

Cosmological Collider Physics :

How to probe BSM physics “of the current universe” through cosmological collider

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Shuntaro Aoki, MY, 2012.13667, JHEP 04 (2021) 127

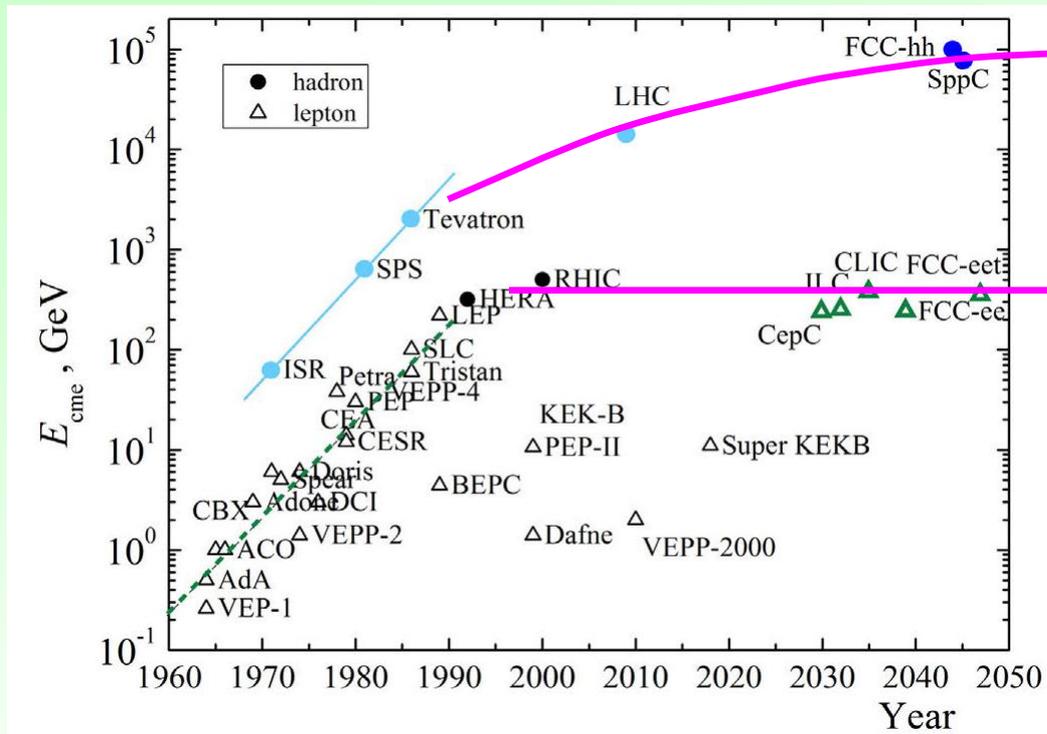
Lucas Pinol, Shuntaro Aoki, Sébastien Renaux-Petel, MY, 2112.0570, PRD107 (2023)2, L21301

Shuntaro Aoki, Toshifumi Noumi, Fumiya Sano, MY, 2312.09642, JHEP 03 (2024) 073

$$c = \hbar = M_G^2 = 1/(8\pi G) = 1$$

Collider on earth

History of colliders on earth



(Figure taken from Gray 2021)

The energy scale of colliders on earth is going to saturate and then we need alternative.

What can be an alternative ?

 **Cosmology** will be the unique place for alternative collider.

A **higher energy state** is easily excited and realized in the **universe**.
(We have **natural accelerators** in the universe.)

New ways to probe high energy physics

Higher energy state and new particles are produced in **early universe** and **astrophysical objects**.

Cosmological collider :

Heavy particles can be excited at tree and/or loop level during inflation.

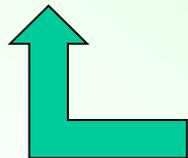
Leave imprints on primordial curvature perturbations.

→ Extract information of heavy particles and new physics from them.

High energy astrophysics :

Particles are accelerated in **astrophysical objects**.

But, the acceleration mechanism and the origin of high energy cosmic rays have not yet been understood well.



This talk

**Any fields (particles) can be excited
during inflation
as a result of (quantum) fluctuations !!**

**This phenomena is similar to
the production of particles by colliders on earth.**

Contents

- **Introduction**

 - Collider on earth and in (early) cosmology

- **How to probe “BSM of the current universe” ?**

 - Masses during inflation vs Masses in current universe

 - => How to probe current masses

 - Couplings of BSM

 - => Can we discriminate e.g.

 - derivative vs non-derivative couplings ?

- **Summary and discussions**

Cosmological collider is a special tool to probe BSM physics

In the standard techniques to probe BSM **on earth**,

energy scale of a new physics is getting higher and higher



its detection becomes **more and more difficult !!**

- Colliders cannot produce too **heavy particles**.
- Even in the (**indirect**) precision physics, typically, signals get **weaker** as the (breaking) scale of new physics gets **higher**.

Cosmological collider is a special tool to probe BSM physics II

Exceptions :

- Topological defects (especially, cosmic strings) :

The deficit angle and the tension are proportional to the breaking scale (squared) of new physics.

=> We have upper bound on new physics (breaking) scale.

- Cosmological collider :

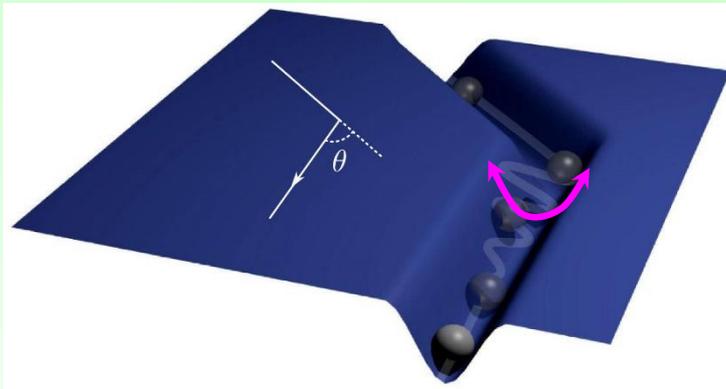
Powerful to probe “physics with almost fixed Hubble scale”
(further exception => genesis?)

=> As the Hubble parameter gets higher, the signal gets larger
like the primordial tensor perturbations.

Heavy particles can be excited during inflation !!

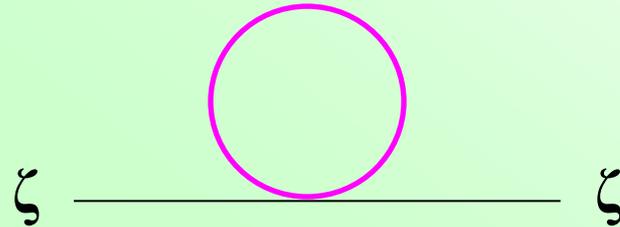
In supergravity and/or superstring theory, there are a lot of fields whose masses are comparable to or larger than the Hubble parameter.

Tree level



(Figure taken from Wang 1303.1523)

Loop effects



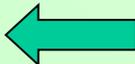
Heavy particles can be excited at tree and/or loop level during inflation.

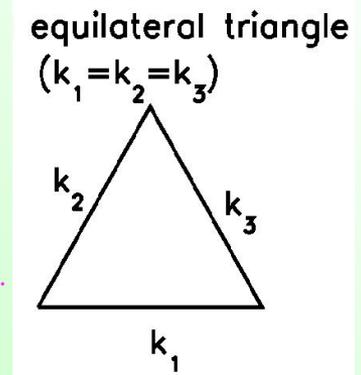


Leave imprints on primordial curvature perturbations, especially, their **non-Gaussianities**.

Shapes of non-Gaussianity (bispectrum)

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3) \rangle = (2\pi)^3 \delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B(k_1, k_2, k_3).$$

Length of three sides !!  triangle
(homogeneity & isotropy)



● Equilateral type :

$$B_{\text{equil}}(k_1, k_2, k_3) = 6\mathcal{P}^2 f_{\text{NL}}^{\text{equil}} \left\{ -\frac{1}{k_1^3 k_2^3} - \frac{1}{k_2^3 k_3^3} - \frac{1}{k_3^3 k_1^3} - \frac{2}{(k_1 k_2 k_3)^2} + \left[\frac{1}{k_1 k_2^2 k_3^3} + (5 \text{ perm.}) \right] \right\}.$$

(P : normalization of powerspectrum)

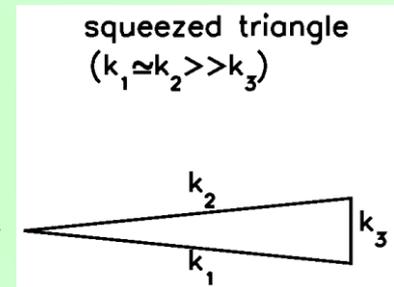
ζ typically originates from an **inflaton** and non-G is generated **at horizon exit**.

PLANCK2018  $f_{\text{NL}}^{\text{equil}} = -26 \pm 47$

Figures taken from
Jeong & Komatsu 2009

● Local (squeezed) type : $\zeta(x) = \zeta_G(x) + \frac{3}{5} f_{\text{NL}} \zeta_G^2(x)$.

$$B_{\text{local}}(k_1, k_2, k_3) = 2\mathcal{P}^2 f_{\text{NL}}^{\text{local}} \left[\frac{1}{k_1^3 k_3^3} + (2 \text{ perm.}) \right],$$



ζ typically originates from **another field** other than inflaton and non-G is generated **during superhorizon evolution**.

PLANCK2018  $f_{\text{NL}}^{\text{local}} = -0.9 \pm 5.1$

Though there are other types such as **orthogonal** and **folded** ...

Cosmological collider

The presence of a new single particle of **mass $m > 3H/2$** and spin s leads to

$$\lim_{k_1 \rightarrow 0} \frac{\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle'}{P_1 P_2} \sim \epsilon e^{-\pi\mu} |c(\mu)| \left[e^{i\delta(\mu)} \left(\frac{k_1}{k_2}\right)^{\frac{3}{2}+i\mu} + e^{-i\delta(\mu)} \left(\frac{k_1}{k_2}\right)^{\frac{3}{2}-i\mu} \right] P_s(\cos\theta)$$

(Noumi, MY, Yokoyama 2013,
Arkani-Hamed & Maldacena 2015)

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

angle between \mathbf{k}_1 & \mathbf{k}_2

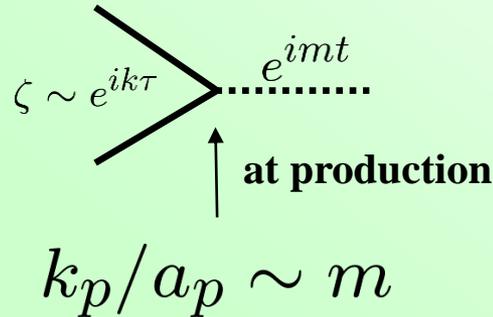
- N.B.**
- The oscillation measures **the mass m** .
 - This oscillatory behavior represents the quantum interference between the inflation and a massive particle, which is pair created and subsequently decays into the inflaton.
 - $3/2$ can be understood as the square of the wavefunction decays as $\exp(-3N) \sim 1/\text{Volume}$.
 - $\exp(-\pi\mu)$ represents the interference effect for creating a pair of massive particles.
 - The angle dependence measures **the spin s** .

More systematic study on the **feature** of a new particle, **multiple particle effects**, **observability**, and so on is necessary.

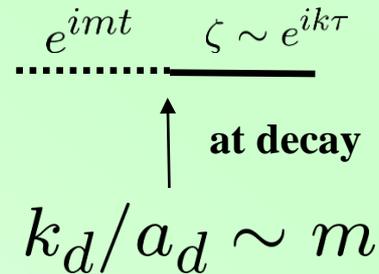
How to understand the oscillatory behavior ?

(Tong, Wang, Zhu 2021)

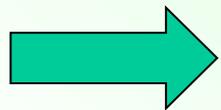
1. Resonant production :



2. Resonant decay :

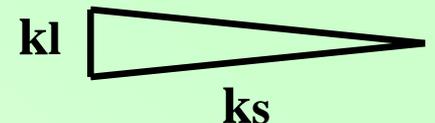


Wavefunction of a heavy field :



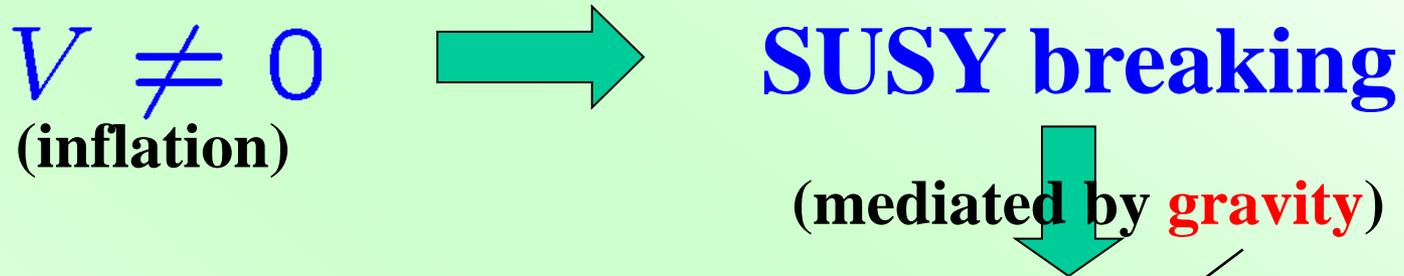
$$e^{im(t_d - t_p)} \sim e^{i\mu(\ln a_d - \ln a_p)} \sim \left(\frac{a_d}{a_p}\right)^{i\mu} \sim \left(\frac{k_d}{k_p}\right)^{i\mu} \sim \left(\frac{k_l}{k_s}\right)^{i\mu}$$

$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}} \sim \frac{m}{H}$$



Natural Hubble mass in supergravity

In supergravity,



Additional soft breaking masses : $m^2 \sim V G_N \sim H^2$

In supergravity, a situation naturally happens, in which there is **only a light field, which could be an inflaton, and the masses of other fields are comparable to the Hubble parameter.**

(Note also that **a non-minimal coupling $R\phi^2$**
and **dimension 6 operators** easily lead to $m \sim H$)

This model **was called quasi-single field inflation** (Chen & Wang 2009)
and **now is called cosmological collider.** (Arkani-Hamed & Maldacena 2015)

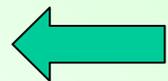
Masses of BSM

Difference between masses during inflation and masses in current Universe

We are interested in **BSM physics**,
such as **masses, spins, etc** of new particles !!

Cosmological collider

=> probe **“effective” masses (squared) during inflation $\sim O(H^2)$**



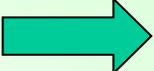
NOT necessarily what particle physicists would like to know.

Of course, it's fantastic to know **the presence of “new particles”**, but
more fantastic if one can know **the information of their “current” masses**.

(To confirm even the presence of new particles, we first need to estimate
the effects of SM particles precisely ← as done by Chen, Wang, Xianyu)

One ideal case : the universal Hubble correction

Canonical Kähler potential : $K = \sum_i |\phi_i|^2$



$$\mathcal{L}_{\text{kin}} = -\frac{\partial^2 K}{\partial \phi_i \partial \phi_j^*} \partial_\mu \phi_i \partial^\mu \phi_j^* = -\partial_\mu \phi_i \partial^\mu \phi_j^* \quad \text{: canonical kinetic term}$$

$$V_F = \exp\left(\sum_i |\phi_i|^2\right) \times$$

$$\left\{ \left[\frac{\partial W}{\partial \phi_i} + (\phi_i^* + \dots)W \right] \sum_{i,j} (\delta_{ij} + \dots) \left[\frac{\partial W^*}{\partial \phi_j^*} + (\phi_j + \dots)W^* \right] - 3|W|^2 \right\}$$

$$= V_{\text{global}} + V_{\text{global}} \sum_i |\phi_i|^2 + \text{other terms,} \quad \left(V_{\text{global}} \equiv \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 \right)$$



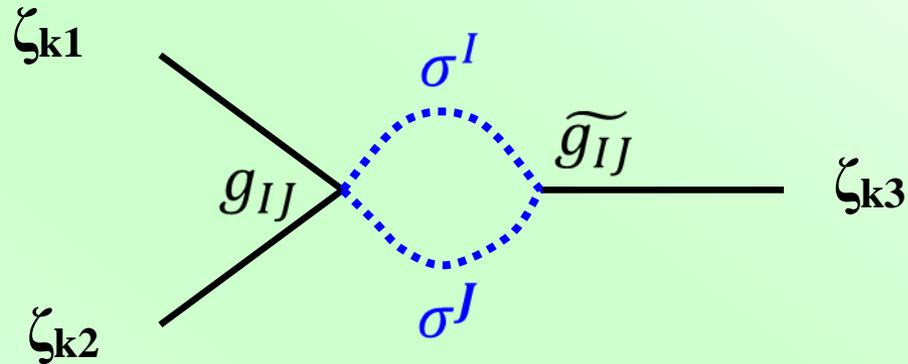
$$m_{i,\text{eff}}^2 = m_i^2 + 3H^2 \quad \left(\leftarrow \xi \sum_i \phi_i^2 R \right) \text{ as well}$$

But, e.g. $\Delta K = -\sum_i \lambda_i |\phi_i|^4 \implies \delta m_{i,\text{eff}}^2 = 12\lambda_i H^2 \left(\leftarrow \sum_i \xi_i \phi_i^2 R \right)$

Multiple isocurvatons σ^I with $m \sim H$

(Aoki & MY 2020,
Pinol, Aoki, Renaux-Petel, MY 2021)

e.g.



$$\left(\subset S_{\text{int}}(\phi, \sigma) = \int d^4x \mathcal{L}_{\text{int}} = - \int d^4x \sqrt{-g} f(\phi) c_{IJ} \sigma^I \sigma^J \right)$$

σ^I ($I=1, \dots, n$) : massive isocurvatons

$g_{IJ}, \widetilde{g}_{IJ}$: couplings, non-diagonal in general

($g_{IJ} = \widetilde{g}_{IJ}$ after the normalization by H for simplicity)

Squeezed limits of bispectra

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' = (2\pi)^4 \mathcal{P}_\zeta^2 \frac{1}{(k_1 k_2 k_3)^2} S(k_1, k_2, k_3),$$

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

● **I = J**

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

$$C(\mu_I, \mu_I) \propto e^{-2\pi\mu_I}$$

(Boltzman suppression factor)

High frequency

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

● **I ≠ 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)

High frequency

low frequency (modulation)

* easily distinguished

* specific to multi particles

Two field case with mixing ($g_{11} = g_{22} = g_{12}$)

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

High frequency

**low frequency
(modulation)**

In degenerate limit ($\mu_1 \sim \mu_2 = \mu$), ← universal Hubble correction case

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

The total signal

~ characterized by the low frequency mode (large wavelength)

Two field case with mixing ($g_{11}=g_{22}=g_{12}$) II

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

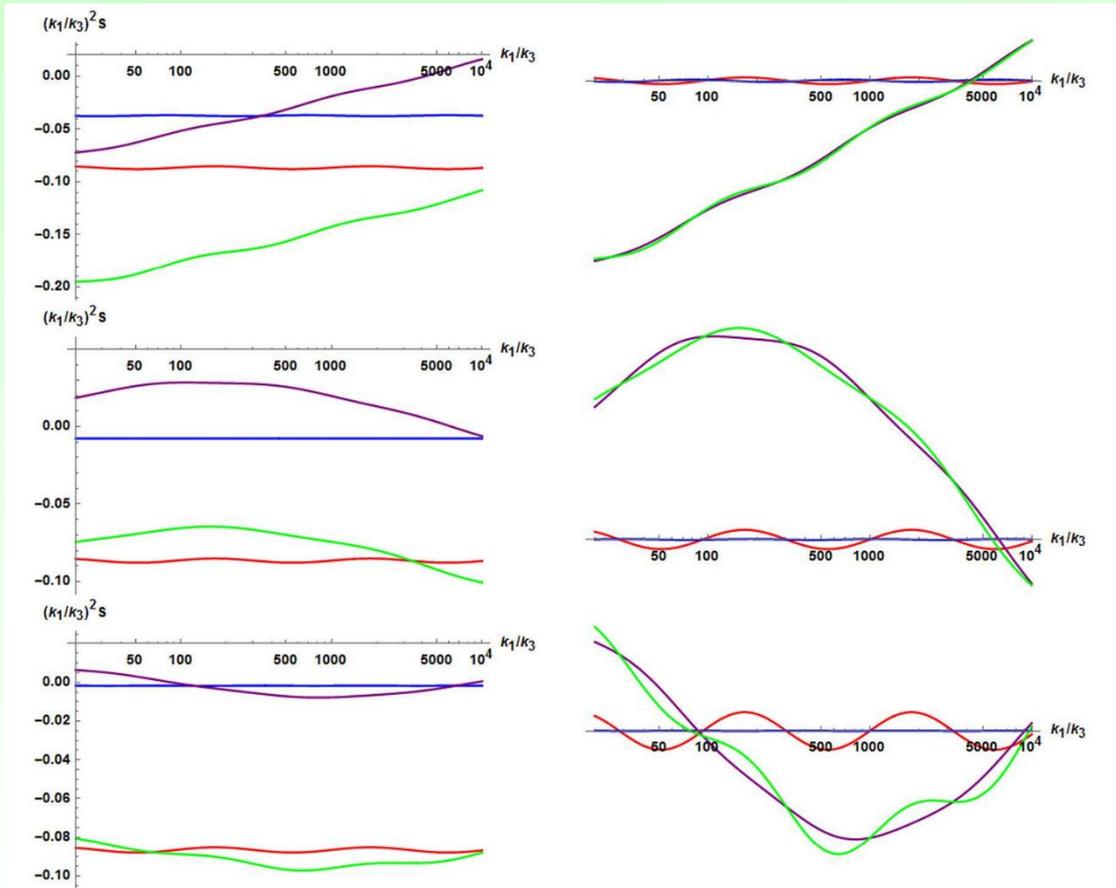


Figure 4. The same figure with figure 2 but the mixing term S_{12} included (purple line). We set $(m_1, m_2)/H = (2, 2.1)$, $(m_1, m_2)/H = (2, 2.3)$, and $(m_1, m_2)/H = (2, 2.5)$ from top to bottom. The couplings are taken universally, $g_{IJ} = \hat{g}_{IJ} = 1$ for $I, J = 1, 2$. The right figures show that the waveforms (momentum dependence) of the total signal are mainly determined by the mixing term S_{12} .

The waveform is mainly determined by S_{12} !!

Small modulations on the large waveform



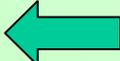
Easily disentangle the mass spectra

Two field case with mixing ($g_{11} = g_{22} = g_{12}$)

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

High frequency

**low frequency
(modulation)**

In degenerate limit ($\mu_1 \sim \mu_2 = \mu$),  **universal Hubble correction case**

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

The total signal

~ characterized by the low frequency mode (large wavelength)

$$\mu^I = \sqrt{\frac{m_{I,\text{eff}}^2}{H^2} - \frac{9}{4}}, \quad m_{I,\text{eff}}^2 = m_I^2 + 3H^2 \quad \text{from GW?} \quad \longrightarrow \quad \mu^I - \mu^J \simeq \frac{2}{\sqrt{3}} \frac{1}{H^2} (m_I^2 - m_J^2)$$

(We might know **the mass (squared) difference** albeit **not its absolute magnitude**.)

Couplings of BSM

Non-derivative OR derivative couplings

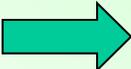
Particle physicists usually interested in

- | | | |
|---|--|--|
| { | ● gauge couplings (gauge structure) | $g^2 \phi ^2 A_\mu A^\mu, \dots$ |
| | ● Yukawa couplings (flavor and mass structure) | $y \phi \bar{\psi} \psi, \dots$ |
| | ● potential terms (symmetry breaking pattern) | $\lambda (\phi ^2 - v^2)^2, \dots$ |
| | ... | $f(\phi, \sigma, \partial\sigma, \dots)$ |

Non-derivative interactions  Break shift symmetry (scale invariance)

- | | | |
|---|---|--|
| { | ● Axion(-like-particle) interaction, | |
| | ● SUGRA | |
| | ● EFT (but, the cutoff scale is larger than Hubble parameter during inflation), | $f(\partial\phi, \sigma, \partial\sigma, \dots)$ |
| | ... | |

Derivative (shift-symmetric) interactions often appear as well

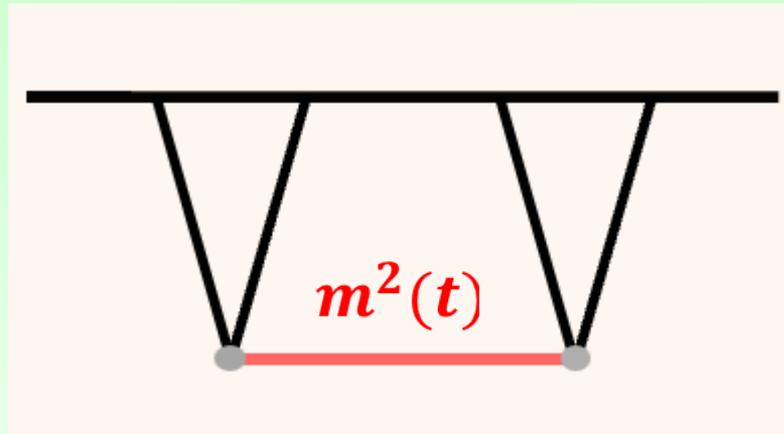
 Preserve shift symmetry (scale invariance)

As a first step, **how much can we discriminate them ?**

Time-dependent mass

$\sigma - \phi$ couplings could lead to an effective mass :

e.g. $\mathcal{L}_{\text{int}} \supset -\frac{1}{2}g(\phi)\sigma^2 \quad \longrightarrow \quad m_{\text{eff}}^2 = g(\phi_0(t))$



Numerical approach : (Reece, Wang, Xianyu 2022)



Analytic approach in our case (Aoki, Noumi, Sano, MY 2024)

Time dependence

Slow-roll approximation with ϵ being almost constant :

$$\phi_0(\tau) = \sqrt{2\epsilon}M_{\text{pl}} \log\left(\frac{\tau}{\tau_0}\right)$$

Linear approximation : $m_{\text{eff}}^2 = g(\phi_0(\tau))$

$$\left\{ \begin{array}{l} \phi_0(\tau) = \phi_{0*} - \sqrt{2\epsilon}M_{\text{pl}} \left(1 - \frac{\tau}{\tau_*}\right) + \dots, \\ \qquad \qquad \qquad \qquad \qquad \qquad \qquad \left(\left|1 - \frac{\tau}{\tau_*}\right| \ll 1\right) \qquad \qquad \qquad A_* \equiv A(\tau_*) \\ \\ m_{\text{eff}}^2(\tau) = g_* - g_{\phi,*} \sqrt{2\epsilon}M_{\text{pl}} \left(1 - \frac{\tau}{\tau_*}\right) + \dots, \\ \qquad \qquad \qquad \qquad \qquad \qquad \qquad \underbrace{\qquad \qquad \qquad}_{\text{Time dependence}} \left(\left|\frac{g_{\phi\phi,*}M_{\text{pl}}}{g_{\phi,*}}\right| \ll \frac{1}{\sqrt{\epsilon}}\right) \end{array} \right.$$

 Scale dependence ($k \tau = -1$: horizon exit)

Sizes of scale dependence

- **Non-derivative interactions :**

$$\mathcal{L}_{\text{int}} \supset -\frac{1}{2}g(\phi)\sigma^2 \quad \longrightarrow \quad m_{\text{eff}}^2 = g(\phi_0(t))$$

$$\left\{ \begin{array}{l} \phi_0(\tau) = \phi_{0*} - \sqrt{2\epsilon}M_{\text{pl}} \left(1 - \frac{\tau}{\tau_*}\right) + \dots, \\ m_{\text{eff}}^2(\tau) = g_* - g_{\phi,*} \sqrt{2\epsilon}M_{\text{pl}} \left(1 - \frac{\tau}{\tau_*}\right) + \dots, \end{array} \right.$$

O($\epsilon^{1/2}$) scale(time) dependence

- **Derivative interactions :**

$$\mathcal{L}_{\text{int}} \supset -\frac{1}{2}g((\partial\phi)^2)\sigma^2 \quad \longrightarrow \quad m_{\text{eff}}^2 = \underline{g(\dot{\phi}_0^2(t))}$$



$$2\epsilon M_{\text{pl}}^2 H^2$$

O(ϵ, η) scale(time) dependence

Mode function and propagators of heavy field

$$v_k'' - \frac{2}{\tau} v_k' + \left(k^2 + \frac{\mu^2 + 9/4}{\tau^2} + \frac{2k\kappa}{\tau} \right) v_k = 0$$

$$\mu^2 \equiv \frac{g_*}{H^2} \left(1 - \frac{\sqrt{2\epsilon} g_{\phi,*} M_{\text{pl}}}{g_*} \right) - \frac{9}{4}, \quad \kappa \equiv -\frac{g_*}{2H^2} \frac{\sqrt{2\epsilon} g_{\phi,*} M_{\text{pl}}}{g_*}.$$

$$\longrightarrow v_k = \frac{e^{\pi\kappa/2}}{\sqrt{2k}} H(-\tau) W_{-i\kappa, i\mu}(2ik\tau)$$

↑
Whittaker function

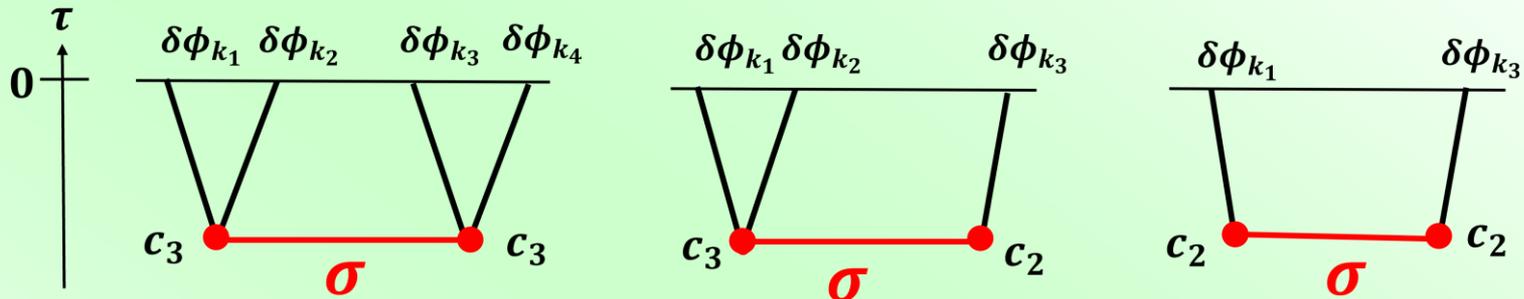
$$\left[\begin{array}{l} m_{\text{eff}}^2 = g(\phi_0(t)) : \text{constant} \Rightarrow \mathbf{g_{\phi,*} = 0} \Rightarrow \mathbf{\kappa = 0} \\ \longrightarrow v_k = e^{-\frac{\pi}{2}\mu + i\frac{\pi}{4}} \frac{\sqrt{\pi}}{2} H(-\tau)^{3/2} H_{i\mu}^{(1)}(-k\tau) \end{array} \right]$$

Propagators



$$\left\{ \begin{array}{l} D_{+-}(k; \tau_1, \tau_2) = v_k(\tau_1) v_k^*(\tau_2) = D_{-+}^*(k; \tau_1, \tau_2) \\ D_{\pm\pm}(k; \tau_1, \tau_2) = D_{\pm\mp}(k; \tau_1, \tau_2) \theta(\tau_1 - \tau_2) + D_{\mp\pm}(k; \tau_1, \tau_2) \theta(\tau_2 - \tau_1) \end{array} \right.$$

Inflationary correlators



$$\mathcal{L}_{2,\text{int}} = c_2(-H\tau)^{-3}\sigma\delta\phi', \quad \mathcal{L}_{3,\text{int}} = c_3(-H\tau)^{-2}\sigma(\delta\phi')^2$$

(shift-symmetric) σ -interactions \leftarrow e.g. $\sigma(\partial\phi)^2/\Lambda$

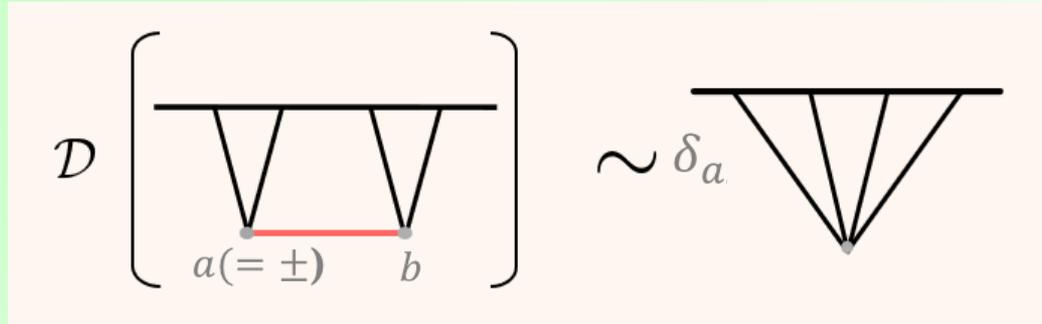
Seed integrals :

$$\mathcal{I}_{ab}^{p_1 p_2} \equiv -abk_s^{5+p_{12}} \int_{-\infty}^0 d\tau_1 d\tau_2 (-\tau_1)^{p_1} (-\tau_2)^{p_2} e^{iak_{12}\tau_1 + ibk_{34}\tau_2} D_{ab}(k_s; \tau_1, \tau_2)$$

$$(k_s = |\mathbf{k}_1 + \mathbf{k}_2|, \quad p_{12} = p_1 + p_2, \dots)$$

\rightarrow e.g. $\langle \zeta^3 \rangle \propto c_2 c_3 H \cdot \frac{1}{8k_1 k_2 k_3^4} \lim_{k_4 \rightarrow 0} \sum_{a,b=\pm} \mathcal{I}_{ab}^{0,-2} + 2\text{perm.}$

Bootstrap equations



$$\mathcal{D}_{\pm, u}^p \equiv (u^2 - u^3) \partial_u^2 - [(4 + 2p)u - (1 + p \pm i\kappa)u^2] \partial_u + \left[\mu^2 + \left(p + \frac{5}{2} \right)^2 \right]$$



$$\left\{ \begin{array}{l} \mathcal{D}_{\pm, u_1}^{p_1} \mathcal{I}_{\pm \mp}^{p_1 p_2} = 0, \\ \mathcal{D}_{\pm, u_1}^{p_1} \mathcal{I}_{\pm \pm}^{p_1 p_2} = H^2 e^{\mp i p_{12} \frac{\pi}{2}} \Gamma(5 + p_{12}) \left(\frac{u_1 u_2}{2(u_1 + u_2 - u_1 u_2)} \right)^{5 + p_{12}}, \end{array} \right.$$

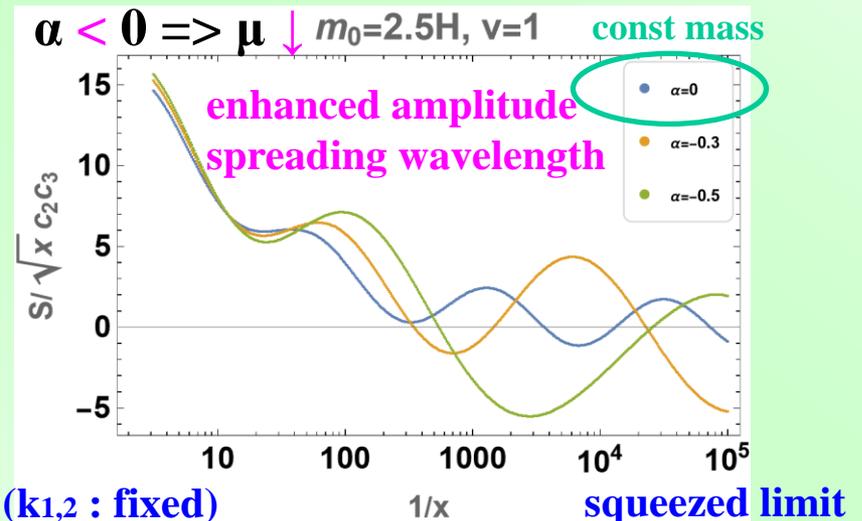
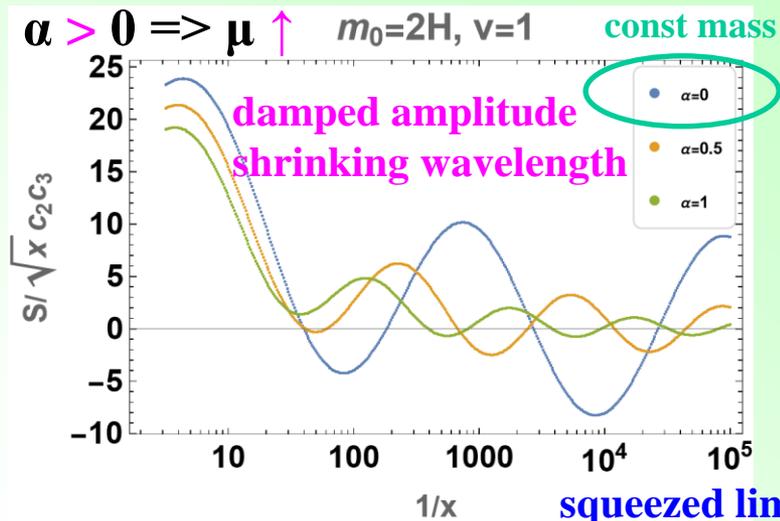
We can solve these equations **analytically !!**

Observational signals

Concrete example : $g(\phi) = m_0^2 \left(1 + \alpha \frac{\phi}{M_{\text{pl}}} \right)$ $m_{\text{eff}}^2 = g(\phi_0(t))$

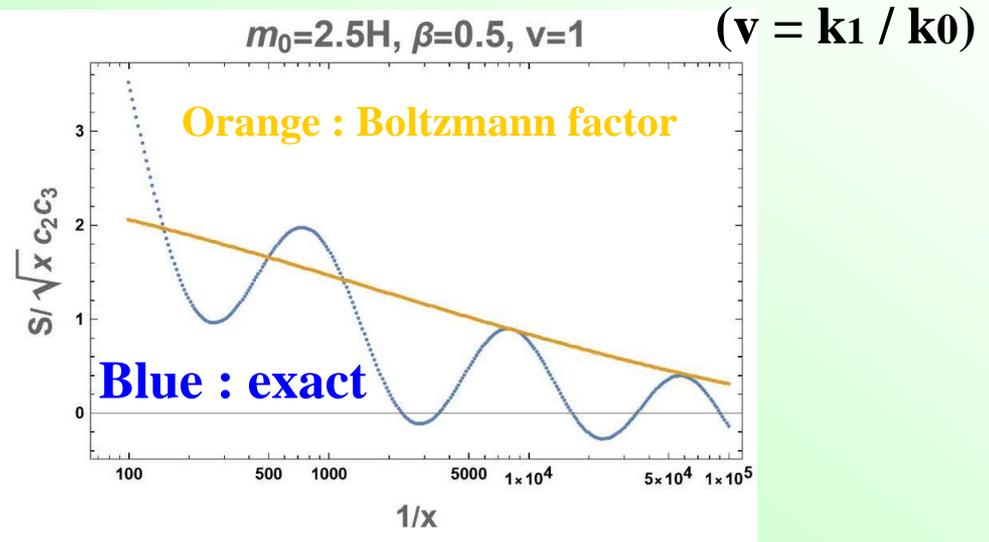
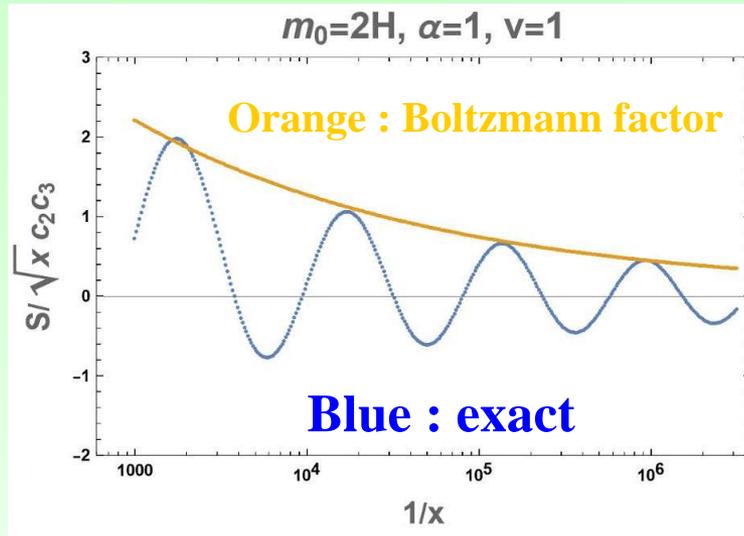
Shape function S : $\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle \equiv (2\pi)^7 \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \frac{P_\zeta^2}{(k_1 k_2 k_3)^2} S$

→ $S = \frac{1}{(2\pi)^4} \cdot \frac{1}{P_\zeta^2} \cdot (2\epsilon M_{\text{pl}}^2)^{-\frac{3}{2}} \cdot (-2c_2 c_3) \cdot \frac{H}{8} \sum_{a,b=\pm} \left[\frac{k_1 k_2}{k_3^2} \mathcal{I}_{ab}^{0,-2} \left(\frac{2k_3}{k_{123}}, 1 \right) + 2\text{per.} \right]$



In the squeezed limit $x = k_3 / k_{1,2} \ll 1$, $S/\sqrt{x} \sim e^{-\pi\mu(x)} x^{\pm i\mu(x)} + \text{c.c.}$,

Observational signals II



Linear : $g(\phi) = m_0^2 \left(1 + \alpha \frac{\phi}{M_{\text{pl}}} \right)$

$$e^{-\pi\mu(x)} \sim e^{-\pi m_0/H} \cdot \left(\frac{1}{\nu x} \right)^{-\pi \frac{m_0}{H} \sqrt{\frac{\epsilon}{2}} \alpha}$$

Quadratic : $g(\phi) = m_0^2 \left(1 + \beta \frac{\phi^2}{M_{\text{pl}}^2} \right)$

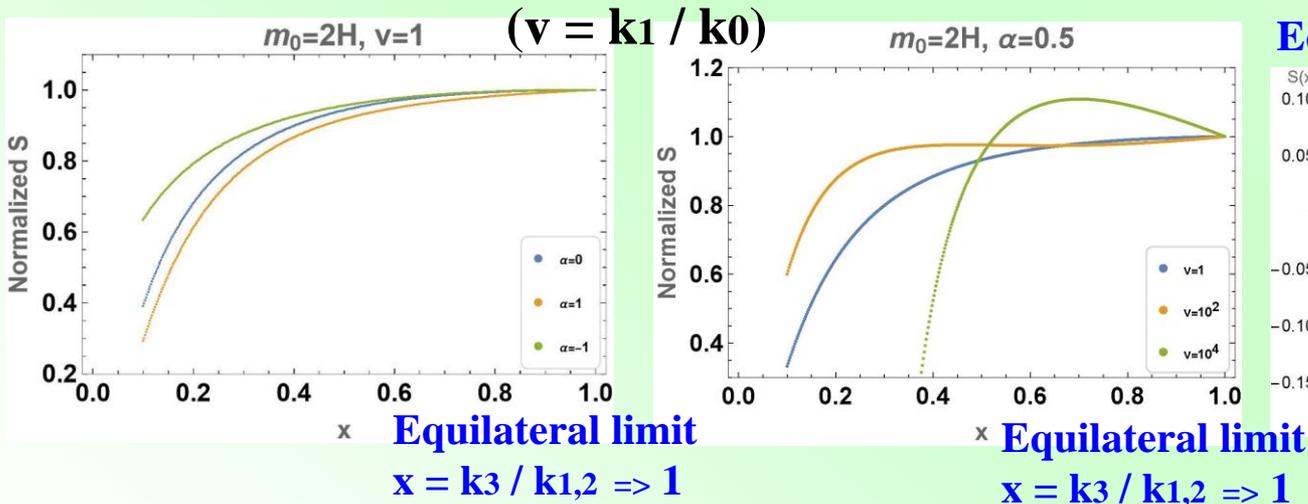
$$e^{-\pi\mu(x)} \sim e^{-\pi m_0/H} \cdot e^{-\pi \frac{m_0}{H} \cdot \beta \epsilon (\log \nu x) (\log \nu x + 2)}$$

In principle, we can discriminate them, but ...

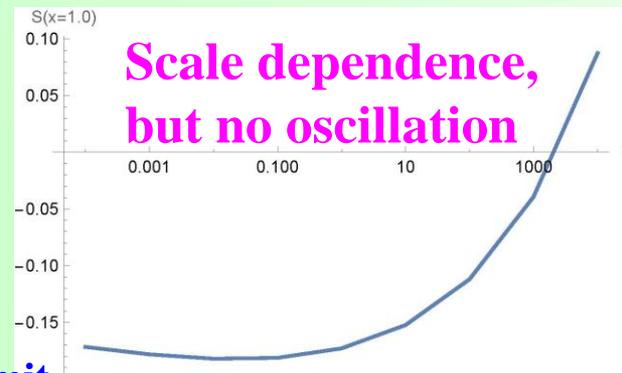
Observational signals III

Concrete example : $g(\phi) = m_0^2 \left(1 + \alpha \frac{\phi}{M_{\text{pl}}} \right)$ $m_{\text{eff}}^2 = g(\phi_0(t))$

$f_{\text{NL}}^{\text{equi}} \sim c_2 c_3 \times \mathcal{O}(10)$ for $\alpha = \mathcal{O}(1)$, $m_0 = \mathcal{O}(H)$



Equilateral limit $x = 1$



We do not find interesting features, unfortunately.

Summary

- Unfortunately, the energy scale of colliders on earth is going to **saturate** in near future.
- As an alternative to colliders on earth, **cosmology, especially, inflation** could offer another collider.
- We tried to address **BSM of the current Universe**, which particle physicists would be more interested in.
- For this purpose, we have discussed **mass spectra and interactions**, and potentially could get useful information. But, the challenge has just started.