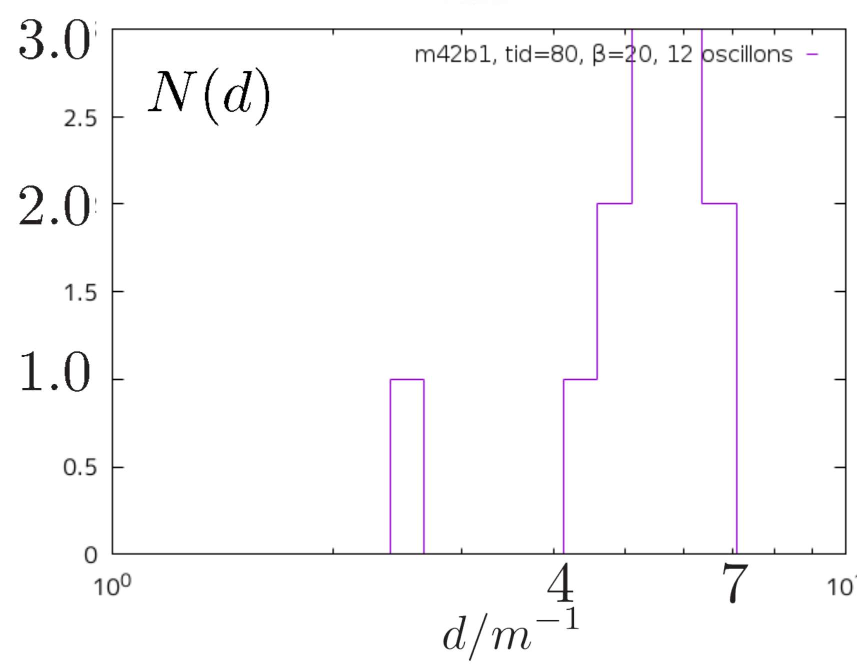
$$V_A(\phi) = \frac{m^2 M^2}{2\alpha_A}\left[\left(1+\frac{\phi^2}{M^2}\right)^{\alpha_A} - 1\right]$$

Zhou et al., JHEP 1310 (2013) 026

$$\alpha_A = 1/2$$







Study : small or large

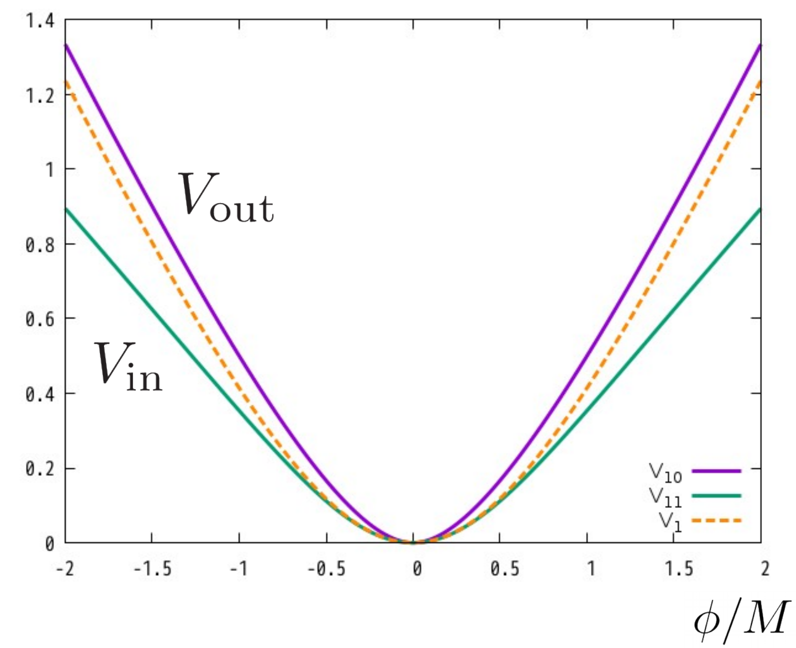
$$V_A(\phi) = m^2 M^2 \left[\left(1 + \frac{\phi^2}{M^2}\right)^{1/2} - 1 \right]$$

$$V_{\rm out}(\phi) = \frac{\alpha_o}{2} m^2 M^2 \frac{(\phi/M)^2}{1 + |\phi/M|}$$

$$\phi \gg M \qquad V_A \approx V_{\rm out}$$

$$V_{\rm in}(\phi) = \frac{1}{2} m^2 M^2 \frac{(\phi/M)^2}{(1 + |\phi/M|^{\alpha_i})^{1/\alpha_i}}$$

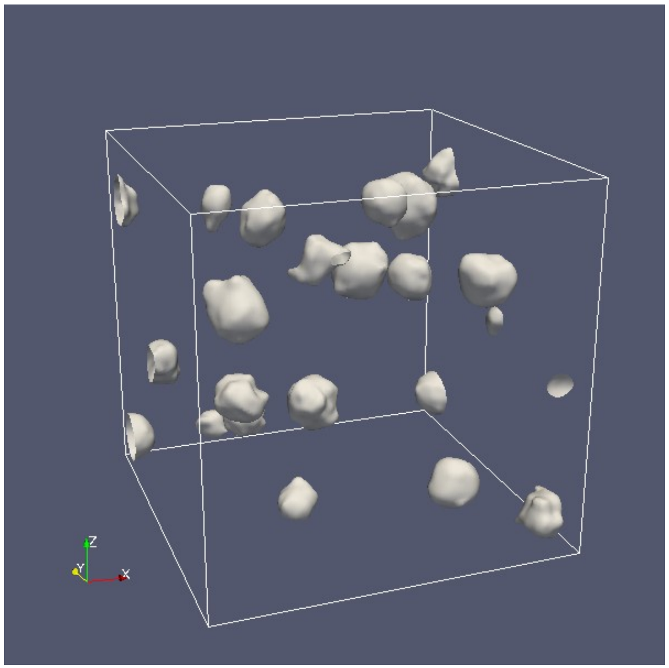
$$\phi \ll M \qquad V_A \approx V_{\rm in}$$



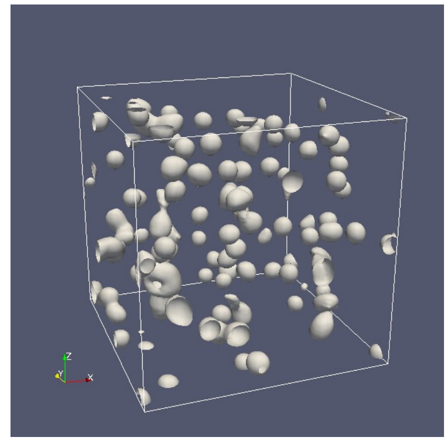
Oscillons can form if the potential is shallower than $m^2\phi^2$

Kawasaki, Takahashi, Takeda, PRD 92 (2015) 105024

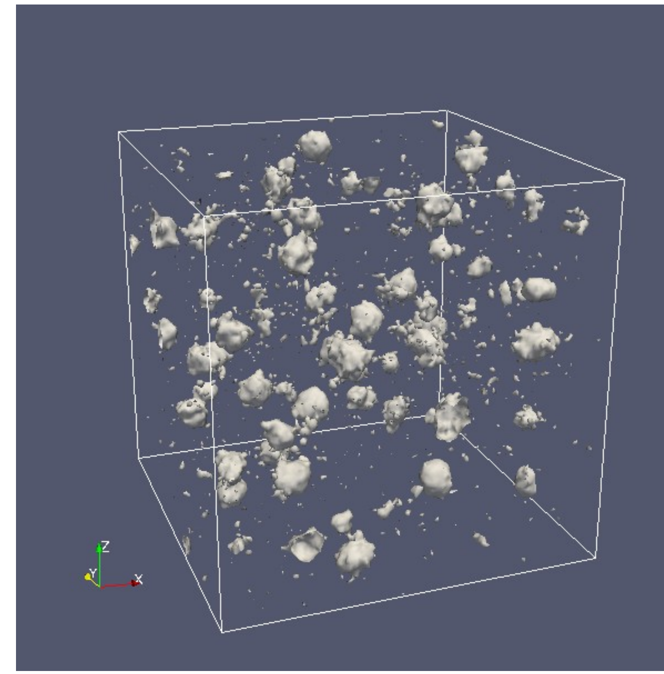
Study : small or large



$\phi \ll M \qquad V_A \approx V_{\rm in}$



V_A

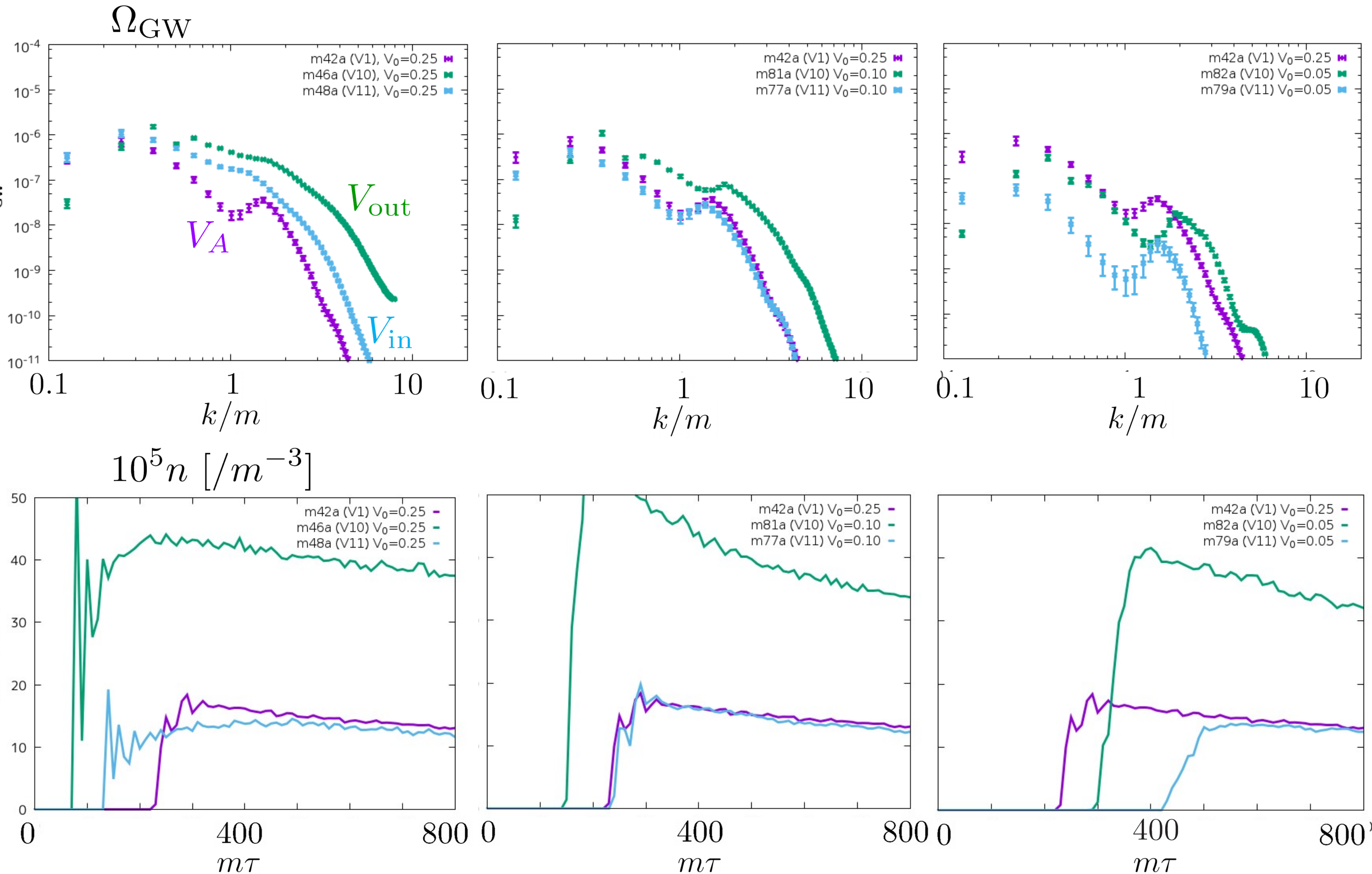


$\phi \gg M \qquad V_A \approx V_{\rm out}$

○ Looks similar $\cdots$?

×

Study : small or large



Potential collections

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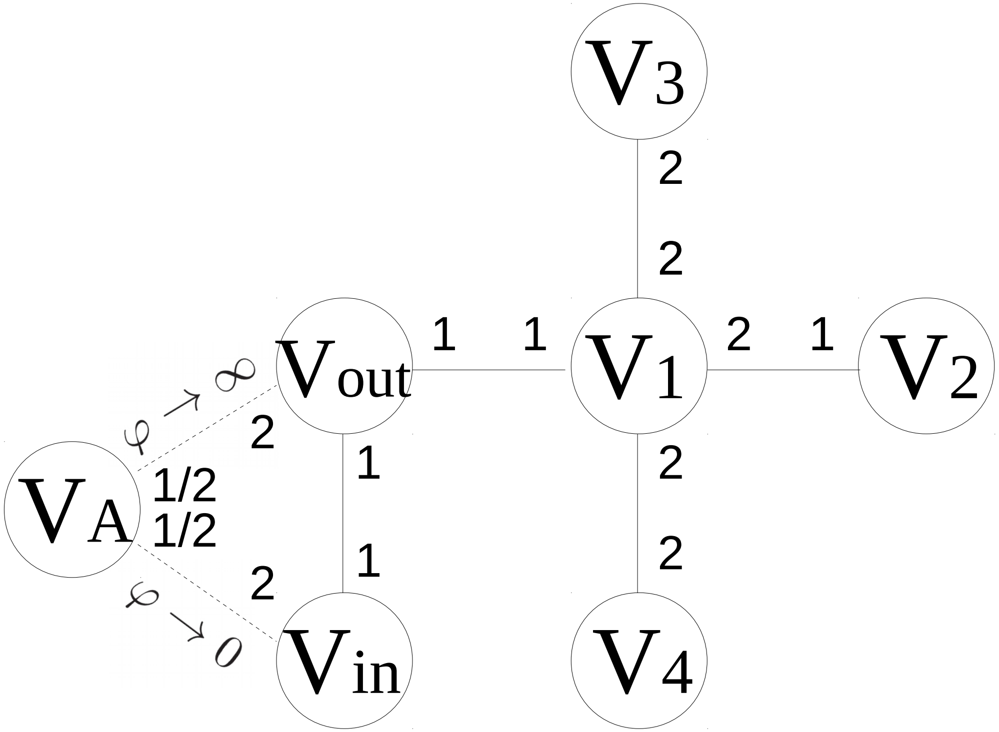


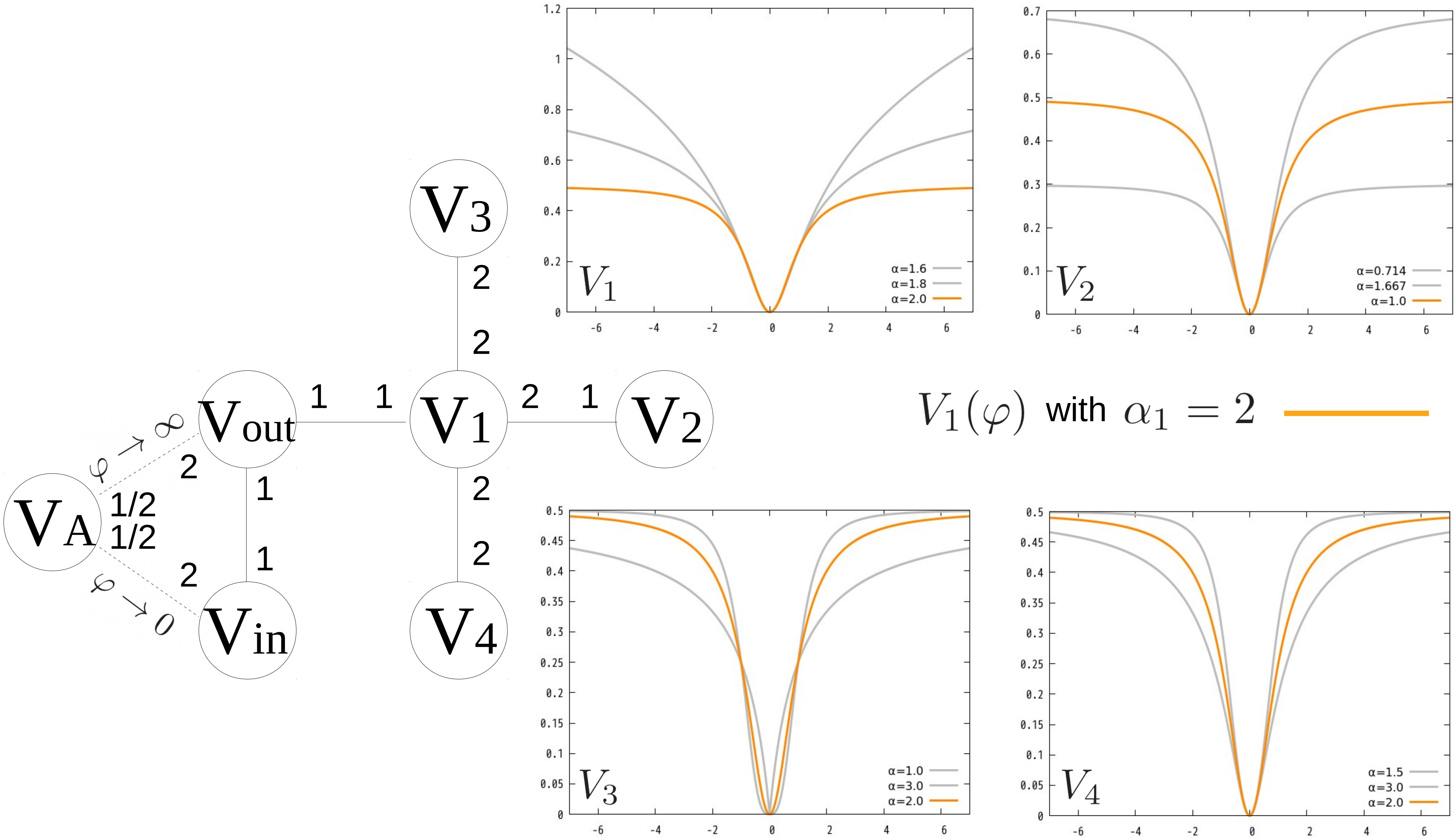
$$V_1 = \frac{1}{2}m^2M^2\frac{(\phi/M)^2}{1+|\phi/M|^{\alpha_1}}$$

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

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

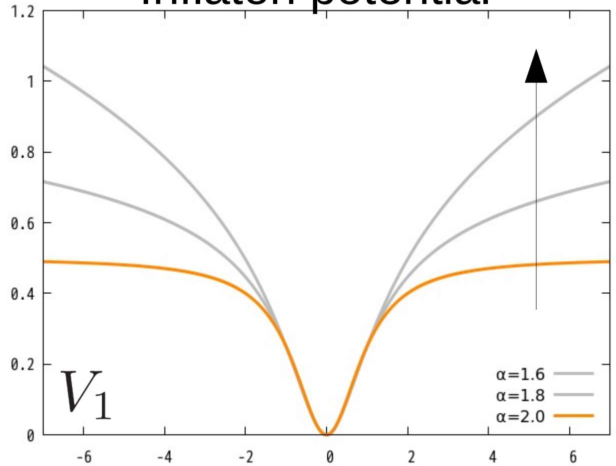
$$V_4 = \frac{1}{2}m^2M^2\frac{(\phi/M)^2}{[1+|\phi/M|^{\alpha_4}]^{2/\alpha_4}}$$

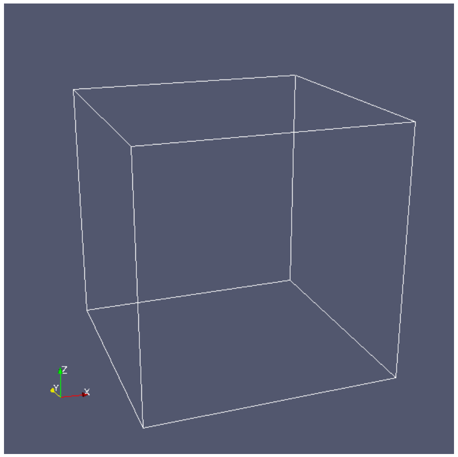
Potential collections



Results : Potential 1

Inflaton potential



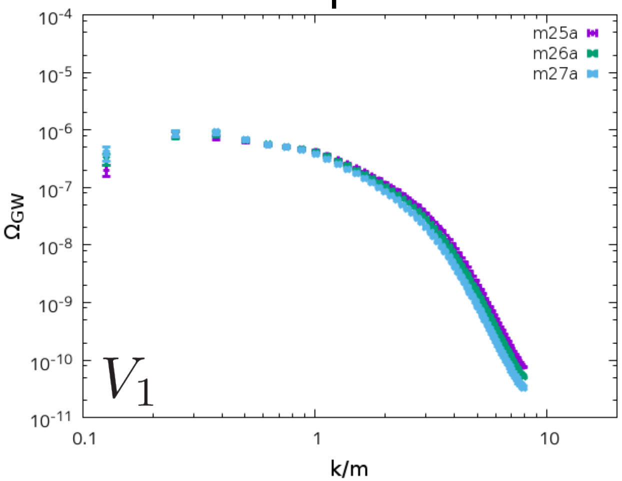


GW : Insensitive

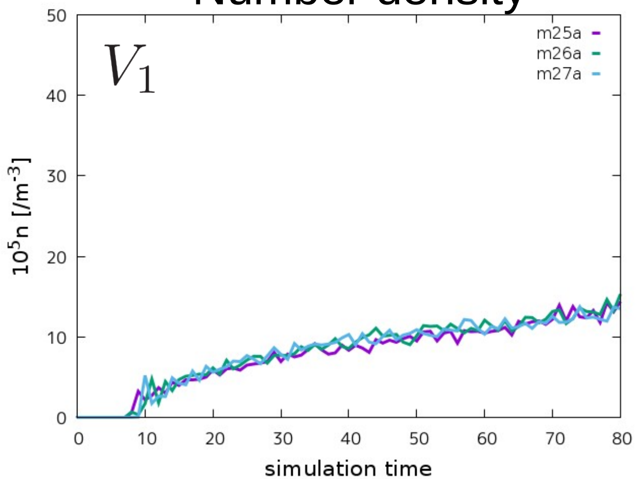
Number : Insensitive

Size : not so changed, but more broadly distributed

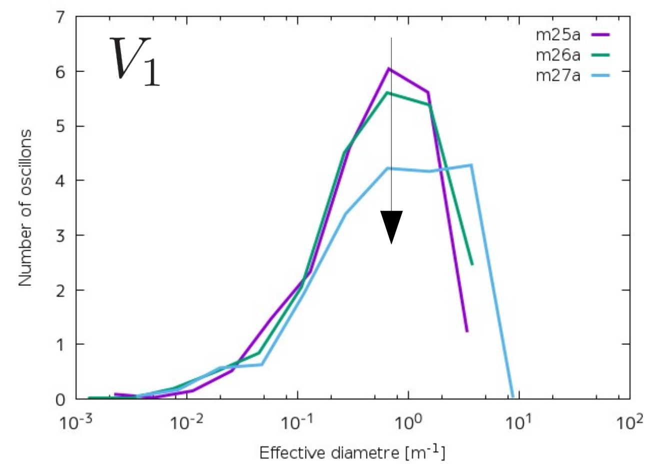
GW spectrum



Number density



Size distribution



(note : $\Omega_{\mathrm{GW},f} \sim 10^{-6} \longrightarrow \Omega_{\mathrm{GW},0} \sim 10^{-10}$)

(note : $k = m \longrightarrow f_0 \sim \mathcal{O}(\mathrm{GHz}) \sim \mathcal{O}(\mathrm{THz}) \propto m T_R^{-1}$)

Results : Potential 2

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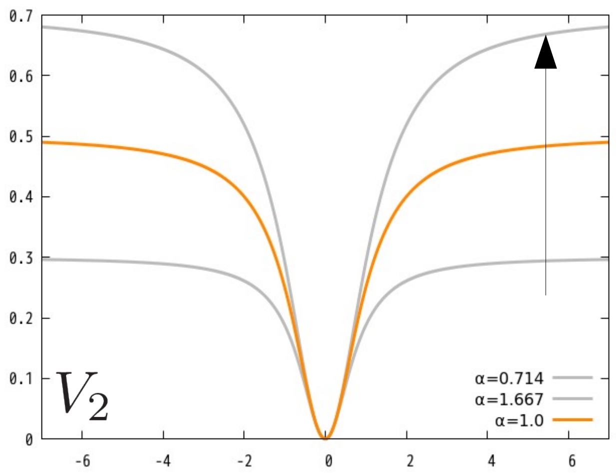
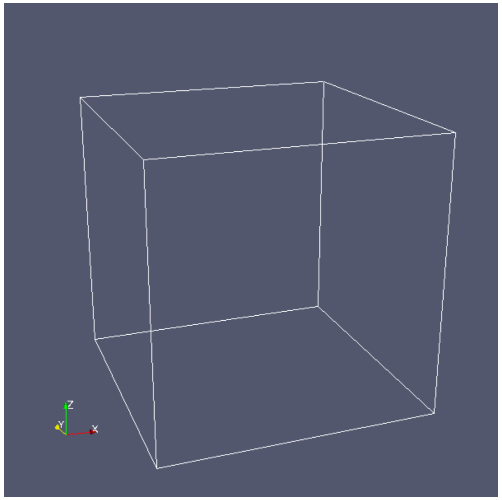
Inflaton potential



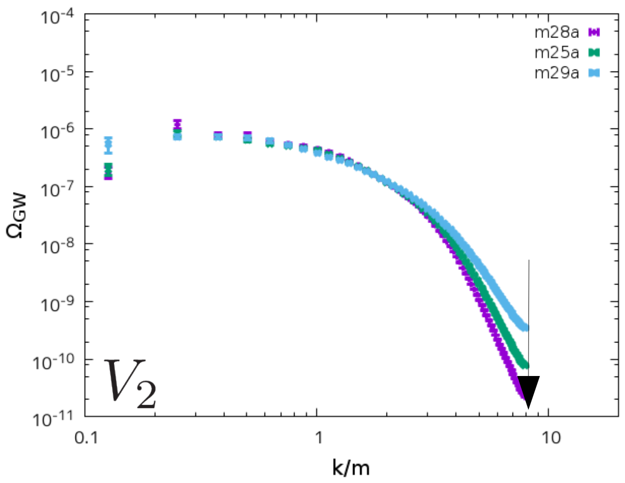


GW : weak dependence on small scales

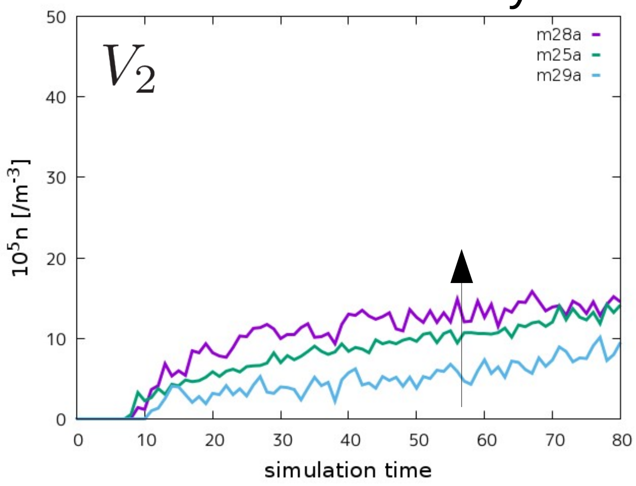
Number : similar evolution, but weak dependence

Size : typical size is weakly sensitive to the height

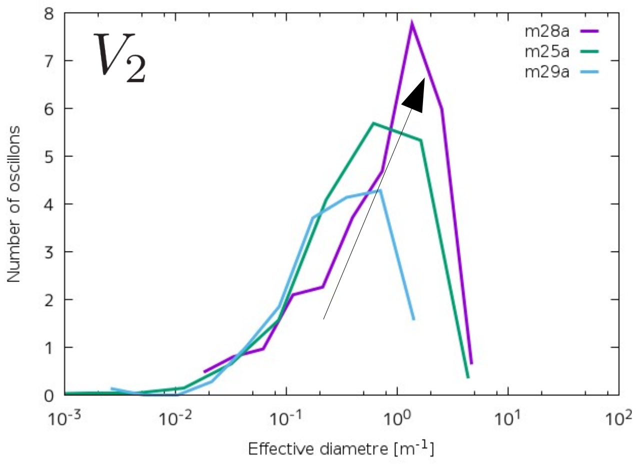
GW spectrum



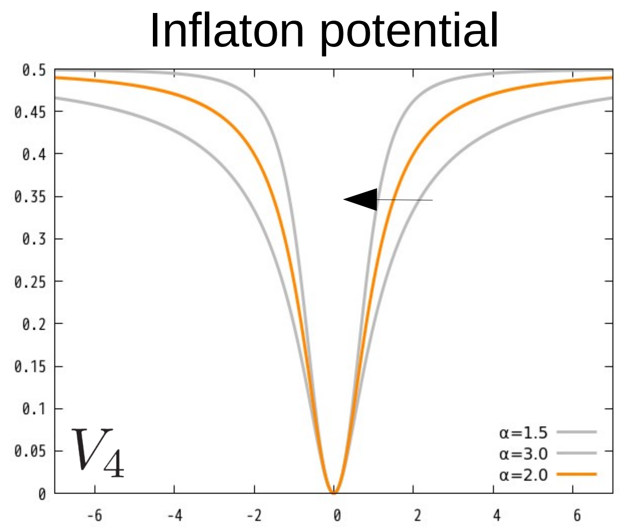
Number density

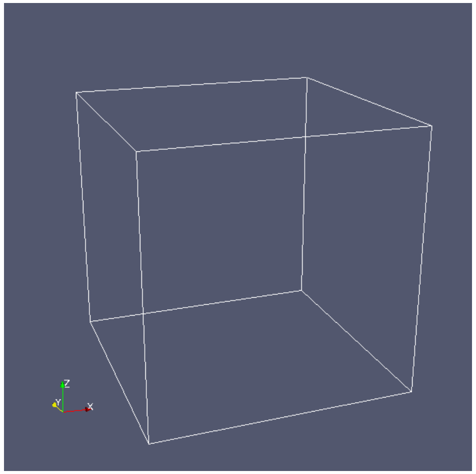


Size distribution



Results : Potential 4

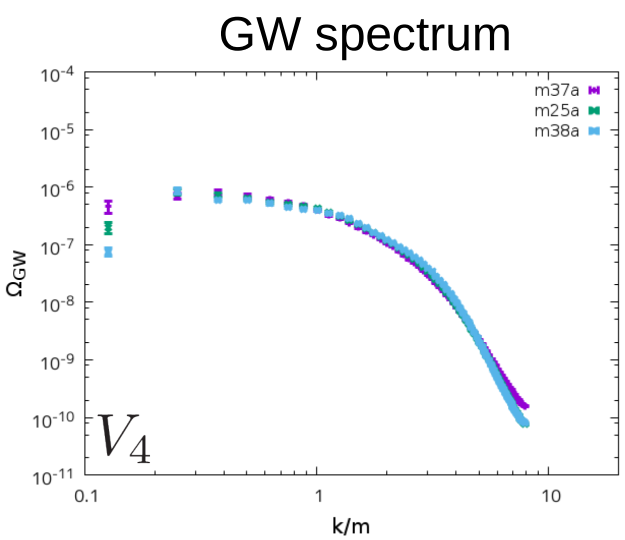


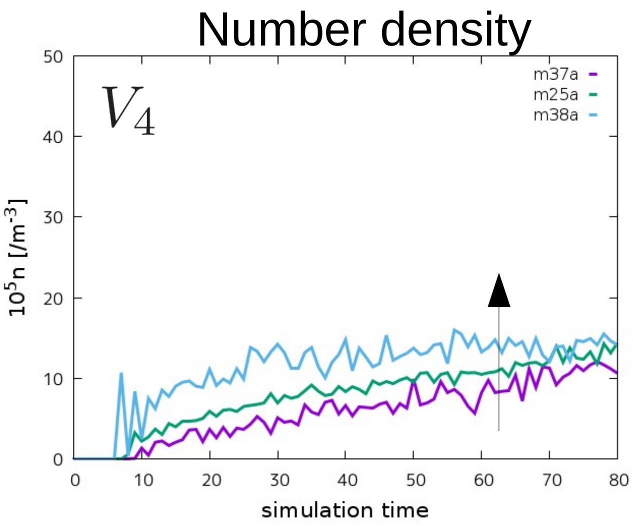


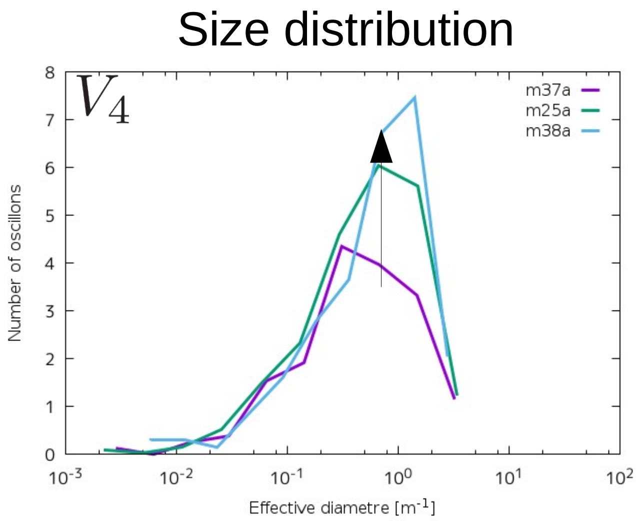
GW : insensitive

Number : increasing for shallower potential

Size : not so changed

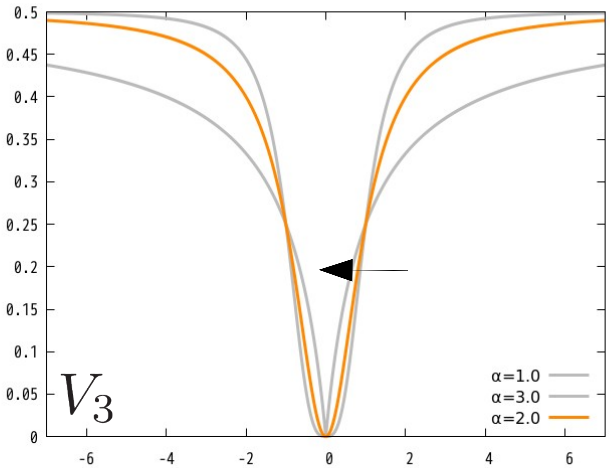




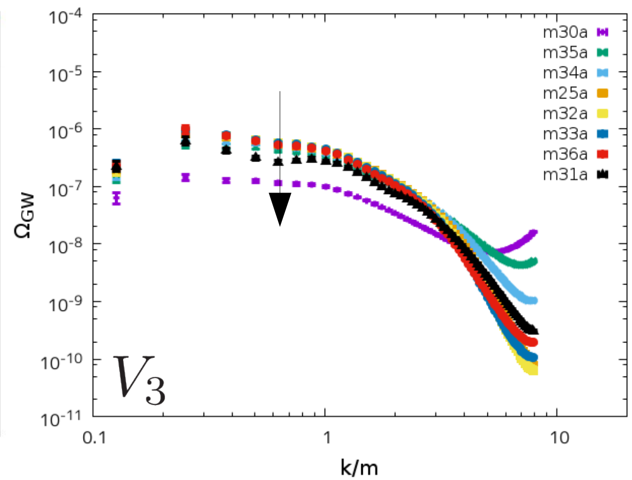


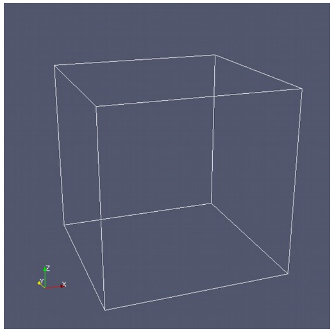
Results : Potential 3

Inflaton potential



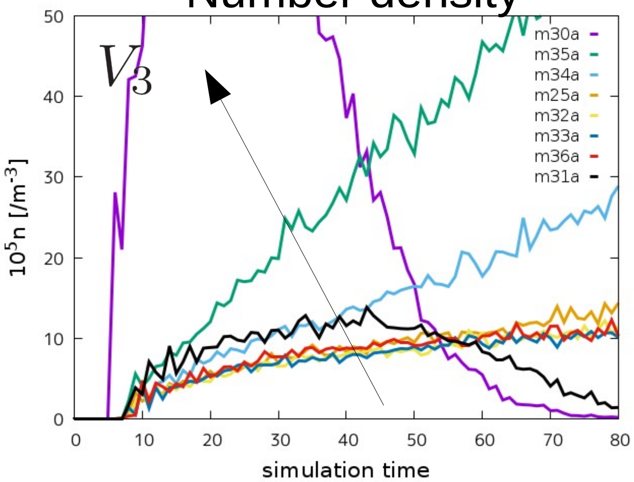
GW spectrum



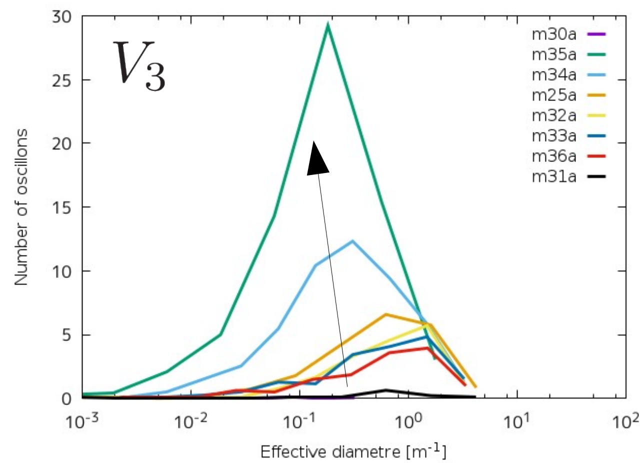


GW : sensitive to the shape at small field

Number density



Size distribution



Number :
- violent formation at earlier time and quick decay for sharp potential.
- mild formation and quick decay for potential with large power

Size : fragmentation if the potential is sharper.

→ non-conservation of adiabatic invariant

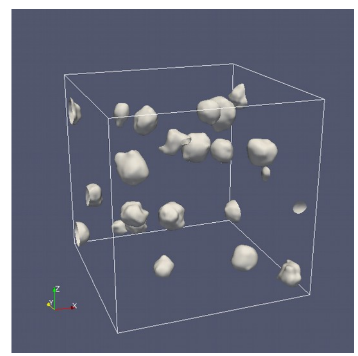
Ibe, Kawasaki, Nakano, Sonomoto, arXiv:1901.06130
Kawasaki, Takahashi, Takeda, PRD 92 (2015) 105024

To-do : Instability bands

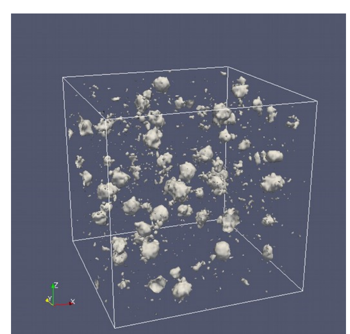
Linear analysis (Mathieu equation)

$$\delta\ddot{\varphi} + \left(k^2 + V''(\varphi_0)\right)\delta\phi = 0$$

Instability bands ⇔ Oscillon's size and shape



Simply spherical
→ only a few modes are unstable



Fragmentated
→ many modes are unstable

Summary

- Oscillons in reheating are unwelcome ?

- Study the oscillon formation and associating GW spectra with various potentials.

- Oscillon's life highly depends on small-field feature in the potential
  → influences GW spectra
  → implication : possible to reconstruct ?