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

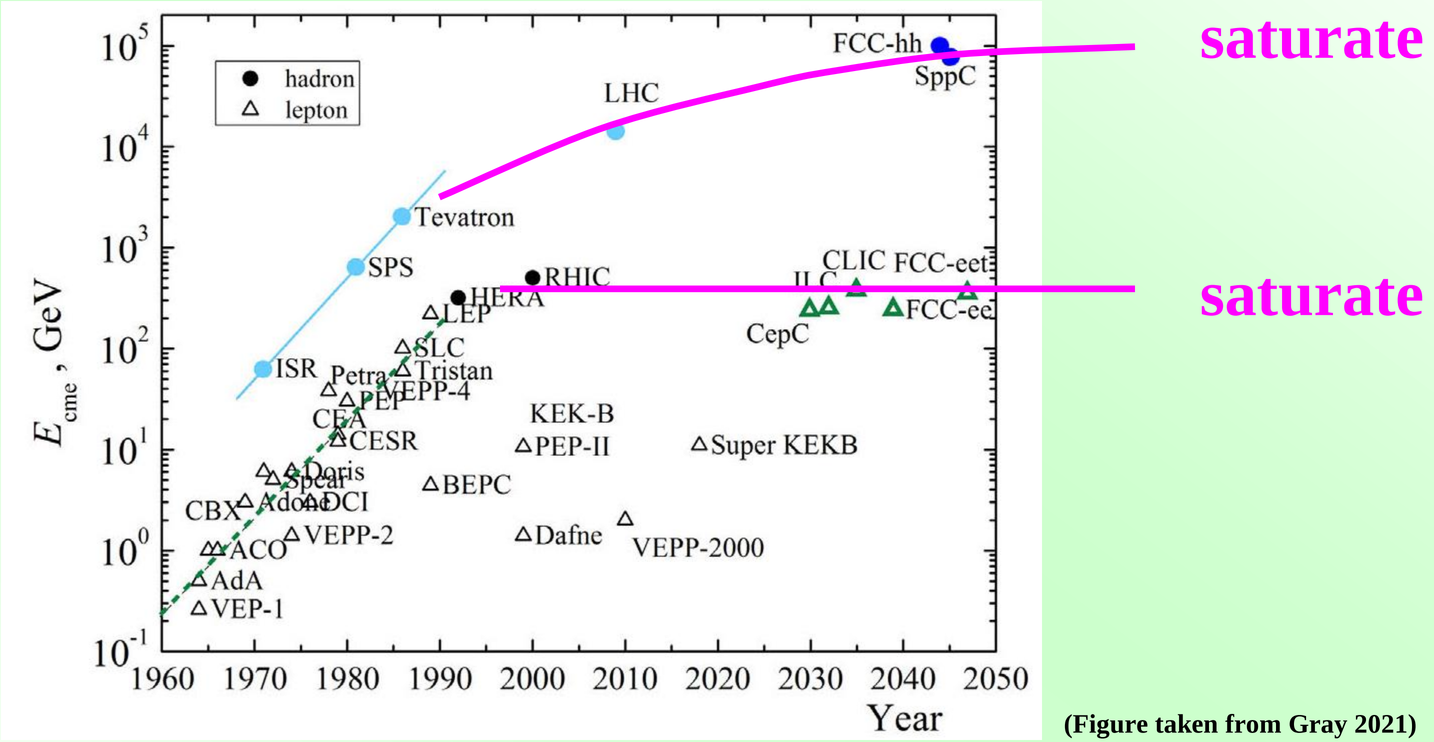
Lucas Pinol, Shuntaro Aoki, Sébastien Renaux-Petel, MY, 2112.0570, PRD107 (2023)2, L21301

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 :**

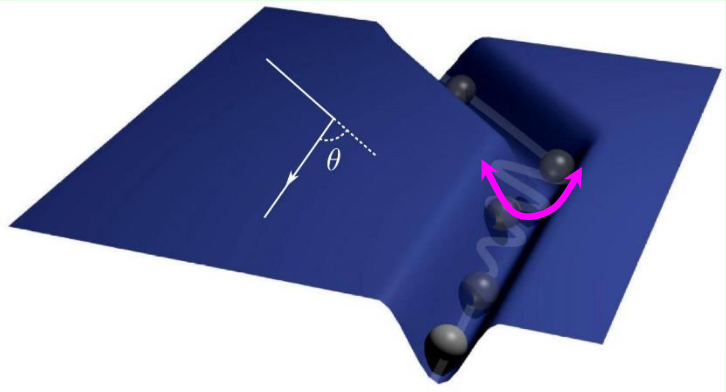
  Powerful to probe "physics with almost fixed Hubble scale" (further exception => genesis?)

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

Heavy particles can be excited during inflation !!

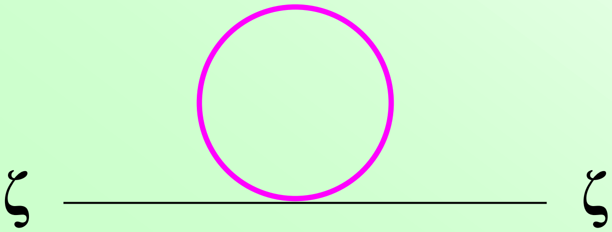
In supergravity and/or superstring theory, there are a lot of fields whose masses are comparable to or larger than the Hubble parameter.

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.

Natural Hubble mass in supergravity

In supergravity,

$V \neq 0$ → **SUSY breaking**

(inflation)

(mediated by gravity)

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 $R\varphi^2$ and dimension 6 operators easily lead to m ~ H) → **Yi's talk**

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 ~ $O(H^2)$

⟸ 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 : $K = \sum_i |\phi_i|^2$

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

$$\begin{aligned} V_F &= \exp\left(\sum_i|\phi_i|^2\right)\times \\ &\quad \left\{\left[\frac{\partial W}{\partial\phi_i}+(\phi_i^*+\cdots)W\right]\sum_{i,j}\left(\delta_{ij}+\cdots\right)\left[\frac{\partial W^*}{\partial\phi_j^*}+(\phi_j+\cdots)W^*\right]-3|W|^2\right\} \\ &= V_{\rm global}+V_{\rm global}\sum_i|\phi_i|^2+\text{other terms}, \end{aligned}$$

$$\left(V_{\rm global}\equiv\sum_i\left|\frac{\partial W}{\partial\phi_i}\right|^2\right)$$

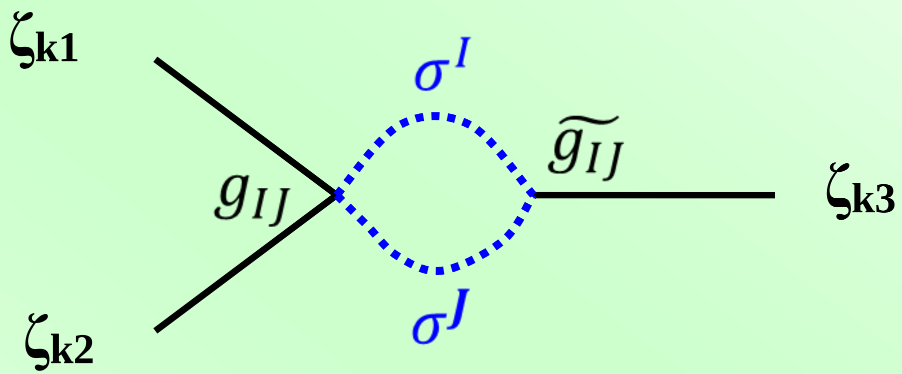
$$m_{i,\rm eff}^2 = m_i^2 + 3H^2$$ $$\left(\longleftarrow \xi\sum_i\phi_i^2R\right)$$ **as well**

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

Multiple isocurvatons σ^I with m ~ H

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

e.g.



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

σ^I (I=1, …, 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

$$\langle \zeta_{\boldsymbol{k}_1}\zeta_{\boldsymbol{k}_2}\zeta_{\boldsymbol{k}_3}\rangle' = (2\pi)^4 \mathcal{P}_\zeta^2 \frac{1}{(k_1k_2k_3)^2} S(k_1,k_2,k_3),$$

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

- **I = J**

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

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

(Boltzman suppression factor)

High frequency

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

- **I≠J**

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

mixing (new effect)

High frequency

low frequency (modulation)

∗ easily distinguished

∗ specific to multi particles

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

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

High frequency

low frequency (modulation)

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

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

The total signal

~ characterized by the low frequency mode (large wavelength)

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

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

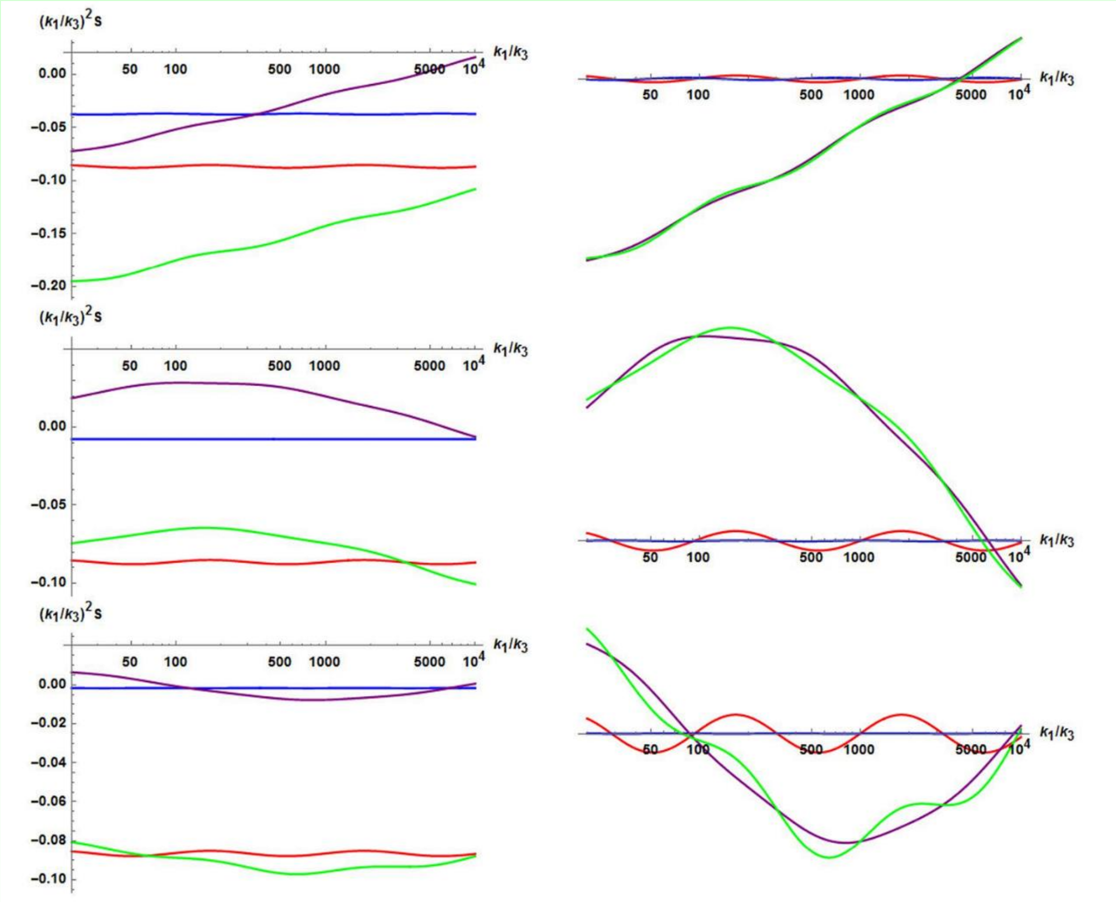


Figure 4. The same figure with figure 2 but the mixing term S_{12} included (purple line). We set $(m_1, m_2)/H = (2, 2.1)$, $(m_1, m_2)/H = (2, 2.3)$, and $(m_1, m_2)/H = (2, 2.5)$ from top to bottom. The couplings are taken universally, $g_{IJ} = \tilde{g}_{IJ} = 1$ for $I, J = 1, 2$. The right figures 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 S12 !!

Small modulations on the large waveform

Easily disentangle the mass spectra

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

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

High frequency

low frequency (modulation)

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

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

⇓

The total signal

~ characterized by the low frequency mode (large wavelength)

$$\mu^I = \sqrt{\frac{m_{I,\mathrm{eff}}^2}{H^2} - \frac{9}{4}}, \quad m_{I,\mathrm{eff}}^2 = m_I^2 + 3H^2 \quad \Rightarrow \quad \mu^I - \mu^J \simeq \frac{2}{\sqrt{3}} \frac{1}{H^2} \left(m_I^2 - m_J^2\right)$$

↖ **from GW ?**

(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)** $g^2|\phi|^2 A_\mu A^\mu, \ \ldots$
- **Yukawa couplings (flavor and mass structure)** $y\phi\overline{\psi}\psi, \ \ldots$
- **potential terms (symmetry breaking pattern)** $\lambda\left(|\phi|^2 - v^2\right)^2, \ \ldots$

…

$f(\phi, \sigma, \partial\sigma, \cdots)$

Non-derivative interactions $\Rightarrow$ **Break shift symmetry (scale invariance)**

- **Axion(-like-particle) interaction,**
- **SUGRA**
- **EFT (but, the cutoff scale is larger than Hubble parameter during inflation),**

…

$f(\partial\phi, \sigma, \partial\sigma, \cdots)$

Derivative (shift-symmetric) interactions often appear as well

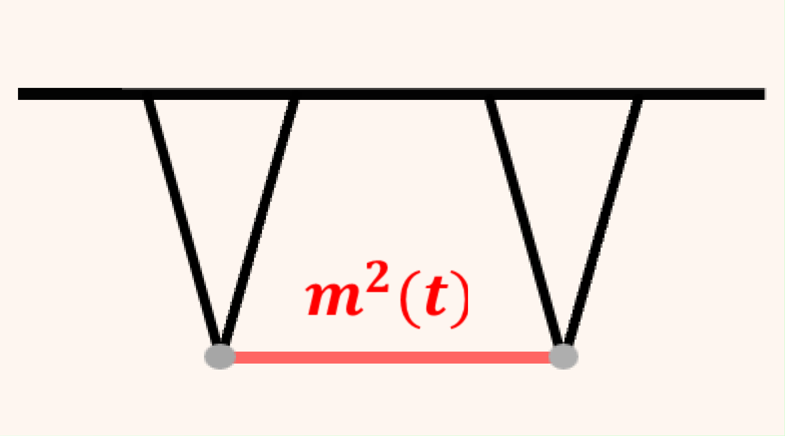
$\Rightarrow$ **Preserve shift symmetry (scale invariance)**

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

Time-dependent mass

σ – φ couplings could lead to an effective mass :

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



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 :

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

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

$$\begin{cases} \phi_0(\tau) = \phi_{0*} - \sqrt{2\epsilon} M_{\rm pl}\left(1 - \dfrac{\tau}{\tau_*}\right) + \cdots \,, \quad \left(\left|1 - \dfrac{\tau}{\tau_*}\right| \ll 1\right) \\ m_{\rm eff}^2(\tau) = g_* - g_{\phi,*}\sqrt{2\epsilon} M_{\rm pl}\underbrace{\left(1 - \dfrac{\tau}{\tau_*}\right)}_{\text{Time dependence}} + \cdots \,, \quad \left(\left|\dfrac{g_{\phi\phi,*} M_{\rm pl}}{g_{\phi,*}}\right| \ll \dfrac{1}{\sqrt{\epsilon}}\right) \end{cases}$$

$$A_* \equiv A(\tau_*)$$

Scale dependence (k τ = -1 : horizon exit)

Sizes of scale dependence

- **Non-derivative interactions :**

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

$$\begin{cases} \phi_0(\tau) = \phi_{0*} - \sqrt{2\epsilon} M_{\rm pl}\left(1 - \dfrac{\tau}{\tau_*}\right) + \cdots \,, \\ m_{\rm eff}^2(\tau) = g_* - g_{\phi,*}\sqrt{2\epsilon} M_{\rm pl}\underline{\left(1 - \dfrac{\tau}{\tau_*}\right)} + \cdots \,, \end{cases}$$

O(ε[1/2]) scale(time) dependence

- **Derivative interactions :**

$$\mathcal{L}_{\rm int} \supset -\frac{1}{2} g((\partial\phi)^2)\sigma^2 \quad \Rightarrow \quad m_{\rm eff}^2 = g\,\underline{\left(\dot\phi_0^2(t)\right)}$$

$$\parallel$$

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

O(ε, η) scale(time) dependence

Mode function and propagators of heavy field

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

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

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

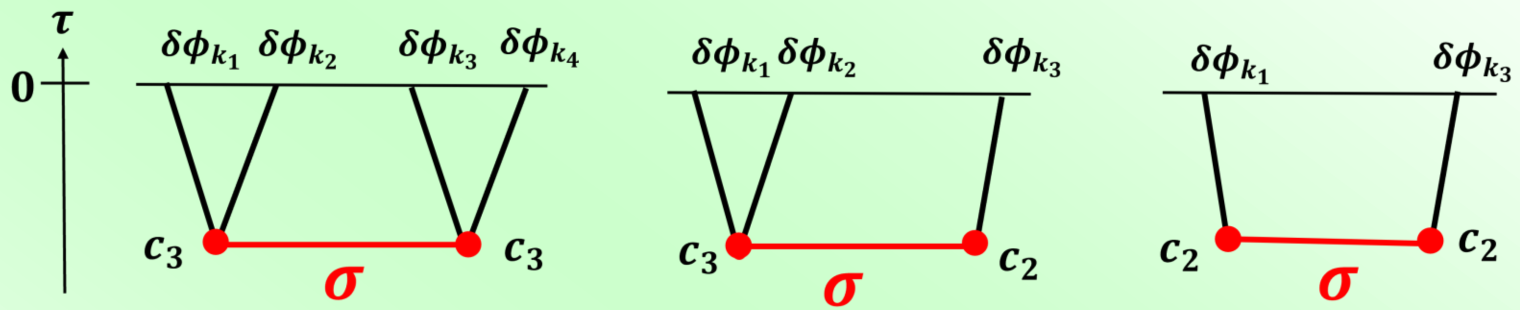
Whittaker function

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

Propagators $\Rightarrow$

$$\begin{cases} D_{+-}(k;\tau_1,\tau_2) = v_k(\tau_1)\, v_k^*(\tau_2) = D_{-+}^*(k;\tau_1,\tau_2) \\ D_{\pm\pm}(k;\tau_1,\tau_2) = D_{\pm\mp}(k;\tau_1,\tau_2)\,\theta(\tau_1 - \tau_2) + D_{\mp\pm}(k;\tau_1,\tau_2)\,\theta(\tau_2 - \tau_1) \end{cases}$$

Inflationary correlators



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

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

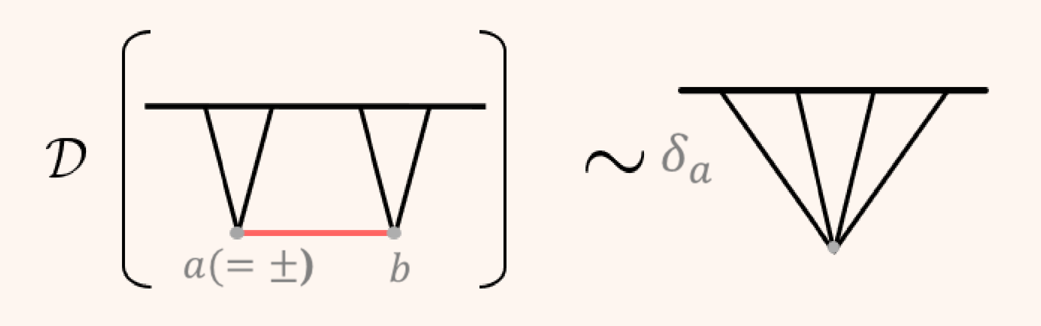
Seed integrals :

$$\mathcal{I}^{p_1p_2}_{\mathrm{ab}} \equiv -\mathrm{ab}k_s^{5+p_{12}} \int_{-\infty}^{0} d\tau_1 \, d\tau_2 \, (-\tau_1)^{p_1} \, (-\tau_2)^{p_2} \, e^{i\mathrm{a}k_{12}\tau_1 + i\mathrm{b}k_{34}\tau_2} D_{\mathrm{ab}}\,(k_s;\tau_1,\tau_2)$$

$$(k_s = |\boldsymbol{k}_1 + \boldsymbol{k}_2|, \ p_{12} = p_1 + p_2, \cdots)$$

e.g. $\langle\zeta^3\rangle \propto c_2 c_3 H \cdot \dfrac{1}{8k_1k_2k_3^4} \lim\limits_{k_4\to 0} \sum\limits_{\mathrm{a,b}=\pm} \mathcal{I}^{0,-2}_{\mathrm{ab}} + 2\mathrm{perm.}$

Bootstrap equations



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

$$\begin{cases} \mathcal{D}^{p_1}_{\pm,u_1}\mathcal{I}^{p_1p_2}_{\pm\mp} = 0, \\ \mathcal{D}^{p_1}_{\pm,u_1}\mathcal{I}^{p_1p_2}_{\pm\pm} = H^2 e^{\mp \mathrm{i} p_{12}\frac{\pi}{2}}\Gamma\left(5+p_{12}\right)\left(\dfrac{u_1u_2}{2\left(u_1+u_2-u_1u_2\right)}\right)^{5+p_{12}}, \end{cases}$$

We can solve these equations analytically !!

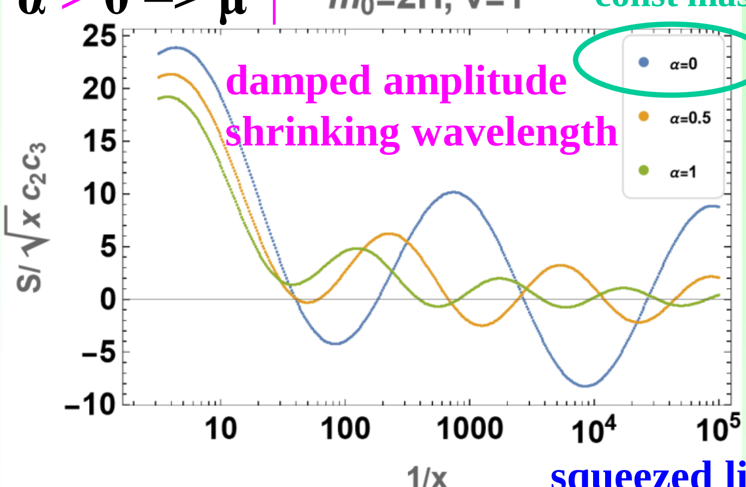
Observational signals

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

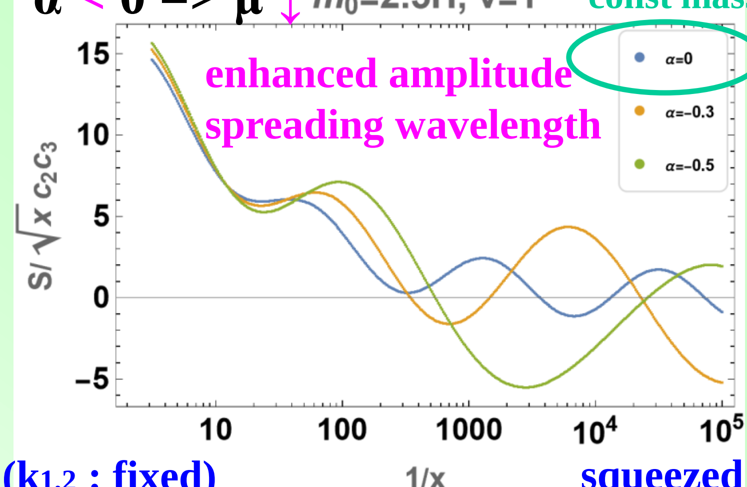
Shape function S : $\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle \equiv (2\pi)^7\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\frac{P_\zeta^2}{(k_1k_2k_3)^2}S$

$$\Rightarrow \quad S = \frac{1}{(2\pi)^4}\cdot\frac{1}{P_\zeta^2}\cdot(2\epsilon M_{\rm pl}^2)^{-\frac{3}{2}}\cdot(-2c_2c_3)\cdot\frac{H}{8}\sum_{\rm a,b=\pm}\left[\frac{k_1k_2}{k_3^2}\mathcal{I}_{\rm ab}^{0,-2}\left(\frac{2k_3}{k_{123}},1\right)+2\text{per.}\right]$$

α > 0 => μ ↑ $\quad$ const mass



α < 0 => μ ↓ $\quad$ const mass

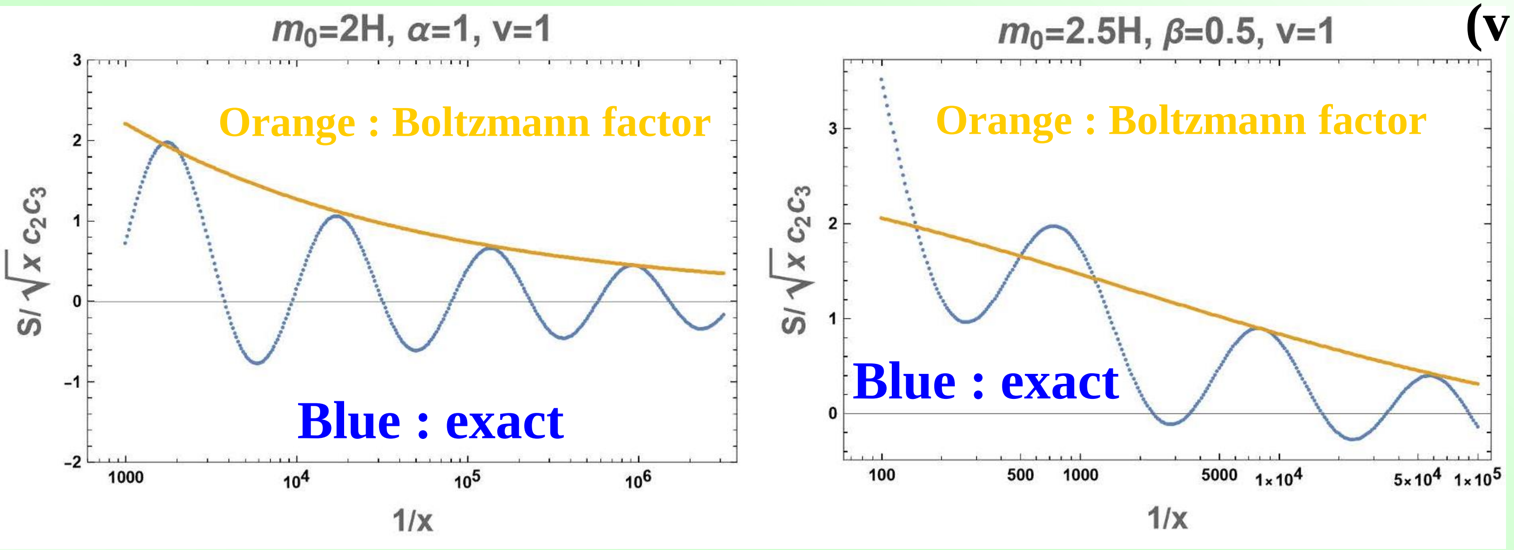


squeezed limit ($k_{1,2}$: fixed) $\quad$ squeezed limit

In the squeezed limit x = k3 / k1,2 << 1, $\quad S/\sqrt{x} \sim e^{-\pi\mu(x)}x^{\pm i\mu(x)} + \text{c.c.},$

Observational signals II

$(v = k_1 / k_0)$



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

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

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

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

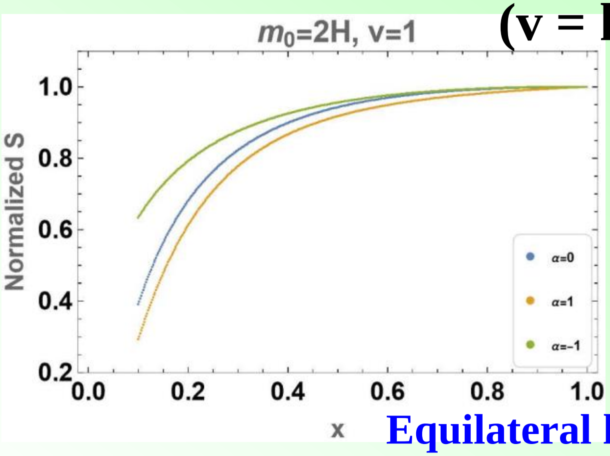
In principle, we can discriminate them, but …

Observational signals III

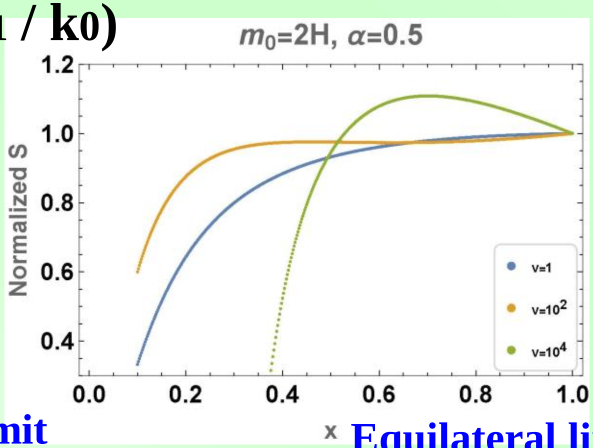
Concrete example : $g(\phi) = m_0^2 \left(1 + \alpha \frac{\phi}{M_{\rm pl}}\right)$ $\quad m_{\rm eff}^2 = g\left(\phi_0(t)\right)$

$f_{\rm NL}^{\rm equi} \sim c_2 c_3 \times \mathcal{O}\left(10\right)$ **for α = O(1), m_0 = O(H)**

($v = k_1 / k_0$)

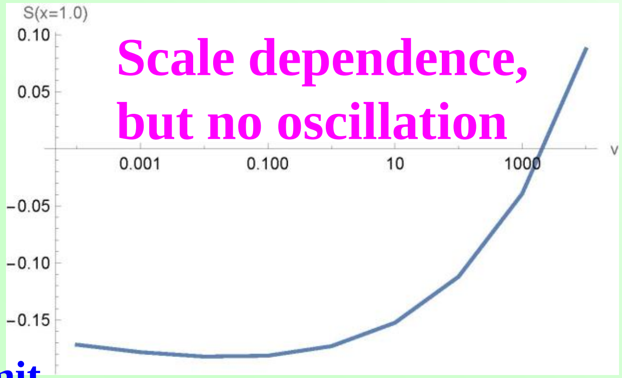


Equilateral limit
$x = k_3 / k_{1,2}$ => 1



Equilateral limit
$x = k_3 / k_{1,2}$ => 1

Equilateral limit x = 1



Scale dependence, but no oscillation

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.**