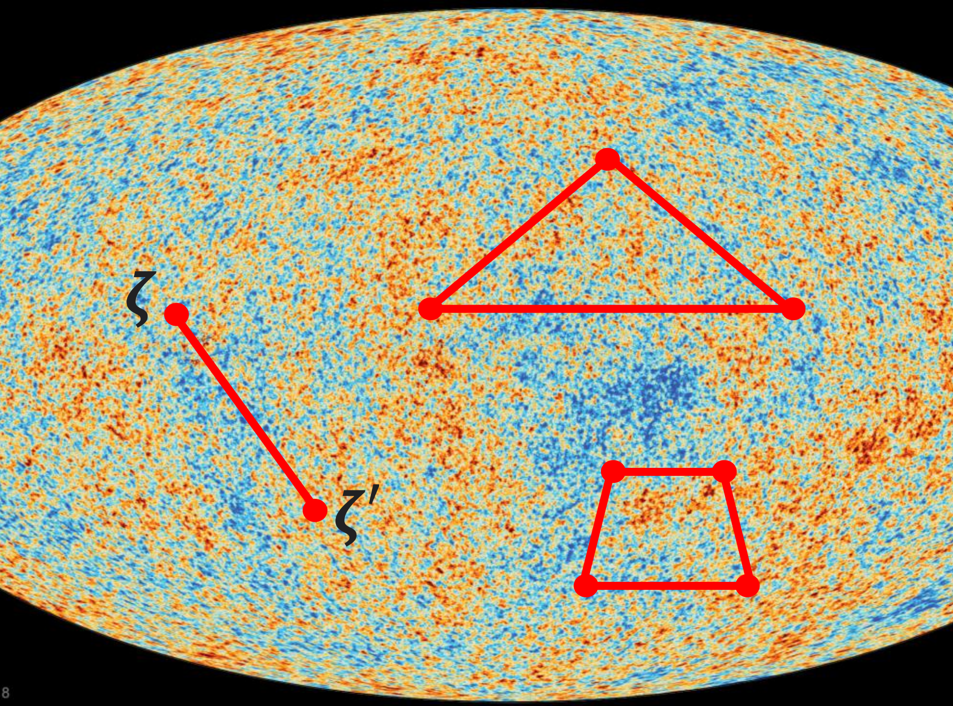
Disentangling mass spectra of multiple fields in cosmological collider

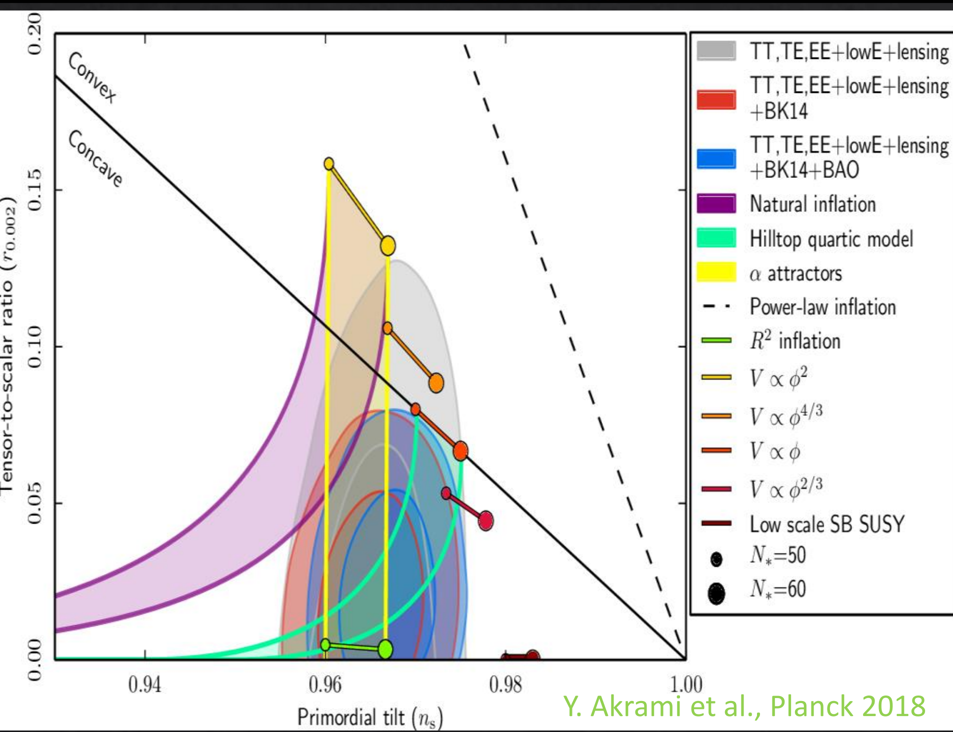
Shuntaro Aoki

(Chung-Ang University)

Based on JHEP 04 (2021) 127
with Masahide Yamaguchi

PASCOS 2021 @ IBS
6/17/2021





Y. Akrami et al., Planck 2018

Inflationary observables : Correlation functions of ζ, γ_{ij}

Strong restrictions on inflation models (high energy physics)

$*$ 2 pt. correlation & tilt

➡ e.g., Inflaton potential

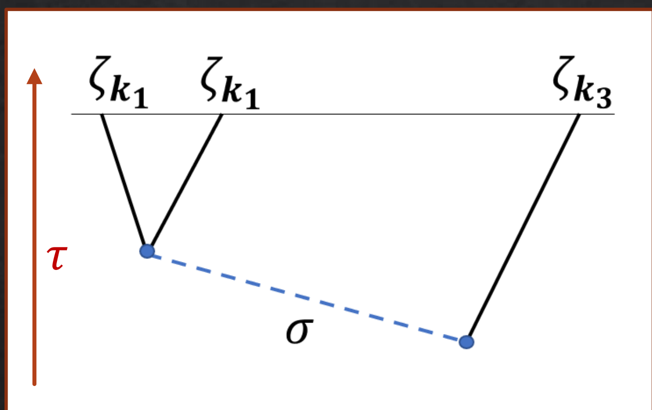
$*$ 3 or higher pt. correlations

➡ e.g.,
multi field inflation scenario,
higher derivative couplings,
…

Cosmological collider

* Higher pt. functions contain robust information (mass & spin) of heavy ($m_\sigma \sim H$) particles σ

e.g., a scalar σ



oscillation

$$S\left(\propto\langle\zeta^3\rangle\right) \sim C(\mu)\left(\frac{k_l}{k_s}\right)^{2i\mu} + \text{c.c.}$$

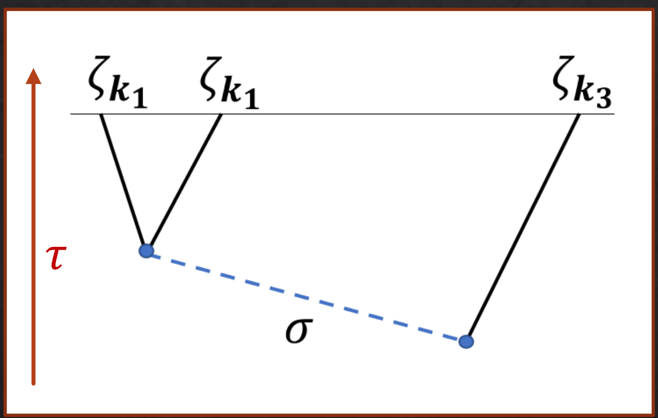
$$\mu \equiv \sqrt{\left(\frac{m_\sigma}{H}\right)^2 - \frac{9}{4}}$$

squeezed limit ($k_l \equiv k_3 \ll k_{1,2} \equiv k_s$)

Cosmological collider

- Higher pt. functions contain robust information (mass & spin) of heavy ($m_\sigma \sim H$) particles σ

e.g., a scalar σ



oscillation

$$S\left(\propto \langle \zeta^3 \rangle\right) \sim C(\mu) \left(\frac{k_l}{k_s}\right)^{2i\mu} + \text{c.c.}$$

$$\mu \equiv \sqrt{\left(\frac{m_\sigma}{H}\right)^2 - \frac{9}{4}}$$

- Explore very high scale :
  $m_\sigma \sim H \sim 10^{13}$(GeV) $\gg$ energy scale of terrestrial experiment

Many works

* Quasi single field inflation (Chen, Wang, '10)
* Signature of SUSY (Baumann, Green, '12)
* General int. by EFT approach (Noumi, Yamaguchi, Yokoyama, '13)
* Spinning particle (Arkani-Hamed, Maldacena, '15)
* Standard model particles, Neutrino (Chen, Wang, Xianyu, '16)

…

Question

✓ single particle with a definite mass and spin

↓

Q. What about multiple particles case?

Question

✓ single particle with a definite mass and spin

⬇

Q. What about multiple particles case?

Natural setup in realistic situation

* SM particles acquire masses $\sim H$ by loop effects   Chen, Wang, Xianyu, '16

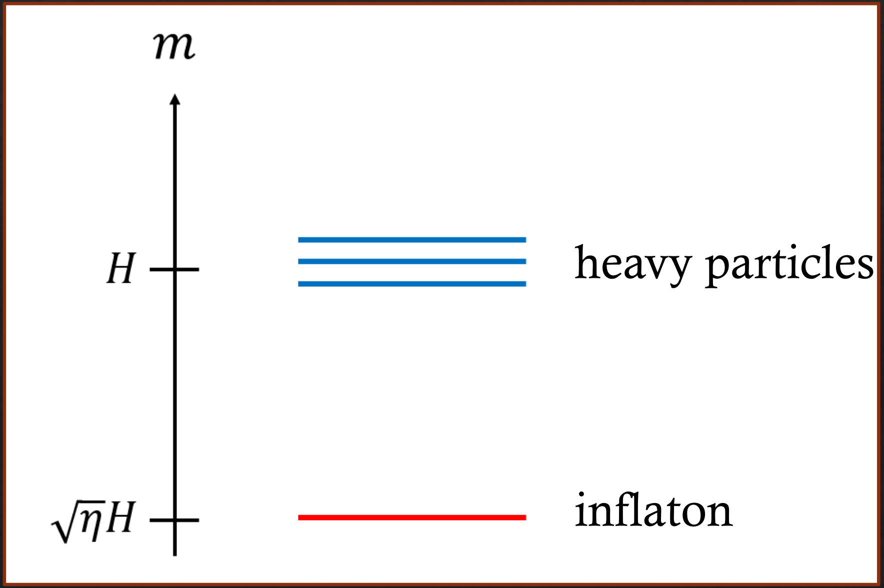
* Supergravity

    Hubble induced masses for scalar particles at tree level   Stewart '95

Question

✓ single particle with a definite mass and spin

Q. What about multiple particles case?



Question

✓ single particle with a definite mass and spin

↓

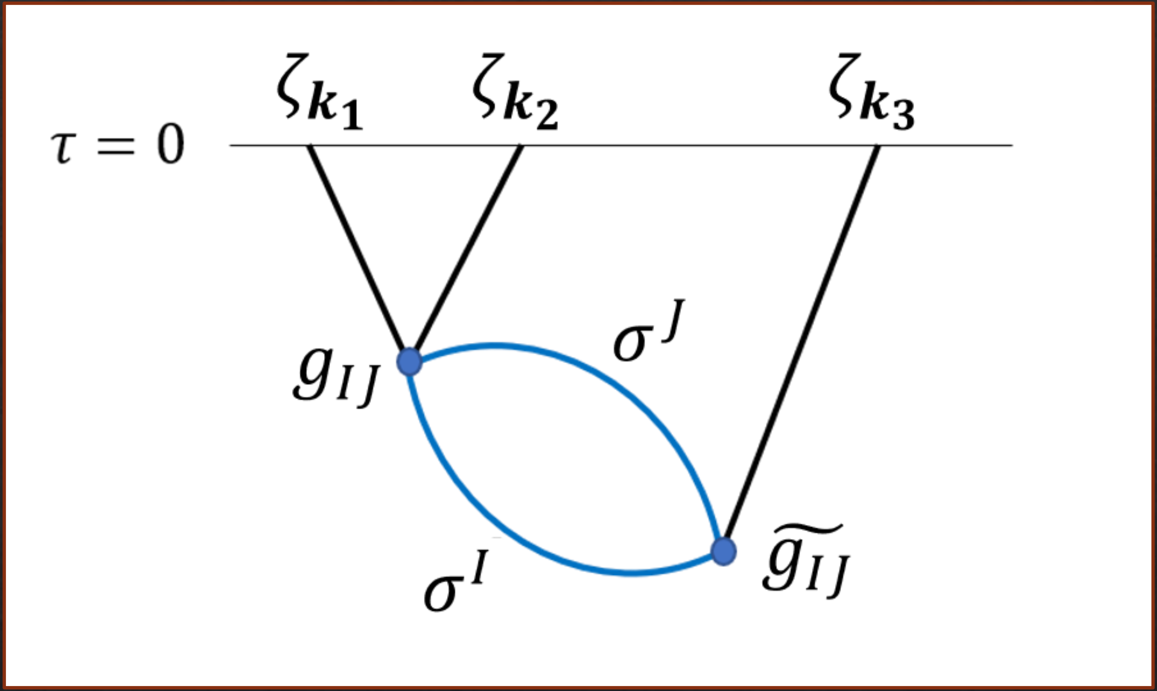
Q. What about multiple particles case?

More specifically,

Q. Can we distinguish single and multi cases?
(specific signal in multi case?)

Q. How to disentangle degenerate mass spectra?

Setup



massive scalars : σ^I $(I = 1, \dots, n)$
g_{IJ}, $\widetilde{g_{IJ}}$: non-diagonal in general
$g_{IJ} = \widetilde{g_{IJ}}$ for simplicity

Result (in squeezed limit)

$$S = \sum_{I,J} S_{IJ}$$

$I = J$

$$S_{II} \propto g_{II}^2 C(\mu_I, \mu_I) \left(\frac{k_l}{k_s}\right)^{2i\mu_I} + \text{const.} + \text{c.c.}$$

← same as single but superposed

$I \neq J$

$$S_{IJ} \propto g_{IJ}^2 C(\mu_I, \mu_J) \left(\frac{k_l}{k_s}\right)^{i(\mu_I+\mu_J)} + g_{IJ}^2 C(\mu_I, -\mu_J) \left(\frac{k_l}{k_s}\right)^{i(\mu_I-\mu_J)} + \text{c.c.}$$

← mixing (new effect)

Result (in squeezed limit)

$$S = \sum_{I,J} S_{IJ}$$

$I = J$

$$S_{II} \propto g_{II}^2 C(\mu_I, \mu_I) \left(\frac{k_l}{k_s}\right)^{2i\mu_I} + \text{const.} + \text{c.c.}$$

High frequency

$$\mu^I \equiv \sqrt{\left(\frac{m^I}{H}\right)^2 - \frac{9}{4}}$$

$I \neq J$

$$S_{IJ} \propto g_{IJ}^2 C(\mu_I, \mu_J) \left(\frac{k_l}{k_s}\right)^{i(\mu_I+\mu_J)} + g_{IJ}^2 C(\mu_I, -\mu_J) \left(\frac{k_l}{k_s}\right)^{i(\mu_I-\mu_J)} + \text{c.c.}$$

High frequency

low frequency (modulation)

* easily distinguished
* specific to multi particles

Example : n=2 (two fields)

$$S = S_{11} + S_{22} + S_{12}$$

Case (i) : without mixing ($g_{12} = 0$)

Case (ii) : with mixing ($g_{12} \neq 0$)

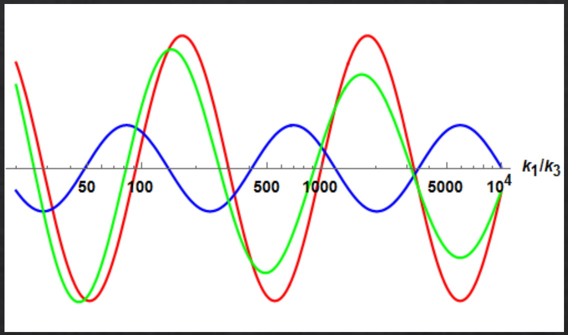
Note :

* Boltzmann suppression factor in $C(\mu^I, \mu^J)$
* When $\mu^1 \ll \mu^2 \rightarrow |S_{22}| \ll |S_{12}| \ll |S_{11}|$

Case (i) : Without mixing ($g_{12} = 0$ & $g_{11} = g_{22}$)

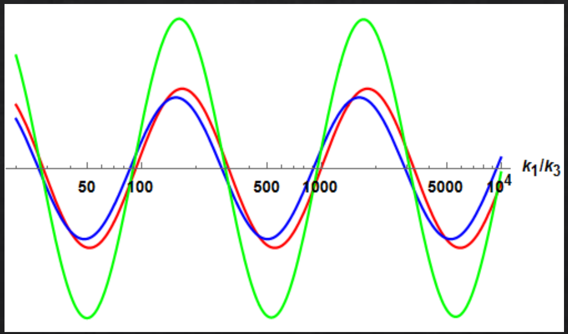
$S = S_{11} + S_{22}$: just superposition of two independent modes with μ^I

① $m_1 \ll m_2$
→ light mode dominates
→ $S_{\mathrm{total}} \sim S_{11}$



$(m_1, m_2)/H = (2, 2.5)$

② $m_1 \sim m_2$
→ $S_{11} \sim S_{22}$
→ $S_{\mathrm{total}} \sim 2 \times S_{11}$

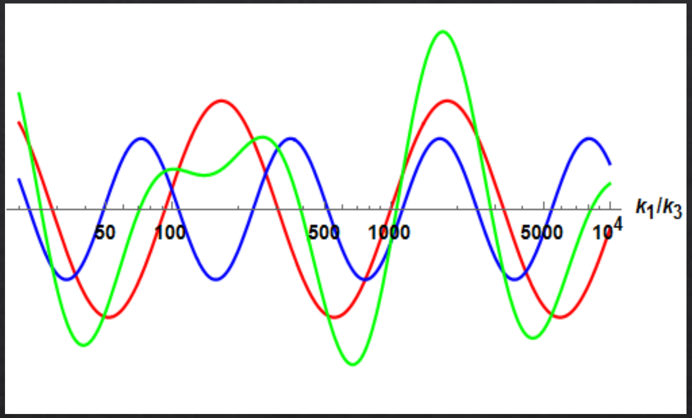


$(m_1, m_2)/H = (2, 2.1)$

Nothing interesting happens though a slight difference appears

Case (i) : Without mixing ($g_{12} = 0$ & $g_{11} \ll g_{22}$)

③ $m_1 \ll m_2$, but $g_{11} \ll g_{22}$
$\to$ g_{22} compensates suppression



$(m_1, m_2)/H = (2, 2.5)$ and $g_{11}/g_{22} = 0.1$

* Nontrivial superposition
  = proof of multi particles with hierarchical couplings
* However, such hierarchy seems to be unnatural.

Case (ii) : With mixing ($g_{11} = g_{22} = g_{12}$)

$$S = S_{11} + S_{22} + S_{12}$$

① when $\mu^1 \ll \mu^2 \rightarrow |S_{22}| \ll |S_{12}| \ll |S_{11}|$
($S_{\text{total}} \sim S_{11}$)

② $\mu^1 \sim \mu^2$ degenerate case

Case (ii) : With mixing ($g_{11} = g_{22} = g_{12}$)

$$S_{12} \propto g_{12}^2 C(\mu_1, \mu_2) \left(\frac{k_l}{k_s}\right)^{i(\mu_1+\mu_2)} + g_{12}^2 C(\mu_1, -\mu_2) \left(\frac{k_l}{k_s}\right)^{i(\mu_1-\mu_2)} + \text{c.c.}$$

High frequency ($i(\mu_1+\mu_2)$)

low frequency (modulation) ($i(\mu_1-\mu_2)$)

Case (ii) : With mixing ($g_{11} = g_{22} = g_{12}$)

$$S_{12} \propto g_{12}^2 C(\mu_1, \mu_2) \left(\frac{k_l}{k_s}\right)^{i(\mu_1+\mu_2)} + g_{12}^2 C(\mu_1, -\mu_2) \left(\frac{k_l}{k_s}\right)^{i(\mu_1-\mu_2)} + \text{c.c.}$$

High frequency

low frequency (modulation)

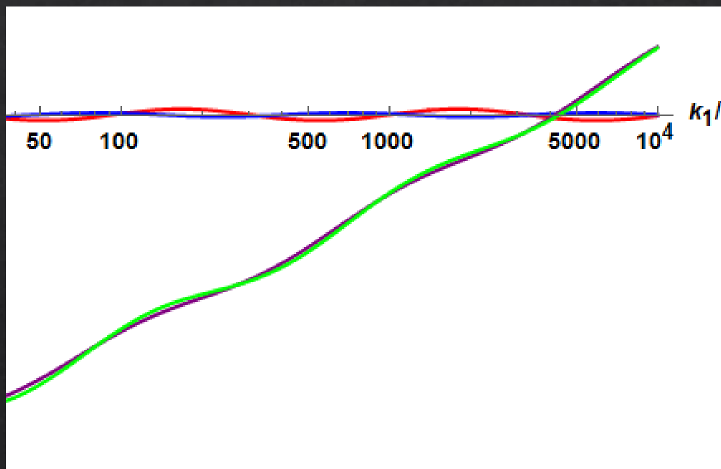
In degenerate limit ($\mu_1 \sim \mu_2 = \mu$)

$$|C(\mu_1, \mu_2) / C(\mu_1, -\mu_2)| \sim 2 \times 10^{-2} \times \mu^{-5/2} \ll 1$$

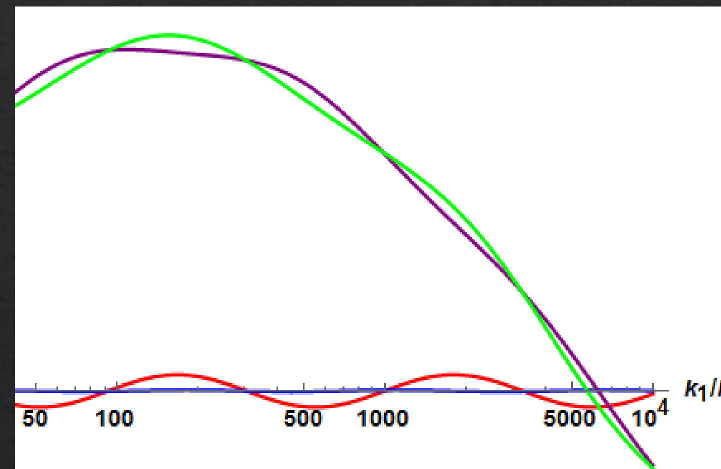
The total signal

~ characterized by the low frequency mode (large wavelength)

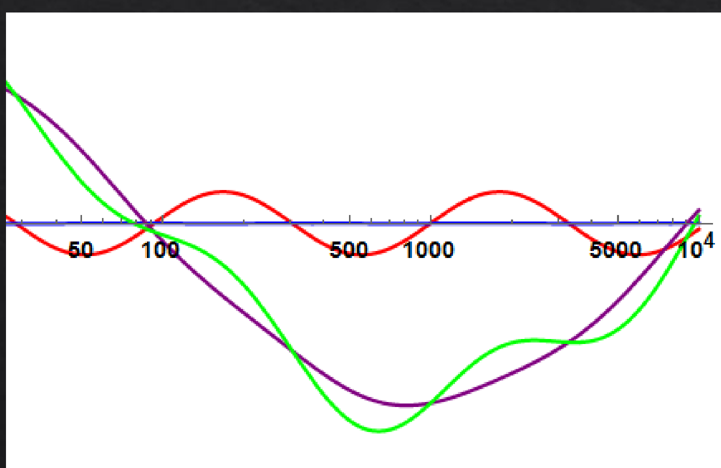
Case (ii) : With mixing ($g_{11} = g_{22} = g_{12}$)



$(m_1, m_2)/H$=(2, 2.1)



$(m_1, m_2)/H$=(2, 2.3)



$(m_1, m_2)/H$=(2, 2.5)

- $S_{\text{total}} \sim S_{12}$!!
- large wavelength
- disentangle the spectra

Summary

Multi particles effects on cosmological collider

✓ Superposition

- Nontrivial waveforms appear when there exists a hierarchy in m^I and g_{IJ} (rare case)

✓ Mixing effect

- Exists in general
- S is characterized by wavelength with $1/|\mu^1 - \mu^2|$, when $\mu^1 \sim \mu^2$
- Easily specified → existence of degenerate particles
- Depends on details of interaction (e.g., does not exist in derivative interactions)

Thank you very much

Appendix

Interaction

$$\mathcal{L}_{\rm int}(\phi,\sigma) = f(\phi, X) g_{IJ}\sigma^I\sigma^J$$

$X \equiv (\partial\phi)^2$, neglect it just for simplicity
g_{IJ} : real and symmetric const.

$$\mathcal{L}^3_{\rm int} = a^3 c_3 \delta\phi g_{IJ}\sigma^I\sigma^J$$
$$\mathcal{L}^4_{\rm int} = a^3 c_4 (\delta\phi)^2 g_{IJ}\sigma^I\sigma^J$$

$$c_3 \equiv f_\phi$$
$$c_4 \equiv f_{\phi\phi}/2$$

Assume
they are slowly varying ~ const.