Fermionic Signals in Primordial Non-Gaussianities

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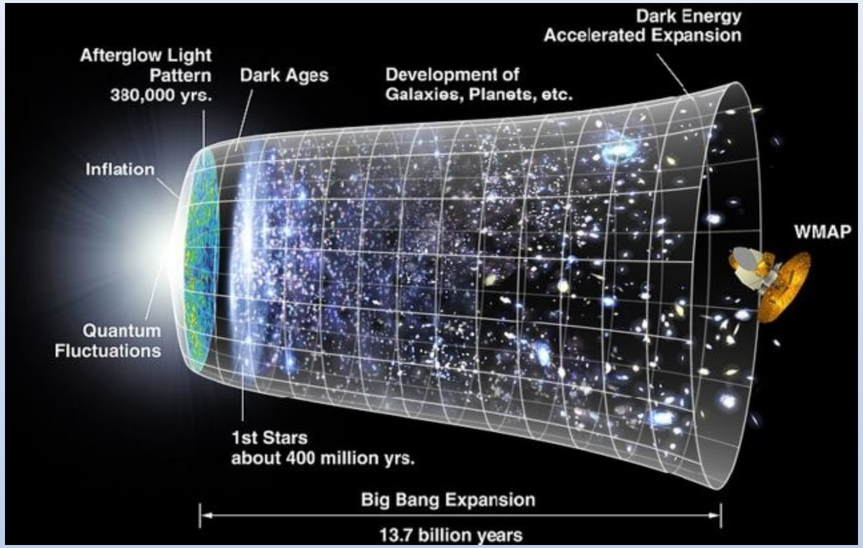
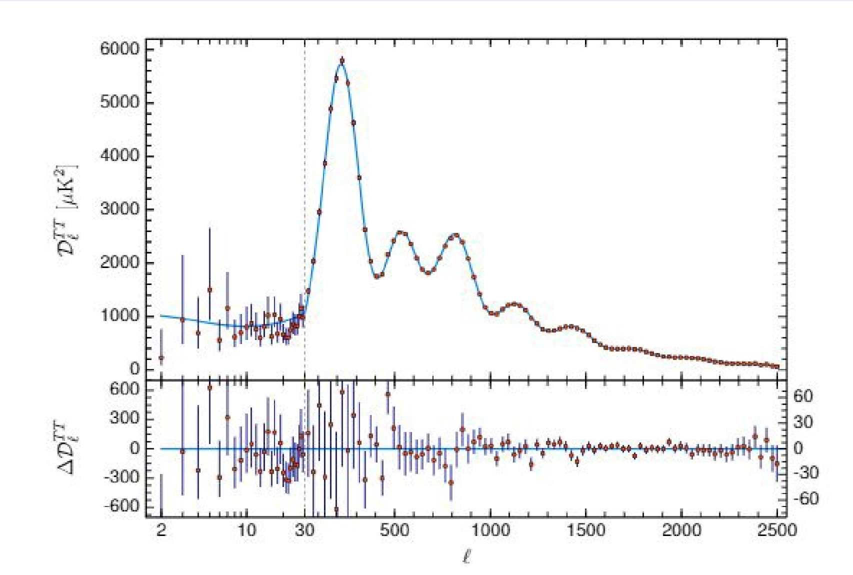
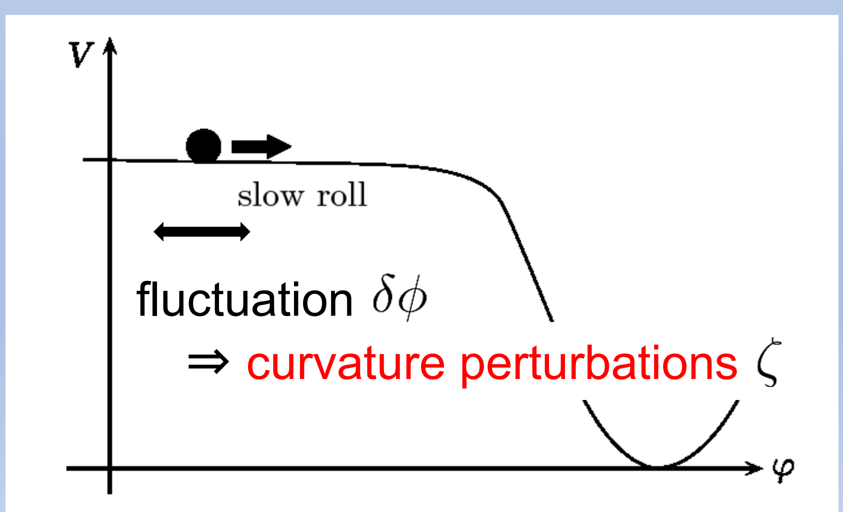
Inflation and primordial perturbations



[WMAP]



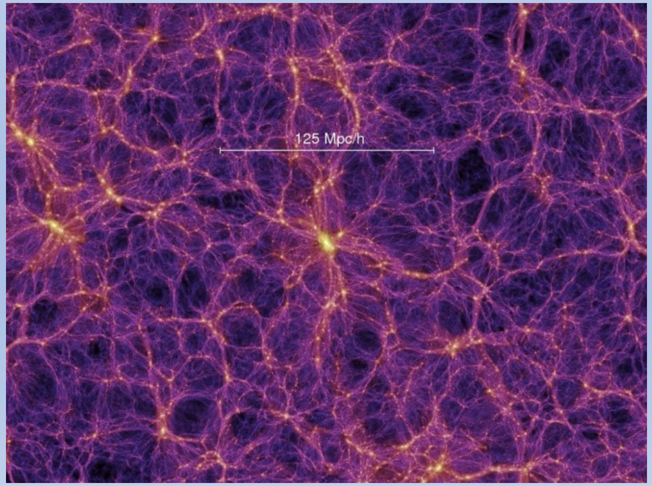
[Planck]



Primordial perturbations

➡ Structure formation

[Millennium Simulation]



Signals of new physics in inflation

Approaches to new physics related to inflation

- Specifying inflaton and inflation model (Higgs, R^2, axion, …)
- Detecting new particles (Generation, SUSY, GUT, …)

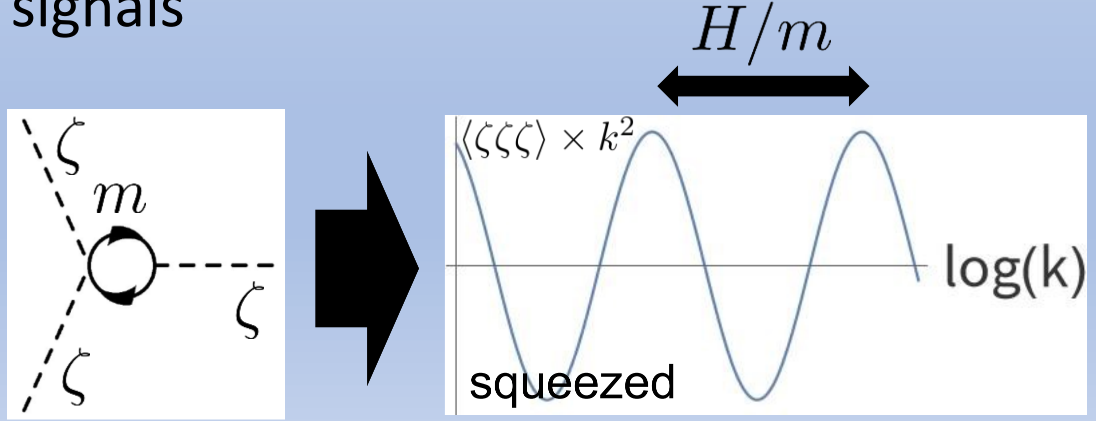
They can be seen in non-Gaussianities

- Higher energy scale than the colliders on ground: $H_{\rm inf} \sim \mathcal{O}(10^{13}\ {\rm GeV})$
- Each models of inflation would yield different signals
- Some characteristic signs of particles

  (Cosmological Collider [Maldacena, 2015])

  e.g. Mass of particles

  Wavelength of oscillatory signal



Observation of non-Gaussianities

Up to 2nd order action ➡ (basically) free theory, which is consistent to observation

Higher than 3rd order action ➡ interaction terms, not yet sufficiently observed

➡ Non-Gaussianities $\langle\zeta\zeta\zeta\rangle\,,\langle\zeta\zeta\zeta\zeta\rangle\,,\ldots$

Three point correlation function (Bispectrum):

Effects of interactions between k_1, k_2, k_3 (not scale invariant)

➡ Model dependent functions of k

Observables:

Amplitude $f_{\rm NL}$ (theory: $f_{\rm NL}\sim\mathcal{O}(0.1)$, observation: $f_{\rm NL}\sim\mathcal{O}(1)$)

Dimensionless shape function $\mathcal{F}(k_3/k_1, k_2/k_1)$

Specific regions in k_1, k_2, k_3 : Squeezed limit $k_3 \ll k_1 \simeq k_2$

(Model dependence are in k_3/k_1 axis)

Bosonic signals in non-Gaussianities

Observation prefers to single field slow-roll inflation.

➡ Effects of other fields must be small.

e.g. Quasi-single inflation [Chen, 2009]

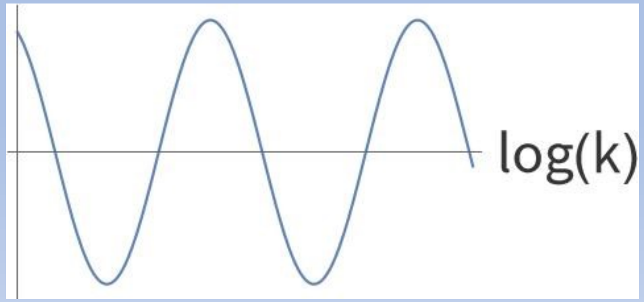
Inflaton ϕ + heavy scalar σ ($m_\sigma \sim H \gg m_\phi$)

➡ σ has no effect to inflationary background dynamics.

Leading bispectrum: $(k_3/k_1)^{i\mu}$, $f_{\rm NL} \lesssim \mathcal{O}(1)$ ($\mu = \sqrt{\left(\frac{m}{H}\right)^2 - \frac{9}{4}}$)

Other works: gauge boson [Wang, 2020], graviton [Tong, 2022], etc.

They all would produce oscillatory signals.



Few works for fermionic fields (mainly technical reasons)

despite the importance of fermion in both SM and BSM.

Fermionic interactions

Allowed setting:

De Sitter: shift symmetric scalar field potential $V(\phi + c) = V(\phi)$

➡ Slow roll: shift symmetric terms + small breaking terms in interactions

Fermionic interactions:

Previous research [Chen, 2018]

- Shift symmetric terms: $\frac{1}{\Lambda}\partial_\mu\phi\bar{\psi}\bar{\sigma}^\mu\psi, \quad \frac{1}{\Lambda^2}\Box\phi\psi\psi, \ldots$

Unrenormalizable interactions (EFT, SUGRA, …)

Leading ➡ $\partial_\mu\phi\bar{\psi}\sigma^\mu\psi$ (dim 5)

Our work

- Breaking terms: $y\phi\psi\psi, \quad \frac{1}{\Lambda}\phi^2\psi\psi, \ldots$

Leading and renormalizable ➡ Yukawa coupling

[Chen, 2018]

Previous research: derivative coupling

Action:

$$S = \int d^4x \sqrt{-g} \Big[\frac{R}{2} - \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi) + i\bar{\psi}\bar{\sigma}^\mu D_\mu \psi - \frac{1}{2} m(\psi\psi + \text{h.c.}) - \frac{1}{\Lambda}\partial_\mu \phi \bar{\psi}\bar{\sigma}^\mu \psi \Big]$$

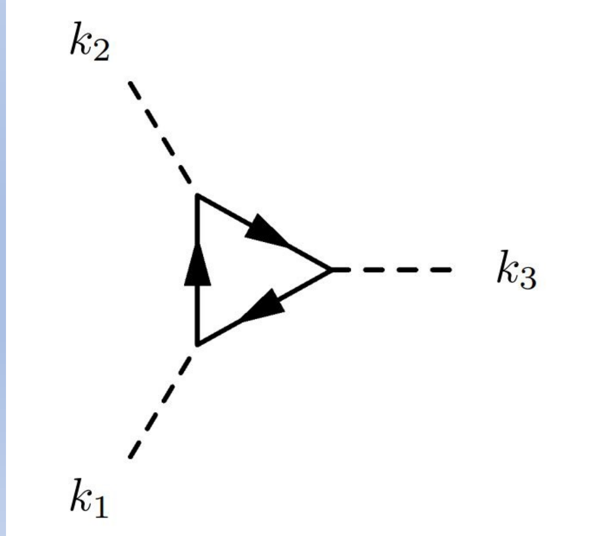
Correction in 2nd order action: $-\lambda \bar{\psi}\bar{\sigma}^0\psi, \quad \lambda = \frac{\dot{\phi}_0}{\Lambda}$

~~Time dependent mass-like coupling λ(t)~~

1st order of slow roll: λ = Const.

Approx. of loop integral: Extracting oscillatory signals

(IR modes $|k\tau| \ll 1$ of the loop)



[Chen, 2018]

Physical interpretation of λ

Considering the effects to energy:

Hamiltonian density of matter: $\mathcal{H} = \pi_\phi \dot{\phi} + \pi_\psi \dot{\psi} - \mathcal{L}$

Coupling $\frac{1}{\Lambda}\partial_\mu \phi \bar{\psi} \bar{\sigma}^\mu \psi$ changes the Hamiltonian:

$\mathcal{H} \to \tilde{\mathcal{H}} = \mathcal{H} - \lambda \mathcal{Q},$ $\mathcal{Q} = \bar{\psi}\bar{\sigma}^0 \psi$: Charge density

e.g. $\lambda > 0$

$\mathcal{Q}\uparrow$ (more particles) ➡ $\tilde{\mathcal{H}}\downarrow$ (more stable state)

λ: chemical potential ($H = H_0 - \mu N$)

The value is bounded by unitarity bound:

$\Lambda \gtrsim \sqrt{|\dot{\phi}|}$ ➡ $\lambda \lesssim (4\pi^2 P_\zeta)^{-1/4} H \sim 60 H$

[Chen, 2018]

Observational signals

Result:

$$\langle\zeta_1\zeta_2\zeta_3\rangle = (2\pi)^4 \frac{P_\zeta^2}{(k_1k_2k_3)^2} \mathrm{Re}\left[D(m,\lambda)\left(\frac{k_3}{k_1}\right)^{2-2i\sqrt{m^2+\lambda^2}/H}\right]$$

Wavelength: $\frac{H}{2\sqrt{m^2+\lambda^2}}$

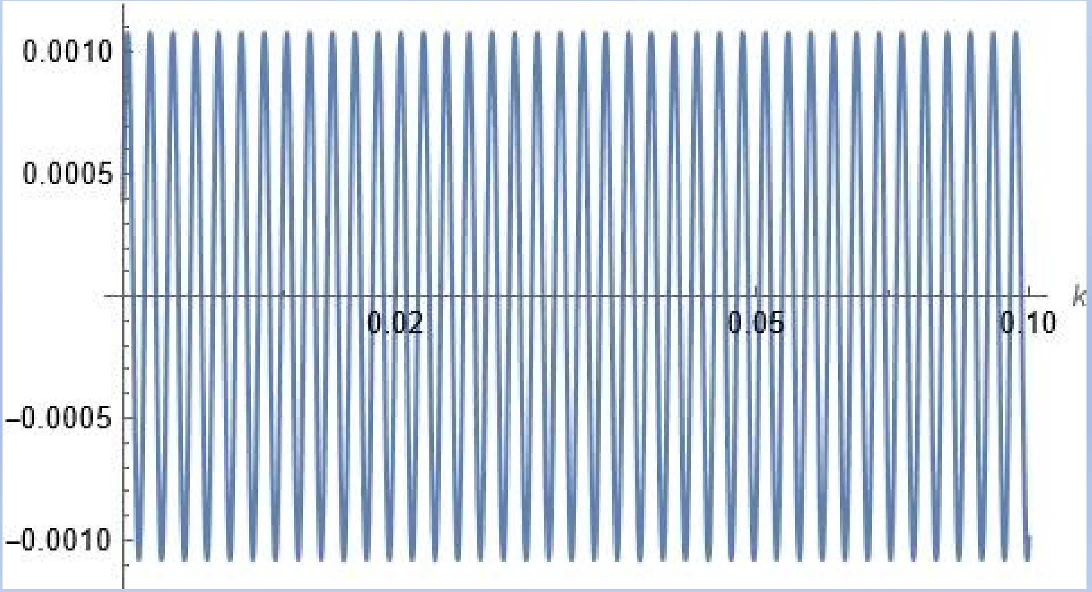
Amplitude: $f_{\mathrm{NL}}^{\mathrm{osc}} \lesssim \mathcal{O}(0.1)$

$$\lambda \lesssim (4\pi^2 P_\zeta)^{-1/4} H \sim 60H$$

Current observation: $f_{\mathrm{NL}} \sim \mathcal{O}(1)$

Future observation: $f_{\mathrm{NL}} \sim \mathcal{O}(10^{-2})$
(21 cm line)

$\lambda = 50H, m = H$



Yukawa coupling

Action:

$$S = \int d^4x\sqrt{-g}\Big[\frac{R}{2} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$
$$+ i\bar{\psi}\bar{\sigma}^\mu D_\mu\psi - \frac{1}{2}m(\psi\psi + \mathrm{h.c.}) - y\phi(\psi\psi + \mathrm{h.c.})\Big]$$

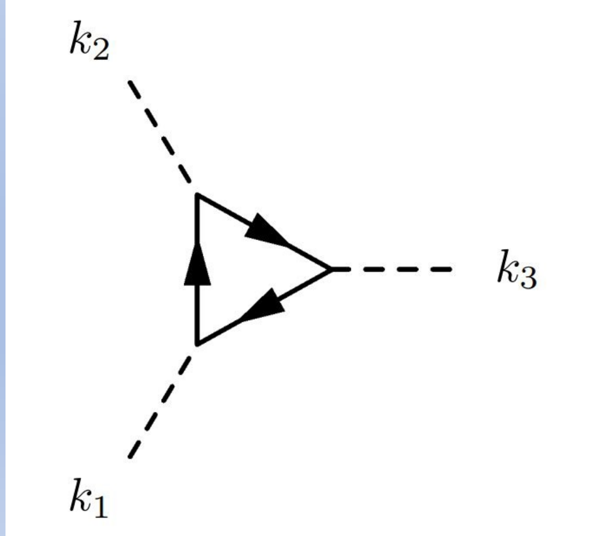
Mass correction: $m \to m + 2y\phi_0$

~~Time dependent mass m(t)~~

De Sitter approx.: m = Const.

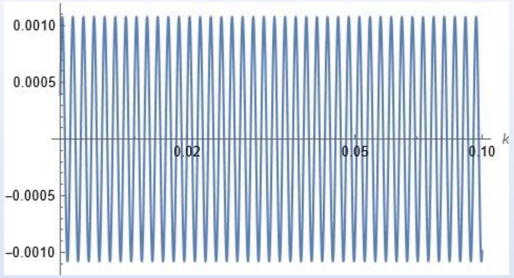
Approx. of loop integral: Extracting oscillatory signals

(Following previous work)



Observational signals

Derivative coupling case



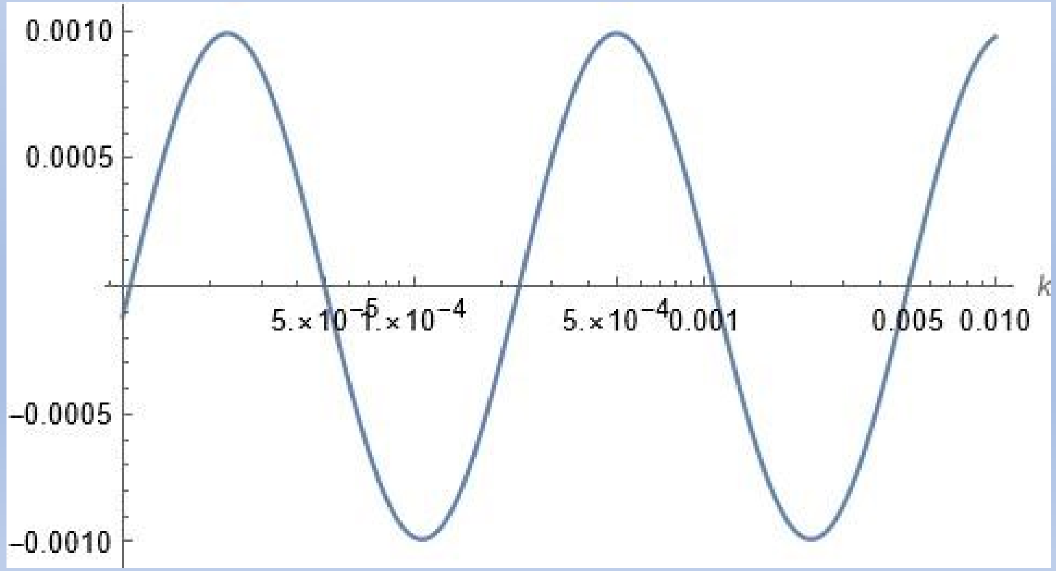
Result:

$$\langle \zeta_1 \zeta_2 \zeta_3 \rangle = (2\pi)^4 \frac{P_\zeta^2}{(k_1 k_2 k_3)^2} \mathrm{Re}\left[y^3 C(m + 2y\phi_0) \left(\frac{k_3}{k_1} \right)^{2 - 2i(m+2y\phi_0)/H} \right]$$

Wavelength: $\frac{H}{2(m + 2y\phi_0)}$

Longer than derivative case

$y = 0.01, m = H, \phi = H$



Amplitude: $f_{\rm NL}^{\rm osc} \lesssim \mathcal{O}(0.1)$

$y < 1, \phi \gtrsim H$

Same order as derivative case

Distinguishing these signals

Observable: amplitude and wavelength of the bispectrum

Yukawa: Positive mass shift $y\phi_0$ suppress particle production

Large amplitude ➡ small m, ϕ_0, neither large nor small y(~ 0.1)

Wavelength $\dfrac{H}{2(m+2y\phi_0)}$ is large in large amplitude.

Derivative: Chemical potential (promote particle production)

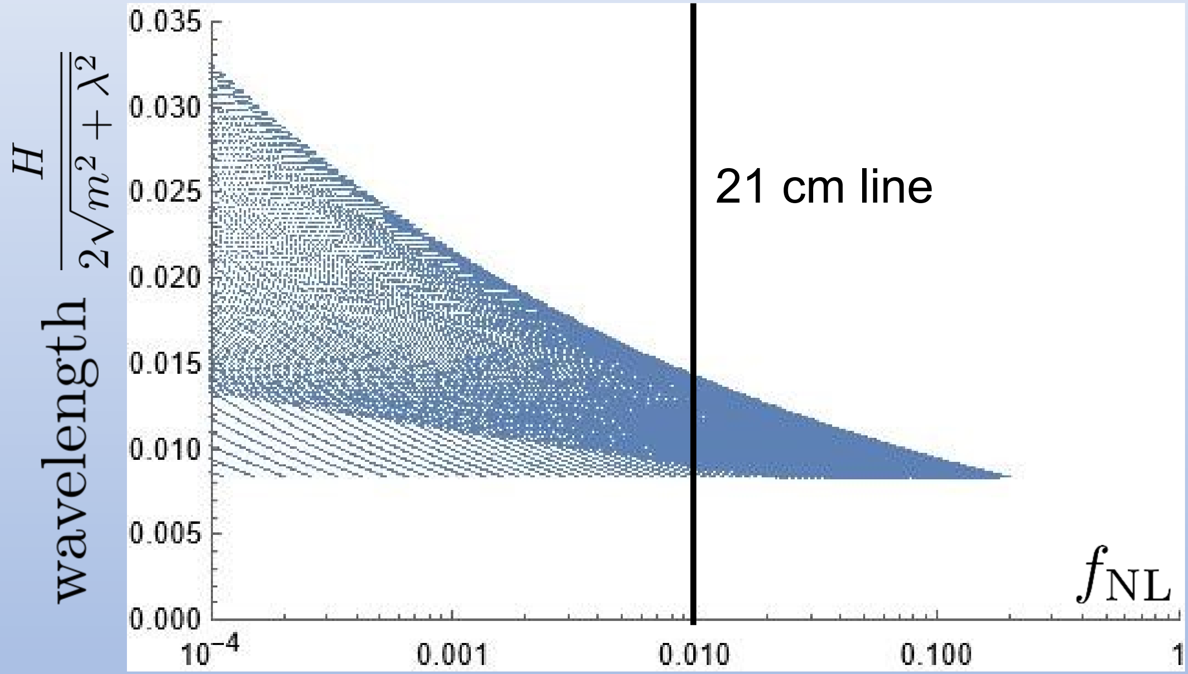
Large amplitude ➡ small m, large λ

Wavelength $\dfrac{H}{2\sqrt{m^2+\lambda^2}}$ is small in large amplitude.

➡ Wavelength is different in large amplitude signals

Distinguishing these signals (figures)

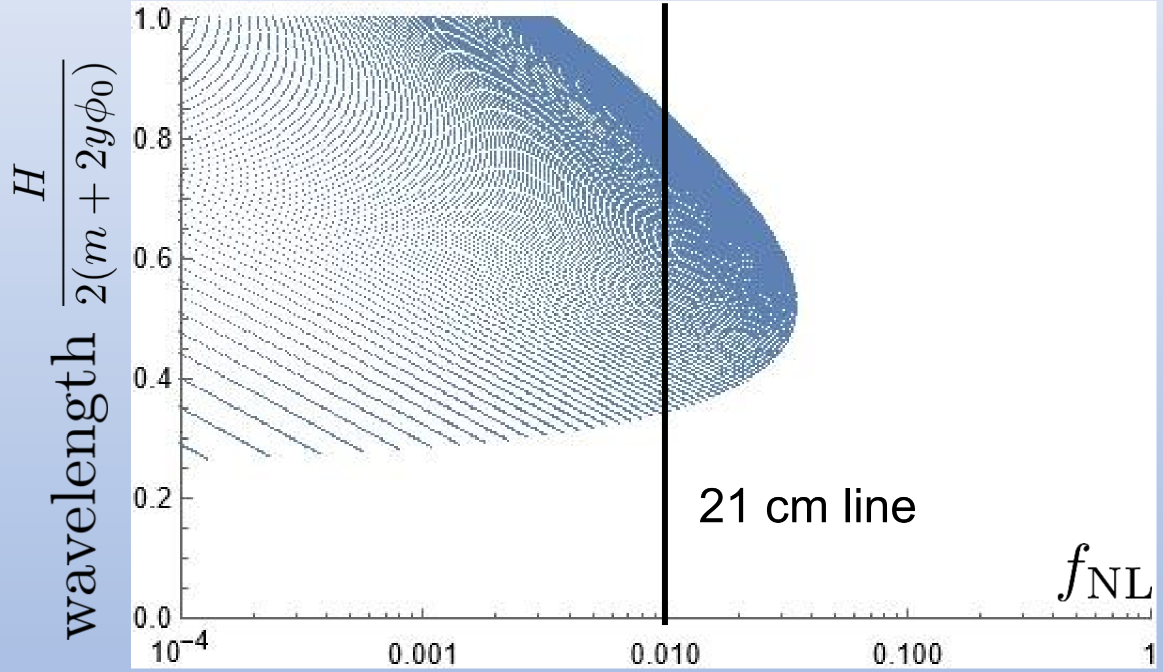
Derivative coupling



wavelength $\lesssim 0.02$

$\lambda \lesssim (4\pi^2 P_\zeta)^{-1/4} H \sim 60H$

Yukawa coupling



wavelength $\gtrsim 0.3$

$y < 1, \phi \gtrsim H$

Ongoing works

Generally both interactions are in action.

Both mass shift and chemical potential exist in mode functions.

➡ Parameter regions are overlapped.

- Same wavelength: $$\frac{H}{2\sqrt{(m+2y\phi_0)^2+\lambda^2}}$$
- Large amplitude in large λ (i.e. short wavelength)

Wavelength does not extract physical essence of the interactions

What is the most crucial difference between these interactions?

(More generally, how to know interactions from oscillatory signals?)

Our strategy: UV behavior (expected: logarithmic v.s. quadratic)

How about supersymmetric theory? Quadratic divs. are canceled?

Summary

Cosmological perturbations

are explained well by linear order inflationary perturbations.

would have rich information of new physics in higher order correlations.

Fermionic signals in non-Gaussianities have similar behavior.

The case either Yukawa or derivative coupling

➡ Distinguishable by wavelength of signals

The case both interactions exist

➡ Not distinguishable by wavelength in IR approx.

➡ (our ongoing work) UV behavior differs?

➡ New physics (e.g. supersymmetric theory)