Dynamical screening of scalar waves in Cubic Galileon model

Takashi Hiramatsu

Rikkyo University

Collaboration with Kazuya Koyama (ICG, Portsmouth)

Introduction – Screening

Takashi Hiramatsu

Many attempts to extend General Relativity in the context of scalar(vector)-tensor theories

Required : GR should recover around the Sun
  = scalar d.o.f. must be screened around a massive object

Screening mechanisms
- Potential : Chameleon/Symmetron
- 1st-derivative : k-moflage
- 2nd-derivative : Vainshtein **e.g. Babichev, Deffayet, CQG30 (2013) 184001 [arXiv:1304.7240]**

We use the Cubic Galileon model (with $g_{\mu\nu} = \eta_{\mu\nu}$)

Nikolis, Rattazzi, Trincherini, PRD79 (2009) 064036 [arXiv:0811.2197]
Deffayet, Esposito-Farese, Vikman, PRD79 (2009) 084003 [arXiv:0901.1314]
Deffayet, Deser, Esposito-Farese, PRD80 (2009) 064015 [arXiv:0906.1967]

$$S = \int d^4x \left[\frac{c_2}{2}(\partial\varphi)^2 + \frac{c_3}{2M^3}\Box\varphi(\partial\varphi)^2 + \frac{\beta}{2m_{\rm pl}}\rho\varphi \right]$$

⇓

$$c_2\Box\varphi + \frac{c_3}{M^3}\left[(\Box\varphi)^2 - \partial_\mu\partial_\nu\varphi\partial^\mu\partial^\nu\varphi\right] = \frac{\beta}{2m_{\rm pl}}\rho$$

Introduction – Vainshtein screening

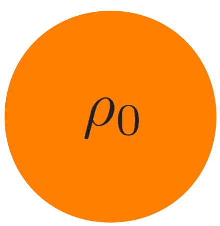
Takashi Hiramatsu

Static case

$$c_2\nabla^2\varphi + \frac{c_3}{M^3}\left[(\nabla^2\varphi)^2 - \partial_i\partial_j\varphi\partial^i\partial^j\varphi\right] = -\frac{\beta}{2m_{\rm pl}}\rho$$

Spherical star

$$\varphi'(r) = \frac{r}{4c_3}\left(-1+\sqrt{1+\frac{r_*^3}{r^3}}\right)$$



$$\varphi'(r) \propto \frac{1}{r^{1/2}}$$

$$\varphi'(r) \propto \frac{1}{r^2}$$

Vainshtein radius : $r_* = \left(\frac{4c_3\beta\rho_0}{3c_2^2M^3m_{\rm pl}}r_s^3\right)^{1/3}$

Introduction – Vainshtein screening

Spherical star

→ scalar dof is suppressed near the star

Non-spherical cases

→ the suppression becomes weak

Bloomfield, Burrage, Davis, PRD91 (2015) 083510 [arXiv:1408.4759]

Binary star

→ deviating from superposition of Galileon fields sourced by them

TH, Hu, Koyama, Schmidt, PRD, arXiv:1101.5210

Disk system

→ anti-screening near the centre of disk

Ogawa, TH, Kobayashi, CQG, arXiv:1802.04969

Introduction – Dynamical effects

Yet another effect on Vainshtein mechanism

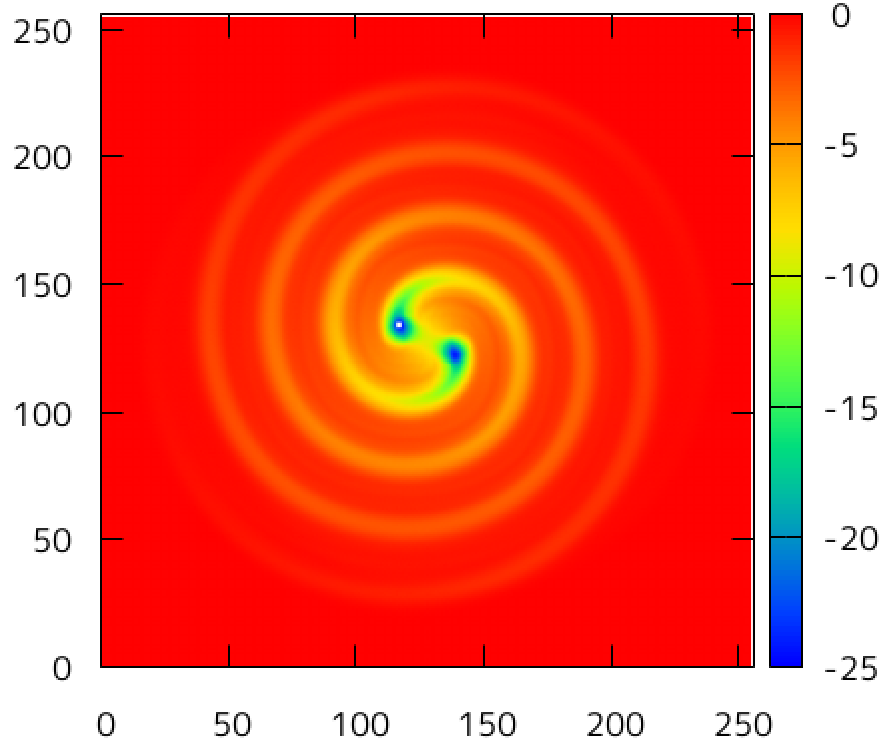
$$\partial_\mu \partial_\nu \varphi \partial^\mu \partial^\nu \varphi \ \ni \ (\partial_i \dot{\varphi})^2$$

This term emerges when the system is dynamical,
e.g., scalar wave radiation.

Can this term suppress the scalar wave radiation ?

3D simulations are too heavy to survey the parameter space

(→ Claudia de Rham's talk last week)



So, let us switch to 1D spherical system

RIKKYO UNIVERSITY 立教大学
Takashi Hiramatsu

Field redefinition

$$c_2\Box\varphi + \frac{c_3}{M^3}\left[(\Box\varphi)^2 - \partial_\mu\partial_\nu\varphi\partial^\mu\partial^\nu\varphi\right] = \frac{\beta}{2m_{\rm pl}}\rho$$

$$\rho(t,x) = \rho_0[1+\Xi(t)]\Theta(x)$$

$$x = \frac{r}{r_0} \qquad \frac{t}{r_0} \to t \qquad \frac{\varphi}{c_2 M^3 r_0^2} \to \varphi \qquad \mu = \frac{\beta\rho_0}{c_2^2 M^3 m_{\rm pl}}$$

$$\Box\varphi + c_3\left[(\Box\varphi)^2 - \partial_\mu\partial_\nu\varphi\partial^\mu\partial^\nu\varphi\right] = \frac{\mu}{2}[1+\Xi(t)]\Theta(x)$$

Basic equations

立教大学 RIKKYO UNIVERSITY
Takashi Hiramatsu

Static part + time-dependent part

$$\varphi(t,x) = \varphi_0(x) + \pi(t,x)$$

Evolution equation of $\pi(t,x)$

$$\ddot{\pi} = \frac{2x^2K^2\pi'' + 4xL\pi' + 4c_3K(x^2\dot{\pi}'^2 + 2x\pi'\pi'' + \pi'^2) - \mu x^2 K\Xi(t)\Theta(x)}{2x\left[2c_3K(2\pi' + x\pi'') + xJ\right]}$$

Linearised equation

$$\ddot{\pi} = \frac{K^2}{J}\pi'' + \frac{2L\pi'}{xJ} - \frac{\mu K}{2J}\Xi(t)\Theta(x)$$

$$\left\{\begin{aligned} y(x) &= \frac{1}{4}\left[-1 + \sqrt{1 + 4c_3\mu\frac{U(x)}{x^3}}\right] \\ K(x) &= 4y(x) + 1 \\ L(x) &= 4y(x)^2 + 2y(x) + 1 + c_3\mu\Theta(x) \\ J(x) &= 12y(x)^2 + 4y(x) + 1 + c_3\mu\Theta(x) \end{aligned}\right.$$

Basic equations

Time-dependent density field (sinusoidal + Gaussian-like)

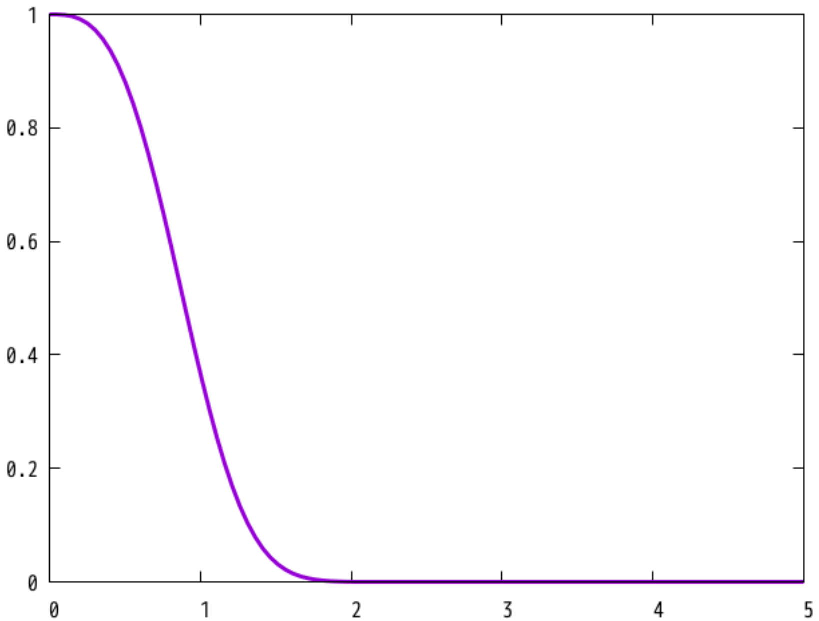
$$\rho(t,x) = \rho_0[1+\Xi(t)]\Theta(x)$$

Density profile $\Theta(x) = e^{-x^3}$

Enclosed mass $U(x) = \int \Theta(x) x^2\, dx = \frac{1}{3}(1-e^{-x^3})$

Time-dependence $\Xi(t) = A\sin(\omega t)$

$(A<1)$



Numerical parameters

$$\Xi(t) = A \sin(\omega t)$$

$$\Box\varphi + c_3 \left[(\Box\varphi)^2 - \partial_\mu \partial_\nu \varphi \partial^\mu \partial^\nu \varphi \right] = \frac{\mu}{2} [1 + \Xi(t)] \Theta(x)$$

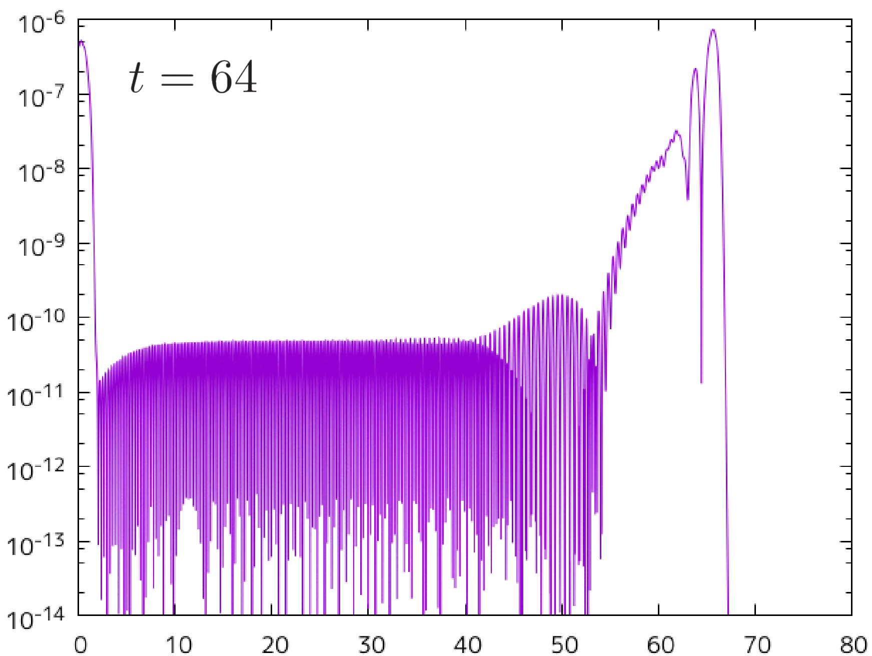
		Fiducial parameters
A	Amplitude of pulsation	$A = 0.3$
ω	Frequency of pulsation	$\omega = 4\pi$
μ	Matter coupling constant	$\mu = 1$
c_3	Non-linear coupling constant	$c_3 = 100$

Results : scalar waves

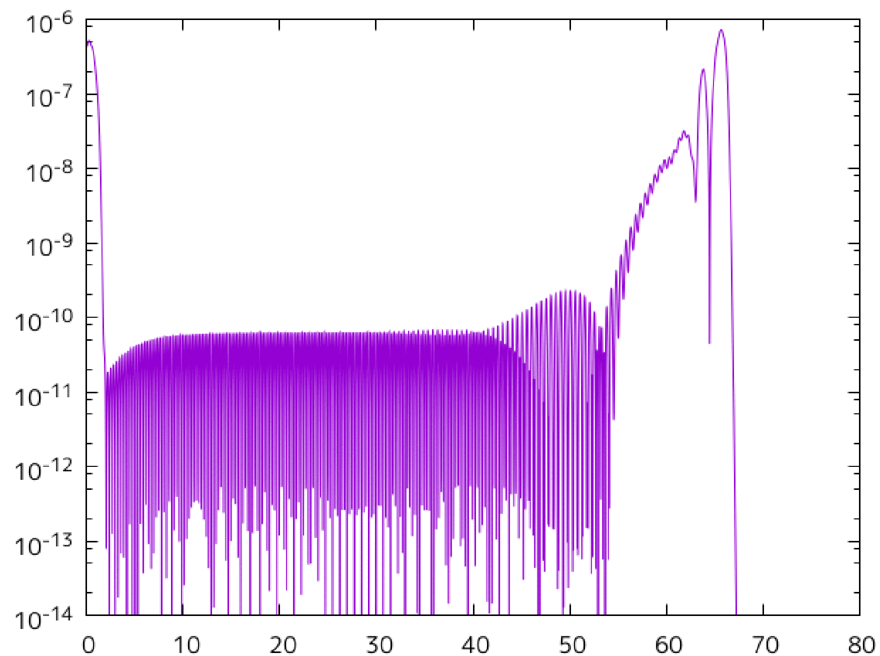
立教大学 RIKKYO UNIVERSITY
Takashi Hiramatsu

Energy density of $\pi(t,x)$: $\rho_\pi = \dot{\pi}^2 + \pi'^2$

Non-linear



Linearised



Star

Artifacts caused by
initial conditions

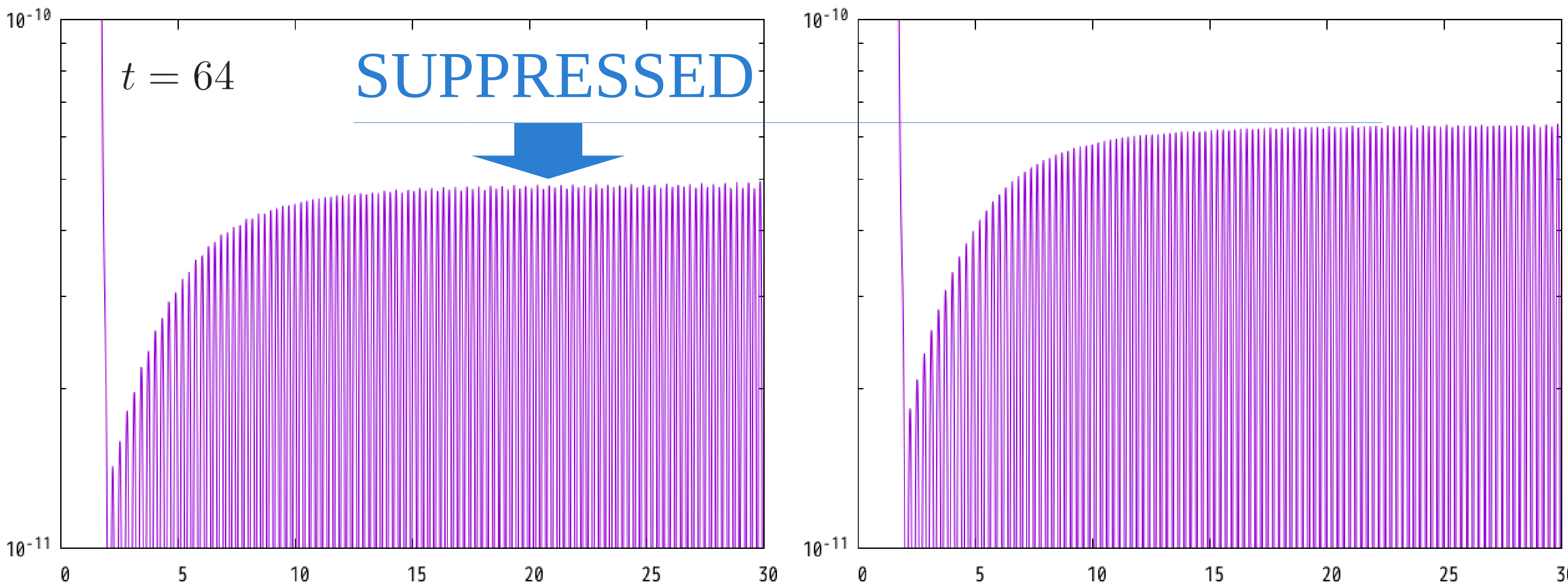
zoom..

Results : scalar waves

Takashi Hiramatsu

Energy density of $\pi(t,x)$: $\rho_\pi = \dot{\pi}^2 + \pi'^2$

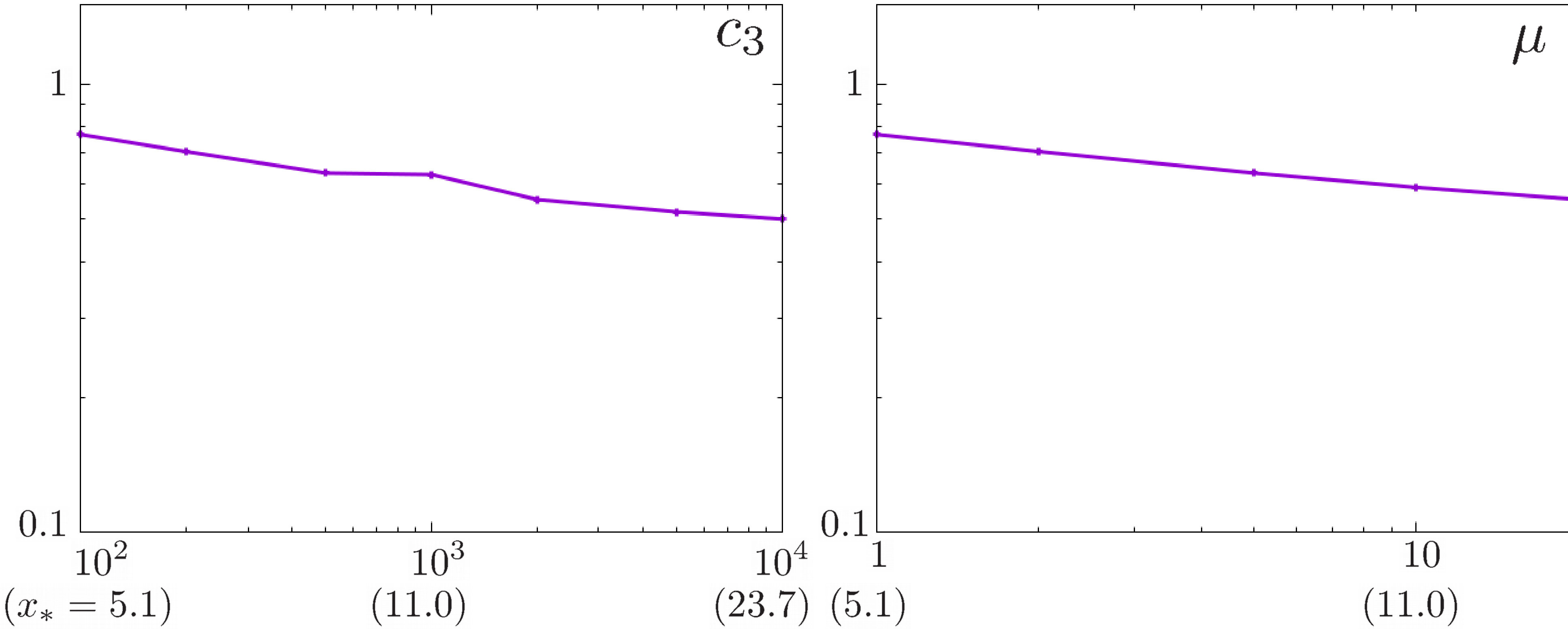
Non-linear Linearised



Amplitude of radiated scalar wave is suppressed by ~20%.

Results : c_3, μ

Non-linear/Linearised

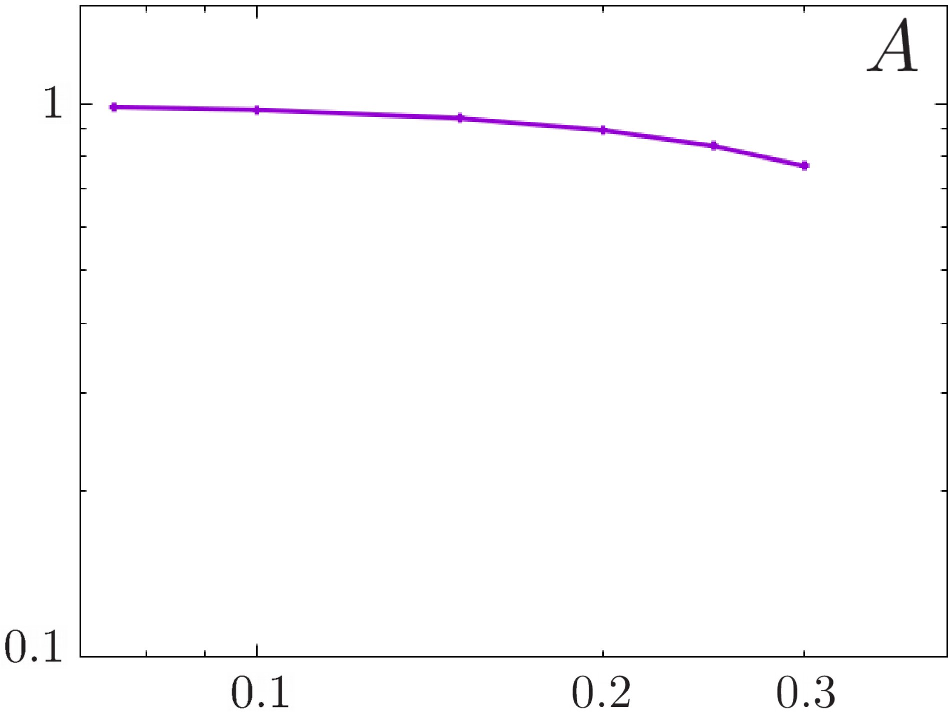


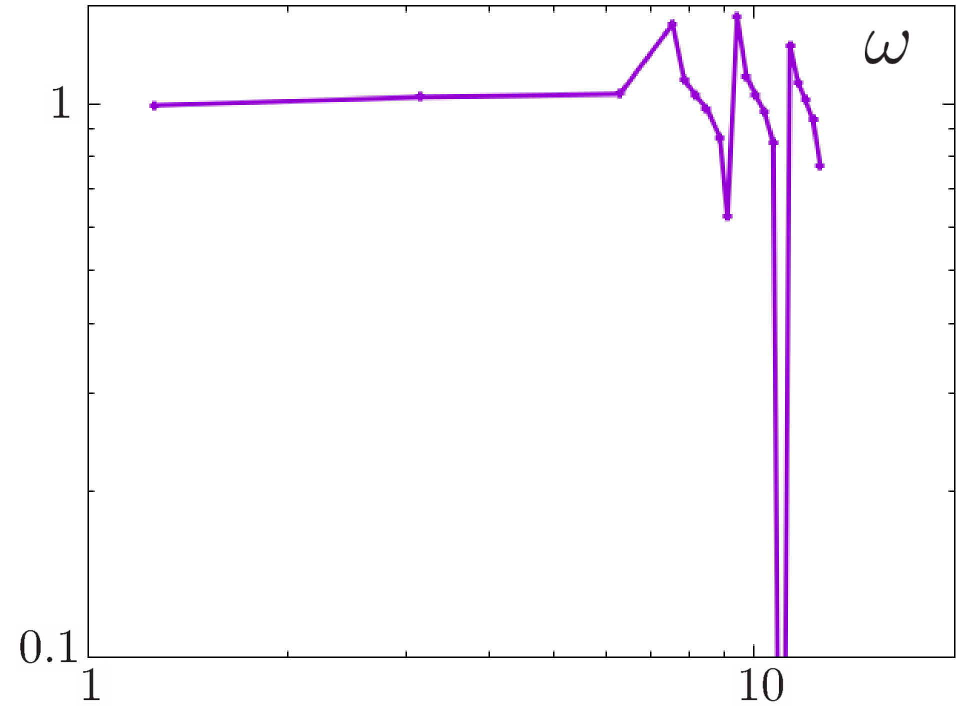
$$x_* \equiv \frac{r_*}{r_s} = \left(\frac{4}{3} c_3 \mu\right)^{1/3}$$

As the non-linearity or matter coupling becomes stronger, the wave is more suppressed.

Results : A, ω

Non-linear/Linearised





For larger pulsation amplitude, the wave is more suppressed.

Linear equation has resonant nature.
→ we should carefully consider

Summary

We investigate dynamical effects of Vainshtein mechanism in the cubic Galileon model.

Finding : scalar waves from a pulsating star are suppressed by non-linear effects.

To-do

- resonant nature of the linearised equation (ω dependence)
- should go to 3D again ?